

J/ ψ and $\psi(2s)$ production in p+p collisions at $\sqrt{s} = 500$ GeV from STAR experiment

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Outline

Introduction

- Motivation
- STAR Detector

J/ ψ measurement and analysis technique

- Dataset and Trigger
- J/ ψ analysis method

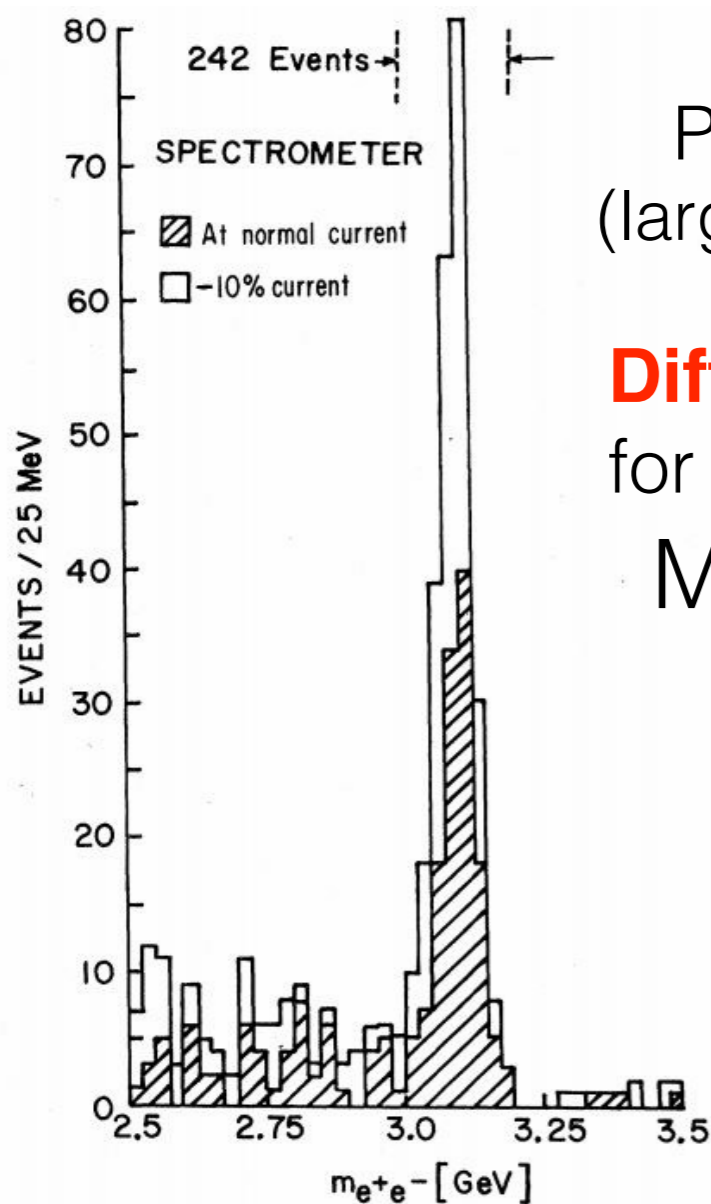
Results

- J/ ψ p_T spectrum
- $\psi(2s)$ to J/ ψ ratio

Summary

Motivation

J/ψ is one of the simplest QCD bound states, but its production mechanism in $p+p$ is not well understood.



PRL 33,1404(1974)

Production of the $c\bar{c}$ (large momentum transfer) \longrightarrow evolution of the $c\bar{c}$ pair into J/ψ (small dynamical scale)

Difficulty: Perturbative theoretical calculation is not applicable for the evolution of c and anti- c pair into J/ψ (soft process).

Models:

Color singlet model

($c\bar{c}$ pair has the same quantum numbers as J/ψ)

Color evaporation model

(constant probability for $c\bar{c}$ evolve into J/ψ)

NRQCD model (most successful so far)

($c\bar{c}$ pair in a color-singlet state or a color-octet state)

