Measurement of the production cross section of prompt J/ψ mesons in association with a $W^{\pm}$ boson in pp collisions at $\sqrt{s}$=7 TeV with the ATLAS detector

Constantinos Melachrinos (University of Chicago), melachrinos@gmail.com
University of Birmingham Particle Physics Seminar
21st January 2014

Outline

SUBMITTED TO JHEP
HTTP://ARXIV.ORG/ABS/1401.2831
ADDITIONAL FIGURES FROM
ATLAS-CONF-2013-042

1. Theoretical Motivation
- Standard Model of Particle Physics
- J/ψ production
- Double Parton Scattering

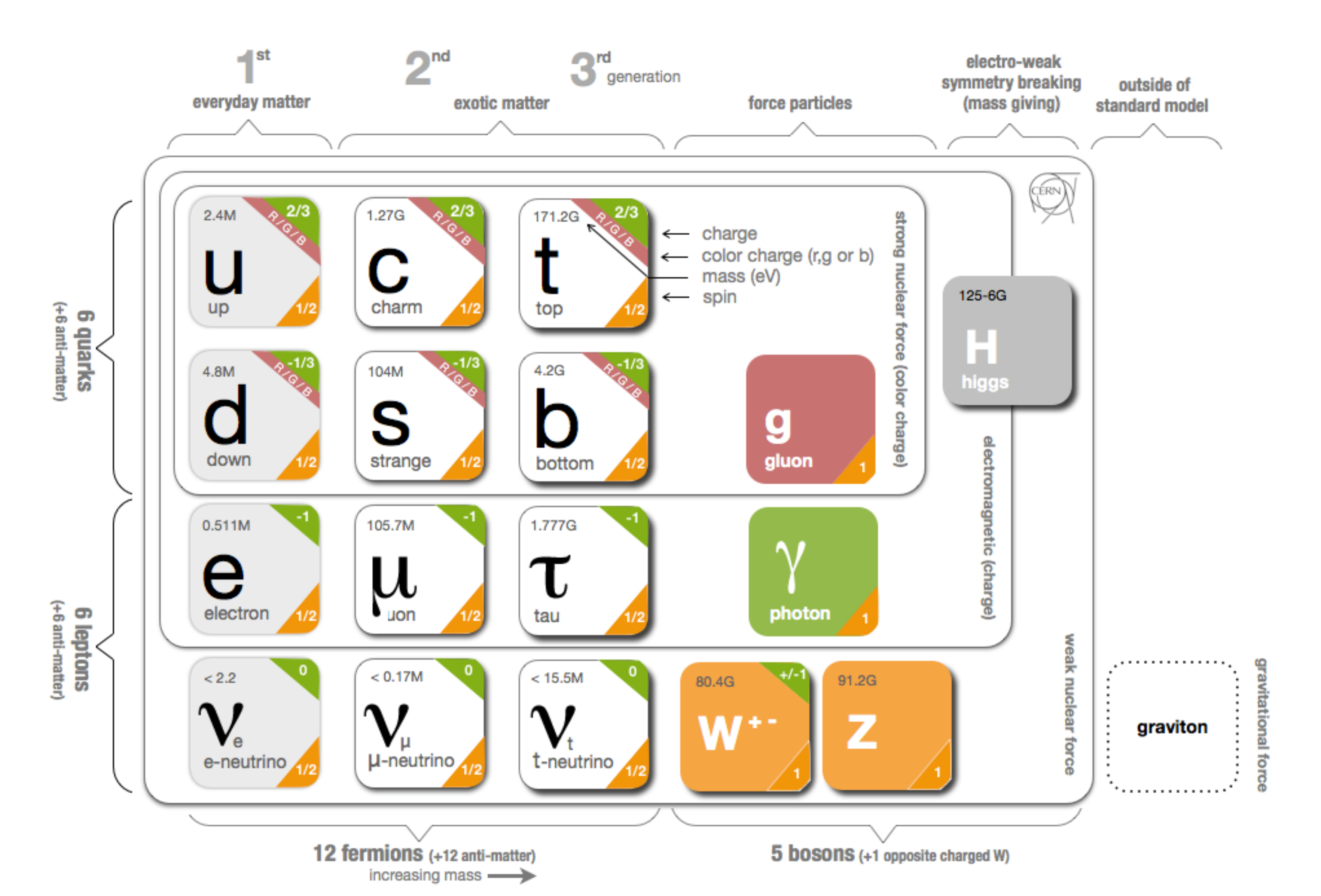
2. Experimental Apparatus
- Large Hadron Collider
- A Toroidal LHC Apparatus

3. Analysis
- Strategy
- Background sources
- Fit procedure

4. Results
- Observation of W+J/ψ process
- Measurement of cross-section ratio W+J/ψ : W
- Double Parton Scattering
- Uncertainties

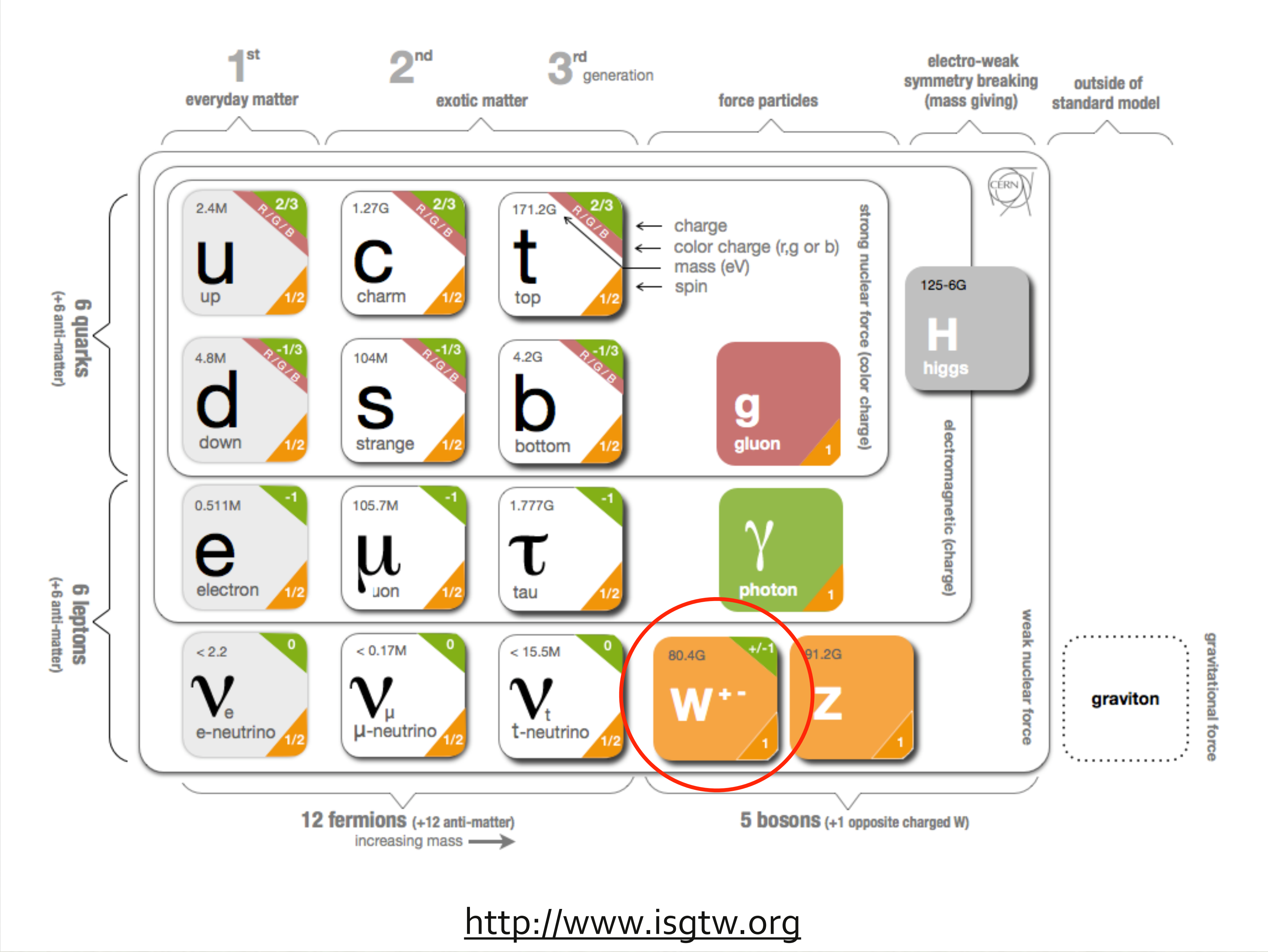
5. Conclusions
- Significance
- Next steps

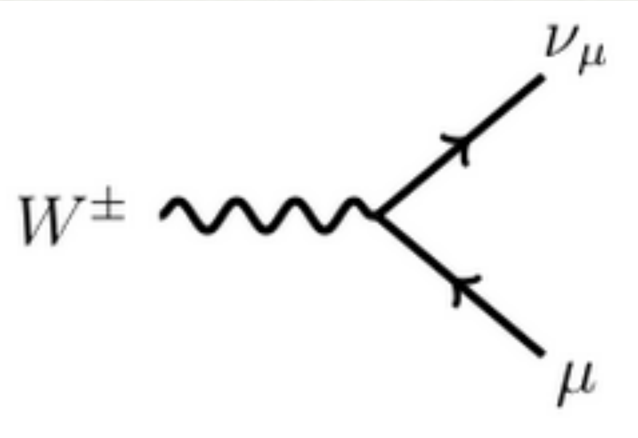
Standard Model of Particle Physics



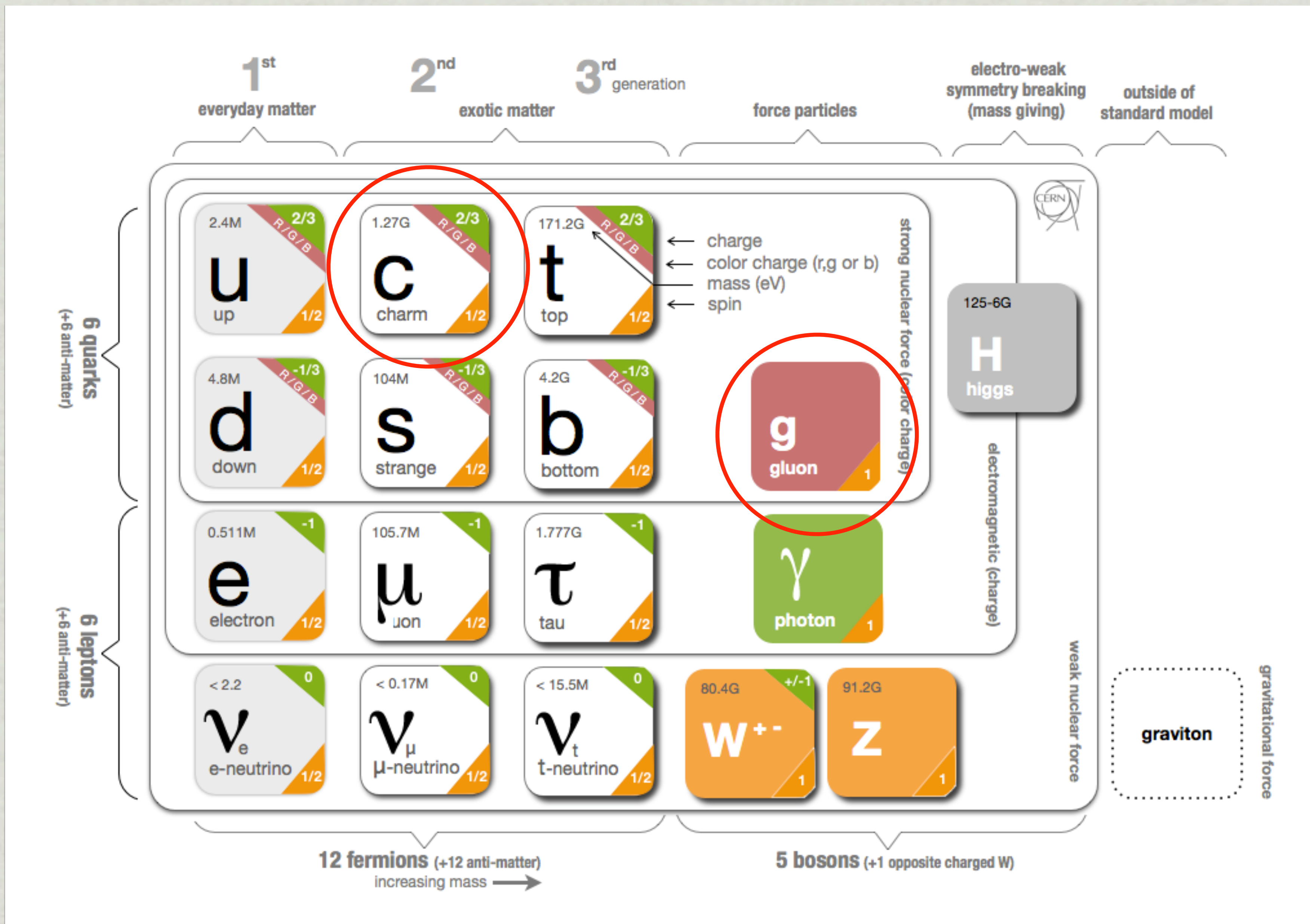
http://www.isgtw.org

Standard Model of Particle Physics





Standard Model of Particle Physics



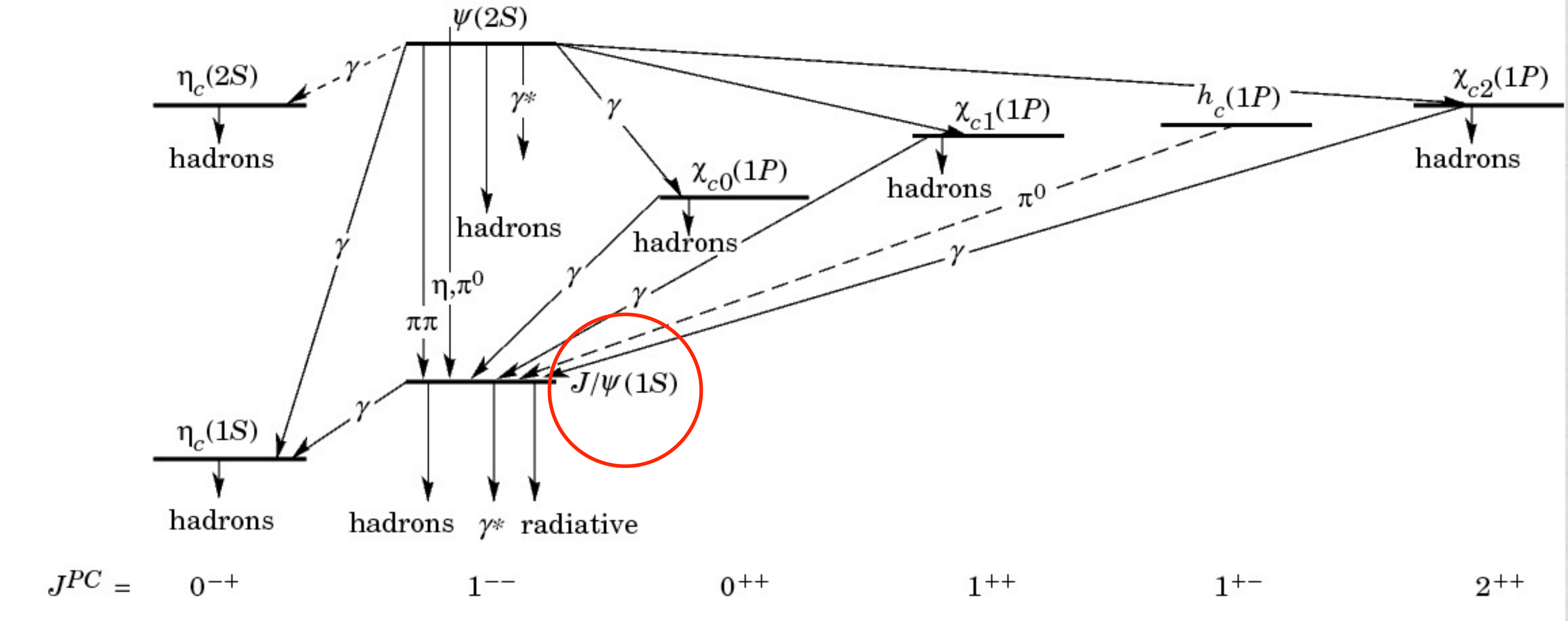
http://www.isgtw.org

J/ψ meson

Mass	3.096916 ± 0.000011 GeV/c^2
Decay width	91.0 ± 3.2 keV
Decays	88% hadrons, 6% e^+e^-, 6% $\mu^+\mu^-$
Quantum properties	Spin=1, Angular Momentum=0, Odd parity, Odd charge conjugation

Charmonium

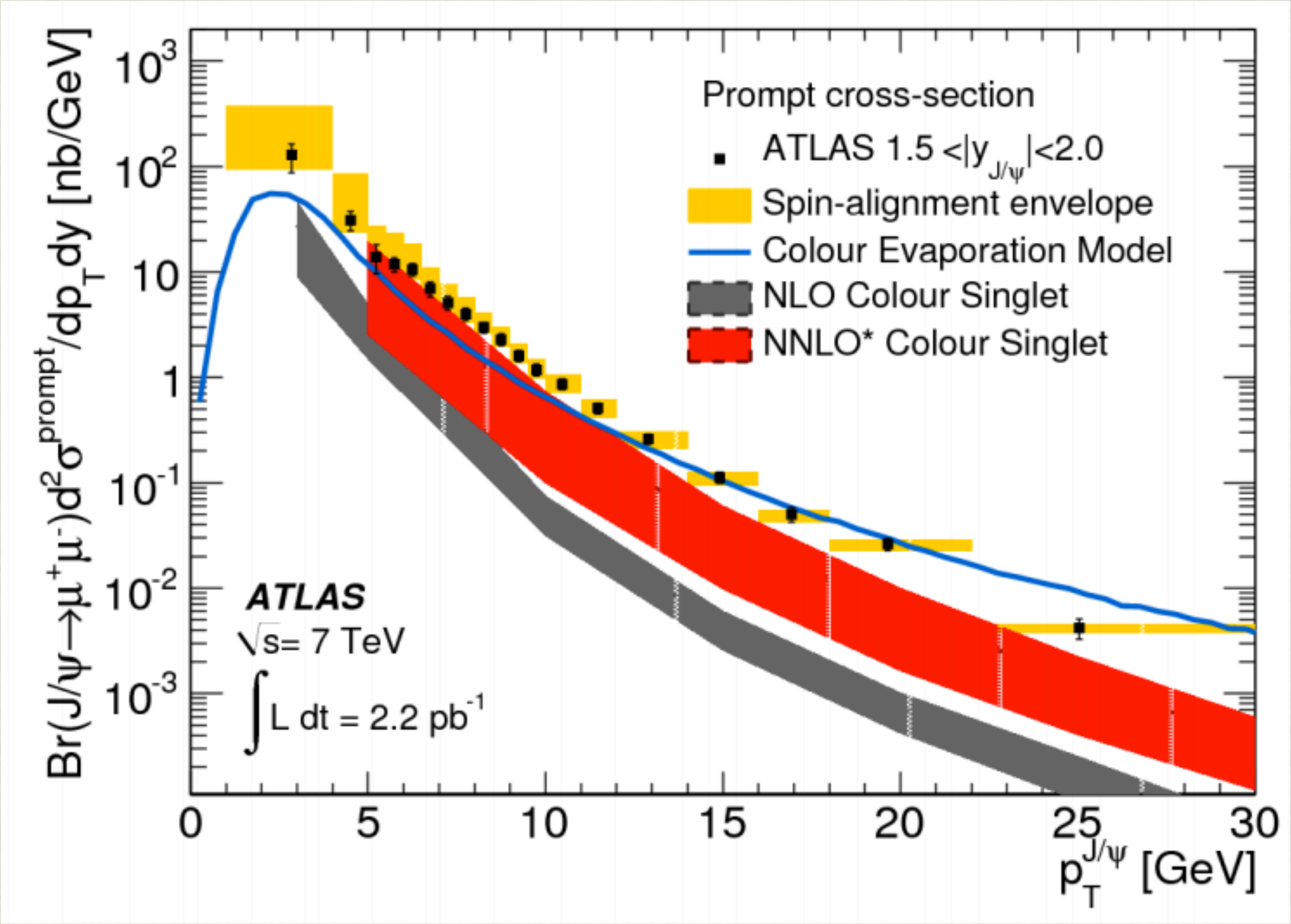
Phys. Lett. B 592 1 (2004)



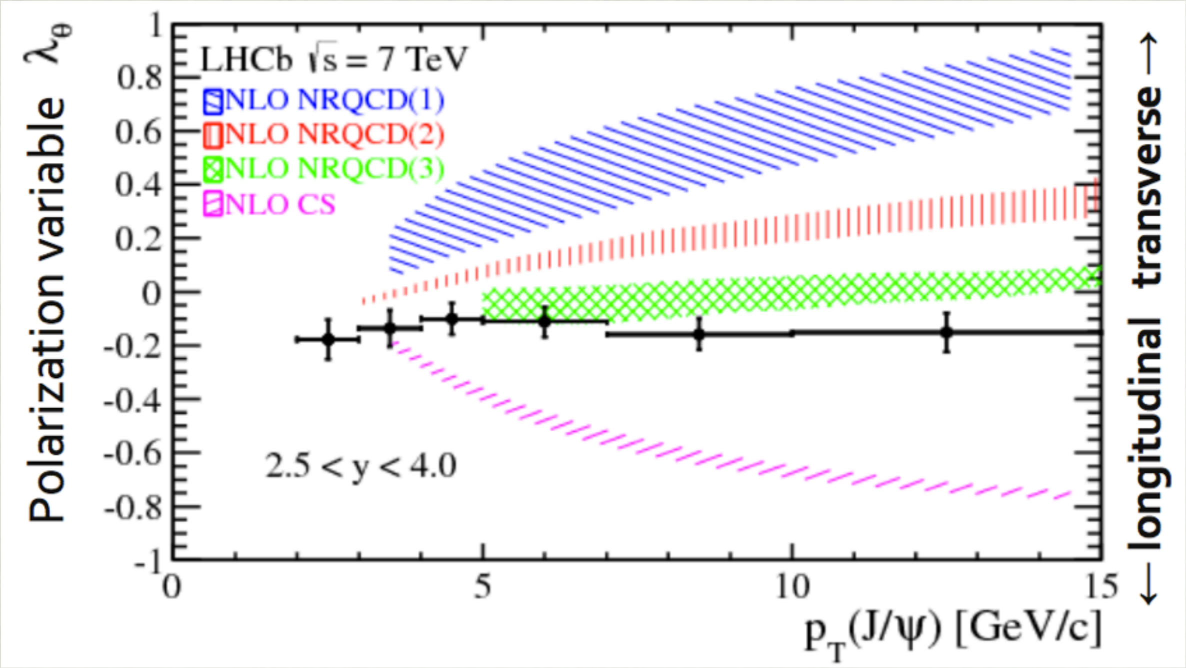
Mass	3.096916 ± 0.000011 GeV/c^2
Decay width	91.0 ± 3.2 keV
Decays	88% hadrons, 6% e^+e^-, 6% $\mu^+\mu^-$
Quantum properties	Spin=1, Angular Momentum=0, Odd parity, Odd charge conjugation

