Quarkonium production measurements as a tool for (gluon) TMD studies

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Outline

- General introduction
- Inclusive quarkonium production
- Associated production of quarkonium with another quarkonium
- Associated production of quarkonium with W or Z
- Associated production of quarkonium with a virtual photon or Z
- Associated production of quarkonium with a real photon

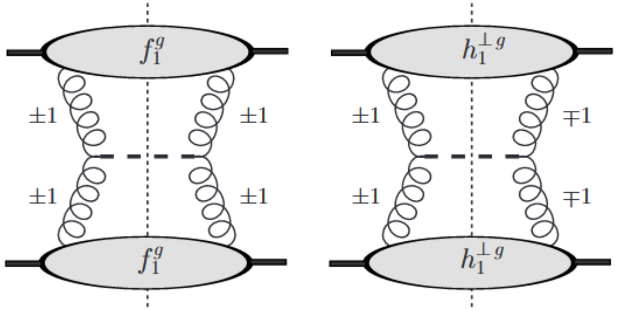
General introduction

- Will assume throughout that colliding hadrons are unpolarised
- Studying quark TMDs is more convenient with Drell-Yan type or other, purely electroweak subprocess final states
- Quarkonium as a tool for TMD studies may/should be useful for gluon TMD determination – with a wishlist of conditions:
  - assume the pair(s) of heavy quarks are produced in an SPS perturbative subprocess
  - possibly in association with another (colour-singlet) object
  - the subprocess has a "two gluon fusion" structure with a colour-singlet final state
  - the required two-scale kinematics $q_t^2 \ll Q^2$ is experimentally accessible
- Different final states may provide access to different TMD objects

Example: formalism for fusion into a (pseudo)scalar

PRL 108.03200 D.Boer, J.den Dunnen, C. Pisano, M.Schlegel

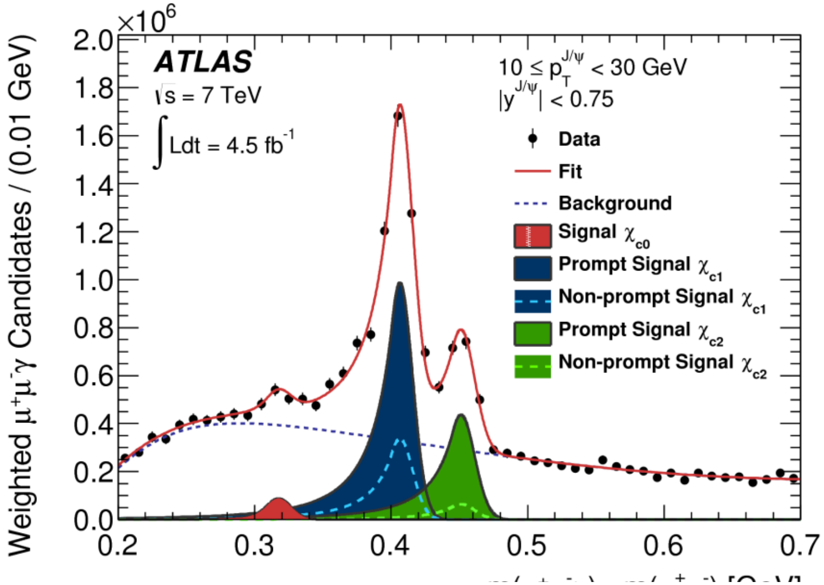
$$\left.\frac{E\,\mathrm{d}\sigma^{H(A)}}{\mathrm{d}^3\vec{q}}\right|_{q_T\ll m_H} = \frac{\pi\sqrt{2}G_F}{128 m_H^2 S}\left(\frac{\alpha_s}{4\pi}\right)^2 \left|\mathcal{A}_{H(A)}(\tau)\right|^2$$
$$\times\left(\mathcal{C}\left[f_1^g\, f_1^g\right] \pm \mathcal{C}\left[w_H\, h_1^{\perp g}\, h_1^{\perp g}\right]\right) + \mathcal{O}\left(\frac{q_T}{m_H}\right), \quad (6)$$

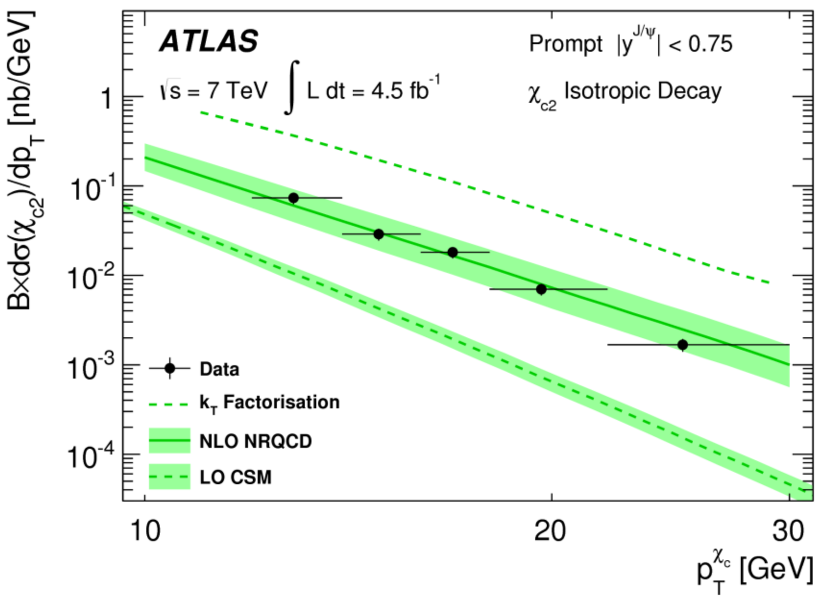


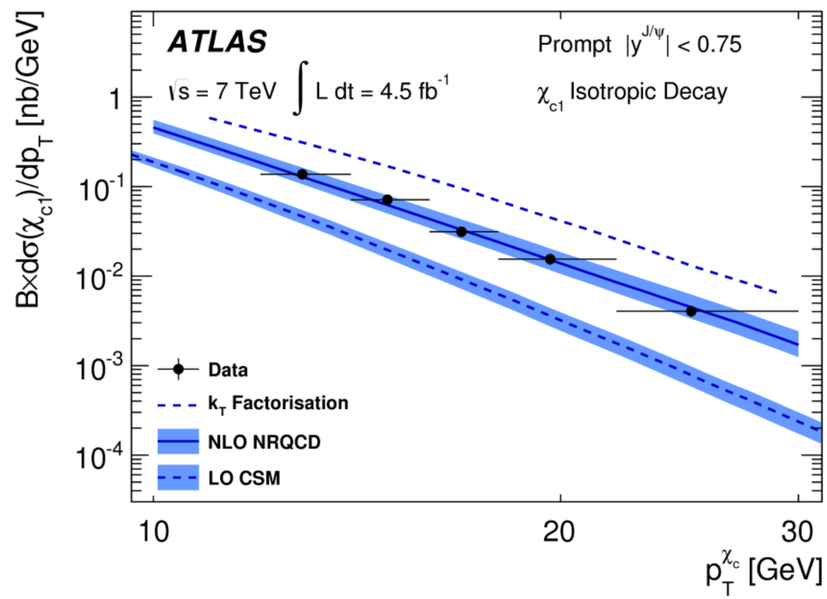
- **Simplest case kinematically: gluon-gluon fusion into a single (pseudo)scalar**
- **f_1 describes the unpolarised gluons, h_1 stands for linearly polarised gluons**
- **Presence of polarised gluons may change the cross section, but not sure for how much...**
- **Sign of the second term is opposite for a scalar and a pseudoscalar**
- **Once integrated over the transverse momentum, the expression should reduce to the collinear result**

C-even charmonium production in ATLAS

- Two-gluon fusion into 1++ and 2++ states of quarkonium is a viable process
- Measurement from ATLAS in J/ψ γ mode
  ATLAS Coll. JHEP07(2014)154
- Acceptance restricted to p_t >12 GeV, probably not good for TMD studies
- 1++ state cannot couple to 2 `real' gluons, but 2++ can – can one trace any differences in p_t spectra?

