DIRECT PHOTON PRODUCTION FROM EFFECTIVE FIELD THEORY

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ICHEP 2010, Paris
OUTLINE

• Introduction

• Soft-Collinear Effective Theory

• Photon production cross section

• NNLL resummation for at large $p_T$ photon production

• Resummation by RG evolution

• Numerical results and comparison to Tevatron data

• NNLL resummation for W and Z production
SOFT-COLLINEAR EFFECTIVE THEORY
Bauer, Pirjol, Stewart et al. 2001, 2002; Beneke et al. 2002

- EFTs split physics into high- and low-energy part. In collider processes, we have an *interplay of three momentum regions*

- Hard
- Collinear
- Soft

- Correspondingly, EFT for such processes has two low-energy modes:
  - **Collinear fields** describing the energetic partons propagating in a given direction, and
  - **soft fields** which mediate long range interactions among them.
RESUMMATIONS WITH SCET

• EFT provides an elegant framework to factorize contributions associated with different scales.

• Terms enhanced by large log’s of scale ratios are resummed by RG evolution

• By now, many applications of SCET to collider processes. Resummations in many cases up to $N^3$LL:

  • thrust distribution in $e^+e^-$
  • Drell-Yan rapidity dist.
  • Drell-Yan, low $p_T$
  • inclusive Higgs production
  • ...

  all of these involve two directions of large energy flow

TB, Schwartz ‘08; Abbate et al. ‘10
TB, Neubert, Xu ‘07
Gao, Li, Liu ‘05; Idilbi, Ji, Yuan ‘05;
Petriello, Sonny ‘09;
TB, Neubert to appear Monday
Idilbi, Ji, Ma and Yuan ‘06;
Ahrens, TB, Neubert, Yang ‘08, update for ICHEP, see M. Neubert’s talk
N-JET PROCESSES

• Important progress in past year towards higher-log resummation of processes with large energy flow in several directions.

• All-order constraints on the anomalous dimensions from soft-collinear factorization, factorization in collinear limit, non-abelian exponentiation.
  TB, Neubert ’09; Gardi, Magnea ’09 + Dixon ’09

• General result for hard anomalous dimensions relevant for NNLL of $n$-jet processes
  • massless: determined by constraints explains two-loop results of Aybat, Dixon and Sterman ’06
  • massive: two-loop computation of three-particle correlations Ferroglia, Neubert, Pecjak, Yang ’09
PHOTON PRODUCTION $pp \rightarrow \gamma + X$ AT LARGE $p_T$

- First SCET calculation of a physical cross section with energetic particles in three directions.
- Perform NNLL resummation of $\alpha_s^n \log^{2n}(M_X/p_T)$ corrections arising for at large $p_T$.
  - NLL was known Laenen et al. '98, Catani et al. '98, Kidonakis and Owens '99
- In the meantime we have extended the result also to $W^\pm$ and $Z$ production TB, Lorentzen, Schwartz, to appear
- Other examples involving multiple directions
  - top-production Ahrens, et al. '10
  - EW Sudakov resummation Chiu, et al. '08, '09
PHOTON PRODUCTION MECHANISMS

• Direct production
  • sensitive to gluon PDF
  • dominates fragmentation very at high $p_T$
  • perform NNLL resummation for this part match to NLO (own code for inclusive case; JetPhox for isolation)

• Fragmentation
  • needs non-perturbative fragmentation function
  • can be suppressed by putting isolation cone around $\gamma$
  • included in NLO (Jetphox)
FACTORIZATION THEOREM AT LARGE $p_T$

- Have derived factorization theorem for prompt photon production at large $p_T \gg M_X$

$$\frac{d^2\sigma}{dydp_T} = H \otimes J \otimes S \otimes f_1 \otimes f_2$$

- (there are different partonic channels, with different $H, J, S$ and $f$'s)
• Hard function is square of on-shell $qg \rightarrow q\gamma$ amplitude. \cite{Ellis:1983ix}

• Jet functions are quark and gluon propagators in light-cone gauge.

• Soft function is matrix element of Wilson lines $Y_i$ from 0 ... $\infty$ along the beam and jet directions.

\[
S_{\bar{q}q}(k^+) = \frac{1}{N_c} \sum_{X_s} \left| \langle X_s | \mathcal{T} \left[ Y_1^{\dagger}(0) Y_J(0) \gamma^\alpha Y_J^{\dagger}(0) Y_2(0) \right] 0 \rangle \right|^2 (2\pi)\delta(n_J \cdot p_{X_s} - k^+) 
\]
RESUMMATION BY RG EVOLUTION

- Evaluate each part at its characteristic scale, evolve to common scale:

\[
\mu^2
\]

\[
\frac{m_X^2}{p_T}
\]

\[
\mu_f^2
\]

\[
p_T
\]

\[
m_X
\]

Hard func. | Jet function | Soft function | PDFs

\[
f_i(x_1)f_j(x_2)
\]
**ANOMALOUS DIMENSIONS**

- Have analytic solution for the RGs of H, J and S. TB and Neubert '06

- Using RG invariance and known results, we are able to extract all anomalous dimensions to *three loops*

- Hard anomalous dimension $\Gamma_H$ from general result TB and Neubert '09 (see also Gardi and Magnea '09 + Dixon '09)

  - For $n=3$, the constraints determine $\Gamma_H$ uniquely.

