Resummation and fragmentation in $pp^{(\bar{s})} \rightarrow \gamma\gamma X$

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Today: NNLL/NLO $Q_T$ resummation for $\gamma\gamma$ event distributions

Tomorrow in Higgs/Top/EW session: application to Higgs searches
Distributions of $\gamma \gamma$ pairs...

- ...are measured with increasing precision at the Tevatron

- ...constitute a large irreducible background in searches for light Higgs bosons in $H \rightarrow \gamma \gamma$ decay channel at the LHC
  
  - assumptions about the $\gamma \gamma$ transverse momenta $Q_T$ affect significance of Higgs discovery and measurements of Higgs production cross sections (see tomorrow’s talk)

- ... test rich properties of QCD interactions!
  
  - large radiative contributions distributed in a complex kinematical pattern
Isolated prompt diphotons

Definition

Prompt photons = photons produced directly in perturbative QCD scattering or via parton fragmentation as opposed to nonperturbative photon production in $\pi, \eta$ decays, etc. (suppressed by isolation)

- Several classes of production processes
  - direct production
  - single-photon fragmentation
  - low-$Q$ diphoton fragmentation

- Several sources of enhanced logarithmic corrections
  - $Q_T$ logarithms from initial-state radiation $\Rightarrow$ resummation
  - final-state collinear singularities $\Rightarrow$ fragmentation functions
Theoretical studies of $\gamma\gamma$ production

- Successful computations of $\gamma\gamma$ cross sections by many groups; some relevant questions are still unanswered
  - Perturbative contributions to direct $\gamma\gamma$ production
    Aurenche et al.; Berger, Braaten, Field; Bailey, Owens, Ohnemus; Balazs, PN, Schmidt, Yuan; de Florian, Kunzst; Bern, De Freitas, Dixon; Bern, Dixon, Schmidt; Del Duca, Maltoni, Nagy, Trocsanyi;...
  - Resummation of initial-state $Q_T$ logarithms
    Balazs, Berger, Mrenna, Yuan; Balazs, PN, Schmidt, Yuan; Catani, de Florian, Grazzini; PN, Schmidt;...
  - $\gamma\gamma$ production via final-state fragmentation at NLO
    Binoth, Guillot, Pilon, Werlen;...

- Our new study
  - computes NNLL/NLO resummed $Q_T$ distributions for direct production
  - includes essential information about photon fragmentation
  - Numerical implementation: improved MC integrator program ResBos (publicly available and user-friendly)
Direct diphotons

The dominant production mode; evaluated up to NLO in $\alpha_s$

Balazs, Berger, Nadolsky, Yuan, 2006

$q\bar{q} + qg$ channel

- NLO matrix elements: Aurenche et al.; Bailey, Owens, Ohnemus
- $q\bar{q}$ scattering dominates at the Tevatron
- $qg$ scattering is strongly enhanced at the LHC by photon radiation off final-state quarks
Direct diphotons

The dominant production mode; evaluated up to NLO in $\alpha_s$

Balazs, Berger, Nadolsky, Yuan, 2006

$q\bar{q}$

$qg$

$gg$

$gq$

$gg + gq$ channel (via the quark box)

- contributes $\sim 20\%$ at the LHC
- NLO $gg$ matrix elements: Balazs, PN, Schmidt, Yuan; de Florian, Kunzst; Bern, De Freitas, Dixon; Bern, Dixon, Schmidt
- $gq$ matrix element: derived from the $q\bar{q}ggg$ matrix element
\( Q_T \) \textbf{resummation}

