Hard photon production with heavy quarks at NLO

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NLO predictions for:

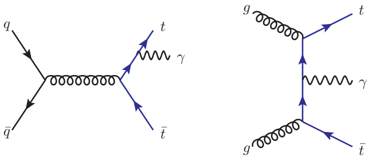
$$p + p(\bar{p}) \rightarrow Q + \bar{Q} + \gamma$$

where we consider both the top and bottom quarks in the final state, $Q = t, b$.

Outline:

- Introduction
- Calculation
- Result: $t\bar{t}\gamma$ production
- Result: $b\bar{b}\gamma$ production
- Summary

$t\bar{t}\gamma$ production



$q\bar{q} \to t\bar{t}\gamma$ $gg \to t\bar{t}\gamma$

⇒ Sensitive to:

- Top quark charge
- Top quark electromagnetic coupling

⇒ NLO QCD corrections have been calculated:

- Peng-Fei Duan, etal., Phys.Rev.D80:014022(2009) → stable top quark.
- Melnikov, Schulze, Scharf, Phys.Rev.D83:074013(2011)
  → corrections & γ radiation in the production and decay stages.

⇒ Cross sections have been measured by CDF and ATLAS.

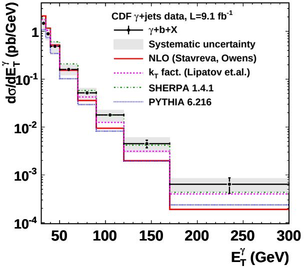
⇒ Reproducing $t\bar{t}\gamma$ (stable top) → important check on $b\bar{b}\gamma$ calculation.

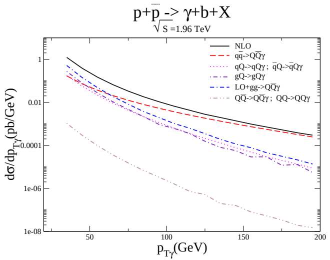
$b\bar{b}\gamma$ production

⇒ Practically $t \leftrightarrow b$, but .....
calculation: new scale (m_b) is introduced, may affect perturbative expansion.
experiment: how many b-jets are tagged in the final state.

⇒ 2b-tag: e.g. study of bottom quark EM coupling

⇒ 1b-tag: 4FNS prediction for $pp(p\bar{p}) \to \gamma b + X$





CDF, arXiv:1303.6136[hep-ex]

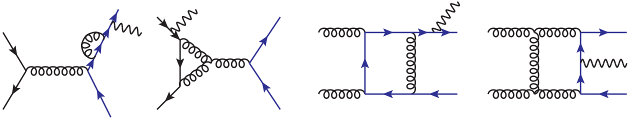
5FNS calc. by Stavreva and Owens
Phys.Rev.D79:054017(2009)

⇒ Impact of the NLO QCD corrections to $(q\bar{q}, gg) \to b\bar{b}\gamma$ subprocesses?

↪ towards the NNLO correction to $\gamma + b$ in 5FNS

$\mathcal{O}(\alpha_s)$ virtual corrections

→ consist of self energy, vertex, box and pentagon one-loop corrections.



$q\bar{q} \to Q\bar{Q}\gamma$ $\quad$ $gg \to Q\bar{Q}\gamma$

→ Reduce tensor integrals to linear combinations of scalar integrals

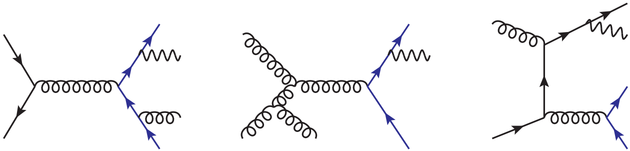
- Reduce integral at $\sum |\mathcal{A}|^2$ level for pentagons
- Use stable reduction scheme for pentagons [Tausk et al; arXiv:0812.2134]
- Small GD expansion for unstable tensor boxes [Fleischer, Riemann; arXiv:0812.2134]

→ Scalar integrals: QCDLoop [Ellis, Zanderighi; arXiv:0712.1851]

→ Independent calculation of virtual matrix element from `NLOX` package

[Schutzmeier, Reina; arXiv:1110.4438]

