Heavy-flavour production at the LHC: challenges and opportunities

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Université Libre de Bruxelles, May 2014

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

- The incredible physics potential of the LHC relies on our ability of providing very accurate theoretical 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, $\ldots$);
  - $\longrightarrow$ 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: $t\bar{t}$, $t\bar{t}+H$, $b\bar{b}+H$, $b\bar{b}+W/Z$, $t\bar{t}+W/Z$, $t\bar{t}b\bar{b}$, $t\bar{t}WW/ZZ$, $\ldots$

Outline

- Theoretical predictions for the LHC:
  - $\rightarrow$ key ingredients: higher orders, PDF, parton shower matching;
  - $\rightarrow$ Higgs discovery: a proof of concept.
- Focusing on Heavy-Quark physics, in particular:
  - $\rightarrow$ $t\bar{t}$ production;
  - $\longrightarrow$ heavy-quark production with Higgs bosons: $Ht\bar{t}$, ($H+b$ jets);
  - $\longrightarrow$ heavy-quark production with weak gauge bosons: $W/Z/\gamma+b$ jets, ($W/Z/\gamma+t\bar{t}$);

  a natural ground to illustrate some of the key ingredients of theoretical predictions, with very strong physical motivations.
- Conclusions and outlook.

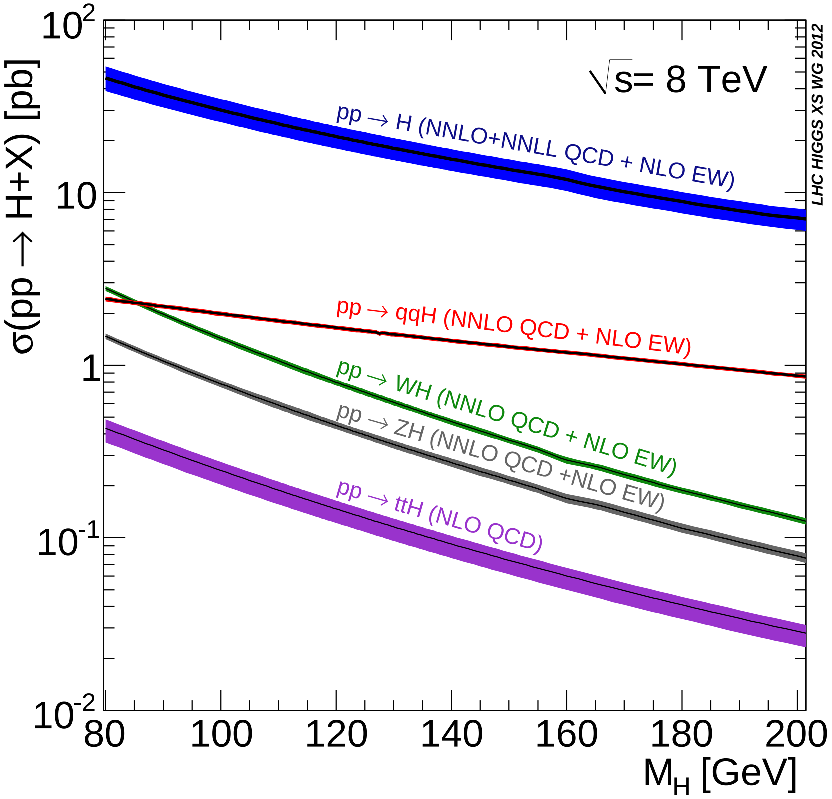
Theoretical predictions for the LHC

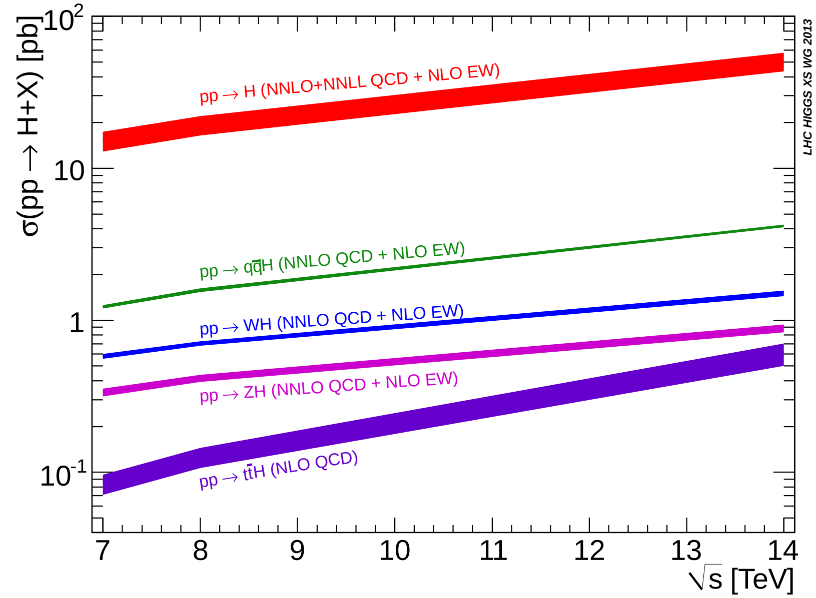
- Higher orders in QCD/EW essential to:
  - → stability and predictivity of theoretical results, since less sensitivity to unphysical renormalization/factorization scales;
  - → more realistic modelling of parton level since higher parton multiplicity (distributions, jets, ...);
  - → first step towards matching with resummed calculations and parton shower Monte Carlo programs.

- NLO QCD, challenges have largely been met:
  - → traditional approach (FD's) made more efficient to handle high multiplicity;
  - → new techniques based on unitarity methods and recursion relations offers a powerful alternative, particularly suited for automation;
  - → interface with parton shower MC well advanced (MC@NLO, POWHEG, Sherpa);
  - → automation mostly achieved (aMC@NLO, BlackHat, GoSam, ...).

- NLO EW and EW+QCD: corrections known for most processes relevant for Run I of the LHC.
- NNLO QCD: conquered or under way for a variety of $2 \to 2$ processes (e.g. $pp \to Q\bar{Q}$, and $pp \to H + j$). Essential when:
  - $\to$ processes involve multiple scales, leading to large logarithms of the ratio(s) of scales;
  - $\to$ new parton level subprocesses first appear at NLO;
  - $\to$ new dynamics first appear at NLO.
- N^3LO results for $2 \to 1$ processes ($gg \to H$ in $m_t \to \infty$ limit)
- Developed systematic resummation techniques for multiscale processes to account for:
  - $\to$ large corrections from dominant kinematic regions (soft/collinear);
  - $\to$ large corrections induced by exclusive cuts/vetos.
- PDF: constant development, NNLO is now the state of the art. Enormous effort to optimize PDF sets for LHC physics.

Proof of concept: Higgs discovery and beyond



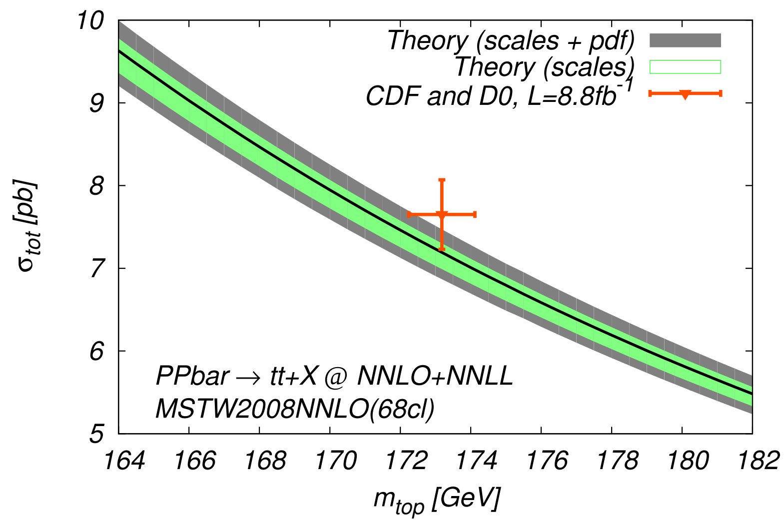


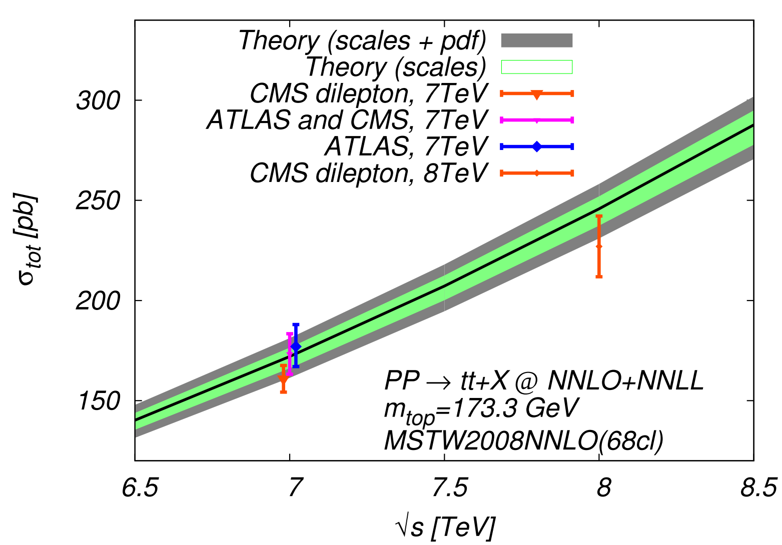
(LHC Higgs Cross Sections Working Group, arXiv:1101.0593,1201.3084 and 1307.1347)

- all orders of calculated higher orders corrections included (tested with all existing calculations);
- theory errors (scales, PDF, α_s, ...) combined according to common recipe.

