Polarization observables in $\chi_{cJ} \to J/\psi + \mu^+\mu^-$ Dalitz decays

Sergey Baranov
P.N.Lebedev Institute of Physics, Moscow

P L A N O F T H E T A L K

– **Motivation**
– **First acquaintance with k_t-factorization**
– **Implementing the Quarkonium physics**
– **Numerical results**
– **Conclusions**

MOTIVATION

– Important observables specifically sensitive to the production mechanism
– Less affected by theoretical uncertainties coming from the choice of quark masses, parton densities, renormalization/factorization scales, wave functions.

Three sets of observables

– χ_{cJ} are polarized, seen in decays $\longrightarrow J/\psi + \gamma^*$;
– J/ψ is polarized, seen in decays $\longrightarrow \mu^+\mu^-$;
– γ^* is polarized, seen in decays $\longrightarrow \mu^+\mu^-$;

Competing theoretical approaches

Color-Singlet versus Color-Octet model; both may be extended to NLO or tree-level NNLO*; both may be incorporated with collinear or k_T-factorization. This talk is devoted to k_T-factorization.

– Deep theory: a method to calculate high-order contributions
(ladder-type diagrams enhanced with "large logarithms").

– Practice: making use of so called k_T-dependent parton densities.
(Unusual properties: nonzero k_T and longitudinal polarization.)

First acquaintance with k_T-factorization

PARTON OFF-SHELLNESS AND NONZERO k_T

QED

Weizsäcker-Williams approximation
(collinear on-shell photons)

$$F_\gamma(x) = \frac{\alpha}{2\pi}\,[1 + (1 - x^2)]\,\log\frac{s}{4m^2}$$

Equivalent Photon approximation

$$F_\gamma(x, Q^2) = \frac{\alpha}{2\pi}\frac{1}{Q^2}\,[1 + (1 - x^2)]$$

$$Q^2 \approx k_t^2/(1 - x)$$

Photon spin density matrix

$$L^{\mu\nu} \approx p^\mu p^\nu$$

use $k = xp + k_t$, then do gauge shift
$\epsilon \longrightarrow \epsilon - k/x$

QCD

Conventional Parton Model
(collinear gluon density)

$$x\,G(x, \mu^2)$$

Unintegrated gluon density

$$\mathcal{F}(x, k_t^2, \mu^2)$$

$$\int \mathcal{F}(x, k_t^2, \mu^2)dk_t^2 = x\,G(x, \mu^2)$$

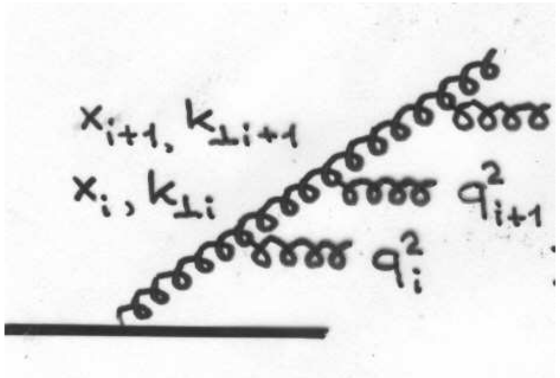
Gluon spin density matrix

$$\epsilon^\mu\epsilon^{\nu *} = k_t^\mu k_t^\nu/|k_T|^2$$

so called nonsense polarization
with longitudinal components

Looks like Equivalent Photon Approximation extended to strong interactions.

The underlying theory: Initial State Radiation cascade



Every elementary emission gives $\alpha_s \cdot 1/x \cdot 1/q^2$
x = *longitudinal momentum fraction*
q^2 = *gluon virtuality*

Integration over the phase space yields
$\alpha_s \cdot \ln x \cdot \ln q^2$ *so called large logarithms, the reason to focus on this type of diagrams*

Random walk in the k_T-plane: $\ldots\ \langle k_{T\,i-1}\rangle \ll \langle k_{T\,i}\rangle \ll \langle k_{T\,i+1}\rangle\ \ldots$
$\ldots\ \langle x_{i-1}\rangle > \langle x_i\rangle > \langle x_{i+1}\rangle\ \ldots$