$\mathcal{O}(\alpha_s)$ real corrections



$q\bar{q} \to Q\bar{Q}\gamma + g$ $\quad$ $gg \to Q\bar{Q}\gamma + g$ $\quad$ $q(\bar{q})g \to Q\bar{Q}\gamma + q(\bar{q})$

- $\rightarrow$ Tree level contributions open up at $\mathcal{O}(\alpha\alpha_s^3)$: qg, $\bar{q}g$ initial state.
- $\rightarrow$ Phase space slicing with 2 cutoffs to cancel the QCD soft and collinear singularities [Harris, Owens; hep-ph/0102128]
- $\rightarrow$ Use matrix element from `MadGraph` for the tree level $2 \rightarrow 4$ processes
- $\rightarrow$ Frixione isolation to handle quark-photon FS singularity
  $\Rightarrow$ no fragmentation contribution [Frixione; hep-ph/9801442]
- $\rightarrow$ Check against CS dipole subtraction method for $t\bar{t}\gamma$ production via `SHERPA` interface (thanks to S. Hoeche)

Result: $t\bar{t}\gamma$ production

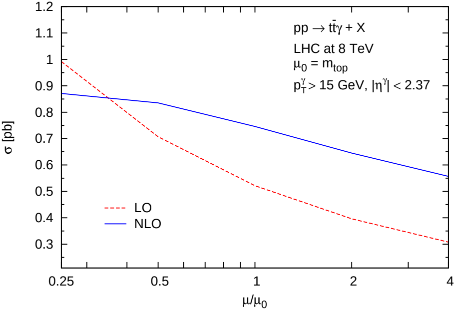
→ PDFs: CTEQ6L1 for LO, CT10 for NLO

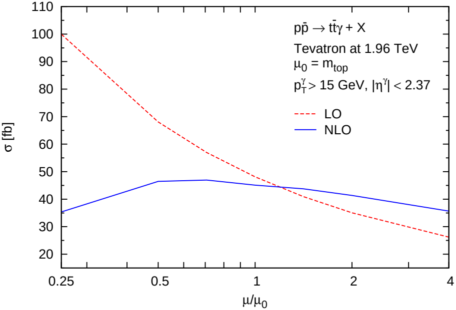
→ Central scale, $\mu_R = \mu_F = \mu_0 = m_t$; $\frac{\mu_0}{2} \leq \mu \leq 2\mu_0$ for distribution.

→ $p_T(\gamma) > 15$ GeV, $|\eta(\gamma)| < 2.37$

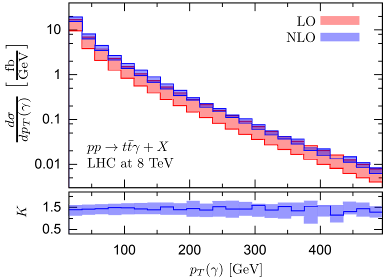
→ Frixione iso: $R_0 = 0.4$, $n = \epsilon_h = 1$

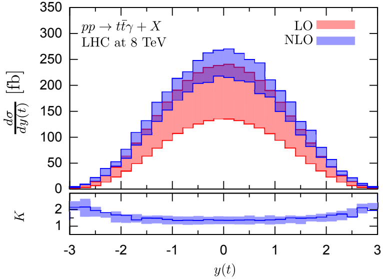
Scale dependence at LHC 8 TeV and Tevatron 1.96 TeV:



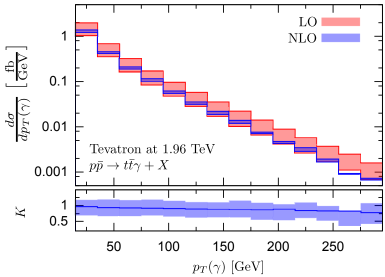


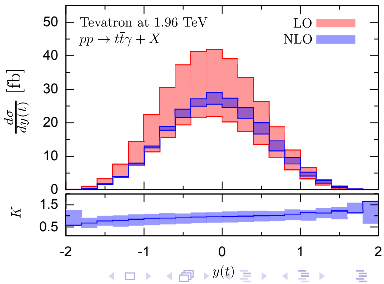
Differential distributions: LHC at 8 TeV