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

physics need for high theoretical accuracy





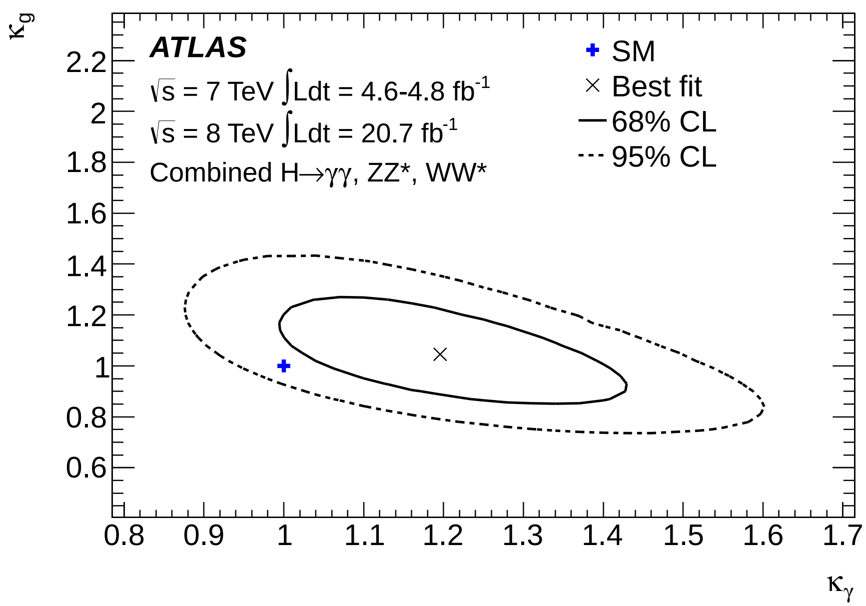
Czakon, Fiedler, Mitov (arXiv:1303.6254)

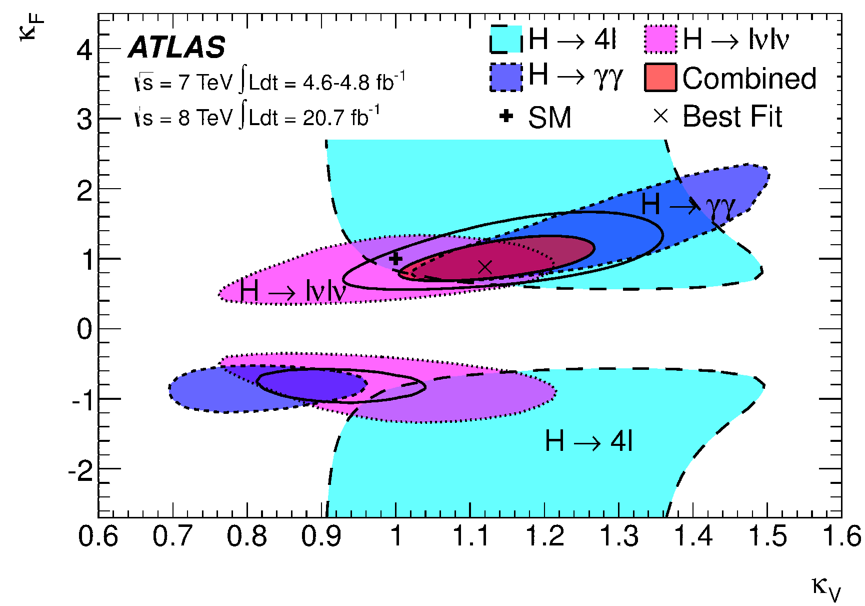
- ▷ full NNLO+NNLL now calculated;
- ▷ theoretical uncertainty reduced to $\simeq 4-5\%$ (scale) and $\simeq 3-4\%$ (PDF) at the LHC, even less at the Tevatron;
- ▷ comparable to current experimental uncertainty: precision requires NNLO;
- ▷ almost a precision measurement of parton densities.

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

- Motivations
  - ▷ $Ht\bar{t}$: instrumental to Higgs couplings determination;
  - ▷ $Hb\bar{b}$: direct evidence of new physics.
- Focus on $t\bar{t}+H$: Interesting aspects of the NLO calculation.
- Latest studies: interface with NLO Parton Shower MC and spin studies.

$t\bar{t}H$: motivation





See studies in:

ATLAS-CONF-2012-127, and arXiv:1307.1427

CMS-PAS-HIG-12-020

Notice:

- ▷ hard to constrain κ_t from $(\kappa_g, \kappa_\gamma)$ fit, direct κ_t measurement is crucial
- ▷ sign of κ_t cannot come from $t\bar{t}H \longrightarrow H + t$ production

  (see Biswah, Gabrielli, Mele, arXiv:1211.0499, $pp \to tq + H \to tq + \gamma\gamma$)

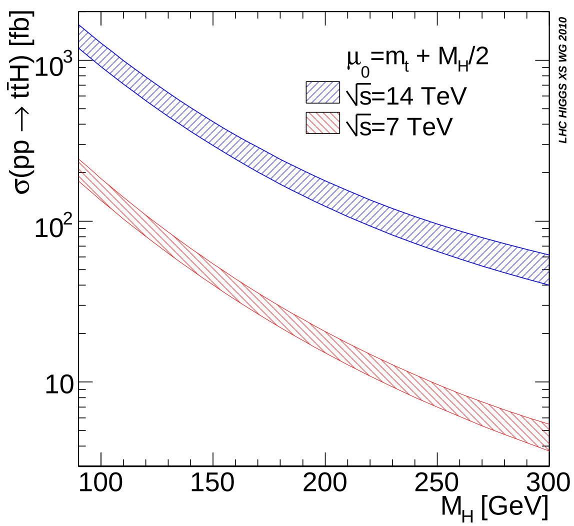
$t\bar{t}H$: towards more accurate theoretical predictions

NLO QCD corrections to $pp \to t\bar{t}H$ from:

$\rightarrow$ Beenakker et al. (arXiv:hep-ph/0107081, arXiv:hep-ph/0211352)
$\rightarrow$ Dawson et al. (arXiv:hep-ph/0107101, arXiv:hep-ph/0211438)

used to estimate the theoretical uncertainties currently used in Higgs searches

$\hookrightarrow$ Higgs Cross Section Working Group (HXSWG-$t\bar{t}H$)
(First Yellow Report, arXiv:1101.059)



$m_H \simeq 125$ GeV, $\sqrt{s} = 14$ TeV

$\delta\sigma^{NLO}|_{scale}(\%) \simeq [+5.9, -3.3]$
$\delta\sigma^{NLO}|_{PDF+\alpha_s} \simeq \pm 8.9$
where

scale: $\mu_0/2 < \mu < 2\mu_0$

PDF:MSTW08, CTEQ6.6, NNPDF2.0

Matched at NLO to Parton Shower Monte Carlo generators

NLO calculation (by Dawson et al.) interfaced with Parton Shower Monte Carlo generators (PYTHIA/HERWIG) within

