Electroweak and Bottom Quark Contributions to Higgs + Jet Production

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PHYSICS AT THE TERA SCALE
Helmholtz Alliance

[see arXiv:1003.XXXX [hep-ph]]

outline :

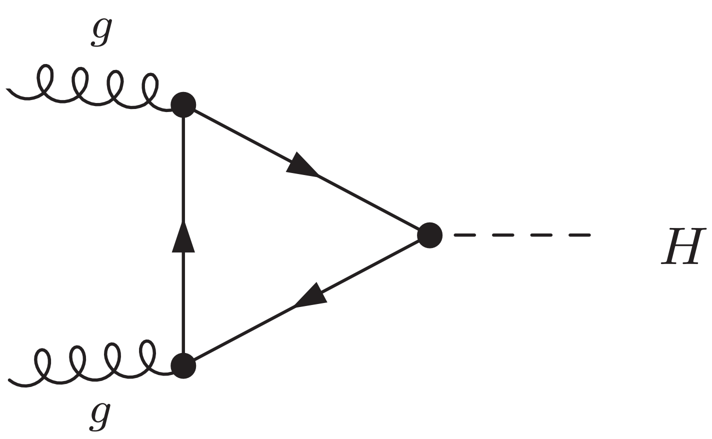
- Higgs + Jet in the Standard Model
- LO Contributions to Higgs + Jet
- Numerical Results

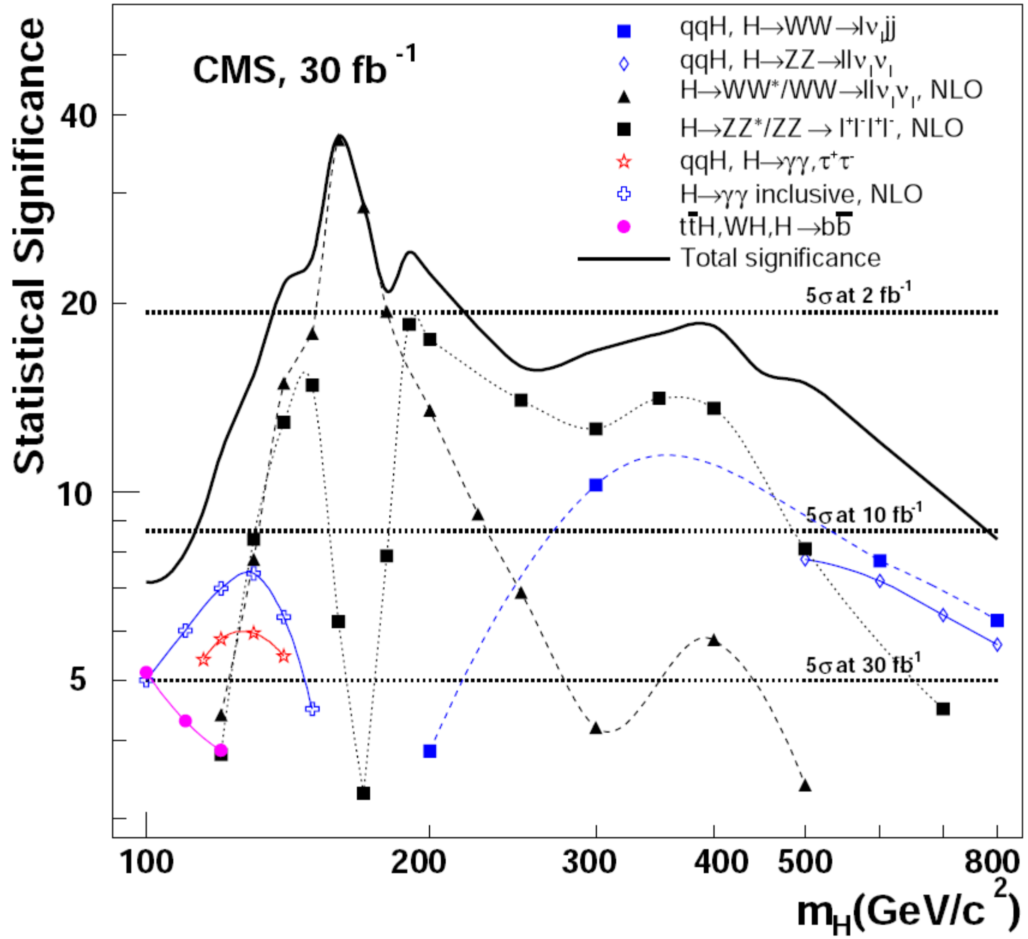
- Higgs + Jet in the Standard Model

• Higgs + Jet in the Standard Model

– Higgs production @ the LHC

SM Higgs production @ LHC mainly via gluon fusion:





Detection ($m_H \approx 100 - 140$GeV): mainly via the rare decay $H \rightarrow \gamma\gamma$.

− Higgs + Jet

suggestion: study Higgs events with a high-p_T hadronic jet

LO QCD $\mathcal{O}(\alpha_S^3\alpha)$: [van der Bij et al. '87; Baur, Glover '89]

NLO QCD $\mathcal{O}(\alpha_S^4\alpha)$: [de Florian, Grazzini, Kunszt '99]

+ NLL soft gluon threshold resummation: [de Florian, Kulesza, Vogelsang '05]

advantages:

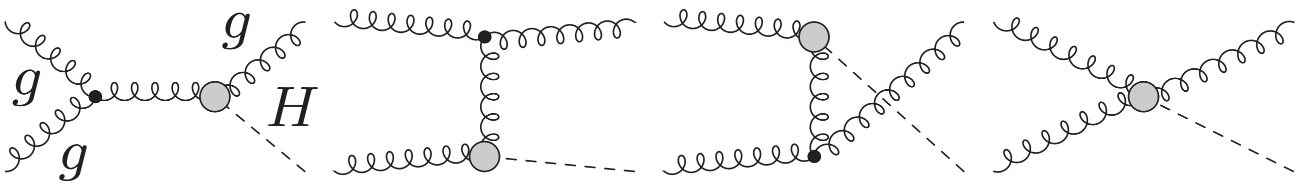
* richer kinematical structure compared to inclusive Higgs production.
  → allows for refined cuts
  → better signal significance ($S/\sqrt{B}$)

* background predictions e.g. for $H \to \gamma\gamma$ under better theoretical control

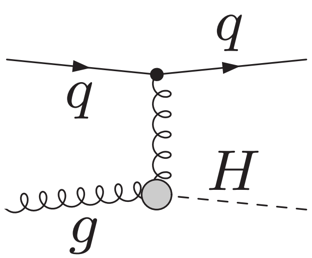
disadvantage:

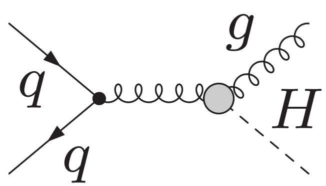
* lower rate than inclusive Higgs production

SM H+jet, partonic processes ($\mathcal{O}(\alpha_S^3\alpha)$, mainly via top loops):



$gg \longrightarrow Hg$ (≈ 60 - 75 % of total rate)





$qg \longrightarrow Hq$ (≈ 25 - 40 %) $q\bar{q} \longrightarrow Hg$ (rate small)

simulations: $pp \to H + \text{jet}, H \to \gamma\gamma$ [Abdullin et al. '98 & '02; Zmushko '02]

$pp \to H + \text{jet}, H \to \tau^+\tau^- \to l^+l^-\not{p}_T$ [Mellado et al. '05]

show: $H + \text{jet}$ production (e.g. with $p_{T,\text{jet}} \geq 30\,\text{GeV}$, $|\eta_{\text{jet}}| \leq 4.5$)
is a promising alternative (supplement)
to the inclusive SM Higgs production
for $m_H \approx 100 - 140\text{GeV}$.

available codes: SM:

- Higgsjet [de Florian, Grazzini, Kunszt '99]
  NLO QCD cross section for $pp \to H + \text{jet}$ (large m_t approx.)
  also: soft gluon resummation [de Florian, Kulesza, Vogelsang '05]

- HqT [Bozzi, Catani, de Florian, Grazzini '03 & '06]
  p_T-distribution for $pp \to H + X$ (large m_t approx.)
  including resummation at $NLL + LO$ and $NNLL + NLO$ QCD accuracy

- MC@NLO [Frixione, Webber '02; Frixione, Nason, Webber '05]
  contains $pp \to H + X$ event generation at NLO QCD accuracy
  (large m_t approx.)

- FEHiP [Anastasiou, Melnikov, Petriello '05]
  NNLO QCD differential cross section for $pp \to H + X$ (large m_t approx.)

- HPro [Anastasiou, Bucherer, Kunszt '09]
  corrects large m_t approx. NNLO QCD differential predictions
  by finite m_t & m_b terms from NLO QCD

NNLO QCD accuracy (large m_t approx.) $\propto$ 10% (scale variation)
$\to$ further improvements need to consider other 10%-ish effects

available codes: MSSM:

- HJET 1.3 [OBr, Hollik '03; '07]
  LO QCD full MSSM (no approximations)
  & LO QCD SM (no approximations):

$$\sigma_{\text{hadronic}}^{\text{total}}, \ \frac{d\sigma_{\text{hadronic}}}{d\sqrt{\hat{s}}}, \ \frac{d\sigma_{\text{hadronic}}}{dp_{T,\text{jet}}}, \ \frac{d\sigma_{\text{hadronic}}}{d\eta_{\text{jet}}}, \ \frac{d^2\sigma_{\text{hadronic}}}{dp_{T,\text{jet}}\, d\eta_{\text{jet}}}, \ \ldots$$

– Higgs + Jet: How to improve the prediction ?