J/ψ production

Nucl. Phys. B 850 (2011) 387-444

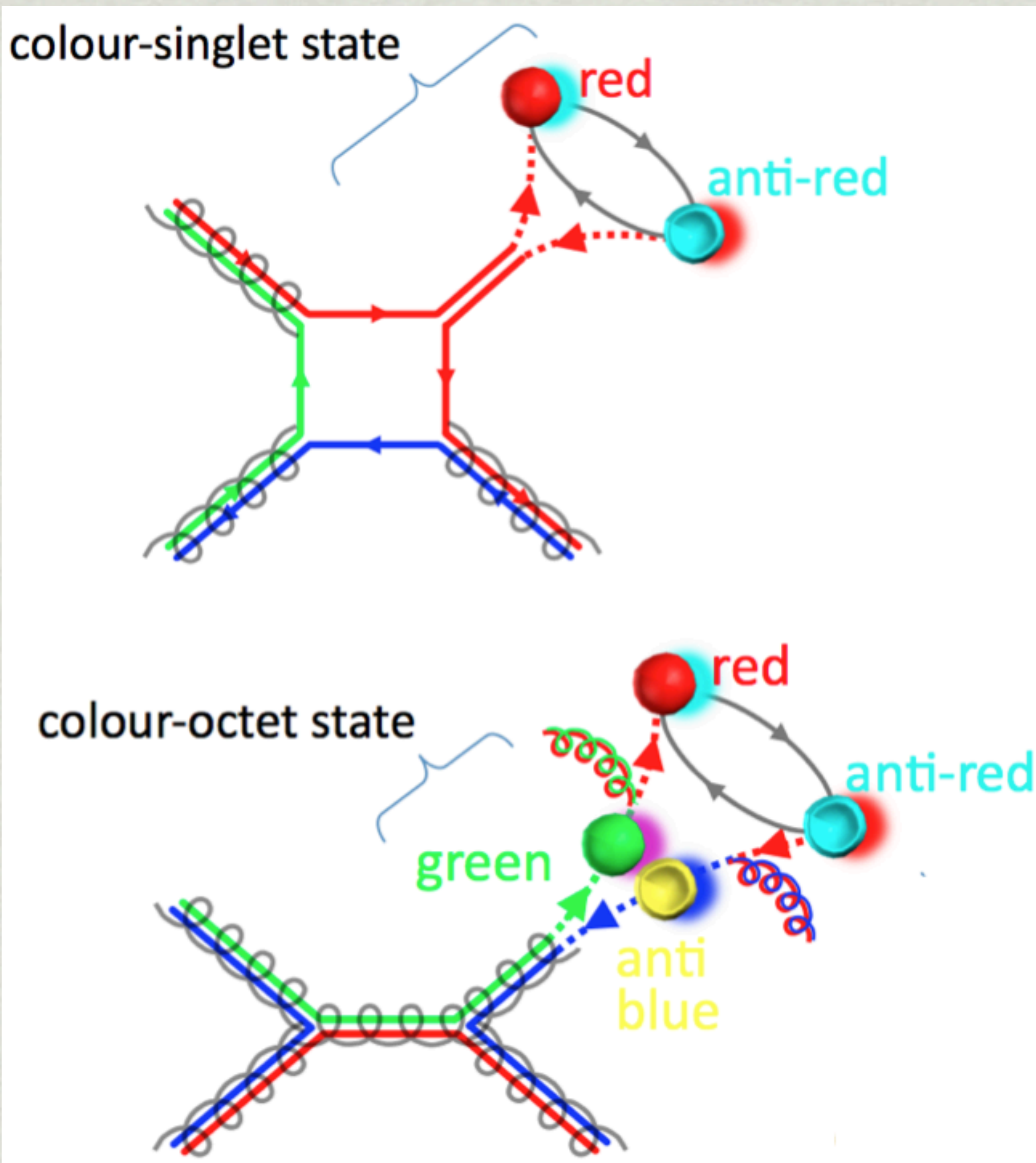


arXiv:1307.6379



- J/ψ production poorly understood
- Models (Colour Singlet, Colour Octet, Colour Evaporation) cannot predict transverse momentum (p_T) spectrum, or polarization profile, or both

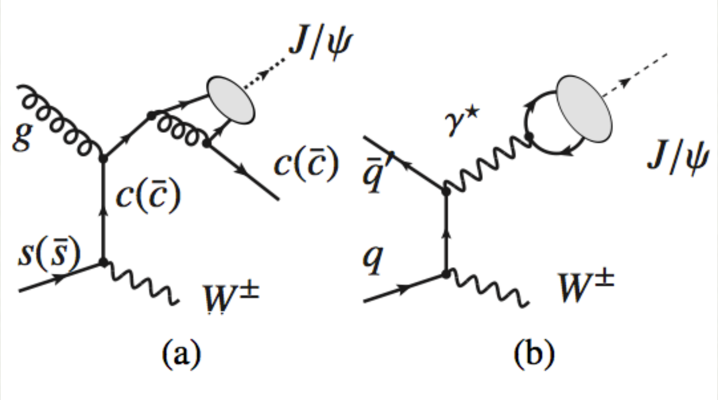
J/ψ production



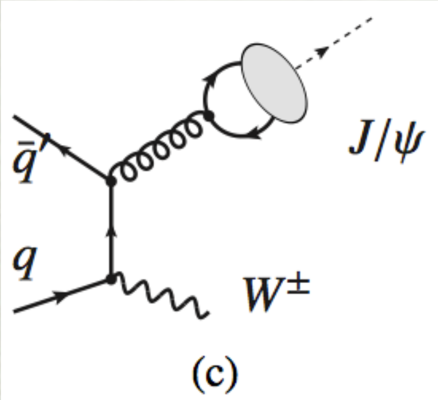
- QCD factorization theorem
- Colour Singlet:
  - creation of two heavy quarks: pQCD
  - binding: wave function
  - assume colour and spin of qq pair do not change during binding
  - two gluons
- Colour Octet:
  - NRQCD
  - short distance: pQCD
  - hadronization of qq: non-perturbative
  - colours can be different
  - one gluon

W+J/ψ production

arxiv:1303.5327



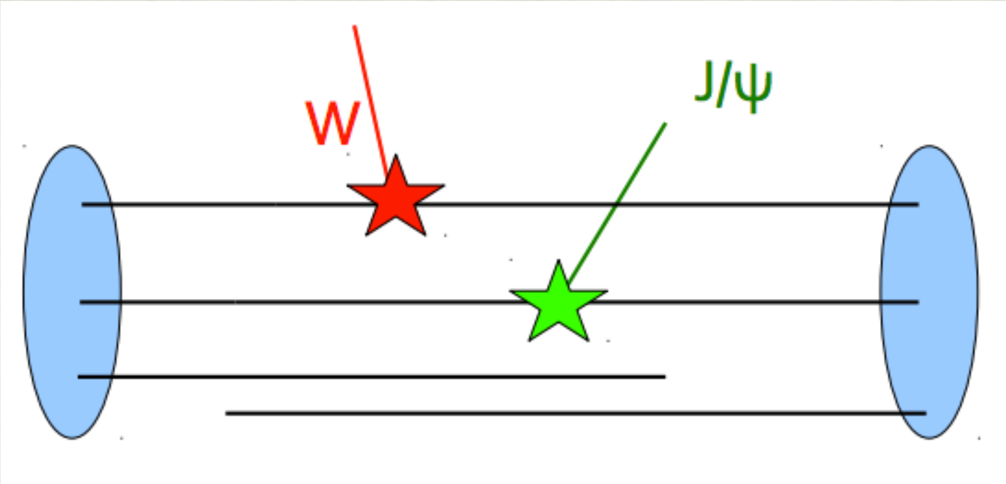
Colour Singlet



Colour Octet

- W+J/ψ is quark-initiated process (Colour Singlet and Colour Octet)
  - Differs from mostly gluon fusion inclusive J/ψ
- Only previous similar search from CDF, W+ϒ, set limits
- Another contribution to W+J/ψ can come from Double Parton Scattering

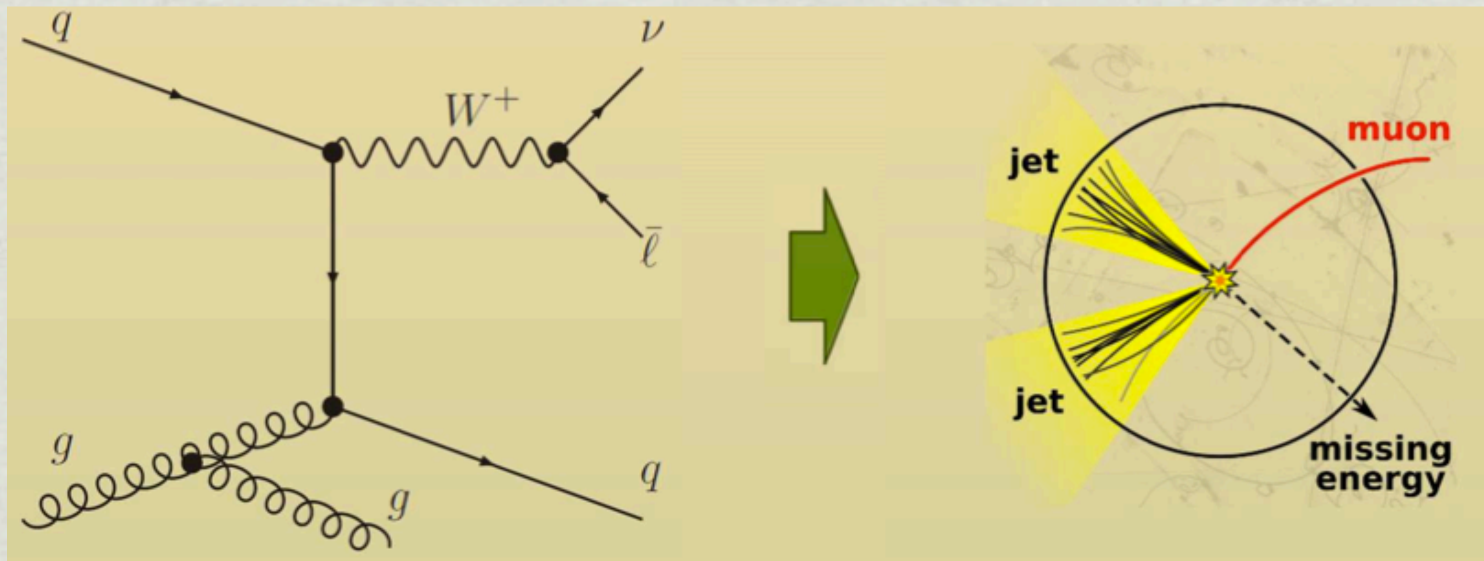
Double Parton Scattering

p  p

- Products of collisions coming from different partons in the protons
- Probes structure of proton (correlations of partons)
- Background for some rare processes
- Need to measure to probe universality
- σ_{eff} measured in different experiments and energies

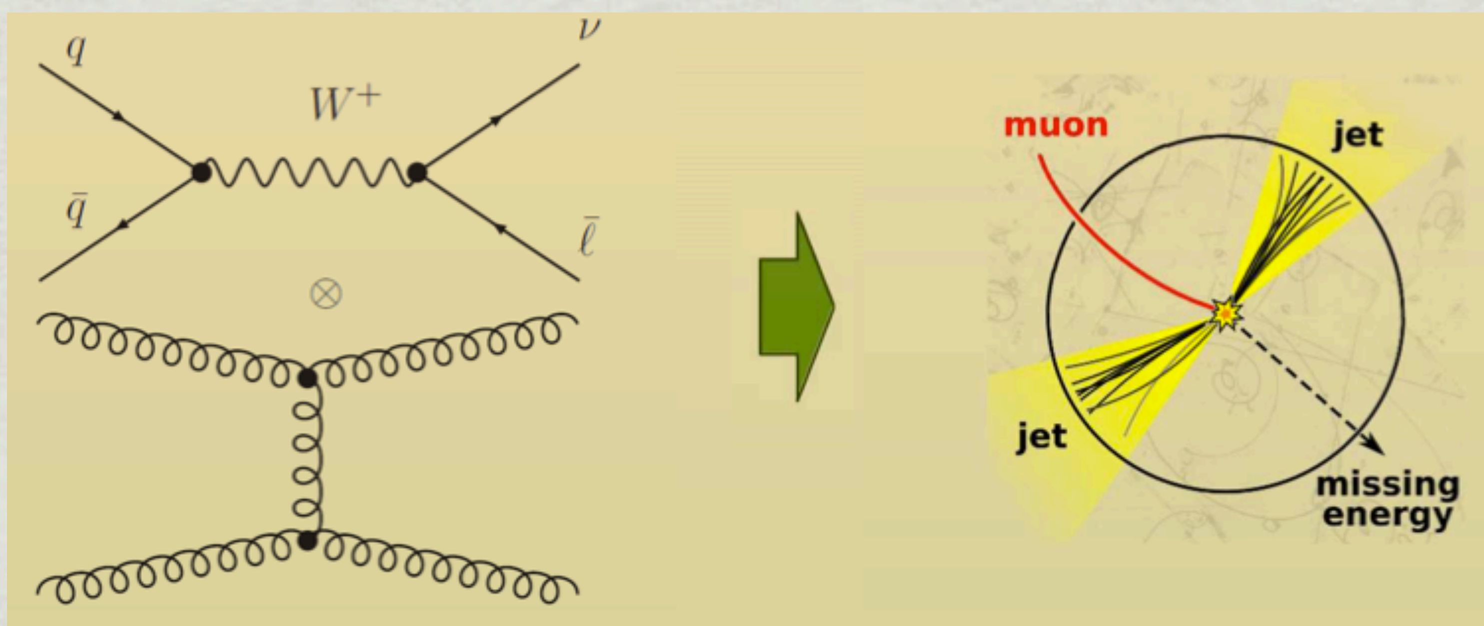
Double Parton Scattering

Single Parton Interaction



- Jets more collinear to each other
- Jets differ in transverse momentum
- Jets associated directly with W production

Double Parton Interaction

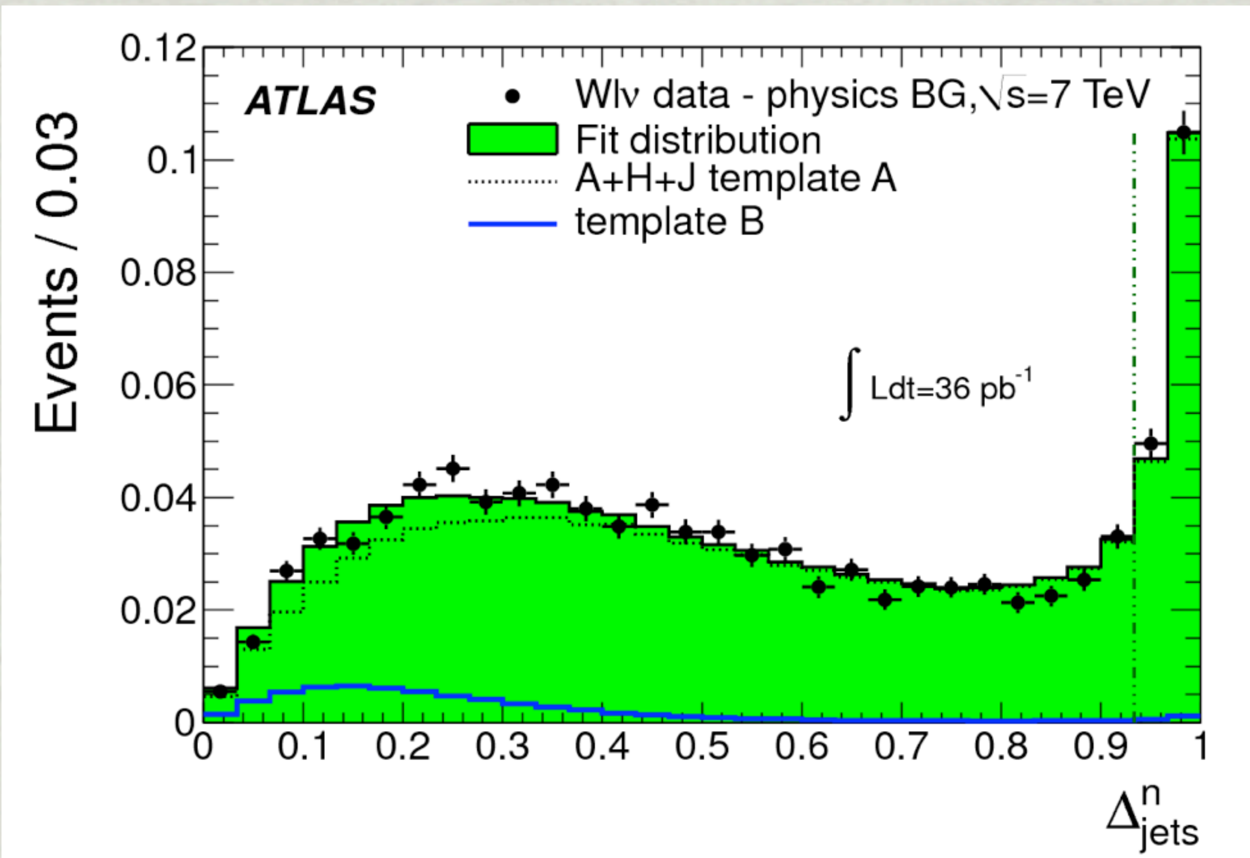


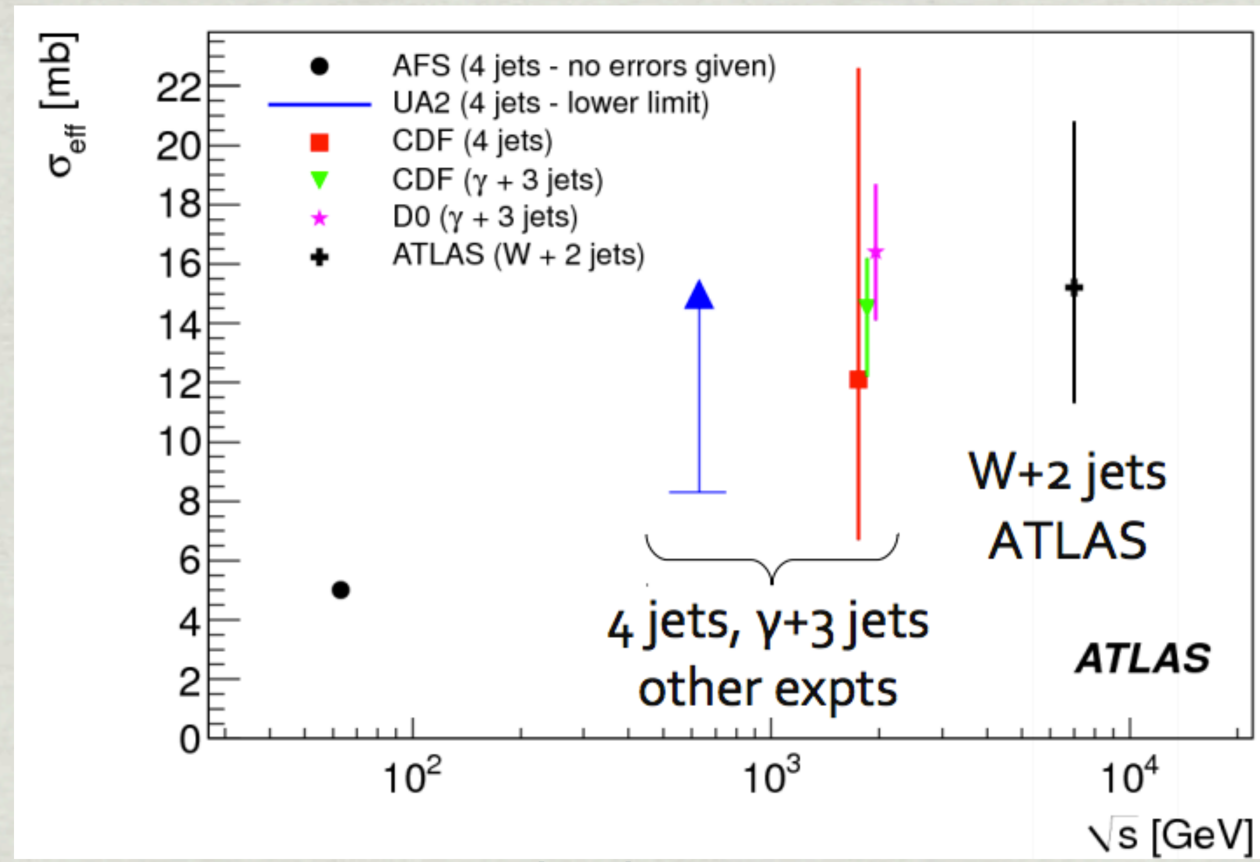
- Jets back-to-back
- Jets balanced in transverse momentum
- Independent W and dijet production

ATL-PHYS-SLIDE-2013-267

Double Parton Scattering

New J. Phys. 15 (2013) 033038





- Use normalized jet pair transverse momentum imbalance as discriminating factor

$$\Delta^{n}_{\text{jets}} = \frac{|\vec{p}_T^{\,j_1} + \vec{p}_T^{\,j_2}|}{|\vec{p}_T^{\,j_1}| + |\vec{p}_T^{\,j_2}|}.$$

template A = SPI-like events

template B = DPI-like events

- fraction of DPI events = 0.076 ± 0.013 (stat) ± 0.018 (syst)
- Measured ATLAS result σ_{eff} = 15 ± 3 (stat) $^{+5}_{-3}$ (syst) mb

Cross-section ratio W+J/ψ:W

$$\frac{\sigma(pp \to W + \text{prompt } J/\psi)}{\sigma(pp \to W)} = \frac{\frac{N^{W+J/\psi}}{\epsilon^{J/\psi}\cdot\alpha^{J/\psi}\cdot\epsilon^{W}\cdot\mathcal{L}}}{\frac{N^{W}}{\epsilon^{W}\cdot\mathcal{L}}}$$

- cross-section: σ
- efficiency (J/ψ): $\epsilon^{J/\psi}$
- acceptance (J/ψ): $\alpha^{J/\psi}$
- number of W +prompt J/ψ: $N^{W+J/\psi}$
- number of W: N^{W}
- efficiency (W): ϵ^{W}
- luminosity: $\mathcal{L}$

- Measurement of cross-section ratio provides input to theorists who study J/ψ and W+J/ψ production

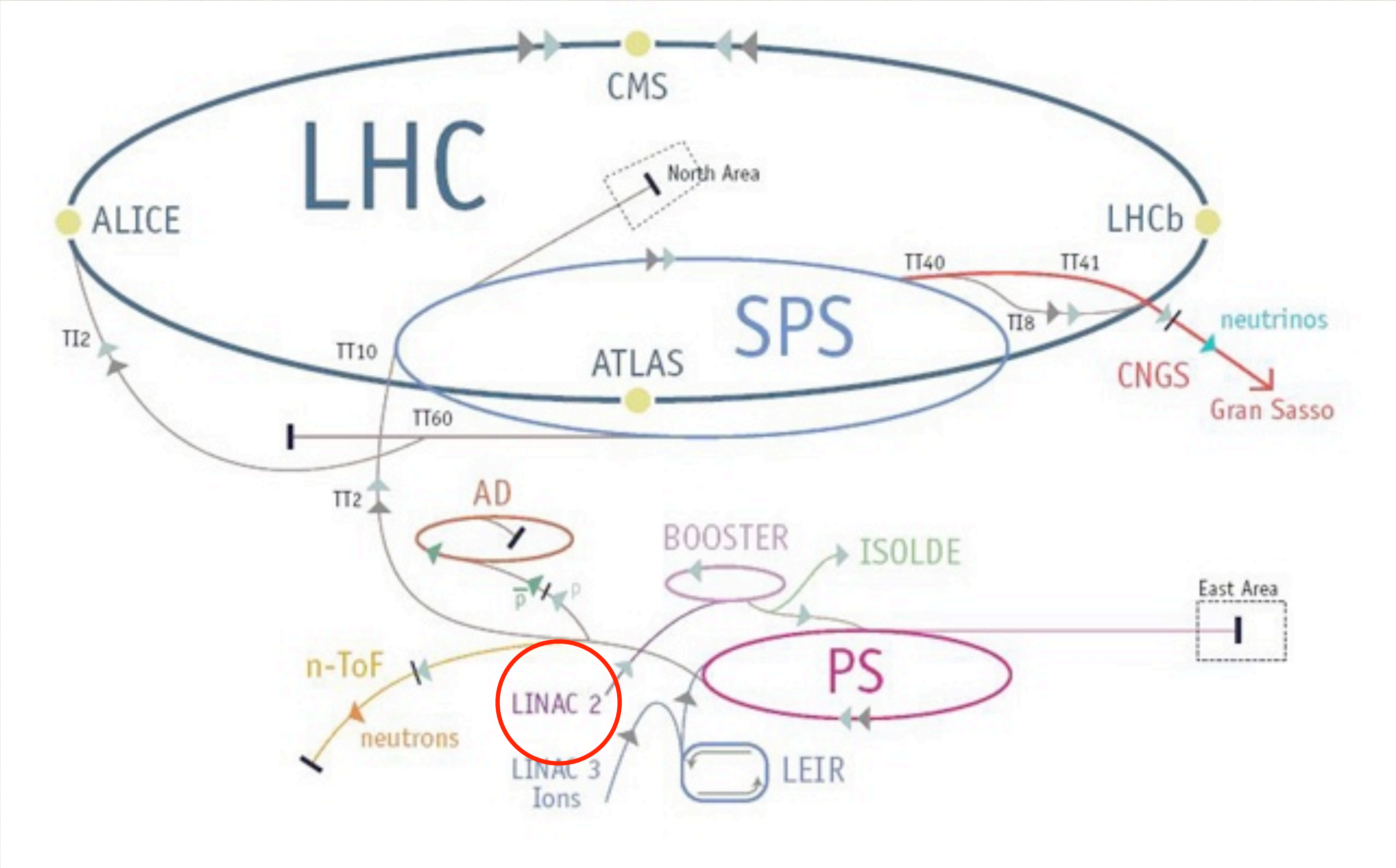
Cross-section ratio W+J/ψ:W

$$\frac{\sigma(pp \to W + \text{prompt } J/\psi)}{\sigma(pp \to W)} = \frac{\dfrac{N^{W+J/\psi}}{\epsilon^{J/\psi} \cdot \alpha^{J/\psi} \cdot \epsilon^{W} \cdot \mathcal{L}}}{\dfrac{N^{W}}{\epsilon^{W} \cdot \mathcal{L}}}$$

cross-section
efficiency (J/ψ)
acceptance (J/ψ)
number of W +prompt J/ψ
number of W
efficiency (W)
luminosity

