Quarkonium and TMDS in hh: Past and future measurements

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Introduction

- Transverse momentum dependent parton distribution functions (TMDs) are a consequence of extending collinear factorisation to include the transverse dynamics of partons.
- This aims to account for the intrinsic transverse momentum k_T of quarks and gluons inside the nucleon.
- There a variety of types of TMDs that have been defined, each encodes the probability density for certain polarizations of nucleons and partons. Shown here are the gluon TMDs, there is a similar mirror to these for the quark TMDs.

gluon polarisation

nucleon polarisation	U	circular	linear
U	f_1^g		$h_1^{\perp g}$
L		g_1^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	h_1^g, $h_{1T}^{\perp g}$

- This talk will focus mainly on f_1^g and $h_1^{\perp g}$.
- These two TMDs encapsulate the dynamics of unpolarised gluons and linearly polarised gluons respectively, inside the unpolarised nucleon.
- Part of what motivates the study of these TMDs is not only is the option to study the nucleon in multiple dimensions of momentum, but the opportunities to test our understanding of QCD in a range of ways at the LHC.

Introduction

- Although a fair amount of work has been done in terms of quark TMDs, less is known about their gluon counterpart.
- This is due to a variety of problems in obtaining a clean measurement.
- One issue to bear in mind is that there are not a lot of processes that are sufficiently sensitive to TMDs in the kinematic regions accessible in active experiments.
- Fortunately, quarkonium production is considered by many to be a good option in terms of both sensitivity and its availability in data.
- There are two main ways that the TMD effects are expected to be present;
  - TMDs directly affecting the p_T distributions in the final state
  - TMDs generating azimuthal asymmetries in the Collins-Soper (CS) frame.

Introduction

- Here are some of the final states in hadron-hadron collisions that include quarkonia that are expected to be sensitive to TMD effects;
  - $gg \to \eta_{c,b}$
  - $gg \to J/\psi(\Upsilon) + \gamma$
  - $gg \to J/\psi(\Upsilon) + \ell\bar{\ell}$
  - $gg \to \eta_c + \eta_c$
  - $gg \to J/\psi(\Upsilon) + J/\psi(\Upsilon)$
- Processes are often favoured when they are dominantly produced by color singlet contributions. The processes with significant color octet contributions generate final state interactions that can break the TMD factorisation.
- Single production states do present a simpler channel to analyse in comparison to associated production.
- However, even with the larger cross sections available at the HL-LHC, accessing the regions with near-zero transverse momentum and where the factorisation is valid with detectors like ATLAS and CMS still presents an experimental challenge.
- In comparison, at HL-LHC, the increased integrated luminosity available for associated production channels should make them more accessible.
- Single production modes also differ in that $h_1^{\perp g}$ is not accessible directly, but does show up via the effects in p_T, alongside f_1^g.
- Associated productions are different in this manner as the effects on $h_1^{\perp g}$ can be accessed via azimuthal asymmetries in the final state.

Theoretical outline

- The region where TMDs are present is constrained by the scale of Λ_{QCD} on the lower bound and the subprocess scale on the upper bound.
- Therefore, for any system or single particle the transverse momentum p_T must be less than half of the invariant mass M_{inv}.

$$p_T \lesssim M_{inv}/2$$

- So to take a look at the TMDs, the observed p_T distribution should reach from this limit down to nearly 0.
- This presents a number of complications for detectors where there are p_T thresholds affecting the acceptance of particles in the final state.
- A cross section in the gg fusion processes seen at modern hadron colliders can be expressed as the convolution of the short distance matrix elements $\mathcal{M}^{\mu\rho}$ with gluon correlators Φ_g

$$\frac{d\sigma}{d\mathcal{R}} = \frac{(2\pi)^4}{8s^2} \int d^2\boldsymbol{k}_{1T} d^2\boldsymbol{k}_{2T} \delta^2(\boldsymbol{k}_{1T} + \boldsymbol{k}_{2T} - \boldsymbol{p}_T) \mathcal{M}_{\mu\rho} (\mathcal{M}_{\nu\sigma})^* \times \Phi_g^{\mu\nu}(x_1, \boldsymbol{k}_{1T}) \Phi_g^{\rho\sigma}(x_2, \boldsymbol{k}_{2T})$$

