Exploring Proton Structure: Gluon TMDs at ATLAS

The ATLAS Collaboration

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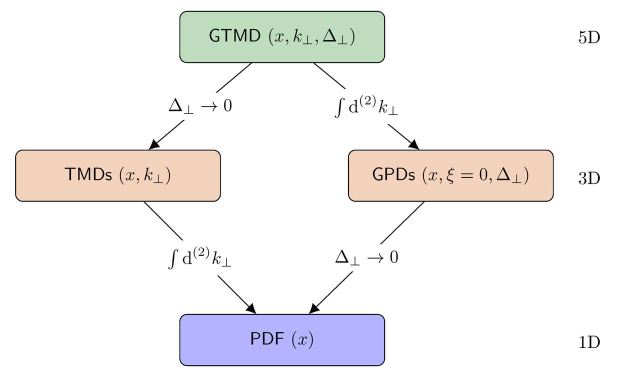
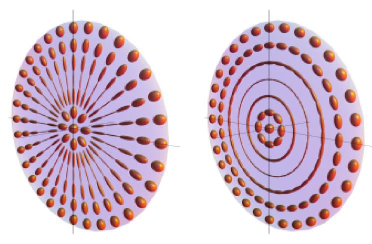
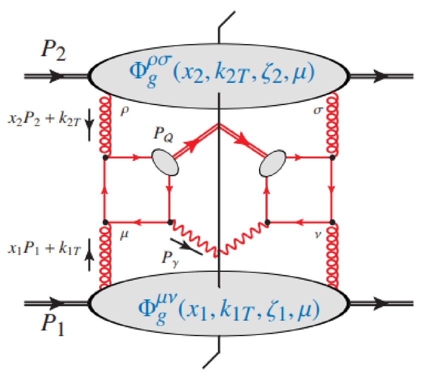
1. What are TMDs?

- TMDs are one of the possible extensions of one dimensional collinear PDFs, they expand the parameterisation to include the transverse momentum as well as longitudinal momentum







- Apart from direct access to the transverse dynamics of gluons in the proton, why should we measure them?
- -TMDs evolve with scale, can help constrain our understanding of QCD in multi-scale processes.
- -Gluon k_T contributes to p_T of observables and also contribute to cross sections (e.g. the higgs), especially in cases with polarised gluons, even within unpolarised protons.
- Interested in two Gluon TMDs - f_1^g and $h_1^{\perp g}$, the unpolarised and polarised contributions.
- Following theoretical recommendations, [0009343], [2012.14161], [1401.7611], [1710.01684], use subprocess $gg \to J/\psi(\mu\mu) + \gamma$.
- Back to back $J/\psi + \gamma$ is helpful as a clean probe, allows not only lower q_T, but CO contributions that obscure the TMD are suppressed.

2. Accessing TMDs at ATLAS.

- The general cross section for processes including TMDs takes this typical form;

$$\frac{d\sigma}{dMdYd^2Pd\Omega} = \mathcal{J}\Big\{F_1\mathcal{C}\left[f_1^g f_1^g\right] + F_2\mathcal{C}\left[w_2 h_1^{\perp g} h_1^{\perp g}\right] + F_3\cos(2\phi_{cs})\mathcal{C}\left[w_3 f_1^g h_1^{\perp g}\right] + F_4\cos(4\phi_{cs})\mathcal{C}\left[w_4 h_1^{\perp g} h_1^{\perp g}\right]\Big\}$$

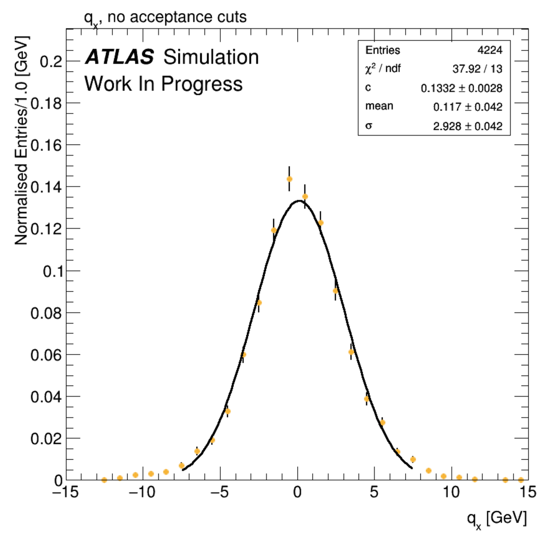
- Expect that the TMD factorisation holds for where total invariant mass Q is much higher than the gluon k_T.
- For a $J/\psi + \gamma$ final state in the region, cross section can be simplified, $F_2 = 0$, and F_3 is small, so the cross section is simplified;

$$\frac{d\sigma}{dMdYd^2Pd\Omega} = \mathcal{J}F_1\mathcal{C}\left[f_1^g f_1^g\right]\left\{1 + \frac{F_4}{F_1}\cos(4\phi_{cs})\frac{\mathcal{C}\left[w_4 h_1^{\perp g} h_1^{\perp g}\right]}{\mathcal{C}\left[f_1^g f_1^g\right]}\right\}$$