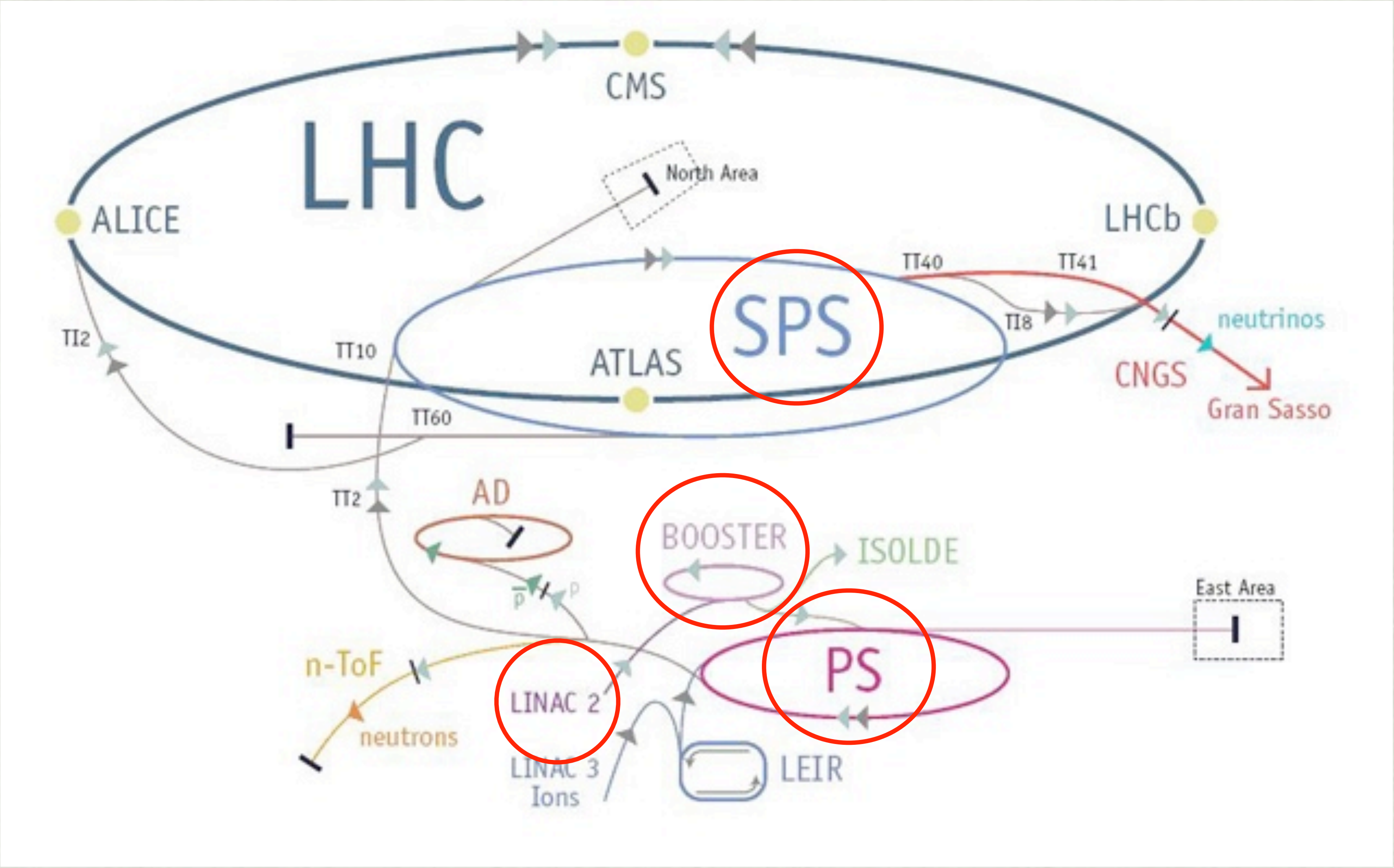
- Measurement of cross-section ratio provides input to theorists who study J/ψ and W+J/ψ production
- Ratio reduces or cancels systematic uncertainties associated with luminosity and W boson

Large Hadron Collider



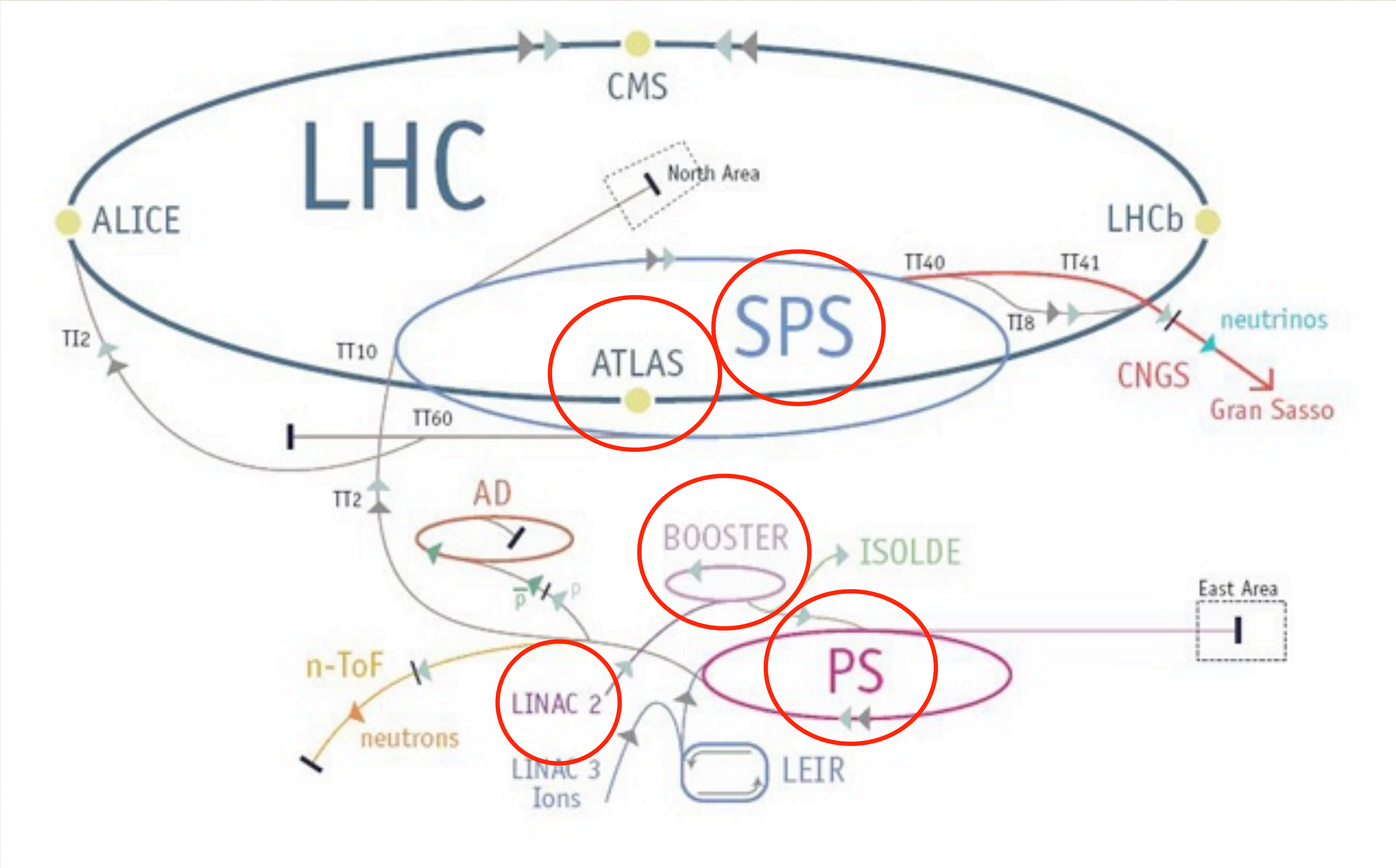
CERN-Brochure-2008-001-Eng

Large Hadron Collider



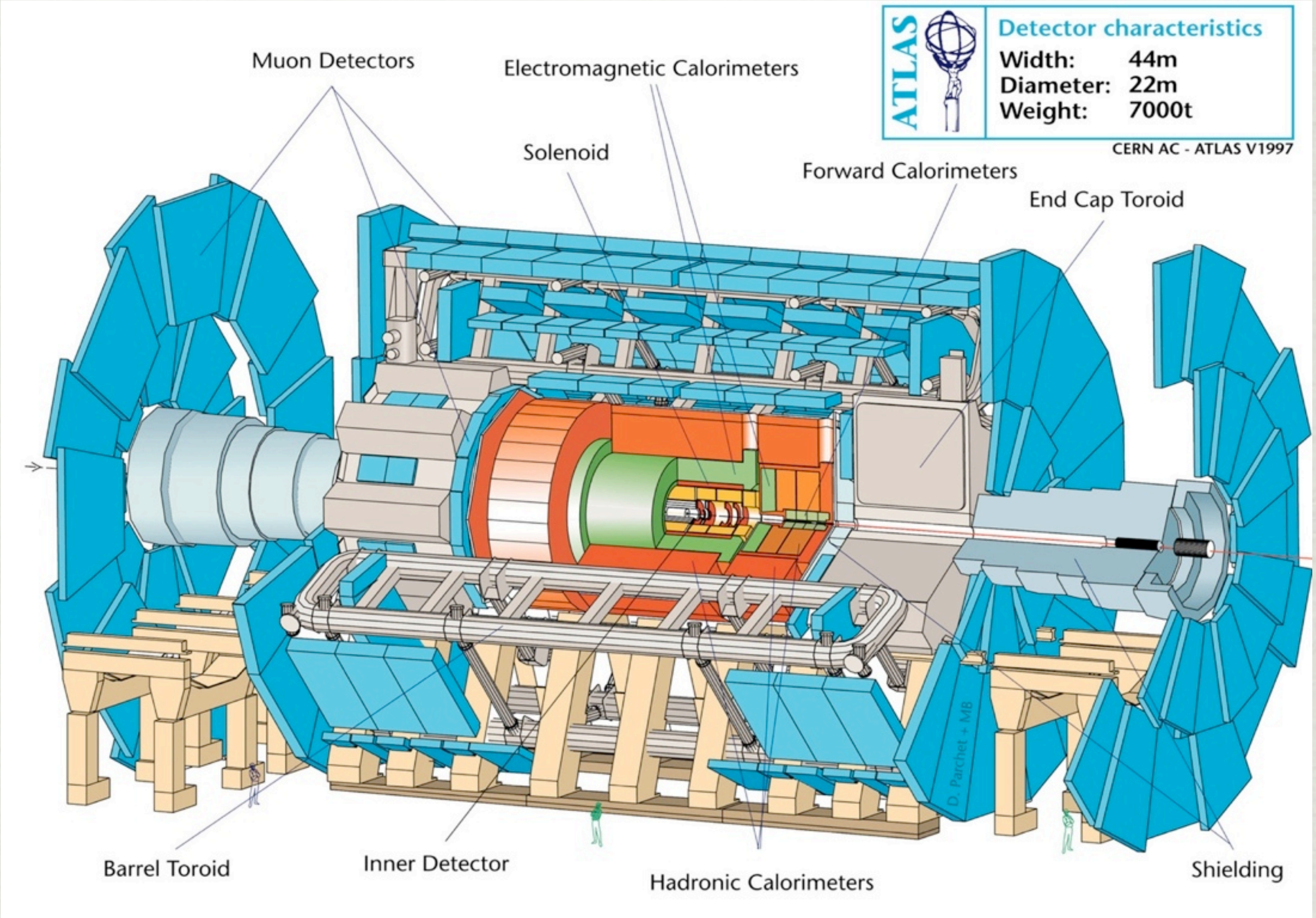
CERN-Brochure-2008-001-Eng

Large Hadron Collider

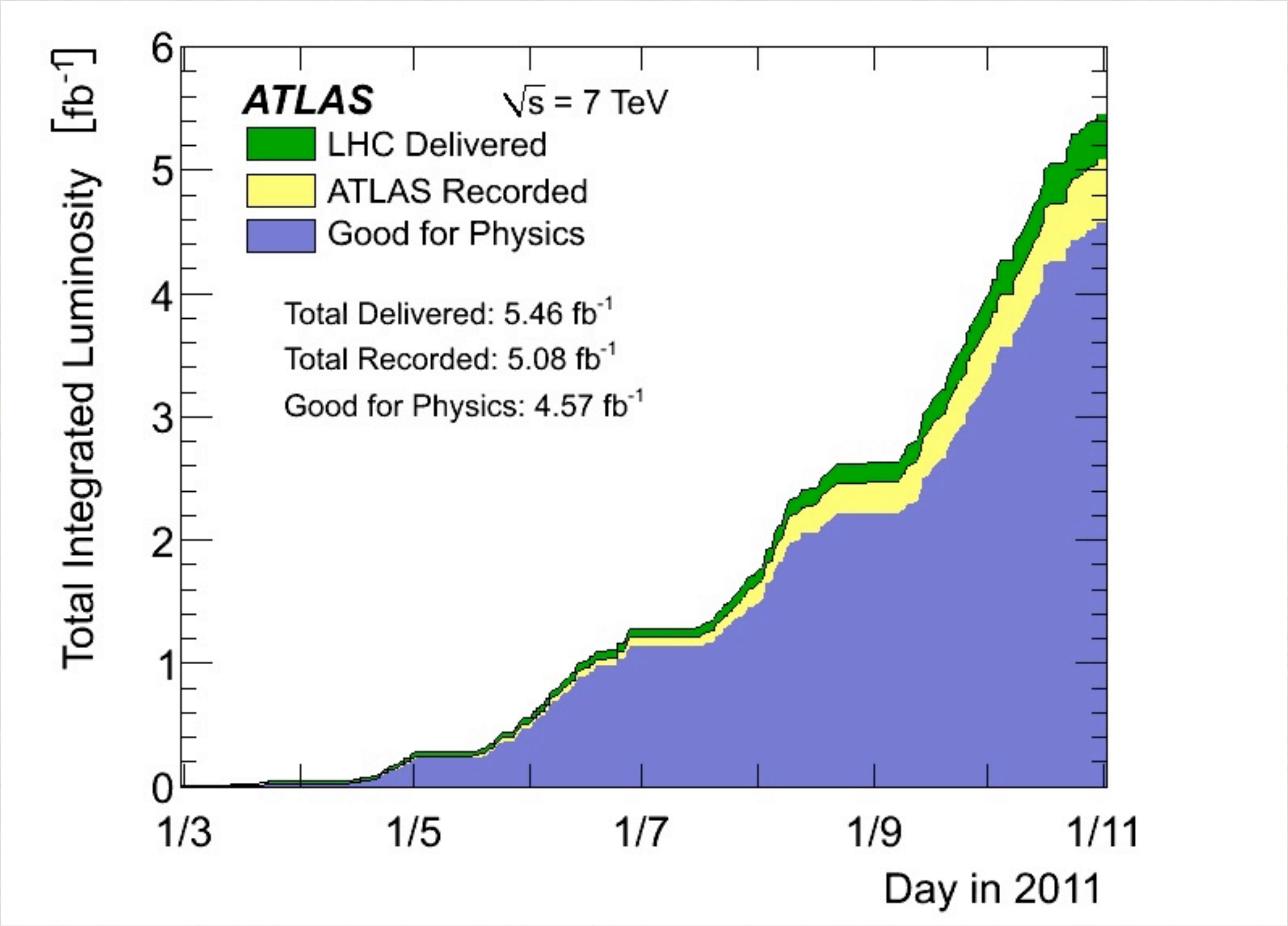


CERN-Brochure-2008-001-Eng

A Toroidal LHC Apparatus



Data collection

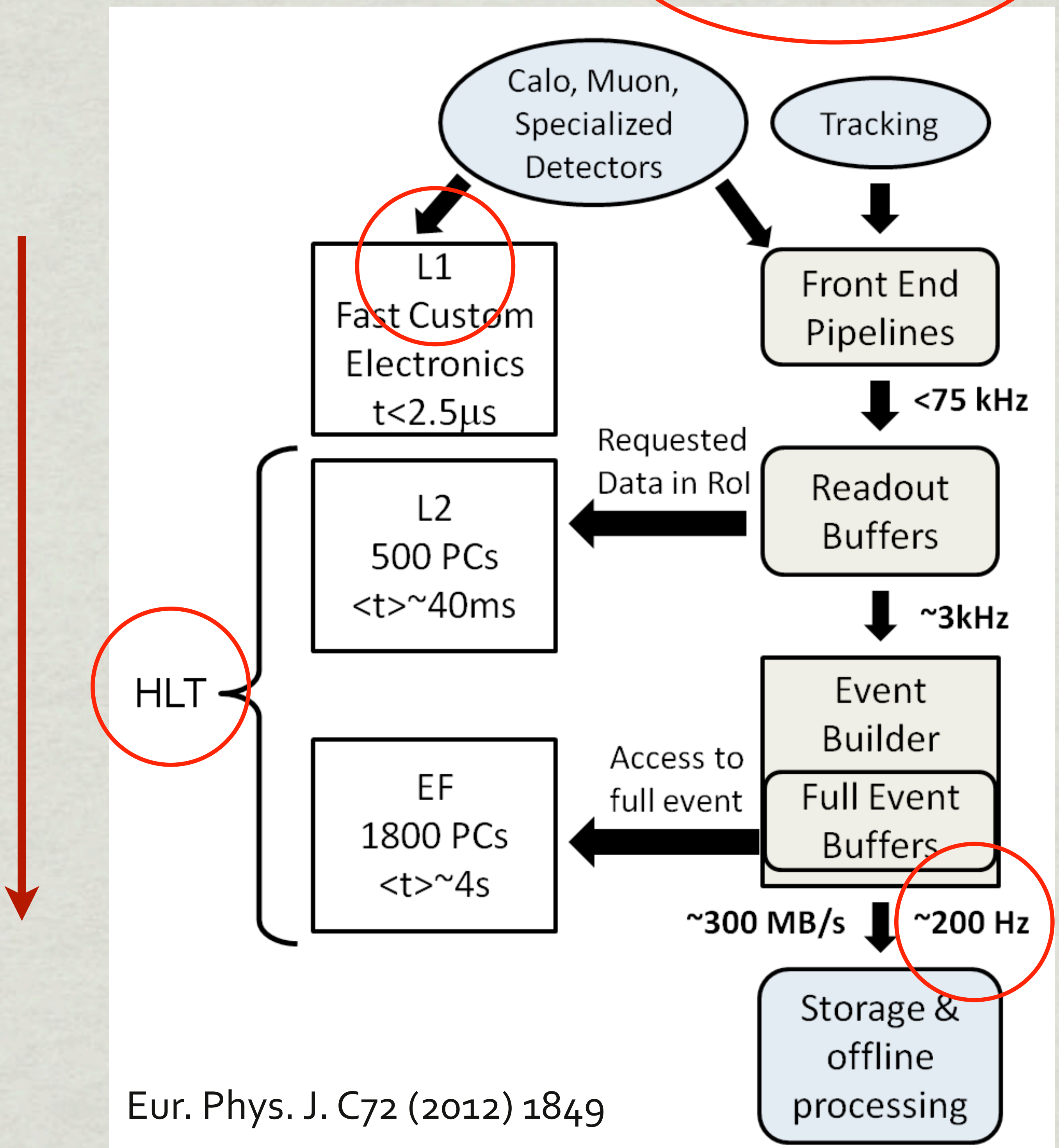


Eur. Phys. J. C73 (2013) 2518

- LHC delivered 5.5 fb^{-1} of data in 2011 with pp collisions at $\sqrt{s}$=7 TeV
- ATLAS recorded 5.1 fb^{-1}
- 4.6 fb^{-1} of data were deemed to be good for physics

Trigger

Bunch crossing rate
40 MHz

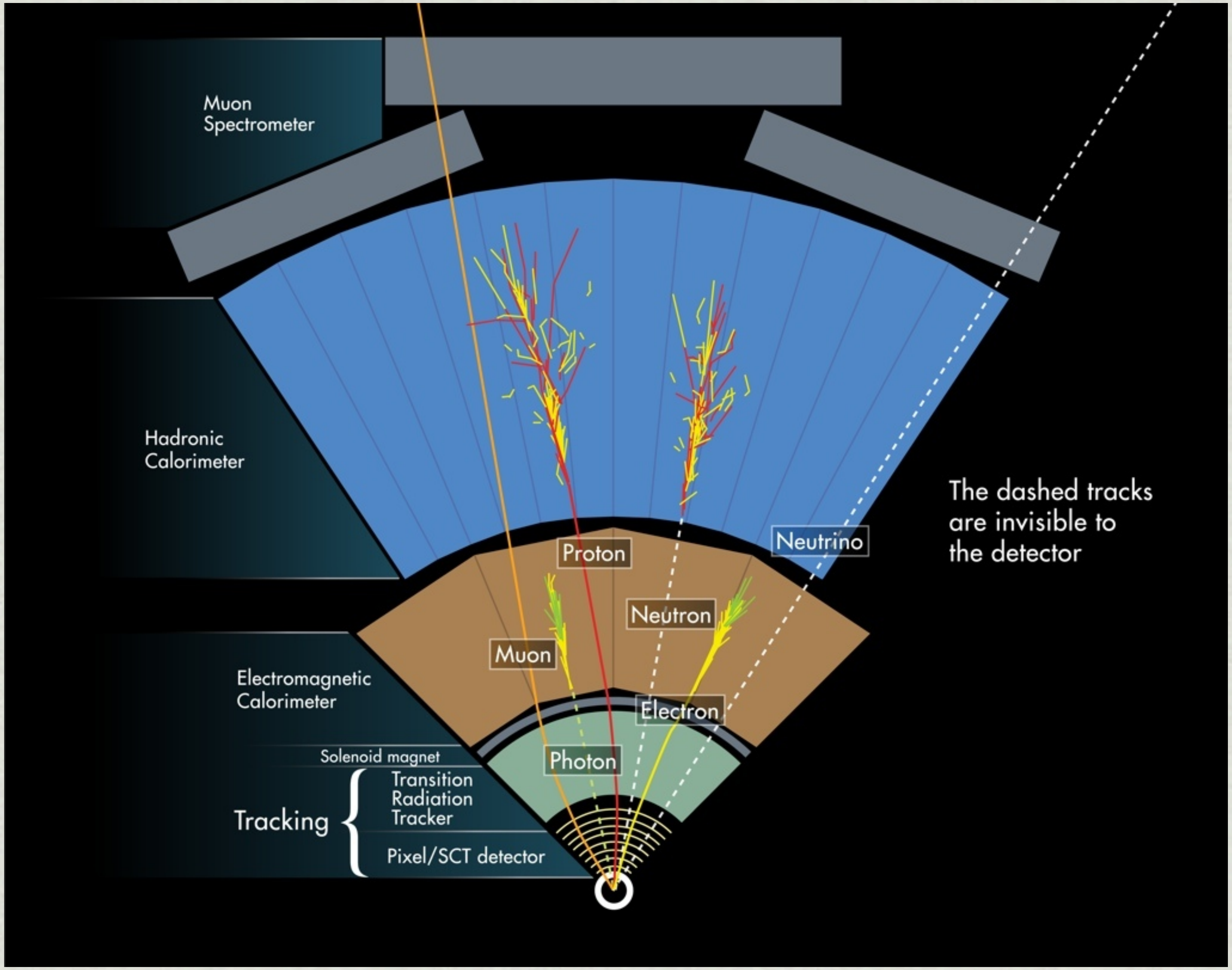


- Decisions on which data to save for further analysis
- Fast, efficient

- Select events with muon with high transverse momentum (p_T>18 GeV)