- $d\mathcal{R}$ is the outgoing phase space element and the rest of the symbols have their typical meaning.
- For the unpolarised proton, the gluon correlators Φ_g can be expressed in terms of the TMDs

$$\Phi_g^{\mu\nu}(x, \boldsymbol{k}_T) = \frac{1}{2x} \left\{ g_T^{\mu\nu} f_1^g - \left(\frac{k_T^\mu k_T^\nu}{M_p^2} + g_T^{\mu\nu} \frac{\boldsymbol{k}_T^2}{2M_p^2} h_1^{\perp g} \right) \right\}$$

Theoretical outline

- The general form for the differential cross section with TMDs is

$$\frac{d\sigma}{dMdYd^2Pd\Omega} = \mathcal{J} \times \Big\{ F_1\mathcal{C}\left[f_1^g f_1^g\right] + F_2\mathcal{C}\left[w_2 h_1^{\perp g} h_1^{\perp g}\right] + \cos(2\phi_{CS})\left(F_{3a}\mathcal{C}\left[w_{3a} f_1^g h_1^{\perp g}\right] + F_{3b}\mathcal{C}\left[w_{3b} h_1^{\perp g} f_1^g\right]\right) + \cos(4\phi_{CS}) F_4\mathcal{C}\left[w_4 h_1^{\perp g} h_1^{\perp g}\right] \Big\}$$

- For associated production ϕ_{cs} and θ_{cs} are the angles in the CS frame.

$$d\mathcal{R} = dMdYd^2p_T d\cos\theta_{cs} d\phi_{cs}$$

- All the terms in $\{\ldots\}$ contain the interesting dependencies, $\mathcal{J}$ depends on the masses.
- The convolutions $\mathcal{C}$ have the following form, where f and g would be TMDs.

$$\mathcal{C}[wfg] = \int d^2\boldsymbol{k}_{1T} \int d^2\boldsymbol{k}_{2T}\delta^2(\boldsymbol{k}_{1T} + \boldsymbol{k}_{2T} - \boldsymbol{p}_T)w(\boldsymbol{k}_{1T}, \boldsymbol{k}_{2T})f(x_1, \boldsymbol{k}_{1T}^2)g(x_2, \boldsymbol{k}_{2T}^2)$$

- The factors F_i should not depend on either the rapidity or transverse momentum of the system. These factors contain $\cos(\theta_{cs})$ dependence but no ϕ_{cs} dependence.
- w terms are some general weights and it can be noted that $F_1 \geq F_{2,3a,3b,4}$, so F_1 is the leading term in the effects of TMDs.
- As f_1^g alone is associated with F_1, this suggests that the contribution of this TMD should be the largest relative to the others, and hence the most accessible.

TMD models and accessing them

- What is known about TMDs true form is limited by the lack of experimental data, simple forms are assumed.
- For f_1^g is assumed to have a Gaussian dependence on the intrinsic gluon $\boldsymbol{k}_T$;

$$f_1^g(x, \boldsymbol{k}_T^2) = \frac{G(x)}{\pi \langle \boldsymbol{k}_T^2 \rangle} \exp\left\{ -\frac{\boldsymbol{k}_T^2}{\langle \boldsymbol{k}_T^2 \rangle} \right\}$$

- Here $G(x)$ is the collinear distribution function for gluons and $\langle \boldsymbol{k}_T^2 \rangle$ is assumed to be independent of x
- A relation has been established between f_1^g and $h_1^{\perp g}$ with a model-independent positivity bound.
- Taking theoretical suggestions, two forms of $h_1^{\perp g}$ are established with Model 2 saturating this positivity bound.

$$h_{1\ \text{Model 1}}^{\perp g} = \frac{M^2 G(x)}{\pi \langle k_T^2 \rangle^2} \exp\left\{1 - k_T^2 / r \langle k_T^2 \rangle\right\} \qquad h_{1\ \text{Model 2}}^{\perp g} < \frac{2M^2}{k_T^2} f_1^g$$

- In this picture, there is one value that needs to be established from experiment to parameterise f_1^g, $\langle k_T^2 \rangle$.
- This can be done by taking the width of a gaussian fitted to the p_T distribution of the channel under examination in the applicable region.
- Theoretically, the azimuthal modulations can be accessed by evaluating the following;

$$\langle \cos(n\phi_{cs}) \rangle = \frac{\int d\phi_{cs} \cos(n\phi_{cs}) \frac{d\sigma}{d\mathcal{R}}}{\int d\phi_{cs} \frac{d\sigma}{d\mathcal{R}}}$$

- This works when there is the availability of the full phase space and there are no distortions which is not a true generally in experiment. Instead, modulations can be accessed by fitting the cross section in terms of ϕ_{cs} to an expansion of $P_0 \left\{1 + \left[\sum_{n=1}^{n<6} P_n \cos(n\phi_{cs})\right]\right\}$