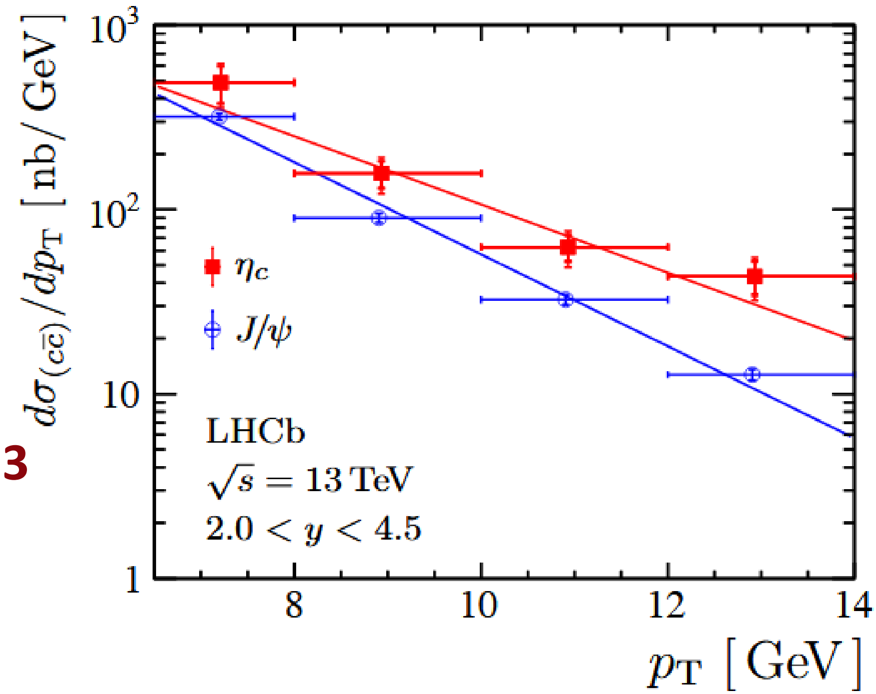


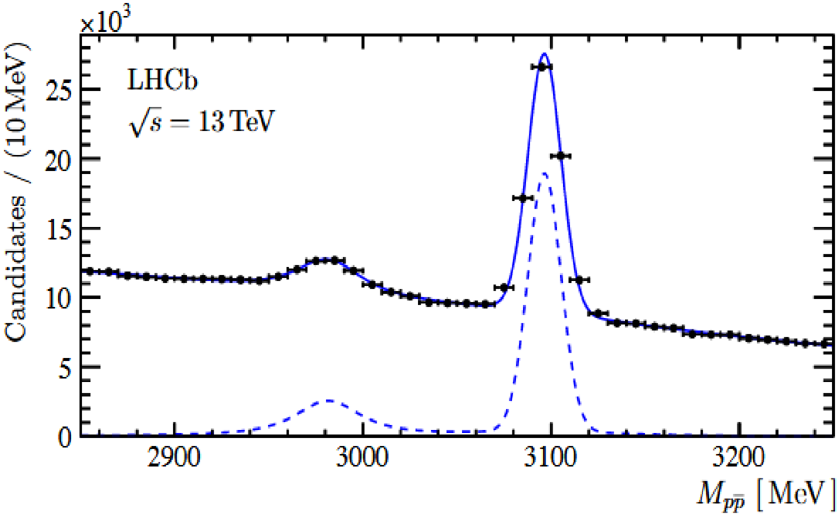




Pseudoscalar quarkonium production at LHCb

- Two-gluon fusion into (pseudo)scalar quarkonium is also a viable process!
- NEW! Fresh results from LHCb:
  LHCb collaboration, arXiv:1911.03326
- J/ψ and η_c production was measured at 13 TeV in ppbar decay mode
- Separated into prompt production and from B decays
- Even measured the mass difference to be 113.0+/-0.3 +/- 0.1 MeV
- J/ψ seems softer than η_c – does this make sense in TMD context?





Associated production: DPS and SPS

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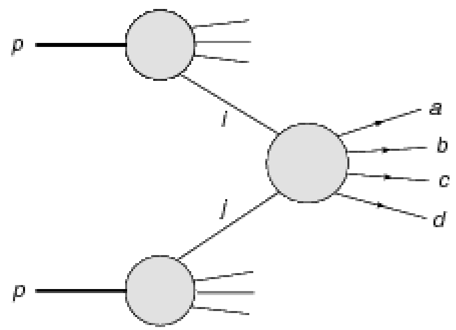
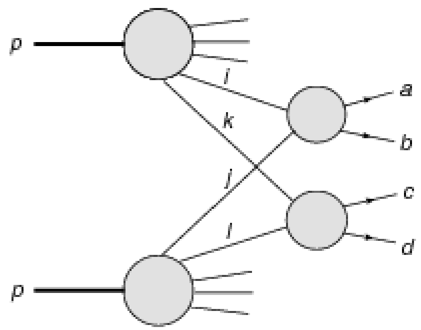
The production of two objects in the same pp collision can be due to

Single-Parton Scattering (SPS):



the two objects are produced via a subprocess in a single interaction of two partons

Double-Parton Scattering (DPS):

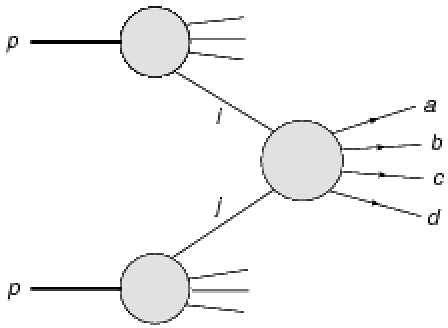


simultaneous interaction of two pairs of partons, each producing one of the two objects, assumed to be uncorrelated

E. Berger et al. Phys.Rev. D84 (2011) 074021 arXiv:1107.3150 [hep-ph]

SPS

- **Single-Parton Scattering (SPS) can be treated in the usual way, once the subprocess cross section is calculated**
- **After all, this is just "another subprocess"**

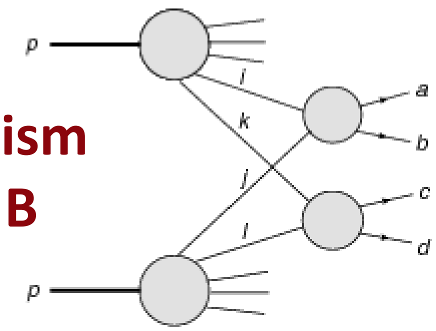


- **If the final particles are colourless, all the usual factorisation theorems are valid**
- **(at least as valid as for other subprocesses, may be more)**
- **Since the initial partons are unlikely to have large transverse momenta, the final state objects are expected to be produced back-to-back in transverse plane**
- **(up to some smearing due to initial- and final-state radiation etc)**

DPS

- **Double-Parton Scattering (DPS) can be treated in as two subprocesses happening simultaneously in the same pp collision**

- **Assuming the masses and momenta are much smaller than collision energy, one can ignore correlations due to overall Energy-momentum conservation**



- **So one can apply the usual parton model / QCD formalism TWICE, once for subprocess A and once for subprocess B**

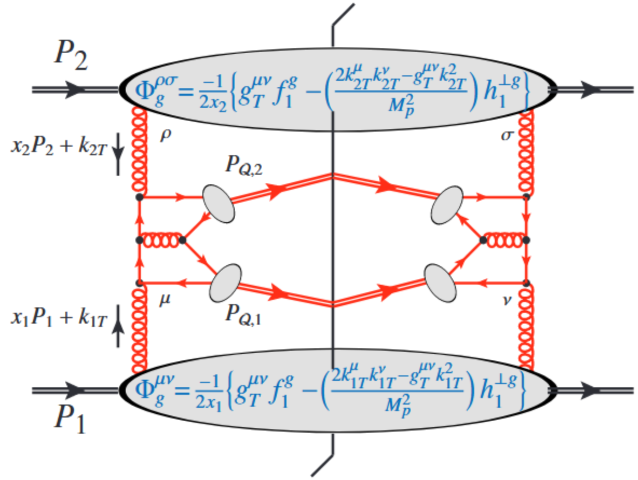
- **The problem is the cross sections are dimensional, and one needs a dimensional factor σ_{eff} as a scale**

$$\sigma_{A+B}^{\text{DPS}} = \frac{1}{1+\delta_{AB}} \frac{\sigma_A \sigma_B}{\sigma_{\text{eff}}}$$

σ_{eff} **~(2 - 20) mb**, **assumed (hoped?) to be independent of process and** $\sqrt{s}$

Formalism for prompt J/ψ + J/ψ Production

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



J.P Lansberg, C.Pisano, F.Scarpa, M.Schlegel

arXiv:1710.01684v1

- **This expansion into the 4 structures with F_1, F_2, F_3, F_4 is quite general, although not all terms are present for all final states**
- **Once integrated over transverse momentum (and Collins-Soper angles), the expression should reduce to the collinear result**
- **Functions F_1, F_2, F_3, F_4 depend on M_{QQ} and θ_{CS}, but NOT on ϕ_{CS}**
- **Dependence on P_{QQT} (otherwise known as q_T) is concentrated in the convolution terms $C[\ldots]$**
- **The grand aim is to extract f_1 and h_1 which are hidden inside these terms**