- go beyond the large m_t approximation
  in the NLO QCD prediction for the Higgs p_T distribution

- NNLO QCD corrections (in the large m_t approximation)

- consider other LO effects
  * non-QCD: electroweak LO contributions
  * QCD 5-flavour scheme: b quark parton process contributions

- LO Contributions to Higgs + Jet

• LO Contributions to Higgs + Jet

– Previous Study [Keung, Petriello '09]

SM Higgs p_T distribution with

1. finite quark mass effects (m_t, m_b) in one-loop QCD amplitude:

   $\longrightarrow$ already included in [. . ., OBr, Hollik '03; '07]

   comparison of approximations:

   * large-m_t limit (no b in loops) $\longrightarrow$ effective ggH vertex [SIZE]
   * finite m_t (no b in loops) [SIZE]
   * finite m_t and m_b [SIZE]

2. electroweak one-loop effects [SIZE]

$\longrightarrow$ 5-flavour PDFs used but b quark parton processes not considered.

– Our Study [OBr '10]

SM Higgs p_T, η_{jet} (and double differential) distribution with

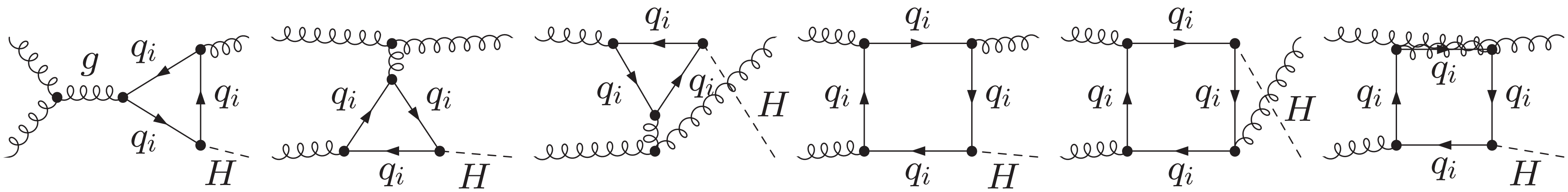
1. finite quark mass effects (m_t, m_b) in one-loop QCD amplitude:

2. electroweak one-loop effects

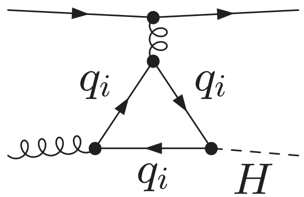
3. contributions from b-quark parton processes
   * leading QCD and electroweak effects

– Gluon & Light Quark (u, d, s, c) QCD Contribution : $\mathcal{O}(\alpha_S^3\alpha)$

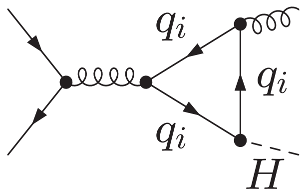
gluon fusion, $gg \to Hg$



quark gluon scattering, $qg \to Hq$

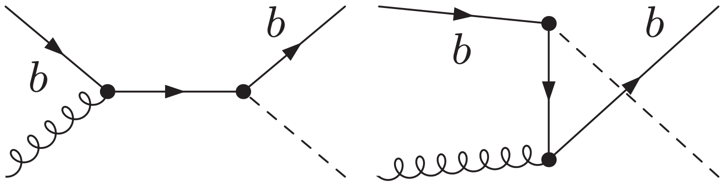


quark anti-quark annihilation, $q\bar{q} \to Hg$

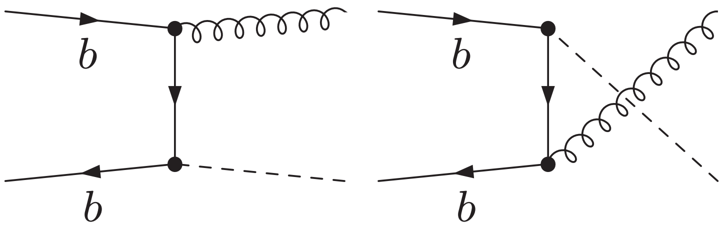


– Bottom Quark QCD Contribution : $\mathcal{O}(\alpha_S\alpha)$

quark gluon scattering, $bg \to Hb$



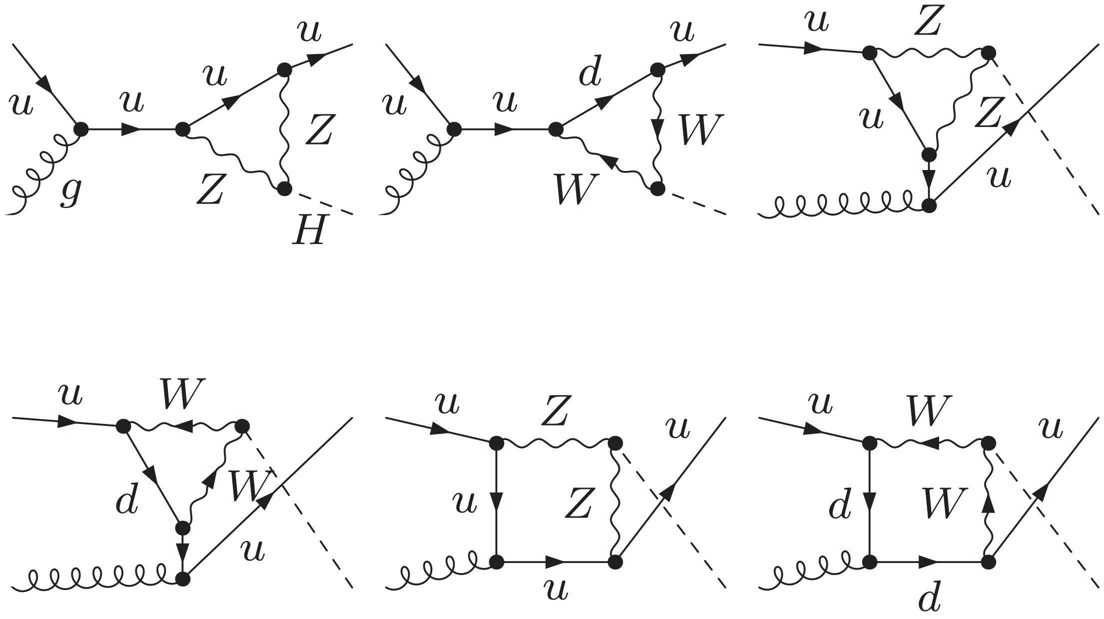
quark anti-quark annihilation, $b\bar{b} \to Hg$



– Light Quark (u, d, s, c) EW Contribution : $\mathcal{O}(\alpha_S \alpha^3)$

[Mrenna, Yuan '96; Keung, Petriello '09]

quark gluon scattering, $qg \longrightarrow Hq$



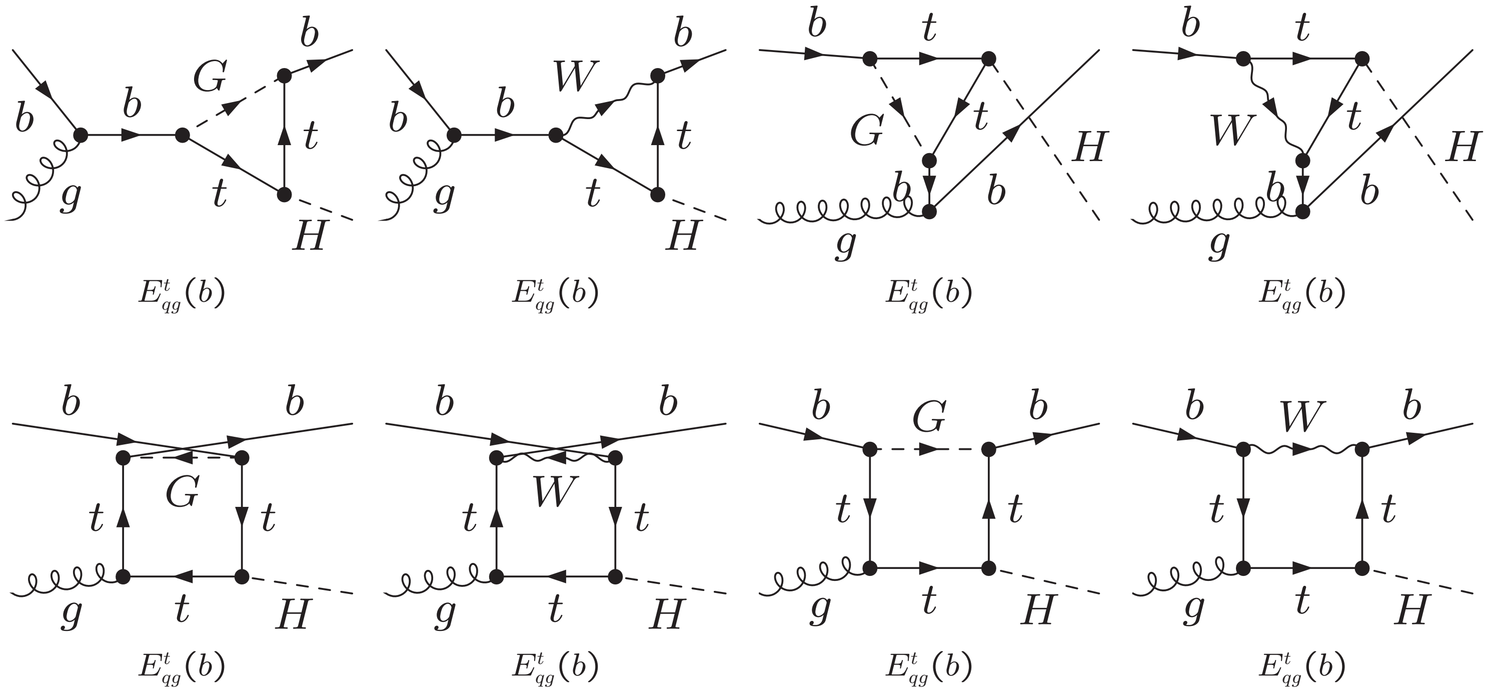
quark anti-quark annihilation, $q\bar{q} \longrightarrow Hg$

crossed diagrams

– Bottom Quark EW Contribution : $\mathcal{O}(\alpha_S \alpha^3)$

[Mrenna, Yuan '96]

