Quarkonium Physics in CASCADE

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PLAN OF THE TALK

1. Preface on k_t-factorization
2. Theoretical framework
3. Numerical results
4. Conclusions

1. PREFACE ON k_t-FACTORIZATION

CASCADE is a Monte-Carlo generator using the CCFM equation for the evolution of parton densities (in the backward evolution scheme). On the technical side, similar to other generators.

Point of importance: using the k_t-, not the collinear factorization.

In the collinear scheme, the evolution is only used to calculate the parton densities and has no effect on the hard interaction subprocess.

In the k_t-factorization, the parton evolution changes the character of the hard interaction: both the kinematics (due to the initial parton transverse momentum) and polarization properties (longitudinal component for the off-shell gluons).

The evolution cascade is part of the hard interaction. By means of the evolution equation we resum a subset of Feynman diagrams (up to infinitely high order) representing higher-order contributions: i.e., the ladder diagrams enhanced with $\alpha_s^n[\ln(1/x)]^n$.

THE BENEFIT:

With the LO matrix elements for the hard subprocess we get access to effects requiring complicated next-to-leading order calculations in the collinear scheme. Many important results have been obtained in the k_t-factorization much earlier than in the collinear case.

Upon including more NLO, NNLO,.. corrections, the collinear results become closer to the k_t-factorization predictions.

EXAMPLES:

– Azimuthal correlations in open Heavy Flavor production;

– p_t dependence of the J/ψ and Υ cross sections $(1/p_t^8$ versus $1/p_t^4)$

– J/ψ and Υ spin alignement (transverse versus longitudinal)

Now concentrate on the Quarkonium physics, see below

2. THEORETICAL FRAMEWORK

2.1 Color-Singlet Gluon-Gluon Fusion

Perturbative production of a heavy quark pair within QCD;
Gluon polarization vectors: $\epsilon_g^\mu = k_T^\mu/|k_T|$

E.A. Kuraev, L.N. Lipatov, V.S. Fadin, Sov. Phys. JETP 45, 199 (1977);
Ya. Balitsky, L.N. Lipatov, Sov. J. Nucl. Phys. 28, 822 (1978);
L.V. Gribov, E.M. Levin, M. G. Ryskin, Phys. Rep. 100, 1 (1983).

Spin projection operators to guarantee the proper quantum numbers:

for Spin-triplet states $\mathcal{P}(^3S_1) = \not\epsilon_V(\not p_Q + m_Q)/(2m_Q)$

for Spin-singlet states $\mathcal{P}(^1S_0) = \gamma_5(\not p_Q + m_Q)/(2m_Q)$

Probability to form a bound state is determined by the wave function:

for S-wave states $|R_S(0)|^2$ is known from leptonic decay widths;

for P-wave states $|R'_P(0)|^2$ is taken from potential models.

E. J. Eichten, C. Quigg, Phys. Rev. D 52, 1726 (1995)

If $L \neq 0$ and $S \neq 0$ we use the Clebsch-Gordan coefficients to reexpress the $|L, S\rangle$ states in terms of $|J, J_z\rangle$ states, namely, the χ_0, χ_1, χ_2 mesons.

2.2 ACCESSING THE POLARIZATION OF VECTOR MESONS

Polarization is measured via the angular distributions of the decay products. The most general form for $V \to \mu^+\mu^-$:

$$\frac{d\sigma}{d\cos\theta\, d\phi} \propto 1 + \lambda\cos^2\theta + \mu\sin 2\theta\ \cos\phi + \frac{\nu}{2}\sin^2\theta\ \cos 2\phi$$

Four conventional frame definitions:

- **Recoil** $\vec{z} = -\vec{p}_1 - \vec{p}_2$
- **Gottfried-Jackson** $\vec{z} = \vec{p}_1$
- **Target** $\vec{z} = -\vec{p}_2$
- **Collins-Soper** $\vec{z} = \vec{p}_1/|p_1| - \vec{p}_2/|p_2|$

and always $\vec{y} = [\vec{p}_1 \times \vec{p}_2]$, $\vec{x} = [\vec{y} \times \vec{z}]$