Formalism for prompt J/ψ + J/ψ Production

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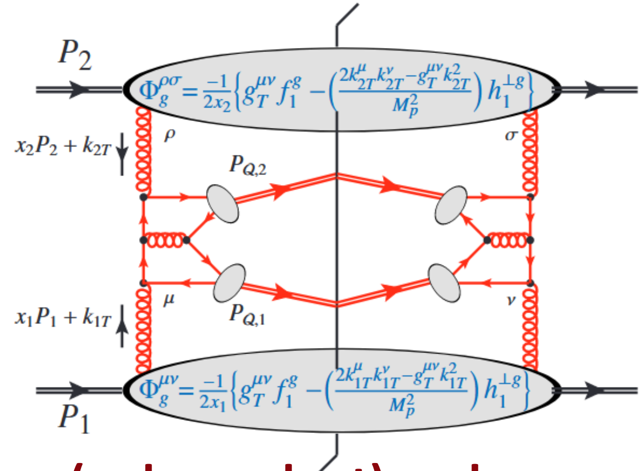


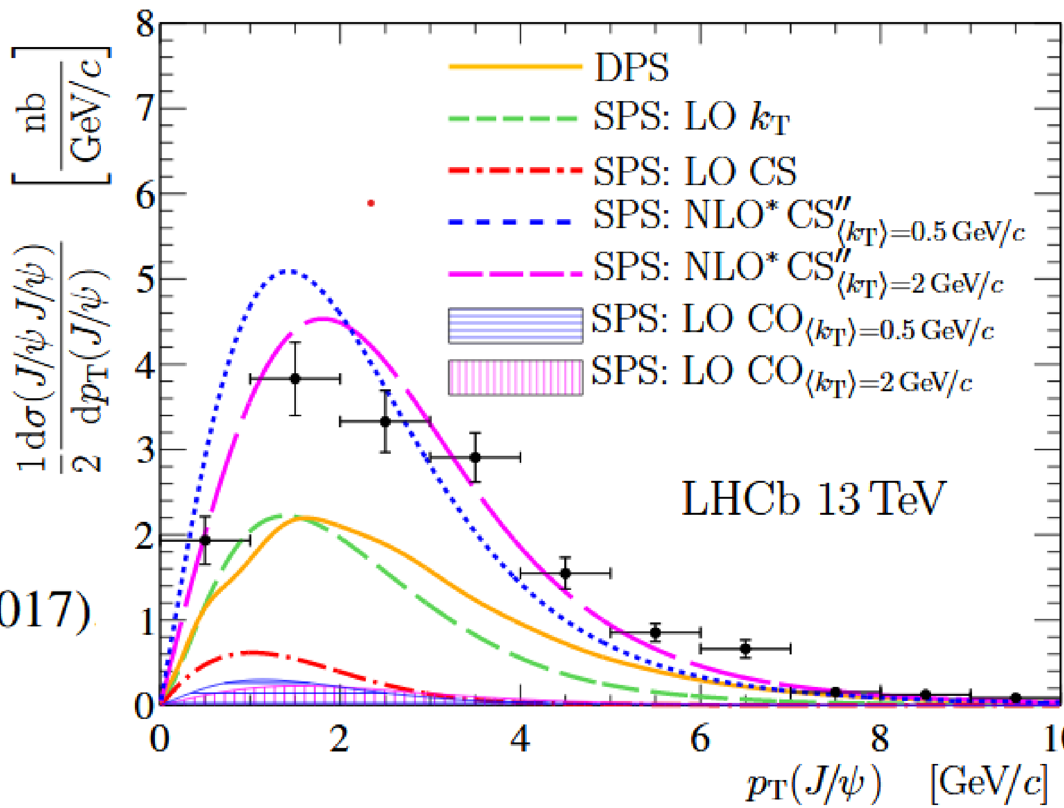
J.P Lansberg, C.Pisano, F.Scarpa, M.Schlegel

- ***f_1* and *h_1* are assumed to be factorizable into collinear (*x*-dependent) and transverse-momentum dependent parts**
- **Precious little detail is known about *q_T* dependence for each of these so far**
- **Explicit dependence of each term on ϕ_{CS} is the key to separating individual convolution terms, and hence *f_1* and *h_1* TMDs**
- **This, however, may be severely hindered by experimental acceptance**
- **... and needs to be separated from Double-Parton Scattering contribution**
- **In any case, the experiments can only hope to extract the individual convolution term, one need (good) models to extract TMDs proper**
- ***F_4 / F_1* constant at large M_{QQ}, so potentially useful for extracting double-spin-flip term and hence *h_1***

Experimental results: di-J/ψ from LHCb

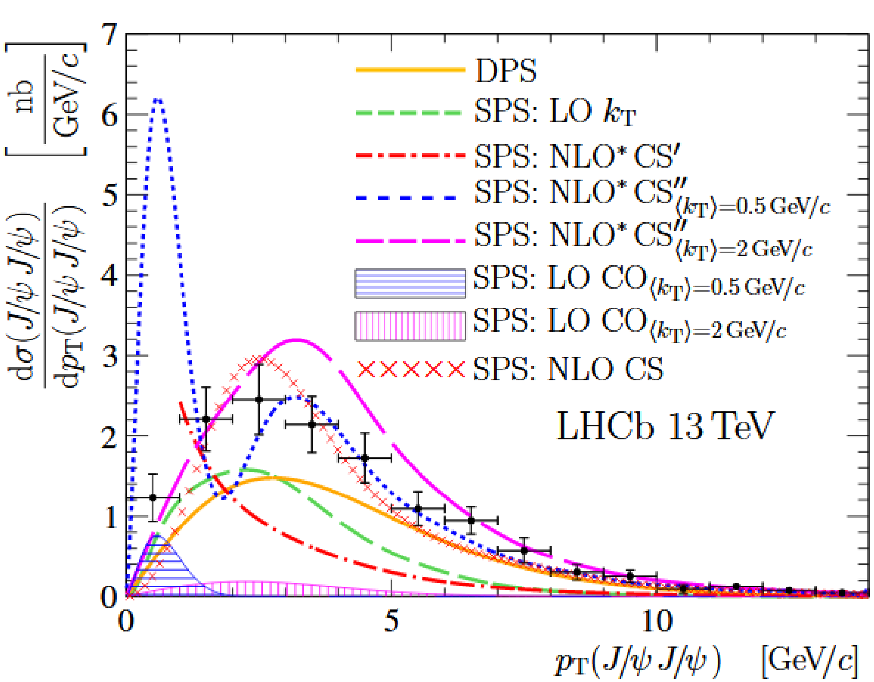
- LHCb detector acceptance limited to between 2 -- 4.5 in muon pseudorapidity, and p_T below about 10 GeV for a single J/ψ
- Can access di-J/ψ q_t down to zero, but limited to small invariant masses near threshold
- Used a fairly robust procedure of estimating DPS contributions
- Fully corrected p_t distribution is compared to a few model calculations

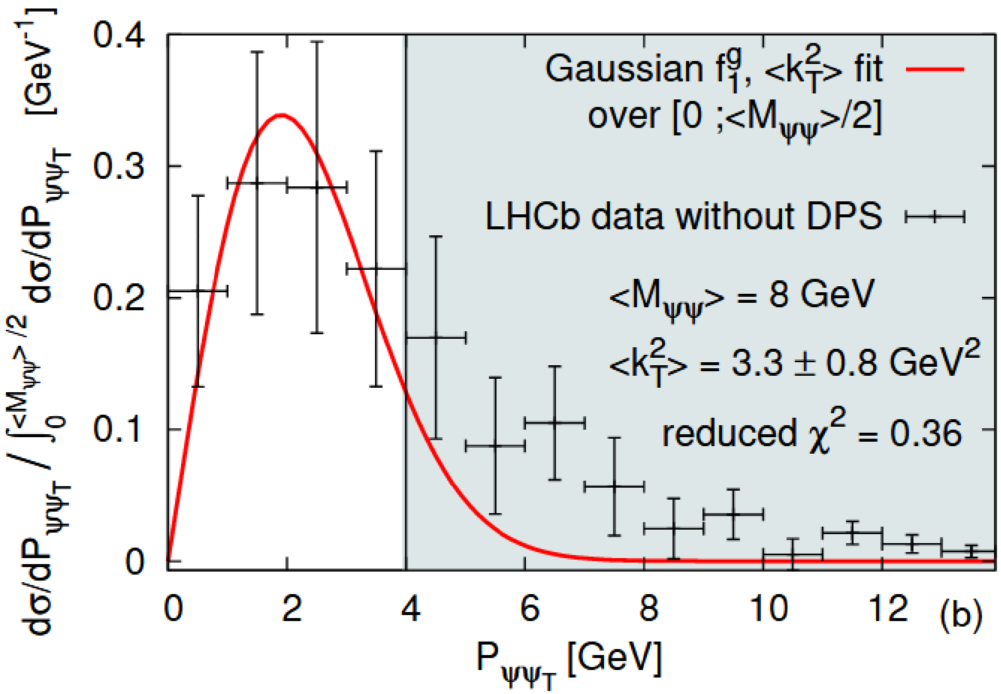
R. Aaij, *et al.*, *JHEP* **06**, 047 (2017)



