Thesis Defense

J/ψ meson in association with a $W^{\pm}$ boson cross section ratio measurement with the ATLAS detector using proton-proton collisions at center of mass energy $\sqrt{s}$ = 8 TeV from the Large Hadron Collider

for the degree of

Doctor of Philosophy

in the area of

Experimental High Energy Particle Physics

from the

Homer L. Dodge Department of Physics and Astronomy

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April 26th 2016

The University of Oklahoma

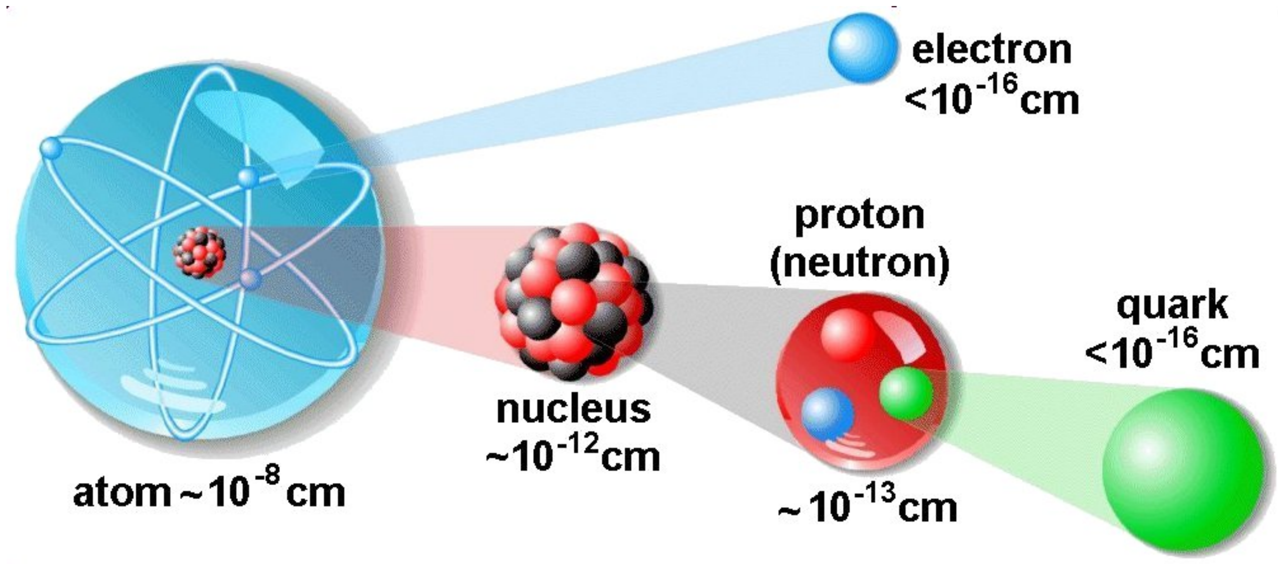
Outline

- Particle Physics Overview
- Theoretical Motivation for $J/\psi + W^{\pm}$ Analysis
- Experimental Apparatus

  The Large Hadron Collider

  The ATLAS Detector
- Analysis Procedure and Results

Particle Physics - What is everything made of and what holds it together?



- 460 - 370 B.C. **Democritus** — All matter is made of indivisible particles called **atoms**
- 1773 - 1829 **Thomas Young** — **Wave** theory of light
- 1923 **Arthur Compton** — Discovers the **quantum** (particle) nature of x rays, photons are particles
- 1924 **Louis de Broglie** — Proposes that matter has **wave properties**

- 1953 --- *Beginning of a proliferation of particle discoveries, modern era of collider experiments* ---

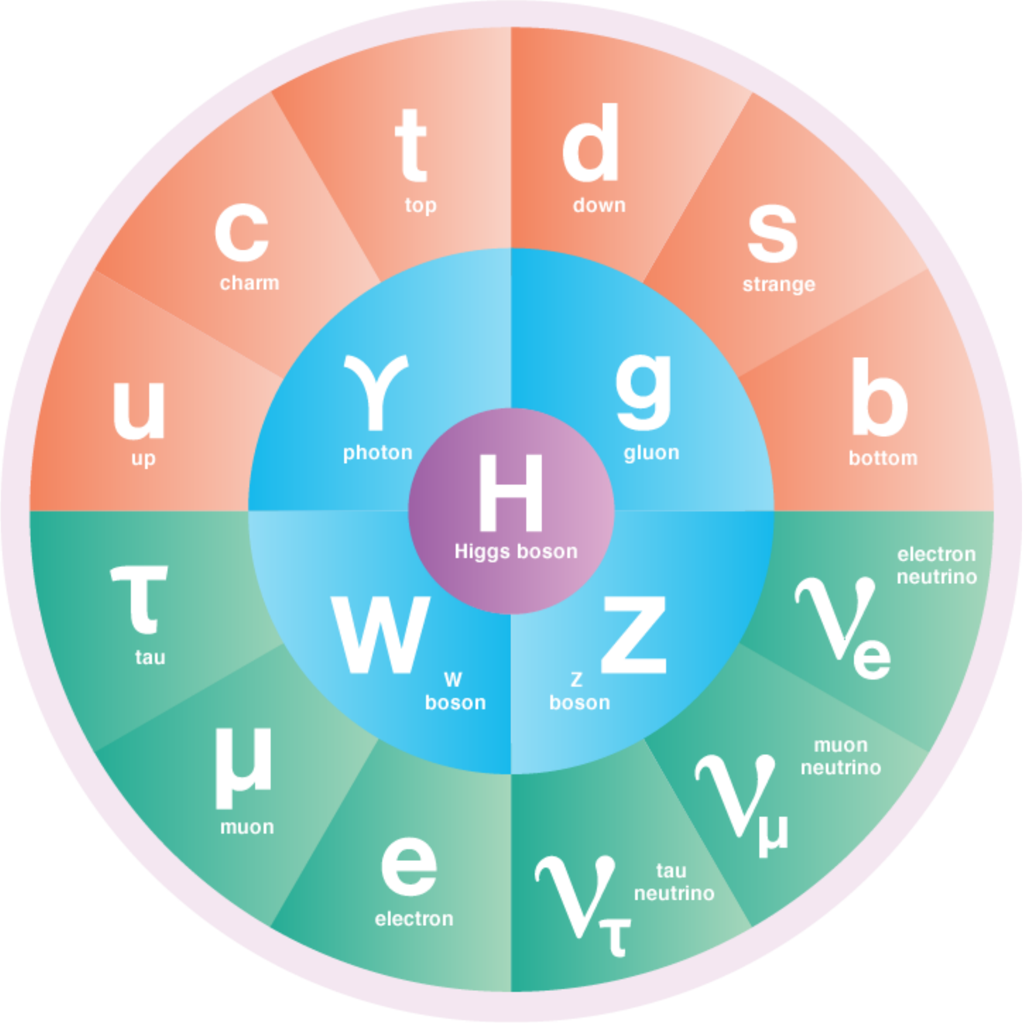
Standard Model of Particle Physics

Field theory, Particles have associated fields.

- 3 principles:
  - Relativity
  - Quantum Mechanics
  - Gauge Invariance

- Outside Ring
  Fermions: matter particles – spin 1/2
- Center
  Bosons: force carriers – integer spin

- All Standard Model fundamental particles now discovered:
  - electron: ~1898
  - Higgs: 2012



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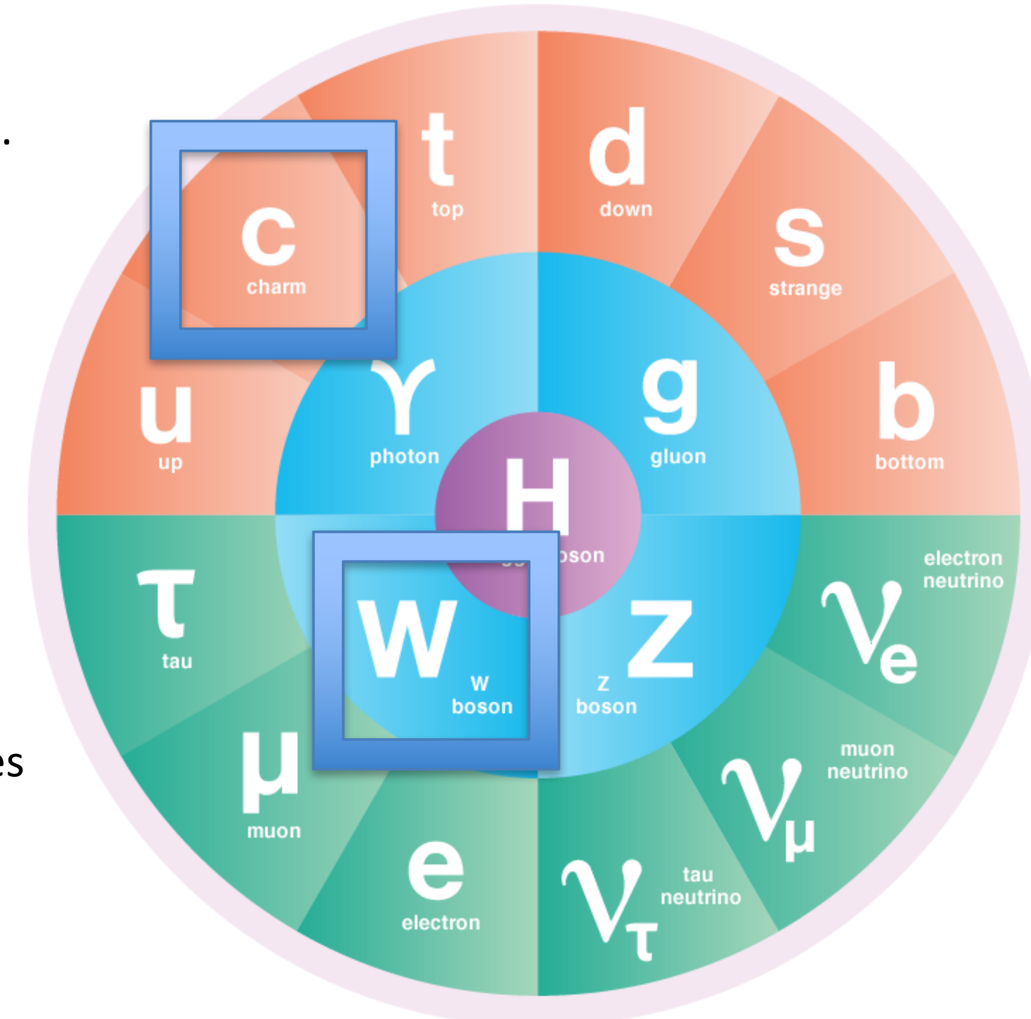
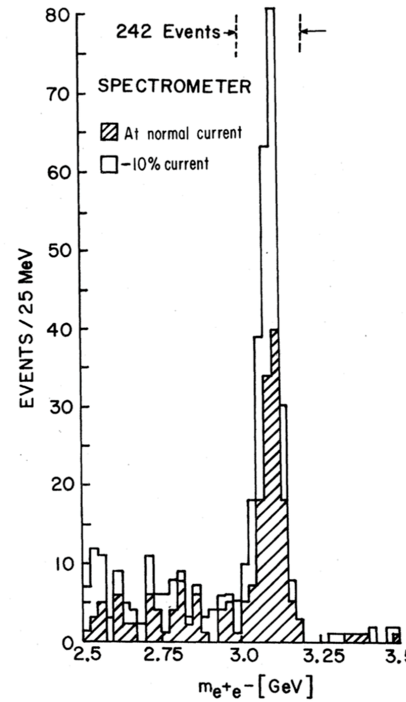


J/ψ Meson

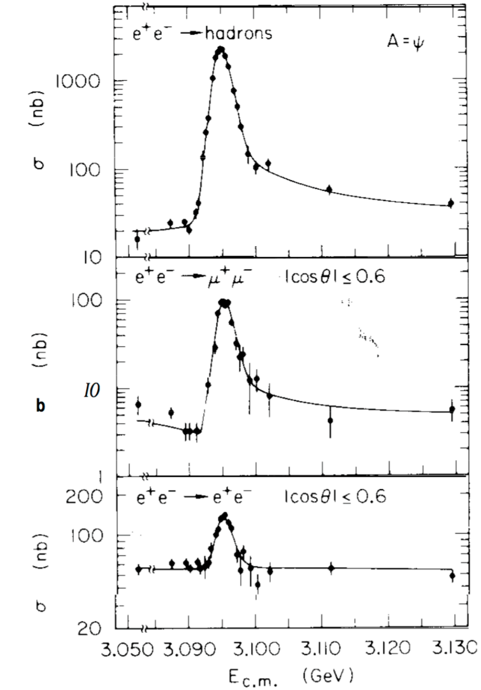
- Bound state $c\bar{c}$ 'charmonium'
- Discovered November 1974
- Validated the quark model
- 1976 Nobel Prize in Physics
- 12% decay to:

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

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



AGS experiment, BNL
(Sam Ting, J)



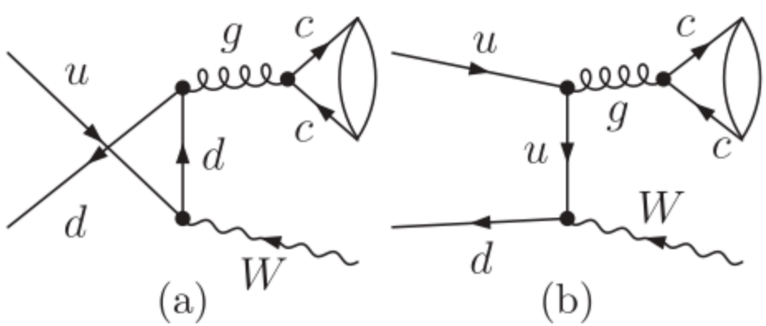
SPEAR detector, SLAC
(Burton Richter, ψ)

W± Boson

- Fundamental particle, carries the weak nuclear force
- Discovered 1983, SPS accelerator at CERN
- Validated the electroweak model
- 1984 Nobel Prize in Physics (Rubbia and van der Meer)
- 10.9% decay to: $W^\pm \rightarrow \ell^\pm \bar{\nu}$

J/ψ + W± measurement: Theory Motivation

- Production mechanism of charmonium in hadronic collisions not fully understood
- Relative contribution of Color Octet (CO) vs Color Singlet (CS) models unknown
- Requiring an associated object (W ± in this case) filters the possible diagrams



Leading Order Color Octet

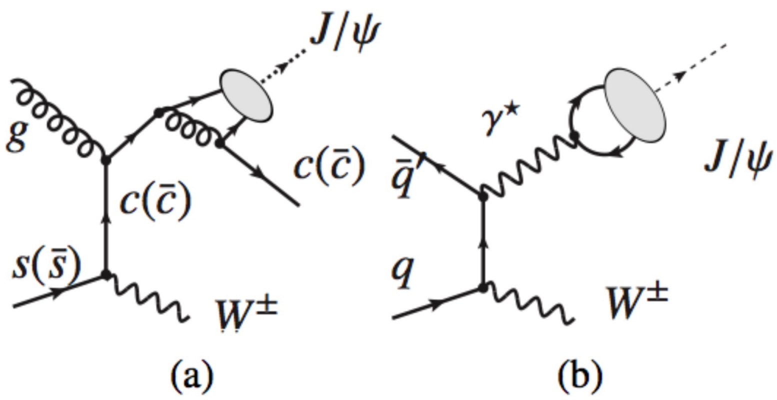
$$u\bar{d} \rightarrow c\bar{c}[J/\psi] + W^{+}$$

J/ψ + W± can be produced at leading order only in the CO model because the W ± does not interact strongly.

CO was initially considered the dominant mechanism.

J/ψ + W± measurement: Theory Motivation

- In 2013, theorists proposed that the next to leading order (NLO) Color Singlet (CS) model could have a comparable contribution. Evidence corroborates this.



Next to Leading Order Color Singlet

(a) $s + g \rightarrow W + c + J/\psi$

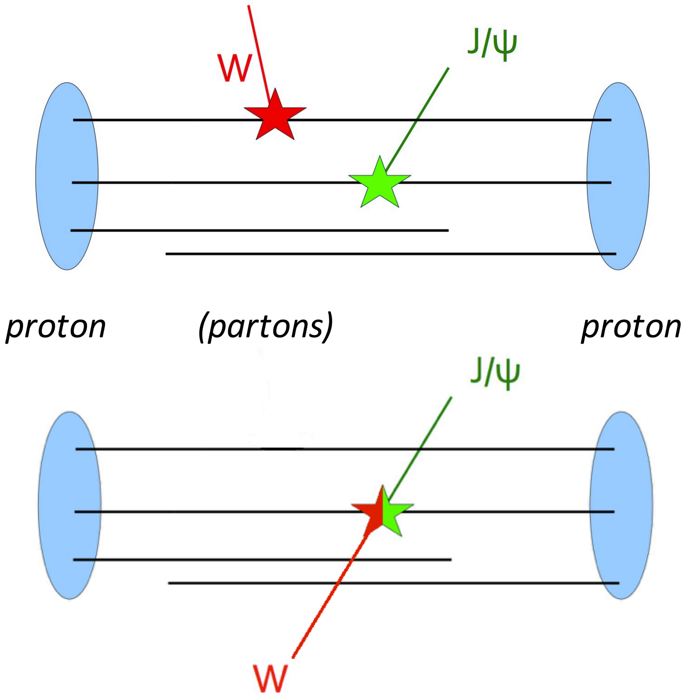
(b) $q + \bar{q}' \rightarrow W + \gamma^* \rightarrow W + J/\psi$

(a) Strange quark - gluon fusion, charm hadronizes into J/ψ

(b) Quark - antiquark interaction, off shell photon produces J/ψ

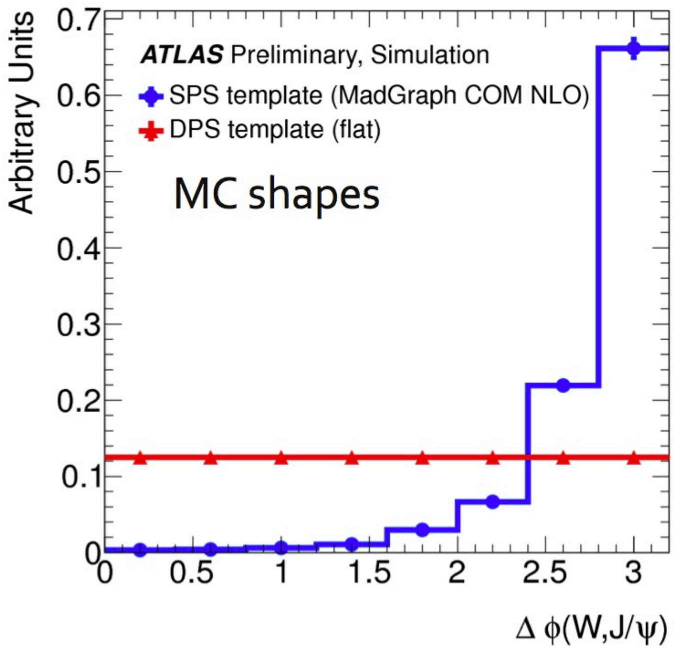
J/ψ + W± measurement: Theory Motivation

- Contribution of double parton scattering (DPS) vs single parton scattering (SPS) processes unknown
- J/ψ + W± measurements can probe this using the opening angle, Δϕ(J/ψ,W) between the two particles

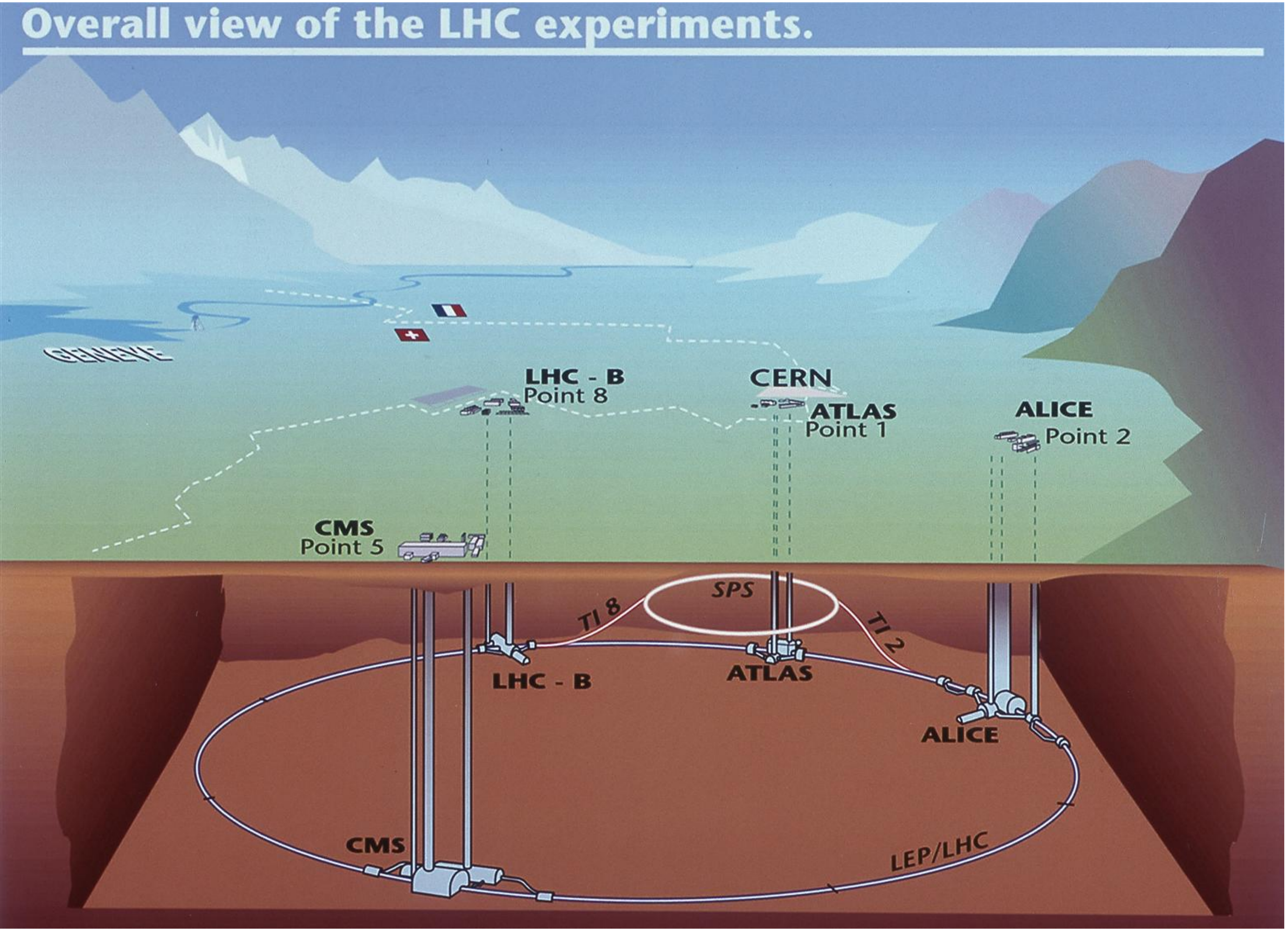


DPS
Arbitrary Δϕ

SPS
$\Delta\phi \simeq \pi$
(momentum conservation)



The Large Hadron Collider (LHC)

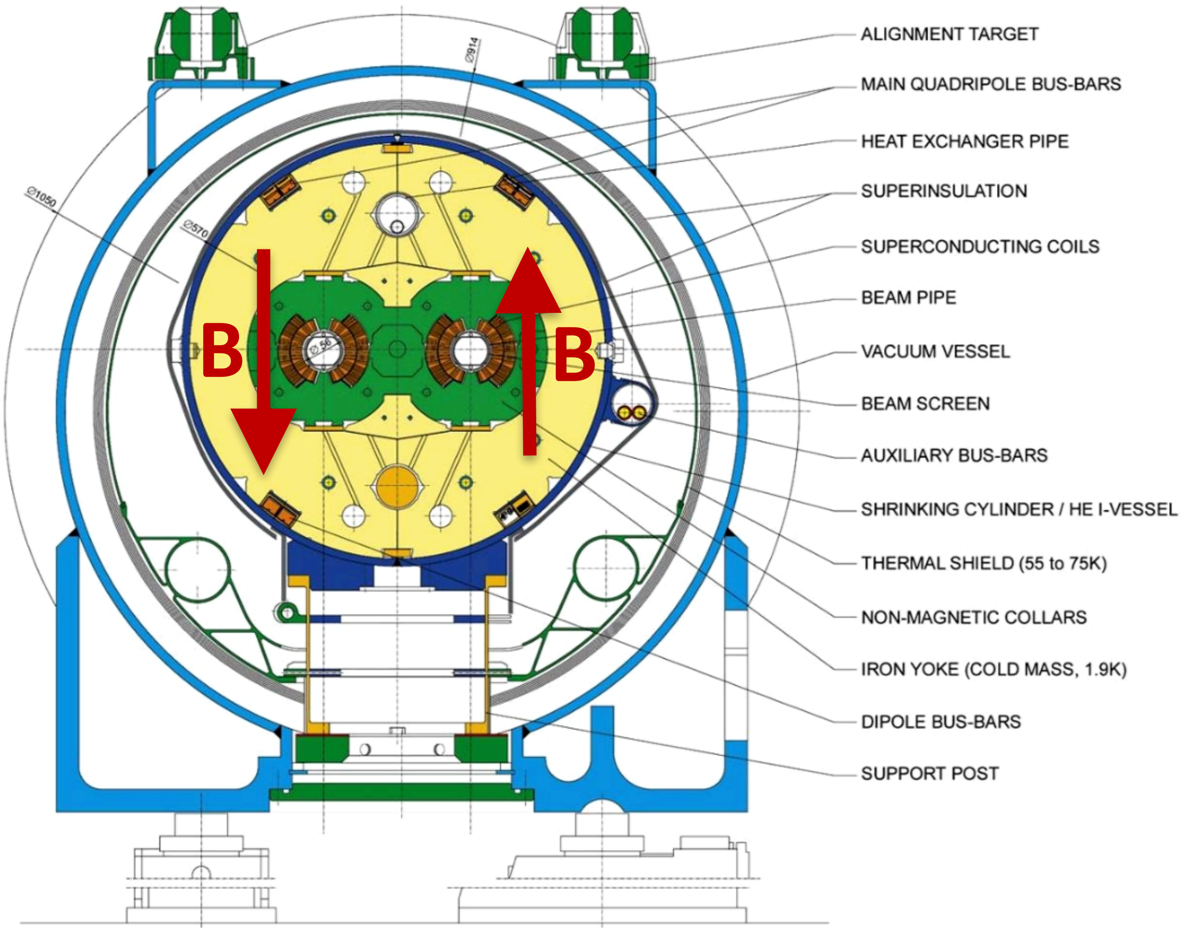


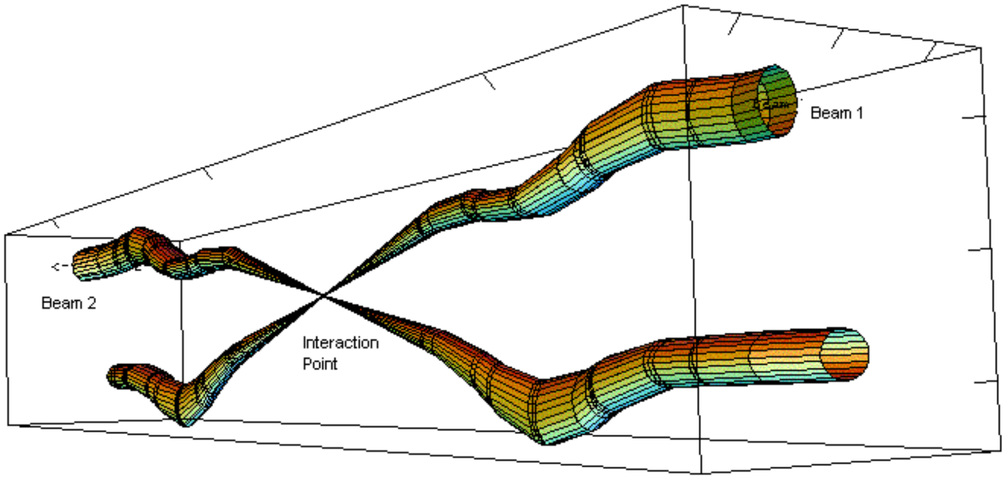
Est. 1954

- 27 km circumference
- ~100 m underground
- Began operations 2008
- Accelerates *protons* to 99.9999 % *c*
- *proton-proton* collisions briefly create exotic particles
- Detectors quickly photograph them

LHC Dipole Magnet

- NbTi superconducting wire with liquid He at 1.9 K
- Opposite 8 T fields in each beampipe
- 14 TeV design energy
- 25 ns bunch crossing (40 million per second)
- 160 billion protons/bunch
- 10-20 collisions/crossing





Relative beam sizes around IP1 (Atlas) in collision

Luminosity, *L*

- Determines the number of events
- Accelerators try to maximize *L*
- LHC $L_{max} = 10^{34} cm^{-2} s^{-1}$

$$N_{\text{event}} = L\sigma_{\text{event}}$$

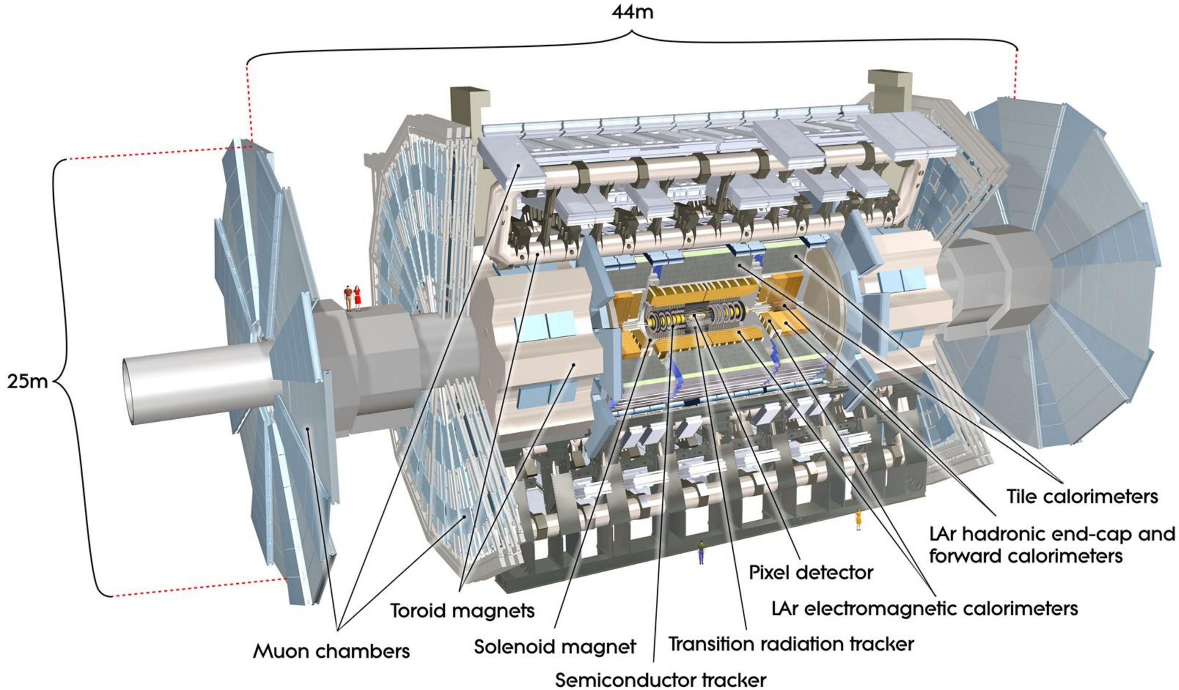
$$L = \frac{N_b^2 n_b f_{\text{rev}} \gamma_r}{4\pi \epsilon_n \beta^*} F$$

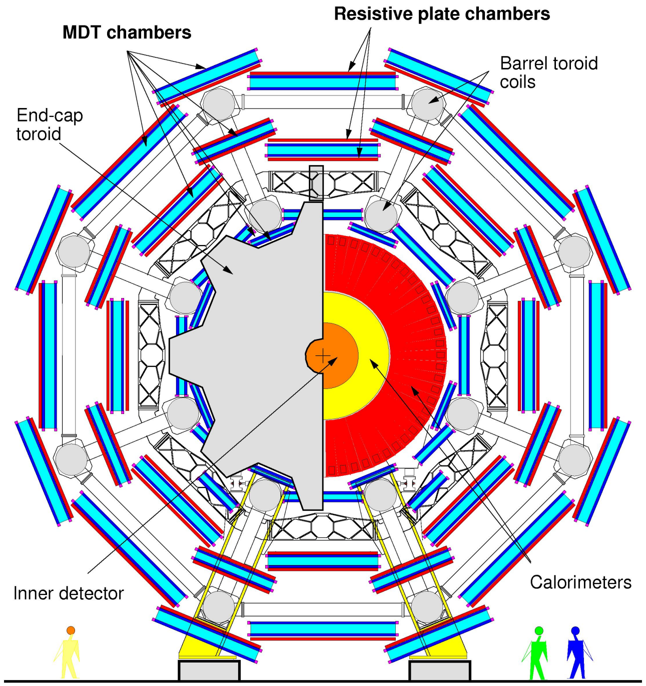
N_b = particles/bunch
n_b = bunches/beam
f_{rev} = revolution frequency
γ_r = relativistic gamma factor

ϵ_n = normalized transverse beam emittance
β^* = beta star function
F = geometric luminosity reduction factor

ATLAS EXPERIMENT

- Photographs exotic particles created by the *p-p* collision
- Weight: 7,000 tons
- 46 m long; 25 m diameter
- ~3,000 collaborators, >177 institutes, 38 countries
- Layers have specialized functions

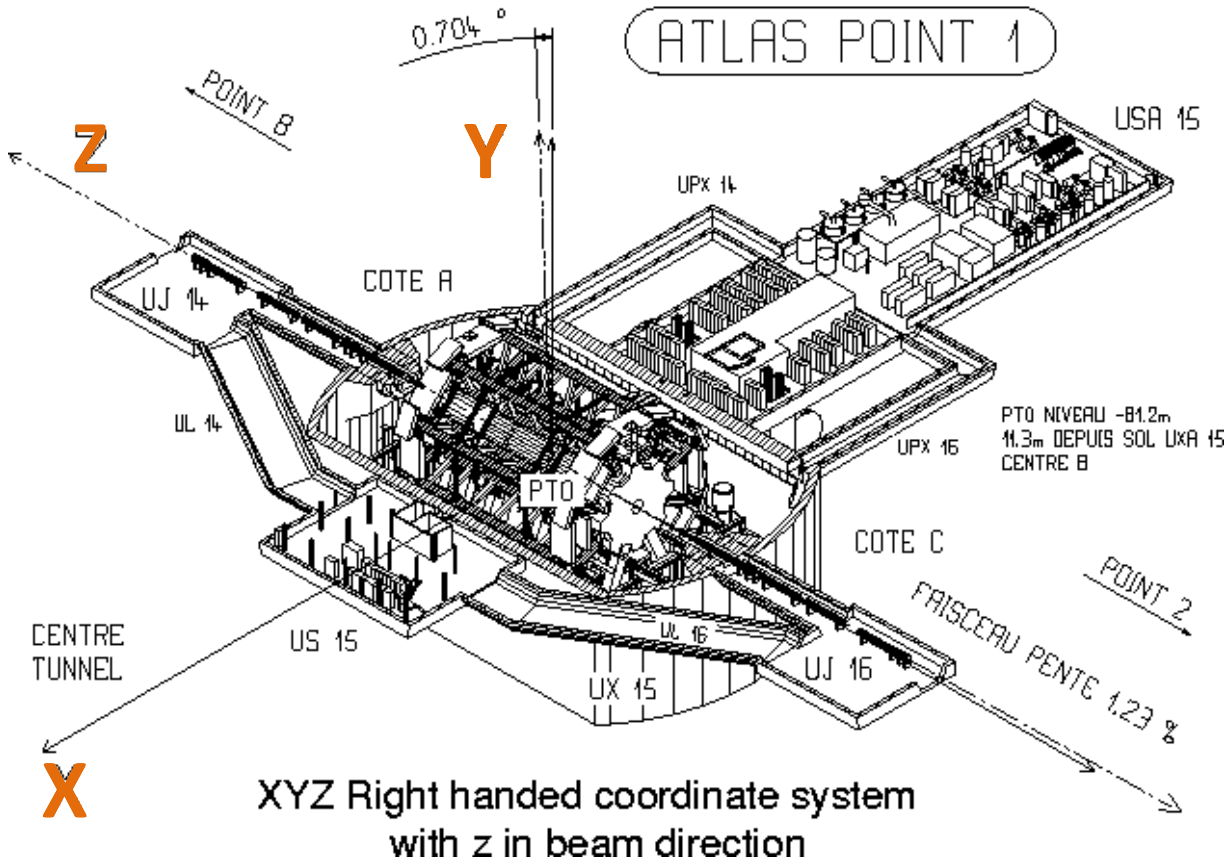




ATLAS Detector Coordinates

Cartesian Coordinates

- Beam: *z* – direction
- Transverse plane: *x* – *y*



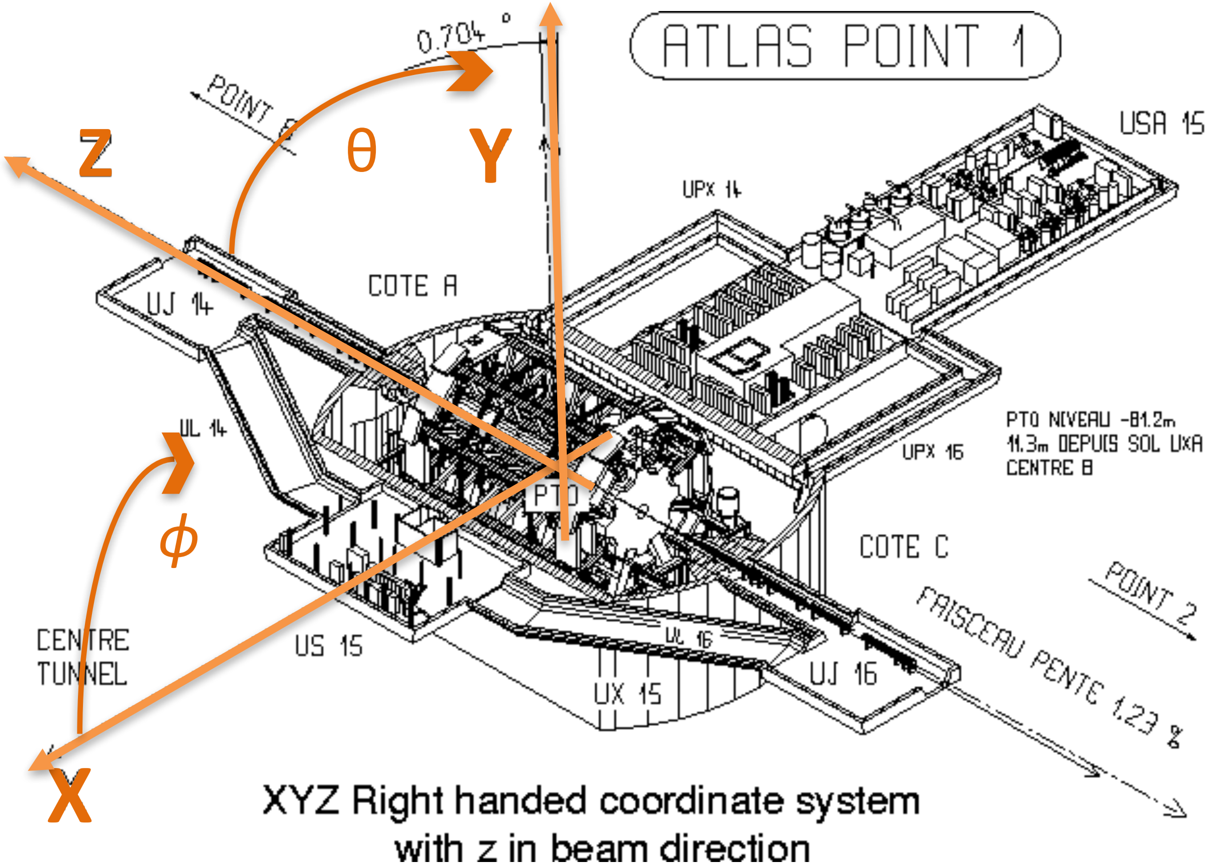
ATLAS Detector Coordinates

Cartesian Coordinates

- Beam: z – direction
- Transverse plane: $x - y$

Spherical Coordinates

- Azimuthal angle: ϕ
- Polar angle: θ



ATLAS Detector Coordinates

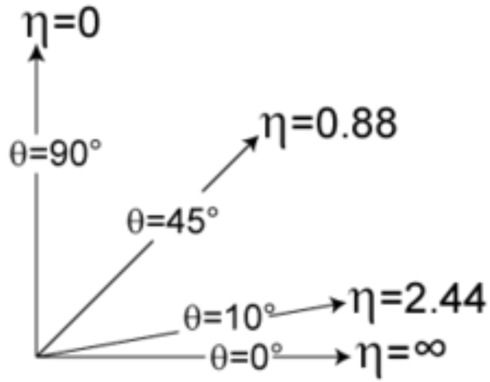
We transform θ into rapidity (y) because differences in y are Lorentz invariant under boosts along the z - axis.

