Vector-meson production in ATLAS

Gabriella Pásztor
University of Geneva

for the ATLAS Collaboration

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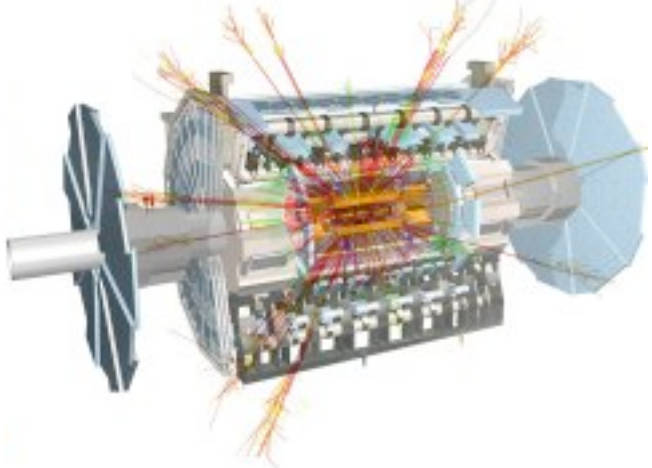


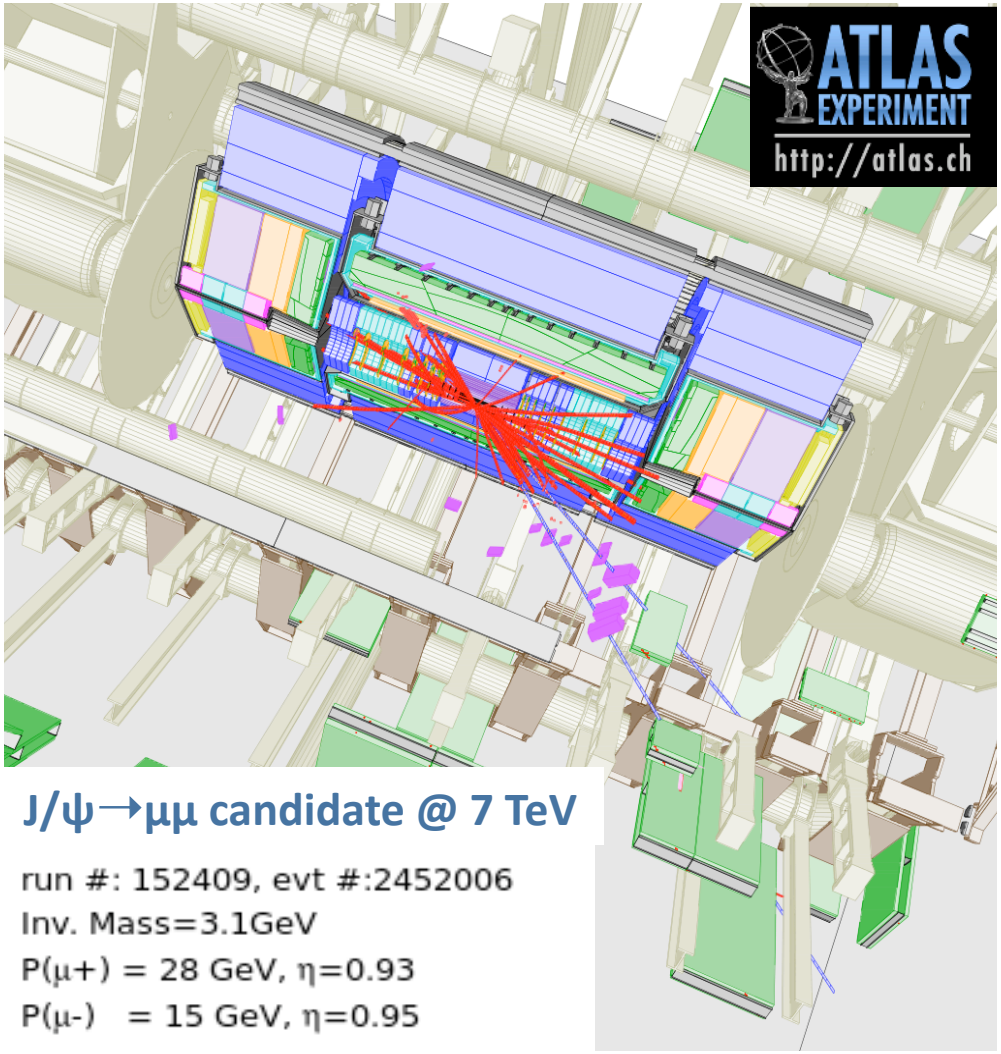
Outline

p - p collisions @ $\sqrt{s}$=7 TeV

- Dilepton mass spectrum
- Quarkonium (J/ψ, ψ', ϒ) observation
- Double differential inclusive J/ψ production cross-section ($p_T^{J/\psi}$=1-70 GeV, $|y|$<2.4)
- Non-prompt J/ψ fraction
- Prompt and non-prompt J/ψ cross-section compared to theoretical predictions

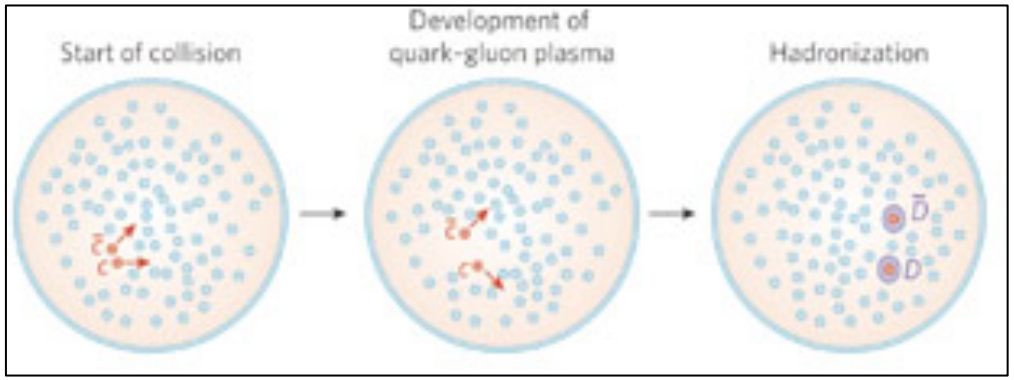
Pb – Pb collisions @ $\sqrt{s_{NN}}$=2.76 TeV

- Centrality dependent J/ψ production



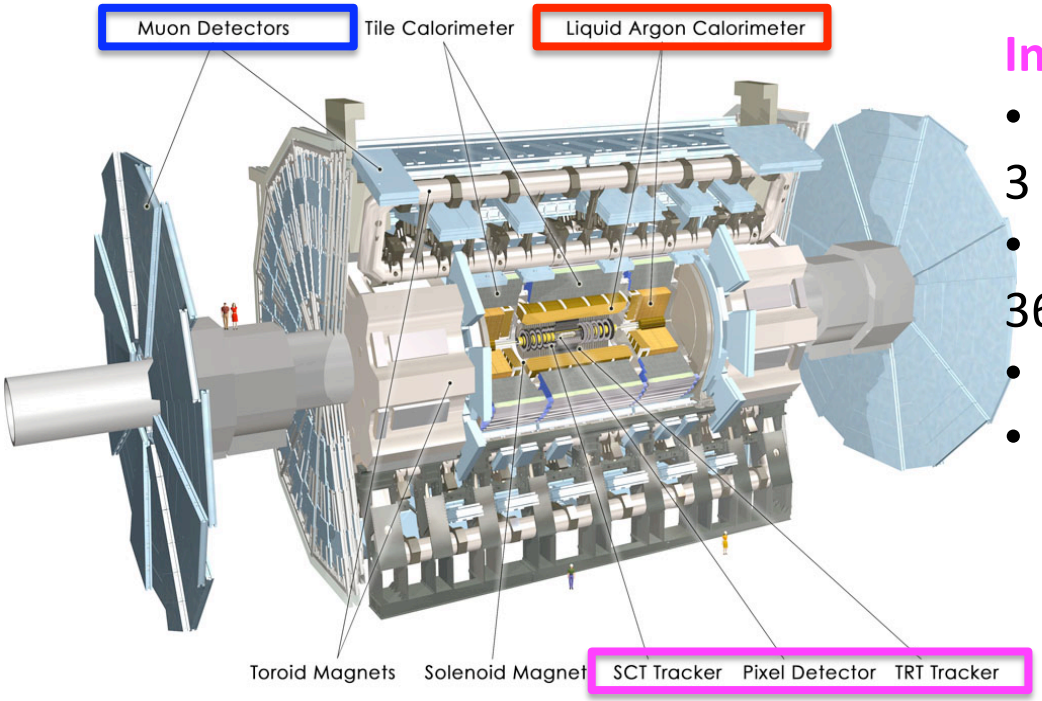
Motivation

- QCD quarkonium production mechanism not understood
  - Boundary of the perturbative and non-perturbative regimes
  - Can not explain both cross-section and spin-alignment measurements
- Test existing theoretical models of quarkonium and b production in a new energy regime, at higher p_T and wider y ranges
- pp collision data provides a reference point for **H**eavy **I**on collision studies
- J/ψ suppression is expected in HI collisions due to color screening in hot, dense matter (Phys. Lett. B178 (1986) 416)
  - Sensitive to medium temperature via the screening length (Phys. Rev. Lett. 99 (2007) 211602)
  - Proposal of J/ψ enhancement at LHC from charm recombination (Phys. Rev. C73 (2006) 014904)



  - Z production could be used as reference in LHC HI collisions
- Key signatures of B-meson decays go via charmonium states ($B_d \rightarrow J/\psi\ K_s$, $B_s \rightarrow J/\psi\ \Phi$,…)
- J/ψ is a "standard candle" for calibration, detector performance studies

ATLAS detector



Inner Tracking Detector

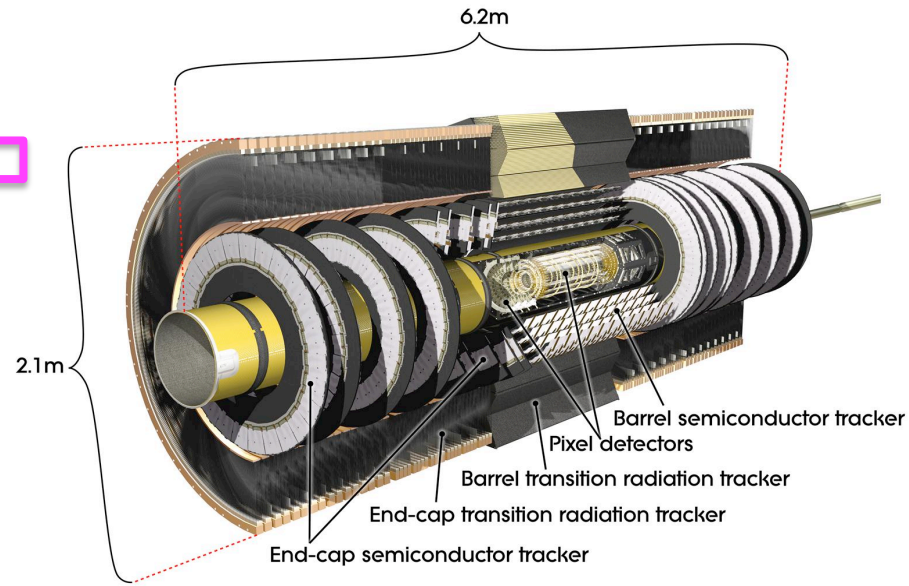
- Silicon pixel & strip tracking $|\eta|<2.5$

3 pixel, 8 SCT measurements in barrel

- **T**ransition **R**adiation **T**racker: $|\eta|<2.0$

36 measurements @ $\eta \approx 0$

- Axial magnetic field: 2T
- $\sigma(p_T)/p_T = 0.05\%/pT \oplus 1\%$

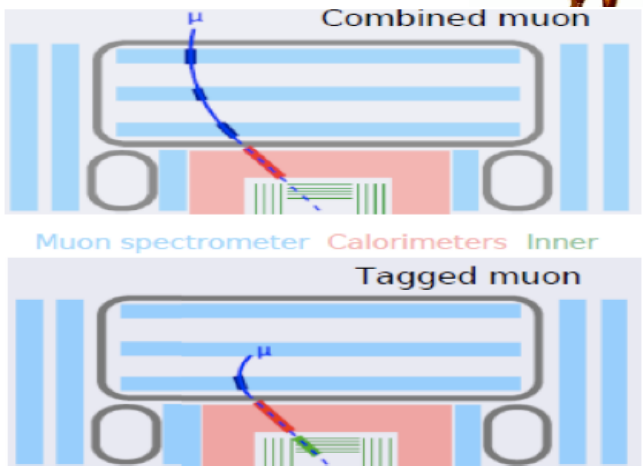


Muon System ($|\eta|<2.7$)

- 3 measurements / track
- Toroidal magnetic field: ~0.5 T
- $\sigma(p_T)/p_T < 10\%$ at $p_T<1$ TeV

Muon reconstruction

- Combined muon (high-quality):
  ID track matched to MS track and refitted
- Tagged muon (typical for low p_T):
  ID track extrapolated to MS and matched with a muon segment, limited to $|\eta|<2$
- Muon track parameters from ID