Single $\mathcal{Q}$ production

- Work pertaining to these channels is centered around η_c,χ_{c0},η_b, and χ_{b0}.
- This is due to single vector quarkonia being inaccessable via a clean gluon fusion at leading order.
- There are several useful properties of these scalar and pseudoscalar states;
  - The C-even quarkonia production should not be subject to large QCD corrections at low p_t
  - They have extremely simple kinematics.
- These channels are be more easily accessible with forward region or fixed target style detectors.
- This is due to their production at low p_T causing them to be lost to the acceptance limits of detectors like ATLAS or CMS.
- For single quarkonium production, the differential cross section with TMDs is quite simple;

$$\frac{d\sigma}{dYd^2p_t} = \mathcal{J} \times \left\{ F_1 \mathcal{C}\left[f_1^g f_1^g\right] \pm F_2 \mathcal{C}\left[w_2 h_1^{\perp g} h_1^{\perp g}\right] \right\}$$

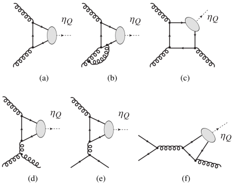
- $+$ for scalar quarkonia, $-$ for pseudoscalar.
- Here F_1 and F_2 are equal, and the F_{3ab} and F_4 terms are zero.

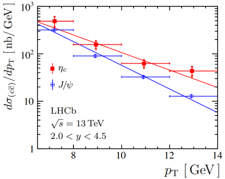
Single $\mathcal{Q}$ production

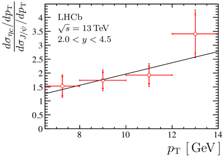
- There have been no extractions of TMDs from single $\mathcal{Q}$ production through experimental means, though it is worth examining recent measurements of the $\eta_c(1S)$ cross section at LHCb [arXiv:1911.03326v2].
- Although interesting, the measurement does not cover the area of interest as η_c production is constrained to $p_T \lesssim 1.5$GeV
- This analysis measurement was constrained to $6.5 > p_T > 14.0$GeV and the η_c was measured via a $p\bar{p}$ channel alongside a J/ψ, in the region $2.0 < y < 4.5$

$$\frac{\sigma^{\text{prompt}}_{\eta_c}}{\sigma^{\text{prompt}}_{J/\psi}} = \frac{N^{\text{prompt}}_{\eta_c}}{N^{\text{prompt}}_{J/\psi}} \times \frac{\epsilon_{J/\psi}}{\epsilon_{\eta_c}} \times \frac{\mathcal{B}_{J/\psi \to p\bar{p}}}{\mathcal{B}_{\eta_c \to p\bar{p}}}$$

- $N^{\text{prompt}}_{\mathcal{Q}}$ are the yields, $\epsilon_{\mathcal{Q}}$ is the combined efficiencies of trigger, reconstruction and selection, and $\mathcal{B}$ the branching ratios.
- Interestingly, from the plots on the right detailing the cross section with respect to p_T of the J/ψ and η_C, it can be seen that the p_T tails of the J/ψ are more narrow than that of the η_c.
- Is this a consequence of some higher order correction that would be seen in a production model at higher p_T?







Single $\mathcal{Q}$ production

- If possible, future analyses of these process using a fixed-target setup (such as the AFTER proposal $\sqrt{s} = 115\text{GeV}$) may offer the required sensitivity to the low p_T regions sensitive to the TMDs
- This is mainly a product of the reduced combinatorical backgrounds at from lower energies, and the understanding that the pseudoscalar quarkonium cross sections should behave similarly to those of the vector quarkonium.
- η_b may also be promising for future studes due to its larger mass and hence extended range where TMD factorisation is applicable.
- There are caveats for use the χ_c and χ_b, discussed in [arXiv:1405.3373], suggesting TMD factorisation could break down as a consequence of CO content.
- However, some data from LHCb [arXiv:1307.4285v3] suggests that CO contributions are not in line with some predictions, hence $\chi_{c,b}$ states should be included in searches for a complete perspective.

Di-$\mathcal{Q}$ production

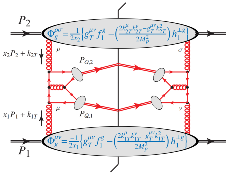
- Di-Quarkonia channels have features that offer some benefits for the measuring of TMDs [arXiv:1710.01684v2]
  - Behaviour of the F factors in certain kinematic regions affecting the sensitivity to $h_1^{\perp g}$.
  - Suppression of CO and DPS production contributions, in some kinematic regions, that would otherwise break TMD factorisation.
- The differential cross section for di-$\mathcal{Q}$ takes the form seen before, though when exploring the limit of large invariant masses $M_{\mathcal{Q}\mathcal{Q}} \gg M_{\mathcal{Q}}$, low Δy, with $\cos(\theta_{cs}) \to 0$, the F factors take a different form.