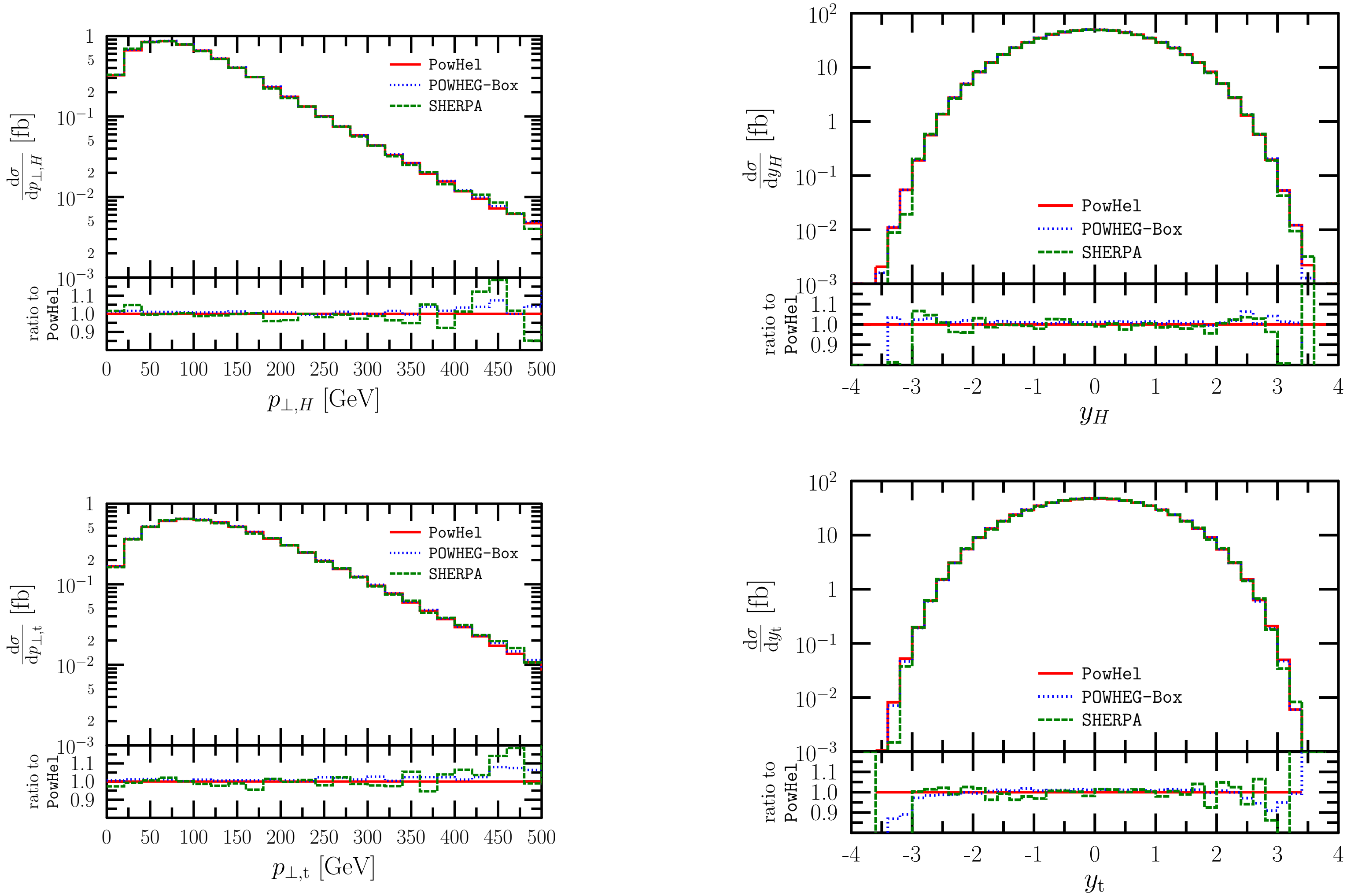
- ▷ POWHEG-BOX
- ▷ Sherpa

and successfully compared to PowHel (HELAC-NLO+POWHEG-BOX)

↪ Garzelli, Kardos, Trócsányi ; Jäger, Hartanto, Reina, Wackeroth
Les Houches Higgs Working Group (2013)

for a standard choice of selection cuts, and assuming $H \to \gamma\gamma$ (all decays implemented through the PS MC),

- $p_T^{jet} > 20$ GeV, $|y^{jet}| < 4.5$
- $p_T^{l} > 20$ GeV, $|y^{l}| < 2.5$
- $\Delta R_{l,jet} > 0.4$

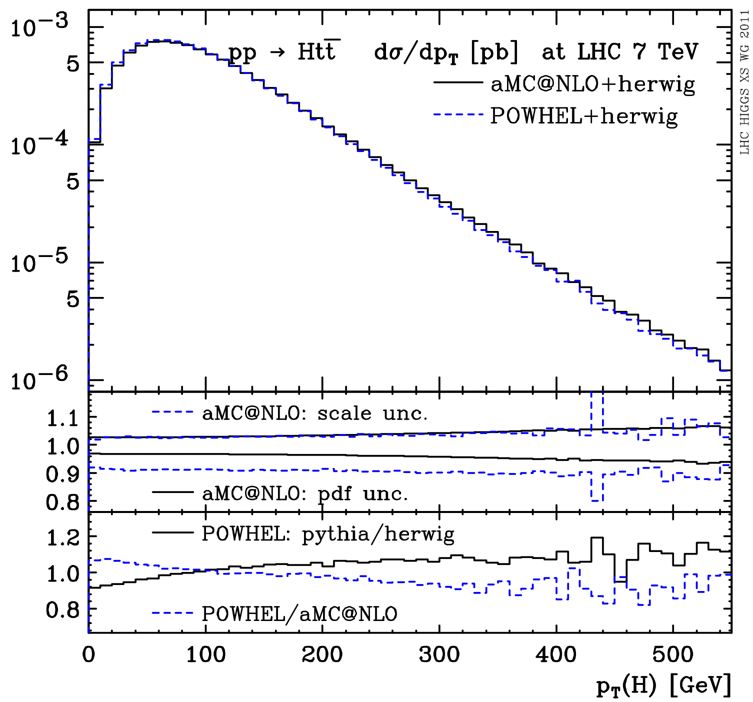


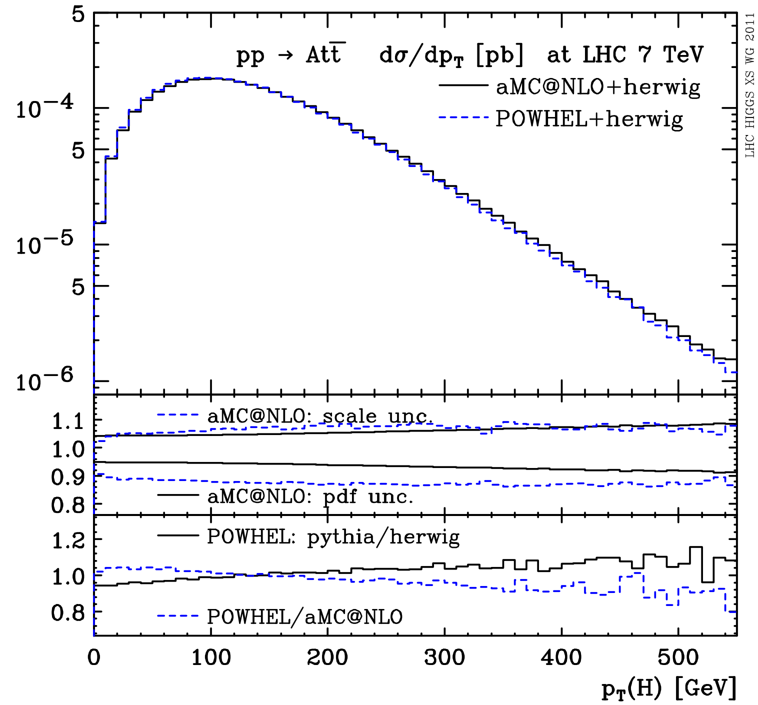
PowHel
POWHEG-Box
SHERPA
$\frac{d\sigma}{dp_{\perp,H}}$ [fb]
ratio to PowHel
$p_{\perp,H}$ [GeV]
$\frac{d\sigma}{dy_H}$ [fb]
y_H
$\frac{d\sigma}{dp_{\perp,t}}$ [fb]
$p_{\perp,t}$ [GeV]
$\frac{d\sigma}{dy_t}$ [fb]
y_t

Independent calculation from aMC@NLO, also successfully compared with PowHel (both $t\bar{t}H$ and $t\bar{t}A$)

↪ Garzelli, Kardos, Trócsányi ; Frederix

(HXSWG-$t\bar{t}H$, Yellow Report II, arXiv:1201.3084)





New: study of spin correlation in $t\bar{t}H$

Spin-correlation effects can be used to distinguish scalar vs pseudoscalar associated production, i.e. SM from non-SM effects

$\hookrightarrow$ Artoisenet, Frederix, Mattelaer, Rietkerk, arXiv:1212.3460

and can be very visible in decay product's kinematic distributions,

$\hookrightarrow$ Ellis, Hwang, Sakurai, Takeuchi, arXiv:1312.5736

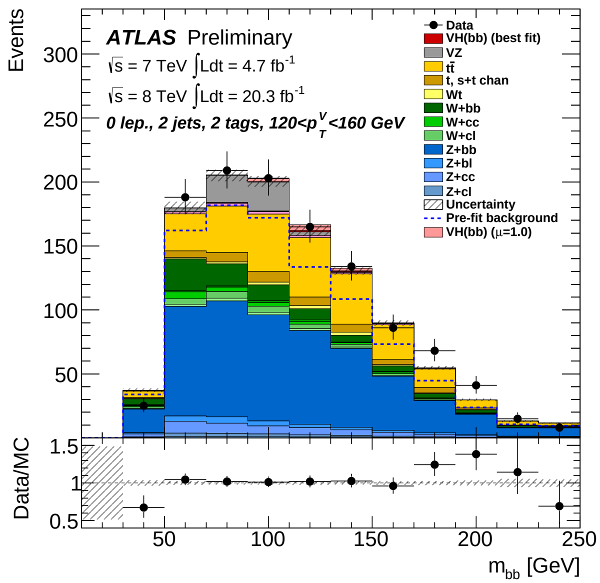
and even more can be used to improve the separation of signal ($t\bar{t}H$) and some irreducible backgrounds (e.g. $t\bar{t}\gamma\gamma$)

