Problems, pitfalls, and remedies of gluon TMD measurement

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- Our objective is to measure the gluon Transverse Momentum Dependent Parton Distribution Functions (TMDs) f_1^g and $h_1^{\perp g}$.
- These two TMDs encapsulate the distribution of unpolarised and polarised gluon transverse momentum, respectively.
- Presence of $h_1^{\perp g}$ can affect the cross sections of many gg initiated processes.
- This $h_1^{\perp g}$ should show up as azimuthal modulations of $\cos(2\phi)$ or $\cos(4\phi)$ in the Collins-Soper (CS) frame.
- We look at the $gg \to J/\psi + \gamma$ channel, we assume that the relation between the gluon transverse momentum k_T and the system transverse momentum q_T is preserved.
- In order to make a successful measurement a number of obstacles need to be removed.
 - Kinematic biases due to experimental acceptances
 - Signal to background separation
- The signal to background separation can be discussed after the measurements is completed and is not the topic of this talk.



 Following from previous calculations in [1], performing TMD factorisation, we arrive at a differential cross section in the Collins-Soper Frame;

$$\frac{d\sigma}{dM_{\gamma\mathcal{Q}}dY_{\mathcal{Q}\gamma}d^{2}q_{T}d\Omega} \propto \frac{M_{\gamma\mathcal{Q}}^{2} - M_{\mathcal{Q}}^{2}}{sM_{\mathcal{Q}}^{3}M_{\gamma\mathcal{Q}}^{3}} \{F_{1}\mathcal{C}[f_{1}^{g}f_{1}^{g}] + F_{3}\mathcal{C}[w_{3}f_{1}^{g}h_{1}^{\perp g}]\cos(2\phi_{cs}) + F_{4}\mathcal{C}[w_{4}h_{1}^{\perp g}h_{1}^{\perp g}]\cos(4\phi_{cs})\}$$
(1)

- This is valid for the kinematic region where q_T of our system is much smaller than $M_{Q\gamma}$.
- C represents a convolution of weights w_i and the TMDs. The relevant F factors and weights are listed within [1].
- We expect the F_3 and F_4 terms to be much smaller than F_1 , which we are much more likely to be able to measure from the cross section, after we integrate out angular dependence, giving us f_1^g .
- ullet Ideally we could also measure the distribution of $F_{3,4}$ in ϕ_{cs} , to give us access to $h_1^{\perp g}$

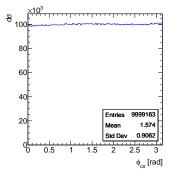


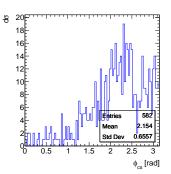
Acceptance Cuts

- The final state that we're looking for is two muons from the J/ψ decay and an isolated photon.
- We are looking to maximise our statistics and kinematic coverage, hence we want the lowest achievable cuts.
- However, our detector and trigger system is blind to low p_T muons so we cut $p_{T,\mu^\pm} > 4 GeV$.
- Consequentially, we expect the p_T of J/ψ to be above $8 \, GeV$
- To get a clean reading of our photon we need some isolation cuts and similarly, some p_T cuts. $p_{T,\gamma} > 5$ GeV should be sufficient (445 cuts).
- To balance this system out we would need $p_{T,\gamma} \gtrsim 9 \text{GeV}$ (449 cuts), though there are reasons this is not advisable.
- We consider basic minimum cuts of 445.

Angular distortions

- ullet The distortion of the ϕ_{cs} distribution from the acceptance cuts and the methods to account for it have been presented here last year by A. Tee, we will cover these briefly.
- ullet An MC simulation with $h_1^{\perp g}=0$ and view ϕ_{cs} under 000 cuts gives us a flat distribution.
- Though when we apply the 445 cuts to our system we see that the distortion is severe.





- Measuring any possible ϕ_{cs} modulation will be difficult here.
- Another acute effect of the acceptance cuts is heavy reduction our statistics though this is from an MC simulation with generator level cuts of 000.

- We want recreate the effects of the TMDs in some MC samples to gain an idea of their visibility, hence we need to have some models describing them.
- For $f_1^{\mathcal{B}}$ we assume a Gaussian dependence of $\frac{G(\mathbf{x})}{\langle k_T^2 \rangle} e^{-k_T^2/\langle k_T^2 \rangle}$ with gluon transverse momentum k_T .
- ullet We do have a model independent bound between $f_1^{\it g}$ and $h_1^{\perp \it g}$ with $h_1^{\perp \it g} \leq 2 M^2 f_1^{\it g}$ from [2]
- In past we've picked two models for $h_1^{\perp g}$, with one of them satisfying $h_1^{\perp g} = \frac{MG(x)}{(k^2)^2} e^{1-k_T^2/r(k_T^2)}$, from [3].
- We pick the other to saturate the previous positivity bound.

