TMDs in Associated Production : Experimental Review

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Presented 13h January 2020

Quarkonia as Tools Workshop

Aussois

Introduction and Outline

- Talk is an experimental overview of the prospects of accessing gluon TMDs in associated production, mainly through double quarkonium and/or quarkonium + photon, via experimental methods, in the near or distant future.

- Gave a similar talk last year: TMDs in Associated Production: Experimental Review

- Want to focus on experiments interpreted in the context of TMDs, however, there are other experiments which *could* be useful for future TMD studies which are discussed here: Quarkonium Production Measurements as a Tool for TMD Studies

Areas of Interest

Associated Production of quarkonium with another quarkonium

Non-Prompt J/ψ + J/ψ production at the LHC
Prompt J/ψ + J/ψ production at LHCb

Associated production of quarkonium with W or Z

prompt W + J/ψ production by ATLAS at 7 TeV JHEP 04 2014 172
prompt and non-prompt Z + J/ψ production by ATLAS at 8 TeV EPJ c75 (2015) 229
Prompt and non-prompt W + J/ψ by ATLAS at 8 TeV arXiv:1909.13626

Not discussed here, but do not look promising

See
Quarkonium Production Measurements as a Tool for TMD Studies

Associated production of quarkonium with a real photon

Prompt J/ψ + ɣ by ATLAS at 13 TeV (ongoing)

Associated Production of quarkonium with a lepton

Non-prompt J/ψ + μ production at ATLAS

Future: Associated production of a dilepton and (J/ψ)

Non-Prompt $J/\psi + J/\psi$ Production at the LHC

Non-Prompt J/ψ + J/ψ Production at LHCb

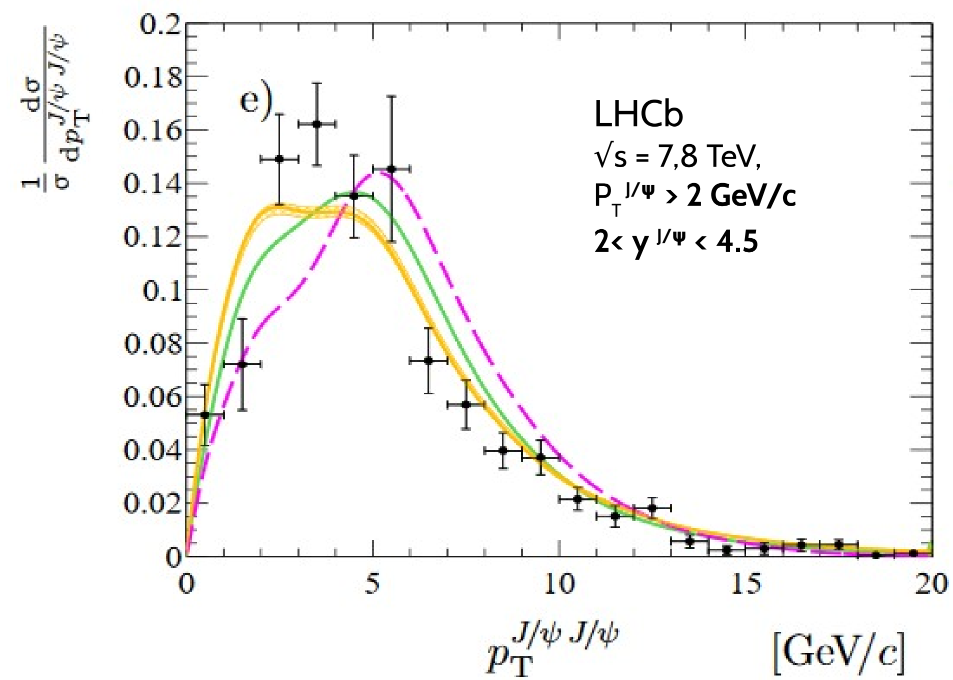
Production of J/ψ mesons from *b*-hadron decays

Part One

LHCb Experimental Data

LHCb Collaboration at √s = 7,8 TeV: Kinematic correlations for pairs of *b*-hadrons reconstructed via their inclusive decays into J/ψ mesons measured in forward rapidity region. **arXiv: 1708.05994** *LHCb Collaboration*

Several differential cross sections, including different angular correlations between the final decay muons, was measured for the first time. Hence corresponding calculations performed within framework of k_T factorization, and compared to LHCb data.



Theory paper then written to extract gluon TMD density information based on aforementioned data.
arXiv: 1808.06233 *S.P Baranov, A..V Lipatov, M.A, Malyshev.*

Powheg = orange, Pythia = green, Expectations for uncorrelated $b\bar{b}$ production = magenta, Uncertainties in Powheg + Pythia predictions due to choice of factorization and normalization scales = orange hatched.

TMD Cross Section

The cross sections of *b*-hadron production in *pp* collisions was calculated using the k_T factorization approach, based on the (α_s^2) off-shell gluon-gluon fusion subprocess:

$$g^*(k_1) + g^*(k_2) \to b(p_1) + \bar{b}(p_2)$$

Four-momenta of particles

K_T factorization approach uses two prescriptions for gluon dynamics at small *x*, that easily includes higher order radiative corrections, in the form of predictions for TMD parton distributions.

The *b*-flavour production cross section, obtained as a convolution of the off-shell partonic cross section $\hat{\sigma}^*_{gg}(x_1, x_2, \mathbf{k}^2_{1T}, \mathbf{k}^2_{2T}, \mu^2)$ and the TMD gluon distributions in a proton $f_g(x, \mathbf{k}^2_T, \mu^2)$

$$\sigma = \int dx_1 dx_2\, d\mathbf{k}^2_{1T} d\mathbf{k}^2_{2T}\, d\hat{\sigma}^*_{gg}(x_1, x_2, \mathbf{k}^2_{1T}, \mathbf{k}^2_{2T}, \mu^2) f_g(x_1, \mathbf{k}^2_{1T}, \mu^2) f_g(x_2, \mathbf{k}^2_{2T}, \mu^2),$$

$\mathbf{K}_{iT,}$ component of the off-shell gluon momentum k_i perpendicular to beam axis

X_i, fraction of longitudinal momentum of the colliding proton

μ^2 , corresponding hard scale

Non-Prompt J/ψ + J/ψ Production at the LHC

Part Three

TMD gluon densities

Two approaches of the TMD gluon distribution functions in a proton were tested. For details see **ArXiv: 1808.0633** *_S.P Baranov, A..V Lipatov, M.A, Malyshev.*

.......Summarising

CCFM: Using a numerical solution of the equation (labelled *JH'2013*), which smoothly interpolates between small-*x* BFKL gluon dynmaics and high-*x* DGLAP dynamics. Two sets of predictions for TMD gluon densities have been determined from fits to high precision HERA data on the proton structure functions:

JH'2013 Set 1: Determined from fit to inclusive $F_2(x,Q^2)$ data only.

JH'2013 Set 2: Determined from fit to $F_2(x,Q^2)$ and $F_2^c(x,Q^2)$.

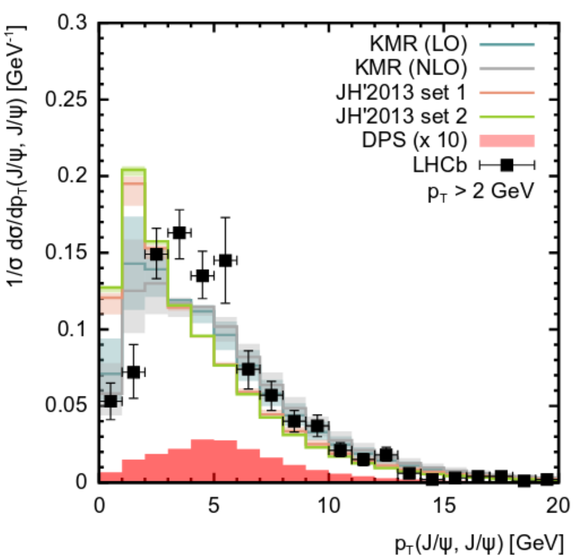
KMR: Construct TMD parton (quark and gluon) densities from well-known conventional ones, at LO and NLO. This approach assumes k_T dependence enters at the last evolution step, so DGLAP evolution can be used up to this step.