At \( Q_T \ll Q \):

\[
\left( \frac{d\sigma}{dQ_T^2} \right) \approx \sum_{k=0}^{\infty} \alpha_s^k \left[ c_k \delta(Q_T) + Q_T^{-2} \cdot \sum_{n=0}^{2k-1} d_n \ln^n(Q^2/Q_T^2) \right];
\]

the large logarithms are summed up to NNLL accuracy in all channels using impact-parameter method (Collins, Soper, Sterman)

\[
\left( \frac{d\sigma}{dQ_T^2} \right) = \int \frac{d^2 \vec{b}}{(2\pi)^2} e^{i\vec{Q}_T \cdot \vec{b}} \tilde{W}(b, Q) + \left( \frac{d\sigma}{dQ_T^2} \right)_{NLO} - \text{overlap}
\]

- resummed functions \( A, B, P(x, b) = (C \otimes f)(x, b) \) in \( \tilde{W}(b, Q) \) are evaluated up to orders \( \alpha_s^3, \alpha_s^2, \alpha_s \)
  - \( A^{(3)} \) derived by Moch, Vermaseren, Vogt

- the resummed cross section (valid at \( Q_T \ll Q \)) is combined with the NLO cross section (valid at \( Q_T \approx Q \))
Resummation for $gg + gq \rightarrow \gamma\gamma X$ at $\mathcal{O}(\alpha_s^3)$

**Born contribution**

- Described by a loop diagram with a complicated spin structure
- Nonzero matrix elements for all 16 combinations of photon and gluon spins
- Incomplete spin factorization between the hard-scattering contribution and PDF spin matrices
- In addition to conventional (spin-diagonal) $k_T$-dependent PDF, a new "spin-flip" $k_T$-dependent PDF arises and changes azimuthal angle dependence
- The "spin-flip" terms need not to be small compared to the spin-diagonal terms
Resummation for $gg + gq \to \gamma\gamma X$ at $O(\alpha_s^3)$

**gg NLO contribution**

$O(\alpha_s^3)$ 1-loop 5-leg (pentagon) diagrams
- are derived in the helicity amplitude formalism from 1-loop $ggggg$ amplitude *in* Bern, Dixon, Kosower, 1991
- numerically agree with the “sector decomposition” calculation *(Binoth, Guillet, Mahmoudi, 2003)*
- Small-$Q_T$ limit is derived at the matrix-element level with the splitting amplitude method *(Bern, Chalmers, Dixon, Dunbar, Kosower)*
- **Soft singularities** are cancelled against 2-loop box diagrams *(Bern, De Freitas, Dixon; P.N., Schmidt)*
- **Collinear singularities** are resummed in the conventional and spin-flip gluon PDF’s
Resummation for $gg + gq \rightarrow \gamma\gamma X$ at $\mathcal{O}(\alpha_s^3)$

**gq 5-leg matrix element**

- Obtained from the color-decomposed $q\bar{q}ggg$ matrix element \cite{Bern:1995db} by replacement of two SU(3) generator matrices $T_{cd}^a$ by identity matrices $I_{cd}$

\[ M_5(q_{1i}, \bar{q}_{2j}, g_3^{a_3}, g_4^{a_4}, g_5^{a_5}) \]
\[ \sim g^5 \sum_{\sigma \in S_3^{(345)}} (T_{3}^{\sigma_3} T_{4}^{\sigma_4} T_{5}^{\sigma_5})_{ij} A_{5;1}^{L, [1/2]} (1_q, 2_{\bar{q}}; \sigma_3, \sigma_4, \sigma_5) + ... \]

- To obtain $M_5(q_{1i}, \bar{q}_{2j}, \gamma_3, \gamma_4, g_5^{a_5})$, replace

\[ gT_{cd}^{a_3,4} \rightarrow e e i \sqrt{2} I_{cd} \]
Resummation for $gg + gq \rightarrow \gamma \gamma X$ at $\mathcal{O}(\alpha_s^3)$