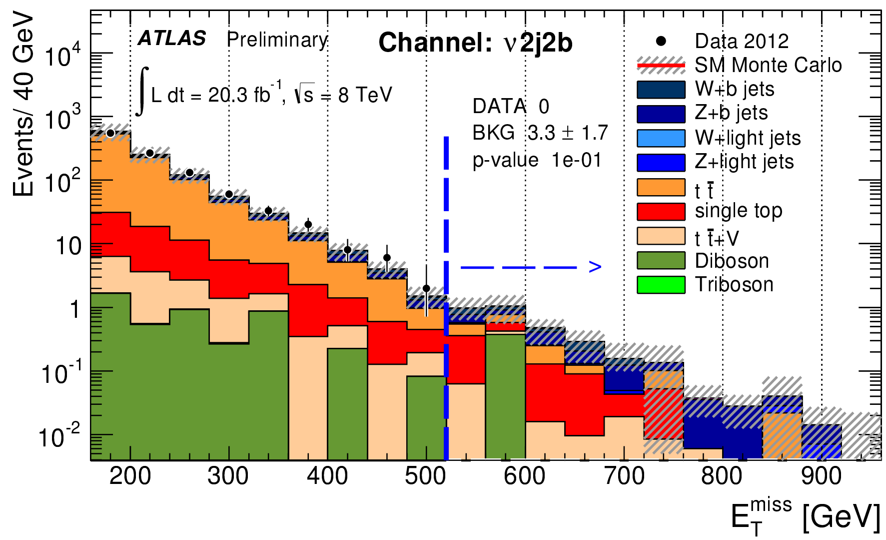
$\hookrightarrow$ (Biswah,Frederix, Gabrielli, Mele, arXiv:1403.1790)

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

- 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

Motivations
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, $m_b = 0$),

$\rightarrow$ $b\bar{q} \rightarrow Wb + q'$

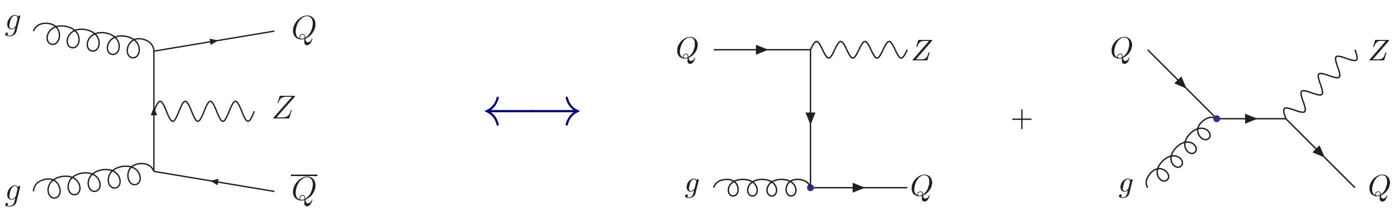
$\rightarrow$ $bg \rightarrow Zb/\gamma b$

and corresponding higher-order corrections.

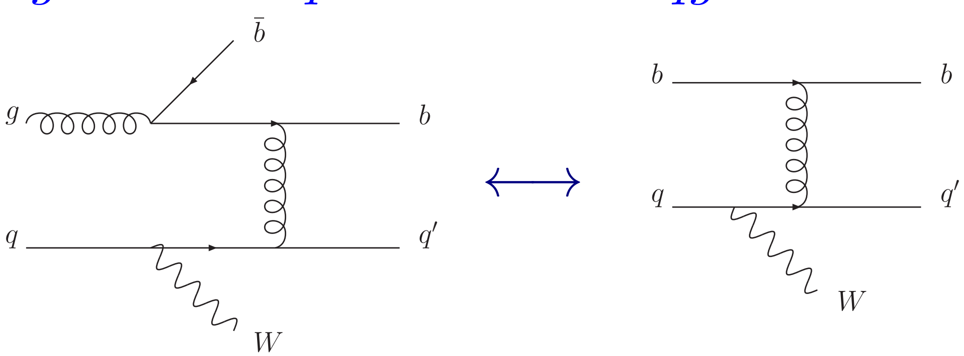
Different processes dominate in different kinematic regions and at different scales (relative to m_b). Why? $\longrightarrow$ look at origin of b-initiated processes

Observe that: when HQ is not tagged ...

▷ $bg \to Zb/\gamma b$ 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.

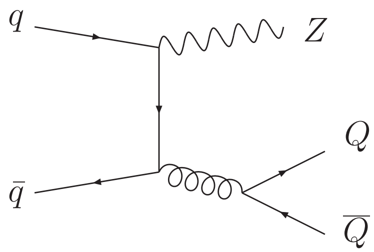
. . . and yet:

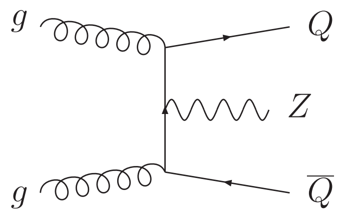
- fixed-order expansion of b-initiated processes does not match fixed-order calculation (missing non-log terms).
- when should we make the transition $n_{lf} = 4 \rightarrow n_{lf} = 5$?
- do we understand the interplay of $n_{lf} = 4$ and $n_{lf} = 5$ in different processes ($W + b$ jets vs $Z + b$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

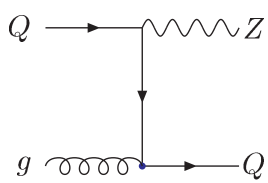
$V + 2b$ jets and $V + 1b$ jet for $V = \gamma, Z$:

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

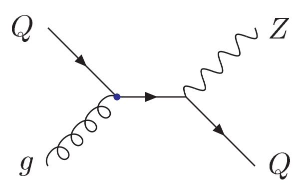




$+$ $O(\alpha_s)$ corrections



$+$



$+$ $O(\alpha_s)$ 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

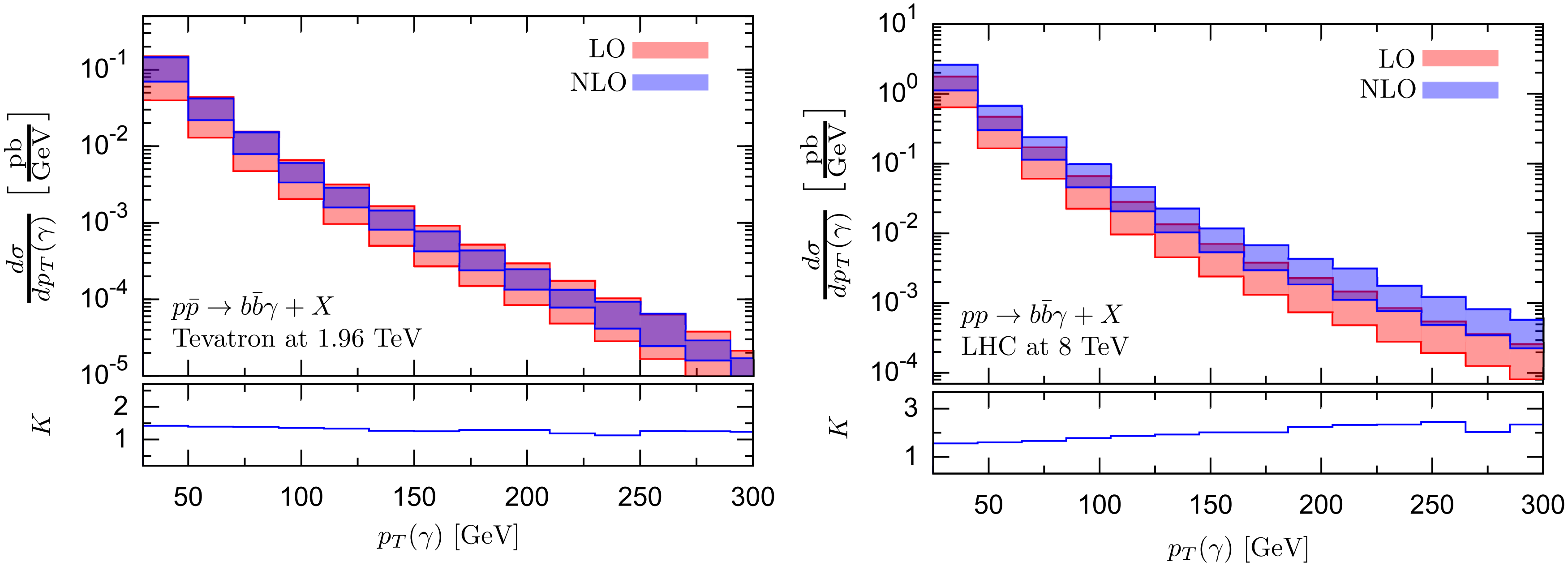
H. Hartanto, L.R., arXiv:1312.2384

- NLO 4FNS and 5FNS calculation
- Studied dependence on
  - → dynamical-scale choice ($p_T(\gamma)$, H_T, ...),
  - → 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: $\sum_{i,R\leq R_0} E_T^i\,\theta(R-R_{i,\gamma}) < \epsilon E_T^\gamma \left(\frac{1-\cos R}{1-\cos R_0}\right)$