Differential distributions: Tevatron at 1.96 TeV





Result: $b\bar{b}\gamma$ production

Final states:

- $\gamma + 2b + X$ (2b-tag): two or more b-jets identified in the final state
- $\gamma + 1b + X$ (1b-tag): one or more b-jets identified in the final state

→ Experimental Cuts:

- Tevatron: $p_T(\gamma) > 30$ GeV, $|\eta(\gamma)| < 1.0$
  $p_T(b,j) > 20$ GeV, $|\eta(b,j)| < 1.5$
- LHC: $p_T(\gamma) > 25$ GeV, $|\eta(\gamma)| < 1.37$
  $p_T(b,j) > 25$ GeV, $|\eta(b,j)| < 2.1$

→ Jet Algorithm: anti-k_T with R=0.4

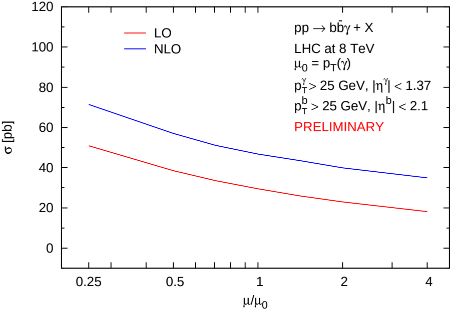
→ Central scale: $\mu_R = \mu_F = \mu_0 = p_T(\gamma)$, $\frac{\mu_0}{4} \leq \mu \leq 4\mu_0$ for distribution.

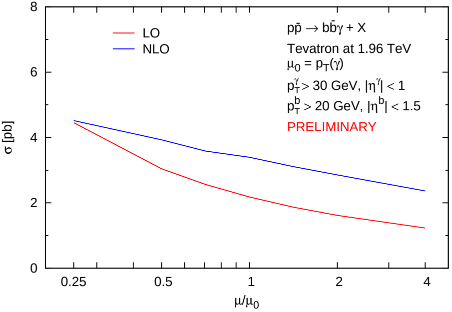
→ Perform the calculation in 4-flavor Number Scheme (4FNS) and take $n_{\rm lf} = 4$.

→ Frixione isolation is also applied to the b-jets

$b\bar{b}\gamma$ production: 2b-tag

Scale dependence for LHC 8 TeV and Tevatron 1.96 TeV



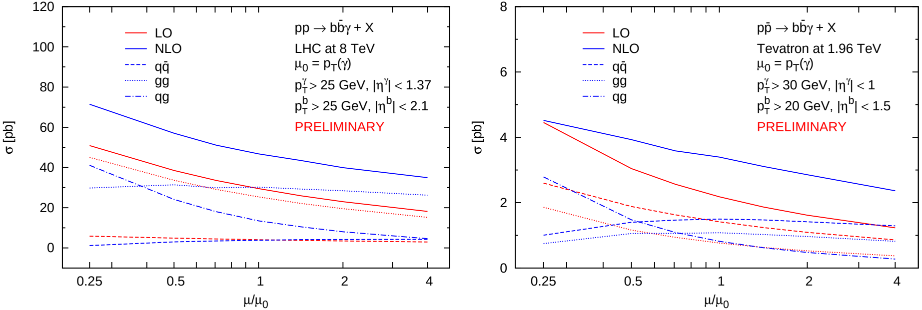


- strong scale dependence still present at NLO
- same behavior also observed in $Zb\bar{b}$ production

  [Febres Cordero, Reina, Wackeroth; arXiv:0806.0808, arXiv:0906.1923]