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

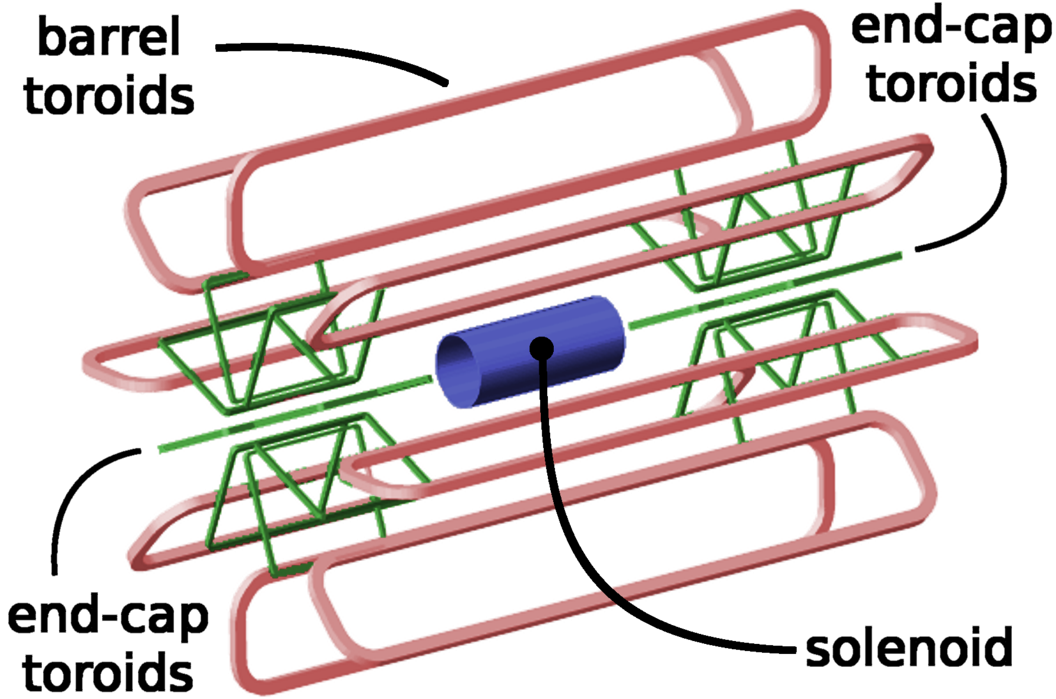
where: $p_z = p\cos\theta$

Pseudo-rapidity (η) is the massless particle approximation of y.

$$\eta = -ln\tan\frac{\theta}{2}$$



Magnet Systems



Their size, position and strength determined overall detector design.

- Solenoid = 2 T
- Barrel Toroid ~ 0.5 T
- End-cap Toroid ~ 1 T

Their purpose is to curve the path of charged particles. Using the Lorentz force:

$$\vec{F} = q\vec{v} \times \vec{B}$$

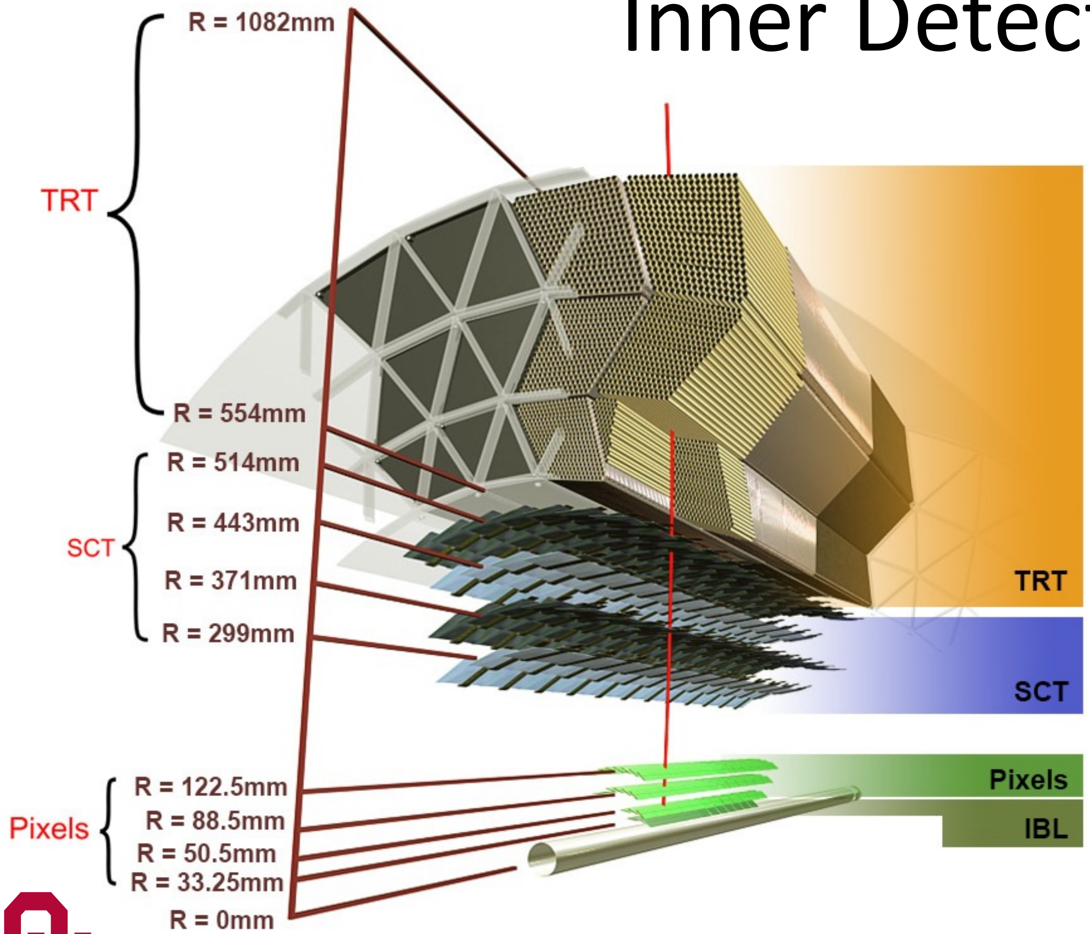
given circular motion:

$$F = \frac{mv^2}{r}$$

relates transverse momentum (p_T) and radius of curvature (r):

$$p_{\mathrm{T}} = qBr$$

Inner Detector



Enclosed by the Solenoid

- Performs:
  - Tracking
  - Vertex Identification

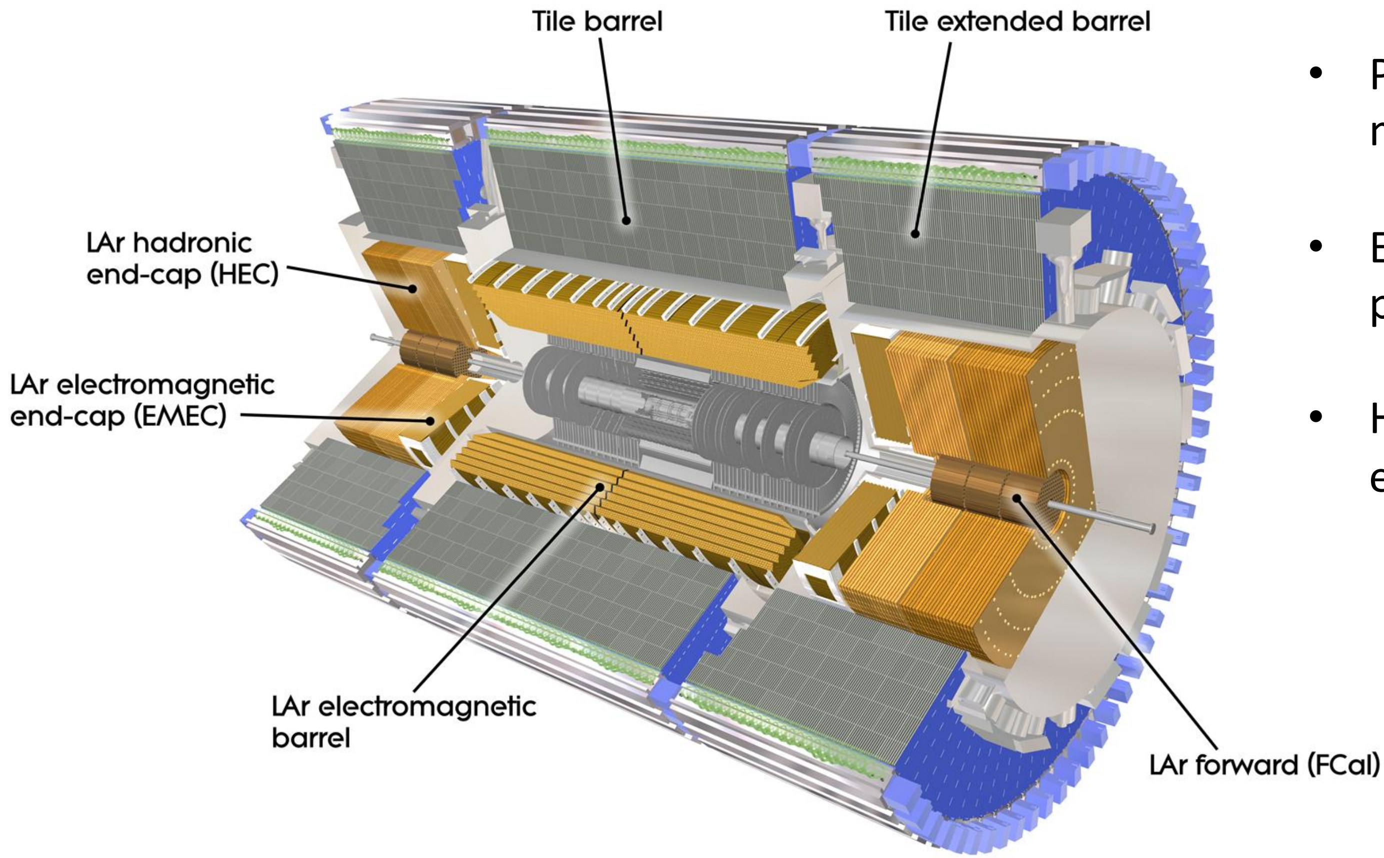
3 technologies used:

- Silicon pixels
- Silicon strips
- Straw tubes

Red track shows hypothetical charged particle of:
p_T = 10 GeV and η=0.3

supports the Pixel/IBL sub-detector

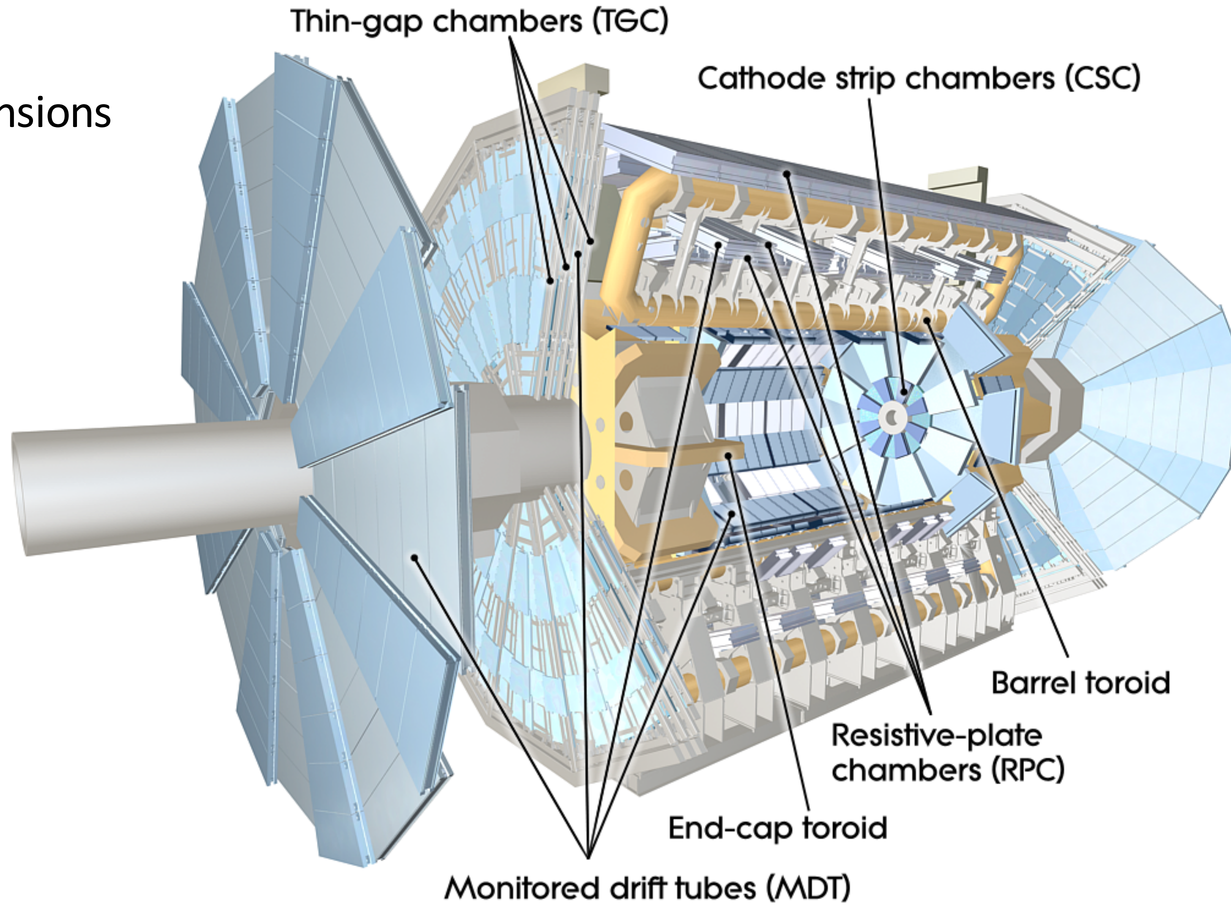
Calorimeters



- Provides particle energy measurements
- Electromagnetic: photons and electrons
- Hadronic: e.g. protons, neutrons

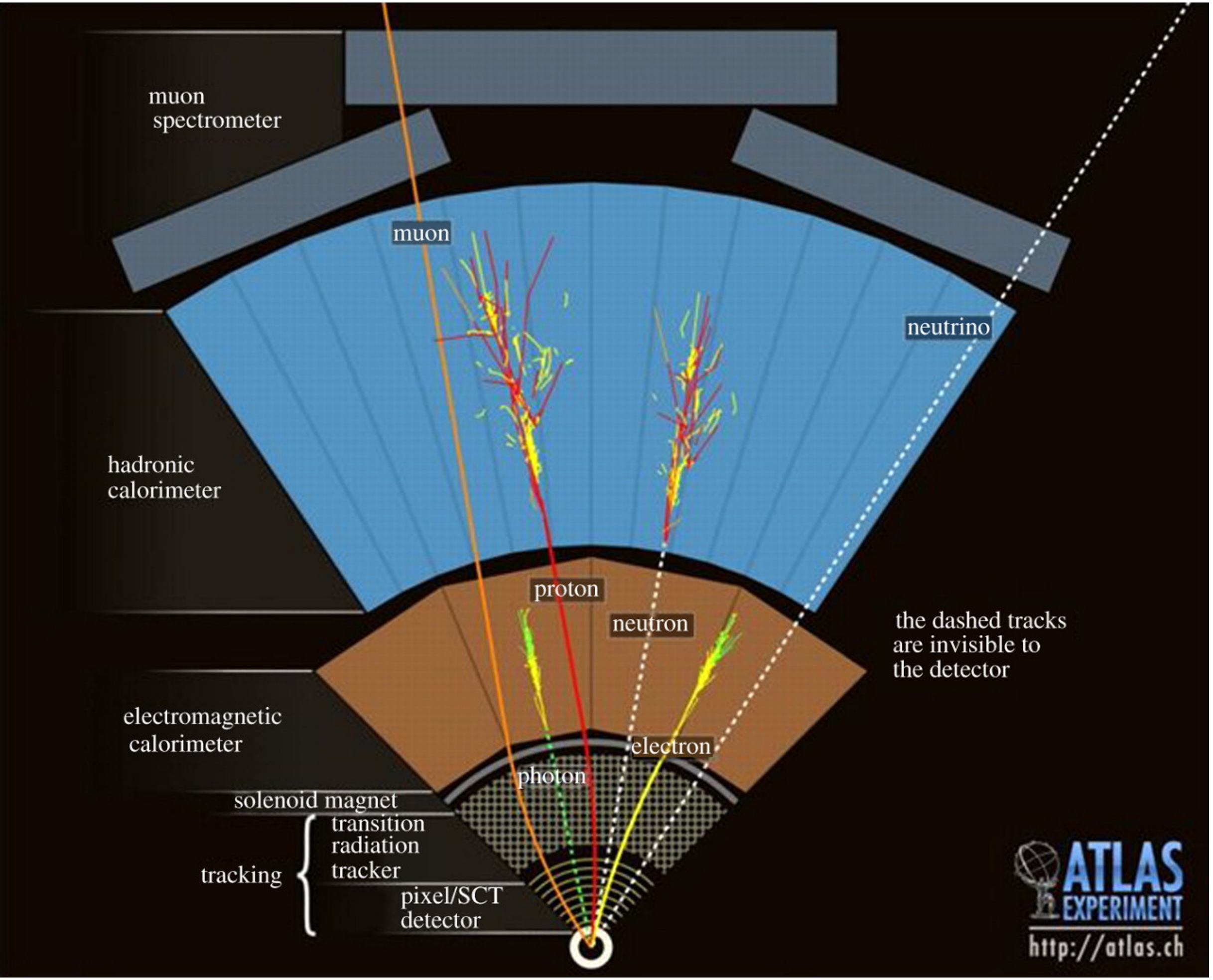
Muon Spectrometer

- Defines overall ATLAS dimensions
- Identifies and tracks muons



- Four types of chambers
- Three tracking layers

Particle/Object Identification



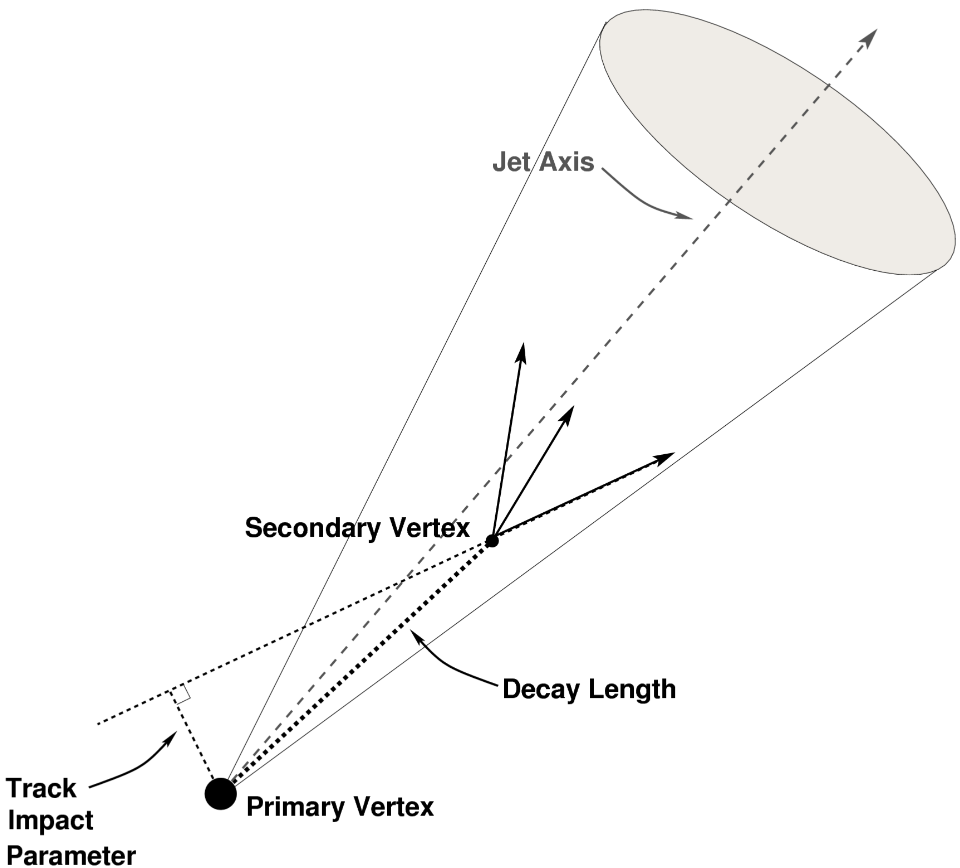
Charged particles leave tracks:

- Curve direction shows charge sign
- Curve radius $\propto$ transverse momentum (p_T)

Undetected particles result in Missing Transverse Energy (MET or E_T^{miss}):

$$\vec{E}_{\mathrm{T}}^{\mathrm{miss}} = \vec{E}_{\mathrm{Tx}}^{\mathrm{miss}} + \vec{E}_{\mathrm{Ty}}^{\mathrm{miss}}$$

Particle/Object Identification



Primary Vertex: Initial *proton-proton* collision

Many particles produced at the primary vertex travel travel some distance and decay at a secondary vertex.

Their transverse time of flight or decay time is:

$$\tau \equiv L_{xy} \frac{m}{p_{\mathrm{T}}}$$

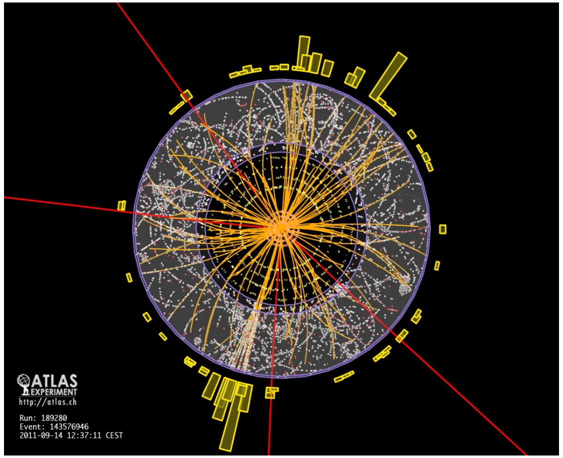
Where L_{xy} is the transverse decay length.

A conical boundary around a track is defined:

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

Triggering and Data Acquisition

More data is generated than can be stored, triggers select the interesting data.



40 million bunch crossings per second

Level 1 trigger: rough selections every 2 µs

< 75 thousand bunch crossings per second

Level 2 trigger: analysis specific selections every 40 µs

~ 1,000 events per second

Event selection: detailed event analysis

~ 100 events per second stored on disk @ ~1.5 MB/event

$J/\psi + W^{\pm}$ boson measurement: Method

Event Channel: $J/\psi \rightarrow \mu^+\mu^-$ and $W^{\pm} \rightarrow \mu^{\pm}\nu$

Analysis Goals:

Measure the ratio given by the cross section of associated prompt $J/\psi + W^{\pm}$ production divided by the cross section of inclusive $W^{\pm}$ production.

$$R_{J/\psi} \equiv \frac{\sigma_{W+J/\psi}}{\sigma_W}$$

J/ψ + $W^{\pm}$ boson measurement: Method

Event Channel: $J/\psi \to \mu^+\mu^-$ and $W^{\pm} \to \mu^{\pm}\nu$

Analysis Goals:

Measure the ratio given by the cross section of associated prompt J/ψ + $W^{\pm}$ production divided by the cross section of inclusive $W^{\pm}$ production.

$$R_{J/\psi} \equiv \frac{\sigma_{W+J/\psi}}{\sigma_W} \equiv \frac{\frac{N_{W+J/\psi}}{\mathcal{T}\times\mathcal{L}\times\epsilon_W\times\mathcal{A}_W\times\epsilon_{J/\psi}\times\mathcal{A}_{J/\psi}}}{\frac{N_W}{\mathcal{T}\times\mathcal{L}\times\epsilon_W\times\mathcal{A}_W}}$$

Where:

N = number of events

$\mathcal{T}$ = trigger efficiency

$\mathcal{L}$ = luminosity

ϵ = detector efficiency

$\mathcal{A}$ = detector acceptance

J/ψ + W± boson measurement: Method

Event Channel: $J/\psi \to \mu^+\mu^-$ and $W^\pm \to \mu^\pm \nu$

Analysis Goals:
Measure the ratio given by the cross section of associated prompt J/ψ + W± production divided by the cross section of inclusive W± production.

$$R_{J/\psi} \equiv \frac{\sigma_{W+J/\psi}}{\sigma_W} \equiv \frac{\frac{N_{W+J/\psi}}{\cancel{\mathcal{T}} \times \cancel{\mathcal{L}} \times \cancel{\epsilon_W} \times \cancel{\mathcal{A}_W} \times \epsilon_{J/\psi} \times \mathcal{A}_{J/\psi}}}{\frac{N_W}{\cancel{\mathcal{T}} \times \cancel{\mathcal{L}} \times \cancel{\epsilon_W} \times \cancel{\mathcal{A}_W}}} \equiv \frac{1}{N_W}[\frac{N_{W+J/\psi}}{\epsilon_{J/\psi} \times \mathcal{A}_{J/\psi}}]$$

Where:

N = number of events

$\mathcal{T}$ = trigger efficiency

$\mathcal{L}$ = luminosity

ϵ = detector efficiency

$\mathcal{A}$ = detector acceptance

$J/\psi + W^{\pm}$ boson measurement: Method

Additional Goals:

- Measure the ratio as a function of J/ψ^{PT}
- Determine the fraction of events from single parton scattering (SPS) vs double parton scattering (DPS).

We need:

1) Inclusive $W^{\pm}$ sample
2) Associated $J/\psi + W^{\pm}$ sample

$W^{\pm}$ Selections

$W^{\pm} \rightarrow \mu^{\pm}\nu$ **Requirements**	
Fire trigger for: isolated muon of p_T = 24 GeV OR muon of p_T = 36 GeV	
High quality muon detected both in tracker and muon system	
Transverse momentum	$p_T > 25$ GeV
Pseudorapidity	$\|\eta\| < 2.4$
Distance from primary vertex in z	$\|z_o\| < 1$mm
Impact parameter significance	$\|d_o\| < 3\sigma_{do}$
Track momentum isolation in cone of $\Delta R < 0.3$	$< 0.05\ p_T$
Track energy isolation in cone of $\Delta R < 0.3$	$< 0.05\ p_T$
Neutrino Requirement	
Missing transverse energy	$E_t^{miss} > 20$ GeV
Reconstructed Mass Requirement	
W transverse mass	$m_T(W) > 40$ GeV

Inclusive $W^{\pm}$ sample – Adjustments Applied

<u>Backgrounds Subtracted</u>

Modeled by processing MC in the same way as data:
- W-> eν
- W-> τν
- Z -> ee,μμ, $\tau\tau$
- Single t
- Diboson (ZZ,WW,WZ)
- $t\bar{t}$

Data driven estimation:
- QCD/multi-jet

<u>MC corrections applied to better model the data</u>
- Pileup Weight
- z Vertex Weight
- Trigger Weight
- Muon Efficiency Weight
- Muon p_{T} Smearing

Background Removal, Inclusive $W^{\pm}$ sample: Multi-jet

ABCD Method for multi-jet background determination

Multijet background is too computationally intensive for MC, so a data driven method is used.

Categories

A: $E_T^{miss} < 20$ GeV, $m_T(W) < 40$ GeV, isolated muon

B: $E_T^{miss} < 20$ GeV, $m_T(W) < 40$ GeV, anti-isolated muon

C: $E_T^{miss} > 20$ GeV, $m_T(W) > 40$ GeV, isolated muon (signal region)

D: $E_T^{miss} > 20$ GeV, $m_T(W) > 40$ GeV, anti-isolated muon

Assumption is that this ratio is constant:

D/B = C/A

Muon Isolation Criteria

P = Track isolation momentum in cone of ΔR < 0.3

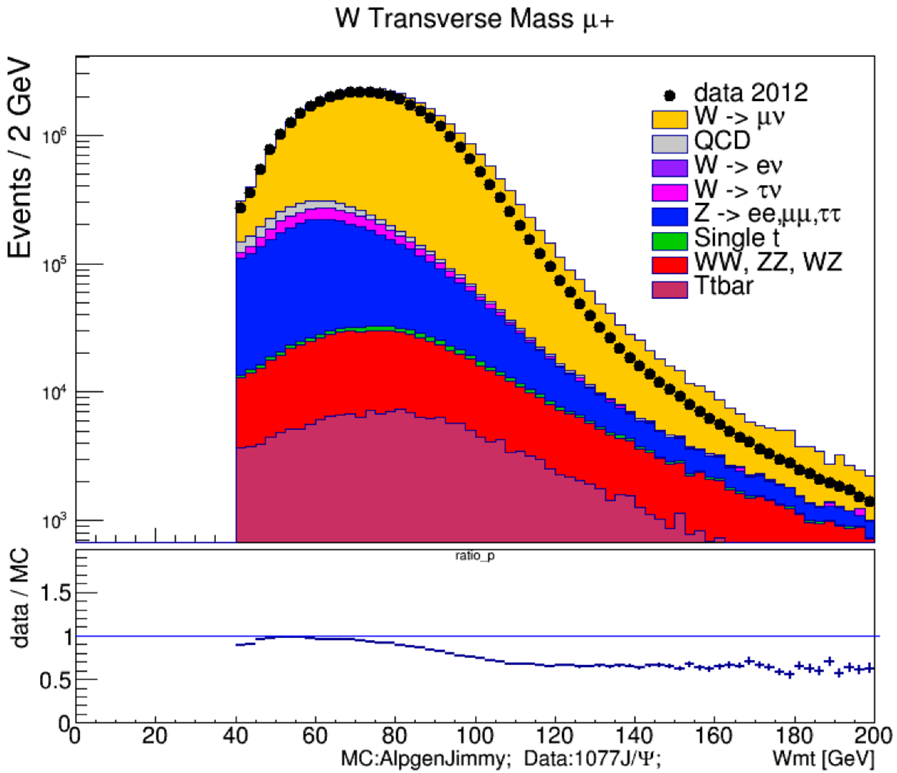
E = Calorimeter isolation energy in cone of ΔR < 0.3

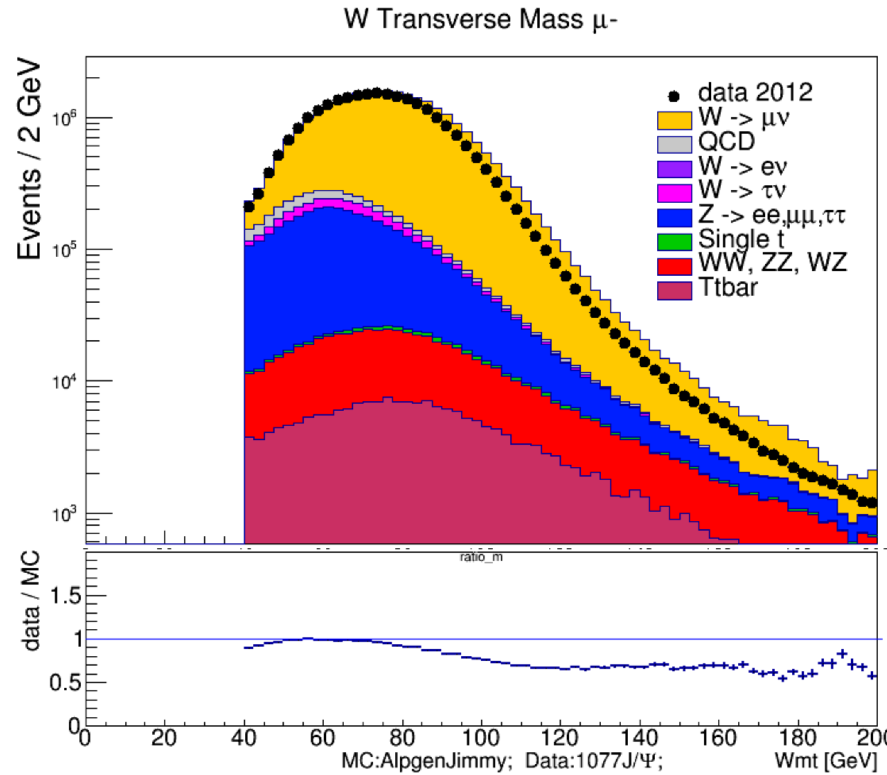
	$P < 0.05p_T$	$P > 0.05p_T$
$E < 0.05p_T$	isolated	
$E > 0.05p_T$		anti-isolated

Method:

1. Subtract events in all other known MC modeled backgrounds from the data events in each region
2. (Events in A)/(Events in B) = muon isolation *fake factor*
3. *fake factor* x D = multi-jet background

Inclusive W Sample





Our total model contains ~90% MC signal and ~10% **backgrounds** (MC backgrounds + ABCD method QCD)

Subtracting **background** events from **data** events gives $(5.21285 \pm 0.00135)\times 10^{7}$ events in the inclusive W sample

Inclusive $W^{\pm}$ Sample Uncertainty Estimation

$$\frac{N_{events} \text{ measured in Data}}{N_{events} \text{ predicted by Model}} = 0.9$$

Assuming our model of just the **backgrounds** is similarly off by the same factor:

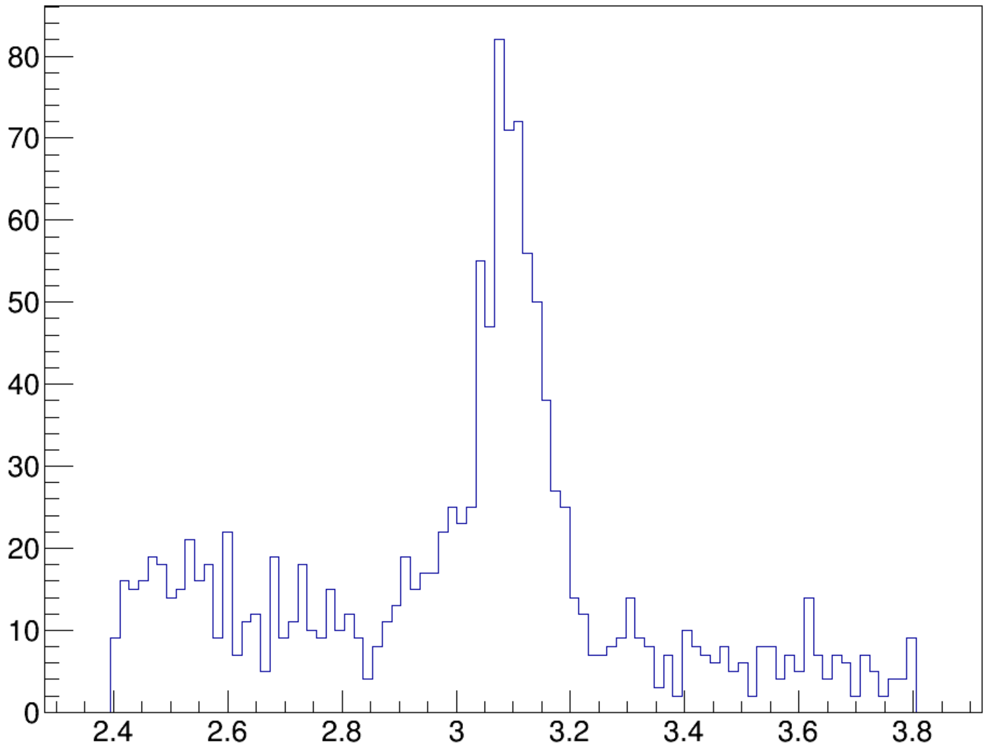
This gives an estimated **~2% systematic uncertainty** on the **Inclusive $W^{\pm}$ yield**

Total number of data events: 6.229×10^7
Total number of events given by model of signal MC +background MC +QCD: 6.919×10^7
Data – (MC backgrounds + QCD)*0.9 = 5.31447×10^7

J/ψ Selections

Individual μ Requirements	
High quality muon	
Transverse momentum	$p_T > 2.5$ GeV for $\|\eta\| > 1.3$
Transverse momentum	$p_T > 3.5$ GeV for $\|\eta\| < 1.3$
Pseudorapidity	$\|\eta\| < 2.5$
Distance from primary vertex in *z*	$\|z_0\| < 10$ mm
μ Pair Requirements	
Opposite charges	
At least one muon detected in both tracker and muon system with	$p_T > 4$ GeV
J/ψ invariant mass	$\in (2.4, 3.8)$ GeV
J/ψ transverse momentum	$p_T > 8.5$ GeV
J/ψ rapidity	$\|y\| \in (0, 2.1)$

J/ψ Candidates (with associated $W^{\pm}$)



$\mu^+\mu^-$ invariant mass [GeV]

Next Steps:

- Identify prompt candidates (not from secondary decays e.g. *b*-hadrons)
- Correct for acceptance and efficiency
- Remove backgrounds

J/ψ (with associated $W^{\pm}$) sample – Adjustments Applied

Backgrounds Estimated and Subtracted

- QCD/multi-jet – Estimated using modified data driven method
- Pileup

Backgrounds Studied and not Observed:

- W-> eν,τν; Z -> ee,μμ, ττ; Single top; Diboson (ZZ,WW,WZ); $t\bar{t}$; $B_c^{\pm} \rightarrow J/\psi\, \ell^{\pm} \nu X$

J/ψ candidates acceptance and efficiency corrections

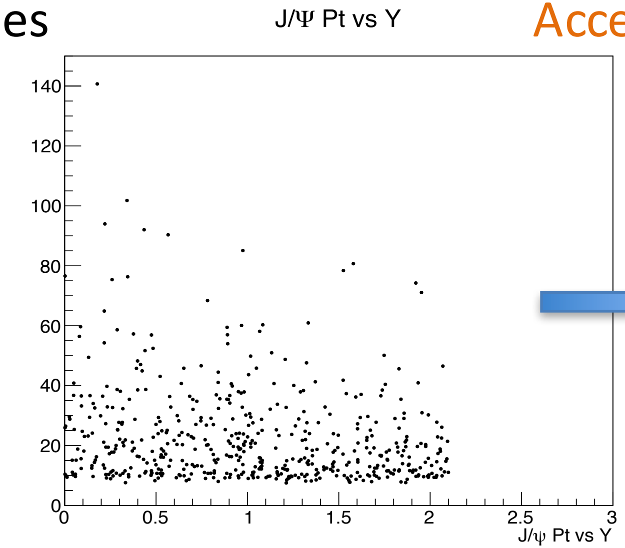
Applied with weighting maps:

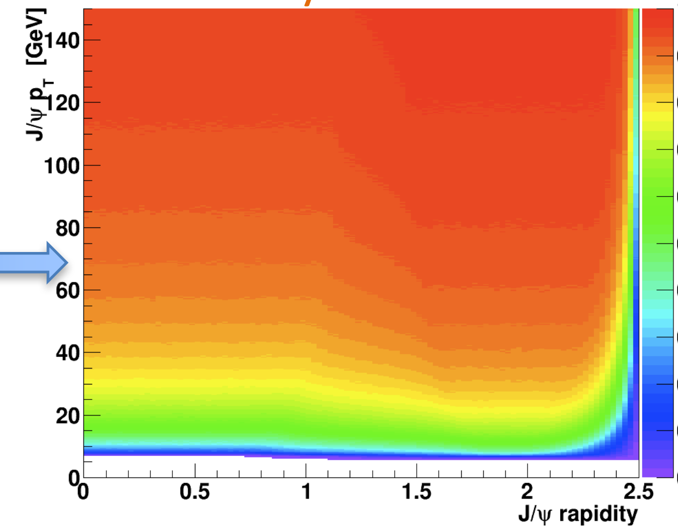
- Acceptance accounts for the unknown J/ψ spin polarization.
- Efficiency corrects the detector's ability to measure muons.

