Studies of J/Ψ Production Mechanisms Near Threshold and the 3D Structure of the Nucleon

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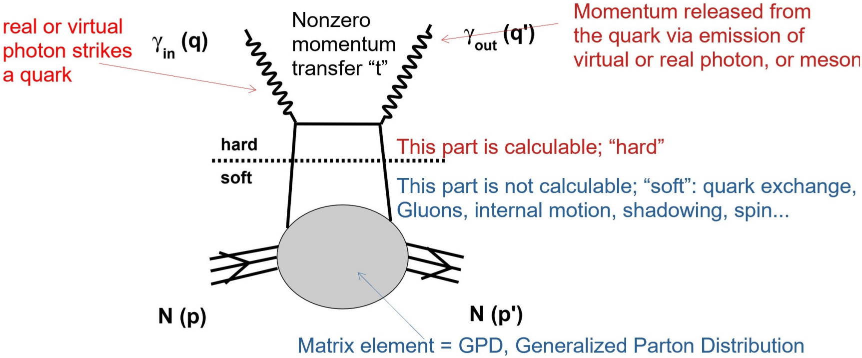
CNP Research Day May 06, 2022

Overview

Introduction

- The focus and motivation for this study is the extraction of Generalized Parton Distributions (GPDs) allowed through the analysis of the production of vector mesons [1].
- In addition to the following justifications for the study of J/Ψ, it is currently the heaviest meson produceable at JLab during the 12 GeV era.

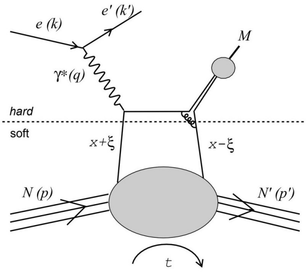
Generic handbag diagram for hard exclusive reaction involving photons



Contain correlation between quark's longitudinal momentum & transverse position

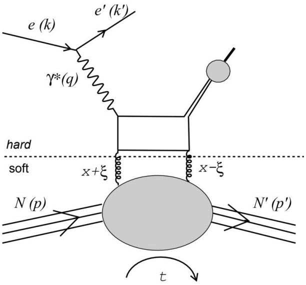
Hard Exclusive Meson Production with a virtual photon

“off quark”



Dominant at low energy (JLab…)
Light vector meson: rho, omega...

“off gluon”



Dominant at colliders (high) energy
Leading order process for heavy mesons
J/psi…: no intrinsic c-quark in proton

Reasons to Study J/Ψ

- As expressed before, producing various mesons in Exclusive Deep Inelastic Scattering events allows for the ability to probe different GPDs with more accuracy [1].
- Recent "pentaquark" (J/Ψ-nucleon bound states) study has led to increased interest in J/Ψ particularly as it applies to the color Van Der Waals force [2].
- J/Ψ is also a quarkonia ($c\bar{c}$) bound state and can be produced in a fairly attainable region in exclusive reactions.

Reasons to Study J/Ψ Near Threshold

- Near threshold, J/Ψ production is more likely to occur exclusively (leaving the target intact) [3].
- This exclusive reaction does allows for the access of different GPDs than at high energies which probe the gluon GPDs.
- J/Ψ "pentaquark" bound states have only been seen in the lower reaches of J/Ψ production thresholds [2].
- Transfer momentum dependence has been proven for two-gluon exchange production models for vector mesons [4], but charm has shown evidence of having multi-gluonic dependence near its production threshold as higher order terms are not suppressed as well [5].

Figuring Out the J/Ψ Production Method

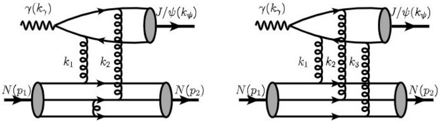


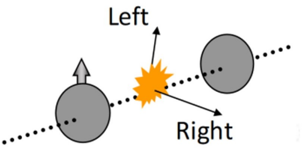
Figure: 2-gluon and 3-gluon production diagrams for J/Ψ [6].

- The 3-gluon production scheme was recently proposed to be dominant in the threshold region of J/Ψ production [6].
- This can only really be experimentally resolved because an asymmetry is produced when 2-gluon production occurs where production will "favor" one side when striking a polarized proton and this asymmetry is not present in 3-gluon production.

What induces target spin asymmetries?