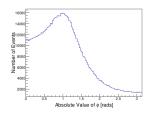
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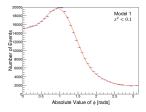


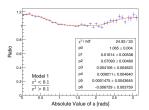


Fixing the distortion

- ullet As mentioned in previous presentations we have a possible solution to the $\phi_{\it cs}$ distortion.
- We can note the fact that $z^2=\cos^2\theta_{\rm cs}$ is effected almost equally by 445 cuts across the full range.
- The advantage of this is our theory tells us our TMDs affect kinematic regions of z^2 most.
- Hence, we can split our distribution into two regions of roughly equal statistics and ratio out the distortion, leaving the modulation.

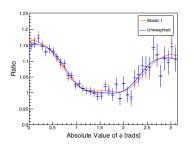


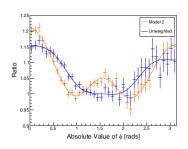




A possible solution

 Applying the method of dividing out our distortion and plotting the results overlaid with the unweighted distributions yields the following;

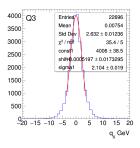


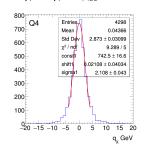


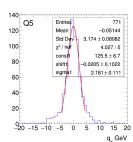
ullet We can see here that this method offers us an opportunity to measure these the h_1^g distribution.



- ullet We have similar difficulties when it comes to measuring the $f_1^{\mathcal{E}}$ distribution but the problem is more difficult to illustrate than before
- These are $q_X = q_T \cos \phi_{lab}$ distributions of the system at truth level with 000 cuts.
- Since ϕ_{lab} , the azimuthal angle in the lab frame, is random with respect to the $J/\psi + \gamma$ system, we can recognise that $q_Y = q_T \sin \phi_{lab}$ will have a similar distribution.



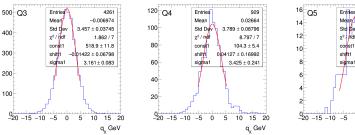


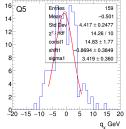


- We have essentially no evolution of the fit across mass ranges Q3, Q4, and Q5.
- Q3 15.5 22GeV. Q4 22 31GeV. Q5 31 44GeV



- Applying our acceptance cuts, means our q_T distribution is not the same as it would be before, without the cuts.
- Moving our q_X up to 221 cuts;

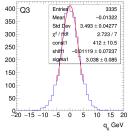


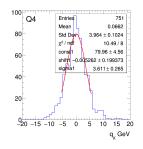


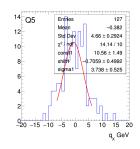
• We see a broadening, distortion of shape, and reduction of statistics.



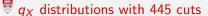
• Moving along a little to a more balanced 224 cut upon q_X ;



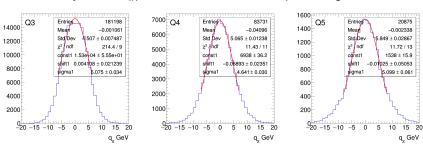




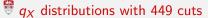
• We see that σ_1 has increased, and that it has begun to increase with the invariant mass range.



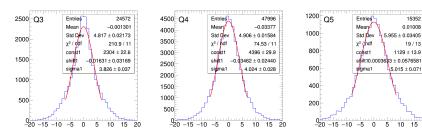
• When we try 445 cuts q_X , we have moved to a new sample with higher statistics;



- Again we have the broadening of our distributions and the dependence on the mass range.
- This time we also note that our distribution starts to change shape in Q3, becoming slightly more rectangular.
- If we were to measure this we might be mistaken in thinking that the underlying gluon distribution has k_T somewhere in the range of 4.8-5.1 GeV, and not what it really is, around 2.1 GeV.



• Finally, placing our q_X distribution under 449 cuts, in an attempt to balance out our event;



- Again the shape differs and we have the appearance of a narrower peak in Q3.
- Our σ_1 is lower but we have variation in both the shape and σ_1 with the mass ranges.
- This is still very different for what we should be seeing.

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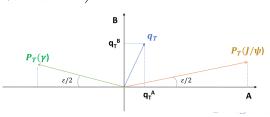
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\P Introducing q_T^A and q_T^B

- If the photon and J/ψ are almost back to back we can say $\epsilon=\pi-\Delta\phi$ and we define $q_T^2=(\vec{p}_{T,J/\psi}+\vec{p}_{T,\gamma})^2$
- ullet Using truncated series expansions of sin and cos we can use this ϵ to arrive at q_T^A and q_T^B