J/ψ candidates

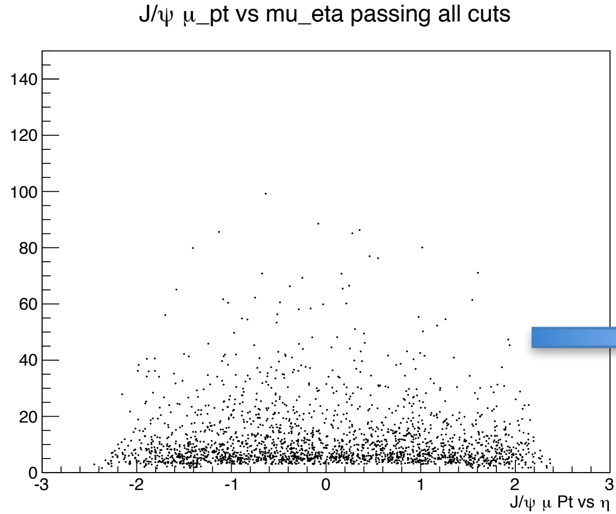
Acceptance and Efficiency Corrections

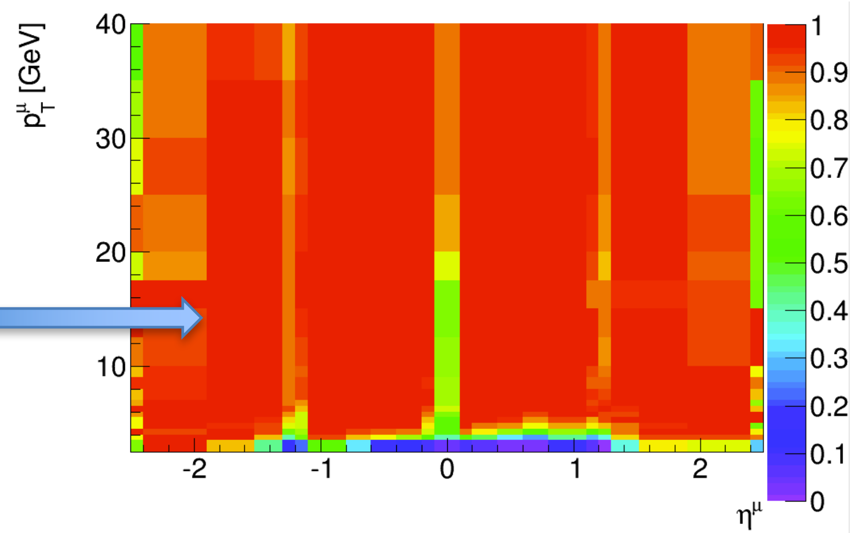
Each J/ψ candidate is weighted based on p_T and rapidity by an acceptance (spin polarization) map.





Each J/ψ candidate muon is weighted based on p_T and η by an efficiency map.





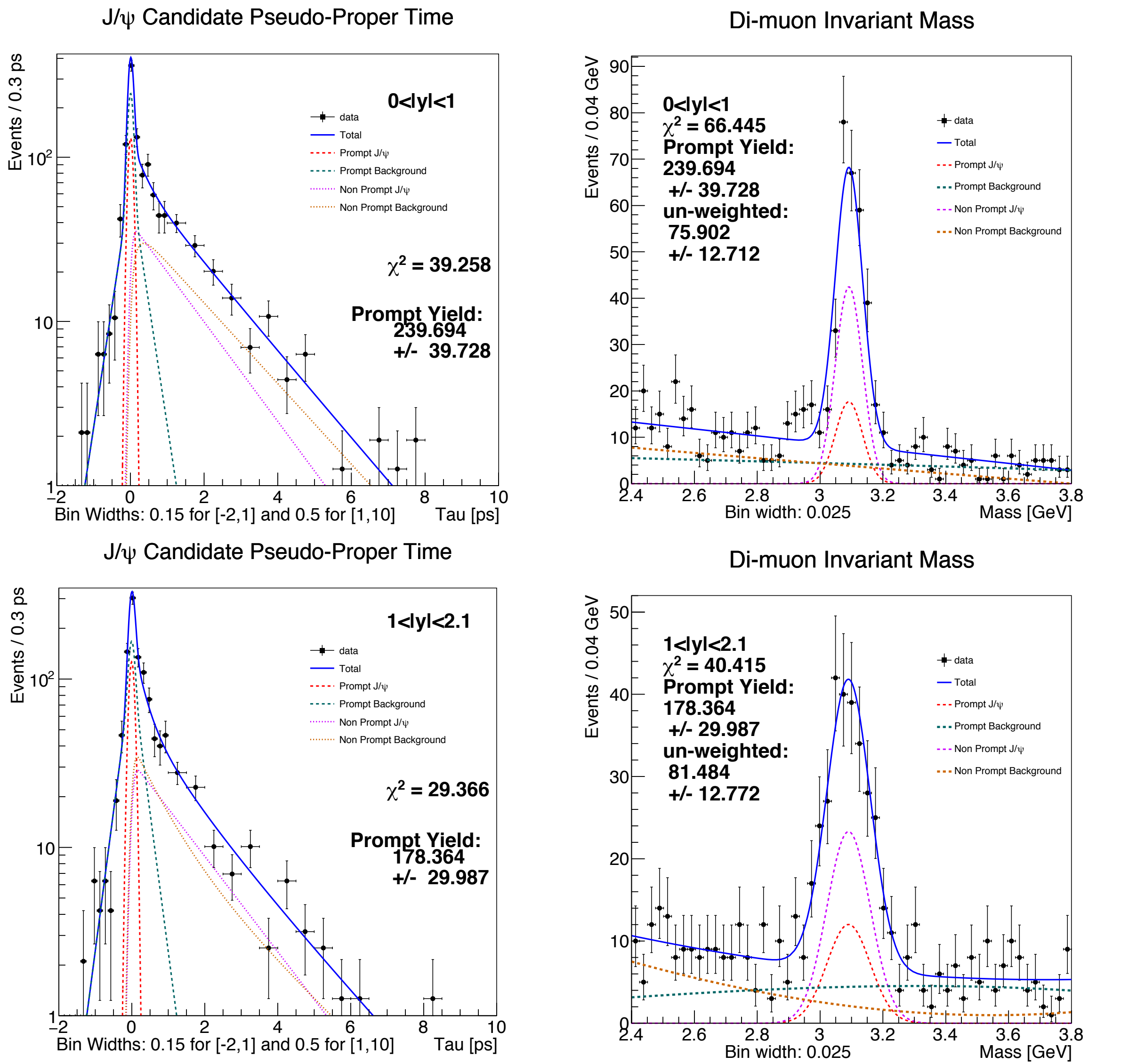
J/ψ Yield

A two-dimensional, unbinned, simultaneous, maximum likelihood fit in mass and lifetime was performed to separate out the prompt J/ψ component.

Fit performance verified with independent, higher statistics data sample. Nominal fit parameters:

- Mass peak fixed
- Mass backgrounds 2nd O pol

Two rapidity (y) regions because of differing resolutions.



Background Removal, Associated $J/\psi + W^{\pm}$: QCD/Multi-jet

Data driven ABCD method

Region D prompt J/ψ events = 25 ± 11

J/ψ + W sample *fake factor* = A/B = 0.150 ± 0.015

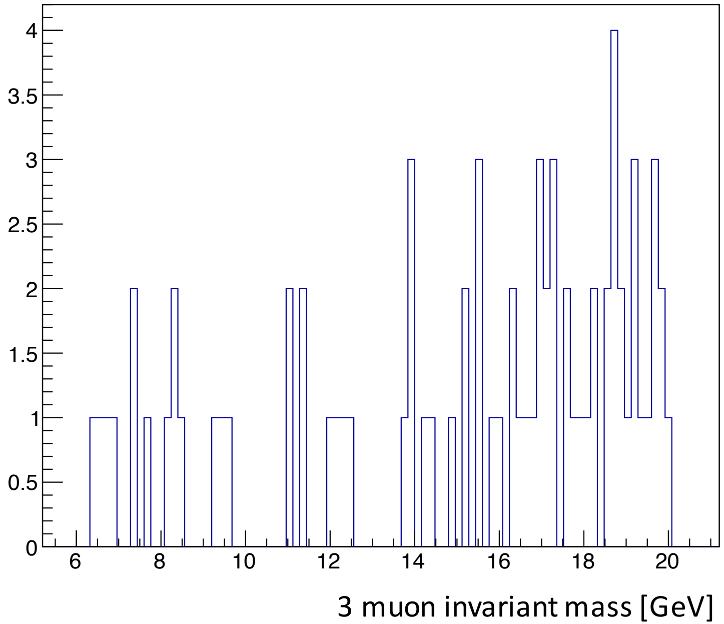
# of signal events in J/ψ + W sample = 417 ± 28

QCD fraction = D x A/B ÷ signal = 0.8 +/- 0.4%

→ QCD background = 4±2 events

Background Removal, Associated $J/\psi + W^{\pm}$: $B^{\pm}_{c}$ decays

- The $B^{\pm}_{c}$ meson decay can mimic the $J/\psi + W^{\pm}$ signature.
- The $B^{\pm}_{c}$ has a short lifetime, so it can appear like a prompt signal.
- The invariant mass of the $W^{\pm}$ muon and the two J/ψ muons is calculated.



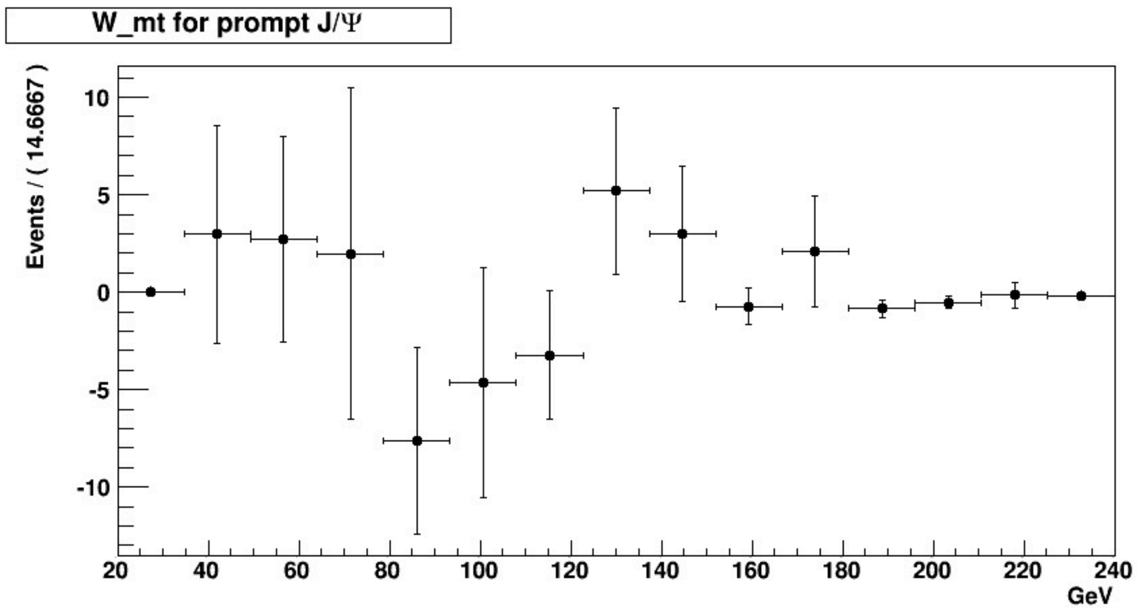
$$B_c^{\pm} \rightarrow J/\psi \; l^{\pm} \nu X$$

- $B^{\pm}_{c}$ mass = 6.277±0.006 GeV.
- All measured masses of M(3μ) alone are > 6.3 GeV,

No backgrounds are observed.

Background Removal, Associated J/ψ + $W^{\pm}$: MC backgrounds

W→eν ; W→τν ; Z→ee ; Z→μμ ; Z→ττ ; Diboson ; single top; $t\bar{t}$



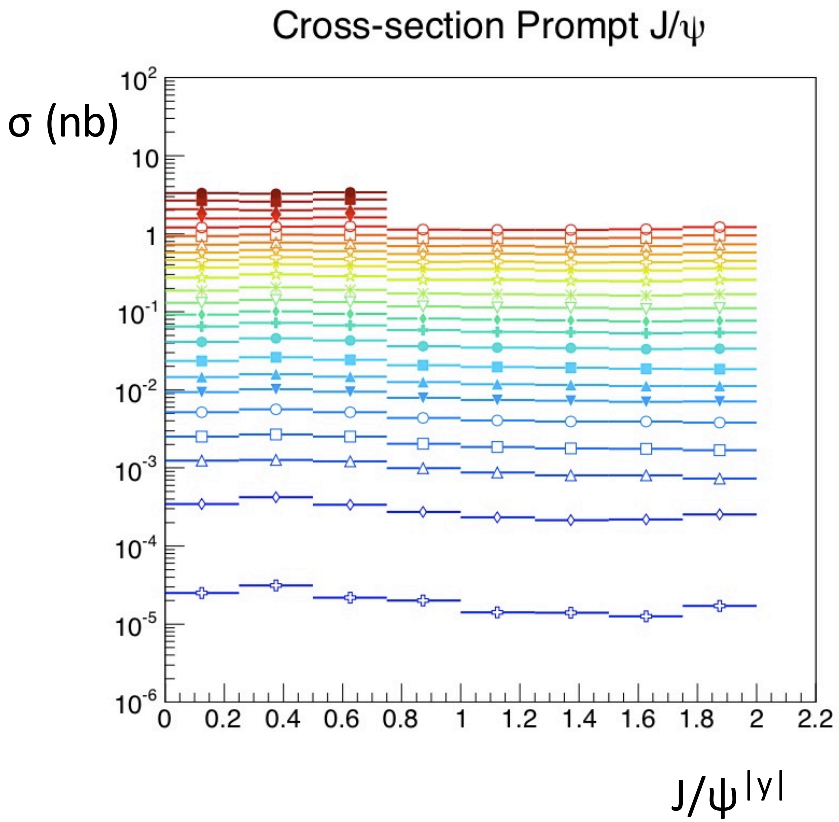
- The MC background samples were processed identically to the data, plot shows the number of prompt J/ψ+W events present is consistent with zero.

Background Removal, Associated J/ψ + $W^{\pm}$: Pileup

Pileup means that the J/ψ and $W^{\pm}$ particles were produced in two different *proton-proton* collisions.

Begin with J/ψ→μμ cross section measured by ATLAS
arxiv.org/abs/1512.03657v1

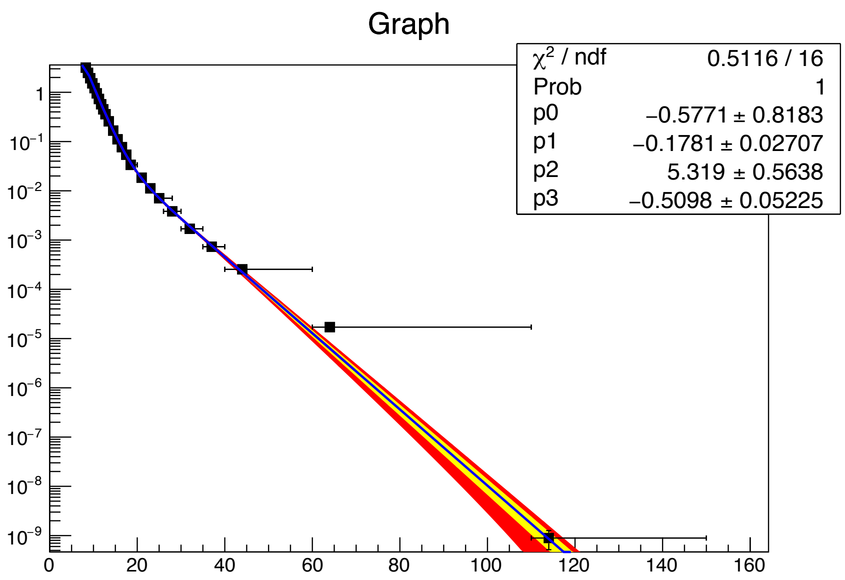
But we must extrapolate their measurements to J/ψ^{pT} = 150 GeV and $J/\psi^{|y|}$ = 2.1.



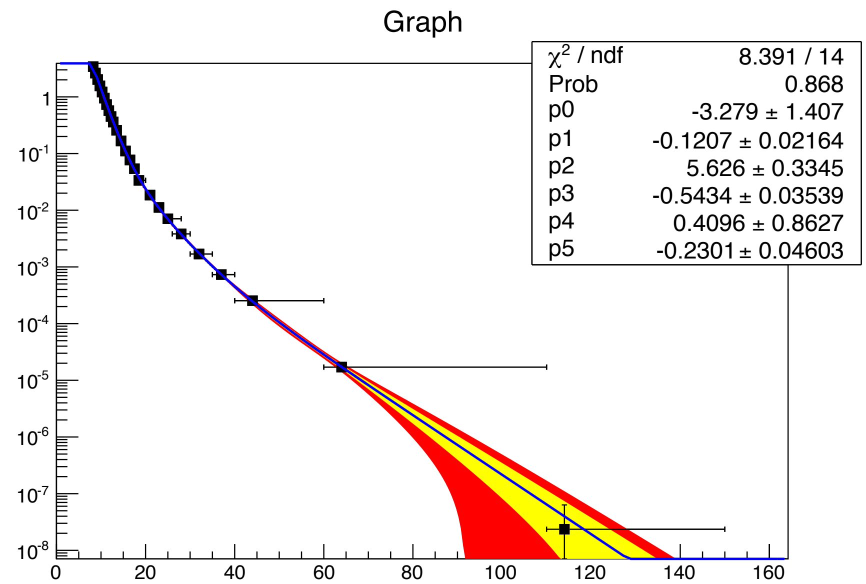
(colors show different J/ψ^{pT} bins in the range 8 – 110. GeV)

Background Removal, Associated J/ψ + W ± : Pileup

J/Ψ→μμ Cross Section Extrapolations

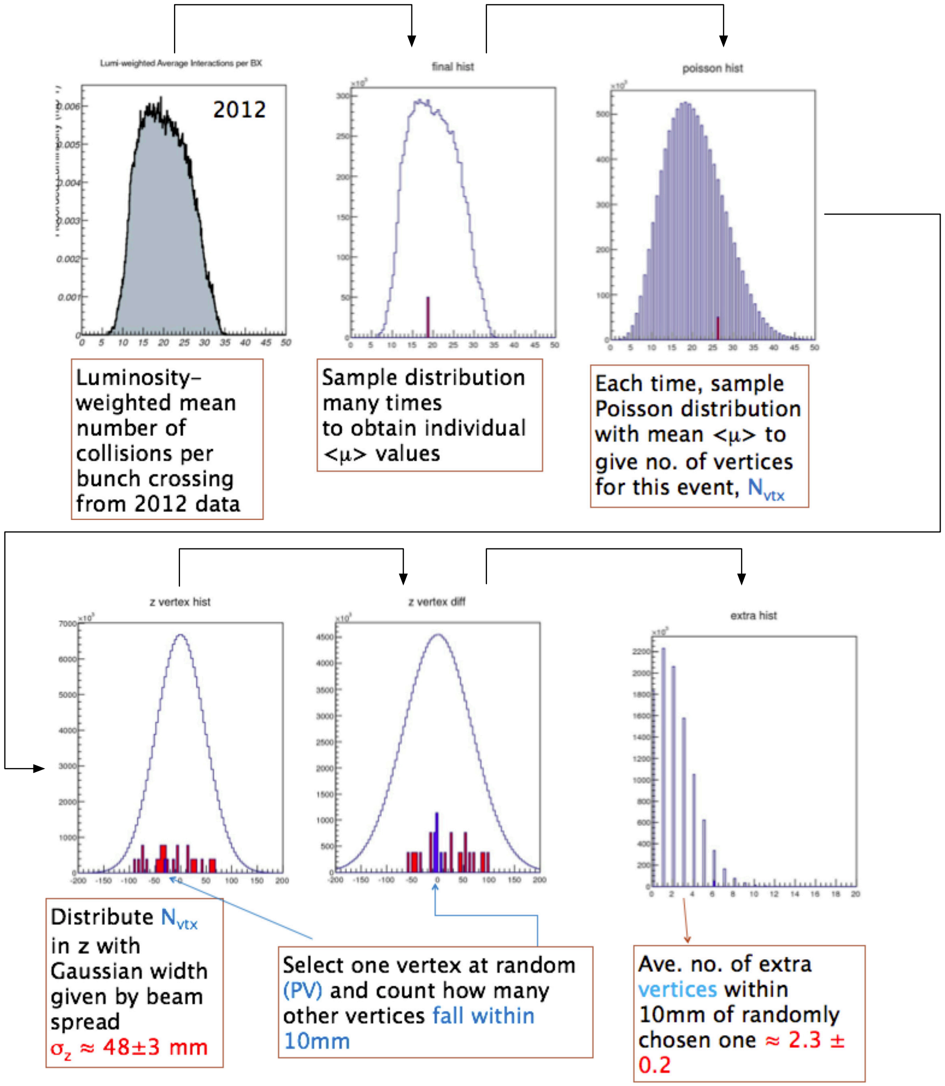


Double exponential fit J/ψ^{pT}



Triple exponential fit J/ψ^{pT}

Background Removal, Associated $J/\psi + W^{\pm}$: Pileup



MC strategy used to determine average number of extra pileup vertices $\approx 2.3 \pm 0.2$

Associated J/ψ + $W^{\pm}$: Pileup Background

Calculated in 2 y and 6 p_T bins:

J/ψ -> μμ cross section measurement
× average number of extra pileup vertices (2.3)
÷ inclusive cross section (0.73×10^{-8} b)
× average inclusive J/ψ <acceptance x efficiency>
× inclusive $W^{\pm}$ yield (5.21×10^{7})

➔ 7.9±0.3 pileup events

Associated J/ψ + $W^{\pm}$: Systematic Uncertainty

Mass Fit

Estimated by taking the divergence between the cross-section ratio calculated with a nominal fit and an alternate fit.

- Nominal: single Gaussian for signal, 2^{nd} order polynomial for the backgrounds
- Alternative 1: Introduce a ψ(2S) mass peak into the fit model
- Alternative 2: let the J/ψ mass peak float
- Alternative 3: exponential background functions

Results: 9.5% and 3.9% (for $|y_{J/\psi}| < 1$, $1 < |y_{J/\psi}| < 2.1$)

Pileup

Events due to pileup determined to be 7.89 +/- 0.25. We calculate the result subtracting the max(min) values and then take the difference from the nominal result as a systematic.

Results: 0.1% and 0.3% (for $|y_{J/\psi}| < 1$, $1 < |y_{J/\psi}| < 2.1$)

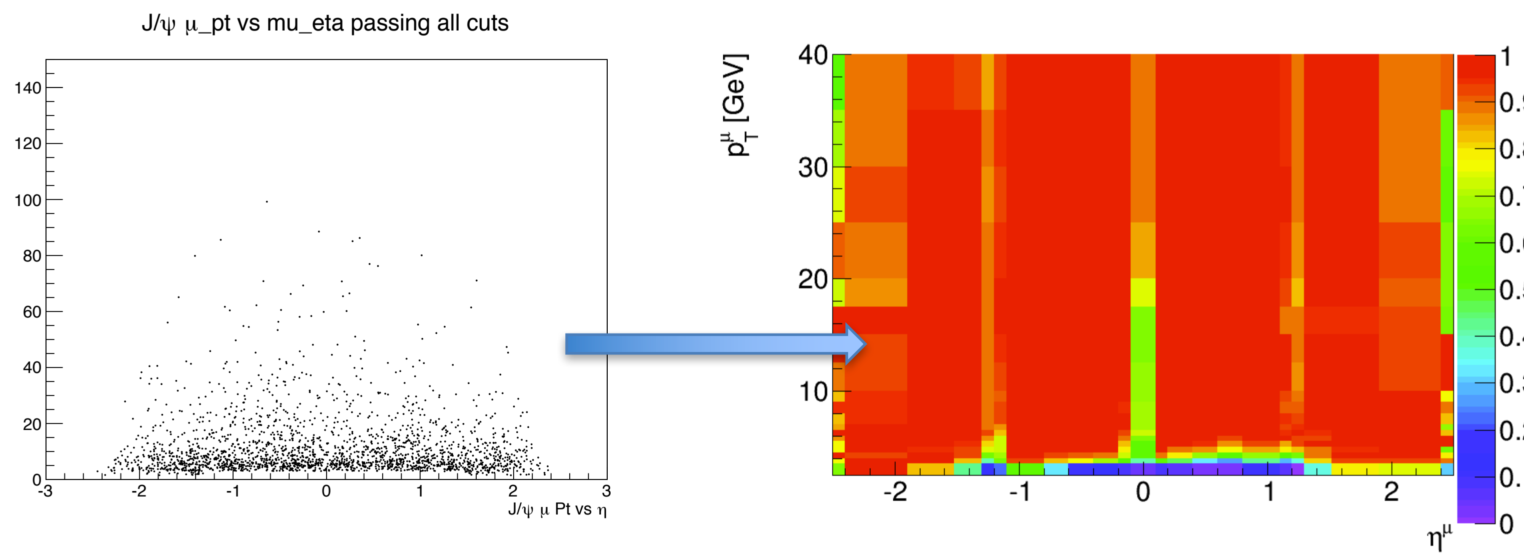
Associated J/ψ + $W^{\pm}$: Systematic Uncertainty

J/ψ muon efficiency

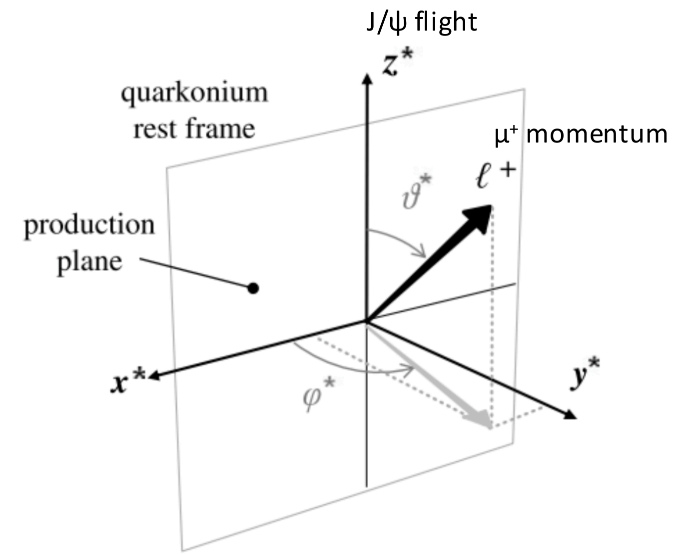
Randomly sample J/ψ muon efficiency from a Gaussian distribution about the nominal value.

Repeat 100 times, the deviation between the mean of this result and the nominal result is taken as a systematic uncertainty.

Results: 1.2% and 0.9% (for $|y_{J/\psi}| < 1$, $1 < |y_{J/\psi}| < 2.1$)



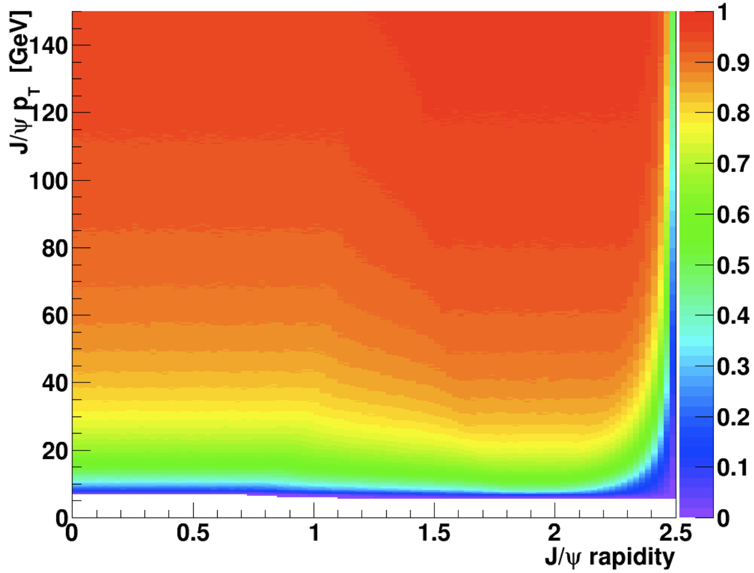
Associated J/ψ + $W^{\pm}$: Systematic Uncertainty



J/ψ Acceptance

The maximum difference in alternate results compared to the nominal is used as a systematic.

Results: 30.0% and 25.4% (for $|y_{J/\psi}| < 1$, $1 < |y_{J/\psi}| < 2.1$)



J/ψ → $\mu^+\mu^-$ angular distribution:

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

1. Isotropic (nominal): $\lambda_\theta = \lambda_\phi = \lambda_{\theta\phi} = 0$
2. Longitudinal: $\lambda_\theta = -1$, $\lambda_\phi = \lambda_{\theta\phi} = 0$
3. Transverse-0: $\lambda_\theta = +1$, $\lambda_\phi = \lambda_{\theta\phi} = 0$
4. Transverse-M: $\lambda_\theta = +1$, $\lambda_\phi = -1$, $\lambda_{\theta\phi} = 0$
5. Transverse-P: $\lambda_\theta = \lambda_\phi = +1$, $\lambda_{\theta\phi} = 0$

Systematic Uncertainty Summary

Source of Uncertainty	Percent Contribution	
	$\lvert y_{J/\psi}\rvert < 1$	$1 < \lvert y_{J/\psi}\rvert < 2.1$
J/ψ mass fit	9.5%	3.9%
$\mu_{J/\psi}$ efficiency	1.2%	0.9%
Pileup	0.1%	0.3%
Inclusive W yield	1.9%	1.9%
J/ψ spin-alignment	30.0%	25.4%

Associated J/ψ + $W^{\pm}$: DPS Contribution Estimation

Assume:

1) Two uncorrelated hard scatters
2) σ_{eff} is process-independent

Then: probability of both J/ψ and $W^{\pm}$ = $$P^{ij}_{J/\psi|W} = \frac{\sigma_{J/\psi}}{\sigma_{\text{eff}}}$$

Calculated in 2 y and 6 p_T bins:

J/ψ -> μμ cross section measurement

÷ σ_{eff} (15 mb, from W+2 jet ATLAS measurement)

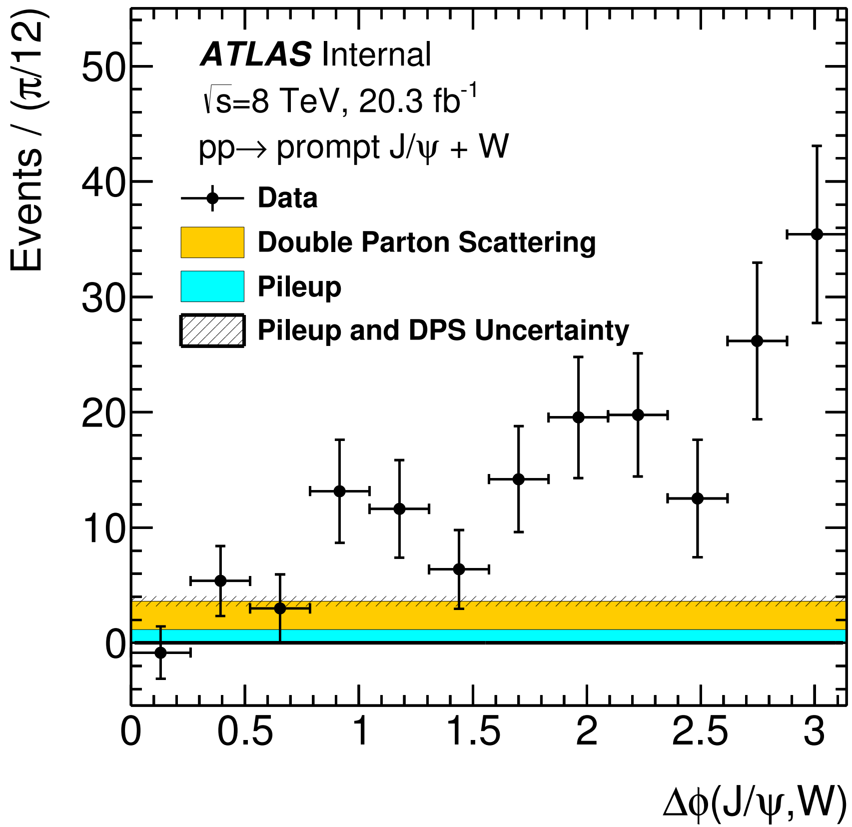
÷ bin size in $|y|$ × p_T space

× average inclusive J/ψ <acceptance x efficiency>

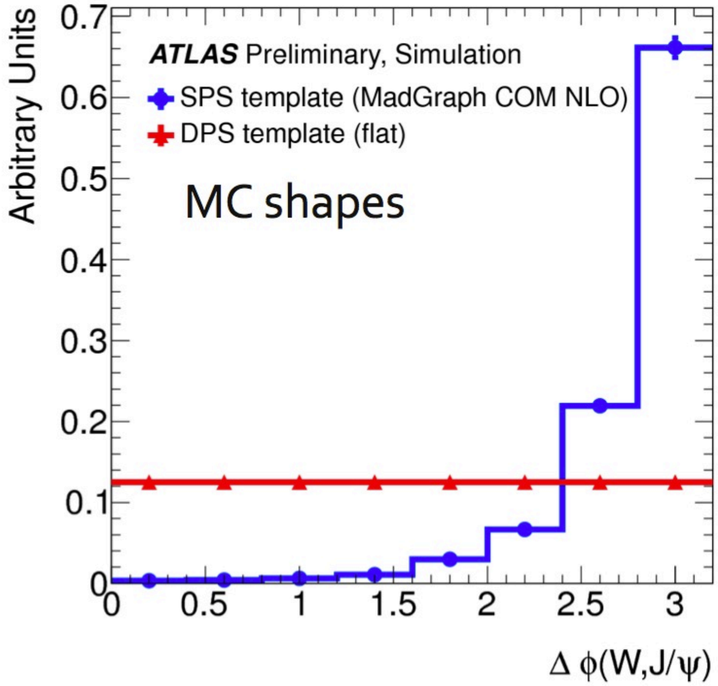
× inclusive $W^{\pm}$ yield (5.21×10^{7})

➔ 34.3±5.7 DPS events

SPS and DPS contribution

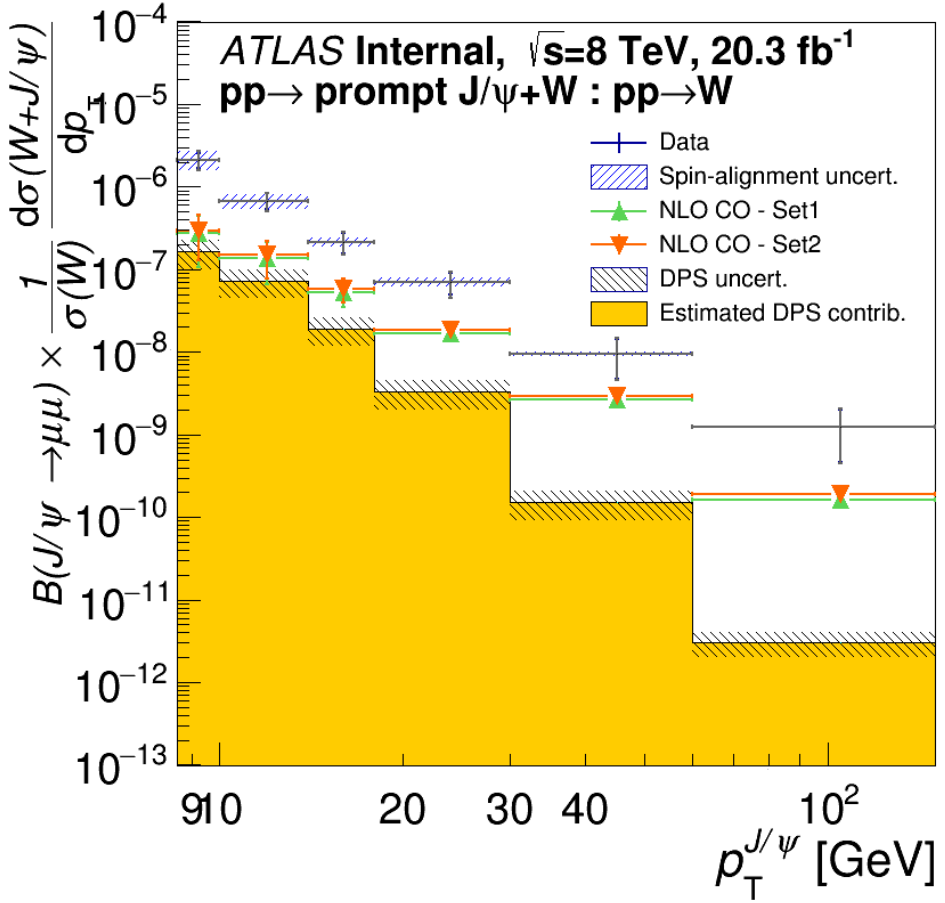


Δϕ(J/ψ,W) for prompt J/ψ +W events, showing the DPS contribution in yellow.