Technical method of summation: integro-differential QCD equations
BFKL
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);
or CCFM
S.Catani, F.Fiorani, G.Marchesini, Phys.Lett.B **234**, 339 (1990); Nucl.Phys. **B336**, 18 (1990);
G.Marchesini, Nucl.Phys. **B445**, 49 (1995); M.Ciafaloni, Nucl.Phys. **B296**, 49 (1998);

CCFM is more convenient for programming because of strict angular ordering $\ldots\theta_{i-1} < \theta_{i-1} < \theta_{i+1}\ldots \Rightarrow$ A step-by-step solution.

k_t-factorization is:

A method to collect contributions of the type $\alpha_s^n[\ln(1/x)]^n[\ln(Q^2)]^n$ up to infinetly high order. Sometimes it may be better than conventional calculations to a fixed order. (None of the methods is complete.)

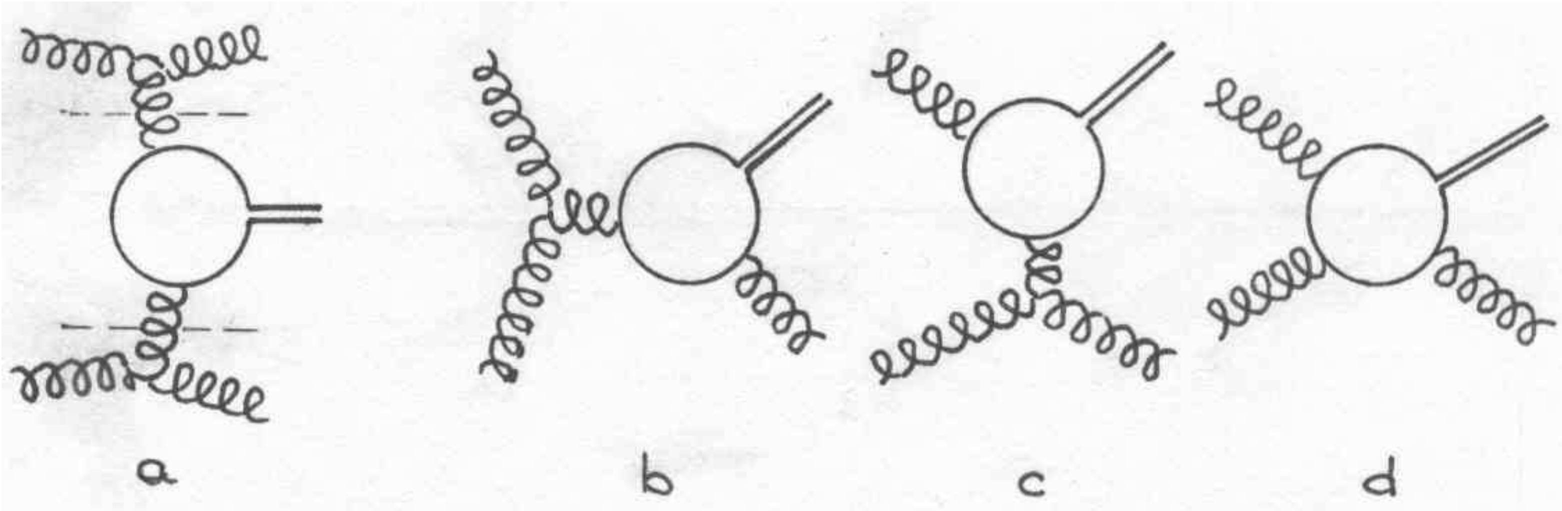
The evolution cascade is part of the hard interaction process; it affects both the kinematics (initial k_T) and the polarization (off-shell spin density matrix). The corrections always have the same (ladder) structure, irrespective of the 'central' part of hard interaction, and can be conveniently absorbed into redefined parton densities $\Rightarrow$ k_T-dependent = "unintegrated" distribution functions $\mathcal{F}(x, k_t^2, \mu^2)$

Advantages:

With the LO matrix elements for 'central' 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 approach much earlier than in the collinear case.

Includes effects of soft resummation and makes predictions applicable even to small p_t region.

Implementing the Quarkonium states



(a) k_t-factorization; the central part is for partonic subprocess $g + g \to \chi_{cJ}$, the upper and the lower parts represent parton evolution.
(b)-(d) leading order collinear contributions from $g + g \to \chi_{cJ} + g$.