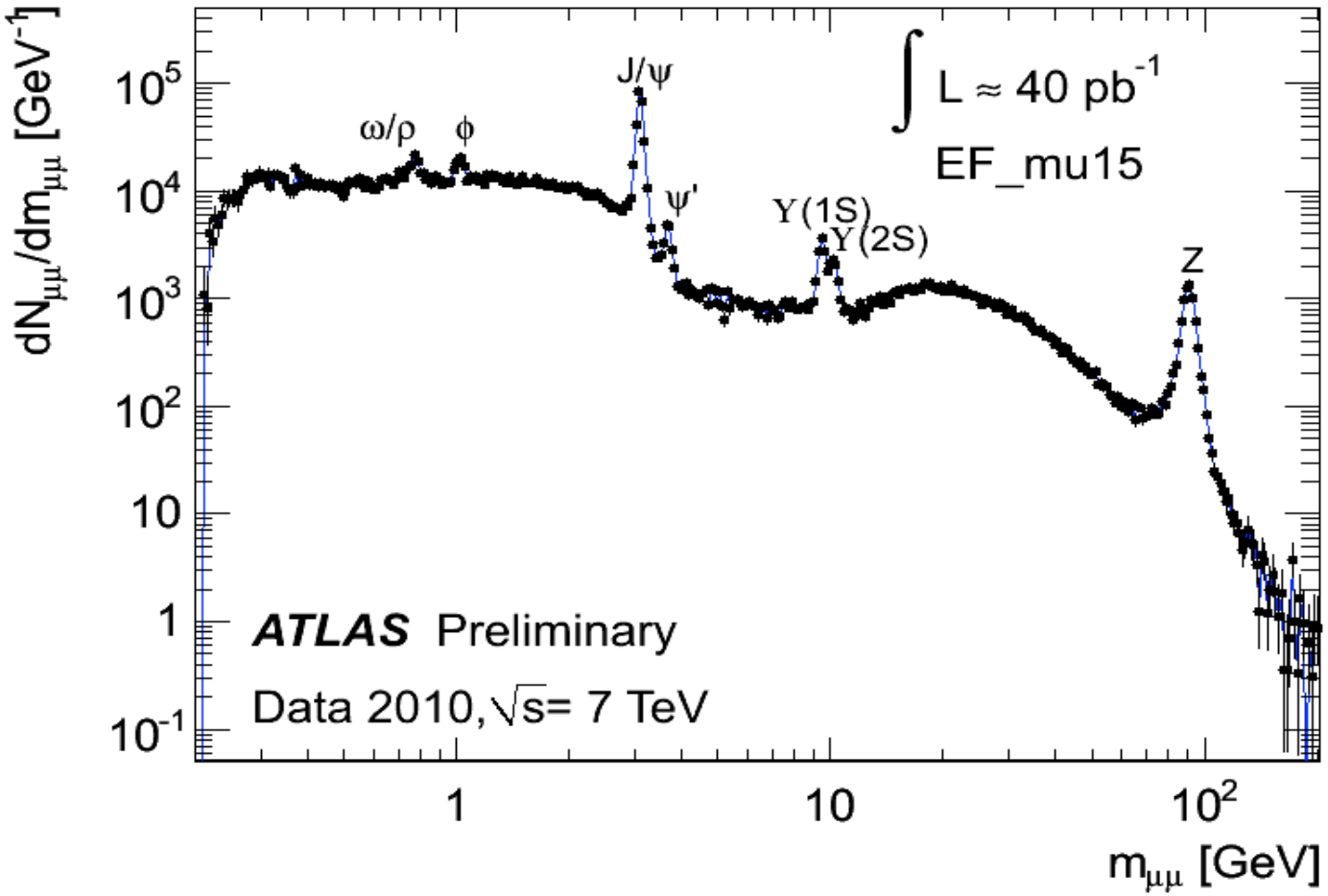
Triggers

- Quickly changing luminosity conditions in 2010
- Various triggers with increasing p_T thresholds (0, 4, 6,… GeV):
  - Minimum bias (MBTS)
  - Single muon
  - Di-muon
- Early data taking period essential to access low p_T

Minimum Bias Trigger Scintillators: Z=±3.56m, 8 units in ϕ, 2 units in η (|η|=2.09-2.82-3.84)

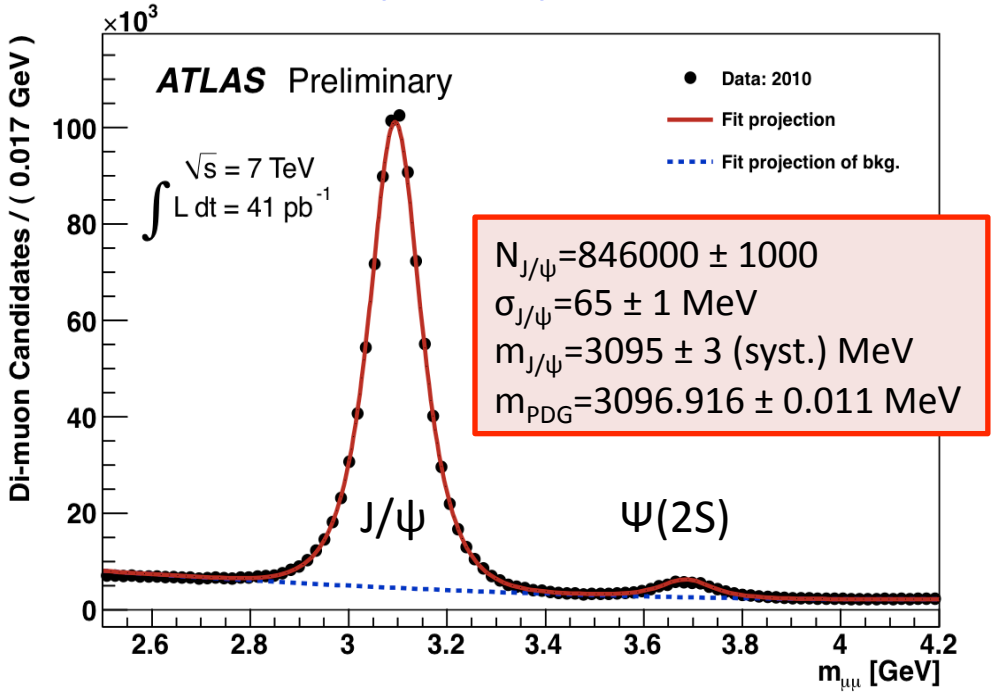
Dimuon mass spectrum

Opposite-charge "combined" muon pairs with $p_{T,1}$>15 GeV, $p_{T,2}$>2.5 GeV

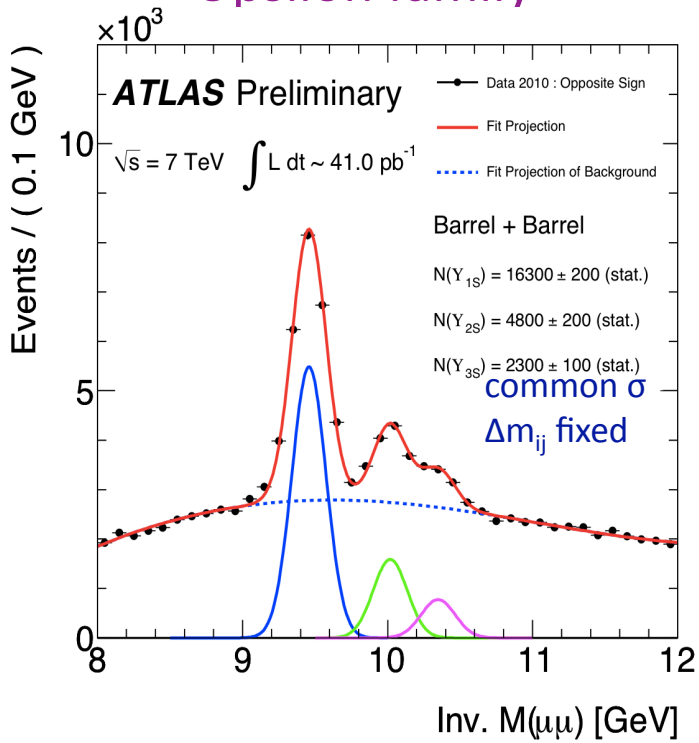


Quarkonia observation

J/ψ and ψ(2S)



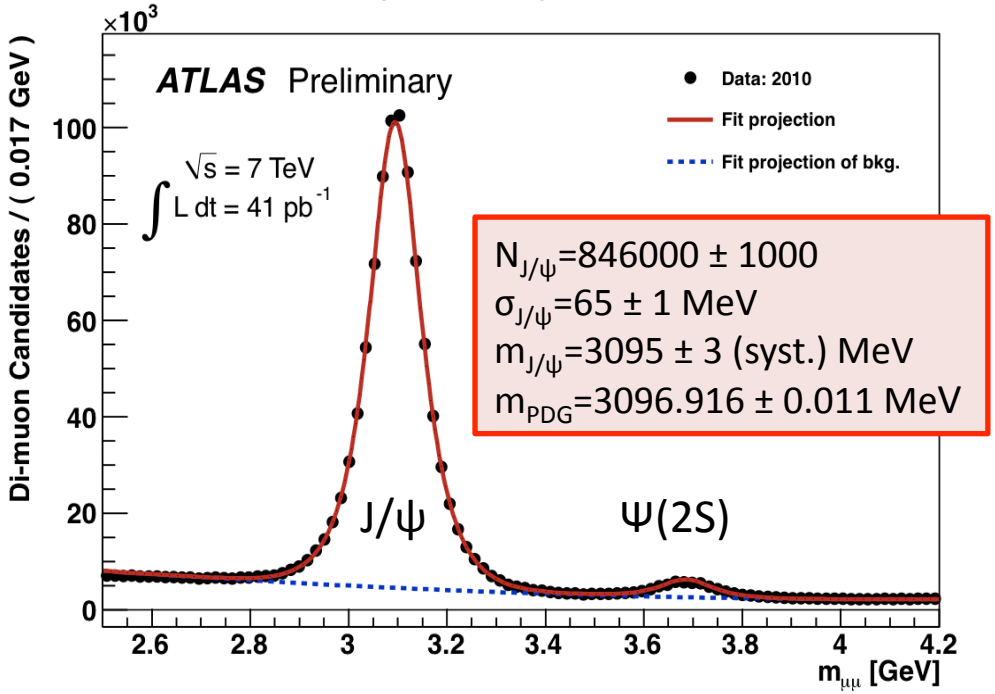
Upsilon family



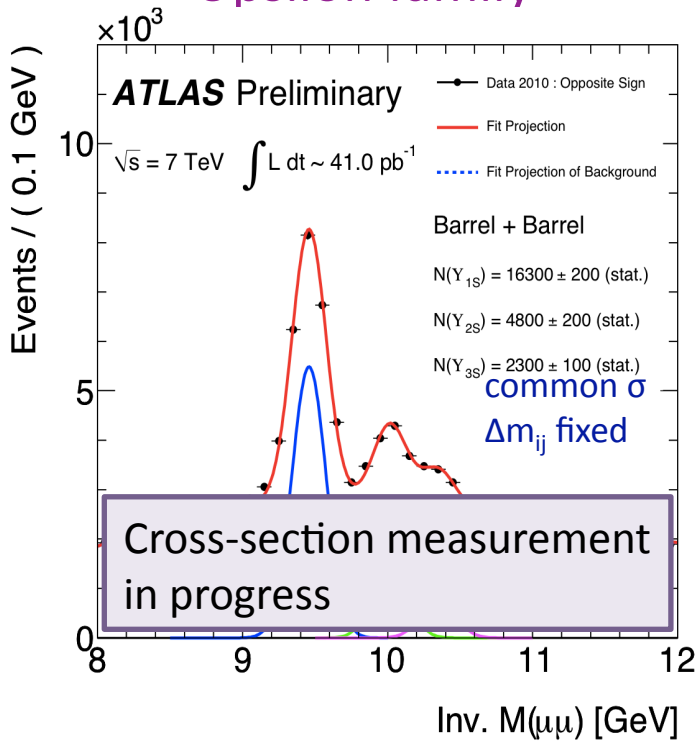
- Opposite-charge muon pairs passing vertexing
- $p_{T,1}$> 4 GeV, $p_{T,2}$>2.5 GeV
- At least one "combined" muon
- Fit: Gaussian + 3rd order polinomial (or 4th order Chebyshev polinomial for Υ's)

Quarkonia observation

J/ψ and ψ(2S)



Upsilon family



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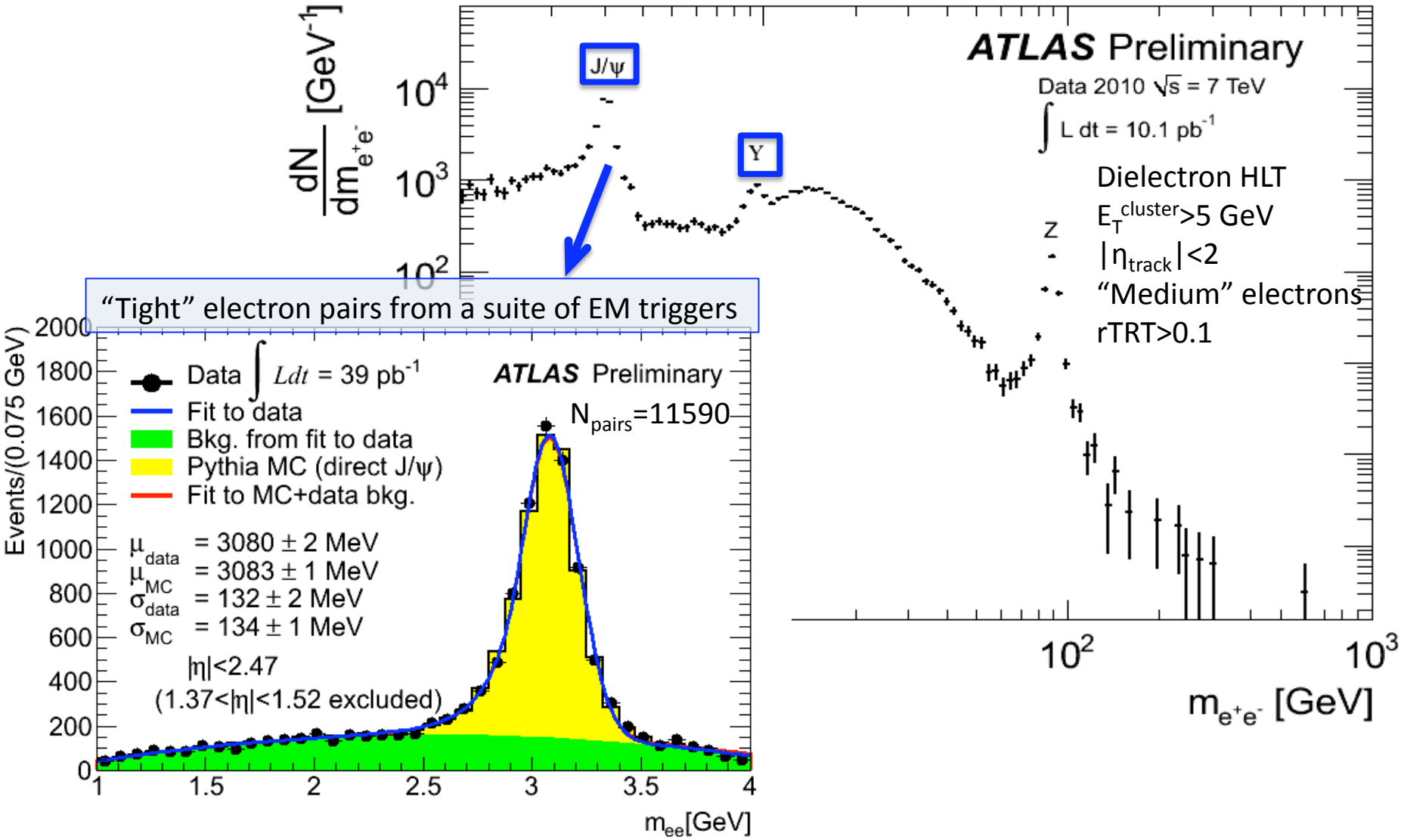
Dielectron mass spectrum