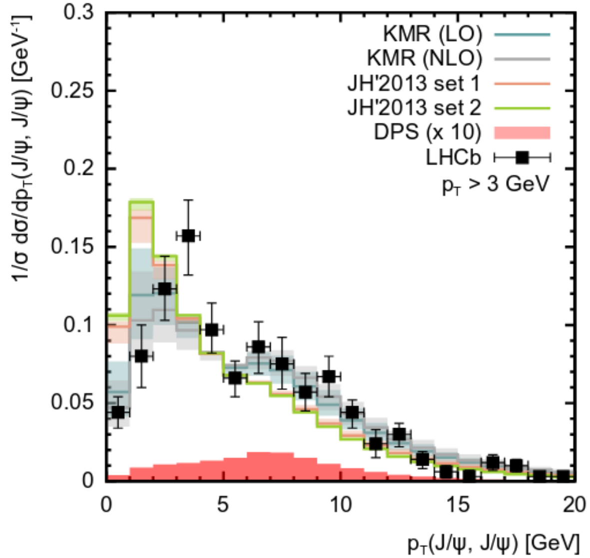
Non-Prompt J/ψ + J/ψ Production at the LHC

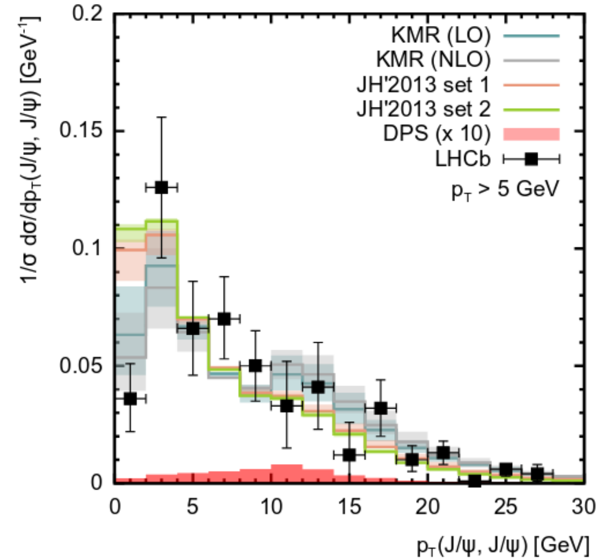
Part Four

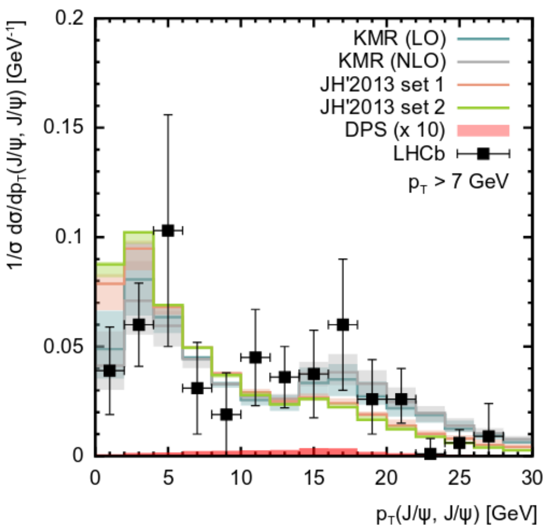
View in 2018 : Predictions for different gluon TMD densities

Results









Conclusions:

TMD gluon densities describe the data reasonably well for distributions within uncertainties.

CCFM evolved gluons tend to overestimate the measured transverse momentum spectra of the pair at low P_T.

KMR calculations agree well with LHCb data.

Figs: Normalized differential cross sections of non-prompt J/ψ + J/ψ production at √ s = 8 TeV as a function of the transverse momentum of the pair, using experimental data from LHCb. Predictions are made using the KMR (with NO and NLO accuracy) and the CCFM evolved TMD gluon distributions. Shaded bands represent the scale uncertainties of the calculation.

Non-Prompt $J/\psi + \mu$ Production at the LHC

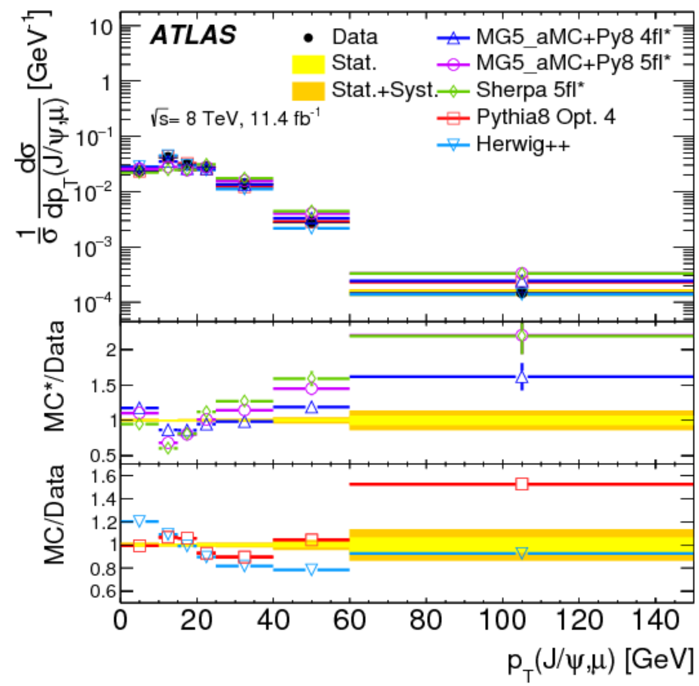
Non-Prompt J/ψ + μ Production at the LHC

Part One

…Similar story as for J/ψ + J/ψ production

ATLAS Collaboration at √s = 8 TeV : Measurement of the production of two *b*-hadrons, where one *b*-hadron decays into a J/ψ meson, and the other decays into μ + *X* ***arXiv: 1705.03374***.

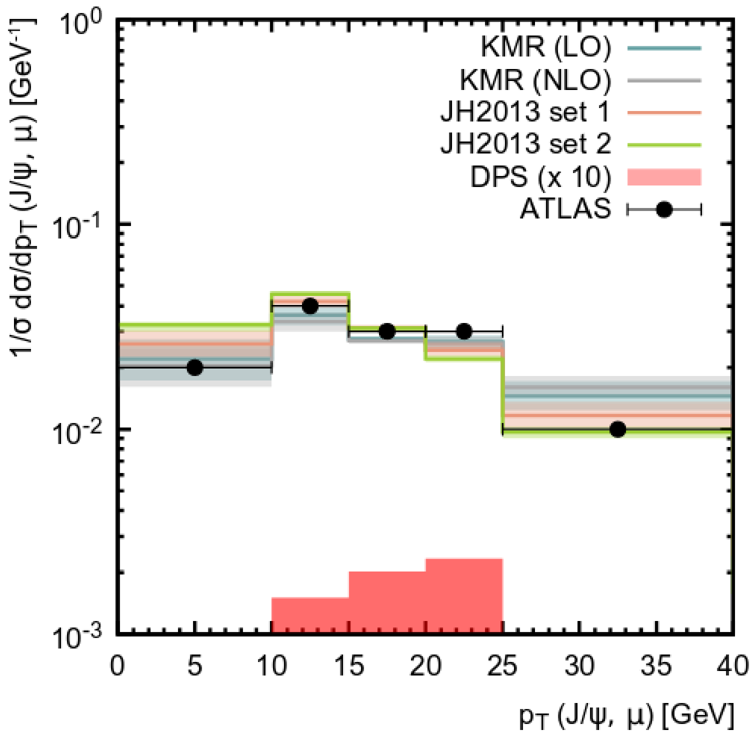
ATLAS collaboration measured the total and differential cross sections in a restricted part of the phase space (fiducial volume). Each muon was required to have transverse momentum $p_T > 6$ GeV, the two muons originating from J/ψ decay must have pseudorapidities $|\eta| < 2.3$ and the third muon must have $|\eta| < 2.5$.