$p^{\uparrow}$+p collisions

$$A_N = \frac{\sigma_L^{\uparrow} - \sigma_R^{\uparrow}}{\sigma_L^{\uparrow} + \sigma_R^{\uparrow}}$$



Products may be deviated due to magnetic effects coming from the non-zero spin of the proton and the correlation with the transverse position of the quark or gluon within the proton

If we expect to see this effect in 2-gluon exchanges,
Will it dilute the (measured) asymmetry if we are dominated by 3+ gluons exchanges?

My Study

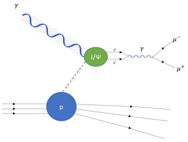
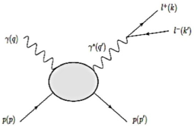


Figure: Photoproduction model of J/Ψ production

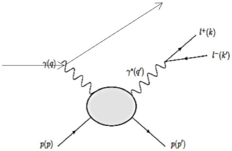
- My goal is to develop a simulation to predict the production of the vector meson J/Ψ.
- DEEPSim is new event generator developed by Dr. Boër here at Virginia Tech that I am contributing to that includes modes to select for anything from low energies to J/Ψ or DDVCS.

- Photoproduction was specifically chosen due its relatively simpler structure as well as the fact that the incident electron in electroproduction may introduce a selection bias in the electron pair decay scheme of J/Ψ.



Photoproduction
J/psi decays into e+e-, mu+mu-…
Each mode has different branching ratio
Electron vs muon is similar

We study photoproduction



Electroproduction
- we can study muon mode
- can't for electrons: anti-symmetrization,
GPD interpretation?, cross term & GPD extraction…
Can't distinguish the 2 electrons

- In Spring 2021, I implemented the initial production methods for J/Ψ mesons in a fixed target simulator.
- In Summer 2021, Tyler Schroder improved my implementation by creating a meson object with J/Ψ properties and implemented a production mechanism of two gluons that is known to hold at high energies.

DEEPSim

```
//START JPSI UNPOLARIZED FUNCTIONS
double JPsiMeson::xsecPhotonUnpol(double eGamma, double M, double t) { // picobarns | eGamma = energy of incoming photon | M = mass of charmonium pair | t = squared transfer of momentum
    return 1000 * (1 / (16 * PI)) * G_Gluon(t) * (crossSectionRatio * xsecPhotonTwoGluonUnpol(eGamma, M, t) + (1 - crossSectionRatio) * xsecPhotonThreeGluonUnpol(eGamma, M, t)); // fudge by using the same
 basic form factor for both 2 and 3 gluons
}

double JPsiMeson::xsecPhotonTwoGluonUnpol(double eGamma, double M, double t) { // nanobarns
    double x = energyThreshold / eGamma;
    return TMath::Power(1 - x, 2) / (TMath::Power(R_Proton * M, 2));
}

double JPsiMeson::xsecPhotonThreeGluonUnpol(double x, double M, double t) { // nanobarns
    return 1 / (TMath::Power(R_Proton * M, 4));
}

double JPsiMeson::xsecElectronUnpol(double yy, double Q2, double eGamma, double M, double  t) {
        return fluxFactor(yy, Q2) * xsecPhotonUnpol(eGamma, M, t);
}

double JPsiMeson::xsecPhotonUnpolHE(double x, double Q, double t, double Qp2) {
    double firstSummand = ((4 * pow(n_colors, 4)) / (pow(pow(n_colors, 2) - 1, 2))) * exp(1.13 * t) * cdfTable.parton(0, x, Q);
    cout << "gluon pdf: " << cdfTable.parton(0, x, Q) << endl;

    double secondSummand = 0;

    for(int f = 1; f <= 3; f++) {
        secondSummand += exp(1.13 * t) * abs(cdfTable.parton(f, x, Q) + cdfTable.parton(-f, x, Q));
    }

    return 1000 * (firstSummand + secondSummand) * quarkXsecPhotonUnpol(t, Qp2); // 1000x converts from nb to pb
}

double JPsiMeson::quarkXsecPhotonUnpol(double t, double Qp2) {
    double tau = -t / Qp2;

    double C = sqrt(3 * electronDecayWidth * pow(sqrt(Qp2), 3) / alphaEM);
    double Iqq = 1 / n_colors;

    double firstFactor = (4 * pow(tau, 2)) / (1 - pow(tau, 2));
    double secondFactor = log(pow(1 + tau, 2) / (4 * tau));
    double phaseSpaceFactor = PI / (4 * pow(t, 4));

    return phaseSpaceFactor * pow(abs(C * pow(Iqq, 2) * firstFactor * secondFactor), 2);
}

double JPsiMeson::xsecElectronUnpolHE(double y, double Q2, double x, double Q, double t, double Qp2) {
        return fluxFactor(y, Q2) * xsecPhotonUnpolHE(x, Q, t, Qp2);
}
//END JPSI UNPOLARIZED SECTION
```

Figure: Screenshot of the cross section methods for J/Ψ production off an unpolarized target.

