V + B QUARKS: NEW PREDICTIONS, NEW OPPORTUNITIES

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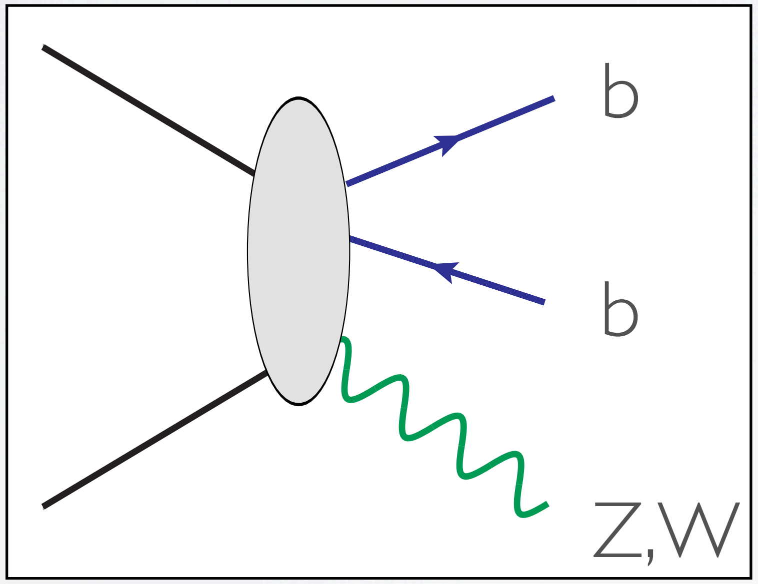
PLAN

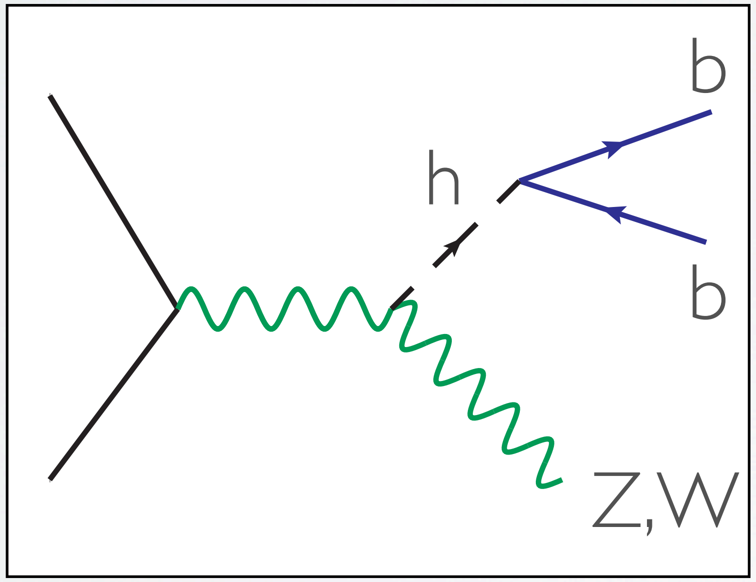
- The (rich) physics of V+b quarks
- The old way : NLO predictions
- The new way : aMC@NLO and POWHEG

A WINDOW ON SM AND BSM PHYSICS



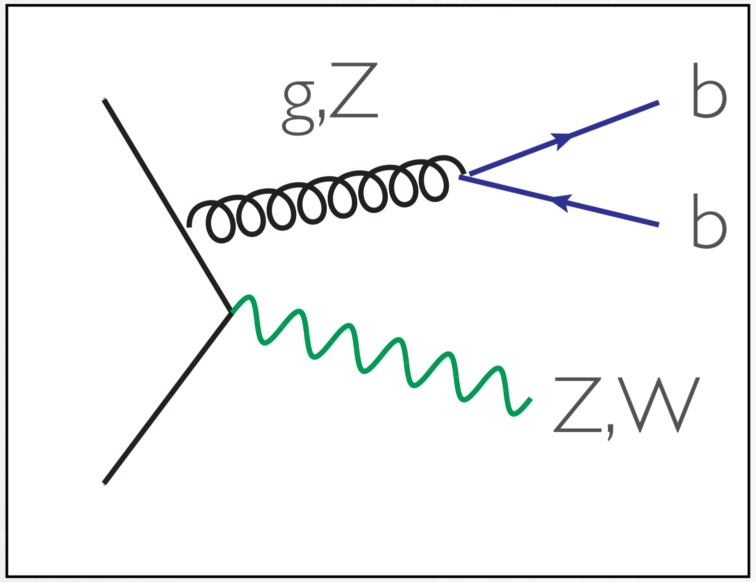
Very rich phenomenology associated to V+b's, interesting from both the SM (QCD and EW) and the BSM points of view.

A WINDOW ON SM AND BSM PHYSICS



SM Higgs searches in the associated W,Z channel both at the Tevatron and the LHC. At the LHC special attention/interest is devoted to the boosted Higgs case.

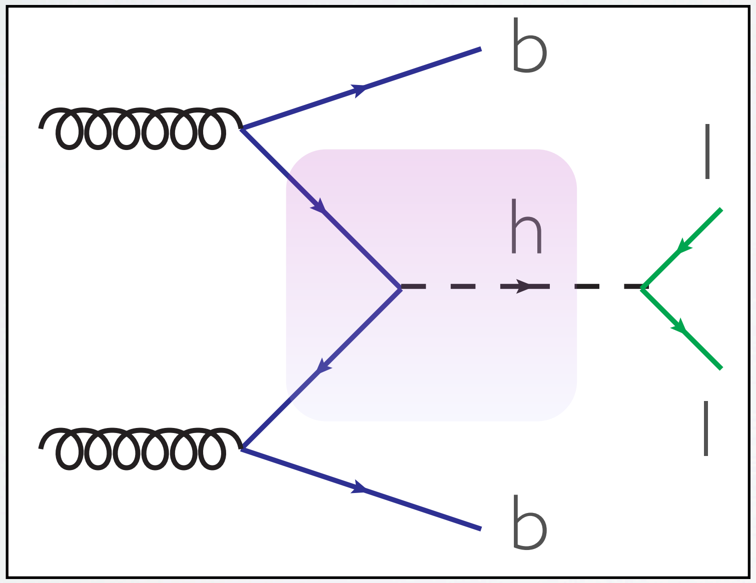
Observables: m_{bb}, radiation from bb, cos θ_{bb}, Δ_{bb}, j_{bb},



Gluon splitting (or Z decay) in the final state. Radiation pattern, jet substructure,....

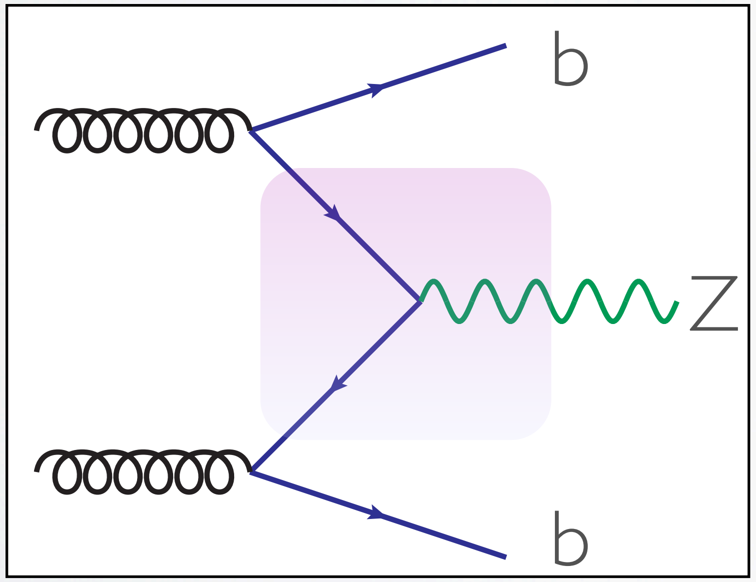
Observables: m_{bb}, radiation from bb, cos θ_{bb}, Δ_{bb}, j_{bb},,,,

A WINDOW ON SM AND BSM PHYSICS



BSM Higgs searches with enhanced couplings to b quarks, with the Higgs decay into taus or muons. Issue of what is the best QCD description, 4F ($gg \to bbh$ or 5F schemes ($bb \to h$, $m_b=0$) and use of b-pdf.

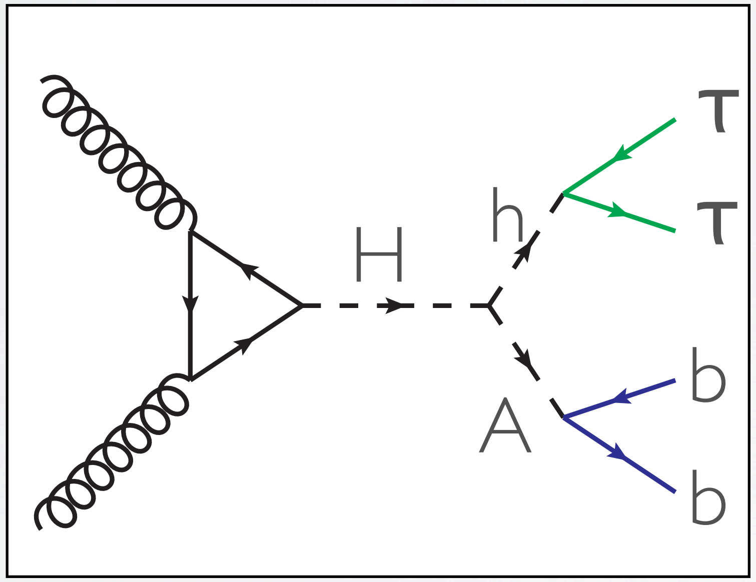
Observables: 0,1,2 b-jet cross sections, $p^T(b1)$, $\eta(b1)$, $p^T(b2)$, $\eta(b2)$, $p^T(ll)$, $\eta(ll)$



Gluon splitting in the initial state, 4F and 5F flavor schemes, b-pdf.

