QCD@LHC:
challenges and opportunities in heavy flavor production

Laura Reina

Anticipating Physics at the LHC, KITP, June 2008

- The Large Hadron Collider (LHC) will test new ground and answer some of the fundamental open questions of Particle Physics:
  $\longrightarrow$ Electroweak (EW) symmetry breaking: Higgs mechanism?
  $\longrightarrow$ New Physics (NP) in the TeV range?
  $\longrightarrow$ ...

- The incredible physics potential of the LHC relies on our ability of providing very accurate QCD predictions:
  $\longrightarrow$ Discovery: precise prediction of signals/backgrounds;
  $\longrightarrow$ Identification: precise extraction of parameters (α_s, m_t, M_H, $y_{t,b}$, M_X, y_X, ...);
  $\longrightarrow$ Precision: $\sigma_{W/Z}$ as parton luminosity monitors (PDF's), ...

- Heavy Quark production w/o associated particles crucial to control:
  $\longrightarrow$ top/bottom-quark properties;
  $\longrightarrow$ signatures involving hard (b)-jets, multi-leptons and missing E_T (background to new physics signatures).

Think of: $t\bar{t}$, $t\bar{t}+H$, $b\bar{b}+H$, $b\bar{b}+W/Z$, $t\bar{t}+W/Z$, $t\bar{t}b\bar{b}$, $t\bar{t}WW/ZZ$, ...

Outline

- Overview of precision QCD for the LHC ($\longrightarrow$ see Zvi Bern's talk).
- Focusing on Heavy Quark physics:
  $\longrightarrow$ toward a precise prediction of $Q\bar{Q}$ production;
  $\longrightarrow$ heavy quark production with weak gauge bosons: $Wb\bar{b}$, $Zb\bar{b}$;
  $\longrightarrow$ heavy quark production with Higgs bosons: $Ht\bar{t}$, $Hb\bar{b}$;

  physical impact, theoretical progress and perspectives.
- Conclusions and outlook

State of the art of QCD calculations

for hadronic processes

Relative order	$2 \to 1$	$2 \to 2$	$2 \to 3$	$2 \to 4$	$2 \to 5$	$2 \to 6$
1	LO					
α_s	NLO	LO				
α_s^2	NNLO	NLO	LO			
α_s^3		NNLO	NLO	LO		
α_s^4			NNLO	NLO	LO	
α_s^5				NNLO	NLO	LO

(from N. Glover)

Green light $\longrightarrow$ Done!

Red light $\longrightarrow$ Still work in progress!

NLO: $V + 2j$ $(V = Z, W)$, $V + b\bar{b}/t\bar{t}$, $VV + j$, VVV, $H + 2j$, $Ht\bar{t}/b\bar{b}$, $t\bar{t} + j$, ...

NNLO: recent progress in $2 \to 2$ (Czakon, Mitov, Moch: $q\bar{q}, gg \to Q\bar{Q}$ at $O(m_Q^2/s)$ (07-08), Chachamis,Czakon: $q\bar{q} \to W^+W^-$ at $O(m_W^2/s)$ (08))

(plus: NNLO splitting functions (Moch,Vermaseren,Vogt (04))).

Why pushing the Loop Order . . .

- Stability and predictivity of theoretical results, since less sensitivity to unphysical renormalization/factorization scales. First reliable normalization of total cross-sections and distributions. Crucial for:
  $\longrightarrow$ precision measurements (M_W, m_t, M_H, $y_{b,t}$, ...);
  $\longrightarrow$ searches of new physics (precise modelling of signal and background);
  $\longrightarrow$ reducing systematic errors in selection/analysis of data.

- Physics richness: more channels and more partons in final state, i.e. more structure to better model (in perturbative region):
  $\longrightarrow$ differential cross-sections, exclusive observables;
  $\longrightarrow$ jet formation/merging and hadronization;
  $\longrightarrow$ initial state radiation.

- First step towards matching with algorithms that resum particular sets of large corrections in the perturbative expansion: resummed calculations, parton shower Monte Carlo programs.

Main challenges . . .

- Multiplicity and Massiveness of final state: complex events leads to complex calculations. For a $2 \to N$ process one needs:
  - $\longrightarrow$ calculation of the $2 \to N+1$ (NLO) or $2 \to N+2$ real corrections;
  - $\longrightarrow$ calculation of the 1-loop (NLO) or 2-loop (NNLO) $2 \to N$ virtual corrections;
  - $\longrightarrow$ explicit cancellation of IR divergences (UV-cancellation is standard).

- Flexibility of NLO/NNLO calculations via Automation:
  - $\longrightarrow$ algorithms suitable for automation are more efficient and force the adoption of standards;
  - $\longrightarrow$ faster response to experimental needs (think to the impact of projects like MCFM).

- Matching to Parton Shower Monte Carlos.
  - $\longrightarrow$ MC@NLO (Frixione,Webber)
  - $\longrightarrow$ POWHEG (Nason)

- NLO: challenges have largely been faced and enormous progress has been made. From Zvi Bern's talk:

  - $\longrightarrow$ traditional approach (FD's) becomes impracticable at high multiplicity;
  - $\longrightarrow$ new techniques based on unitarity methods and recursion relations offers a powerful and promising alternative, particularly suited for automation;
  - $\longrightarrow$ interface to parton shower well advanced.

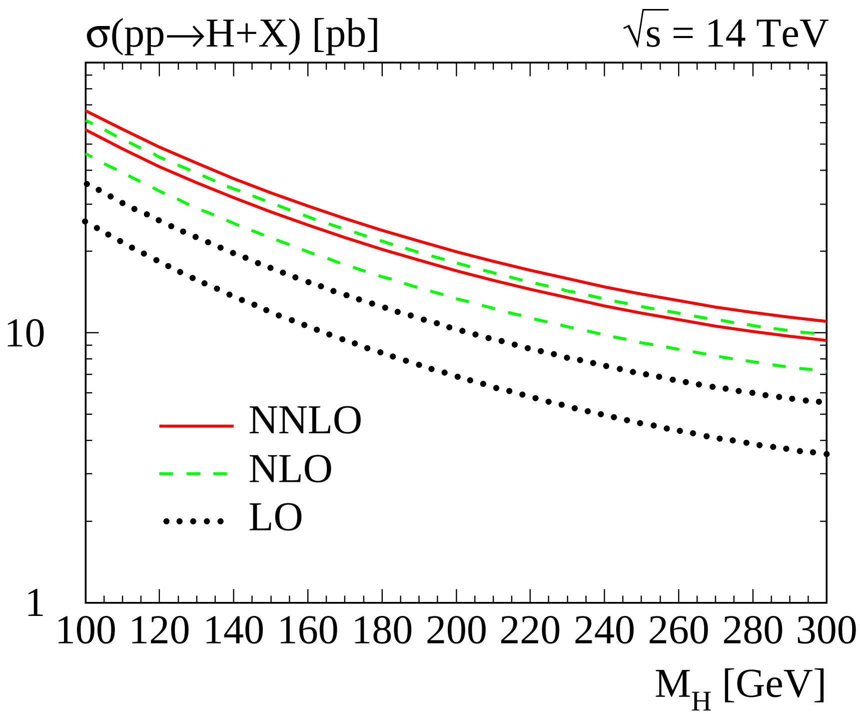
- When is NLO not enough?

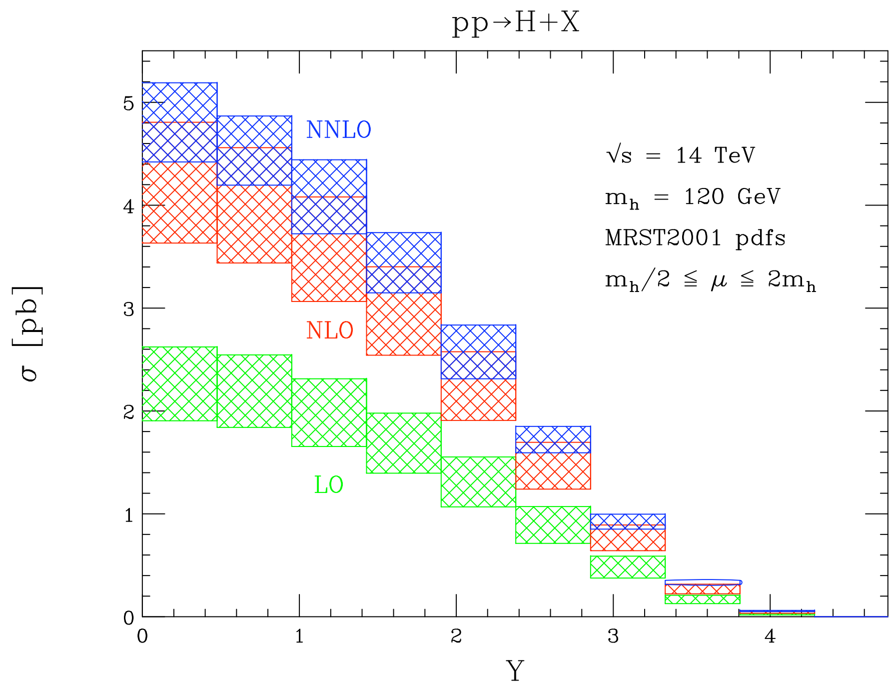
  - $\longrightarrow$ When NLO corrections are large, to tests the convergence of the perturbative expansion. This may happen when:
    - ▷ processes involve multiple scales, leading to large logarithms of the ratio(s) of scales;
    - ▷ new parton level subprocesses first appear at NLO;
    - ▷ new dynamics first appear at NLO;
    - ▷ ...
  - $\longrightarrow$ When truly high precision is needed (very often the case!).
  - $\longrightarrow$ When a really reliable error estimate is needed.

Ex. 1: $gg \to H$ production at the Tevatron and LHC

Harlander, Kilgore (03)

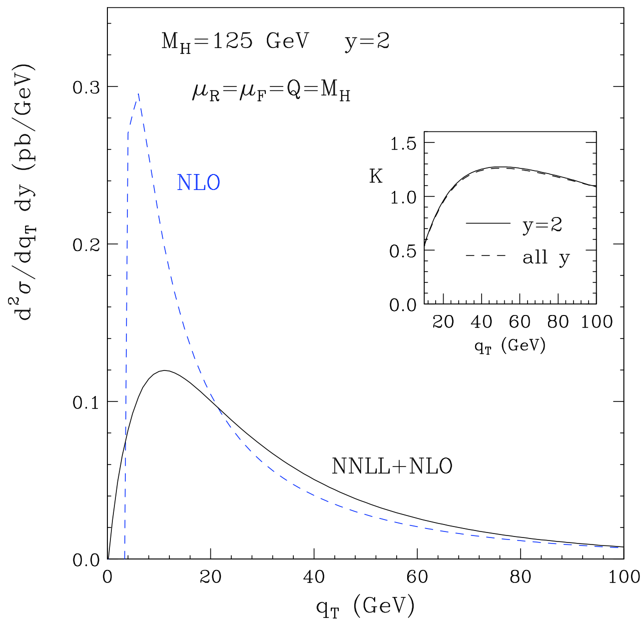
Anastasiou, Melnikov, Petriello (03)





- dominant production mode in association with $H \to \gamma\gamma$ or $H \to WW$ or $H \to ZZ$;
- dominated by soft dynamics: effective ggH vertex can be used ($3 \to 2$-loop);
- perturbative convergence LO $\to$ NLO (70%) $\to$ NNLO (30%): residual 10% theoretical uncertainty.