DEEPSim Notes

- In addition to tweaking the cross sections to run a bit more cleanly, I have begun the process of creating cross section calculation methods for J/Ψ production off of a polarized target.
- There were also hard coding changes made throughout the code to allow DEEPSim to have a fixed target mode to reflect an experiment at JLab.

Analysis

- Analysis must be performed on the data generated by DEEPSim to determine the amount of production that falls within the physical limitations of JLab.
- We are trying to do something similar to TCS experiments such as that discussed in Brannon Semp's talk today.
- Experiments like HERA had the advantage of large acceptances for detecting J/Ψ production [7] that JLab does not currently have so knowing the acceptance range for J/Ψ production is very pertinent to any simulation.

TCSAna

```
// definition of variables (gen)
// // proton
phi_recoil_lab = atan2(ALV_Recoil_lab[2],ALV_Recoil_lab[1]);
if (phi_recoil_lab<0) phi_recoil_lab+=2.*PI;
P_recoil_lab = sqrt(pow(ALV_Recoil_lab[1],2)+pow(ALV_Recoil_lab[2],2)+pow(ALV_Recoil_lab[3],2));
theta_recoil_lab = acos(ALV_Recoil_lab[3]/P_recoil_lab);

// mu minus for jpsi
// pi minus for rho
phi_minus_lab = atan2(ALV_minus_lab[2],ALV_minus_lab[1]);
if (phi_minus_lab<0) phi_minus_lab+=2.*PI;
P_minus_lab = sqrt(pow(ALV_minus_lab[1],2)+pow(ALV_minus_lab[2],2)+pow(ALV_minus_lab[3],2));
theta_minus_lab = acos(ALV_minus_lab[3]/P_minus_lab);

// mu plus for jpsi
// pi plus for rho
phi_plus_lab = atan2(ALV_plus_lab[2],ALV_plus_lab[1]);
if (phi_plus_lab<0) phi_plus_lab+=2.*PI;
P_plus_lab = sqrt(pow(ALV_plus_lab[1],2)+pow(ALV_plus_lab[2],2)+pow(ALV_plus_lab[3],2));
theta_plus_lab = acos(ALV_plus_lab[3]/P_plus_lab);


// jpsi = mu+ + mu-
// rho = pi+ + pi-
ALV_virtual_lab[0] = (ALV_minus_lab[0]+ALV_plus_lab[0]);
ALV_virtual_lab[1] = (ALV_minus_lab[1]+ALV_plus_lab[1]);
ALV_virtual_lab[2] = (ALV_minus_lab[2]+ALV_plus_lab[2]);
ALV_virtual_lab[3] = (ALV_minus_lab[3]+ALV_plus_lab[3]);

// jpsi angles in the lab frame
phi_virtual_lab = atan2(ALV_virtual_lab[2],ALV_virtual_lab[1]);
if (phi_virtual_lab<0) phi_virtual_lab+=2.*PI;
P_virtual_lab = sqrt(pow(ALV_virtual_lab[1],2)+pow(ALV_virtual_lab[2],2)+pow(ALV_virtual_lab[3],2));
theta_virtual_lab = acos(ALV_virtual_lab[3]/P_virtual_lab);
PT_virtual_lab = sqrt(pow(ALV_virtual_lab[1],2)+pow(ALV_virtual_lab[2],2));

//Calculate the mass based off of the detector readings
mass_meson = sqrt( pow(ALV_virtual_lab[0], 2) - pow(P_virtual_lab,2));
//Calculate the mass directly from Q'^2 which should ideally equal the mass of the messon
//This is used as a check on the above calculated method
mass_meson_2 = sqrt(Qp2);

// some kinematics that was not in the tree
float ss = pow(M_proton, 2.) + 2. * M_proton * Egamma;
float xi = Qp2/(2.*(ss-pow(M_proton,2)) + tt - Qp2);
```

```
if(mass_meson >= 1.5) {
        h_mass_meson[0]->Fill(mass_meson);
        h_mass_meson[1]->Fill(mass_meson_2);
}

//Fill 2-D Histograms
//0 - virtual combined phi
//1 - minus half of phi indicating the detection of l-
//2 - positive half of phi indicating the detection of l+

h_xi_v_phi[0]->Fill(xi, phi_virtual_lab);
h_t_v_phi[0]->Fill(-tt, phi_virtual_lab);
h_theta_v_phi[0]->Fill(theta_virtual_lab, phi_virtual_lab);
//h_integral_theta_v_phi[0]->Fill(     , phi_virtual_lab);
h_Egam_v_phi[0]->Fill(Egamma, phi_virtual_lab);
//h_integral_Egam_v_phi[0]->Fill(     , phi_virtual_lab);
//h_integral_phi_v_xi[0]->Fill(     , xi);
//h_integral_phi_v_t[0]->Fill(     , -tt);

h_xi_v_phi[1]->Fill(xi, phi_minus_lab);
h_t_v_phi[1]->Fill(-tt, phi_minus_lab);
h_theta_v_phi[1]->Fill(theta_minus_lab, phi_minus_lab);
//h_integral_theta_v_phi[1]->Fill(     , phi_minus_lab);
h_Egam_v_phi[1]->Fill(Egamma, phi_minus_lab);
//h_integral_Egam_v_phi[1]->Fill(     , phi_minus_lab);
//h_integral_phi_v_xi[1]->Fill(     , xi);
//h_integral_phi_v_t[1]->Fill(     , -tt);

h_xi_v_phi[2]->Fill(xi, phi_plus_lab);
h_t_v_phi[2]->Fill(-tt, phi_plus_lab);
h_theta_v_phi[2]->Fill(theta_plus_lab, phi_plus_lab);
//h_integral_theta_v_phi[2]->Fill(     , phi_plus_lab);
h_Egam_v_phi[2]->Fill(Egamma, phi_plus_lab);
//h_integral_Egam_v_phi[2]->Fill(     , phi_plus_lab);
//h_integral_phi_v_xi[2]->Fill(     , xi);
//h_integral_phi_v_t[2]->Fill(     , -tt);

//if (phi_minus_lab>2)  h_mass_meson[1]->Fill(mass_meson_2);  // angles are in radian

h_mass_meson[2]->Fill(mass_meson - mass_meson_2);
```

