Vector boson production with b jets: from the Tevatron to the LHC

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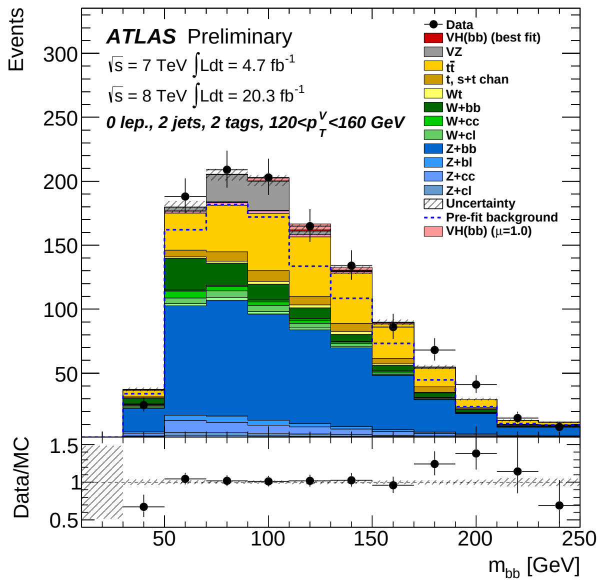
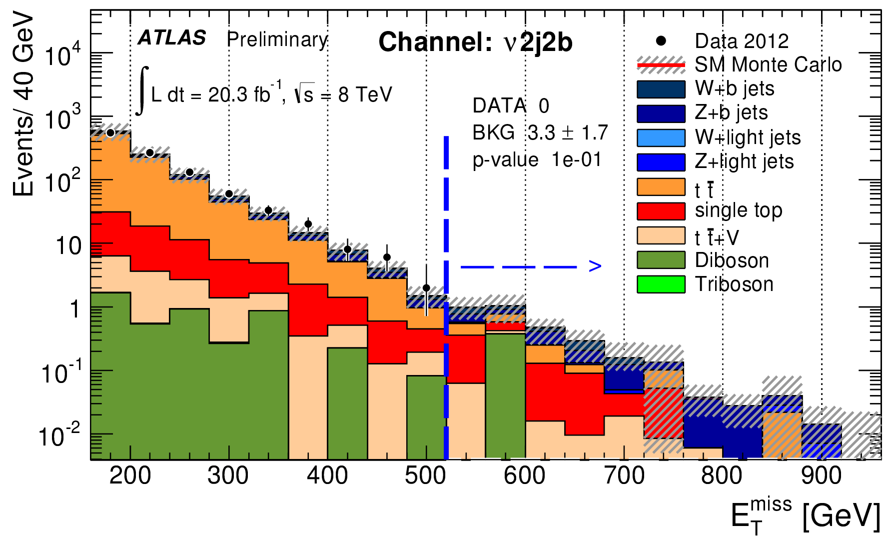
Outline

- V+HQ, Motivations:
  - ▷ important test of QCD;
  - ▷ testing ground of cutting edge techniques in perturbative QFT;
  - ▷ $Vt\bar{t}$ ($V = W/Z/\gamma$):
    - → testing EW top-quark couplings;
  - ▷ $Vb\bar{b}$, Vb, and $Vc\bar{c}$, Vc ($V = W/Z/\gamma$):
    - → direct access to b and c intrinsic densities in nucleons;
    - → main background to several important SM and BSM signatures,
      - ▷ WH/ZH associated production, $H \to b\bar{b}$;
      - ▷ single-top production;
      - ▷ several non-standard model signatures.
- Main focus: QCD studies for $V + b$ jets ($V = W/Z/\gamma$):
  - → new study of $\gamma + b$ jets;
  - → review and current developments in $W/Z + b$ jets.
- Comparison with Tevatron and LHC data
- Outlook

Ex.: Higgs searches and New Physics searches





→ Higgs searches: $W/Z + b\bar{b}$ largest irreducible background in $VH, H \to b\bar{b}$ associated production (signal known very accurately).

→ New physics searches: $W/Z + b$ jets important irreducible background were largest deviations are expected.

What makes $V + HQ$ special

- New mass scale (m_{HQ}) comes into play.
- b and c-quark production prone to large corrections induced by logarithmic dependence on large mass ratios (m_{HQ}/M_X).
- Theoretical predictions may require resummation of large logarithmic corrections.
- Behavior of perturbative expansion depends on number of HQ jets required in the final state.
- Behavior of perturbative expansion may change drastically depending on energy scale or kinematic regime.

Detailed discussion of $V + 2b$ and $V + 1b$ next

$V + 2b$ jets:

only via the tree-level processes

$\rightarrow$ $q\bar{q}' \rightarrow Wb\bar{b}$
$\rightarrow$ $q\bar{q}, gg \rightarrow Zb\bar{b}/\gamma b\bar{b}$

and corresponding higher-order corrections.

$V + 1b$ jet:

still via the tree-level processes ($n_{lf} = 4 \rightarrow$ 4FNS, $m_b \neq 0$)

$\rightarrow$ $q\bar{q}' \rightarrow Wb\bar{b}$
$\rightarrow$ $q\bar{q}, gg \rightarrow Zb\bar{b}/\gamma b\bar{b}$

but also ($n_{lf} = 5 \rightarrow$ 5FNS, $m_b = 0$),

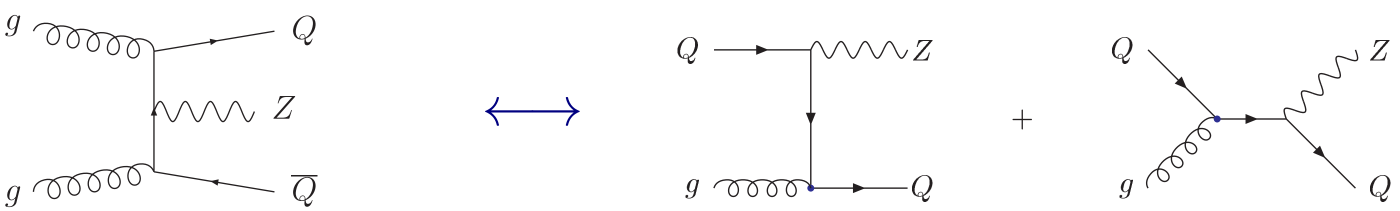
$\rightarrow$ $b\bar{q} \rightarrow Wb + q'$
$\rightarrow$ $bg \rightarrow Zb/\gamma b$

and corresponding higher-order corrections.

