Gluon uPDF and K_T factorization: From the Higgs boson production at LHC to J/ψ production at EIC

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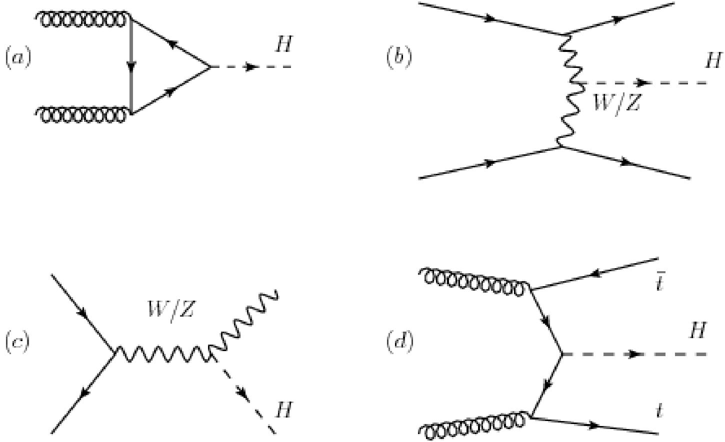
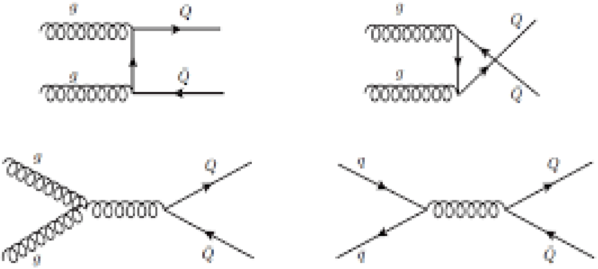
(REF 2022)

R. Islam, M. Kumar and **VR**, Eur. Phys. J. C **79**, no.3, 181 (2019)

Gluon distribution and the Higgs boson production

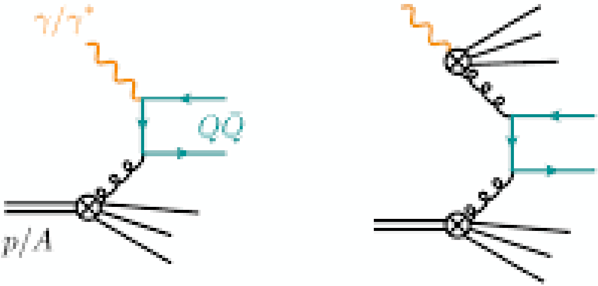


Hadron-hardon collision (Ex. LHC).



Gluon distributions and the J/ψ production

Electron-proton collision (Ex. EIC).



QCD factorization theorem

- Collinear factorization

$$\sigma(h_1 h_2 \to F) = f_{a/h_1}(x_1, Q^2) \otimes f_{b/h_2}(x_2, Q^2) \otimes \hat{\sigma}_{(ab\to F)}(Q^2) + \mathcal{O}(\Lambda/Q)$$

- Process dependent partonic cross section

$$\begin{array}{ccl} \hat{\sigma}(Q^2) & = & \hat{\sigma}^{(0)} + \alpha_s(Q^2)\hat{\sigma}^{(1)} + \alpha_s^2(Q^2)\hat{\sigma}^{(2)} + ... \\ & & LO \qquad NLO \qquad\qquad NNLO \end{array}$$

- Collinear approximation in parton model and evolution of parton densities discribed by Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) evolution equation.
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Heavy quark production

- Numerical predictions of comparison of two approaches for heavy quark production.
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HNNLO and HRes

- Parton level monte carlo event generators.
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- HNNLO: Parton level Monte Carlo program that computes the cross sections for Higgs production in pp and $p\bar{p}$ collisions up to NNLO in QCD perturbation theory.

- HRes: Fixed order cross sections for SM Higgs boson production up to NNLO by consistently including all-order resummation of soft-gluon effects at small transverse momenta up to NNLL $\Rightarrow NNLO + NNLL$

- $H \to \gamma\gamma, H \to ZZ \to l'\bar{l}'l\bar{l}, H \to WW \to l\nu l'\nu'$

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CASCADE

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- CASCADE2: Manual
- CASCADE1: Manual

CASCADE3
Hadron level Monte Carlo generator for ep and pp scattering applying Transverse Momentum Dependent (TMD) parton densities and parton shower.