Extracting mean k_T^2 from LHCb data

- LHCb have compared their result on p_t of di-J/ψ system with a few models
- No attempt was made to fit any of the parameters
- Lansberg et al. have tried to fit the DPS-subtracted distribution to obtain the value 3.3 +/- 0.8 GeV^2
- The tail is attributed to hard gluon radiation (in the initial state)
- Final state radiation should be suppressed since final state is colourless

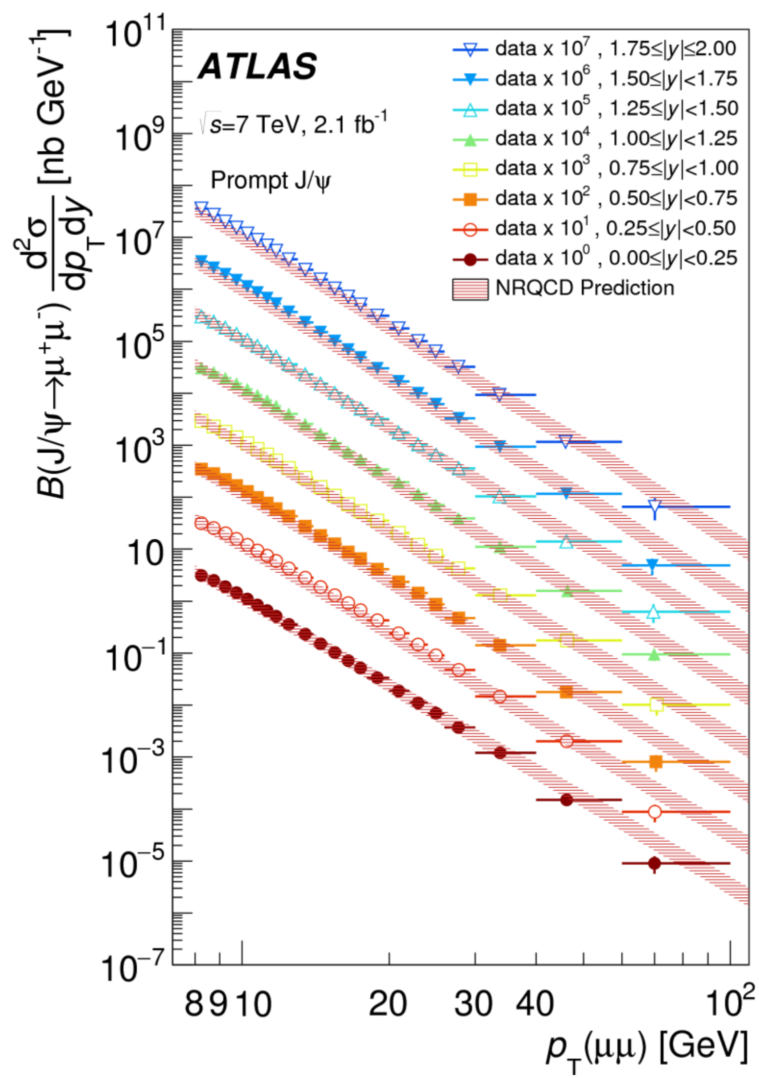




ATLAS-specific challenges for di-J/ψ production

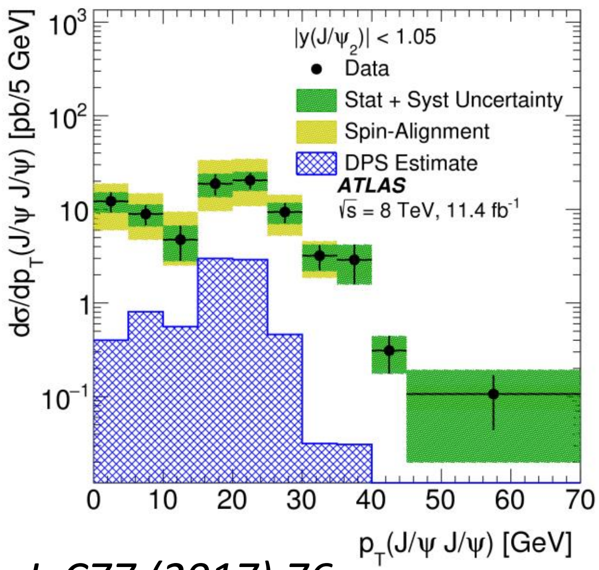
Eur.Phys.J.C76(2016)283

- ATLAS: lowest p_T dimuon trigger is 2mu4, thus effectively limiting acceptance for a single J/ψ to above 8 GeV in p_t
- Even that trigger has been only active for a small fraction of Run2
- Reaching near-zero q_t of the di-J/ψ system effectively means that the lowest realistically achievable ratio of M_{QQ}/M_Q is about 5
- Cross section within acceptance suffers significantly, statistics not too high
- Many distributions distorted by acceptance, corrections hard to make
- Similar challenges exist for CMS



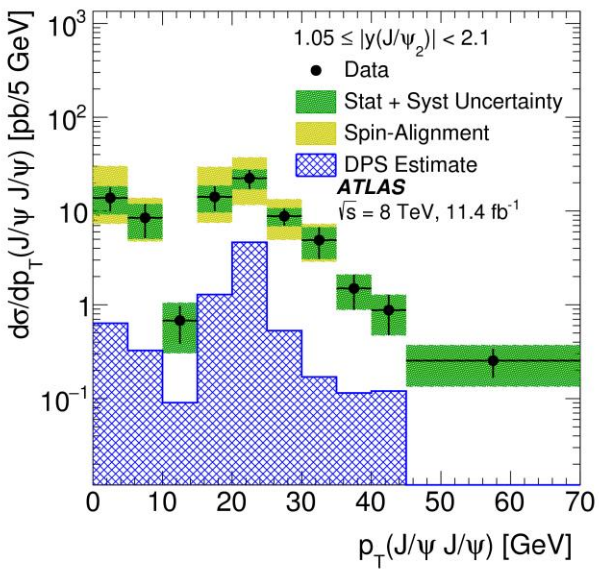
ATLAS results on prompt di-J/ψ production

- Split into 2 slices of J/ψ rapidity, but both slices seem consistent with each other, can be combined
- Figures show the corrected cross section
- Includes an extrapolation to zero p_t cuts on muons...
- ...but limited to J/ψ p_t above 8.5 GeV
- DPS contribution also estimated, can be corrected for
- Similar analysis of $\langle k_T^2 \rangle$ may be possible...



Eur. Phys. J. C77 (2017) 76

- Different topologies responsible for the structure:
  - Bump at lowest p_T corresponds to back-to-back topology
  - Second bump peaking at around 25 GeV probably has a recoil jet or two
- Measurement not really optimised for TMD studies...