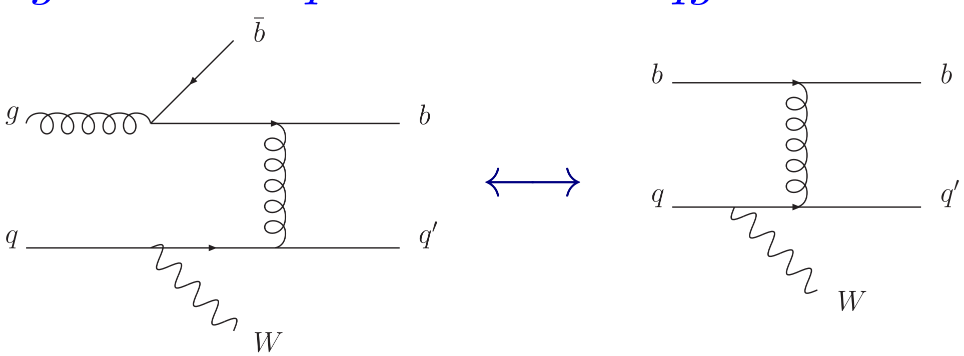
Different processes dominate in different kinematic regions and at different scales (relative to m_b). Why? $\longrightarrow$ look at origin of b-initiated processes

Observe that:

▷ $bg \to Zb/\gamma b$ is related to $gg \to Zb\bar{b}/\gamma b\bar{b}$,



▷ $bg \to Wb + q'$ is related to $qg \to Wb\bar{b} + q'$,



by defining a purely perturbative b-quark density (from $g \to b\bar{b}$), e.g.

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

[expansion at first order of the RGE evolved $b(x,\mu)$]

Where:

- ▷ potentially large logarithmic corrections arise from phase-space integration of untagged b quark;
- ▷ they can be resummed using RG techniques into $b(x, \mu)$;
- ▷ combination of processes requires subtraction terms to avoid double-counting.

... and yet:

- ▷ fixed-order expansion of b-initiated processes does not match fixed-order calculation (missing non-log terms).
- ▷ when should we make the transition $n_{lf} = 4 \rightarrow n_{lf} = 5$?
- ▷ do we understand the interplay of $n_{lf} = 4$ and $n_{lf} = 5$ in different processes ($W + b$ jets vs $Z + b$ jets vs $\gamma + b$ jets)?
- ▷ do we understand the different energy regimes (Tevatron vs LHC)?
- ▷ is this picture correct? (intrinsic b?)

Only a thorough comparison with data using the most accurate theoretical predictions will tell us $\rightarrow$ see results in this talk

$W + b$ 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-BOX
  - Frederix, et al., arXiv:1106.6019 $\longrightarrow$ aMC@NLO
  - Höche, L.R. $\longrightarrow$ SHERPA
  - the CMS collaboration, arXiv:1312.6608.
- $W + 2b+$ jet:
  - L.R., Schutzmeier, arXiv:1110.4438 (one-loop corrections)
- $W + 2$ jets with at least one b jet:
  - Campbell, et al., arXiv:0809.3003, arXiv:1107.3714
  - the CDF collaboration, arXiv:0909.1505,
  - the D0 collaboration, arXiv:1210.0627
  - the ATLAS collaboration, arXiv:1109.1470, arXiv:1302.2929.

$Z + b$ 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
  - Frederix, et al., arXiv:1106.6019 $\longrightarrow$ aMC@NLO
  - the CMS collaboration, arXiv:1310.1349

- $Z + 1b$ 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:1301.2233
  - the ATLAS collaboration, arXiv:1109.1403
  - the CMS collaboration, arXiv:1402.1521

$\gamma + b$ jets

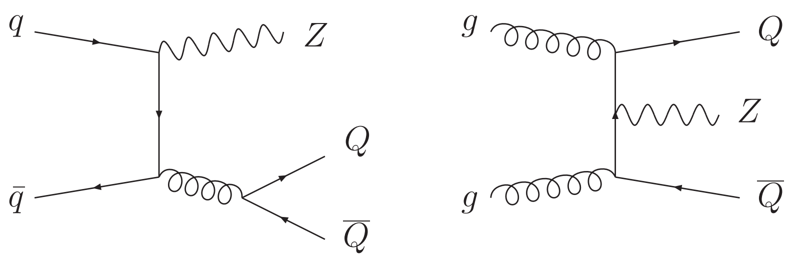
Studied at NLO in QCD/measured in experiments :

- $\gamma + 2b$ jets ($m_b \neq 0$):
  - Hartanto, L.R., arXiv:1312.2384
  - Frederix, et al., arXiv:1106.6019 (virtual γ) $\longrightarrow$ aMC@NLO

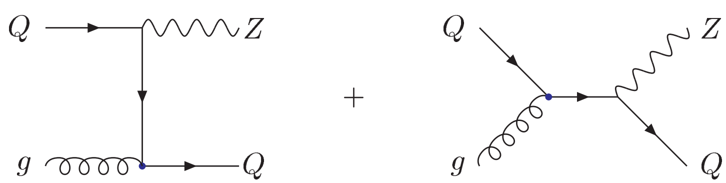
- $\gamma + 1b$ jet, $\gamma + 2$ jets with at least one b jet:
  - Stavreva, Owens, arXiv:0901.3791 $\big($5FNS$\big)$
  - Hartanto, L.R., arXiv:1312.2384 $\big($4FNS$\big)$
  - the CDF collaboration, arXiv:1303.6136,
  - the D0 collaboration, arXiv:1203.5865.

$V+2b$ jets and $V+1b$ jet for $V=\gamma, Z$:

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



$+ \qquad O(\alpha_s)$ corrections



$+ \qquad O(\alpha_s)$ corrections

Correspondently, at NLO:

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

$V+2b$ jets: processes $1+2$

$V+1b$ jet: processes $3+4+(1+2)_{LO}$ (5FNS) or $(1+2)_{NLO}$ (4FNS)

Direct photon $+b$ jet study

H. Hartanto, L.R., arXiv:1312.2384

- NLO 4FNS and 5FNS calculation
- Studied dependence on

  → dynamical-scale choice ($p_T(\gamma)$, H_T, $\ldots$),
  → scale variation (μ_R and μ_F, $\mu_0/4 < \mu_{R,F} < 4\mu_0$),
  → photon isolation prescription: fixed- vs smooth-cone isolation:

    – Fixed-cone: $\sum_{\in R_0} E_T(\text{had}) < E_T^{\text{max}}$+fragmt. functions
    – Smooth-cone: $\sum_{i,R\leq R_0} E_T^i\,\theta(R - R_{i,\gamma}) < \epsilon E_T^\gamma \left(\frac{1-\cos R}{1-\cos R_0}\right)$

  (for $R_0 = 0.4$, $\epsilon = 1$).