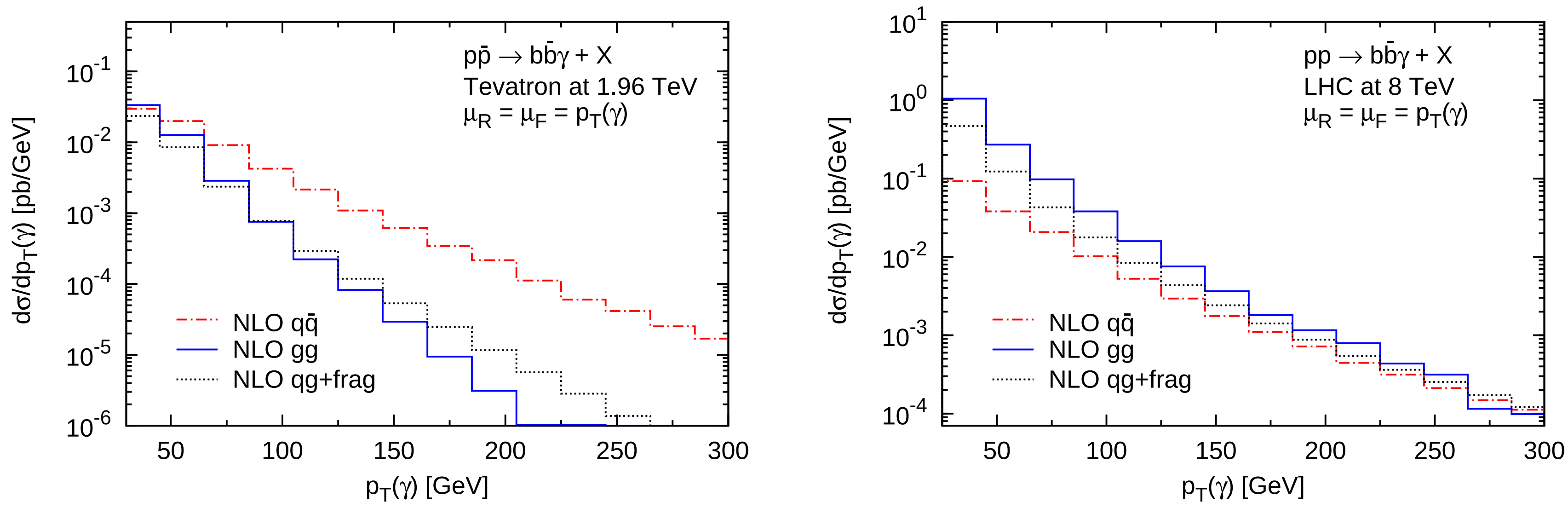
  (for $R_0 = 0.4$, $\epsilon = 1$).
- PDF: CT10nlonf4 (4FNS), CT10nlo (5FNS).
- Photon selection cuts:
  - – Tevatron: $p_T(\gamma) > 30$ GeV, $|\eta(\gamma)| < 1$
  - – LHC: $p_T(\gamma) > 25$ GeV, $|\eta(\gamma)| < 1.37$
- Jet selection cuts (used anti-k_T with $R = 0.4$):
  - – Tevatron: $p_T(b,j) > 20$ 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, $\mu_0 = p_T(\gamma)$)

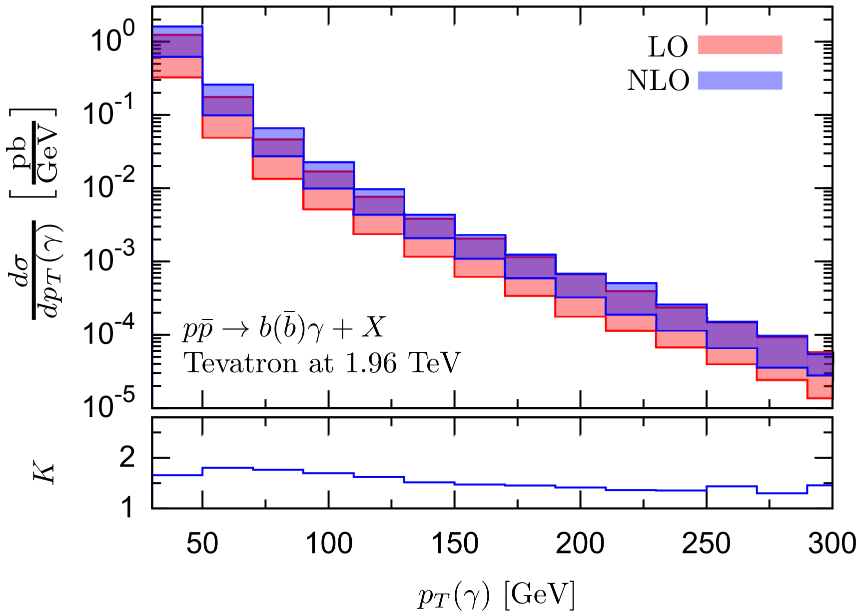


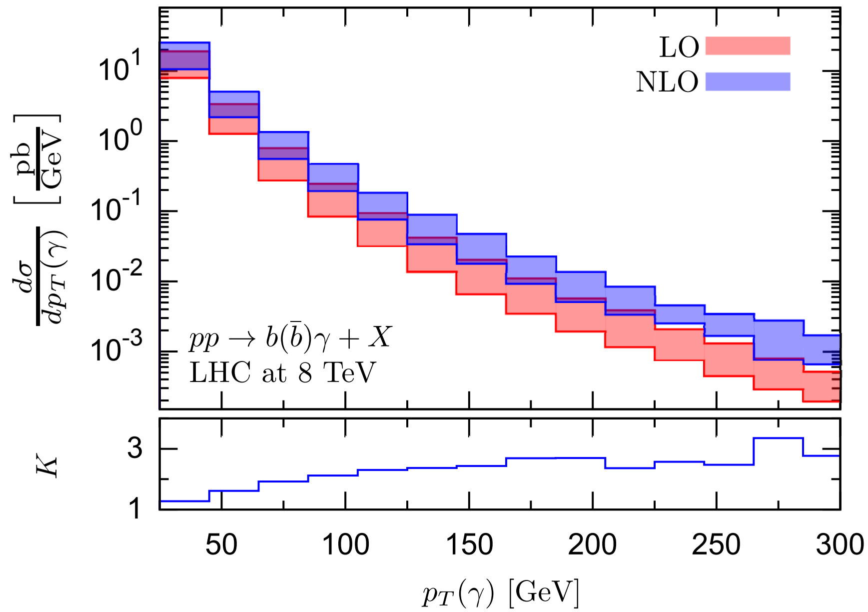
Understanding residual scale-dependence,



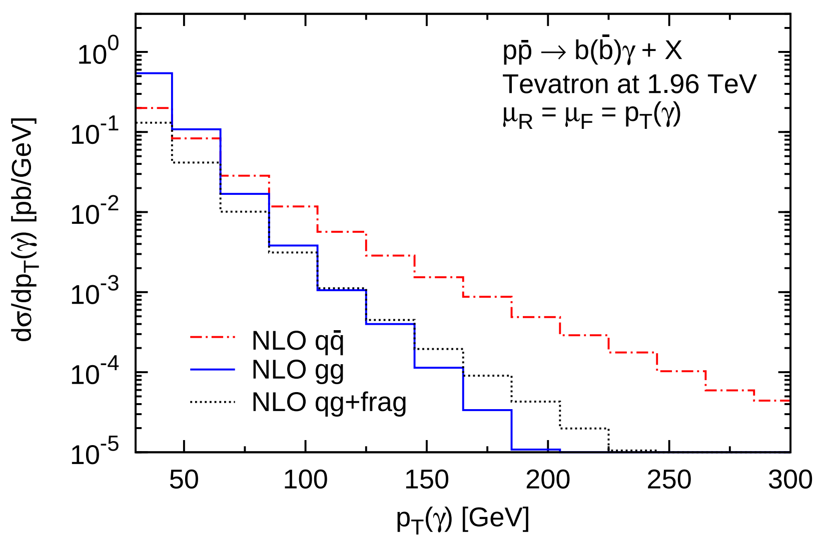
Ex.: $\gamma + 1b$, 4FNS

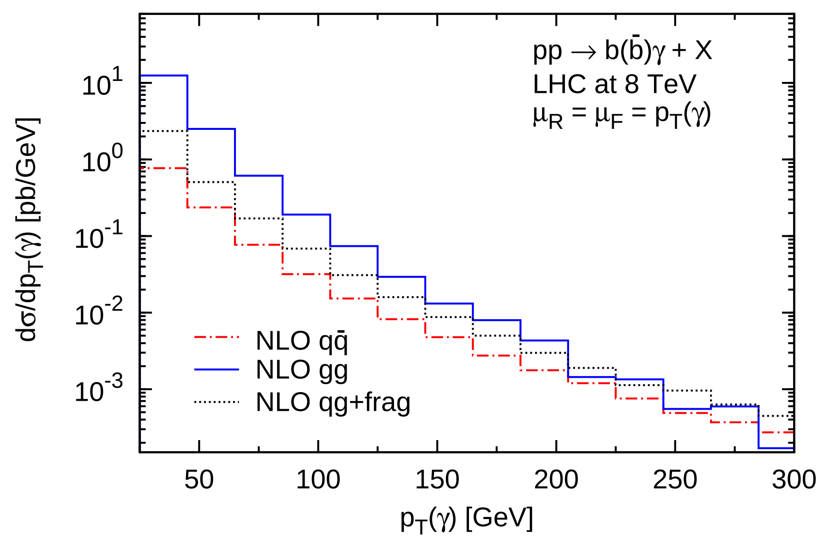
Perturbative theoretical accuracy (μ_R and μ_F dependence, $\mu_0 = p_T(\gamma)$)