- 4.5 fb^{-1} data selected by our trigger

Muon reconstruction



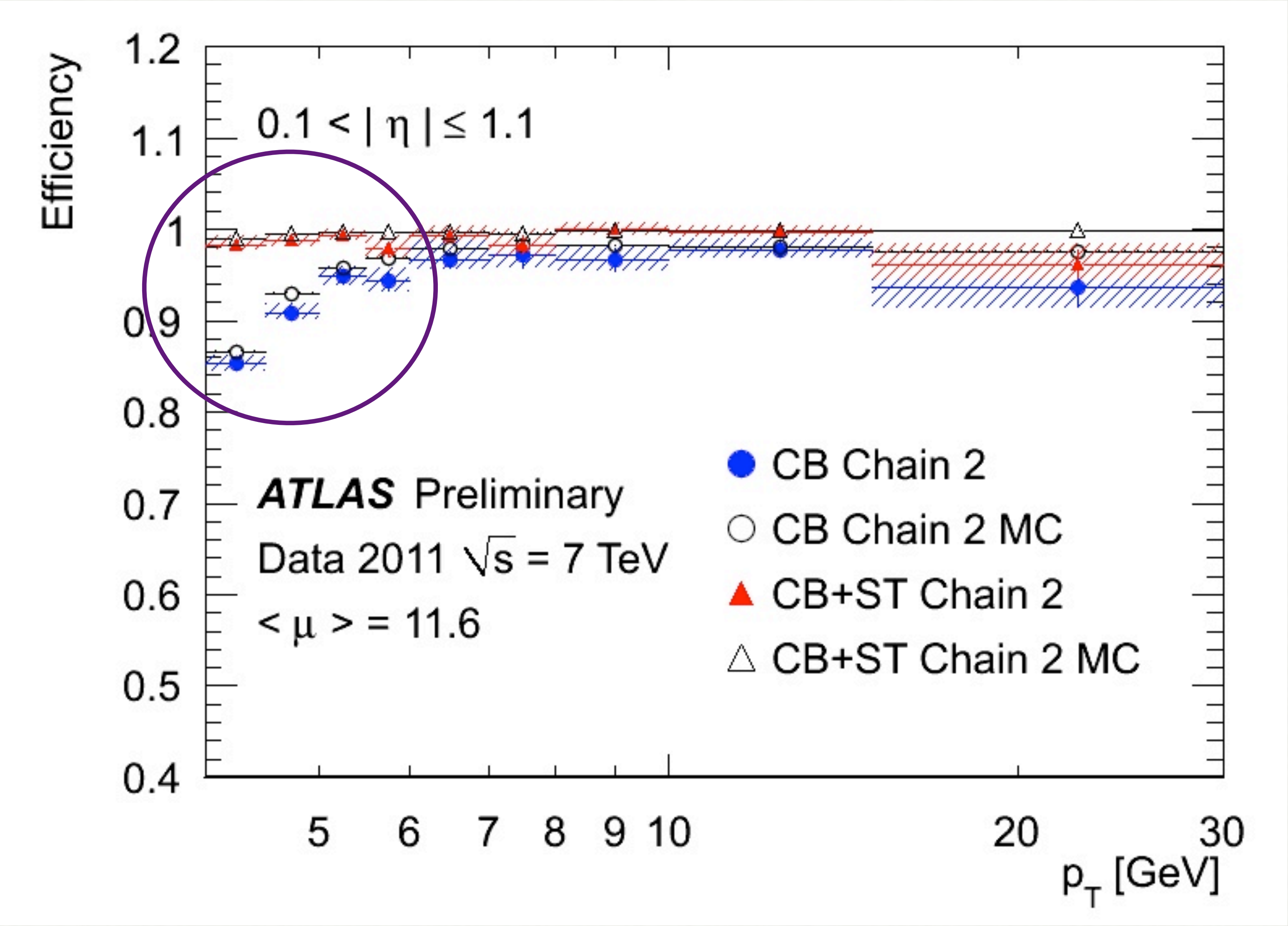
$W^{\pm} \rightarrow \mu^{\pm}\nu_{\mu}$

$J/\psi \rightarrow \mu^{+}\mu^{-}$

- Tracks in inner detector
- Minimum ionization in calorimeters
- Hits and tracks in muon detectors

- Low transverse momentum muons may not escape calorimeter

Muon efficiency

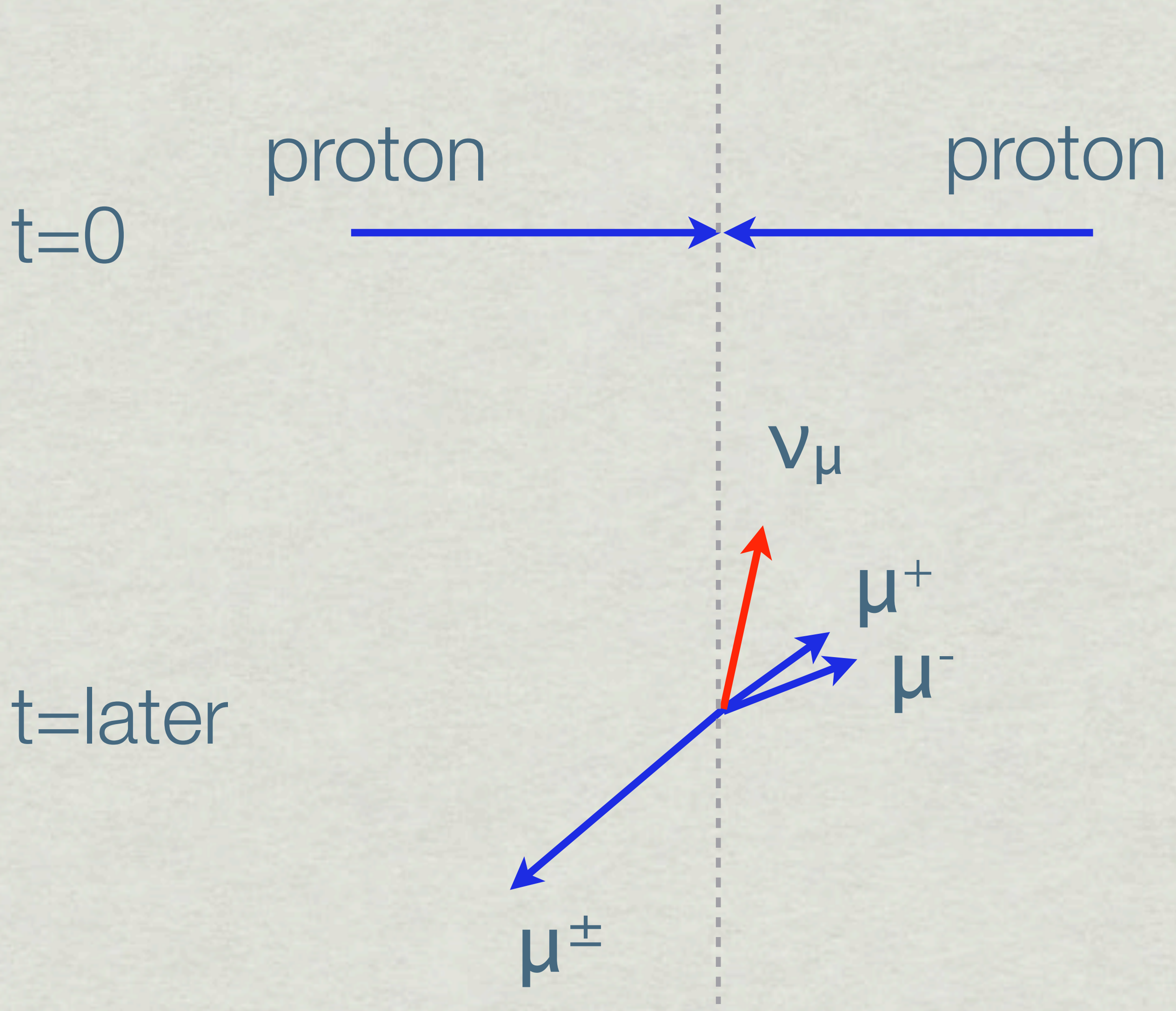


ATL-COM-MUON-2012-013

CB = combined
ST = segment-tagged

ST more efficient at low transverse momentum

Missing transverse energy

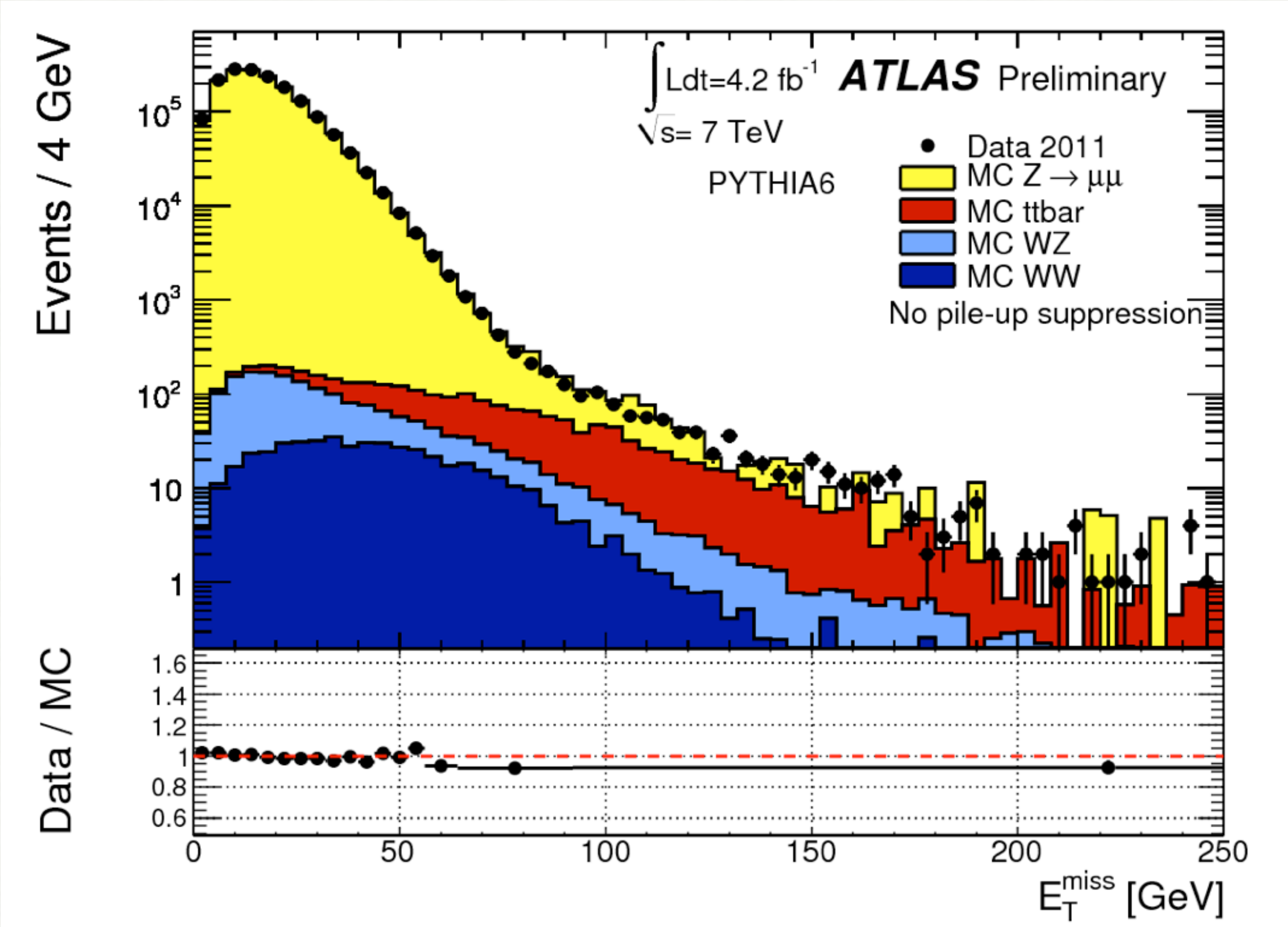


$W^\pm \rightarrow \mu^\pm \nu_\mu$

$J/\psi \rightarrow \mu^+ \mu^-$

- Neutrinos cannot be detected at ATLAS
- Principle of energy-momentum conservation
- Initial transverse momentum is 0

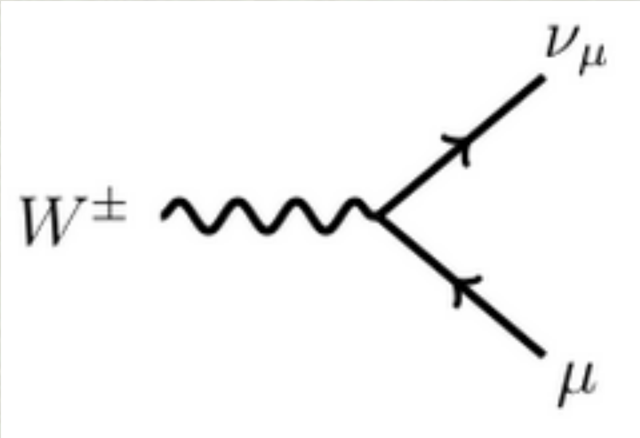
Missing transverse energy



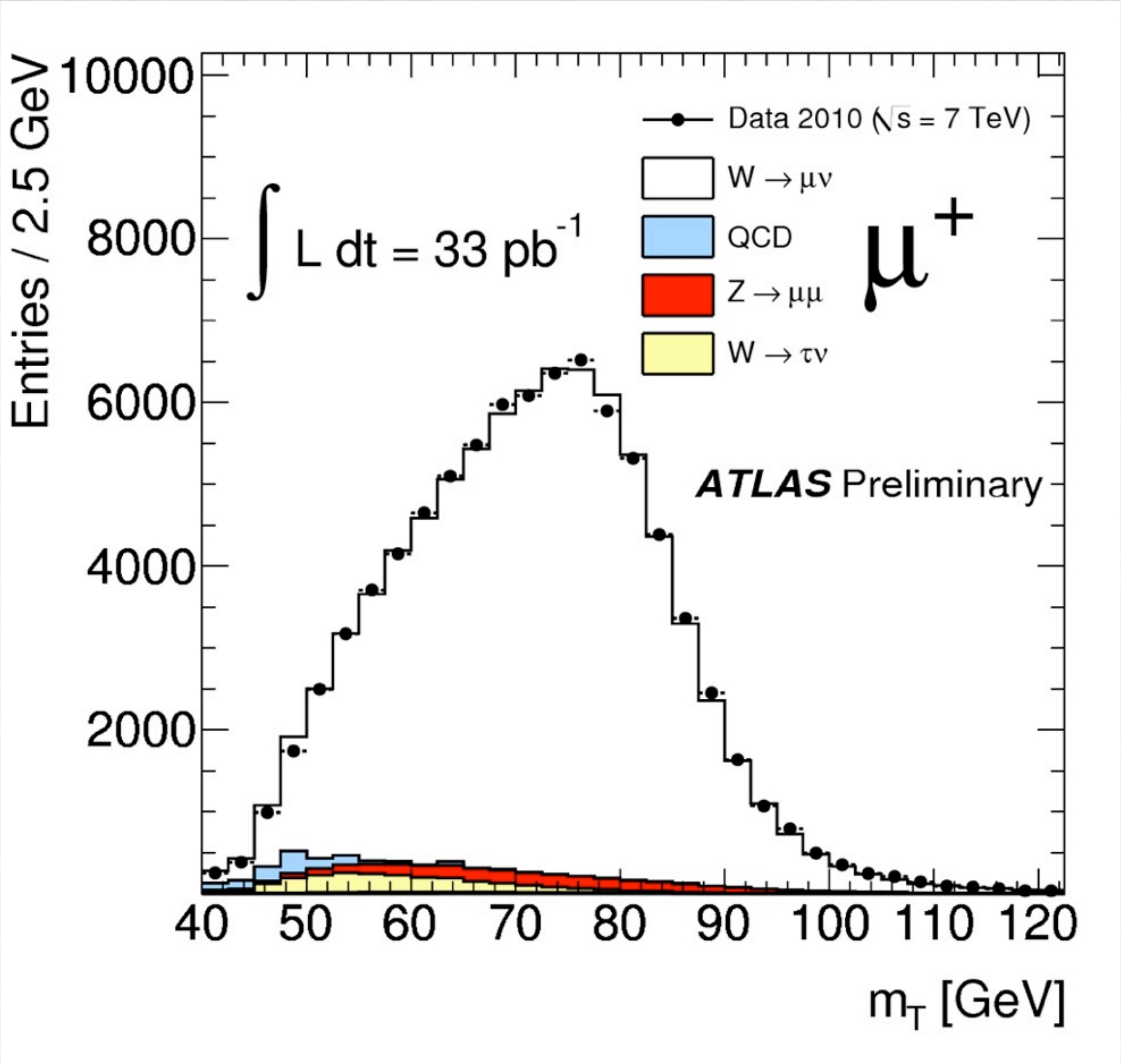
ATLAS-CONF-2012-101

Missing transverse energy well described by simulation

W observation



ATLAS-CONF-2010-044

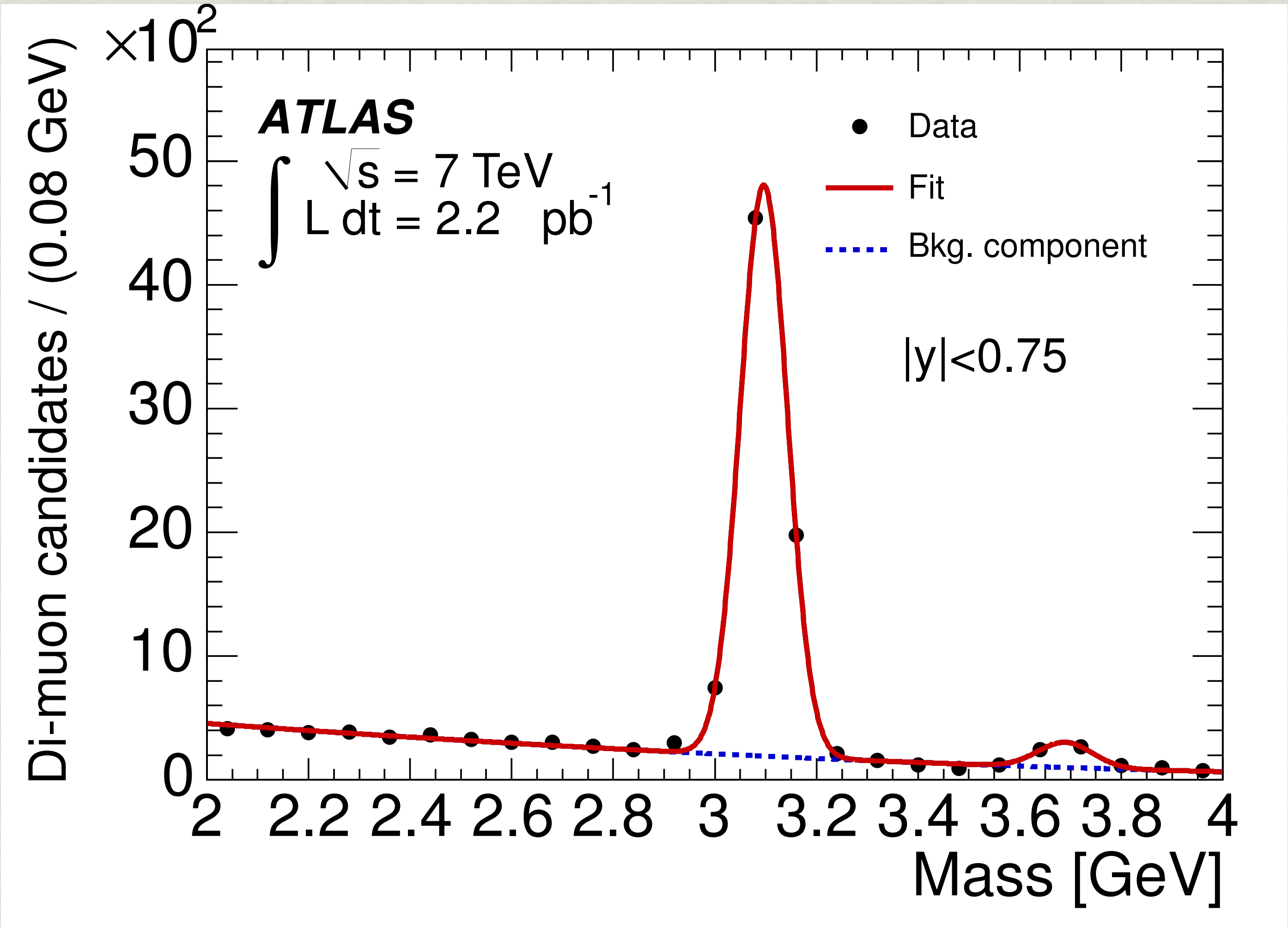


- W boson observed in ATLAS already with 33 pb^{-1} of data
- W transverse mass $M_T(W)$ combines **μ** and **ν** in the transverse plane

$$M_T(W) = \sqrt{2E^T_{\text{miss}} p_{\text{T}}(\ell)(1 - \cos\Delta\phi(\ell, E^T_{\text{miss}}))}$$

J/ψ observation

Nucl. Phys. B 850 (2011) 387-344

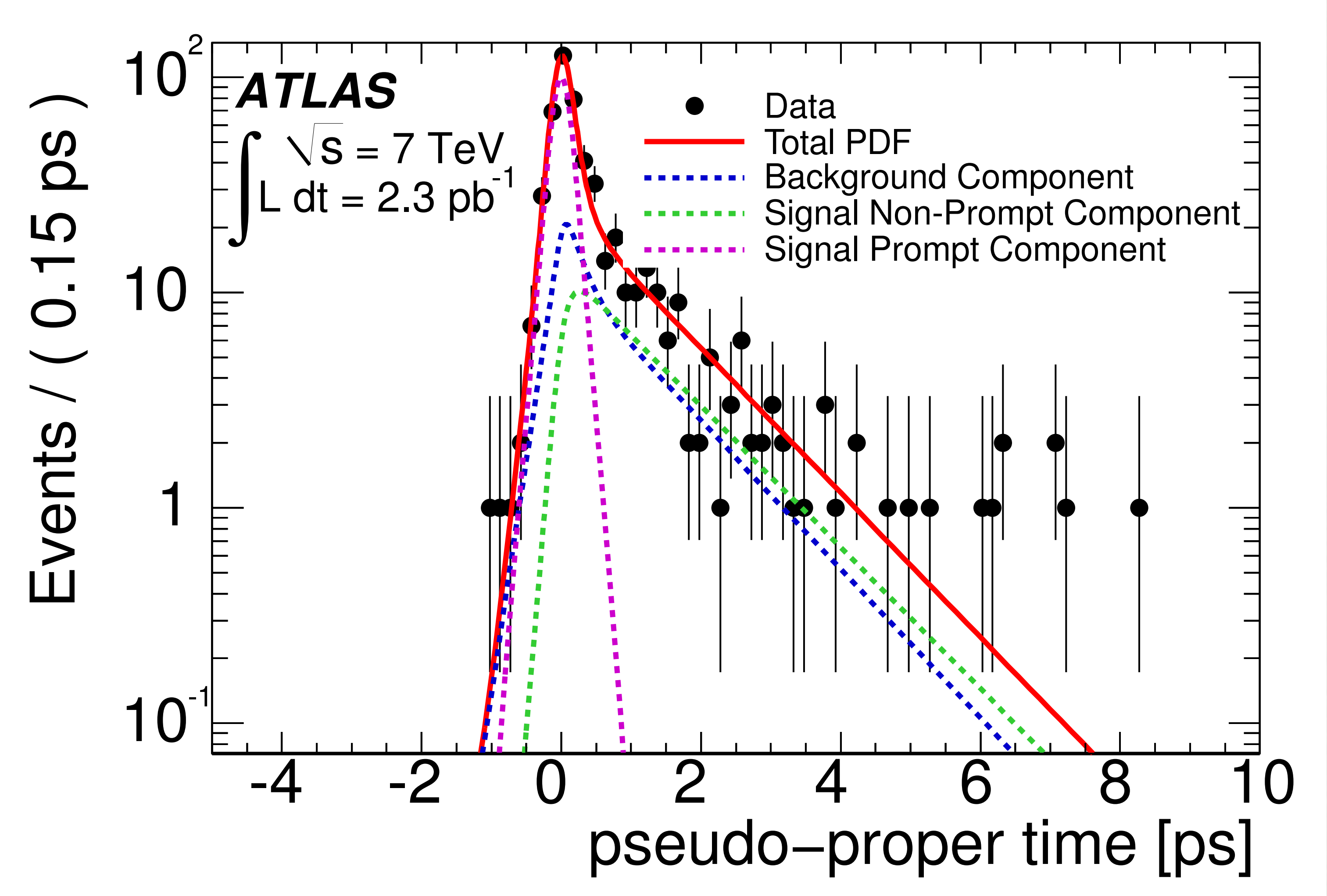


$$y = \frac{1}{2} \ln \frac{E + p_z c}{E - p_z c}$$

- J/ψ meson observed in ATLAS already with 2.2 pb^{-1} of data
- Invariant mass of two oppositely-charged muons peaks at 3.1 GeV for J/ψ
- ψ at 3.7 GeV
- Background combinatorics
- rapidity y is measure of angle at which particle is traveling

J/ψ pseudo-proper time

$$\tau = \frac{L_{xy} m^{\mathrm{PDG}}_{J/\psi}}{p_{\mathrm{T}}^{J/\psi}}$$



Nucl. Phys. B 850 (2011) 387-344

- Measure of distance travelled by J/ψ before its decay
- J/ψ pseudo-proper time to separate prompt from non-prompt J/ψ production (B-decays)