- PDF: CT10nlonf4 (4FNS), CT10nlo (5FNS).
- Photon selection cuts:

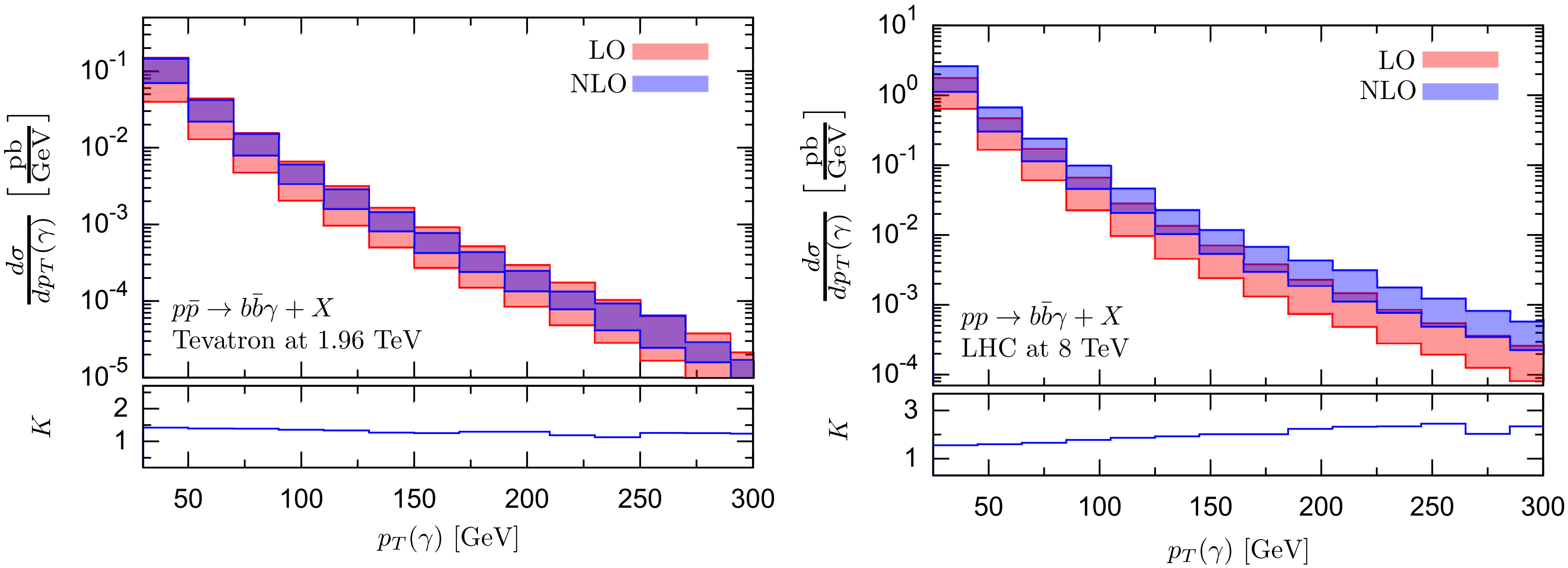
  – Tevatron: $p_T(\gamma) > 30$ GeV, $|\eta(\gamma)| < 1$
  – LHC: $p_T(\gamma) > 25$ GeV, $|\eta(\gamma)| < 1.37$

- Jet selection cuts (used anti-k_T with $R = 0.4$):

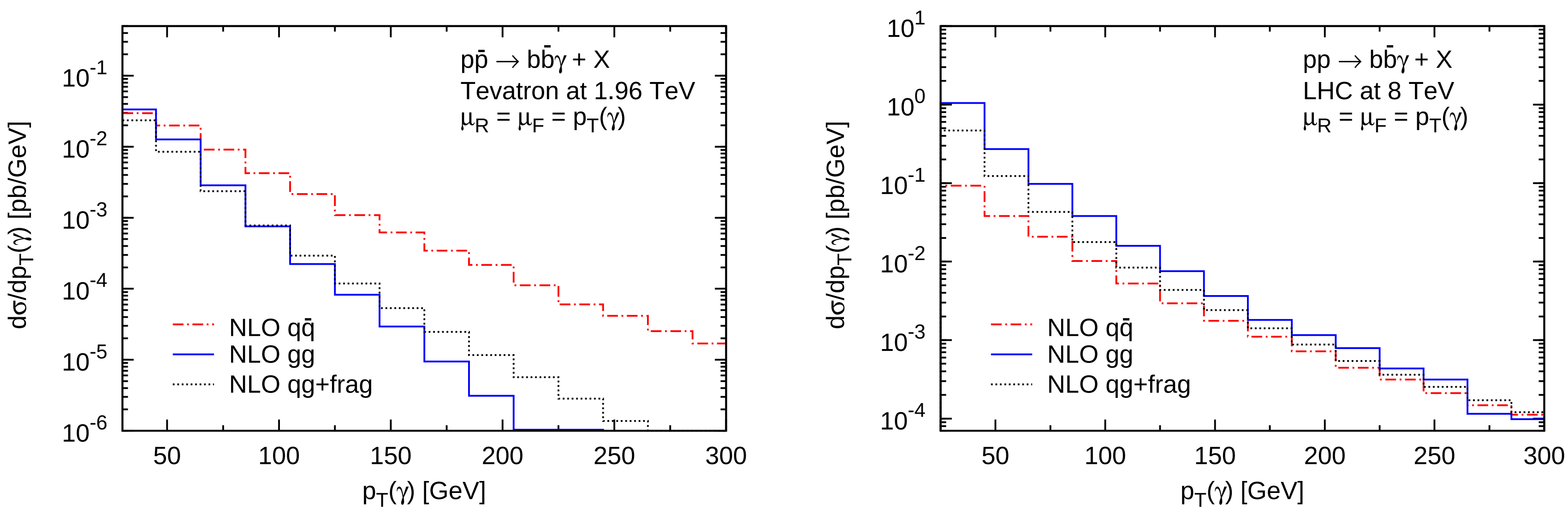
  – Tevatron: $p_T(b, j) > 20$ GeV, $|\eta(b, j)| < 1.5$
  – LHC: $p_T(b, j) > 25$ GeV, $|\eta(b, j)| < 2.1$

Ex.: $\gamma + 2b$

Perturbative theoretical accuracy (μ_R and μ_F dependence, $\mu_0 = p_T(\gamma)$)