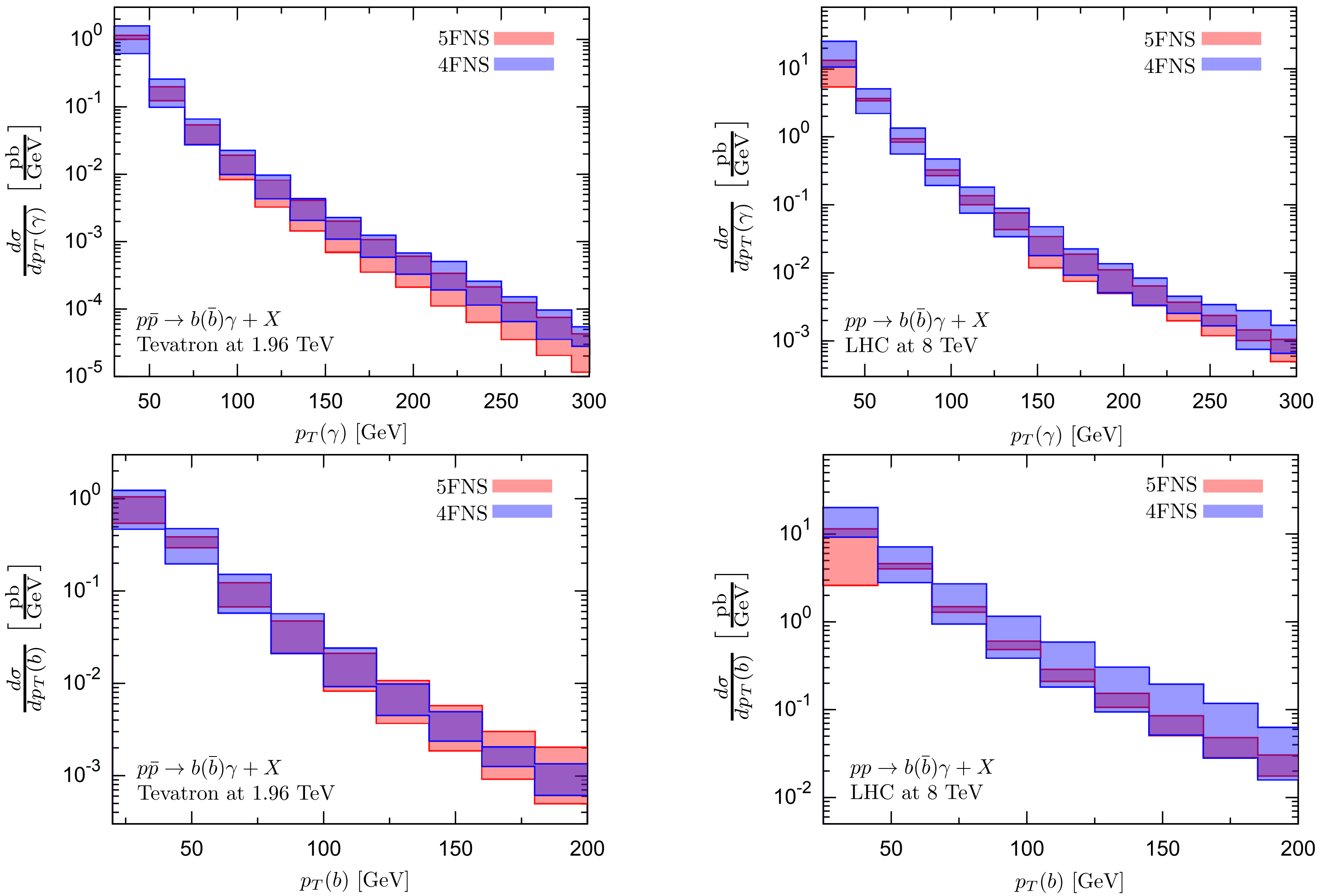


Looking at individual contributions:





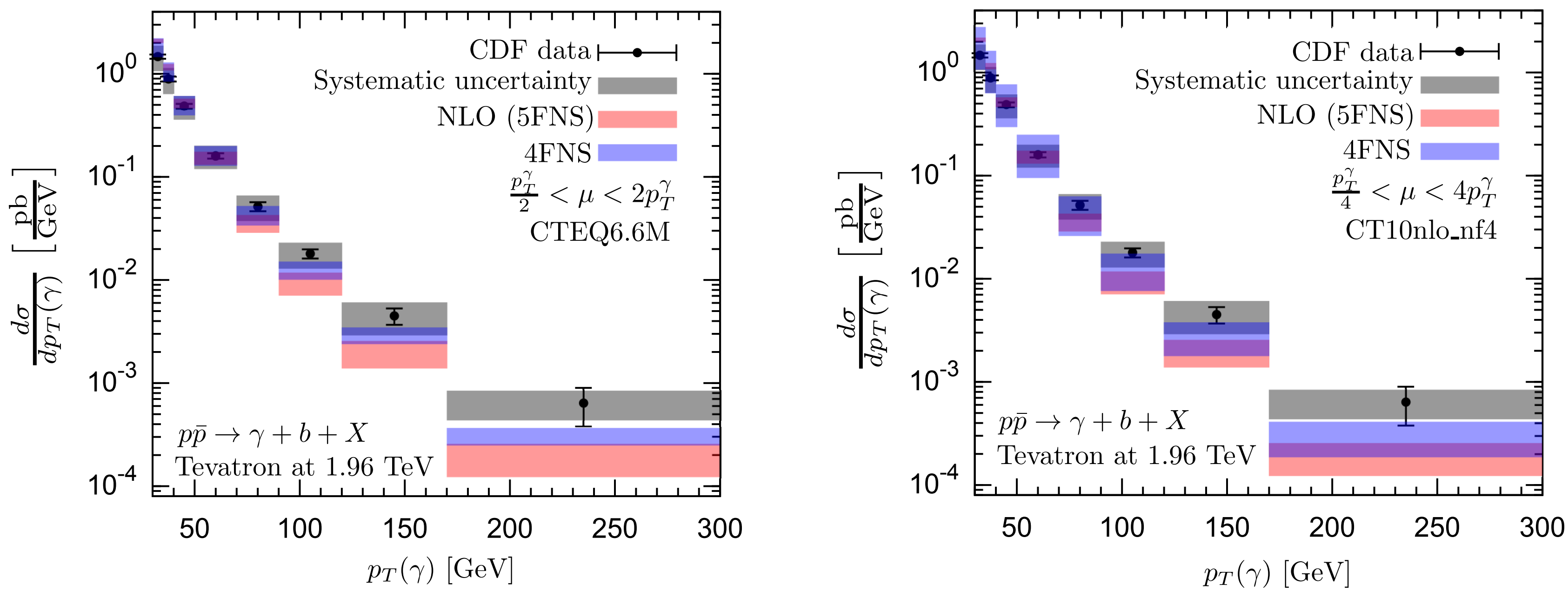
$\gamma + 1b$, 4FNS vs 5FNS



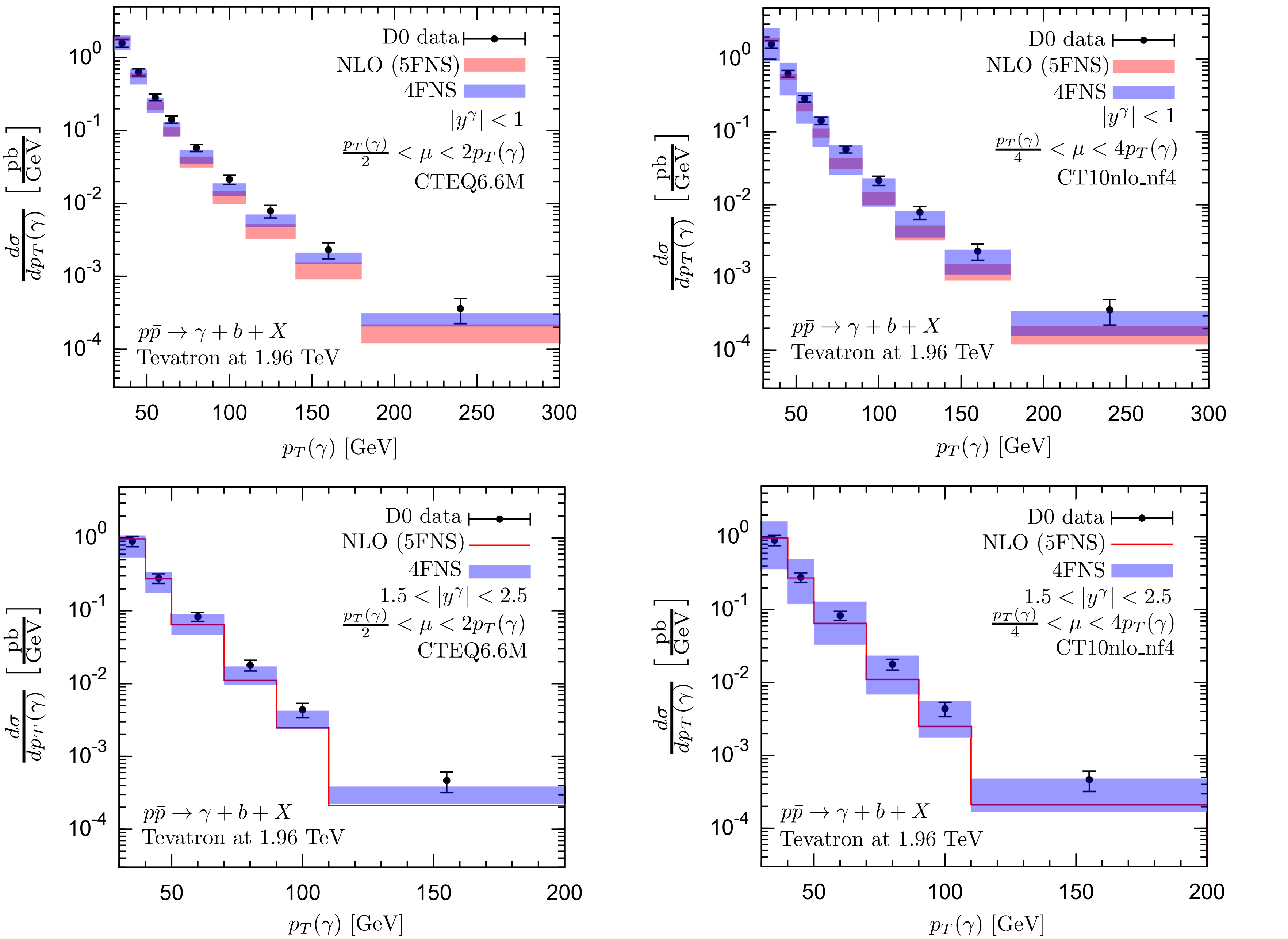
Notice:

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

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



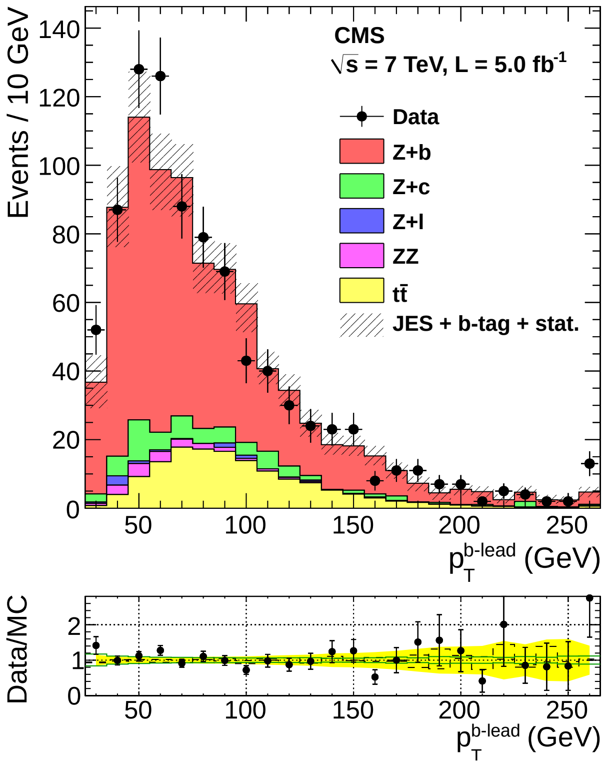
- $\rightarrow$ signature: γ plus at least one b jet ($\gamma + b + X$)
- $\rightarrow$ adopted full match with experimental selection cuts
- $\rightarrow$ used anti-k_T jet algorithm ($R = 0.4$) and fixed-cone photon isolation
- $\rightarrow$ 5FNS: from Stavreva and Owens (arXiv:0901.3791)
- $\rightarrow$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

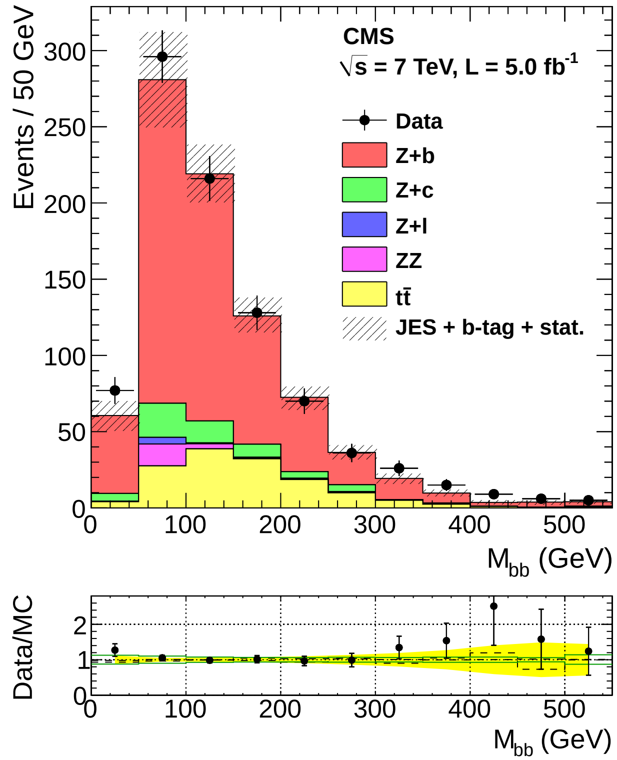


D0 data
NLO (5FNS)
4FNS
$|y^\gamma| < 1$
$\frac{p_T(\gamma)}{2} < \mu < 2p_T(\gamma)$
CTEQ6.6M
$p\bar{p} \to \gamma + b + X$
Tevatron at 1.96 TeV
$\frac{d\sigma}{dp_T(\gamma)}$ $\left[\frac{\text{pb}}{\text{GeV}}\right]$
$p_T(\gamma)$ [GeV]
$\frac{p_T(\gamma)}{4} < \mu < 4p_T(\gamma)$
CT10nlo_nf4
$1.5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

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

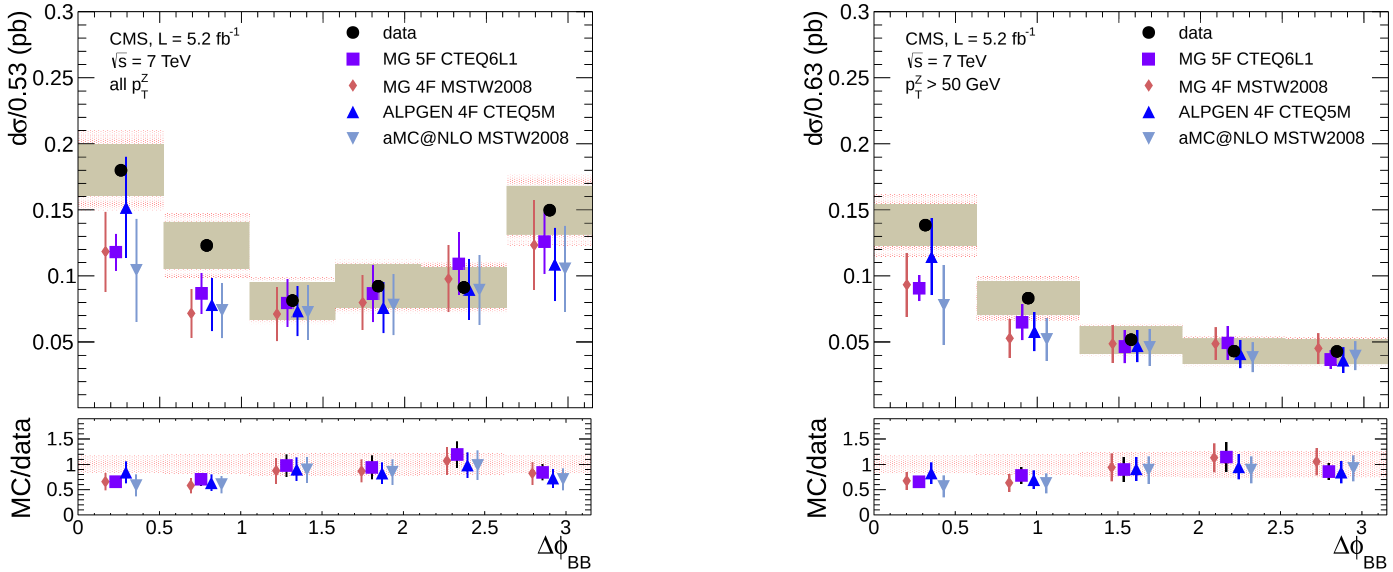
New measurements from CMS (arXiV:1402.1521, arXiv:1310.1349)