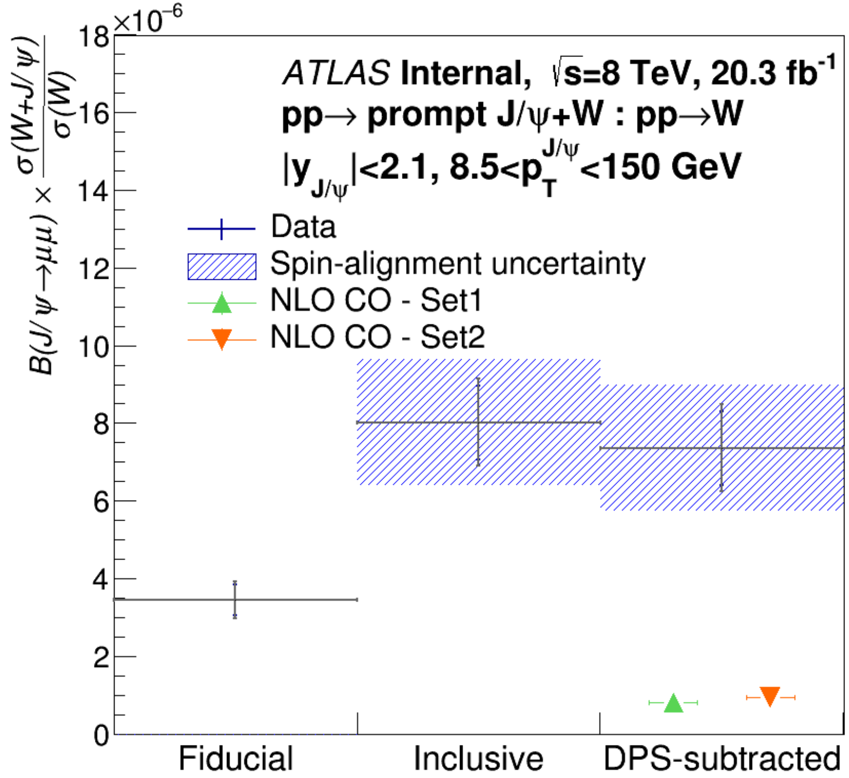


Single parton scattering (SPS) peaks at π rad, and DPS is flat.

Differential Results



The inclusive differential cross section ratio for $|y|<2.1$ is shown in 6 $p_T^{J/\psi}$ bins.



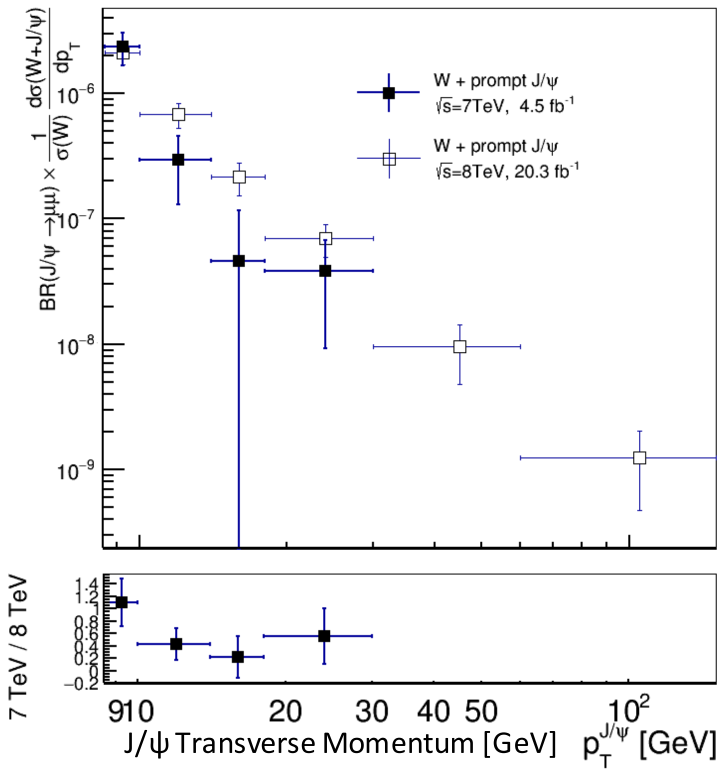
Total Results

A total integrated cross section ratio is also calculated using three different methods:

1. *Fiducial* only corrects for J/ψ muon efficiency
2. *Inclusive* corrects for J/ψ muon efficiency and J/ψ spin acceptance
3. *DPSsub* removes double parton scattering events to compare with theory

$y_{J/\psi}$	Fiducial $[\times10^{-6}]$ value ± (stat) ± (syst)	Inclusive $[\times10^{-6}]$ value ± (stat) ± (syst) ± (spin)	DPS-subtracted $[\times10^{-6}]$ value ± (stat) ± (syst) ± (spin)
$\|y_{J/\psi}\| < 1.0$	$1.78 \pm 0.29 \pm 0.23$	$4.60 \pm 0.76 \pm 0.45 \pm 1.38$	$4.33 \pm 0.76 \pm 0.45 \pm 1.38$
$1.0 < \|y_{J/\psi}\| < 2.1$	$1.67 \pm 0.28 \pm 0.10$	$3.42 \pm 0.58 \pm 0.40 \pm 0.87$	$3.03 \pm 0.58 \pm 0.40 \pm 0.87$

Inclusive Differential Cross section Measurements



Comparison with theory and 7 TeV measurement

	Theory, Color Octet	Measurement $\pm$ stat $\pm$ syst $\pm$ pol
7 TeV	$(22.68 \pm 3.36) \times 10^{-8}$	$(328 \pm 134 \pm 92^{+172}_{-105}) \times 10^{-8}$
8 TeV	$(81.282 \pm 3.251) \times 10^{-8}$	$(736 \pm 96 \pm 61 \pm 163) \times 10^{-8}$
8 TeV†	$(94.408 \pm 3.776) \times 10^{-8}$	

DPS-Subtracted Cross-Section Ratio Numbers

†Alternate polarization set

	7TeV/ 8TeV Results Ratio
Theory (NLO CO set 1)	0.279 ± 0.043
(NLO CO set 2)	0.240 ± 0.037
Measurement	0.446 ± 0.191

Theory consistently under-predicts the measurements.

Conclusions

- A measurement of the cross section ratio $R_{J/\psi} \equiv \frac{\sigma_{W+J/\psi}}{\sigma_W}$ is presented.

- Currently only theory predictions for single parton scattering in the color octet model are available, these results can be compared to new theory predictions as they develop.

- Theory numbers for both 7 TeV and 8 TeV underpredict measurements by the same amount within statistical errors.

- An estimated 8.2 ± 1.9 % of signal events are due to double parton scattering.

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Backup Information

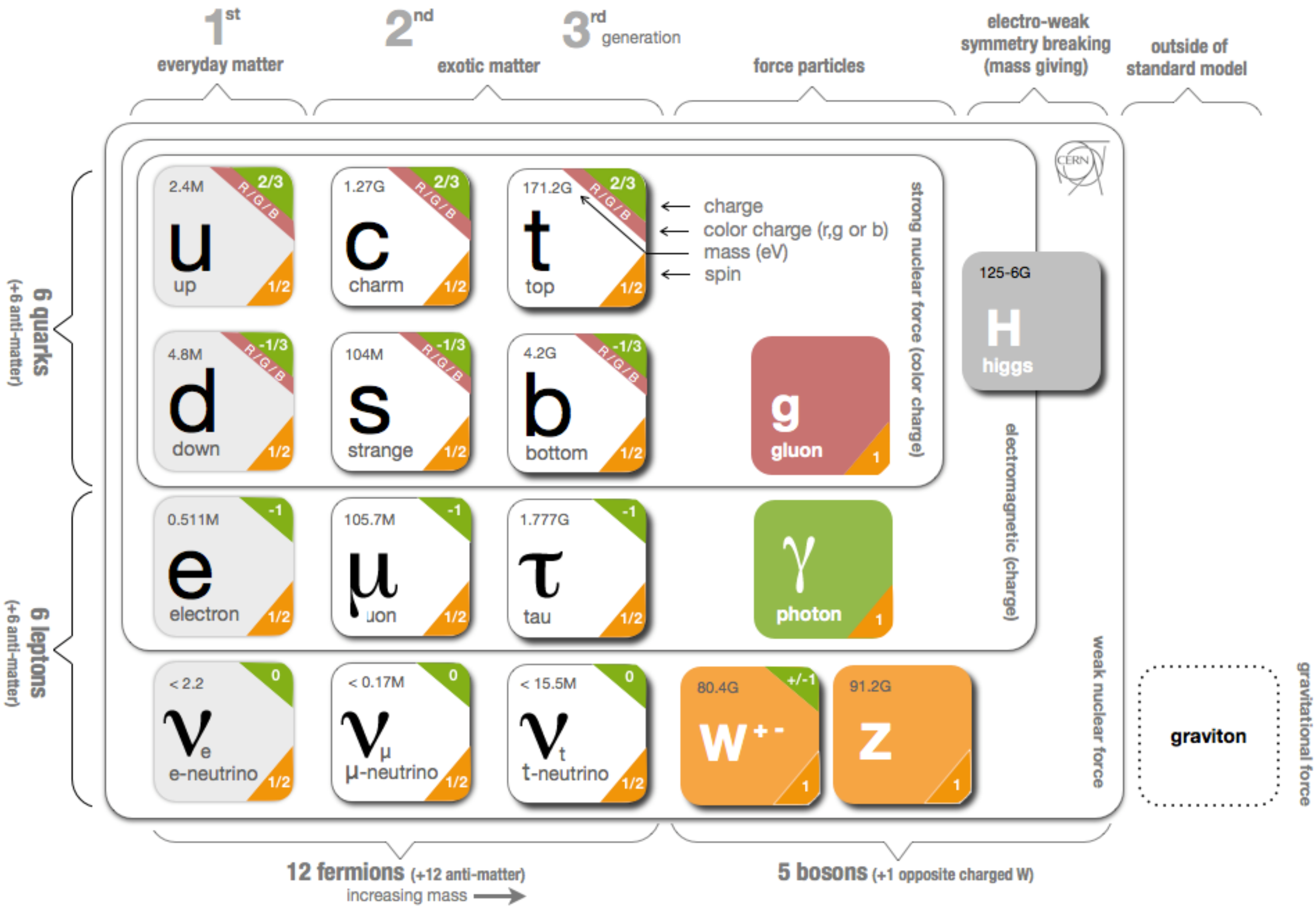
Particle Physics - What is everything made of and what holds it together?

- 460 - 370 B.C. **Democritus** — All matter is made of indivisible particles called **atoms**
- 1773 - 1829 **Thomas Young** — **Wave** theory of light
- 1874 **George Stoney** — Theorizes the **electron**, estimates its mass
- 1895 **Wilhelm Röntgen** — Discovers x rays
- 1898 **Joseph Thompson** — Measures the **electron**, develops "plum-pudding" model of the atom
- 1919 **Ernest Rutherford** — First evidence for a **proton**
- 1921 **James Chadwick** and **E.S. Bieler** — **Strong force** holds the nucleus together.
- 1923 **Arthur Compton** — Discovers the **quantum** (particle) nature of x rays, photons are particles
- 1924 **Louis de Broglie** — Proposes that matter has **wave properties**
- 1930 **Wolfgang Pauli** — **Neutrino** explains the continuous electron spectrum for beta decay
- 1931 **Paul Dirac** — Proposes positron, first **antiparticle**
- 1937 **Anderson and Neddermeyer** — **Muon** discovered in cosmic rays

- 1953 --- *Beginning of a proliferation of particle discoveries* ---

- 1968-69 **James Bjorken**, **Richard Feynman** — Propose **quark** model based on SLAC data
- 1974 **Samuel Ting**, **Burton Richter** — Separately discover **J/ψ particle** on the same day
- 1976 **Martin Perl** — **τ lepton** unexpectedly discovered at SLAC.
- 1977 **Leon Lederman** — **Bottom quark** discovered at Fermilab
- 1983 **Carlo Rubbia**, **Simon Van der Meer** — **$W^{\pm}$ and Z^0** bosons discovered at CERN
- 1995 **CDF and D0 experiments** — **Top quark** discovered at Fermilab
- 2012 **ATLAS and CMS experiments** — **Higgs** boson discovered at CERN

Backup: SM



1st
everyday matter
2nd
exotic matter
3rd generation
force particles
electro-weak symmetry breaking (mass giving)
outside of standard model
6 quarks (+6 anti-matter)
6 leptons (+6 anti-matter)
2.4M u up 2/3 R/G/B 1/2
1.27G c charm 2/3 R/G/B 1/2
171.2G t top 2/3 R/G/B 1/2
charge
color charge (r,g or b)
mass (eV)
spin
4.8M d down -1/3 R/G/B 1/2
104M s strange -1/3 R/G/B 1/2
4.2G b bottom -1/3 R/G/B 1/2
g gluon 1
strong nuclear force (color charge)
125-6G H higgs
0.511M e electron -1 1/2
105.7M μ μon -1 1/2
1.777G τ tau -1 1/2
γ photon 1
electromagnetic (charge)
< 2.2 ν e-neutrino 0 1/2
< 0.17M ν μ-neutrino 0 1/2
< 15.5M ν t-neutrino 0 1/2
80.4G W+- +/-1 1
91.2G Z 1
weak nuclear force
graviton
gravitational force
CERN
12 fermions (+12 anti-matter)
increasing mass
5 bosons (+1 opposite charged W)

$J/\psi(1S)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	hadrons	(87.7 ± 0.5) %	
Γ_2	virtual $\gamma \to$ hadrons	(13.50 ± 0.30) %	
Γ_3	ggg	(64.1 ± 1.0) %	
Γ_4	γgg	(8.8 ± 0.5) %	
Γ_5	$e^+ e^-$	(5.94 ± 0.06) %	
Γ_6	$\mu^+ \mu^-$	(5.93 ± 0.06) %	

Decays involving hadronic resonances

Γ_7	$\rho\pi$	(1.69 ± 0.15) %	S=2.4
Γ_8	$\rho^0 \pi^0$	$(5.6 \pm 0.7) \times 10^{-3}$	
Γ_9	$a_2(1320)\rho$	(1.09 ± 0.22) %	
Γ_{10}	$\omega\pi^+\pi^+\pi^-\pi^-$	$(8.5 \pm 3.4) \times 10^{-3}$	
Γ_{11}	$\omega\pi^+\pi^-\pi^0$	$(4.0 \pm 0.7) \times 10^{-3}$	
Γ_{12}	$\omega\pi^+\pi^-$	$(8.6 \pm 0.7) \times 10^{-3}$	S=1.1

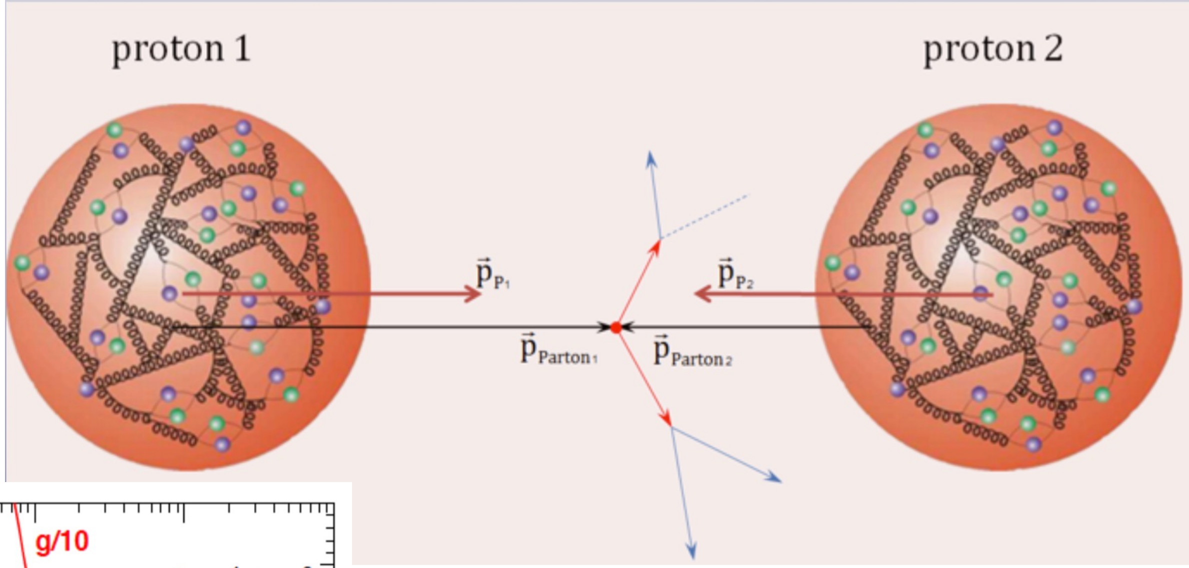
W^+ DECAY MODES

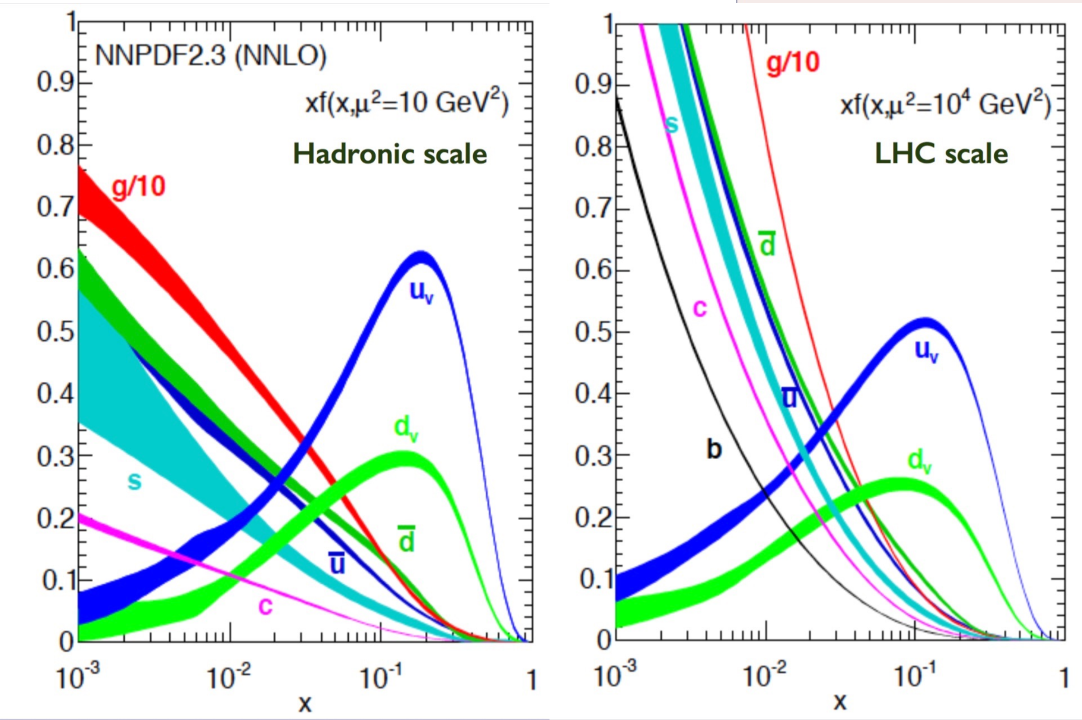
W^- modes are charge conjugates of the modes below.

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\ell^+\nu$	[a]	(10.80 ± 0.09) %	
Γ_2	$e^+\nu$		(10.75 ± 0.13) %	
Γ_3	$\mu^+\nu$		(10.57 ± 0.15) %	
Γ_4	$\tau^+\nu$		(11.25 ± 0.20) %	
Γ_5	hadrons		(67.60 ± 0.27) %	
Γ_6	$\pi^+\gamma$		$< 8 \times 10^{-5}$	95%
Γ_7	$D_s^+\gamma$		$< 1.3 \times 10^{-3}$	95%
Γ_8	cX		(33.4 ± 2.6) %	
Γ_9	$c\bar{s}$		$(31 {}^{+13}_{-11})$ %	
Γ_{10}	invisible	[b]	(1.4 ± 2.9) %	

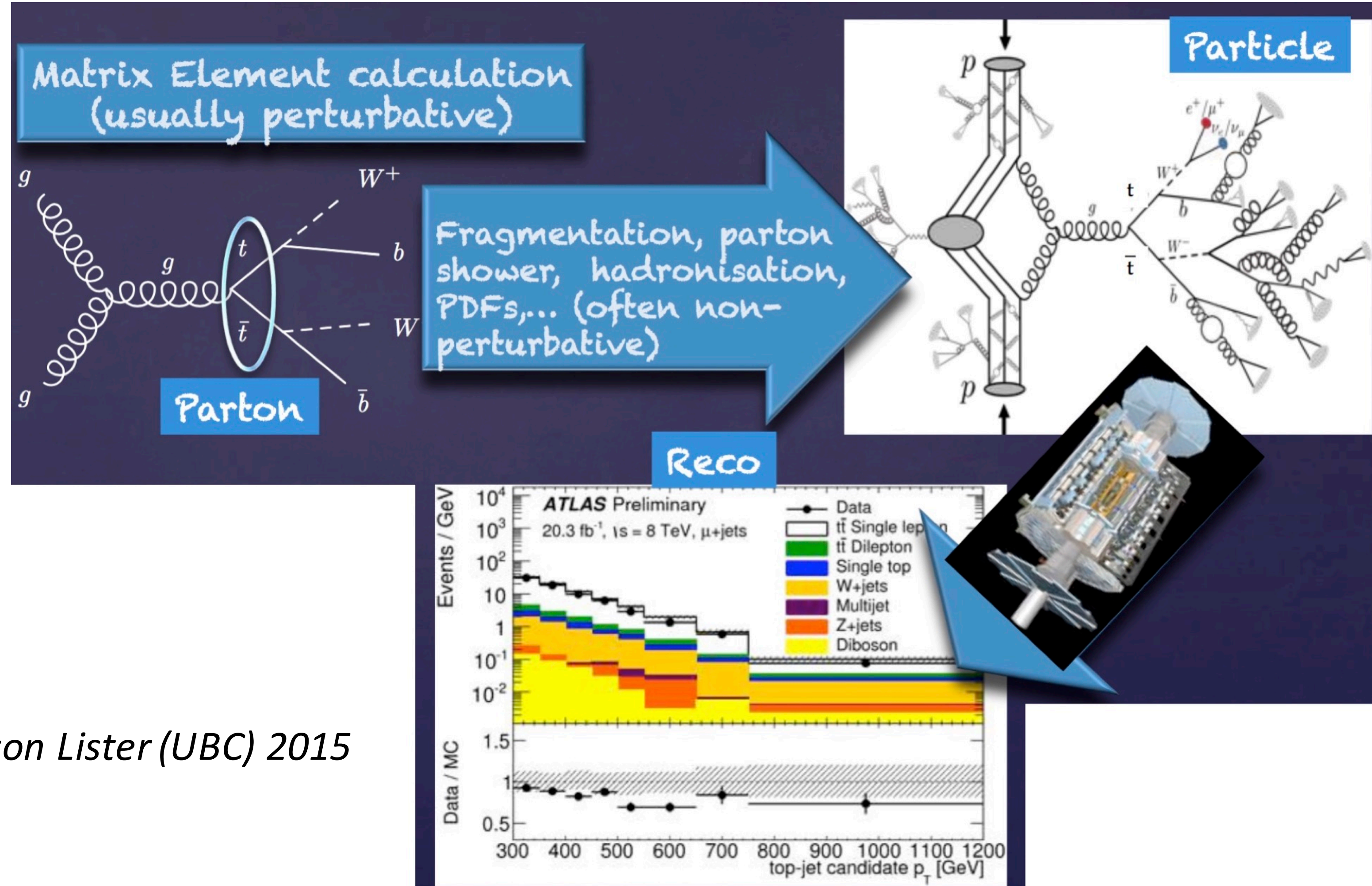
[a] ℓ indicates each type of lepton (e, μ, and τ), not sum over them.

[b] This represents the width for the decay of the W boson into a charged particle with momentum below detectability, $p < 200$ MeV.


proton 1
proton 2
$\vec{p}_{P_1}$
$\vec{p}_{P_2}$
$\vec{p}_{Parton_1}$
$\vec{p}_{Parton_2}$

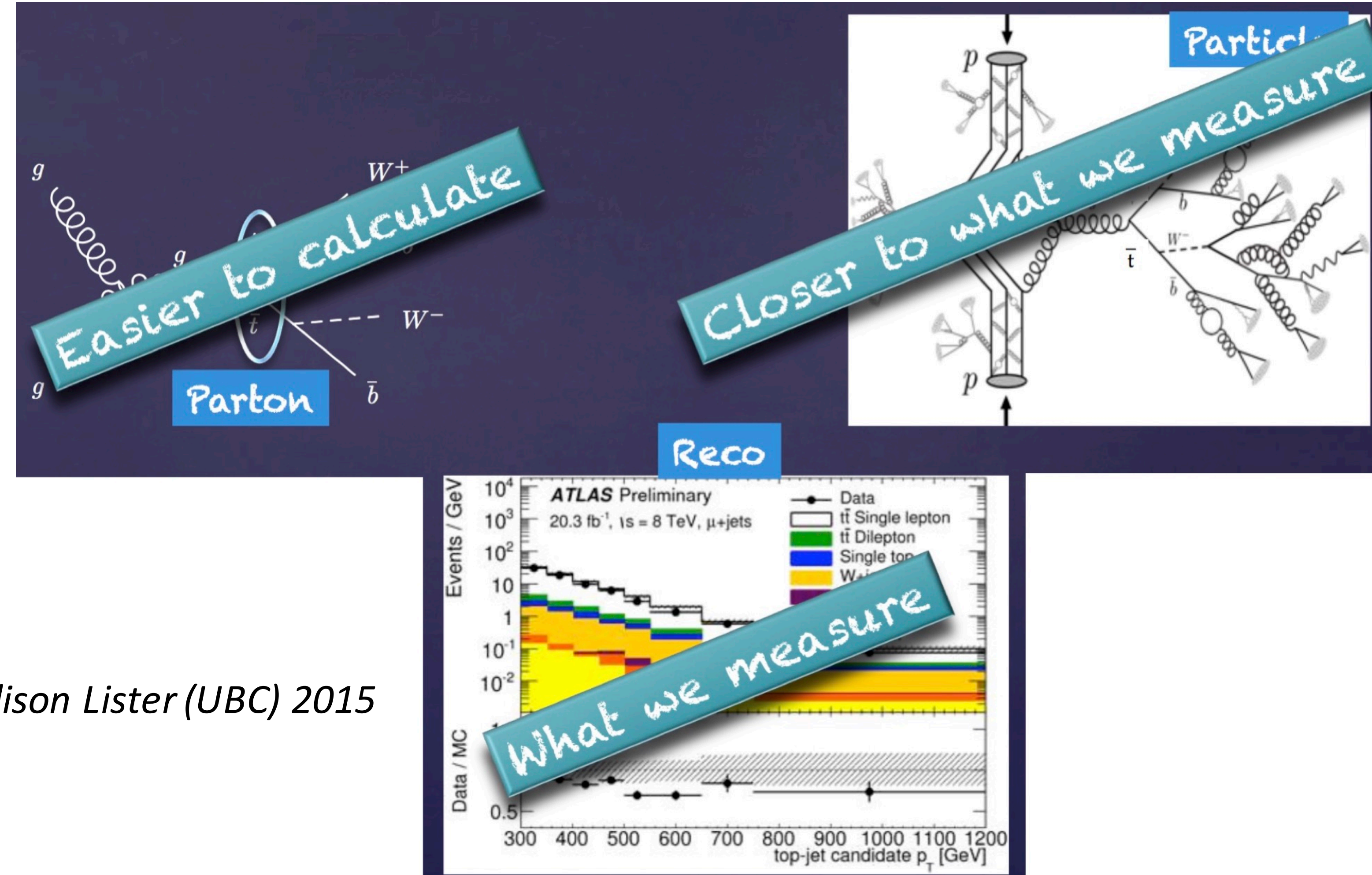

NNPDF2.3 (NNLO)
$xf(x,\mu^2=10\ GeV^2)$
Hadronic scale
g/10
u_v
d_v
s
$\bar{d}$
$\bar{u}$
c
$xf(x,\mu^2=10^4\ GeV^2)$
LHC scale
g/10
s
$\bar{d}$
c
u_v
$\bar{u}$
b
d_v
x
x

Particle Level



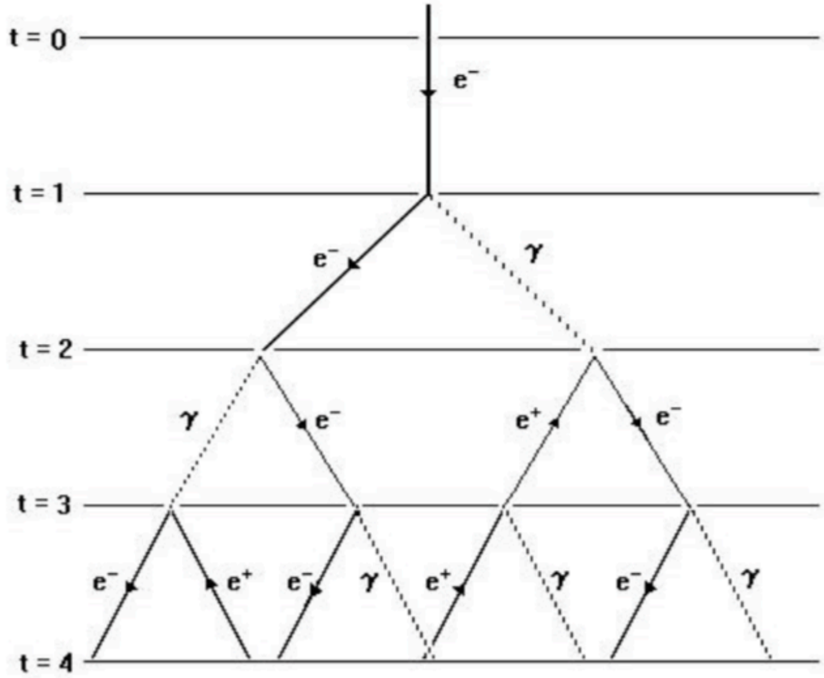
Alison Lister (UBC) 2015

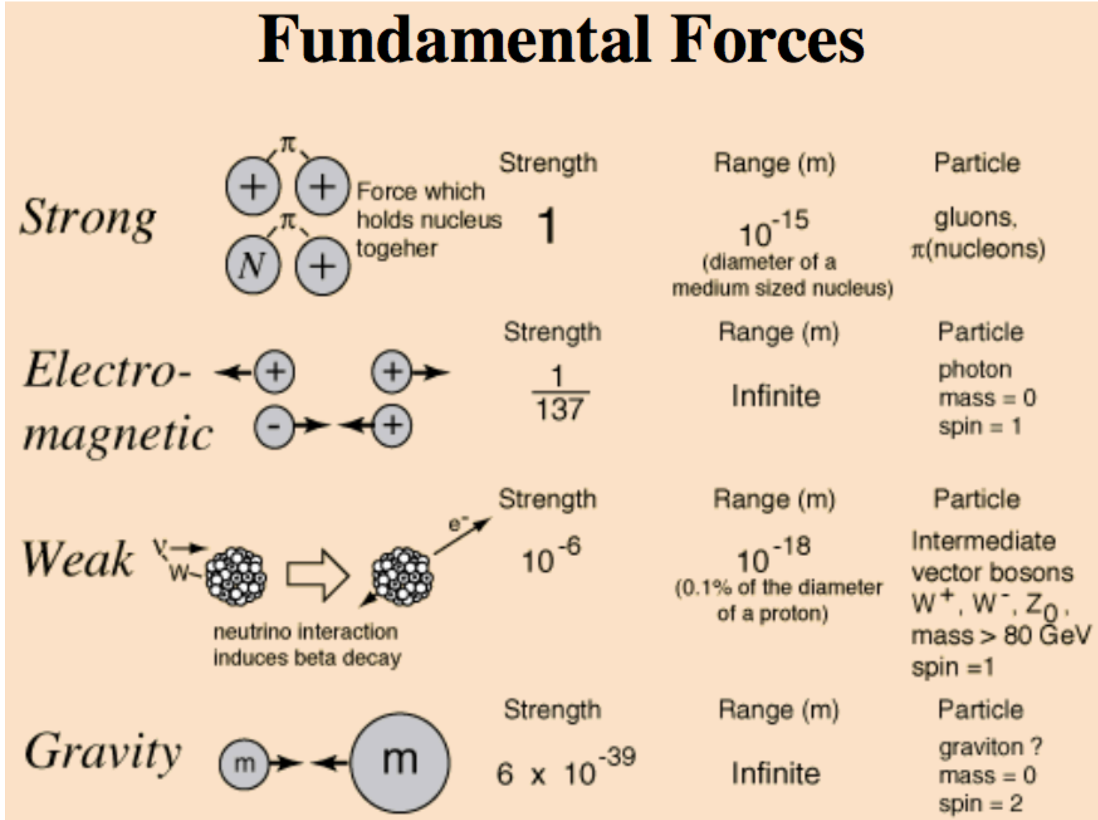
Particle Level



Alison Lister (UBC) 2015

Electromagnetic Shower





hyperphysics.phy-astr.gsu.edu

Beta Star (β*) and F functions for L

- Beta star is a function of the magnet settings at a given point
- F is the geometric luminosity reduction factor due to the interaction point crossing angle

$$F = \left(1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2\right)^{-\frac{1}{2}}$$

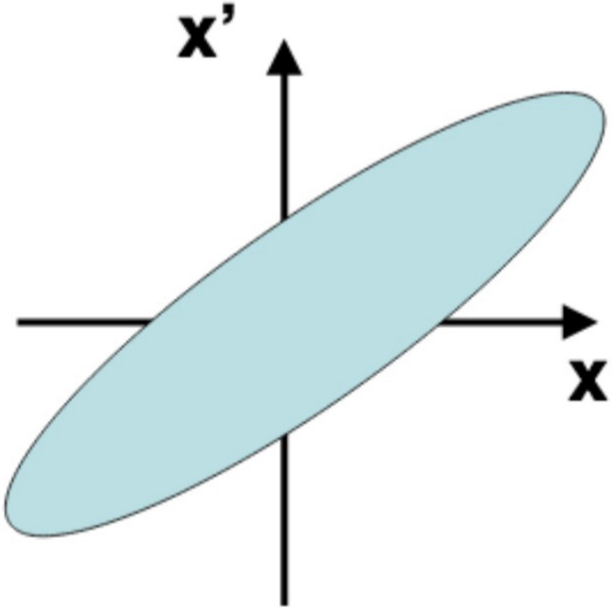
Θc = crossing angle

σz = RMS bunch length

σ* = RMS bunch width

Emittance (ϵ) for L

- The "area in phase space" occupied by the beam = π x ϵ
- Invariant around the beam
- For a Gaussian distribution ϵ_{rms} contains 39% of the beam, where:



$$\epsilon_{rms} = \sqrt{< x^2 >< x'^2 > - < xx' >^2}$$

Muon Definition

- The muon definition may be different between the uncorrected and corrected files.

The W muon type information from the uncorrected flatNtupler

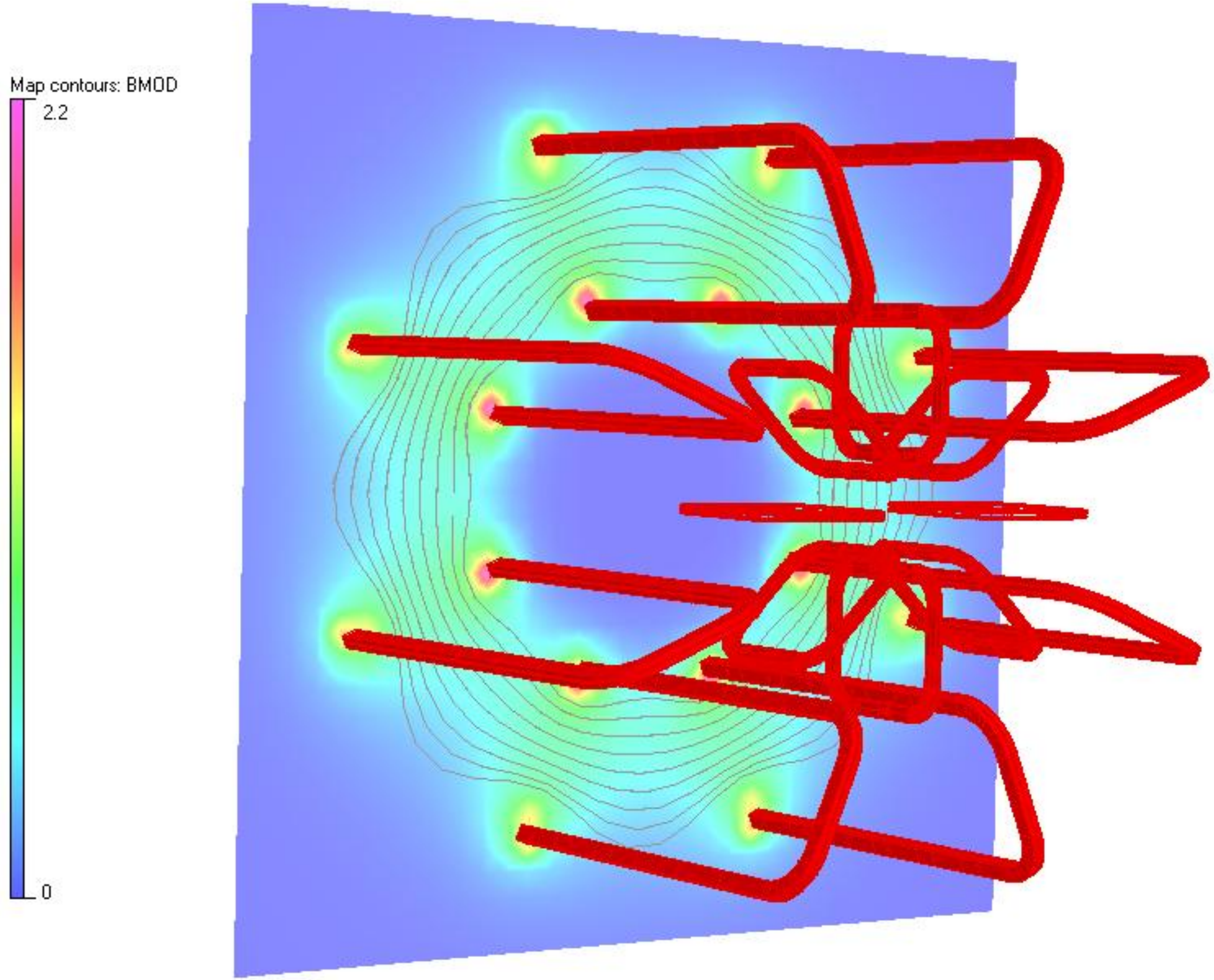
- Must be a STACO muon
  - mu_type == 0
- Must be combined muon
  - mu_iscombined == TRUE
- Must pass muon quality cuts
  - mu_passes_mcp == TRUE

The W muon type information from the uncorrected flatNtupler

- Must be a MuidCo muon
  - m.author() = 12
- Must pass muon quality cuts
  - m.nPixHits() + m.nPixelDeadSensors() >= 0
  - m.nPixHoles() + m.nSCTHoles() < 3
  - int nTRTtotal = m.nTRTHits() + m.nTRTOutliers();

```
if (fabs(m.eta()) >= 0.1 && fabs(m.eta()) <= 1.9){
    const bool cut = (nTRTtotal > 5 && (double)m.nTRTOutliers()/(double)nTRTtotal > 0.9);
}
```

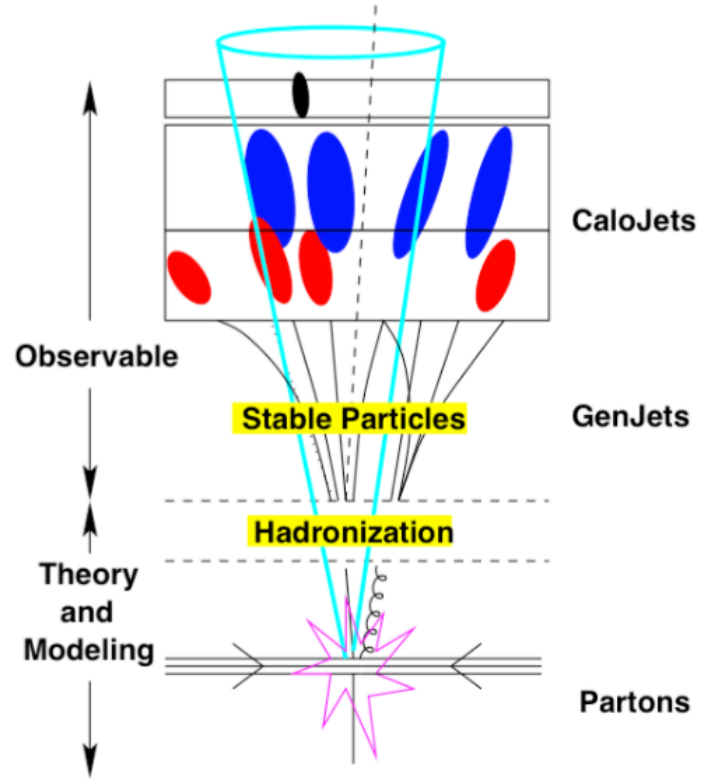
ATLAS Toroid Magnet



Detector Component	η **coverage**	**Required Resolution**
Inner detector	± 2.5	$\frac{\sigma_{p_T}}{p_T} = 0.05\% \, p_T \oplus 1\%$
EM calorimetry	± 3.2	$\frac{\sigma_E}{E} = \frac{10\%}{\sqrt{E}} \oplus 0.7\%$
Hadronic calorimetry (jets)		
barrel and end-cap	± 3.2	$\frac{\sigma_E}{E} = \frac{50\%}{\sqrt{E}} \oplus 3\%$
forward	$3.1 < \|\eta\| < 4.9$	$\frac{\sigma_E}{E} = \frac{100\%}{\sqrt{E}} \oplus 10\%$
Muon spectrometer	± 2.7	$\frac{\sigma_{p_T}}{p_T} = 10\%$ at $p_T = 1\,\text{TeV}$

What is a Jet?