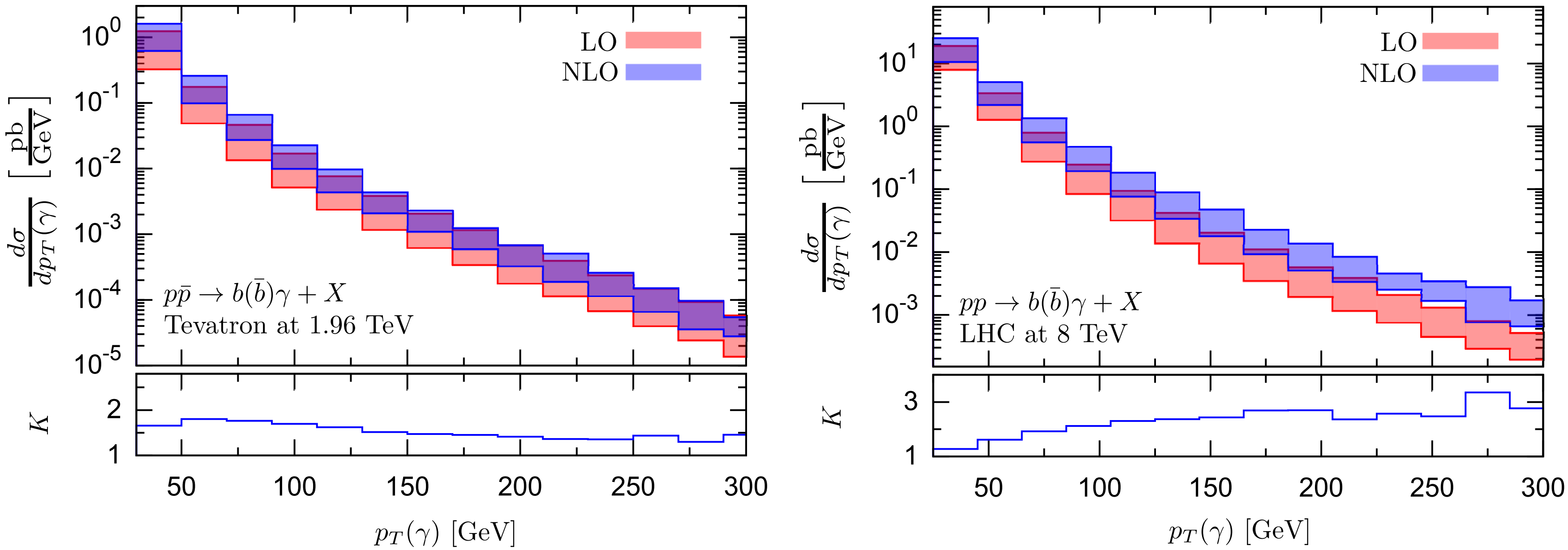


Understanding residual scale-dependence,

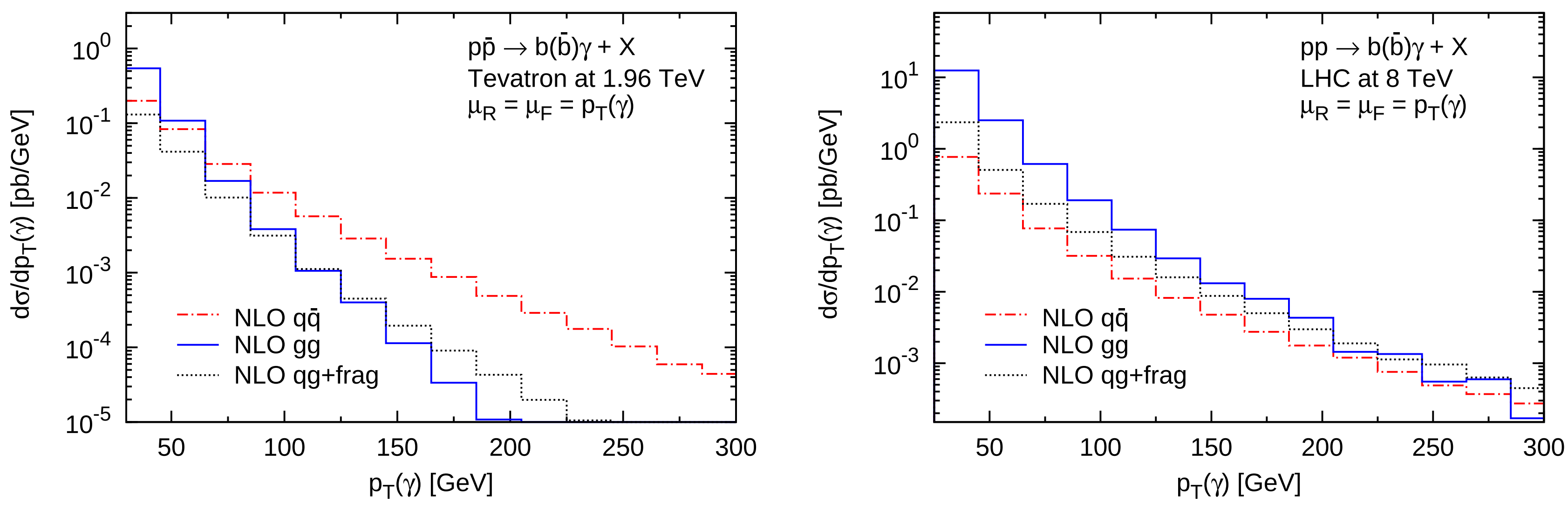


Ex.: $\gamma + 1b$, 4FNS

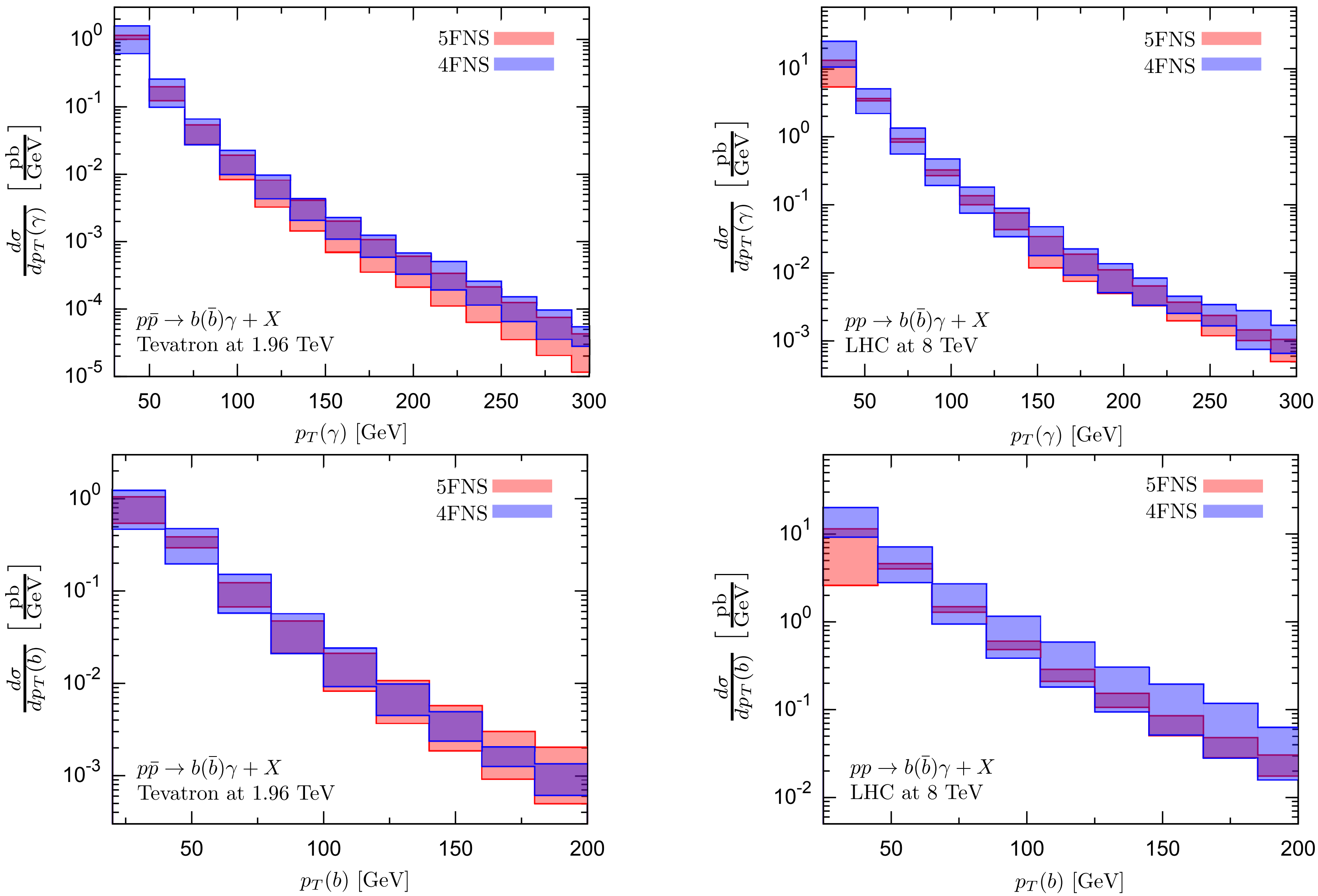
Perturbative theoretical accuracy (μ_R and μ_F dependence, $\mu_0 = p_T(\gamma)$)



