# Heavy-quark production at large rapidities

in collaboration with
Andersen, Del Duca, Frixione and Stirling
hep-ph/0408239

# The role of b-pdf in Higgs and Vector Boson production

from work done in collaboration with
Campbell, Ellis, Willenbrock and
the Les Houches "b-Higgs" group

Fabio Maltoni
Cern

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# Motivations

- To find evidence for "BFKL" type of resummation, typical of the high-energy limit of QCD.
- Inclusive measurements, such as that of $F_2(x, Q^2)$ at small x, are difficult to associate only to one kind of resum (vs. DGLAP)
- More exclusive quantities have been studied and compared to both analytic results and dedicated MonteCarlo's
- No smoking gun has been found yet!

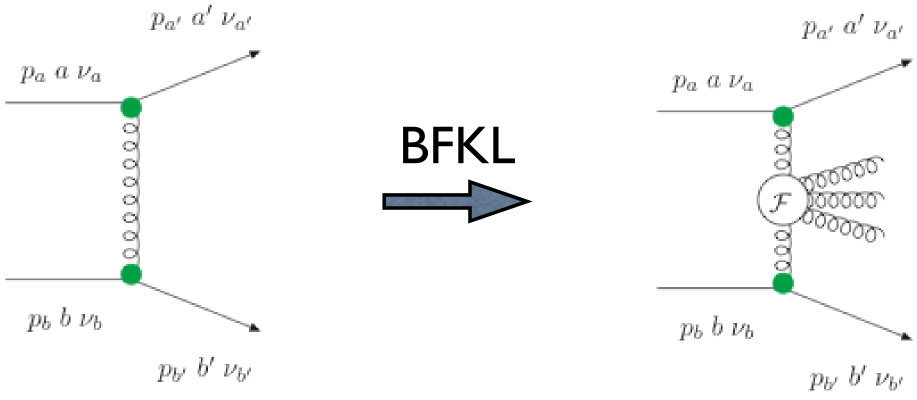
Continuous on-going effort!

# Main ingredients & strategy

- Scattering processes in the high-energy limit $s \gg |t|$ , are dominated by sub-processes with a gluon exchanged in the t-channel

- BFKL resums multiple gluon radiation out of such a gluon, resumming $\alpha_S^n \log^n \frac{s}{t}$ terms

Example: Dijet production




$\sigma_{res} = e^{\lambda \Delta y}$

# Main ingredients & strategy

1. Consider a process that in given kinematic configuration is dominated by a t-channel gluon.

2. Quantify how well the HE approximation works (Born BFKL) for the actual energies in the experiment.

3. Include the best fixed-order prediction for the observable and check if it describes the data.

4. Check that other resummations (soft or collinear) are not important.

5. Include BFKL radiation possibly conserving energy and momentum, ie with a dedicated MonteCarlo.

6. Estimate uncertaintes and...

7. Compare with data!

# Phenomenology

- Forward jet in DIS

  Mueller, 1991
  Bartels, De Roeck, Loewe 1992
  ...

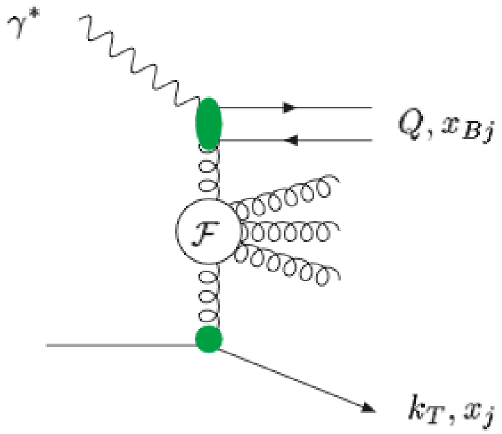
- $\gamma^*\gamma^* \rightarrow$ hadrons