Prompt centered at 0 ps
Non-prompt exponential tail

Analysis strategy

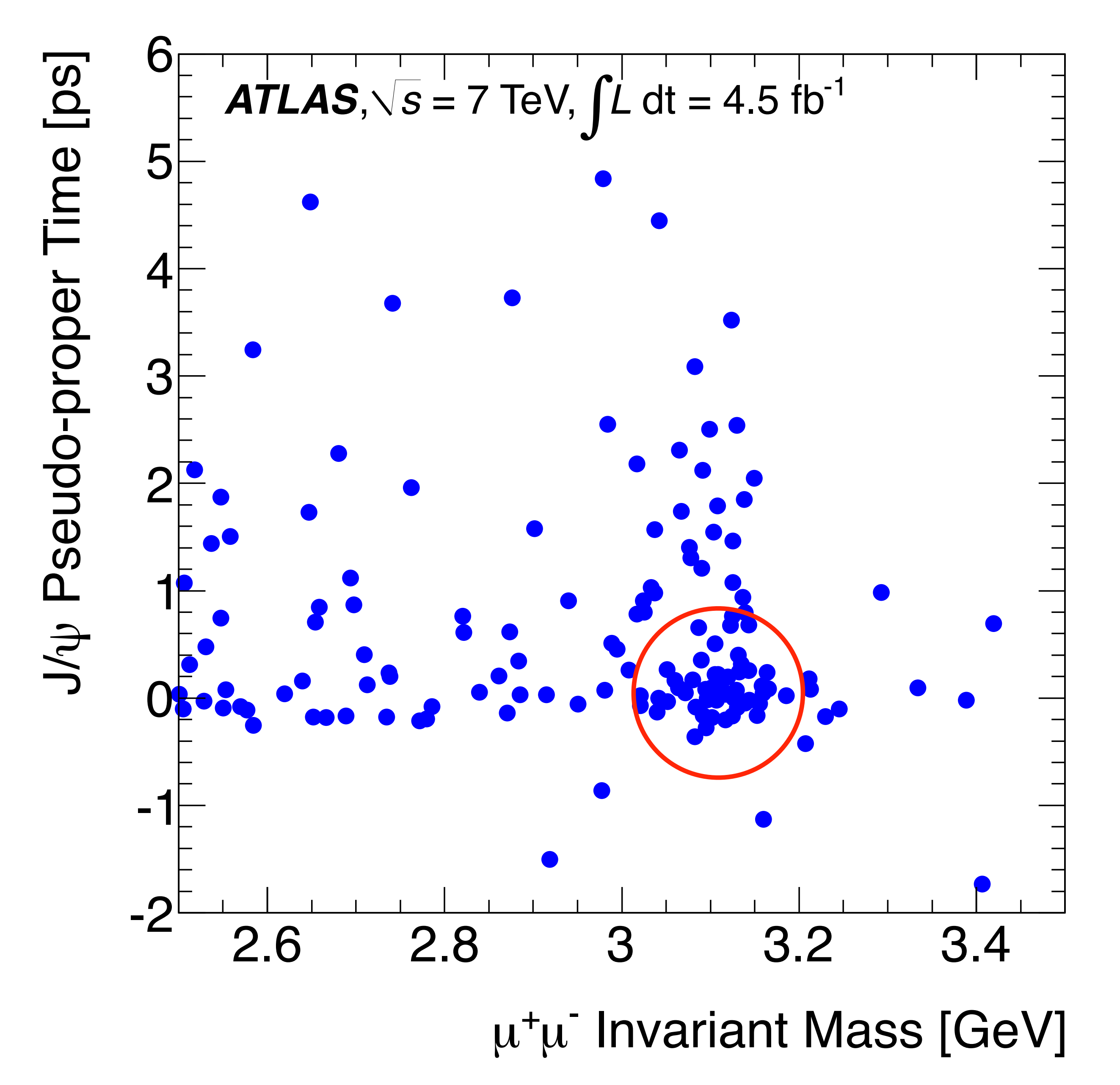
1. Select W+J/ψ candidates
- High pT μ and high E_T^{miss}
- Two oppositely charged muons

3. W+J/ψ observation
- Evaluate backgrounds
- Evaluate significance

2. Fit W+J/ψ spectra
- Simultaneously fit mass and pseudo-proper time distributions to get prompt J/ψ component

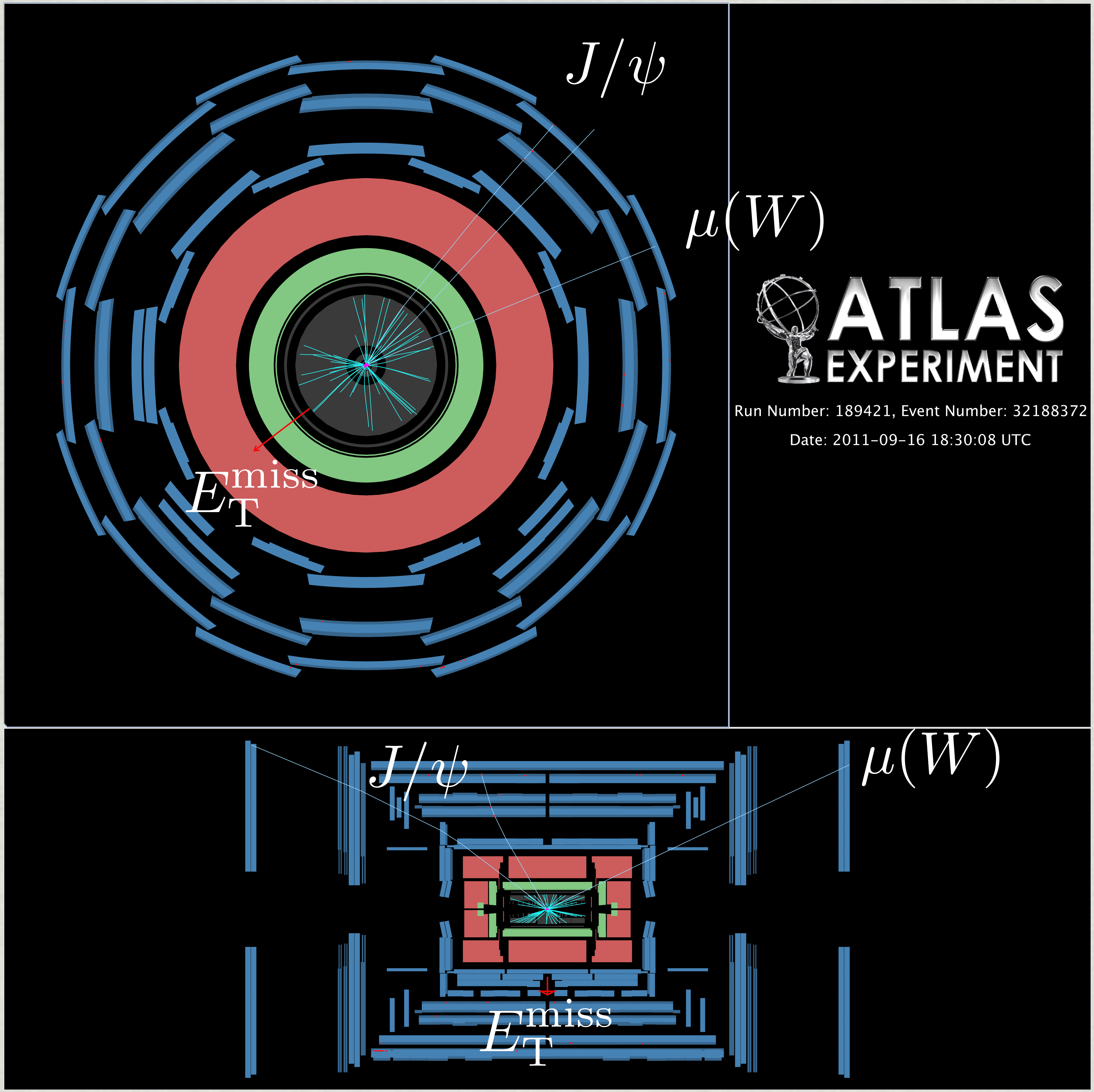
4. W+J/ψ:W ratio
- Subtract backgrounds
- Evaluate uncertainties
- Measure ratio

W+J/ψ pre-selection

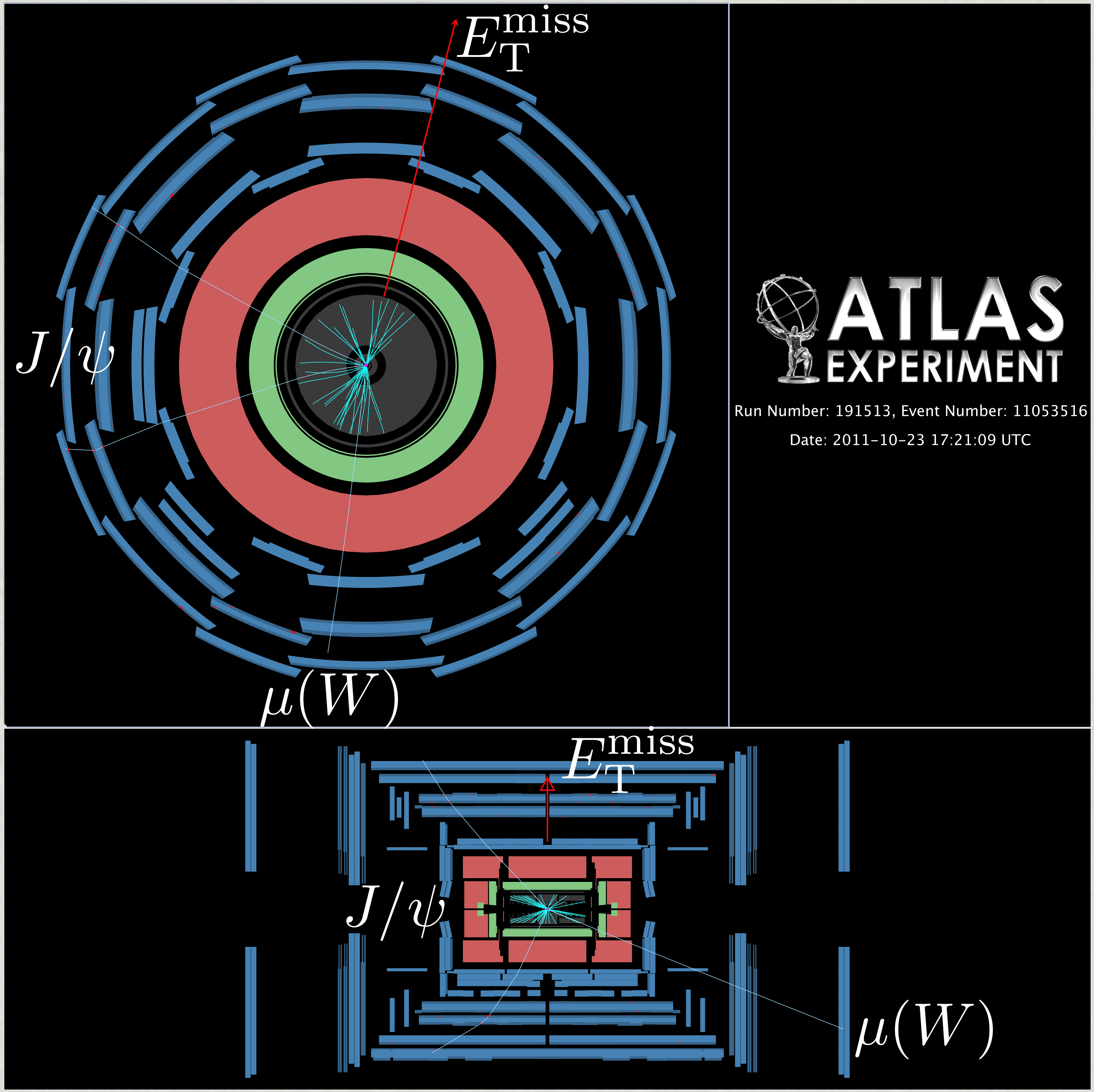


Requiring:

- Trigger (μ p_T>18 GeV)
- μ (from W) p_T > 25 GeV
- strict isolation for μ from W
- E_T^{miss} > 20 GeV
- $M_T(W)$ > 40 GeV
- Two oppositely-charged muons
- μ (from J/ψ) p_T > 2.5 GeV



J/ψ
$\mu(W)$
E_T^{miss}
ATLAS EXPERIMENT
Run Number: 189421, Event Number: 32188372
Date: 2011-09-16 18:30:08 UTC
J/ψ
$\mu(W)$
E_T^{miss}



$E_{\mathrm{T}}^{\mathrm{miss}}$
J/ψ
$\mu(W)$
ATLAS
EXPERIMENT
Run Number: 191513, Event Number: 11053516
Date: 2011-10-23 17:21:09 UTC
$E_{\mathrm{T}}^{\mathrm{miss}}$
J/ψ
$\mu(W)$

Background sources

$$t \to Wb$$

$$b \overset{\text{fragmentation}}{\to} B^{\pm/0}$$

$$B^+ \to J/\psi K^+$$

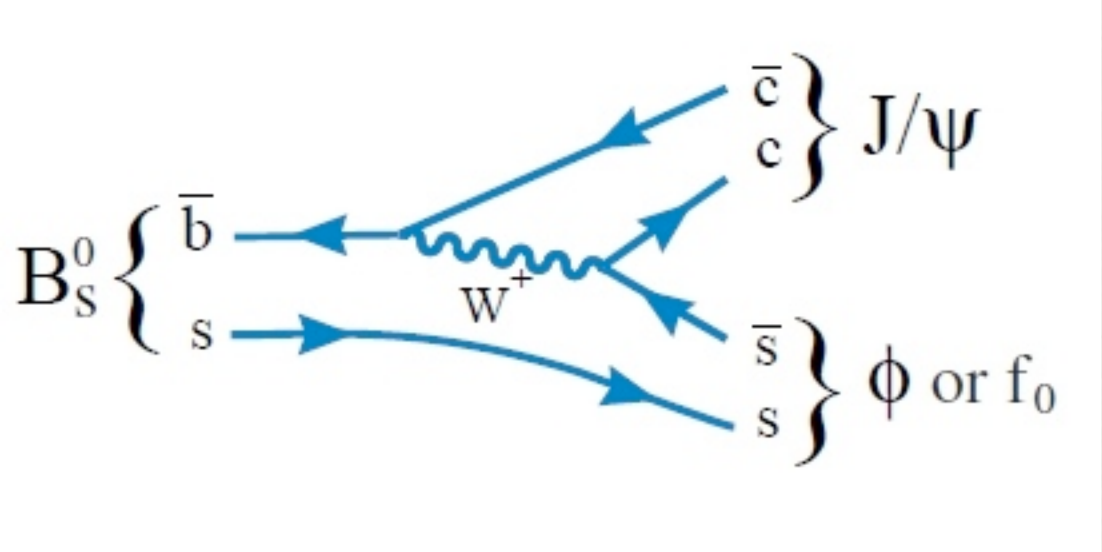
$$B^0 \to J/\psi K^0$$

$$B^+ \to J/\psi K^*(892)^+$$

$$B^0 \to J/\psi K^*(892)^0$$

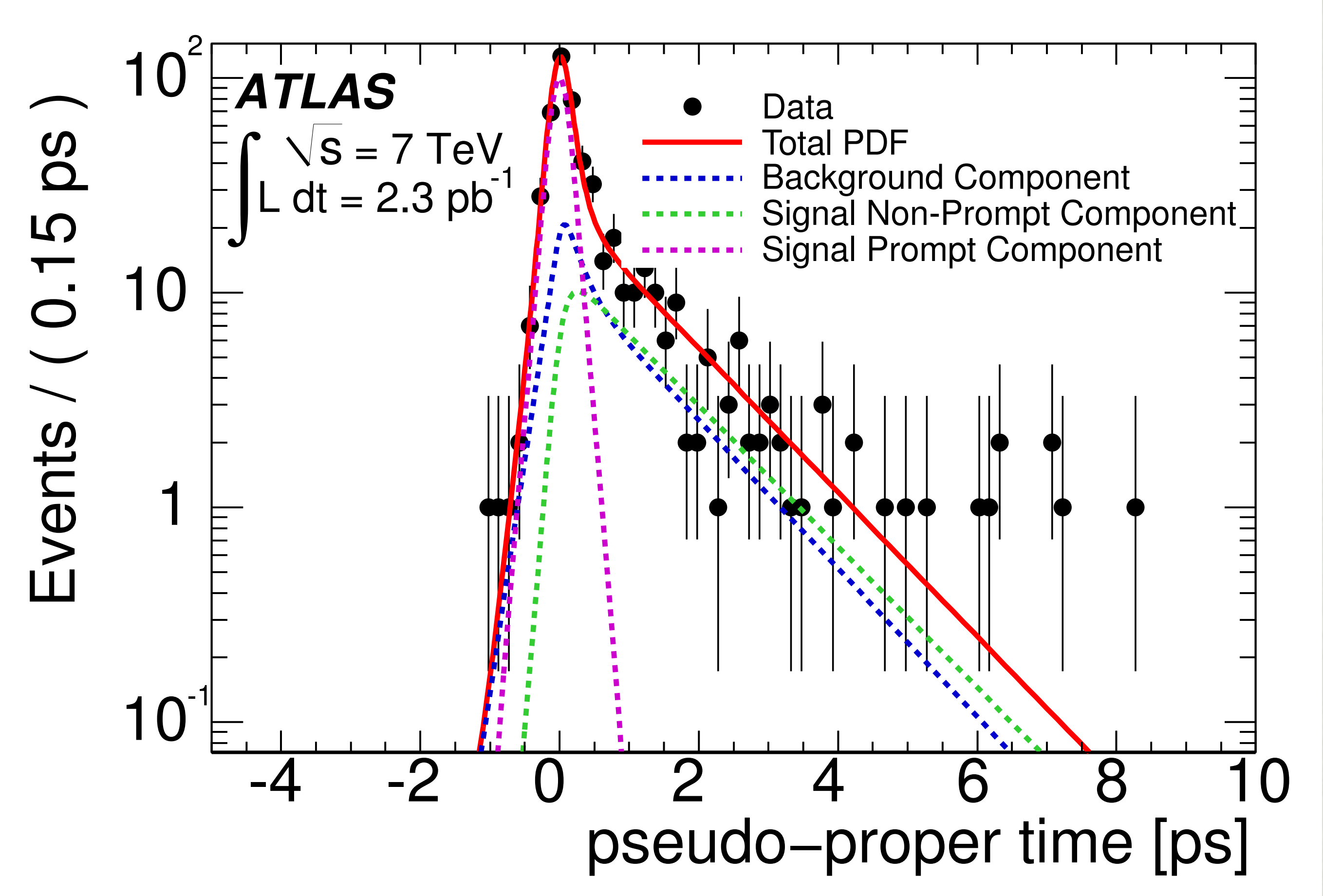
$$B_s^0 \to J/\psi \phi(1020)$$

Background	Rejection
top-antitop pair	non-prompt
W+bottom	non-prompt



- top decays predominantly to W+bottom
- bottom fragmentation can result to B meson
- B meson can decay to J/ψ

Background sources



Nucl. Phys. B 850 (2011) 387-344

Background	Rejection
top-antitop pair	non-prompt
W+bottom	non-prompt

- J/ψ from bottom or top decays tend to be non-prompt, since b is long-lived
- Would be incorporated in the exponential tail in the fit

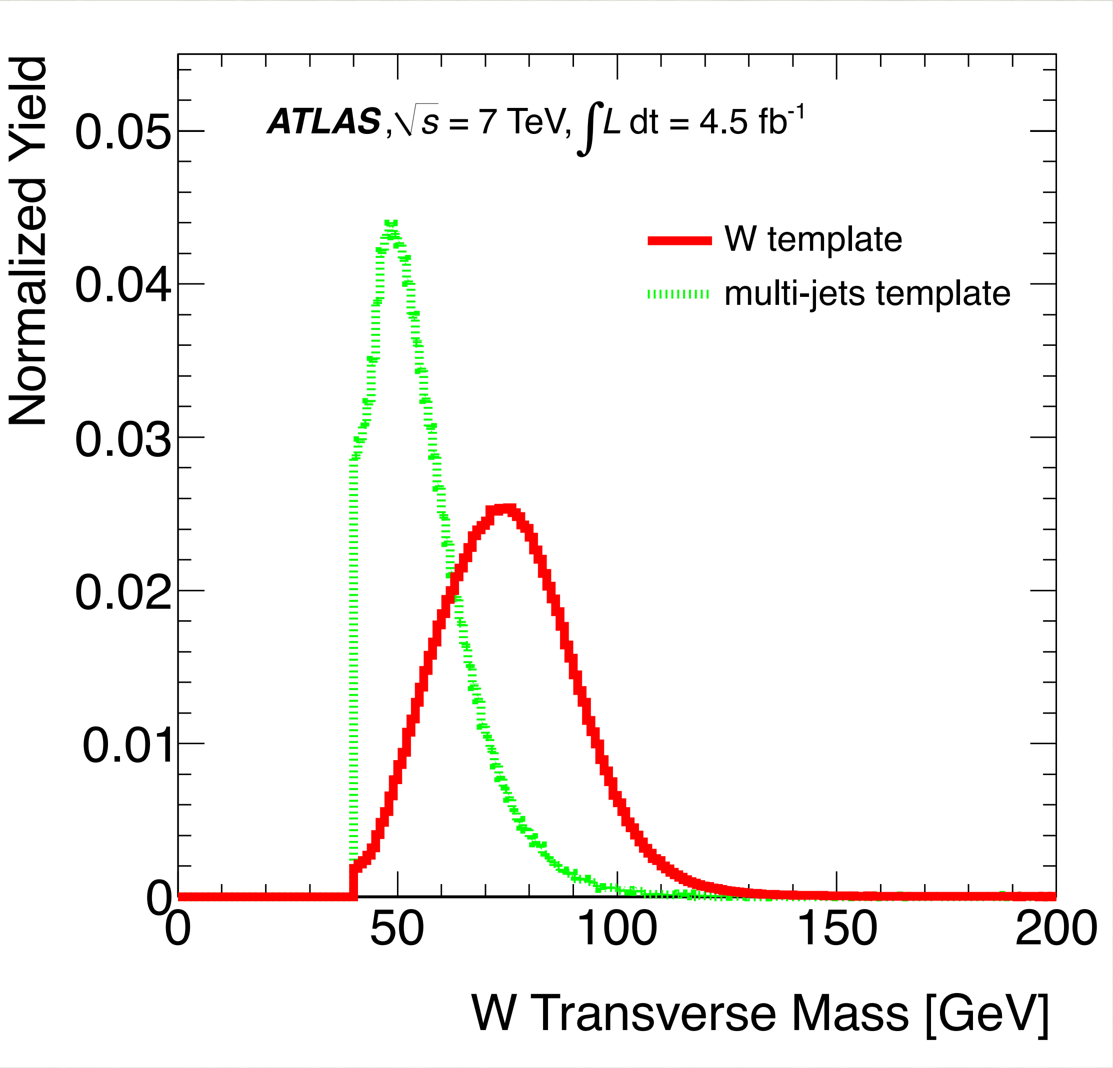
Background sources

A	C
A E_T^{miss}<20 and $M_T(W)$<40 isolated muon	**C** **E_T^{miss}>20 and** **$M_T(W)$>40** **isolated muon**
B E_T^{miss}<20 and $M_T(W)$<40 anti-isolated muon	**D** E_T^{miss}>20 and $M_T(W)$>40 anti-isolated muon

Background	Rejection
top-antitop pair	non-prompt
W+bottom	non-prompt
multi-jet	**fit $M_T(W)$ distribution**

- multi-jets can mimic W
- "ABCD" method, based on isolation cut
- C is signal region, B is multi-jet enriched region
- kinematically-independent multi-jet fake-factor (AxD)/B to derive templates