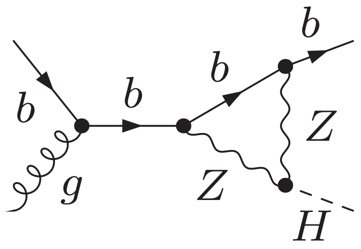
quark gluon scattering, $bg \to Hb$, $\mathcal{O}(\alpha_S \alpha^2 \alpha_t)$



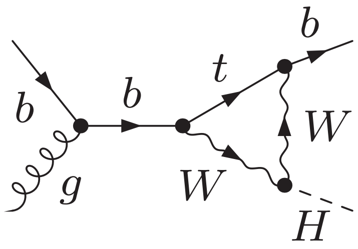
– Bottom Quark EW Contribution : $\mathcal{O}(\alpha_S \alpha^3)$

[Mrenna, Yuan '96]

quark gluon scattering, $bg \to Hb$, $\mathcal{O}(\alpha_S \alpha^3)$ "non α_t"



$C_{qg}(b)$



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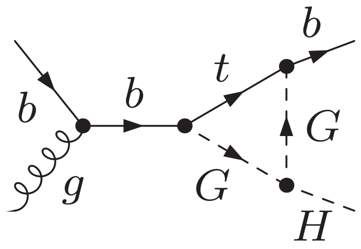
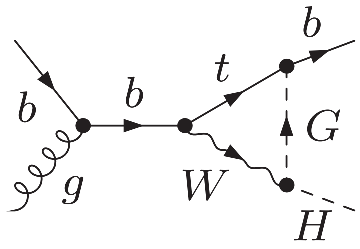


$F_{qg}(b)$



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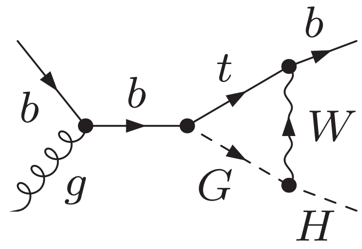

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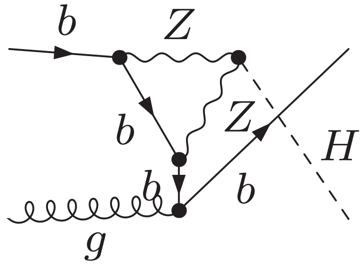

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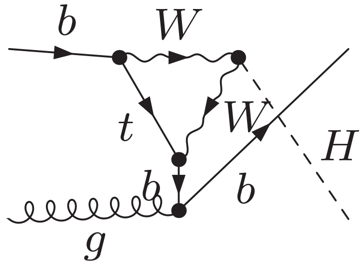

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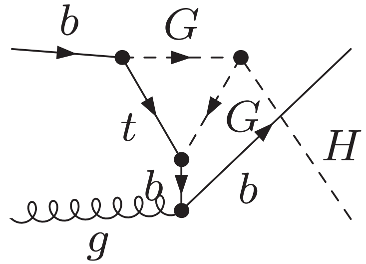

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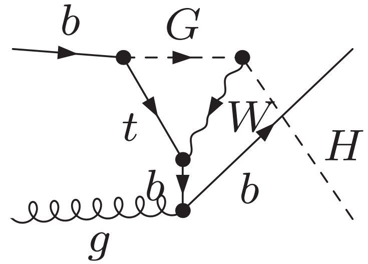

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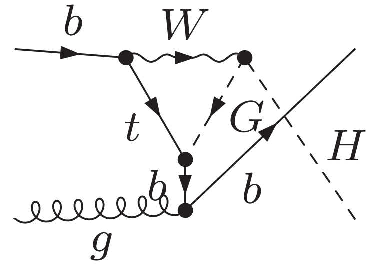

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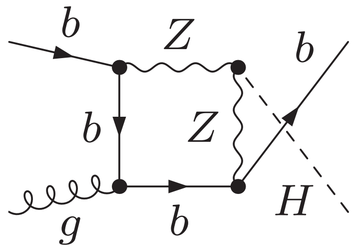

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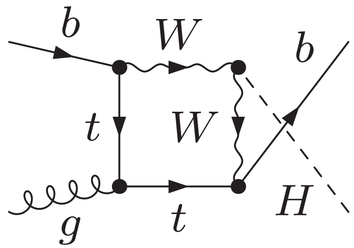

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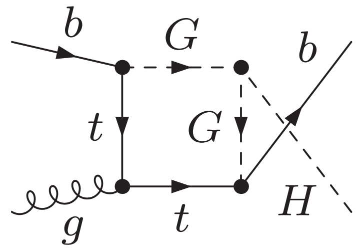

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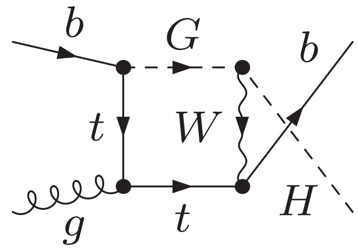

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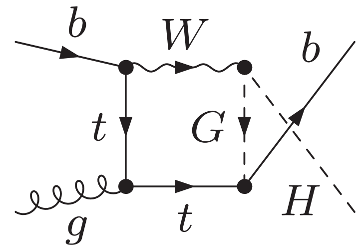


$F_{qg}(b)$

– Calculational Approach

- respect the hierarchy of Yukawa couplings:

  $\alpha_q = y_q^2/4\pi = \frac{1}{4\pi} m_q^2/v^2$ ($v = 246\,\text{GeV}$)

  $\rightarrow$ $\alpha_t = 3.9 \cdot 10^{-2}$, $\alpha_b = 2.3 \cdot 10^{-6}$ and $\frac{\alpha_b}{\alpha_t} \approx \alpha^2(0) < \alpha_S^4(m_Z)$

  $\rightarrow$consider LO QCD and EW contributions to the full polynomial in $\sqrt{\alpha_t}$ and $\sqrt{\alpha_b}$ in the cross section predictions

- light quark (u, d, s, c) processes:
  * full mass dependence in m_t, m_b

- bottom-quark processes:
  * 5-flavour scheme:
    – $m_b = 0$ to be consistent with parton model
    – only b Yukawa coupling y_b retained non-zero

  * for the tree-level amplitude: eff. Born approx. to NLO QCD corrections
    – factorisation scale choice $\mu_F^{(b)} = m_H/4$
    – NLO running m_b in b Yukawa coupling

scattering amplitudes

$$\mathcal{M}_{gg} = A_t g_S^3 y_t + A_b g_S^3 y_b \,,$$
$$\mathcal{M}_X(q) = B_X^t(q) g_S^3 y_t + B_X^b(q) g_S^3 y_b + C_X(q) g_S e^3 \,,$$
$$\mathcal{M}_X(b) = D_X(b) g_S y_b + B_X^t(b) g_S^3 y_t + E_X^t(b) g_S e^2 y_t + \left(C_X(b) + F_X(b)\right) g_S e^3 \,,$$

with $X \in \{qg, \bar{q}g, q\bar{q}\}$ and $q = u, d, s, c$.

