Probing the theoretical description of central exclusive production

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Deep Inelastic Scattering, Florence
- 20^{th} April 2010

Overview.

Central exclusive production and the Durham model

Next-to-leading order corrections

Phenomenological impact

Central exclusive production

- Central exclusive production is the process

$$h_1(p_1) + h_2(p_2) \to h_1(p_1') \oplus X \oplus h_2(p_2')$$

- Hadrons remain intact, but lose energy to produce the central system, X, which is observed in the central detector.

- Scattered hadrons bent out of the beam pipe by magnets (like a spectrometer). At the LHC, adding detectors at ~ 220 m, ~ 420 m down the beam pipe enables one to measure their four-momenta.

- The $\oplus$ denote rapidity gaps; the central system is produced, but nothing else i.e. exclusive.

Why is it interesting?

- Can provide, potentially unique, information on the central system:
  - Gives quantum numbers of central system (non $J^{PC} = 0^{++}$ production heavily suppressed).
  - Reconstructed proton momenta give central system invariant mass, $\sqrt{\hat{s}}$, with a resolution ~ 2-3 GeV (*per event*), via a missing mass method (Albrow and Rostovtsev - arXiv:hep-ph/0009336).

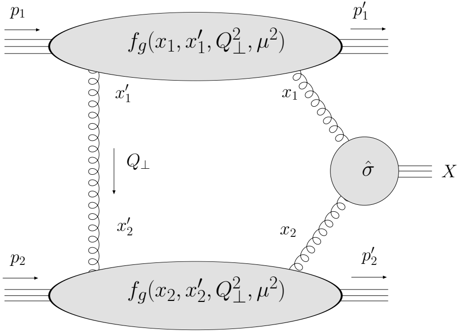
- Central exclusive $b\bar{b}$ production suppressed (due to a $J_z = 0$ selection rule).

- Di-jet, χ_c and $\gamma\gamma$ production observed by CDF at the Tevatron (*Phys. Rev. D77, Phys. Rev. Lett. 102, 99*).

- Feasibility at the LHC studied by the FP420 R&D collaboration (arXiv:0806.0302). Groups in ATLAS and CMS working to install additional detectors.

Theoretical predictions - the Durham model

- Central exclusive production calculated in perturbative QCD by Khoze, Martin and Ryskin.
- Schematically:



The Durham model - cross-section

- The cross-section is assumed to factorise as (Khoze, Martin and Ryskin, *Eur. Phys. J. C23*)

$$\frac{\partial\sigma}{\partial\hat{s}\partial y\partial \boldsymbol{p}'^2_{1\perp}\partial \boldsymbol{p}'^2_{2\perp}} = S^2 e^{-b(\boldsymbol{p}'^2_{1\perp}+\boldsymbol{p}'^2_{2\perp})}\frac{\partial\mathcal{L}}{\partial\hat{s}\partial y} d\hat{\sigma}(gg\to X)\ .$$

- Sub-process cross-section:

$$d\hat{\sigma}(gg\to X) = \frac{1}{2\hat{s}}\left|\bar{\mathcal{M}}(gg\to X)\right|^2 d\mathrm{PS}_X$$

where,

$$\bar{\mathcal{M}}(gg\to X) = \frac{1}{2}\frac{1}{N^2-1}\sum_{a_1a_2}\sum_{\lambda_1\lambda_2}\delta_{a_1a_2}\delta_{\lambda_1\lambda_2}\mathcal{M}^{a_1a_2}_{\lambda_1\lambda_2}(gg\to X)\ .$$

The sum over equal helicities here gives the $J_z = 0$ selection rule.

The Durham model - effective luminosity

- Effective luminosity, $\frac{\partial \mathcal{L}}{\partial \hat{s} \partial y}$, given by

$$\frac{\partial \mathcal{L}}{\partial \hat{s} \partial y} = \frac{1}{\hat{s}} \left(\frac{\pi}{N^2 - 1} \int \frac{d\boldsymbol{Q}_\perp^2}{\boldsymbol{Q}_\perp^4} f_g(x_1, x_1', \boldsymbol{Q}_\perp^2, \mu^2) f_g(x_2, x_2', \boldsymbol{Q}_\perp^2, \mu^2) \right)^2 \ .$$