Inclusive cross section, resum effects of soft radiation:



large $q_T \xrightarrow{q_T > M_H}$ perturbative expansion in $\alpha_s(\mu)$

small $q_T \xrightarrow{q_T \ll M_H}$ need to resum large $\ln(M_H^2/q_T^2)$

Bozzi,Catani,de Florian,Grazzini (04-08)

Exclusive NNLO results: e.g. $gg \to H \to \gamma\gamma, WW, ZZ$

Extension of (IR safe) subtraction method to NNLO:

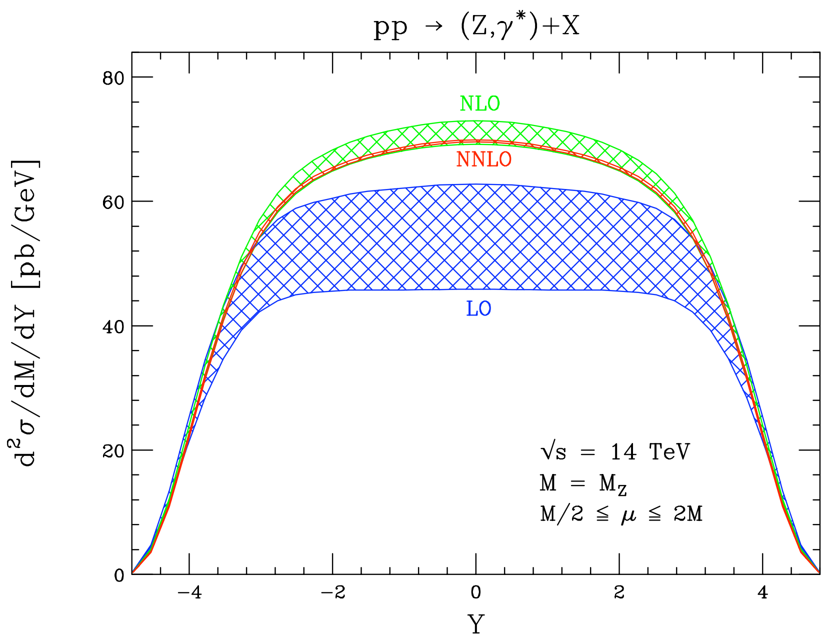
$\longrightarrow$ HNNLO (Catani,Grazzini)

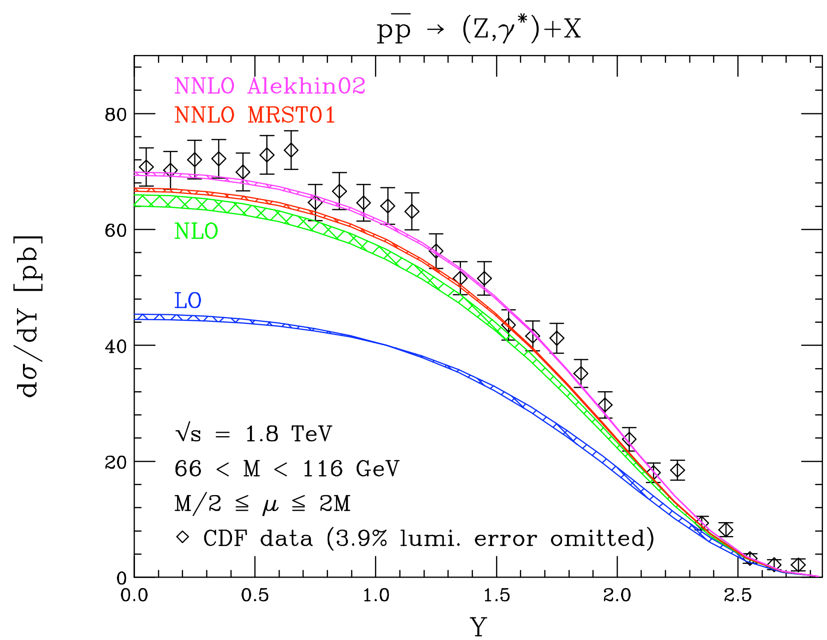
$\longrightarrow$ FEHiP (Anastasiou,Melnikov,Petriello)

Ex. 2: W/Z production at the Tevatron and LHC.

Anastasiou, Dixon, Melnikov, Petriello (03)

Rapidity distributions of W and Z boson calculated at NNLO:





- W/Z production processes are standard candles at hadron colliders.
- Testing NNLO PDF's: parton-parton luminosity monitor, detector calibration (NNLO: 1% residual theoretical uncertainty).

Ex. 3: $Q\bar{Q}$ production at the Tevatron and LHC

- NNLO: both $q\bar{q} \to Q\bar{Q}$ and $gg \to Q\bar{Q}$ channels calculated at $O(m_Q^2/s)$. Neglected terms may be large for $t\bar{t}$ production ($\to$ work in progress)

Czakon,Mitov,Moch (07-08)

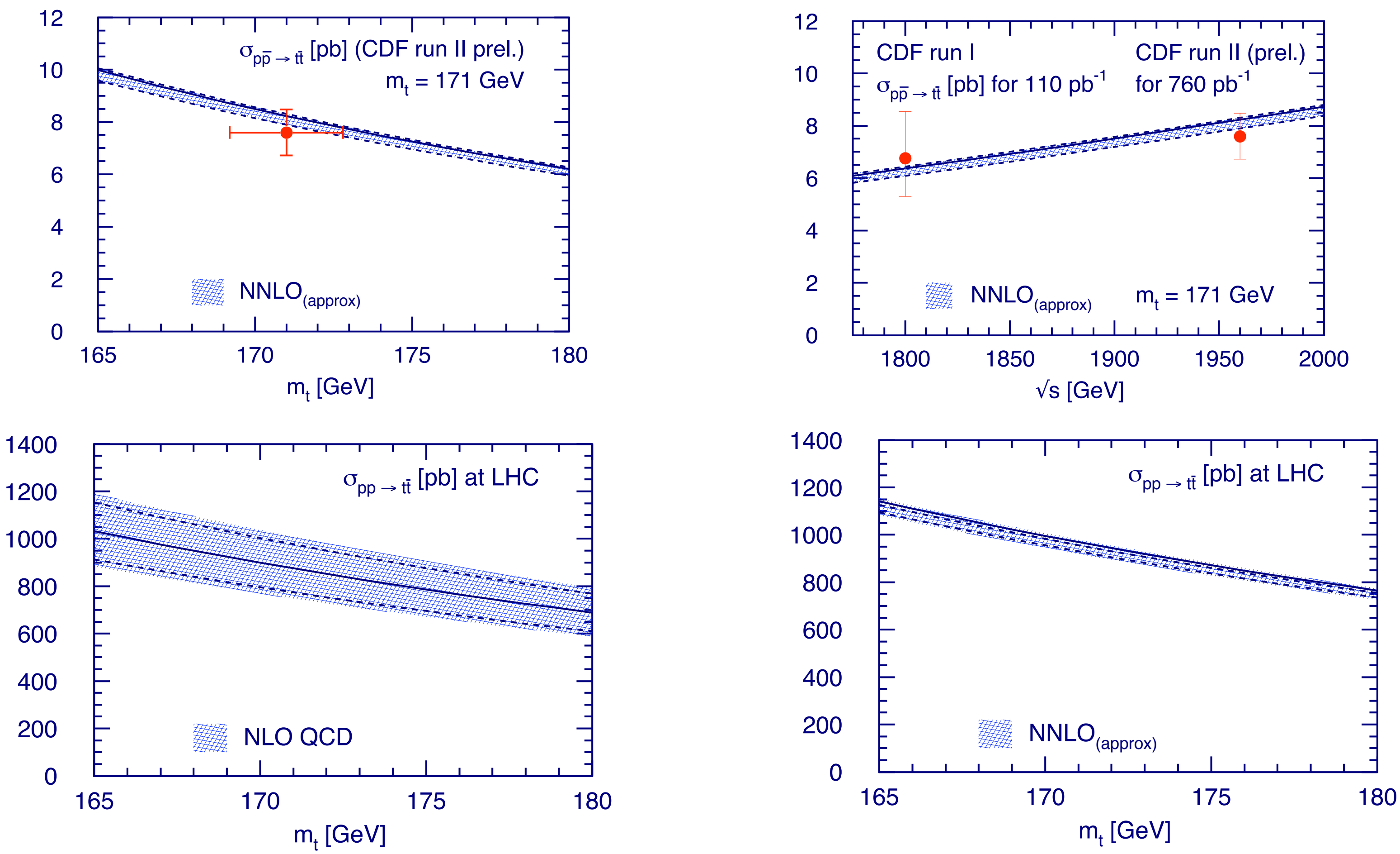
- NLL-NLO: resumming soft threshold corrections
$\sigma_{t\bar{t}}^{NLO+NLL}(m_t = 171\,\mathrm{GeV}, \mathrm{CTEQ6.5}) = 908^{+82(9\%)}_{-85(9.3\%)}(\mathrm{scales})^{+30(3.3\%)}_{-29(3.2\%)}(\mathrm{PDFs})$ pb
$\sigma_{t\bar{t}}^{NLO+NLL}(m_t = 171\,\mathrm{GeV}, \mathrm{MSTW2006nnlo}) = 961^{+89(9.2\%)}_{-91(9.4\%)}(\mathrm{scales})^{+11(1.1\%)}_{-12(1.2\%)}(\mathrm{PDFs})$ pb

Cacciari,Frixione,Mangano,Nason Ridolfi (08)

- NNLOapprox: NNLL truncated at $O(\alpha_s^4) \to$ exact NLO plus exact 2-loop threshold logarithms and scale dependence.

Moch,Uwer (08)

Kidonakis,Vogt (08)



Moch, Uwer (08)

At the LHC:

$\longrightarrow$ theoretical precision: $4-6\%$ (possible indirect determination of m_t);

$\longrightarrow$ $t\bar{t}$ production additional calibration process for parton luminosity.

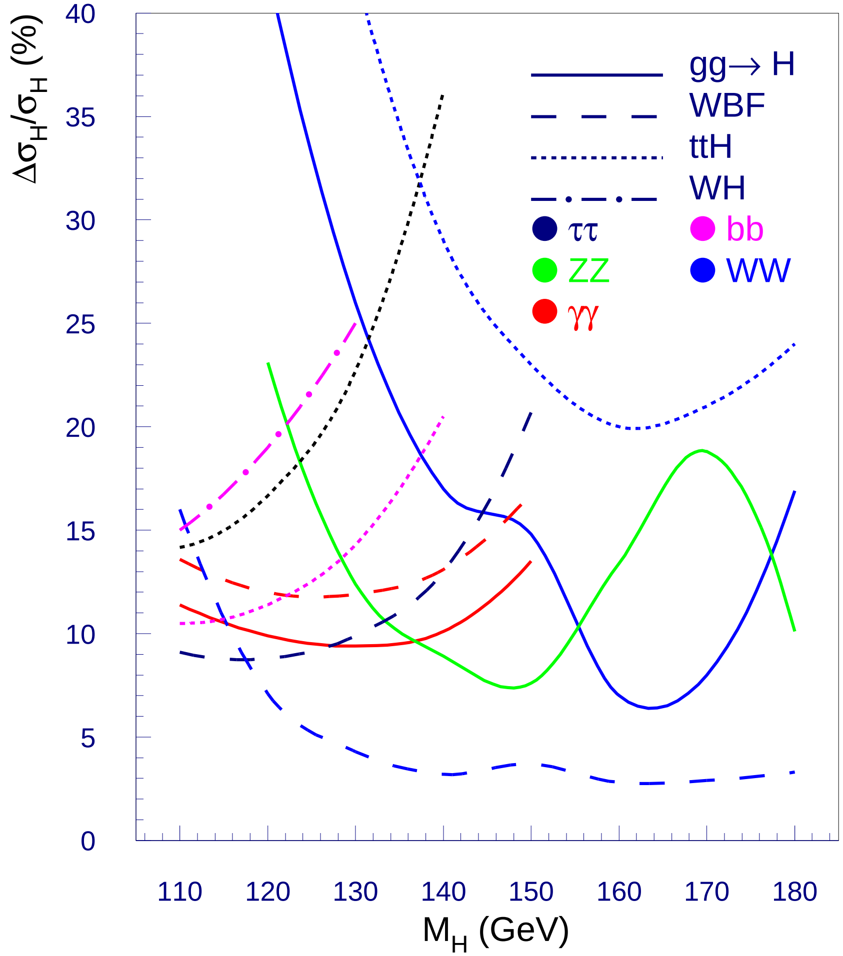
$Q\bar{Q}$ associated production of with a Higgs boson

- Motivations
  - ▷ $Ht\bar{t}$: important channel when $H \to \gamma\gamma$ ($H \to b\bar{b}$?);
  - ▷ $Ht\bar{t}$: instrumental to Higgs couplings determination;
  - ▷ $Hb\bar{b}$: direct evidence of new physics.
- Interesting aspects of the NLO calculation.
- Results.