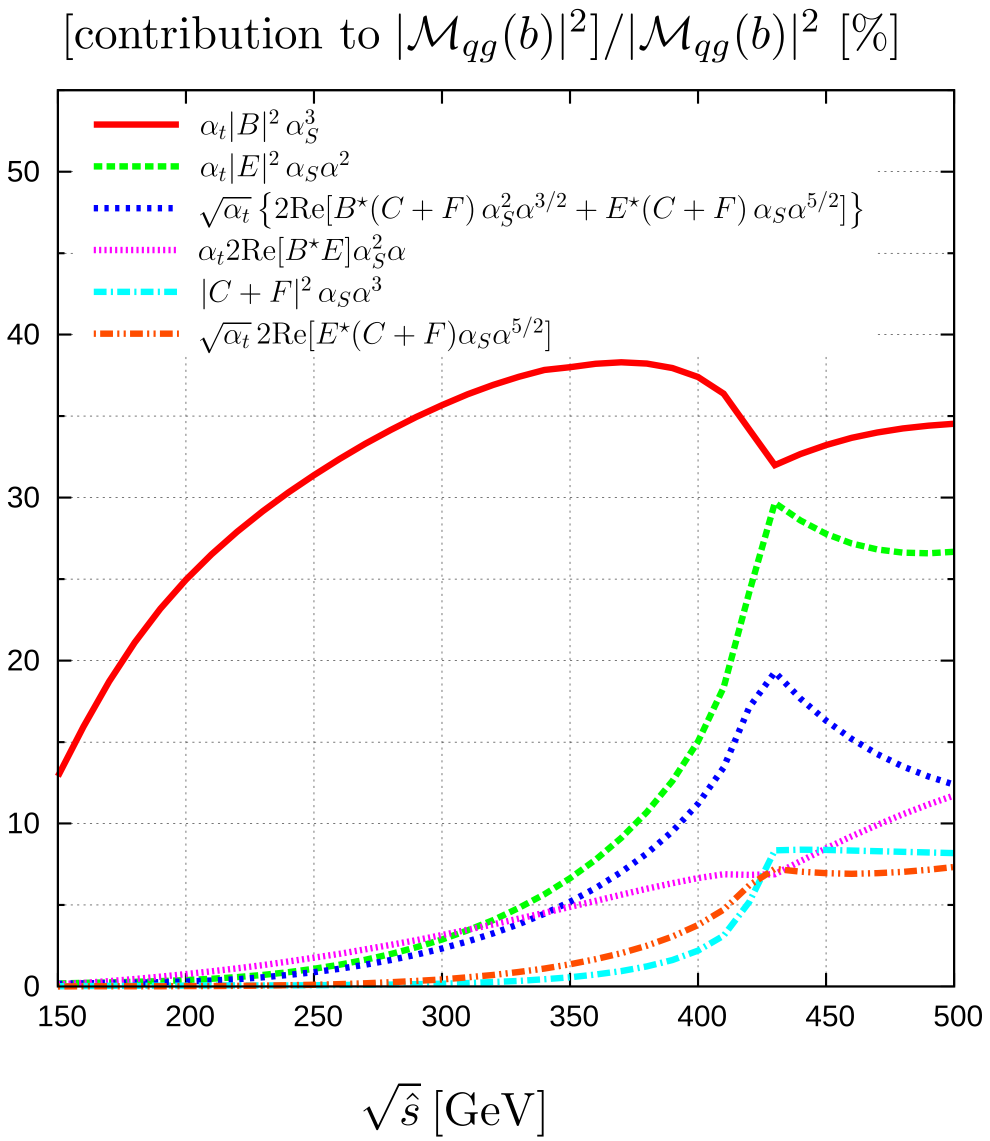
squared matrix elements, for $m_b = 0$:

$$|\mathcal{M}_{gg}|^2/(4\pi)^4 = \alpha_t |A_t|^2 \alpha_S^3 + \alpha_b |A_b|^2 \alpha_S^3 + \sqrt{\alpha_t \alpha_b} 2\text{Re}[A_t{}^\star A_b] \alpha_S^3 \,,$$

squared matrix elements, for $m_b = 0$:

$$|\mathcal{M}_X(q)|^2/(4\pi)^4 = \\ \alpha_t |B_X{}^t(q)|^2 \alpha_S^3 + \alpha_b |B_X{}^b(q)|^2 \alpha_S^3 \\ + \sqrt{\alpha_t \alpha_b} \left\{ 2\mathrm{Re} \left[(B_X{}^t(q))^\star B_X{}^b(q) \right] \alpha_S^3 \right\} \\ + \sqrt{\alpha_t} \left\{ 2\mathrm{Re} \left[(B_X(q)^t)^\star C_X(q) \right] \alpha_S^2 \alpha \sqrt{\alpha} \right\} \\ + \sqrt{\alpha_b} \left\{ 2\mathrm{Re} \left[(B_X(q)^b)^\star C_X(q) \right] \alpha_S^2 \alpha \sqrt{\alpha} \right\} \\ + |C_X(q)|^2 \alpha_S \alpha^3 ,$$

$$|\mathcal{M}_X(b)|^2/(4\pi)^4 = \\ \alpha_t \left\{ |B_X{}^t(b)|^2 \alpha_S^3 + 2\mathrm{Re} \left[(B_X{}^t(b))^\star E_X{}^t(b) \right] \alpha_S^2 \alpha + |E_X{}^t(b)|^2 \alpha_S \alpha^2 \right\} \\ + \alpha_b \left\{ |D_X(b)|^2 \alpha_S \right\} (4\pi)^{-2} \\ + \sqrt{\alpha_t} \left\{ 2\mathrm{Re} \left[(B_X{}^t(b))^\star (C_X(b) + F_X(b)) \right] \alpha_S^2 \alpha \sqrt{\alpha} \right. \\ \left. + 2\mathrm{Re} \left[(E_X{}^t(b))^\star (C_X(b) + F_X(b)) \right] \alpha_S \alpha^2 \sqrt{\alpha} \right\} \\ + |C_X(b) + F_X(b)|^2 \alpha_S \alpha^3 .$$



$$\mathcal{M}_{qg}(b) = D_{qg}(b) g_S y_b + B^t_{qg}(b) g_S^3 y_t + E^t_{qg}(b) g_S e^2 y_t + (C_{qg}(b) + F_{qg}(b))\, g_S e^3$$

$$|\mathcal{M}_{qg}(b)|^2/(4\pi)^4 = \alpha_b \Big\{ \; |D_{qg}(b)|^2 \alpha_S \Big\} (4\pi)^{-2}$$
$$+\, \alpha_t \Big\{ \; |B_{qg}{}^t(b)|^2 \alpha_S^3 + 2\mathrm{Re}\left[B^\star_{qg}{}^t(b) E_{qg}{}^t(b) \right] \alpha_S^2 \alpha + |E_{qg}{}^t(b)|^2 \alpha_S \alpha^2 \Big\}$$
$$+\, \sqrt{\alpha_t}\, \Big\{ 2\mathrm{Re}\left[B^\star_{qg}{}^t(b)(C_{qg}(b) + F_{qg}(b)) \right] \alpha_S^2 \alpha \sqrt{\alpha} + 2\mathrm{Re}\left[E^\star_{qg}{}^t(b)(C_{qg}(b) + F_{qg}(b)) \right] \alpha_S \alpha^2 \sqrt{\alpha} \Big\}$$
$$+\, |C_{qg}(b) + F_{qg}(b)|^2 \alpha_S \alpha^3 \,.$$