- Feasibility studies show that with current setup, statistics, and triggers, polarised TMD $h_1^{\perp g}$ is still beyond ATLAS sensitivity
- Unpolarised f_1^g is still within reach, and remains unmeasured. Integrate out angular terms leaving just f_1^g, then the main obstacles remaining consist of acceptance cuts distorting observed distributions and performing signal/background separation.

3. Acceptance and Distortion.

- Transverse momentum of $J/\psi + \gamma$ system q_T, should reflect the gluon transverse momentum k_T.
- Only the case with a perfect detector, without a p_T threshold on measured physics objects.



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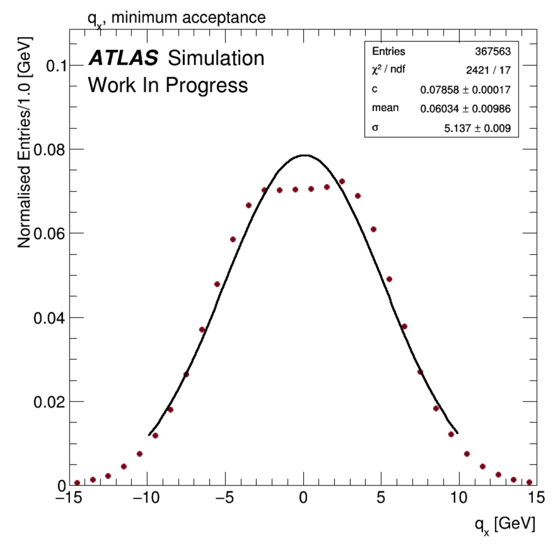
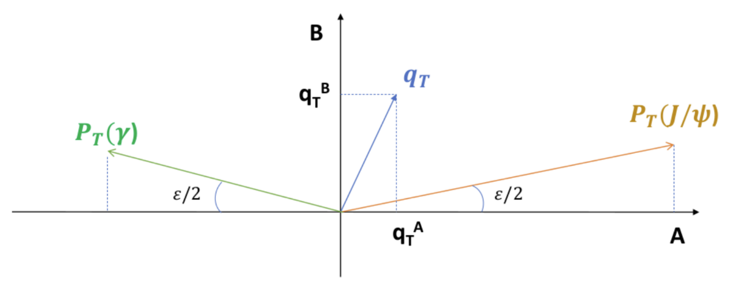
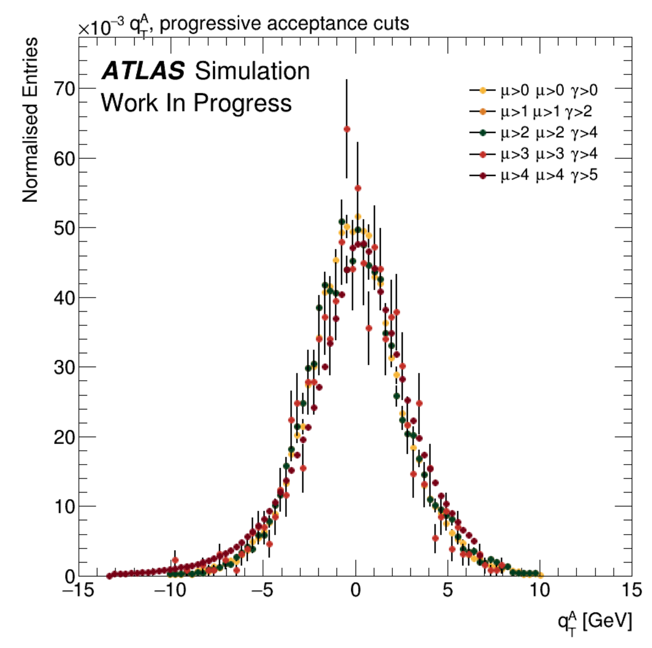