(in collaboration with S.Dawson, C.B.Jackson, L.Orr, D.Wackeroth)

$pp \to t\bar{t}H$: unique direct measurement of top Yukawa coupling

Probably not a discovery mode, but crucial in the Higgs coupling game.



$\longleftarrow$ mostly $200\,\mathrm{fb}^{-1}$

- Below 130-140 GeV

  $gg \to H\ ,\ H \to \gamma\gamma, WW, ZZ$

  $qq \to qqH\ ,\ H \to \gamma\gamma, WW, ZZ, \tau\tau$

  $q\bar{q}, gg \to t\bar{t}H\ ,\ H \to b\bar{b}, \tau\tau$

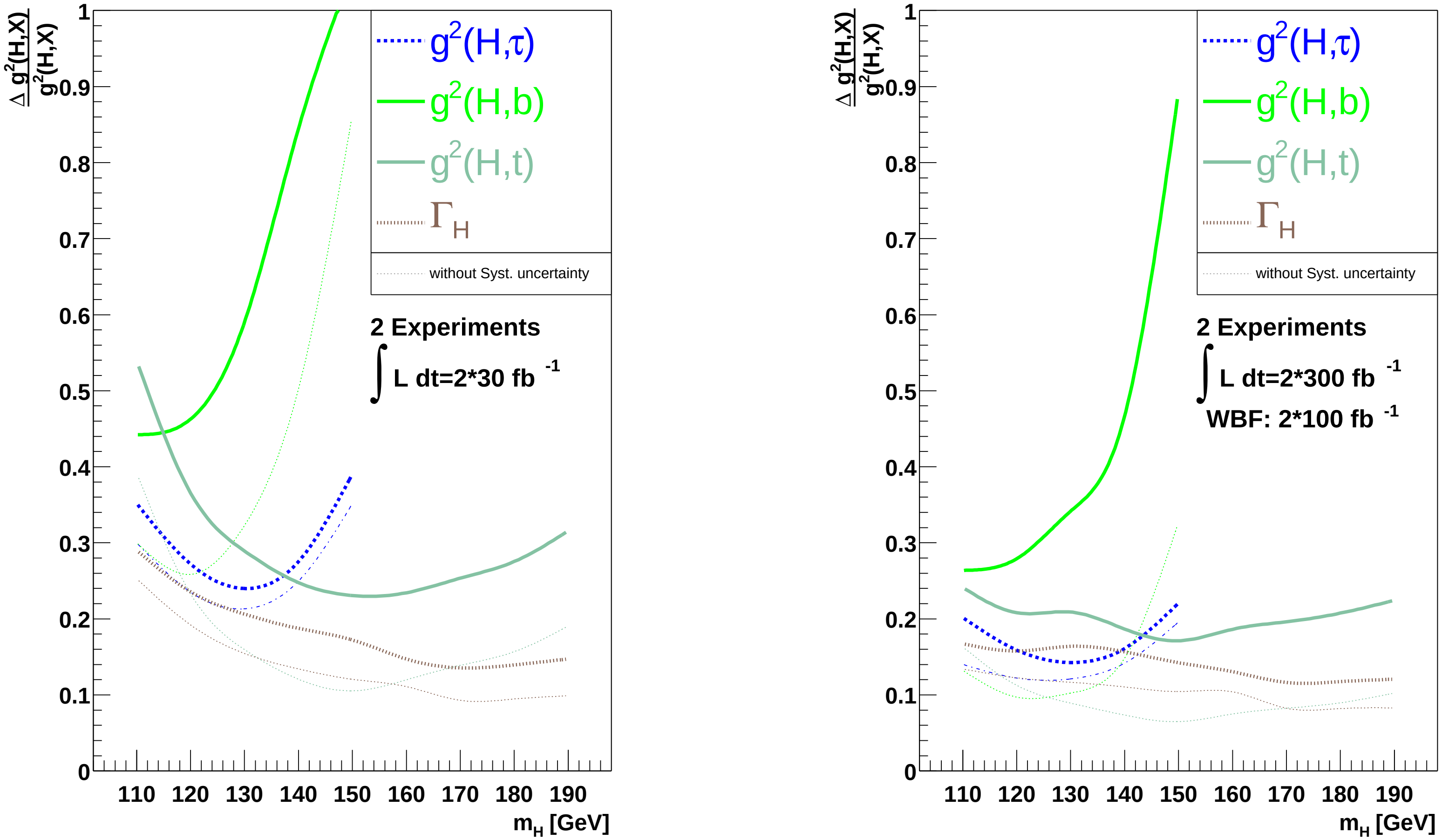
- Above 130-140 GeV

  $gg \to H\ ,\ H \to WW, ZZ$

  $qq \to qqH\ ,\ H \to \gamma\gamma, WW, ZZ$

  $q\bar{q}, gg \to t\bar{t}H\ ,\ H \to WW$

$t\bar{t}H$: F.Maltoni, D.Rainwater, S.Willenbrock, A.Belyaev, L.R.



Global χ^2 fit assuming

$\longrightarrow\ g^2(H,V) < g^2(H,V,SM) \pm 5\%\quad (V = W, Z)$

$\longrightarrow\ g^2(H,W)/g^2(H,Z) = g^2(H,W)/g^2(H,Z) \pm 1\%$

$\longrightarrow$ no new particles in loop production/decay modes

M.Dührssen, S.Heinemeyer, H.Logan, D.Rainwater, G.Weiglein, D.Zeppenfeld (04)

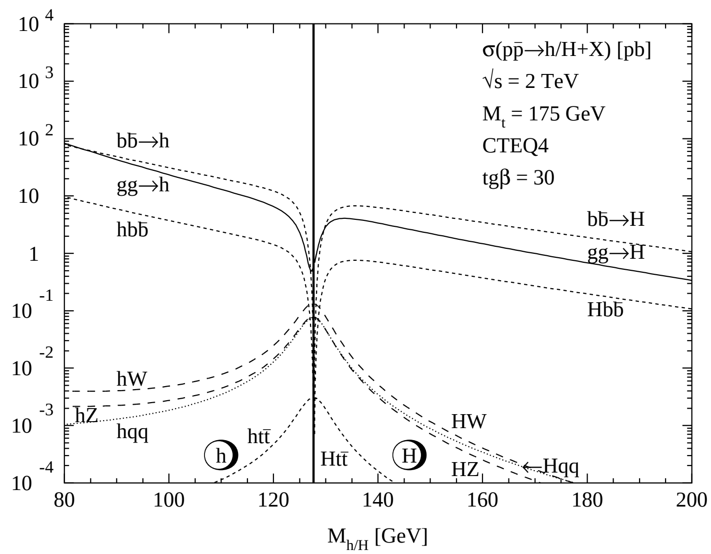
$p\bar{p}, pp \longrightarrow b\bar{b}H$ important as a signal of new physics

Example: in the MSSM the bottom-quark Yukawa coupling can be enhanced with respect to the Standard Model:

$$g^{MSSM}_{b\bar{b}h^0,H^0} = \frac{(-\sin\alpha, \cos\alpha)}{\cos\beta} g_{b\bar{b}H} \quad \text{and} \quad g^{MSSM}_{b\bar{b}A^0} = \tan\beta \; g_{b\bar{b}H}$$

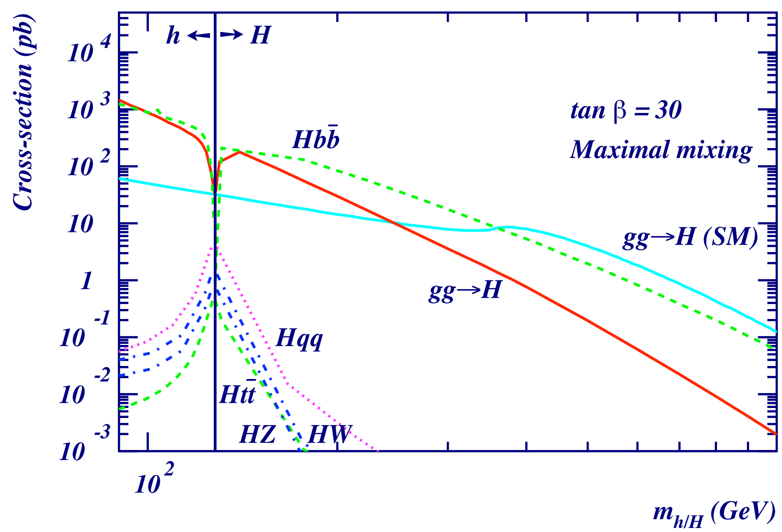
where $g_{b\bar{b}H} = m_b/v \simeq 0.02$ (Standard Model) and $\tan\beta = v_1/v_2$ (MSSM).