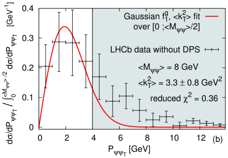
$$F_4 \to F_1 \qquad F_2 \to \frac{81 M_{\mathcal{Q}}^4 \cos^2(\theta_{cs})}{2 M_{\mathcal{Q}\mathcal{Q}}^4} F_1 \qquad F_{3a} = F_{3b} \to \frac{-24 M_{\mathcal{Q}}^2 \cos^2(\theta_{cs})}{M_{\mathcal{Q}\mathcal{Q}}^2} F_1 \qquad F_1 = \frac{256\mathcal{N}}{M_{\mathcal{Q}\mathcal{Q}}^4 M_{\mathcal{Q}}^2}$$

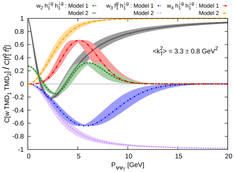
- With $\mathcal{N} = 2^{11} 3^{-4} \pi^2 \alpha_s^4 |R_{\mathcal{Q}}(0)|^4$
- In this high $M_{\mathcal{Q}\mathcal{Q}}$ limit, F_2 and F_3 are essentially suppressed. Even over the whole phase space F_2 is still expected to give a relative contribution of less than 1% in comparison to F_1
- As such, this is a good opportunity for studying $h_1^{\perp g}$, measuring $\langle \cos(4\phi_{cs}) \rangle$ should give a reading of the relative presence of $h_1^{\perp g}$ against f_1^g.
- Similarly, integrating out ϕ_{cs} and performing the appropriate fit should give a measure of f_1^g.
- In this same kinematic region, the applicability of TMDs is not disrupted by either CO or DPS contributions.
- CO contributions to SPS are suppressed by a factor of v^4 per $\mathcal{Q}$, which, in the Di-J/ψ case should push the CO/CS fraction to less than 0.01.
- This fraction is expected to be even lower in the Di-Υ case.

Di-$\mathcal{Q}$ production

- DPS contributions in the Di-J/Ψ production, in the regions where the greatest sensitivity to $h_1^{\perp g}$ is expected, are expected to be on the order of 10%. This DPS contribution is expected to be $\sim 5\%$ at low p_T and central rapidities for Di-Υ [arXiv:1909.05769v1]
- These contributions may be dominant at large Δy and small in the regions used to probe TMDs, they should still be subtracted in the interests of minimizing uncertainty.
- This can be done with the assumption that two $\mathcal{Q}$ produced by DPS are uncorrelated, this should be given extra care in current LHCb analyses where the contribution is expected to be higher.
- The first constraints placed on f_1^g using this channel (and in general) were produced in [arXiv:1710.01684v2] from LHCb data at $\sqrt{s} = 13\text{TeV}$. These results yielded $\langle k_T^2 \rangle = 3.3 \pm 0.8\text{GeV}^2$.
- It is crucial that in this measurement that the sensitivity to individual J/ψ stretches down to p_T of 0GeV, in order to have a valid determination of TMDs, undisturbed by
- The ratios of the TMD convolutions based on the previously given models for $h_1^{\perp g}$, with the measured $\langle k_T^2 \rangle$ are given in the bottom right.

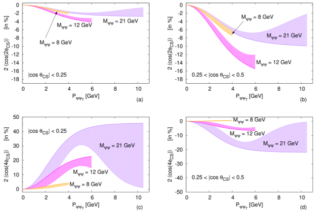


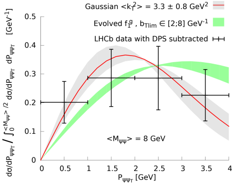


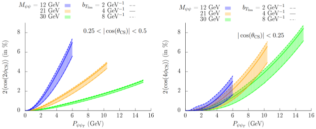


Di-$\mathcal{Q}$ production

- These models were then used to produce predictions of the azimuthal modulations. Of note here is the particularly large size of the azimuthal modulation of $> 40\%$ in the ranges that would be probed by ATLAS and CMS measurements.
- The authors of this study suggest that should these models prove to be accurate, ATLAS and CMS could make a measurement with data already recorded.
- Since this measurement, further work has been performed in [arXiv:1909.05769v1] augmenting the previous results by including TMD evolution effects.
- As a result of this, the azimuthal modulation was constrained to a more realistic region, shown bottom right, though the effects are still in an accessible range. Plots for the strength in modulation were also produced for $M_{\mathcal{Q}\mathcal{Q}}$
- Furthermore, Di-Υ pair production has been studied [arXiv:1610.07095v2], though the results are still limited by a lack of available statistics, which should improve in future.
- Continued studies in this direction are encouraged as larger data samples are produced, allowing further fits of f_1^g and constraints on $h_1^{\perp g}$