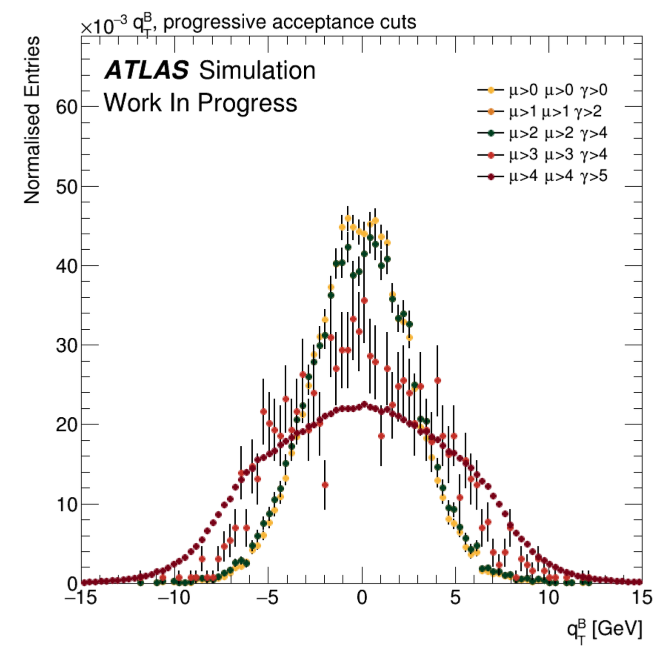
- $q_x = q_T\cos\phi_{lab}$ distribution broadens and deforms with ATLAS minimum acceptance cuts of $p_{T,\mu} > 4$GeV and $P_{T,\gamma} > 5$GeV
- Parameterising the TMD with this would be incorrect $\rightarrow$ switch to a new q_T measure, q_T^A, & q_T^B, with A and B axes defined uniquely in each event.

$$q_T^2 = (p_{T,J/\psi} - p_{T,\gamma})^2 + p_{T,J/\psi}p_{T,\gamma}\sin^2\epsilon = (q_T^A)^2 + (q_T^B)^2$$



- Somewhat similar in principle to Collins-Soper frame, though this is two dimensional, and just a simple rotation in ϕ.
- q_T^A appears resistant to the distortion of increasing acceptance cuts, no broadening like q_x distribution, q_T^B absorbs the broadening effect, leaving q_T^A as a clean probe of the gluon k_T.