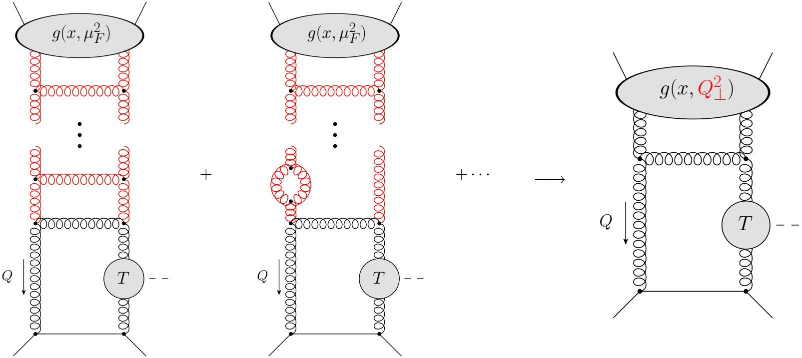
- The kinematics are such that $x_i' \ll x_i$. In this limit:

$$f_g(x, x', \boldsymbol{Q}_\perp^2, \mu^2) \approx R_g \frac{\partial}{\partial \ln \boldsymbol{Q}_\perp^2} \left(\sqrt{T(\boldsymbol{Q}_\perp, \mu)} x g(x, \boldsymbol{Q}_\perp^2) \right) \ .$$

- $T(\boldsymbol{Q}_\perp, \mu)$ is a Sudakov factor and R_g accounts for the off-forward kinematics ($x_i' \neq x_i$).

Form of the Durham result - pdf evolution

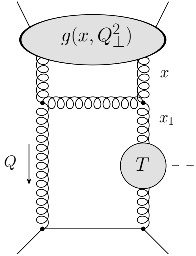
- $p_\perp$ ordered ladders evolve pdfs to scale $Q_\perp$



- Corrections to the Higgs vertex, after final s-channel emission, generate Sudakov factor, T.

Form of the Durham result - pdf and Sudakov derivatives

- Final rung gives



$$\propto \sqrt{T}\frac{\alpha_s}{2\pi}\sum_{a=q,g}\int \frac{dx}{x}\tilde{P}_{ga}\left(\frac{x_1}{x}\right)a(x, Q_\perp^2)$$

$$\approx \sqrt{T}\frac{\partial g(x_1, Q_\perp^2)}{\partial \ln Q_\perp^2} + g(x_1, Q_\perp^2)\frac{\partial\sqrt{T}}{\partial \ln Q_\perp^2}$$

- First term generated by DGLAP equation.
- Second term due to lack of plus-prescription for final emission:

$$P_{gg}(z) \propto \left(\frac{1}{1-z}\right)_+ = \frac{1}{1-z} - \delta(1-z)\int_0^1 \frac{dz'}{1-z'}$$

$$\tilde{P}_{gg}(z) \propto \frac{1}{1 - z + \frac{Q_\perp^2}{(1-z)m_H^2}}$$

Form of the Durham result - Sudakov factor (1)

- The focus of this talk will be the Sudakov factor, $T(\boldsymbol{Q}_\perp, \mu)$.
- Sudakov factor previously found to be given by (Kaidalov, Khoze, Martin and Ryskin *Eur. Phys. J. C33*)

$$T(\boldsymbol{Q}_\perp, \mu) = \exp\left(-\int_{\boldsymbol{Q}_\perp^2}^{\hat{s}/4} \frac{dk_\perp^2}{k_\perp^2} \frac{\alpha_s(k_\perp^2)}{2\pi} \int_0^{1-\Delta} dz \, \left[zP_{gg}(z) + \sum_q P_{qg}(z) \right] \right)$$

where

$$\Delta = \frac{k_\perp}{k_\perp + \mu} \, , \qquad \qquad \mu = 0.62\sqrt{\hat{s}} \, .$$

- To collect all terms of order $\alpha_s^n \ln^m(\hat{s}/\boldsymbol{Q}_\perp^2)$, with $m = 2n, 2n-1$, require precise upper z and lower $k_\perp^2$ cutoffs.

Form of the Durham result - Sudakov factor (2)

- To understand the lower limit, consider the $k_\perp \sim Q_\perp$ region in the BFKL formalism. This leads to the replacement:

$$\int_{k_0} \frac{d^2 k_\perp}{k_\perp^2} \to \int_{k_0} \frac{d^2 k_\perp}{k_\perp^2} \left(1 - \frac{\boldsymbol{Q}_\perp^2}{k_\perp^2 + (\boldsymbol{Q}_\perp - \boldsymbol{k}_\perp)^2} \right) \approx \int_{\boldsymbol{Q}_\perp^2} \frac{d^2 k_\perp}{k_\perp^2}$$

  i.e. the region with $k_\perp^2 < \boldsymbol{Q}_\perp^2$ is cancelled.