J/ψ differential cross-section and non-prompt fraction measurements

Data sample and trigger

- A suite of single muon triggers in data from April-August 2010
- Inclusive cross-section: 2.27 pb^{-1}
- Non-prompt fraction: 2.44 pb^{-1}

Selection

- Vertex with at least 3 high quality ($N_{pixel} \geq 1$, $N_{SCT} \geq 6$), pointing tracks
- Two, opposite sign muon candidates with $p_T > 3$ GeV, $|\eta| < 2.5$
- High quality ID tracks fitted to a common vertex
  (loose fit quality cut keeping 99% for inclusive, Prob>0.005 for fraction measurement)
- At least one muon should be "combined"
- One of the muons should match the trigger ($\Delta R \leq 0.4$ for L1, ≤ 0.005 for HLT)
- For fraction measurement, the ID tracks should come from the same primary vertex

Background sources: fakes, decays in flight, muons from heavy flavour decays

Inclusive differential cross-section

$$\frac{d^2\sigma(J/\psi)}{dp_T dy} \cdot Br(J/\psi \to \mu^+\mu^-) = \frac{N^{J/\psi}_{corr}}{\mathcal{L} \cdot \Delta p_T \Delta y}$$

Binned minimum-χ^2 fit to $\sum w$ of Gaussian + 4th order polynomial as a function of $M_{\mu\mu}$ in p_T, y bins

Event weight: $$w^{-1} = \mathcal{A} \cdot \mathcal{M} \cdot \mathcal{E}^2_{trk} \cdot \mathcal{E}^+_{\mu}(p_T^+, \eta^+) \cdot \mathcal{E}^-_{\mu}(p_T^-, \eta^-) \cdot \mathcal{E}_{trig}$$

Acceptance (p_T, y, λ) (depends on spin-alignment)

Bin migration: correction ~3% at high p_T, high y

ID tracking efficiency (~100%)

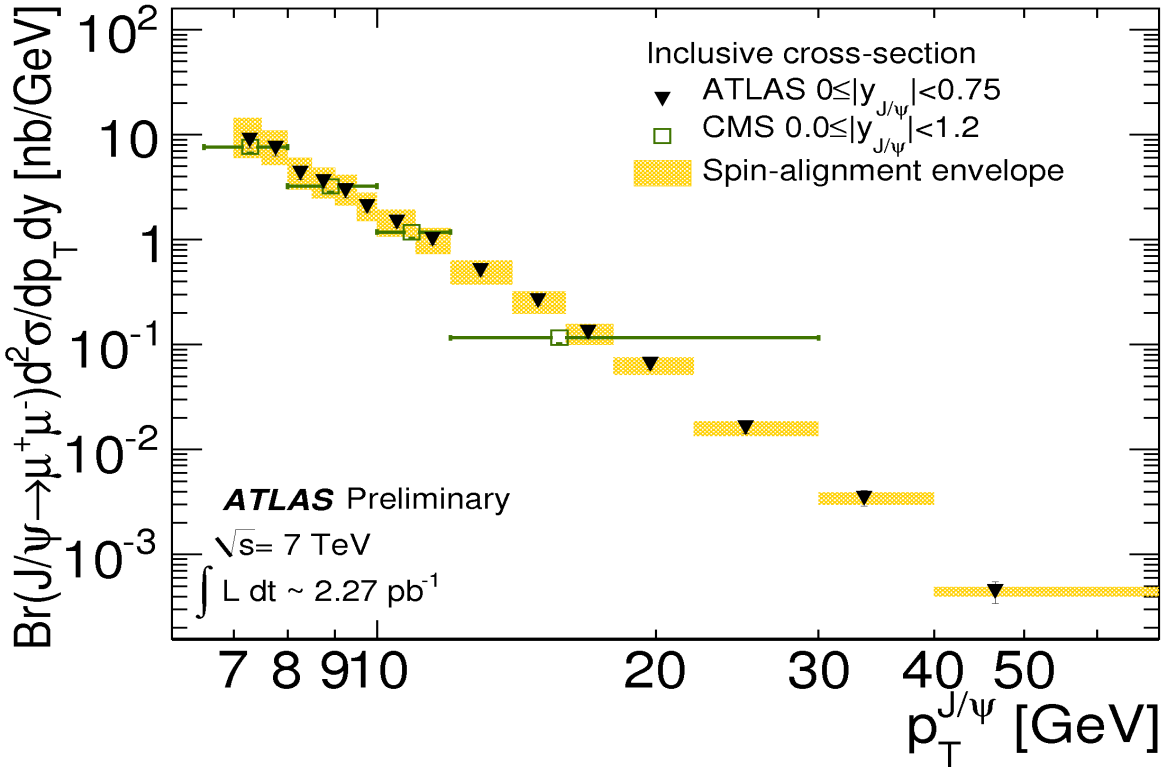
Single muon reconstruction efficiencies

Trigger efficiency

Trigger efficiency: $$\mathcal{E}_{trig} = 1 - \left(1 - \mathcal{E}^+_{trig}(p_T^+, \eta^+)\right) \cdot \left(1 - \mathcal{E}^-_{trig}(p_T^-, \eta^-)\right)$$

- ID tracking and muon reconstruction efficiencies from in-situ (tag&probe) measurement
- Single muon trigger efficiency also extracted from data for each trigger for each muon type and charge, use MC for fine binning
- Resolution for bin migration correction derived from data

Inclusive J/ψ differential cross-section



- Measurements in 4 η bins up to |η|=2.4 (see in backup)
- Complementarity: CMS (low p_T), ATLAS (high p_T)

- Detector acceptance depends strongly on spin-alignment
  - central value from "flat" configuration,
  - systematic uncertainty from envelop of 5 configurations covering maximum variations
- Largest experimental systematics from reconstruction and trigger efficiencies
- 3.4% luminosity uncertainty not shown

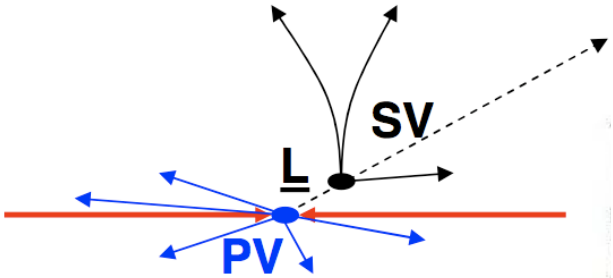
Non-prompt fraction measurement

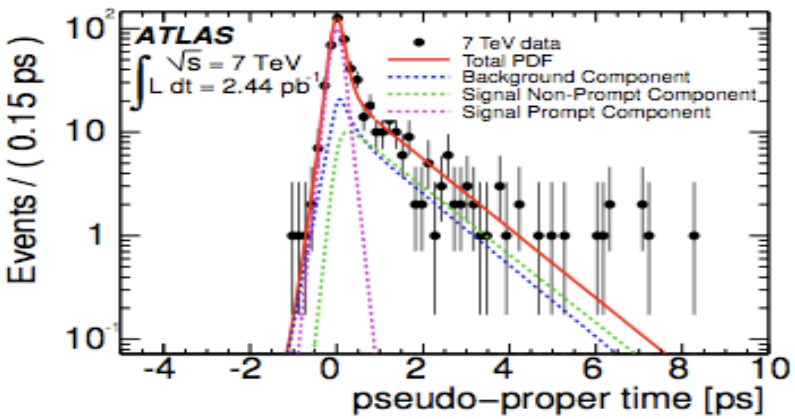
Prompt: direct production in the hard interaction
feed-down from excited charmonium states produced in the hard interaction
Non-prompt: from decays of long-lived B hadrons (→displaced vertex)

Simultaneous max LH fit of mass and pseudo-proper time distributions per (p_T, y) bin

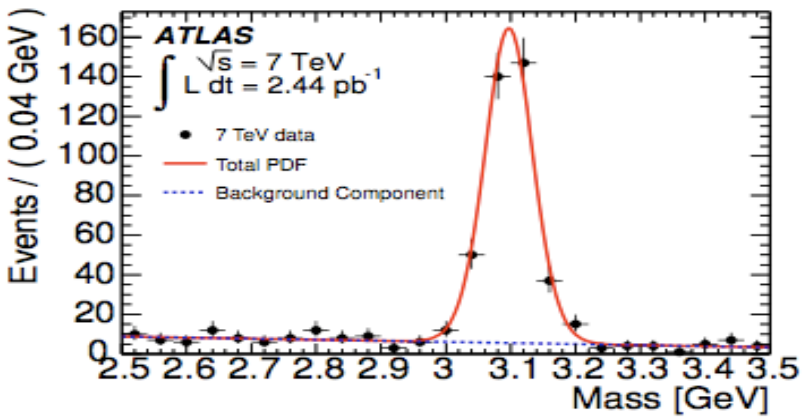
Pseudo-proper time: $$\tau = \frac{L_{xy}\, m_{\mathrm{PDG}}(J/\psi)}{p_T(J/\psi)}$$

Transverse decay length: $$L_{xy} \equiv \vec{L} \cdot \vec{p}_T(J/\psi)/p_T(J/\psi)$$





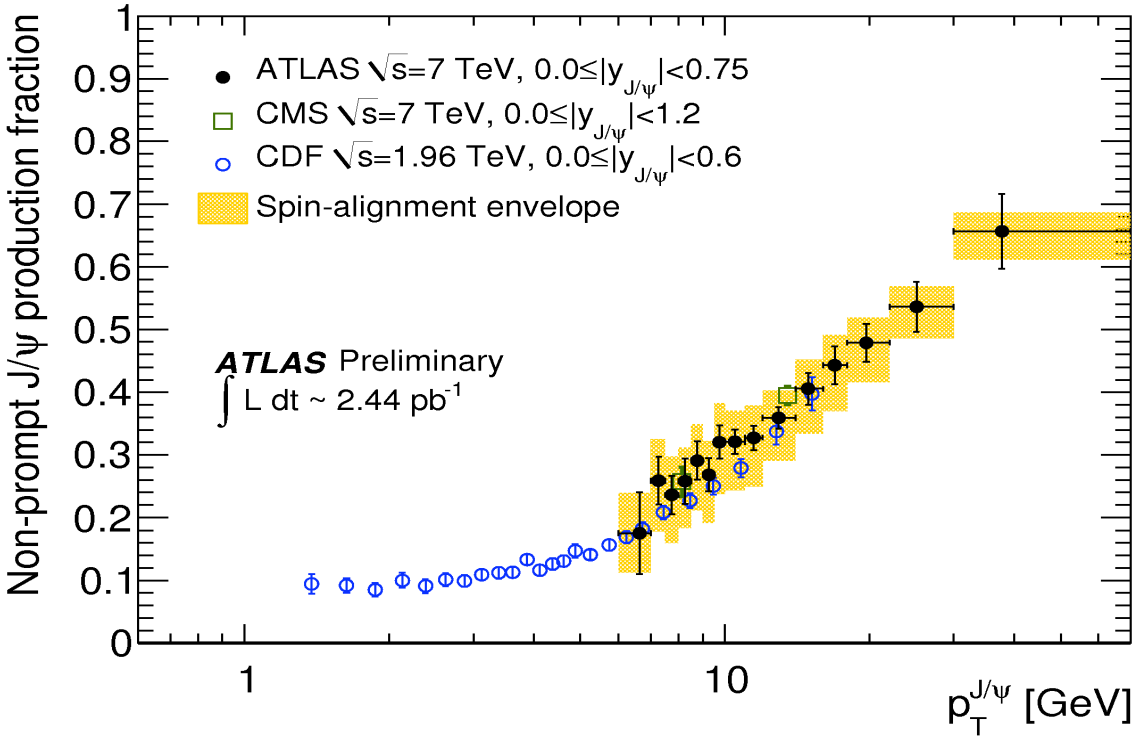
(a) $0.0 \leq |y_{J/\psi}| < 0.75$



(b) $0.0 \leq |y_{J/\psi}| < 0.75$

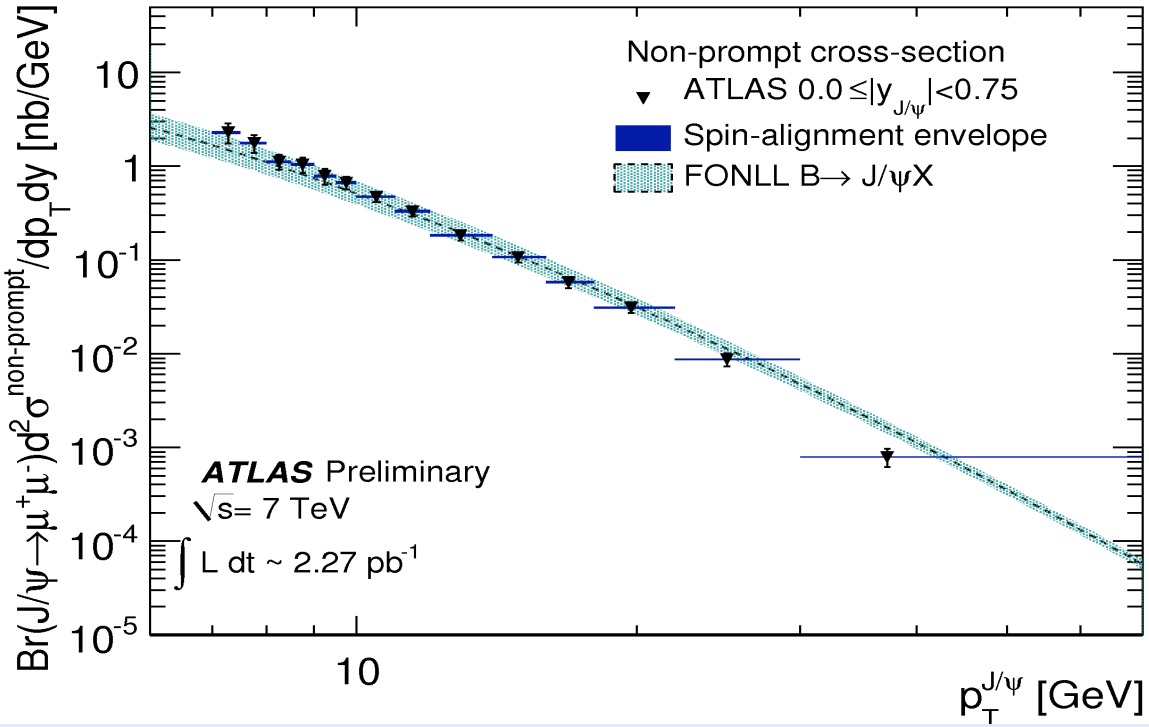
Non-prompt fraction

$$f_B \equiv \frac{d\sigma(pp \to B + X \to J/\psi X')}{d\sigma(pp \xrightarrow{\text{Inclusive}} J/\psi X'')}$$