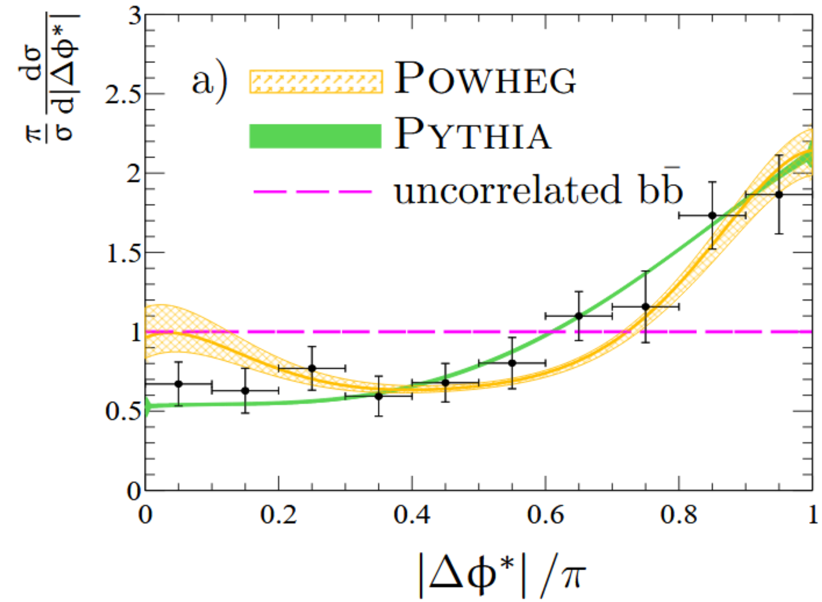


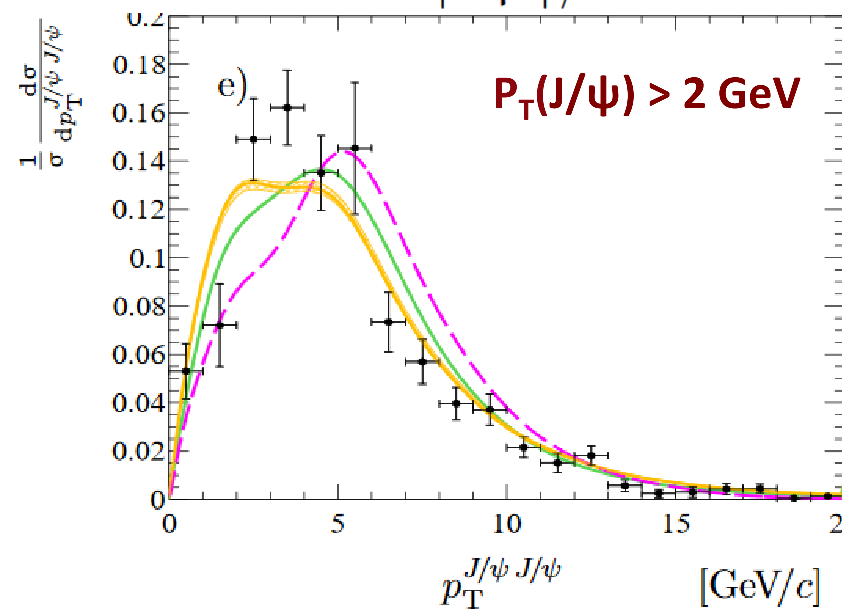
Non-prompt di-J/ψ production at LHCb

- 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

  LHCb -- arXiv: 1708.05994

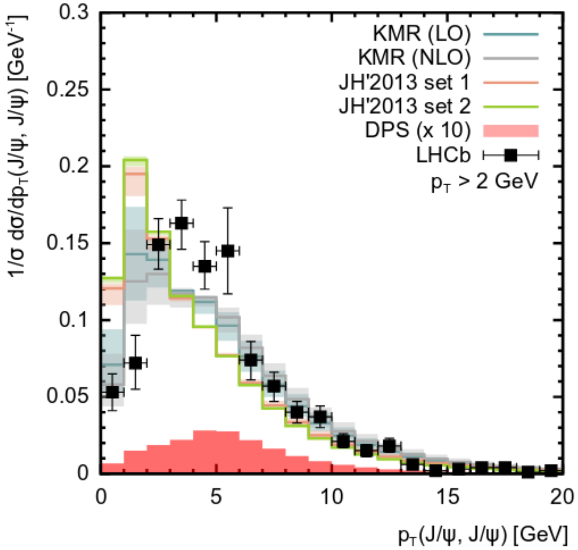
- Final state of bbbar not exactly colourless, but one could assume validity of fragmentation picture to justify some sort of factorisation
- Uncorrelated bbbar production should be suppressed
- Normalised differential cross sections shown in many variables
- Need further analysis to extract gluonic mean transverse momentum

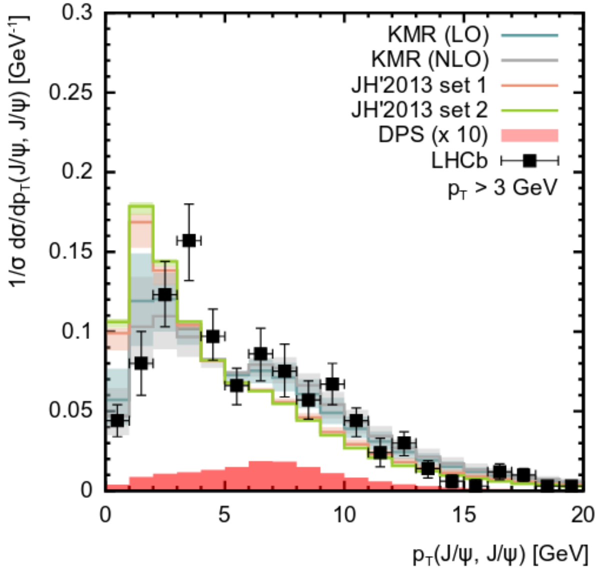


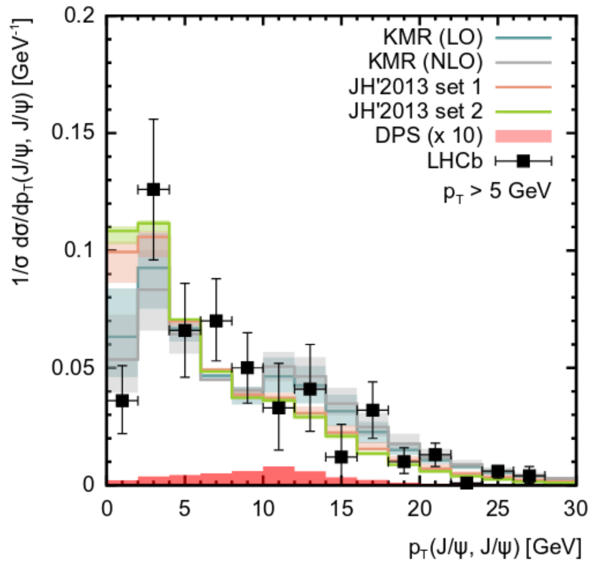


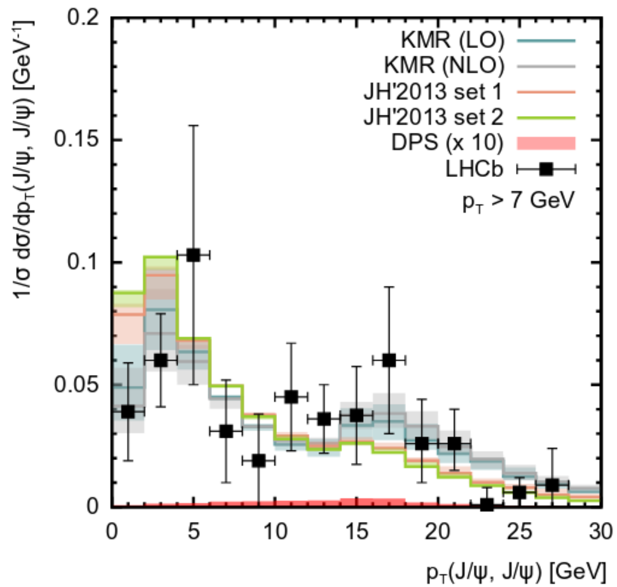
Testing various gluon TMD distributions

- Increasingly tight cuts applied by LHCb:
- From $P_T(J/\psi) > 2$ GeV to > 7 GeV
- ***Baranov et al*** used TMD formalism to describe various kinematic variables
- A variety of gluon TMDs were used, based on `KMR' and `JH2013' approaches
- Better agreement found with KMR variations