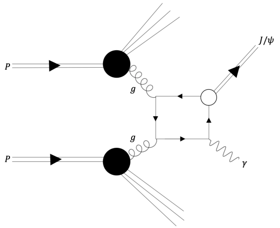






$\mathcal{Q} + \gamma$ production

- $\mathcal{Q} + \gamma$ offers another promising channel for accessing the TMDs of interest.
- CO contributions are suppressed by the back to back production of $\mathcal{Q} + \gamma$, and further reduction of any possible CO contribution can be accessed by applying isolation criterea to $\mathcal{Q}$
- Moreover, as well as escaping the constraints on p_T seen in $2 \to 1$ production, allowing $\mathcal{Q}$ to be produced at high enough transverse momenta to be detected at ATLAS and CMS, production of a real photon has benefits.
- With a real photon $F_2 \to 0$, allowing f_1^g to be studied in isolation after integrating out $\cos(\phi_{cs})$ dependence.
- The scaling of the remaining F factors offers some interesting features, F_4 scales like F_1, allowing the extraction of $h_1^{\perp g}$ via $\cos 4\phi_{cs}$ modulations, though F_4/F_1 is expected to be small.
- There is, however, concern about contamination sourcing from DPS in the kinematic regions currently available the LHC which needs to be separated.
- It's conceivably possible to measure f_1^g and $h_1^{\perp g}$ in this channel with an ATLAS like experiment. Work on this is in progress and will be shown in the context of managing the detrimental effects of some acceptance cuts.

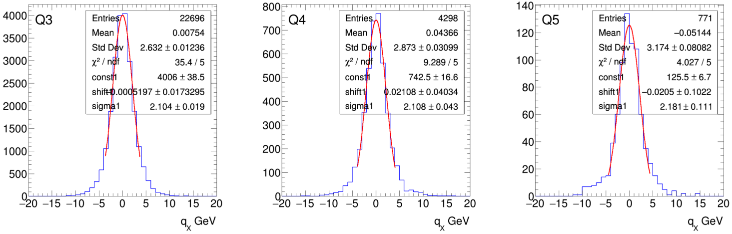


Barriers to measurement - acceptance and background

- There's sufficient reason to attempt to extract details of gluon TMDs with $gg \to J/\psi + \gamma$ at ATLAS and CMS.
- However, as well the contributions from DPS, there are other factors that need to be accounted for.
- There are other sources contributing to the background, such as those J/ψ produced from b decays.
- A more prominent issue is the management of acceptance cuts that are imposed by the nature of the detector.
- In the case of ATLAS, the detector and trigger system is blind to muons below 4GeV and as a consequence to decect a J/ψ, it must have p_T above 8GeV
- Similarly, the photons are subject to a p_T threshold of about 5GeV.
- It's worth noting that the acceptance requirements for Υ are expected to be different.
- The rest of this section will dicuss simulation studies with ATLAS kinematics using a $J/\psi + \gamma$ final state.

Distortion from acceptance

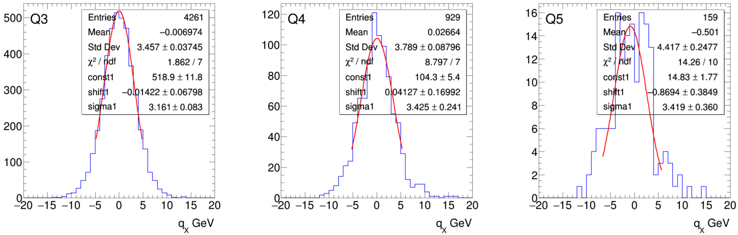
- An assumption made when measuring f_1^g is that the p_T distribution of the system, called q_T here, is actually reflective of the gluon transverse momentum.
- Lets examine this by looking at Truth-level similations of $q_x = q_T \cos\phi_{lab}$, firstly with no acceptance cuts.
- As this is ϕ in the lab frame, we can expect the distribution if $q_y = q_T \sin\phi_{lab}$ to essentially be a mirror of this.



