QUARKONIA PRODUCTION WITH THE ATLAS EXPERIMENT
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(on behalf of the ATLAS Collaboration)

Results in Talk

In this talk I will focus on two different methods of studying quarkonium at ATLAS.

- The first is trying to understand exotic quarkonium through searches for the bottomonium counterpart for X(3872).
  - "Search for the X_b and other hidden-beauty states in the $\pi^+\pi^-\Upsilon(1S)$ channel at ATLAS": **arXiv:1410.4409 [hep-ex]**, Phys. Lett. B740 (2015) 199-217

- The second is through studying rare production models of quarkonium.
  - "Observation and measurements of the production of prompt and non-prompt J/ψ mesons in association with a Z boson in pp collisions at $\sqrt{s}$ = 8 TeV with the ATLAS detector": **arXiv:1412.6428 [hep-ex]**, **submitted to EPJC**.

X(3872) and X_b

- X(3872) is the first and best-studied hidden-charm state in the last decade. First observed by Belle in $B^{\pm} \rightarrow K^{\pm} X(\rightarrow \pi^+\pi^- J/\psi)$ (arXiv:hepex/0309032v2).

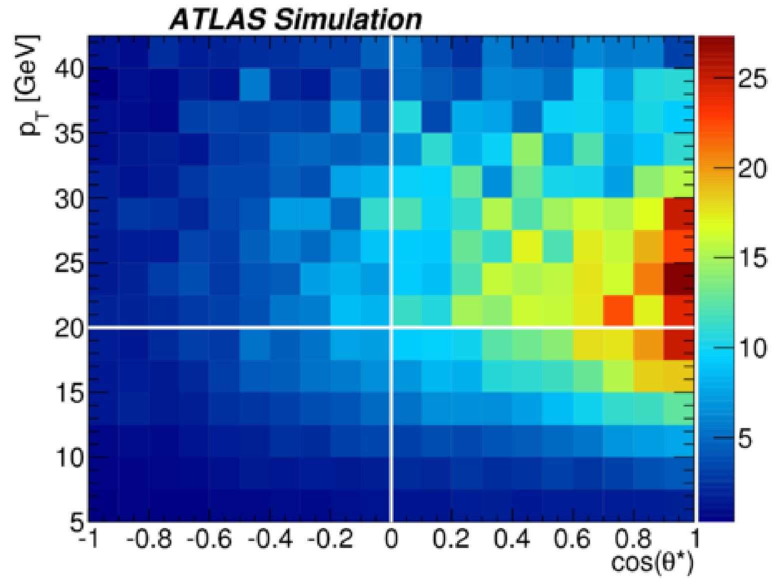
- CMS has measured the product of the cross section of prompt X(3872) times BF($X(3872) \rightarrow \pi^+\pi^- J/\psi$) to be ($6.56 \pm 0.29 \pm 0.65$)% of the value for the product of the cross section of ψ(2S) and BF($\psi(2S) \rightarrow \pi^+\pi^- J/\psi$) (arXiv:1302.3968).

- Due to the mass, small width, and $J^{PC} = 1^{++}$ (LHCb: arXiv:1504.0633) it is unlikely to be a conventional quarkonium state.
  - $D^0\overline{D^{*0}}$ molecular models (arXiv:hep-ph/ 0311229) and tetraquark states (arXiv:hep-ph/0412098) are popular.

- Heavy-quark symmetry suggests the presence of hidden-beauty partner X_b. We will look at the analogous decay to $\pi^+\pi^-\Upsilon(1S)$.
  - CMS found no signal and set an upper limit on the cross section times BF($X_b \rightarrow \pi + \pi^- \Upsilon(1S)$) at values between 0.9-5.4% of the Υ(2S) rate (arXiv:1309.0250).
  - Using this decay we also search for $\Upsilon(1^3D_J)$, Υ(10860), and Υ(11020).

$X_b \rightarrow \pi^+\pi^-\Upsilon(1S)$

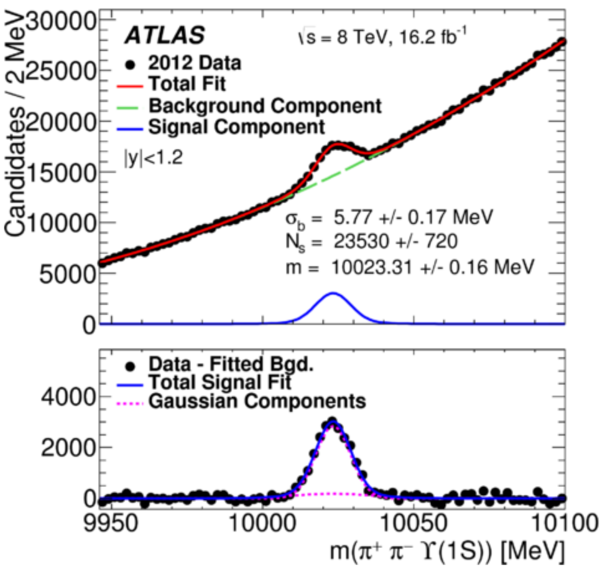
- 16.2 fb^{-1} of $\sqrt{s}$ = 8 TeV ATLAS Data.
- Each event passes a trigger requiring two opp. sign muons with $p_T > 4$ GeV and 8 GeV < M(μμ) < 12 GeV.
  - $\Upsilon(1S)$: $|\eta^\mu|<2.3$, $|M(\mu\mu) - M(\Upsilon(1S))| < 350$ MeV.
  - π: opp. charge, $|\eta^\pi|<2.5$, $p_T > 400$ MeV.
  - $\pi^+\pi^-\Upsilon(1S)$: $M(\pi^+\pi^-\Upsilon(1S))<11.2$ GeV, $p_T > 5$ GeV, $|y|<2.4$.

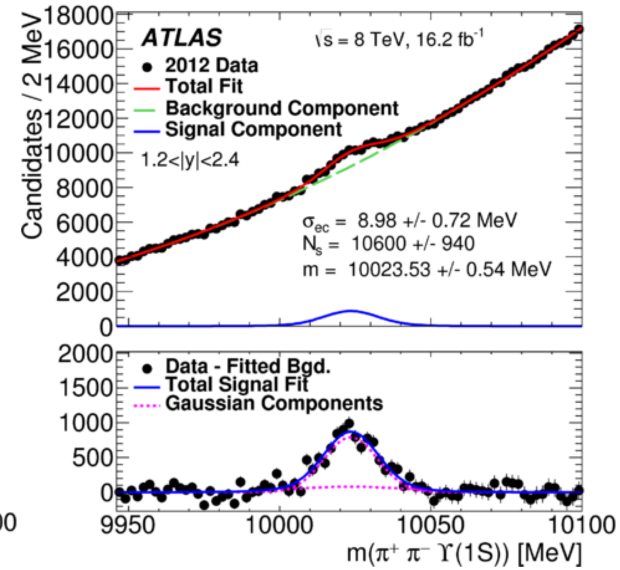


- ATLAS measurements of $\Upsilon(nS)$ production cross sections at $\sqrt{s}$ = 7 TeV (in the di-muon channel) are reweighted using Pythia 8 MC to provide predictions for $\Upsilon(nS)$ cross sections at $\sqrt{s}$ = 8 TeV.