Note the different understanding of what the true Leading Order is !

Gluon densities used in calculations:

k_t-factorization: A0 set H.Jung, http://www.desy.de/~jung/cascade/updf.html

Collinear: MSTW'08 A.D.Martin, W.J.Stirling, R.S.Thorne, G.Watt, Eur.Phys.J. C **63**, 189 (2009)

Color-Singlet mechanism

Fortunately, the production of χ_{cJ} mesons is totally dominated by color singlets. True for collinear A.K.Likhoded, A.V.Luchinsky, S.V.Poslavsky, Phys.Rev.D **90**, 074021 (2014) and k_t-factorization S.P.Baranov, A.V.Lipatov, N.P.Zotov, Phys.Rev.D **93**, 094012 (2016).

Use perturbative QCD Feynman rules and nonrelativistic bound state formalism. Gluon polarization vectors are $e^{\mu} = k_t^{\mu}/|k_t|$. Fit both collinear and k_t cases.

The production amplitudes contain projection operators for spin $\mathbf{S}$

$$\mathcal{P}(S{=}1, L{=}1) = (\tfrac{1}{2}\not{p}_{\chi} - \not{q} - m_c)\, \not{\epsilon}_S\, (\tfrac{1}{2}\not{p}_{\chi} + \not{q} + m_c)/(2m_c)^{3/2}$$

and orbital momentum $\mathbf{L}$

$$\mathcal{M}(q) = \mathcal{M}|_{q=0} + q^{\alpha}(\partial\mathcal{M}/\partial q^{\alpha})|_{q=0} + \ldots$$

$$\int \frac{d^3q}{(2\pi)^3}\, q^{\alpha}\Psi(q) = -i\epsilon_L^{\alpha}\frac{\sqrt{3}}{\sqrt{4\pi}}R'(x{=}0)$$

with q the relative momentum of quarks in a bound state, and ϵ_S and ϵ_L the polarization vectors associated with spin and orbital angular momentum.

Using the Clebsch-Gordan coefficients we reexpress the $|L,S\rangle$ states in terms of $|J,J_z\rangle$ states, namely, the physical χ_0,χ_1,χ_2 mesons with their helicities.

The probability to form a meson is determined by the derivative of the wave function:
We take $|R'(0)|^2 = 0.075$ GeV^5 E.J.Eichten, C.Quigg, Phys.Rev.D **52**, 1726 (1995)
(Buchmüller-Tye potential model)

Electric Dipole transitions for radiative decays

$$\mathcal{A}\,(\chi_{c0}(p) \to J/\psi(p-k) + \gamma(k)) \;\propto k_\mu p^\mu \varepsilon^\nu_{(J/\psi)}\varepsilon^{(\gamma)}_\nu$$

$$\mathcal{A}\,(\chi_{c1}(p) \to J/\psi(p-k) + \gamma(k)) \;\propto \epsilon^{\mu\nu\alpha\beta}\, k_\mu\, \varepsilon^{(\chi_{c1})}_\nu\, \varepsilon^{(J/\psi)}_\alpha\, \varepsilon^{(\gamma)}_\beta$$