The Monte Carlo program CASCADE generates a full hadron event record according to the HEP common standards.

CASCADE was originally intended for small x processes and used only gluon chains in the initial state cascade.

With the development of the Parton Branching TMDs, which are valid over a large range in x and Q2, new developments were possible in CASCADE3:

CASCADE3 (apart from the older features) makes use of LHE files (either from collinear NLO calculations like MC@NLO or off-shell calculations from KaTie/Pegasus) and has a full flavor initial state parton shower, which follows directly the TMD from the Parton Branching method.

Different sets of TMDs are now accessed via TMDlib.

Ref: S. Baranov, A. Bermudez Martinez, L. I. Estevez Banos, F. Guzman, F. Hautmann, H. Jung, A. Lelek, J. Lidrych, A. Lipatov and M. Malyshev, *et al.* "CASCADE3 A Monte Carlo event generator based on TMDs," Eur. Phys. J. C **81**, no.5, 425 (2021)

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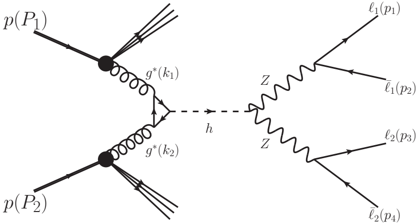

$$\sigma = \int dy_1 dy_2 dy_3 dy_4 d^2\boldsymbol{p}_{1T} d^2\boldsymbol{p}_{2T} d^2\boldsymbol{p}_{3T} d^2\boldsymbol{p}_{4T} \frac{d^2\boldsymbol{k}_{1T}}{\pi}\frac{d^2\boldsymbol{k}_{2T}}{\pi}\frac{1}{(2^{12})\pi^8(x_1x_2s)^2}|\bar{\mathcal{M}}$$

$$\delta^2(\boldsymbol{k}_{1T} + \boldsymbol{k}_{2T} - \boldsymbol{p}_{1T} - \boldsymbol{p}_{2T} - \boldsymbol{p}_{3T} - \boldsymbol{p}_{4T}) f_g(x_1, \boldsymbol{k}^2_{1T}) f_g(x_2, \boldsymbol{k}^2_{2T}$$

with

$$x_1 = \frac{|\boldsymbol{p}_{1T}|}{\sqrt{s}}e^{y_1} + \frac{|\boldsymbol{p}_{2T}|}{\sqrt{s}}e^{y_2} + \frac{|\boldsymbol{p}_{3T}|}{\sqrt{s}}e^{y_3} + \frac{|\boldsymbol{p}_{4T}|}{\sqrt{s}}e^{y_4}$$

and

$$x_2 = \frac{|\boldsymbol{p}_{1T}|}{\sqrt{s}}e^{-y_1} + \frac{|\boldsymbol{p}_{2T}|}{\sqrt{s}}e^{-y_2} + \frac{|\boldsymbol{p}_{3T}|}{\sqrt{s}}e^{-y_3} + \frac{|\boldsymbol{p}_{4T}|}{\sqrt{s}}e^{-y_4}$$

$pp \to H \to ZZ \to l_1\bar{l_2}l_2\bar{l_2}$

$$\frac{d\sigma}{dy_1 dy_2 dy_3 dy_4 d\boldsymbol{p}_{1T}^2 d\boldsymbol{p}_{2T}^2 d\boldsymbol{p}_{3T}^2} = \int d\boldsymbol{k}_{1T}^2 d\boldsymbol{k}_{2T}^2 \frac{d\phi_1}{2\pi} \frac{d\phi_2}{2\pi} \frac{1}{(2^{12})\pi^5 (x_1 x_2 s)^2} |\bar{\mathcal{M}}|^2 f_g(x_1, \boldsymbol{k}_{1T}^2) f_g(x_2, \boldsymbol{k}_{2T}^2)$$

$$\boldsymbol{k}_{1T} + \boldsymbol{k}_{2T} = \boldsymbol{p}_{1T} + \boldsymbol{p}_{2T} + \boldsymbol{p}_{3T} + \boldsymbol{p}_{4T}$$