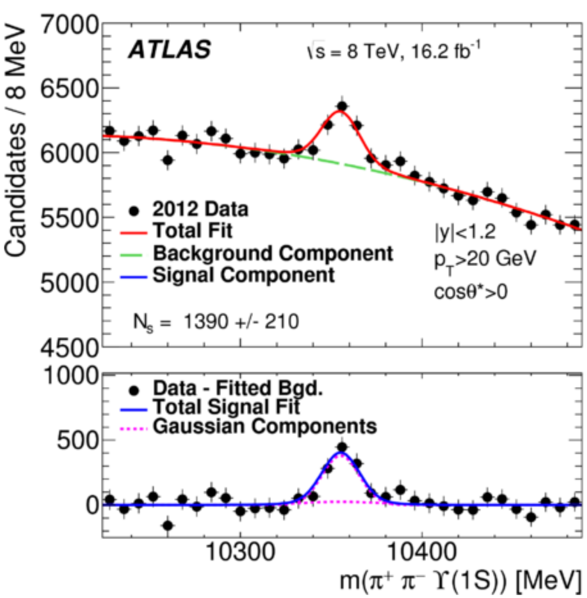
- The data are split into 8 kinematic bins and the signal is extracted via three splitting functions and their complements.
  - Bins are at $|y|$ = 1.2, p_T = 20 GeV, and $\text{Cos}(\vartheta^*) = 0$. Determined by the $S/\sqrt{B}$ significance.

ϒ(2S) and ϒ(3S) Test





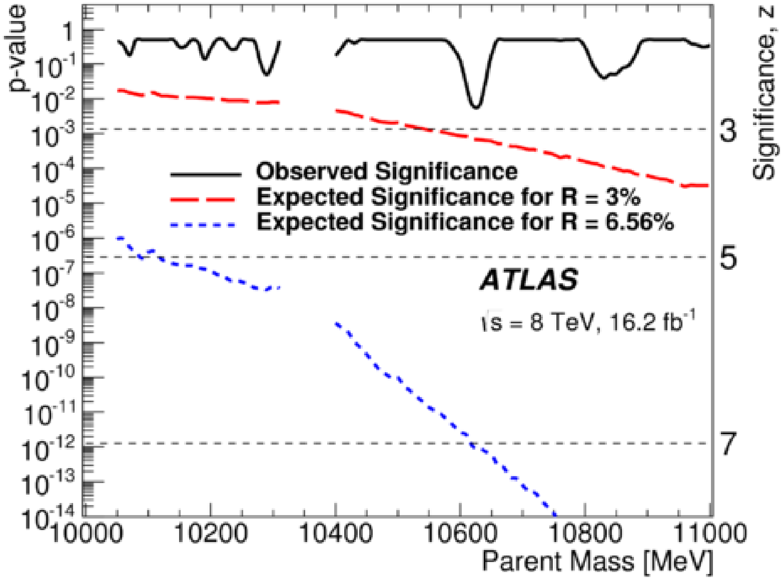
- The ϒ(2S) and ϒ(3S) peaks are fit to validate the measurement techniques.
- The signal shape parameters are fixed to the simulated values.



- The expected yield (calculated in the backup) is compared to the total fitted yield.

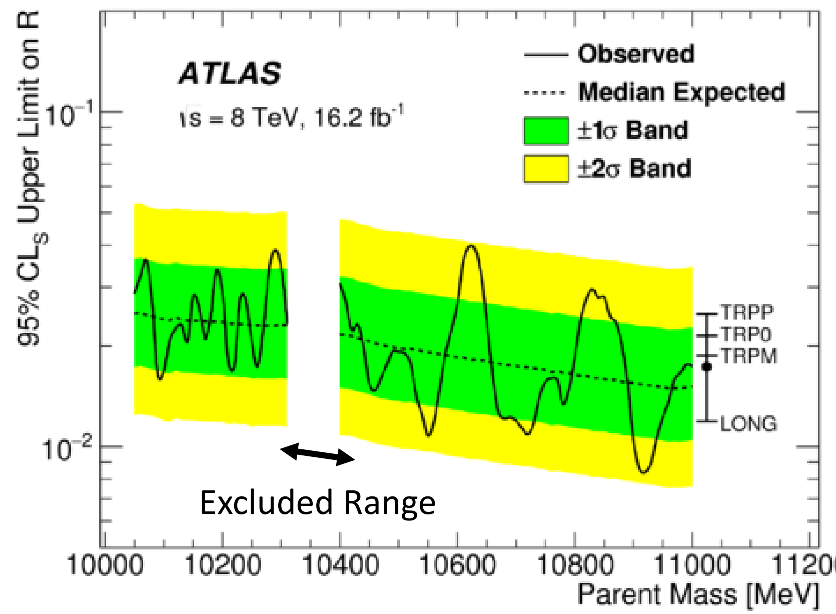
- ϒ(2S): $N_{2S} = 34{,}300 \pm 800$.
  - $N_{2S}^{expect.} = 33{,}300 \pm 2{,}500$.
- ϒ(3S): $N_{3S} = 11{,}600 \pm 1{,}300$.
  - $N_{3S}^{expect.} = 11{,}400 \pm 1{,}500$.

Results for X_b search



- The data is fit every 10 MeV excluding the range around ϒ(2S) and ϒ(3S). The range is:
  - 10.05–10.31 and 10.40–11.00 GeV.
  - **No excess with a local significance of 3σ or greater is observed.**
- $N = N_{2S} * R * \frac{A}{A_{2S}} * \frac{\epsilon}{\epsilon_{2S}}$.
  - $R \equiv (\sigma BF)/(\sigma BF)_{2S.}$

- **Upper limits on R = 0.8-4.0% at 95% CL.**
  - **Excludes analogous R =6.56% from X(3872).**
- Upper limit is more restrictive than the CMS results above ~ 10.1 GeV.
- If X_b exists in this range:
  - The BF or production cross section relative to ϒ(2S) is smaller than X(3872) relative to ψ(2S)
  - There are no strong isospin-violating effects present as in X(3872)→ $\pi^+\pi^- J/\psi$.
    - If so X_b would have more prominent decays to $\pi^+\pi^-\chi_{b1}$ or $\pi^+\pi^-\pi^0$ ϒ(1S).



