QCD@LHC:
challenges and opportunities in heavy flavor production

Laura Reina

Università di Roma I, “La Sapienza”, 31 Agosto, 2012

- The Large Hadron Collider (LHC) is testing new ground and will 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 QCD benchmarks for hadronic colliders.
- Focusing on Heavy Quark physics:
  $\longrightarrow$ toward a precise prediction of $Q\bar{Q}$ production;
  $\longrightarrow$ heavy quark production with Higgs bosons: $Ht\bar{t}$, $Hb\bar{b}$;
  $\longrightarrow$ heavy quark production with weak gauge bosons: $Wb\bar{b}$, $Zb\bar{b}$;

  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, updated)

Green light $\longrightarrow$ Done!

Red light $\longrightarrow$ Still work in progress!

NLO: $V + 4j$, $VV + 2j$, $t\bar{t} + 2j$, $t\bar{t} + b\bar{b}$,$Ht\bar{t}/b\bar{b}$, $V + b\bar{b}/t\bar{t}$, VVV, $H + 2j$,...
(so many people!)

NNLO: since '07 steady progress towards $q\bar{q}, gg \to Q\bar{Q}$ at NNLO
(Czakon, Mitov, Moch, Beneke, Falgari, Schwinn, Bonciani, Ferroglia, Gehrmann, ...)
plus NNLO PDFs.

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 modeling 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.

- NLO: challenges have largely been faced and enormous progress has been made:

  → traditional approach (FD's) made more efficient to handle high multiplicity;

  → new techniques based on unitarity methods and recursion relations offers a powerful and promising alternative, particularly suited for automation;

  → interface with parton shower MC well advanced (MC@NLO, POWHEG, Sherpa)

- When is NLO not enough?

  → 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;

    ▷ ...

  → When truly high precision is needed (very often the case!).

  → When a really reliable error estimate is needed.

$Q\bar{Q}$ production at the Tevatron and LHC

- NNLO: 2-loop corrections to both $q\bar{q} \to Q\bar{Q}$ and $gg \to Q\bar{Q}$ calculated in the limit $m_Q^2 \gg \hat{s}, -\hat{t}$, step by step. Czakon,Mitov,Moch (since 07-08)

- NNLO: full 2-loop corrections to $q\bar{q} \to Q\bar{Q}$ calculated numerically. Czakon(08)

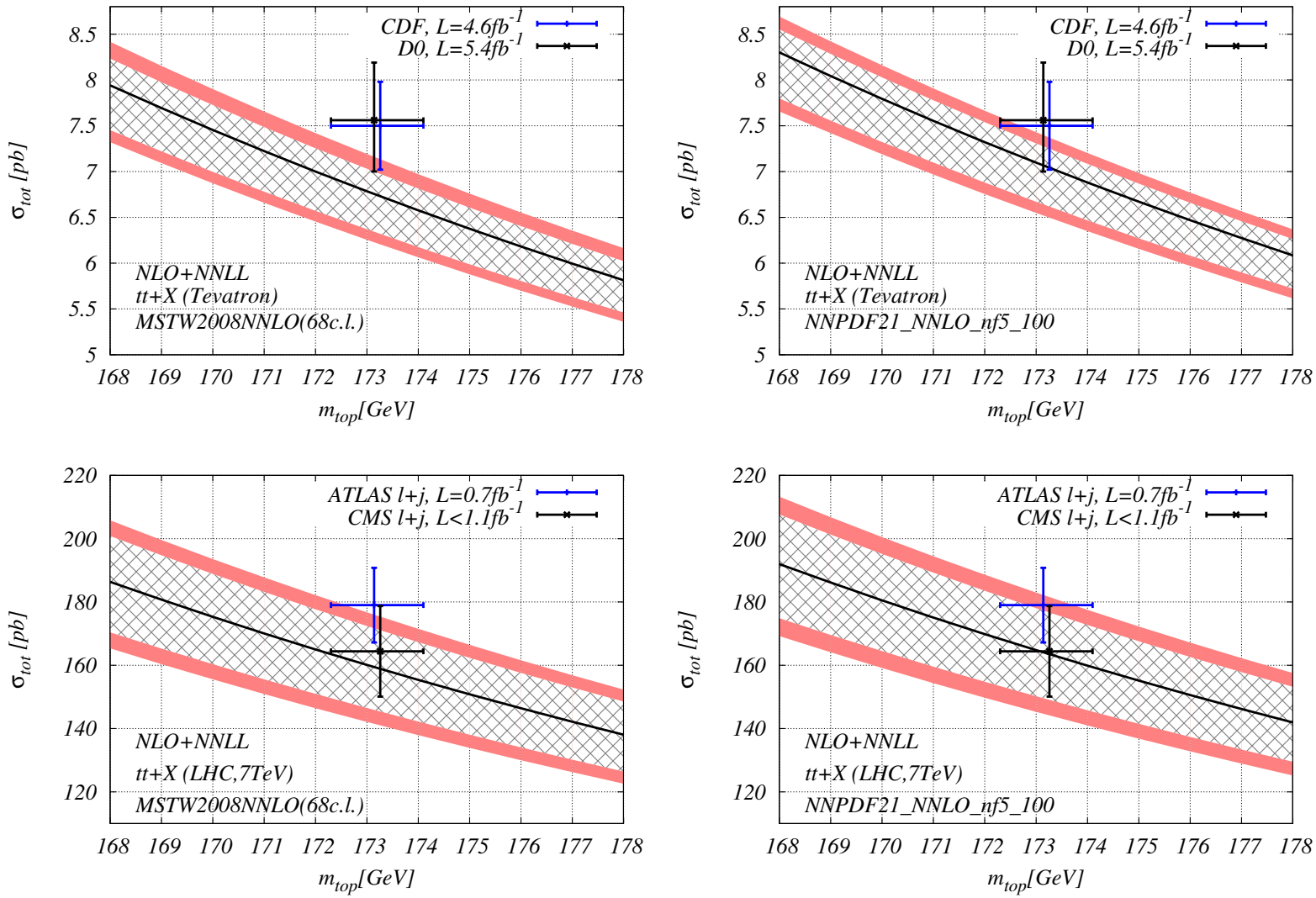
- NNLO: partial 2-loop corrections to $q\bar{q} \to Q\bar{Q}$ calculated analytically.

  Bonciani,Ferroglia,Gerhmann,Maitre,Studerus, (08-09)

- NNLL-NLO: resumming soft threshold corrections at NNLL,

  Cacciari,Czakon,Mangano,Mitov, Nason (11)

  (using results derived by Beneke,Czakon,Falgari,Mitov, Schwinn (09))



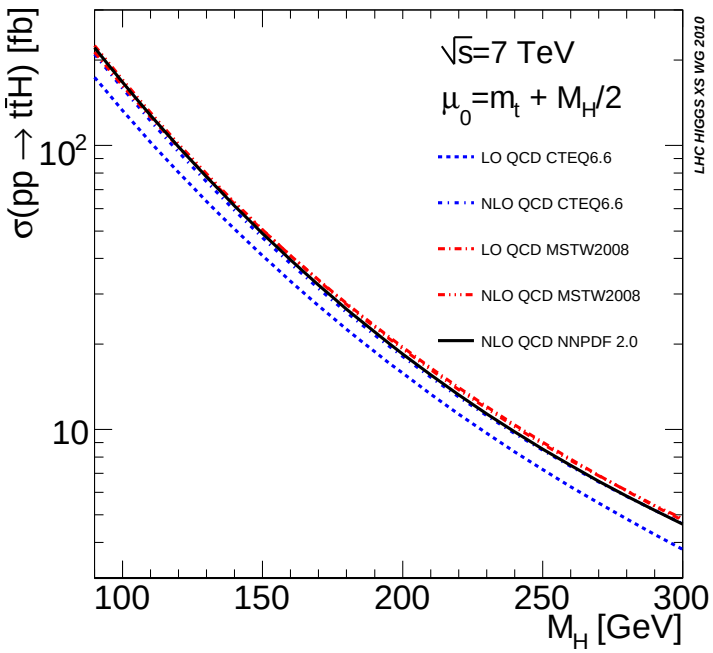
Cacciari, Czakon, Mangano, Mitov, Nason (arXiv:1111.5869)

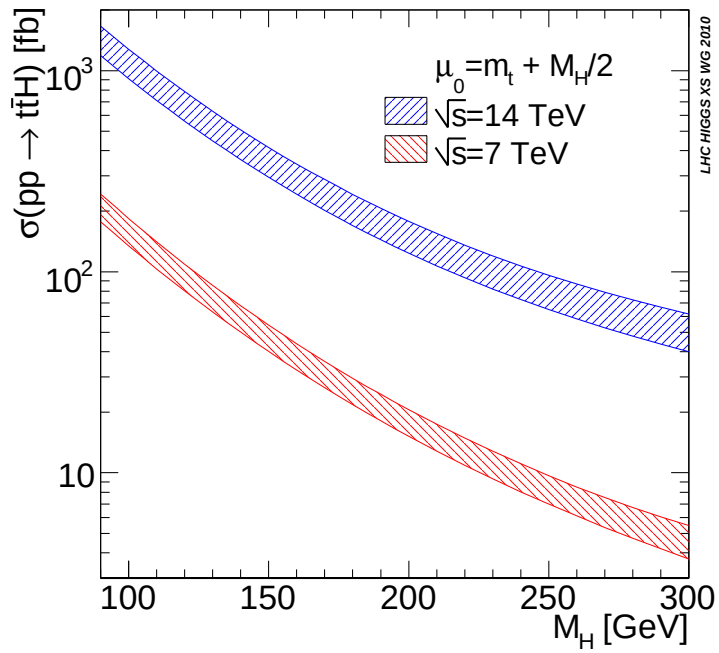
- ▷ scale+PDF uncertainty: $10 - 15\%$ (conservative b/c incomplete NNLO)
- ▷ comparable to current experimental uncertainty: precision requires NNLO.