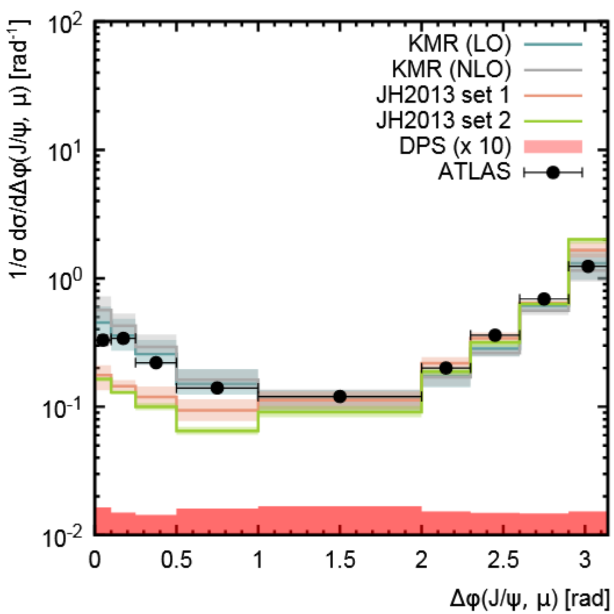


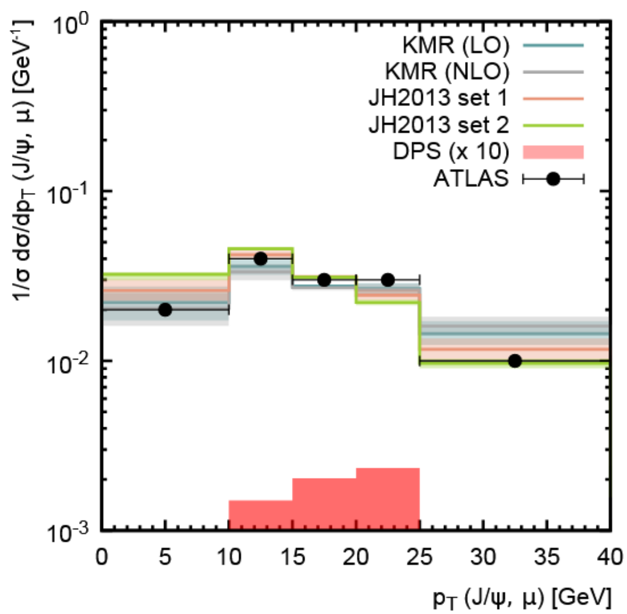


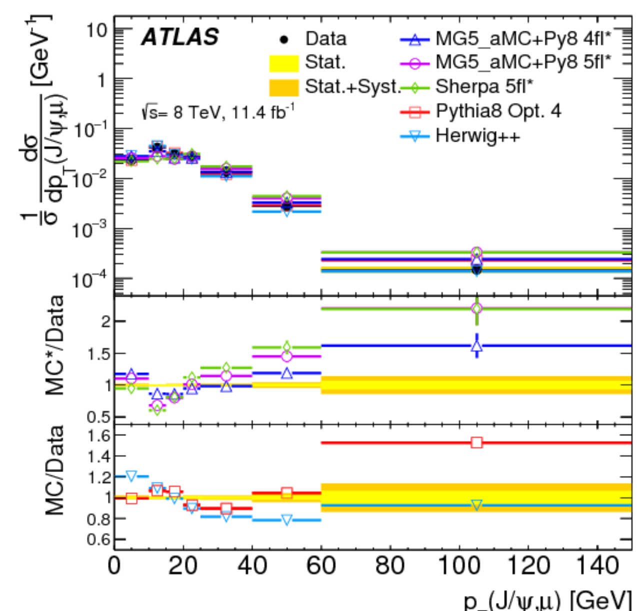
arXiv: 1808.0633 *S.P Baranov, A..V Lipatov, M.A, Malyshev.*

Associated production of J/ψ+μ from ATLAS

- Non-prompt J/ψ plus associated muon from the other B hadron
- Similar bbbar physics, somewhat different kinematics
- DPS significantly suppressed (needs two bbbar pairs?)
- Distribution in Δφ shows a peak at π from back-to-back production...
- ...and a peak at 0 from gluon-splitting
- The latter underestimated by 'JH' sets, but hard to see any correlated p_t mismatch





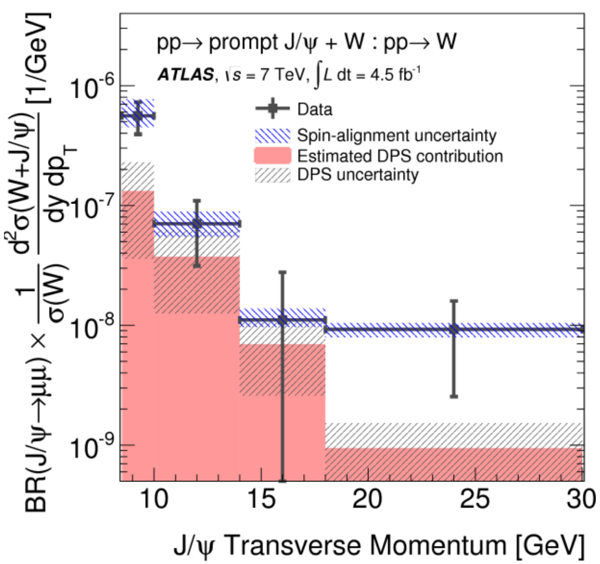


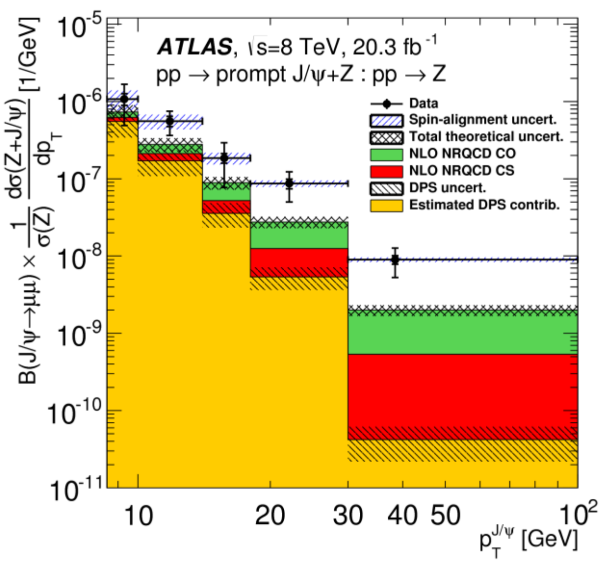
arXiv: **1808.0633**_*S.P Baranov, A..V Lipatov, M.A, Malyshev.*

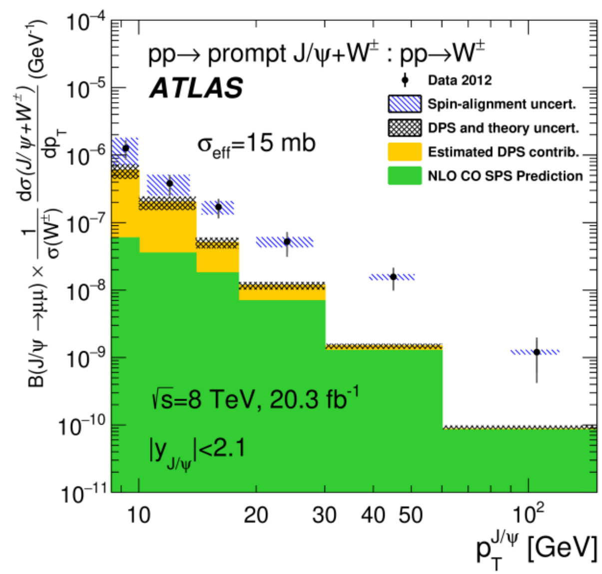
ATLAS Collaboration, JHEP **11**, 62 (2017)

Associated production of J/ψ and Z (or W)