Tevatron



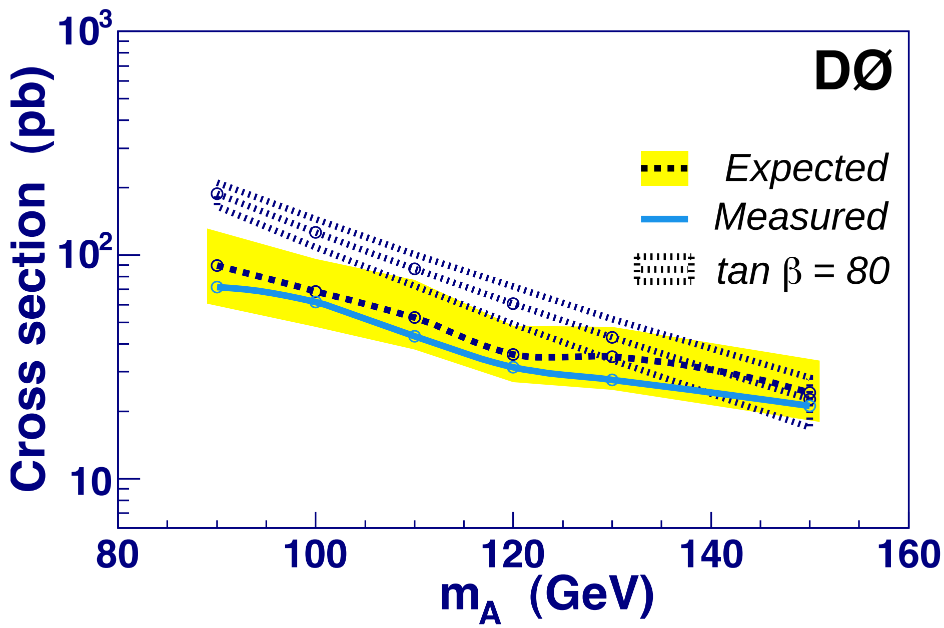
M.Spira

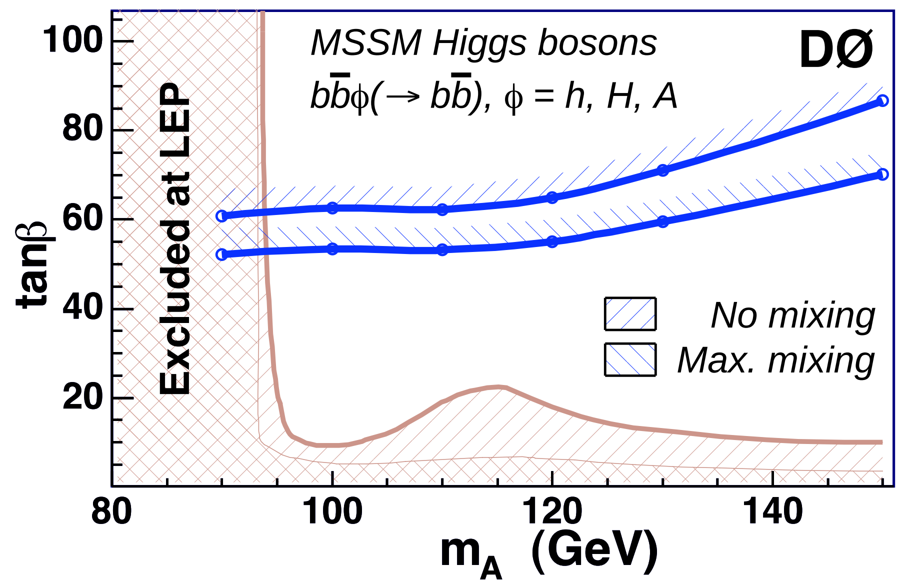
LHC



M.Carena and H.Haber

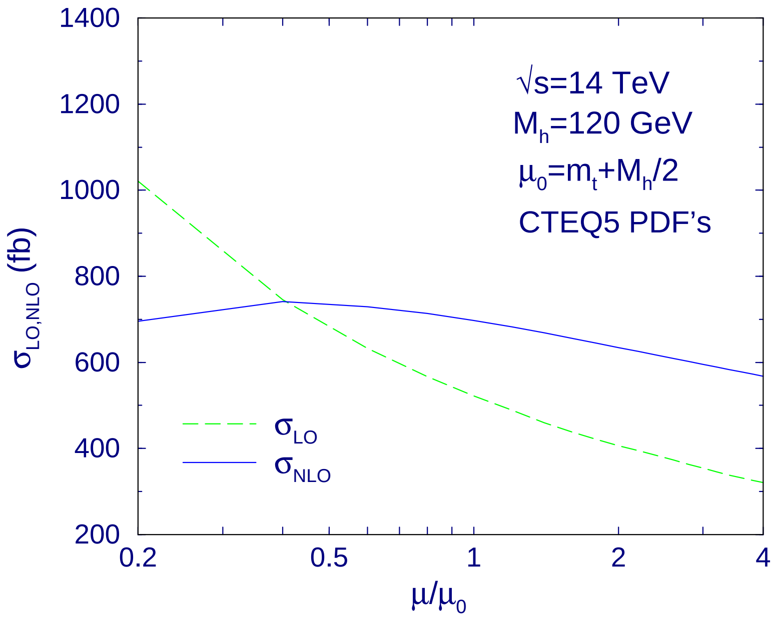
Tevatron searches: DØ Run II data with 3 b-tagged events (PRL 95 (2005) 151801)

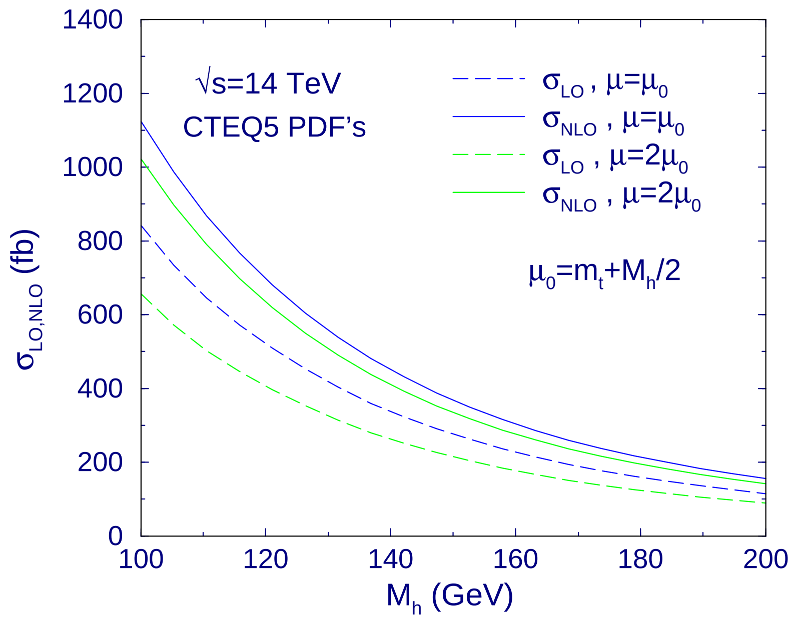




Significant region of the MSSM parameter space can be excluded

LHC, $pp \to t\bar{t}H$: NLO cross section





Dawson, Jackson, Orr, L.R., Wackeroth

$\longrightarrow$ Fully massive $2 \to 3$ calculation: testing the limit of FD's approach (pentagon diagrams with massive particles).

$\longrightarrow$ Independent calculation: Beenakker et al., full agreement.

$\longrightarrow$ Theoretical uncertainty reduced to about 15%

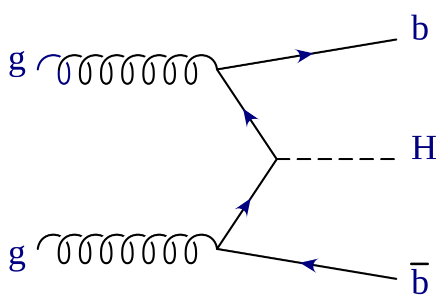
$\longrightarrow$ Several crucial backgrounds: $t\bar{t}+j$ (NLO, Dittmaier,Uwer,Weinzierl), $t\bar{t}b\bar{b}$, $t\bar{t}+2j$, $VV+b\bar{b}$.

$p\bar{p}, pp \longrightarrow b\bar{b}H$: exclusive vs inclusive cross section

- b-quarks identification requires tagging (p_T^b and η^b cuts): exclusive (1 b-,2 b-tags) vs inclusive (1 b-,0 b-tags) cross section.

- Exclusive modes have smaller cross section, but also smaller background and they measure the bottom-quark Yukawa coupling unambiguously.

- Inclusive modes enhanced by large collinear $\ln(\mu_H^2/m_b^2)$ arising in the PS integration of untagged b-quarks in $gg \longrightarrow b\bar{b}H$



$\longrightarrow$ large collinear logs ($g \rightarrow b\bar{b}$)
regulated by m_b

They can be resummed by introducing a b-quark PDF:

$$b(x,\mu) = \frac{\alpha_s(\mu)}{2\pi} \log\left(\frac{\mu^2}{m_b^2}\right) \int_x^1 \frac{dy}{y} P_{qg}\left(\frac{x}{y}\right) g(y,\mu)$$

- Semi-inclusive and inclusive cross sections: 2 approaches

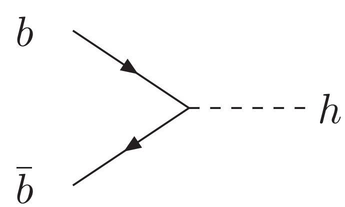
$\longrightarrow$ Use $q\bar{q}, gg \to b\bar{b}h$ (at NLO) $\longrightarrow$ 4FNS

imposing tagging cuts on only one or no final state b quarks.

$\longrightarrow$ Use b-quark PDF, resumming the large collinear logs $\longrightarrow$ 5FNS

$\longrightarrow$ 1 b-tag

$(bg \to bH)$



$\longrightarrow$ 0 b-tags

$(b\bar{b} \to H)$

Perturbative series ordered in Leading and SubLeading powers of $\alpha_s \ln(\mu_H^2/m_b^2)$.

$\longrightarrow$ Expect consistence at higher order when comparing $q\bar{q}, gg \to b\bar{b}H$ (NLO) to

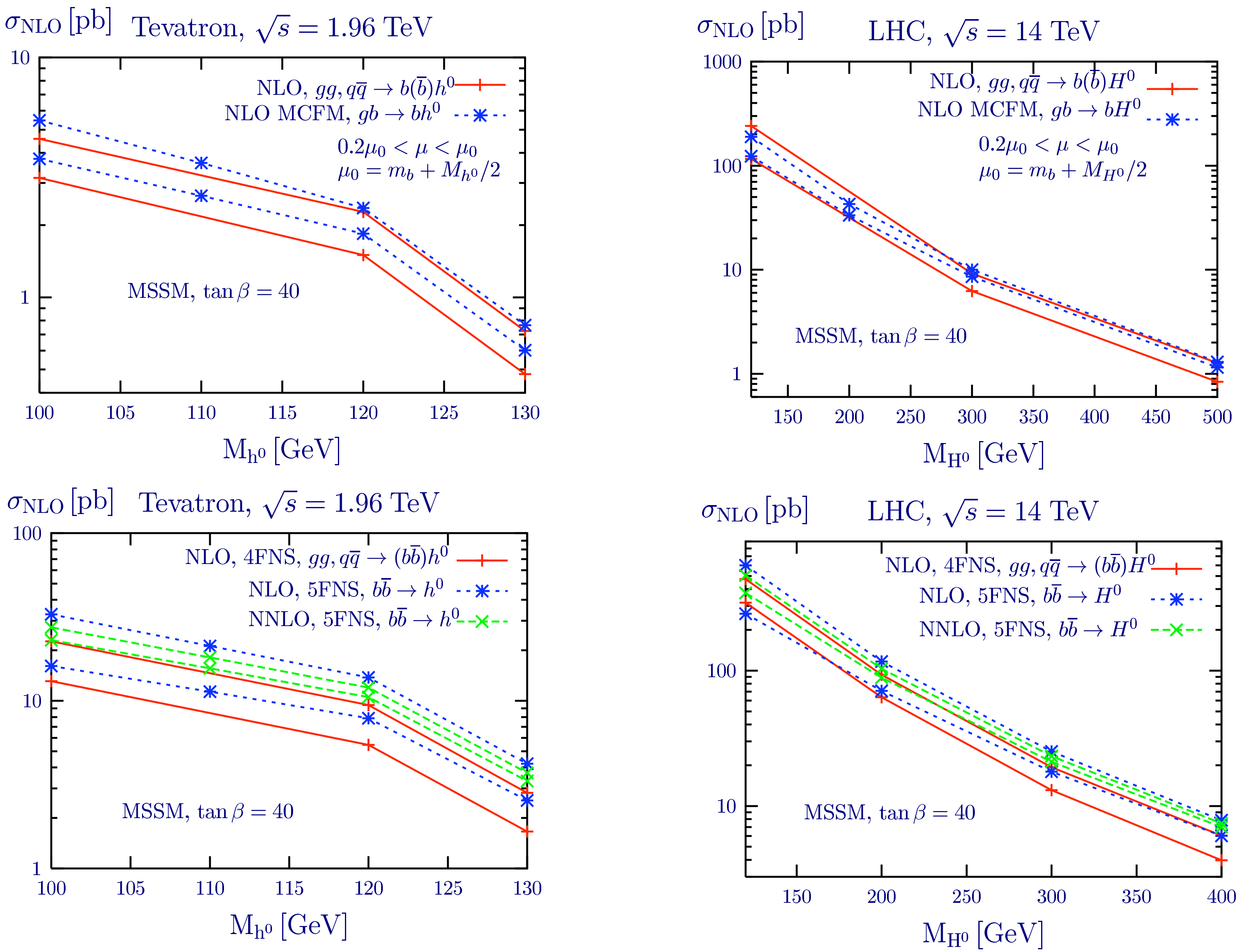
- $b\bar{b} \to H$ (NNLO) (no b-tag)