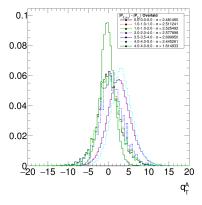
$$\begin{split} q_T^2 &= \rho_{T,J/\psi}^2 + \rho_{T,\gamma}^2 + 2\rho_{T,J/\psi} p_{T,\gamma} \cos \Delta \phi \\ &= \rho_{T,J/\psi}^2 + \rho_{T,\gamma}^2 - 2p_{T,J/\psi} p_{T,\gamma} \cos \epsilon \\ &\simeq \rho_{T,J/\psi}^2 + \rho_{T,\gamma}^2 - 2p_{T,J/\psi} p_{T,\gamma} \left(1 - \frac{\epsilon^2}{2}\right)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

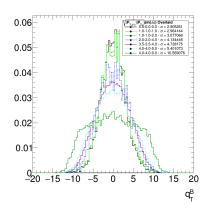
• We now have a separation, into two orthogonal components q_T^A and q_T^B with the dependence on momentum magnitude difference expressed in term q_T^A , and angular difference expressed in $q_T^B \left(= \sqrt{|p_{T,J/\psi}||p_{T,\gamma}|} \sin \Delta \phi \right)$.



g_T^A and g_T^B under progressive cuts

• Here are our first images of q_T^A and q_T^B in Q3 for different acceptance cut values.

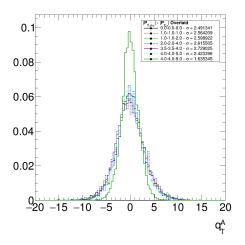




- q_T^A (left), begins to shift right with unbalanced cuts, but retains most of its shape until the 449 cut begins to squeeze things, violating $q_T \ll M_{\mathcal{O}\gamma}$.
- In q_T^B (right) we have a mean, stable at 0, however we get the distortion of our width instead.

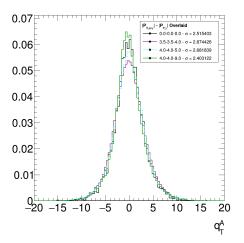
Recentering q_T^A

ullet Once we manually re-centre q_T^A the distributions we can see the shape is preserved



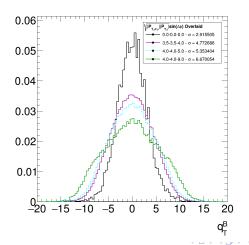
\P Restoring the $q_{\mathcal{T}} \ll M_{\mathcal{Q}\gamma}$ condition

- When we merge our Q3 and Q4 invariant mass ranges to encompass 15.5 31GeV we see that our statistics begin to improve
- ullet Along with this, the $q_T \ll M_{\mathcal{Q}_{\gamma}}$ condition is restored.





- ullet If we view our q_T^B variable in the compound Q3 + Q4 (15.5-31GeV) mass range again we can see a cleaner picture
- The distribution exhibits no significant shift in mean and broadens progressively with increasing cuts



Problems and pitfalls of gluon TMD measurement



A cross check of the new axes

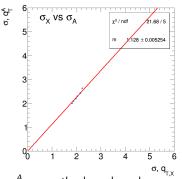
- As a cross check of the validity of these new q_T^A and q_T^B variables, and check they are still appropriate reflections of the gluon k_T^2 , we perform a reweighting of the original q_T^2 distribution.
- As q_X at 000 is still directly tied to q_T , we fit the distribution of this variable, being sure to exclude any tails, and extract the standard deviation, σ_1 .
- We then step above and below σ_1 in intervals of 0.05 to create σ_2 for calculating the weight for our distributions:

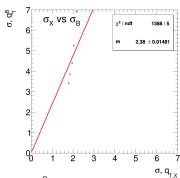
$$W = \exp \left\{ rac{1}{2} q_T^2 \left[rac{1}{\sigma_1^2} - rac{1}{\sigma_2^2}
ight]
ight\}$$

• Ideally what we'd like to see is that as we reweight q_T^A or q_T^B under our acceptance cuts alongside the reweighting of the original distribution, of q_X at 000 cuts, that they both widen or thin at similar rates

Reweighting results

- Here we've performed the reweighting of q_T^A and q_T^B with 445 cuts in our Q3 range.
- Although our relationship here is quite skewed in mass range Q3, we still see a linear relationship.





• For q_T^A we see the dependence has some promise, but q_T^B is not looking too hopeful



- In the process of applying realistic acceptance cuts to our data, our general q_T distribution is heavily biased.
- With our selection of the right axis (A and B) for each event we can avoid this distortion to a degree.
- We've seen a lot of reasonably odd behaviour of variables.
- Not all of it is very helpful but we have gained an understanding of what's at play.
- There's reason to say that we have some hope for using q_T^A but not so much for q_T^B .
- We have known for some time how to handle the issues in the $h_1^{\perp g}$ direction and we hope to have sufficient statistics for a measurement.
- For the f₁^g sector, if everything goes well we could have a measurement more directly related to the underlying gluon distribution for the next workshop.





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Thanks for listening, any questions?