- Numerical Results

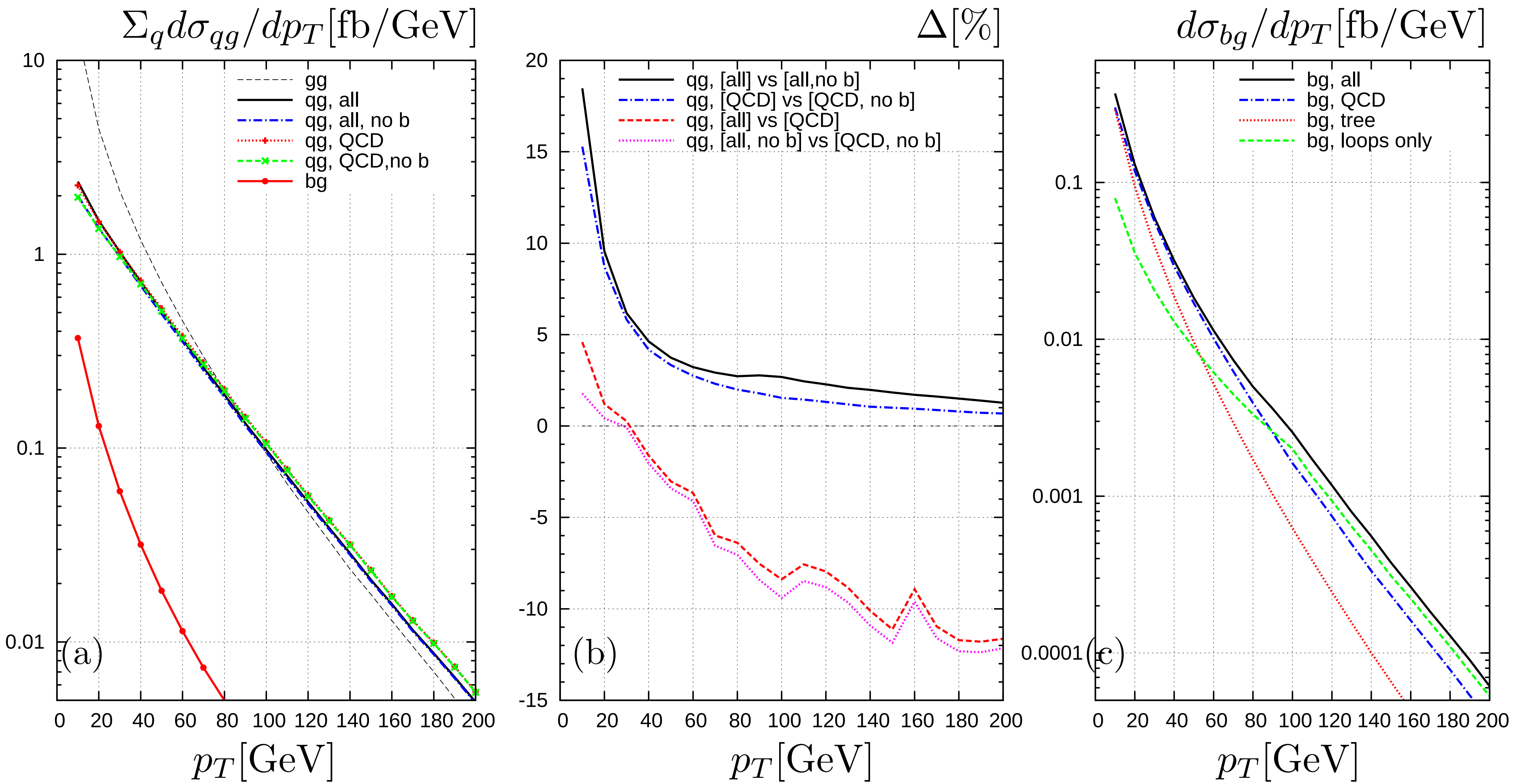
– Tevatron

differential hadronic cross sections for $\sqrt{S} = 1.96\,\text{TeV}$

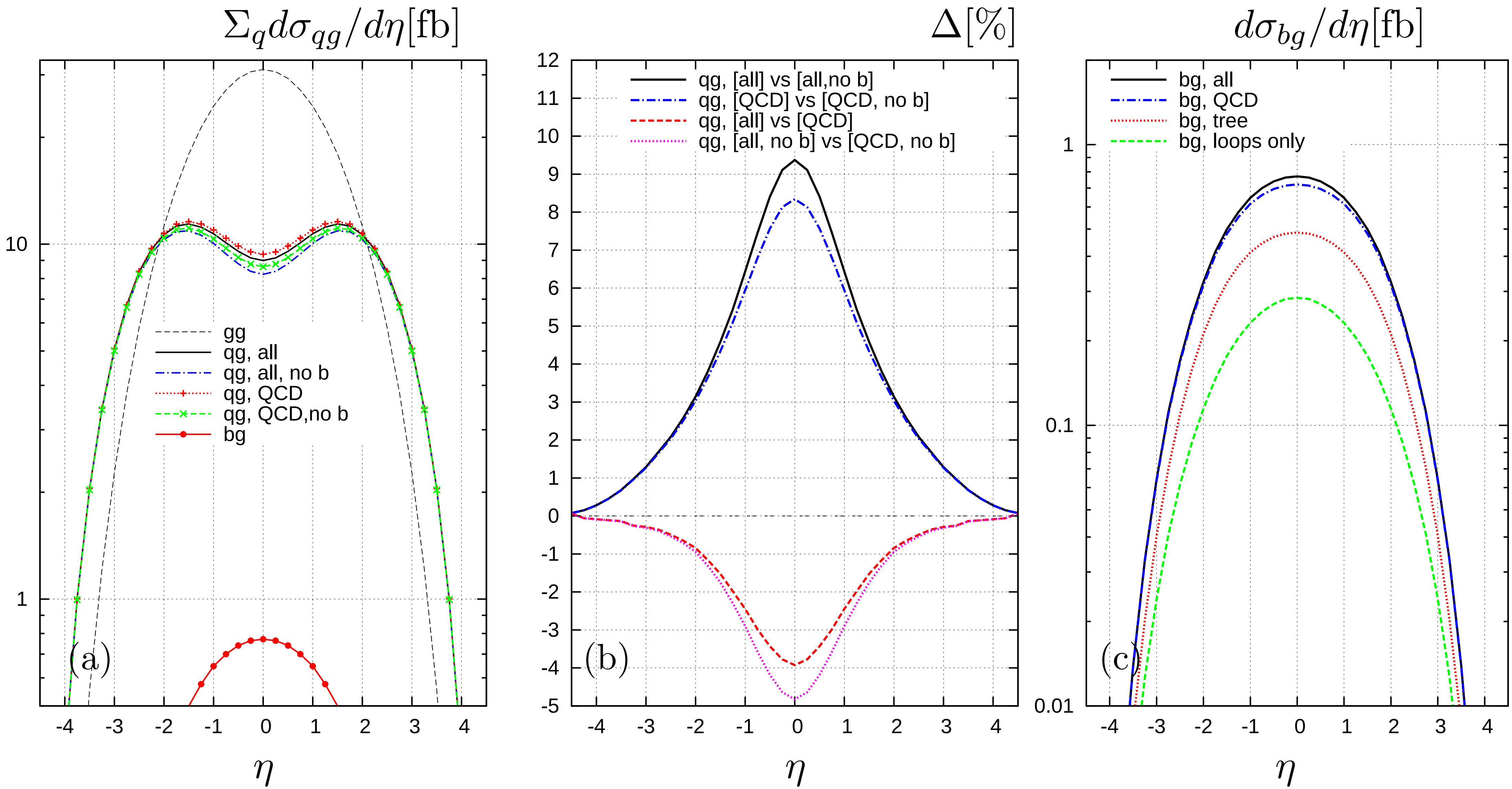
$$\frac{d\sigma(S, p_{T,\text{jet}})}{dp_{T,\text{jet}}}, \;\; |\eta_{\text{jet}}| < 2.5$$

$$\frac{d\sigma(S, \eta_{\text{jet}})}{d\eta_{\text{jet}}}, \;\; p_{T,\text{jet}} > 15\,\text{GeV}$$

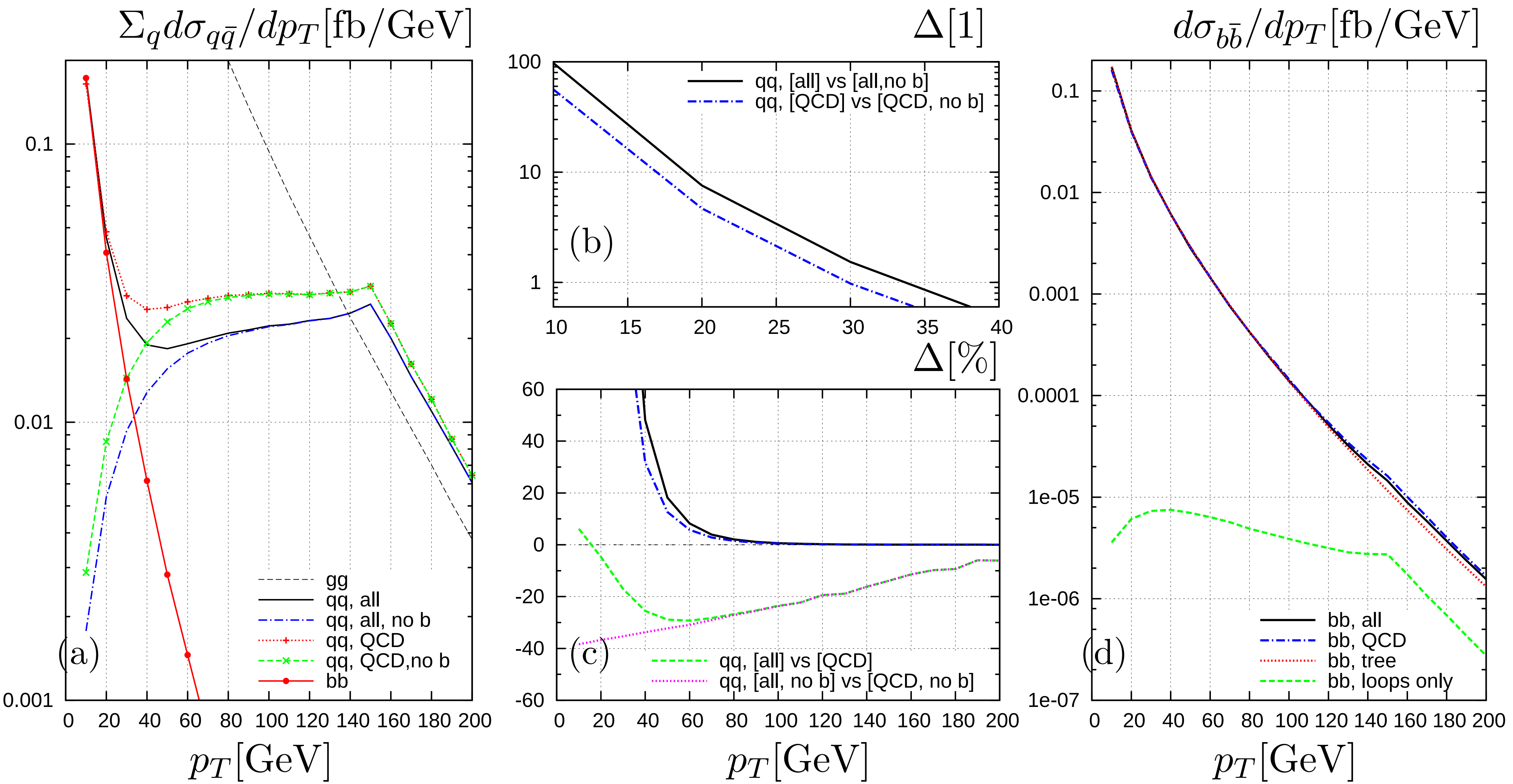
$p_{T,\text{jet}}$ distribution : quark–gluon scattering ($m_H = 120\,\text{GeV}$)