- From left to right is the Entries/1GeV in the mass ranges of $15.5-22$GeV, $22-31$GeV, and $31-44$GeV, labelled Q3, Q4, and Q5, respectively.
- In this MC there is no visible evolution in the shape and width of these fits across all three mass ranges.

Distortion from acceptance

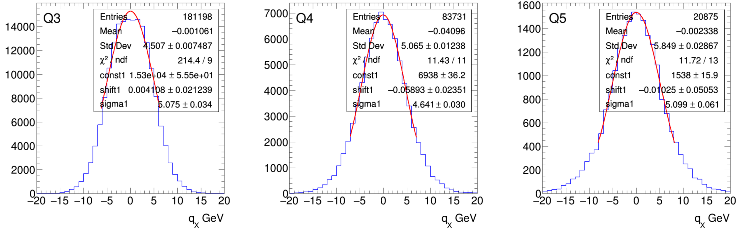
- If the cuts are increased to $p_{T,\mu} > 2\text{GeV}$ and $p_{T,\gamma} > 4\text{GeV}$, and the q_x is plotted again, notable changes are visible.



- There is a noticable progression of σ_1 across the three mass ranges.
- Along with this, the shape of the distributions change, and there is a significant reduction in statistics.

Distortion from acceptance

- Now, move on to cuts that would satisfy minimal realistic acceptance cuts at ATLAS
- $p_{T,\mu} > 4\text{GeV}$ and $p_{T,\gamma} > 5\text{GeV}$.

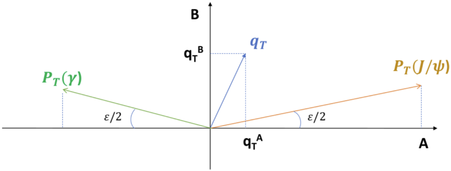


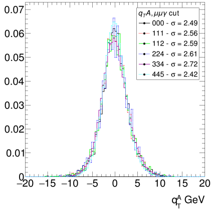
- Both σ_1 and the shape of the distribution are variable across mass ranges, and the width of the distribution is significantly increased.
- If $\sigma \approx 5.1\text{GeV}$ were taken to parameterise f_1^g this would not be sufficient to quantify the actual distribution with $\sigma \approx 2.1\text{GeV}$.

A remedy for acceptance cuts

- These acceptance effects can hopefully be avoided if a special kinematic selection is used.
- This involves using the fact that if the photon and $\mathcal{Q}$ are roughly back to back, it's possible to define $\epsilon = \pi - \Delta\phi$, where epsilon is small.
- Expressing $q_T^2 = \left(\vec{p}_{T,J/\psi} + \vec{p}_{T,\gamma}\right)^2$, then using truncated series expansions, we can arrive at new variables.
- These new variables q_T^A and q_T^B are the components of q_T along the axes A and B, which are defined uniquely in each event.
- This A axis forms the same angle between the J/ψ and γ each time, and is aligned along the J/ψ direction.
- Exposing q_T^A to these progressive acceptance cuts, a decent resistance to the detrimental effects can be demonstrated.
- Using this in place of q_T should allow the connection between the initial k_T of the gluons and the final state to be preserved through the cuts.

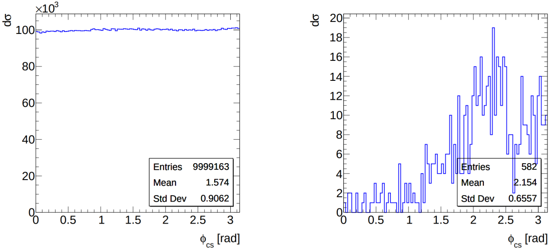
$$
\begin{aligned}
q_T^2 &= p_{T,J/\psi}^2 + p_{T,\gamma}^2 + 2p_{T,J/\psi}p_{T,\gamma}\cos\Delta\phi \\
&= p_{T,J/\psi}^2 + p_{T,\gamma}^2 - 2p_{T,J/\psi}p_{T,\gamma}\cos\epsilon \\
&\simeq p_{T,J/\psi}^2 + p_{T,\gamma}^2 - 2p_{T,J/\psi}p_{T,\gamma}\left(1 - \frac{\epsilon^2}{2}\right) \\
&= \left(p_{T,J/\psi} - p_{T,\gamma}\right)^2 + p_{T,J/\psi}p_{T,\gamma}\sin^2\epsilon = (q_T^A)^2 + (q_T^B)^2
\end{aligned}
$$