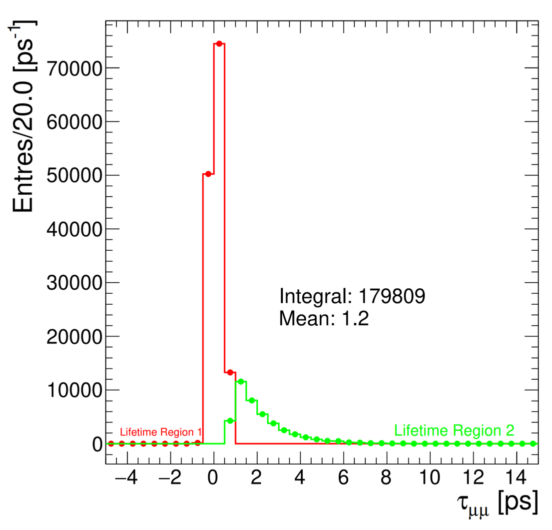


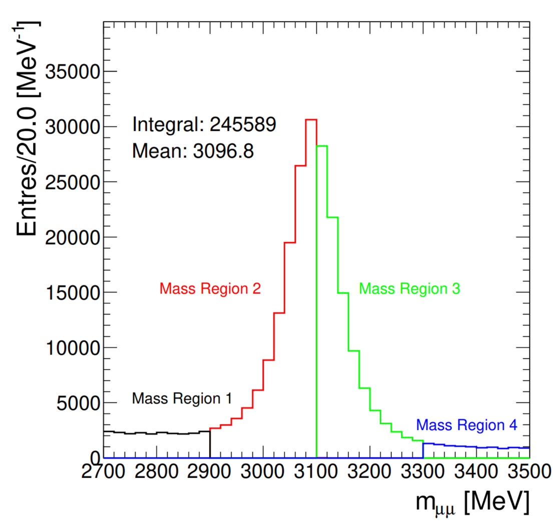


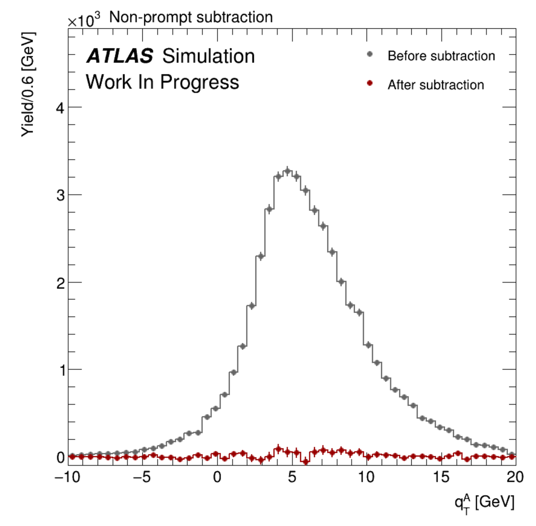
- Acceptance cuts also have a severe impact on statistics, only hundreds of events survive this out of a 10M event signal MC sample with no cuts.

4. Background Subtraction.

- After avoiding the detrimental effects of acceptance, contributions from non-prompt J/ψ and the $\mu\mu$ continuum must be removed.



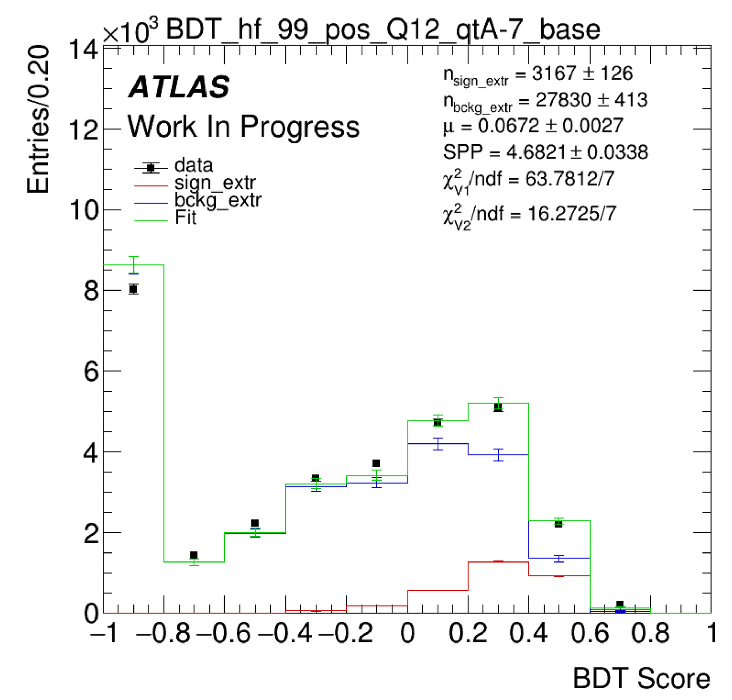




- Identifying the mass and lifetime regions corresponding to these contributions allows them to be subtracted easily.
- This doesn't account for contributions from random uncorrelated $J/\psi + \gamma$ pairs, these have TMD information in them that's smeared out or inaccessable.
- Train a Boosted Decision Tree to characterise these events.

5. Signal Extraction.

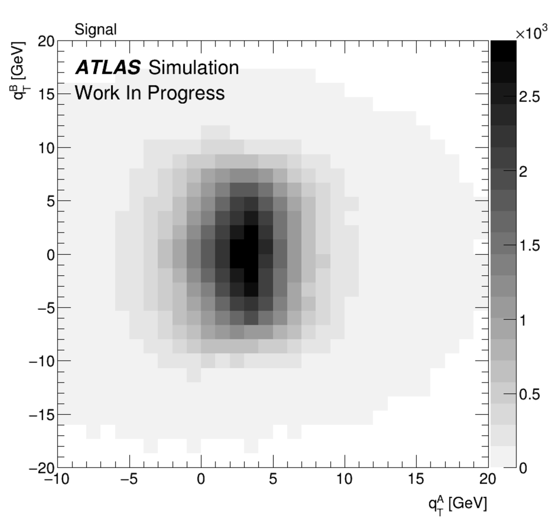
- Use the BDT to condense all information about an event into a single score, the shape of this score distribution differs between signal and uncorrelated background events.
- Fit BDT score differentially in individual q_T^A bins to extract μ and s_{pp} in $D = s_{pp}\cdot B + \mu\cdot S$.