- Quark-jet function anomalous dimension $\Gamma_{Jq}$ known

- Soft anom. dim. for $qg$ channel is

  $$\Gamma_{S_{qq}} = \Gamma_{H_{qq}} - \Gamma_{Jq}$$

- Soft anom dim. for $qq$ channel is

  $$\Gamma_{S_{\bar{q}q}} = \frac{2C_F - C_A}{C_A} \Gamma_{S_{qq}}$$

- Gluon-jet function anom. dim. is

  $$\Gamma_{Jg} = \Gamma_{H_{\bar{q}q}} - \Gamma_{S_{\bar{q}q}}$$
• Have analytic solution for the RGs of H, J, and S.

• Using RG invariance and known results, we are able to extract all anomalous dimensions to three loops.

• Hard anomalous dimension \( \Gamma_H \) from general result TB and Neubert '09 (see also Gardi and Magnea '09 + Dixon '09).

• For \( n=3 \), the constraints determine \( \Gamma_H \) uniquely.

• Quark-jet function anomalous dimension \( \Gamma_{Jq} \) known.

• Soft anom. dim. for qg channel is \( \Gamma_{S_{qg}} = \Gamma_{H_{qg}} - \Gamma_{J_q} \).

• Soft anom. dim. for \( \bar{q}q \) channel is \( \Gamma_{S_{\bar{q}q}} = \frac{2C_F - C_A}{C_A} \Gamma_{S_{qg}} \).

• Gluon-jet function anom. dim. is \( \Gamma_{Jg} = \Gamma_{H_{\bar{q}q}} - \Gamma_{S_{\bar{q}q}} \).

Anomalous dimensions sufficient for NNNLL resummation! (but would need two-loop matching).
SCALE CHOICE

• Natural choice for scale in hard function is $\mu_h \sim p_T$

• Choice of jet scale $\mu_j$ is more difficult, since partonic invariant mass varies $m_X = 0 \ldots \hat{M}_X$ where the hadronic $M^2_X = E^2_{CM} (1 - p_T/p_T^{\text{max}})$

  • For small $M_X$, i.e. very large $p_T$, $\mu_j \sim M_X$ is appropriate

  • Choice $\mu_j = m_X$ leads to Landau pole ambiguities; is implicit in trad. resummation method.

• Convolution with PDF dynamically enhances threshold region of low $m_X$. TB Neubert ’08

  • Would like to set $\mu_j$ to the average value of $m_X$, but convolution with PDFs can only be done numerically.

  • Determine $\mu_j$ by looking at jet-function corrections as a function of $\mu_j$. Reasonable scale choice gives moderate corrections.
As a default, we choose

\[ \mu_h = p_T , \]

\[ \mu_j = \frac{p_T}{2} \left( 1 - 2 \frac{p_T}{E_{CM}} \right) , \]

\[ \mu_s = \mu_j^2 / \mu_h \]

and vary by a factor two.
Matching scales variations are small, factorizations scale uncertainty dominates. Matching to NLO reduces factorization scale dep.
MATCHING TO FIXED ORDER

- We match the NLO fixed order result in JETPHOX. This allows us to account for isolation cuts and fragmentation contributions.

\[
\left( \frac{d^2\sigma}{dv dw} \right)_{\text{matched}} = \left( \frac{d^2\sigma}{dv dw} \right)_{\text{NNLL}} - \left( \frac{d^2\sigma}{dv dw} \right)_{\text{NNLL}}^{\mu_h=\mu_j=\mu_s=\mu_f} + \left( \frac{d^2\sigma}{dv dw} \right)_{\mu_f}^{\text{NLO}}.
\]
• Rapidly falling, so in the next slides I will plot \( \frac{d\sigma}{dp_T} \) for the direct photon production w/o isolation cuts.

• \( d\sigma_{\text{NLO}}^{(\text{dir})} \) is the direct photon production w/o isolation cuts.

FIGURE 7: Direct photon distributions at the Tevatron, compared to SCET. Green bands are scale uncertainty. On the left, comparison is made to CDF data. On the right, the rapidity distribution is shown for \( p_T = 200 \) GeV. The SCET prediction, matched to NLO, is compared to the scale uncertainty on the NLO prediction (solid red lines) and to the PDF uncertainty (dashed blue lines).
Fragmentation and isolation from JETPHOX. Additional hadronisation correction (a factor 0.91) as determined in CDF paper from MC studies.
LHC RESULTS

- Direct contribution only: no fragmentation or isolation cuts.
• Factorization theorem has exactly the same structure as in the photon case
\[
\frac{d^2\sigma}{dy dp_T} = H \otimes J \otimes S \otimes f_1 \otimes f_2
\]
• Same soft and jet function, but different hard function and kinematics.
W AND Z PRODUCTION

- Use MCFM for NLO
- All scales varied by a factor 2 around default
W AND Z PRODUCTION

- NNLL+NLO has somewhat larger central value, reduced scale dependence.

PRELIMINARY!
CONCLUSIONS

• A lot of progress during the past year towards the analysis of more complex collider observables in SCET
  • n-jet anomalous dimensions
    • completely known to NNLL
    • fulfills stringent all-order constraints
  • First application involving three directions of large momentum flow
    • Photon production at large $p_T$ to NNLL
    • Computation of $W$ and $Z$ finished, phenomenological analysis in progress