The normalized cross section is presented time for the transverse momentum of the three muon system p_T(J/ψ, μ). Studying the normalized differential cross section could lead to more stringent comparison between data and theory due to the reduced experimental (systematic) uncertainties.

Non-Prompt J/ψ + μ Production at the LHC

Part Two



Normalized differential cross section of associated non prompt J/ψ + μ production at √s = 8 TeV with ATLAS experimental data.

Solid histogram represents central predictions calculated with fixed renormalization μ_R and factorization μ_F at default values (cite). Shaded regions correspond to scale uncertainties in predictions

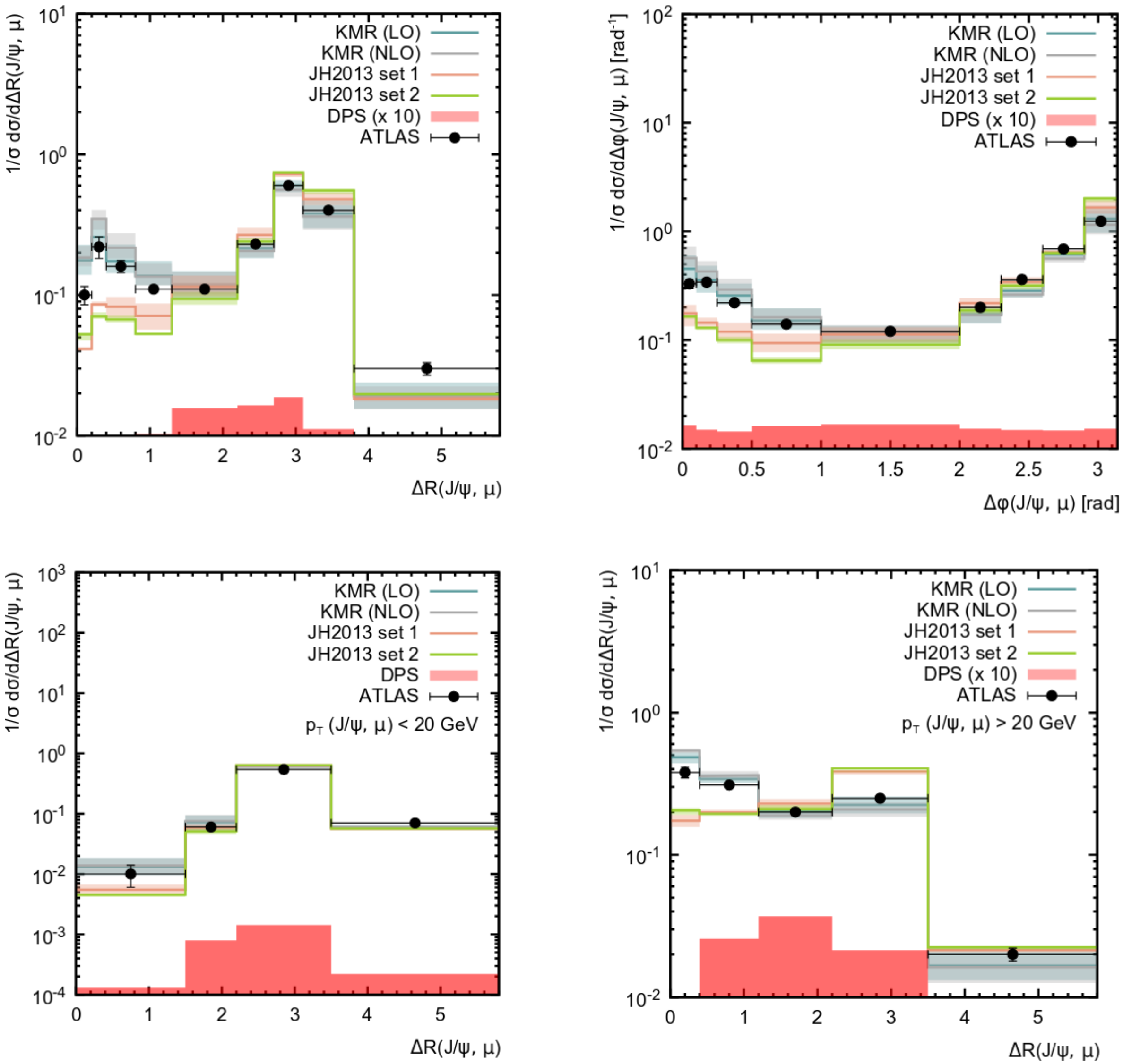
Predictions compared with available data.

Calculated cross sections strongly depend on TMD gluon density used. Clear difference in shape between the *JH'2013* and KMR predictions is observed, where a better description is achieved with the KMR gluon distributions.

Small overestimation of the data in the last bins of p_T(J/ψ, μ), although data is close to estimated uncertainty bands.

Non-Prompt J/ψ + μ Production at the LHC

Part Three



Clear difference in shape between *JH'2013* and KMR predictions is observed for Δ*R*(J/ψ, μ) and Δϕ(J/ψ, μ).