Looking at individual contributions:



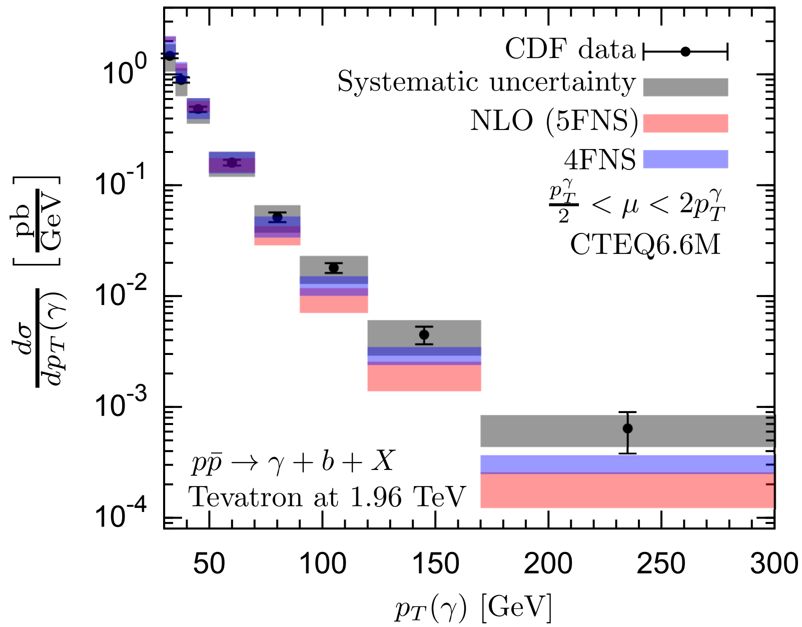
$\gamma + 1b$, 4FNS vs 5FNS

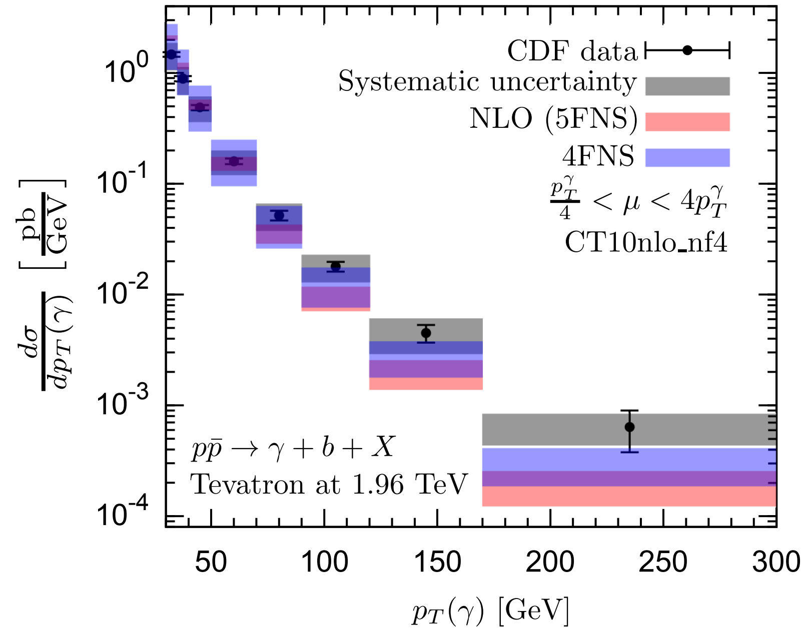


Notice:

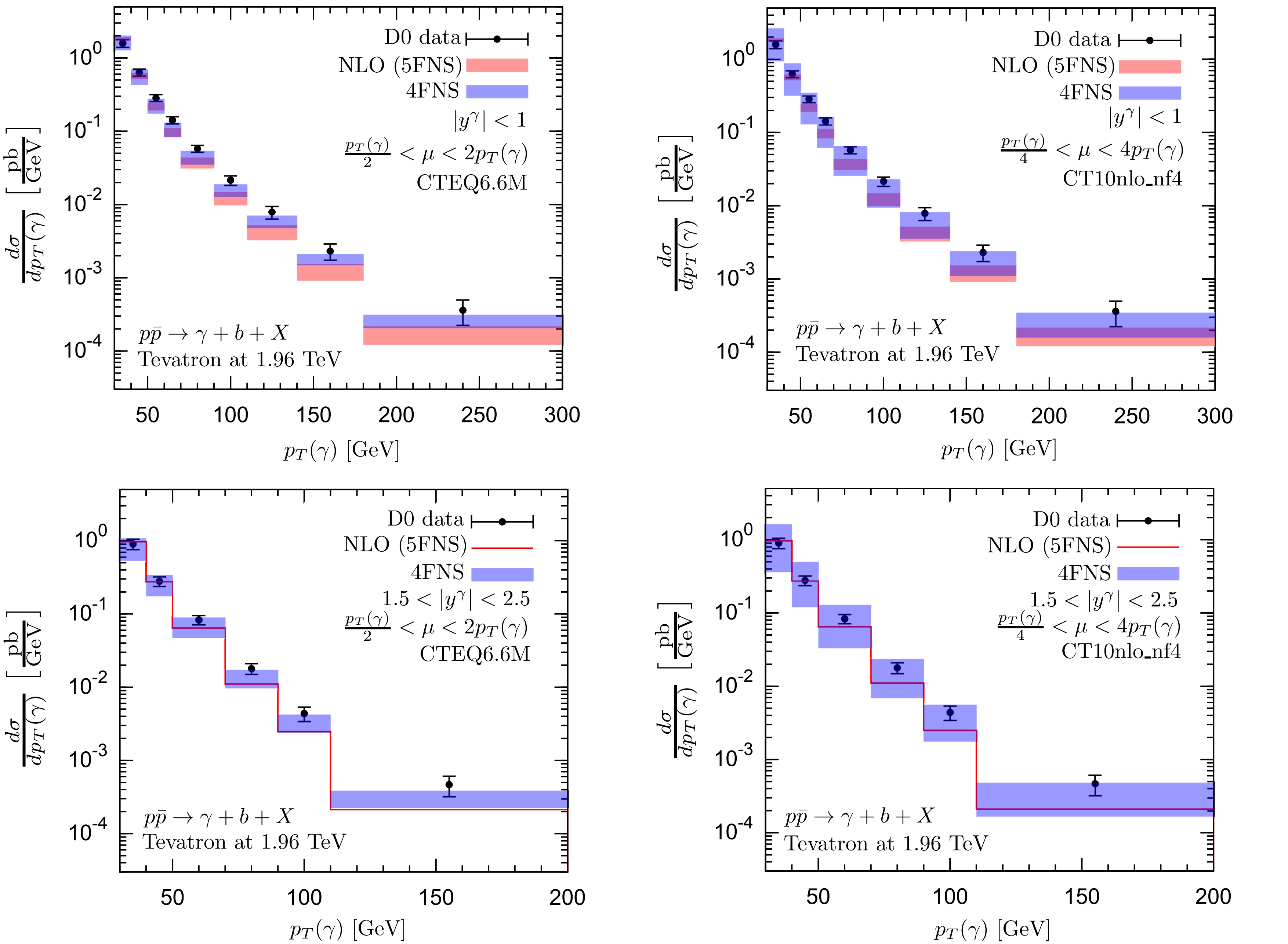
- → overall compatibility within accuracy;
- → difference between high and low $p_T(\gamma)$;
- → difference between Tevatron and LHC.