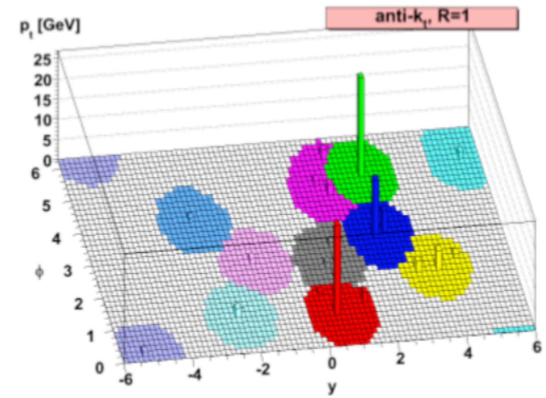
- Collimated bunches of stable hadrons, originating from **partons** (quarks & gluons) after **fragmentation** and **hadronization**
- Jet Finding is the **approximate** attempt to reverse-engineer the quantum mechanical processes of fragmentation and hadronization
  - ★ not a unique procedure -> **several** different approaches
- Jets are the observable objects to relate experimental **observations** to theory **predictions** formulated in terms of quarks and gluons

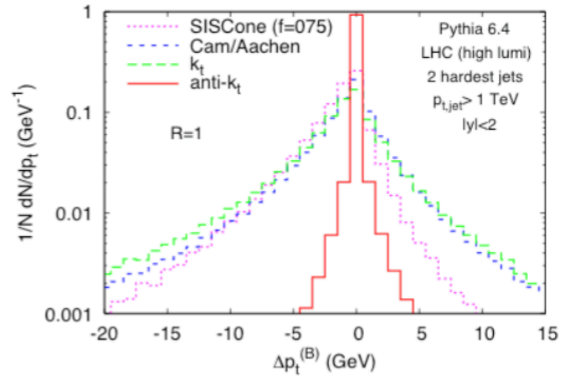


Philipp Schieferdecker (KIT) 2009

Anti-k_T Algorithm

- Despite being a IRC-safe sequential clustering algorithm: produces **cirular cone-shaped jets**!
- Many similar features and performance (expected, under study) as iterative cone, without the assoc. short-commings
- Shown to be particularly **insensitive to UE & PU**
  - ★ "back-reaction": net transverse momentum change of 200GeV leading jets in QCD dijet sample when adding high-lumi PU to the event

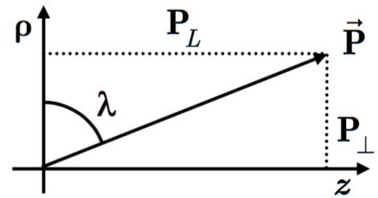




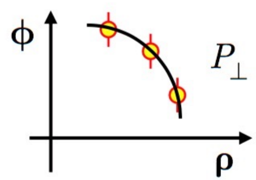
Philipp Schieferdecker (KIT) 2009

Momentum Measurement

The momentum of the particle is projected along two directions

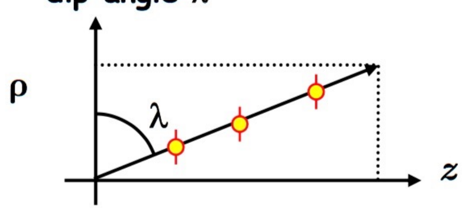


in ρ - ϕ plane we measure the transverse momentum $P_\perp$



$$P_\perp = P\cos\lambda = 0.3BR$$

in the ρ - z plane we measure the dip angle λ

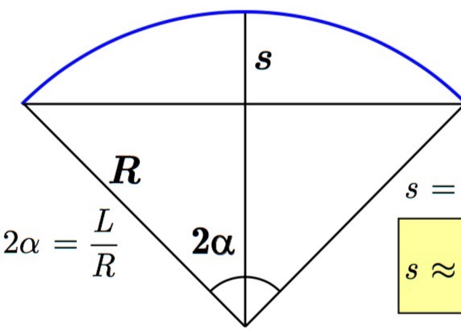


orders of magnitude

$$P_\perp = 1GeV \quad B = 2T \quad R = 1.67\,m$$

$$P_\perp = 10GeV \quad B = 2T \quad R = 16.7\,m$$

the sagitta s



$$2\alpha = \frac{L}{R}$$

$$s = R(1-\cos\alpha)$$

$$s \approx R\frac{\alpha^2}{2} = \frac{L^2}{8R}$$

assume a track length of $1\ m$

$$P_\perp = 1GeV \quad s = 7.4\ cm$$

$$P_\perp = 10GeV \quad s = 0.74\ cm$$

An Introduction to Charged Particles Tracking - Francesco Ragusa

Backup: Samples Used

Data set used: data12_8TeV.periodAllYear.physics_Muons.PhysCont.AOD.pro14_v01

MC used:

Sample	Full AOD Name	DSID	x-sec [pb]	k-factor
W e,nu 0_jet	mc12_8TeV.107680.AlpgenJimmy_AUET2CTEQ6L1_WenuNp0.merge.AOD.e1571_s1499_s1504_r3658_r3549	107680	8037.8	1.1760
W e,nu 1_jet	mc12_8TeV.107681.AlpgenJimmy_AUET2CTEQ6L1_WenuNp1.merge.AOD.e1571_s1499_s1504_r3658_r3549	107681	1579.5	1.1760
W e,nu 2_jet	mc12_8TeV.107682.AlpgenJimmy_AUET2CTEQ6L1_WenuNp2.merge.AOD.e1571_s1499_s1504_r3658_r3549	107682	477.31	1.1760
W e,nu 3_jet	mc12_8TeV.107683.AlpgenJimmy_AUET2CTEQ6L1_WenuNp3.merge.AOD.e1571_s1499_s1504_r3658_r3549	107683	133.89	1.1760
W e,nu 4_jet	mc12_8TeV.107684.AlpgenJimmy_AUET2CTEQ6L1_WenuNp4.merge.AOD.e1571_s1499_s1504_r3658_r3549	107684	35.614	1.1760
W e,nu 5_jet	mc12_8TeV.107685.AlpgenJimmy_AUET2CTEQ6L1_WenuNp5.merge.AOD.e1571_s1499_s1504_r3658_r3549	107685	10.545	1.1760
W mu,nu 0_jet	mc12_8TeV.107690.AlpgenJimmy_AUET2CTEQ6L1_WmunuNp0.merge.AOD.e1571_s1499_s1504_r3658_r3549	107690	8040.9	1.1760
W mu,nu 1_jet	mc12_8TeV.107691.AlpgenJimmy_AUET2CTEQ6L1_WmunuNp1.merge.AOD.e1571_s1499_s1504_r3658_r3549	107691	1581	1.1760
W mu,nu 2_jet	mc12_8TeV.107692.AlpgenJimmy_AUET2CTEQ6L1_WmunuNp2.merge.AOD.e1571_s1499_s1504_r3658_r3549	107692	477.53	1.1760
W mu,nu 3_jet	mc12_8TeV.107693.AlpgenJimmy_AUET2CTEQ6L1_WmunuNp3.merge.AOD.e1571_s1499_s1504_r3658_r3549	107693	133.83	1.1760
W mu,nu 4_jet	mc12_8TeV.107694.AlpgenJimmy_AUET2CTEQ6L1_WmunuNp4.merge.AOD.e1571_s1499_s1504_r3658_r3549	107694	35.579	1.1760
W mu,nu 5_jet	mc12_8TeV.107695.AlpgenJimmy_AUET2CTEQ6L1_WmunuNp5.merge.AOD.e1218_s1469_s1470_r3542_r3549	107695	10.561	1.1760
W tau,nu 0_jet	mc12_8TeV.107700.AlpgenJimmy_AUET2CTEQ6L1_WtaunuNp0.merge.AOD.e1218_s1469_s1470_r3753_r3549	107700	8036.2	1.1760
W tau,nu 1_jet	mc12_8TeV.107701.AlpgenJimmy_AUET2CTEQ6L1_WtaunuNp1.merge.AOD.e1218_s1469_s1470_r3605_r3549	107701	1579.5	1.1760
W tau,nu 2_jet	mc12_8TeV.107702.AlpgenJimmy_AUET2CTEQ6L1_WtaunuNp2.merge.AOD.e1218_s1469_s1470_r3753_r3549	107702	477.5	1.1760
W tau,nu 3_jet	mc12_8TeV.107703.AlpgenJimmy_AUET2CTEQ6L1_WtaunuNp3.merge.AOD.e1218_s1469_s1470_r3753_r3549	107703	133.78	1.1760
W tau,nu 4_jet	mc12_8TeV.107704.AlpgenJimmy_AUET2CTEQ6L1_WtaunuNp4.merge.AOD.e1218_s1469_s1470_r3605_r3549	107704	35.593	1.1760
W tau,nu 5_jet	mc12_8TeV.107705.AlpgenJimmy_AUET2CTEQ6L1_WtaunuNp5.merge.AOD.e1571_s1499_s1504_r3658_r3549	107705	10.534	1.1760
Z e,e 0_jet	mc12_8TeV.107650.AlpgenJimmy_AUET2CTEQ6L1_ZeeNp0.merge.AOD.e1571_s1499_s1504_r3658_r3549	107650	711.76	1.2290
Z e,e 1_jet	mc12_8TeV.107651.AlpgenJimmy_AUET2CTEQ6L1_ZeeNp1.merge.AOD.e1571_s1499_s1504_r3658_r3549	107651	155.2	1.2290
Z e,e 2_jet	mc12_8TeV.107652.AlpgenJimmy_AUET2CTEQ6L1_ZeeNp2.merge.AOD.e1218_s1469_s1470_r3542_r3549	107652	48.739	1.2290
Z e,e 3_jet	mc12_8TeV.107653.AlpgenJimmy_AUET2CTEQ6L1_ZeeNp3.merge.AOD.e1571_s1499_s1504_r3658_r3549	107653	14.222	1.2290
Z e,e 4_jet	mc12_8TeV.107654.AlpgenJimmy_AUET2CTEQ6L1_ZeeNp4.merge.AOD.e1571_s1499_s1504_r3658_r3549	107654	3.7471	1.2290
Z e,e 5_jet	mc12_8TeV.107655.AlpgenJimmy_AUET2CTEQ6L1_ZeeNp5.merge.AOD.e1571_s1499_s1504_r3658_r3549	107655	1.0942	1.2290
Z mu,mu 0_jet	mc12_8TeV.107660.AlpgenJimmy_AUET2CTEQ6L1_ZmumuNp0.merge.AOD.e1571_s1499_s1504_r3658_r3549	107660	712.06	1.2290
Z mu,mu 1_jet	mc12_8TeV.107661.AlpgenJimmy_AUET2CTEQ6L1_ZmumuNp1.merge.AOD.e1218_s1469_s1470_r3542_r3549	107661	154.78	1.2290
Z mu,mu 2_jet	mc12_8TeV.107662.AlpgenJimmy_AUET2CTEQ6L1_ZmumuNp2.merge.AOD.e1571_s1499_s1504_r3658_r3549	107662	48.884	1.2290
Z mu,mu 3_jet	mc12_8TeV.107663.AlpgenJimmy_AUET2CTEQ6L1_ZmumuNp3.merge.AOD.e1571_s1499_s1504_r3658_r3549	107663	14.496	1.2290
Z mu,mu 4_jet	mc12_8TeV.107664.AlpgenJimmy_AUET2CTEQ6L1_ZmumuNp4.merge.AOD.e1571_s1499_s1504_r3658_r3549	107664	3.8024	1.2290
Z mu,mu 5_jet	mc12_8TeV.107665.AlpgenJimmy_AUET2CTEQ6L1_ZmumuNp5.merge.AOD.e1571_s1499_s1504_r3658_r3549	107665	1.1094	1.2290
Z tau,tau 0_jet	mc12_8TeV.107670.AlpgenJimmy_AUET2CTEQ6L1_ZtautauNp0.merge.AOD.e1571_s1499_s1504_r3658_r3549	107670	711.89	1.2290
Z tau,tau 1_jet	mc12_8TeV.107671.AlpgenJimmy_AUET2CTEQ6L1_ZtautauNp1.merge.AOD.e1571_s1499_s1504_r3658_r3549	107671	155.09	1.2290
Z tau,tau 2_jet	mc12_8TeV.107672.AlpgenJimmy_AUET2CTEQ6L1_ZtautauNp2.merge.AOD.e1571_s1499_s1504_r3658_r3549	107672	48.805	1.2290
Z tau,tau 3_jet	mc12_8TeV.107673.AlpgenJimmy_AUET2CTEQ6L1_ZtautauNp3.merge.AOD.e1571_s1499_s1504_r3658_r3549	107673	14.14	1.2290
Z tau,tau 4_jet	mc12_8TeV.107674.AlpgenJimmy_AUET2CTEQ6L1_ZtautauNp4.merge.AOD.e1571_s1499_s1504_r3658_r3549	107674	3.7711	1.2290
Z tau,tau 5_jet	mc12_8TeV.107675.AlpgenJimmy_AUET2CTEQ6L1_ZtautauNp5.merge.AOD.e1571_s1499_s1504_r3658_r3549	107675	1.1122	1.2290
Ttbar	mc12_8TeV.105200.McAtNloJimmy_CT10_ttbar_LeptonFilter.merge.AOD.e1513_s1499_s1504_r3658_r3549	105200	112.94	1.2158
sTop e	mc12_8TeV.117360.AcerMCPythia_AUET2BCTEQ6L1_singletop_tchan_e.merge.AOD.e1195_s1469_s1470_r3542_r3549	117360	8.5878	1.1037
sTop mu	mc12_8TeV.117361.AcerMCPythia_AUET2BCTEQ6L1_singletop_tchan_mu.merge.AOD.e1346_s1499_s1504_r3658_r3549	117361	8.5889	1.1035
sTop tau	mc12_8TeV.117362.AcerMCPythia_AUET2BCTEQ6L1_singletop_tchan_tau.merge.AOD.e1195_s1469_s1470_r3542_r3549	117362	8.581	1.1045
WW	mc12_8TeV.105985.Herwig_AUET2CTEQ6L1_WW.merge.AOD.e1576_s1499_s1504_r3658_r3549	105985	12.416	1.6833
ZZ	mc12_8TeV.105986.Herwig_AUET2CTEQ6L1_ZZ.merge.AOD.e1576_s1499_s1504_r3658_r3549	105986	0.99081	1.5496
WZ	mc12_8TeV.105987.Herwig_AUET2CTEQ6L1_WZ.merge.AOD.e1576_s1499_s1504_r3658_r3549	105987	3.6706	1.9011

MC normalized to data

Backup: Samples Used

Sample	name tag
W e,nu 0_jet	147025.AlpgenPythia_Auto_P2011C_WenuNp0
	117680.AlpgenPythia_P2011C_WenuNp0
W e,nu 1_jet	147026.AlpgenPythia_Auto_P2011C_WenuNp1
	117681.AlpgenPythia_P2011C_WenuNp1
W e,nu 2_jet	147027.AlpgenPythia_Auto_P2011C_WenuNp2
	117682.AlpgenPythia_P2011C_WenuNp2
W e,nu 3_jet	147028.AlpgenPythia_Auto_P2011C_WenuNp3
	117683.AlpgenPythia_P2011C_WenuNp3
W e,nu 4_jet	147029.AlpgenPythia_Auto_P2011C_WenuNp4
	117684.AlpgenPythia_P2011C_WenuNp4
W e,nu 5_jet	147030.AlpgenPythia_Auto_P2011C_WenuNp5incl
	117685.AlpgenPythia_P2011C_WenuNp5
W mu,nu 0_jet	147033.AlpgenPythia_Auto_P2011C_WmunuNp0
	117690.AlpgenPythia_P2011C_WmunuNp0
W mu,nu 1_jet	147034.AlpgenPythia_Auto_P2011C_WmunuNp1
	117691.AlpgenPythia_P2011C_WmunuNp1
W mu,nu 2_jet	147035.AlpgenPythia_Auto_P2011C_WmunuNp2
	117692.AlpgenPythia_P2011C_WmunuNp2
W mu,nu 3_jet	147036.AlpgenPythia_Auto_P2011C_WmunuNp3
	117693.AlpgenPythia_P2011C_WmunuNp3
W mu,nu 4_jet	147037.AlpgenPythia_Auto_P2011C_WmunuNp4
	117694.AlpgenPythia_P2011C_WmunuNp4
W mu,nu 5_jet	147038.AlpgenPythia_Auto_P2011C_WmunuNp5incl
	117695.AlpgenPythia_P2011C_WmunuNp5
W tau,nu 0_jet	147041.AlpgenPythia_Auto_P2011C_WtaunuNp0
	117700.AlpgenPythia_P2011C_WtaunuNp0
W tau,nu 1_jet	147042.AlpgenPythia_Auto_P2011C_WtaunuNp1
	117701.AlpgenPythia_P2011C_WtaunuNp1
W tau,nu 2_jet	147043.AlpgenPythia_Auto_P2011C_WtaunuNp2
	117702.AlpgenPythia_P2011C_WtaunuNp2
W tau,nu 3_jet	147044.AlpgenPythia_Auto_P2011C_WtaunuNp3
	117703.AlpgenPythia_P2011C_WtaunuNp3
W tau,nu 4_jet	147045.AlpgenPythia_Auto_P2011C_WtaunuNp4
	117704.AlpgenPythia_P2011C_WtaunuNp4
W tau,nu 5_jet	147046.AlpgenPythia_Auto_P2011C_WtaunuNp5incl
	117705.AlpgenPythia_P2011C_WtaunuNp5

Z e,e 0_jet	147105.AlpgenPythia_Auto_P2011C_ZeeNp0
	117650.AlpgenPythia_P2011C_ZeeNp0
Z e,e 1_jet	147106.AlpgenPythia_Auto_P2011C_ZeeNp1
	117651.AlpgenPythia_P2011C_ZeeNp1
Z e,e 2_jet	147107.AlpgenPythia_Auto_P2011C_ZeeNp2
	117652.AlpgenPythia_P2011C_ZeeNp2
Z e,e 3_jet	147108.AlpgenPythia_Auto_P2011C_ZeeNp3
	117653.AlpgenPythia_P2011C_ZeeNp3
Z e,e 4_jet	147109.AlpgenPythia_Auto_P2011C_ZeeNp4
	117654.AlpgenPythia_P2011C_ZeeNp4
Z e,e 5_jet	147110.AlpgenPythia_Auto_P2011C_ZeeNp5incl
	117655.AlpgenPythia_P2011C_ZeeNp5
Z mu,mu 0_jet	147113.AlpgenPythia_Auto_P2011C_ZmumuNp0
	117660.AlpgenPythia_P2011C_ZmumuNp0
Z mu,mu 1_jet	147114.AlpgenPythia_Auto_P2011C_ZmumuNp1
	117661.AlpgenPythia_P2011C_ZmumuNp1
Z mu,mu 2_jet	147115.AlpgenPythia_Auto_P2011C_ZmumuNp2
	117662.AlpgenPythia_P2011C_ZmumuNp2
Z mu,mu 3_jet	147116.AlpgenPythia_Auto_P2011C_ZmumuNp3
	117663.AlpgenPythia_P2011C_ZmumuNp3
Z mu,mu 4_jet	147117.AlpgenPythia_Auto_P2011C_ZmumuNp4
	117664.AlpgenPythia_P2011C_ZmumuNp4
Z mu,mu 5_jet	147118.AlpgenPythia_Auto_P2011C_ZmumuNp5incl
	117665.AlpgenPythia_P2011C_ZmumuNp5
Z tau,tau 0_jet	147121.AlpgenPythia_Auto_P2011C_ZtautauNp0
	117670.AlpgenPythia_P2011C_ZtautauNp0
Z tau,tau 1_jet	147122.AlpgenPythia_Auto_P2011C_ZtautauNp1
	117671.AlpgenPythia_P2011C_ZtautauNp1
Z tau,tau 2_jet	147123.AlpgenPythia_Auto_P2011C_ZtautauNp2
	117672.AlpgenPythia_P2011C_ZtautauNp2
Z tau,tau 3_jet	147124.AlpgenPythia_Auto_P2011C_ZtautauNp3
	117673.AlpgenPythia_P2011C_ZtautauNp3
Z tau,tau 4_jet	147125.AlpgenPythia_Auto_P2011C_ZtautauNp4
	117674.AlpgenPythia_P2011C_ZtautauNp4
Z tau,tau 5_jet	147126.AlpgenPythia_Auto_P2011C_ZtautauNp5incl
	117675.AlpgenPythia_P2011C_ZtautauNp5

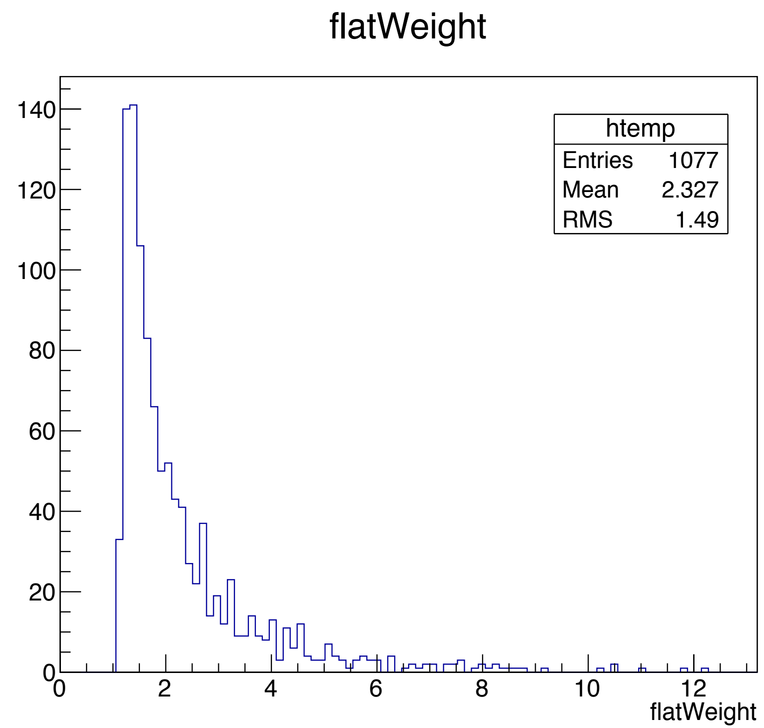
J/ψ Weight Calculation

A total weight was calculated for each J/ψ candidate using this formula:

$$\text{Weight} = \frac{1}{J/\psi \text{ acceptance} \times \mu^{+} \text{ efficiency} \times \mu^{-} \text{ efficiency}}$$

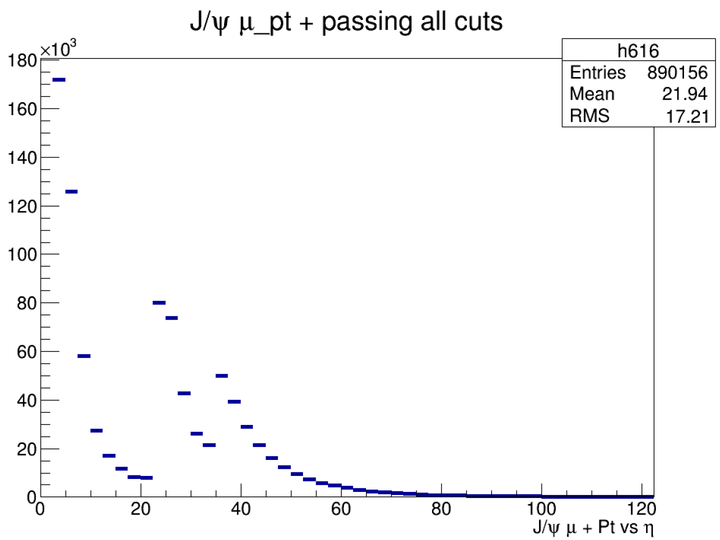
This increases the number of J/ψ candidate events.

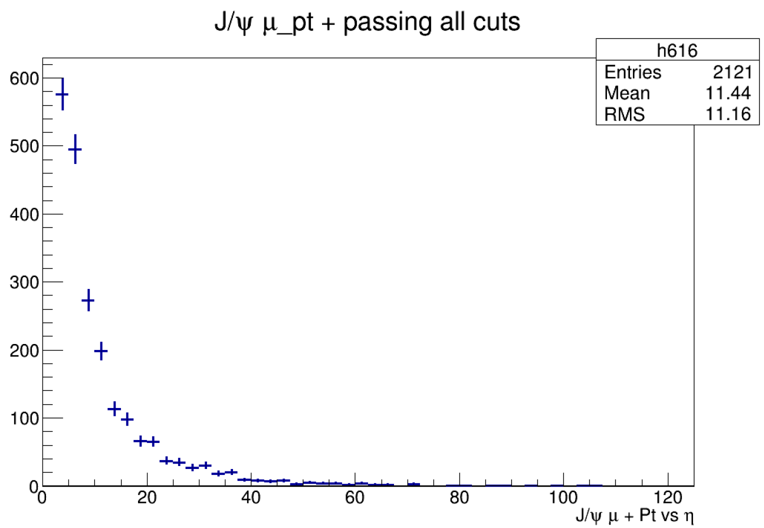
There are 8 possible J/ψ polarizations, leading to 8 possible weights. This is the flat or un-polarized weight.



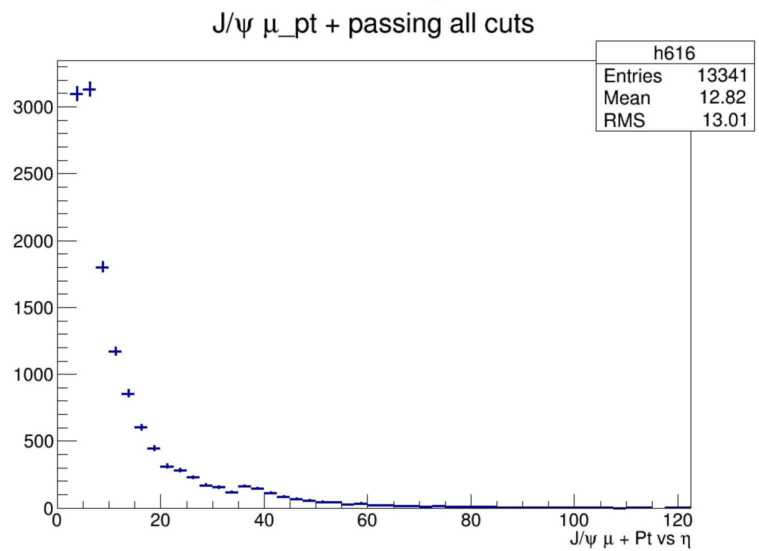
Additions:

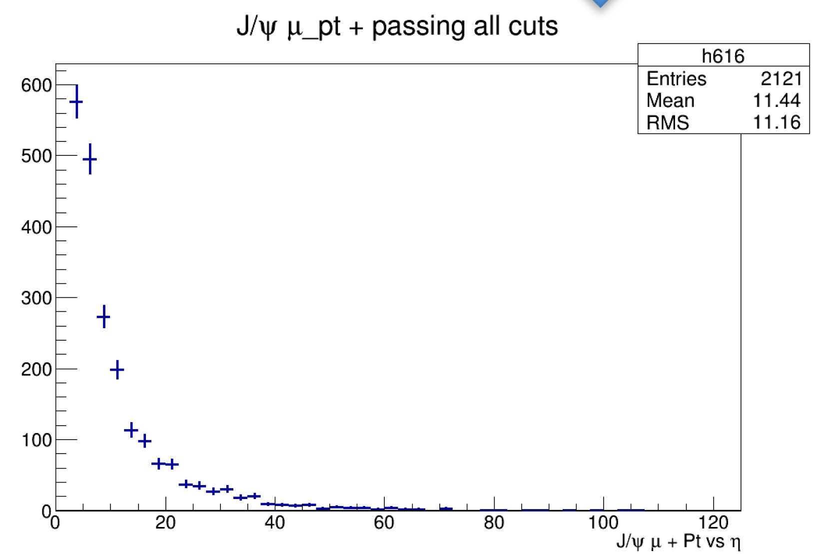
- Previously we looked at an inclusive J/ψ sample to determine the best fit parameters.
- But the $pT_{\mu}^{J/\psi}$ distribution does not well match that of the associated J/ψ+W.





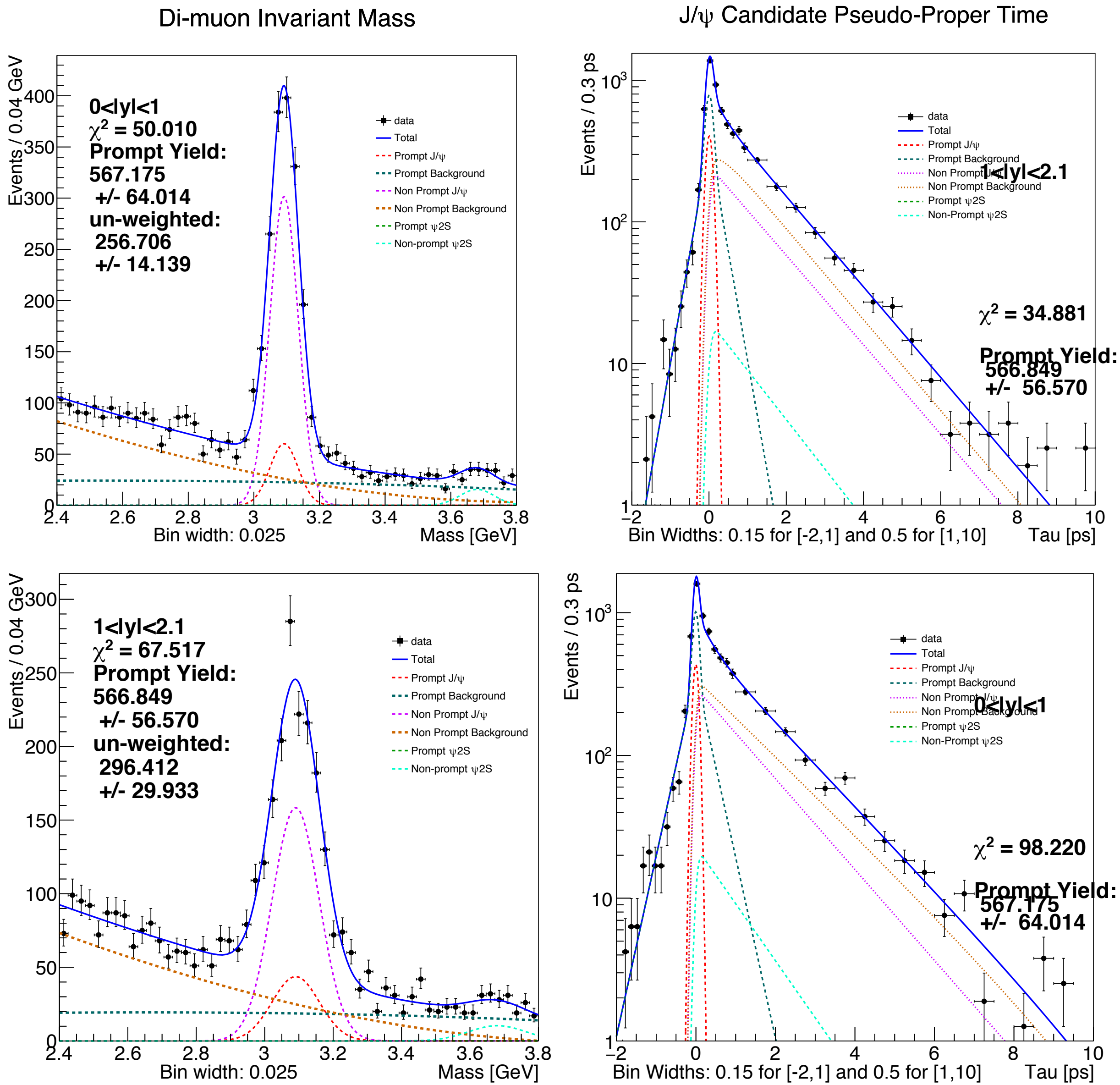
- So we made a sample of J/ψ+anti_W, meaning that if the any of the W muon requirements or the MET requirement failed then the event was kept.
- This provided a $pT_{\mu}^{J/\psi}$ distribution better matching that of the associated J/ψ+W.





- The J/ψ mass distribution of this J/ψ +anti_W sample was fit to determine the best fit parameters.