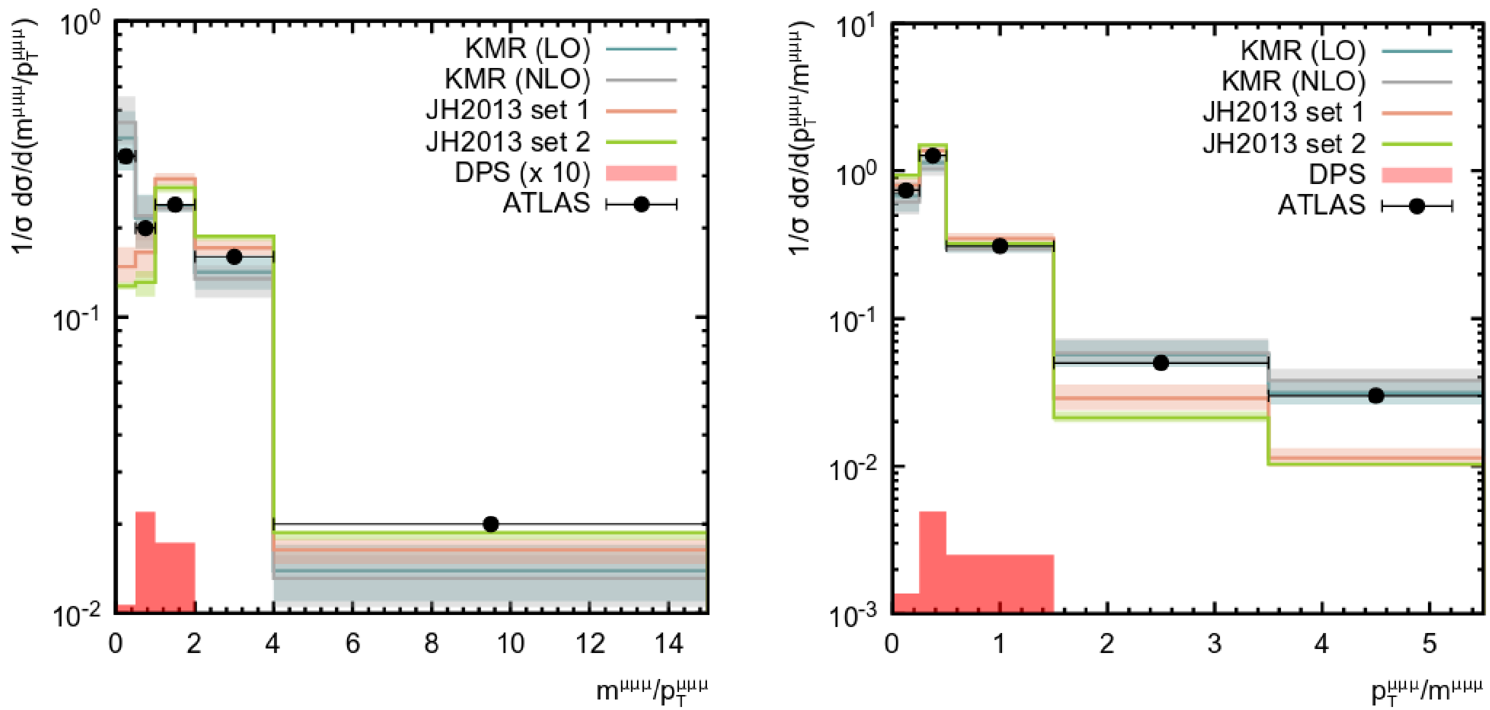
Small over estimation of the data at low ΔR(J/ψ, μ) and Δϕ(J/ψ, μ), but data close to estimated uncertainty bands.

Both *JH'2013* do not reproduce well the measured shape of angular correlations. Underestimate the data at low ΔR(J/ψ, μ) and Δϕ(J/ψ, μ), especially for p_T(J/ψ , μ) > 20 GeV. Overestimate the data at Δϕ(J/ψ, μ) ~ .

Normalized differential cross sections of associated non-prompt J/ψ+ μ production at √s = 8 TeV as functions of Δ*R*(J/ψ, μ), Δϕ(J/ψ, μ), for low and high P_T ranges. Predictions made using KMR (LO and NLO accuracy) and CCFM evolved TMD gluon densities. Shaded bands represent the scale uncertainties of the calculations. Experimental data from ATLAS.

Non-Prompt J/ψ + μ Production at the LHC

Part Four



Observable differences between KMR and *JH'2013* predictions is very noticeable here.

Calculated that the ratio of KMR and *JH'2013* prediction reaches ~2.5-3 at $P_t^{\mu\mu\mu}/m^{\mu\mu\mu} > 2$. P_t/m is akin to k_T.

.... Observables are sensitive to non-collinear gluon dynamics. Well known properties of angular correlations between the momenta of produced particles could be very promising to constrain TMD gluon densities in a proton

Prompt J/ψ+ J/ψ production at the LHC

Prompt J/ψ + J/ψ Production at the LHC

Di-Q production and TMD factorization

Part One

arXiv:1710.01684v1 *J.P Lansberg, C.Pisano, F.Scarpa, M.Schlegel*

Argue that di-J/ψ production, amongst the several quarkonium associated production processes has seen numerous studies at the LHC and Tevatron, is the ideal process to perform the first measurement of linearly polarized gluons, $h_1^{\perp g}(x,\boldsymbol{k}_T^2)$. It exhibits the largest possible azimuthal asymmetries in regions already accessed by ATLAS and CMS experiments.

For TMD factorization to apply, di-Q production needs to satisfy:

- Should result from Single Parton Scattering
- Final State Interactions should be negligible, which is satisfied when quarkonia are produced via Colour-Singlet Transitions.

$$\frac{d\sigma}{dM_{QQ}dY_{QQ}d^2\boldsymbol{P}_{QQ_T}d\Omega} = \frac{\sqrt{Q^2-4M_Q^2}}{(2\pi)^2 8s\,Q^2}\Big\{F_1\,\mathcal{C}\big[f_1^g f_1^g\big] + F_2\,\mathcal{C}\big[w_2 h_1^{\perp g} h_1^{\perp g}\big] + \cos 2\phi_{CS}\Big(F_3\mathcal{C}\big[w_3 f_1^g h_1^{\perp g}\big] + F_3'\mathcal{C}\big[w_3' h_1^{\perp g} f_1^g\big]\Big) + \cos 4\phi_{CS} F_4\mathcal{C}\big[w_4 h_1^{\perp g} h_1^{\perp g}\big]\Big\}, \quad (3)$$

Prompt J/ψ + J/ψ Production at the LHC

Di-Q production and TMD factorization F factors

Part Two

As for the F_i we have

$$F_1 = \frac{\mathcal{N}}{\mathcal{D} M_Q^2}\Big[(6\alpha^8 - 38\alpha^6 + 83\alpha^4 + 480\alpha^2 + 256) + 2(1-\alpha^2)\left(6\alpha^8 + 159\alpha^6 - 2532\alpha^4 + 884\alpha^2 + 208\right) c_\theta^2$$
$$+ 2\left(1-\alpha^2\right)^2\left(3\alpha^8 + 19\alpha^6 + 7283\alpha^4 - 8448\alpha^2 - 168\right) c_\theta^4 - 2\left(1-\alpha^2\right)^3\left(159\alpha^6 + 6944\alpha^4 - 17064\alpha^2 + 3968\right) c_\theta^6$$
$$+ \left(1-\alpha^2\right)^4\left(4431\alpha^4 - 27040\alpha^2 + 17824\right) c_\theta^8 + 504\left(1-\alpha^2\right)^5\left(15\alpha^2 - 28\right) c_\theta^{10} + 3888\left(1-\alpha^2\right)^6 c_\theta^{12}\Big],$$

$$F_2 = \frac{2^4 3 M_Q^2 \mathcal{N}}{\mathcal{D} M_{QQ}^4}\Big[\alpha^4 - 2\left(\alpha^6 + 17\alpha^4 - 126\alpha^2 + 108\right) c_\theta^2 + \left(1-\alpha^2\right)^2\left(\alpha^4 + 756\right) c_\theta^4 - 36\left(1-\alpha^2\right)^3\left(\alpha^2 + 24\right) c_\theta^6 + 324\left(1-\alpha^2\right)^4 c_\theta^8\Big],$$

$$F_3' = F_3 = \frac{-2^3(1-\alpha^2)\mathcal{N}}{\mathcal{D} M_{QQ}^2} \times \Big[\alpha^2\left(16 - 3\alpha^2\right) + (6\alpha^6 + 159\alpha^4 - 1762\alpha^2 + 1584)\, c_\theta^2 + (1-\alpha^2)\left(3\alpha^6 + 19\alpha^4 + 5258\alpha^2 - 6696\right) c_\theta^4$$
$$- \left(1-\alpha^2\right)^2\left(159\alpha^4 + 5294\alpha^2 - 10584\right) c_\theta^6 + 18\left(1-\alpha^2\right)^3\left(99\alpha^2 - 412\right) c_\theta^8 + 1944\left(1-\alpha^2\right)^4 c_\theta^{10}\Big],$$