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

- Motivations
  - ▷ $Ht\bar{t}$: important channel when $H \to \gamma\gamma, b\bar{b}, \tau^+\tau^-$;
  - ▷ $Ht\bar{t}$: instrumental to Higgs couplings determination;
  - ▷ $Hb\bar{b}$: direct evidence of new physics.
- Interesting aspects of the NLO calculation.
- Latest studies: LHC Higgs Cross Section Working Group.

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



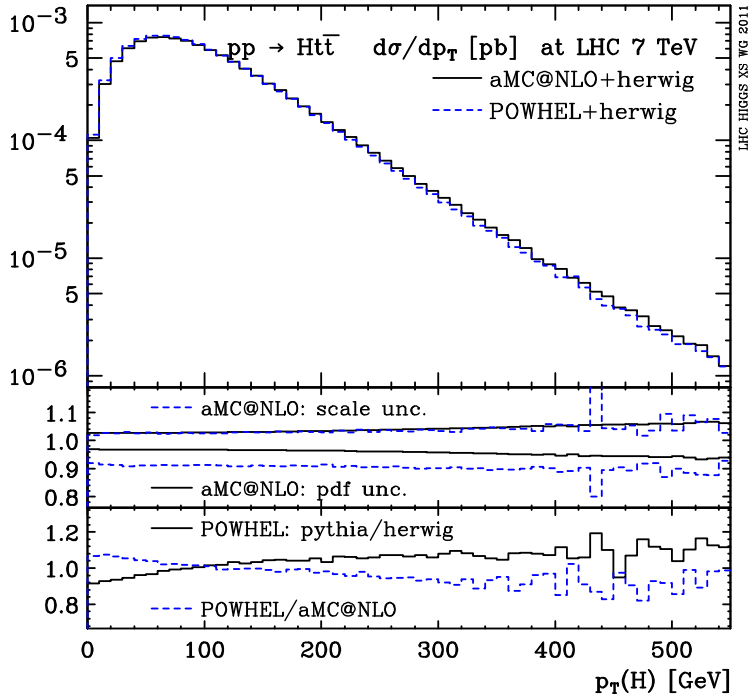


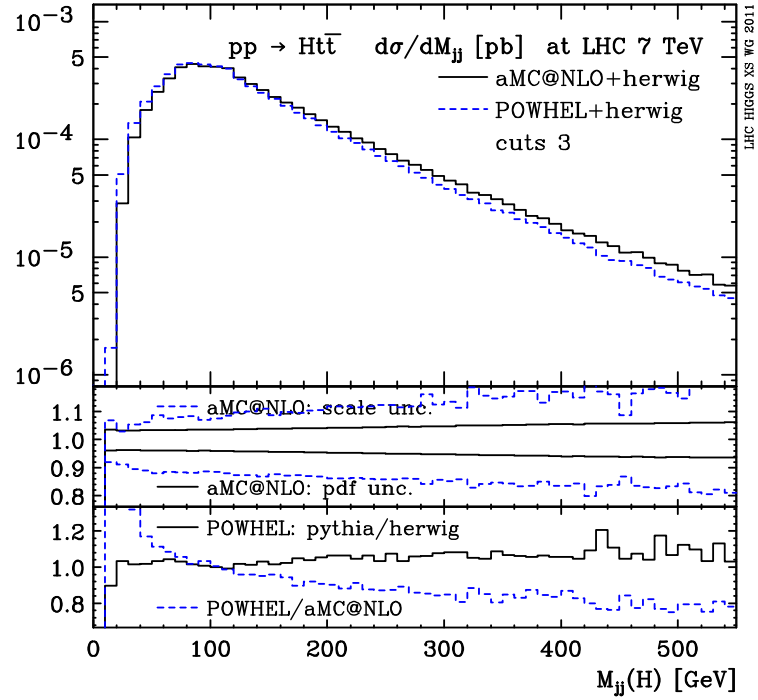
Dawson, Jackson, Orr, L.R., Wackeroth

Beenakker, Dittmaier, Krämer, Plümper, Spira, Zerwas

- ▷ Independent calculations show full agreement.
- ▷ Theoretical uncertainty from scale dependence, α_s, PDFs: below 15%.
- ▷ Several crucial backgrounds: $t\bar{t} + j$ (NLO, Dittmaier, Uwer,Weinzierl), $t\bar{t}b\bar{b}$ (Dittmaier et al.,Bevilacqua et al.), $t\bar{t} + 2j$ (Bevilacqua et al.).

LHC, $pp \to t\bar{t}H$: interface with parton-shower MC





Frederix, Garzelli, Kardos, Papadopoulos, Trócsányi

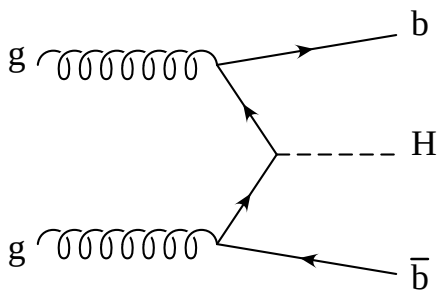
- ▷ Very good agreement between MC@NLO and POWHEG.
- ▷ Provided state-of-the-art tools to experimental analyses.
- ▷ Need to focus on backgrounds, in particular $t\bar{t} + b\bar{b}$ and $t\bar{t} + jj$.

$p\bar{p}, pp \to H + b$ jets: 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 $gg \to b\bar{b}H$



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

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

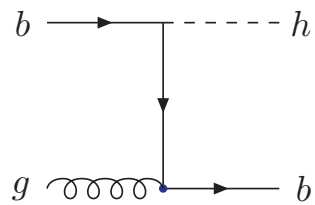
$$b(x,\mu) = \frac{\alpha_s(\mu)}{2\pi} \log\left(\frac{\mu^2}{m_b^2}\right) \int_x^1 \frac{dy}{y} P_{qg}\left(\frac{x}{y}\right) g(y,\mu)$$

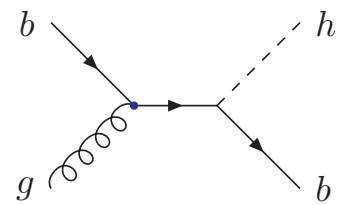
- Semi-inclusive and inclusive cross sections: 2 approaches

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

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

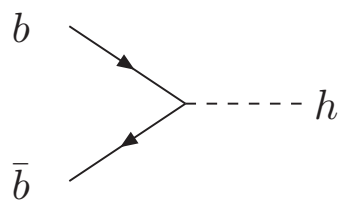
$\longrightarrow$ Use b-quark PDF, resumming the large collinear logs $\longrightarrow$ $\boxed{\text{5FNS}}$





$\longrightarrow$ $\boxed{\text{1 b-tag}}$

$(bg \to bH)$



$\longrightarrow$ $\boxed{\text{0 b-tags}}$

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

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

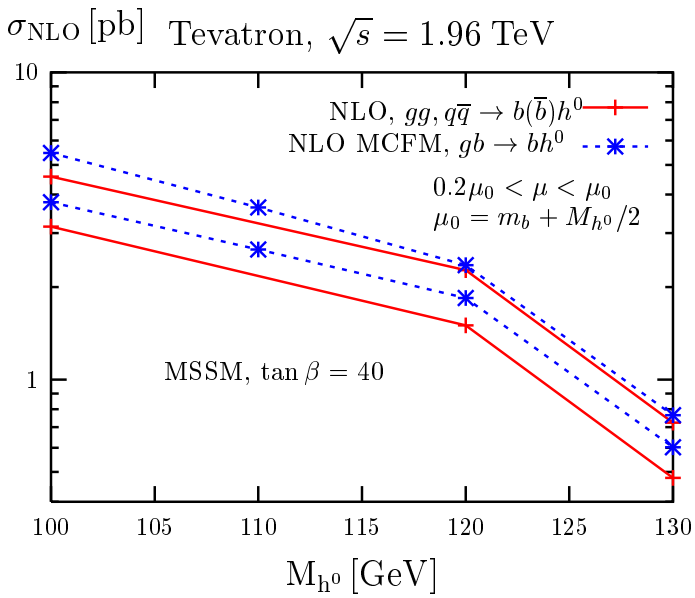
- ▷ $b\bar{b} \to H$ (NNLO) (no b-tag)

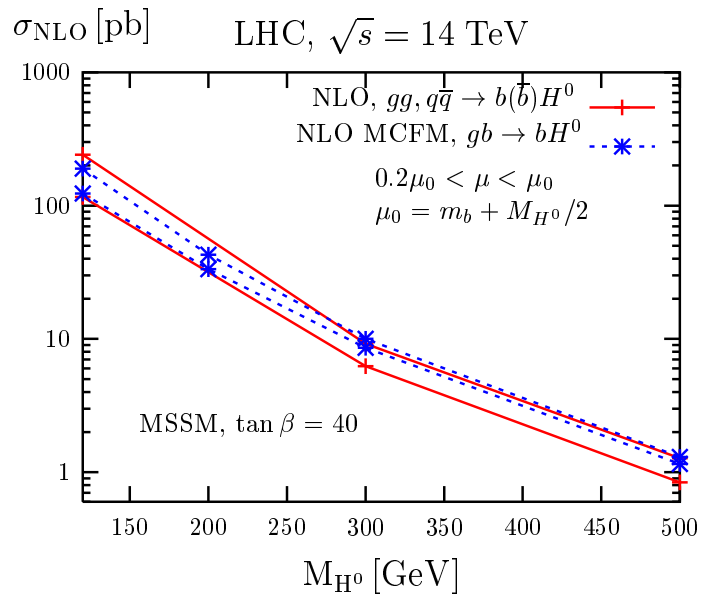
  (R.Harlander, W.Kilgore; D.Dicus, T.Stelzer, Z.Sullivan, S.Willenbrock)