- Many uncertainties cancel in fraction
- Largest experimental uncertainty from fit
- Spin alignment assumed to be the same ("flat") for central value
- Spin-alignment uncertainty for prompt decays as for inclusive measurement, for non-prompt either isotropic or reweighted to CDF results
- Good agreement with CMS, CDF

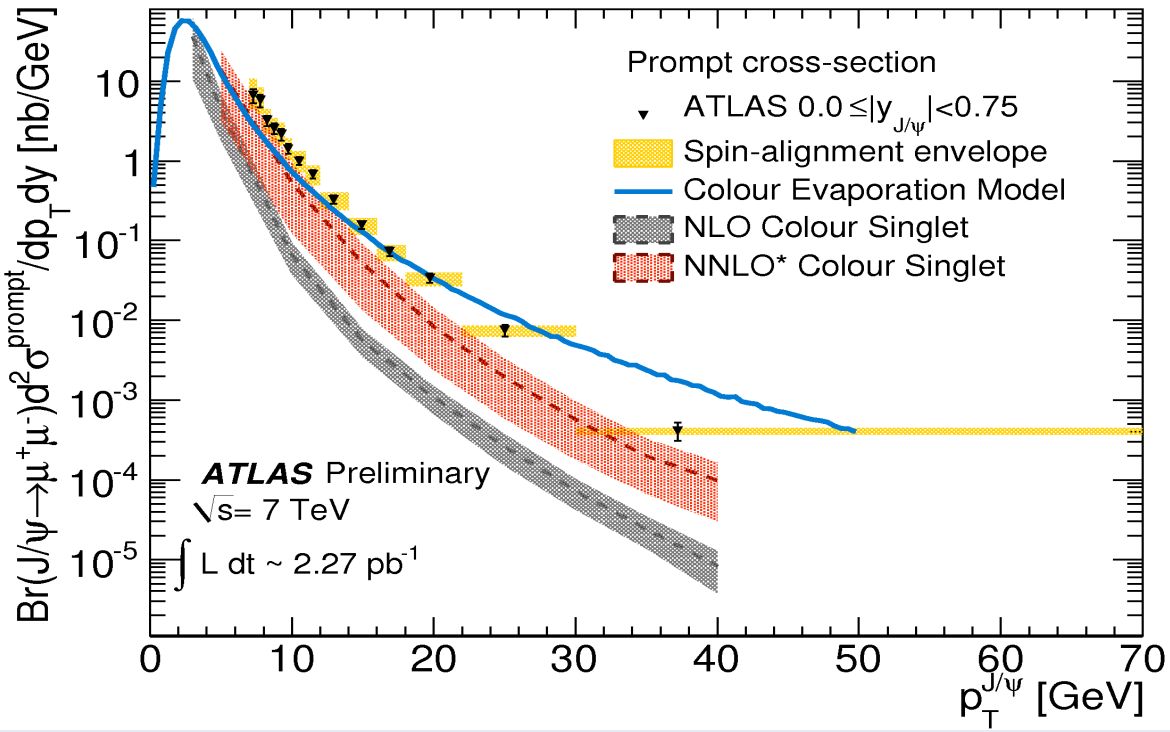
Non-prompt (B→J/ψ) production cross-section



- From combination of inclusive cross-section and non-prompt fraction measurements
- Very good agreement with FONLL (JHEP 9805 (1998) 007, JHEP 0103 (2001) 006652)

  bb production in fixed order NLO + NLL resummation, CTEQ6.6 pdf, BR(B→J/ψ)=0.0116
  non-perturbative fragmentation parameters extracted from LEP data at same order
- Spin alignment uncertainty is less important (averaging effect due to the summing up of different B hadron production processes)

Prompt J/ψ production cross-section



Color Evaporation model (Phys. Rept. 462 (2008) 125)

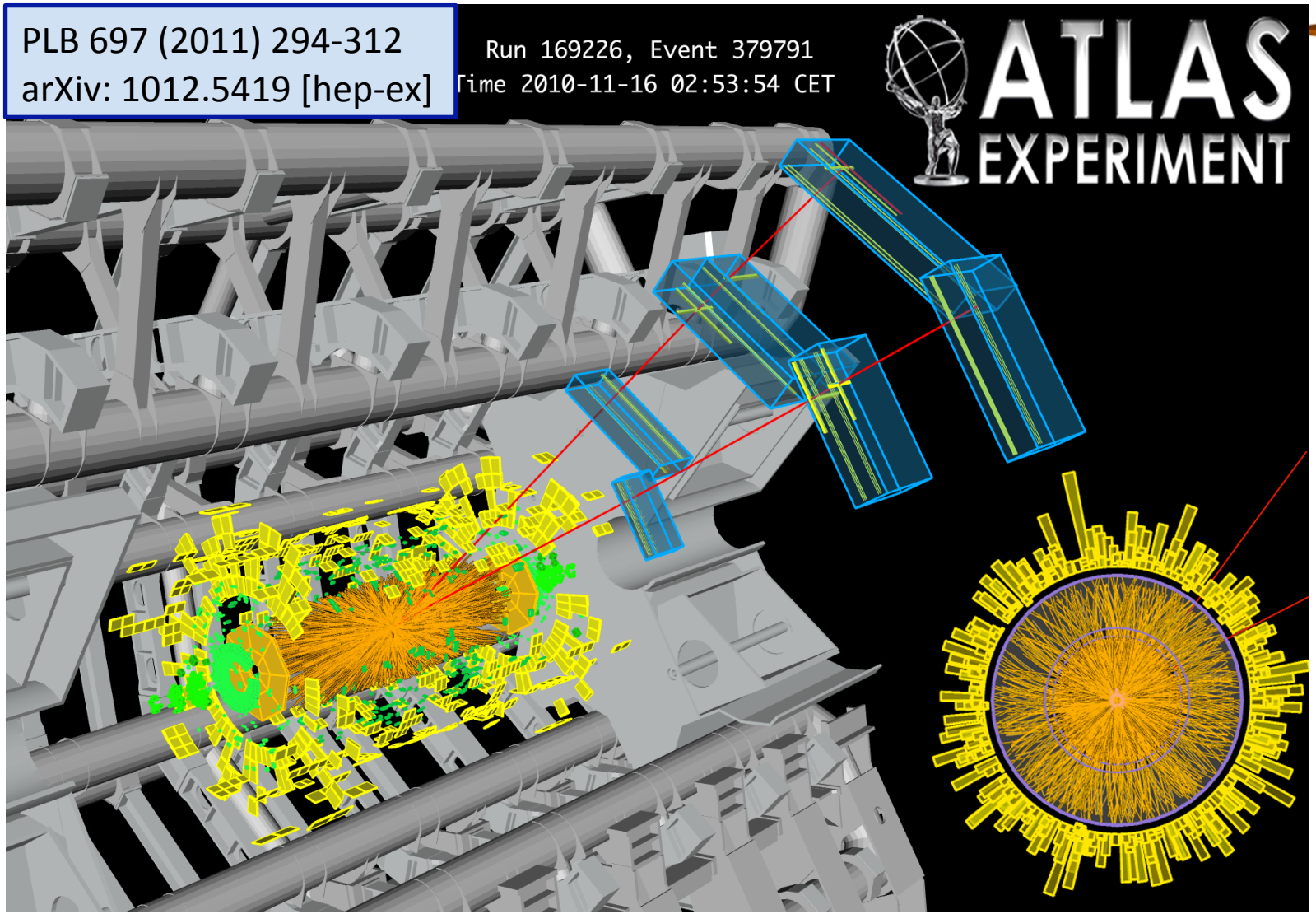
- CTEQ6M pdf, m_c=1.2 GeV, scale parameter from fit to data, includes χ_c/ψ' feed-down
- Deviates from data in normalization at low p_T, in shape at high p_T (no previous data)

Color Singlet model (Phys. Rev. Lett. 101 (2008) 152001654, Eur. Phys. J. C 71 (2011) 1534655)

- CTEQ6M pdf, m_c=1.5 GeV, 50% correction for χ_c ψ' feed-down (no related uncertainty)
- Even partial NNLO deviates from data at high p_T (higher order corrections)

J/ψ production in Pb-Pb collision

PLB 697 (2011) 294-312
arXiv: 1012.5419 [hep-ex]

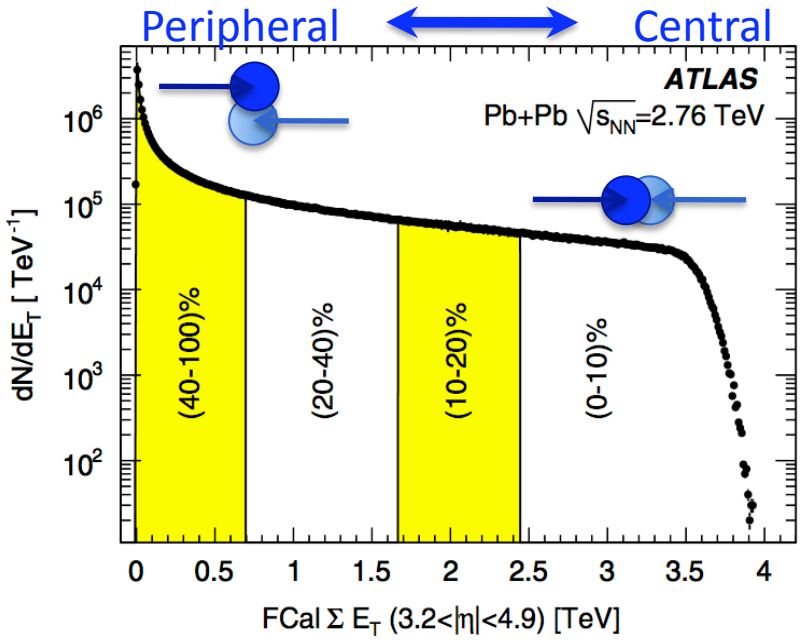


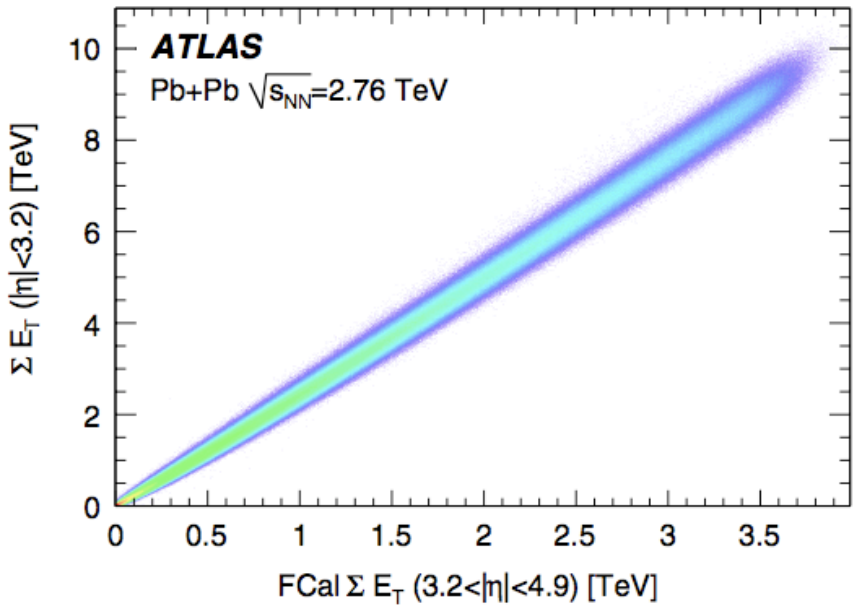
Pb-Pb data sample and centrality

Data collected by Minimum Bias Trigger: $\int \mathscr{L} dt$ = 6.7 μb^{-1} @ $\sqrt{s_{NN}}$=2.76 TeV (14x RHIC)

Centrality

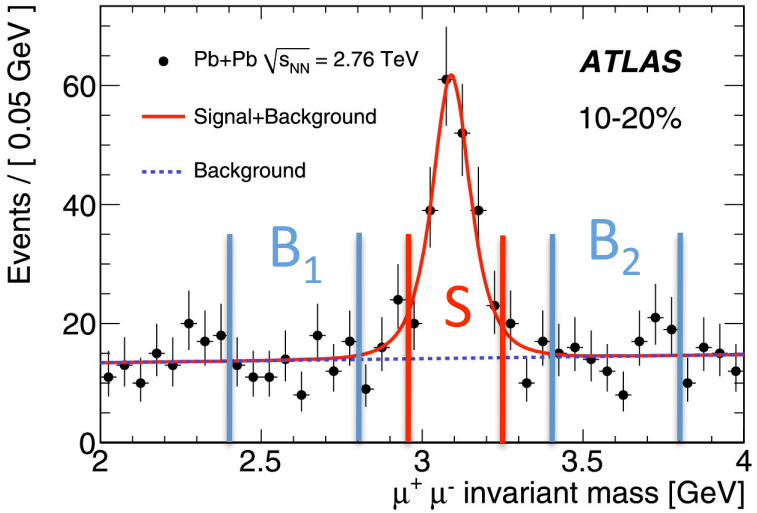
- characterized by percentile of total cross-section binned in $\sum E_T^{FCAL}$ (3.2<|η|<4.9)
- 80-100% range excluded due to larger systematics on the number of binary nucleon-nucleon collisions





J/ψ signal extraction in Pb-Pb

- Reconstruced primary vertex
- MBTS hit on both sides with $\Delta t < 3$ ns
- Opposite-charge muon pair
- Combined muons with p_T>3 GeV, $|\eta|$<2.5
- Stringent requirements on ID track (≥9 Si hits, no pixel and max. 1 SCT hit missing)



- Sideband subtraction (cross-checked with unbinned maximum LH fit)
- Signal detection efficiency from MC as a function of # of hits per unit η in first pixel layer (strongly correlated to $\sum E_T^{FCAL}$)

Centrality dependence and uncertainties

Only the centrality dependence is relevant as *relative yields* are measured

J/ψ yield:

$$N_c^{\mathrm{corr}}(J/\psi \to \mu^+\mu^-) = \frac{N^{\mathrm{meas}}(J/\psi \to \mu^+\mu^-)_c}{\epsilon(J/\psi)_c \cdot W_c}$$

Centrality	$N^{\mathrm{meas}}(J/\psi)$	$\epsilon(J/\psi)_c/\epsilon(J/\psi)_{40-80}$	Systematic Uncertainty		
			Reco. eff.	Sig. extr.	Total
0-10%	190 ± 20	0.93 ± 0.01	6.8 %	5.2 %	8.6 %
10-20%	152 ± 16	0.91 ± 0.02	5.3 %	6.5 %	8.4 %
20-40%	180 ± 16	0.97 ± 0.01	3.3 %	6.8 %	7.5 %
40-80%	91 ± 10	1	2.3 %	5.6 %	6.1 %