Vector meson $(V = J/\psi,\ \psi',\ \Upsilon,\ \Upsilon',\ \Upsilon'')$ **spin density matrix:**

$$\epsilon_V^\mu \epsilon_V^{*\nu} = 3(l_1^\mu l_2^\nu + l_2^\mu l_1^\nu - m_V^2 g^{\mu\nu}/2)/m_V^2$$

Equivalent to $-g^{\mu\nu} + p_V^\mu p_V^\nu/m_V^2$ **but gives access to the decay variables. Mode d'emloi: generate MC events including decays and apply a three-parametric fit.**

2.3 FEED-DOWN FROM P-WAVE STATES

Assuming the dominance of electric dipole transitions, we have:

Angular distributions in the polarized χ_J decays

$$d\Gamma(\chi_1 \to V\gamma)/d\cos\theta \propto \left[\left(1+\tfrac{1}{2}\rho\right)+\left(1-\tfrac{3}{2}\rho\right)\cos^2\theta\right]$$
$$d\Gamma(\chi_2 \to V\gamma)/d\cos\theta \propto \left[\left(\tfrac{5}{6}-\tfrac{1}{12}\xi-\tfrac{1}{3}\tau\right)-\left(\tfrac{1}{2}-\tfrac{1}{4}\xi-\tau\right)\cos^2\theta\right]$$

where $\rho = d\sigma_{\chi_1(|h|=1)}/d\sigma_{\chi_1}, \quad \xi = d\sigma_{\chi_2(|h|=1)}/d\sigma_{\chi_2}, \quad \tau = d\sigma_{\chi_2(|h|=2)}/d\sigma_{\chi_2}$
(all known from the χ_J production matrix elements)