  Bartels, De Roeck, Lotter 1996
  Brodsky, Hautmann, Soper 1997

- Dijet production in pp

  Mueller, Navelet 1987
  Schmidt, Del Duca; Stirling 1993-95

# Forward jet in DIS

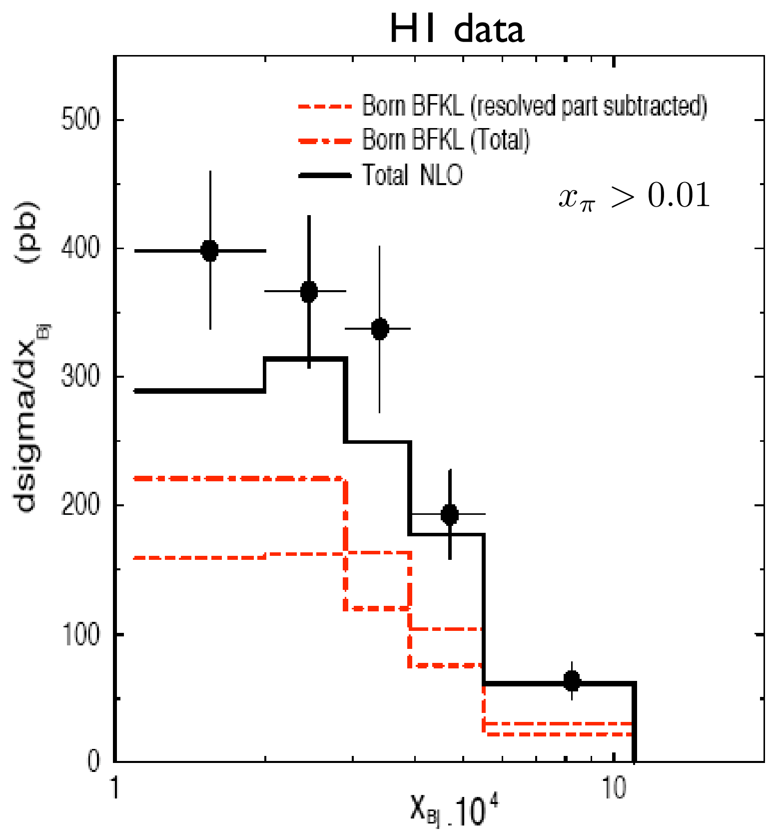


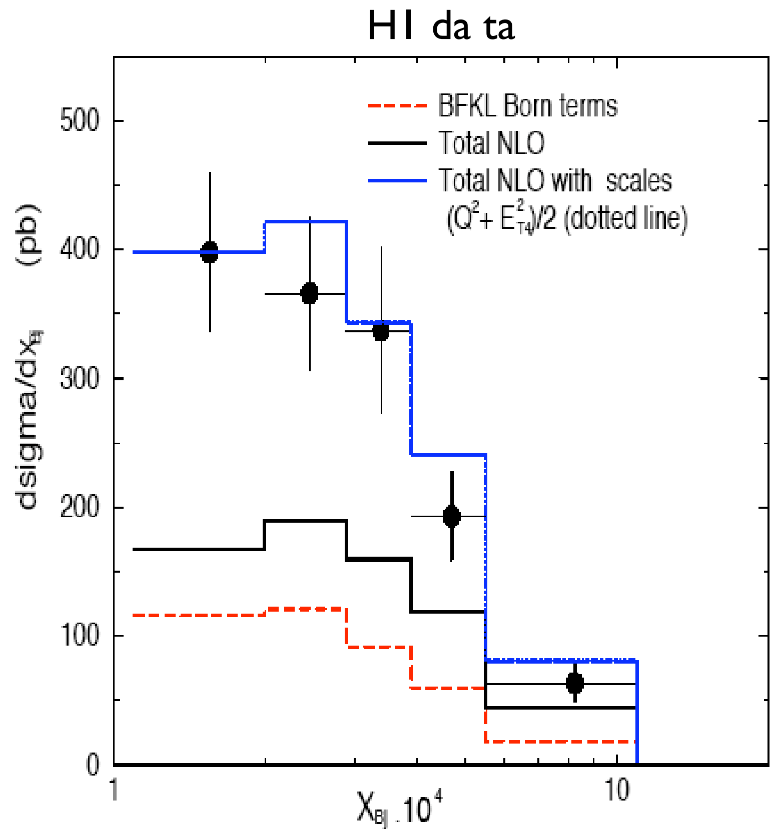

$$\log \frac{\hat{s}_{\gamma j}}{Q^2} = \log \frac{x_j}{x_{Bj}} \gg 1$$

$$\hat{\sigma}_{jet} = \left( \frac{x_j}{x_{Bj}} \right)^{\lambda}$$

$$Q^2 \simeq k_T^2$$

# Forward jet in DIS




Aurenche, Basu, Fontannaz, Godbole, 2004

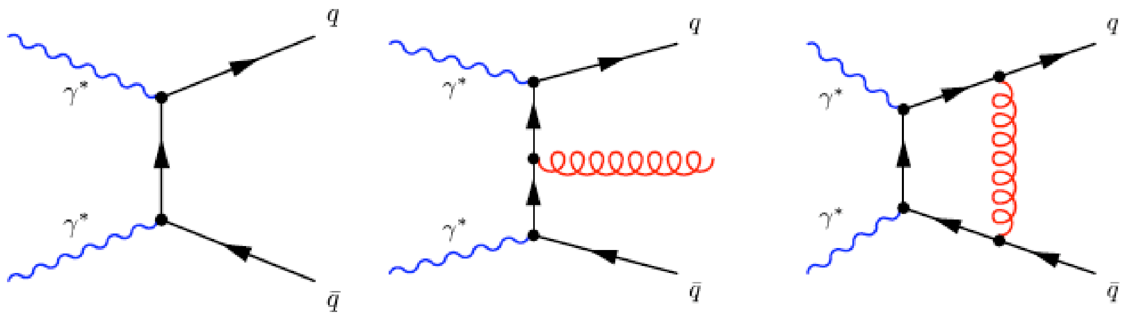
Large contribution from HO terms:

1. LO BFKL diagrams first appearing at NLO
2. Resolved photon which is "ad hoc" since $Q^2 \simeq E_T^2$

Large scale dependence ➡ NNLO calculation would help

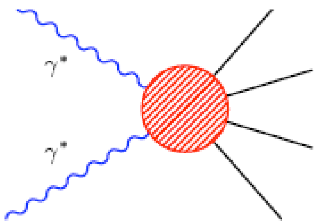
# $\gamma^* \gamma^* \to$ hadrons

The fixed order expansion in $\alpha_S$




LO

NLO

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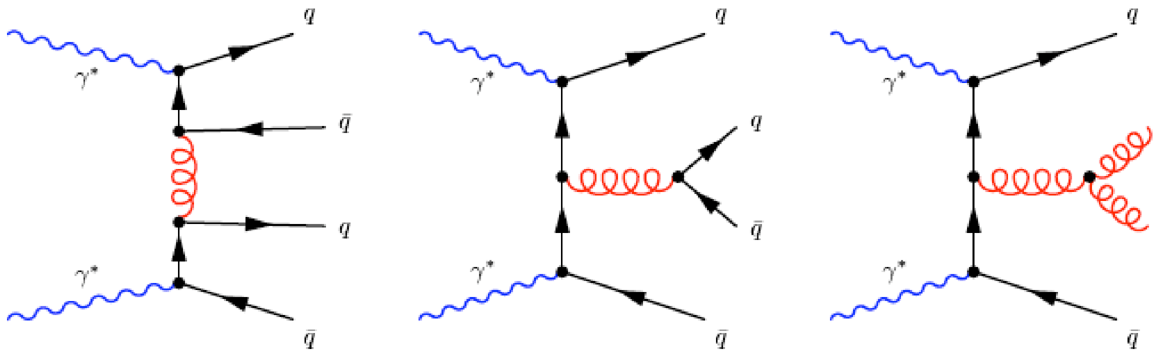
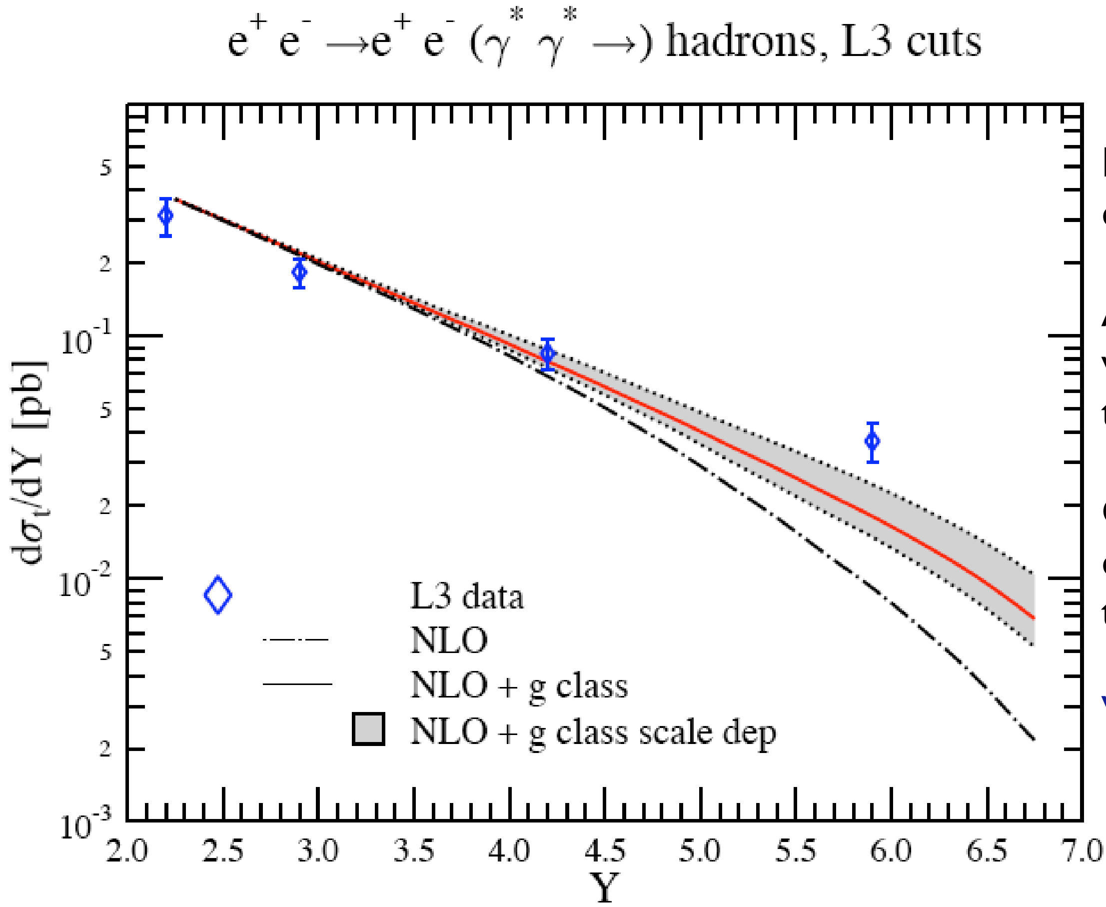



BFKL (Born)

NNLO (4-partons)

# $\gamma^*\gamma^* \to$ hadrons




NLO is not enough to describe the data

Adding some NNLO (finite) terms, which correspond to the BFKL LO term, softens the discrepancy.

Considering the strong scale dependence there is no evidence for the need of resummation.

Very similar to the DIS situation!