- Upper z limit corresponds to soft gluons. Fix it by exploiting unitarity (Bloch-Nordsieck theorem).

Form of the Durham result - Sudakov factor (3)

- Calculate $\sigma(gg \to Hg)$. By unitarity, soft logarithms in this process will be equal and opposite to those in the $gg \to H$ process.

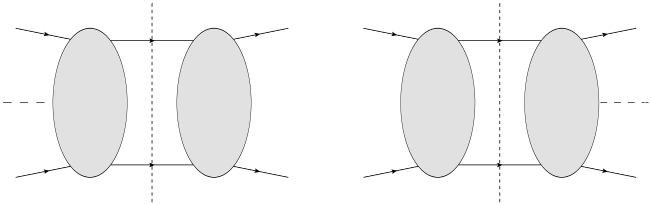
- KMR obtain

$$\sigma(gg \to gH) \propto \int \frac{dk_\perp^2}{k_\perp^2} \frac{C_A \alpha_s}{\pi} \left(\ln(0.62) + \ln\left(\frac{m_H}{k_\perp}\right) - \frac{11}{12} \right)$$
$$= \int \frac{dk_\perp^2}{k_\perp^2} \frac{\alpha_s}{2\pi} \int_0^{1-\Delta} dz \; z P_{gg}(z)$$

- We find that this result is not correct. Specifically, we find one should replace $0.62 \to 1$ (TC, J. Forshaw - *JHEP 1001*).

Next-to-leading order corrections - our calculation

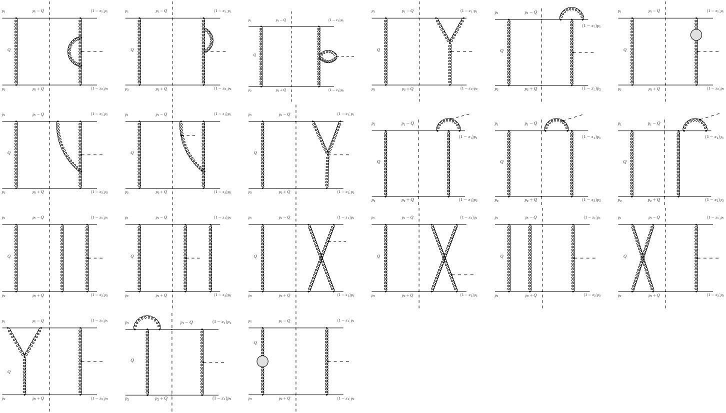
- Take the process $qq \to qHq$.
- Imaginary part of the amplitude dominates, $A \approx i\Im m(A)$, so use the Cutkosky rules.
- Compute the one-loop corrections to each side of the cut



- Use these to extract the Sudakov factor.

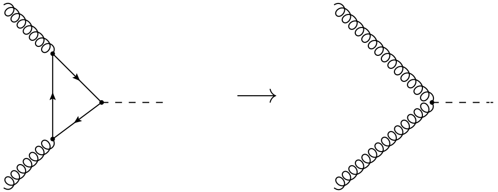
Next-to-leading order diagrams

- Full set of diagrams with the Higgs to the right of the cut (not including those related by $x_1 \leftrightarrow x_2$)



Method of calculation (1)

- Use $m_{\text{top}} \to \infty$ effective theory (Shifman et al, Voloshin, Ellis et al).



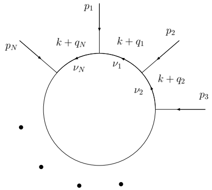
- Interaction described by an effective Lagrangian:

$$\mathcal{L}_{\text{eff}} = -\frac{H}{4} C_1^R(\mu)\, G^a_{\mu\nu} G^{a\mu\nu} + \cdots$$

where

$$C_1^R(\mu) = -\frac{1}{3v}\frac{\alpha_s(\mu)}{\pi}\left(1 + \frac{11}{4}\frac{\alpha_s(\mu)}{\pi}\right) + \mathcal{O}(\alpha_s^3)$$

Method of calculation (2)



- Need to calculate tensor integrals:

$$I^{\mu_1\cdots\mu_m}(d;\{\nu_k\}_{k=1}^N) = \int \frac{d^dk}{i\pi^{d/2}} \frac{k^{\mu_1}\ldots k^{\mu_m}}{(k+q_1)^{2\nu_1}\cdots(k+q_N)^{2\nu_N}}$$

- Two steps:

  1. *Tensor reduction to scalar integrals* (Davydychev):

$$I^{\mu_1\cdots\mu_m}(d;\{\nu_k\}_{k=1}^N) = \sum c^{\mu_1\cdots\mu_m} I(d';\{\nu'_k\}_{k=1}^N)$$

     where $d+m \leq d' \leq d+2m$ and $\nu'_k \geq \nu_k$.