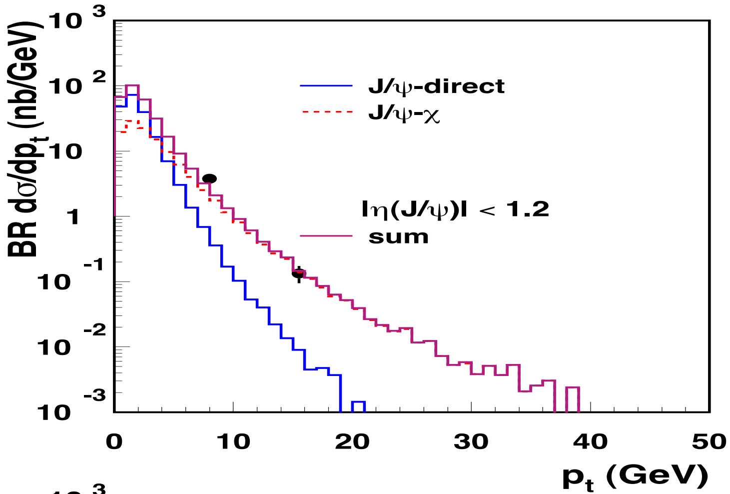
Polarization of the decay products

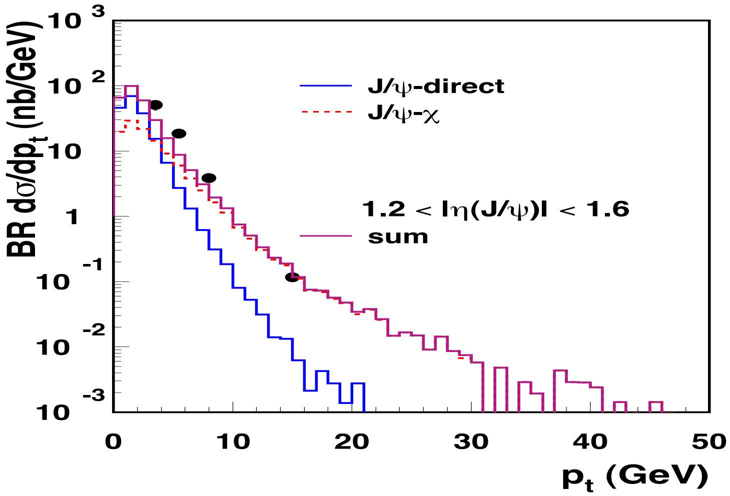
$$\begin{aligned}
\sigma_{V(h=0)} &= B(\chi_1 \to V\gamma)\left[(1/2)\,\sigma_{\chi_1(|h|=1)}\right] \\
&+ B(\chi_2 \to V\gamma)\left[(2/3)\,\sigma_{\chi_2(h=0)}+(1/2)\,\sigma_{\chi_2(|h|=1)}\right] \\
\sigma_{V(|h|=1)} &= B(\chi_1 \to V\gamma)\left[\sigma_{\chi_1(h=0)}+(1/2)\,\sigma_{\chi_1(|h|=1)}\right] \\
&+ B(\chi_2 \to V\gamma)\left[(1/3)\,\sigma_{\chi_2(h=0)}+(1/2)\,\sigma_{\chi_2(|h|=1)}+\sigma_{\chi_2(|h|=2)}\right].
\end{aligned}$$

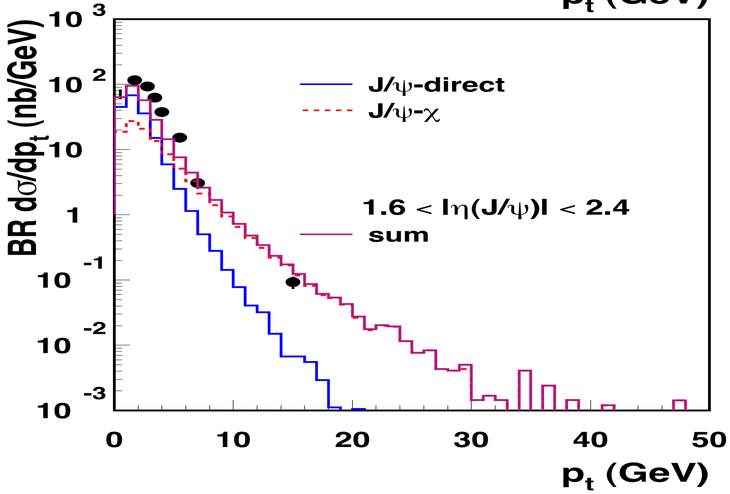
P.Cho, M.Wise, S.Trivedi, Phys. Rev. D 51, R2039 (1995)