Azimuthal distortion from acceptance

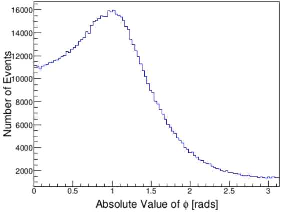
- The method on the previous slide hopes to recover some sensitivity to f_1^g, though maintaining sensitivity to $h_1^{\perp g}$ is a separate matter.
- Effects of cuts on $h_1^{\perp g}$ are different, and require a different solution, though they are much easier to illustrate.
- By viewing a truth-level simulation of the cross section with respect to ϕ_{cs} and applying the acceptance cuts of $p_{T,\mu} > 4\text{GeV}$ and $p_{T,\gamma} > 5\text{GeV}$, the issue is plain.

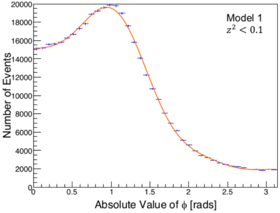


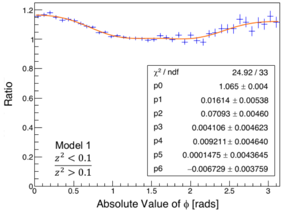
- Note that this is a simulation with $h_1^{\perp g} = 0$.
- Not only is there a severe reduction in statistics, but there are no realistic hopes of measuring any form of $\cos 2\phi_{cs}$ or $\cos 4\phi_{cs}$ modulations from the distribution after the acceptance cuts.
- These acceptance cuts develop a strong dependence on ϕ_{cs} on their own.

Fixing the azimuthal distortion

- The hopeful breakthrough in managing this distortion comes from understanding of what regions are more sensitive to our TMDs.
- When examining the $\cos(4\phi_{cs})$ modulation, it can be seen that the modulation is much stronger in regions corresponding to lower values of $\cos^2(\theta_{cs})$.
- This combined with the fact that it appears that the distortion of ϕ_{cs} from the acceptance cuts is present almost independently of $\cos^2\theta_{cs}$.
- Hence, if the cross section is split into two parts of roughly equal statistics, around a working point of $\cos^2(\theta_{cs}) = 0.1$, then the two regions can be divided, cancelling out the bulk of the distortion and leaving the modulation.

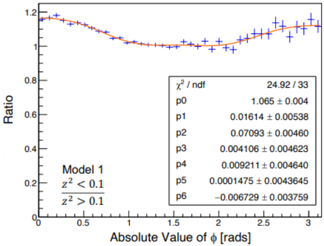


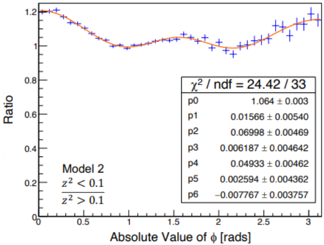




Fixing the azimuthal distortion

- Some simulation of this has been performed, this is comparison of the ratios that result from distributions with a weight applied to simulate the effects of Models 1 and 2 of $h_1^{\perp g}$.

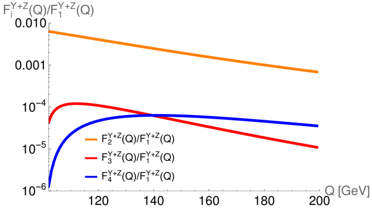


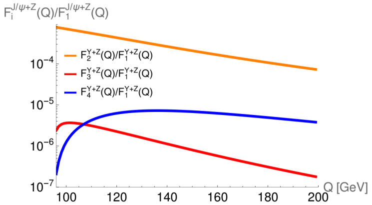


- If this sensitivity can be maintained through experimental data, there is some chance to measure h_1^g with current samples, though demonstration does not have the statistical limitiations that would be seen in experiment.