$\Upsilon(1^3D_J)$, $\Upsilon(10860)$, and $\Upsilon(11020)$

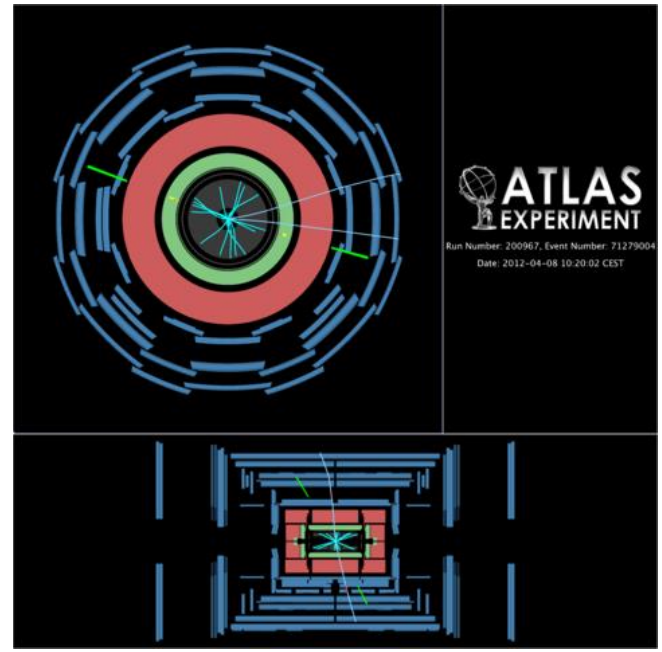
- To fit the $\Upsilon(1^3D_J)$ triplet two extra peaks are added.
  - CLEO (arXiv:hep-ex/0404021) and BaBar (arXiv:1004.0175) measured an average $M(\Upsilon(1^3D_2)) = (10163.7 \pm 1.4)$ MeV.
  - Averaging over multiple models gives 10156, 10164, and 10170 MeV.
  - **Assuming a common lineshape model for J=0,1,2, no significant signals are observed.**
  - Assuming J = 2 dominates or the mass splitting is larger than the resolution and $BF(\Upsilon(1^3D_2)\rightarrow\pi^+\pi^-\Upsilon(1S))$ (arXiv:1004.0175) gives:
    - **$\sigma(\Upsilon(1^3D_2))/\sigma(\Upsilon(2S)) \leq 0.55$.**

- Broader range for $\Upsilon(10860)$, and $\Upsilon(11020)$.
  - Assuming the world average for the mass and width, significances of 0.6σ and 0.3σ are found for $\Upsilon(10860)$ and $\Upsilon(11020)$.
  - If the mass and width are calculated in a grid with $m\pm20$ MeV and $\Gamma\pm\Delta\Gamma$:
    - **$\Upsilon(10860)$: Significance of 1.1σ at m = 10856 MeV and Γ = 55 MeV.**
    - **$\Upsilon(11020)$: Significance of 0.6σ at m = 11039 MeV and Γ = 95 MeV.**

Z+J/ψ

- The first measurement of Z+J/ψ.
  - 20.3 fb^{-1} of $\sqrt{s}$ = 8 TeV ATLAS Data.
  - Look at both di-electron and di-muon decay modes of Z boson.
- Interests:
  - Spin-alignment of charmonium and distinguish between color octet and singlet models.
  - Improve perturbative convergence of calculations.
  - Heavy flavor production in association with a Z boson.
  - ZZ* and a background to Z→l^+l^-J/ψ.
  - Rare Higgs decay, charm couplings, and CP properties.
  - Double Parton Scattering.

Z(→e^+e^-) + J/ψ



Z boson selection
p_T (trigger lepton)> 25 GeV, p_T (sub-leading lepton)> 15 GeV
$\lvert\eta(\text{lepton from } Z)\rvert < 2.5$
$\lvert m(Z) - 91.1876 \text{ GeV}\rvert < 10$ GeV
J/ψ selection
$2.6 < m(J/\psi) < 3.6$ GeV
$8.5 < p_T(J/\psi) < 100$ GeV, $\lvert y(J/\psi)\rvert < 2.1$
p_T (leading muon)> 4.0 GeV, $\lvert\eta(\text{leading muon})\rvert < 2.5$
$\left\{ \begin{array}{ll} \text{either } p_T \text{ (sub-leading muon)} > 2.5 \text{ GeV}, & 1.3 \le \lvert\eta(\text{sub-leading muon})\rvert < 2.5 \\ \text{or } p_T \text{ (sub-leading muon)} > 3.5 \text{ GeV}, & \lvert\eta(\text{sub-leading muon})\rvert < 1.3 \end{array} \right\}$

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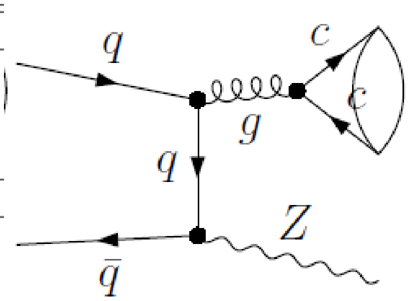
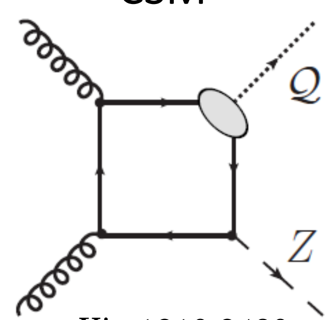