3. NUMERICAL RESULTS

COMPARISON WITH LHC DATA ON THE J/ψ PRODUCTION



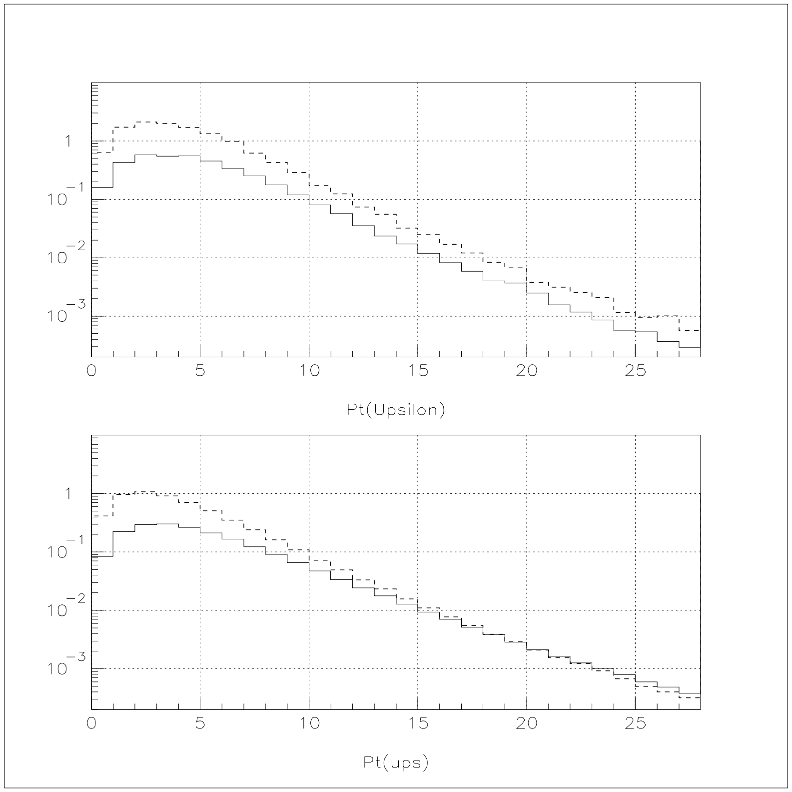




A0 gluon distribution

$\alpha_s(k_{t1}^2)\ \alpha_s(k_{t2}^2)$

More on theoretical uncertainties

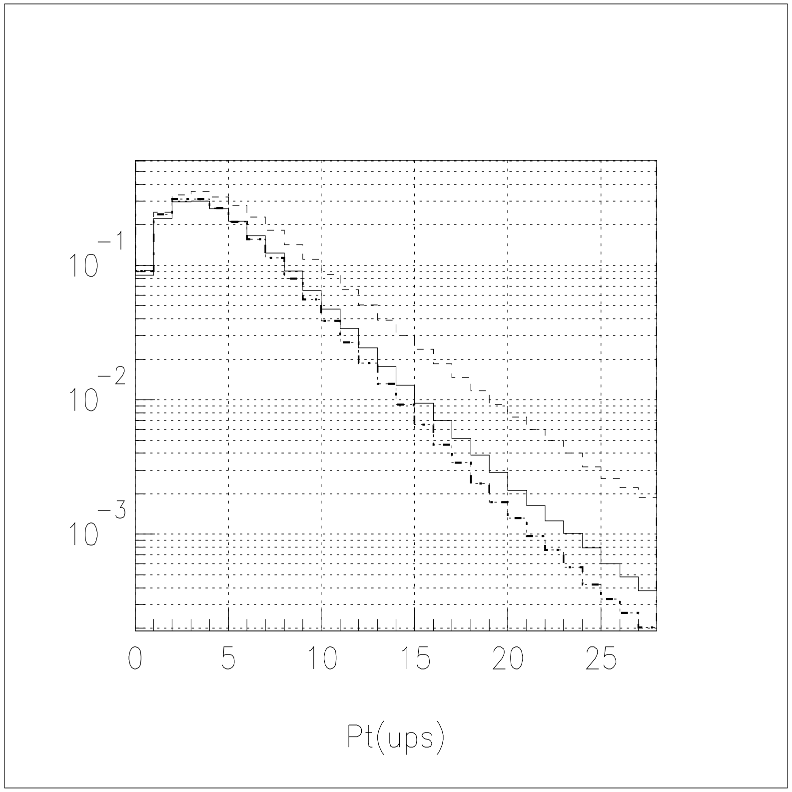


Effect of the scale in the $\alpha_s(\mu^2)$:

Upper (dashed) lines – $\mu^2 = k_t^2$;