Cacciari, Del Duca, Frixione, Trocsanyi, 2001

Del Duca, F.M., Trocsanyi, 2002

# Phenomenology

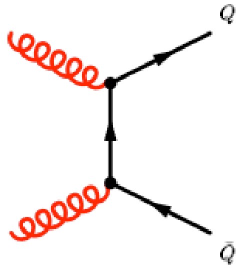
- Forward jet in DIS — Mueller, 1991; Bartels, De Roeck, Loewe 1992; ...
- $\gamma^* \gamma^* \to$ hadrons — Bartels, De Roeck, Lotter 1996; Brodsky, Hautmann, Soper 1997
- Dijet production in pp — Mueller, Navelet 1987; Schmidt, Del Duca; Stirling 1993-95
- $pp \to Wjj$ — Andersen, Del Duca, F.M., Stirling, 2001
- $pp \to Q\overline{Q}Q\overline{Q}$ — Andersen, Del Duca, Frixione, F.M., Stirling 2004

# The perturbative expansion for two b's at large rapidity

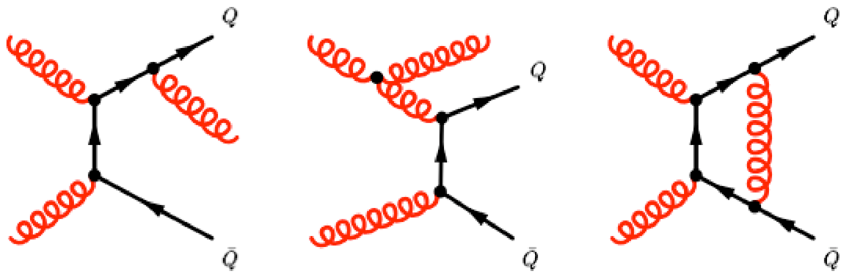
$$\frac{d\sigma_{Q\bar{Q}}}{d\Delta y} \sim \alpha_S^2 \sum_{j=0}^{\infty} a_{0j}\alpha_S^j$$

$$+\alpha_S^4 \sum_{j=0}^{\infty} a_{1j}(\alpha_S L)^j$$

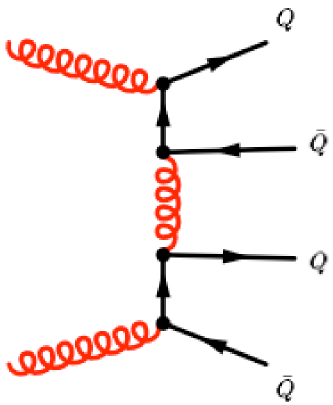
$a_{00}$



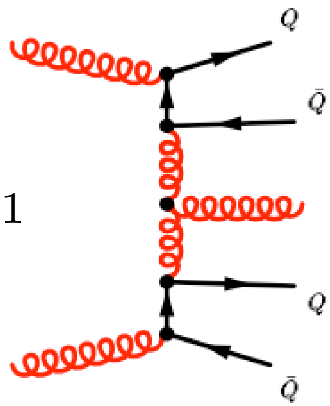

$a_{01}$



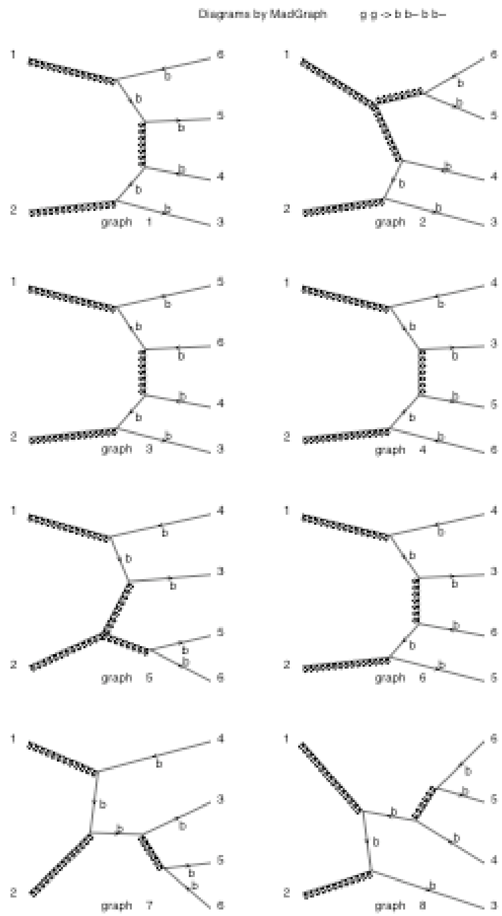

$a_{10}$




$a_{11}$

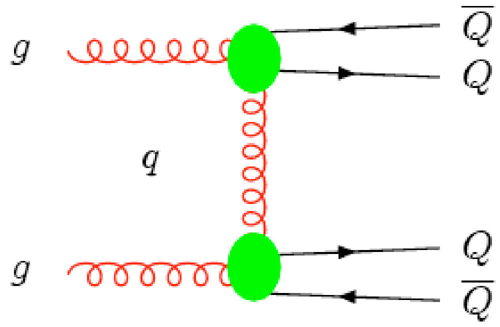


# The high-energy limit of pp → 4Q




76 diagrams

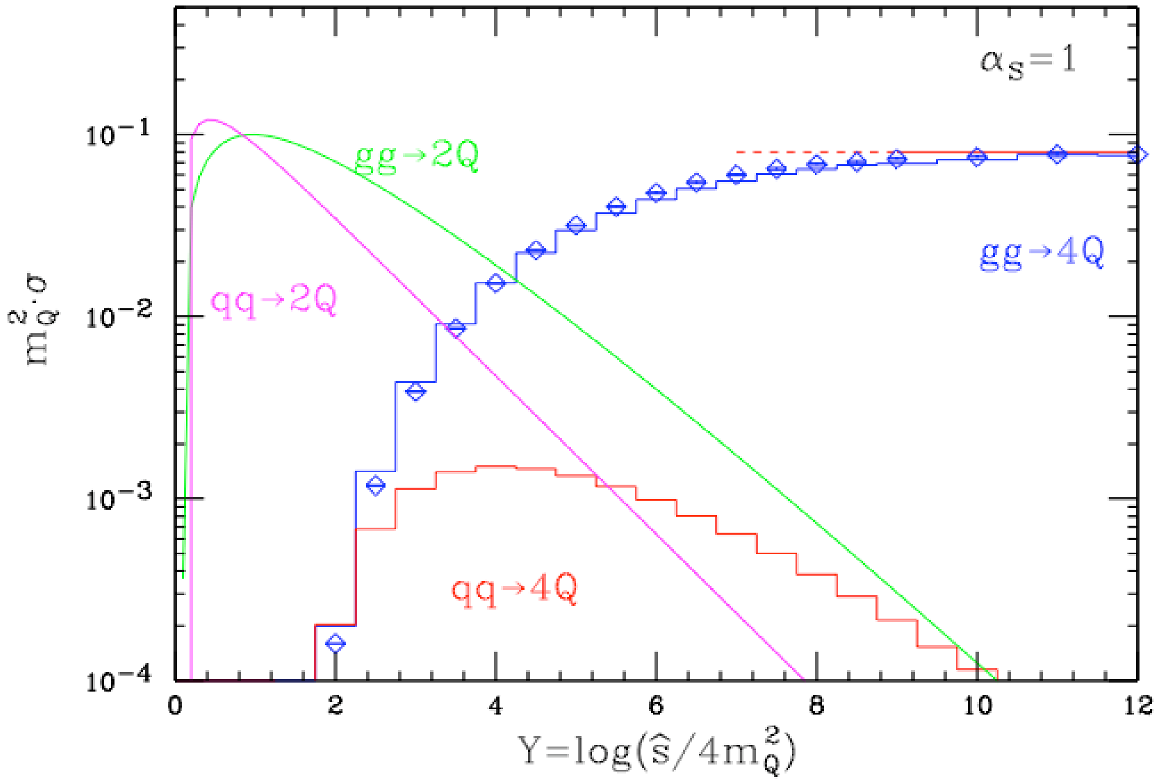
$$y1_{QQ} \gg y2_{QQ}$$




$$|\mathcal{M}|^2 \to \frac{4\hat{s}^2}{\hat{t}^2} I^{Q\overline{Q}}(q) I^{Q\overline{Q}}(-q)$$

☞ The HE limit is even more powerful than the collinear limit for unraveling the structure of QCD amplitudes!

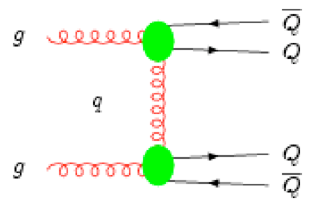
# How well the HE limit works?