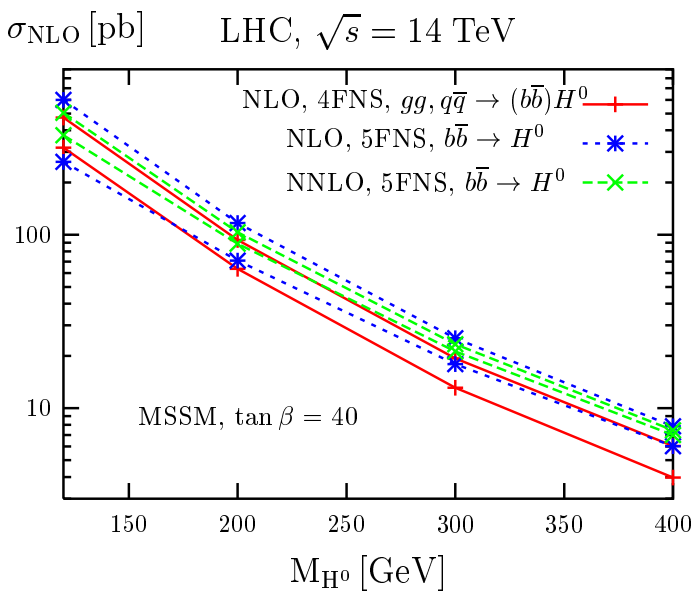
- ▷ $bg \to bH$ (NLO) (one b-tag)

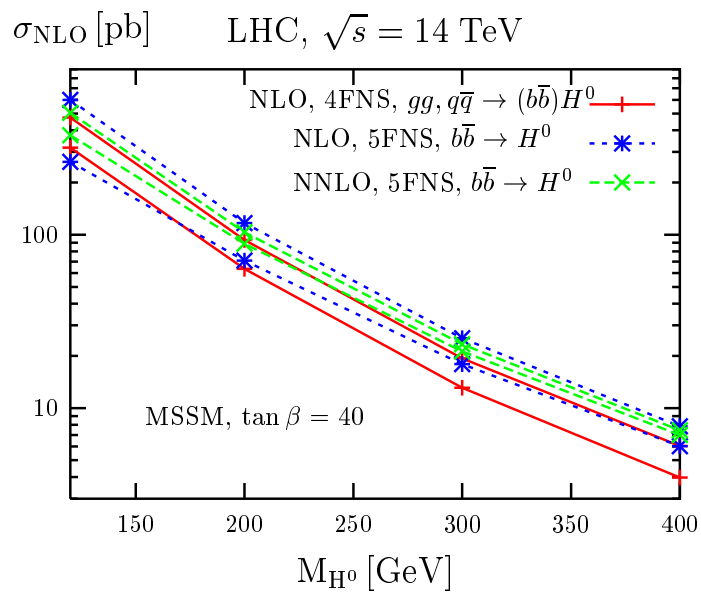
  (J.Campbell, R.K.Ellis, F.Maltoni, S.Willenbrock)

Inclusive cross sections: 4FNS vs 5FNS







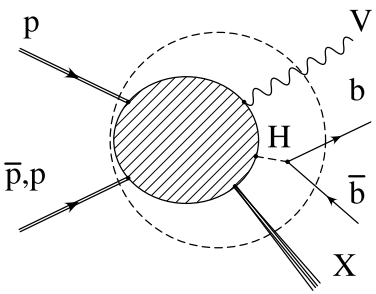


Dawson, Jackson, L.R., Wackeroth

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

- Motivations:
  - ▷ important test of QCD
  - ▷ main background to several important signatures, for example,
    - → WH/ZH associated production;
    - → single-top production;
    - → Higgs production with $H \to ZZ$;
    - → several non-standard model signatures.
- Main QCD studies:
  - → $Wb\bar{b}/Zb\bar{b}$ at NLO, b massless/massive;
  - → $Wb+$ jet, $Zb+$ jet: 4FNS vs 5FNS at NLO;
  - → interface of NLO $Wb\bar{b}/Zb\bar{b}$ with parton shower Monte Carlo programs;
  - → $Wb\bar{b}+j$ at NLO, b massive: one-loop contributions.
- Comparison with Tevatron and LHC data

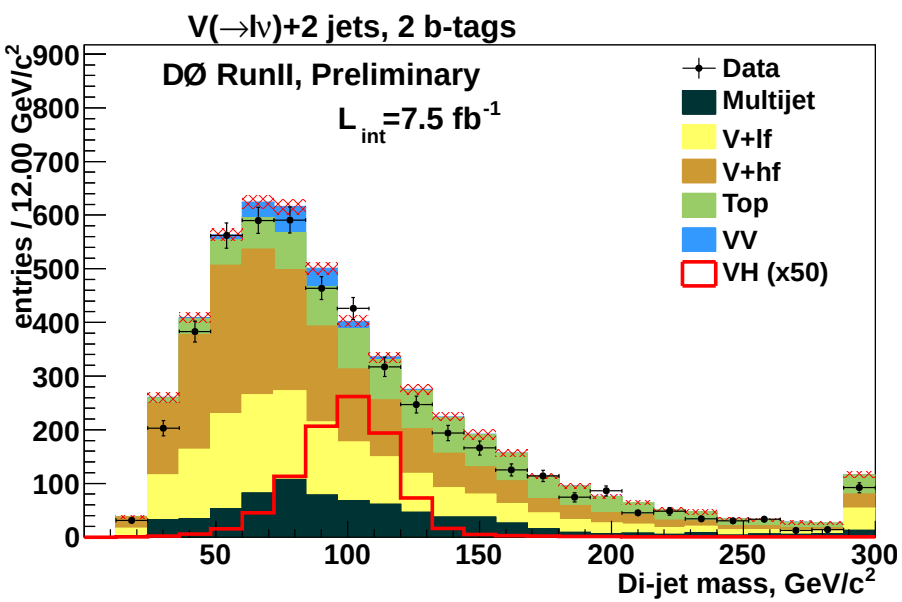
Associated production of SM Higgs with weak vector bosons

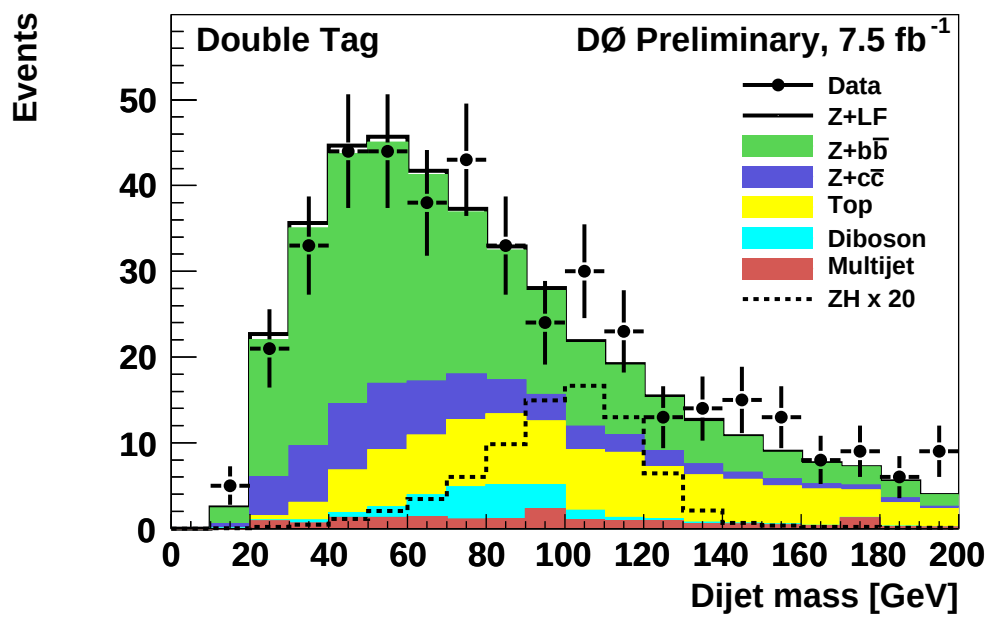


$\longrightarrow$ NNLO QCD corrections have been calculated for the signal [O.Brien, A.Djouadi and R.Harlander, 2004]

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

$\rightarrow$ Results for WH/ZH associated production, Summer 2011





$W + b$ jets

Studied at NLO in QCD/measured in experiments:

- $W + 2b$ jets ($m_b \neq 0$):
  - Febres Cordero, L. R., Wackeroth, hep-ph/0606102, arXiv:0906.1923
  - Badger, Campbell, Ellis, arXiv:1011.6647 (with $W \to l\nu$)
  - Oleari, L. R., arXiv.1105.4488 $\longrightarrow$ POWHEG
  - Frederix, Frixione, Hirschi, Maltoni, Pittau, Torrielli, arXiv:1106.6019 $\longrightarrow$ MC@NLO
- $W + 2b +$ jet:
  - L.R., Schutzmeier, arXiv:1110.4438 (one-loop corrections)
- $W + 2$ jets with at least one b jet:
  - Campbell, Ellis, Febres Cordero, Maltoni, L.R., Wackeroth, Willenbrock, arXiv:0809.3003
  - the CDF collaboration, arXiv:0909.1505,
    Campbell, Febres Cordero, L.R., arXiv:1001.3362, arXiv:1001.2954
  - the ATLAS collaboration, arXiv:1109.1470,
    Campbell, Caola, Febres Cordero, L.R., Wackeroth, arXiv:1107.3714