Binary collision rate:

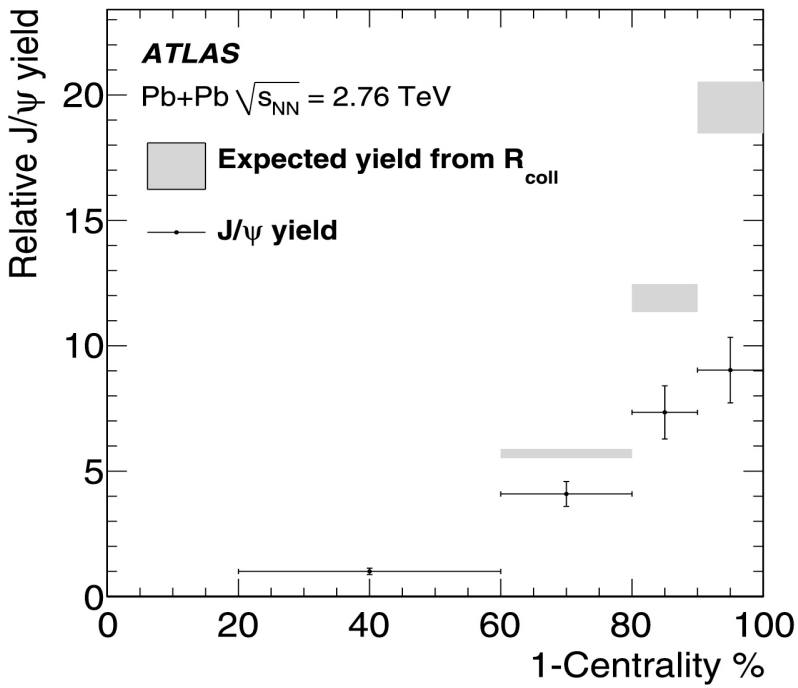
$$R_c^{coll} = N_c^{coll}/N_{40-80\%}^{coll}$$

Centrality	R_{coll}	Uncertainty
0-10%	19.5	5.3 %
10-20%	11.9	4.7 %
20-40%	5.7	3.2 %
40-80%	1.0	–

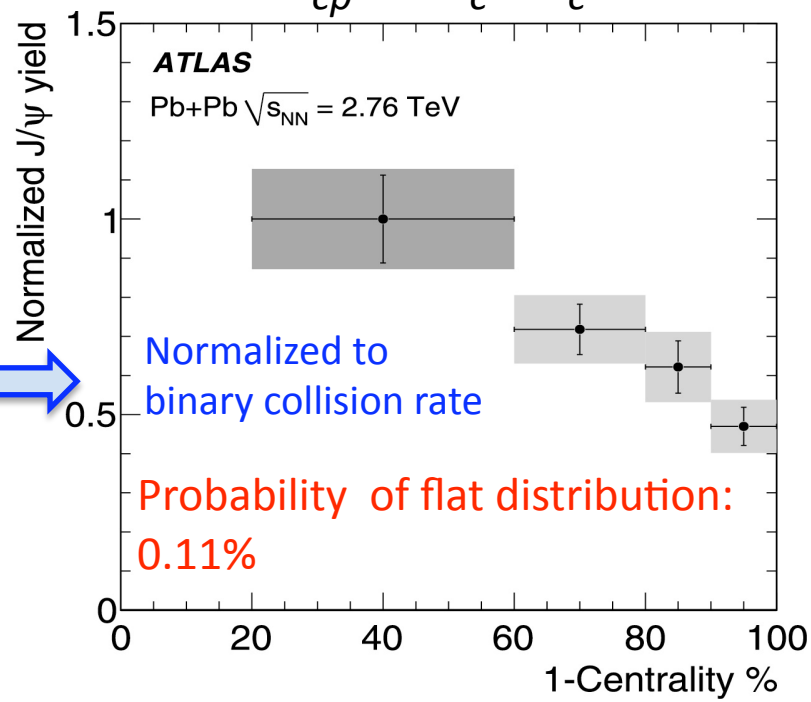
- ID tracking: centrality dependence due to high occupancy
- MS performance: no centrality dependence
- Background subtraction
- Theoretical uncertainty on number of binary nucleon-nucleon collisions

Centrality dependence of J/ψ yield

$$R_c = N_c^{corr} / N_{40-80\%}^{corr}$$



$$R_{cp} = R_c / R_c^{coll}$$



- Centrality dependent J/ψ suppression observed
- Systematics on the 40-80% bin not propagated to the ratio in other bins
- Result agrees with low energy ($\sqrt{s_{NN}}$=200 GeV) data from PHENIX
- Z production observed in HI collisions but more data needed to draw firm conclusions

Conclusion

A succesful 1st year at LHC

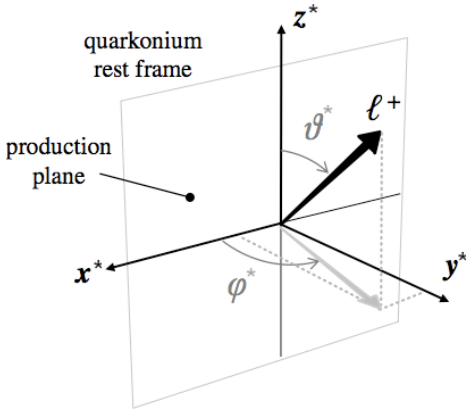
- Observation and 1st cross-section measurements of quarkonia and other heavy flavour hadrons
- Inclusive J/ψ cross-section and non-prompt fraction measurements
- Double differential cross-sections for prompt and non-prompt production compared to other experimental data and theoretical predictions
  - Agreement with CMS and CDF data
  - Non-prompt production agrees well with theory
  - Prompt production shows differences in shape and normalization
- Important theoretical uncertainties on detector acceptance from spin-alignment → to be measured at LHC
- J/ψ and Z production observed in Pb-Pb collisions
- Clear dependence of J/ψ yield on centrality

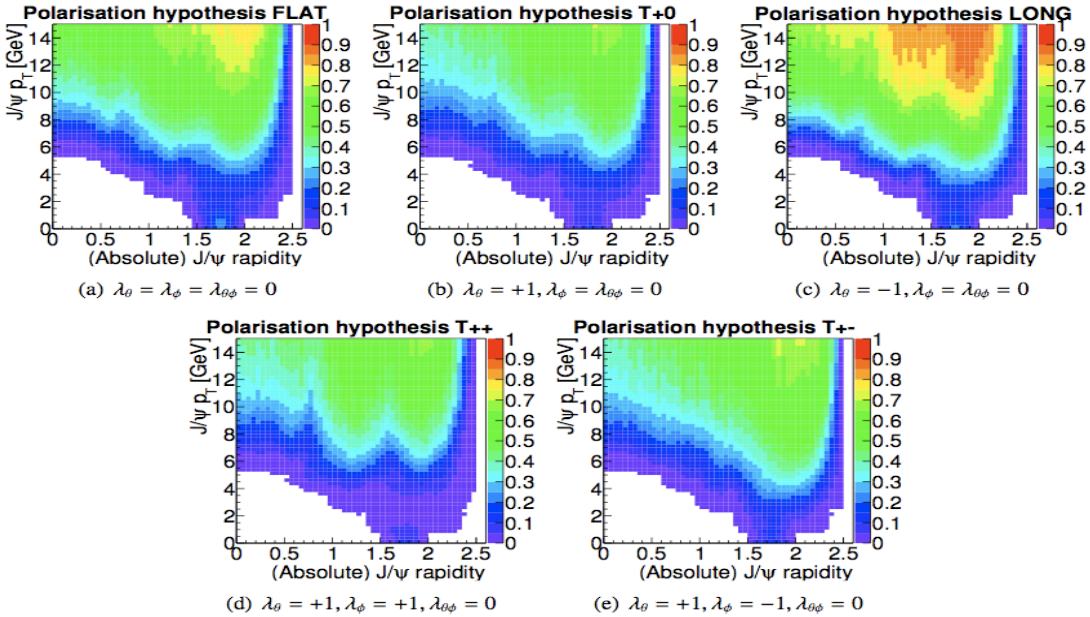
Backup: J/ψ production in pp

Acceptance

- Depends strongly on spin alignment
- Not yet measured at LHC → important later measurement
- Take 5 working points to cover maximum acceptance variation
- Reweight MC produced with isotropic distributions to get acceptance maps
- Consider as theoretical uncertainty (taking "flat hypothesis as central value)

$$\frac{d^2N}{d\cos\theta^\star d\phi^\star} \propto 1 + \lambda_\theta \cos^2\theta^\star + \lambda_\phi \sin^2\theta^\star \cos 2\phi^\star + \lambda_{\theta\phi} \sin 2\theta^\star \cos\phi^\star$$

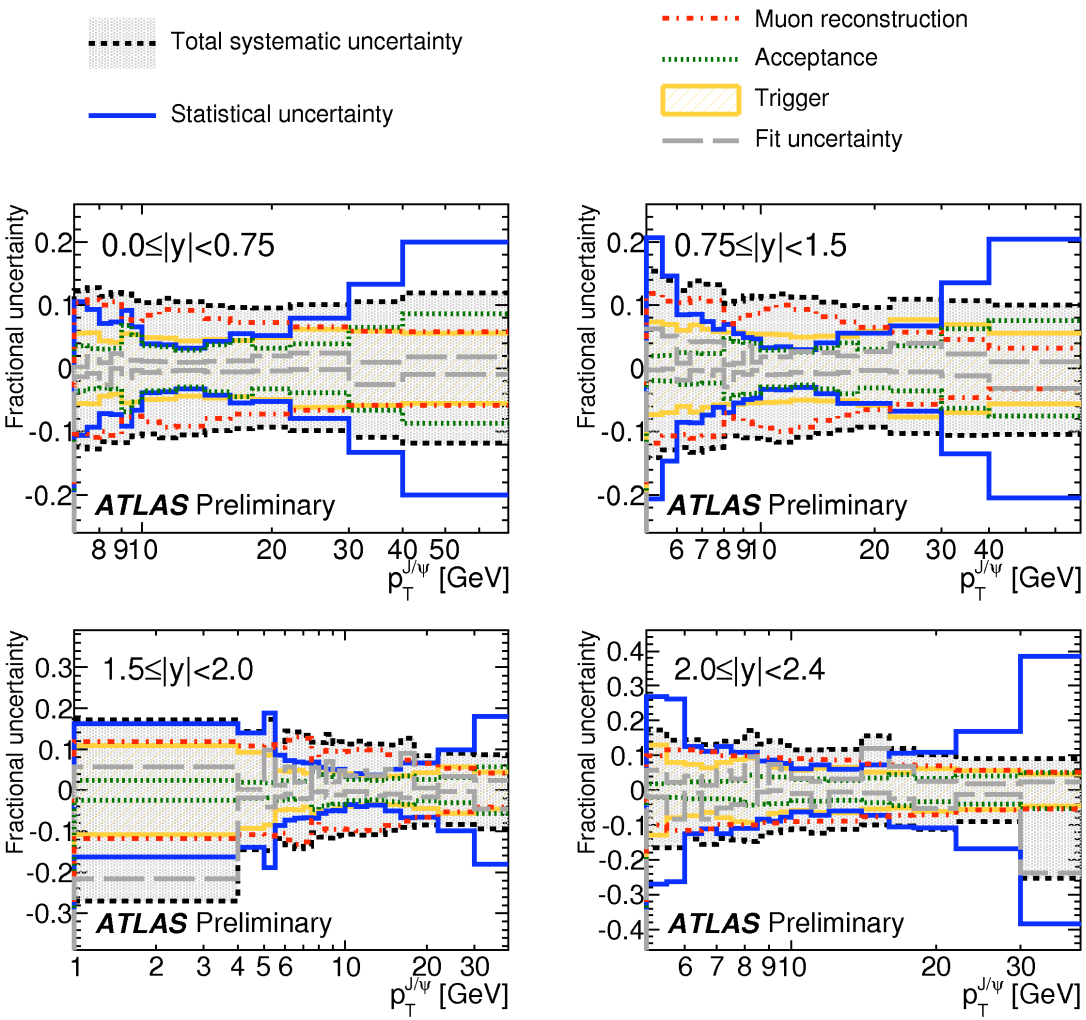




(a) $\lambda_\theta = \lambda_\phi = \lambda_{\theta\phi} = 0$ (b) $\lambda_\theta = +1, \lambda_\phi = \lambda_{\theta\phi} = 0$ (c) $\lambda_\theta = -1, \lambda_\phi = \lambda_{\theta\phi} = 0$

(d) $\lambda_\theta = +1, \lambda_\phi = +1, \lambda_{\theta\phi} = 0$ (e) $\lambda_\theta = +1, \lambda_\phi = -1, \lambda_{\theta\phi} = 0$

Systematic uncertainties on inclusive J/ψ measurements



Fit function to extract non-prompt fraction

$$L = \prod_{i=1}^{N} \left[f_{\mathrm{sig}} P_{\mathrm{sig}}(\tau, \delta_\tau) F_{\mathrm{sig}}(m_{\mu\mu}, \delta_m) + (1 - f_{\mathrm{sig}}) P_{\mathrm{bkg}}(\tau, \delta_\tau) F_{\mathrm{bkg}}(m_{\mu\mu}) \right]$$

$$F_{\mathrm{sig}}(m_{\mu\mu}, \delta_m) \equiv \frac{1}{\sqrt{2\pi}\, S\, \delta_m} e^{\frac{-(m_{\mu\mu} - m_{J/\psi})^2}{2(S\delta_m)^2}}$$

Inputs to the fit
Free parameters

$F_{\mathrm{bkg}}(m_{\mu\mu})$ => 2nd order polinomial

$$P_{\mathrm{sig}}(\tau, \delta_\tau) = f_B P_B(\tau, \delta_\tau) + (1 - f_B) P_P(\tau, \delta_\tau)$$