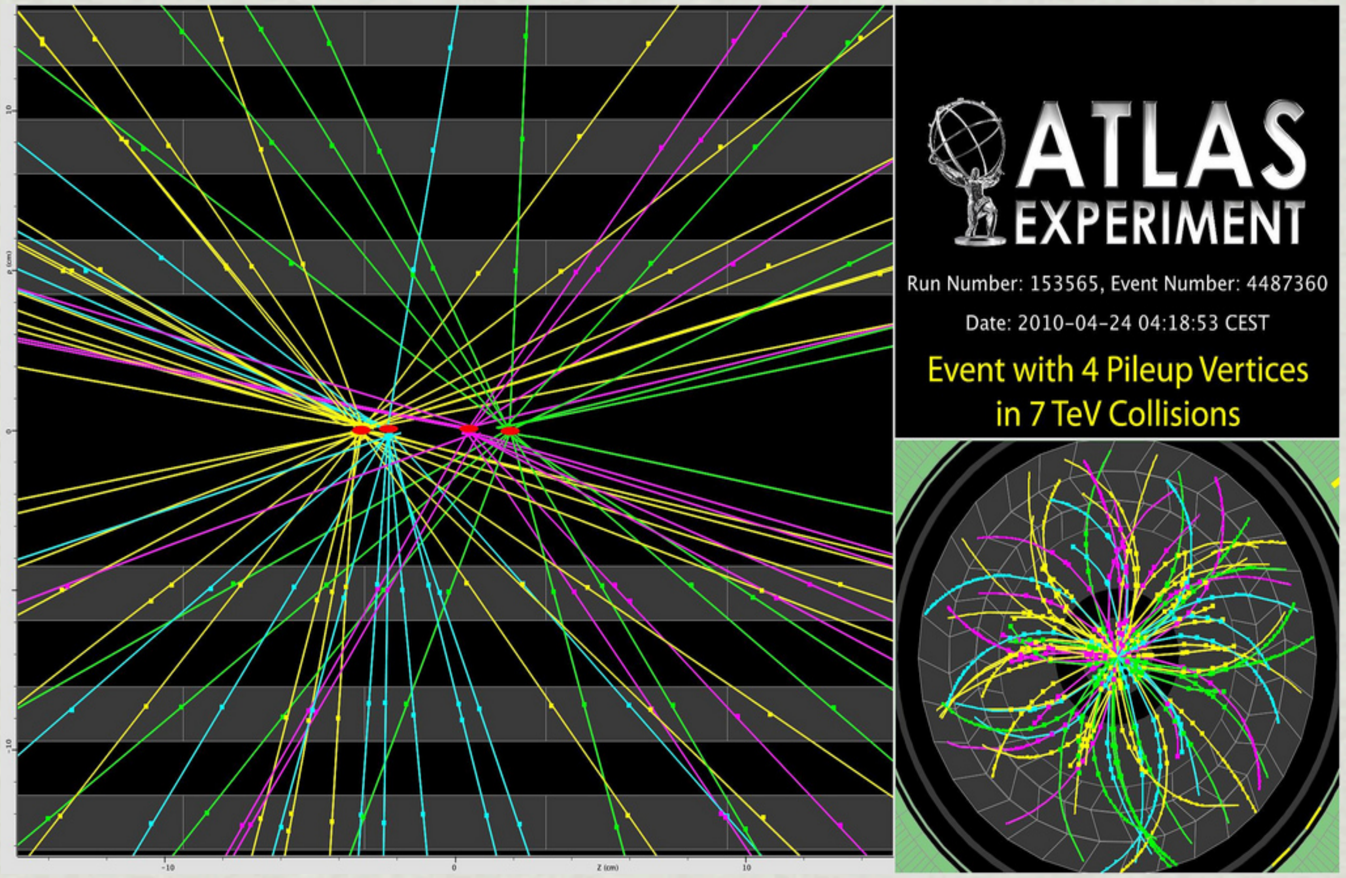
Background sources



Background	Rejection
top-antitop pair	non-prompt
W+bottom	non-prompt
multi-jet	**fit $M_T(W)$ distribution**

- Data-driven templates for multi-jets and W shapes in W transverse mass $M_T(W)$
- Fit data to determine multi-jet yield

Background sources



Background	Rejection
top-antitop pair	non-prompt
W+bottom	non-prompt
multi-jet	fit $M_T(W)$ distribution
pileup	**independent estimate**

Extra interactions from other proton-proton collisions during the same event are called “pileup”

Background sources

$$P_{J/\psi} = \frac{\sigma^{\text{bin}}_{J/\psi}}{\sigma_{\text{inel}}} = \frac{1}{\sigma_{\text{inel}}} \int_{\text{bin}} \frac{\mathrm{d}^2\sigma(pp \to J/\psi\ X)}{\mathrm{d}y\ \mathrm{d}p_{\mathrm{T}}} \mathrm{d}y\ \mathrm{d}p_{\mathrm{T}}$$

$$N_{\text{extra}} = 0.81 \pm 0.08$$

$$N_{\text{pileup}} = N_{\text{extra}} P_{J/\psi} \mathcal{L} \sigma_{W^{\pm}}$$

Background	**Rejection**
top-antitop pair	non-prompt
W+bottom	non-prompt
multi-jet	fit $M_T(W)$ distribution
pileup	**independent estimate**

- Multiply rate of W production with probability for additional J/ψ
- Estimate using σ_{inel}=71.5 mb, measured J/ψ cross-section and mean number of extra vertices in data
- Estimated yield 1.8 ± 0.2 events, subtract from result

Background sources

- Same experimental signature as W+J/ψ: $B_c^{\pm} \rightarrow J/\psi\ \mu^{\pm}\ \nu_{\mu}\ X$
- Inspect sPlot of invariant mass of three muons
- No events found with mass less than 6.3 GeV (B_c mass)

Background	Rejection
top-antitop pair	non-prompt
W+bottom	non-prompt
multi-jet	fit $M_T(W)$ distribution
pileup	independent estimate
B_c	**invariant mass**
Z+jets	**rejected by cut**

- Combining μ from W and oppositely-charged μ from J/ψ
- Reject events with invariant mass within 10 GeV of Z mass
- No Z+jets events remain

Fit procedure

Gaussian

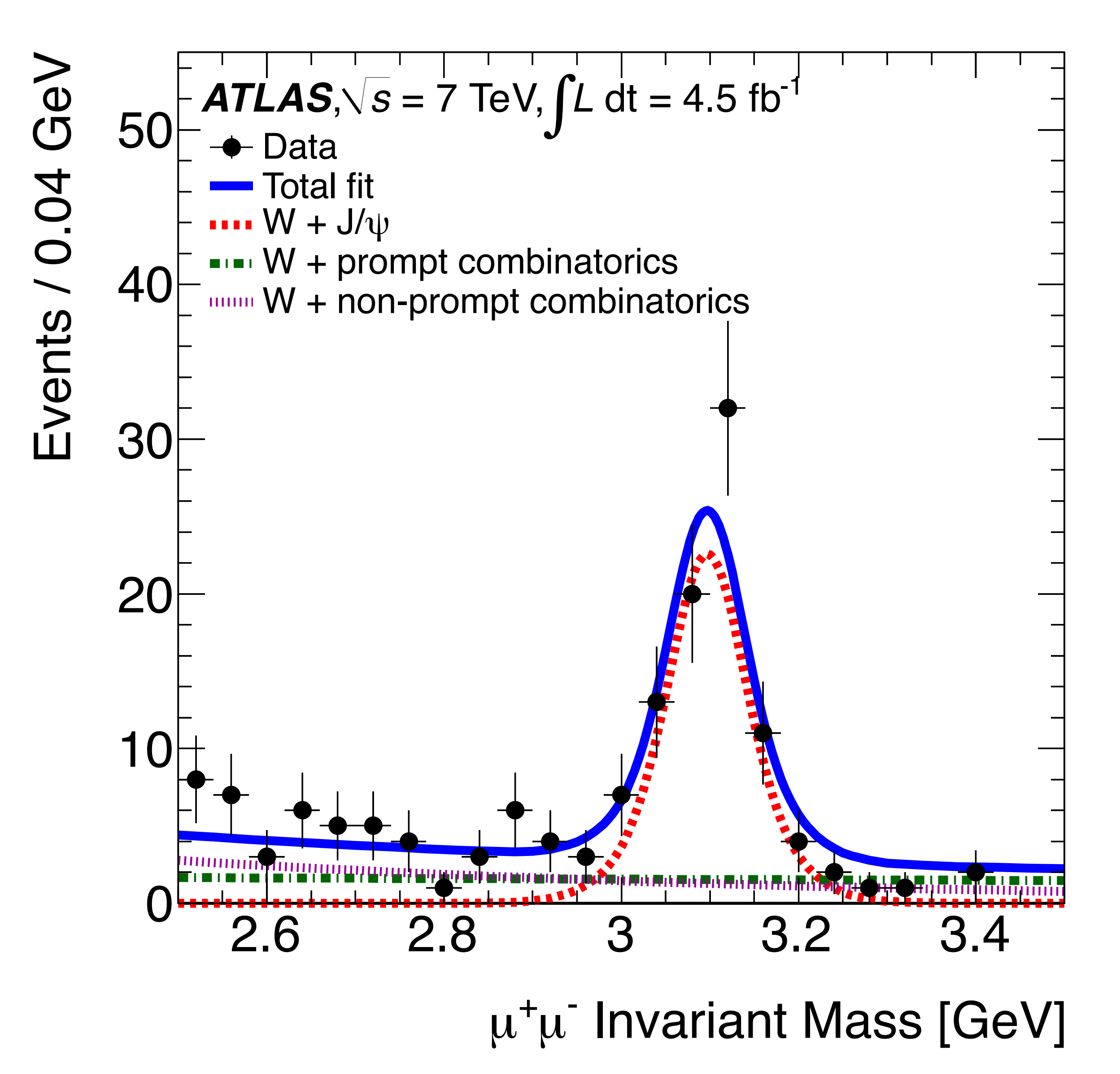
Gaussian+2-sided exponential

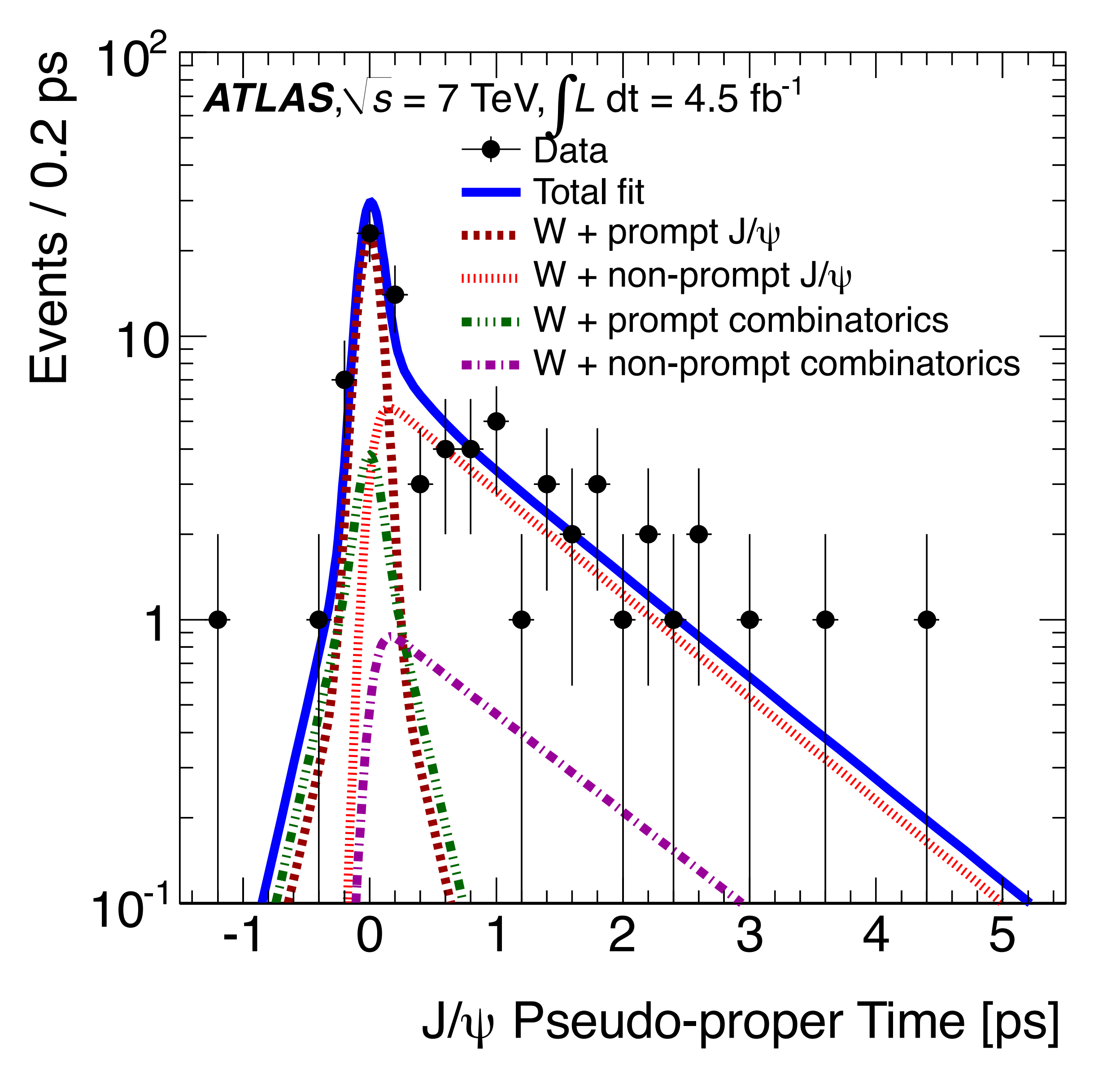
exponential

$$
\begin{aligned}
M_{J/\psi}(m_{\mu^+\mu^-}) &= G(m_{\mu^+\mu^-}; m_{J/\psi}^{\mathrm{PDG}}, \sigma_m) \\
T_{\text{prompt } J/\psi}(\tau) &= G(\tau; 0, \sigma_\tau) \otimes \left((1-a)\delta(\tau) + aC_0 \mathrm{e}^{-|\tau|/\tau_0}\right) \\
T_{\text{non-prompt } J/\psi}(\tau) &= G(\tau; 0, \sigma_\tau) \otimes \left(C_1 \theta(\tau) \mathrm{e}^{-\tau/\tau_1}\right) \\
M_{\text{prompt bkg}}(m_{\mu^+\mu^-}) &= C_2 \mathrm{e}^{-m_{\mu^+\mu^-}/k_0} \\
M_{\text{non-prompt bkg}}(m_{\mu^+\mu^-}) &= C_3 \mathrm{e}^{-m_{\mu^+\mu^-}/k_1} \\
T_{\text{prompt bkg}}(\tau) &= G(\tau; 0, \sigma_\tau) \otimes \left((1-b)\delta(\tau) + bC_4 \mathrm{e}^{-|\tau|/\tau_0}\right) \\
T_{\text{non-prompt bkg}}(\tau) &= G(\tau; 0, \sigma_\tau) \otimes \left(C_5 \theta(\tau) \mathrm{e}^{-\tau/\tau_2}\right).
\end{aligned}
$$

- Simultaneously fit dimuon mass and pseudoproper time
- Extract prompt J/ψ, non-prompt J/ψ, prompt combinatorics and non-prompt combinatorics yields
- Nuisance parameters from inclusive J/ψ fit due to better statistics