$Z + b$ jets

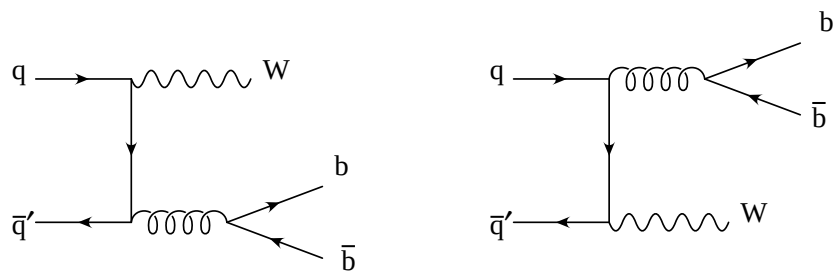
Studied at NLO in QCD/measured in experiments :

- $Z + 2b$ jets ($m_b \neq 0$):
  - Febres Cordero, L.R., Wackeroth, arXiv:0806.0808, arXiv:0906.1923
  - Oleari, L.R., in preparation $\longrightarrow$ POWHEG
  - Frederix, Frixione, Hirschi, Maltoni, Pittau, Torrielli, arXiv:1106.6019 $\longrightarrow$ MC@NLO

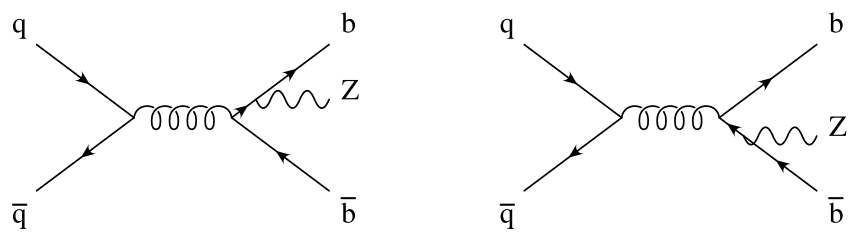
- $Z + 1b$ jet, $Z + 2$ jets with at least one b jet:
  - Campbell, Ellis, Maltoni, Willenbrock, hep-ph/0312024
  - Campbell, Ellis, Maltoni, Willenbrock, hep-ph/0510362
  - the CDF collaboration, hep-ex/0812.4458,
  - the D0 collaboration, arXiv:1010.6203
  - the ATLAS collaboration, arXiv:1109.1403

$W/Z + 2b$ jets: based on $Wb\bar{b}/Zb\bar{b}$

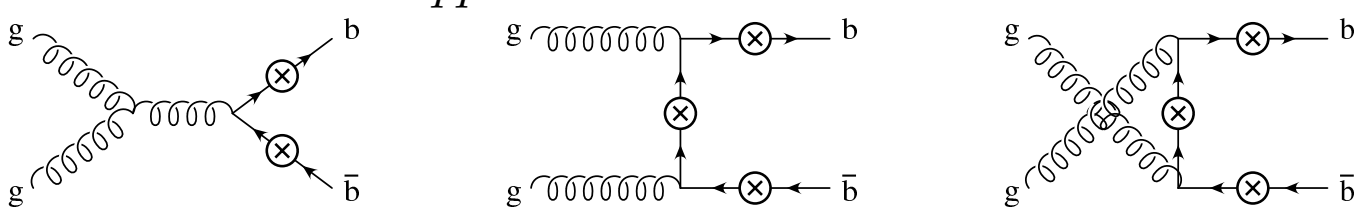
LO Feynman diagrams:



$q\bar{q}' \to Wb\bar{b}$ and $q\bar{q} \to Zb\bar{b}$



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



$gg \to Zb\bar{b}$

Subprocesses at LO:

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

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

$gg \to Zb\bar{b}$

Virtual corrections: $\hat{\sigma}_{ij}^{\rm virt}$

$$\hat{\sigma}_{ij}^{\rm virt} = \hat{\sigma}(ij \to W/Z\, b\bar{b}) = \int d\,(PS_3) \overline{\sum} \left(\mathcal{A}_0 \mathcal{A}_{1-{\rm loop}}^{\dagger} + \mathcal{A}_0^{\dagger} \mathcal{A}_{1-{\rm loop}} \right)$$

where, using traditional Feynman-diagram techniques,

$$\mathcal{A}_{1-{\rm loop}} = \sum_{D_i} \mathcal{A}_{D_i} \qquad (D_i \to \text{Feynman diagrams})$$

or using new techniques based in unitarity properties of scattering amplitudes,

$$\mathcal{A}_{1-{\rm loop}} = \sum_i d_i I_4^i + \sum_i c_i I_3^i + \sum_i b_i I_2^i + \sum_i a_i I_1^i + R$$

given $I_i^{4,3,2,1} \to$ 4-point, ..., 1-point scalar integrals.

Notice:

- $\longrightarrow$ Use dimensional regularization to regularize UV and IR divergencies.
- $\longrightarrow$ UV divergencies are canceled by a suitable set of counterterms.
- $\longrightarrow$ IR divergencies will cancel with $\hat{\sigma}_{ij}^{\rm real}$.

Real corrections: $\hat{\sigma}_{ij}^{\rm real}$

$$\hat{\sigma}_{ij}^{\rm real} = \hat{\sigma}(ij \to W/Z\ b\bar{b} + k) = \int d\,(PS_4) \overline{\sum} |\mathcal{A}_{\rm real}(ij \to W/Z\ b\bar{b} + k)|^2$$

$\longrightarrow$ IR divergencies associated with the integration over the PS of the extra parton, can be extracted using standard techniques

Phase Space Slicing method with *one* or *two cutoffs*;

Dipole Subtraction method.

$\longrightarrow$ Non-singular (hard) phase space region: integrated numerically using Monte Carlo techniques.

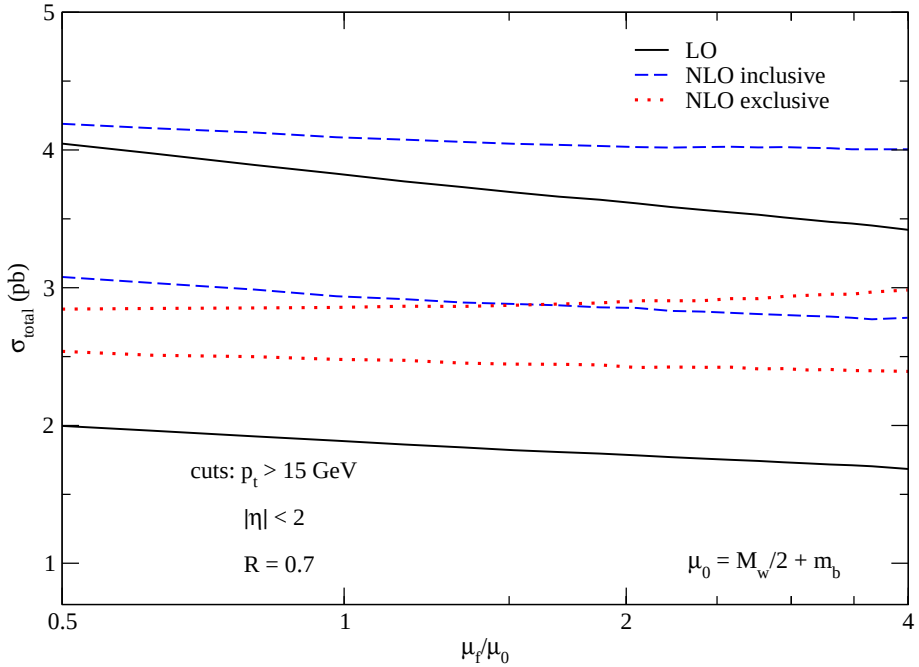
Theoretical uncertainty meaningfully defined at NLO::

- ▷ residual renormalization/factorization scale dependence;
- ▷ large variations due to particular NLO effects;
- ▷ parton distribution function dependence;
- ▷ parametric dependencies (ex.: m_b)

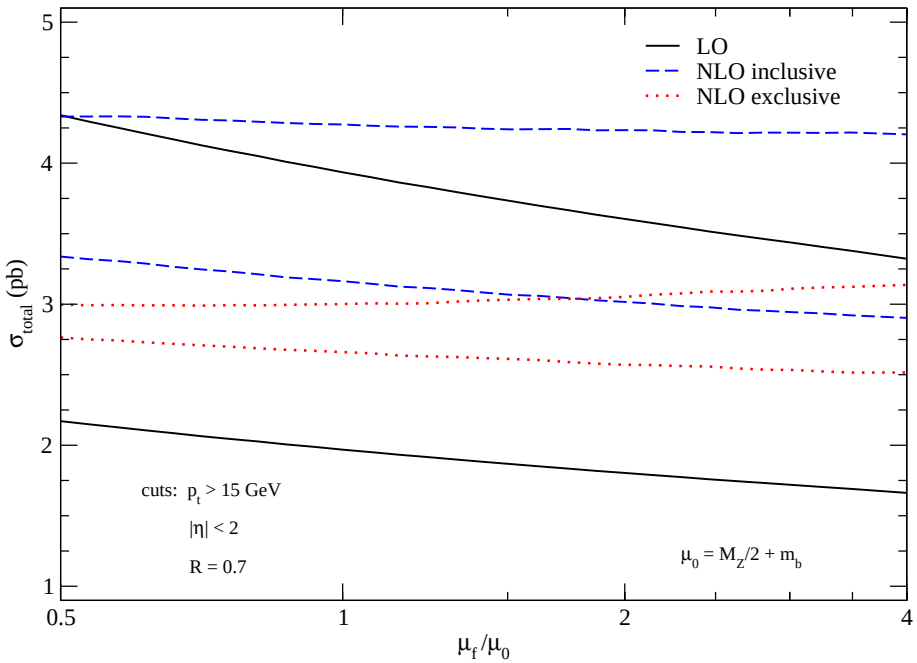
In the following (unless differently specified):

- b-jets defined using:
  - k_T algorithm with R=0.7 ;
  - p_T and η cuts.
- used CTEQ6M or CTEQ6.6 parton distributions functions;
- $m_b = 4.7$ GeV.
- inclusive: 2 b jets (+ light jet);
- exclusive: 2 b jets only.