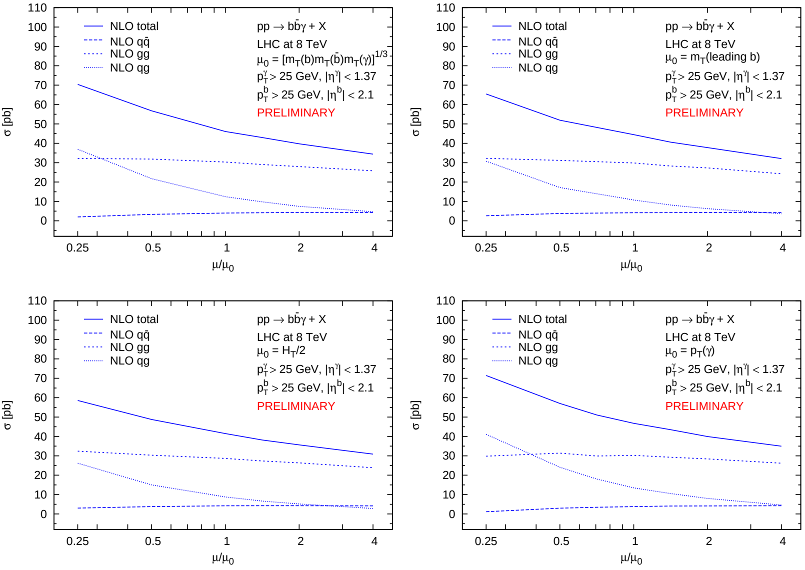
$b\bar{b}\gamma$ production: 2b-tag

Scale dependence for LHC 8 TeV and Tevatron 1.96 TeV



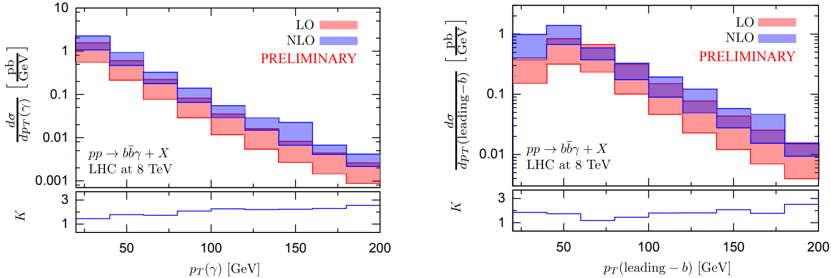
- strong scale dependence at NLO due to tree level *qg* subprocess
- scale dependence of the $q\bar{q}$ and gg channels are reduced at NLO

Different scale choice (take LHC 8 TeV as an example):

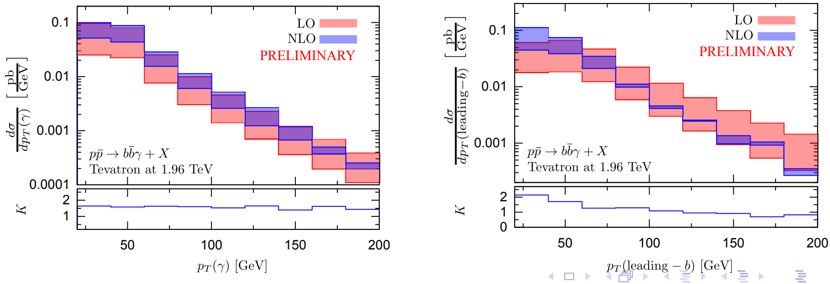


$\Rightarrow$ $q\bar{q}$ and gg channels are insensitive to different μ_0.

Differential distributions: LHC at 8 TeV

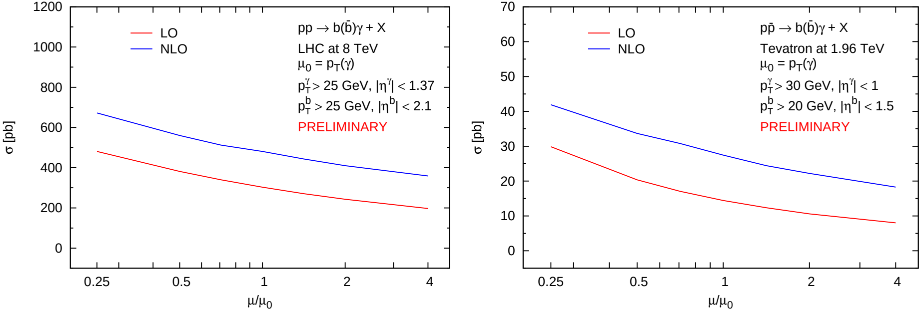


Differential distributions: Tevatron at 1.96 TeV



$b\bar{b}\gamma$ production: 1b-tag

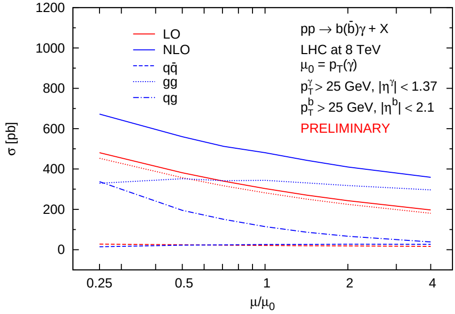
Scale dependence for LHC 8 TeV and Tevatron 1.96 TeV