arXiv:1102.0398

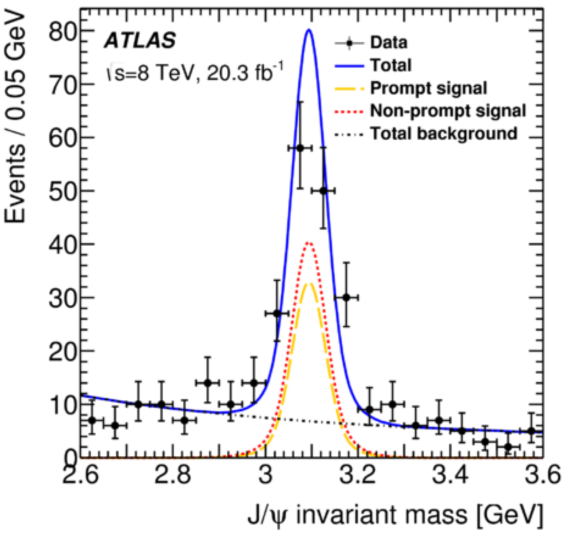
CSM



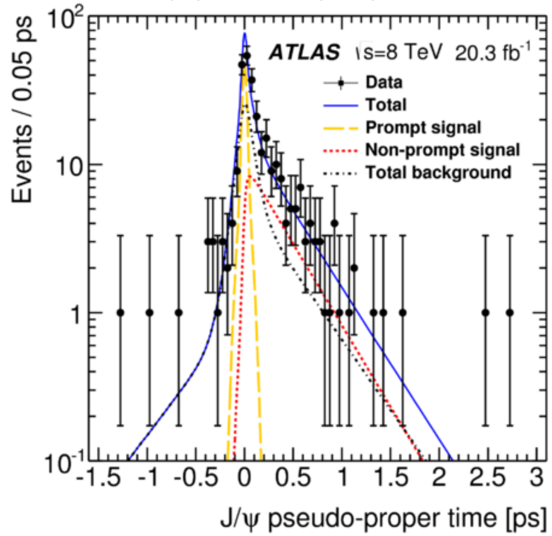
arXiv:1210.2430

Extracting Signal

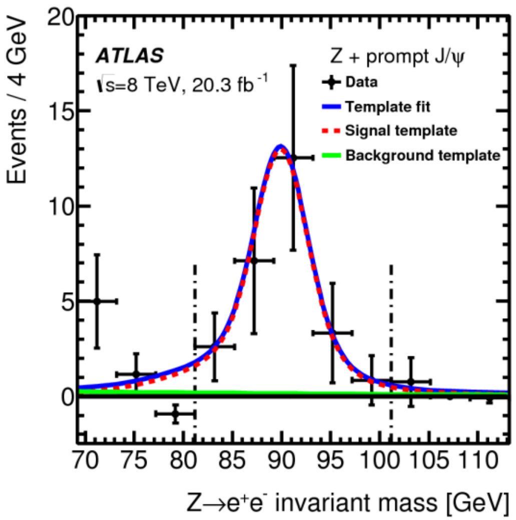
J/ψ invariant mass



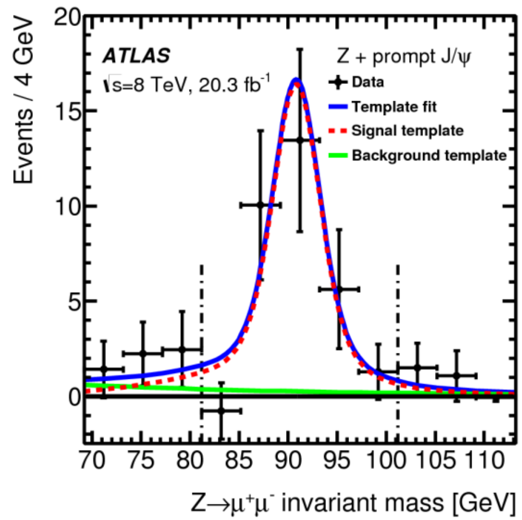
J/ψ pseudo-proper time



Z(→e⁺e⁻) + Prompt J/ψ



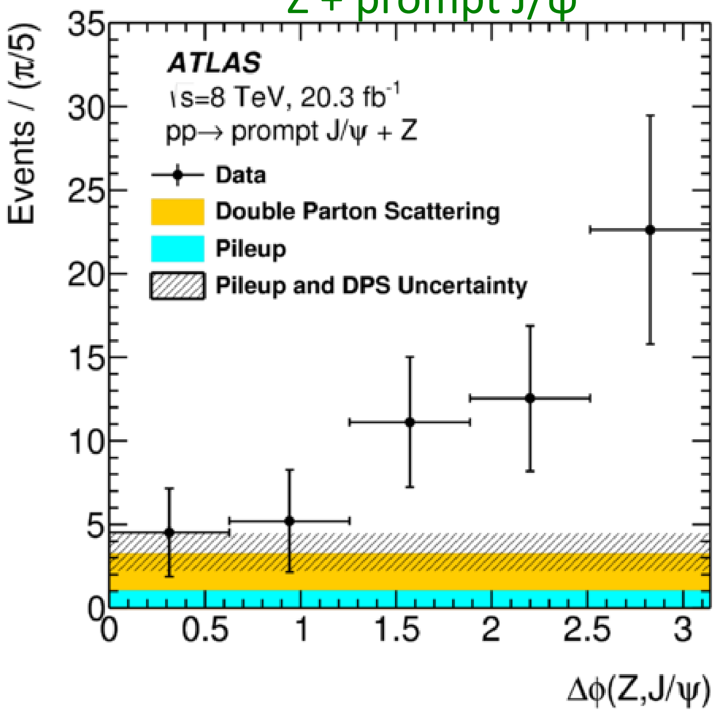
Z(→μ⁺μ⁻) + Prompt J/ψ



- Z→ττ, W→lν, $t\bar{t}$, single top and diboson backgrounds are modeled by MC.
- Multijet and misidentified leptons are modelled by reversing isolation req.
- Pileup background events are estimated (backup).

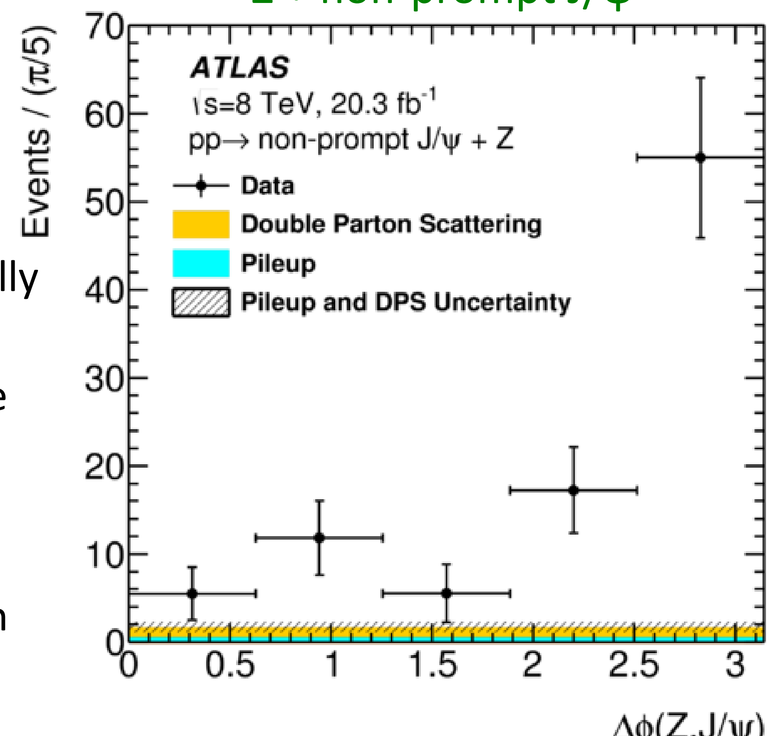
Double Parton Scattering

Z + prompt J/ψ



- **Double Parton Scattering (DPS)**: two parton-parton interactions in a single hadron-hadron collision.
- $\sigma_{DPS} = \frac{\sigma_Z \sigma_{J/\psi}}{\sigma_{Eff}}$.
  - σ_{Eff} = 15±3(stat)$^{+5}_{-3}$(sys) mb taken from ATLAS W+2j results (arXiv:1301.6872[hep-ex]) for DPS estimates.
- DPS events are distributed uniformly in Δϕ(Z,J/ψ).

Z + non-prompt J/ψ

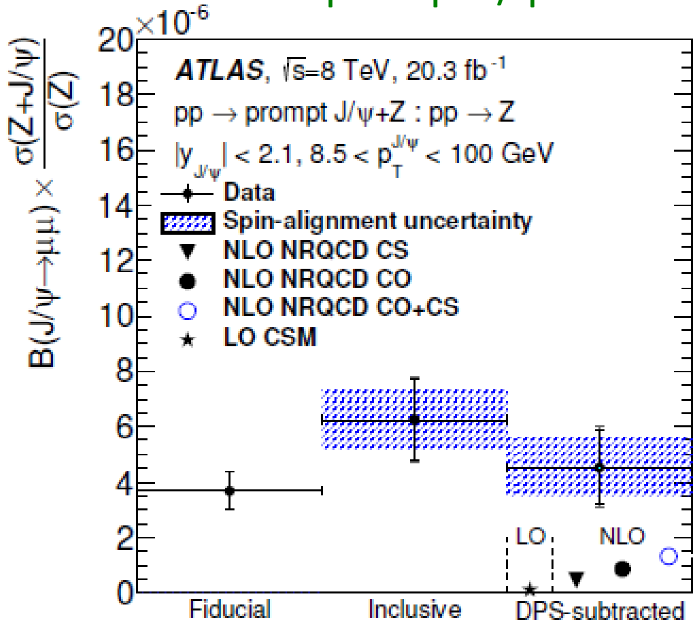


- **Single Parton Scattering (SPS)** events preferentially produced back-to-back, peaking at Δϕ = π.
- We set a conservative lower limit on the effective cross-section (upper limit on DPS production) by assuming |Δϕ|<π/5 is purely DPS.
  - **σ_{Eff} > 5.3 mb (3.7 mb) at 68% (95%) CL**.
- Results are measured in the fiducial volume, then the inclusive volume, and finally after DPS subtraction.