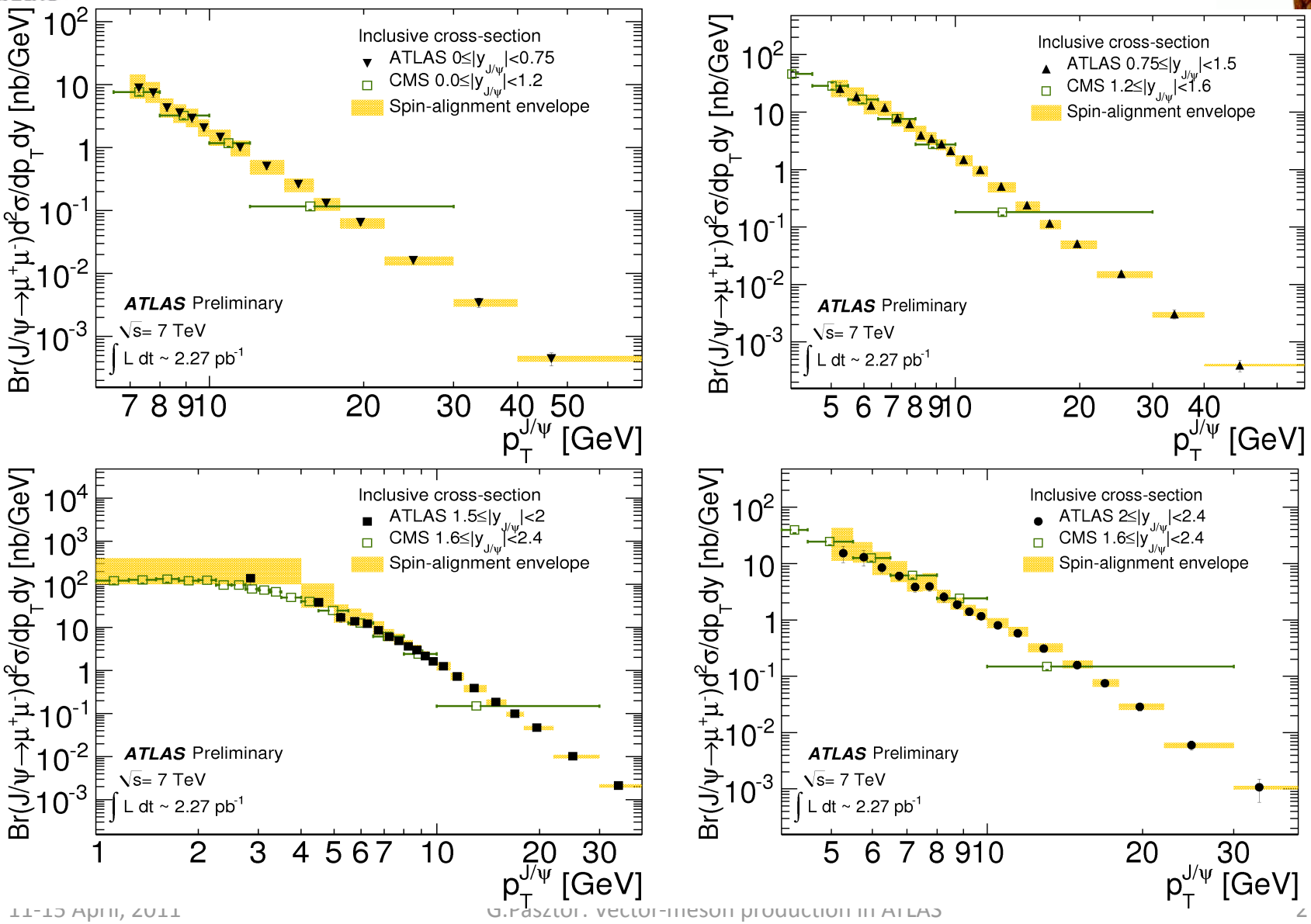
$$P_B(\tau, \delta_\tau) = R(\tau' - \tau, \delta_\tau) \otimes E(\tau') \qquad E(\tau) = \exp(-\tau/\tau_{\mathrm{eff}})$$

$$P_P(\tau, \delta_\tau) = R(\tau' - \tau, \delta_\tau) \otimes \delta(\tau') = R(\tau, \delta_\tau)$$ => Gaussian of width $S_t \cdot \delta_\tau$

$$P_{\mathrm{bkg}}(\tau, \delta_\tau) = \left(b_1 \times \exp\left(\frac{-\tau'}{\tau_{\mathrm{eff1}}}\right) + (1 - b_1) \times \exp\left(\frac{-|\tau'|}{\tau_{\mathrm{eff2}}}\right) + \delta(\tau') \right) \otimes R_{\mathrm{bkg}}(\tau' - \tau, \delta_\tau),$$

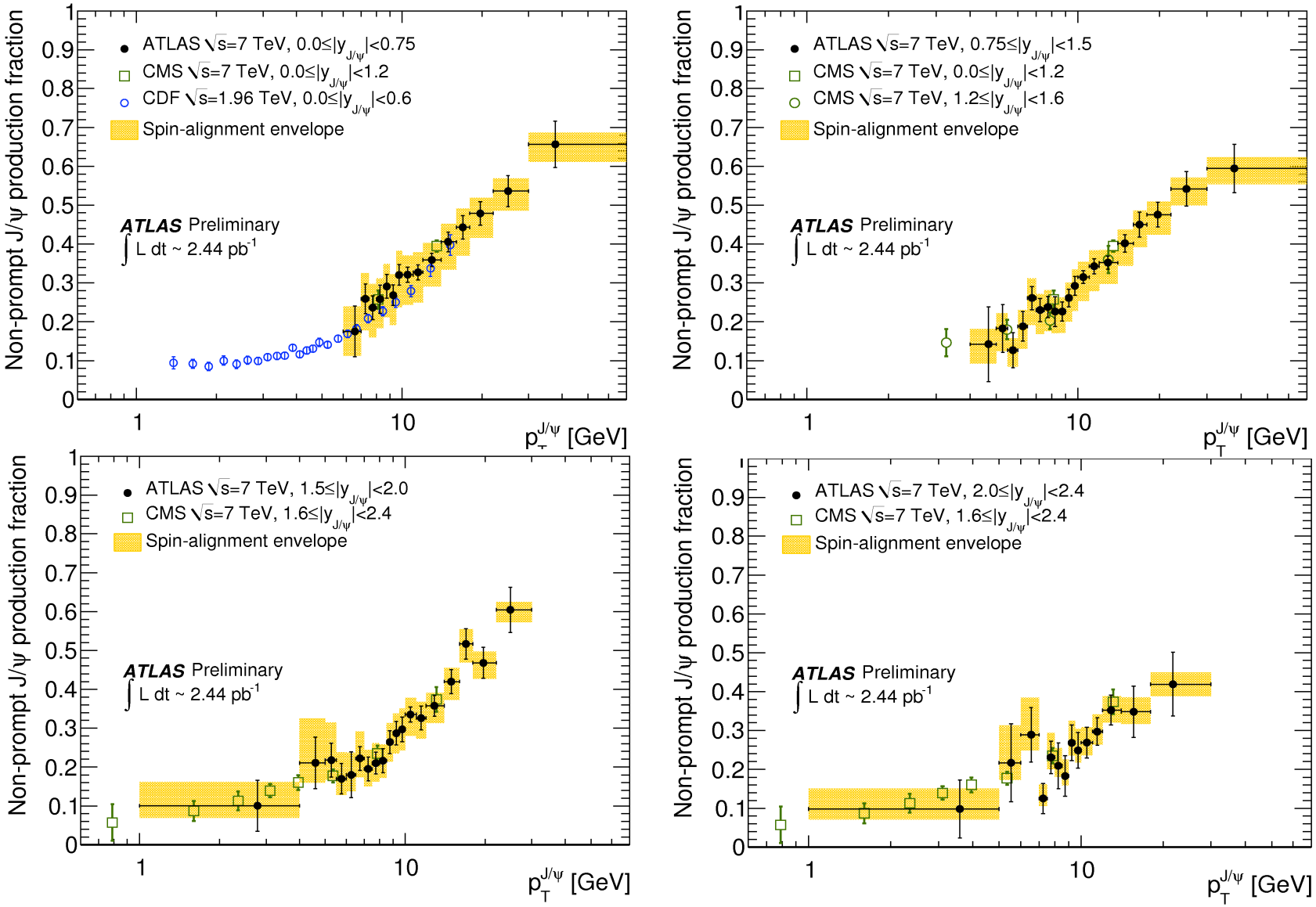
=> Gaussian of width $S_{\mathrm{bkg}} \cdot \delta_\tau$

Inclusive J/ψ differential cross-section

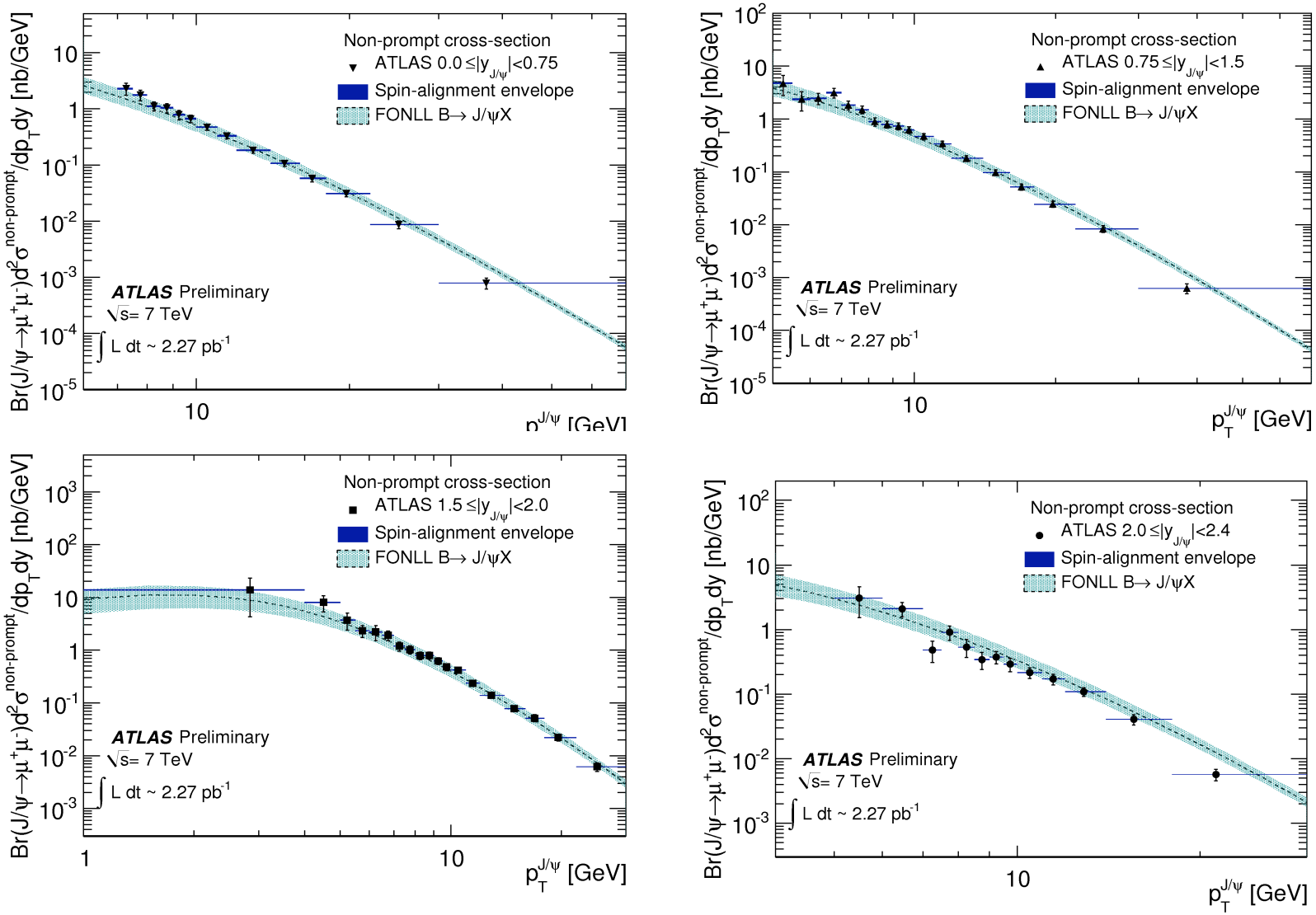


Non-prompt fraction

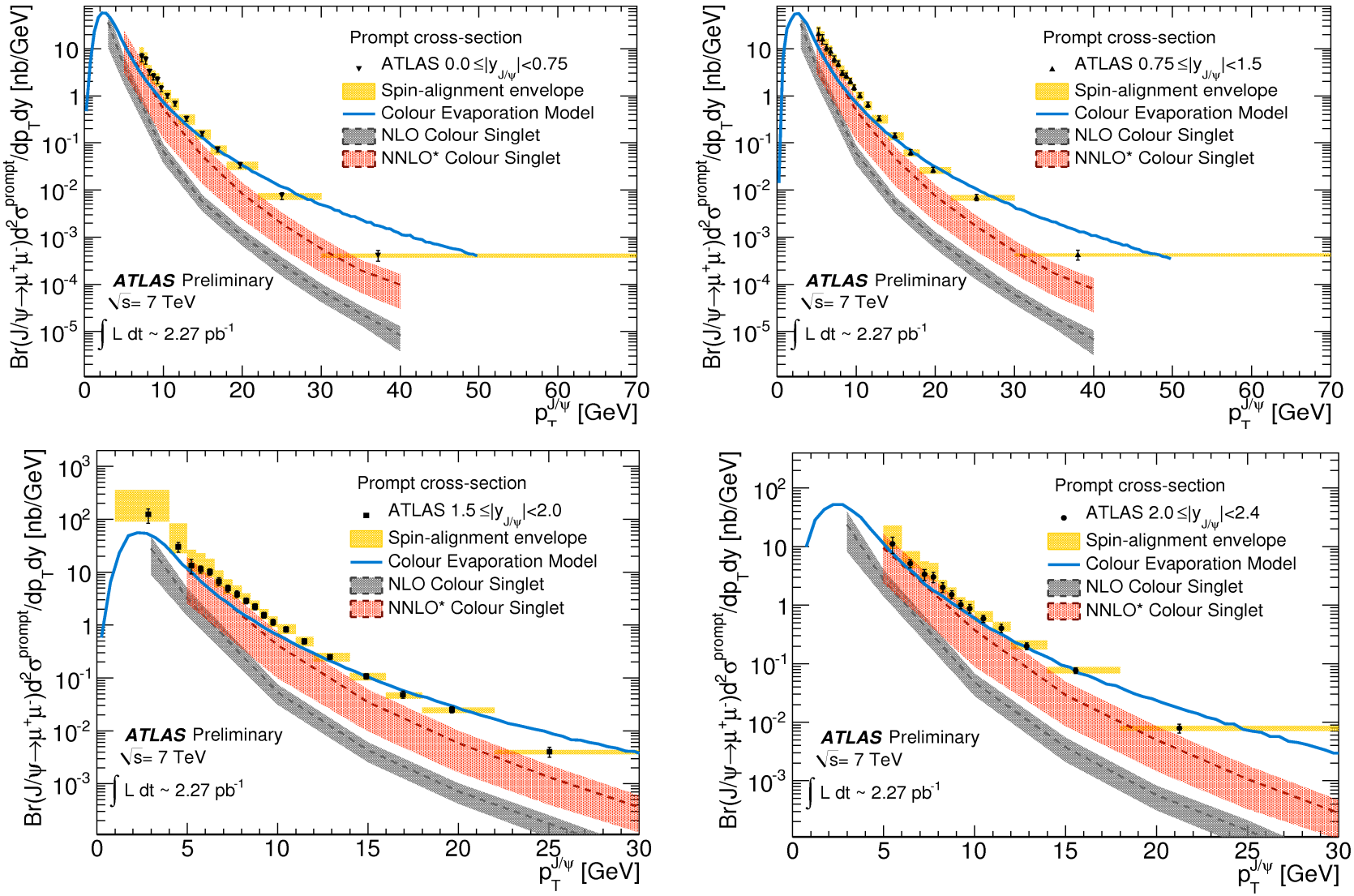
$$f_B \equiv \frac{d\sigma(pp \to B + X \to J/\psi X')}{d\sigma(pp \xrightarrow{\text{Inclusive}} J/\psi X'')}$$