Backup: Signal Extraction



Sample:

- J/ψ+anti_W

Fit parameters:

- $2.4 < M^{J/\psi} < 3.8$
- $M_{bkg}^{J/\psi}$ 2nd O pol
- Ψ(2S): Gaussian

- Using a 2nd order polynomial as the J/ψ mass background model and including the Ψ(2S) peak gives these parameters:

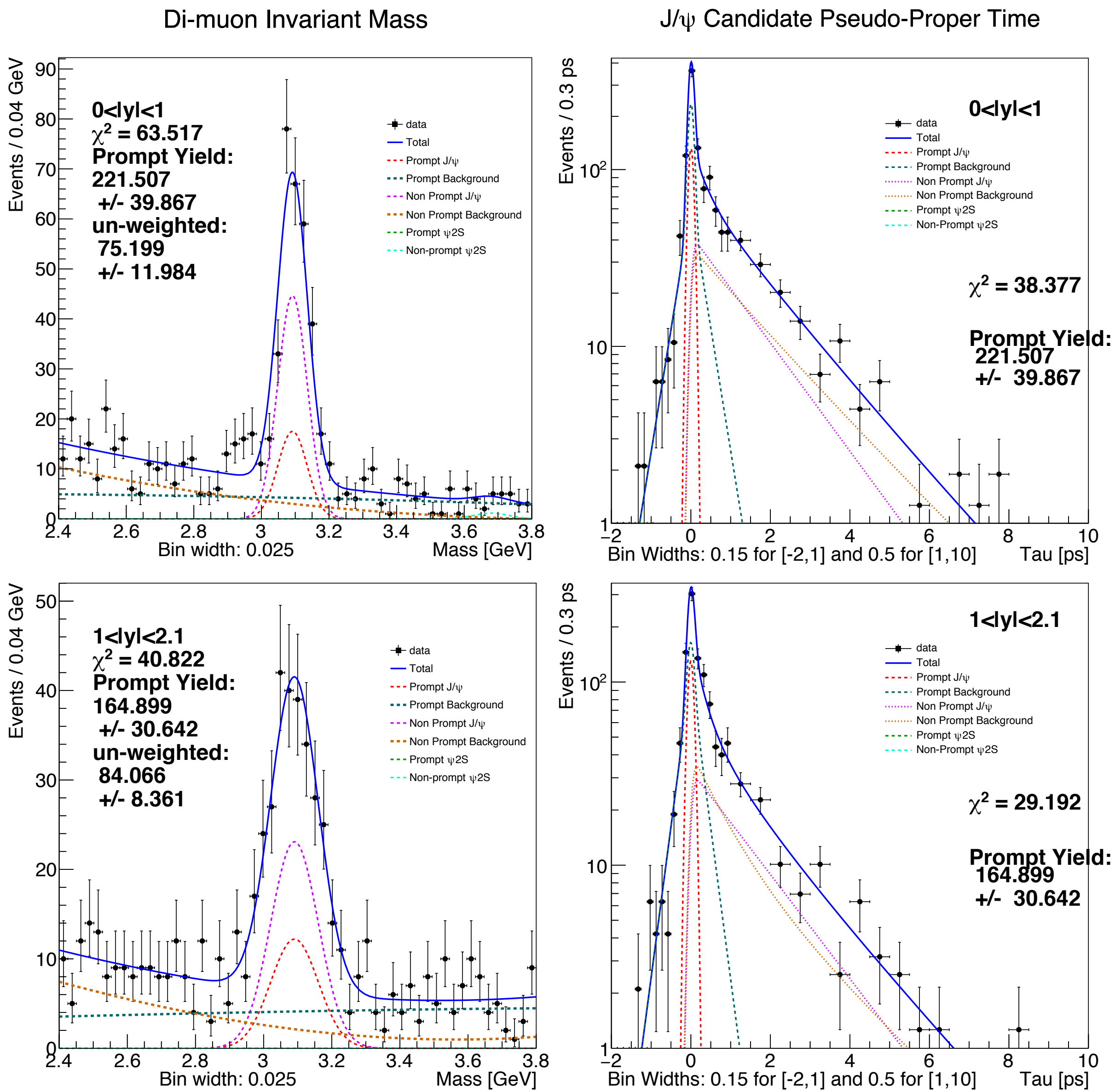
central

NO.	NAME	VALUE	ERROR
1	Tau2s	1.08760e+00	1.18887e-01
2	bkgTau1	2.95177e+00	2.16996e+00
3	bkgTau2	1.61892e+00	2.61635e-01
4	bkgTau3	3.43400e-01	1.26278e-02
5	c0	7.01507e+00	3.07095e-01
6	c1	-4.59626e-01	6.41679e-02
7	c2	-2.46112e-01	1.50481e-02
8	fittedTau	1.36427e+00	3.80151e-02
9	**mMean**	**3.09193e+00**	**8.76738e-04**
10	**mSigma**	**4.33588e-02**	**7.64136e-04**
11	n_2S	9.47638e-03	5.92398e+00
12	n_np_2S	7.88114e+01	8.51577e+00
13	n_npj	1.28722e+03	2.58692e+01
14	n_npj_bk	1.71394e+03	3.08782e+01
15	n_pj	2.56706e+02	1.41395e+01
16	n_pj_bk	1.18506e+03	2.68243e+01
17	nonPromptRatio	-5.51039e-02	2.34216e-01
18	npc0	-3.74208e-01	4.32556e-04
19	npc1	-7.26059e-03	1.18239e-04
20	npc2	9.73654e-03	3.24053e-05
21	promptRatio	3.57495e-01	1.78779e-02
22	tMean	-3.73363e-03	2.39413e-03
23	tSigma	7.45019e-02	2.40505e-03

forward

NO.	NAME	VALUE	ERROR
1	Tau2s	1.24623e+00	2.31165e-01
2	bkgTau1	2.85691e-01	1.96788e-01
3	bkgTau2	1.35254e+00	5.83599e-02
4	bkgTau3	2.81121e-01	2.57449e-02
5	c0	7.18031e-01	1.84893e+00
6	c1	2.30015e-01	4.03340e-01
7	c2	-9.14389e-02	9.62876e-02
8	fittedTau	1.37404e+00	5.62603e-02
9	**mMean**	**3.09065e+00**	**2.55961e-03**
10	**mSigma**	**6.89297e-02**	**2.56097e-03**
11	n_2S	8.58729e-06	7.80382e+00
12	n_np_2S	7.86031e+01	2.31638e+01
13	n_npj	1.07496e+03	4.78669e+01
14	n_npj_bk	1.56718e+03	7.13539e+01
15	n_pj	2.96412e+02	2.99329e+01
16	n_pj_bk	9.87735e+02	6.13279e+01
17	nonPromptRatio	-6.50222e-02	5.71885e-02
18	npc0	-3.67145e-01	1.29307e-02
19	npc1	-3.72517e-03	4.34024e-03
20	npc2	8.18779e-03	9.85155e-04
21	promptRatio	3.86754e-01	6.21018e-02
22	tMean	6.08855e-03	6.85421e-03
23	tSigma	9.25518e-02	6.86076e-03

- mMean and mSigma for J/ψ mass are fixed and applied to the data on the following slide:



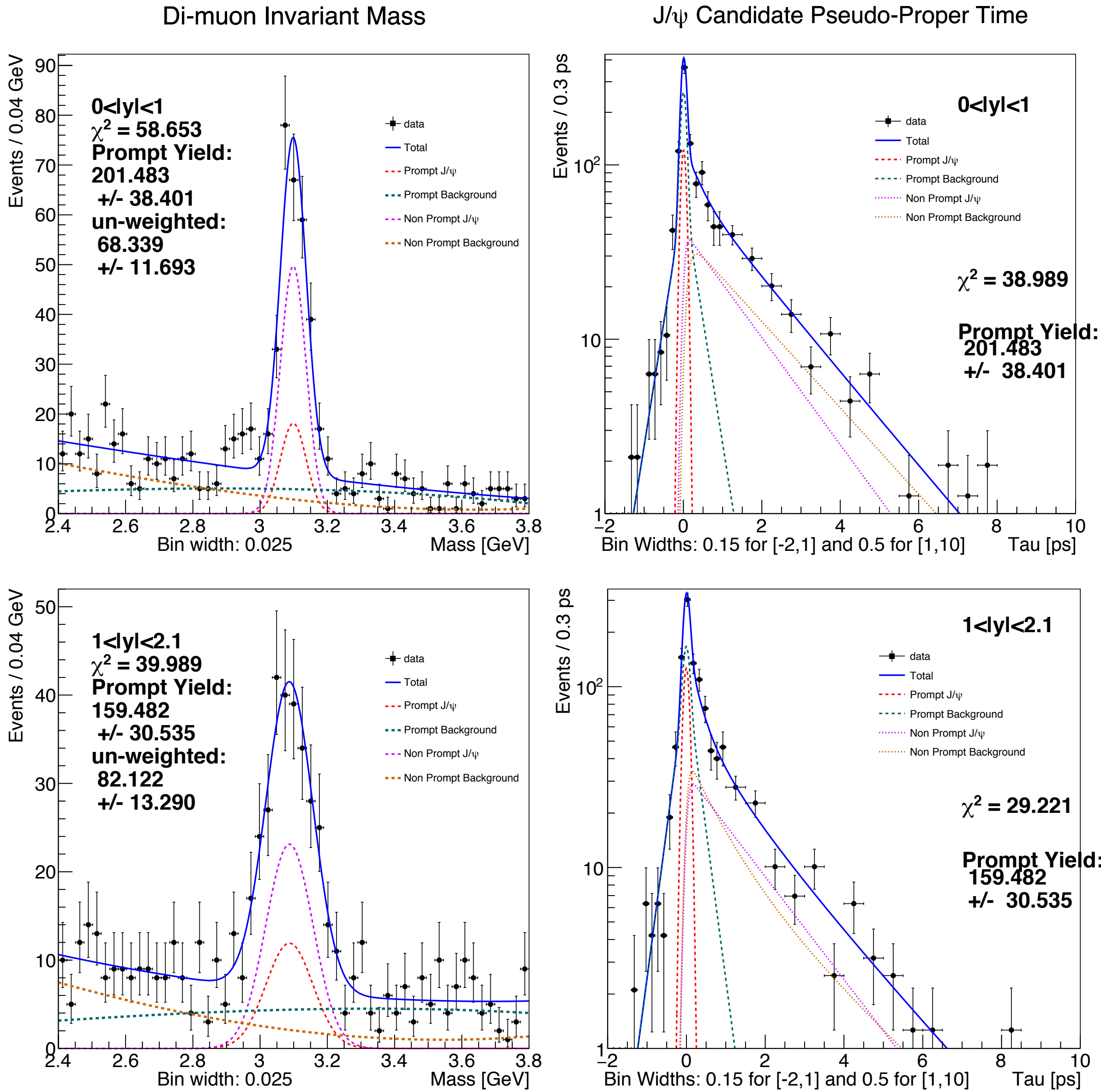
Sample:

- J/ψ+W data

Fit parameters:

- $2.4 < M^{J/\psi} < 3.8$
- $M^{J/\psi}$ Fixed
- $M_{bkg}^{J/\psi}$ 2^{nd} O pol
- Ψ(2S): Gaussian

Backup: Signal Extraction



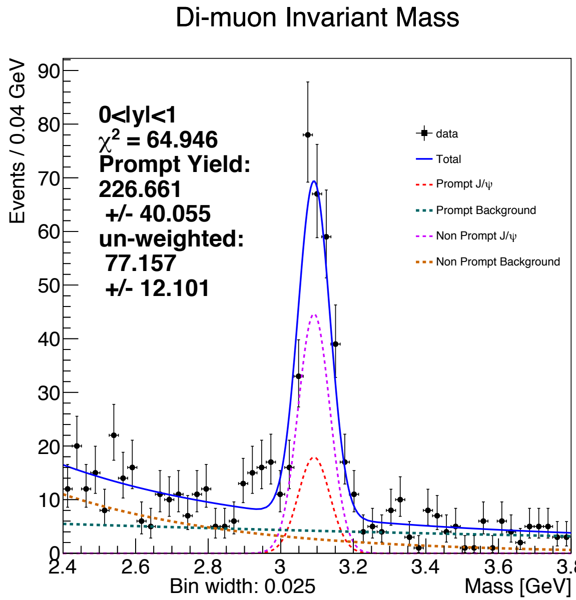
Sample:

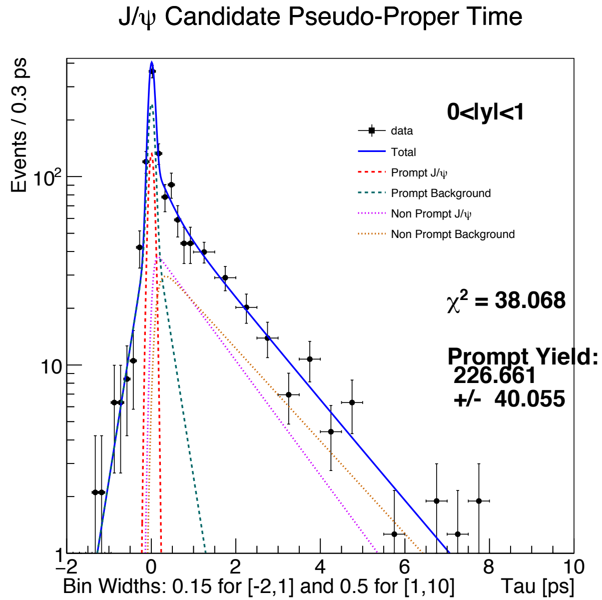
- J/ψ+W data

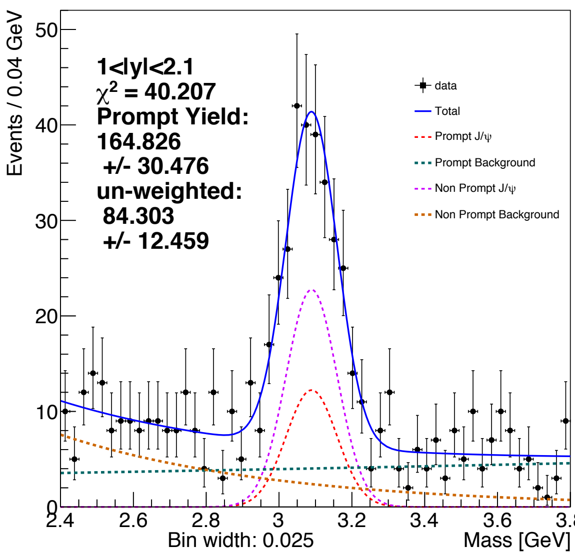
Fit parameters:

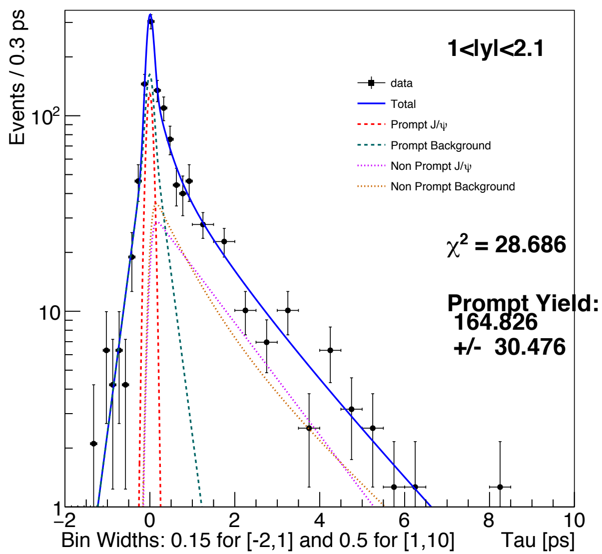
- $2.4 < M^{J/\psi} < 3.8$
- $M^{J/\psi}$ Floating
- $M_{bkg}^{J/\psi}$ 2^{nd} O pol

Backup: Signal Extraction









Sample:

- J/ψ+W data

Fit parameters:

- $2.4 < M^{J/\psi} < 3.8$
- $M^{J/\psi}$ Fixed
- $M_{bkg}^{J/\psi}$ exp

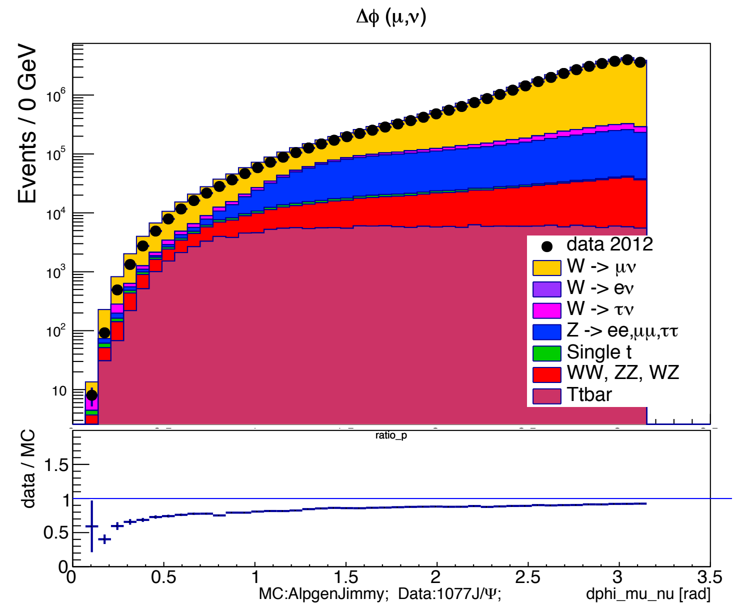
Backup: Backgrounds

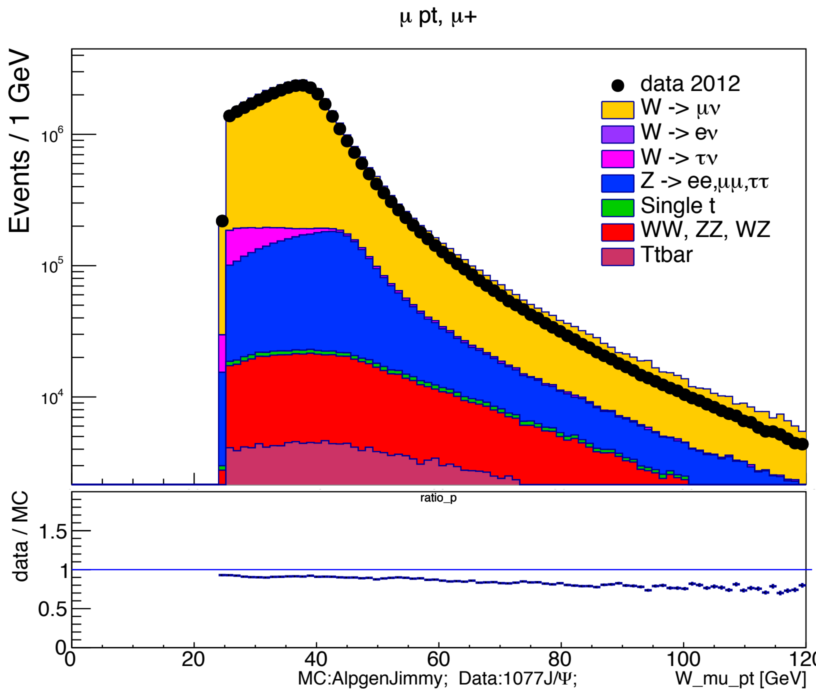
<u>Component variables of Wmt</u>

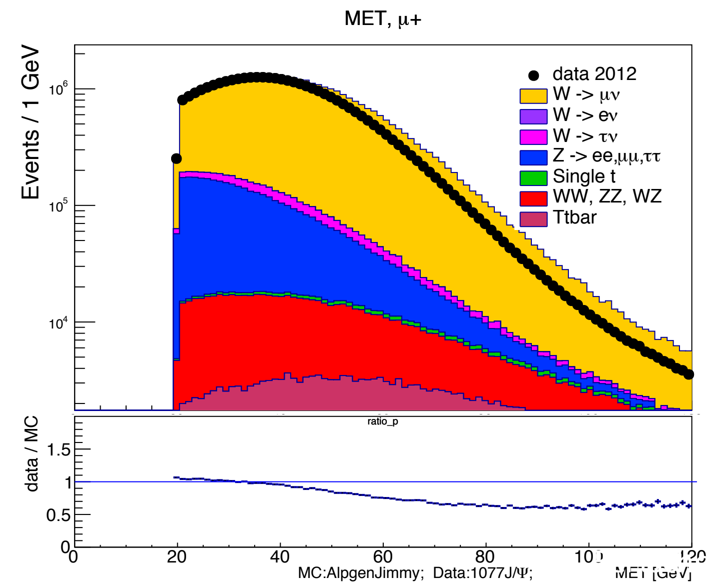
These plots show the 3 variables used to calculate Wmt.

$$m_T(W) \equiv \sqrt{2p_T(\mu)E_T^{miss}(1 - cos(\phi^\mu - \phi^\nu))}$$

μ_pt, MET (met_reffinal) and Δϕ(μ,ν) MC all show regions of more accurate modeling and regions of poorer modeling of the data.

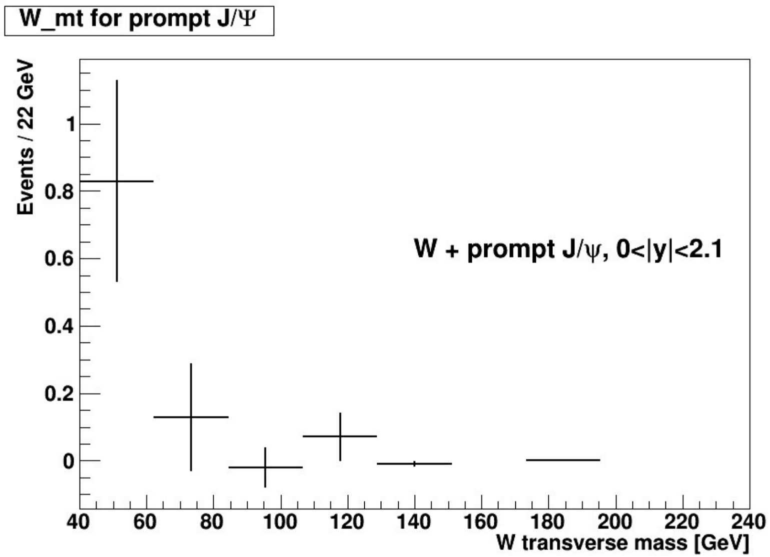


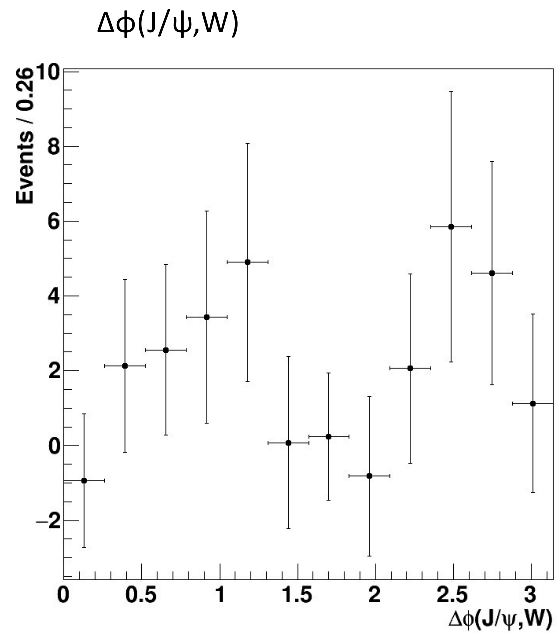




Background Removal, Associated $J/\psi + W^{\pm}$: QCD/Mulitjet

ABCD + sPlot method





2012 data, Region D associated with prompt J/ψ events (using sPlot), # of events = 25 ± 11

J/ψ + W sample *fake factor* = A/B = 0.150 ± 0.015
# of signal events in J/ψ + W sample = 430 ± 28

QCD fraction found with ABCD + sPlot method = D x A/B ÷ signal = 0.8 +/- 0.4%

Associated J/ψ + W$^{\pm}$: Pileup and DPS

Cross section, J/ψ -> μμ measurement ⇩

Average number of extra pileup vertices ≈ 2.3 ± 0.2 ⇩

Number of W candidates in inclusive W sample applied here: 5,213 x 10^{7} ⇩

	pileup background estimation			prompt									
Bin y x PT	sig(Prompt Jpsi -> mu,mu)(nb)			n_extr_vert sg_ibin/sig_inel (10^-8)			d^2 sig / sig_bin dy PT (10^-8)			<eff x Acc>	Expected Yield		
		+err	-err		+err	-err		+err	-err			+err	-err
(0,1) x (8.5,10)	5,985	0,116	0,116	9,182	0,679	0,679	3,061	0,226	0,226	0,23	1,101	0,081	0,081
(0,1) x (10,14)	4,585	0,092	0,092	7,035	0,522	0,522	0,879	0,065	0,065	0,39	1,430	0,106	0,106
(0,1) x (14,18)	0,956	0,020	0,020	1,467	0,109	0,109	0,183	0,014	0,014	0,53	0,405	0,030	0,030
(0,1) x (18,30)	0,434	0,008	0,008	0,665	0,049	0,049	0,028	0,002	0,002	0,65	0,225	0,017	0,017
(0,1) x (30,60)	0,050	0,001	0,001	0,077	0,006	0,006	0,0013	9,51E-05	0,000	0,73	0,029	0,002	0,002
(0,1) x (60,150)	0,002	0,000	0,000	0,004	0,000	0,000	2E-05	1,83E-06	0,000	0,84	0,002	0,000	0,000
(1,2.1) x (8.5,10)	6,008	0,119	0,119	9,218	0,683	0,683	1,047	0,078	0,078	0,39	1,874	0,139	0,139
(1,2.1) x (10,14)	5,232	0,097	0,097	8,027	0,592	0,592	0,912	0,067	0,067	0,49	2,050	0,151	0,151
(1,2.1) x (14,18)	0,996	0,018	0,018	1,528	0,112	0,112	0,174	0,013	0,013	0,63	0,502	0,037	0,037
(1,2.1) x (18,30)	0,425	0,006	0,006	0,652	0,048	0,048	0,025	0,002	0,002	0,73	0,248	0,018	0,018
(1,2.1) x (30,60)	0,043	0,001	0,001	0,067	0,005	0,005	0,001	7,44E-05	0,000	0,74	0,026	0,002	0,002
(1,2.1) x (60,150)	0,002	0,000	0,000	0,003	0,000	0,000	1E-05	1,19E-06	0,000	0,81	0,001	0,000	0,000
											7,894	0,251	0,251

Pileup

	DPS estimation			prompt									
Bin y x PT	sig(Prompt Jpsi -> mu,mu)(nb)			n_extr_vert sg_ibin/sig_inel (10^-8)			d^2 sig / sig_bin dy PT (10^-8)			<eff x Acc>	Expected Jpsi+W Yield		
		+err	-err		+err	-err		+err	-err			+err	-err
(0,1) x (8.5,10)	5,985	0,116	0,116	39,898	15,446	15,446	13,299	5,149	5,149	0,23	4,784	1,852	1,852
(0,1) x (10,14)	4,585	0,092	0,092	30,569	11,836	11,836	3,821	1,479	1,479	0,39	6,215	2,406	2,406
(0,1) x (14,18)	0,956	0,020	0,020	6,373	2,468	2,468	0,797	0,308	0,308	0,53	1,761	0,682	0,682
(0,1) x (18,30)	0,434	0,008	0,008	2,891	1,119	1,119	0,120	0,047	0,047	0,65	0,980	0,379	0,379
(0,1) x (30,60)	0,050	0,001	0,001	0,334	0,129	0,129	0,006	0,002	0,002	0,73	0,126	0,049	0,049
(0,1) x (60,150)	0,002	0,000	0,000	0,016	0,006	0,006	9,12E-05	3,55E-05	0,000	0,84	0,007	0,003	0,003
(1,2.1) x (8.5,10)	6,008	0,119	0,119	40,053	15,507	15,507	4,552	1,762	1,762	0,39	8,143	3,153	3,153
(1,2.1) x (10,14)	5,232	0,097	0,097	34,881	13,503	13,503	3,964	1,534	1,534	0,49	8,910	3,449	3,449
(1,2.1) x (14,18)	0,996	0,018	0,018	6,640	2,570	2,570	0,755	0,292	0,292	0,63	2,181	0,844	0,844
(1,2.1) x (18,30)	0,425	0,006	0,006	2,833	1,096	1,096	0,107	0,042	0,042	0,73	1,078	0,417	0,417
(1,2.1) x (30,60)	0,043	0,001	0,001	0,290	0,112	0,112	0,004	0,002	0,002	0,74	0,112	0,043	0,043
(1,2.1) x (60,150)	0,002	0,000	0,000	0,012	0,005	0,005	6,18E-05	2,4E-05	0,000	0,81	0,005	0,002	0,002
											34,301	5,706	5,706

DPS

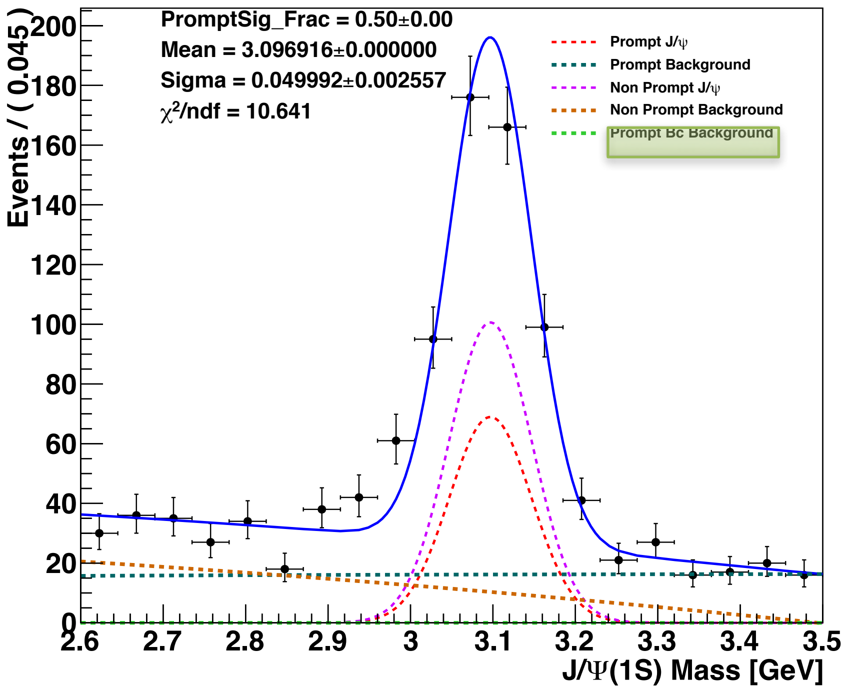
Background Removal: $B^{\pm}_{c}$ decays

$$B_c^{\pm} \rightarrow J/\psi \; l^{\pm} \nu X$$

- A second estimate was made using sPlot
- An additional parameter was added and given the value of:

$$\frac{B_c \text{ lifetime}}{B^0 \text{ lifetime}} \times \text{ fittedTau} = \frac{0.46}{1.52} \times 1.51776 \simeq 0.46 \; ps$$

- No evidence of any $B^{\pm}_{c}$

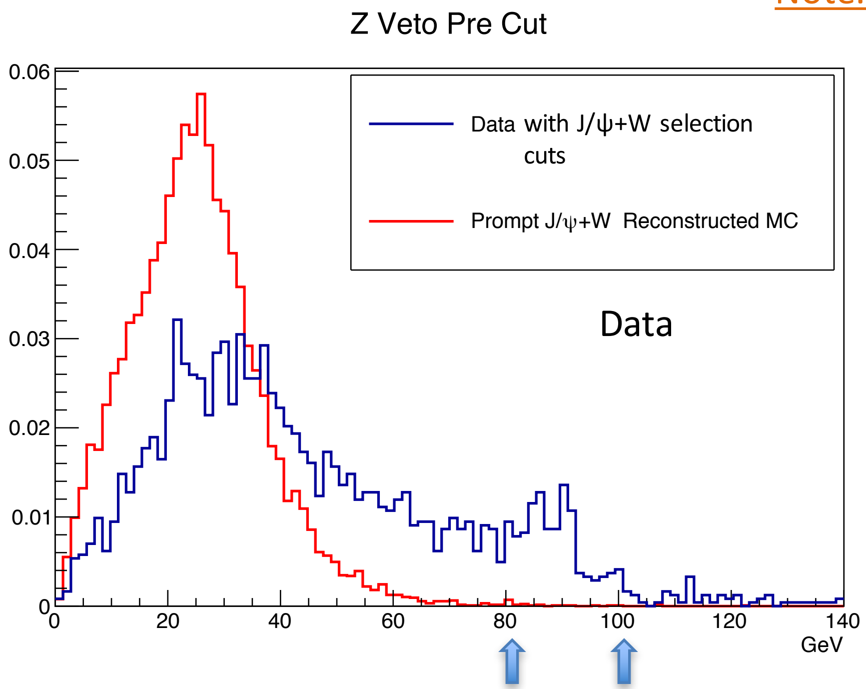


EXT NO.	PARAMETER NAME	VALUE	APPROXIMATE ERROR	IN ST
1	bkgTau1	9.31903e-01	1.36841e-01	6.
2	bkgTau2	2.99992e+00	4.28802e-01	6.
3	bkgTau3	3.66415e-01	3.52348e-02	2.
4	c0	5.30967e-01	5.69520e-01	5.
5	c1	-7.42628e-02	7.12176e-01	1.
6	fittedTau	1.51776e+00	7.70119e-02	1.
7	mSigma	4.99922e-02	2.55734e-03	3.
8	n_Bc_bk	6.49114e-02	2.87519e+01	8.
9	n_npj	6.51138e+02	3.17902e+01	1.
10	n_npj_bk	5.12589e+02	3.57530e+01	1.
11	n_pj	4.46163e+02	2.78018e+01	1.
12	n_pj_bk	7.48952e+02	3.90811e+01	1.
13	nonPromptRatio	6.39307e-01	6.84294e-02	
14	npc0	6.20787e-01	3.96530e-02	1.
15	npc1	-2.59586e-01	1.17902e-02	4.
16	promptRatio	4.34640e-01	4.78859e-02	5
17	tMean	3.10916e-03	4.15477e-03	3.
18	tSigma	8.69008e-02	4.25519e-03	5.

Testing No Z-veto Cut:

Number of Prompt Events	Absolute Rapidity	With Z Veto Cut	No Z Veto Cut	% change
Data	0<|y|<2.1	487.5±52.1	489.4 ±52.5	0.4% (no change within uncertainties)
Reconstructed MC	0<|y|<2.1	12,689	12,704	0.1%

Note: Chapter 7.2

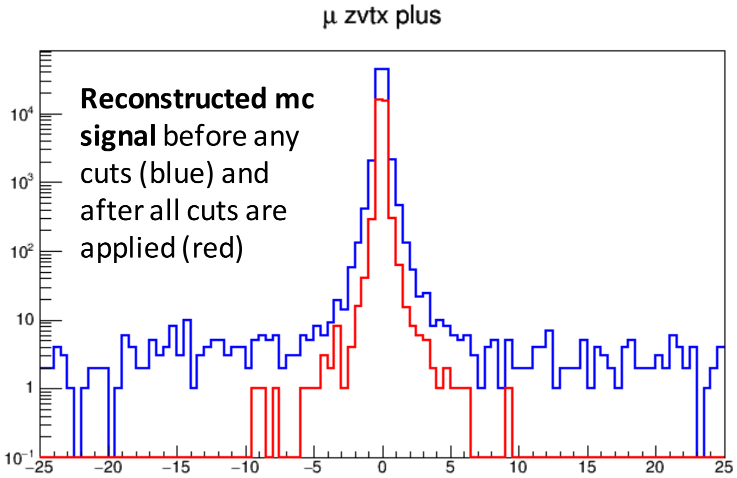


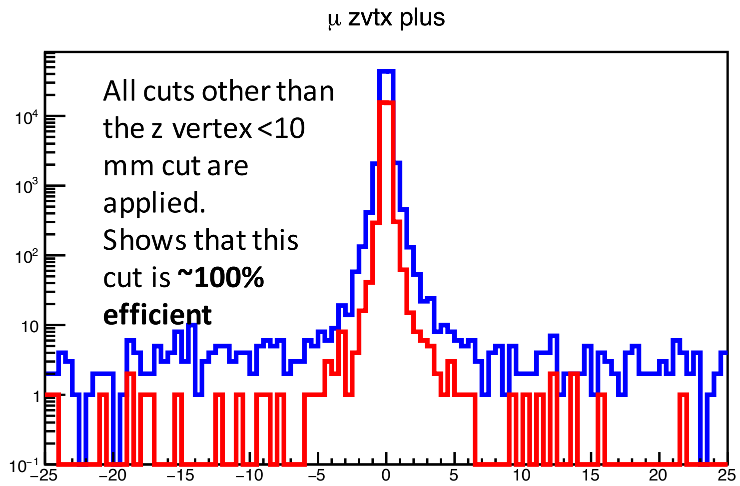
Background Removal: Z+jets

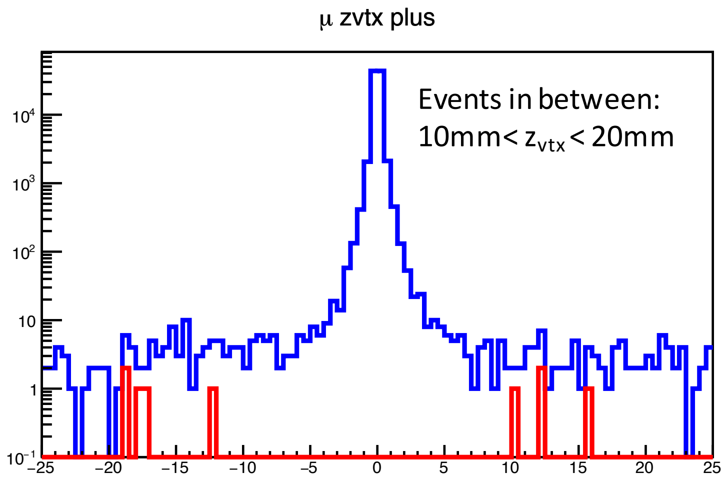
$$Z \rightarrow \mu^+ \mu^-$$

- The invariant mass of the W muon and opposite sign "J/ψ" muon is calculated.
- If it's near the Z mass (81-101 GeV), the event is cut.
- EB ok to remove this cut.

Testing no *z* vertex cut Cut:



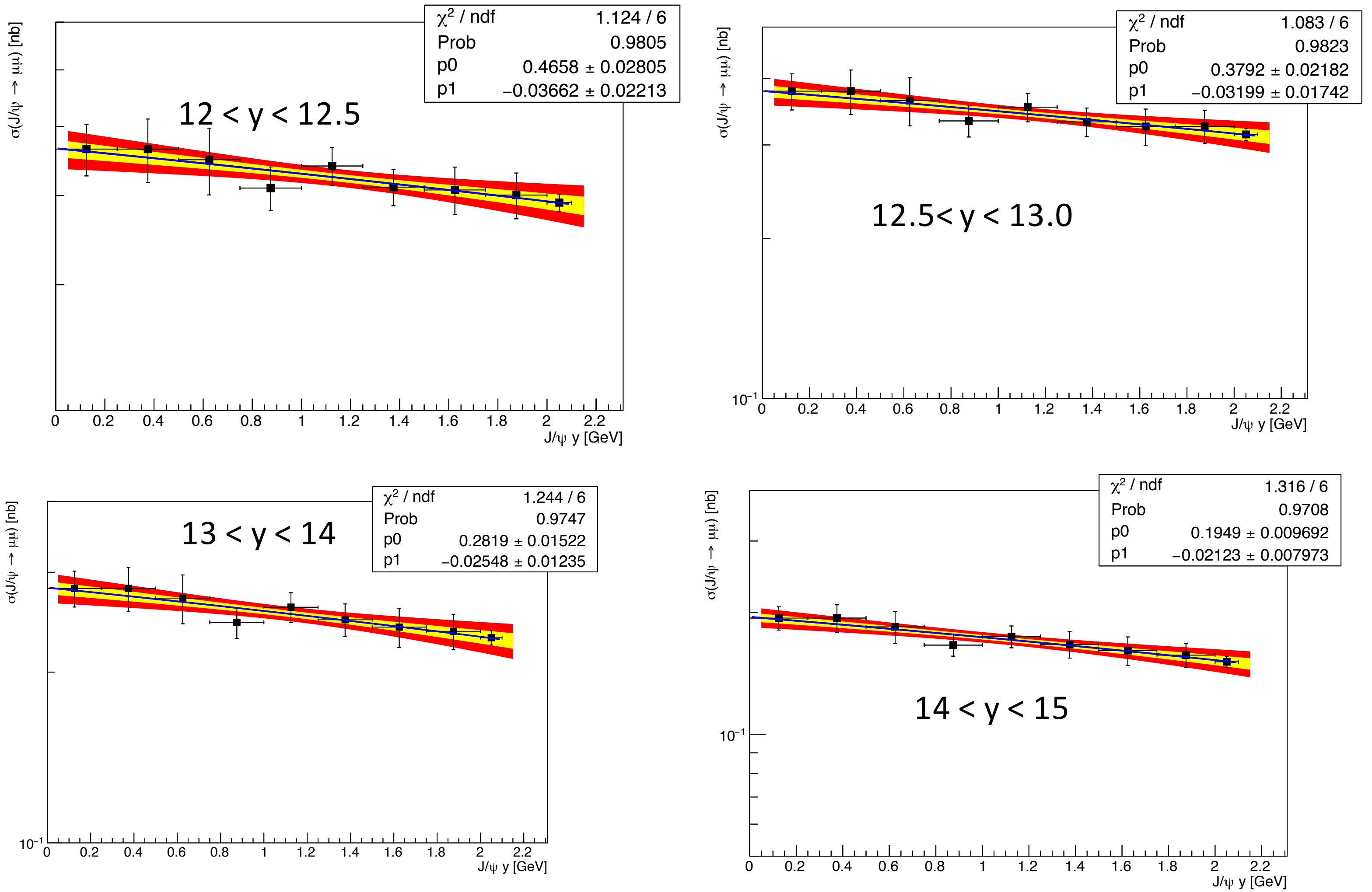




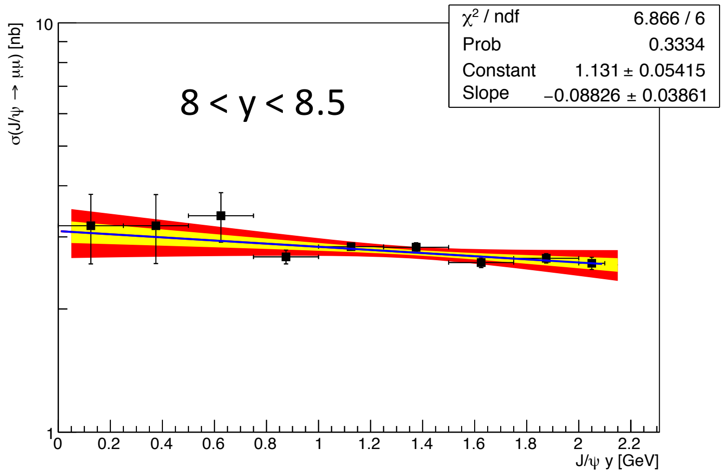
Pileup Interactions:
~4 for <5mm cut
~8 for <10mm cut
~16 for <20 mm cut

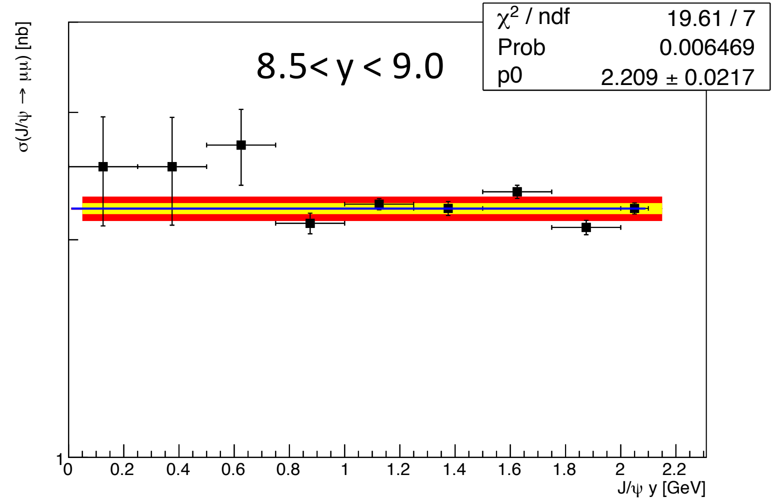
The extra ~8 events seen in-between cuts of 10mm and 20 mm are accounted for by pileup interactions