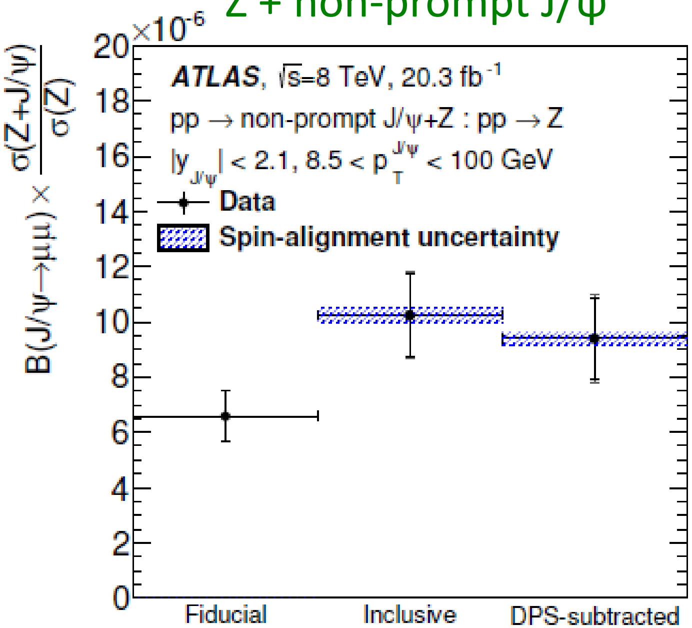
Results: Z+J/ψ

- **First measurement of Z+J/ψ. Null hypothesis excluded at 5σ for prompt and 9σ for non-prompt.**
- $R_{Z+J/\psi} = \mathrm{BF}(J/\psi \to \mu^+\mu^-)\,\dfrac{\sigma(pp \to Z+J/\psi)}{\sigma(pp \to Z)}$
  - $R^{fid}_{Z+J/\psi} = (36.8 \pm 6.7 \pm 2.5) \times 10^{-7}$ (prompt).
  - $R^{fid}_{Z+J/\psi} = (65.8 \pm 9.2 \pm 4.2) \times 10^{-7}$ (non-prompt).

Z + prompt J/ψ



Z + non-prompt J/ψ



- f_{DPS} = (29±9)% prompt, (8±2)% non-prompt.

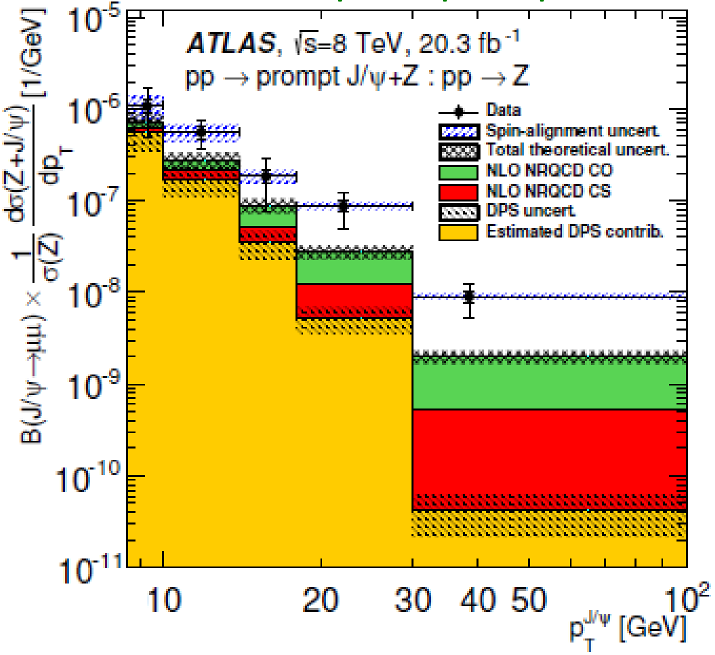
- Theory underestimates SPS production.
  - Does not include feed-down from excited charmonium states, but only accounts for about 20%.

LO Theory: arXiv:1210.2430 [hep-ph].

NLO Theory: arXiv:1102.0398 [hep-ph].

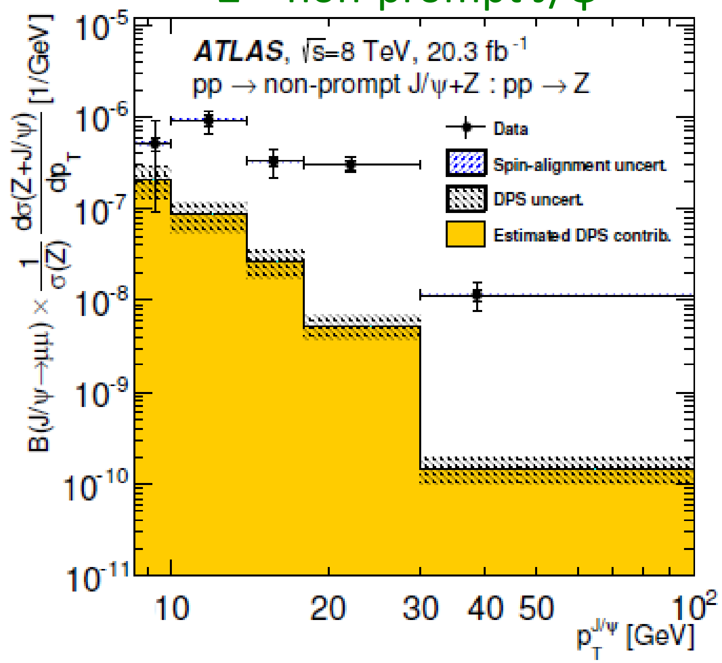
Differential Cross Section Ratio

Z + prompt J/ψ



- Prompt differential cross section ratio is compared to NLO SPS predictions and DPS expectations.
- Theory predicts CO > 2*CS with CO increasing with p_T.
- DPS + NLO SPS predictions underestimate the data by a factor of 4-5 for $p_T^{J/\psi}$ > 18 GeV.

Z + non-prompt J/ψ



- Significant SPS contribution to Z + non-prompt J/ψ is expected from Z + b-jet production.
- The data presents the opportunity to test Z + b-jet production at low p_T.

NLO Theory: arXiv:1102.0398 [hep-ph].

Summary

- Search for X_b and other hidden beauty states (**arXiv:1410.4409 [hep-ex]**):
  - No evidence of new states for masses 10.05–10.31 GeV and 10.40–11.00 GeV.
  - **Upper limit set on R = $(\sigma BF)/(\sigma BF)_{2S}$ ranging from 0.8 – 4.0%. The X_b limit is the most stringent in this channel to-date.**
    - Excludes the analogous R = 6.56% of X(3872) for all masses.
  - No significant signal for the $\Upsilon(1^3D_J)$ triplet, Υ(10860), or Υ(11020).
  - **95% CLs upper limit of 0.55 is set on $\sigma(\Upsilon(1^3D_2))/\sigma(\Upsilon(2S))$.**

- Z+J/ψ production (**arXiv:1412.6428 [hep-ex]**):
  - **Measured for the first time. Background-only rejection at 5σ for prompt and 9σ for non-prompt.**
  - DPS plays a large role (~29% for prompt J/ψ). A lower limit on the effective cross section (upper limit on the rate of DPS) is measured:
    - **σ_{Eff} > 5.3 mb (3.7 mb) at 68% (95%) CL.**
  - NLO SPS + DPS predictions underestimate the Z + prompt J/ψ data.
  - Large Z + non-prompt J/ψ SPS component is expected from Z+b-jet.