$\mathcal{M}(g*g* \to H \to ZZ \to 4l)$

$$\mathcal{M}(g{*}g{*} \to H \to ZZ \to 4l) = \mathcal{M}(g{*}g{*} \to H)\frac{1}{\hat{s} - m_H^2 + i\Gamma_H m_H}\mathcal{M}(H \to ZZ \to l_1 \bar{l}$$

$$\begin{aligned} |\mathcal{M}|^2 \quad = \quad & \frac{2}{9}\frac{\alpha_s^2}{\pi^2}\frac{m_Z^4}{v^4}\frac{\left[(\boldsymbol{k}_{\perp 1} + \boldsymbol{k}_{\perp 2})^2 + \hat{s}\right]^2 \cos^2\phi}{(\hat{s} - m_H^2)^2 + \Gamma_H^2 m_H^2} \\ & \frac{[(p_1 \cdot p_4)(p_2 \cdot p_3)\{2g_L^2 g_R^2\} + (p_1 \cdot p_3)(p_2 \cdot p_4)\{g_L^4 + g_R^4\}]}{[(2p_1 \cdot p_2 - m_Z^2)^2 + \Gamma_Z^2 m_Z^2][(2p_3 \cdot p_4 - m_Z^2)^2 + \Gamma_Z^2 m_Z^2]} \end{aligned}$$

$$g_L = \frac{g_W}{\cos\theta_W}\left(-\frac{1}{2} + \sin^2\theta_W\right), \quad g_R = \frac{g_W}{\cos\theta_W}\sin^2\theta_W, \quad \text{and} \quad v = (\sqrt{2}G_F)^{-1/2}$$

ATLAS data for $pp \to H \to 4\,leptons$ and k_T factorization approach

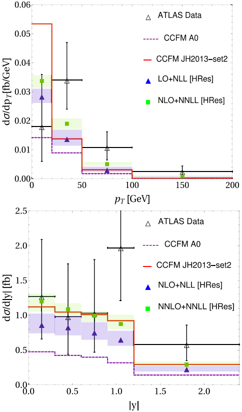

Figure: ATLAS, $\sqrt{s} = 8$ TeV

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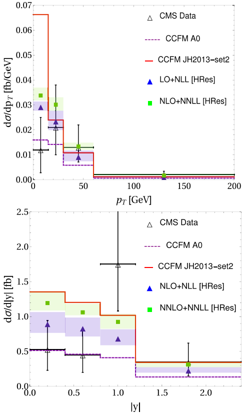

Figure: CMS, $\sqrt{s} = 8$ TeV

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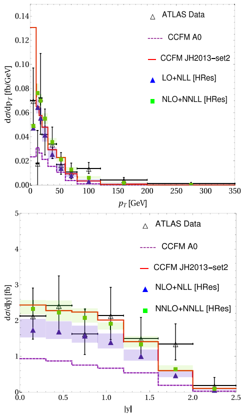

Figure: CMS, $\sqrt{s} = 13$ TeV

Models for J/ψ Production

- Color Singlet Model (CSM).
- Color Evaporation Model (CEM).
- NRQCD factorization approach.
- Improved Color Evaporation Model (ICEM).

Color Singlet Model (CSM)

- Proposed shortly after the discovery of the J/ψ. [*Einhorn and Ellis (1975)*]
- $Q\bar{Q}$ pair is formed in the short-distance process in color-singlet state and has the same spin and angular momentum quantum numbers as the quarkonium.
- Color singlet $Q\bar{Q}$ wave function at origin.

$$A(P) = \frac{1}{\sqrt{4\pi}} R_0 Tr[O(P,0) P_{ss_z}(P,0)]$$

R_0 is the radial function at the origin.

- Recent studies shows the NLO and NNLO corrections to CSM improves the fits at TEVATRON and RHIC.
J.P. Lansberg, Eur. Phys. J. C 61, 693 (2009), Phys. Lett. B 695, 149 (2010).