$\mathcal{Q} + \ell\bar{\ell}$

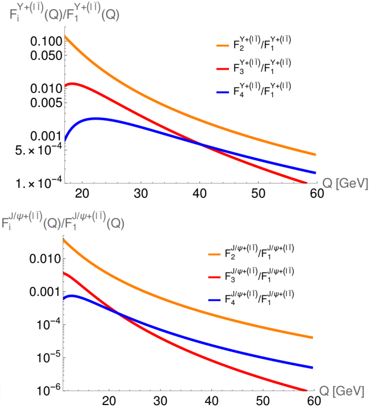
- This state is initiated from either the generation of $\mathcal{Q} + Z$ or $\mathcal{Q} + \gamma^*$ [arXiv:1702.00305v1].
- Essentially, this is an extension of the $\mathcal{Q} + \gamma$ state, motivated by the opportunity to maintain TMD factorisation while using a probe that could be cleaner in experiment than a real photon.
- Detecting a dilepton pair with a recombined invariant mass in the appropriate Z window is preferred to a single real photon, as no isolation method need be applied.
- Here F_2 factors are not expected to be zero and in the case of the Z associated production, the F_2/F_1 ratio is on the order of less than 1% for Υ and less than this for J/ψ
- This is unfortunately a common theme, with F_3 and F_4 also expected to be inconveniently small in Z associated production, with neither ratio against F_1 for Υ or J/ψ rising above the 10^{-4} level.





$\mathcal{Q} + \ell\bar{\ell}$

- The bad news continues when examining these ratios for $\mathcal{Q} + \gamma^*$. Although the F ratios here are larger than with the Z associated production, they are still smaller than in cases with real photons.
- It is also expected that reduced cross sections and available integrated luminosities of these final states are too low for extraction right now.
- There is also reason to believe that there is significant levels of DPS contributions in the kinematic regions accessible by the LHC that would need to be managed.
- With all this considered, the case of $\mathcal{Q} + Z$ production is probably not as well suited to extracting azimuthal modulations, though the authors of the paper suggest that the cross section could be approximated to just those terms including F_1.
- For the meantime, $\mathcal{Q} + \gamma^*$ does appear somewhat viable, though the case of the associated production with a real photon is preferred.



Summary

- Over the last few years there has been a continually developing understanding of the factors that govern the experimental sensitvity to gluon TMDs in channels with quarkonia.
- A number of different processes have been looked at theoretically and the suitibility of these processes has been assessed.
- There are good prospects for extracting gluon TMDs in a variety of different experimental setups.
- Most notably is the potential of future fixed target experiments, the HL-LHC, and continued data collection at detectors such as ATLAS, CMS and LHCb.
- There are some experiemntal barriers to sensititvity at detectors such as ATLAS and CMS though work is underway to mitigate these.

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Thanks for listening, and thanks to everyone who contributed to the materials shown today.

STSAs

Backup slides.

STSAs

- It's worth discussing other TMDs that may be accessible in the future, in particular, potential access to $f_{1T}^{\perp g}$ that encodes the distribution of unpolarised gluons inside a nucleon with transverse polarisation.
- This TMD should be accessible via Single transverse-spin asymmetries (STSAs) at the HL-LHC in a fixed target mode. STSAs are described as;

$$A_N = \frac{1}{\mathcal{P}_{\text{effective}}} \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

- Here $\mathcal{P}_{\text{effective}}$ is the effective polarisation and $\sigma^{\uparrow,\downarrow}$ is the differential cross section with a nucleon polarised in the up or down direction.
- These STSAs were observed in the '70's and a number of theoretical mechanisms have been proposed to account for them. There is collinear twist-3 (CT3), an approach within TMD factorisation, and a phenomenelogical approach with the Generalised Parton Model (GPM), though the details of these are beyond the scope of this talk.
- A number of processes are expected to be sensitive to these asymmetries.
- Fisrtly, vector $\mathcal{Q}$ production, although not directly sensitive due to factorisation breaking effects, GPM and its Colour-Gauge-Invariant extension allows phenomenelogical counterparts to be examined instead.
- This is done by using analagous objects, Gluon Sivers functions (GSFs) to treat STSA's as factorisable.
- GSFs constrained from data at RHIC describe available J/ψ data well, hence the motivation to extend this type of measurement to the quarkonia states accessible in a fixed target experiment.

STSAs

- For C-even quarkonium states, χ and η states could be examined in fixed target mode at low p_T to yield some information on STSAs.
- The lower combinatorical backgrounds in this low energy regime and the favourable production cross section should allow the STSA's to be in reach, and give direct access to $f_{1T}^{\perp g}$.
- There should also be the possibiliity to access the correlators encapsulating Sivers effects in CT3 and the GSFs from GPM.
- Associated production of $\mathcal{Q}$ and another particle is a similarly promising tool, able to access all of the objects that would be able to encapsulate STSAs.
- This channel also presents the option to scan the invariant mass ranges and examine the evolution of the Sivers effect.
- Di-J/ψ is of particular interest in a fixed target setup, there should be sufficient levels of production, and the feed-down to $\psi(2S)$ does not have a detrimental effect.
- Projections also suggest that gluon sivers TMDs should could be parameterised in terms of the transverse momentum of the pair, up to around 4GeV