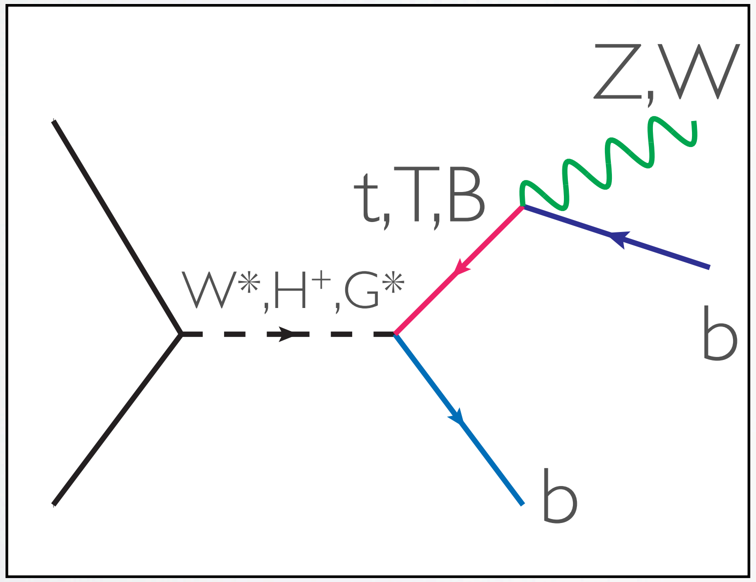
Observables: 0,1,2 b-jet cross sections, $p^T(b1)$, $\eta(b1)$, $p^T(b2)$, $\eta(b2)$, $p^T(ll)$, $\eta(ll)$

A WINDOW ON SM AND BSM PHYSICS



Extended Higgs sectors (2HDM) with light pseudo-scalars.

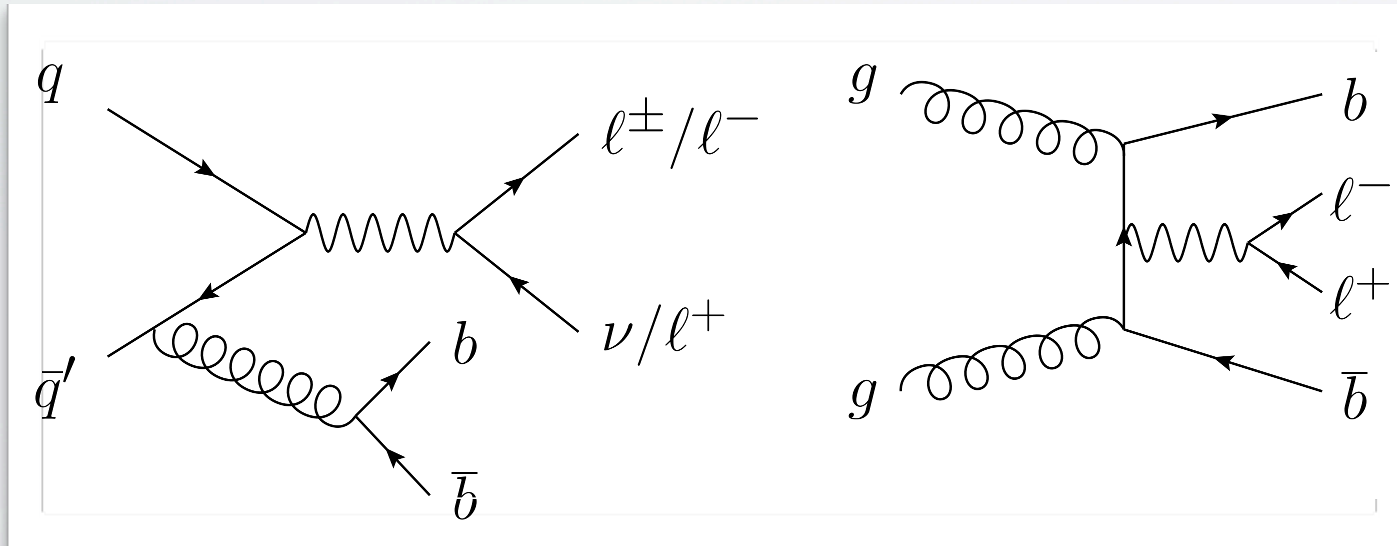
Observables: m_{tt} ,m_{bb}, m_{bbtt} , radiation from bb, cos θ_{bb}, cos θ_{tt}, Δ_{bb}, j_{bb}, $p_T(bb)$



s-channel single-top, charged Higgs, heavy gluon, heavy T and B (chiral and vector-like) searches.

Observables: m_{Vb}, m_{Wbb}, # extra jets, spin correlations.

W+B'S VS Z+B'S



	Cross section (pb)					
	Tevatron $\sqrt{s}$ =1.96 TeV			LHC $\sqrt{s}$ =7 TeV		
	LO	NLO	K factor	LO	NLO	K factor
$\ell\nu b\bar{b}$	4.63	8.04	1.74	19.4	38.9	2.01
$\ell^+\ell^- b\bar{b}$	0.860	1.509	1.75	9.66	16.1	1.67

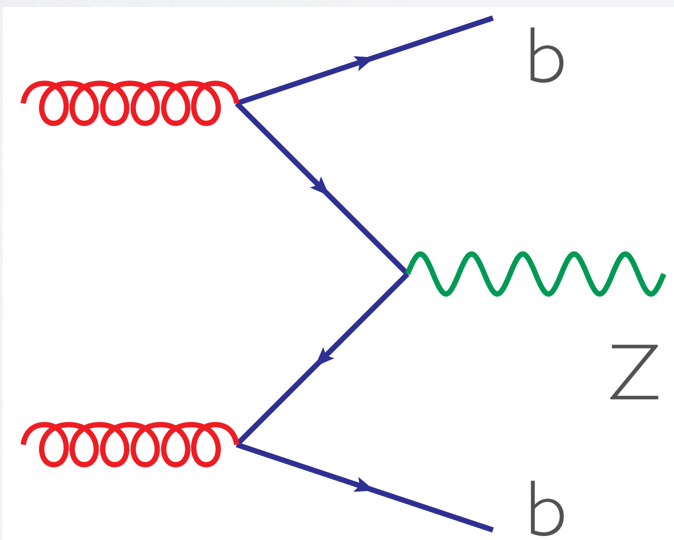
Frederix et al. arXiv: 1106.6019 [hep-ph]

- W+b's and Z+b's productions are of very different nature: with a W gluon splitting in the final state is dominant, while for a Z is initial-state splitting which is dominant.
- This fact accounts for the large increase of cross section of Zbb in passing from Tevatron to the LHC: at Tevatron we are probing the ±same process while at the LHC they are very different!
- Wbb has a large K-factor : some new channels at NLO open up that are important (qg).

FLAVOR SCHEMES

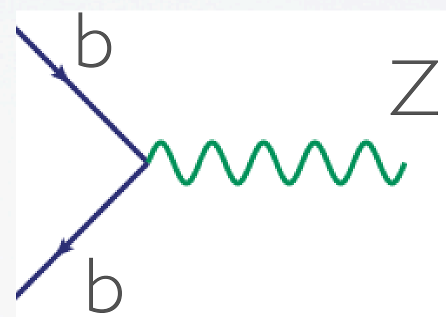
Two different ways of computing the same quantities:

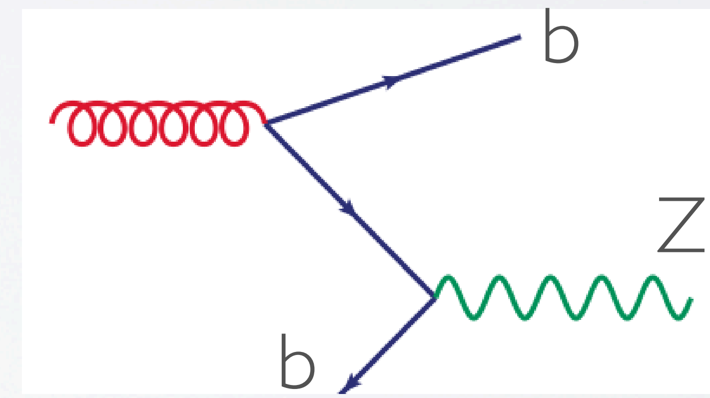
4F



1. It does not resum (possibly) large logs*.
2. Going NLO was more TH expensive.
3. Mass effects are there at any order in PT.
4. NLO+PS is straightforward.

5F





1. It resums initial state large logs in the b pdf*.
2. Going NLO easy and NNLO possible.
3. Mass effects enter at higher orders.
4. MC Implementation might not be very accurate.

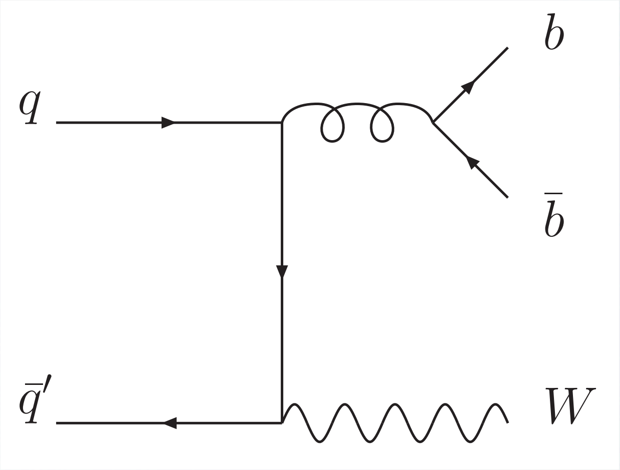
Same results by constructions at all orders, yet at finite order differences can arise.