lower (solid) lines – $\mu^2 = p_t^2{+}m^2$

Upper panel – Υ, lower panel – χ_b



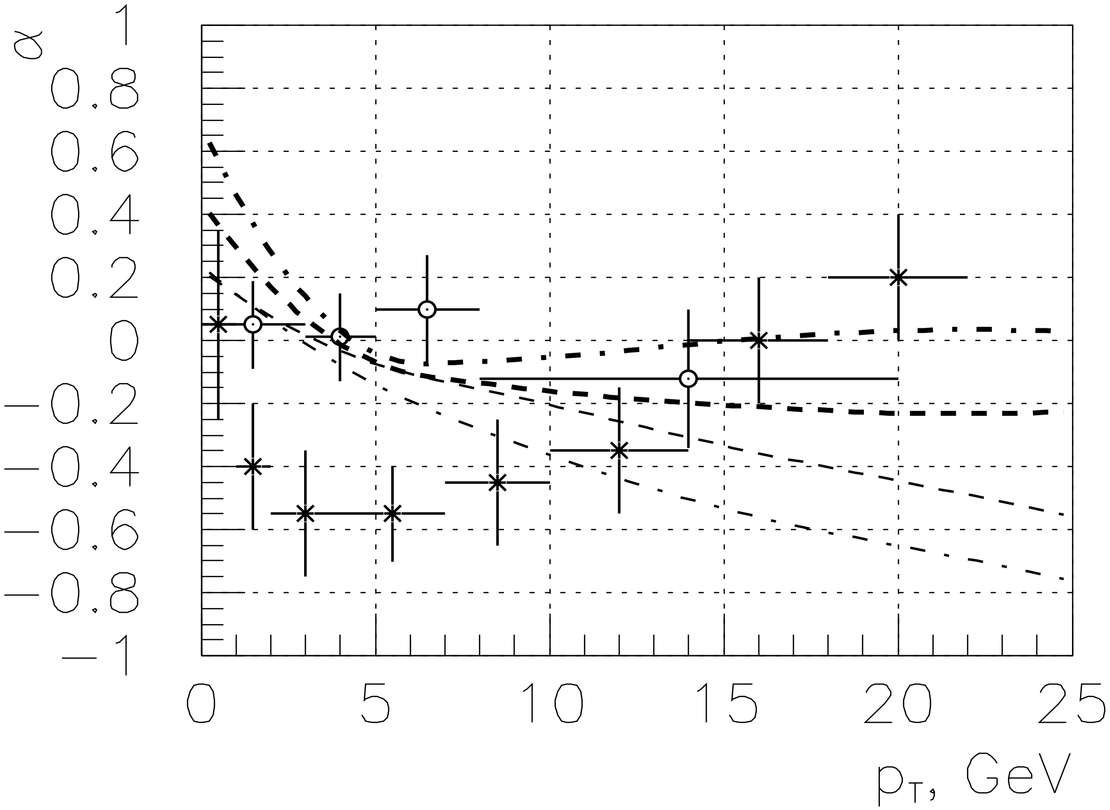
Effect of the flux definition:

Solid lines – $1/\lambda^{1/2}(\hat{s}, k_{t1}^2, k_{t2}^2)$

dashed lines – $1/\hat{s}$

thick dash-dotted – $1/(p_t^2{+}m^2)$

$\Upsilon(1S)$ SPIN ALIGNEMENT AT THE TEVATRON



Dash-dotted lines – JB gluons; dashed – dGRV gluons;

Thin lines – direct Υ only; thick lines – with χ_b decays added.

○ D.Acosta et al.(CDF), Phys. Rev. Lett. **88**, 161802 (2002);

× V.M.Abazov et al.(DO), Phys. Rev. Lett. **101**, 182004 (2008)

4. CONCLUSIONS

For the Quarkonium Physics tasks CASCADE is equipped with:

– **Off-shell** $g^* + g^* \to V + g$ **matrix elements**
  for $V = J/\psi,\ \ \psi(2S),\ \ \Upsilon(1S),\ \ \Upsilon(2S),\ \ \Upsilon(3S)$

– **Full spin density matrix for leptonic decays** $V \to l^+ + l^-$

– **Off-shell** $g^* + g^* \to \chi_J$ **matrix elements**
  for $\chi_J = \chi_{cJ}(1S),\ \ \chi_{bJ}(1S),\ \ \chi_{bJ}(2S)$ **with** $J = 0, 1, 2$

– **Full information on the** χ_J **spin alignement parameters**
  to generate the decays $\chi_J \to V + \gamma$ **followed by** $V \to l^+ + l^-$

All is ready for use

You are welcome!