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BACKUP SLIDES

Splitting Functions

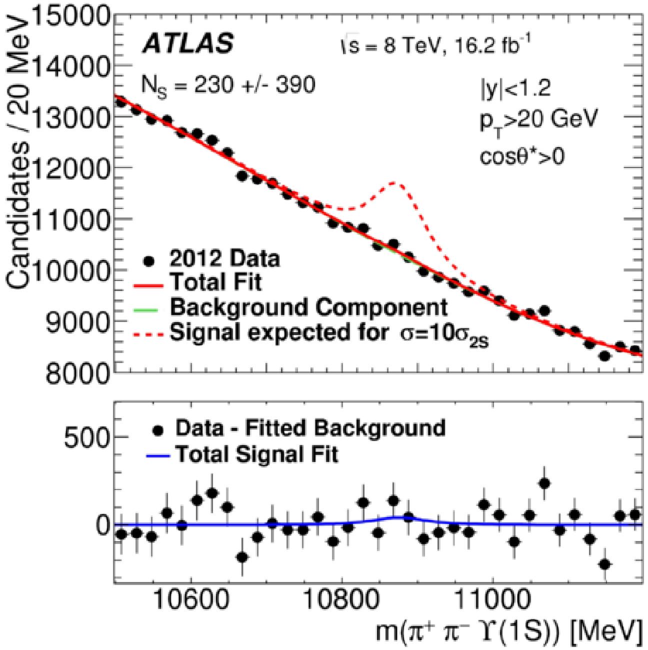
- Splitting functions are used to calculate the signal yield in any particular ($|y|$, p_T, $\cos\vartheta^*$) bin.
  - $S_{|y|} = 0.606 \pm 0.004$ for $|y|<1.2$.
  - $S^{b(ec)}_{p_T}(m) = a/(1+e^{-b(m-c)})$ for $p_T < 20$ GeV.
  - $S_{\cos\vartheta^*}(m) = a + bm + cm^2$ for $\cos\vartheta^* < 0$.

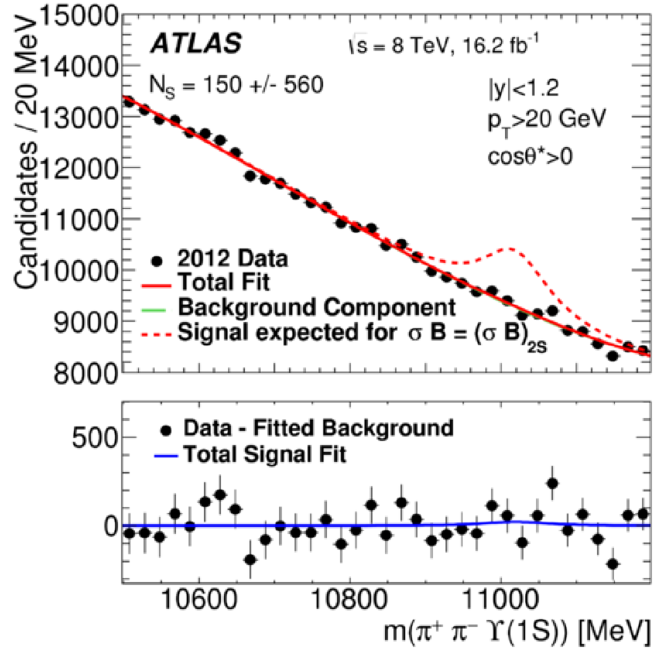
- Multiplying the splitting functions and their complements gives the signal yield. For example in the bin ($|y|< 1.2$, $p_T> 20$ GeV, $\cos\vartheta^* < 0$) the function is:
  - $S_{|y|} \cdot (1 - S^{b}_{p_T}(m)) \cdot S_{\cos\vartheta^*}(m)$.

Calculation of Expected $\Upsilon(2S)$

- $N_2^{exp} = (\sigma \mathrm{BF})_{2S} \cdot L \cdot A \cdot \epsilon$
  - $(\sigma \mathrm{BF})_{2S}$ ≡ The product of the cross section and branching fraction estimated from the extended cross section measurement using world averaged values for BF($\Upsilon(1S) \to \mu^+\mu^-$) and BF($\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$).
  - L ≡ Luminosity.
  - A ≡ The acceptance calculated from the shape of the doubly differential cross section. $A = (1.442 \pm 0.004)\%$ assuming the CLEO dipion mass spectrum (arXiv:hep-ex/9802024) and isotropic signal decays.
  - ϵ ≡ The reconstruction efficiency for decays within the acceptance is taken from the $\Upsilon(2S)$ simulation, $\epsilon = 0.283 \pm 0.002$.

ϒ(10860) and ϒ(11020)





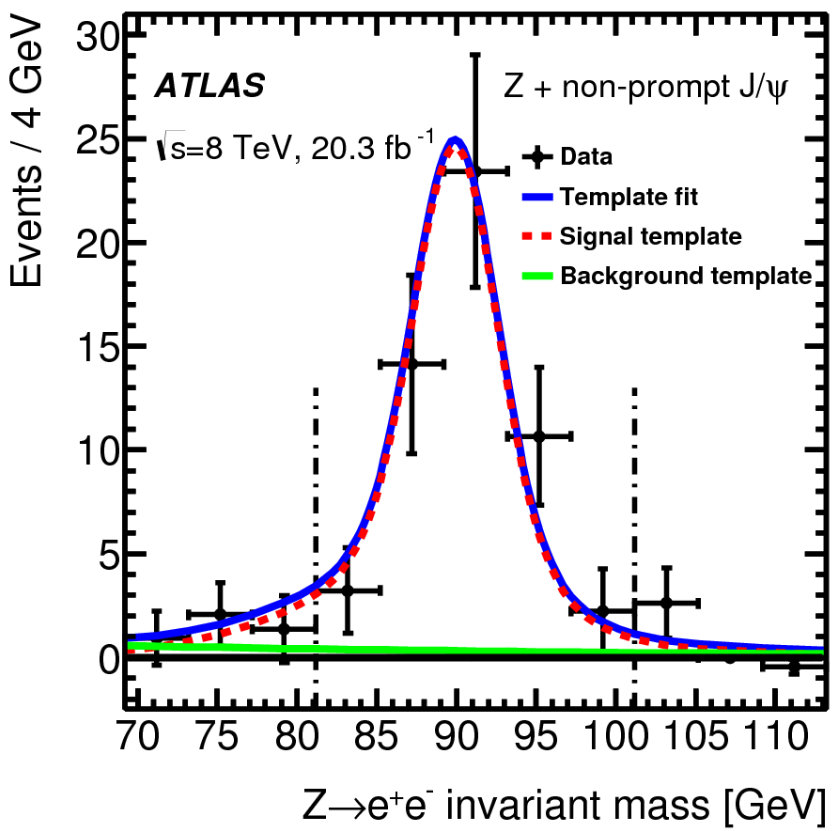
- The ϒ(10860) (left) and ϒ(11020) (right). simultaneous fits projected onto the most sensitive bin.
- The dashed line is a strong signal with $\sigma=10\sigma_{2S}$ for ϒ(10860) and $\sigma B = (\sigma B)_{2S}$ for ϒ(11020).
- No attempt is made to explain the large partial width of ϒ(10860) comparted to ϒ(3S) and ϒ(4S).
- No strong signal is observed for either state.