$\gamma + 1b$: Comparison with experimental results, CDF and D0



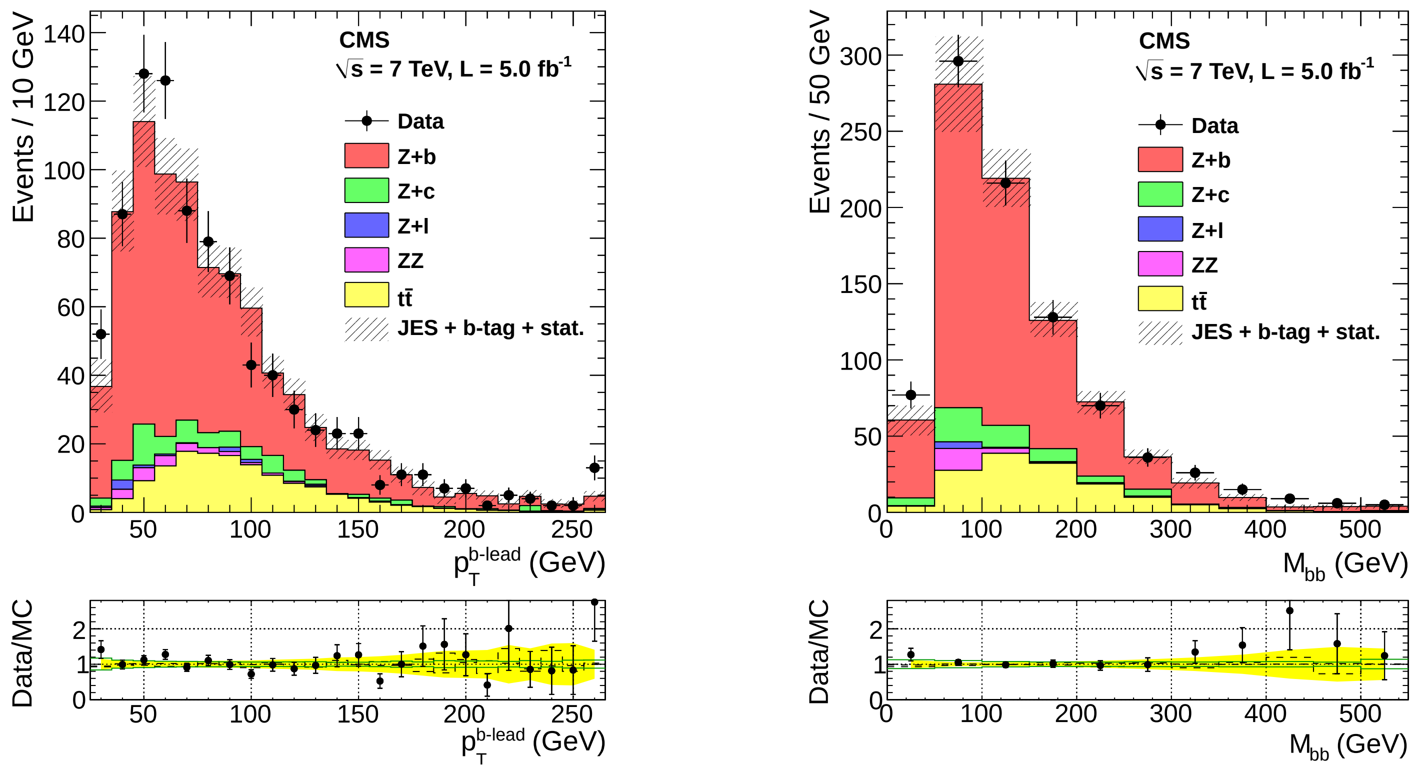


- → signature: γ plus at least one b jet ($\gamma + b + X$)
- → adopted full match with experimental selection cuts
- → used anti-k_T jet algorithm ($R = 0.4$) and fixed-cone photon isolation
- → 5FNS: from Stavreva and Owens (arXiv:0901.3791)
- → 4FNS: from our study (arXiv:1312.2384)
- → L.H.S.: S&O setup
- → R.H.S.: our setup


D0 data
NLO (5FNS)
4FNS
$|y^\gamma| < 1$
$\frac{p_T(\gamma)}{2} < \mu < 2p_T(\gamma)$
CTEQ6.6M
$p\bar{p} \to \gamma + b + X$
Tevatron at 1.96 TeV
$\frac{d\sigma}{dp_T(\gamma)}$ $\left[\frac{\text{pb}}{\text{GeV}}\right]$
$p_T(\gamma)$ [GeV]
D0 data
NLO (5FNS)
4FNS
$|y^\gamma| < 1$
$\frac{p_T(\gamma)}{4} < \mu < 4p_T(\gamma)$
CT10nlo_nf4
$p\bar{p} \to \gamma + b + X$
Tevatron at 1.96 TeV
$\frac{d\sigma}{dp_T(\gamma)}$ $\left[\frac{\text{pb}}{\text{GeV}}\right]$
$p_T(\gamma)$ [GeV]
D0 data
NLO (5FNS)
4FNS
$1.5 < |y^\gamma| < 2.5$
$\frac{p_T(\gamma)}{2} < \mu < 2p_T(\gamma)$
CTEQ6.6M
$p\bar{p} \to \gamma + b + X$
Tevatron at 1.96 TeV
$\frac{d\sigma}{dp_T(\gamma)}$ $\left[\frac{\text{pb}}{\text{GeV}}\right]$
$p_T(\gamma)$ [GeV]
D0 data
NLO (5FNS)
4FNS
$1.5 < |y^\gamma| < 2.5$
$\frac{p_T(\gamma)}{4} < \mu < 4p_T(\gamma)$
CT10nlo_nf4
$p\bar{p} \to \gamma + b + X$
Tevatron at 1.96 TeV
$\frac{d\sigma}{dp_T(\gamma)}$ $\left[\frac{\text{pb}}{\text{GeV}}\right]$
$p_T(\gamma)$ [GeV]