* Recent arguments suggest that such logs are not large at the LHC [Ubiali et al. .arXiv: 1203.6393[hep-ph]]

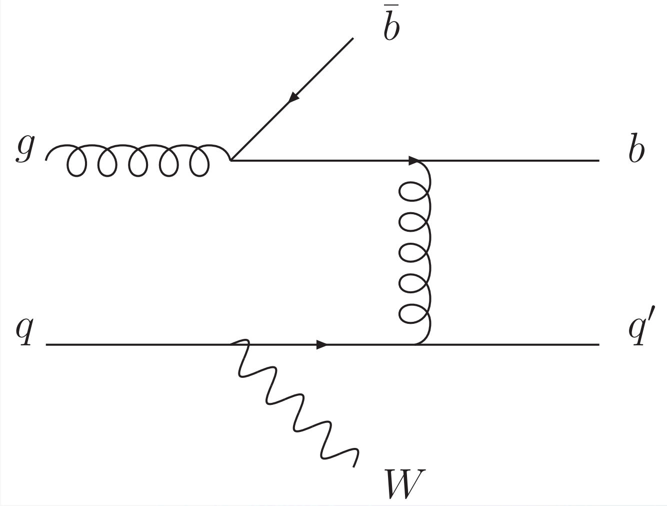
FLAVOR SCHEMES

Example:

1. W+1 jets with 1 b tag
2. W+2 jets with 1 b tag
3. W+2 jets with 2 b tags
4. W+bb-jet

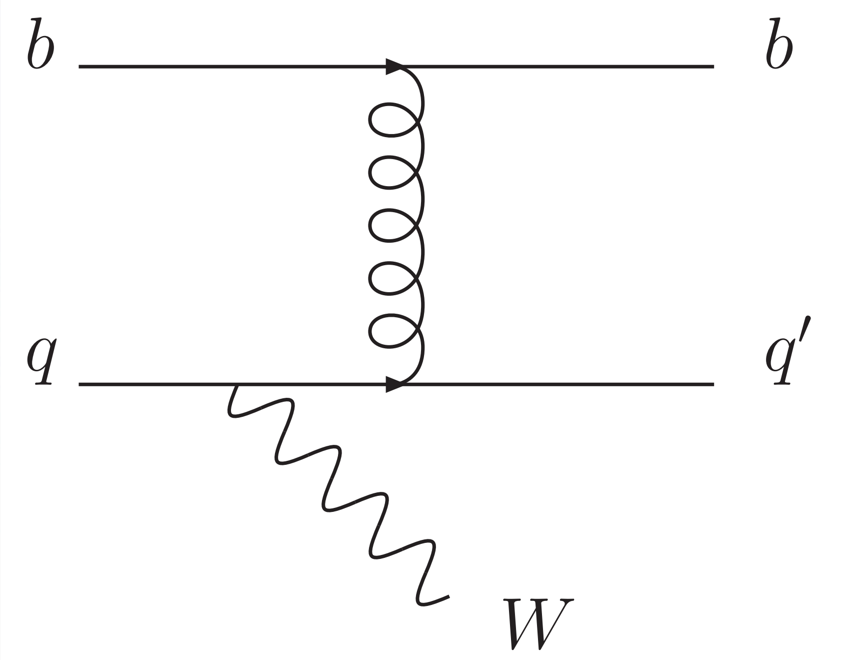


- All the above cross sections are described at NLO with Wbb in the 4-flavor scheme.
- "W+2jets with 1 b tag (inclusive)" could be calculated in the 4FS starting from the process, yet this was a tough calculation.



FLAVOR SCHEMES

- When requiring only 1 b tag, there is a better description with initial state b-quarks
  - Smaller uncertainties compared to 4-flavor scheme for observables that are not sensitive to very soft/forward b quarks
  - NLO study to combine the two approaches in one consistent description for W+1,2 jets with (at least) 1 b tag.
  - 4-flavor scheme calculation is simpler in the sense that "one fits many"



TREE-LEVEL WITH PARTON SHOWER

- Current options/possibilities for generating merged samples with different multiplicities:

  - Alpgen+Pythia/Herwig: both 4FS and 5FS available. 4FS is the recommended option for generating inclusive samples of W,Z with b quarks.

  - MadGraph+Pythia: both 4FS and 5FS available. 5FS has been widely used and tested. 4FS implementation is more recent not widely tested by Exps.

  - SHERPA: both 4FS and 5FS available. 5FS is the recommended option as b-mass corrections are included in the initial state splittings.

No systematic comparison neither among the generators nor between the 4F and 5F schemes has been done in this context!

W + B'S AT NLO (PARTON LEVEL)

- pp→W+1,2 jets @ NLO in the 5FS [Campbell,Ellis, 2000-MCFM]
  ⇒ Suitable to inclusive W+1,2-jets observables.
- pp→Wbb @ NLO, mb=0, [Campbell & Ellis,1999-MCFM]
  ⇒ Suitable to inclusive W + 2 b-jets observables.
- pp→Wbb @ NLO, in the 4FS, [Febres Cordero et al. 2009-(not public)]
  ⇒ Suitable to inclusive W + 1,2 b-jets observables.
- pp→Wb @ NLO in the 5FS+4FS [Campbell et al. + Febres Cordero et al 2011]
  ⇒ Suitable to inclusive W+1 b-jet observables.
- pp→Wbj @ NLO in the 5FS [Campbell,Ellis, FM,Willenbrock;2007-MCFM]
  ⇒ Suitable to inclusive W+2 jets with one b-tag observables.

Z + B'S AT NLO (PARTON LEVEL)

- $pp \to Z+1,2$ jets @ NLO in the 5FS [Campbell,Ellis, 2000-MCFM]
  $\Rightarrow$ Suitable to inclusive Z+1,2-jets observables.

- $pp \to Zbb$ @ NLO, mb=0 [Campbell & Ellis,1999-MCFM]
  $\Rightarrow$ Suitable to inclusive Z + 2 b-jets observables.

- $pp \to Zbb$ @ NLO, in the 4FS [Febres Cordero et al. 2009-(not public)]
  $\Rightarrow$ Suitable to inclusive Z + 1,2 b-jets observables.

- $pp \to Zb$ @ NLO in the 5FS [Campbell,Ellis, FM,Willenbrock;2004-MCFM]
  $\Rightarrow$ Suitable to inclusive Z+1 b-jet observables.

- $pp \to Zbj$ @ NLO in the 5FS [Campbell,Ellis, FM,Willenbrock;2006-MCFM]
  $\Rightarrow$ Suitable to inclusive Z+2 jets with one b-tag observables.

PURE NLO : COMMENTS

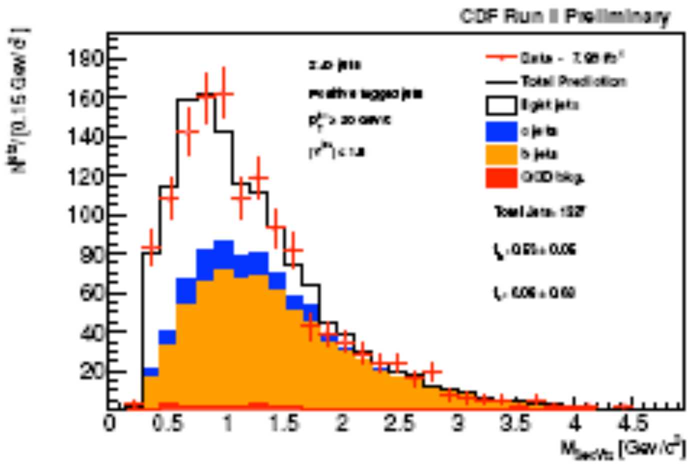
- 5FS predictions at NLO available for many observables, yet different calculations (codes) are needed for different observables.

- In addition, calculations in the 5FS at parton level in general don't allow arbitrarily small cuts on b-jet.

- 4FS calculations are much more flexible as one calculation is able to predict several observables at NLO.

- Pure NLO codes (MCFM) only produce histograms not events and for observables at the parton-level:
  ⇒ not optimal/easiest for TH/EXP comparison.

CURRENT STUDIES : Z+B AT CDF



$$\frac{\sigma_{Z\_bjet}}{\sigma_Z} = 0.293 \pm 0.030^{stat} \pm 0.036^{syst}\%$$

$$\frac{\sigma_{Z\_bjet}}{\sigma_{Zjet}} = 2.31 \pm 0.23^{stat} \pm 0.32^{syst}\%$$