Tevatron: scale dependence and theoretical uncertainty at NLO



$Wb\bar{b}$: Tevatron (PRD 74 (2006) 034007)

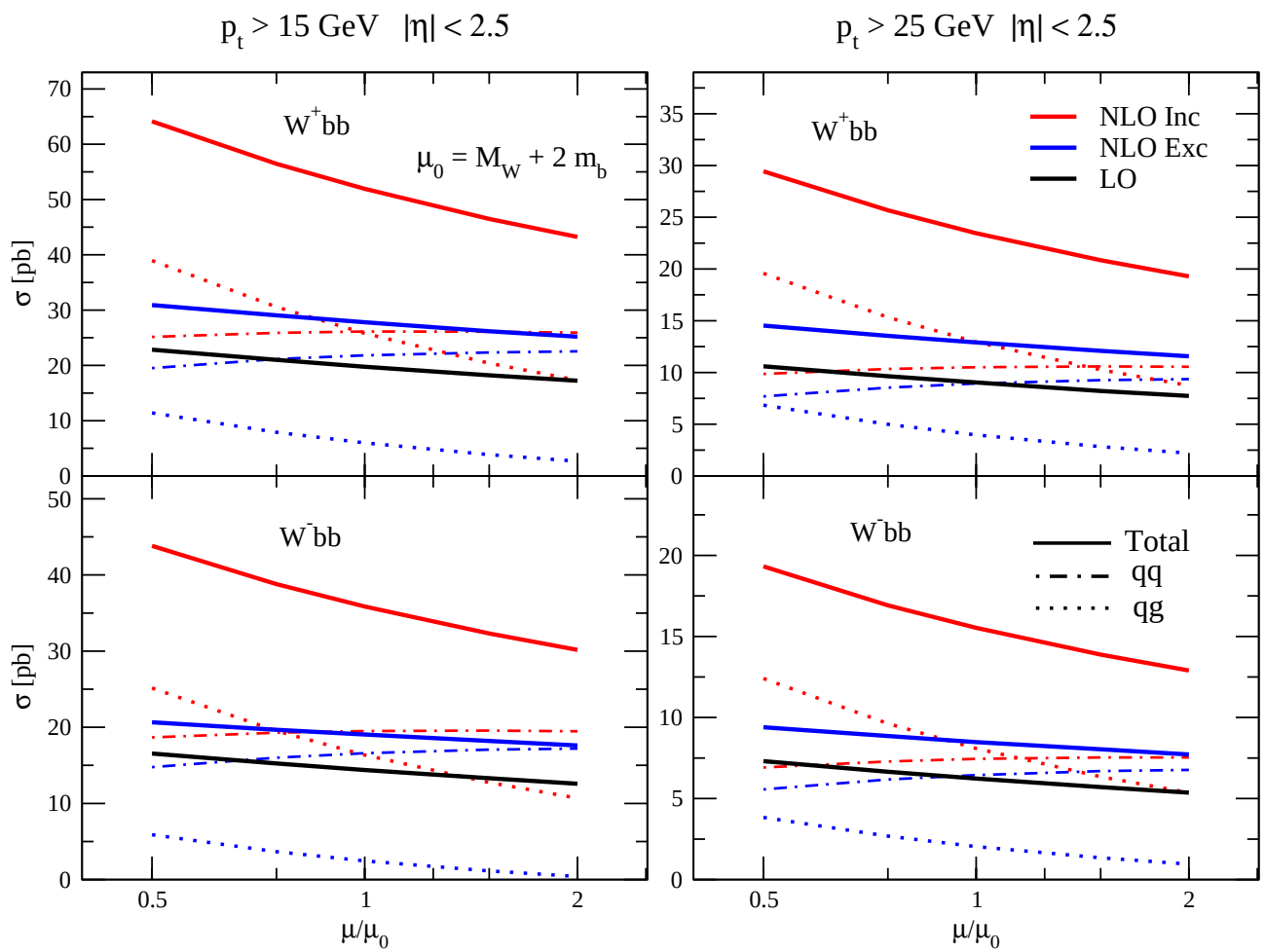


$Zb\bar{b}$: Tevatron (PRD 78 (2008) 074014)

$\longrightarrow$ 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 $\sim 10\%$.

LHC: scale dependence and theoretical uncertainty at NLO

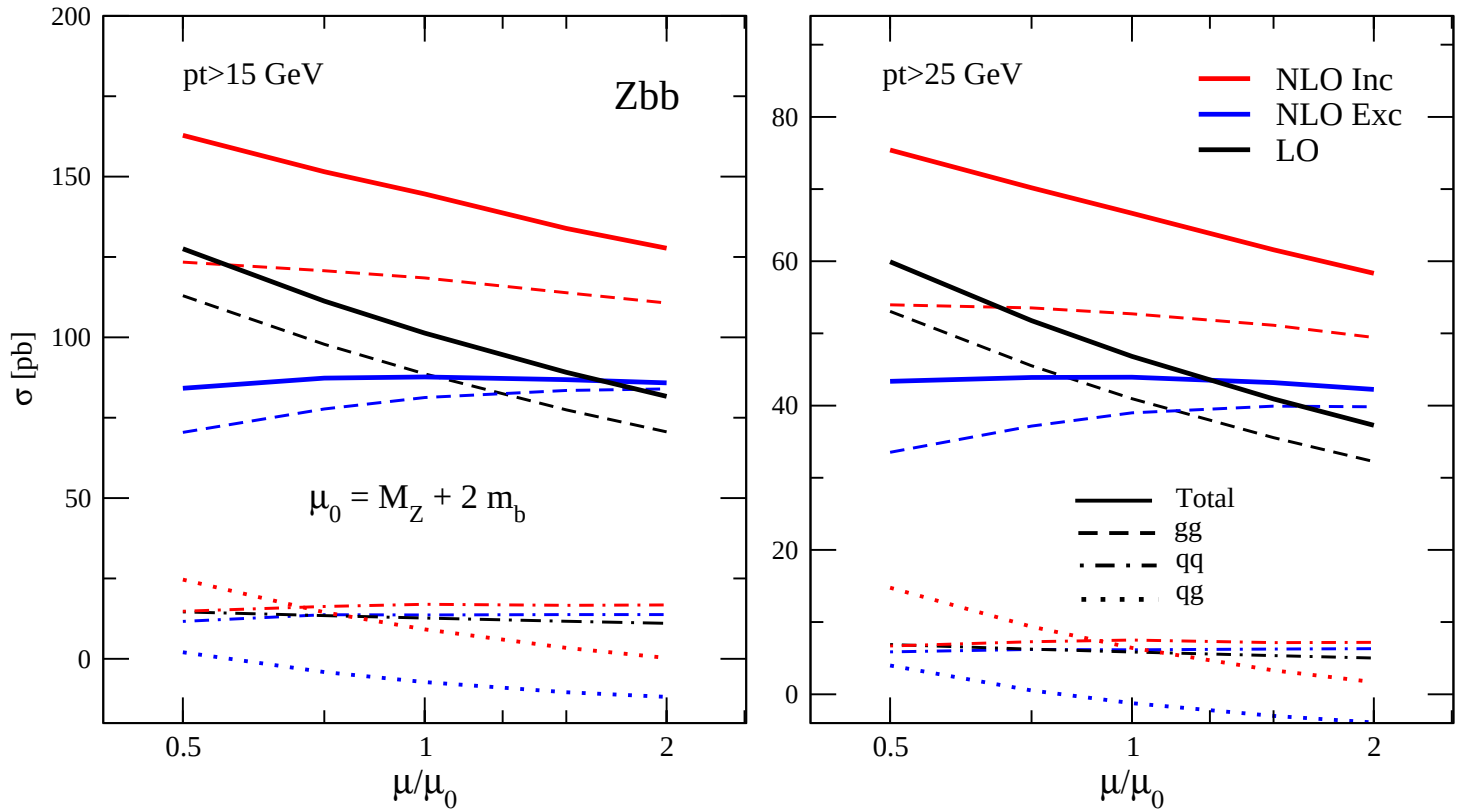


(PRD 80:034015, 2009)

⟶ NLO corrections very large, particularly for inclusive production;

⟶ large NLO scale-dependence (LO: 30%, $\mathrm{NLO_{inc}}$: 50%, $\mathrm{NLO_{exc}}$: 20%), induced by the opening of the $qg(\bar{q}g) \to Wb\bar{b} + q'(\bar{q}')$ channel;

⟶ theoretical uncertainty not only given by scale-dependence!

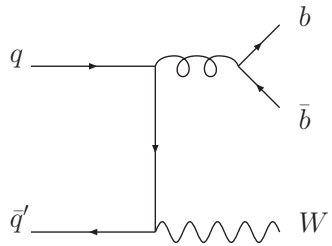


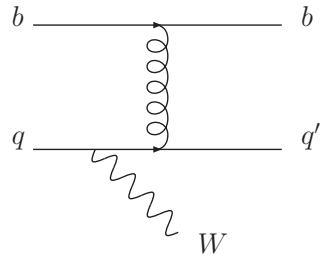
$\longrightarrow$ NLO corrections still large, particularly for inclusive production;

$\longrightarrow$ more moderate NLO scale-dependence (LO: 50%, $\mathrm{NLO_{inc}}$: 30%, $\mathrm{NLO_{exc}}$: 5%): $qg(\bar{q}g) \to Zb\bar{b} + q(\bar{q})$ channel not as dominant.