Non-prompt (B→J/ψ) production cross-section

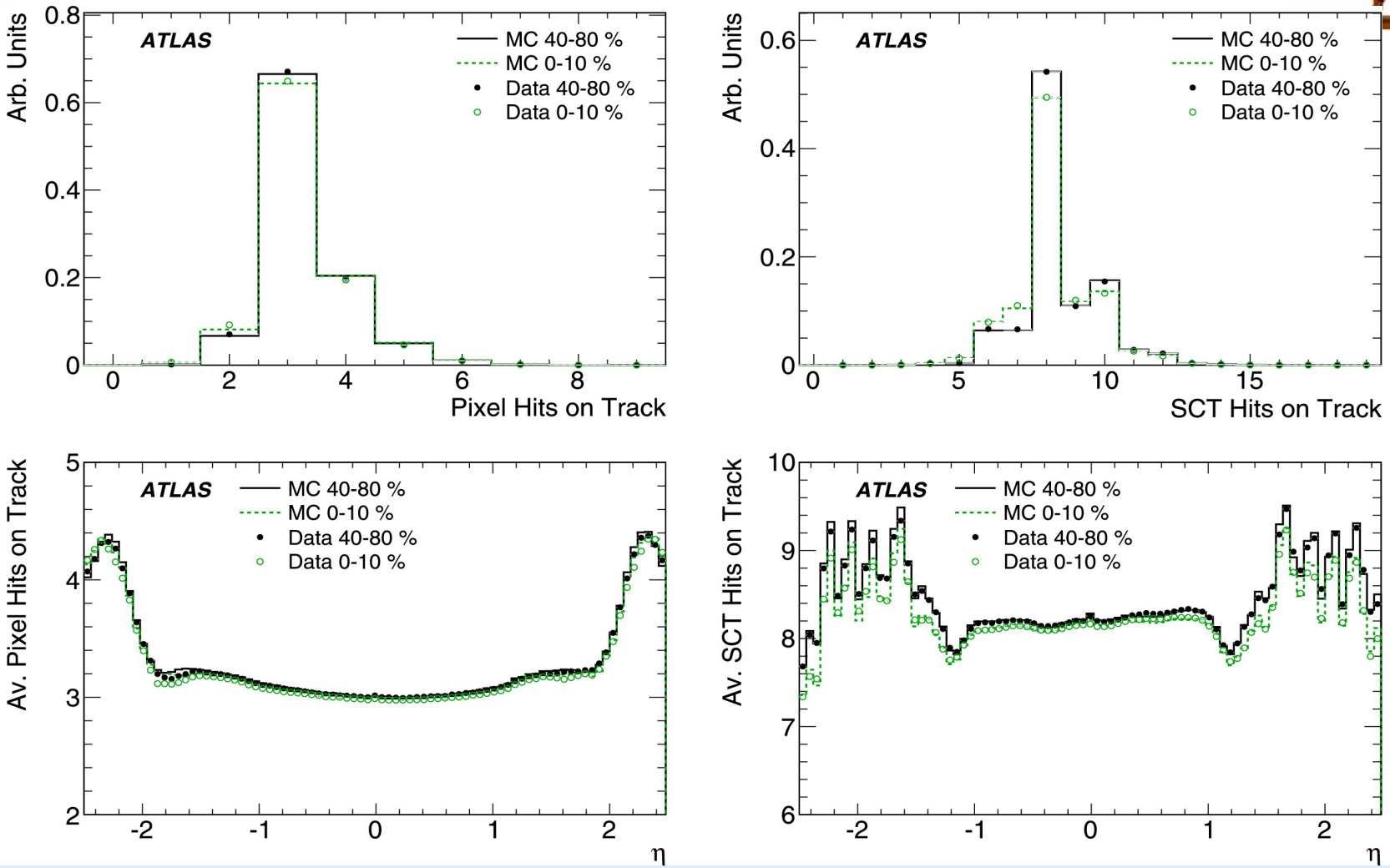


Prompt J/ψ production cross-section



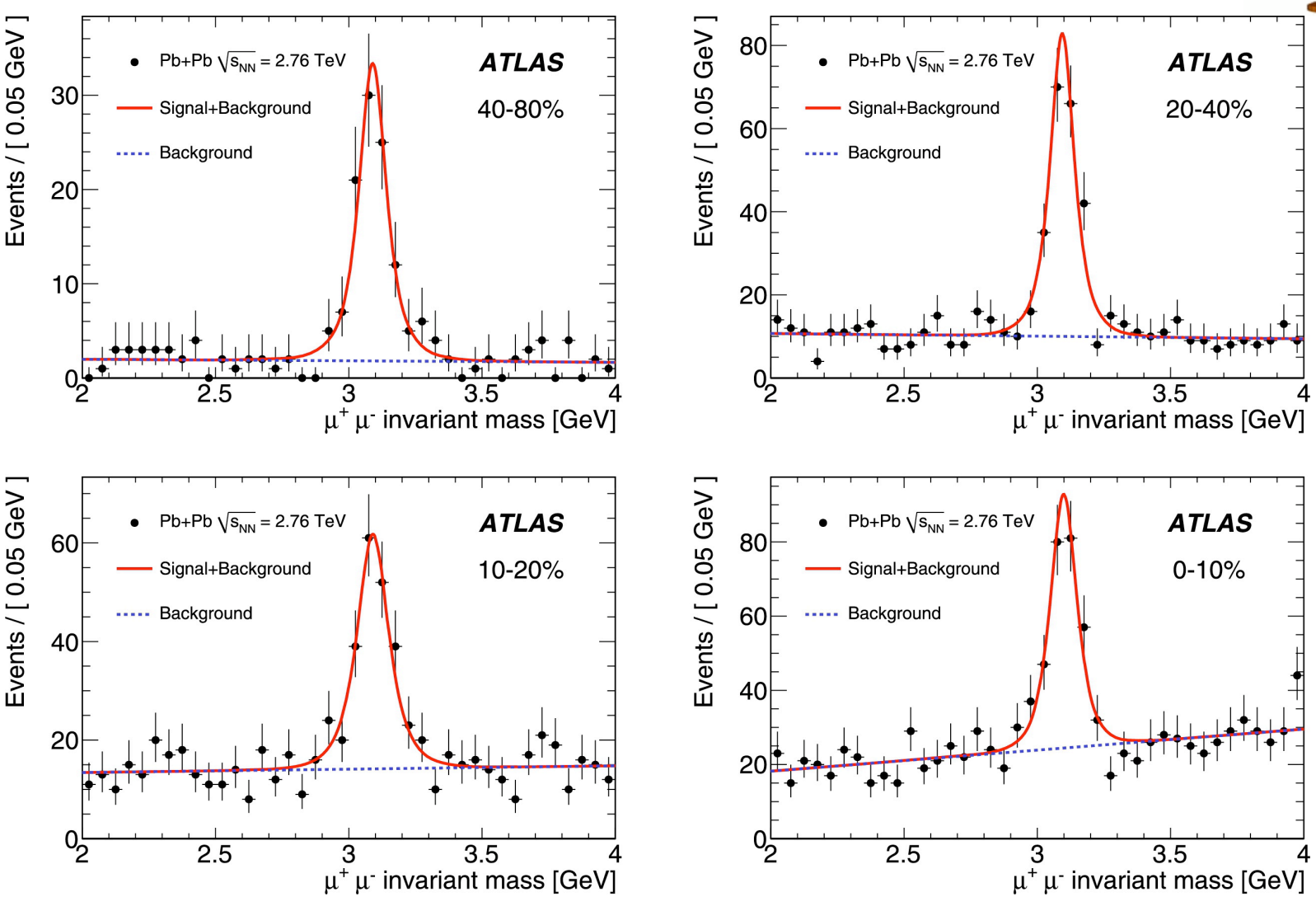
Backup: J/ψ and Z production in HI

Tracking variables in Pb-Pb → J/ψ measurement

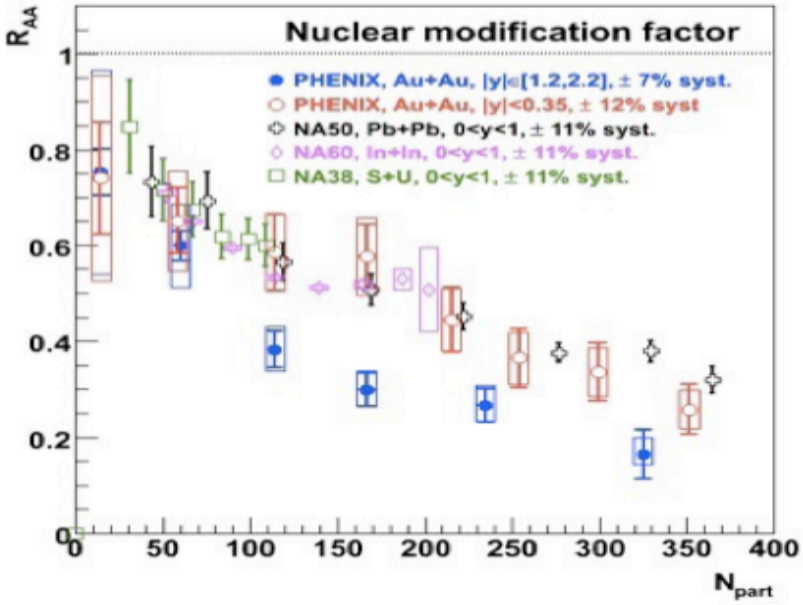


Monte Carlo simulation: Pythia J/ψ events superimposed on HIJING Pb-Pb simulation

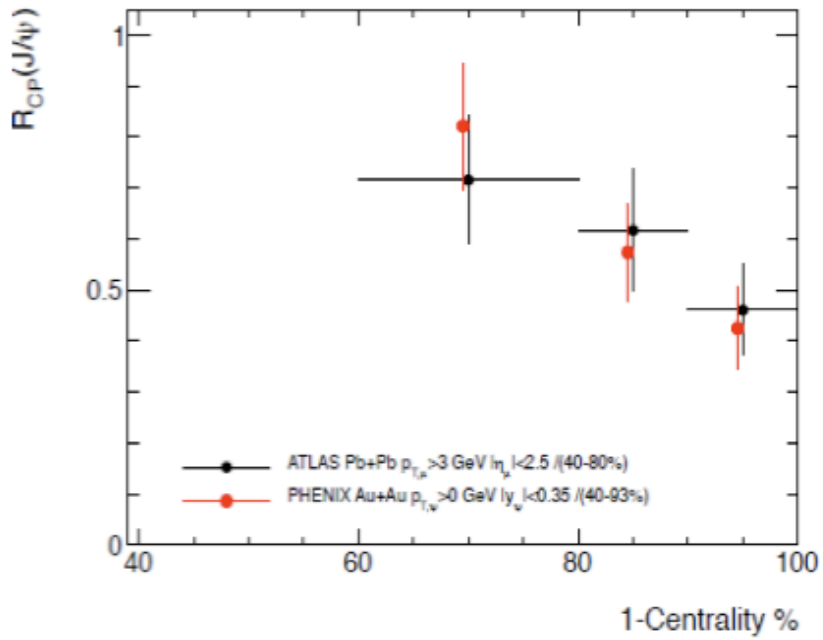
Extraction of the Pb-Pb → J/ψ signal



Comparison with Phenix data

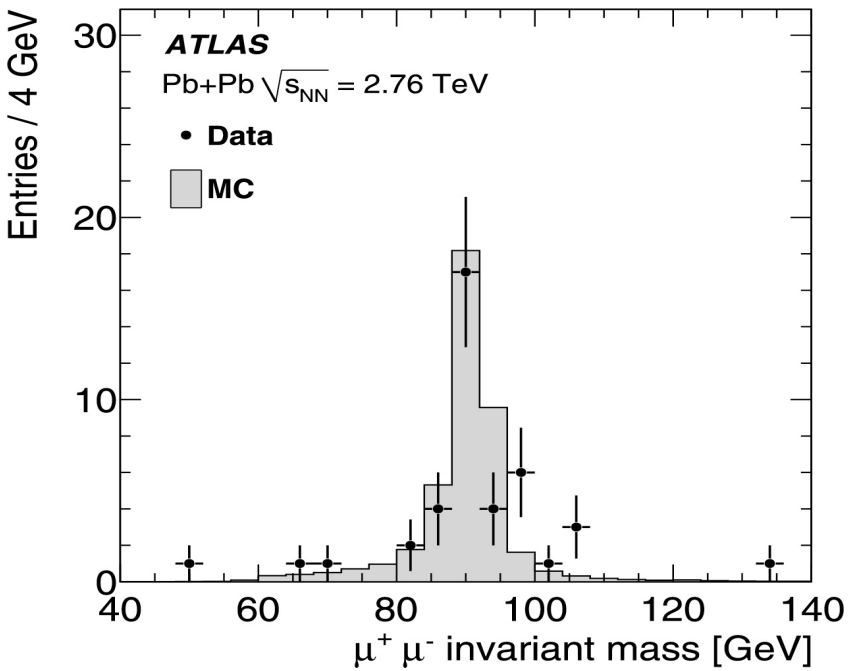


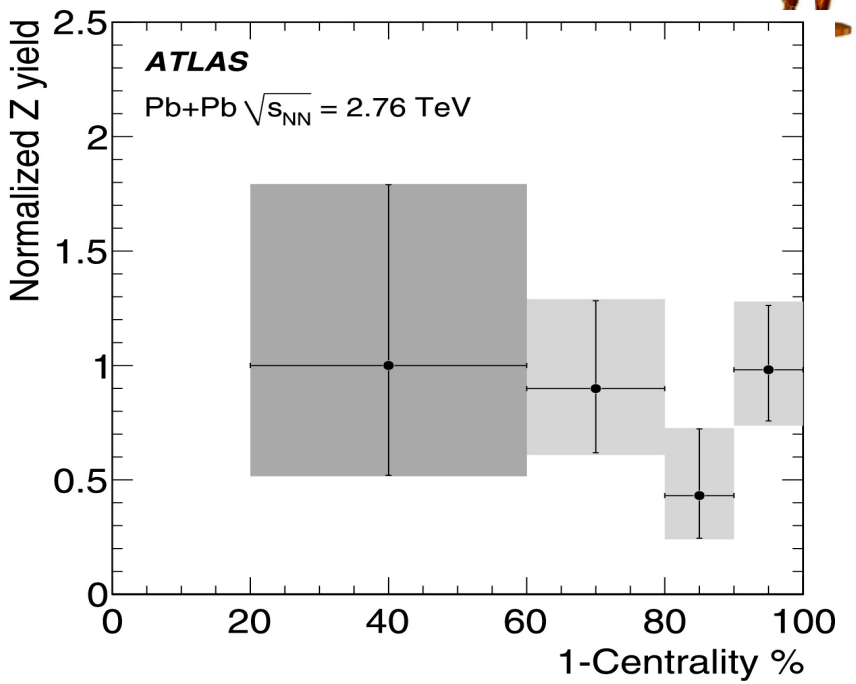
PAS & J. Jia - replotted from public data