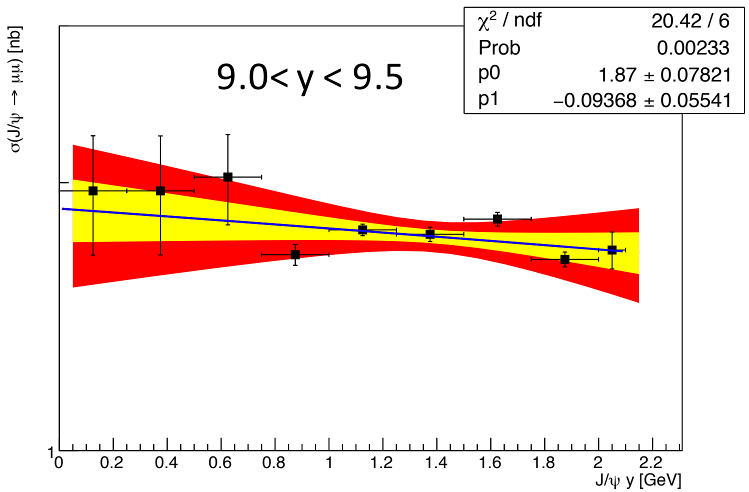
J/Ψ→μμ Cross Section Extrapolations

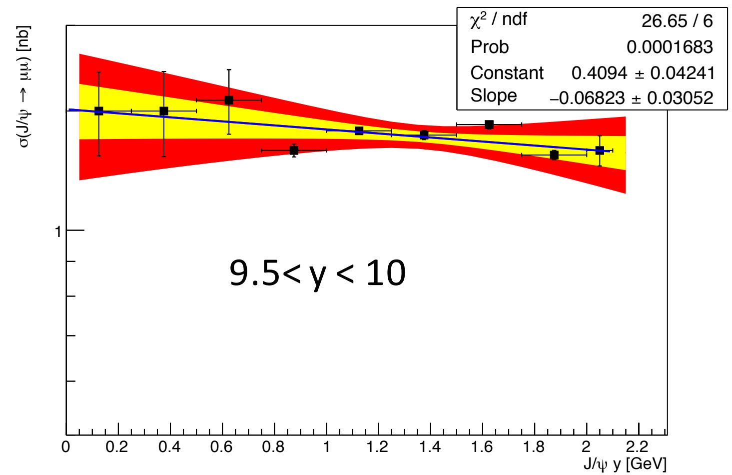


J/Ψ→μμ Cross Section Extrapolations

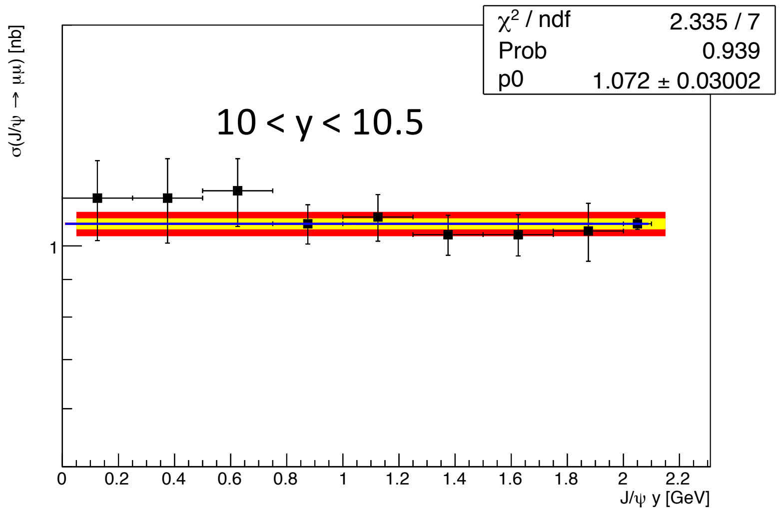


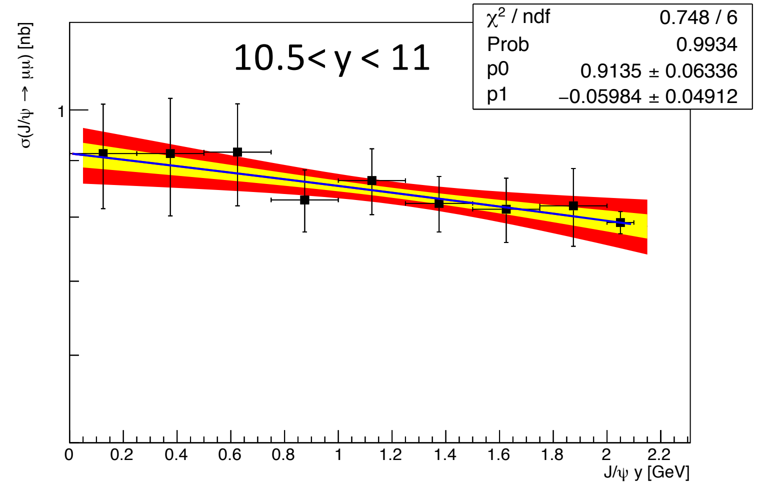


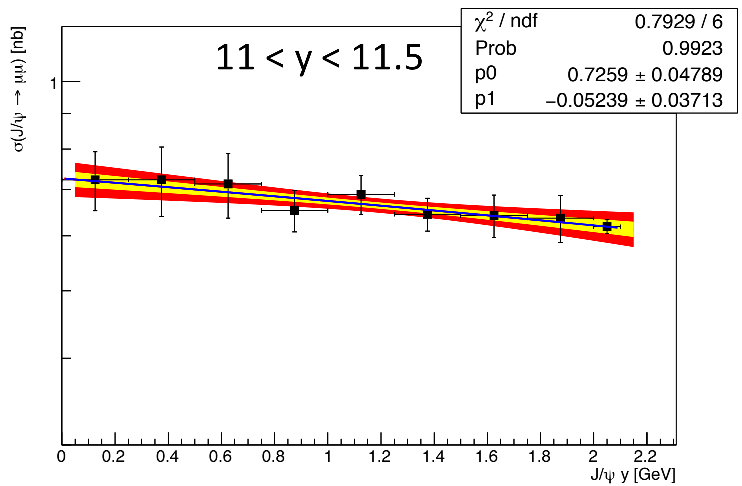


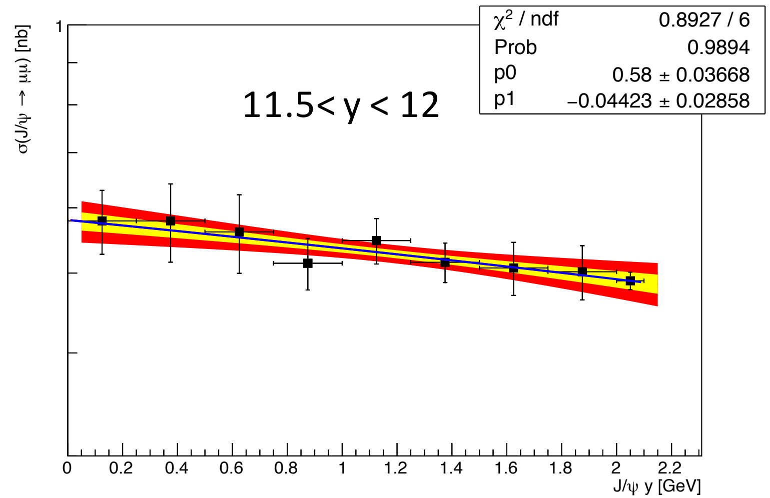


J/Ψ→μμ Cross Section Extrapolations

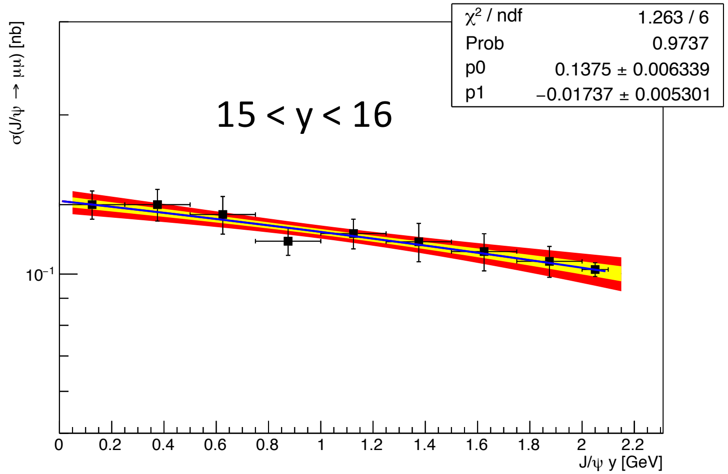


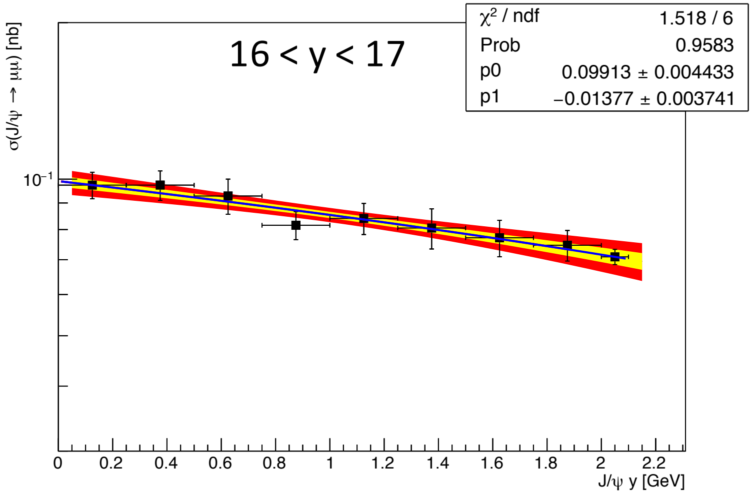


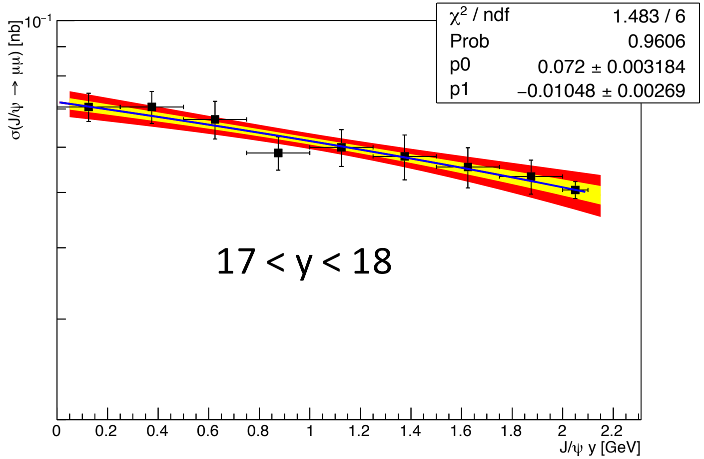


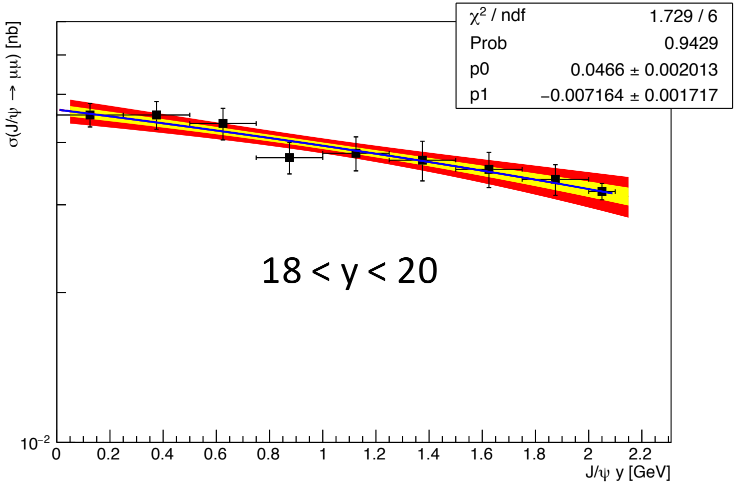


J/Ψ→μμ Cross Section Extrapolations

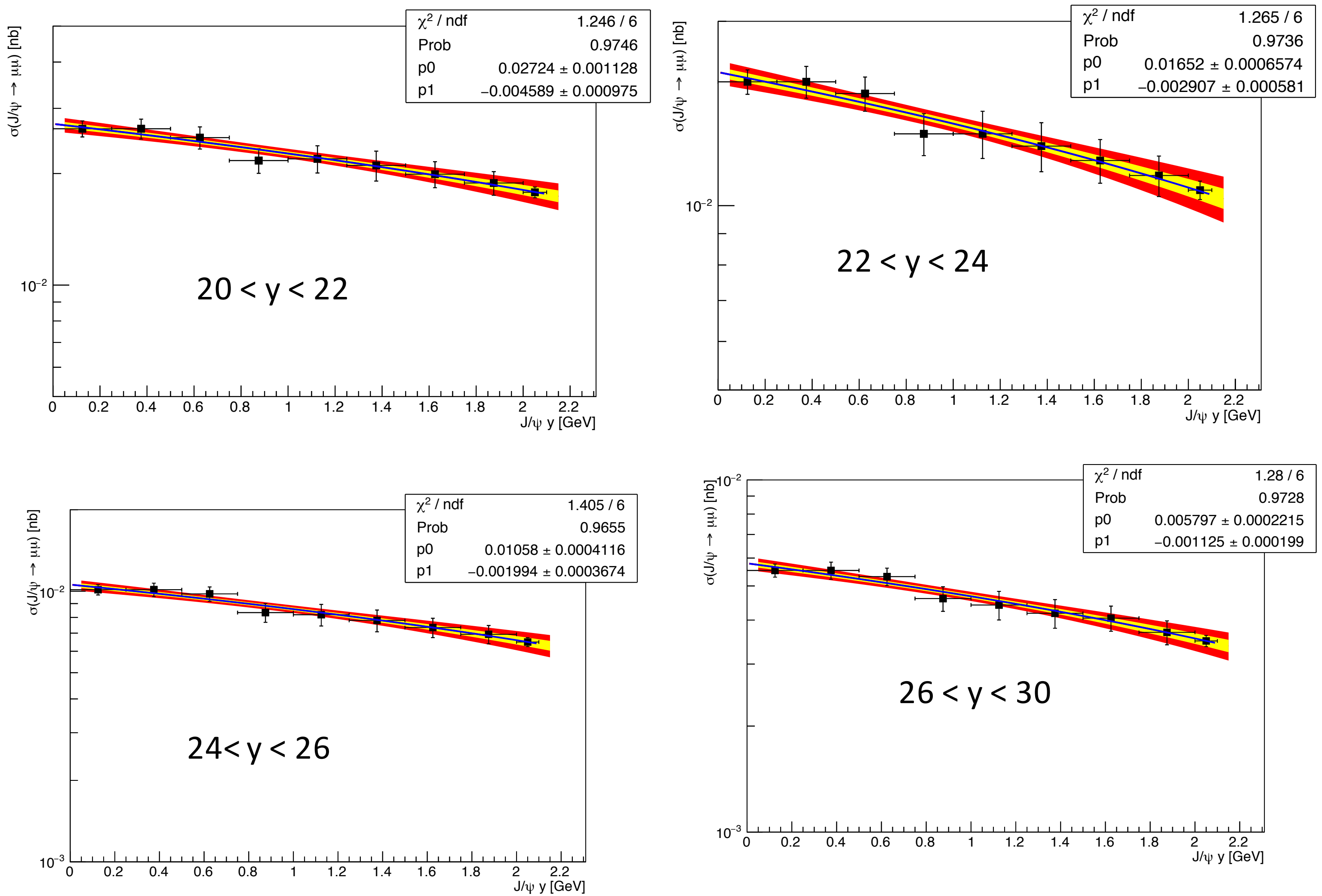




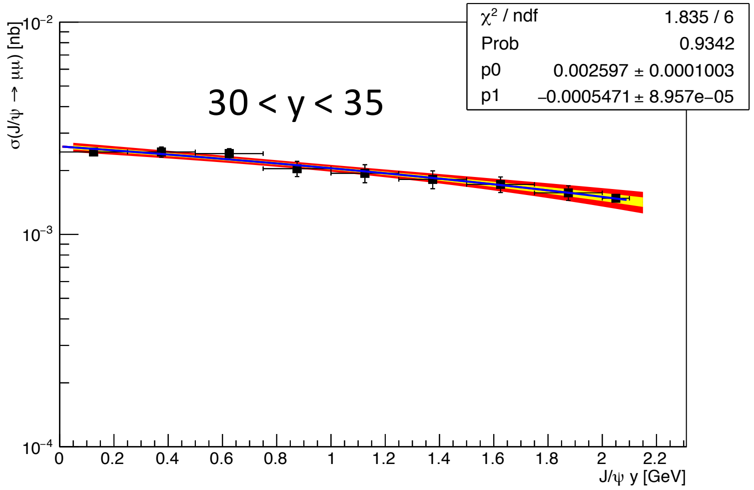


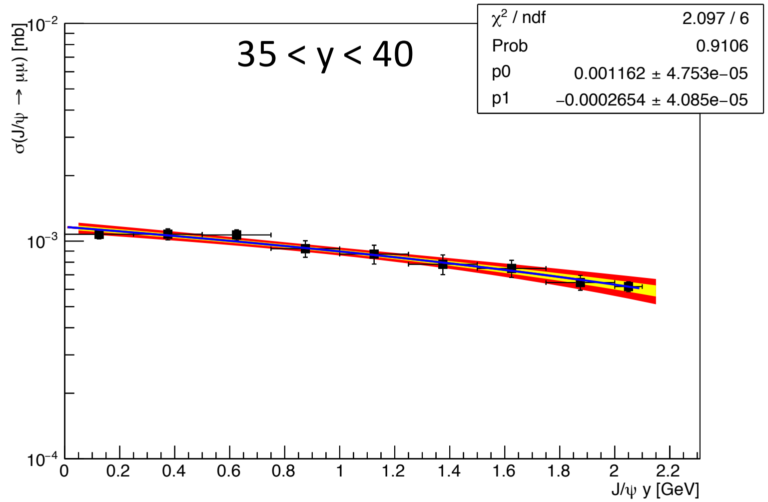


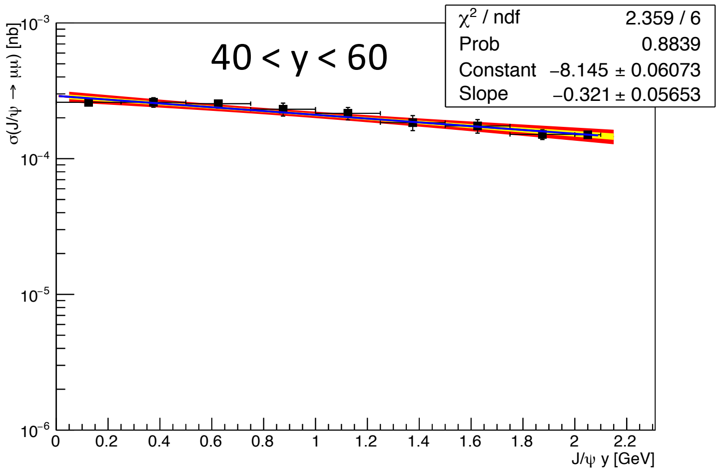
J/Ψ→μμ Cross Section Extrapolations

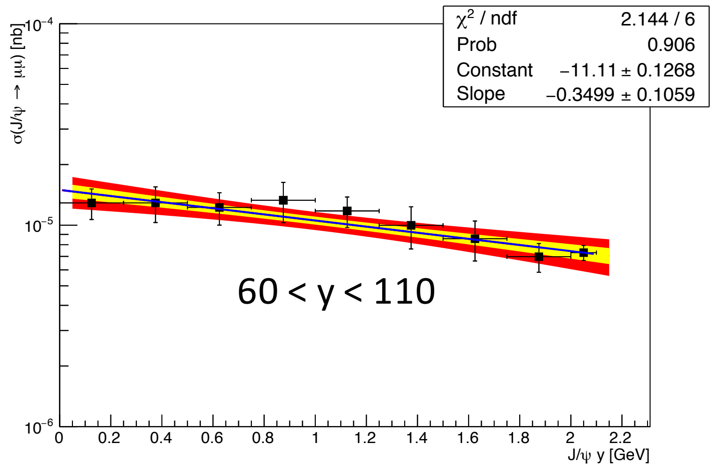


J/Ψ→μμ Cross Section Extrapolations

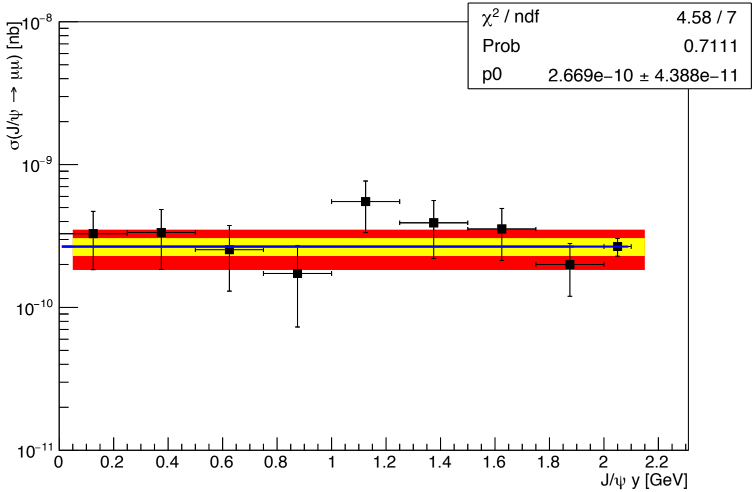








J/Ψ→μμ Cross Section Extrapolations



110< y < 150

- There is an online FONLL tool that can generate **non-prompt** J/ψ cross-sections for any given y and pT: http://www.lpthe.jussieu.fr/~cacciari/fonll/fonllform.html
- It does not generate **prompt** J/ψ cross-sections, so it's not useful for this analysis

Background Removal: Multi-jet

ABCD Method for multi-jet background determination

Multijet background can't be determined from MC, so a data driven method is used.

Categories

A: MET < 20 GeV, MT(W) < 40 GeV, isolated muon

B: MET < 20 GeV, MT(W) < 40 GeV, anti-isolated muon

C: MET > 20 GeV, MT(W) > 40 GeV, isolated muon (signal region)

D: MET > 20 GeV, MT(W) > 40 GeV, anti-isolated muon

Assumption is that this ratio is constant:

D/B = C/A

Muon Isolation Criteria

P = Track isolation momentum in cone of ΔR < 0.3

E = Calorimeter isolation energy in cone of ΔR < 0.3

	P < 0.05pT	P > 0.05pT
E < 0.05pT	isolated	
E > 0.05pT		anti-isolated

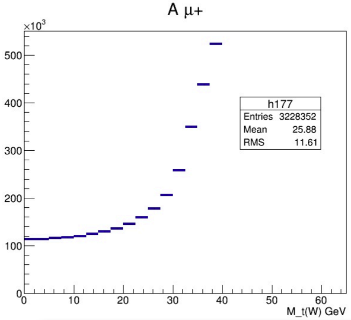
Method:

1. Subtract events in all other known MC modeled backgrounds from the data events in each region
2. (Events in A)/(Events in B) = muon isolation *fake factor*
3. *fake factor* x D = multi-jet background

Background Removal: Multi-jet (ABCD Method)

Example calculation for positive muons in inclusive W sample:

A data: 3,228,350 – mc: 2,892,860 = 335,490 +/- 2470



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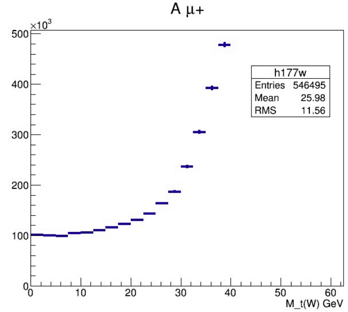

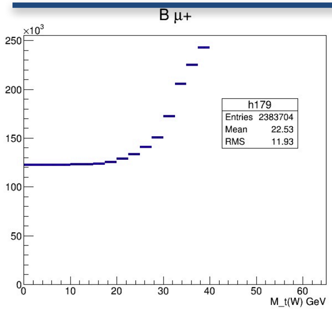

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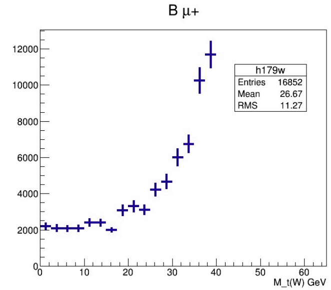
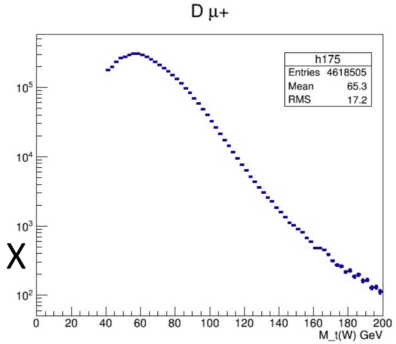


B data: 2,383,700 – mc: 68,172= 2,315,530 +/- 1565

X

D data: 4,617,020 - mc: 947,983 = 3,669,040 +/- 2360



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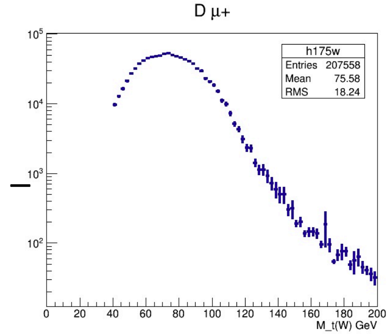

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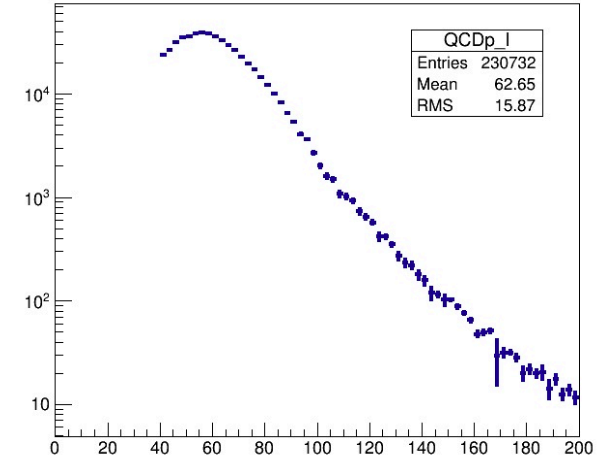
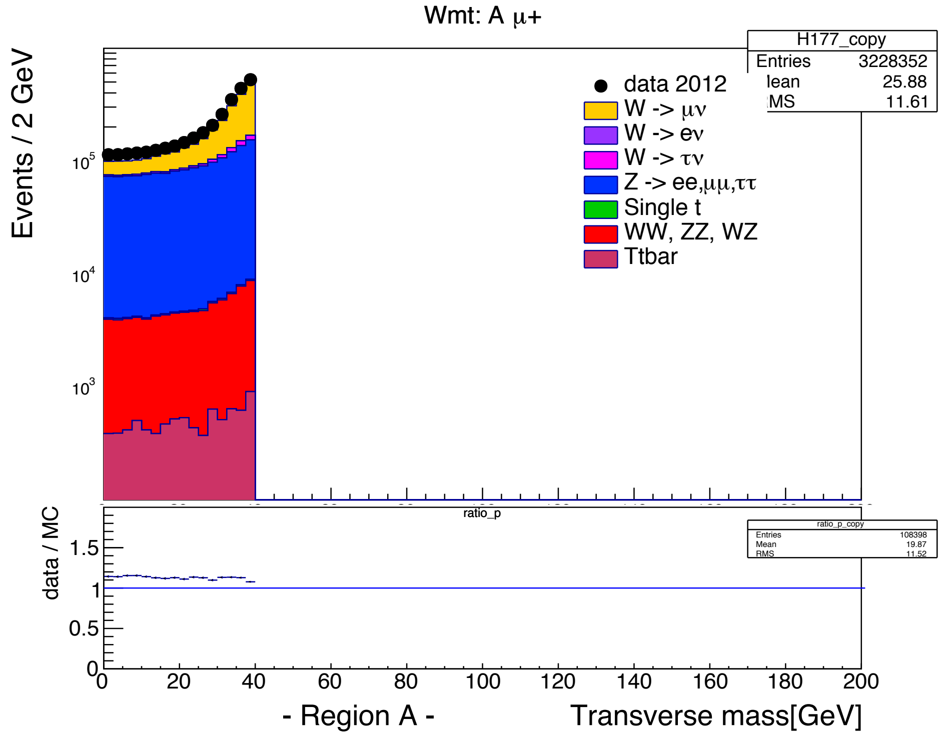
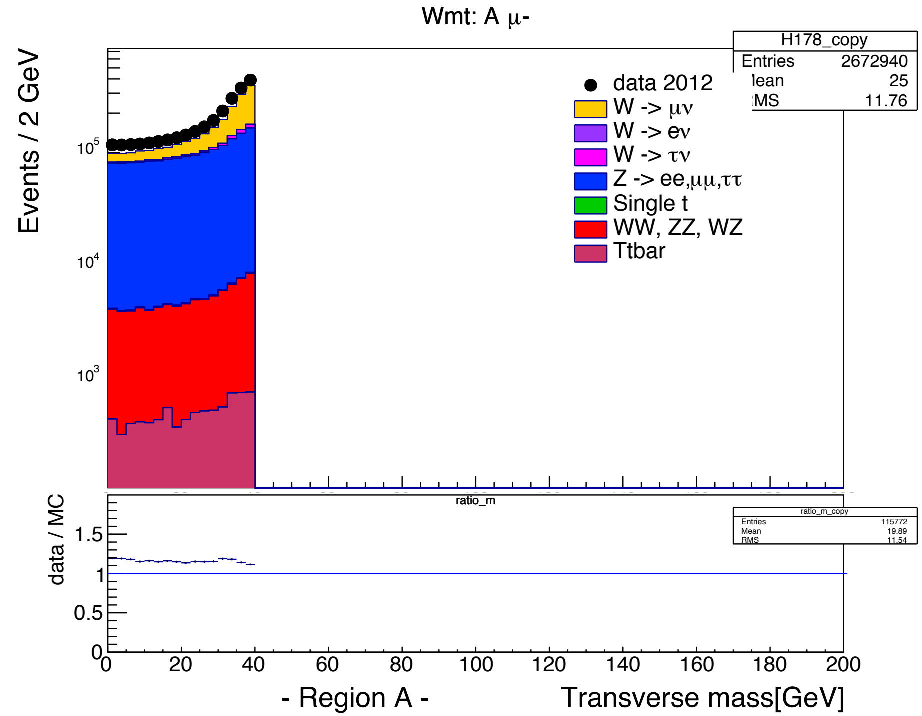


multi-jet background for μ^+ = A/B x D = 531,600 +/- 3,900 events

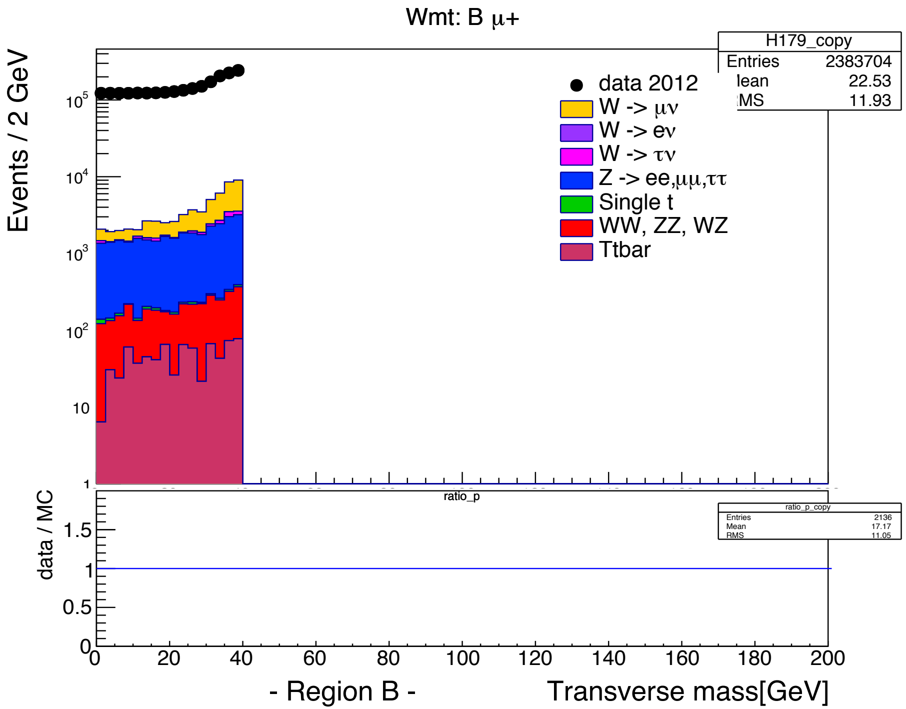
fake factor asymmetry → A/B_p: 0.145 +/- 0.001
A/B_m: 0.181 +/- 0.001