  (R.Harlander, W.Kilgore; D.Dicus, T.Stelzer, Z.Sullivan, S.Willenbrock)

- $bg \to bH$ (NLO) (one b-tag)

  (J.Campbell, R.K.Ellis, F.Maltoni, S.Willenbrock)

Inclusive cross sections in the MSSM: 4FNS vs 5FNS



Dawson, Jackson, L.R., Wackeroth

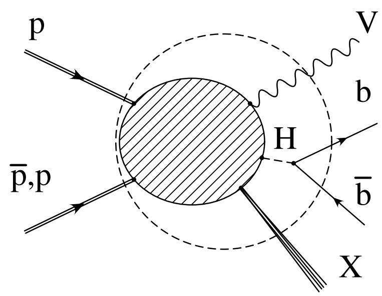
$Q\bar{Q}$ associated production of with weak vector bosons

- Motivations:
  - ▷ $W/Zb\bar{b}$: main background to W/ZH production;
  - ▷ $Wb\bar{b}$: main background to single-top production;
  - ▷ $Wb\bar{b}$: background to $t\bar{t}$ production;
  - ▷ $Zb\bar{b}$: background to beyond the SM discoveries: $(H, A)b\bar{b}$, ...;
  - ▷ access to: b-quark PDF, b-tagging studies, ...
  - ▷ $Zt\bar{t}$: direct measurement of t-quark weak couplings;
  - ▷ $Zt\bar{t}$: background to new physics signatures (ex.: tri-lepton events).

- NLO $2 \rightarrow 3$ calculation with $m_Q \neq 0$: interesting test of new unitarity methods.
- Results.

  (in collaboration with F. Febres Cordero, and D. Wackeroth)

Associated production of SM Higgs with weak vector bosons

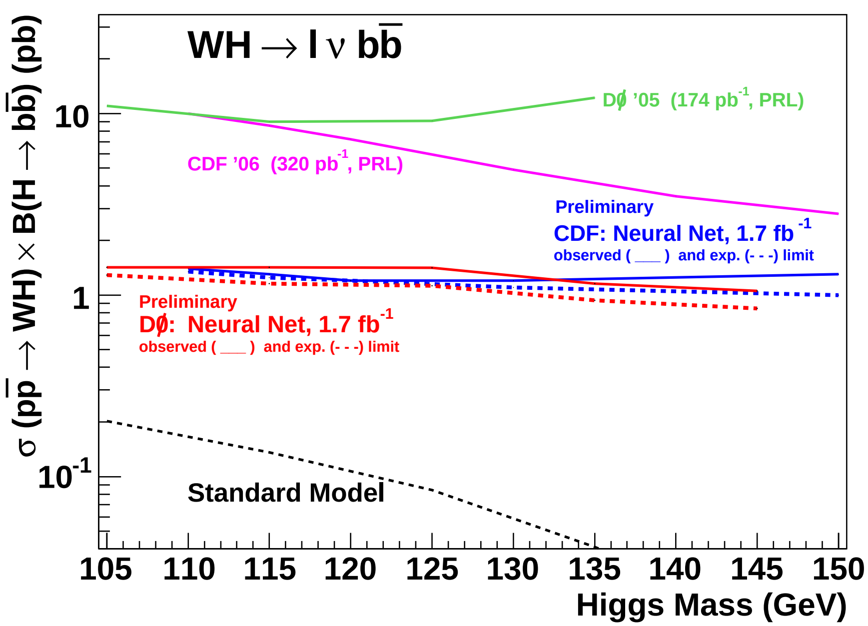


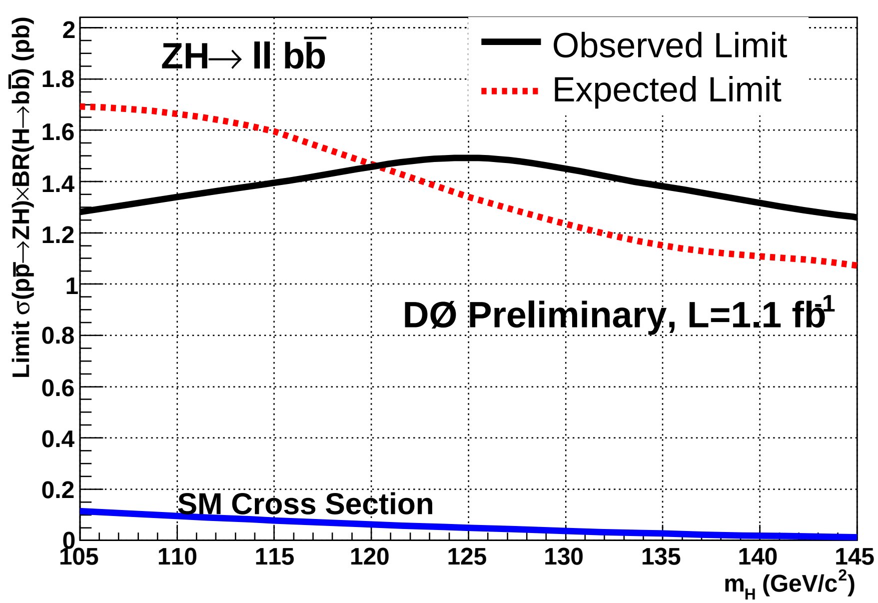
→ NNLO QCD corrections have been calculated for the signal [O.Brien, A.Djouadi and R.Harlander, 2004]

→ $O(\alpha)$ EW corrections have been calculated for the signal [M.L.Ciccolini, S.Dittmaier and M.Kramer, 2003]

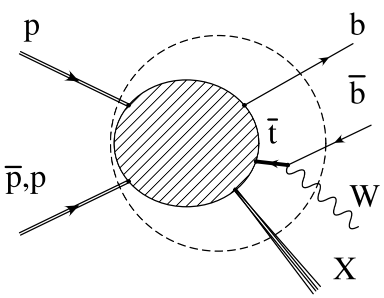
→ Results for WH associated production, August 2007

→ Results for ZH associated production, August 2007





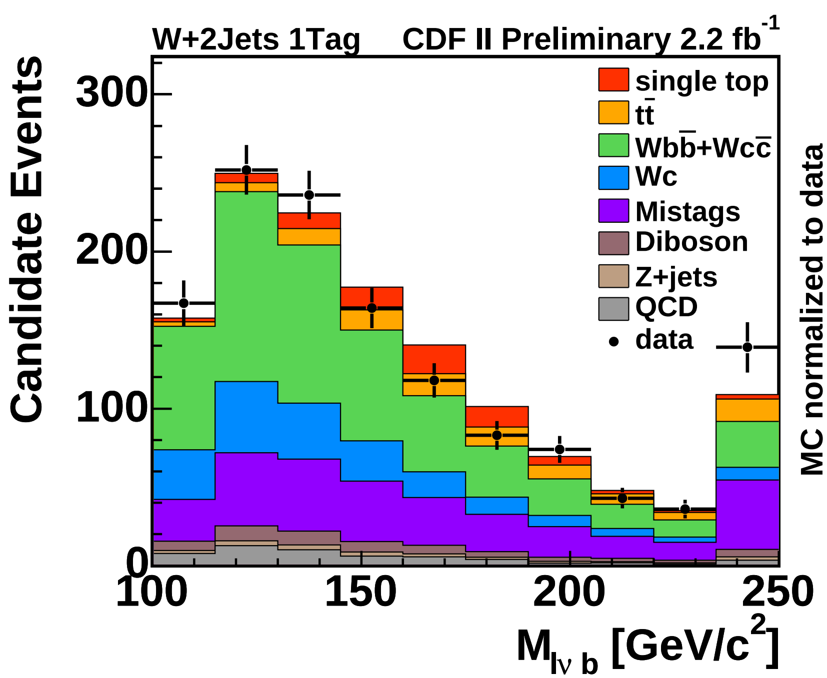
SM Single-Top production



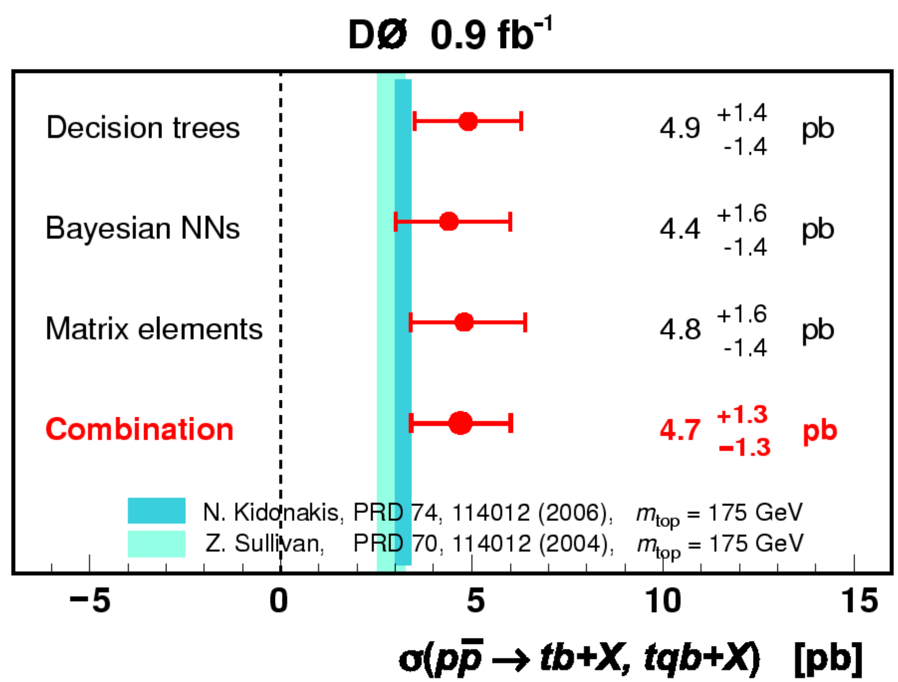
⟶ NLO QCD corrections have been thoroughly studied [T.Stelzer, Z.Sullivan and S.Willenbrock, 1998; B.W.Harris, E.Laenen, L.Phaf, Z.Sullivan and S.Weinzierl, 2002; . . .]

