Resummation and fragmentation in $p\overset{(-)}{p} \rightarrow \gamma\gamma X$

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October 31, 2006

C. Balazs, E. Berger, **P. N.**, *C.-P. Yuan, Phys. Lett., B637, 235 (2006); hep-ph/0611xxx*

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 $H \to \gamma\gamma$ 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

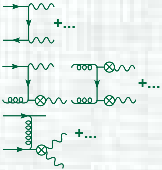
Isolated prompt diphotons

Definition

Prompt photons = photons produced directly in perturbative QCD scattering or via parton fragmentation

as opposed to nonperturbative photon production in π, η 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

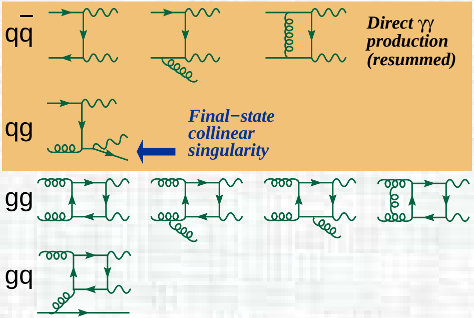
Theoretical studies of $\gamma\gamma$ production

- 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, Guillet, 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 α_s

Balazs, Berger, Nadolsky, Yuan, 2006



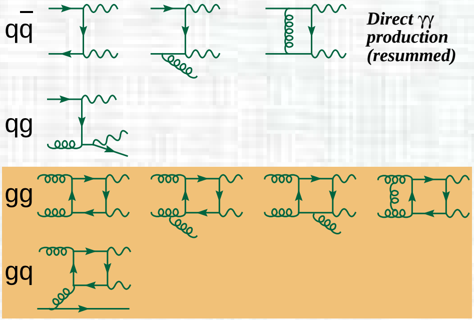
$q\bar{q} + qg$ channel

- 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 α_s

Balazs, Berger, Nadolsky, Yuan, 2006



Direct $\gamma\gamma$ production (resummed)

$gg + gq$ 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 resummation

At $Q_T \ll Q$:

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

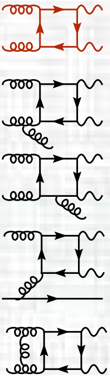
the large logarithms are summed up to NNLL accuracy in all channels using impact-parameter method *(Collins, Soper, Sterman)*

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

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

- the resummed cross section (valid at $Q_T \ll Q$) is combined with the NLO cross section (valid at $Q_T \approx Q$)

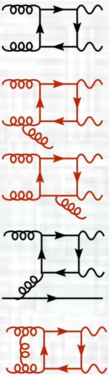
Resummation for $gg + gq \to \gamma\gamma X$ at $\mathcal{O}(\alpha_s^3)$



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 $\mathcal{O}(\alpha_s^3)$

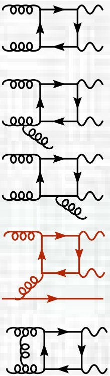


gg NLO contribution

$\mathcal{O}(\alpha_s^3)$ 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 $gg + gq \to \gamma\gamma X$ at $\mathcal{O}(\alpha_s^3)$



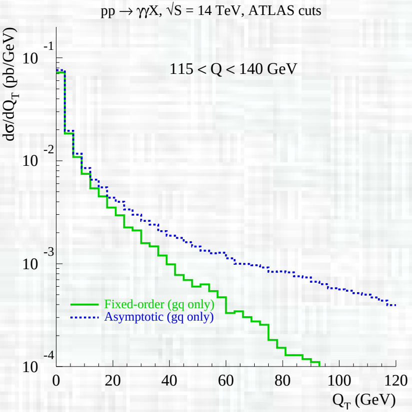
gq 5-leg matrix element

- Obtained from the color-decomposed $q\bar{q}ggg$ matrix element (Bern, Dixon, Kosower, 1995) by replacement of two SU(3) generator matrices T^a_{cd} by identity matrices $\mathcal{I}_{cd}$

$$\mathcal{M}_5(q_{1i}, \bar{q}_{2j}, g_3^{a_3}, g_4^{a_4}, g_5^{a_5})$$
$$\sim \quad g^5 \sum_{\sigma \in S_3^{(345)}} (T^{\sigma_3} T^{\sigma_4} T^{\sigma_5})_{ij} A^{L,[1/2]}_{5;1}(1_q, 2_{\bar{q}}; \sigma_3, \sigma_4, \sigma_5) + \ldots$$

- To obtain $\mathcal{M}_5(q_{1i}, \bar{q}_{2j}, \gamma_3, \gamma_4, g_5^{a_5})$, replace $gT^{a_{3,4}}_{cd} \to ee_i\sqrt{2}\,\mathcal{I}_{cd}$

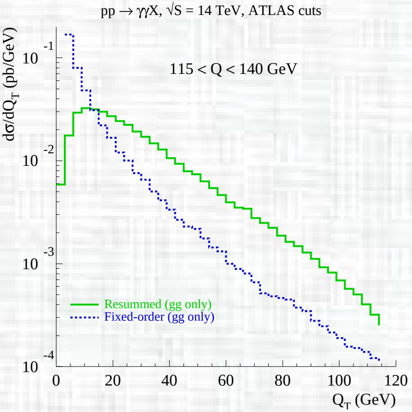
Resummation for $gg + gq \to \gamma\gamma X$ at $\mathcal{O}(\alpha_s^3)$



gq 5-leg matrix element

- $\mathcal{M}_5(gq \to \gamma\gamma q)$ correctly reproduces its known behavior in the collinear asymptotic limit ($Q_T \to 0$)
- It disagrees with an earlier calculation (Yasui), which does not have this asymptotic behavior