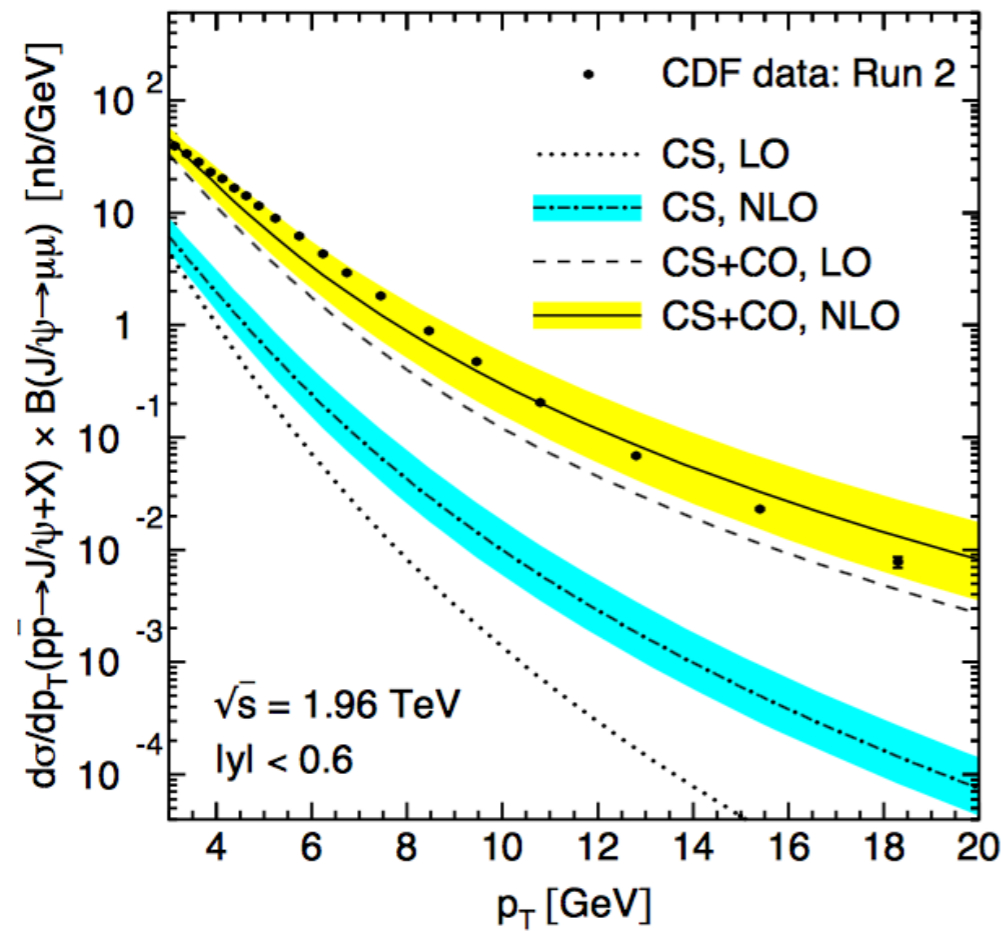
Fragmentation function approach

(high p_T , light-cone fragmentation)

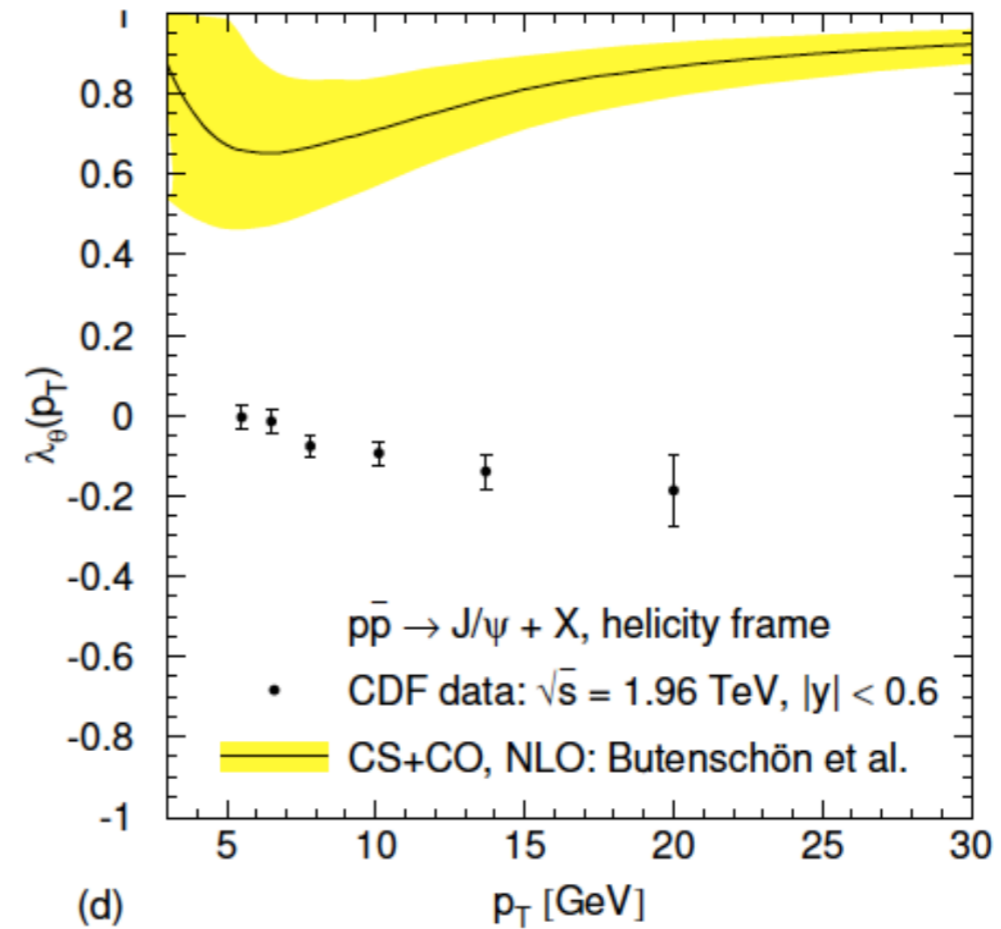
Non-relativistic QCD(NRQCD) factorization approach