- Suppression appears not to be dependent on beam energy

Z production in Pb – Pb collisions





Centrality	N(Z)	$\epsilon(Z)_c/\epsilon(Z)_{40-80}$
0-10%	19	0.99 ± 0.01
10-20%	5	0.97 ± 0.01
20-40%	10	0.98 ± 0.01
40-80%	4	1

ATLAS detector

The ATLAS Muon System

Barrel: $|\eta|<1.05$
Endcap: $1.05<|\eta|<2.7$

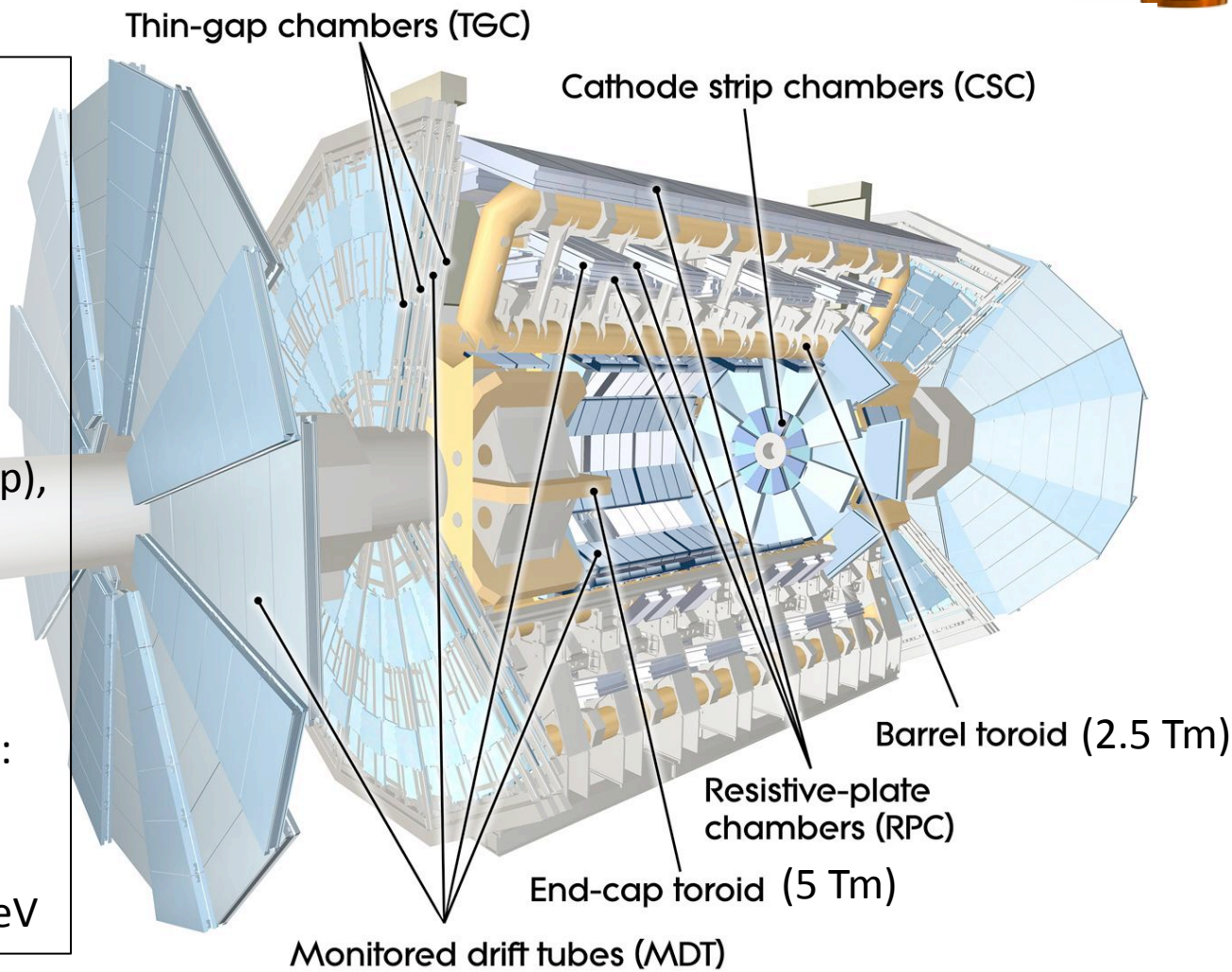
Fast trigger:
- RPC (barrel),
- TGC (endcap)

Precision measurement:
- MDT (barrel+endcap),
- CSC (endcap)

3 points / track

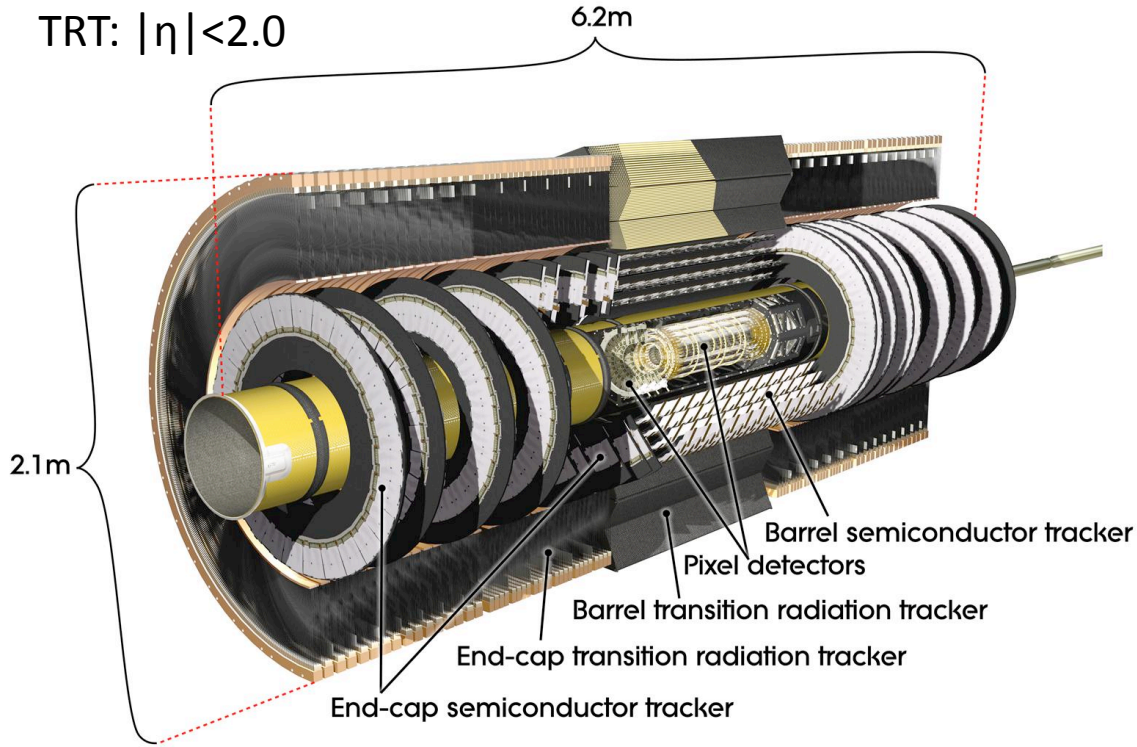
Magnetic field of
- 3x8 air-core toroids:
- average ~0.5T

$\sigma(p_T)/p_T < 10\%$ at $p_T<1$ TeV



The ATLAS Inner Tracking Detector

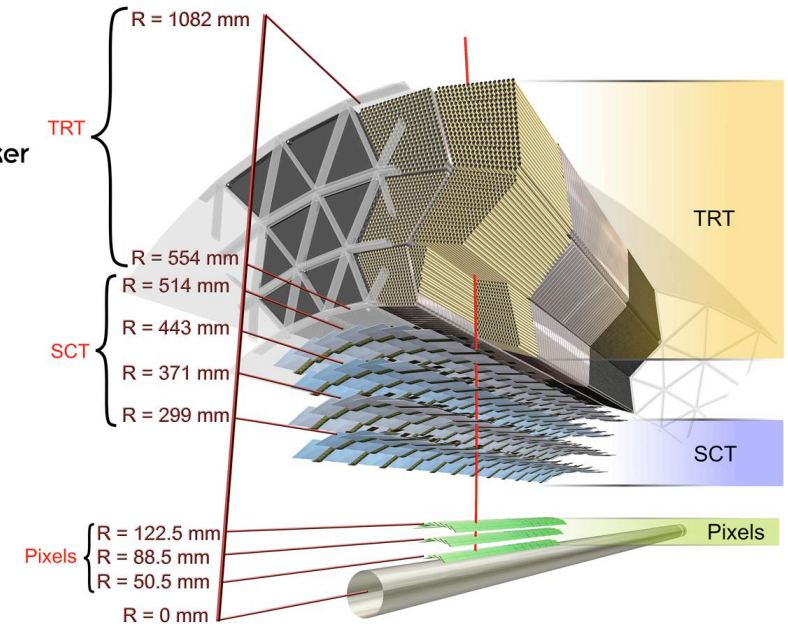
Silicon tracking: $|\eta|<2.5$
TRT: $|\eta|<2.0$

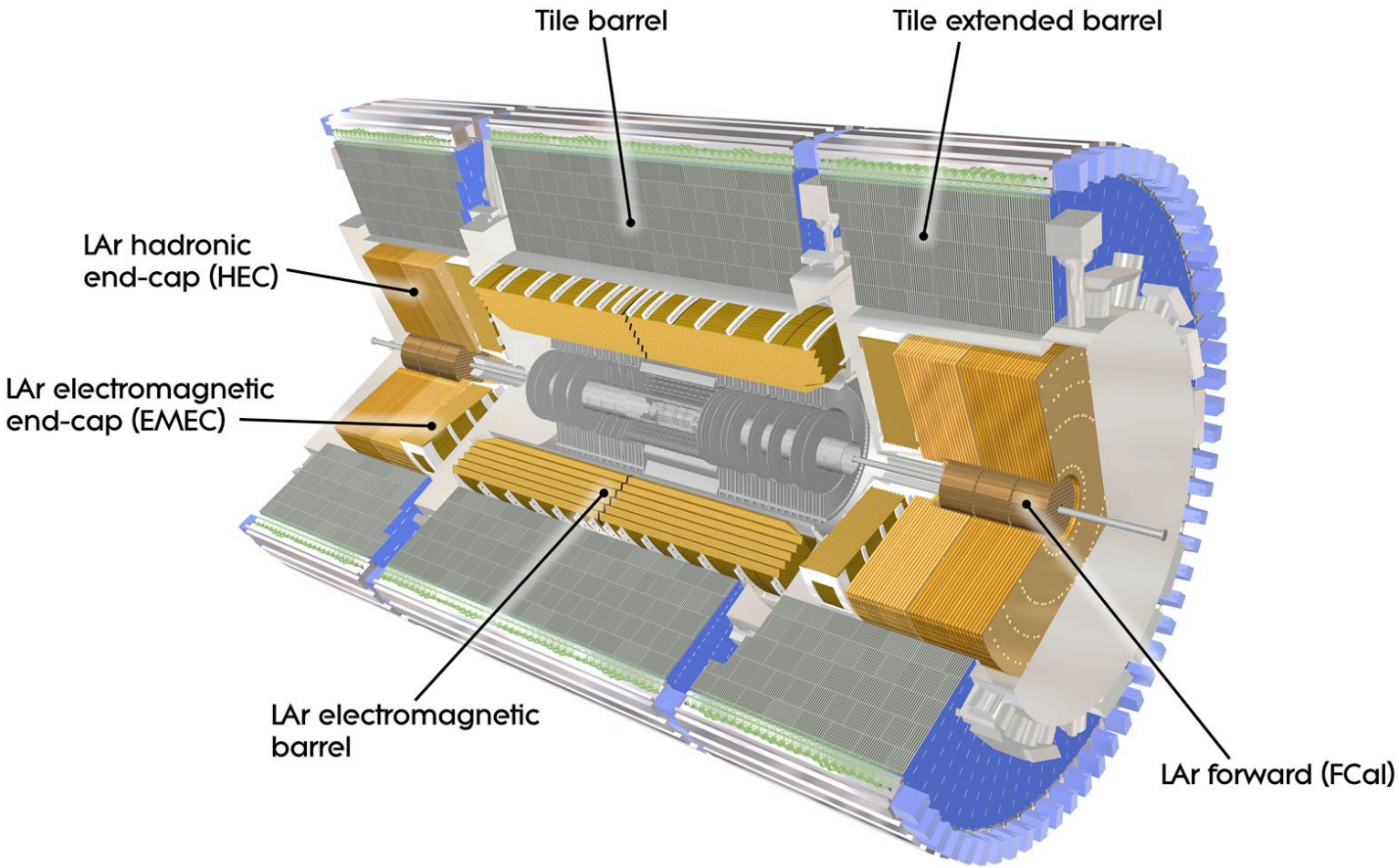


Axial magnetic field: 2T

Si pixels: 10/115 μm in rϕ/z
Si strips: 17/580 μm
TRT: 130 μm

$\sigma(p_T)/p_T = 0.05\%/pT \oplus 1\%$



Si Pixel: 3 layers
Si Strip: 4 double-sided layers (9 in endcaps)
TRT Straws: 73 layers (160 in endcaps)
~30 measurements @ $\eta \approx 0$

The ATLAS Calorimeter System