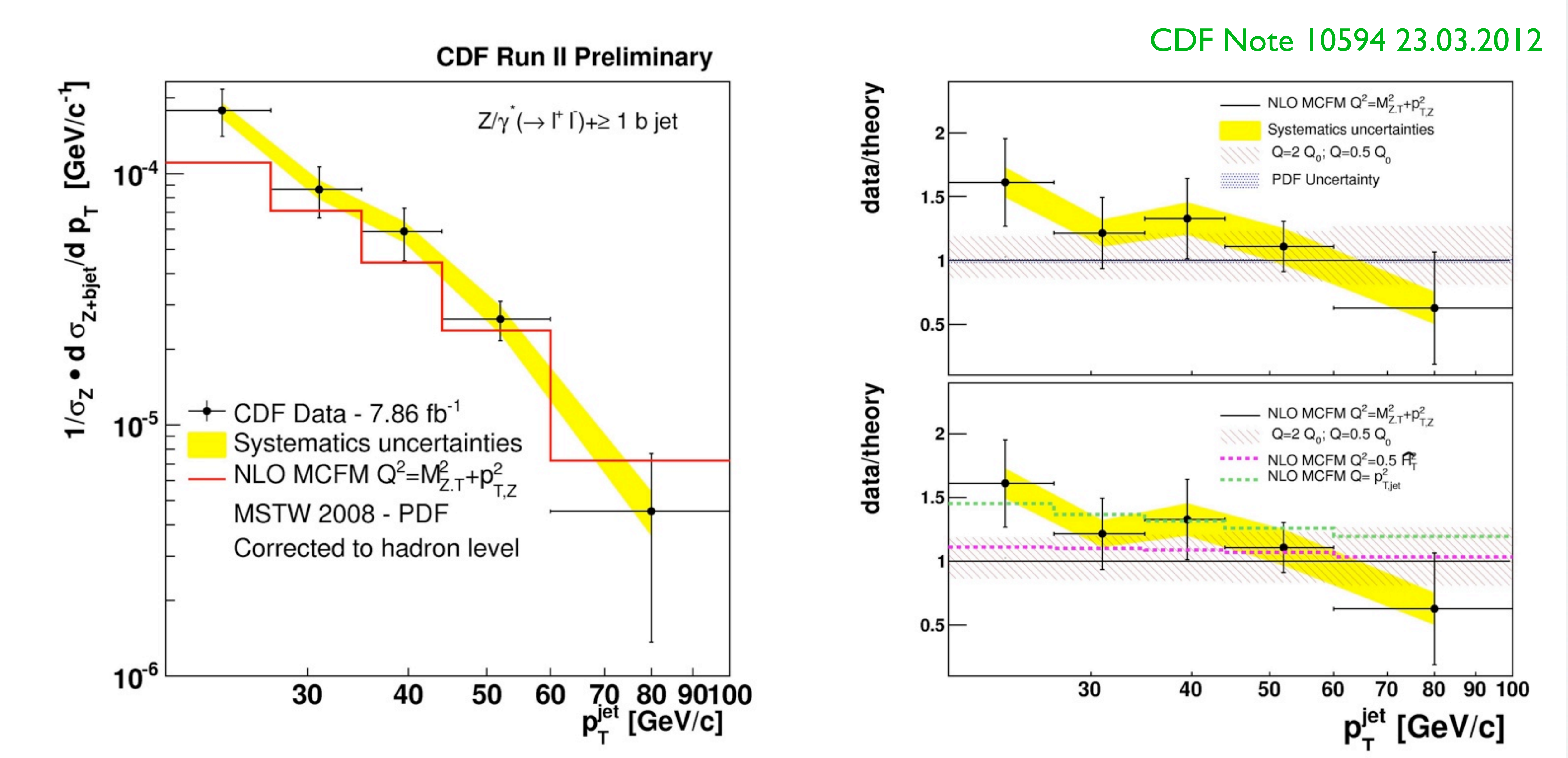
To compare with NLO prediction with MCFM:

	$Q^2 = m_Z^2 + p_{T,Z}^2$	$Q^2 = < p_{T,jet}^2 >$
$\frac{\sigma_{Z\_bjet}}{\sigma_Z}$	0.24 %	0.32 %
$\frac{\sigma_{Z\_bjet}}{\sigma_{Zjet}}$	1.8 %	2.2%

- Good agreement on the ratio...

CDF Note 10594 23.03.2012

CURRENT STUDIES : Z+B AT CDF



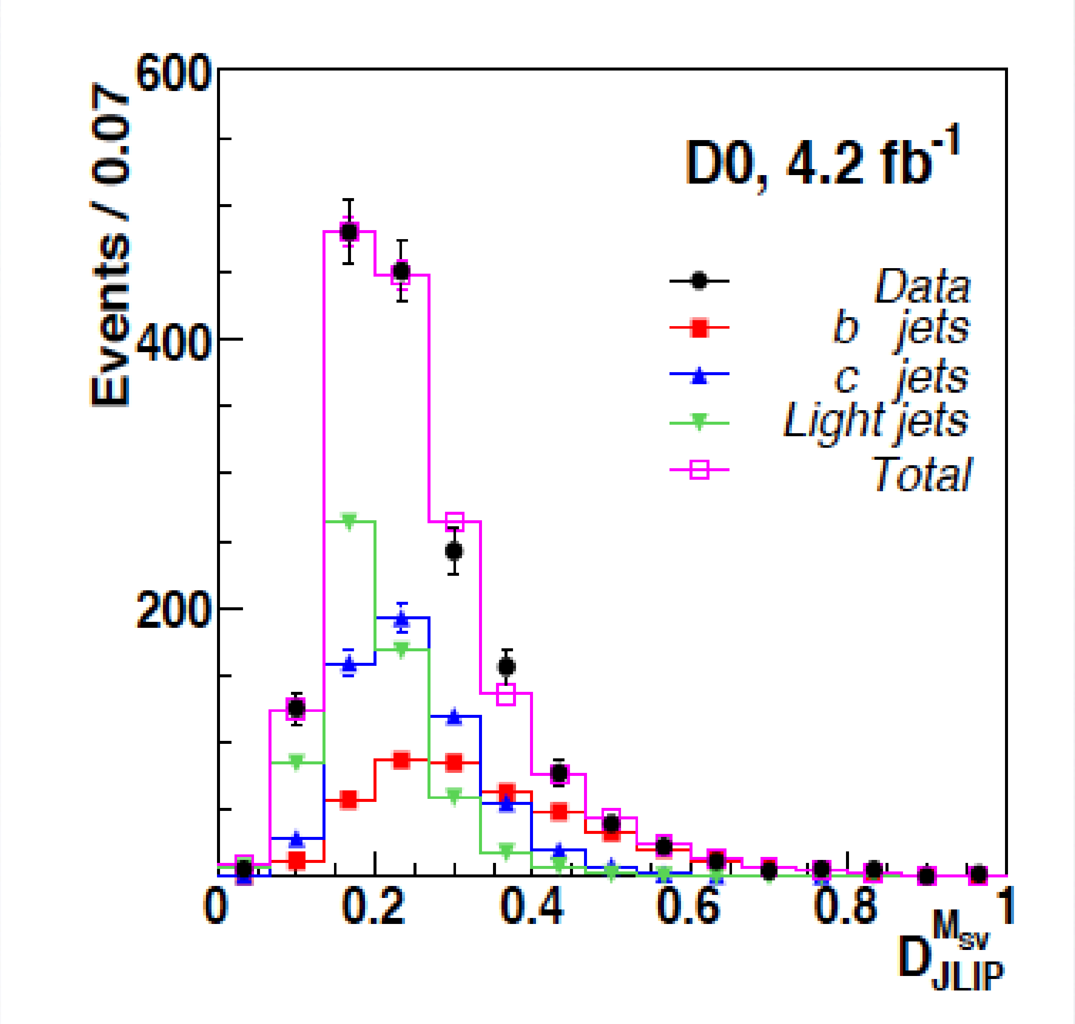
- Yet there is a clear TH/EXP mismatch at small jet pT in both Z+j and Z+b.

CURRENT STUDIES : Z+B AT D0

$$\frac{\sigma(Z + b\mathrm{jet})}{\sigma(Z + \mathrm{jet})} = 0.0193 \pm 0.0022\,(\mathrm{stat.}) \pm 0.0015\,(\mathrm{syst.})$$

$$\mathrm{MCFM} \to 0.0192 \pm 0.0022$$

- Good agreement here.
- Yet not clear if the TH/EXP comparison done in a completely fair way. The sample is inclusive and the b-jet does not need to be highest jet in the analysis. The 5F in MCFM is fully NLO calculation Zb only in that case. In addition qq initial state is very large at the Tevatron and only at LO in the 5FS calculation.



arXiv : 1010.6203 [hep-ex]

CURRENT STUDIES : Z+B AT THE LHC

- CMS (arXiv:1204.1643 [hep-ex])

$$\sigma(Z + 1b\text{–jet}) \cdot \mathrm{Br}(Z \to \ell\ell) = 5.84 \pm 0.07\,(stat.) \pm\, 0.72\,(syst.)^{+0.25}_{-0.55}\,(theory)\,\mathrm{pb}$$

$$\mathrm{MCFM} \to 4.73 \pm 0.54\,\mathrm{pb}$$

- ATLAS (arXiv:1109.1403 [hep-ex])

Experiment	$3.55^{+0.82}_{-0.74}$(stat)$^{+0.73}_{-0.55}$(syst) $\pm$ 0.12(lumi) pb
MCFM	3.88 $\pm$ 0.58 pb
ALPGEN	2.23 $\pm$ 0.01 (stat only) pb
SHERPA	3.29 $\pm$ 0.04 (stat only) pb

Table 4: Experimental measurement and predictions of σ_b, the cross-section for inclusive b-jet production in association with a Z boson, per lepton channel, as defined in the text.

CURRENT STUDIES : W+B AT CDF

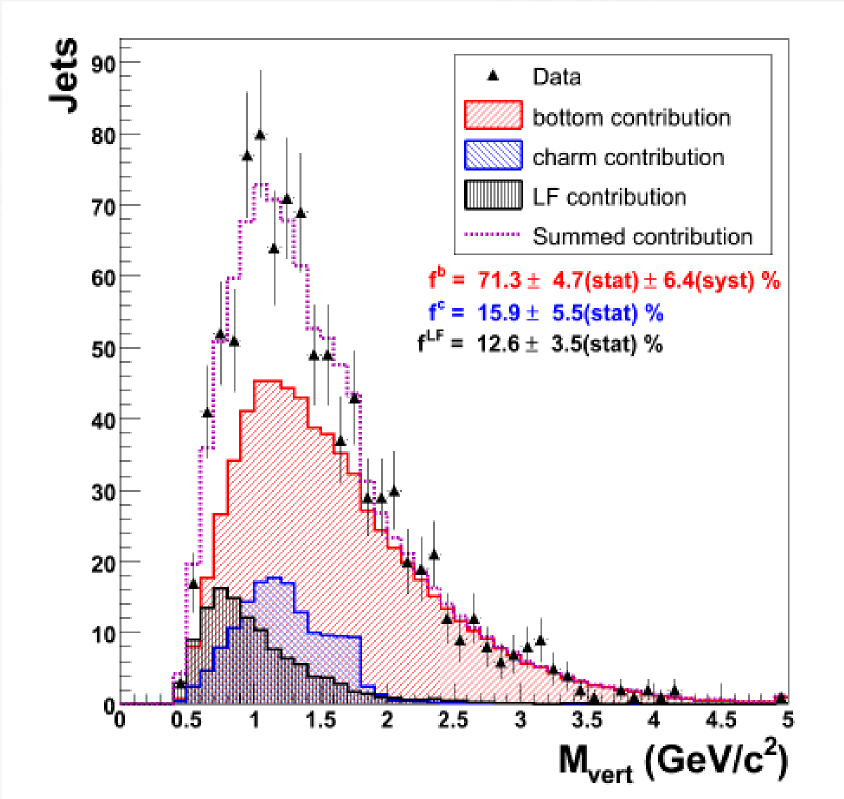
$$\sigma(W)_{b-\mathrm{jets}} \cdot \mathrm{Br}(W \to \ell\nu) = 2.74 \pm 0.27\,(stat.) \pm\, 0.42\,(syst.)\,\mathrm{pb}$$

in events with a $p_T > 20$ GeV/c, |eta| < 1.1 electron or muon, a $p_T > 25$ GeV/c neutrino, and 1 or 2 $E_T > 20$ GeV/c^2, |eta| < 2.0 jets regardless of species.