W+J/ψ fit Whole region 0<|y|<2.1

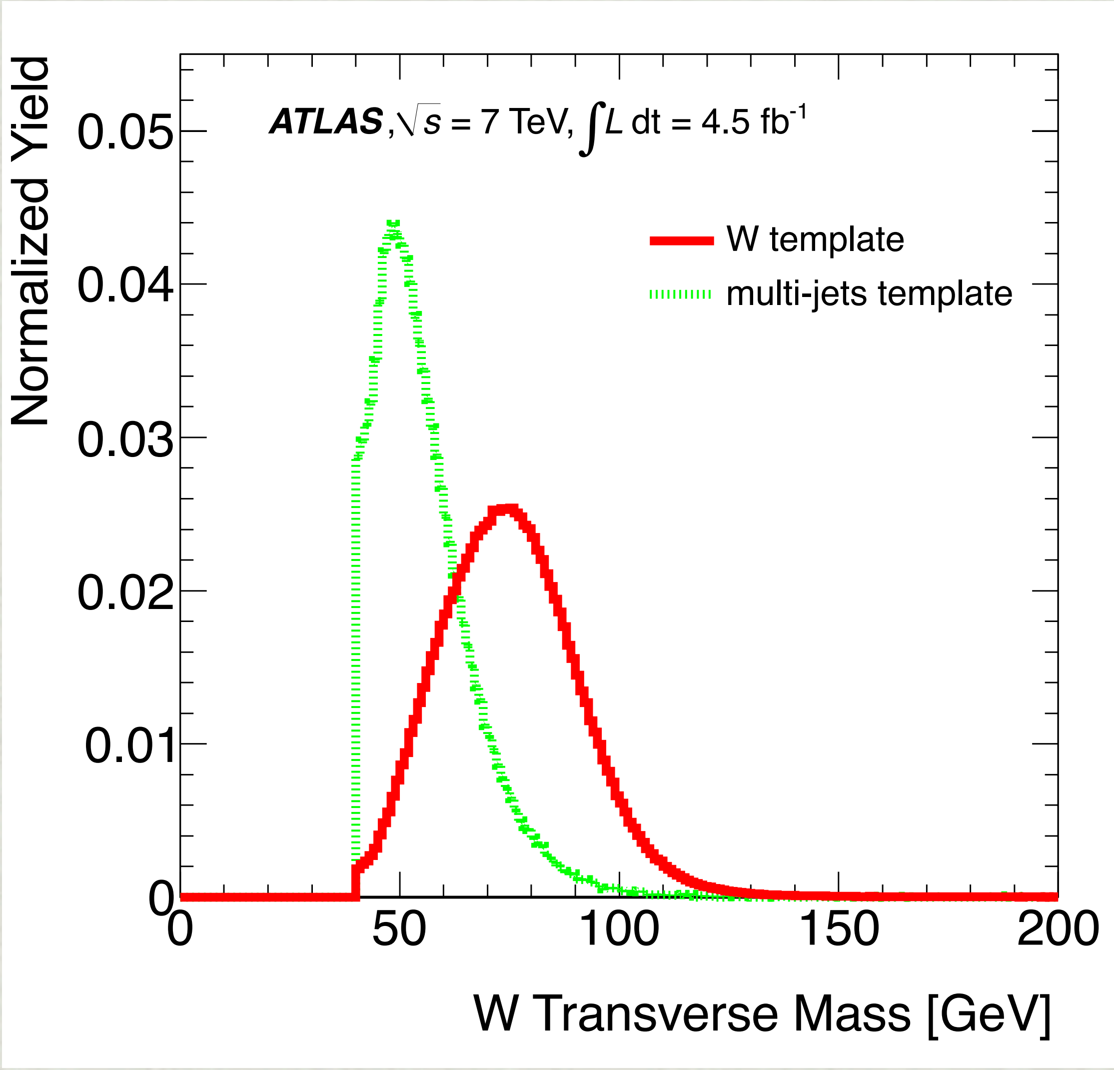


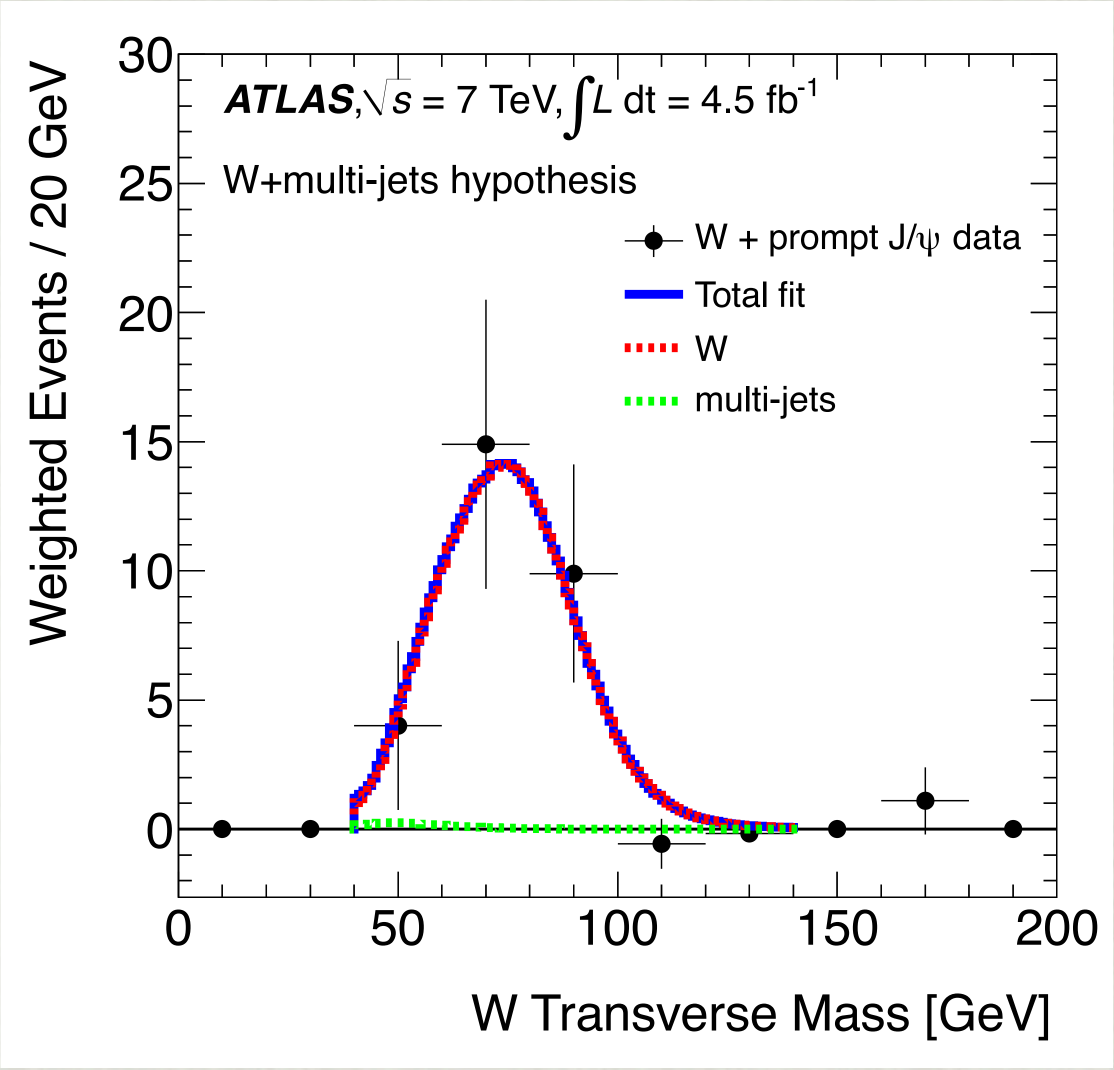


J/ψ: gaussian
Combinatorics: exponential

prompt: gaussian + 2-sided exponential
non-prompt: 1-sided exponential

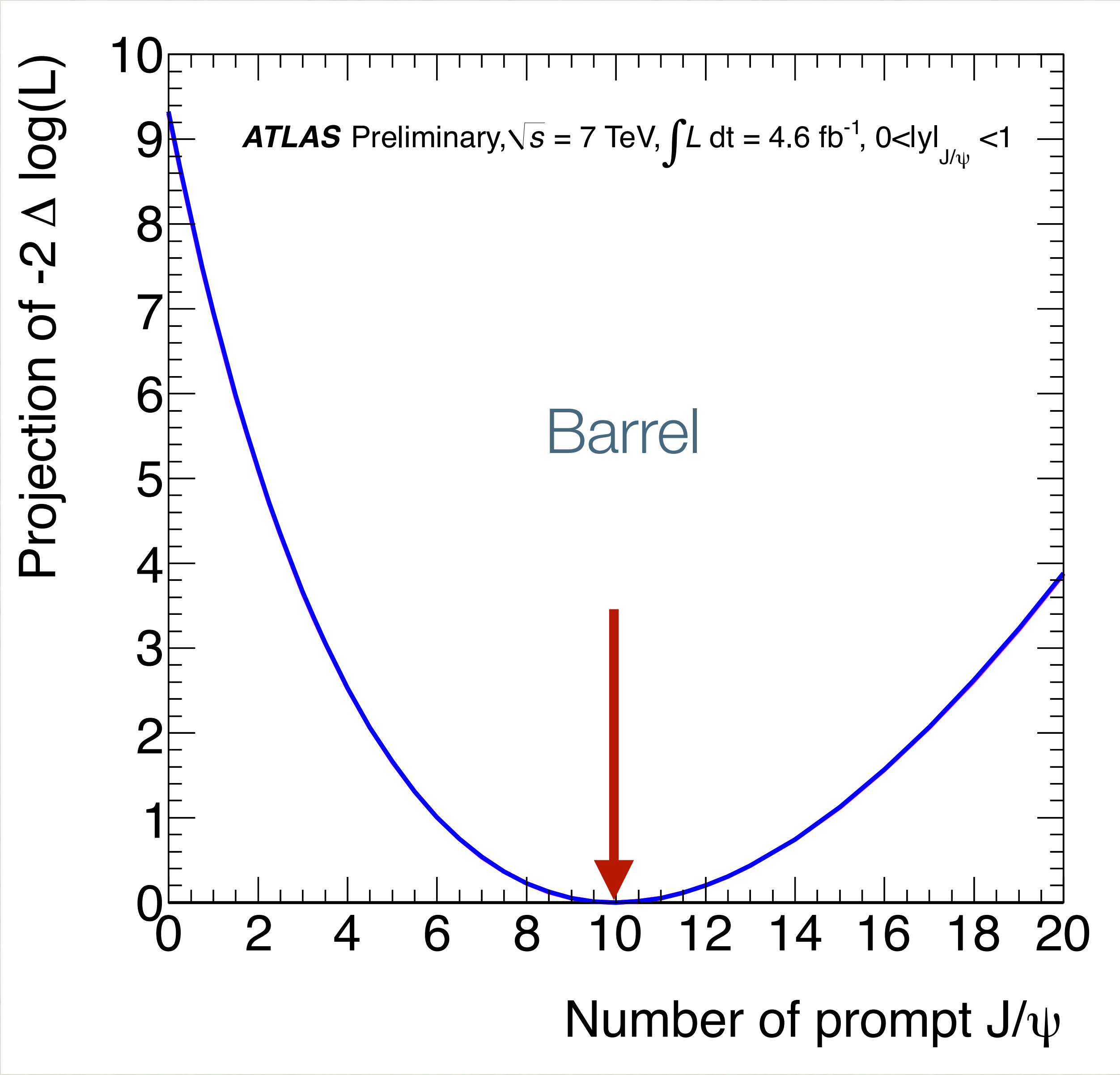
Confirming the W

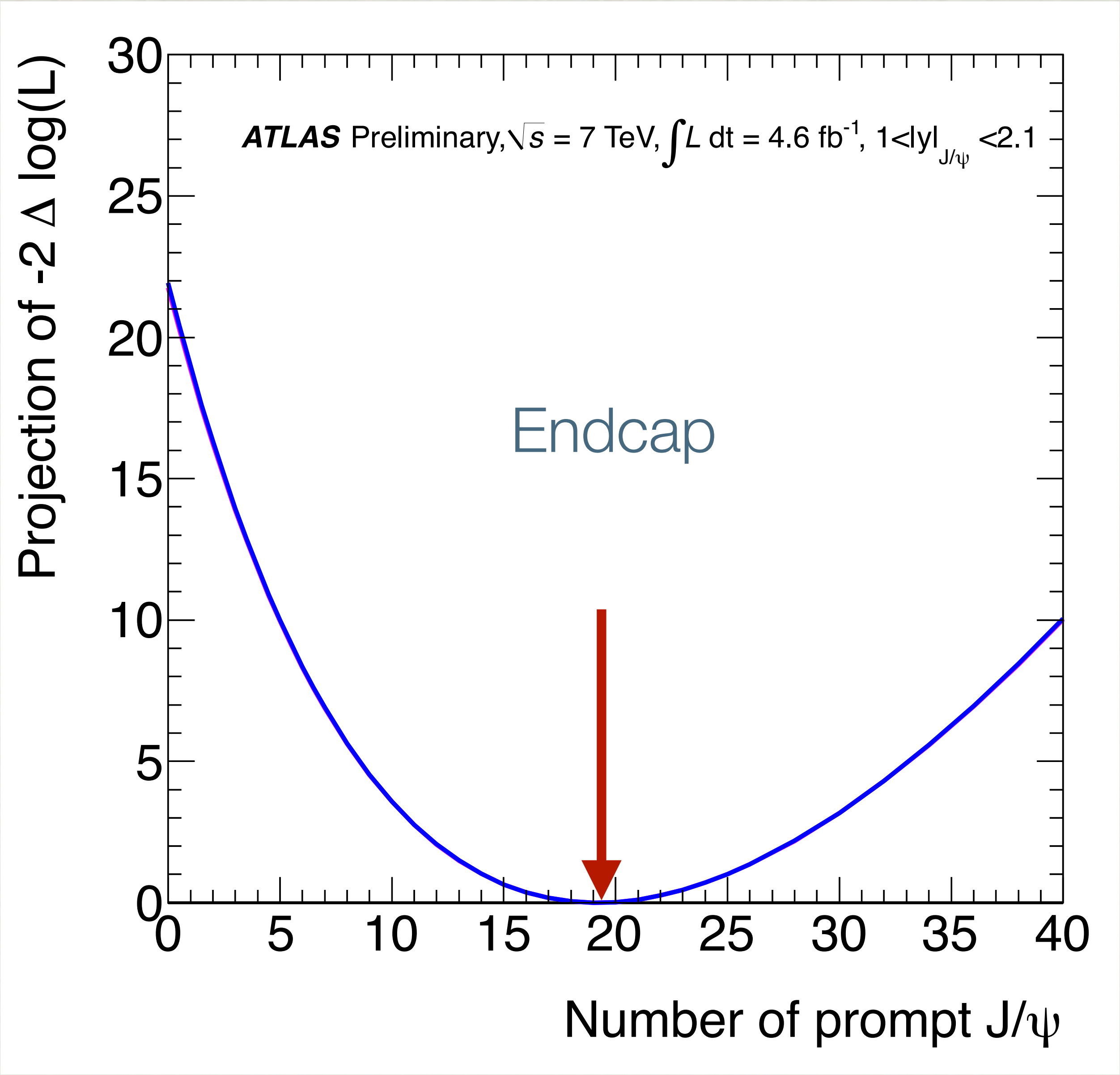




- χ^2 fit with W and multi-jet templates on weighted data
- multi-jet yield < 0.3 events at 95% credibility

Likelihood profile





- Maximum likelihood method to determine yields
- Different regions in rapidity to take advantage of resolution

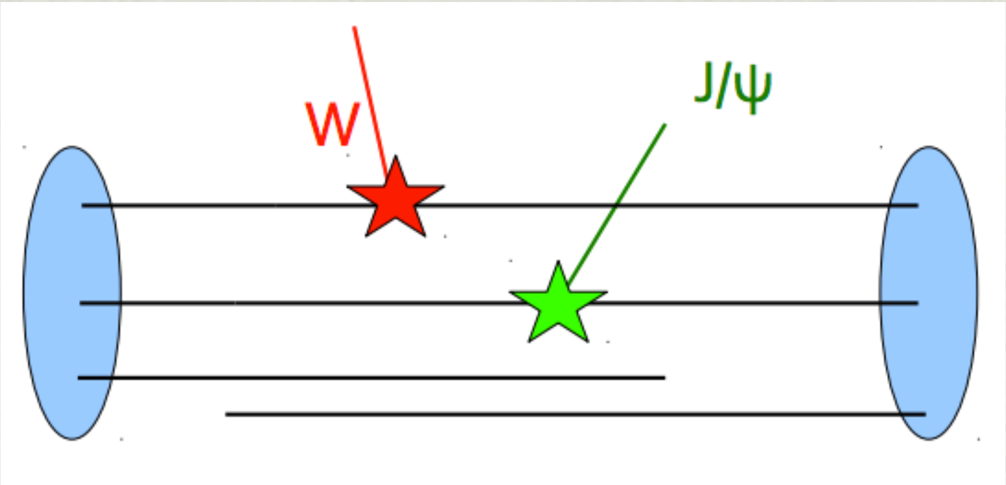
Yields

Yields from two-dimensional fit			
Process	Barrel	Endcap	Total
Prompt J/ψ	$10.0^{+4.7}_{-4.0}$	$19.2^{+5.8}_{-5.1}$	$29.2^{+7.5}_{-6.5}(*)$
Non-prompt J/ψ	$27.9^{+6.5}_{-5.8}$	$13.9^{+5.3}_{-4.5}$	$41.8^{+8.4}_{-7.3}$
Prompt background	$20.4^{+5.9}_{-5.1}$	$18.8^{+6.3}_{-5.3}$	$39.2^{+8.6}_{-7.3}$
Non-prompt background	$19.8^{+5.8}_{-4.9}$	$19.2^{+6.1}_{-5.1}$	$39.0^{+8.4}_{-7.1}$
p-value	8.0×10^{-3}	1.4×10^{-6}	2.1×10^{-7}
Significance (σ)	2.4	4.7	5.1

(*) of which 1.8 ± 0.2 originate from pileup

p-value evaluated with pseudo-experiments with B-only hypothesis to determine how often it fluctuates to S+B hypothesis

Double Parton Scattering

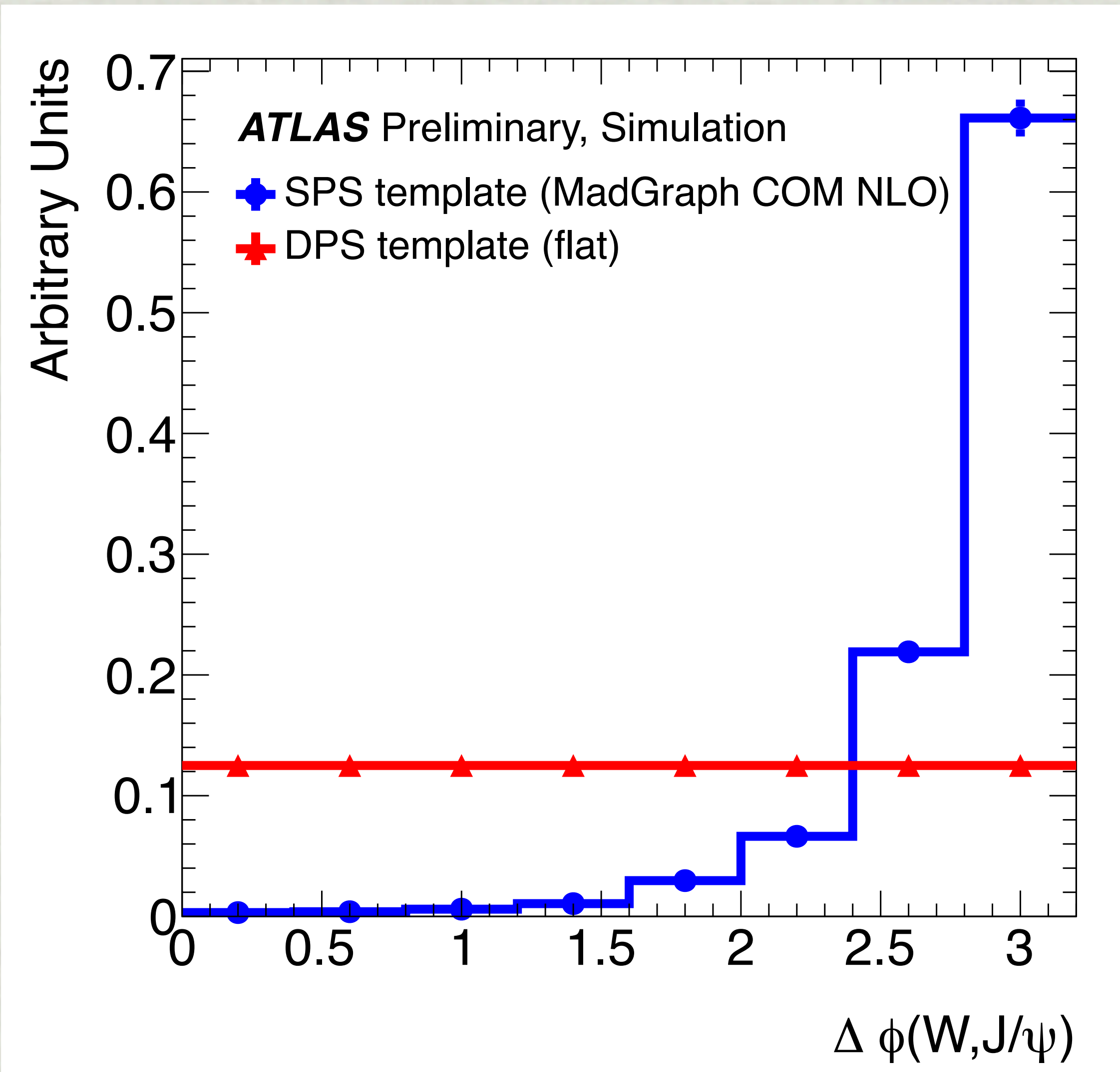


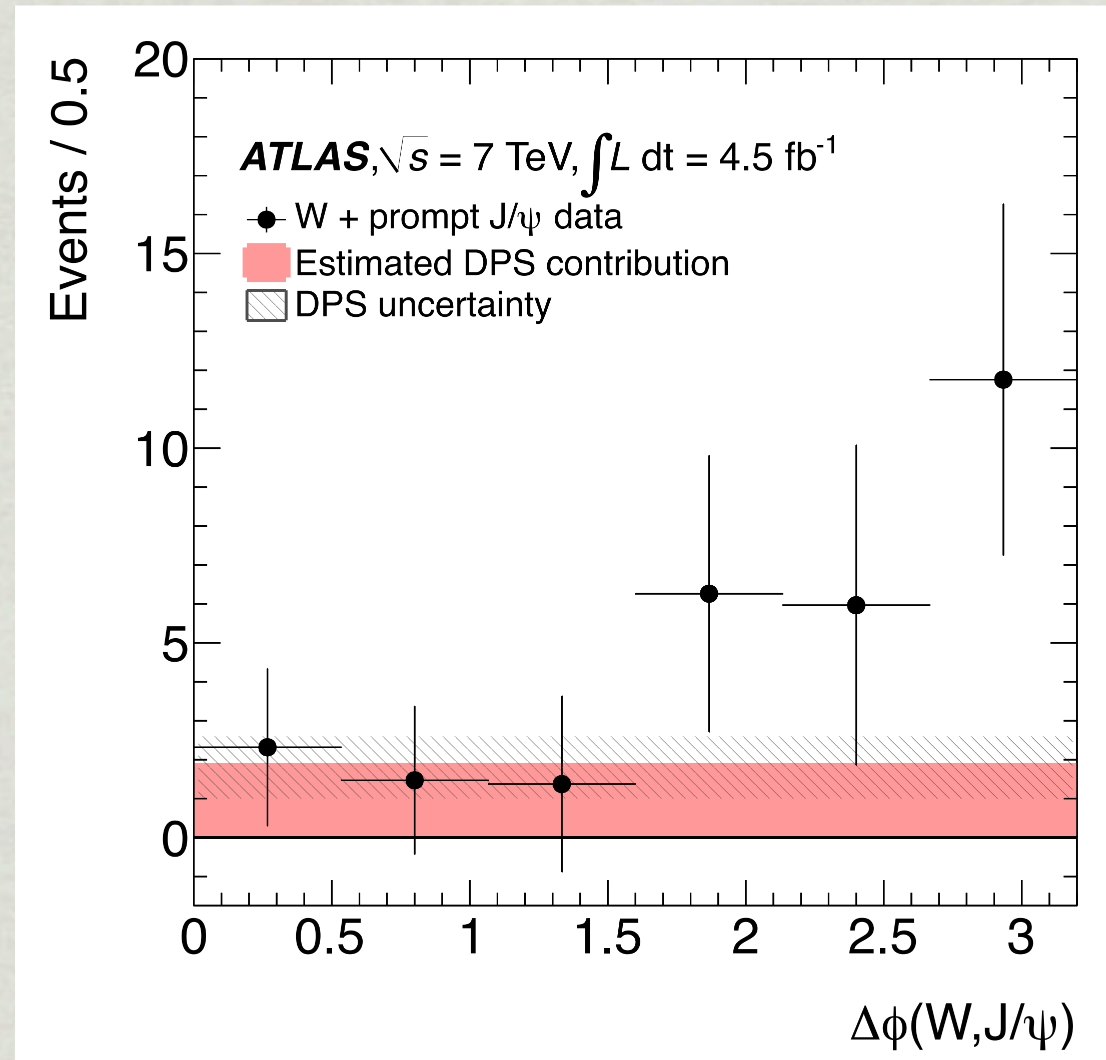
$$P_{J/\psi\,|\,W^\pm} = \sigma_{J/\psi}/\sigma_{\text{eff}}.$$

$$N^{\text{DPS}}_{W+J/\psi} = P_{J/\psi|W^\pm} \times \sigma_W$$

- Multiply rate of W production with probability for additional J/ψ
- Estimate using σ_{eff}=15 mb and measured J/ψ cross-section
- Estimated yield 10.8 +/- 4.2 events

Double Parton Scattering





- Azimuthal **Δφ**(W,J/**ψ**) expected to be flat for Double Parton Scattering (DPS), peak at π for Single Parton Scattering (SPS)
- Both contributions present in sample

Cross-section ratio W+J/ψ:W

cross-section

efficiency (J/ψ)

acceptance (J/ψ)

number of W +prompt J/ψ

$$\frac{\sigma(pp \rightarrow W + \text{prompt } J/\psi)}{\sigma(pp \rightarrow W)} = \frac{\frac{N^{W+J/\psi}}{\epsilon^{J/\psi} \cdot \alpha^{J/\psi} \cdot \epsilon^{W} \cdot \mathcal{L}}}{\frac{N^{W}}{\epsilon^{W} \cdot \mathcal{L}}}$$

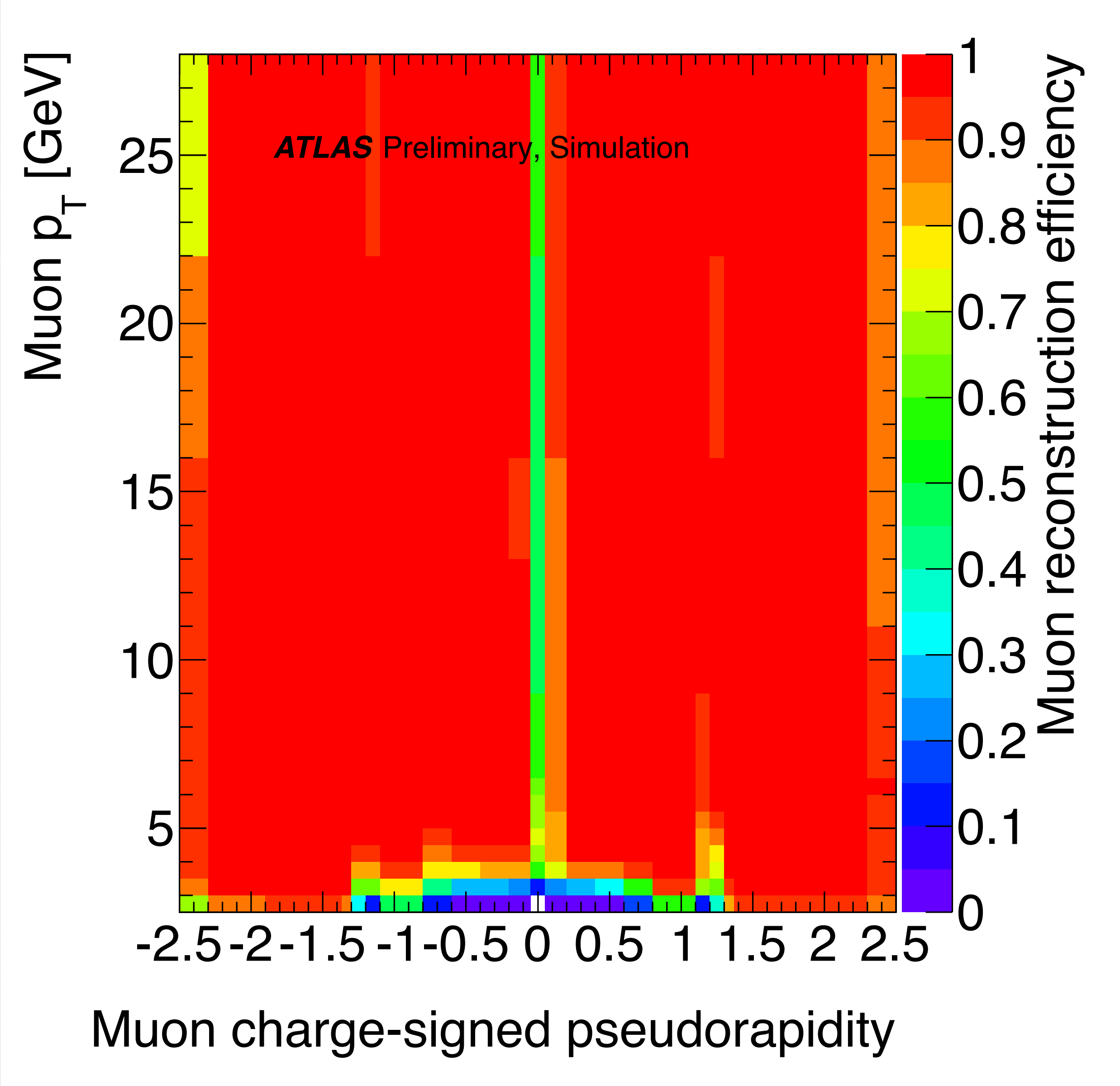
number of W

luminosity

efficiency (W)

- Measurement of cross-section ratio provides input to theorists who study J/ψ and W+J/ψ production
- Ratio reduces or cancels systematic uncertainties associated with luminosity and W boson
- We have measured: N(W), N(W+J/ψ)
- Only unknowns are: efficiency ε(J/ψ), acceptance α(J/ψ)

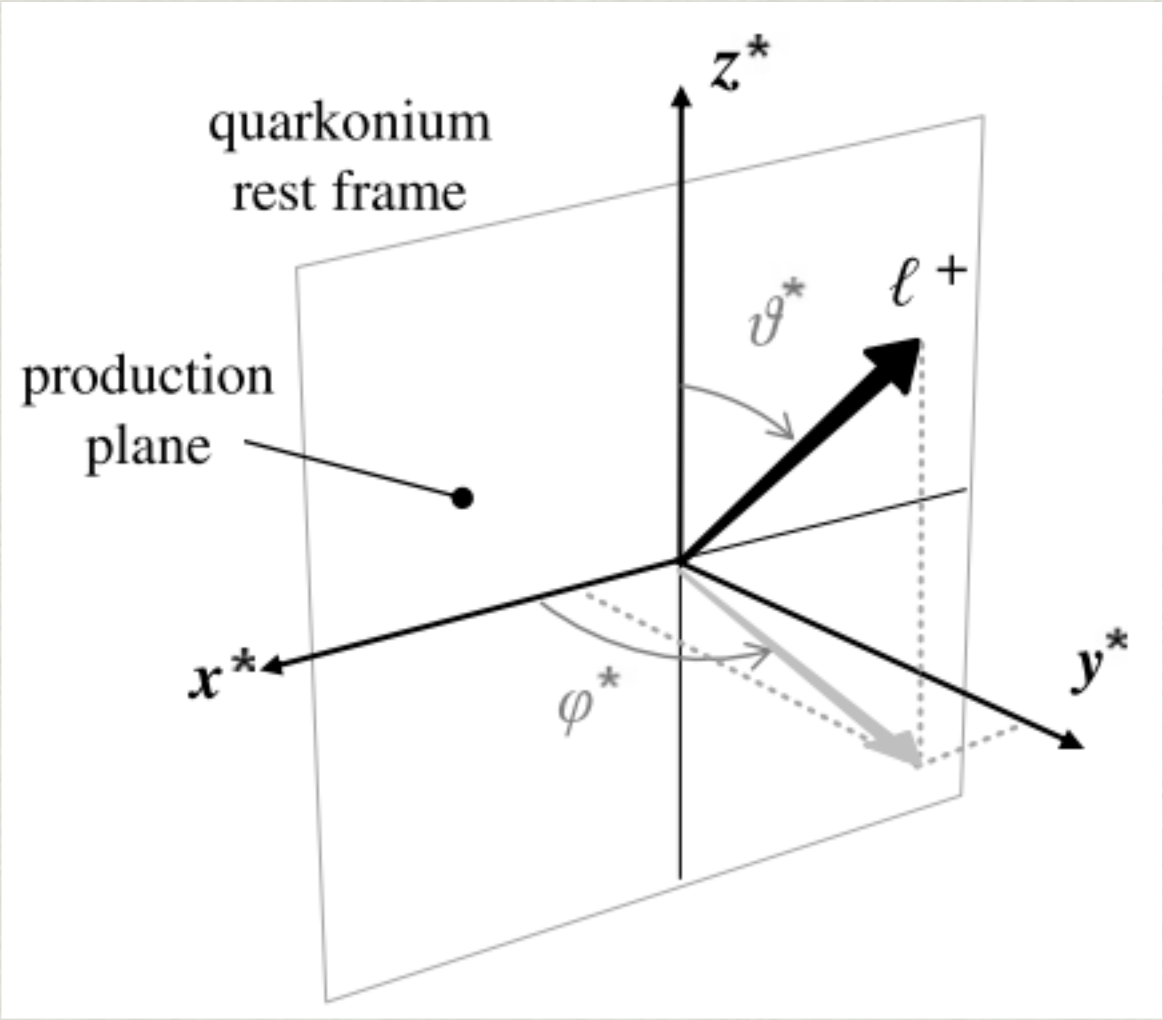
Efficiencies (J/ψ muons)