⟶ NLO EW corrections have been calculated for the (SM and MSSM) signal [M.Beccaria, G.Macorini, F.M.Renard and C.Verzegnassi, 2006]

→ CDF data sample, February 2008



→ $D0$ evidence of single-top, March 2008

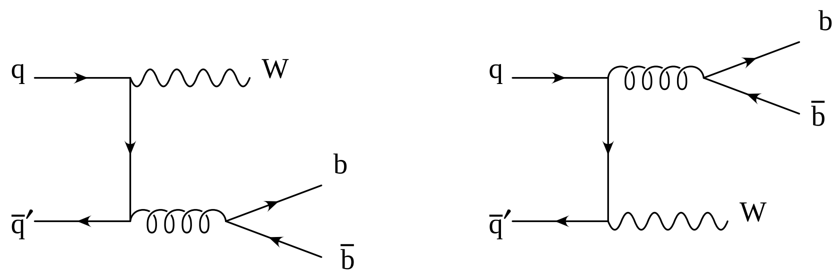


$Wb\bar{b}/Zb\bar{b}$ production at NLO, some history ...

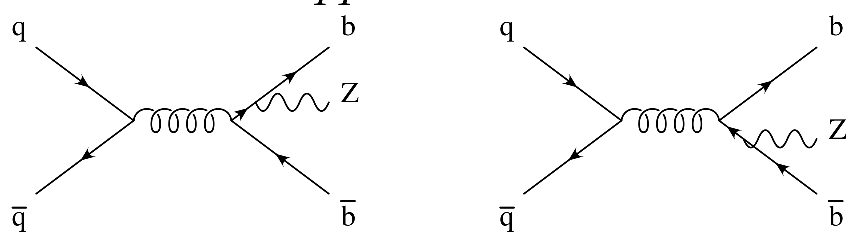
- $\longrightarrow$ $V \longrightarrow 4$ partons (1-loop massless amplitudes) (Bern, Dixon, Kosower (97))
- $\longrightarrow$ $p\bar{p}, pp \rightarrow Vb\bar{b}$ (at NLO, 4FNS, $m_b = 0$) (Campbell, Ellis (99))
- $\longrightarrow$ $p\bar{p}, pp \rightarrow Vb + j$ (at NLO, 5FNS) (Campbell, Ellis, Maltoni,Willenbrock (05,07))
- $\longrightarrow$ $p\bar{p}, pp \rightarrow Wb\bar{b}$ (at NLO, 4FNS, $m_b \neq 0$) (Febres Cordero, L.R., Wackeroth (06))
- $\longrightarrow$ $p\bar{p}, pp \rightarrow Zb\bar{b}$ (at NLO, 4FNS, $m_b \neq 0$) (Febres Cordero, L.R., Wackeroth (08))
- $\longrightarrow$ $p\bar{p}, pp \rightarrow Wb$ (at NLO, 5FNS) (Campbell, Ellis, Febres Cordero, Maltoni, L.R., Wackeroth (in progress))

$Wb\bar{b}/Zb\bar{b}$ production with full m_b effects

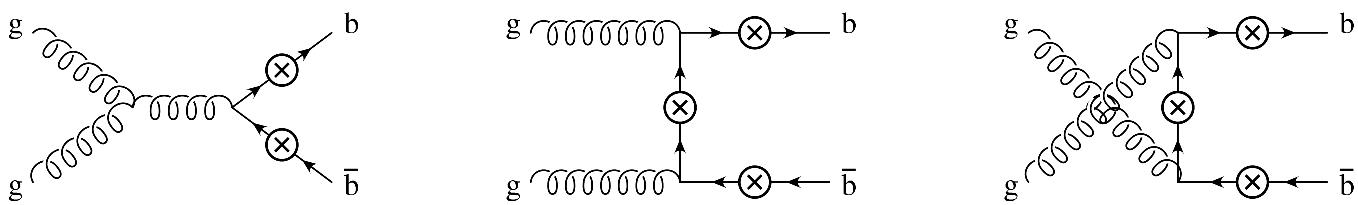
LO Feynman diagrams:



$q\bar{q}' \longrightarrow Wb\bar{b}$



$q\bar{q} \longrightarrow Zb\bar{b}$



$gg \longrightarrow Zb\bar{b}$

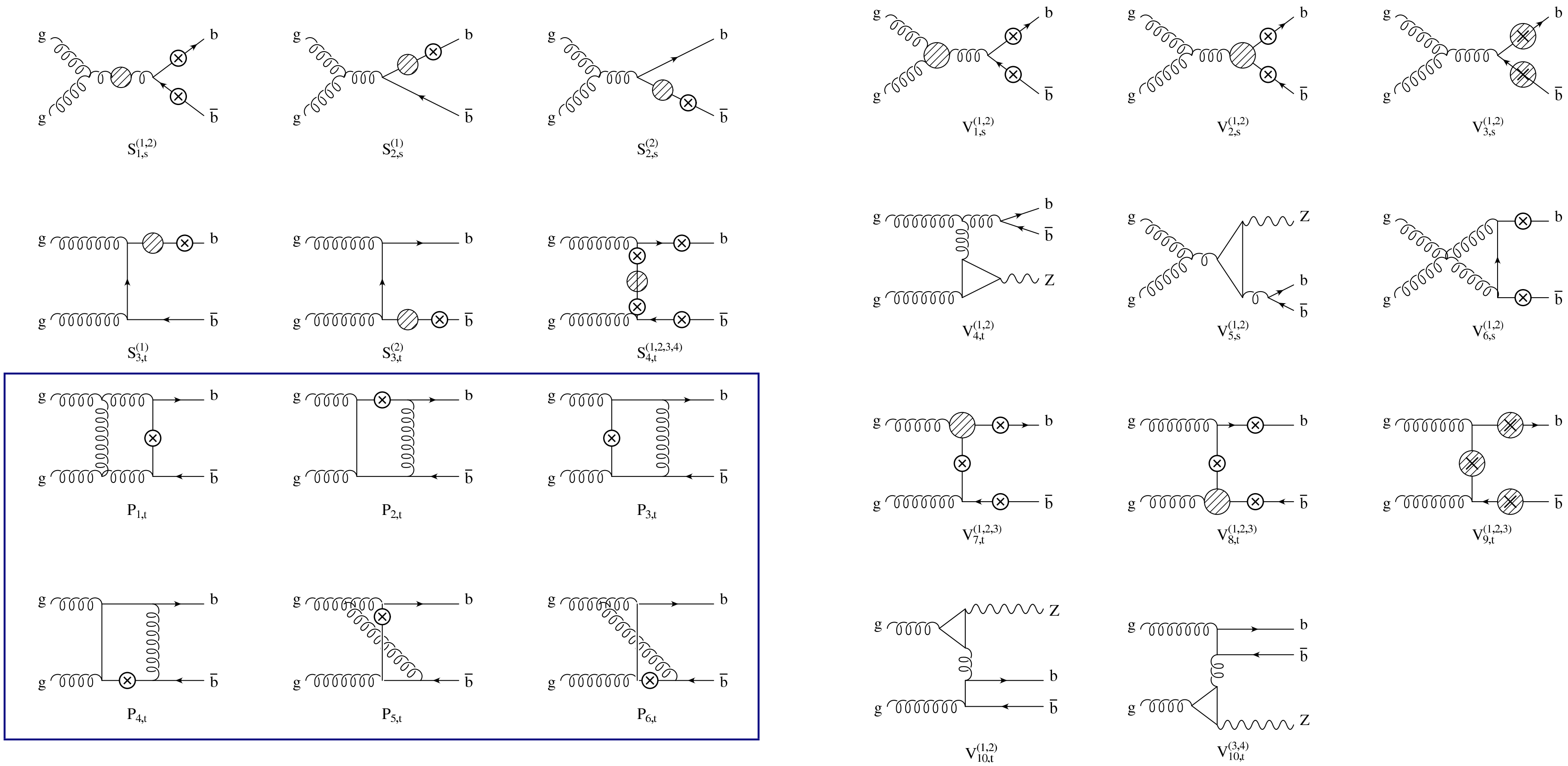
Subprocesses at LO:

$\longrightarrow$ $Wb\bar{b}$: $q\bar{q}' \rightarrow Wb\bar{b}$

$\longrightarrow$ $Zb\bar{b}$: $q\bar{q} \rightarrow Zb\bar{b}$ and

$gg \rightarrow Zb\bar{b}$

NLO at a glance: the $gg \to Zb\bar{b}$ virtual diagrams.



$\longrightarrow$ Counting: 8 diagrams at LO - ~100 at NLO - 12 pentagons

Checking boxes and pentagons using unitarity methods.

The one-loop amplitude can be written as (see Zvi Bern's talk)

$$\mathcal{M} = \sum_i d_i I_4^i + \sum_i c_i I_3^i + \sum_i b_i I_2^i + \sum_i a_i I_1^i$$

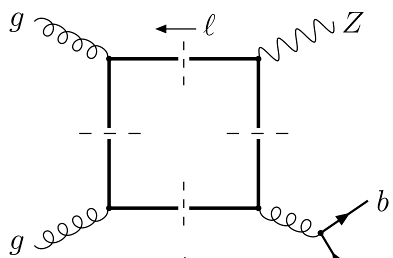
$\longrightarrow$ tadpoles, bubbles and vertices are easy in FD's language;

$\longrightarrow$ boxes and pentagons are the real hurdle (tensor integrals up to rank 4)

$$\Downarrow$$

I_4^i scalar 4-point functions derive from box and pentagons diagrams.

Calculating d_i with unitarity methods is a powerful check!