$$\mathrm{Pythia} \to 1.10\,\mathrm{pb}$$

$$\mathrm{Alpgen} \to 0.78\mathrm{pb}$$

$$\mathrm{MCFM} \to 1.22 \pm 0.14\mathrm{pb}$$

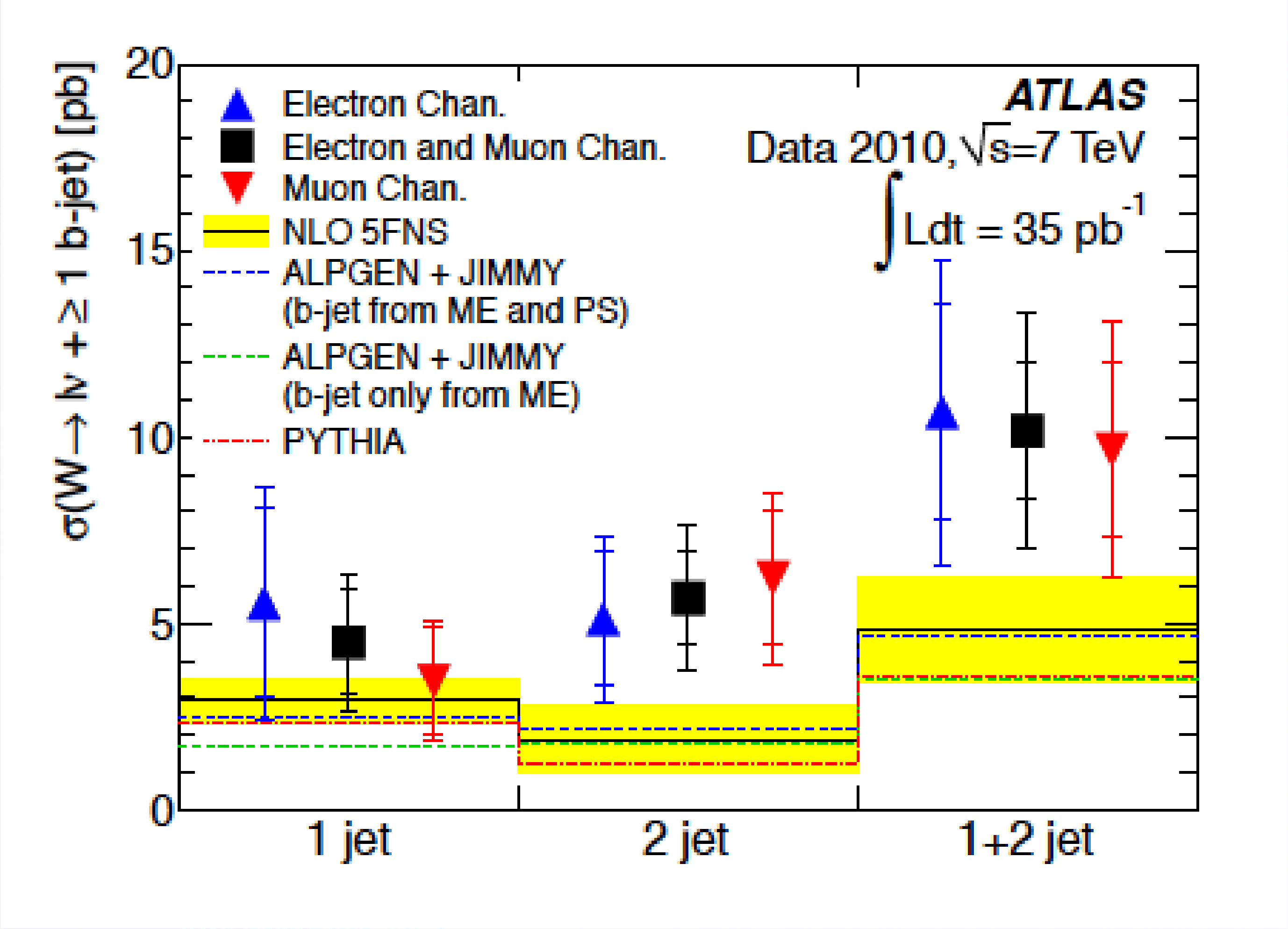


- The b-tagged jet not necessarily the highest-pt one.

arXiv:0909.1505 [hep-ex]

CURRENT STUDIES : W+B AT THE LHC

- ATLAS (arXiv:1109.1470 [hep-ex])



NLO based on:
Campbell et al. : hep-ph/0611348
Campbell et al. : arXiv:0809.3003
and recent update: Caola et al. arXiv:1107.3714 [hep-ph]

- The results in each bin are the sum of various contributions from different calculations: predictions need to be handled by theorists...
- 1 and 2 jet "exclusive" bins with at least one b-tag.
- 1+2 jet is the inclusive bin.

NLO WITH PARTON SHOWER: AMC@NLO AND POWHEG

Currently available predictions in the 4F scheme (m_b>0, no b-pdf). These are fully inclusive event samples (no cuts at the generation level needed) which can be directly compared with experimental data (corrected at the hadron level) and predict several observables at NLO.

- pp→ ($W^\pm \to l^\pm$ ν) bb in POWHEG-BOX [Oleari and Reina, 2011-Public] arXiv: 1105.4488
- pp→($W^\pm \to l^\pm$ ν) bb by aMC@NLO [Frederix et al. 2011, Events public, code available on request] arXiv: 1106.6019
- pp→($Z/\gamma^* \to l^+ l^-$) bb by aMC@NLO [Frederix et al. 2011, Events public, code available on request] arXiv: 1106.6019

No systematic comparison between POWHEG and aMC@NLO has been done in this context yet!

NLO WITH PARTON SHOWER: A BRAVE NEW WORLD

- Fully inclusive event samples (no cuts at the generation level needed) which can be directly compared with experimental data (corrected at the hadron level).

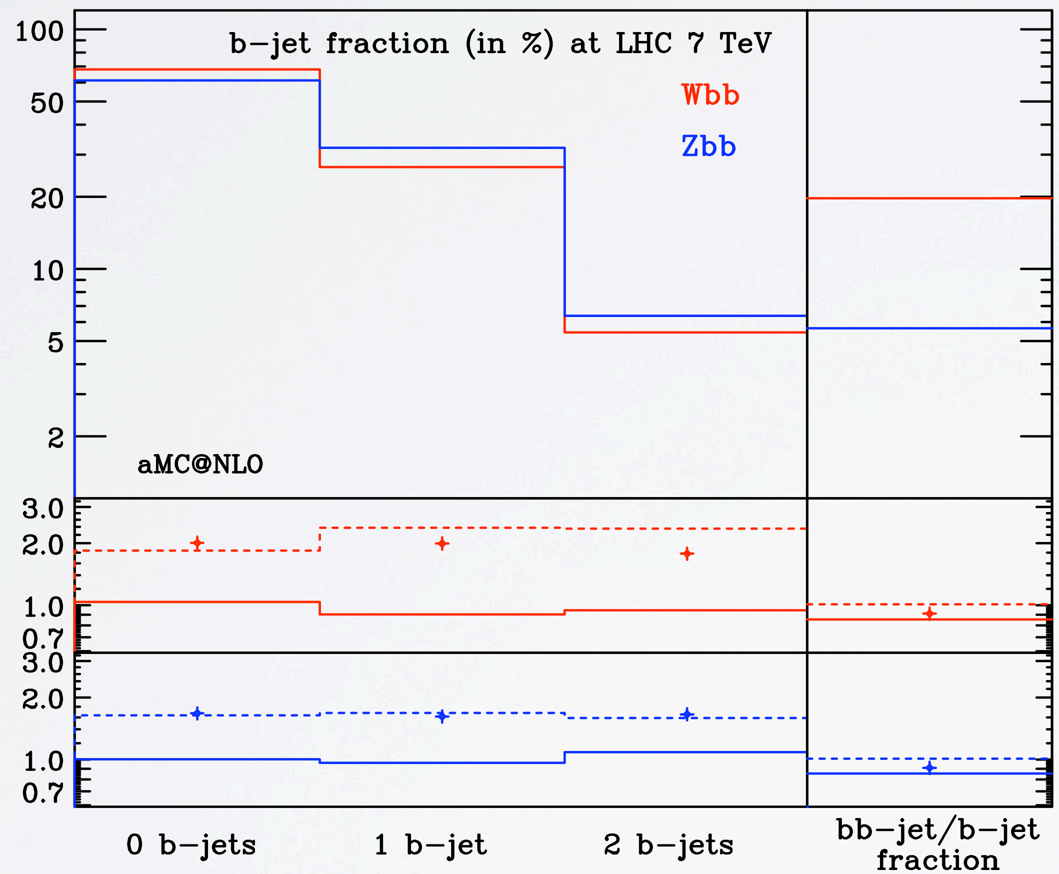
- A bunch of observables (0, 1,2 -jet) are predicted at NLO.

