Calculations with off-shell matrix elements, TMD parton densities and TMD parton showers

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Based on arXiv:1712.05932 (MB, A. van Hameren, H. Jung, K. Kutak, S. Sapeta and M. Serino)

Outline

- Introduction
- High Energy Factorization
- KaTie: parton-level event generator
- TMD densities: Kimber-Martin-Ryskin-Watt procedure
- CASCADE: parton showers
- Example: predictions for high p_t dijets
- Conclusions and outlook

Introduction

- Theoretical predictions for strong interactions have often larger uncertainties than experimental ones
- Loop calculations in HEF too demanding so far (work in progress by A. van Hameren)
- Parton showers are used to simulate higher order corrections
- Collinear IPS changes the kinematics of the hard process by changing transverse momentum
- TMD parton distributions allows us to keep the exact kinematics of the initial state

High Energy Factorization (k_T-factorization)

Catani, Ciafaloni, Hautmann Collins, Ellis

$$\sigma_{AB\to q\bar{q}} = \int d^2k_{T\,A}\frac{dx_A}{x_A}\mathcal{F}\left(x_A, k_{T\,A}\right)\, d^2k_{T\,B}\frac{dx_B}{x_B}\,\mathcal{F}\left(x_B, k_{T\,B}\right)\,\hat{\sigma}_{g^*g^*}\left(\frac{m^2}{x_Ax_Bs}, \frac{k_{T\,A}}{m}, \frac{k_{T\,B}}{m}\right)$$

- reduces to collinear factorization for $s \gg m^2 \gg k_T^2$, but holds also for $s \gg m^2 \sim k_T^2$
- allows for higher-order kinematical effects at leading order

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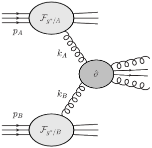
- allows for higher-order kinematical effects at leading order
- requires matrix elements with *off-shell* initial-state partons with $k_i^2 = k_{iT}^2 < 0$



$$k_A^\mu = x_Ap_A^\mu + k_{T\,A}^\mu$$
$$k_B^\mu = x_Bp_B^\mu + k_{T\,B}^\mu$$

- k_T-dependent $\mathcal{F}$ may satisfy BFKL, CCFM, BK, KGBJS evolution equations
- typically associated with small-x and forward physics, saturation, heavy-ions

KaTie: parton-level event generator

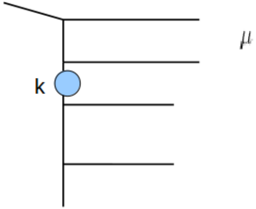
KaTie (A. van Hameren) arXiv:1611.00680

- Complete Monte Carlo program for tree-level calculations
- Any process within the Standard Model
- On-shell and/or off-shell initial-state partons
- Employs numerical Dyson-Schwinger recursion to calculate helicity amplitudes
- Automatic phase space optimization
- Produces weighted parton-level event files in the Les Houches format
- Single- and multi-parton scattering

Survival probability without emissions

$$T_s(\mu^2, k^2) = exp\Big(- \int_{\mu^2}^{k^2} \frac{dk'^2}{k'^2} \frac{\alpha_s(k'^2)}{2\pi} \times \sum_{a'} \int_0^{1-\Delta} dz' P_{aa'}(z') \Big)$$

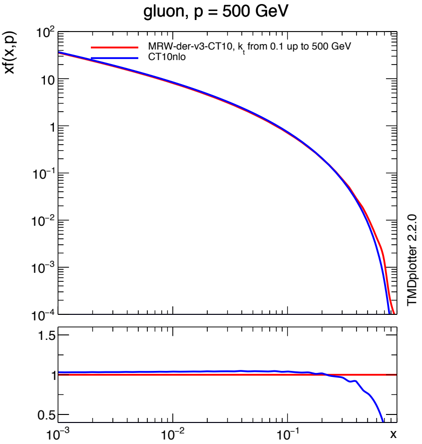
$$\mathcal{F}(x, k^2, \mu^2) \sim \partial_{\lambda^2} \left(T_s(\lambda^2, \mu^2)\, x\, g(x, \lambda^2) \right) \Big|_{\lambda^2 = k^2}$$



$$\Delta = \frac{\mu}{\mu + k}$$

$$\mu = \text{hard scale}$$

TMD densities: Kimber-Martin-Ryskin-Watt procedure



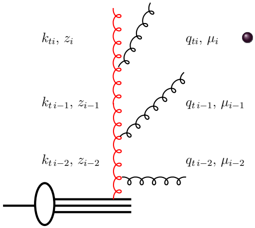
Integrating the updf we get back collinear PDF