$$F_4 = \frac{(1-\alpha^2)^2 \mathcal{N}}{\mathcal{D} M_Q^2} \times \Big[\left(3\alpha^4 - 32\alpha^2 + 256\right) - \left(6\left(\alpha^4 + 36\alpha^2 - 756\right)\alpha^2 + 4768\right) c_\theta^2 + \left(3\alpha^8 + 38\alpha^6 + 11994\alpha^4 - 32208\alpha^2 + 20400\right) c_\theta^4$$
$$- 2\left(1-\alpha^2\right)\left(105\alpha^6 + 5512\alpha^4 - 23120\alpha^2 + 19520\right) c_\theta^6 + \left(1-\alpha^2\right)^2\left(3459\alpha^4 - 30352\alpha^2 + 38560\right) c_\theta^8$$
$$+ 72\left(1-\alpha^2\right)^3\left(105\alpha^2 - 268\right) c_\theta^{10} + 3888\left(1-\alpha^2\right)^4 c_\theta^{12}\Big],$$

with $c_\theta = \cos\theta_{CS}$, $\alpha = 2M_Q/M_{QQ}$, $\mathcal{N} = 2^{11}3^{-4}\pi^2\alpha_s^4|R_Q(0)|^4$, $\mathcal{D} = M_{QQ}^4\left(1-(1-\alpha^2)\,c_\theta^2\right)^4$ and where $R_Q(0)$ is the Q radial wave function at the origin. Note that the expressions are symmetric about $\theta_{CS} = \pi/2$ since the process is forward-backward symmetric.

Prompt J/ψ + J/ψ Production at the LHC

Part Three

F-Factors

- $F^{(\prime)}_{2,3,4} \leq F_1$,but for *QQ* production $F_3^{'} = F_3$

- When $M_{QQ} \gg M_Q$ then for $\cos\theta_{CS} = \cos\theta \rightarrow 0.$ The F-Factors become:

$$F_{1,4} \rightarrow \frac{256\mathcal{N}}{M_{QQ}^4 M_Q^2}, \quad \frac{F_2}{F_1} \rightarrow \frac{81 M_Q^4 c_\theta^2}{2 M_{QQ}^4}, \quad \frac{F_3}{F_1} \rightarrow \frac{-24 M_Q^2 c_\theta^2}{M_{QQ}^2}, \qquad \mathcal{N} = 2^{11} 3^{-4} \pi^2 \alpha_s^4 |R_Q(0)|^4,$$

- At the threshold , $M_{QQ} \rightarrow 2 M_Q$ and the F-factors are transformed to:

$$F_1 \rightarrow \frac{787\mathcal{N}}{16 M_Q^6}, \quad F_2 \rightarrow \frac{3F_1}{787}, \quad F_{3,4} \rightarrow 0.$$

- $F_{2,3}$ are suppressed near $\Delta y \sim 0$, and F_2(F_3) scales like $M_{QQ}^{-4}(M_{QQ}^{-2})$ relative to F_1 and F_4. Hence P_{QQT} dependence due to linearly polarized gluons encoded in F_2 vanishes at large scales, whereas the $\cos 4\phi$ modulation (double helicity flip) takes over the $\cos 2\phi$ one (single helicity flip).

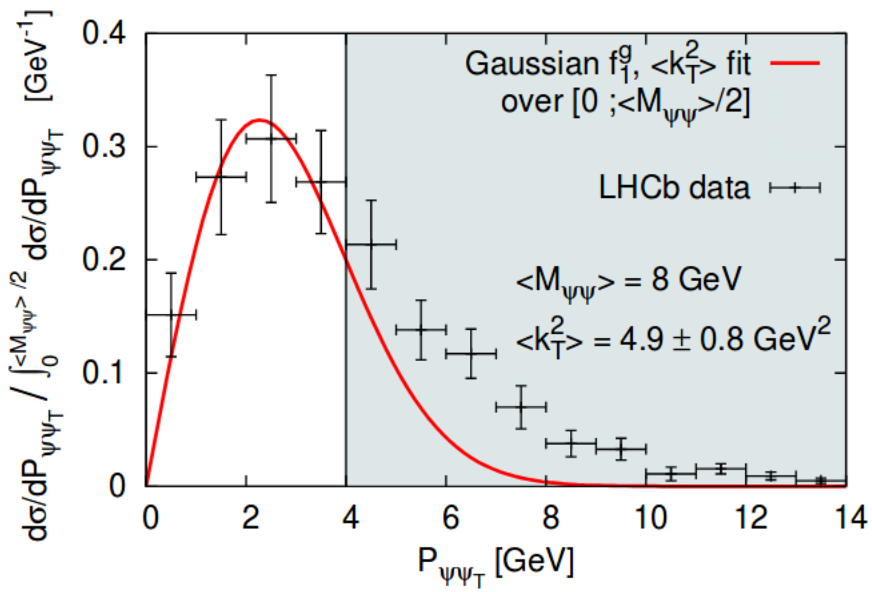
- $F_4 \rightarrow F_1$ for $\cos\theta \rightarrow 0$ away from the threshold (where $\cos\theta_{CS} \sim 0$ and $\Delta y \sim 0$). This is an important result, and a unique feature of di-J/psi and di- production. Hence di-J/ψ is a good candidate to extract linearly polarized gluons from in light of recent experimental data.

- Knowing the F_i and an observed experimental yield one can extract the various TMD convolutions from their azimuthal (in)dependent parts. When the cross section is integrated over θ_{CS}, then the contribution from $F_{3,4}$ drops out of the TMD cross section.

Prompt J/ψ + J/ψ Production at the LHC

Part Four

Results



Normalized P_{QQT} dependence of the J/ψ yield obtained with a gaussian f_1^g with $\langle k_T^2\rangle$ fit to normalized LHCb data at 13 TeV. TMD factorization does not apply in the grey zone.

Have been able to use experimental data to fix $C\,[\,f_1 f_1\,]$ from P_{QQT} spectrum recently measured by the LHCb collaboration at 13TeV. Study was conducted without any TM cuts, so can neglect contributions from $h_1^{\perp g}$ given the size of F_2/F_1 near threshold.

For the TMD ansatze, with factorized dependencies on *x* and $\mathbf{k}^2_T$, the normalized P_{QQT} spectra does not depend on other kinematic variables. Fitting the P_{QQT} spectrum up to $M_{QQ}/2$ then obtain $\langle k_T^2\rangle$=4.9+/- 0.8 GeV^2. This is the first process indepdendent quantity to be experimentally determind in a pure gluon induced process with a colourless final state for which TMD factorization applies.

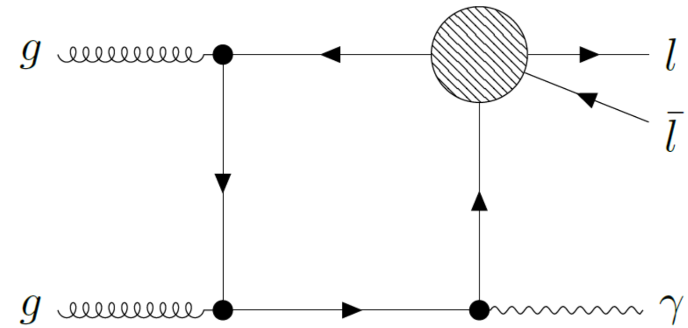
(Potential) future and current analyses

J/Psi + ɣ Production at the LHC

J/ψ + ɣ Production at the LHC

Part One

Cross Section



$g + g \longrightarrow J/\psi + \gamma$

TMD cross section

Motivations

⋮

Measure gluon transverse momentum distributions, and/or

Measure the polarization dependent part of gluon TMDs

Measure the J/ψ + ɣ cross section

$$\frac{d\sigma}{dQdY\,d^2q_T d\Omega} = \frac{4\alpha_s^2\alpha e_Q^2|R_0(0)|^2}{3M_Q^3} \times \frac{Q^2 - M_Q^2}{sQ^3\{(\gamma^2+1)^2 - (\gamma^2-1)^2\cos^2\theta\}^2} \times$$
$$\times \Big\{F_1 C_1\big[f_1^g f_1^g\big] + F_3 C_3\big[w_3 f_1^g h_1^{\perp g} + (x_a \leftrightarrow x_b)\big]\cos 2\phi +$$
$$F_4 C_4\big[w_4 h_1^{\perp g} h_1^{\perp g}\big]\cos 4\phi\Big\}$$

$$F_1 = 1 + 2\gamma^2 + 9\gamma^4 + (6\gamma^4 - 2)\cos^2\theta + (\gamma^2 - 1)^2\cos^4\theta$$
$$F_3 = 4\gamma^2\sin^2\theta$$
$$F_4 = (\gamma^2 - 1)^2\sin^4\theta$$