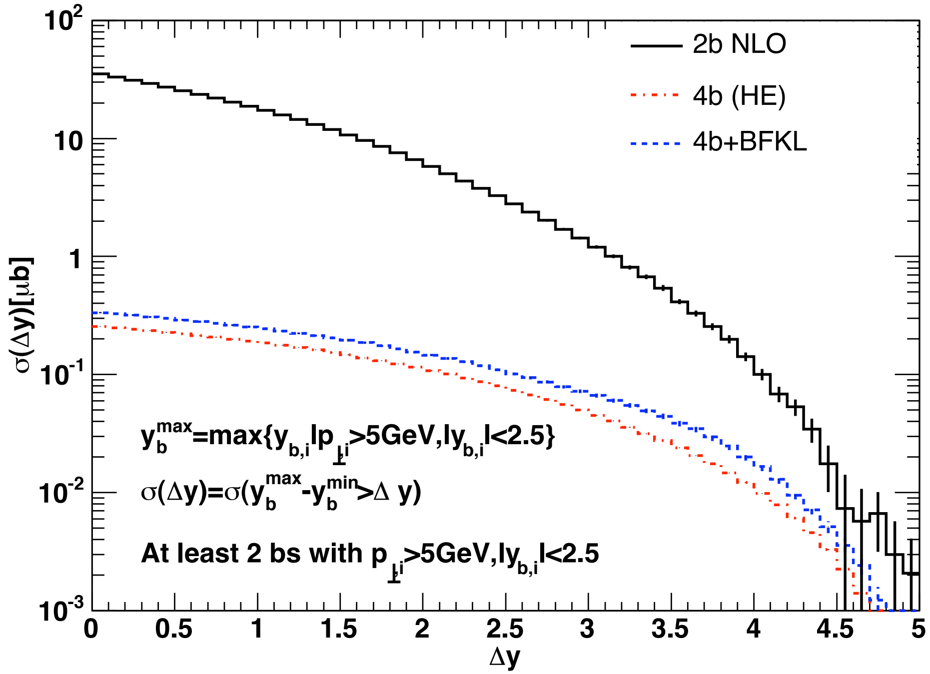



The asymptotic result can be obtained exactly (Ross and Ellis 1990):

$$\sigma_{gg} = \frac{\alpha_S^4}{\pi m_Q^2} \frac{1}{N_c^2 - 1} \left[ \frac{23 N_c^2}{81} - \frac{277}{486} + \left( \frac{175\zeta(3)}{576} - \frac{19}{288} \right) \frac{1}{N_c^2} \right] \simeq \frac{\alpha_S^4}{\pi m_Q^2} 0.803$$

# Results for 4b




The 4b cross section never dominates over the 2b in the allowed kinematical range.

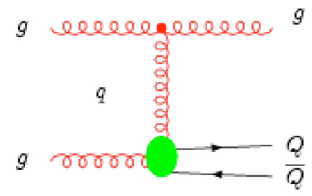
Modest increase due to the BFKL radiation.

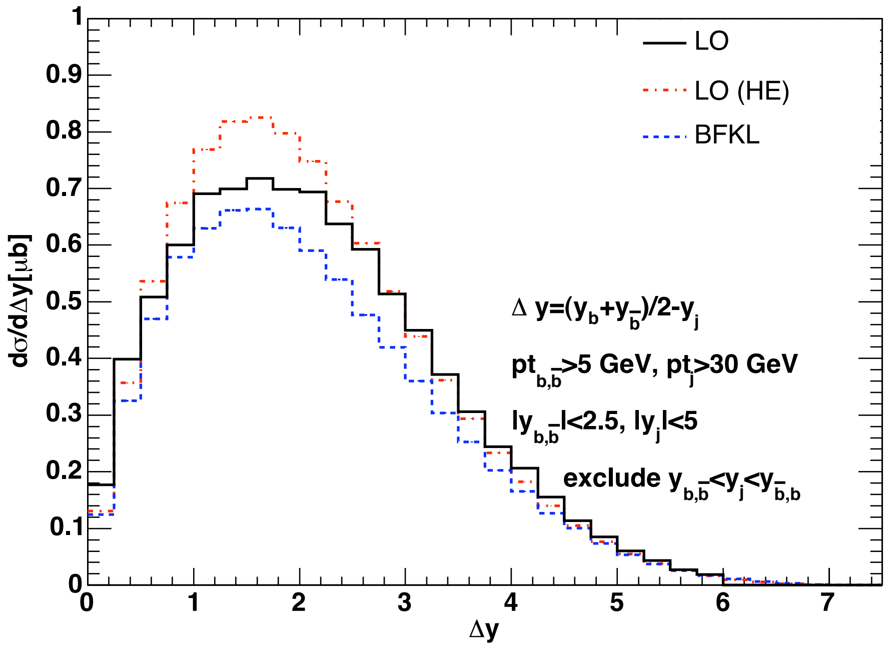
In order to suppress the 2b contribution one could:

1. ask for at least 3b in the final state

2. identify the charge of the b and ask for same two same charge b's at large rapidity

# Results for 2b+jet




The 2b+jet signature is similar to the MN jet setting, but with a QQ pair on one side.

It's part of the bb cross section @ NLO, but features a gluon in the t-channel.

The addition of BFKL radiation slightly reduces the cross section.

Possibility of studying azimuthal angular decorrelation without soft logs?

# Conclusions

Heavy-quark production at large rapidities

- Various studies for the "detection" of BFKL dynamics have been proposed
- No clear evidence of the need to resum BFKL logs yet
- We have studied various signatures involving heavy quarks at large rapidities
- Can something similar, ie with HF, be done at HERA?

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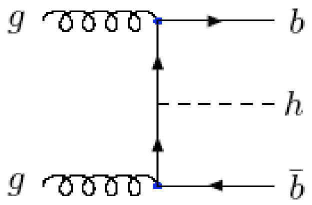
# Some examples of b-initiated processes

| Process | Interest | Accuracy |
|---|---|---|
| single-top t-channel | SM, top EW couplings and polarization, $V_{tb}$. Anomalous couplings. | NLO |
| single-top + W | | NLO |
| Wbj | SM, bkg to single top | (NLO) |
| gamma+b | SM, SUSY bkg, b-pdf | NLO |
| Z+b | | NLO |
| inclusive h,A | SUSY discovery/ measurements at large tan(beta) | NNLO |
| h,A+b | | NLO |
| $H^+$ + t | SUSY discovery, couplings | NLO |

Wide interests and best attainable accuracy

# Higgs production with bottom quarks

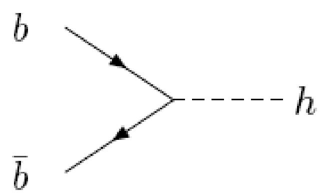
## One way:



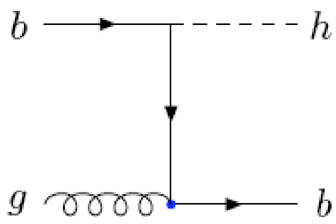

Keep the b massive and use the gg process for all three studies. The b mass acts as an infrared cutoff and there are no divergences. This is the 4 Flavour Scheme (4FS)

## or the other:

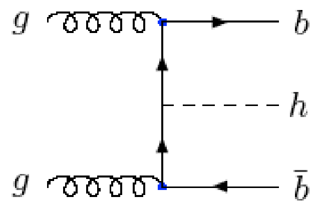
The "leading-order process" depends on how INCLUSIVE is the measurement to be performed:




FULLY INCLUSIVE




1 b at high $p_T$




2 b's at high $p_T$

In so doing the large logs $\alpha_S \ln\left(\frac{m_h^2}{m_b^2}\right)$ are resummed into the $b$ distribution function $b(x, m_h^2)$