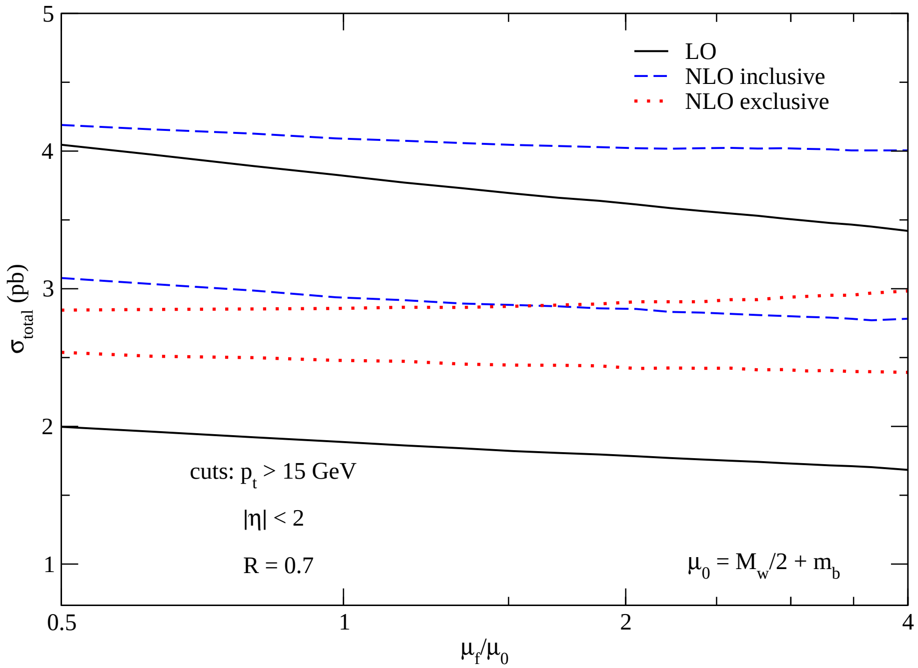
$B_{1,t}^{top}$

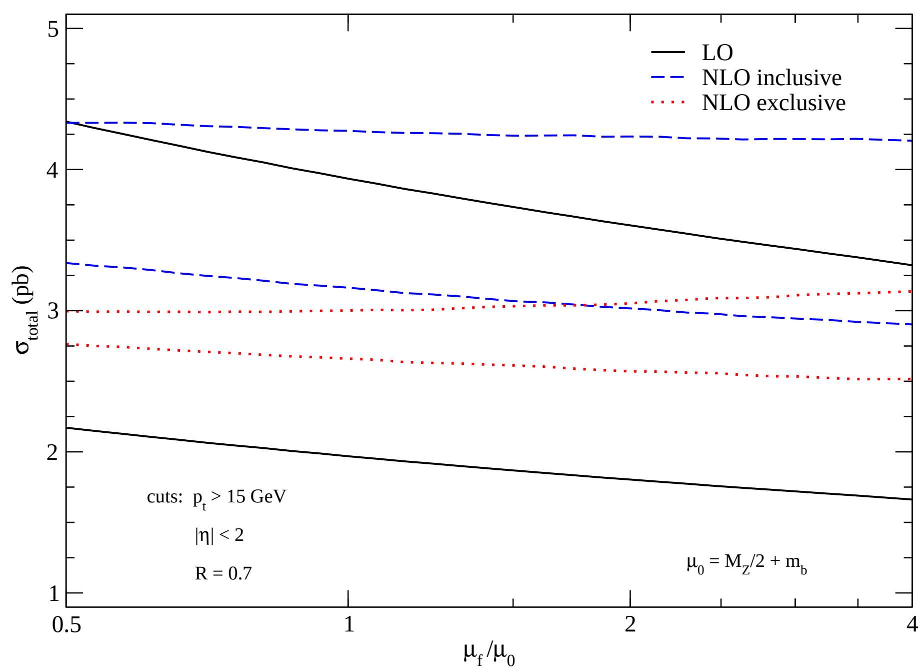
easy using quadrupole cuts!

Britto,Cachazo,Feng

Bern,Dixon,Kosower

Scale dependence and theoretical uncertainty at NLO



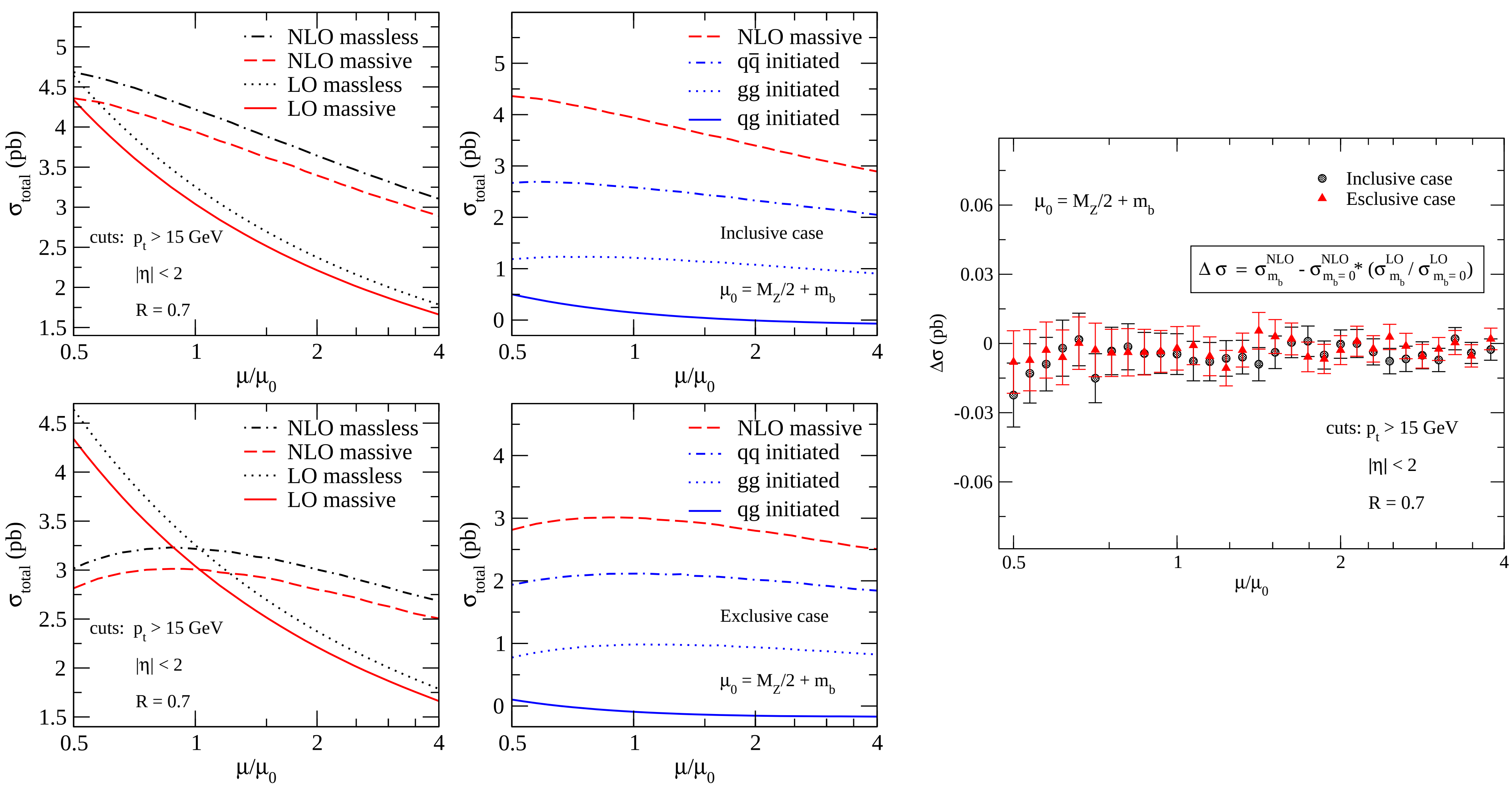


$Wb\bar{b}$: Tevatron (06) $Zb\bar{b}$: Tevatron (arXiv:0806.0808)

$\longrightarrow$ Bands obtained by varying both μ_R and μ_F between $\mu_0/2$ and $4\mu_0$ (with $\mu_0 = m_b + M_V/2$ $(V = W, Z)$).

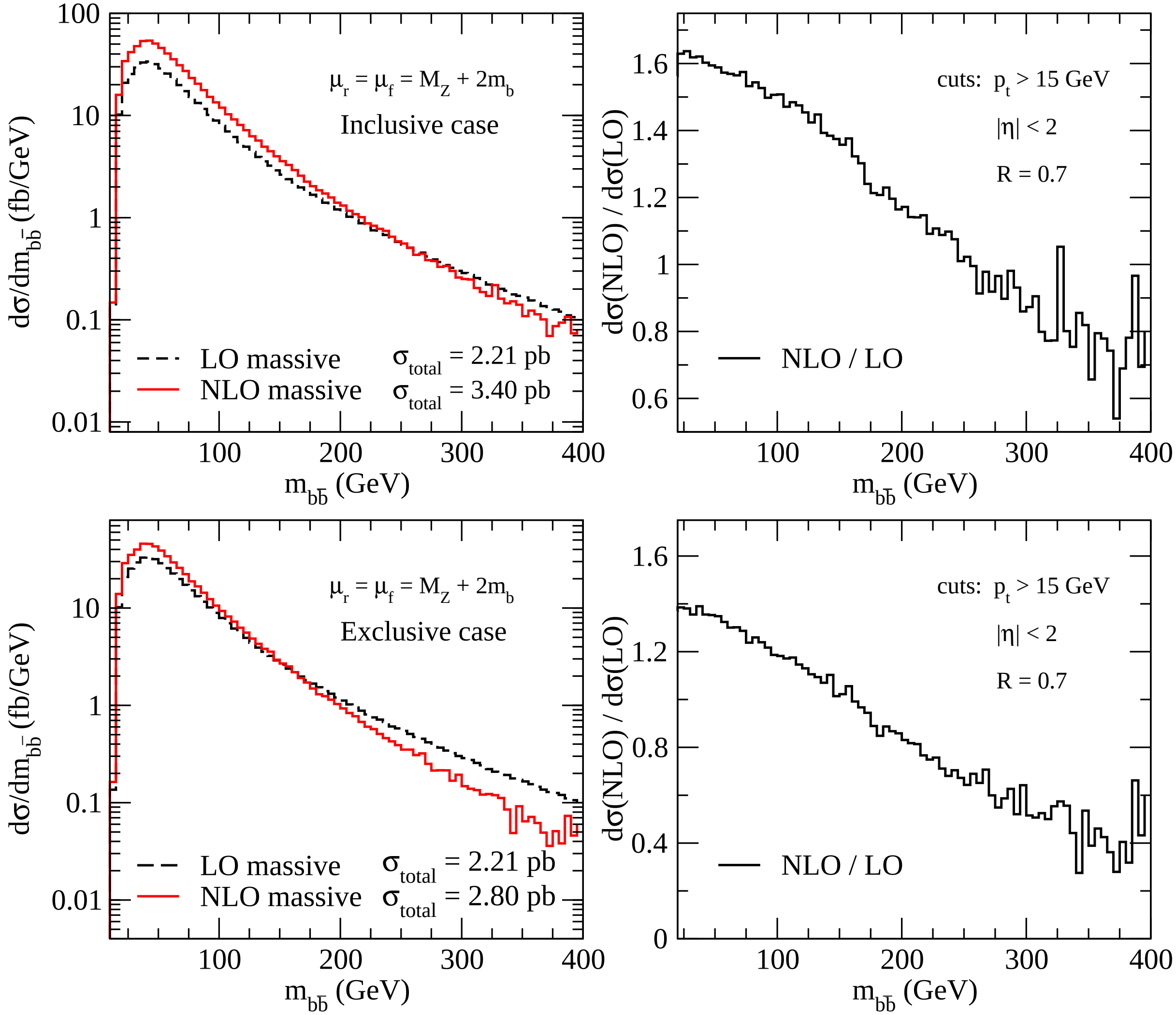
- LO uncertainty $\sim 40\%$.
- Inclusive NLO uncertainty $\sim 20\%$.
- Exclusive NLO uncertainty $\sim 10\%$.