- All pairs with various probabilities - NRQCD matrix elements.

World data fitting constrains the universal NRQCD matrix elements at NLO - predictive power in different collision systems, ee, ep and pp.



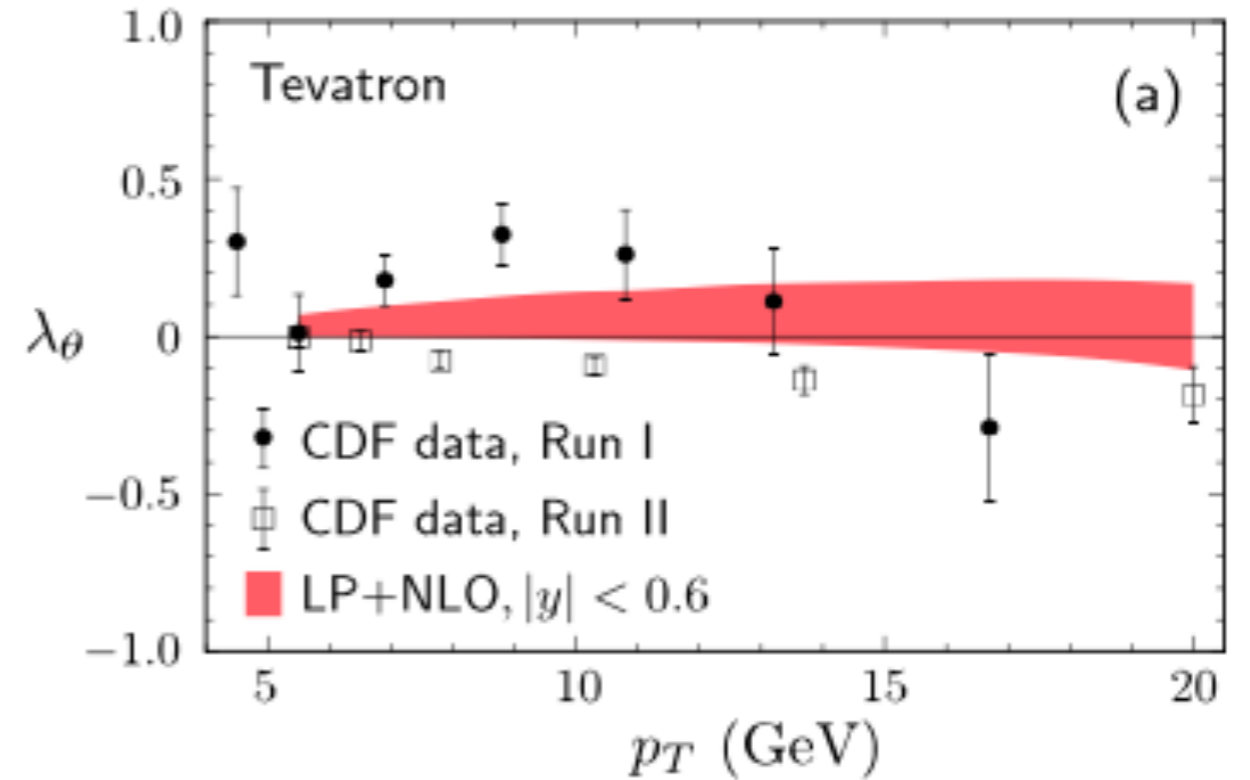