  2. *Integral recursion*: Reduce scalar integrals to a known basis set of "Master Integrals".

Result

$$A_{\mathrm{NLO}} \approx A_0 \int \frac{d\boldsymbol{Q}_\perp^2}{\boldsymbol{Q}_\perp^4} \left(-2\frac{\alpha_s(\boldsymbol{Q}_\perp^2)}{\pi} \mathcal{N} \int_0^{\boldsymbol{Q}_\perp^2} \frac{dk_\perp^2}{(k_\perp^2)^{1+\epsilon}} \int_0^{1-k_\perp/|\boldsymbol{Q}_\perp|} P_{qq}(z) dz \right.$$

$$+2\epsilon_G(Q^2) \ln\left(\frac{s}{\boldsymbol{Q}_\perp^2}\right)$$

$$\left. - \int_{\boldsymbol{Q}_\perp^2}^{m_H^2/4} \frac{dk_\perp^2}{k_\perp^2} \frac{\alpha_s(k_\perp^2)}{2\pi} \int_0^{1-k_\perp/m_H} dz \left[zP_{gg}(z) + \sum_q P_{qg}(z) \right] \right)$$

- Which should be compared with what we would expect expanding out the Durham Sudakov:

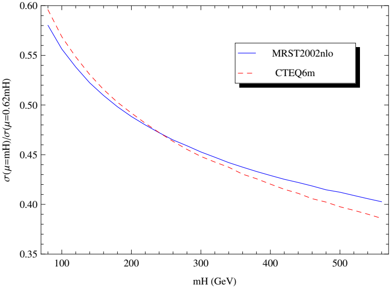
$$A_{\mathrm{NLO}} \approx A_0 \int \frac{d\boldsymbol{Q}_\perp^2}{\boldsymbol{Q}_\perp^4} \left(- \int_{\boldsymbol{Q}_\perp^2}^{m_H^2/4} \frac{dk_\perp^2}{k_\perp^2} \frac{\alpha_s(k_\perp^2)}{2\pi} \int_0^{1-\Delta} dz \left[zP_{gg}(z) + \sum_q P_{qg}(z) \right] \right)$$

with

$$\Delta = \frac{k_\perp}{k_\perp + \mu}\,, \qquad \mu = 0.62 m_H\,.$$

Implications

- New scale suppresses the amplitude relative to the original Durham predictions.
- The suppression increases with central system mass.
- To understand the size of the effect, consider the full (i.e. no cuts) central exclusive Higgs cross-section at the LHC (14 TeV).



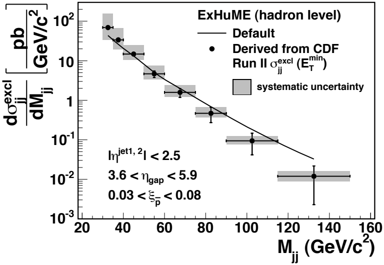
- Approximately a factor two difference.

Comments on predictions at the Tevatron

- Would be interesting to see the effect on predictions for observed processes at the Tevatron ($\gamma\gamma$, di-jets, χ_c).

- However, typical theoretical uncertainties (unintegrated pdfs, soft-survival factor, etc.) of a similar size, so unlikely to find disagreement.

- Di-jet production is especially interesting. The fit is worst at high mass - where the change in Sudakov factor has the largest effect. Could lead to a better shape.



Summary and outlook

- Have computed the subset of next-to-leading order corrections sensitive to the central exclusive production Sudakov factor.
- We find that the Durham result must be modified, by the replacement $\mu = 0.62\sqrt{\hat{s}} \to \sqrt{\hat{s}}$.
- Decreases the cross-section by a factor ~ 2 for $\sqrt{\hat{s}}$ in the range 80-560 GeV.
- May improve the shape of the di-jet invariant mass distribution at the Tevatron.
- Corrections computed so far form part of the full next-to-leading order corrections. Also required are:
  - Other partonic channels in addition to qq.
  - Emissions across the cut (so far only computed in the logarithmic approximation).