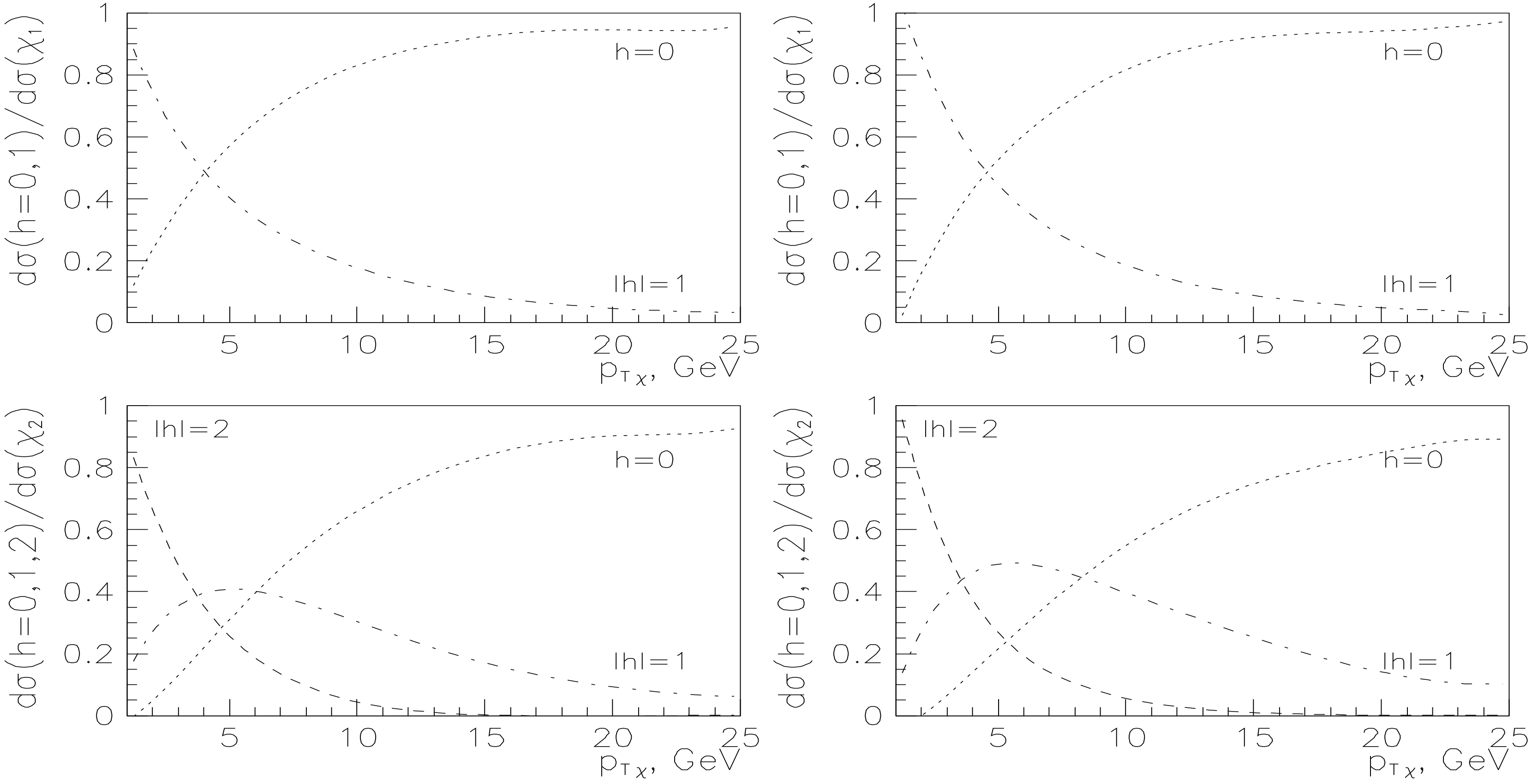
$$\mathcal{A}\,(\chi_{c2}(p) \to J/\psi(p-k) + \gamma(k)) \;\propto p^\mu\, \varepsilon^{\alpha\beta}_{(\chi_{c2})}\, \varepsilon^{(J/\psi)}_\alpha\, [k_\mu\, \varepsilon^{(\gamma)}_\beta - k_\beta\, \varepsilon^{(\gamma)}_\mu]$$

A.V.Batunin, S.R.Slabospitsky, Phys.Lett.B **188**, 269 (1987)
P.Cho, M.Wise, S.Trivedi, Phys.Rev.D **51**, R2039 (1995)

The polarization of every particle is then unambiguously calculable.