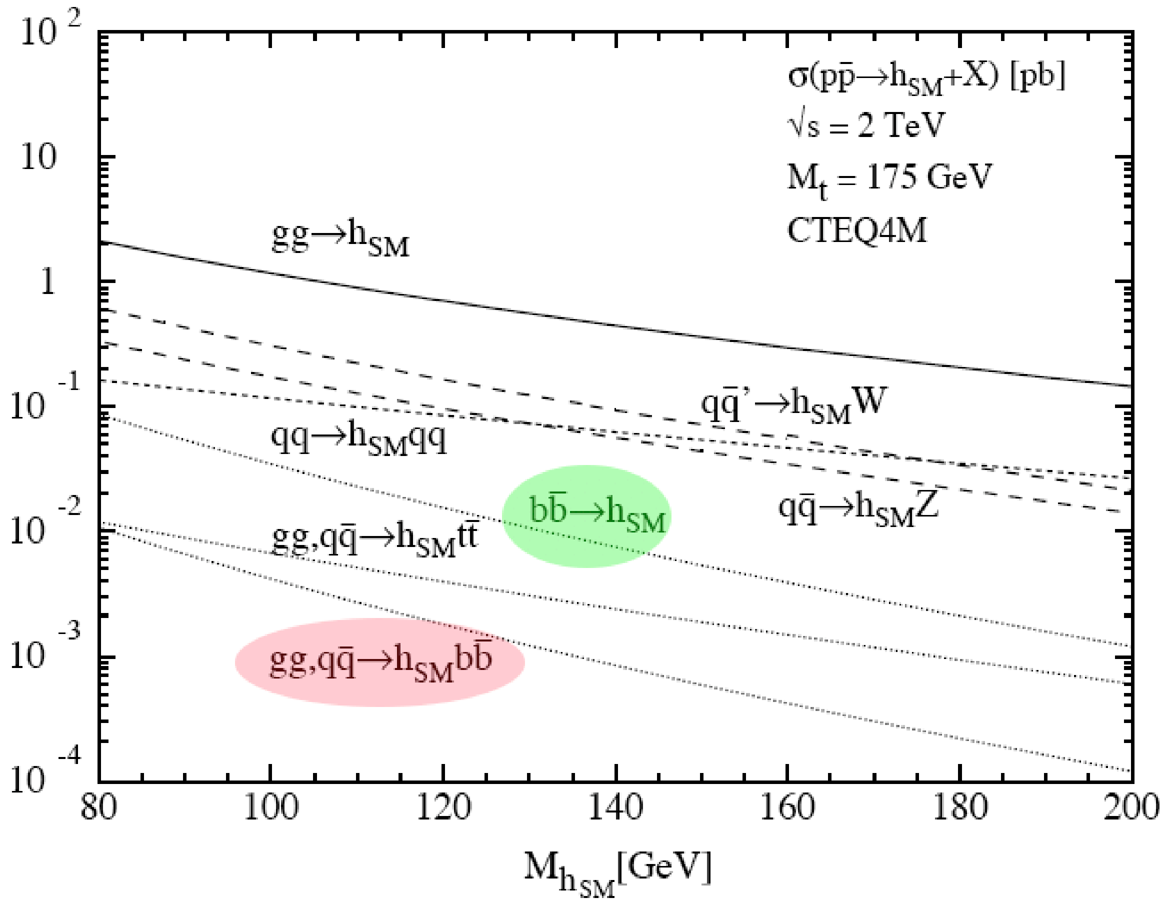
This is the 5 flavour scheme.

# Recent progress

- 1989 Dicus, Willenbrock (LO)
- 1999 Dicus, Stelzer Sullivan Willenbrock (NLO)
- 1999 Balazs, He , Yuan (NLO)
- 2003 F.M., Sullivan, Willenbrock (NLO)
- 2003 Kilgore, Harlander (NNLO)
- 2003 Dittmaier, Kraemer, Spira
- 2003 Dawson, Jackson, Reina, Wackeroth