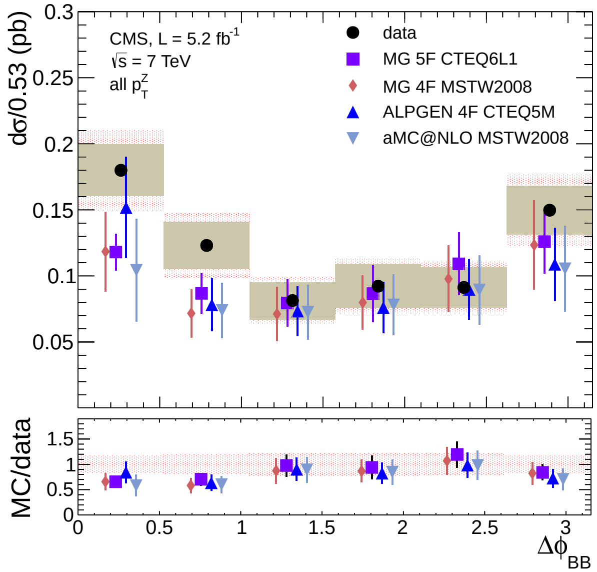
$Z + 1b$ jet vs $Z + 2b$ jets

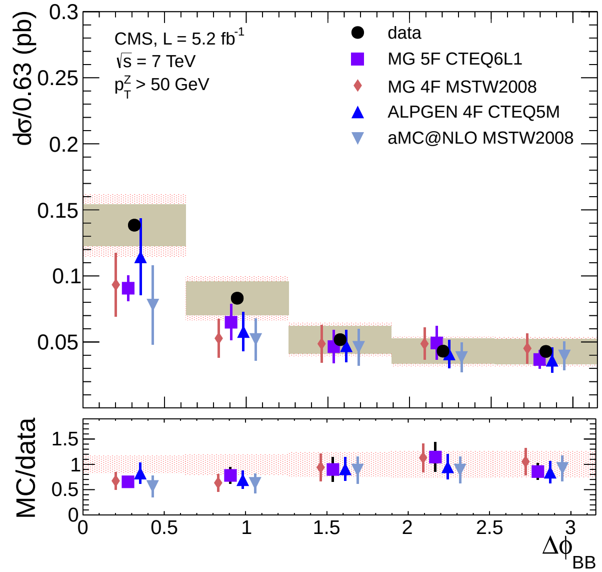
New measurements from CMS (arXiV:1402.1521, arXiv:1310.1349)



Cross section	Measured	MADGRAPH (5F)	aMCATNLO (5F)	MCFM (parton level)	MADGRAPH (4F)	aMCATNLO (4F)
$\sigma_{\mathrm{Z+1b}}$ (pb)	$3.52 \pm 0.02 \pm 0.20$	3.66 ± 0.22	$3.70^{+0.23}_{-0.26}$	$3.03^{+0.30}_{-0.36}$	$3.11^{+0.47}_{-0.81}$	$2.36^{+0.47}_{-0.37}$
$\sigma_{\mathrm{Z+2b}}$ (pb)	$0.36 \pm 0.01 \pm 0.07$	0.37 ± 0.07	$0.29^{+0.04}_{-0.04}$	$0.29^{+0.04}_{-0.04}$	$0.38^{+0.06}_{-0.10}$	$0.35^{+0.08}_{-0.06}$
$\sigma_{\mathrm{Z+b}}$ (pb)	$3.88 \pm 0.02 \pm 0.22$	4.03 ± 0.24	$3.99^{+0.25}_{-0.29}$	$3.23^{+0.34}_{-0.40}$	$3.49^{+0.52}_{-0.91}$	$2.71^{+0.52}_{-0.41}$
$\sigma_{\mathrm{Z+b/Z+j}}$ (%)	$5.15 \pm 0.03 \pm 0.25$	5.35 ± 0.11	$5.38^{+0.34}_{-0.39}$	$4.75^{+0.24}_{-0.27}$	$4.63^{+0.69}_{-1.21}$	$3.65^{+0.70}_{-0.55}$

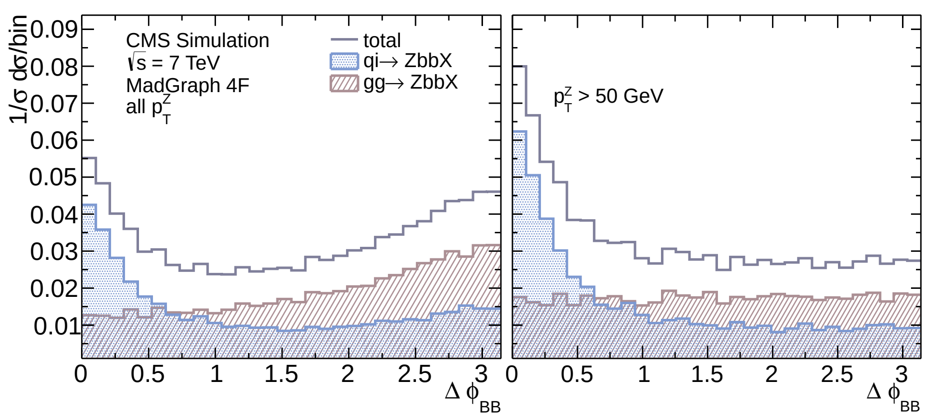
Interesting measurement of b-hadron azimuthal correlation

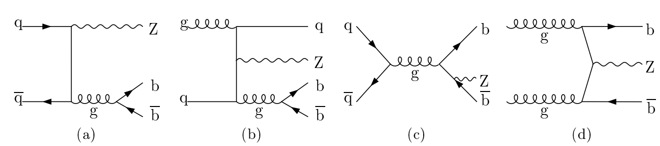




seems to point to resummation of large terms in $b\bar{b}$ collinear region

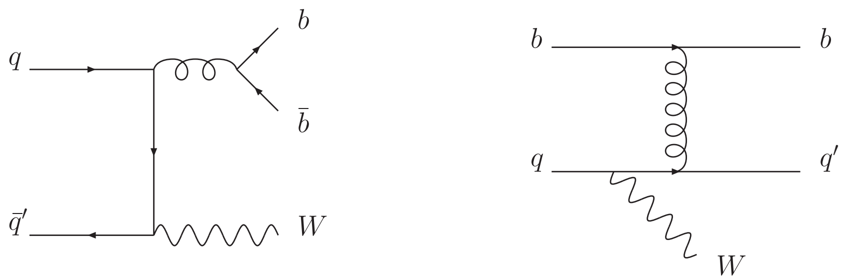
($\hookrightarrow$ Mangano and Nason, PLB 285 (1992) 160, HQ multiplicity in gluon jets)





$W + 1b$ jet vs $W + 2b$ jets

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:

- ▷ $W + 2b$ 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,
  - $\rightarrow$ Wb exclusive: Wb only;
  - $\rightarrow$ $W(b\bar{b})$ exclusive: $W(b\bar{b})$ only;
  - $\rightarrow$ Wb inclusive: Wb, $Wb+j$, $Wb\bar{b}$;
  - $\rightarrow$ $W(b\bar{b})$ inclusive: $W(b\bar{b})$ and $W(b\bar{b})+j$.
- calculate $\sigma_{\rm event}$ and $\sigma_{\rm b-jet}$ where

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

- overall improved scale dependence: NLO corrections to $gq \rightarrow Wb\bar{b}q'$ partially included in 5FNS
- Compared to CDF and D0 measurements ($W+1b$)
- Compared to ATLAS and CMS measurements ($W+1b$ and $W+2b$)