$W + 1b$ jet vs $W + 2b$ jets in a nutshell:

One or two LO processes, depending on choice of 4FNS vs 5FNS:

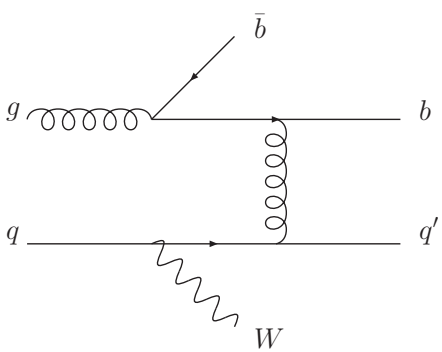




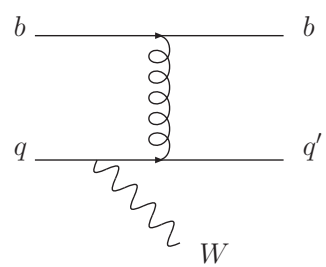
$+ \quad O(\alpha_s)$ corrections

Correspondently, at NLO:

1. $q\bar{q}' \to Wb\bar{b}$ at tree level and one loop ($m_b \neq 0$)
2. $q\bar{q}' \to Wb\bar{b}g$ at tree level ($m_b \neq 0$)
3. $bq \to Wbq'$ at tree level and one loop ($m_b = 0$)
4. $bq \to Wbq'g$ and $bg \to Wbq'\bar{q}$ at tree level ($m_b = 0$)
5. $gq \to Wb\bar{b}q'$ at tree level ($m_b \neq 0$) $\to$ avoiding double counting:



$\longrightarrow$



$$b(x, \mu_F) = \frac{\alpha_s}{2\pi} \ln \frac{\mu^2}{m_b^2} \int_x^1 \frac{dz}{z} P_{qg}(z) g\left(\frac{x}{z}, \mu_F\right)$$

- ▷ $W + 2b$ jets: processes $1 + 2 + 5$
- ▷ $W + 2$ jets with at least one b jet: processes $1 + \cdots + 5$.

- need to keep $m_b \neq 0$ for final state b quarks (one b quark has low p_T): first consistent NLO 5FNS calculation.

- four signatures studied: exclusive/inclusive, with single and double-b jets,

  → Wb exclusive: Wb only;
  → $W(b\bar{b})$ exclusive: $W(b\bar{b})$ only;
  → Wb inclusive: Wb, $Wb + j$, $Wb\bar{b}$;
  → $W(b\bar{b})$ inclusive: $W(b\bar{b})$ and $W(b\bar{b}) + j$.

- calculate $\sigma_{\rm event}$ and $\sigma_{\rm b-jet}$ where

$$\begin{aligned} \sigma_{b-\rm jet} &= \sigma_{\rm event}(Wb\,{\rm incl.}) + \sigma_{\rm event}(Wb\bar{b}) + \sigma_{\rm event}(W(bb)\,{\rm incl.}) \\ &= \sigma_{1j+2j} + \sigma_{\rm event}(Wb\bar{b}) \end{aligned}$$

- overall improved scale dependence: NLO corrections to $gq \to Wb\bar{b}q'$ partially included in 5FNS (see next slide).

- Tevatron study (compared to CDF measurement): $p_T^j > 15$ GeV, $|\eta^j| < 2$, cone algorithm ($R = 0.7$), CTEQ6M;

- LHC study (compared to ATLAS measurement): $p_T^j > 25$ GeV, $|\eta^j| < 2.1$, anti-k_T jet algorithm ($R = 0.4$), 4.2 GeV$\leq m_b \leq 5$ GeV, CTEQ6.6/MSTW08/NNPDF2.1;

Comparison with CDF measurement: a puzzle?

CDF Note 9321 (arXiv:0909.1505):

$$\sigma_{\mathrm{b-jet}}(W + b\,\mathrm{jets}) \cdot Br(W \to l\nu) = 2.74 \pm 0.27(\mathrm{stat}) \pm 0.42(\mathrm{syst})\ \mathrm{pb}$$

[Neu, Thomson, Heinrich]

From our $W + 1b$ jet calculation (arXiv:1001.3362, arXiv:1001.2954):

[Campbell, Febres Cordero, L.R.]

$$\sigma_{\mathrm{b-jet}}(W + b\,\mathrm{jets}) \cdot Br(W \to l\nu) = 1.22 \pm 0.14\ \mathrm{pb}$$

For comparison:

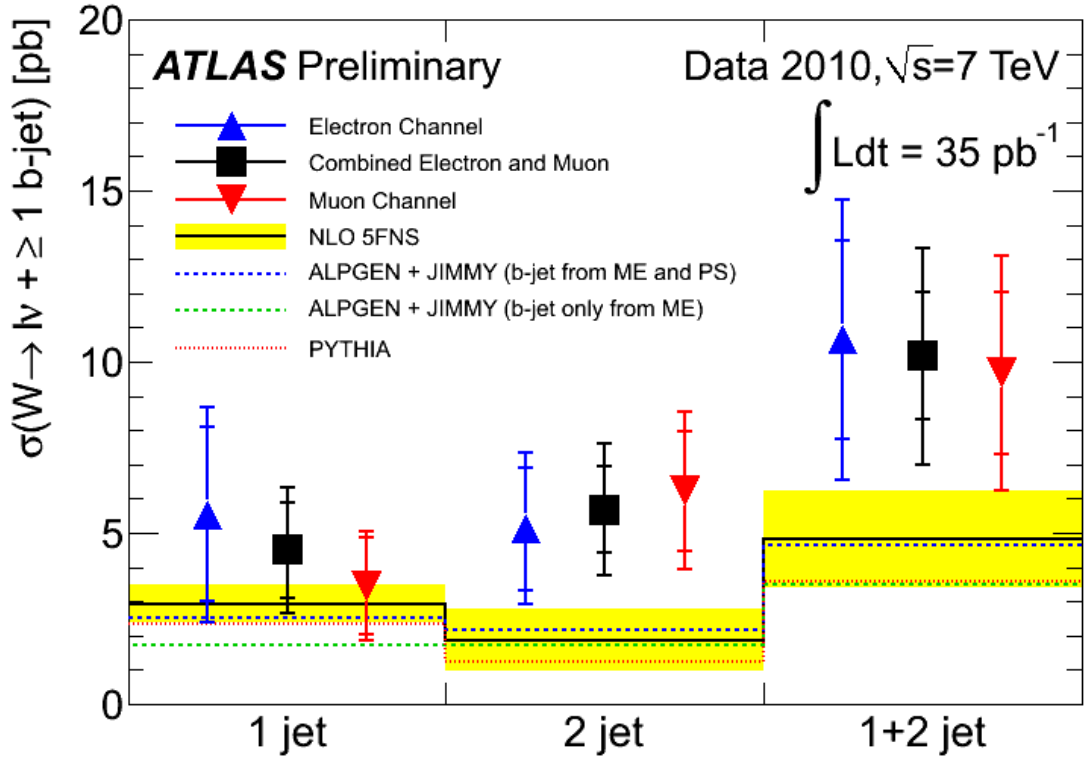
Badger, Campbell, Ellis: $0.913 < \sigma_{\mathrm{b-jet}} \cdot Br < 1.389$ pb

ALPGEN prediction: 0.78 pb

PYTHIA prediction: 1.10 pb

- overall consistency of theoretical results;
- important to have a separate analysis from $D0$!

Comparison with ATLAS



[the ATLAS collaboration, arXiv:1109.1470]

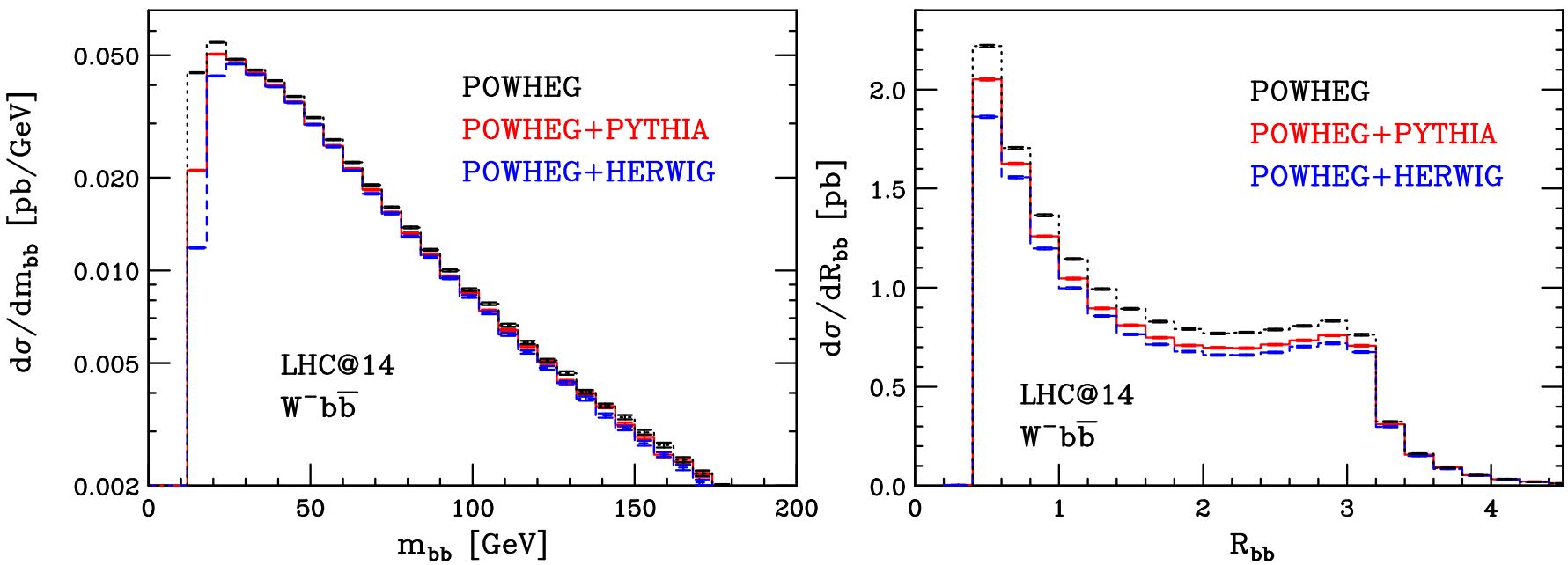
From our calculation (arXiv:1107.3714):

$$\sigma_{1j+2j}(W^+ + W^-) = 109.2\ ^{+27.9}_{-16.6}\,(\text{scale})\ ^{+7.4}_{-1.9}\,(\text{PDF})\ ^{+5.7}_{-3.3}\,(m_b)\ \text{pb}$$

More statistics necessary, possible new result by the end of the year.