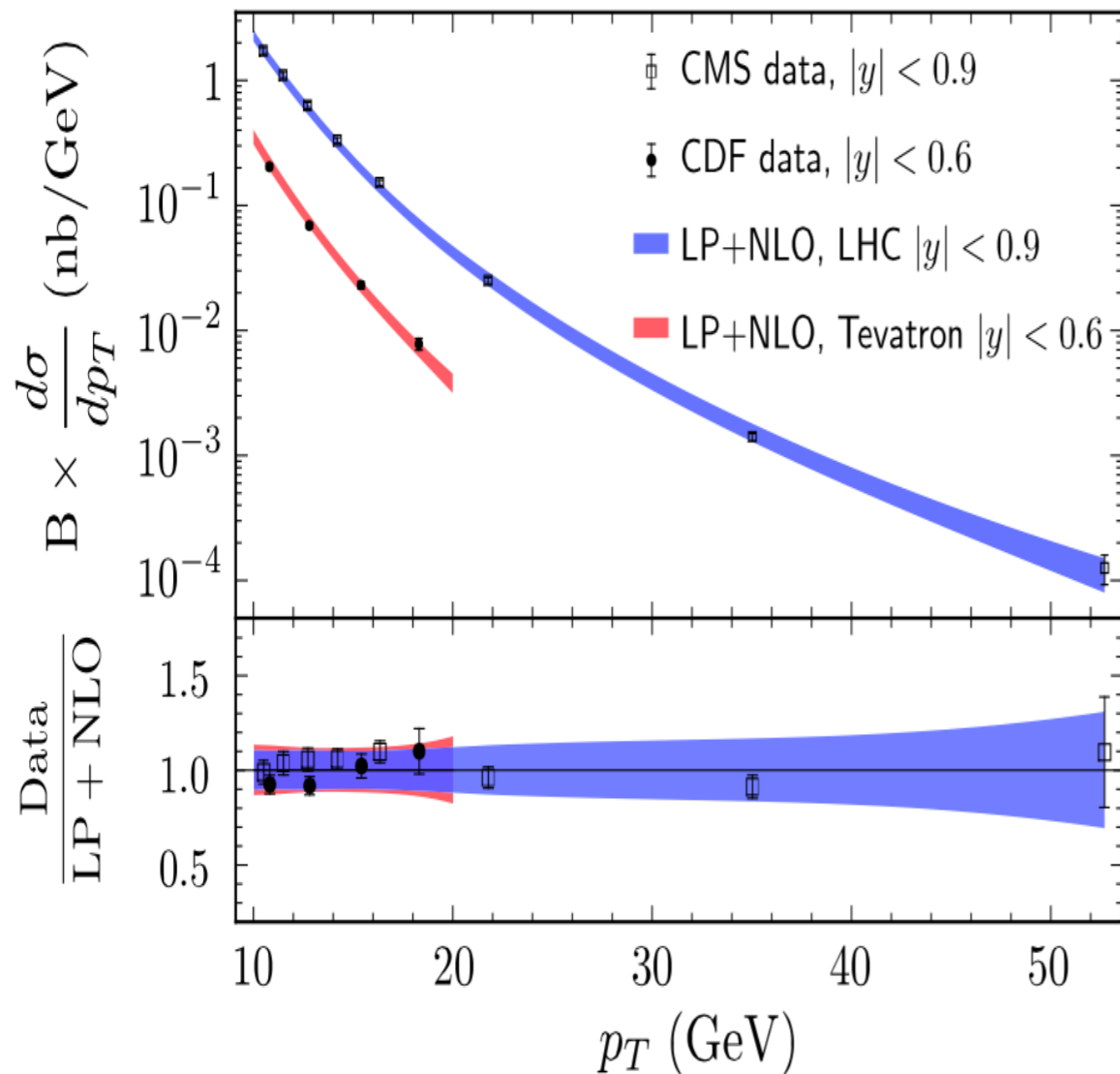
arXiv:1105.0820



PRL 107,232001(2011)

- Polarization is an ultimate test of NRQCD.
- For some channels, NLO corrections are orders of **magnitude larger** than LO.