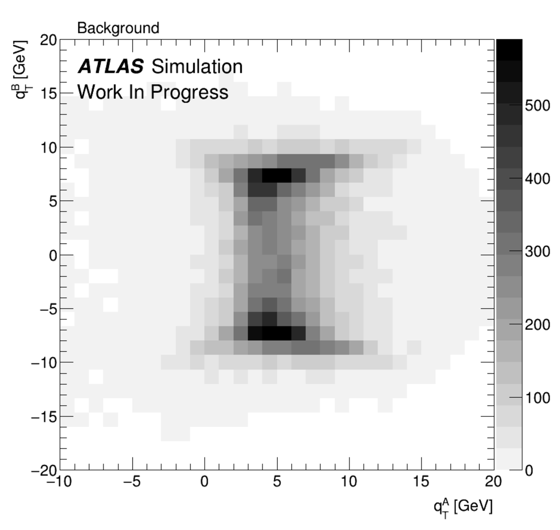


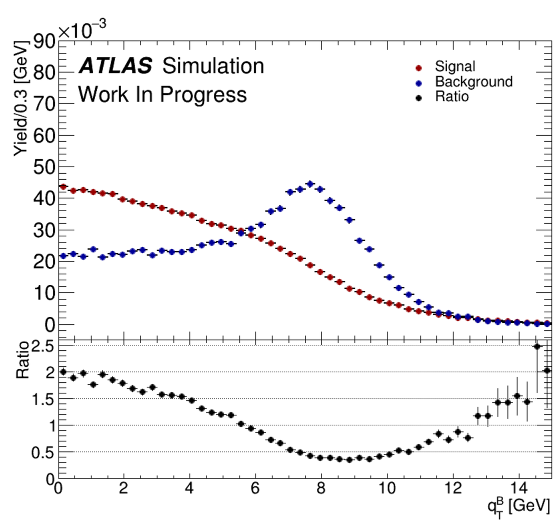
- Using the differences in shape, fit the signal and background distributions to data, and extract the contribution pertaining to only the correlated signal.
- Results of extraction in a single q_T^A bin; the μ parameter gives the signal yield in each q_T^A bin of the data, this allows reconstruction of the full q_T^A distribution, which is then fit to extract its width, parameterising f_1^g.

6. Enhancement.

- Looking for opportunities to enhance the sensitivity, focus the search on regions of higher S/B ratio, this can help improve the fit quality.



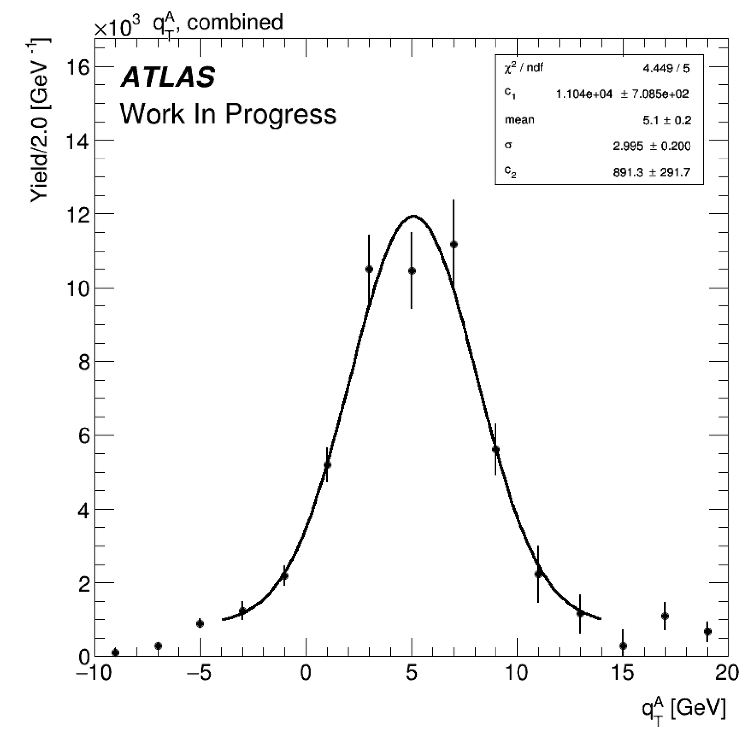




- Examining the signal and background maps of q_T^A vs q_T^B, possible to see in the region $q_T^B < 6$GeV, S/B is much higher. Restrict the fit to this region.

7. An Early Picture.

- Perform the full analysis with this approach and recombine our extracted contributions into a single final signal region, get the following plot;



- With σ_1 of the fit parameterises the convolution of two gaussian gluon TMDs here, assess the unpolarised gluon transverse momentum $\langle k_T\rangle = \sigma_1/\sqrt{2} \approx 2.1 \pm 0.14$GeV
- Several systematic effects included, muon and photon scale factors, background subtraction working points, variations on BDT, etc. There is still some work to be done.