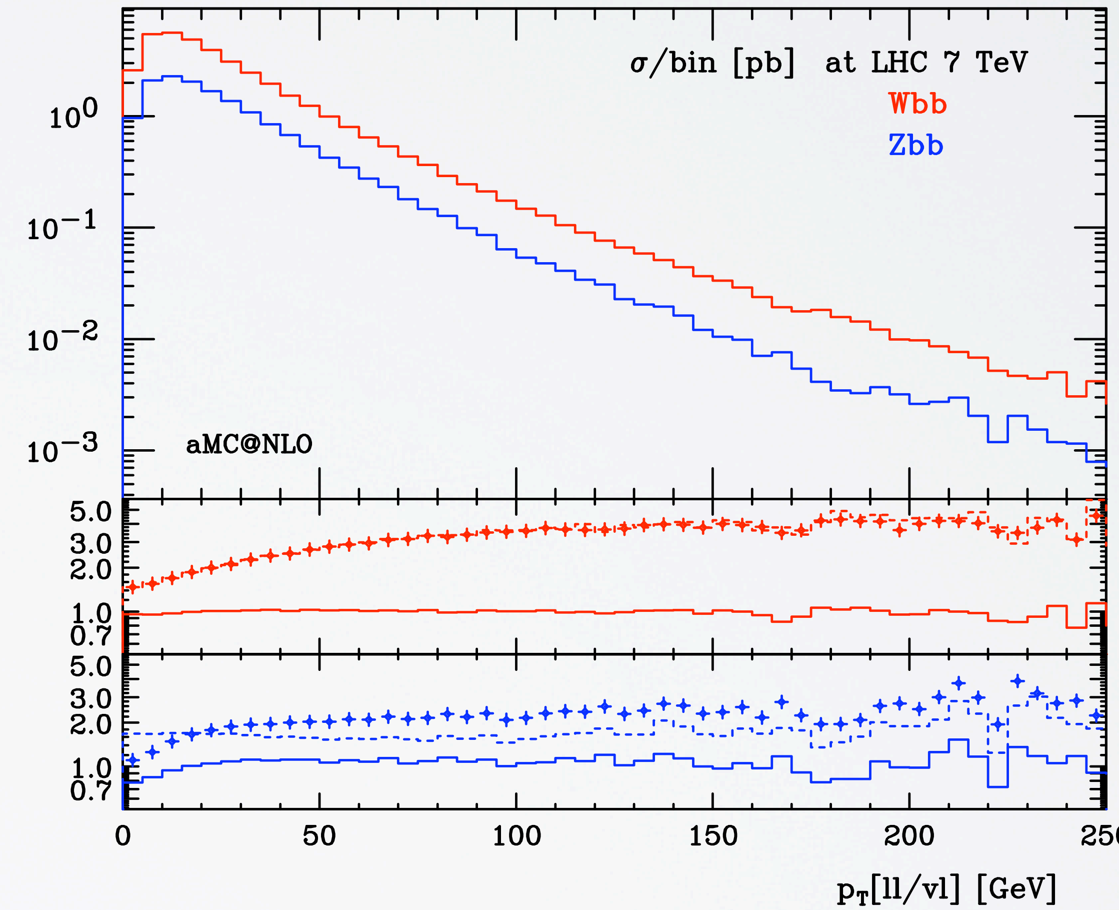
- Observables can be built in terms of B-hadrons or b-jets, as in the EXP analyses. "Difficult" observables such as those probing the gluon splitting are at NLO and do have the contribution soft/collinear resummation of the shower on top.

- In aMC@NLO (last version) TH uncertainty bands for scales and PDF can be generated automatically at no extra cost: any plotted observable has a TH uncertainty band.

- Other effects (underlying event & MPI, tunings and so on) can be included.

PP → WBB/ZBB WITH AMC@NLO

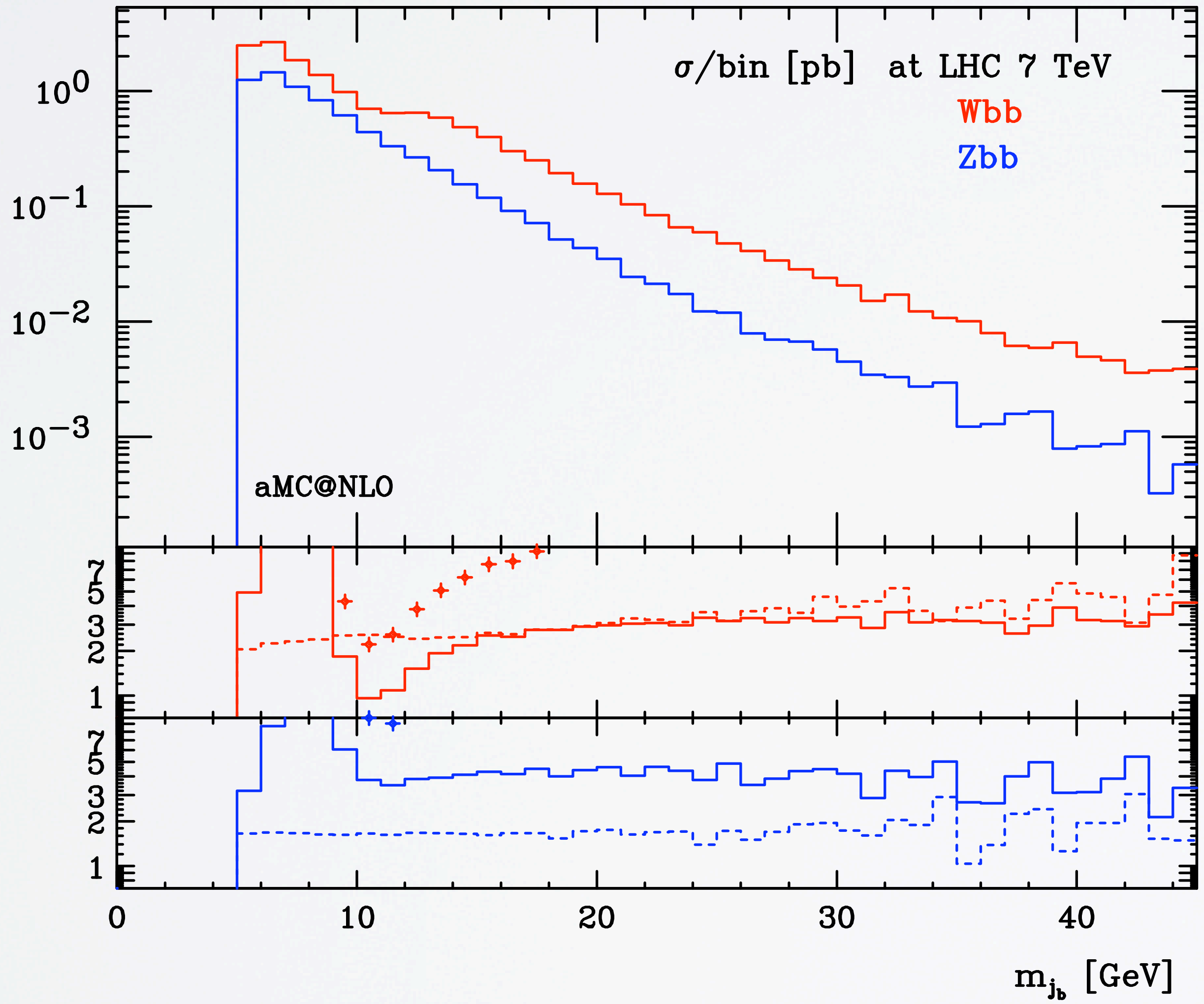




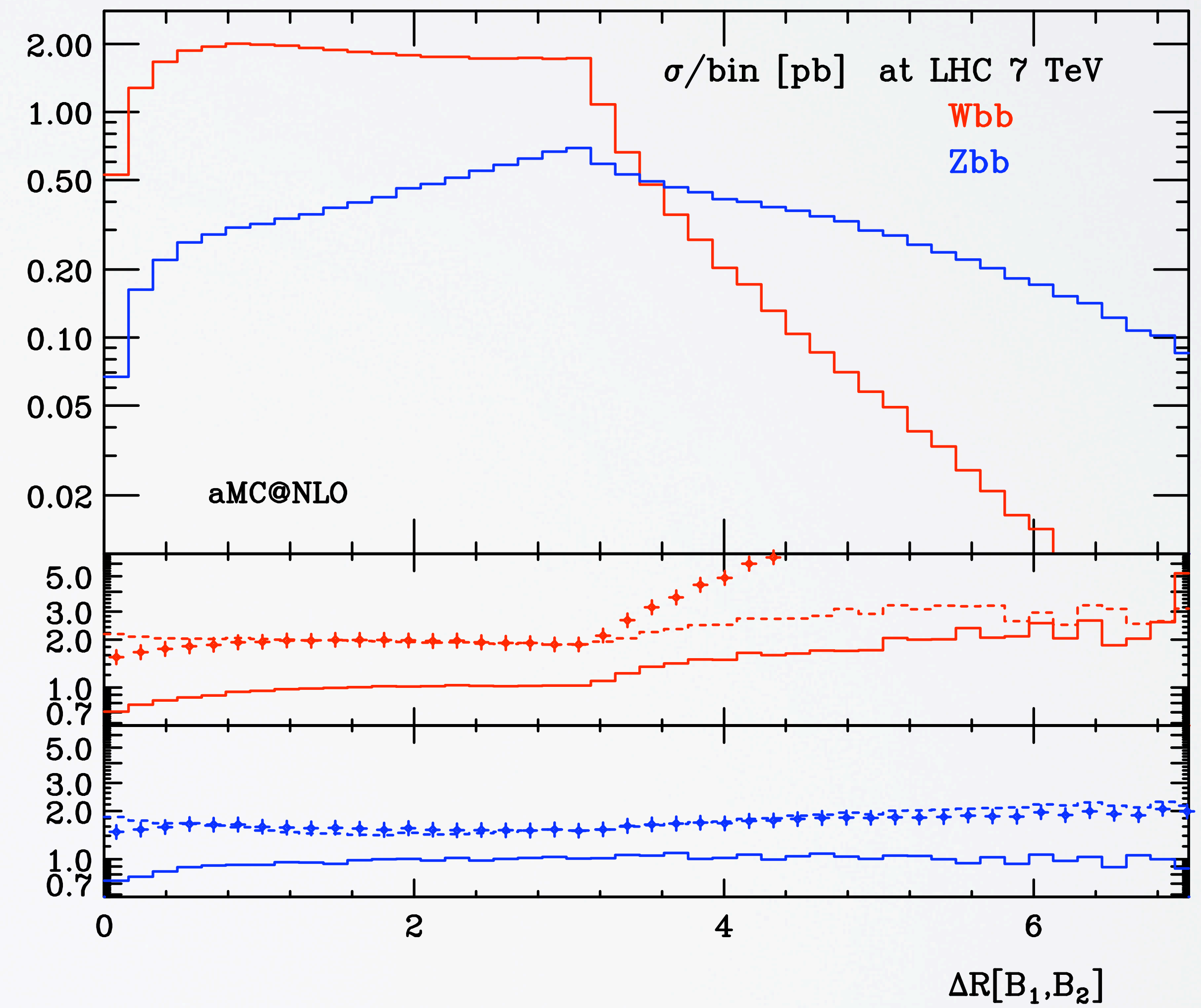
- In Wbb, ~20% of b-jets are bb-jets; for Zbb only ~6%
  - Jets defined with anti-k_T and R=0.5, with $p_T(j)$>20 GeV and $|\eta|$<2.5
- Lower panels show the ratio of aMC@NLO with LO (crosses), NLO (solid) and LOwPS (dotted)
- NLO and aMC@NLO very similar and consistent