Predictions for χ_{cJ} helicity fractions

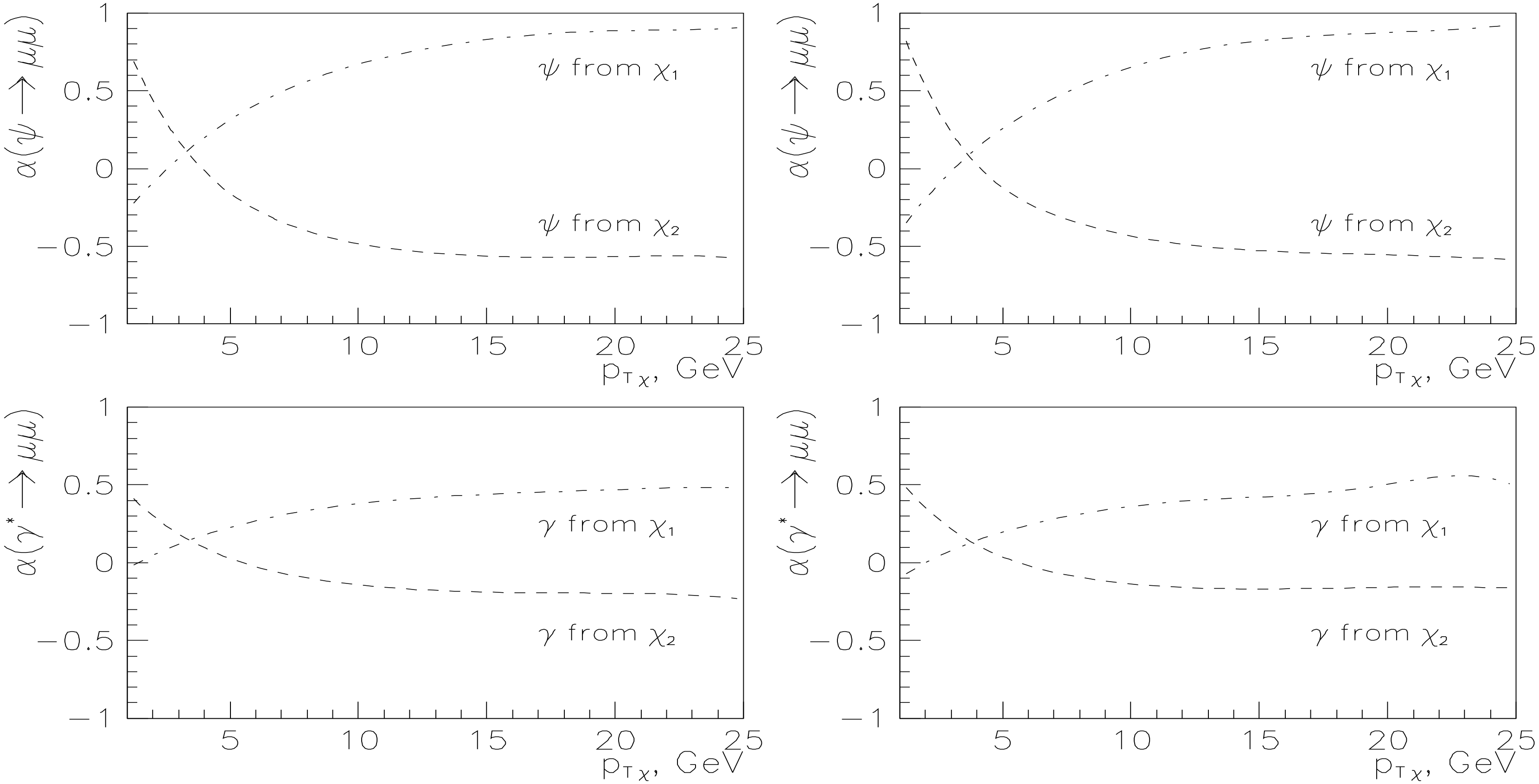
k_t-factorization collinear factorization



$$\chi_{c1}\Big(|h|{=}1 : h{=}0\Big) \approx O(1) : O(\tfrac{E}{m}) \quad \chi_{c2}\Big(|h|{=}2 : |h|{=}1 : h{=}0\Big) \approx O(1) : O(\tfrac{E}{m}) : O(\tfrac{E^2}{m^2})$$