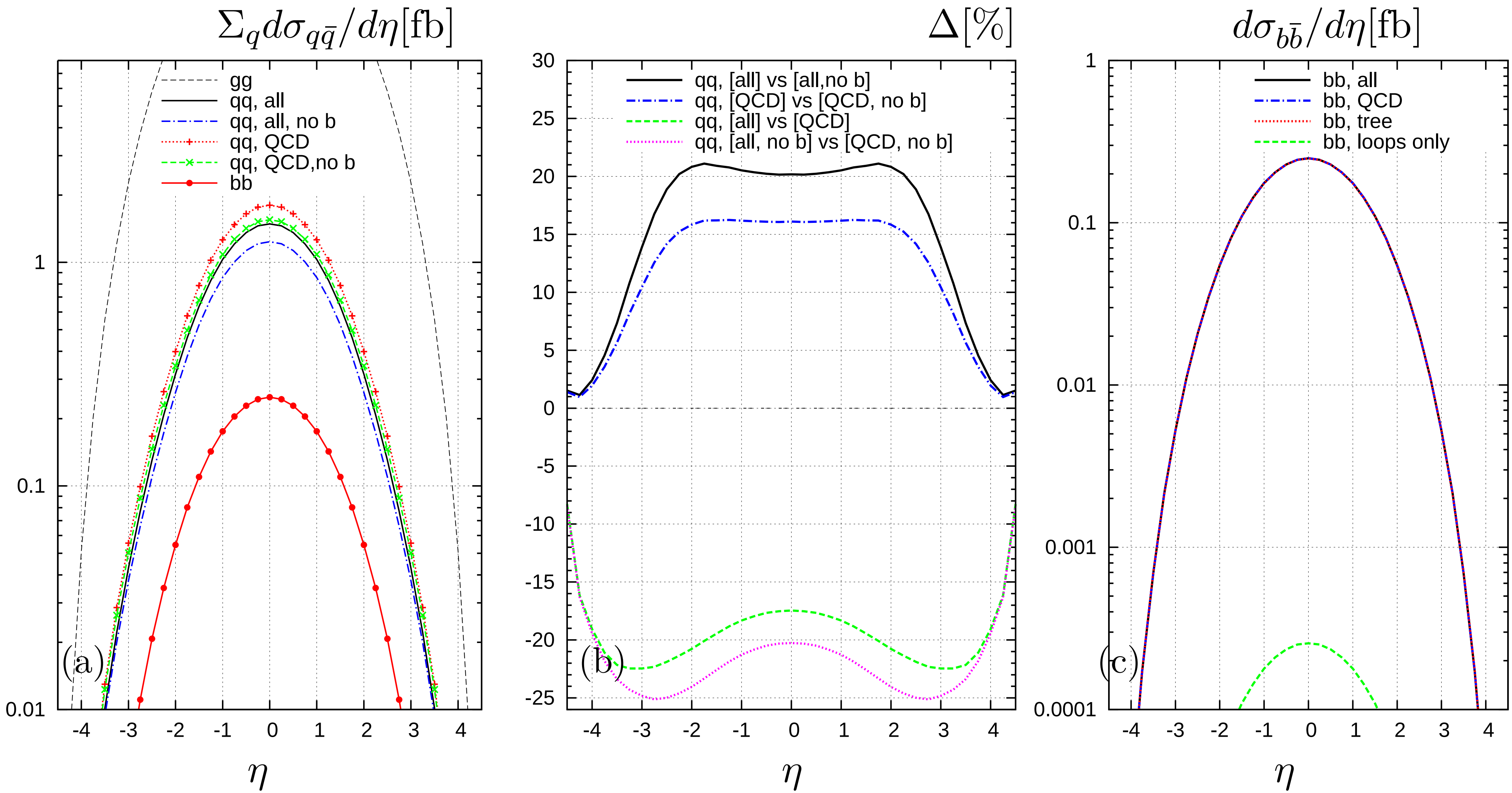
$\eta_{\rm jet}$ distribution : quark–gluon scattering ($m_H = 120$ GeV)



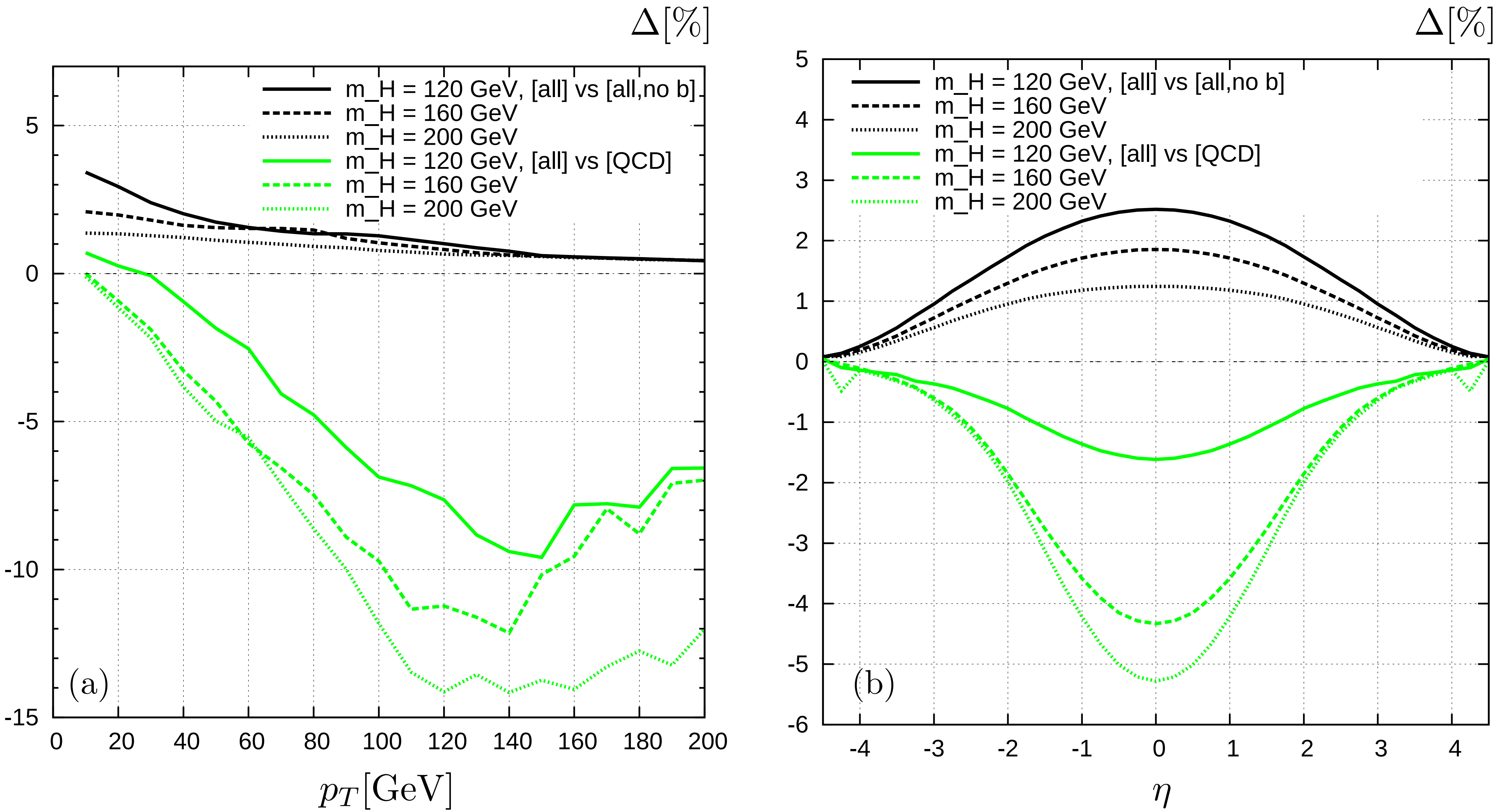
$p_{T,\text{jet}}$ distribution : $q\bar{q}$ annihilation ($m_H = 120\,\text{GeV}$)



$\eta_{\rm jet}$ distribution : $q\bar{q}$ annihilation ($m_H = 120$ GeV)