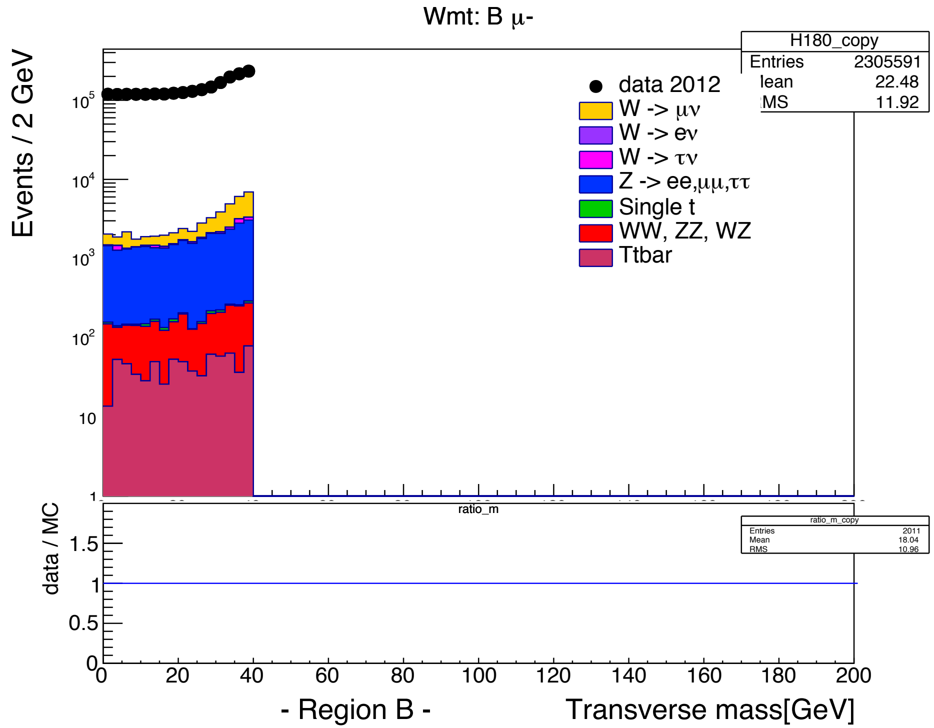
Stack Plots for region A



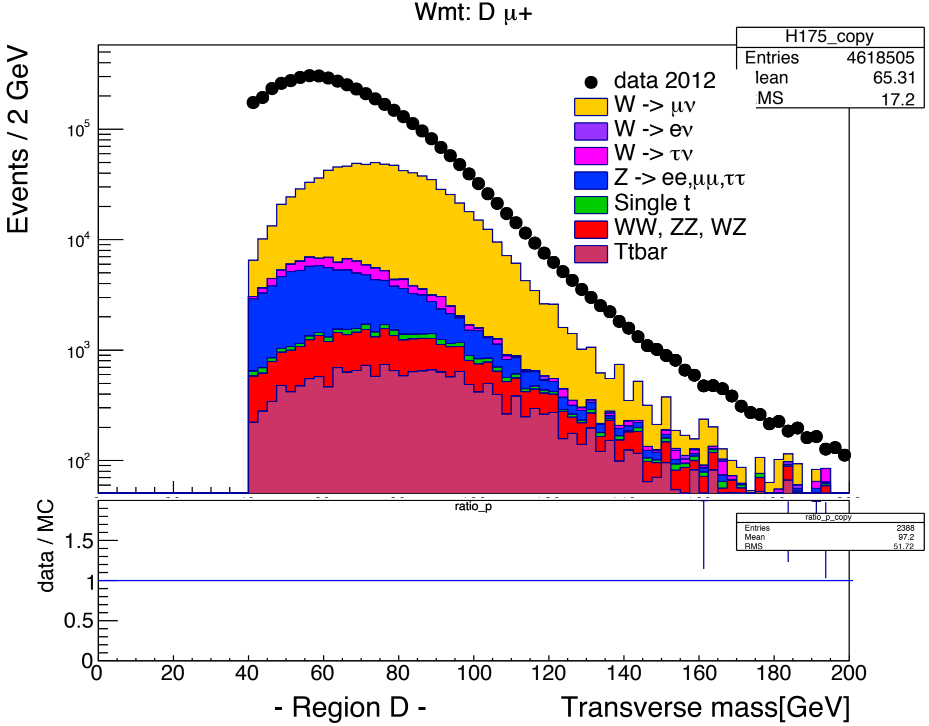


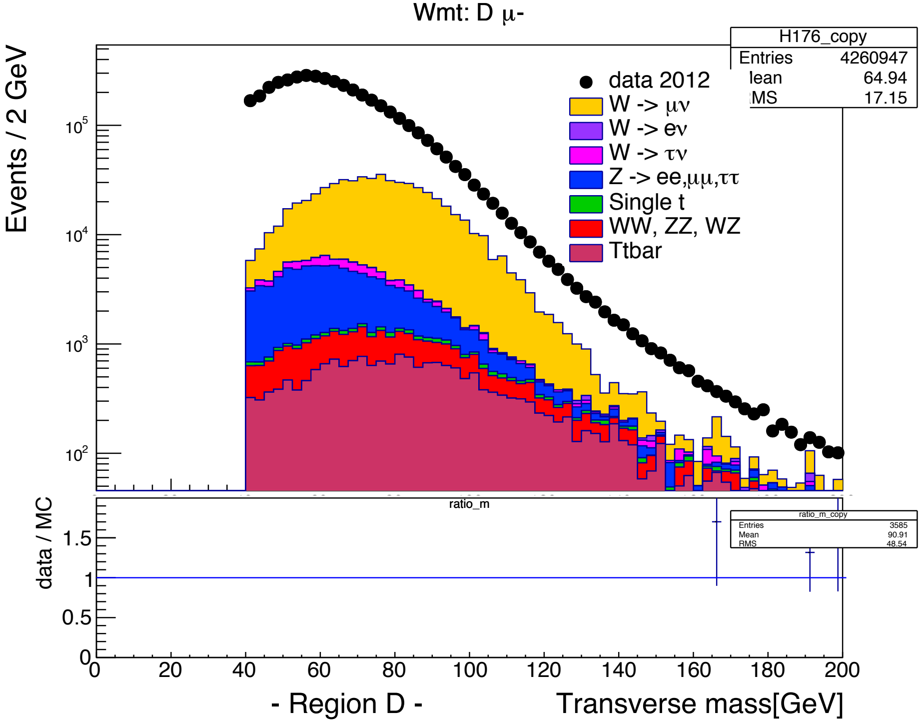
Stack Plots for regions B





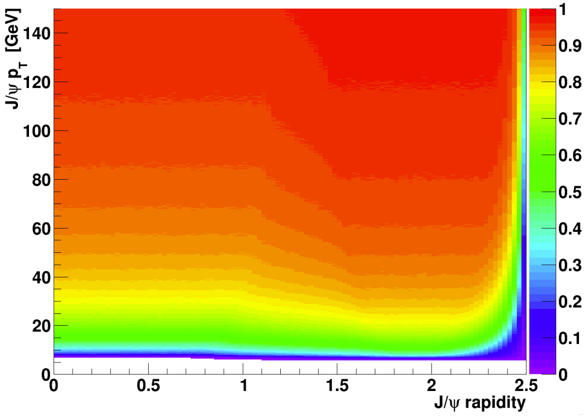
Stack Plots for region D



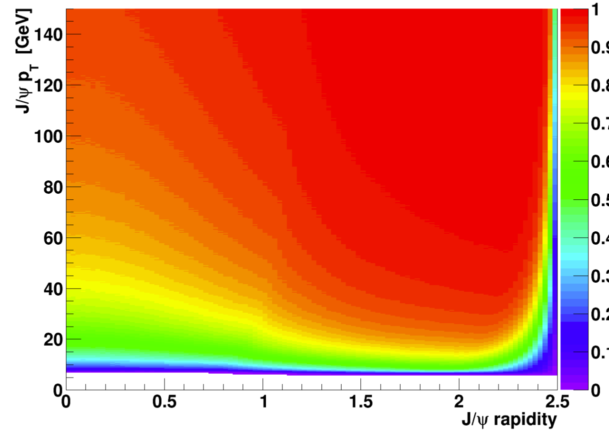


J/ψ Spin Polarization Maps

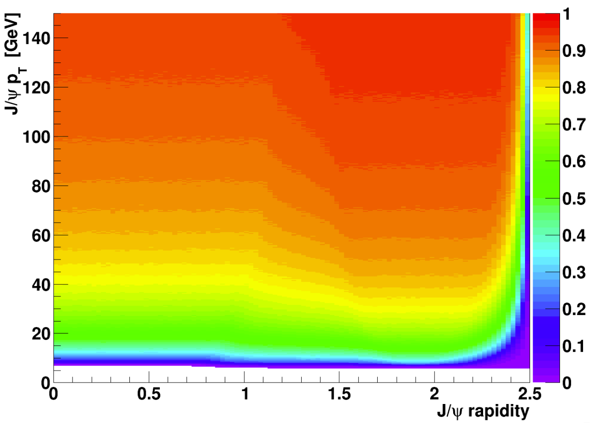
Unpolarised



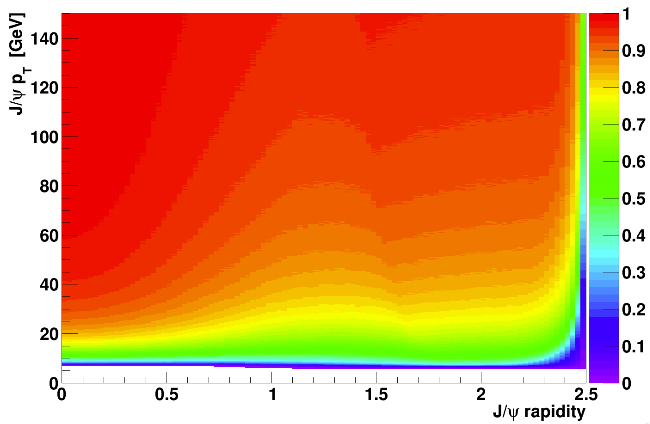
Longitudinal



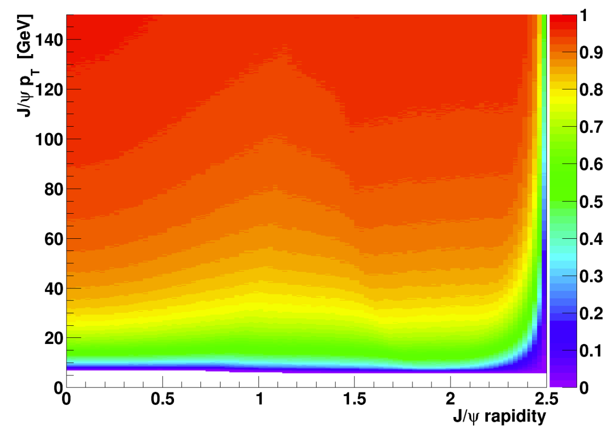
Transverse P



Transverse M



Transverse 0



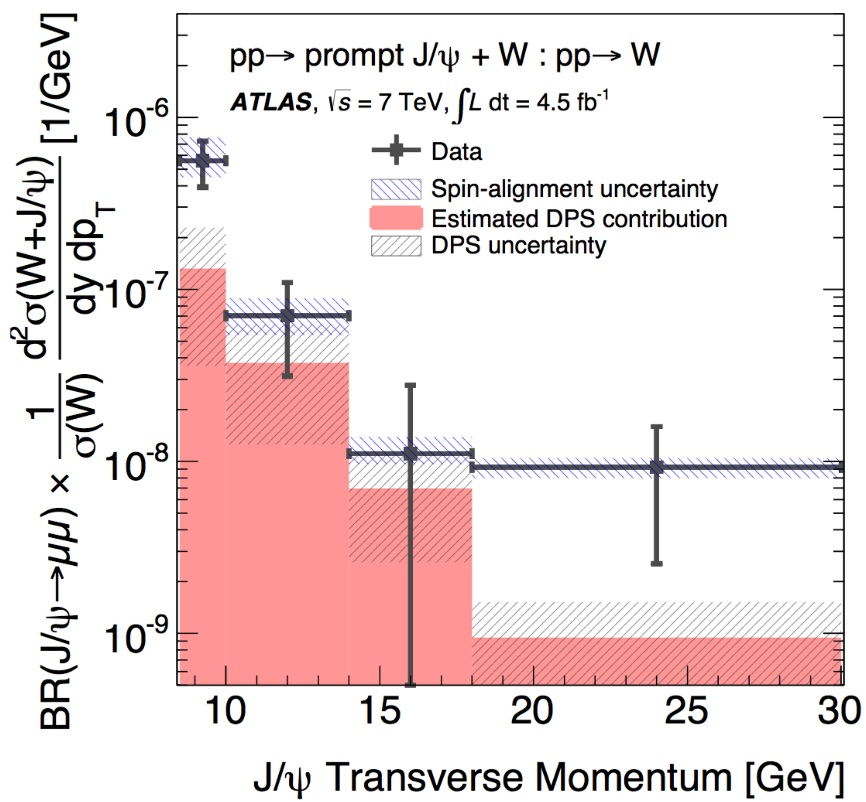
Associated $J/\psi + W^{\pm}$: Systematic Uncertainty

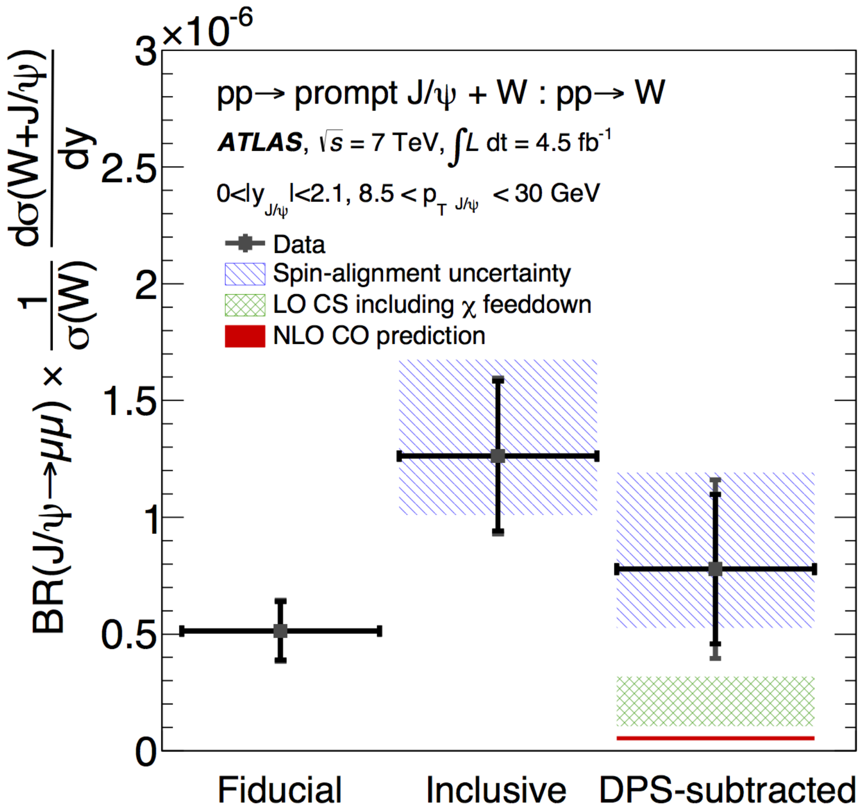
Vertex separation

Requiring J/ψ vertex to be within 10 mm of the W vertex might bias the measurement of the yield.

We use the yield difference between the nominal cut of 10 mm and a cut of 20 mm as a systematic.

7 TeV Cross- Section Ratio Measurement





Theory Prediction Numbers

The theory numbers were refined based on a new acceptance calculation. Calculated by applying our W cuts to PowhegPythia8 $W^{\pm} \rightarrow \mu^{\pm}\nu$ MC samples (with DSIDs 147801 & 147804) of 550,000 events each. Acceptance is defined as the number of events passing cuts over the total number of events generated.

$\alpha+ = 0.460$ $\alpha- = 0.451$

The new theory total σ ratio numbers for **SPS color-octet** processes:

Set 1		Set 2		Measurement	
LO	NLO	LO	NLO	Data	±
0.708	3.67	1.27	4.26	80.10	19.57907

The units are x 10^{-7} GeV and the measured value estimated to come from SPS processes is shown for comparison

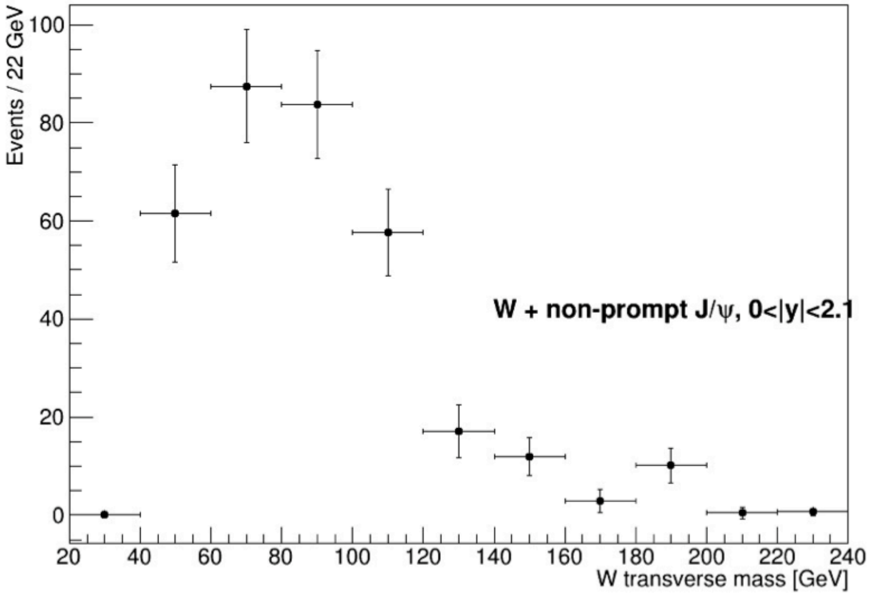
Inclusive Differential Measurement Details

Table 20: The inclusive (SPS+DPS) cross-section ratio $dR^{\text{incl}}_{W+J/\psi}/dp_T$ for prompt J/ψ. Estimated DPS contributions for each bin, based on the assumptions made in this study, are presented.

$\|y^{J/\psi}\| \times p_T^{J/\psi}$ [GeV]	Inclusive prompt ratio [$\times 10^{-7}$ / GeV] value ± (stat)	± (syst)	± (spin)	Estimated DPS [$\times 10^{-7}$ / GeV] assuming $\sigma_{\text{eff}} = 15$ mb
(0, 1) × (8.5, 10)	13.0 ± 3.2	± 1.1	± 4.3	0.63 ± 0.24
(0, 1) × (10, 14)	4.02 ± 1.27	± 1.42	± 1.07	0.30 ± 0.12
(0, 1) × (14, 18)	0.890 ± 0.426	± 0350	± 0189	0.084 ± 0.033
(0, 1) × (18, 30)	0.351 ± 0.141	± 0.038	± 0.066	0.016 ± 0.006
(0, 1) × (30, 60)	0.0343 ± 0.0321	± 0.0073	± 0.0039	0.00081 ± 0.00031
(0, 1) × (60, 150)	0.00886 ± 0.00589	± 0.00055	± 0.00049	0.00002 ± 0.00001
(1, 2.1) × (8.5, 10)	10.67 ± 3.02	± 1.89	± 2.95	1.29 ± 0.55
(1, 2.1) × (10, 14)	3.86 ± 0.87	± 0.50	± 0.82	0.40 ± 0.15
(1, 2.1) × (14, 18)	1.35 ± 0.46	± 0.08	± 0.23	0.095 ± 0.036
(1, 2.1) × (18, 30)	0.282 ± 0.133	± 0.026	± 0.036	0.016 ± 0.006
(1, 2.1) × (30, 60)	0.0408 ± 0.0346	± 0.0051	± 0.0035	0.00063 ± 0.00024
(1, 2.1) × (60, 150)	0.0019 ± 0.0047	± 0.0003	± 0.0001	0.0000096 ± 0.0000037

Non-Prompt J/ψ: Measurement Attempt

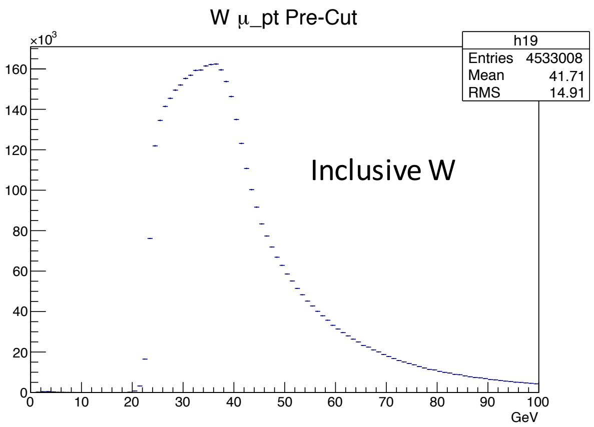
Sample	un-weighted yield	± error
Data	354	23
MC: W→eν	0	0
MC: W→μν	4	3
MC: W→τν	0	0
MC: Z+jets	2.0	1.6
MC: Single t	13	6.4
MC: Diboson	7.70	0.07
MC: $t\bar{t}$(105200)	299	3
MC: $t\bar{t}$(117050)	217	20
MC: All backgrounds*	337.1	0.3
MC: All backgrounds†	248	18

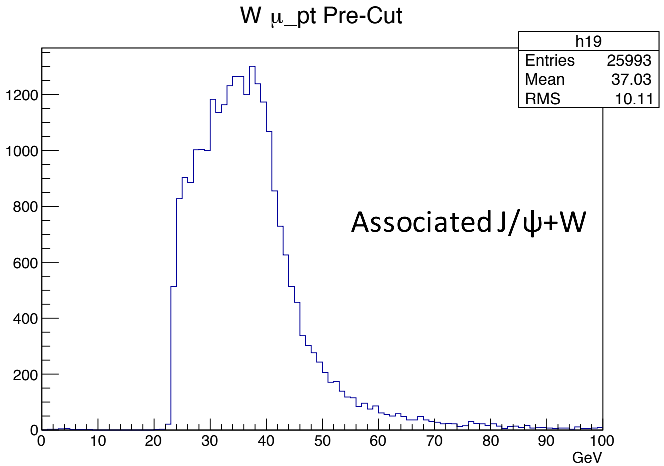


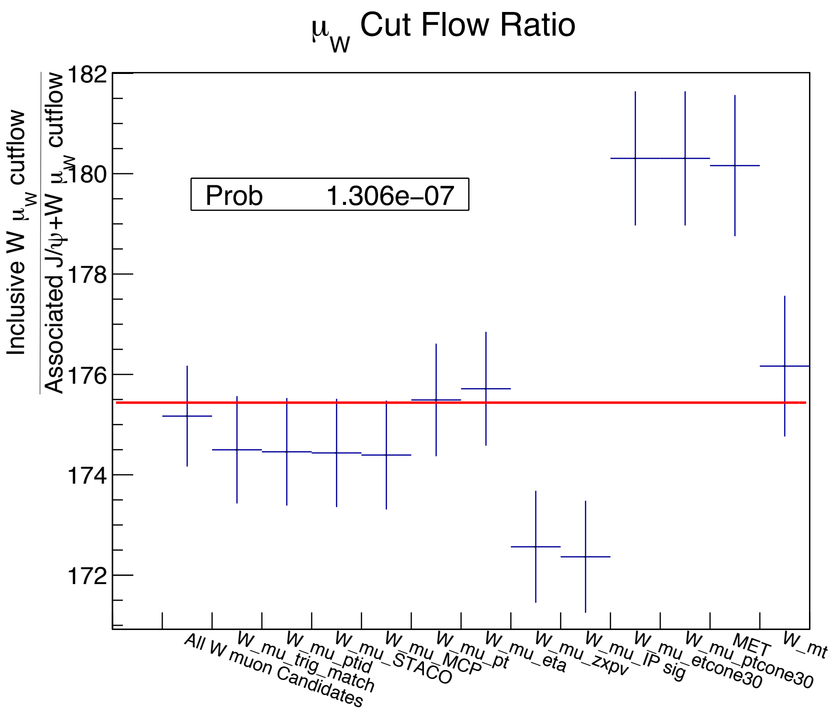
Not feasible due to large backgrounds, dominated by $t\bar{t}$. Furthermore the choice of MC generator (105200* or 117050†) gives very different results and would cause a large systematic uncertainty.

Cutflow Efficiency Ratio

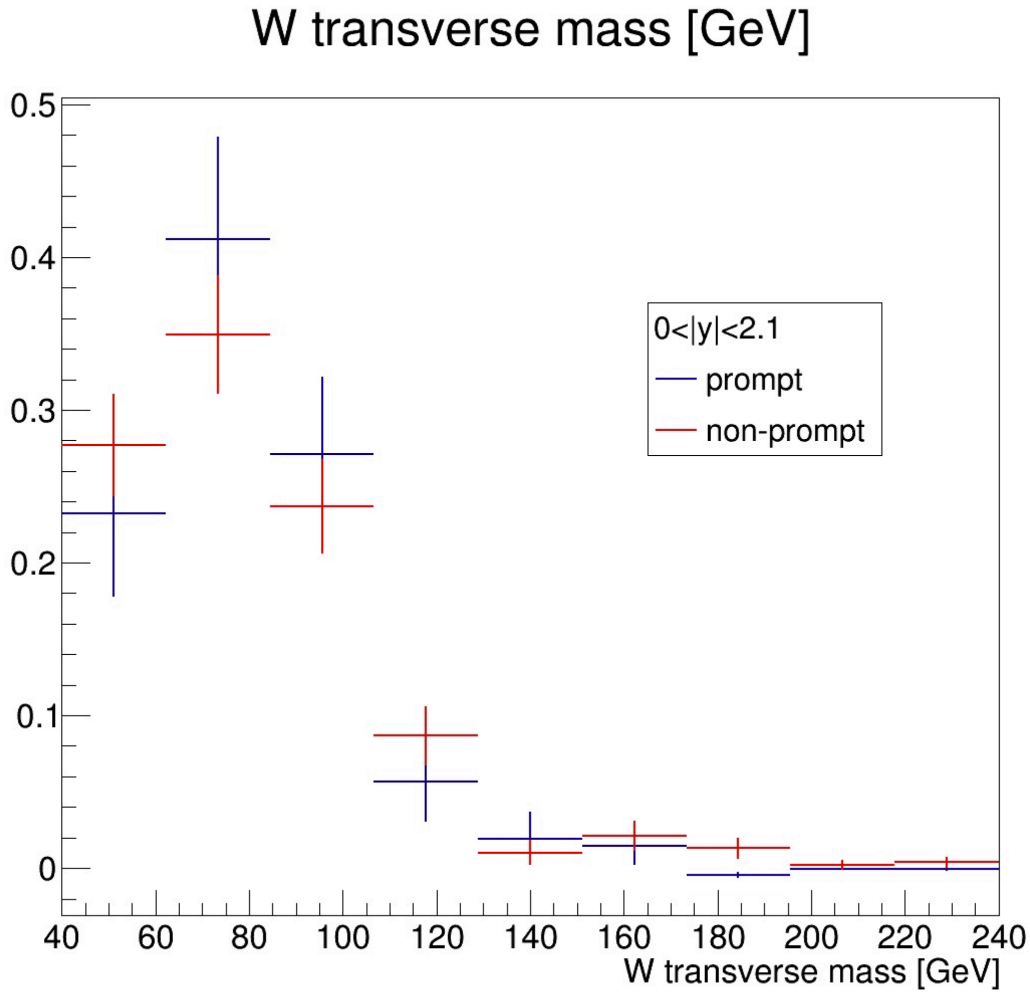
Note: Appendix D.3







New cutflow ratio plot - Figure 26

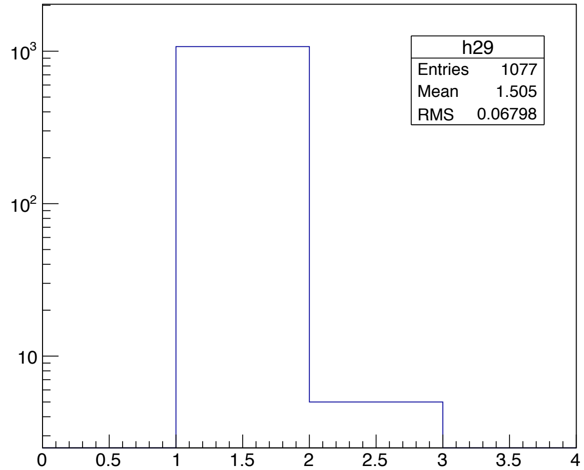


W transverse mass shapes associated with prompt and non-prompt events are compatible.

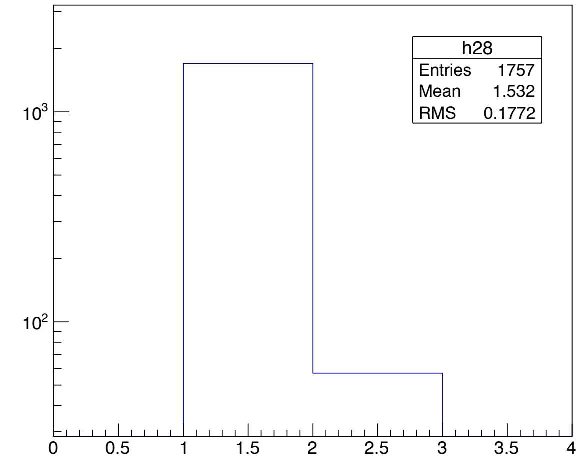
Backup: Cross-Checks

If more than one J/ψ, or more than 3 muons survived all cuts, then further selections were made.

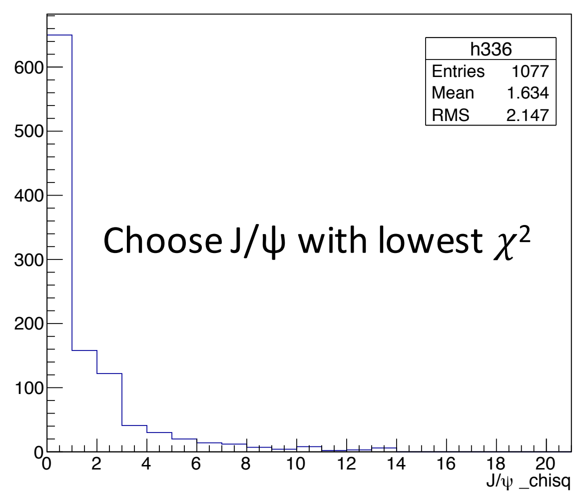
J/ψ Multiplicity



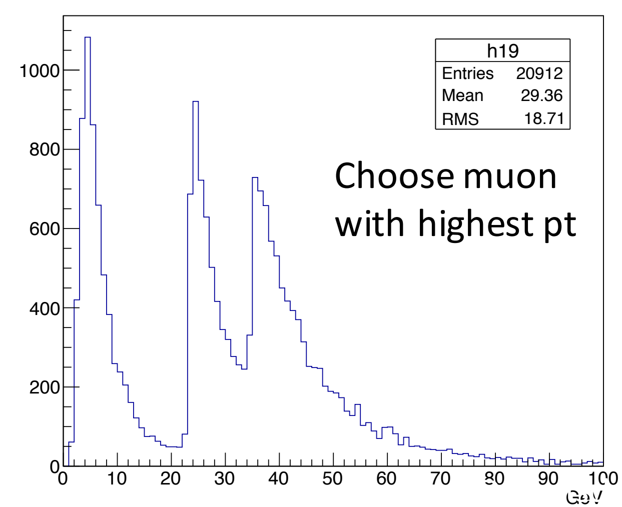
Post J/ψ Muon Multiplicity



J/ψ chisq Post-Selections



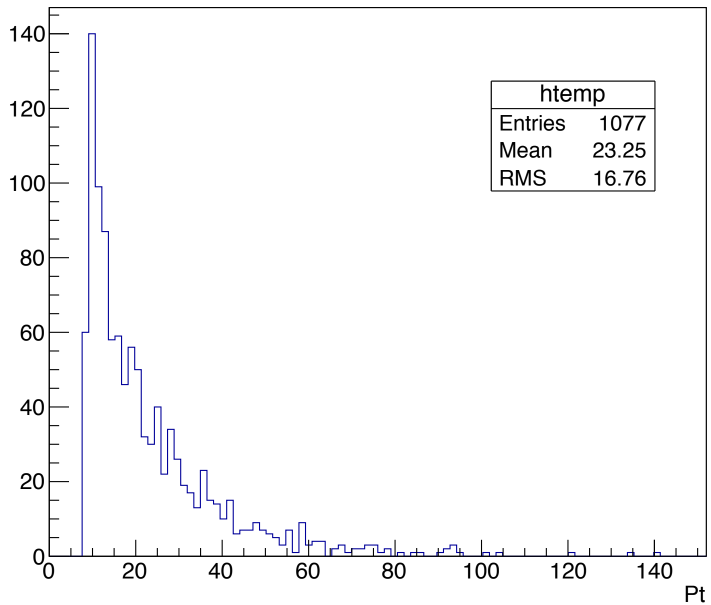
W μ_pt Pre-Cut



After All Cuts

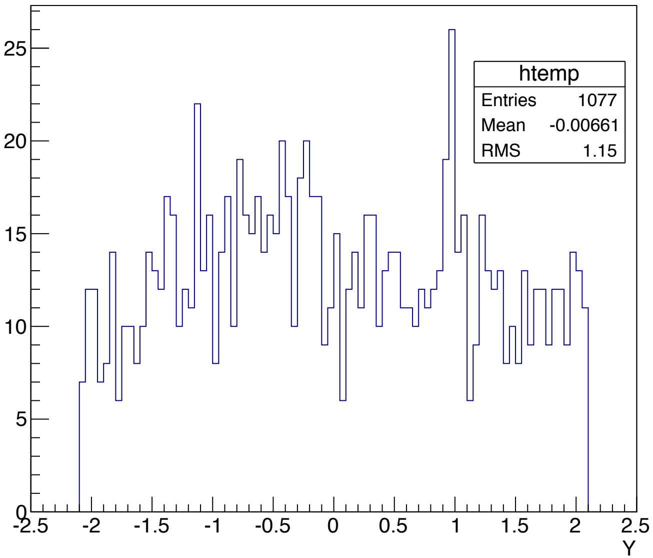
1077 J/ψ + W± Candidates survive all cuts

J/ψ Pt

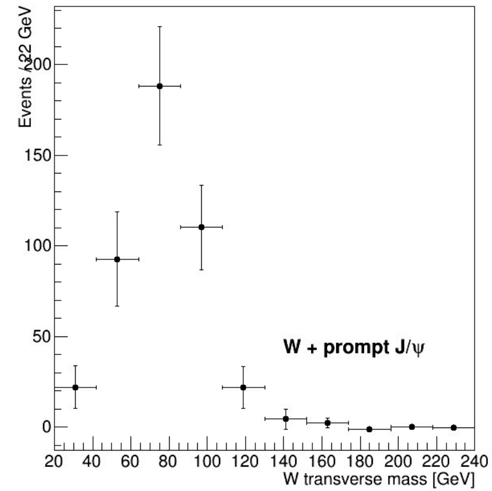


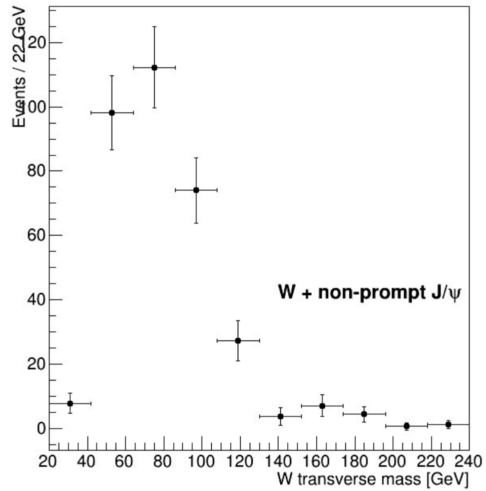
GeV

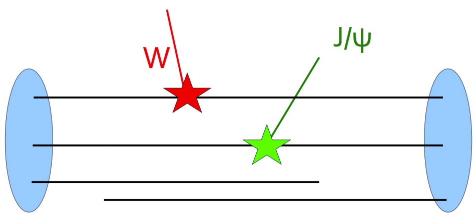
J/ψ Y



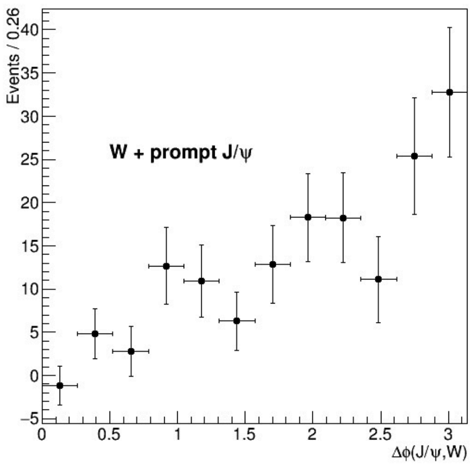
Splot separates out prompt component for: W transverse mass and $\Delta\phi(J/\psi,W)$

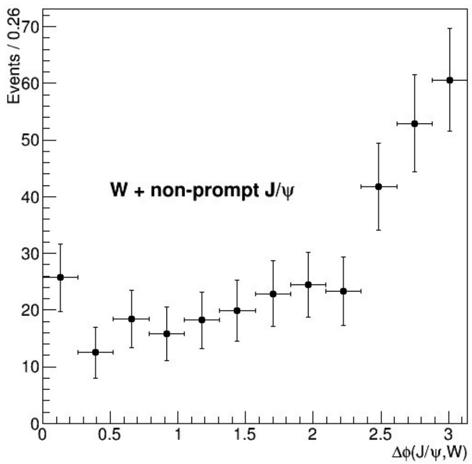


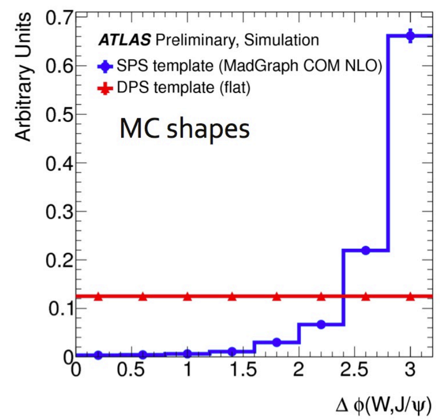




This angle, $\Delta\phi(J/\psi,W)$ is a probe into double parton scattering (DPS) processes. Single parton scattering (SPS) peaks at π, and DPS is flat.



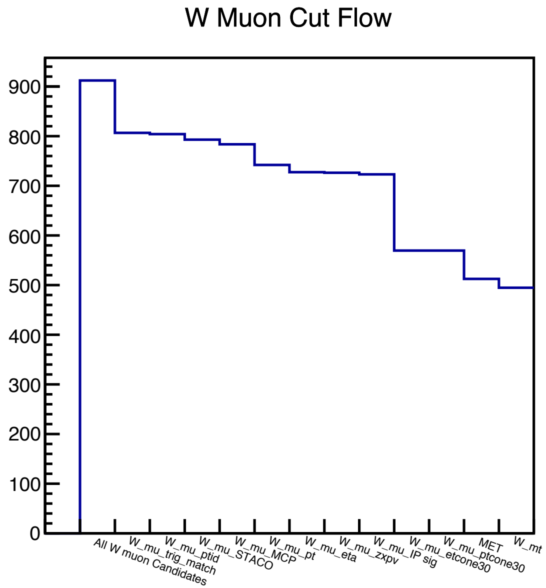


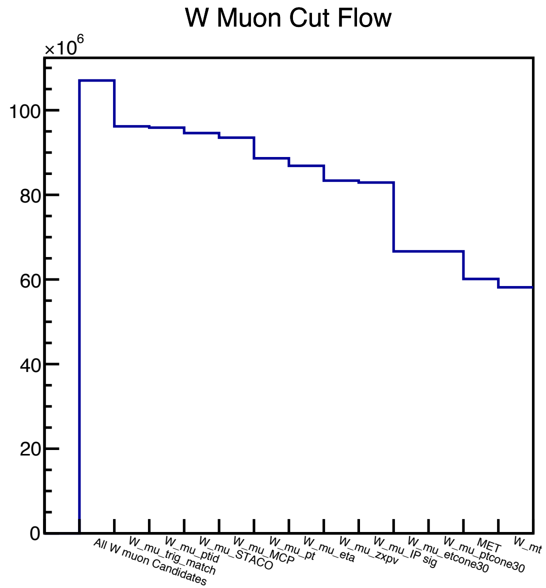


W cuts Efficiency Check – Using truth MC

$$R_{J/\psi} \equiv \frac{\sigma_{W+J/\psi}}{\sigma_W} \equiv \frac{\frac{N_{W+J/\psi}}{\mathcal{L}\times\epsilon_W\times\epsilon_{J/\psi}\times\mathcal{A}_{J/\psi}}}{\frac{N_W}{\mathcal{L}\times\epsilon_W}} \equiv \frac{1}{N_W}\left[\frac{N_{W+J/\psi}}{\epsilon_{J/\psi}\times\mathcal{A}_{J/\psi}}\right]$$

The cross-section ratio calculation (above) depends on the efficiency of the W cuts being the same for the J/ψ+W and Inclusive W samples. A test (below) with MC truth info shows that the efficiency is the same.





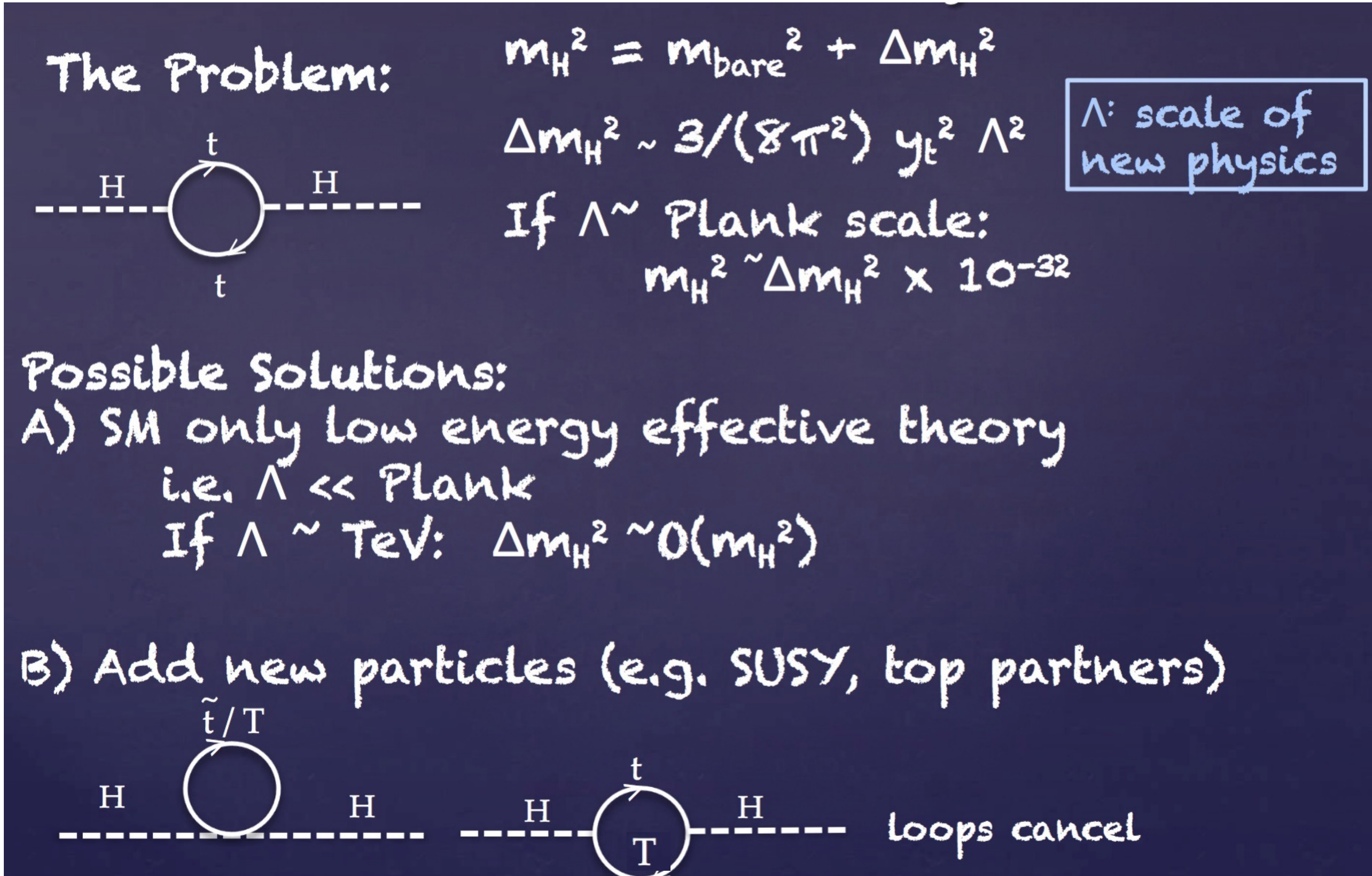
<u>J/ψ + W cutflow</u>

last_bin/first_bin = 495/912 ≃ 0.543

<u>Inclusive W cutflow</u>

last_bin/first_bin = (581/1070)*10^5 ≃ 0.543

The Hierarchy Problem



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