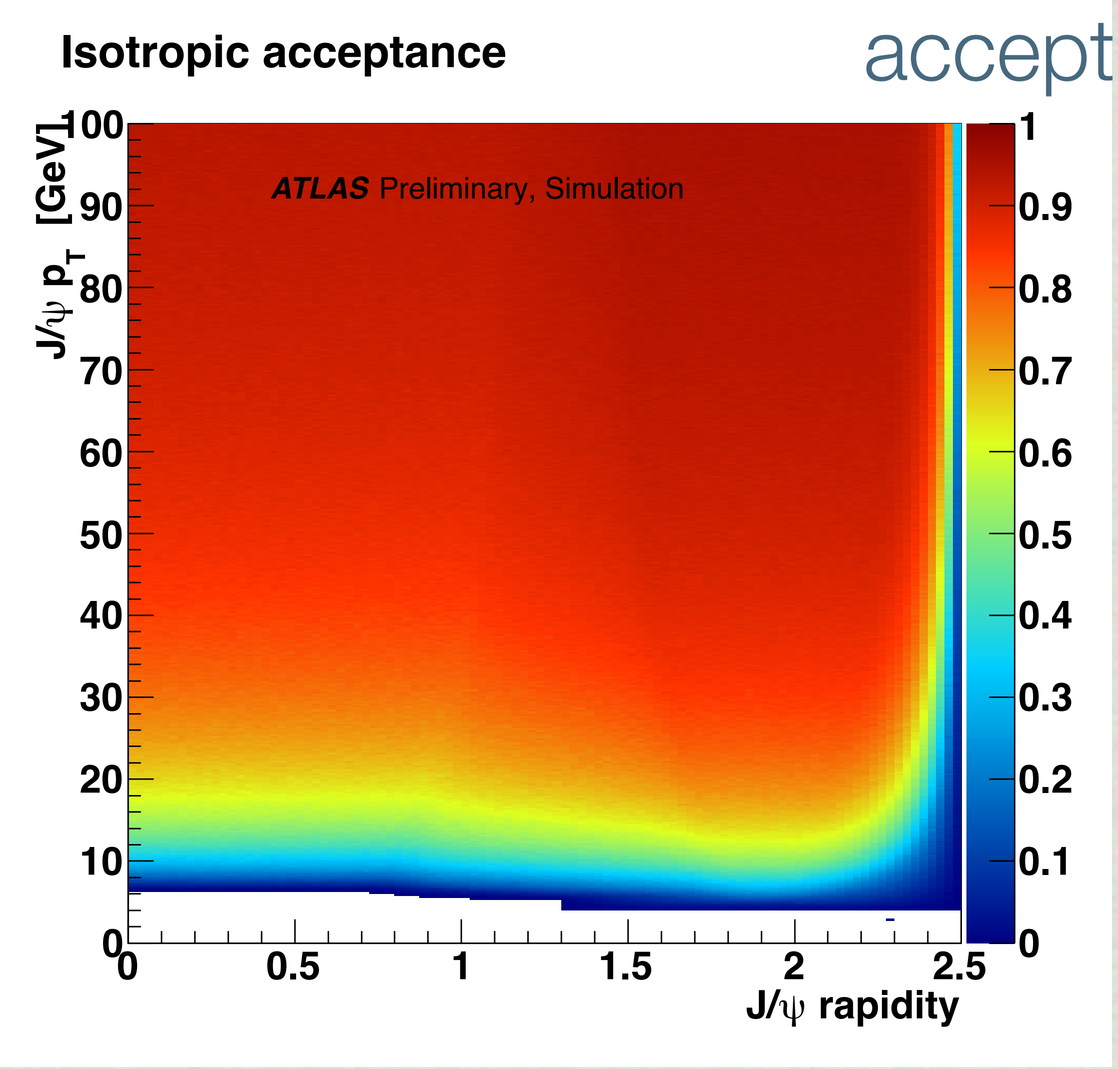


efficiency

Muon efficiencies ε(J/ψ) calculated using J/ψ "tag-and-probe" method, in bins of muon p_T and charged pseudorapidity

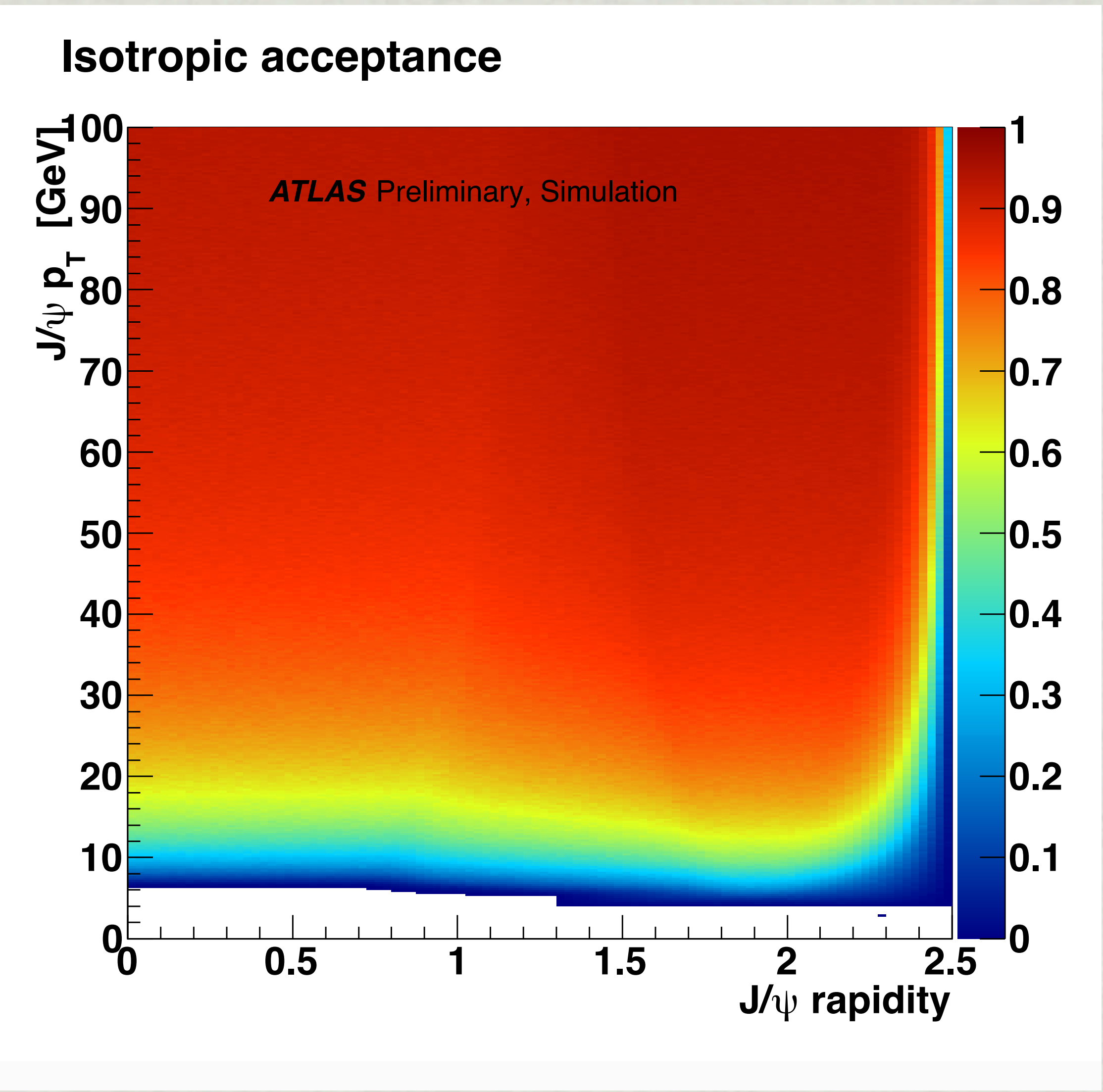
Spin-alignment - Acceptance

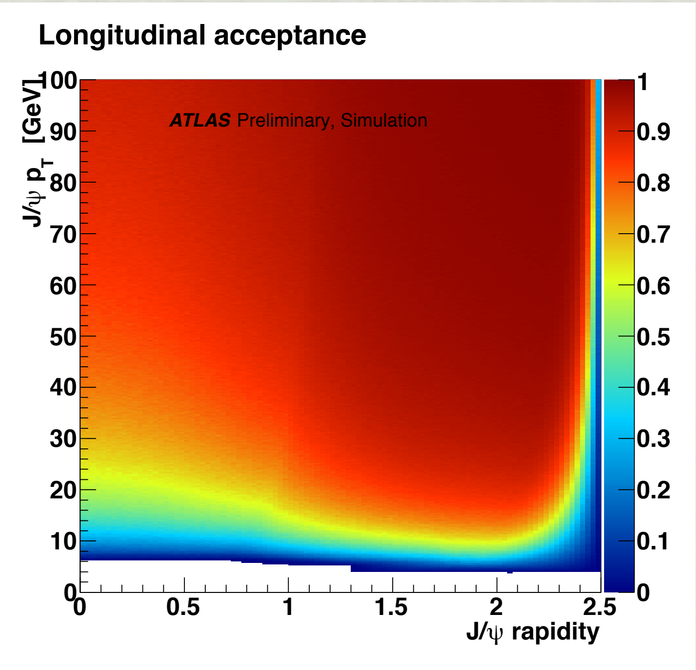


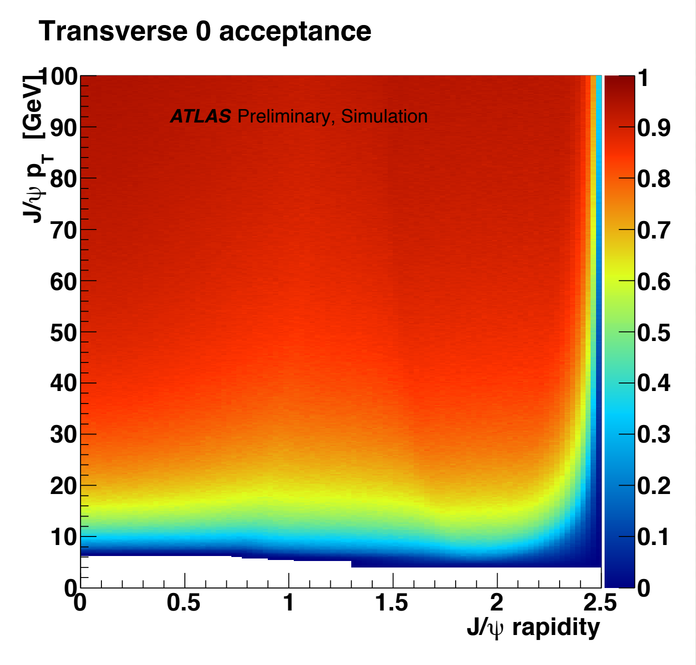


- J/ψ spin-alignment is not known
- Decay muons can follow different paths, depending on the spin-alignment
- The efficiency for these muons to fall in the fiducial region of the detector is called acceptance α(J/ψ), in bins of J/ψ p_T and rapidity

Spin-alignment - Acceptance

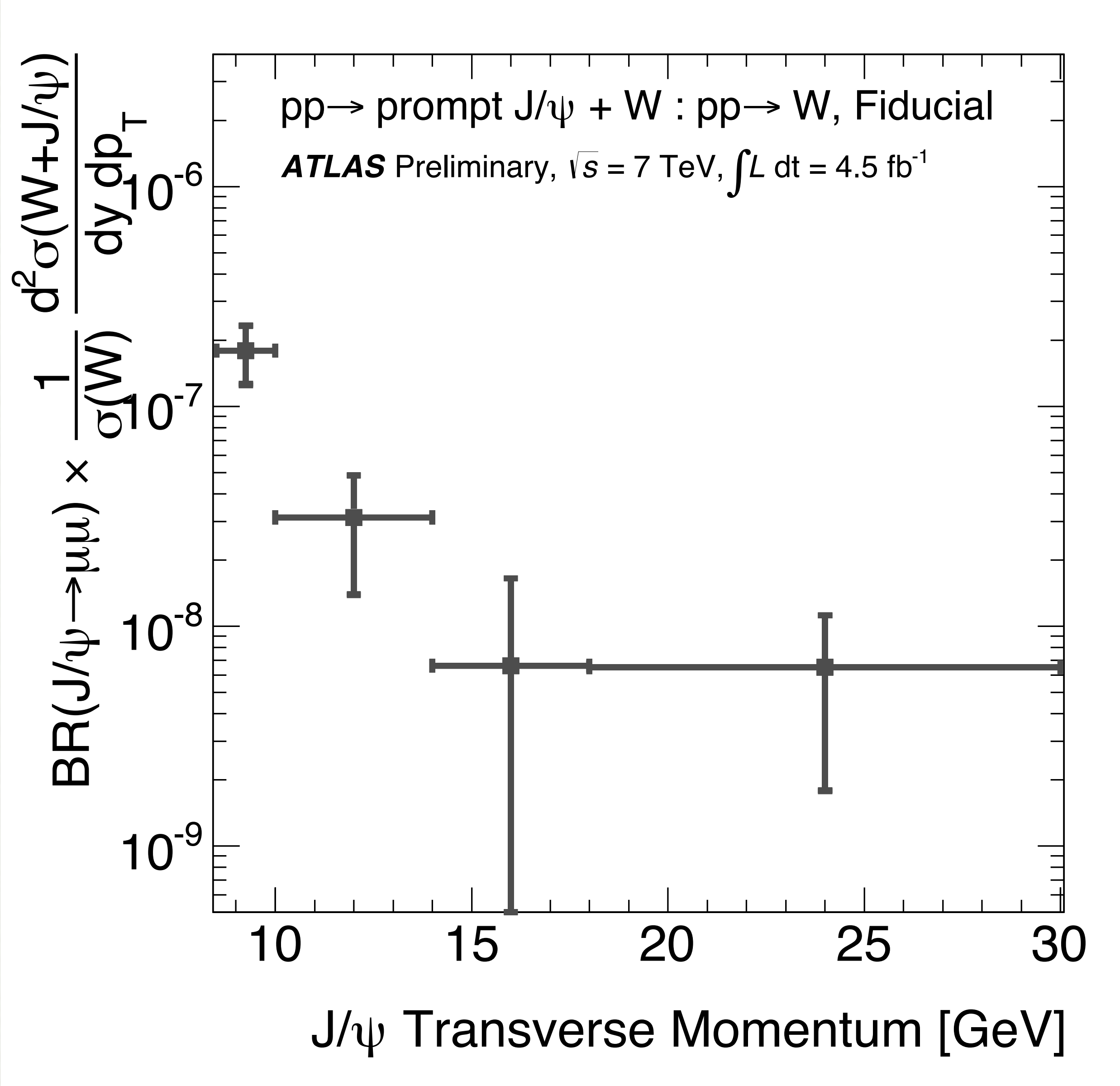






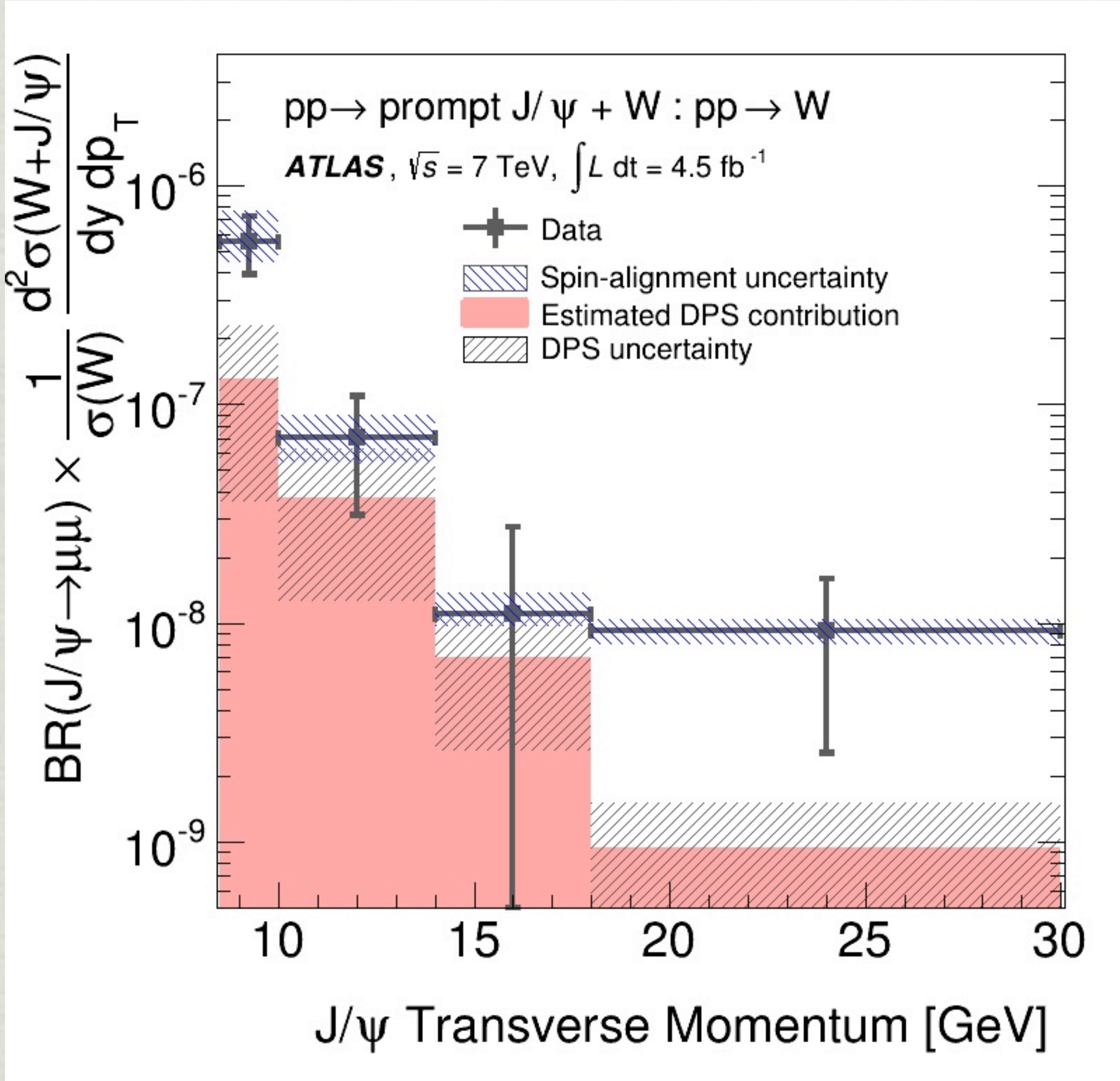
- Different spin-alignment assumptions lead to different acceptance
- Report isotropic scenario as central value, and range of results

Fiducial cross-section ratio



Fiducial: ratio before the acceptance corrections

Inclusive cross-section ratio



Inclusive: ratio after the acceptance corrections

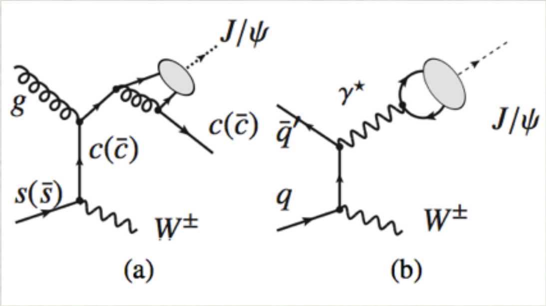
Uncertainties

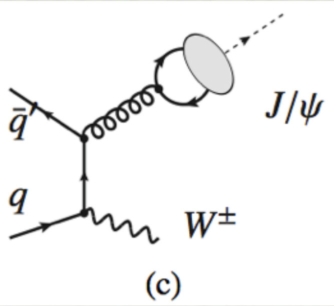
Source	Barrel	Endcap
J/ψ muon efficiency	(3–5)%	(3–5)%
$W^{\pm}$ boson kinematics	2%	5%
Fit procedure	$^{+3}_{-2}\%$	$^{+2}_{-1}\%$
Choice of fit nuisance parameters	1%	1%
Choice of fit functional forms	4%	4%
Muon momentum scale	negligible	
J/ψ spin-alignment	$^{+36}_{-25}\%$	$^{+27}_{-13}\%$
Statistical	$^{+47}_{-40}\%$	$^{+30}_{-27}\%$

- Muon efficiency: Difference between data-driven and Monte Carlo efficiencies
- W boson kinematics: Difference between several MC simulations
- Fit: Tried different functional forms, nuisance parameters
- Dominated by statistical uncertainties

Comparison with theoretical predictions

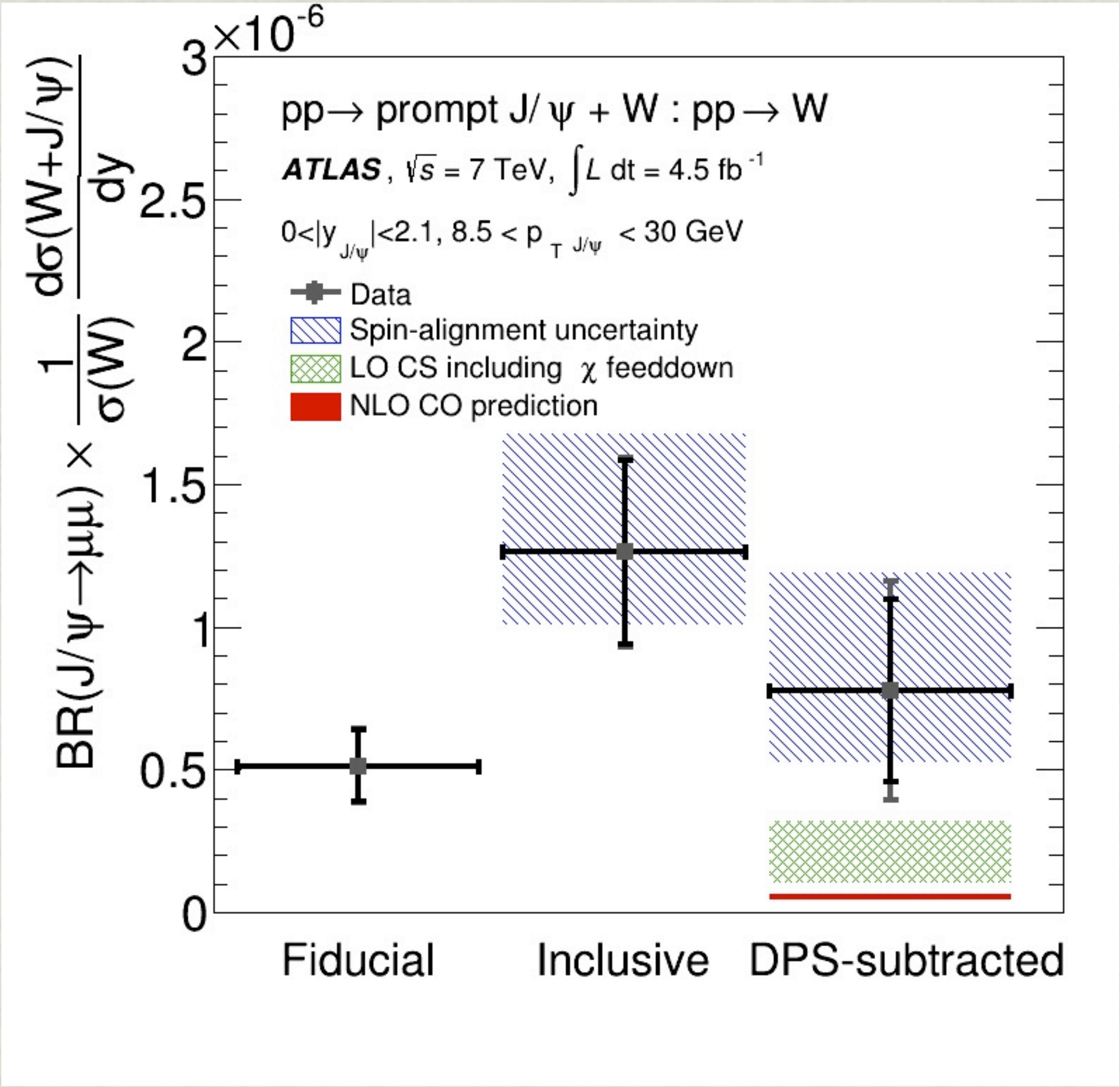
Colour Singlet **Colour Octet**





arxiv:1303.5327

$$R^{\text{fid}}_{J/\psi} = (51 \pm 13 \pm 4) \times 10^{-8}$$
$$R^{\text{incl}}_{J/\psi} = (126 \pm 32 \pm 9^{+41}_{-25}) \times 10^{-8}$$
$$R^{\text{DPS sub}}_{J/\psi} = (78 \pm 32 \pm 22^{+41}_{-25}) \times 10^{-8},$$



- Comparing DPS-subtracted measurement to theoretical predictions
- Leading-order Colour Singlet (CSM) contributions include χ->J/ψ feeddown: (10-32) x 10^{-8}
- Next-to-leading order Colour Octet (COM) contributions below CSM: (4.6-6.2) x 10^{-8}

Summary - Outlook

Set out to search for W+J/ψ associated production

- First observation of Charmonium+Vector boson production
- Measurement of cross-section ratio W+J/ψ : W
- Provide input to theorists who study J/ψ and W+J/ψ production
- Dominated by statistical uncertainties
- Measurement compatible with theoretical predictions within 2σ

Next steps:

- Higher energy: W+J/ψ at 8/14 TeV, differential cross-section
- New undetected signatures: Z+J/ψ, W/Z+ϒ
- Better understanding of J/ψ production

SUBMITTED TO JHEP
HTTP://ARXIV.ORG/ABS/1401.2831
ADDITIONAL FIGURES FROM
ATLAS-CONF-2013-042

sPlot weights

$$\mathcal{L} = \sum_{e=1}^{N} \ln \left\{ \sum_{i=1}^{N_s} N_i \mathrm{f}_i(y_e) \right\} - \sum_{i=1}^{N_s} N_i$$

- Sophisticated method of background subtraction
- Each event attributed a signal or background weight according to likelihood fit
- No cuts are made, all events contribute to the projection
- We use sPlot to inspect prompt J/ψ candidates using all pre-selected events