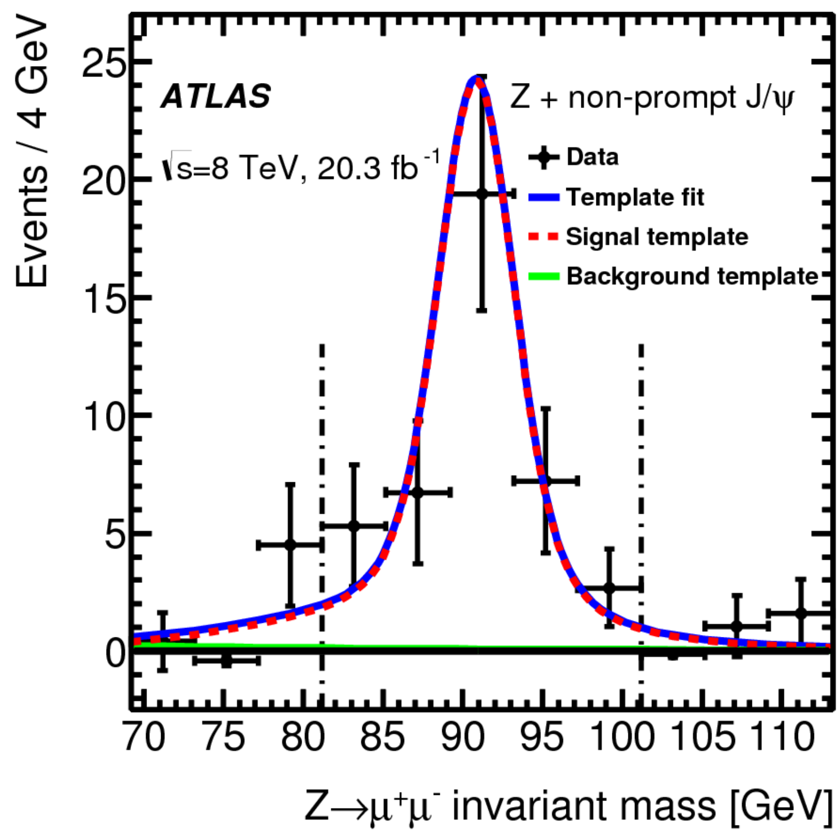
Systematic Uncertainty: Search for X_b

	Signal shape parameters						Signal bin splitting functions						
	$\sigma_{\rm b}$ [%]	$\sigma_{\rm ec}$ [%]	$f_{\rm b}$ [%]	$f_{\rm ec}$ [%]	$r_{\rm b}$ [%]	$r_{\rm ec}$ [%]	$S_{\|y\|}$ [%]	$S^{\rm b}_{p_{\rm T}}$ [%]	$S^{\rm ec}_{p_{\rm T}}$ [%]	$S^{(1)}_{\cos\theta^*}$ [%]	$S^{(2)}_{\cos\theta^*}$ [%]	$S^{(3)}_{\cos\theta^*}$ [%]	$S^{(4)}_{\cos\theta^*}$ [%]
Extracting f, r			0.5	1.1	1.2	1.4							
Extrapolating σ	0.1	0.2											
Data/MC difference in σ	1.9	4.2											
$\|y\|$ scale factors							5.8						
Production weighting							0.3	8.4	7.0	0.9	2.8	2.1	3.4
Bin splittings: fit							0.2	0.5	0.8	2.4	4.2	2.8	6.0
Bin splittings: parameterisation							1.8	1.0	1.2	0.2	0.2	0.4	0.2
$m_{\pi^+\pi^-}$ shape							0.2	8.0	11.5	34.7	16.2	15.9	15.0
Total	2.0	4.2	0.5	1.1	1.2	1.4	6.1	11.6	13.6	34.8	17.0	16.3	16.6

	N_{2S} [%]	ϵ/ϵ_{2S} [%]	$\mathcal{A}/\mathcal{A}_{2S}$ [%]	$\epsilon/\epsilon_{2S}\cdot\mathcal{A}/\mathcal{A}_{2S}$ [%]
N_{2S} yield	2.3			
ϵ vs. m: fit		1.0		
ϵ vs. m: parameterisation		0.5		
Production weighting		1.0		
Acceptance Extrapolation			11.7	
$m_{\pi^+\pi^-}$ shape				17.3
Total	2.3	1.5	11.7	17.3

Z + Non-prompt J/ψ Mass fits





Z + J/ψ Fit Results

Process	$\lvert y_{J/\psi}\rvert < 1.0$	$1.0 < \lvert y_{J/\psi}\rvert < 2.1$	Total	
			Events found	From pileup
Prompt signal	$24 \pm 6 \pm 2$	$32 \pm 8 \pm 5$	$56 \pm 10 \pm 5$	$5.2^{+1.8}_{-1.3}$
Non-prompt signal	$54 \pm 9 \pm 3$	$41 \pm 8 \pm 7$	$95 \pm 12 \pm 8$	$2.7^{+0.9}_{-0.6}$
Background	$61 \pm 11 \pm 6$	$77 \pm 13 \pm 7$	$138 \pm 17 \pm 9$	

"Pile-up": Double Interactions

- Cut on |d_z|>10 mm between J/ψ and Z boson limits DI background without biasing the signal.
  - Need to calculate number of DI events that make it into cut.

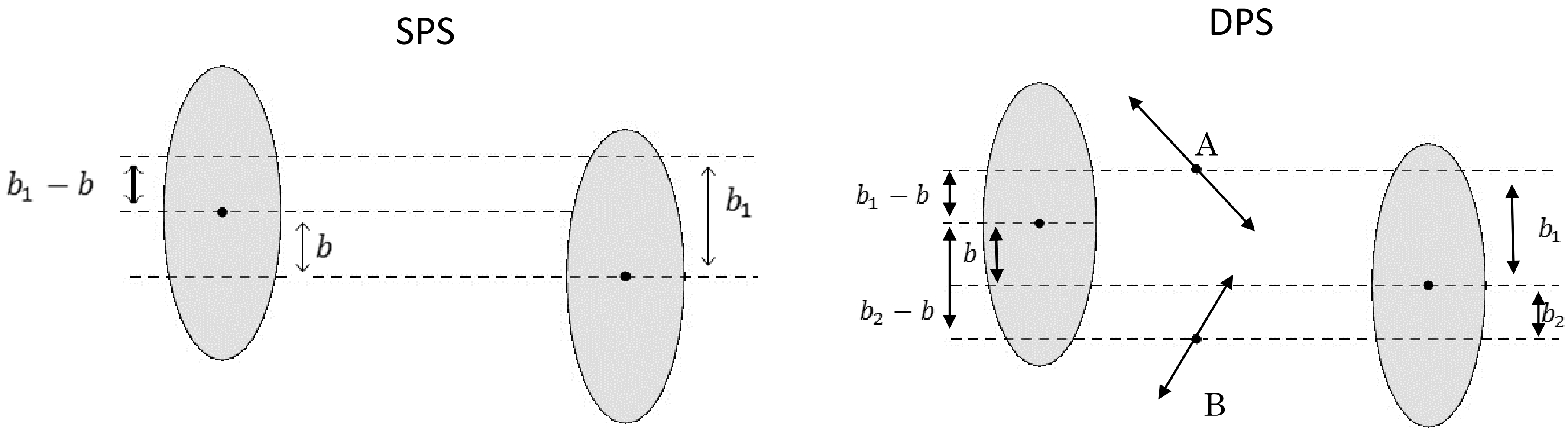
- $N_{DI} = N_{extra} N_Z P_{J/\psi}{}^{ij} = N_{extra} N_Z \frac{\sigma_{J/\psi}{}^{ij}}{\sigma_{inel.}}$.
  - N_{extra} = 2.3 ± 0.2. The number of additional vertices within 10 mm of a randomly selected vertex.
  - N_z ≡ number of Z candidates.
  - $P_{J/\psi}{}^{ij}$ ≡ the probability for a J/ψ to be produced at a given pileup vertex.
  - σ_{inel} = 73 mb (arXiv:1101.2185 [hep-ex]).