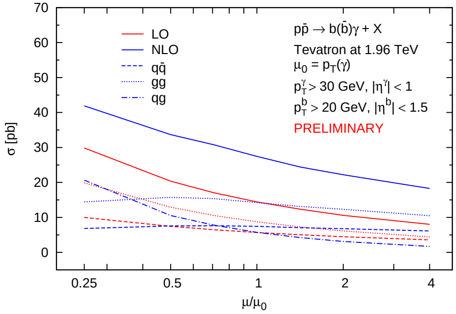


- Similar to $pp(p\bar{p}) \to b\bar{b}\gamma$, strong scale dependence at NLO due to qg subprocesses.

$b\bar{b}\gamma$ production: 1b-tag

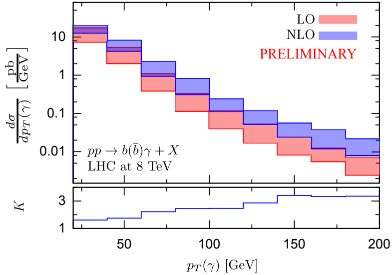
Scale dependence for LHC 8 TeV and Tevatron 1.96 TeV

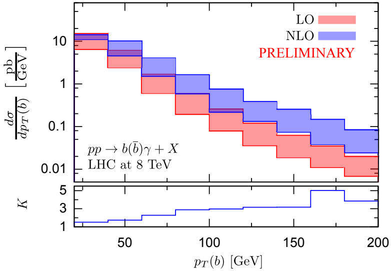




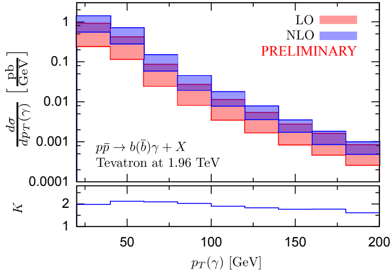
- At Tevatron, gg channel is dominant over the $q\bar{q}$ both at LO and NLO.

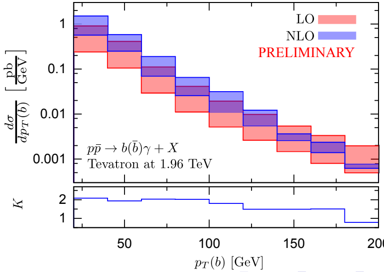
Differential distributions: LHC at 8 TeV





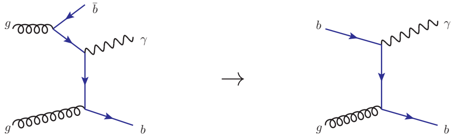
Differential distributions: Tevatron at 1.96 TeV





$pp(p\bar{p}) \to \gamma b + X$: 4FNS vs 5FNS

⇒ 5FNS:



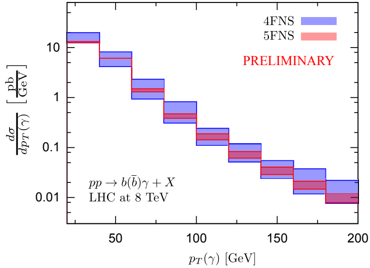
- resum (large) $\ln\left(p_T^b/m_b\right)$ arising from PS integration of untagged b into b-PDF.
- restructure the calculation in terms of α_s and $\ln\left(p_T^b/m_b\right)$

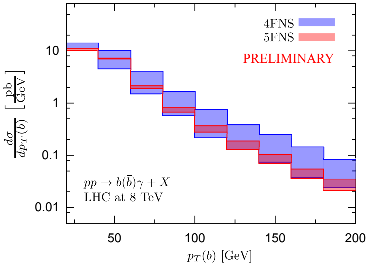
⇒ Ingredients of $\gamma + b$ in 5FNS:

- LO and virtual: $Qg \to \gamma Q$
- Real: $Qg \to \gamma Qg$, $qQ \to \gamma Qq$, $QQ \to \gamma QQ$,
  $q\bar{q} \to \gamma Q\bar{Q}$, $gg \to \gamma Q\bar{Q}$,
  where $q = q, \bar{q}$ and $Q = b, \bar{b}$.