effects on the of the total Higgs + Jet distributions: $(m_H = 120\,\text{GeV})$



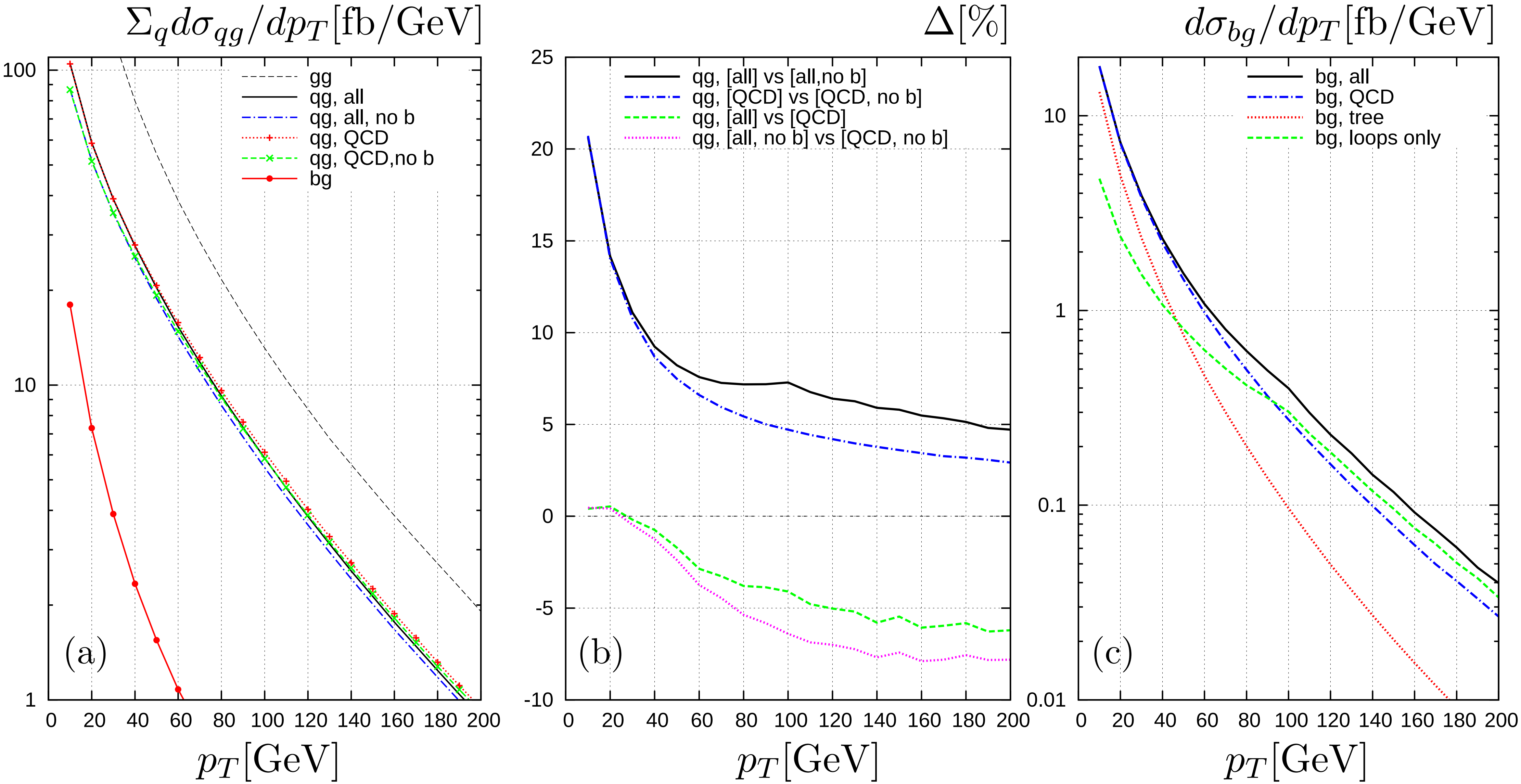
– LHC

differential hadronic cross sections for $\sqrt{S} = 10\,\text{TeV}$

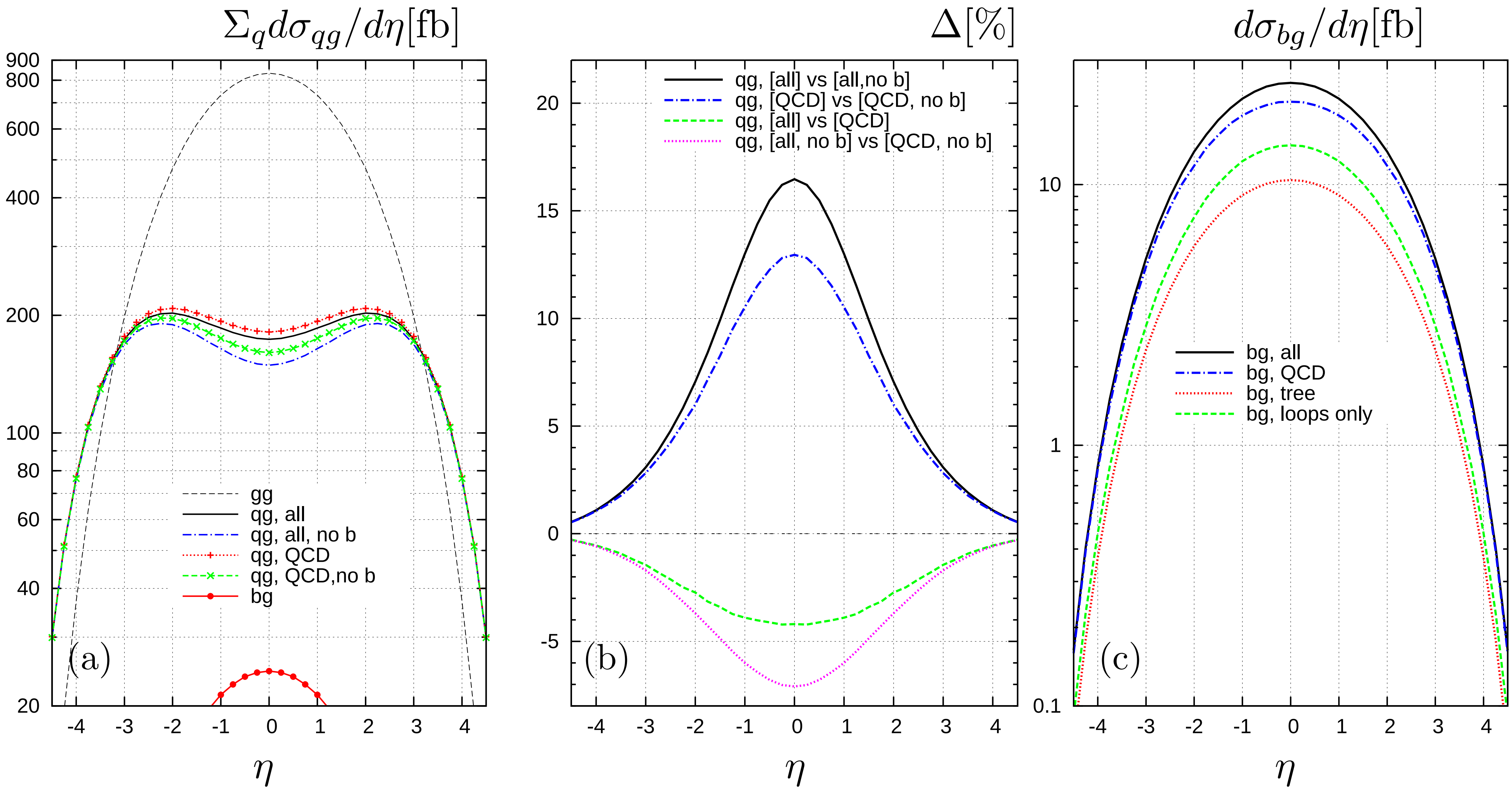
$$\frac{d\sigma(S, p_{T,\text{jet}})}{dp_{T,\text{jet}}}, \; |\eta_{\text{jet}}| < 4.5$$

$$\frac{d\sigma(S, \eta_{\text{jet}})}{d\eta_{\text{jet}}}, \; p_{T,\text{jet}} > 30\,\text{GeV}$$

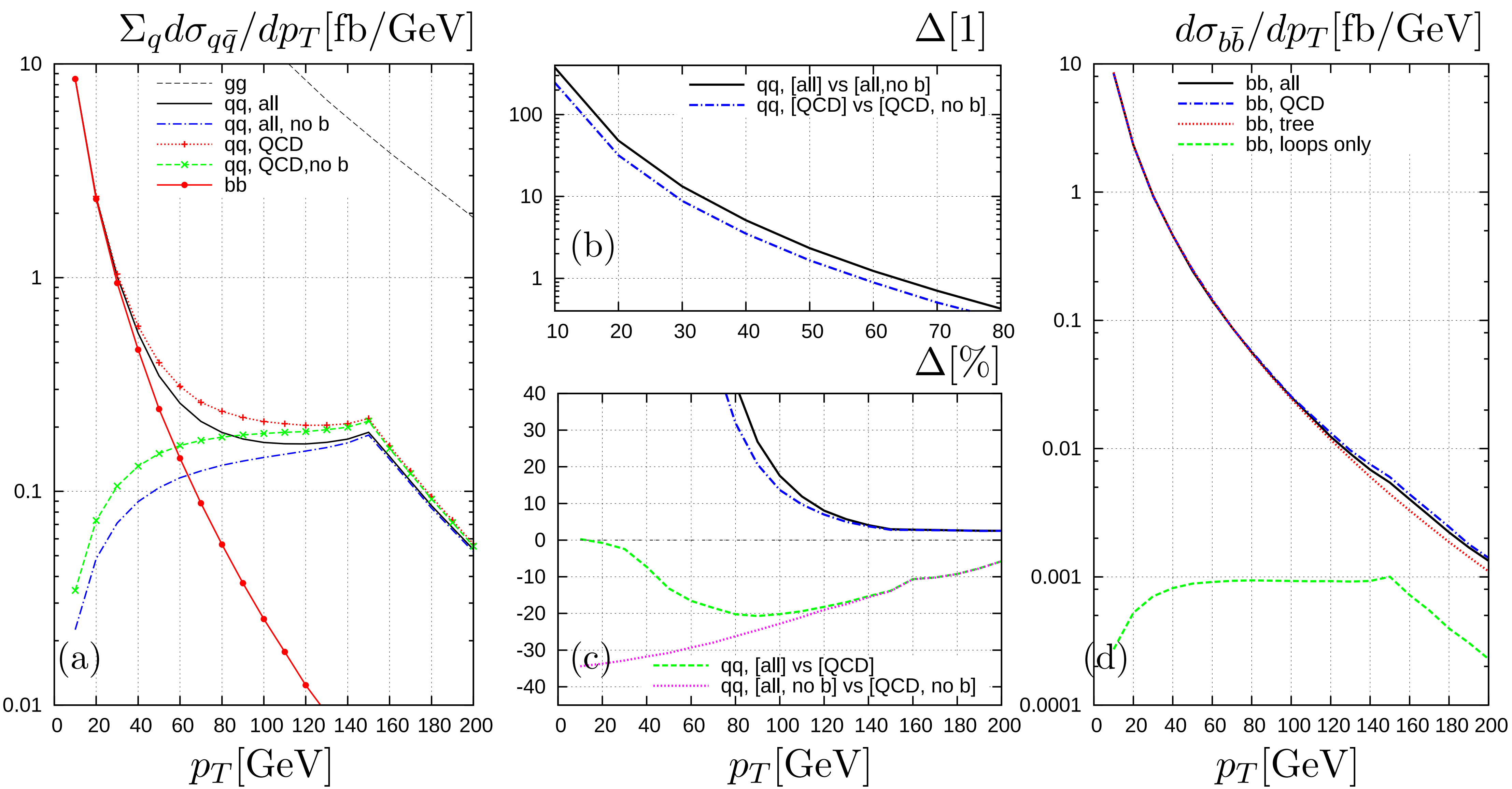
$p_{T,\mathrm{jet}}$ distribution : quark–gluon scattering ($m_H = 120$ GeV)