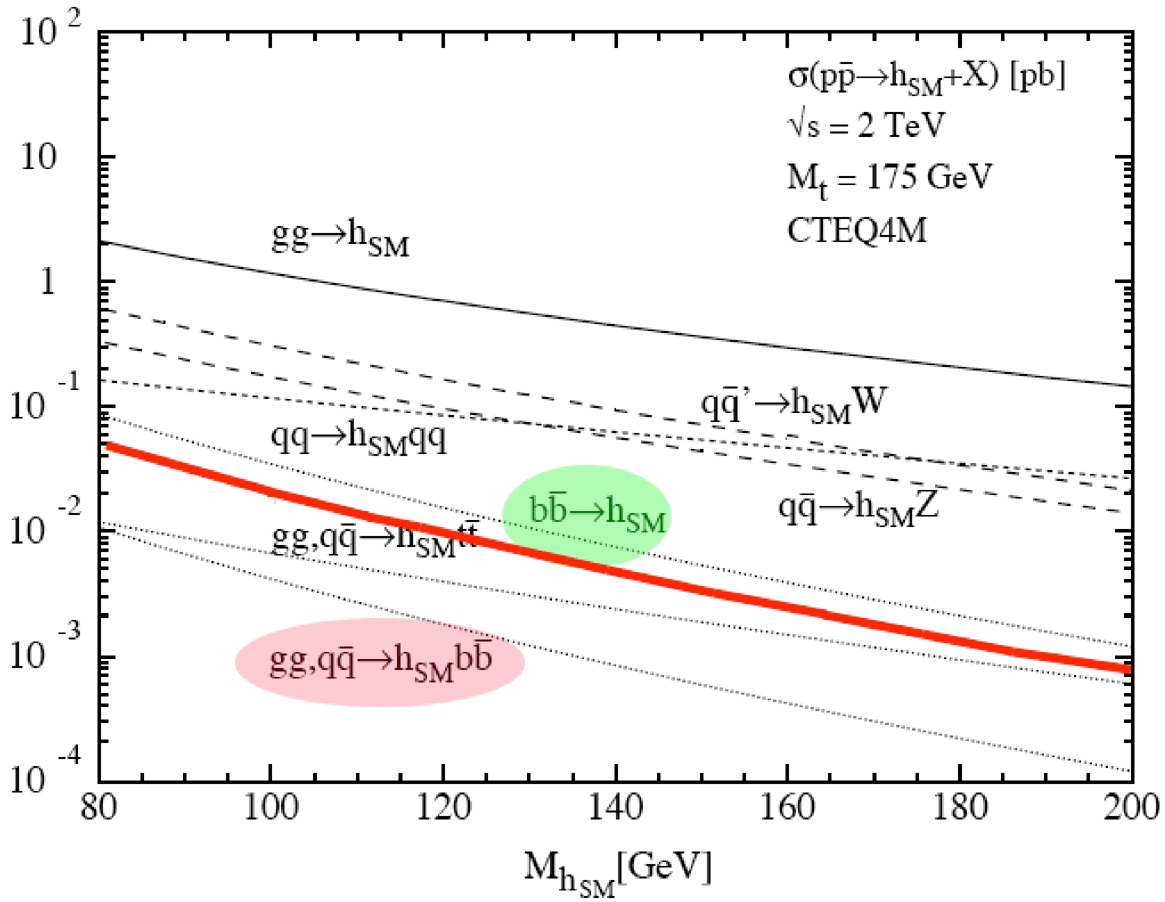
} $pp \to bbh$ at NLO

# Theoretical status in the 1998

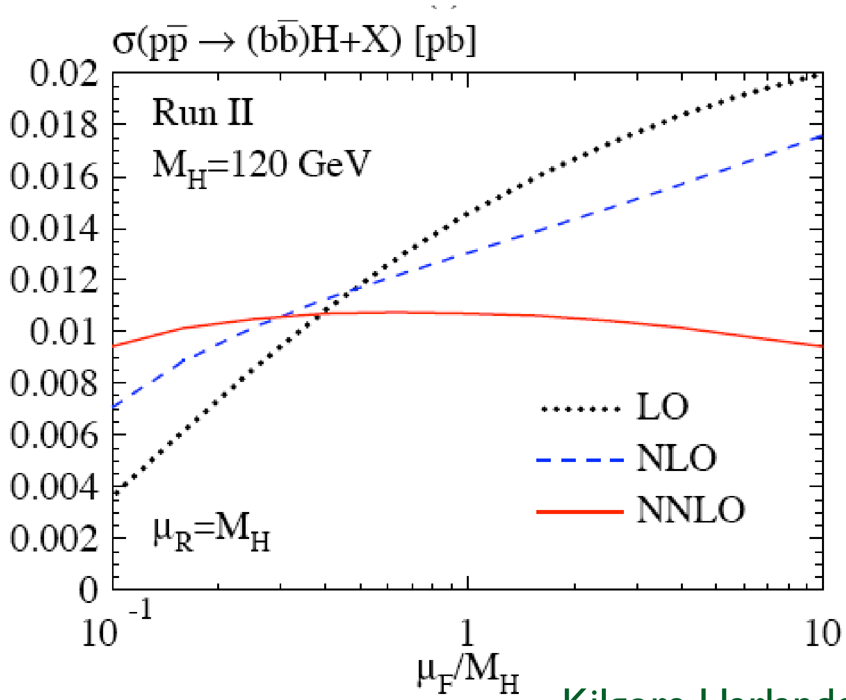



Higgs Tevatron Workshop 1998

# Theoretical status in the 2004



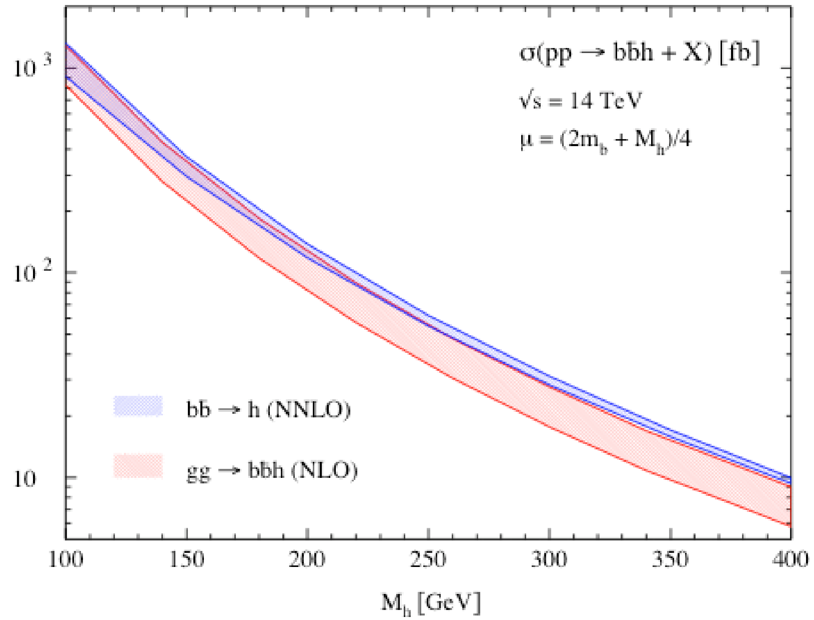
# $b\bar{b} \to h$ @ NNLO




Kilgore Harlander, 2003

NNLO calculation confirms preferred scale choice for NLO calculation ≈ mh/4 (F.M., Sullivan, Willenbrock, 2003).

# $b\bar{b} \to h$
## 4FS vs. 5FS



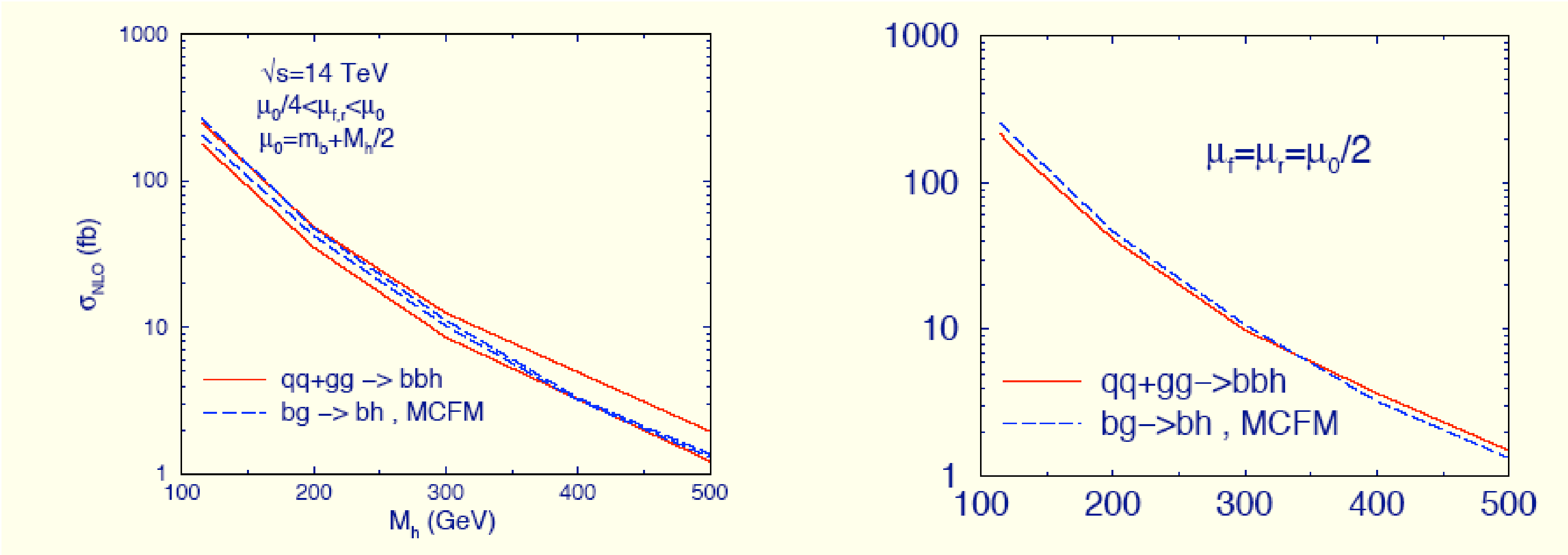

Campbell et al. (Les Houches Higgs Group), 2004

Very satisfactory agreement, but depends on what is chosen for reference scale in the 4FS.

The 5FS calculation has a very small uncertainty, as the Higgs mass increases, as expected.

In the $b\bar{b} \to h$ calculation (5FS) there is no information on the final state b's $\Rightarrow$ Use MC's and compare to the 4FS NLO calculation.

# h + 1 b-jet at high pt
# 4FS vs. 5FS




Dawson, Jackson, Reina, Wackeroth, 2004

- ☞ A very detailed and careful comparison has been made.
- ☞ Very satisfactory agreement on total rates and distributions.
- ☞ For large Higgs masses, the 5FS calc. is less uncertain, as expected.

# Bottom line

The 4FS and 5FS give consistent results⇒

1. The effect of the resummation of the logs, at least for small and intermediate higgs masses, is mild.

2. The b-pdf, as obtained with evolution from the gluon in the 5FS, is consistent with the fixed order calculation in the 4FS.

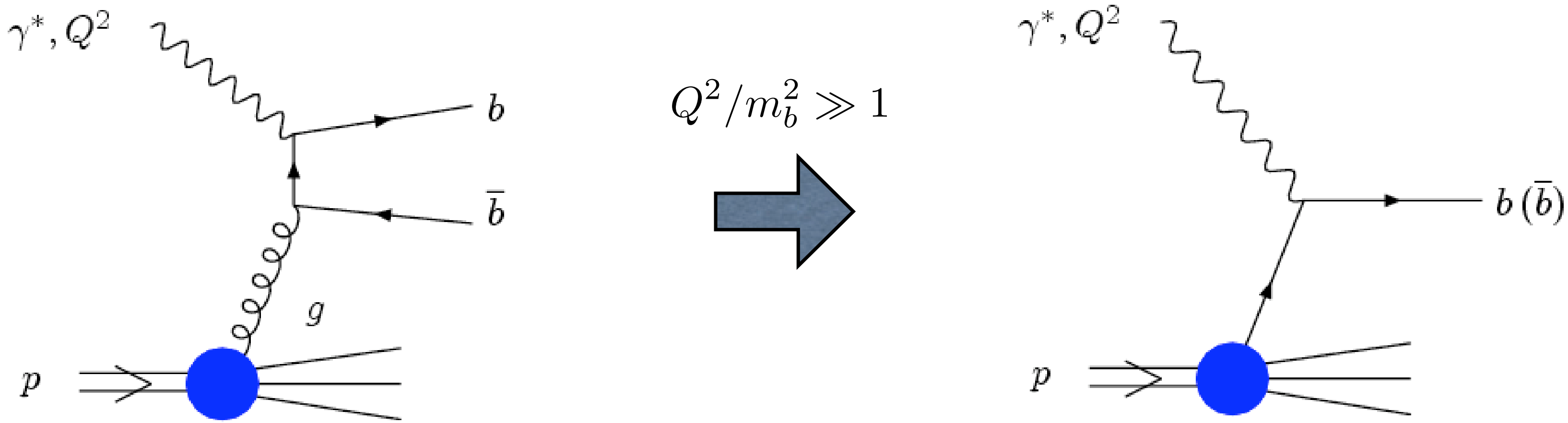
## Can we measure the b-pdf directly?