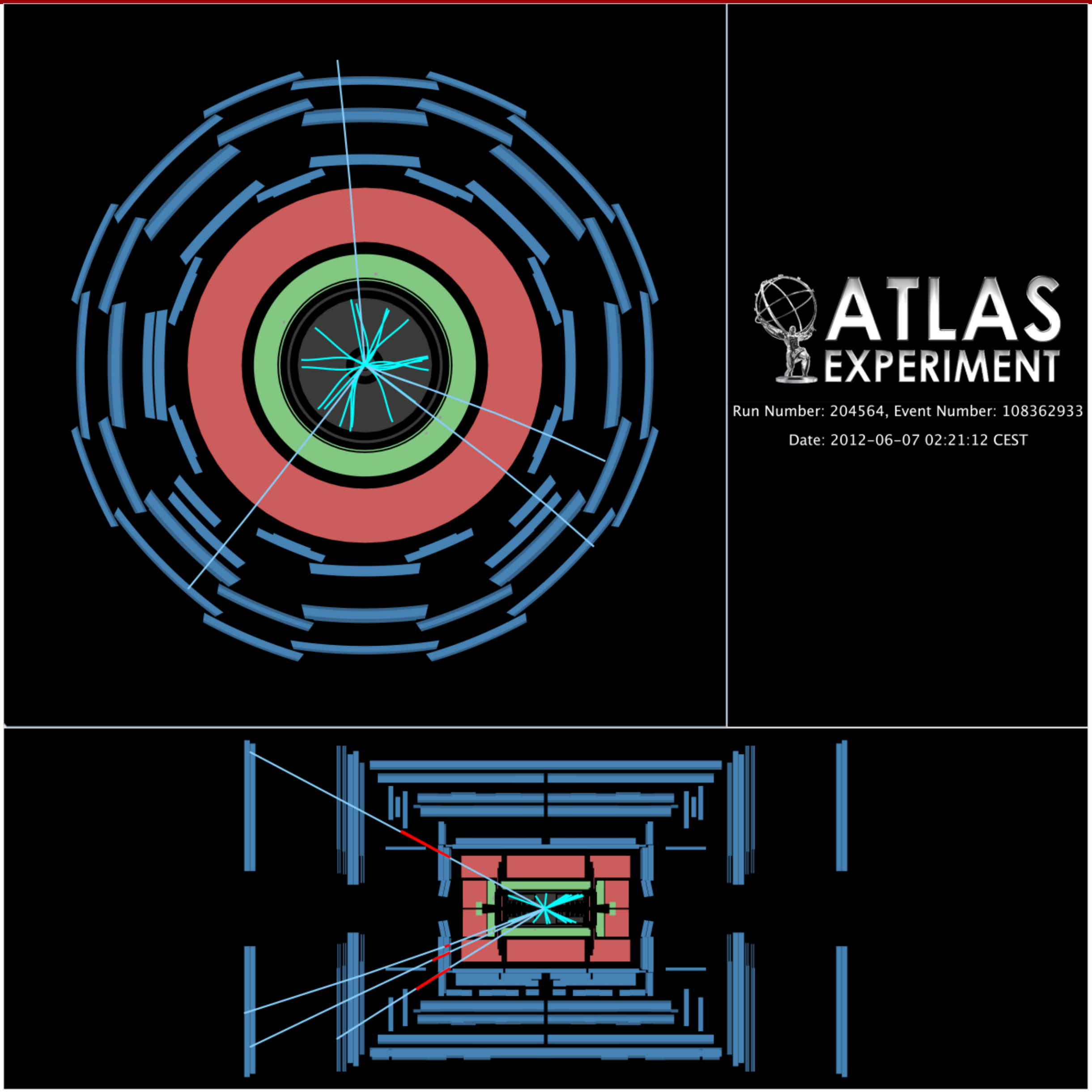
- **Several measurements by ATLAS of such processes**
  - W+J/ψ at 7 TeV JHEP 04 (2014) 172 (prompt only)
  - Z +J/ψ at 8 TeV EPJ C75 (2015) 229 (prompt, non-prompt)
  - W+J/ψ at 8 TeV arXiv:1909.13626 NEW (prompt, non-prompt)
- **Complicated topology, low statistics**
- **Difficult to obtain fully corrected distributions, mainly concentrating on ratios like (J/ψ + V) / $V_{inclusive}$ differentially in J/ψ parameters, SPS-DPS separation**
- **Not very useful in TMD studies (so far) for various reasons**







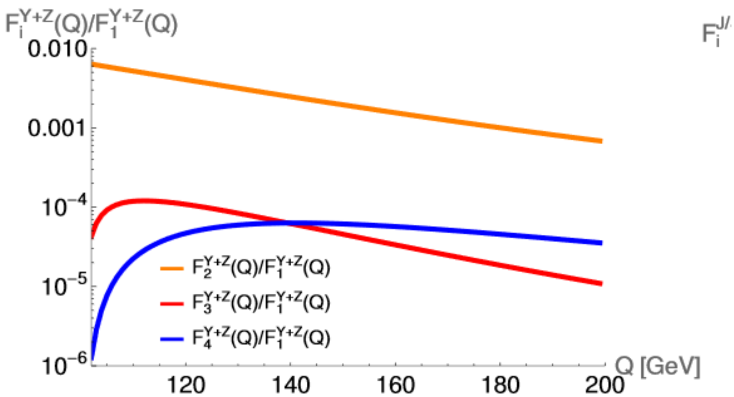
$J/\psi + Z^0$: event candidate

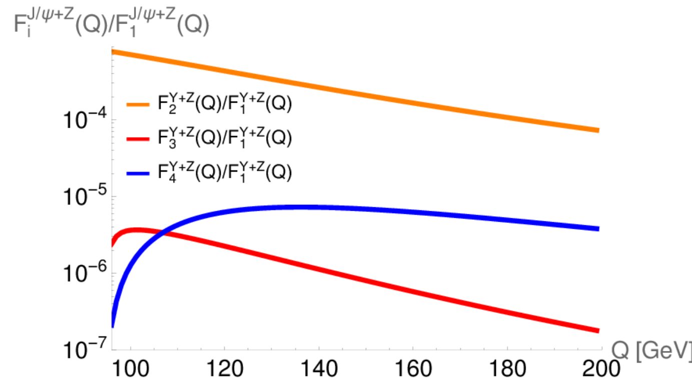


Quarkonium + dilepton: expectations

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

$$\frac{d\sigma^{pp\to J/\psi[\Upsilon]\ell\bar{\ell}X}_{\mathrm{TMD,LO}}}{d^4q\, dM_B^2\, d\Omega} = \hat{F}_1(Q,\alpha,\beta,\theta)\, \mathcal{C}[f_1^g\, f_1^g] + \hat{F}_2(Q,\alpha,\beta,\theta)\, \mathcal{C}[w_2\, h_1^{\perp g}\, h_1^{\perp g}]$$
$$+\left\{\hat{F}_{3a}(Q,\alpha,\beta,\theta)\, \mathcal{C}[w_{3a}\, h_1^{\perp g}\, f_1^g] + \hat{F}_{3b}(Q,\alpha,\beta,\theta)\, \mathcal{C}[w_{3b}\, f_1^g\, h_1^{\perp g}]\right\}\cos 2\phi$$
$$+\hat{F}_4(Q,\alpha,\beta,\theta)\, \mathcal{C}[w_4\, h_1^{\perp g}\, h_1^{\perp g}]\cos 4\phi, \qquad ($$



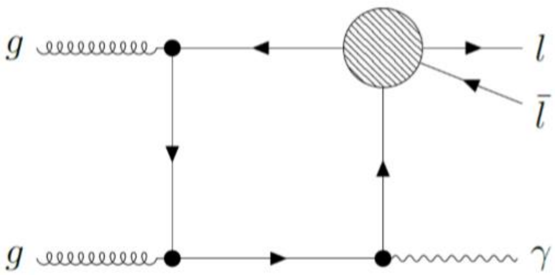


- **F_4 the largest, but still very small**
- **Not much hope to see ϕ modulation**
- **... but a future measurement may produce P_t(QV) distribution, albeit at large invariant mass of the system**

J/ψ + γ : best hope?

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

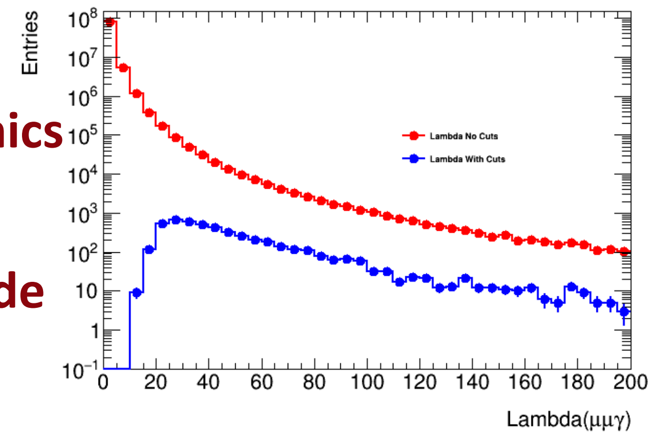
$$\frac{d\sigma}{dQ dY d^2 q_T d\Omega} = \frac{4\alpha_s^2 \alpha e_Q^2 |R_0(0)|^2}{3M_Q^3} \times \frac{Q^2 - M_Q^2}{sQ^3\{(\gamma^2+1)^2 - (\gamma^2-1)^2\cos^2\theta\}^2} \times$$
$$\times \Big\{F_1 C_1\big[f_1^g f_1^g\big] + F_3 C_3\big[w_3 f_1^g h_1^{\perp g} + (x_a \leftrightarrow x_b)\big]\cos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