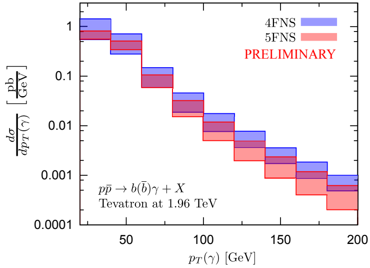
⇒ Compare our 4FNS calculation vs 5FNS calculation as implemented in MCFM, without fragmentation component. Matrix elements from γ+jet process. (thanks to C. Williams)

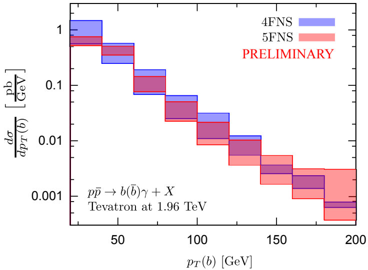
Differential distributions: LHC at 8 TeV



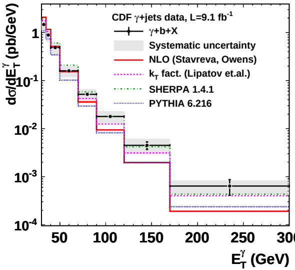


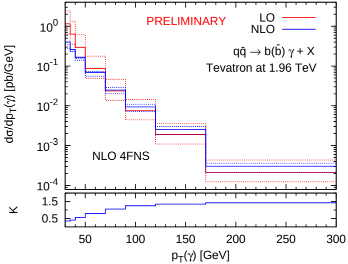
Differential distributions: Tevatron at 1.96 TeV



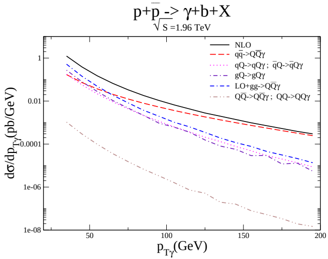


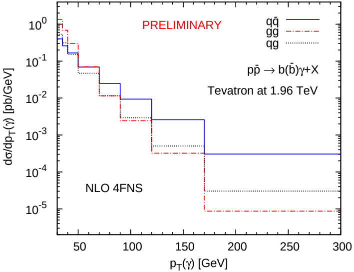
Comparison with Tevatron data





NLO 5FNS (Stavreva, Owens)





Can't compare directly, but we are moving in the right direction...

Summary

- We have computed NLO QCD corrections to $pp(p\bar{p}) \to Q\bar{Q}\gamma$ where $Q = t, b$.
- NLO cross sections and distributions for $t\bar{t}\gamma$ production (for stable top) agree with the existing results. The virtual routine has been interfaced with `SHERPA`.
- The impact of NLO QCD corrections to the $b\bar{b}\gamma$ production, both for 2b- and 1b-tag, are sizeable. NLO cross sections still suffer from strong scale dependence due to the qg subprocess.
- $pp(p\bar{p}) \to \gamma + b + X$ obtained from 4FNS calculation is compatible with the 5FNS calculation.
- 4FNS prediction for $pp(p\bar{p}) \to \gamma + b + X$ improves agreement with Tevatron data.

Outlook

- Systematically include the QCD corrected $pp(p\bar{p}) \to b(\bar{b})\gamma$ to obtained more precise $pp(p\bar{p}) \to \gamma + b + X$ theoretical predictions.
- Improve the perturbative stability of $b\bar{b}\gamma$ production by including the NLO QCD corrections to $qg \to Q\bar{Q}\gamma q$ channel.

Outlook

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THANK YOU