Proposals:

1. Use HERA "inclusive" b measurements

2. Use Tevatron and/or LHC data for Z+b (and gamma+b?)

# Bottom production in DIS

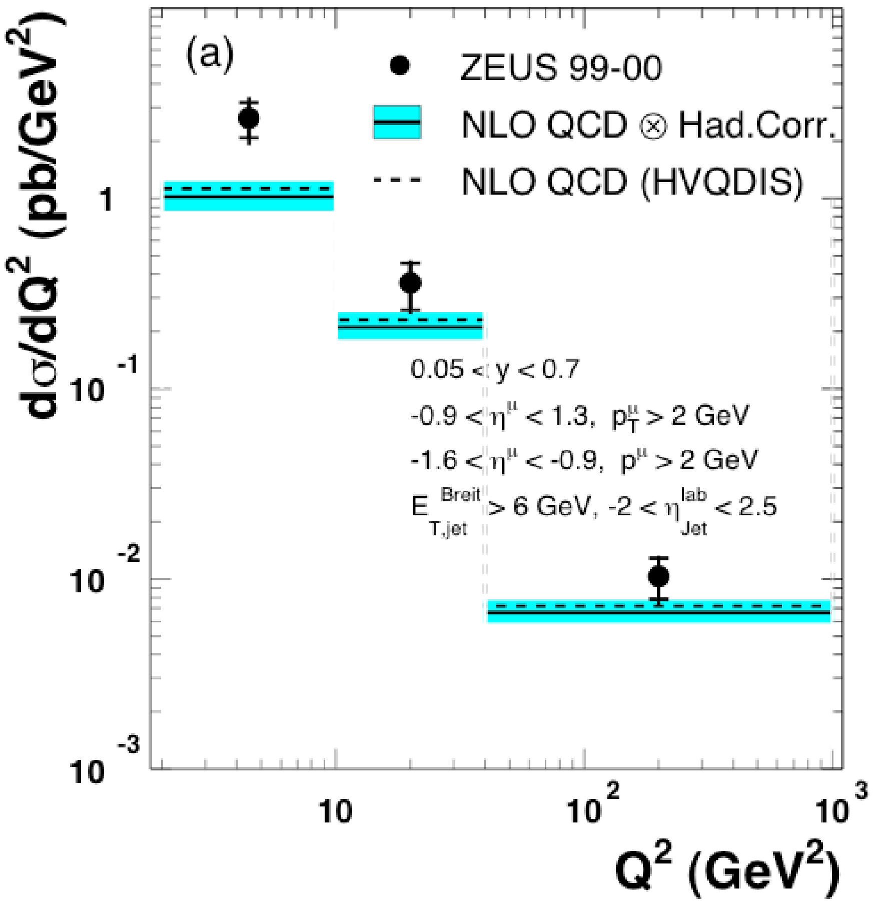



Improved parton model: resums large $\log Q^2/m_b^2$ into the bottom pdf

Advantages:
1. Perturbative expansion is well-behaved
2. Calculations are simpler ⇒ better accuracy (=higher order) achievable

With enough data b-pdf could be measured directly in DIS ⇒ useful input for the LHC

# Bottom production at Zeus

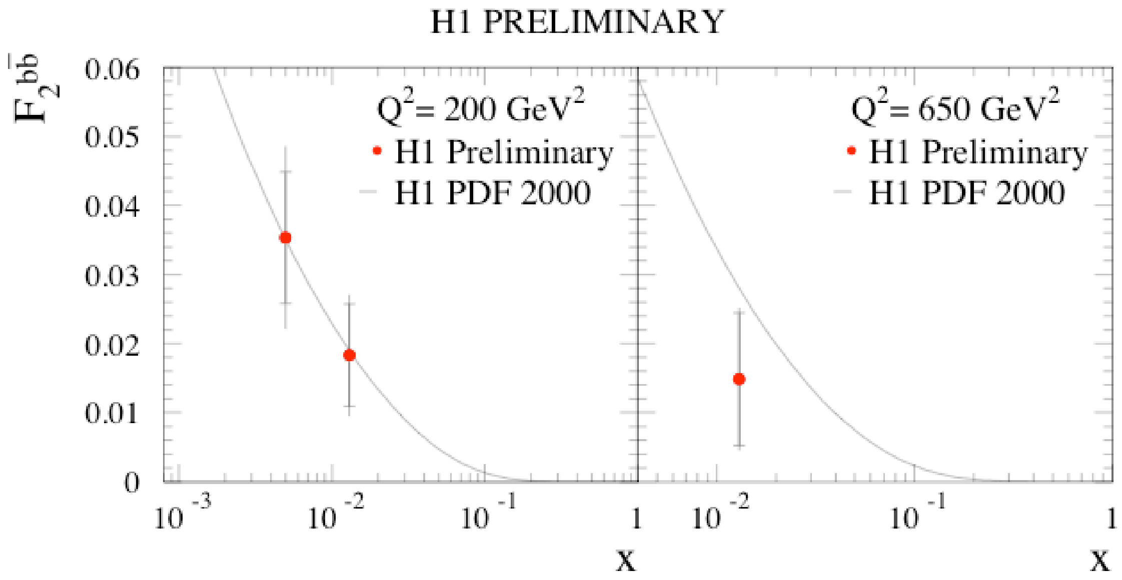



B cross section with a muon and a jet (almost fully inclusive).

Theoretical calculation at NLO in the 4 flavour scheme.

May be not enough data at high Q^2 to measure the b-pdf, but a consistency check with the ones in CTEQ or MRST could certainly be done.

# Bottom production at H1




B cross section with a muon, fully inclusive (nice!)
This gives a measurement of $F_2^b \Rightarrow$ direct information on the b-pdf

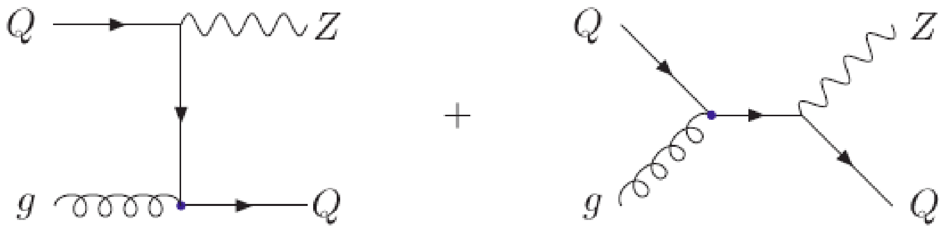
Compared to the H1 PDF at NLO, i.e. with the perturbative evolution of gluon.

This is a useful check for the LHC.

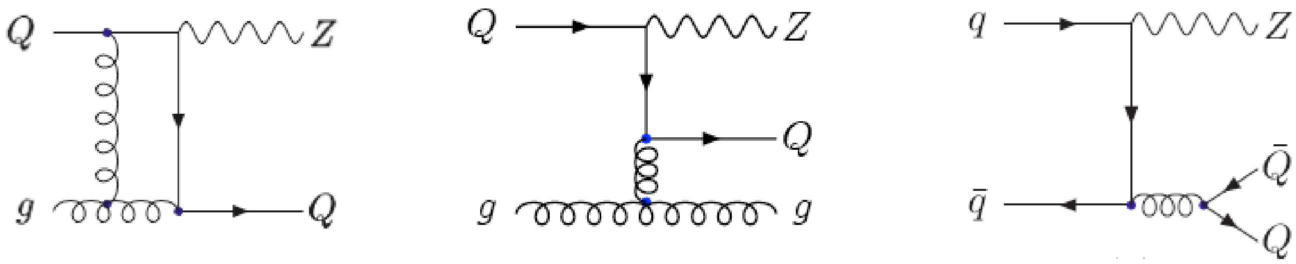
It could be done at NNLO....

# Z + heavy quark at high-pt

## Leading order:




## Next-to-leading order (Campbell, Ellis, F.M., Willenbrock, 2003):




The $q\bar{q}$ contributions are large (50% of gb) at the Tevatron due to the parton lumonisity, but very small the LHC⇒ smaller uncertainty at the LHC.