- $N_{DI} = 5.2^{+1.8}_{-1.3}$ (prompt), $2.7^{+0.9}_{-0.6}$ (non-prompt).

Double Parton Scattering: Features

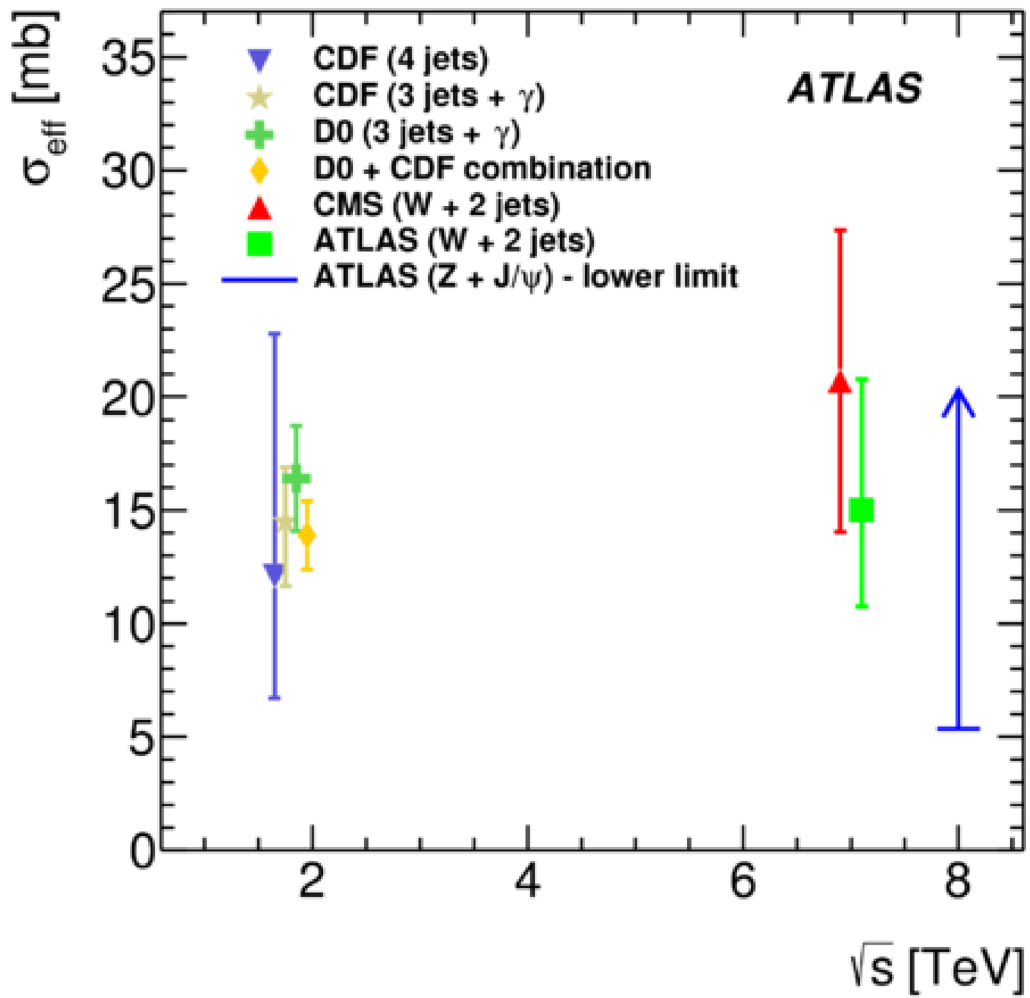
- Double Parton Scattering (DPS) requires large c.m. energies and low values of incoming fractional momenta (x_F). This is possible to achieve at a non-negligible rate at the LHC.
- Because it is dependent on the transverse distance between interactions regions, the DPS cross section decreases quickly as a function of transverse energy.
- Assuming that the two processes (σ_A, σ_B) are independent of each other, DPS cross section can be written as: $\sigma_{DPS}^{(A,B)} = \frac{m}{2}\frac{\sigma_A \sigma_B}{\sigma_{Eff}}$.
  - $m = 1$ if A and B are indistinguishable and $m = 2$ if they are distinguishable
  - $\sigma_{Eff} = \left[\int\left[\int f(\boldsymbol{b}_1) f(\boldsymbol{b}_1 - \boldsymbol{b})\, d^2 b_1\right]^2 d^2 b\right]^{-1}$ where f(b) parton density in the transverse plane and is assumed to be a universal function, same for both protons.
  - $\frac{\sigma_B}{\sigma_{Eff}}$ is the probability for scattering B to occur given scattering A has already occurred.
  - σ_{Eff} measures the size in impact parameter space of the incident hadron's partonic core.
- $\sigma_{Eff} \sim \frac{1}{4}\ \sigma_{Inel}$.
  - If the effective cross section was equal to the inelastic cross section, it would imply uncorrelated scatterings.
  - This result indicates a correlation ("clumpiness") in the hadron structure.
- A constant value of σ_{Eff} has been able to describe results in different kinematical regions. CDF has also tested the dependence of σ_{Eff} on x_F and had compatible results with being independent of x_F.

Double Parton Scattering



- b_1, b_2 are the transverse positions of the two partons.
- b is the impact parameter (distance between the centers of the colliding hadrons).
- pp→A $\oplus$ pp→B.
- A and B with a clean signature, and large rates.
- Example: A = γ + j, B = j + j.

Effective Cross Section



Systematic Uncertainty: Z+J/ψ Production

Source	Prompt		Non-prompt	
	$\lvert y_{J/\psi}\rvert < 1.0$	$1.0 < \lvert y_{J/\psi}\rvert < 2.1$	$\lvert y_{J/\psi}\rvert < 1.0$	$1.0 < \lvert y_{J/\psi}\rvert < 2.1$
Fit procedure	3 %	3 %	4%	8%
Z boson kinematics	1%	1%	1%	1%
$\mu_{J/\psi}$ efficiency	1%	1%	1%	1%
Vertex separation	7%	16%	2%	15%