Predictions for J/ψ and γ^* polarizations

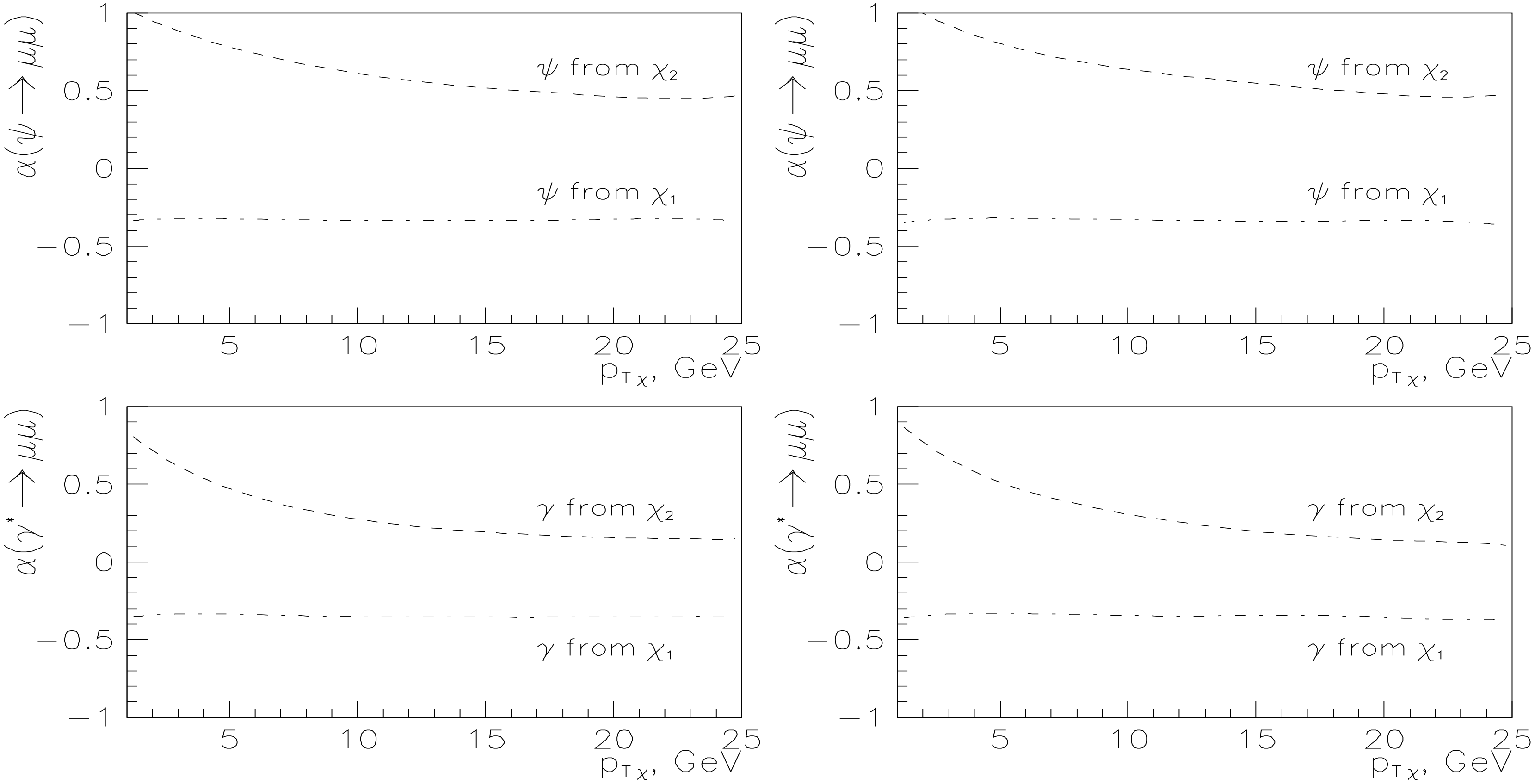
k_t-factorization collinear factorization



Helicity frame everywhere

Predictions for J/ψ and γ^* polarizations

k_t-factorization collinear factorization



Collins-Soper frame everywhere

Conclusions

– **Large, well pronounced polarization of χ_c's and ψ's (and even γ^*'s)**

– **Nontrivial p_T behavior of χ_c helicity fractions.**
Approximate scaling:

$$\chi_{c1}\Big(|h|{=}1 \;:\; h{=}0\Big) \approx O(1) : O(E/m)$$

$$\chi_{c2}\Big(|h|{=}2 \;:\; |h|{=}1 \;:\; h{=}0\Big) \approx O(1) : O(E/m) : O(E^2/m^2)$$

– **Great similarity between k_T-factorization and collinear predictions**
Despite the Feynman diagrams look apparently different, they take into account the same physics under different names (parton evolution in k_t-factorization versus hard subprocess in collinear factorization)

– **Recommendations for experimental analysis**
Three bins in p_T with border points at $\sim$3.5 GeV and $\sim$6.5 GeV

Thanks for patience and attention!