PP → WBB/ZBB WITH AMC@NLO

b-jet mass



Distance between B-mesons



- For some observables NLO effects are large and/or parton showering has large effects

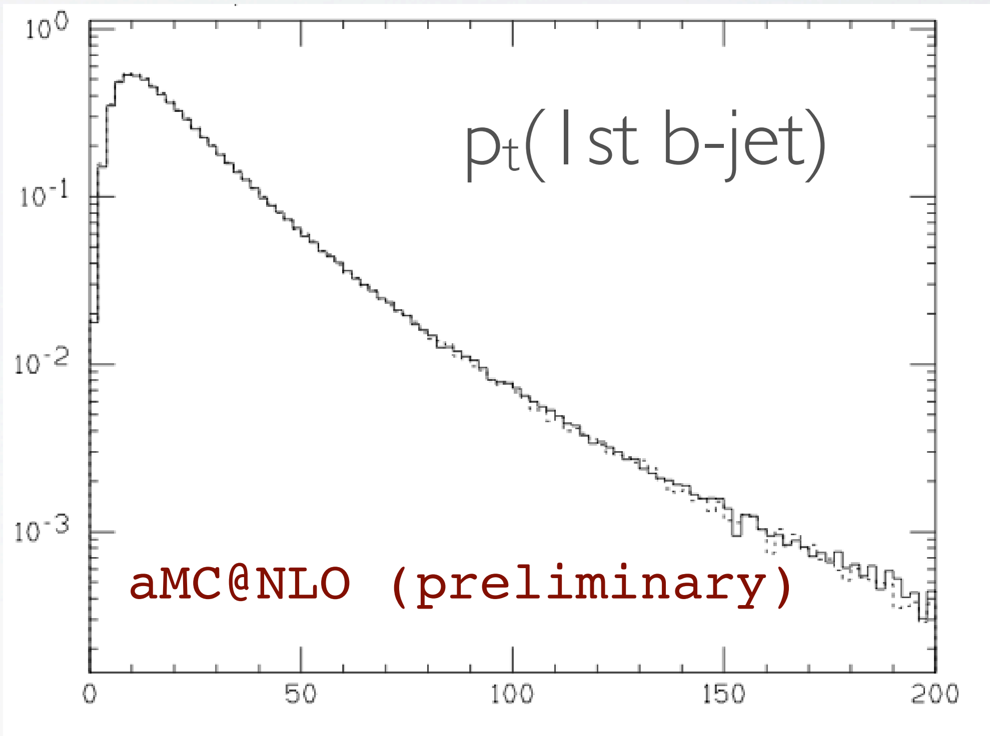
PP → WBBJ WITH AMC@NLO

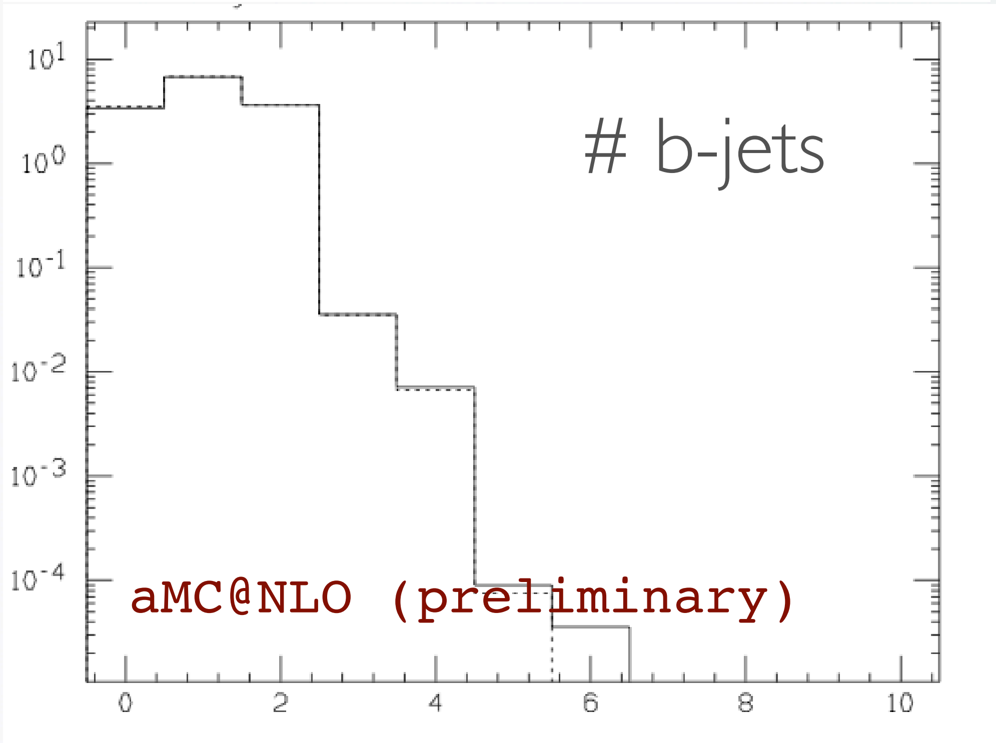
- Wbbj has been considered to be a very tough calculation. See for example [Reina and Schutzmeier, 1110.4438] for the first steps.

- Automatic approach. Available by aMC@NLO v4 since several months now.

- It allows to predict observables like:

W+3 jets with 2 b-tags
W+2 jets with 1 b-tag
W+2 jets with 1 bb-tag





CURRENT STUDIES : GAMMA+B AT DO

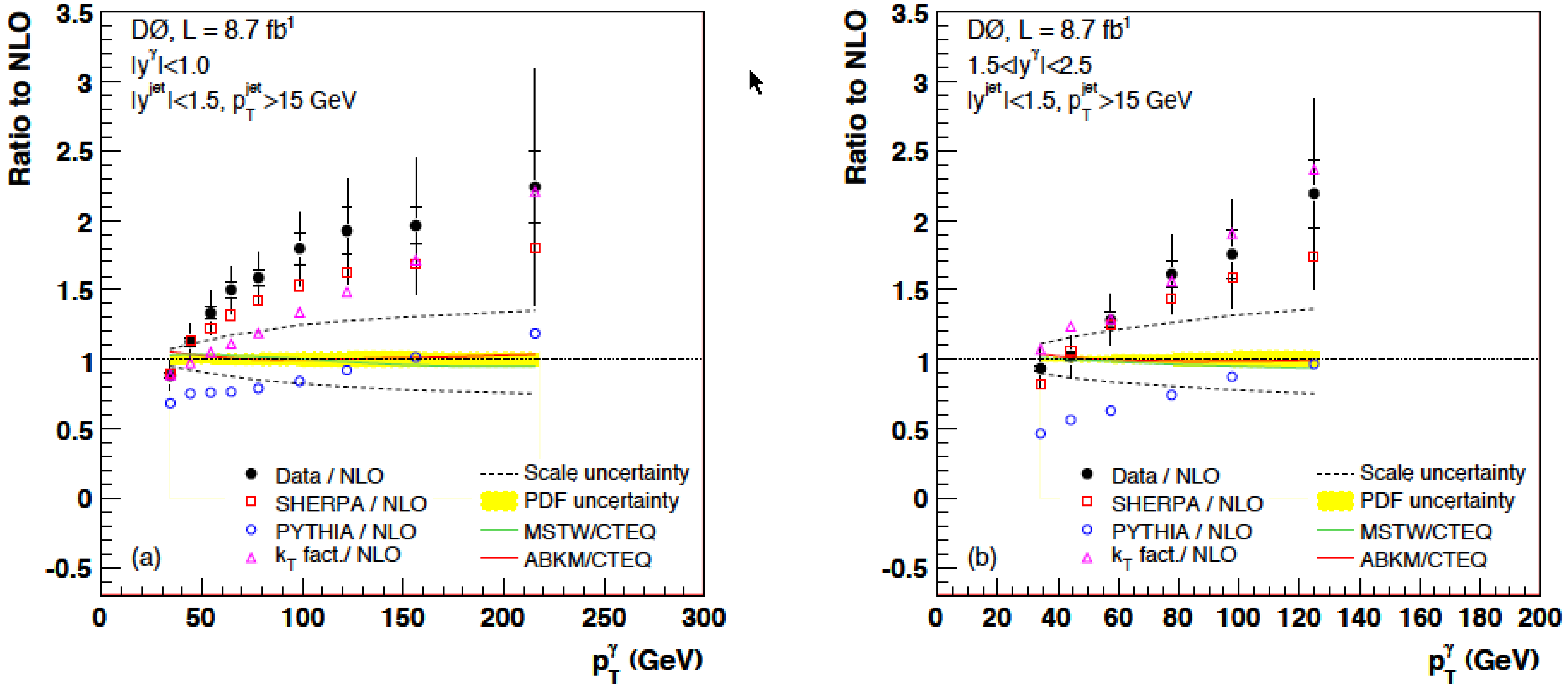
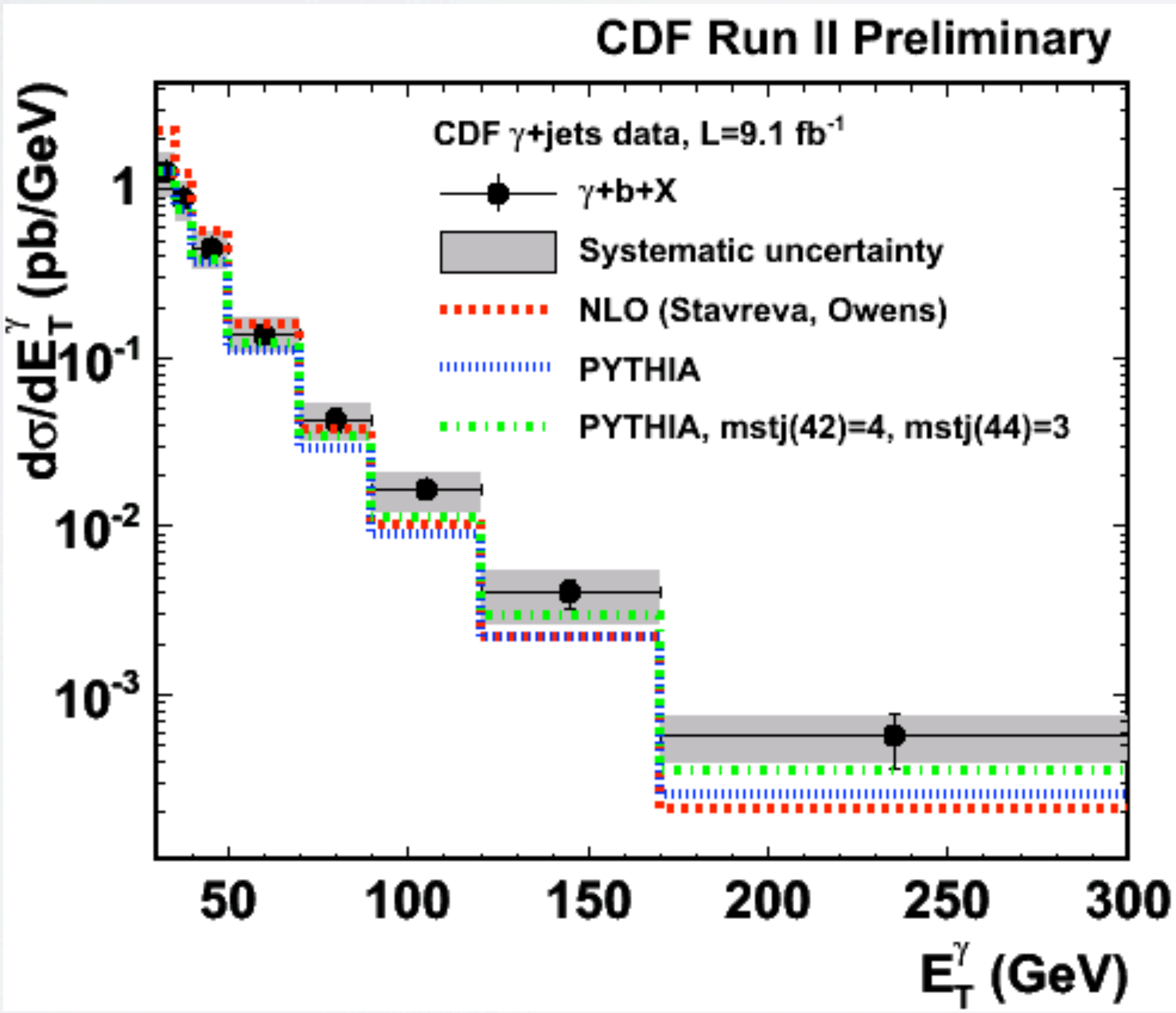
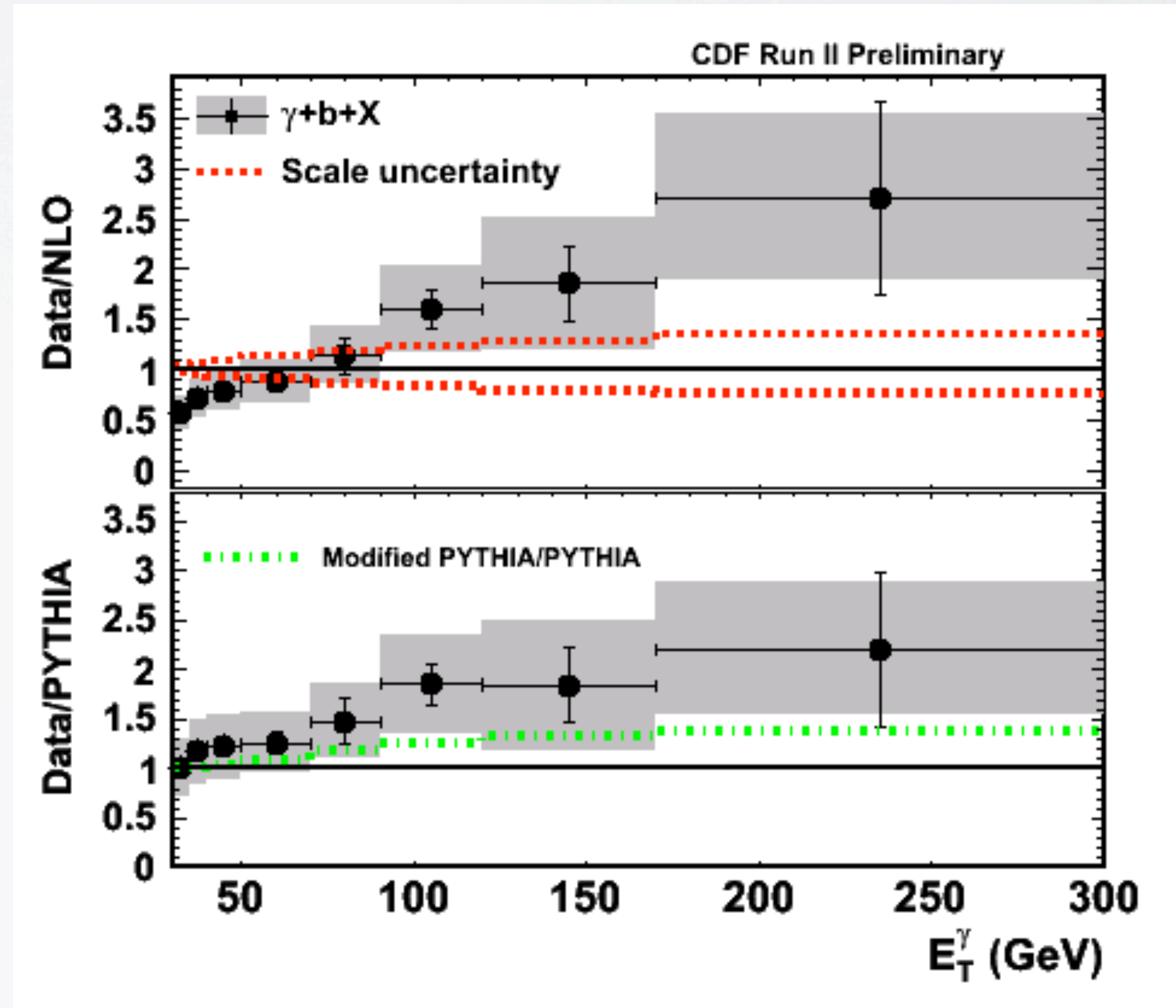


FIG. 6: The ratio of $\gamma + b$ production differential cross sections between data and NLO QCD predictions with uncertainties for the rapidity regions $|y^\gamma| < 1.0$ (a) and $1.5 < |y^\gamma| < 2.5$ (b). The uncertainties on the data include both statistical (inner error bar) and full uncertainties (entire error bar). Also shown are the uncertainties on the theoretical QCD scales and the CTEQ6.6M PDFs. The ratio of NLO predictions with CTEQ6.6M to those with MSTW2008 [31] and ABKM09NLO [32] are also shown.

CURRENT STUDIES : GAMMA+B AT CDF





GAMMA+B AT LHC

- γ +b/c can offer complementary (and possibly precious) information wrt to Z+b/c (different couplings/scales involved).

- Interesting from the point of view of QCD as the typical regions of vailidity of 4FS and 5FS depend on the $p_T(\gamma)$ and could studied at different regimes..

Implementation by aMC@NLO straightforward using Frixione's isolation for the photon....is there any experimental interest?

CONCLUSIONS

- V+b's is a very rich final state.

- New generation of codes at NLO+PS ready for **DIRECT** comparisons with LHC data for Z+b's and W+b's:

  The OLD way of comparing accurate TH predictions (i.e. distributions for IR-safe observables at NLO at the parton level) to experimental data (corrected back to parton-level) is being quickly surpassed.

  The new tools allow to be independent of painful/error-prone/model-dependent and sometimes unphysical "deconstruction" procedures (as e.g. b-tagging defs).

- Work in progress to extend to other processes (Wbbj) to make codes faster and widely accessible to all experimental collaborations.

- Other requests/desiderata (e.g., γ + b/c's) ?