Further development: $Wb\bar{b}$ implemented in POWHEG and MC@NLO, including $W \to l\nu_l$ decay.

Distribution sample:



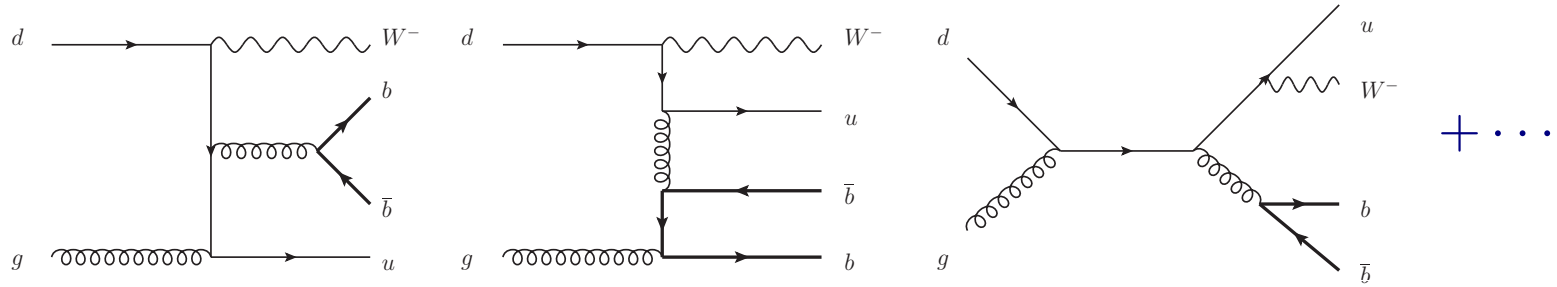
[Oleari, L.R., arXiv.1105.4488]

- used (e.g. in ATLAS analysis) to estimate showering and hadronization uncertainties: $\leq 10 - 20\%$;
- $bq \to bq'W$ process being implemented.

Further development: towards $Wb\bar{b} + j$ at NLO

[L.R., Schutzmeier, arXiv:1110.4438]

- One-loop QCD corrections to $qg \to Wb\bar{b} + q'$:



plus about 300 loop diagrams, keeping full m_b dependence.

- Together with analogous corrections to $q\bar{q}' \to Wb\bar{b} + g$ (obtained by crossing), they represent a well-defined piece of the NNLO QCD corrections to $pp, p\bar{p} \to Wb\bar{b}$: the one-loop virtual corrections from $2 \to 4$ processes.

- They provide the $O(\alpha_s)$ virtual corrections for $pp, p\bar{p} \to W + 2b\,\text{jets} + j$.

- In a fixed-flavor scheme, they also provide the $O(\alpha_s)$ virtual corrections for $pp, p\bar{p} \to W + b\,\text{jet} + j$.

Method's main characteristics

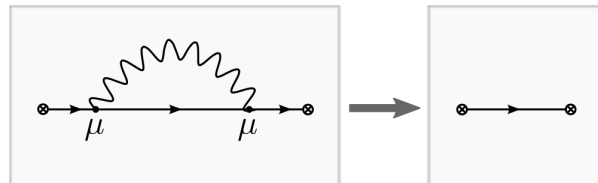
- Based on traditional Feynman-diagram evaluation.
- New techniques developed to
  - reduce diagram structure to small/minimal set of standard spinor structures using graph techniques;
  - combine different reduction methods to optimize calculation of numerically stable tensor integral coefficient.
- Each level of evaluation automatized within an overall interface (`Python`) that only takes as input the desired process:
  - diagram generated with a very modified version of `QGRAPH`;
  - algebraic manipulations to extract first level of SME and tensor structures done with `FORM`;
  - reduction of tensor integral coefficients and spinor structures use `C++`;
  - numerical stability checks use library of scalar integrals based on `QCDLoop` and `LoopTools`;
  - amplitude square calculation uses `C++` to provide a user-friendly interface.

Reduction of spinor structures

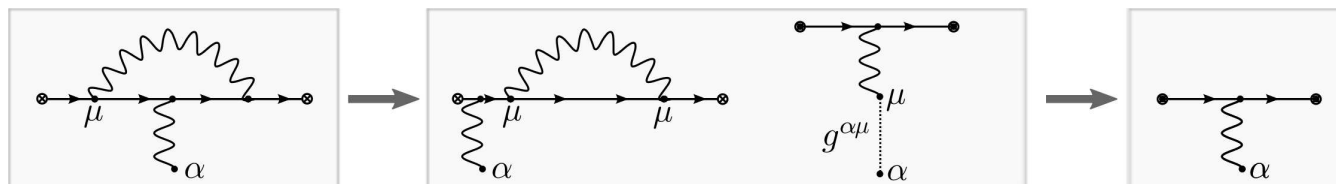
spinor structures (standard matrix element or SME) → oriented graphs:

- nodes → spinor, gamma matrices, projectors, polarizations, ...
- links → contraction of indices and direction.

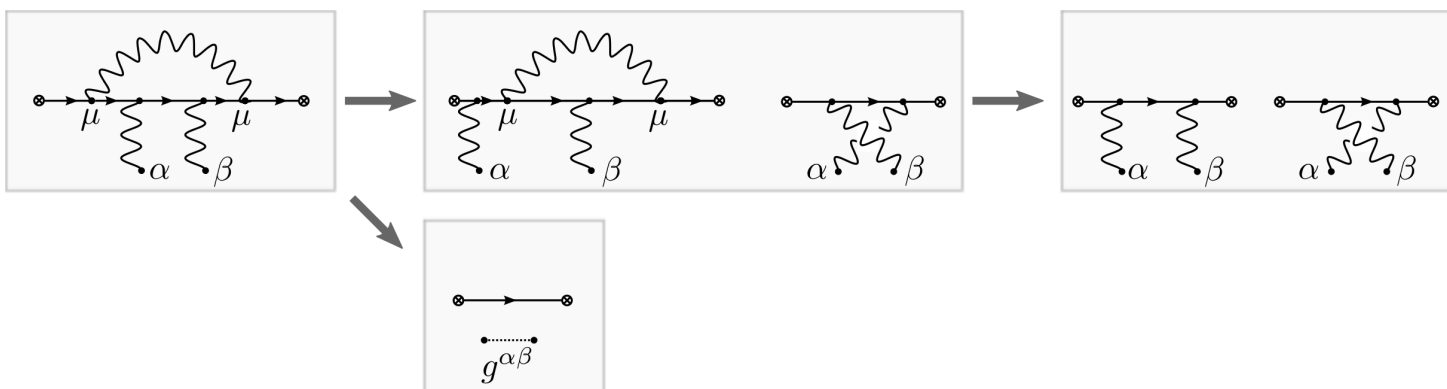
$\gamma^\mu \gamma_\mu$



$\gamma^\mu \gamma^\alpha \gamma_\mu$

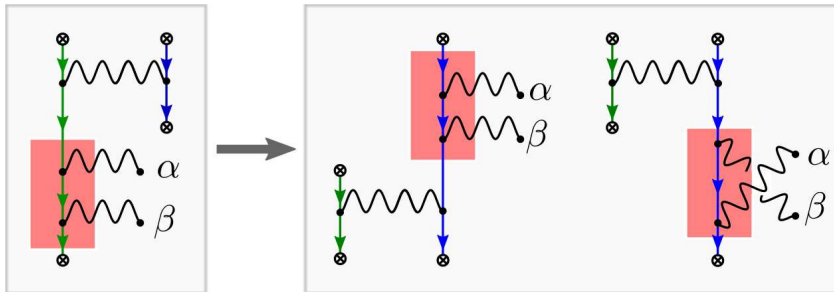


$\gamma^\mu \gamma^\alpha \gamma^\beta \gamma_\mu$

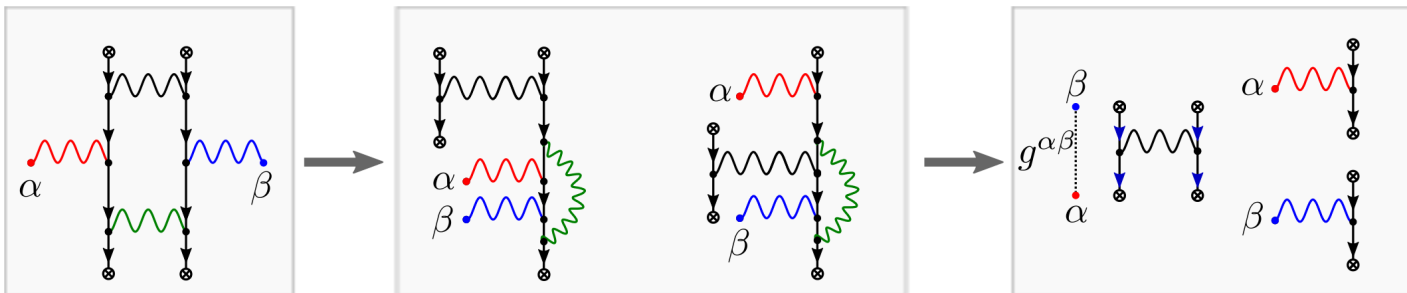


oriented graphs → stored as relations and graph operations that are automatically implemented over the entire structure of a diagram at once,

$$\gamma^\mu\gamma^\alpha\gamma^\beta P_+ \times \gamma_\mu =$$
$$\gamma^\mu P_+ \times (\gamma_\mu\gamma^\beta\gamma^\alpha P_+ + \gamma^\alpha\gamma^\beta\gamma_\mu P_-)$$