$Zb\bar{b}$, scale dependence: LO vs NLO and massless vs massive



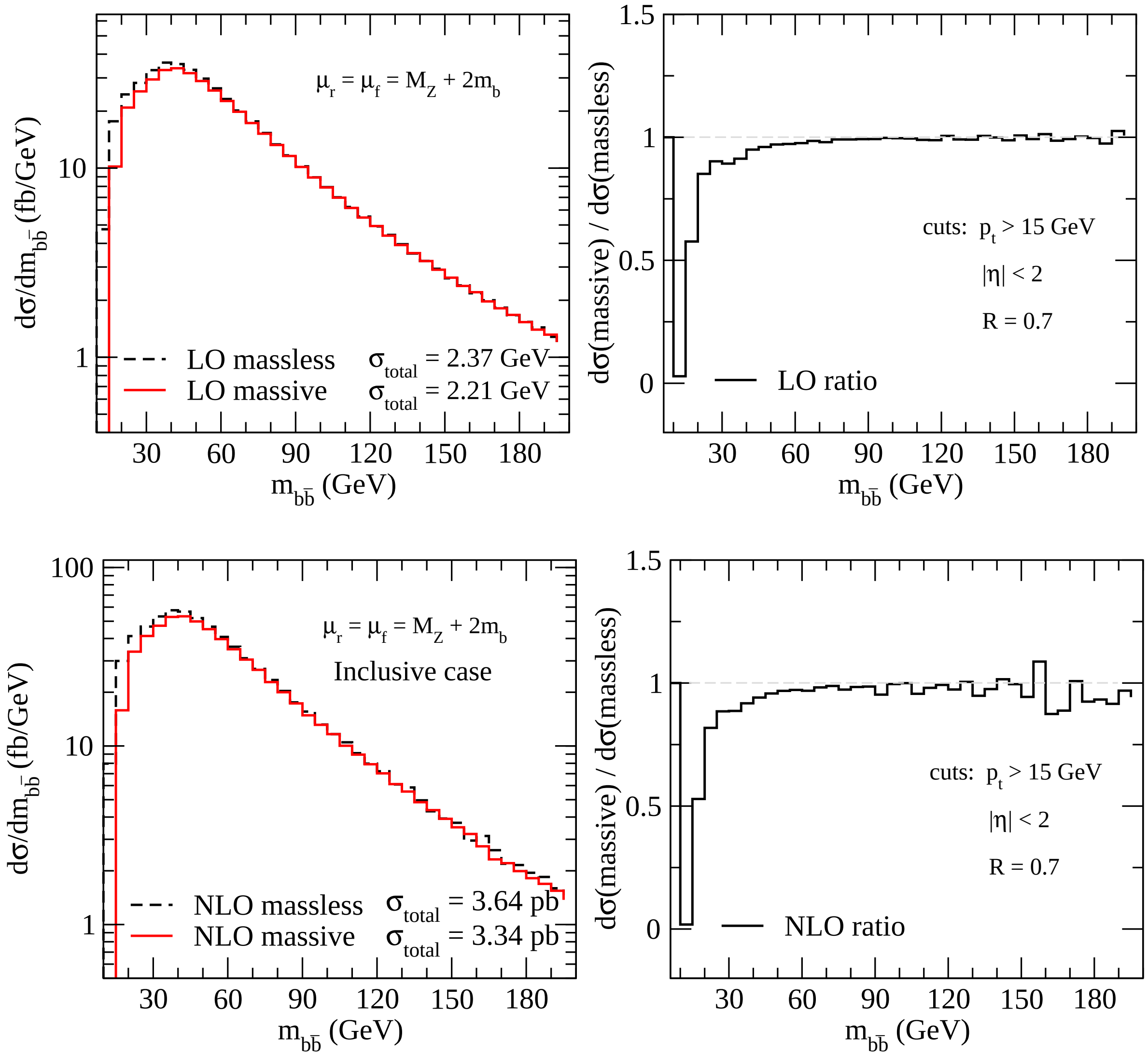
(arXiv:0806.0808)

$Zb\bar{b}$: $m_{b\bar{b}}$ distributions, LO vs NLO



(arXiv:0806.0808)

$Zb\bar{b}$: $m_{b\bar{b}}$ distributions, massive vs massless



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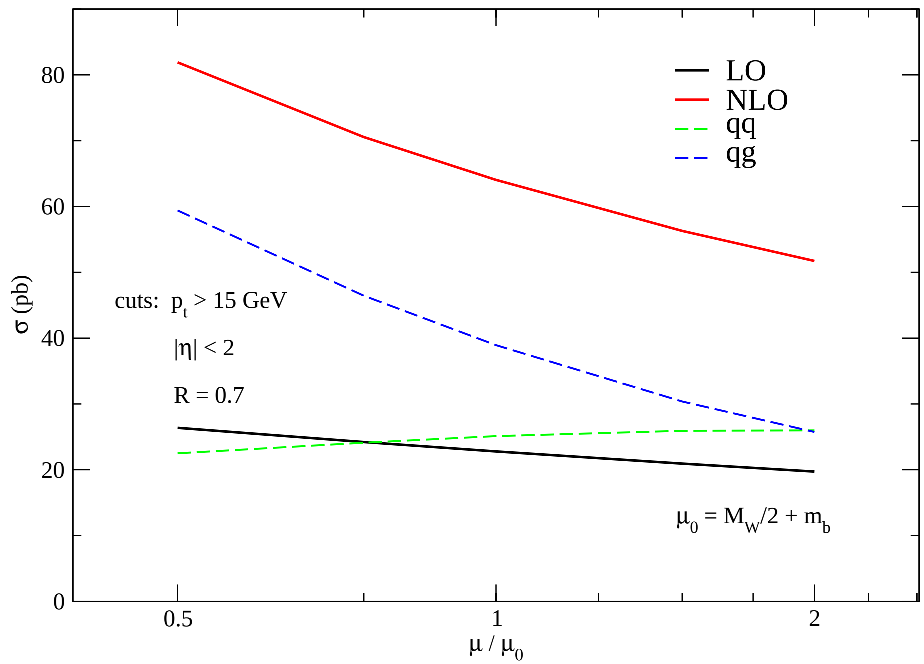
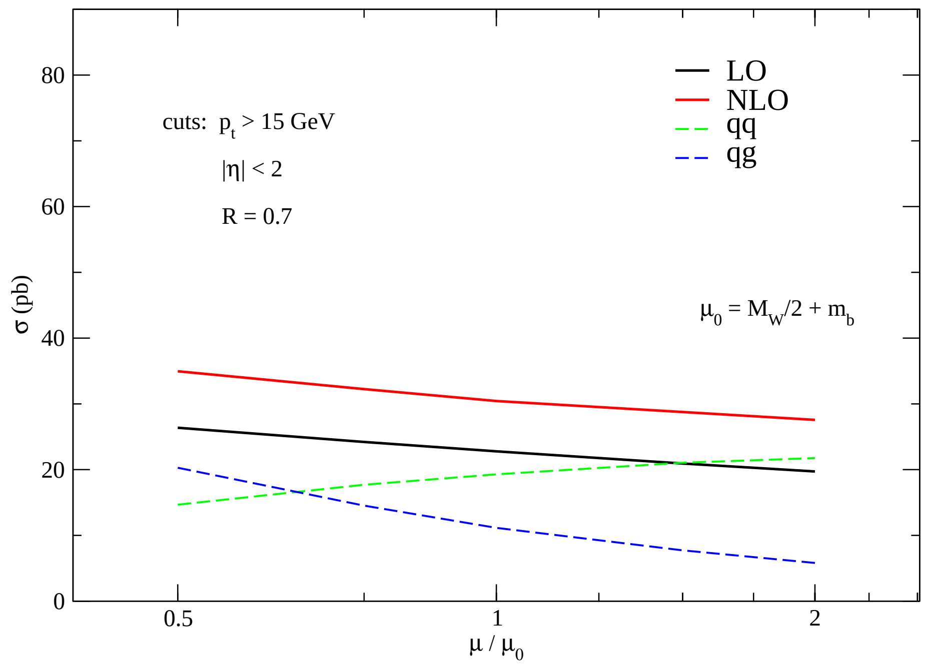


$Wb\bar{b}$: LHC, inclusive (preliminary!)



$Wb\bar{b}$: LHC, exclusive (preliminary!)

$\longrightarrow$ Curves obtained by varying both $\mu_R = \mu_F$ between $\mu_0/2$ and $4\mu_0$ (with $\mu_0 = m_b + M_V/2$ $(V = W, Z)$).

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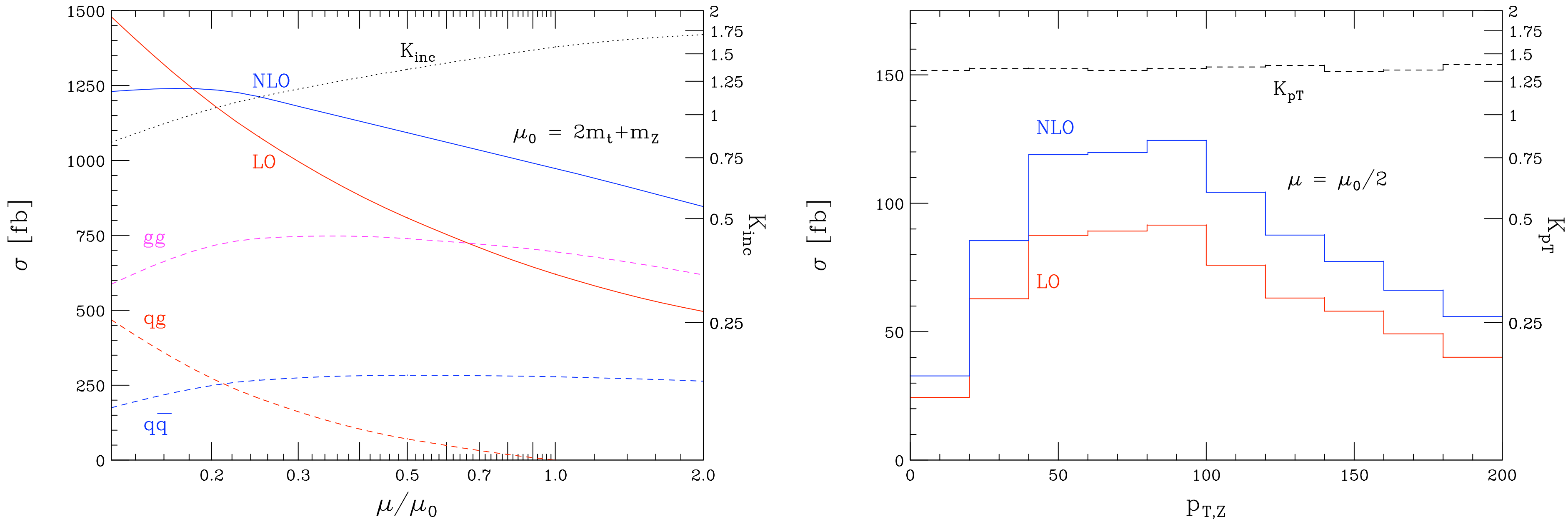
$Zt\bar{t}$: probing the top-quark electroweak properties and background to new physics (SUSY tri-lepton signatures)

Lazopoulos,McElmurry,Melnikov,Petriello (08)



→ very reduced scale dependence, about 11%;

→ large NLO corrections, minor impact on p_T^Z-distribution shape;

→ factor of 1.5-2 improvement with respect to LO analysis of couplings;

→ fully numerical calculation of one-loop matrix elements via sector decomposition and contour deformation.

Conclusions and Outlook

- Heavy quark production ($Q\bar{Q}$) and associated heavy quark production ($Q\bar{Q}+H$, $Q\bar{Q}+W/Z$) play a fundamental role in the physics scenario of the LHC:

  $\longrightarrow$ precision studies (m_t and parton luminosity from $Q\bar{Q}$);

  $\longrightarrow$ signal of new physics: $t\bar{t}H$, $b\bar{b}H$;

  $\longrightarrow$ background to new physics signals: $b\bar{b}W$, $b\bar{b}Z$.

  $\longrightarrow$ test ground of QCD ($2\rightarrow 2$ at NNLO, $2\rightarrow 3$ at NLO);

  $\longrightarrow$ ...

- NNLO (approximate) calculation of $Q\bar{Q}$ production reduces the theoretical uncertainty to precision levels, awaiting a complete NNLO calculation.

- Fully massive NLO calculation of $Wb\bar{b}$ and $Zb\bar{b}$ allows better control of a major background over full kinematic range.

- Combined $Vb\bar{b}$ and $Vb+j$ NLO calculation under construction: looking forward to explaining existing discrepancy between data and existing Monte Carlos (MCFM, Pythia, Herwig).