Boer-Mulders function $h_1^{\perp}(x,k_T,\xi,\mu)$: Distribution of a linearly polarized gluon in an unpolarized proton.

Unpolarized TMD parton dstribution function. $f_1(x,k_T,\xi,\mu)$. Transverse momentum distribution of an unpolarized gluon in an unpolarized proton.

Term responsible to for non trivial angular dependence in Collins-Sopher frame.

- Production of an isolated photon back to back with an isolated J/ψ in *pp* collisions is the ideal to observe transverse dynamics and polarization of gluons in the proton in terms of TMD factorization.

arXiv: 1401.7611v2 *W.J Den Dunnen, J.P Lansberg, C.Pisano, M.Schlegel*

J/ψ + ɣ Production at the LHC

Part Two

TMD cross section

...After some manipulations

$$\frac{d\sigma}{d\lambda dY\, d(q_T^2) d\phi} = \left[\mathbf{B}_0 \frac{1}{\lambda^2(\lambda-1)^3} \int \frac{1}{\left\{G^2 - z^2\right\}^2} \times \left\{F_1 T_1\left[q_T^2\right] + F_3 T_3\left[q_T^2\right] \cos 2\phi + F_4 T_4\left[q_T^2\right] \cos 4\phi\right\}\right] dz$$

$$d\Omega = d\cos\theta d\phi$$

$$z = \cos\theta$$

$$\mathbf{B}_0 = \frac{\pi\alpha_s^2\Gamma}{6M_Q s\alpha}$$

$$G = \left(\frac{\lambda+1}{\lambda-1}\right)$$

$$q_T^2 = [pT\ of\ J/\psi + \gamma]^2$$

$$\lambda = [(Mass\ of\ J/\psi + \gamma)/Mass\ of\ J/\psi]^2$$

$$F_1 = 1 + 2\lambda + 9\lambda^2 + (6\lambda^2 - 2)z^2 + (\lambda-1)^2 z^4$$

$$F_3 = 4\lambda(1-z^2)$$

$$F_4 = (\lambda-1)^2\left(-2z^2 + z^4 + 1\right)$$

Aim is to see modulation in phi distributions once all backgrounds have been removed

Only have access to λ > 20, giving just access to F1 and F4. F1 contains no phi dependence.

Manipulating the F's only (convolutions only contain qT2 dpd.):

$$\underbrace{\lambda^2(9+6z^2+z^4)}_{\text{F1}}\left(1 + \overbrace{\left[\frac{(1-z^2)^2}{9+6z^2+z^4}\right]\cos 4\phi}^{\text{F4}}\right)$$

Plotting the square bracket as a function of z^2: Bigger at lower z^2 and smaller at higher z^2.

→ separate data into two halves. Applying a cut at $\cos^2\theta > 0.095$ separates data 'evenly'.

J/ψ + γ Production at the LHC

Part Three

Monte Carlo

- Subprocess $g + g \longrightarrow J/\psi + \gamma$

- Three Monte Carlo Samples + data

  - Non - Prompt Background (bb): ~ **10** M events, muons > **3.5** GeV, Photons > 5 GeV

  - Signal Subprocess (signal): ~ **8.4**M events, muons > 3.5 GeV pT, Photons > 4 GeV pT

  - Prompt Background (pp): ~ 10M events, muons > 3.5 GeV, Photons > 5 GeV

  - Data: ~ 13 M events, muons > 4 GeV, Photons > 5 GeV
    Using 2015 data as this offers lowest possible thresholds on dimuon triggers

- Can remove bb contribution from data by a tau cut = 0.860 ps.

- Using BDT methods/Fits to separate out the signal and prompt background in data

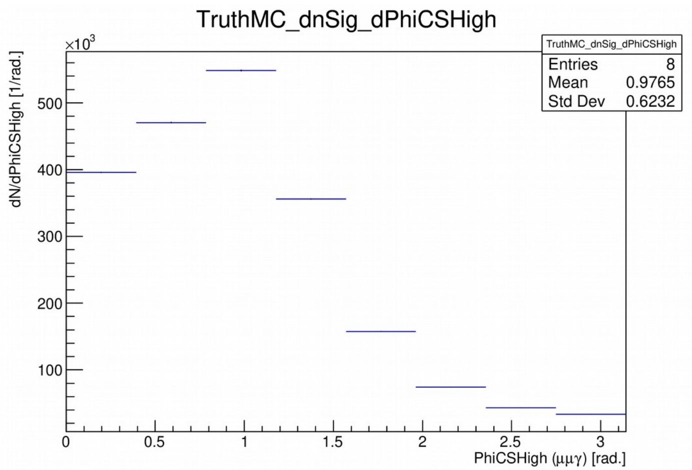
- Correct the data using our signal MC, can see the qT dependence of the convolution in F1.

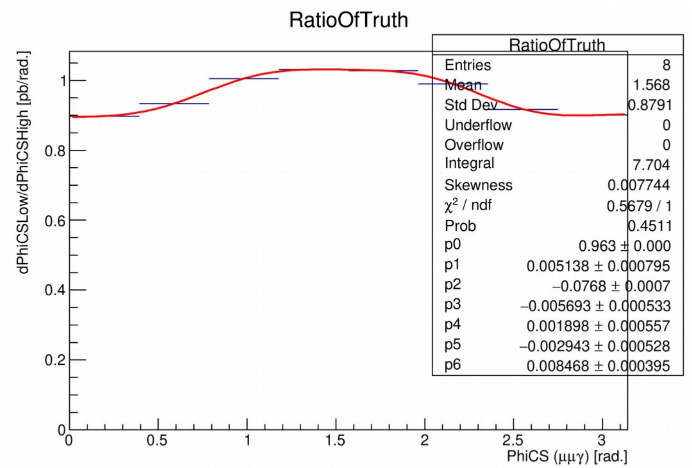
J/ψ + γ Production at the LHC

Part Four

Apologies: cannot show anything involving data

Phi Distributions





Fit Function

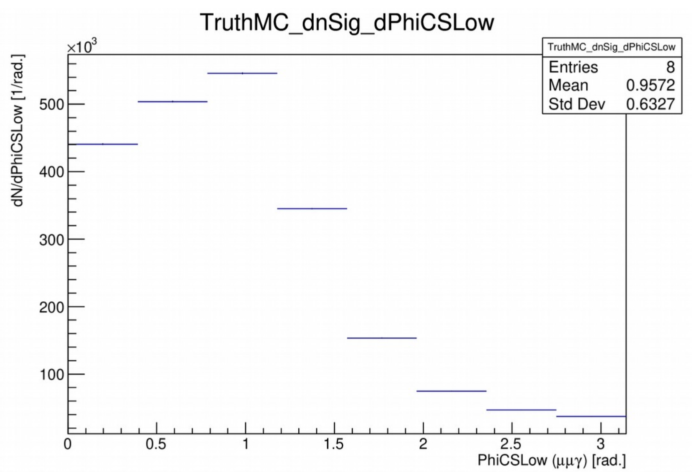
$$P_0\left(1+\sum_{i=1}^{i=6} p_i \cos(ix)\right)$$

$$x = PhiCS$$

$$p_2 \sim \cos 2\phi$$

$$p_4 \sim \cos 4\phi$$

Plots of dN/dX for Truth Signal MC w/ photons > 5 GeV and muons > 4 GeV for two cuts on $\cos^2\theta$