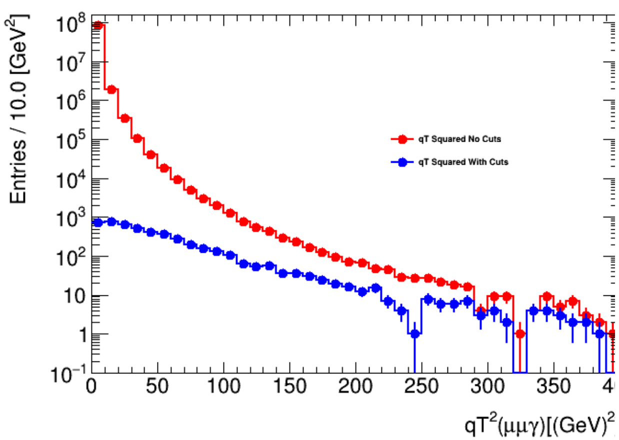


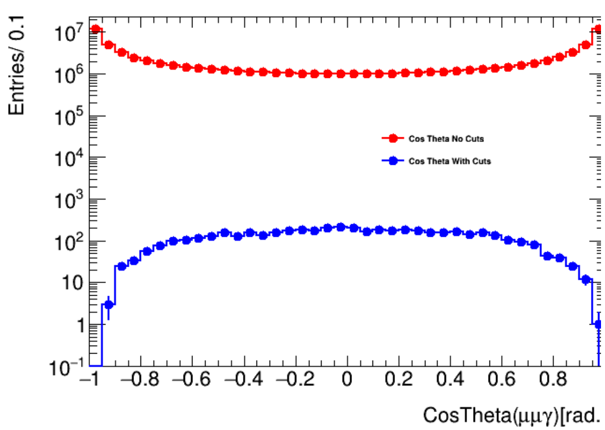
- ❑ As usual in ATLAS, only sensitive to J/ψ with p_t>8 GeV
- ❑ Means invariant mass large, $\lambda = \gamma^2 = (M/m)^2 > 20$ or so (or high p_t of the system)
- ❑ In that regime F_4/F_1 is roughly constant of order 0.1
- ❑ Modulation expected to be the strongest at low cosθ (probably a good thing)
- ❑ Background from DPS (i.e. inclusive J/ψ + random photons) dominates
- ❑ Some nice features of the theoretical cross section lost due to acceptance cuts

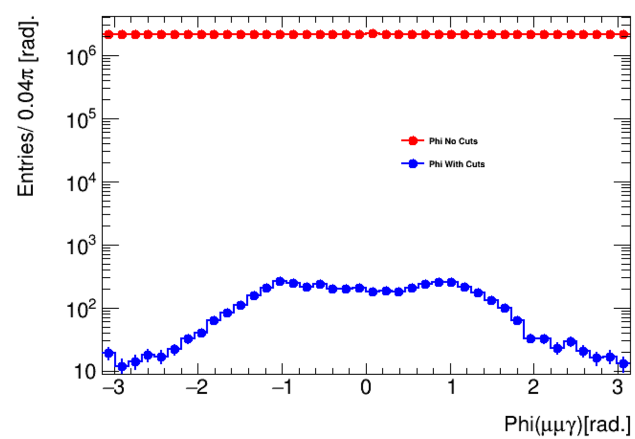
Effects of acceptance cuts on MC

- MC: PYTHIA 8 with LO subprocess g+g -> $J/\psi + \gamma$ => NO TMDs in MC!
- No cuts in RED, cuts $p_t(\mu)$>4 GeV, $p_t(\gamma)$>5 GeV in BLUE
- Low inv. masses of the system not accessible
- $\cos\theta$ spectrum loses "horns" near 1
- ϕ spectrum loses uniformity, contains many harmonics
- Any ϕ modulation in F_4 is unlikely to be measurable
- Low system transverse momenta accessible for a wide range of invariant masses
- Average q_t determination should be possible via F_1



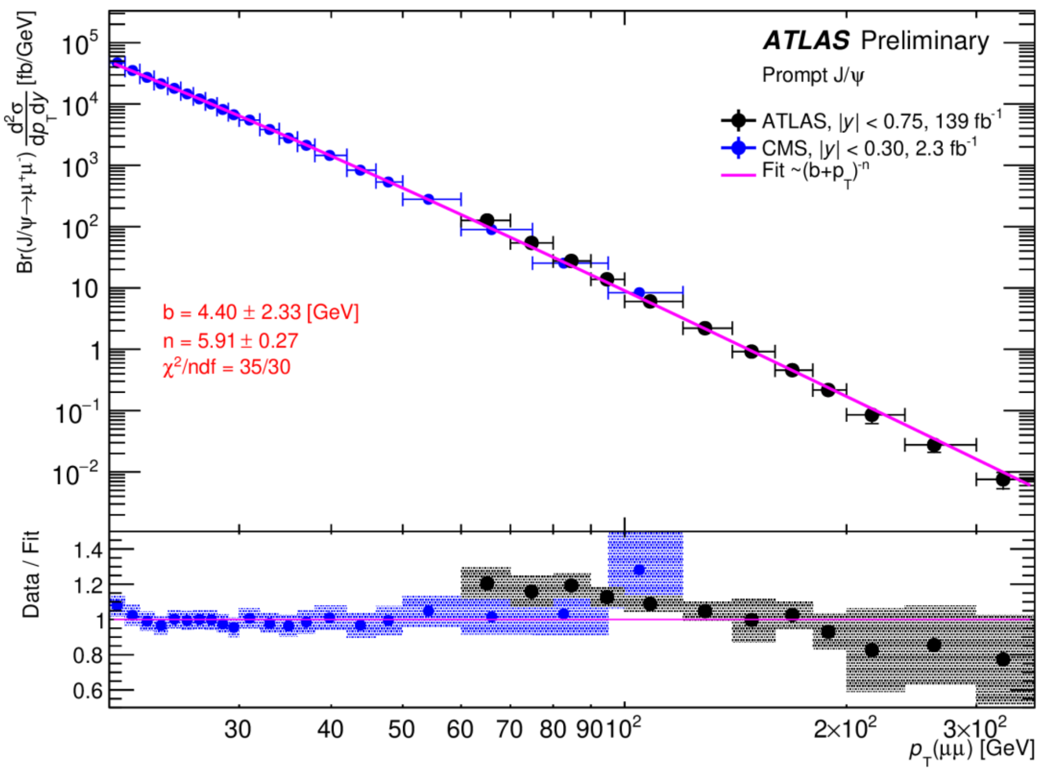


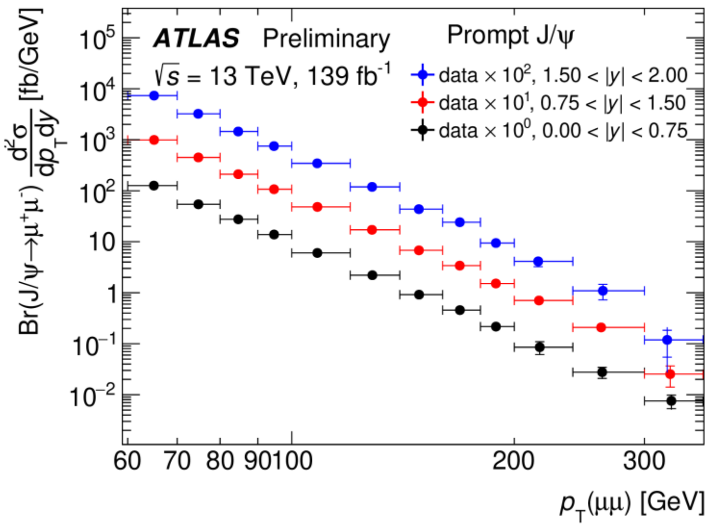




Fresh from ATLAS – on a different topic!

- **NEW:** inclusive J/ψ production at high p_t
- Full 139 /fb luminosity of Run2 used
- J/ψ p_t range 60-360 GeV, 60 to 140 GeV for ψ'
- Combines smoothly with CMS at lower p_t





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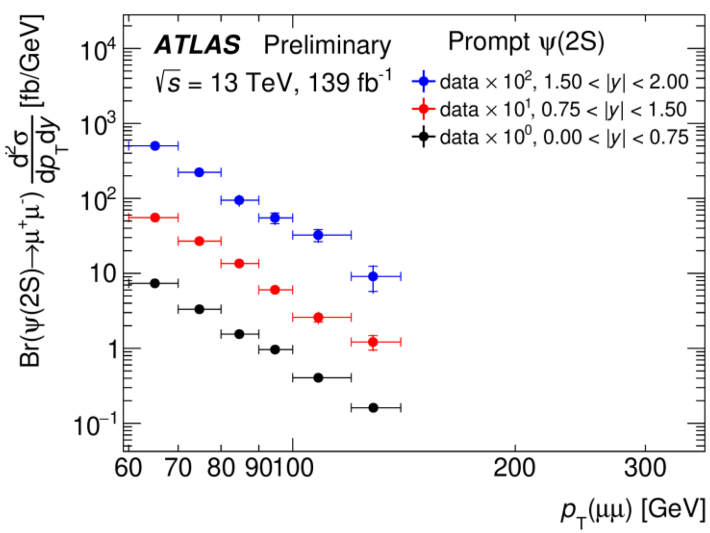

Summary

- A lot of theoretical activity over last few years
- Experimental data related to gluon TMDs still very sparse
- Some relevant measurements start to come through
- Our analysis is still in progress – maybe some results at REF 2020 ?
- As always, bridges between theory and experiment are vital
- Thanks for organising this workshop – and for the invitation!