# Zb at NLO: LHC

| Cross sections (pb) | LHC |
|---|---|
| | $ZQ$ inclusive |
| $gb \to Zb$ | $1040\,^{+70}_{-60}\,^{+70}_{-100}\,^{+30}_{-50}$ |
| $q\bar{q} \to Zb\bar{b}$ | 49.2 |
| $gc \to Zc$ | $1390 \pm 100^{+60}_{-70}\,^{+40}_{-80}$ |
| $q\bar{q} \to Zc\bar{c}$ | 89.7 |
| | $Zj$ inclusive |
| $q\bar{q} \to Zg, gq \to Zq$ | $15870\,^{+900}_{-600}\,^{+60}_{-300}\,^{+300}_{-500}$ |

☞ Large cross section ⇒ differential measurements (ie rapidity)

☞ Small qq contamination

☞ Background "only" factor of 15 larger

More details on Tevatron (D0) measurement and LHC analysis in the next talk by A.Tonazzo

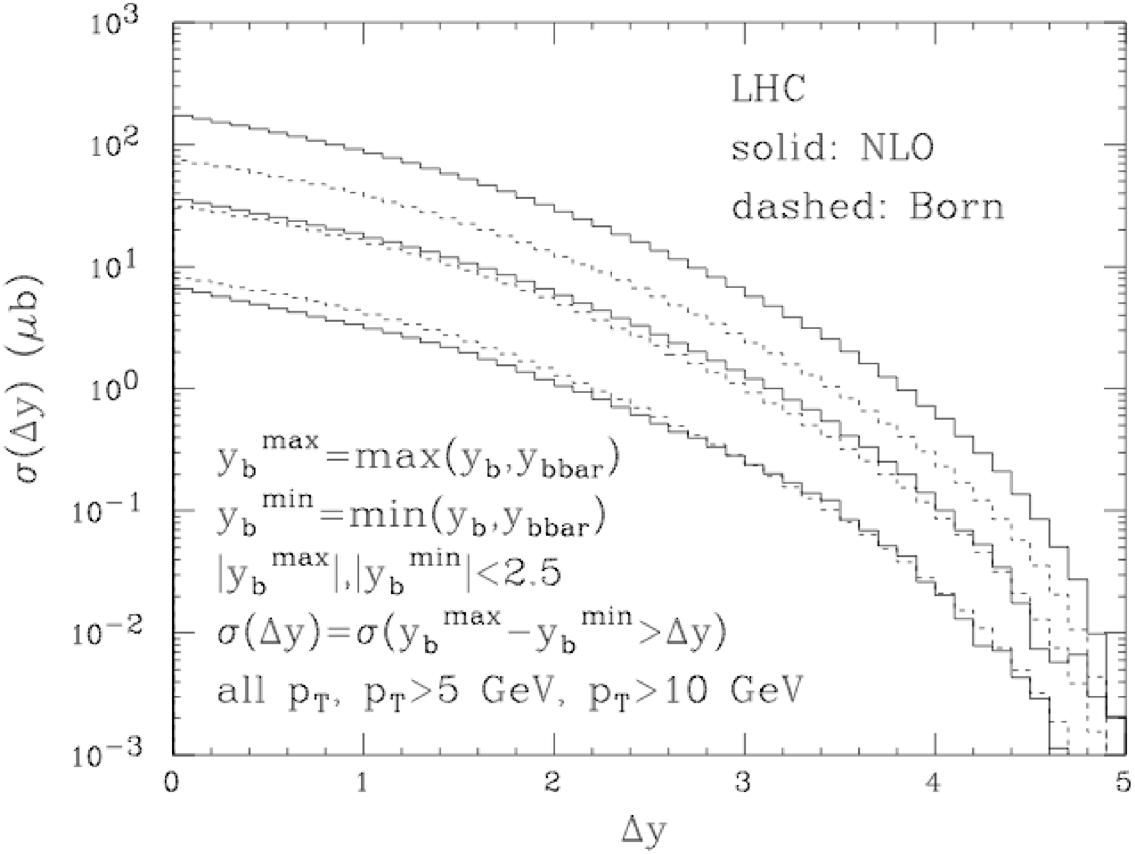
# Conclusions

The role of b-pdf in Higgs and vector boson production

- Many interesting processes, in the SM and in models BSM, can be reliably calculated by using b's in the initial state.
- Significant progress in the last years: new results, even at NNLO, and discrepancies solved.
- Satisfactory agreement between different schemes to calculate same cross-sections.
- New "precision" stage achievable: direct measurement of b-pdf at HERA and LHC.

# Back-up slides

# bb @ NLO




$$\sigma(\Delta y) = \int_{\Delta y}^{\infty} d\Delta y' \frac{d\sigma}{d\Delta y}(\Delta y')$$

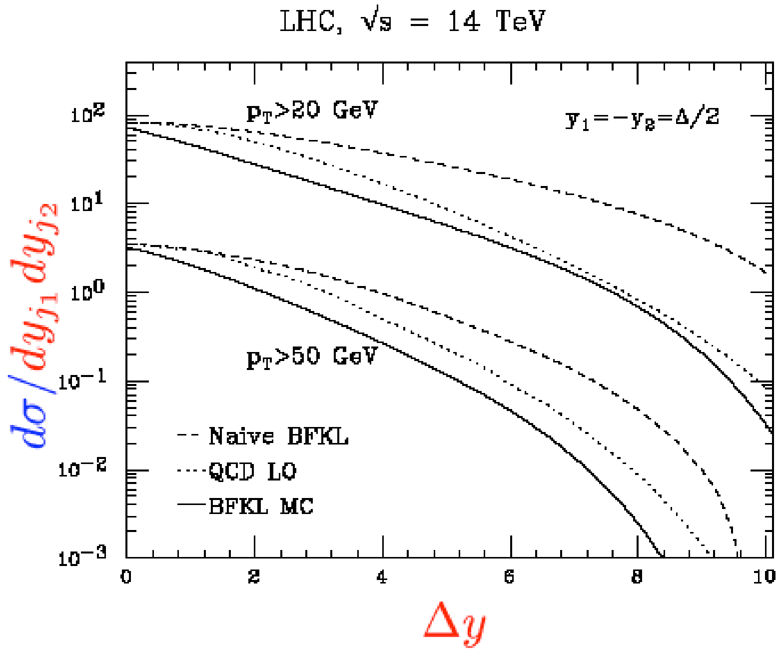
First check that the NLO calculation for bb is under control in the kinematic regime under study.

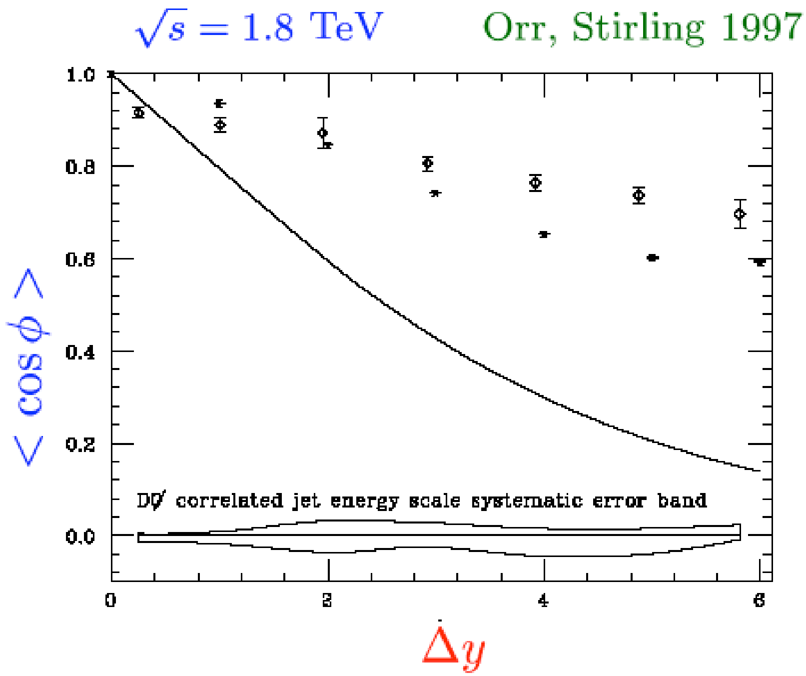
Both FO NLO MC and MC@NLO used.

K-factor is small if a minimum pt is required.

MC@NLO indicates (not shown) that Sudakov effects might be as important as in the dijet case. Ask for an asymmetric ptmin cut.

# Dijet Phenomenology




* in $\frac{d\sigma}{dy_{j_1}dy_{j_2}}$ the BFKL Monte Carlo yields a depletion rather than an enhancement, both for Tevatron & LHC, due to the falling parton luminosities

* $< \cos\phi >$ shows too much azimuthal decorrelation wrt Tevatron D0 data, while it is well described by a parton-shower Monte Carlo (HERWIG)

**CAVEAT** $< \cos\phi >$ is dominated by soft gluon (Sudakov) effects