Comparison with Tevatron measurements

CDF (arXiv:0909.1505):

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

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

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

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

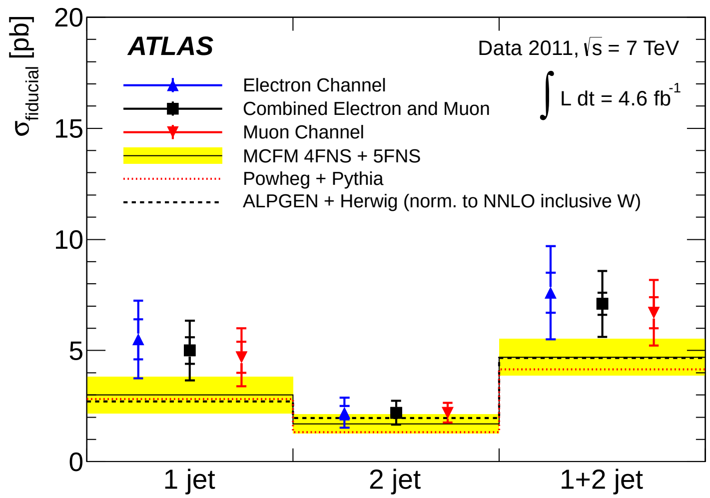
whereas:

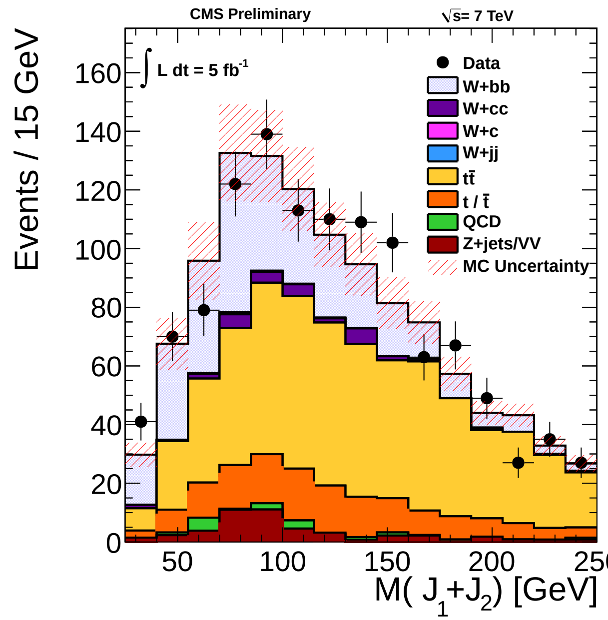
D0 (arXiv:1210.0627):

$$\sigma(W(\to l\nu) + b + X) = 1.05 \pm 0.12(\mathrm{stat} + \mathrm{syst})\ \mathrm{pb}$$

MCFM: $\sigma(W(\to l\nu) + b + X) = 1.34^{+0.41}_{-0.34}(\mathrm{syst})$ pb

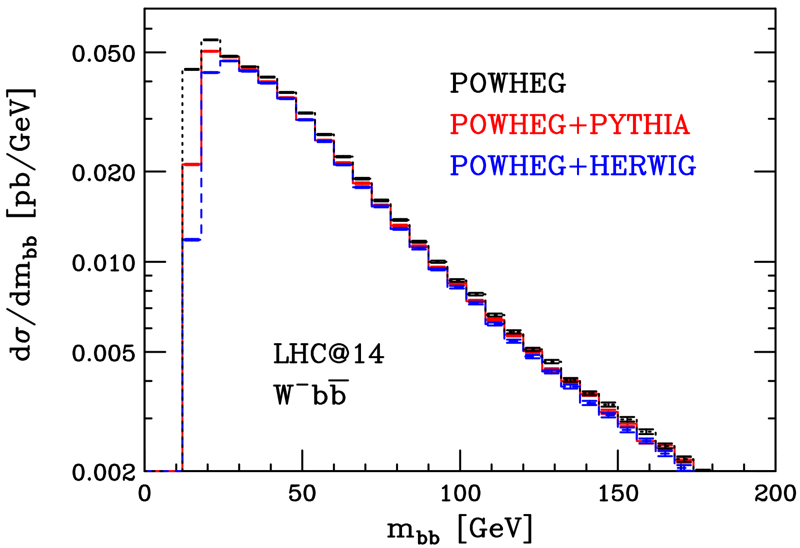
Comparison with ATLAS and CMS

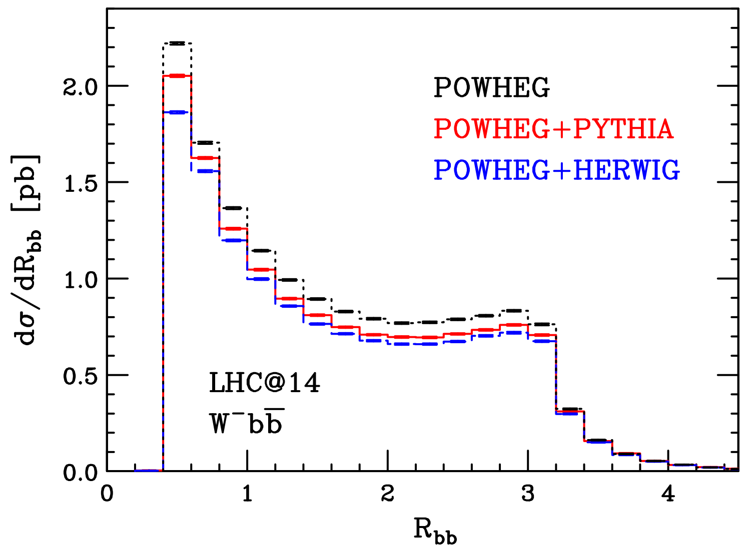




- ATLAS and CMS complementary measurements: $W + b + j$ vs $W + 2b$.
- ATLAS consistent with NLO QCD calculations within 1.5 σ.
- CMS consistent with NLO QCD predictions:
  CMS ($W + 2b$ jets): 0.53 ± 0.05 (stat)± 0.09 (syst) ± 0.06 (theo) pb
  MCFM ($W + 2b$ jets): 0.52 ± 0.03 pb
- Only partial use of NLO parton shower MC $\rightarrow$ fully available for $W + 2b$ jets. Better tool for distributions.

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





- used in ATLAS analysis to estimate showering and hadronization uncertainties: $\leq 10-20\%$ (although $bq \to bq'W$ not yet implemented).
- Could be fully used in CMS analysis.

Outlook

- We seem to be converging towards a more definite understanding of $V + b$ jets at hadron collider.
- Experimental precision now comparable to theoretical accuracy.
- Realistic phenomenological analyses need to embed NLO calculations into NLO parton-shower Monte Carlos:
  $\rightarrow$ $V + 1b$ can be tricky $\rightarrow$ need massive b in initial state.
- $V + c$ jets need to be systematically studied.
- Possible to develop a precision program for HQ PDF from high-energy data.
  $\rightarrow$ NNLO QCD need to be included.
  $\rightarrow$ First order of EW need to be included.