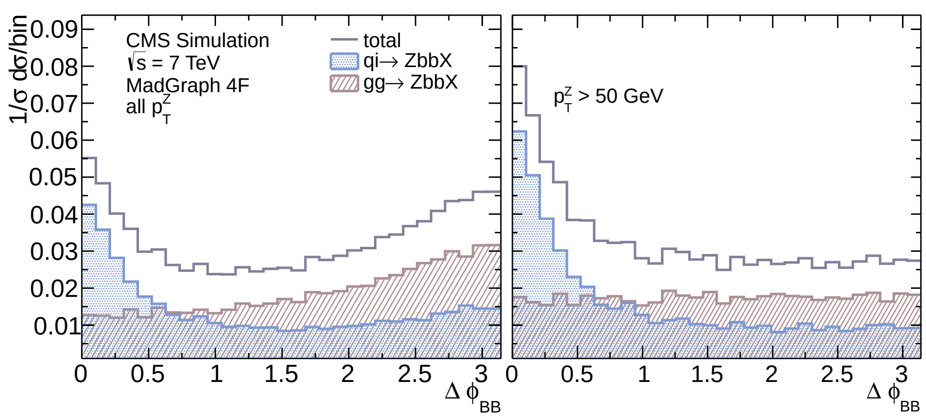
Cross section	Measured	MADGRAPH (5F)	aMCATNLO (5F)	MCFM (parton level)	MADGRAPH (4F)	aMCATNLO (4F)
$\sigma_{\mathrm{Z+1b}}$ (pb)	$3.52 \pm 0.02 \pm 0.20$	3.66 ± 0.22	$3.70^{+0.23}_{-0.26}$	$3.03^{+0.30}_{-0.36}$	$3.11^{+0.47}_{-0.81}$	$2.36^{+0.47}_{-0.37}$
$\sigma_{\mathrm{Z+2b}}$ (pb)	$0.36 \pm 0.01 \pm 0.07$	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	$5.38^{+0.34}_{-0.39}$	$4.75^{+0.24}_{-0.27}$	$4.63^{+0.69}_{-1.21}$	$3.65^{+0.70}_{-0.55}$

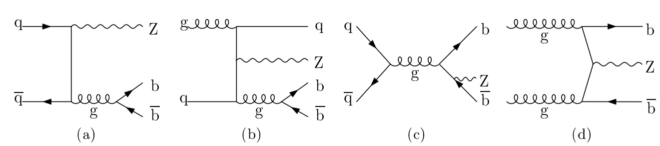
Interesting measurement of b-hadron azimuthal correlation



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

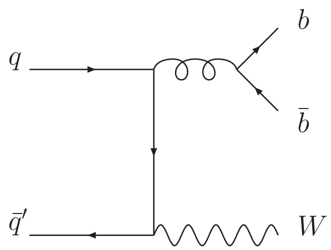
($\hookrightarrow$ Mangano and Nason, PLB 285 (1992) 160, HQ multiplicity in gluon jets)

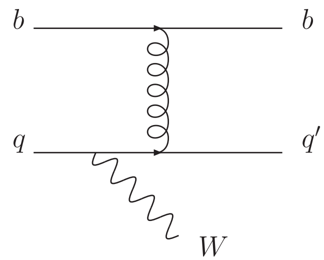




$W + 1b$ jet vs $W + 2b$ jets

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 σ_{event} and $\sigma_{\text{b-jet}}$ where

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

- 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):

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

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

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

For comparison:

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

ALPGEN prediction: 0.78 pb

PYTHIA prediction: 1.10 pb

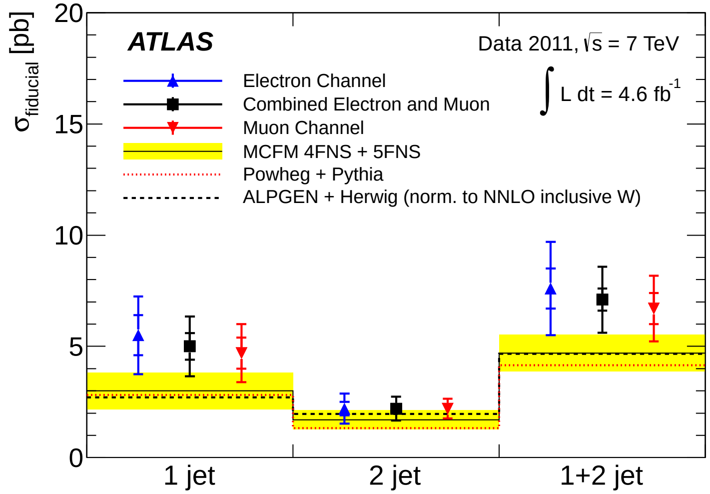
whereas:

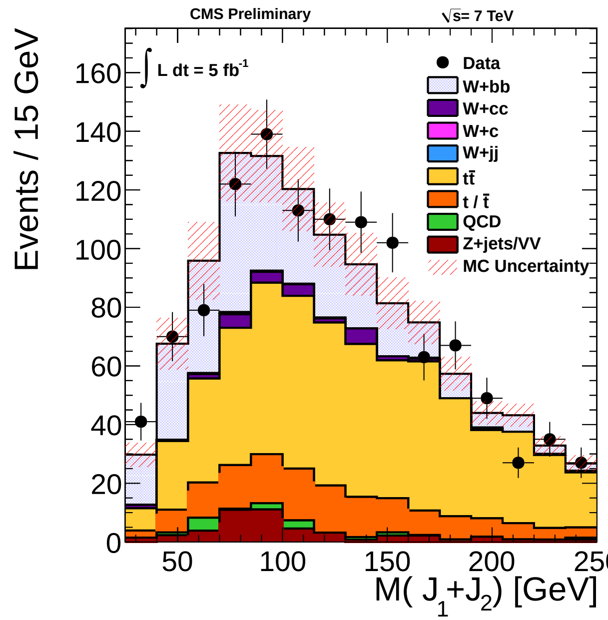
D0 (arXiv:1210.0627):

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

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

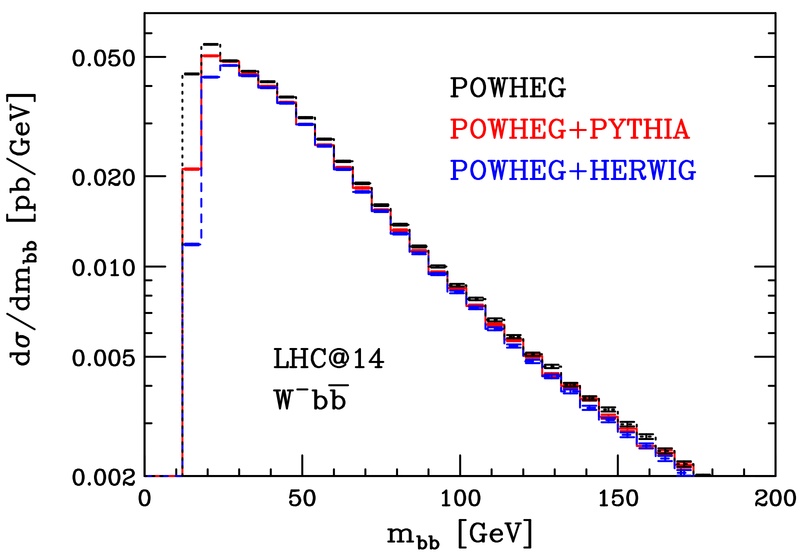
Comparison with ATLAS and CMS

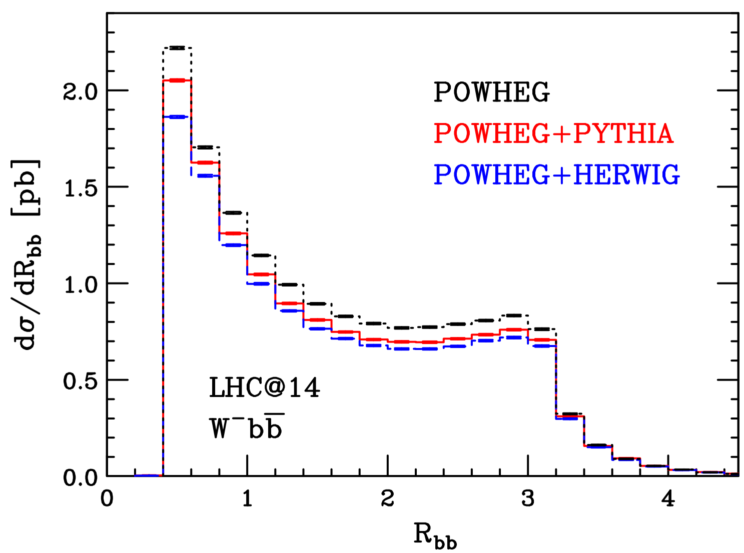




- ATLAS and CMS complementary measurements: $W + b + j$ vs $W + 2b$.
- ATLAS consistent with NLO QCD calculations within 1.5 σ.
- CMS consistent with NLO QCD predictions:
  CMS ($W + 2b$ jets): 0.53 ± 0.05 (stat)± 0.09 (syst) ± 0.06 (theo) pb
  MCFM ($W + 2b$ jets): 0.52 ± 0.03 pb
- Only partial use 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.

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.
- Continue improving $W/Z/\gamma+b$-jets comparison with data.