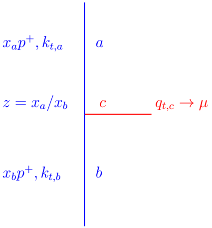
$$\int_0^{\mu^2} \mathrm{d}k_t^2 \, \mathcal{F}_a(x, k_t^2, \mu^2) = x f(x, \mu^2)$$

CASCADE

CASCADE (H. Jung) Comput.Phys.Commun. 143 (2002) 100

- k_t-factorization based Monte Carlo program doing ISR and FSR
- Backward evolution of the initial state
- New features
  - full TMD evolution of all flavour PS
  - interface to LHE files, for input from KaTie and POWHEG
- Hadronization performed via Pythia 6
- Analysis is done with Rivet package
- Jets reconstructed via the anti-k_t algorithm with FastJet



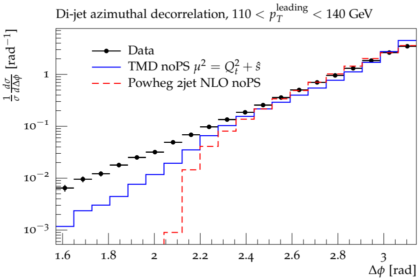


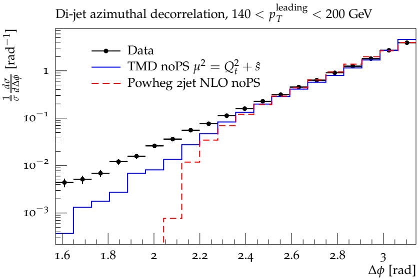
- Starting with the hard scale μ_i, the parton shower algorithm searches for the next scale μ_{i-1}, at which a resolvable branching occurs, which is selected from the Sudakov form factor

$$\Delta_S(x,\mu_i,\mu_{i-1})=\exp\left[-\int_{\mu_{i-1}}^{\mu_i}\frac{d\mu'}{\mu'}\frac{\alpha_S(\tilde{\mu}')}{2\pi}\sum_a\int dz P_{a\to bc}(z)\frac{x'\mathcal{A}_a(x',k_t',\mu')}{x\mathcal{A}_b(x,k_t,\mu')}\right]$$

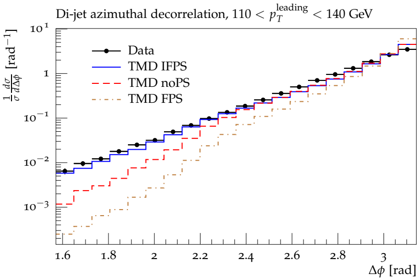
- The transverse momentum can be obtained by giving a physical interpretation to the evolution scale, which is associated with the angle of the emission
- Once the transverse momentum of the emitted parton is known, the k_t of the propagating parton can be calculated
- The whole procedure continues until cutoff (lowest scale) is reached

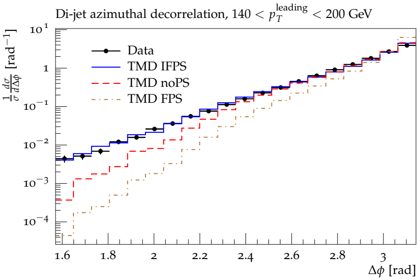
Azimuthal angle correlations - no shower





Azimuthal angle correlations - showers





Conclusions and outlook

Conclusions

- A framework for evaluation of cross section in HEF supplemented with initial- and final-state parton showers
- Full set of TMD parton densities using the KMRW approach
- TMD parton shower including all flavours and following the TMD distribution, without the need for adjusting further parameters

Outlook

- More comparisons to data for $p+p$ and $p+A$ using KaTie + CASCADE
- Refinement of used TMDs i.e. fits to latest data
- Corrections of higher orders to ME