Figure: Screenshots of some sections of TCSAna

TCSAna Notes

- TCSAna was initially a TCS analysis program that had options added to accept ROOT files containing mesons.
- The analysis will have binning added to it once some histograms and graphs are generated with smaller data sets so that large data sets do not overwhelm any print outs of the analysis.

Results

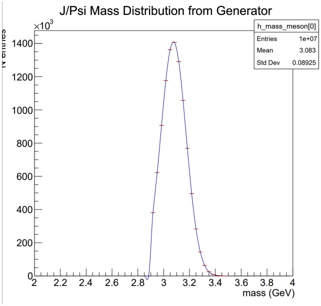


Figure: Mass distribution of J/Ψs produced by DEEPSim

- This coincides with expectations laid out in the PDG.

Issues with Current Results

- Currently there seems to have been some issues with other kinematics when generating the J/Ψ mesons due to the conversion to a fixed target mode.
- These issues are being worked out now, but will ideally give the angle spread of J/Ψ production as this will allow me to bin the results of a larger production run and then determine feasibility at JLab with current acceptances.

Conclusions

- The study of J/Ψ will continue to be a large component in future studies at the edge of heavy meson production with near threshold studies being of particular interest.
- There is work to be done with refining DEEPSim, but this should be attainable soon and allow for an analysis of the feasibility of a real J/Ψ photoproduction experiment at JLab near threshold and potentially with a polarized target.

Future Areas of Study

- Continue refining simulations and decide on adequate binning for the data.
- Implement the kinematics for striking a polarized target.
- Show the feasibility of J/Ψ production being captured at JLab.
- Perform analysis on this data to extract GPDs to give an idea of what can be expected from a real experiment.

- The ultimate goal is to measure J/Ψ production off a transversely polarized proton target in JLab's Hall C.
- We would like to propose a dedicated experiment at JLab.
- **Question: Are we going to see a big asymmetry (2-gluons)? Or a small asymmetry (3-gluons)?**

Acknowledgements

I would like to specifically acknowledge and thank Dr. Marie Boër for allowing me to work with and learn from her this year. Additionally, I wanted to thank everyone in Hall C at Jefferson Lab for all their help on my trip there earlier this year as well as the the institution for providing me with the technological accesses to complete my work. Lastly, I would like to thank the Center for Neutrino Physics here at Virginia Tech for putting together this Research Day and allowing me to present.

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