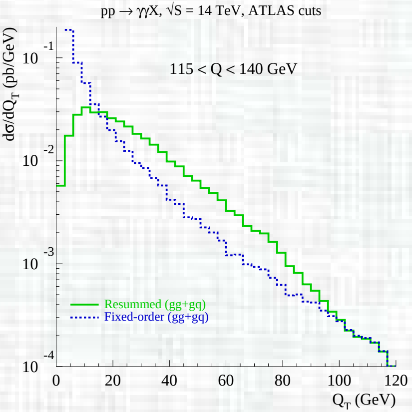
Resummation for $gg + gq \to \gamma\gamma X$ at $\mathcal{O}(\alpha_s^3)$



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 $gg + gq \to \gamma\gamma X$ at $\mathcal{O}(\alpha_s^3)$



gq 5-leg matrix element

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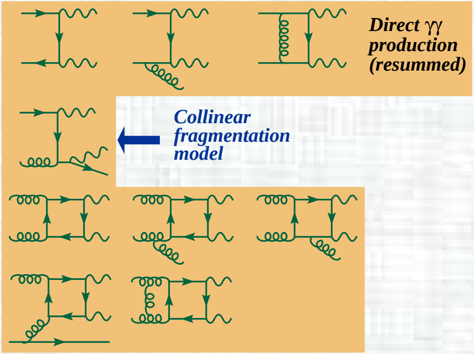
Fragmentation model

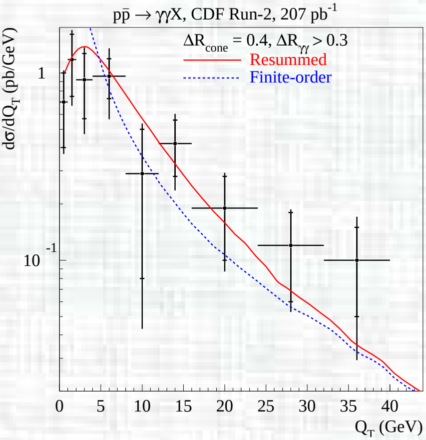
The qg fragmentation collinear singularity is removed by combination of quasi-experimental isolation at $Q_T > E_T^{iso}$, and subtraction or smooth-cone isolation at $Q_T \leq E_T^{iso}$

Balazs, Berger, Nadolsky, Yuan, 2006



- 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

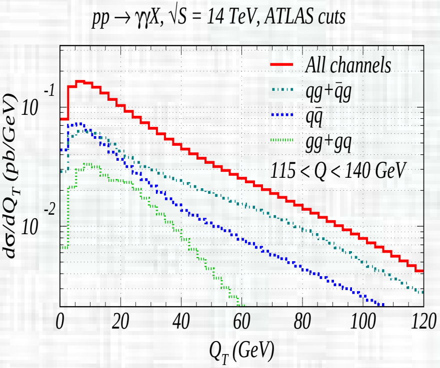
Comparison with the CDF Run-2 data



- 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

$\gamma\gamma$ production at the LHC

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



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

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

$\mathcal{O}(\alpha_s^2)$ corrections to qg are likely important
($\sigma_{NNLO}/\sigma_{NLO} \sim 20\%$?)

$\gamma\gamma$ production at the LHC

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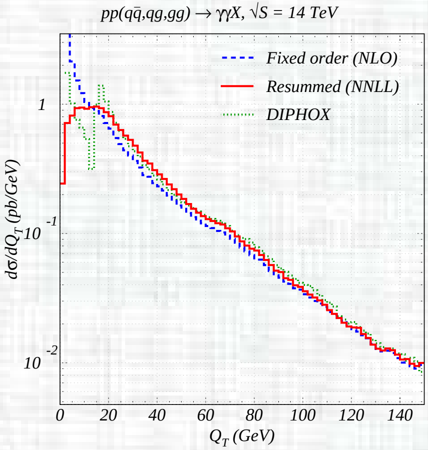
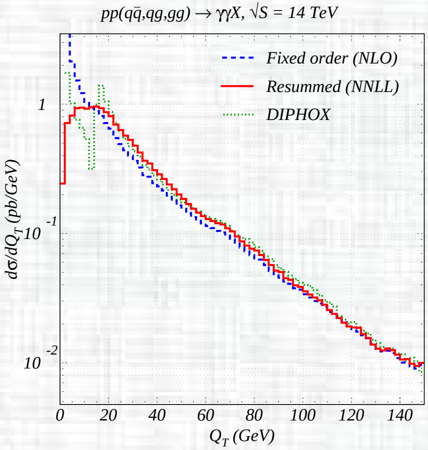
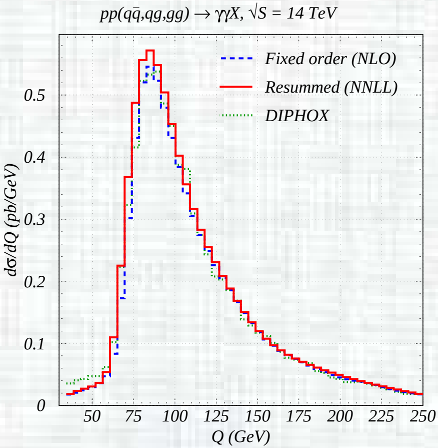


- DIPHOX agrees with the resummation at large q_T; exhibits integrable logarithmic singularities at $q_T < E_T^{iso}$ (E_T^{iso} is the isolation energy)
- RESBOS shows a mild discontinuity at $q_T = E_T^{iso}$

$\gamma\gamma$ production at the LHC

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





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!