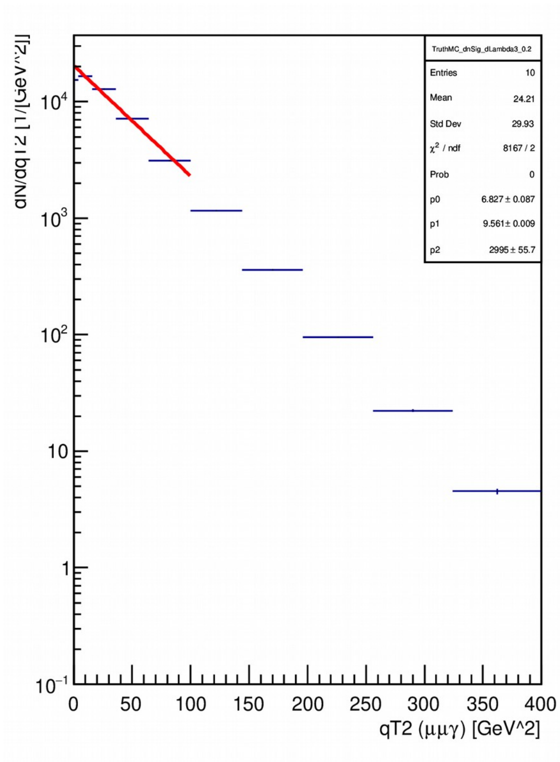
$$\lambda^2(9+6z^2+z^4)\left(1+\left[\frac{(1-z^2)^2}{9+6z^2+z^4}\right]\cos 4\phi\right)$$

- Hope to use our various MC samples to correct the data, and that will affect the first and last term equally. We cannot clean separate out the two terms.
- Plotted dN/dX (X = High or Low PhiCS)
- Cut on PhiCS for events with $\cos^2\theta > 0.095$ (PhiCSHigh) and with $\cos^2\theta < 0.095$ (PhiCSLow)
- Took ratio of Truth MC for the high and low cuts and fitted
- In MC there is NO polarized component hence with full acceptance there should be no p2 or p4, apart from p0. So acceptance cuts generate some p2, but no p4.
- Use this plot, along with others, to correct the data. Can potentially see p4 value in data, which indicates $\cos 4\phi$ dependence.

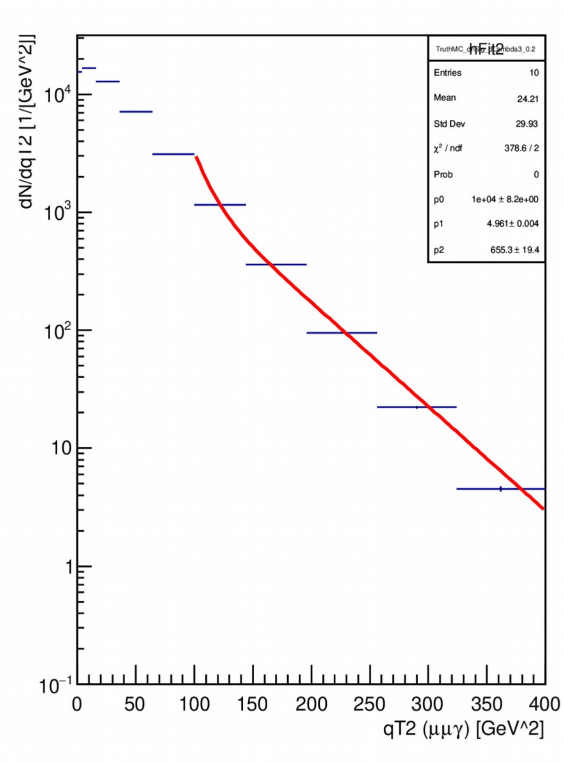
J/ψ + χ Production at the LHC

Part Five

Monte Carlo



$P1 = 9.561 \pm 0.009$



$P1 = 4.961 \pm 0.004$

Truth MC distribution plots of the variable qT2 with a cut of 25 > ƛ < 50.

Fit Function

$$P_0 * \left(\exp\left(\frac{-X}{2P_1^2}\right) + P_2 \exp\left(\frac{-2X}{p_1^2}\right)\right)$$

- Small bump at ƛ ~ 100.
- Fit the same function over two regions
- P1 in the fit function is the average pT of a single gluon in a proton

Associated Production of a Dilepton and a (J/ψ)

Associated Production of a Dilepton and a (J/ψ)

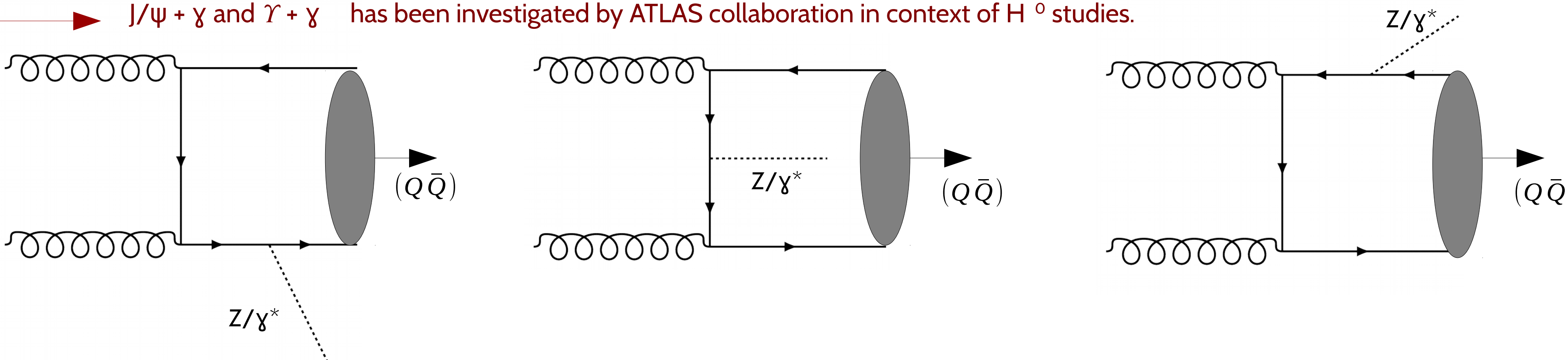
Part One

arXiv:1702.00305v1 *J.P Lansberg, C.Pisano, M. Schlegl*

Motivation

Motivation: Could extract information about linear polarization of gluons from a (J/ψ) produced with a dilepton, be it from a Z boson or a virtual photon, in a kinematical configuration such that their transverse momentum are almost back to back. The detection of a dilepton may be experimentally easier or cleaner compared to a photon.

- Cross section for J/ψ production in association with a Z boson has been studied by the ATLAS collaboration, and compared with theoretical predictions..
- J/ψ + ɣ and Υ + ɣ has been investigated by ATLAS collaboration in context of H ^{0} studies.