$\text{pp} \rightarrow \gamma\gamma X, \sqrt{S} = 14 \text{ TeV, ATLAS cuts}$

$115 < Q < 140 \text{ GeV}$

\begin{itemize}
  \item $M_5(gq \rightarrow \gamma\gamma q)$ correctly reproduces its known behavior in the collinear asymptotic limit ($Q_T \rightarrow 0$)
  \item It disagrees with an earlier calculation (Yasui), which does not have this asymptotic behavior
\end{itemize}
Resummation for $gg + gq \rightarrow \gamma\gamma X$ at $\mathcal{O}(\alpha_s^3)$

$pp \rightarrow \gamma\gamma X$, $\sqrt{S} = 14$ TeV, ATLAS cuts

\begin{align*}
115 < Q < 140 \text{ GeV}
\end{align*}

$gq$ 5-leg matrix element

- The $gq$ contribution is subleading in the inclusive rate, but has more pronounced effect at high $Q_T$ (improves matching)
Resummation for $gg + gq \rightarrow \gamma\gamma X$ at $\mathcal{O}(\alpha_s^3)$

The $gq$ contribution is subleading in the inclusive rate, but has more pronounced effect at high $Q_T$ (improves matching)
The $qg$ fragmentation collinear singularity is removed by combination of quasi-experimental isolation at $Q_T > E_{iso}^T$, and subtraction or smooth-cone isolation at $Q_T \leq E_{iso}^T$.

- sufficient for description of fragmentation contributions at the Tevatron and LHC
- approximately reproduces the inclusive NLO fragmentation rate (Binoth et al.; DIPHOX program) at both colliders
- good agreement with the Tevatron data

Balazs, Berger, Nadolsky, Yuan, 2006
Comparison with the CDF Run-2 data

The NLO prediction (blue) diverges at low $q_T$

The resummed prediction (red) agrees with the data at all $q_T$; matches the NLO prediction at large $q_T$
production at the LHC

$E_{T}^{iso} = 15 \text{ GeV}, \Delta R_{cone} = 0.4$; preliminary

$pp \rightarrow \gamma\gamma X, \sqrt{S} = 14 \text{ TeV}, \text{ATLAS cuts}$

$q\bar{q} : qg : (gg + gq) = 30:50:20$

(compare with $q\bar{q} : qg : (gg + gq) = 70:20:10$ at the Tevatron)

$O(\alpha_s^2)$ corrections to $qg$ are likely important ($\sigma_{NNLO}/\sigma_{NLO} \sim 20\%$?)
**$\gamma\gamma$ production at the LHC**

$E_{T}^{iso} = 15$ GeV, $\Delta R_{cone} = 0.4$; preliminary

\[ pp(q\bar{q}, qg, gg) \rightarrow \gamma\gamma X, \sqrt{S} = 14 \text{ TeV} \]

- **DIPHOX** agrees with the resummation at large $q_T$; exhibits integrable logarithmic singularities at $q_T < E_{T}^{iso}$ ($E_{T}^{iso}$ is the isolation energy)

- **RESBOS** shows a mild discontinuity at $q_T = E_{T}^{iso}$
$\gamma\gamma$ production at the LHC

$E_{iso} = 15$ GeV, $\Delta R_{cone} = 0.4$; preliminary

$pp(q\bar{q},qg,gg) \rightarrow \gamma\gamma X, \sqrt{s} = 14$ TeV

$ds/dQ_T (pb/GeV)$

Fixed order (NLO)
Resummed (NNLL)
DIPHOX

$Q_T (GeV)$

$Q (GeV)$

Pavel Nadolsky (ANL)  
QCD session, APS/DPF-JPS meeting, HI  
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Summary of new features

- Resummation at full NNLL accuracy in direct $q\bar{q} + qg$ and $gg + gq$ channels
- Improved treatment of the fragmentation region
- Improved model for nonperturbative resummed contributions (A. Konychev, P. N., PLB 633, 710 (2006))
  - Non-pert. terms constrained by low-$Q$ and Tevatron $Z$ data
- Resummed form factor in two resummation schemes
- Automated matching at the NTUPLE level; optimized Monte-Carlo integration
- Applications to Higgs boson search tomorrow!