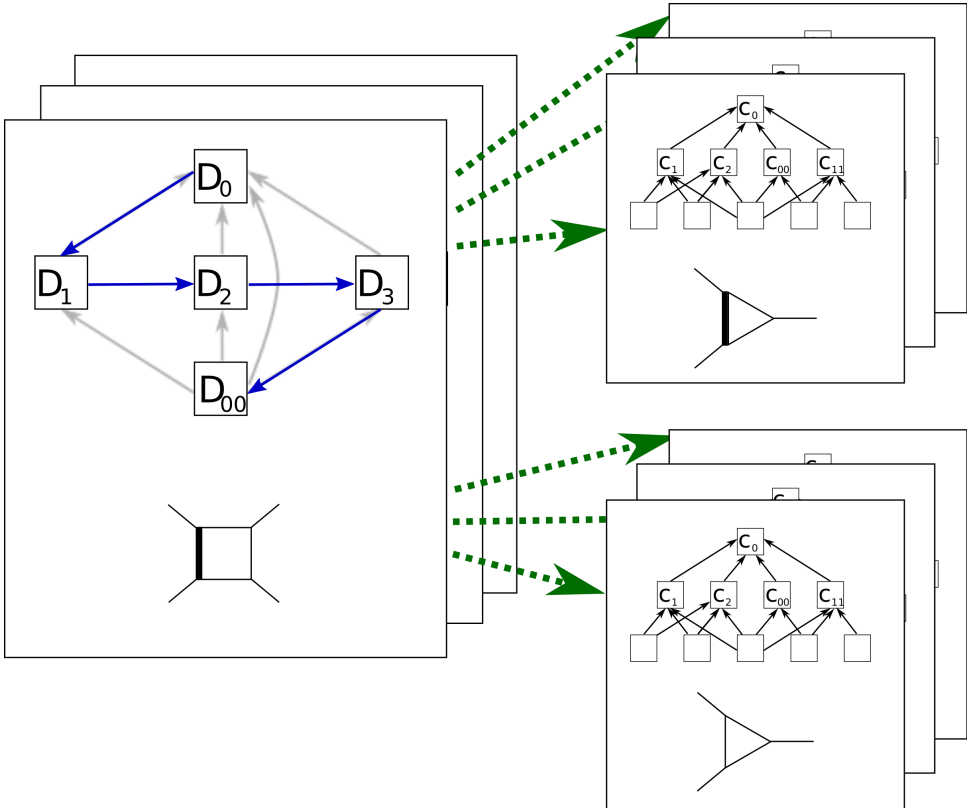
↪



- ▷ algebraic relations (based on d=4 identities) translate into graph operations (e.g. shrinking of edges, exchange or addition of nodes, ...) and result into disconnected elementary graphs;
- ▷ number of final SME much smaller (from thousands to a a few hundreds);
- ▷ coefficients of single elementary graphs collected via systematic labeling .

Reduction of tensor-integral coefficients

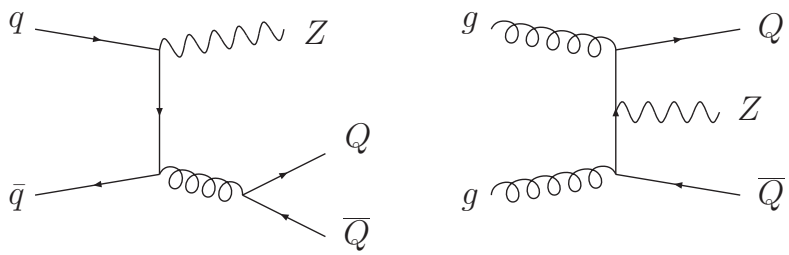
- reduce to standard pattern of momenta and masses;
- create list of dependences that are then reused every time the same pattern appears,including subdiagrams;
- choose evaluation order.



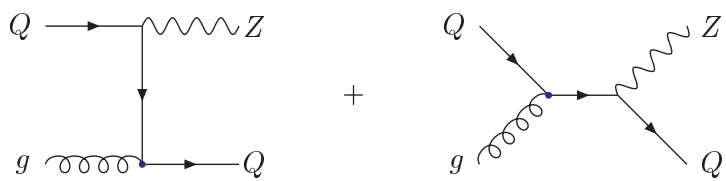
- if presence of numerical instabilities detected, switch to different reduction method.

$Z + 1b$ jet vs $Z + 2b$ jets in a nutshell:

LO processes, depend on choice of 4FNS vs 5FNS:



$+ \quad O(\alpha_s)$ corrections



$+ \quad O(\alpha_s)$ corrections

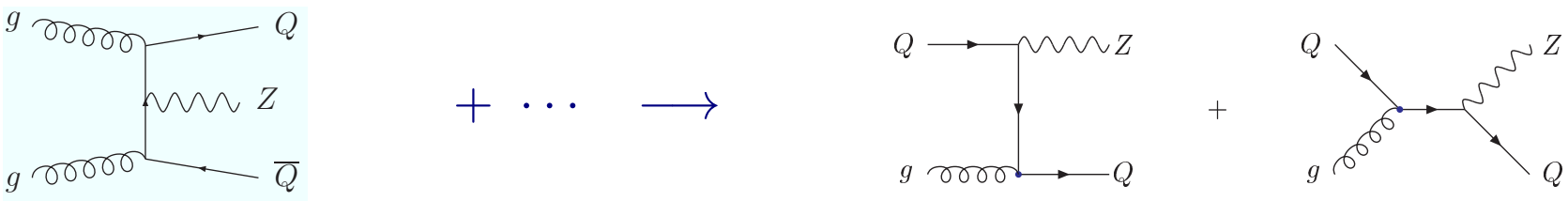
Correspondently, at NLO:

1. $bg \to Zb$ at tree level and one loop (with $m_b = 0$);
2. $bg \to Zb + g$, $bq \to Zb + q$ (with $m_b = 0$);
3. $q\bar{q}, gg \to Zb\bar{b}$ at tree level and one loop (with $m_b \neq 0$);
4. $q\bar{q}, gg \to Zb\bar{b} + g$ and $gq(g\bar{q}) \to Zb\bar{b} + q(\bar{q})$ (with $m_b \neq 0$).

avoiding double counting in (3) and (4).

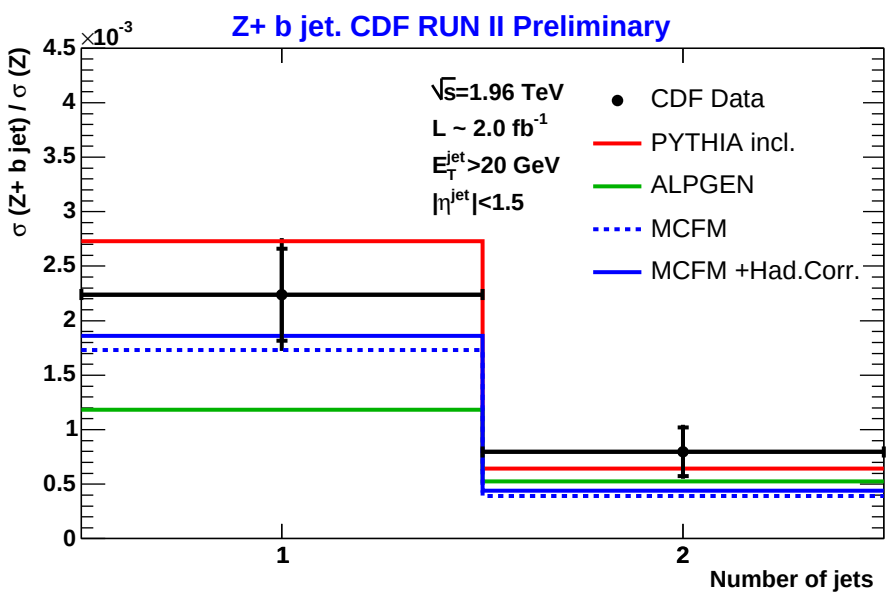
- ▷ $Z + 2b$ jets: processes $3 + 4$
- ▷ $Z + 2$ jets with at least one b jet: processes $1 + \cdots + 4$ (?).

Observe that,



quite different pattern:

- are one loop corrections to $q\bar{q}, gg \to b\bar{b}Z$ to be interpreted as a piece of the NNLO 5FNS calculation, comparable to two-loop corrections to (and double parton emission from) $bg \to Zb$?
- overall better agreement with data.



$$\text{MCFM} \to 1 + 2 + (3 + 4)_{LO}$$

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:
  - ▷ precision studies (m_t and parton luminosity from $Q\bar{Q}$);
  - ▷ signal of new physics: $t\bar{t}H$, $b\bar{b}H$;
  - ▷ background to new physics signals: $b\bar{b}W$, $b\bar{b}Z$.
  - ▷ test ground of QCD ($2 \to 2$ at NNLO, $2 \to 3$ at NLO).
- Prepare to use $t\bar{t}H$, $b\bar{b}H$ to test couplings of the 125 GeV resonance:
  - ▷ interface with parton shower MC available, for both signal and background;
  - ▷ refine $H + 1b$ calculation.
- Improve $W/Z + b$-jets comparison with data.