Leading order diagrams from the subprocess gg ⟶ Q Z/ɣ*. Diagrams where the directions of quark lines are reversed also contribute.

$\alpha \equiv \frac{M_Q}{Q}$ $\beta \equiv \frac{M_B}{Q}$ Collins Sopher

$$\frac{d\sigma^{pp\to J/\psi[\Upsilon]\ell\bar{\ell}X}_{\text{TMD, LO}}}{d^4q\, dM_B^2\, d\Omega} = \hat{F}_1(Q,\alpha,\beta,\theta)\, \mathcal{C}[f_1^g\, f_1^g] + \hat{F}_2(Q,\alpha,\beta,\theta)\, \mathcal{C}[w_2\, h_1^{\perp g}\, h_1^{\perp g}]$$

$$+ \left\{ \hat{F}_{3a}(Q,\alpha,\beta,\theta)\, \mathcal{C}[w_{3a}\, h_1^{\perp g}\, f_1^g] + \hat{F}_{3b}(Q,\alpha,\beta,\theta)\, \mathcal{C}[w_{3b}\, f_1^g\, h_1^{\perp g}] \right\} \cos 2\phi$$

$$+ \hat{F}_4(Q,\alpha,\beta,\theta)\, \mathcal{C}[w_4\, h_1^{\perp g}\, h_1^{\perp g}]\, \cos 4\phi, \qquad ($$

Associated Production of a Dilepton and a (J/ψ)

Part Two

Cross Section

$$N^{(0)} \equiv \int \mathrm{d}\Omega \frac{\mathrm{d}\sigma^{pp\to J/\psi[\Upsilon]\ell\bar{\ell}X}_{\mathrm{TMD,\,LO}}}{\mathrm{d}^4q\,\mathrm{d}M_B^2\,\mathrm{d}\Omega} = \frac{\mathrm{d}\sigma^{pp\to J/\psi[\Upsilon]\ell\bar{\ell}X}_{\mathrm{TMD,\,LO}}}{\mathrm{d}^4q\,\mathrm{d}M_B^2} = \hat{F}_1(Q,\alpha,\beta)\,\mathcal{C}[f_1^g\, f_1^g] + \hat{F}_2(Q,\alpha,\beta)\,\mathcal{C}[w_2\, h_1^{\perp g}\, h_1^{\perp g}]\,,$$

$$N^{(2)} \equiv \int \mathrm{d}\Omega \cos 2\phi\, \frac{\mathrm{d}\sigma^{pp\to J/\psi[\Upsilon]\ell\bar{\ell}X}_{\mathrm{TMD,\,LO}}}{\mathrm{d}^4q\,\mathrm{d}M_B^2\,\mathrm{d}\Omega} = \hat{F}_3(Q,\alpha,\beta)\,\left(\mathcal{C}[w_{3a}\, h_1^{\perp g}\, f_1^g] + \mathcal{C}[w_{3b}\, f_1^g\, h_1^{\perp g}]\right)\,,$$

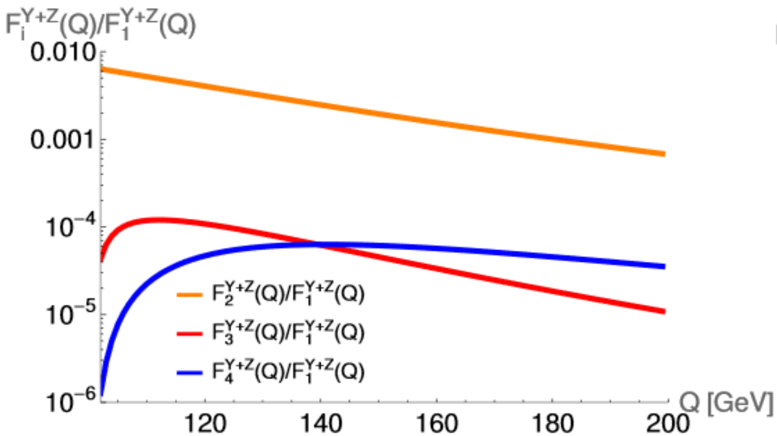
$$N^{(4)} \equiv \int \mathrm{d}\Omega \cos 4\phi\, \frac{\mathrm{d}\sigma^{pp\to J/\psi[\Upsilon]\ell\bar{\ell}X}_{\mathrm{TMD,\,LO}}}{\mathrm{d}^4q\,\mathrm{d}M_B^2\,\mathrm{d}\Omega} = \hat{F}_4(Q,\alpha,\beta)\,\mathcal{C}[w_4\, h_1^{\perp g}\, h_1^{\perp g}]\,. \tag{23}$$

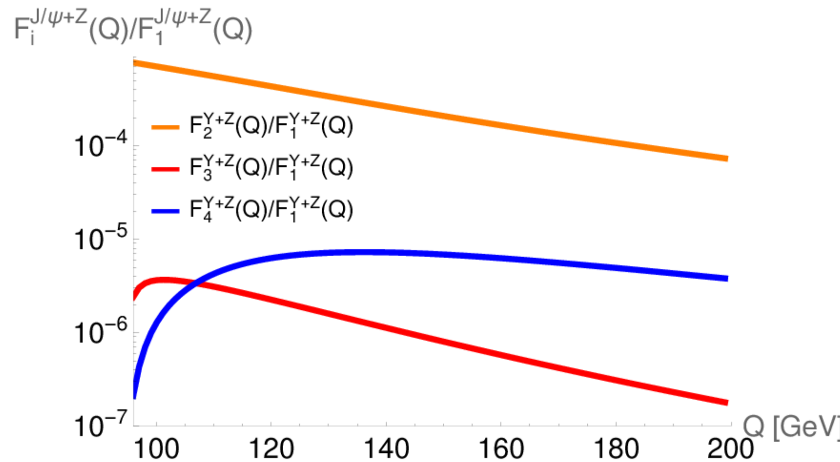
- This is the form of the weighted cross section
- It is more instructive to analyse the cross section that is integrated over Collins-Sopher angles, including a possible azimuthal weighting factor. These weighting factors could enable the theorists to disentangle the various azimuthal contributions in the weighted cross section.
- The integrated cross section over θ can be found in the literature.

Associated Production of a Dilepton and a Υ(J/ψ)

Numerical Predictions for an associated quarkonium + Z

Part Three





- Numerically compare the relative size of both contributions from unpolarized and linearly polarized gluons to the angular integrated cross section, by considering the LO ratios $F_{2,3,4}(Q,, \beta)/F_1(Q,,\beta)$.
- Focus on the production of a real Z , I.e dileptons with an invariant mass around the Z-pole mass, $M_B \simeq m_Z$
- The ratios are rather small: ratio of F_2/F_1 ~ 0.5% at most for Υ production, and even smaller (< 10^{-3}) for J/ψ production.
- The convolution $C[w_2\, h_1^{\perp g}\, h_1^{\perp g}]$ factor from linearly polarized gluons does not exceed in size the convolution factor $C[f_1^g\, f_1^g]$
- Other literature suggest that the scale independent ratic $R = C[w_2\, h_1^{\perp g}\, h_1^{\perp g}]/C[f_1^g\, f_1^g]$ is at most 2/3 for a small scale Q ~ 3 GeV.
- Not reasonable to neglect contribution from linearly polarized gluons from the term N^(0) in the weighted cross section.

LHS: Result for an associated Υ` state with mass m_Υ = 9.46 GeV.

RHS: Result for an associated J/ψ state with mass $m_{J/\psi}$ = 3.1 GeV.

Conclusions

- Active area of theory research
- A lot less is going on experimentally
- Theory papers suggest that future ep colliders would be preferable for TMD measurements