Color Evaporation Model (CEM) *H. Fritzsch (1977)*

- A theory which is known to satisfy all-order factorization is the color evaporation model (CEM)
- Initially introduced in 1977 and was revived in 1996 by Halzen.
- The cross-section for a quarkonium state H is some fraction F_H of the cross-section for producing $Q\bar{Q}$ pair with invariant mass below the $M\bar{M}$ threshold

$$\sigma_{CEM}[h_A h_B \to H + X] = F_H \sum_{i,j} \int_{4m^2}^{4m_M^2} d\hat{s} \int dx_1 dx_2 f_i(x_1,\mu) f_j(x_2,\mu) \times \hat{\sigma}_{ij}(\hat{s}) \delta(\hat{s} - x_1 x_2 s)$$

- M is the lowest mass meson containing the heavy quark Q.
- $Q\bar{Q}$ pair is assumed to neutralize its color by interaction.
- Good description of photoproduction data after inclusion of higher order QCD corrections.
  Eboli etal, arXiv: hep-ph/0211161 (2002).
- k_T smearing in CEM improves the hadroproduction CDF data.
  Bodwin etal. arXiv:hep-ph/0504014 (2005).

NRQCD Factorization approach.

Bodwin, Braaten and Lepage (1995)

- It is the effective theory based on a systematic expansion in both α_s and v, which is heavy quark velocity within the bound state.

$$\sigma[H] = \sum_n \sigma_n(\Lambda)\langle \mathcal{O}_n^H(\Lambda)\rangle$$

- σ_n are short-distance coefficients and perturbatively calculable..
- $\langle \mathcal{O}_n^H(\Lambda)\rangle$ are long distance matrix elements that are formulated in terms of the effective field theory NRQCD.

- The NRQCD factorization approach to heavy-quarkonium production is by far the most sound theoretically and most successful phenomenologically.

  Butenschon and Kniehl, Phys. Rev. Lett. **106**, *022003 (2011)*

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J/ψ production and Improved Color Evaporation Model

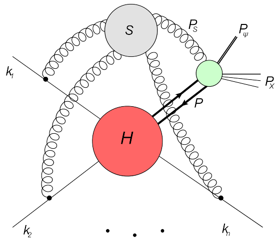
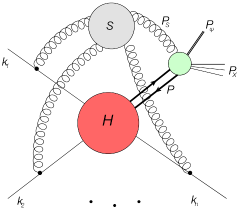


Figure: Charmonium production in High Energy production

Ref': Y. Q. Ma and R. Vogt, Phys. Rev. D **94**, no.11, 114029 (2016)

J/ψ production and Improved Color Evaporation Model



$$P = P_\psi + P_S + P_X$$
$$M_\psi < M - M_X < M$$
$$\langle P_\psi \rangle = \frac{M_\psi}{M} P + O(\lambda^2/m_c)$$

J/ψ production and Improved Color Evaporation Model

$$
\begin{aligned}
\frac{d\sigma_\psi(P)}{d^3P} &= F_\psi \int_{M_\psi}^{2M_D} d^3P' dM \frac{d\sigma_{c\bar{c}}(M,P')}{dM d^3P'} \delta^3(P - \frac{M_\psi}{M} P') \\
&= F_\psi \int_{M_\psi}^{2M_D} dM \frac{d\sigma_{c\bar{c}}(M, P' = (M/M_\psi)P)}{dM d^3P},
\end{aligned}
$$

How to take in to account the momentum conservation in kinematics?

J/ψ production and Improved Color Evaporation Model

$$\frac{d\sigma_\psi}{dy\,d^2p_{T\psi}} = \frac{F_\psi}{s}\int_{M_\psi^2}^{4{M_D}^2} dM^2\,\frac{M_\psi}{M}\int d^2\mathbf{k}_{\perp g} f_{g/p}(x_g,\mathbf{k}_{\perp g}) f_{\gamma/p}(x_\gamma, \frac{M}{M_\psi}[\mathbf{p}_T - \mathbf{k}_{\perp g}$$

- Mass dependence appearing in the PDFs.
- Including off-shell matrix element along with the CCFM evolved PDFs we will have a differential cross-section
- J/ψ production using ICEM will be studied in the context of Electron Ion collider
- The result will have potential to understand unintegrated PDFs using kT factorization approach.
- Comparison of the differential cross section with the results obtained from CASCADE will be cruicial.
- Implementing heavy quarkonium production model in CASCADE is important.

Conclusion

- The Higgs boson production and J/ψ production provide an excellent opportunity to test the k_T factorization together with uPDFs based on CCFM evolution.
- Out results are compared with experimental results from from ATLAS and CMS.
- EIC will provide an opportunity to test it at small x for J/ψ production.

Thank You for your attention.