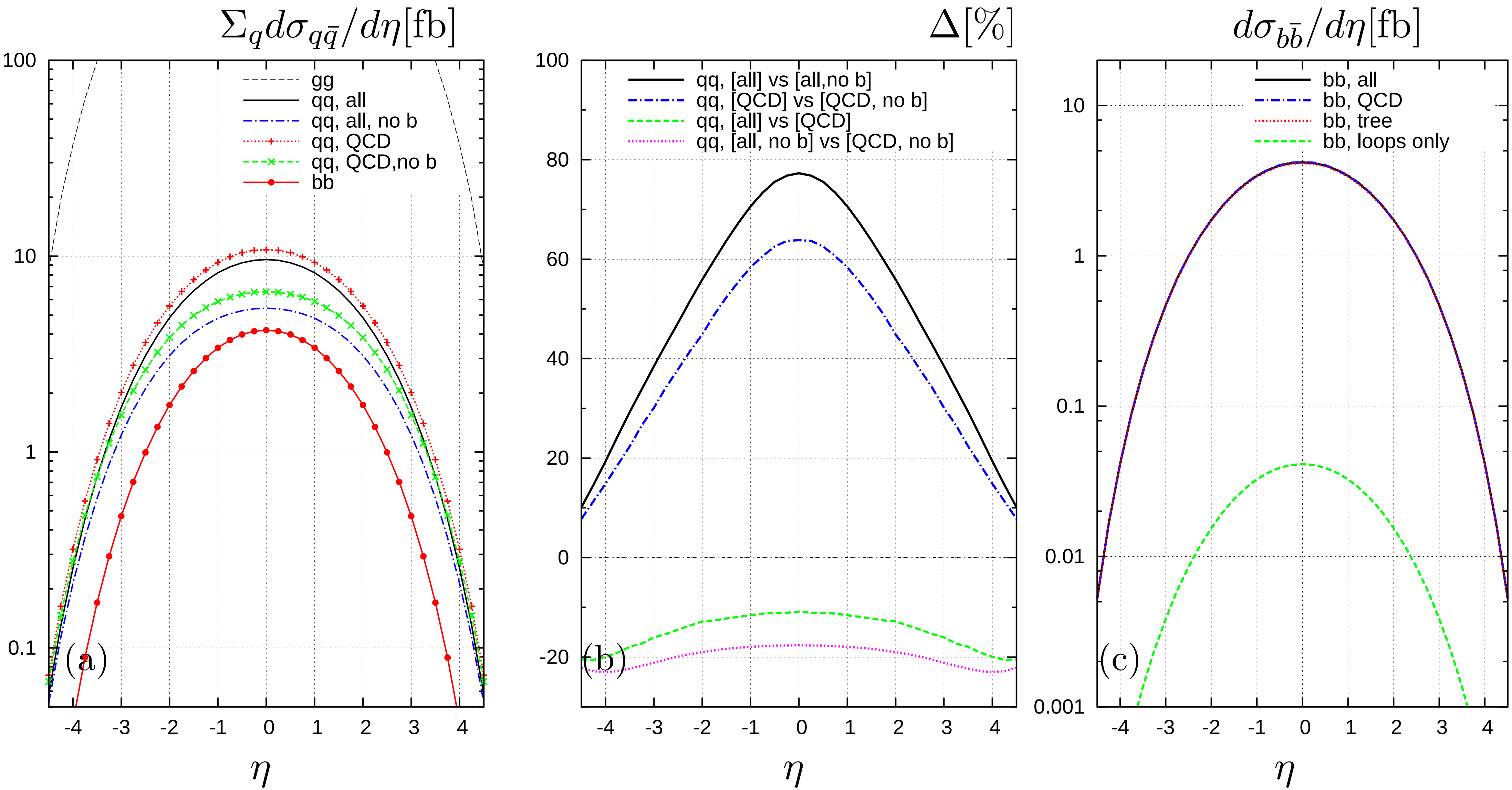
η_{jet} distribution : quark–gluon scattering ($m_H = 120\,\text{GeV}$)



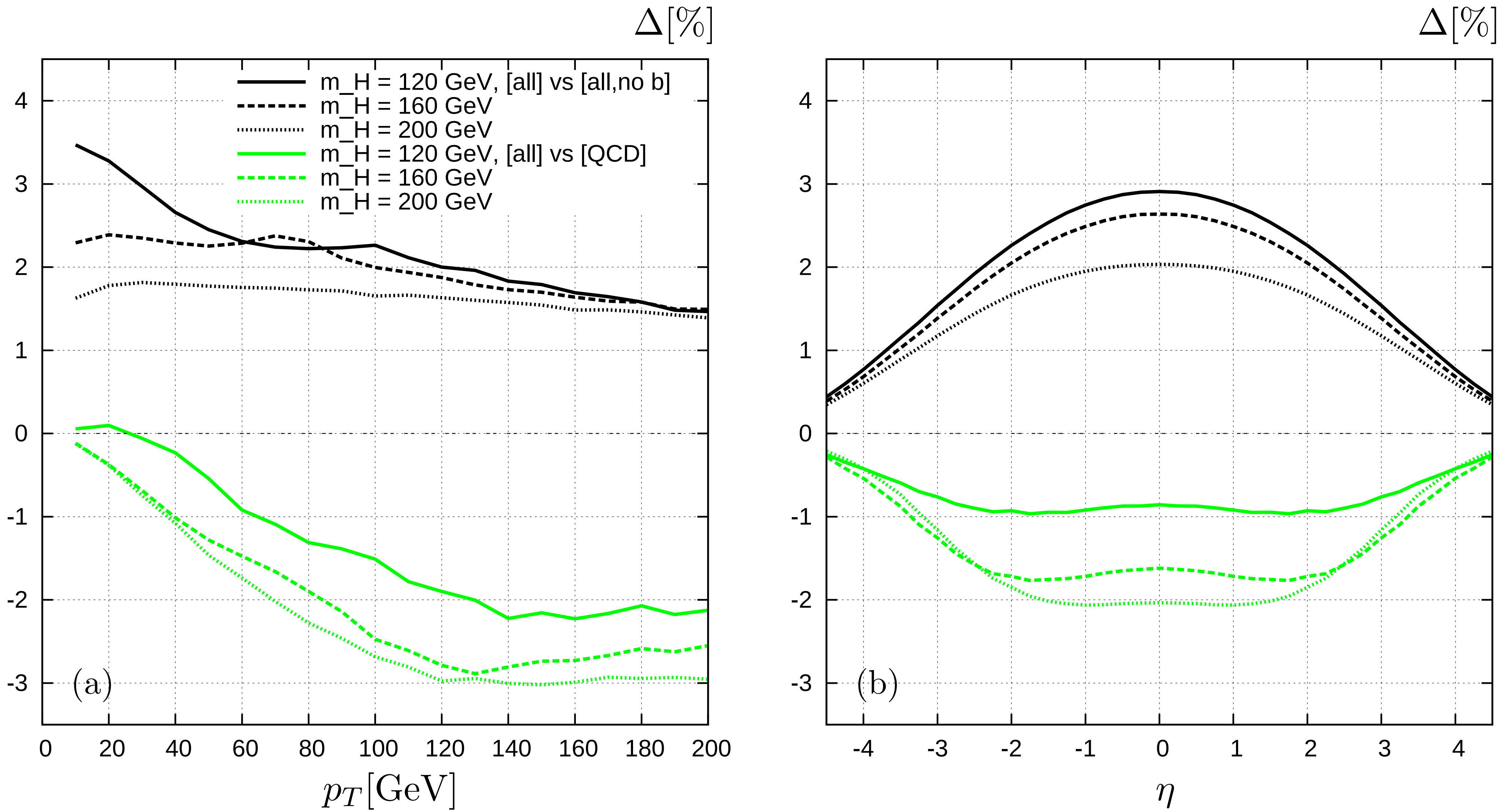
$p_{T,\text{jet}}$ distribution : $q\bar{q}$ annihilation ($m_H = 120\,\text{GeV}$)



η_{jet} distribution : $q\bar{q}$ annihilation $(m_H = 120\,\text{GeV})$



effects on the of the total Higgs + Jet distributions: $(m_H = 120\,\mathrm{GeV})$



summary

- SM simulations show: Higgs + high-p_T jet production is a promising supplement to the inclusive production.

- More precise predictions are needed in order to be useful for experimental analyses at the LHC.

- Improvements over the present NLO QCD accuracy for the H + jet final state can be made by considering:
  - going beyond the large m_t approx in NLO QCD
  - NNLO QCD contributions
  - electroweak one-loop contributions
  - bottom parton process contributions