Fragmentation function approach

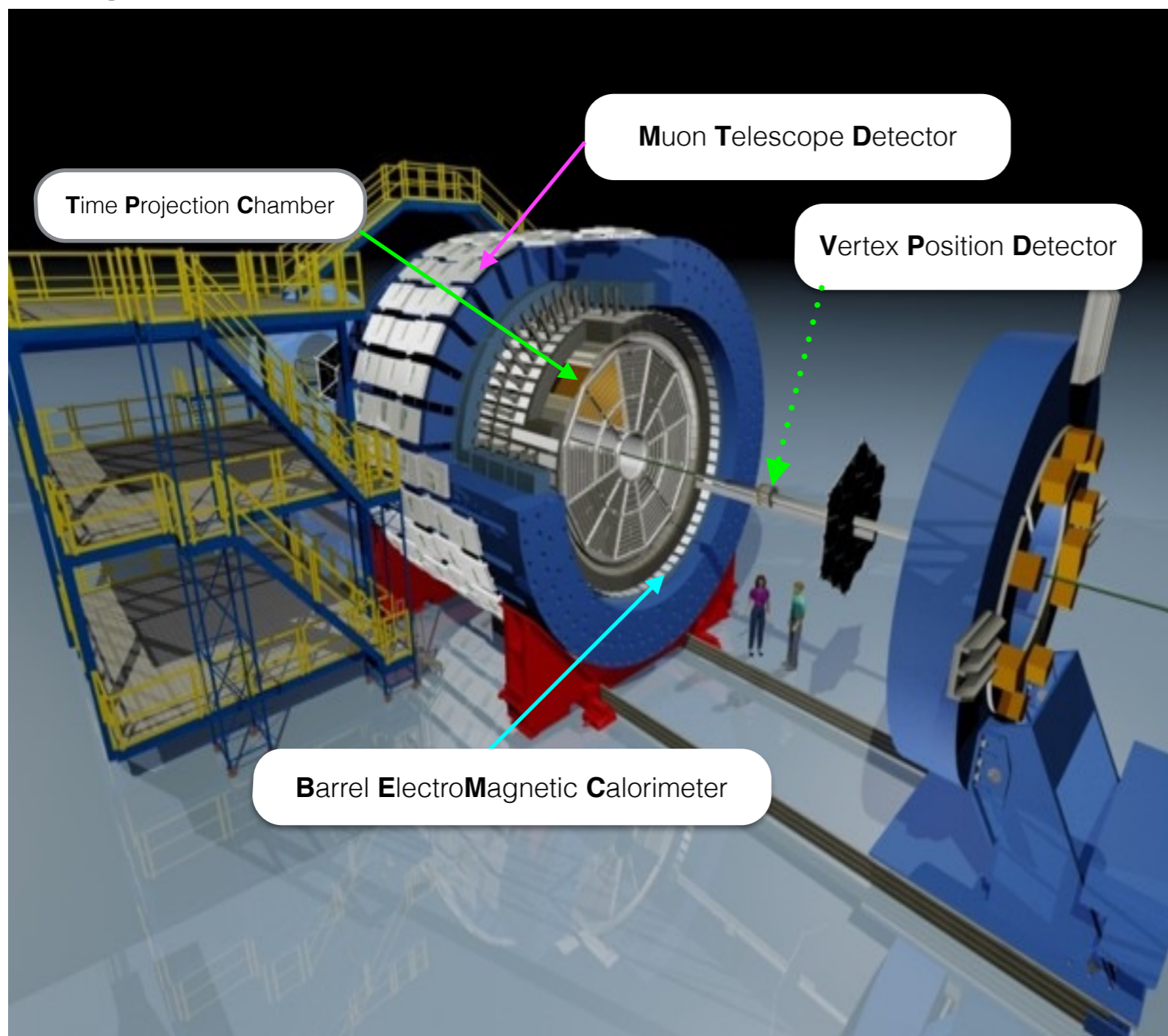


PRL 113,022001(2014)

- Theoretical predictions: **direct** J/ψ .
- Data: **prompt** J/ψ(direct + feed down(χ_{cJ} and $\psi(2s)$))
- Fragmentation function approach are valid only in **high p_T range!!!**

The Solenoid Tracker At RHIC (STAR)

Large acceptance: $|\eta| < 1$, full azimuthal coverage.



Main detectors used in this analysis:

Time Projection Chamber
momentum measurement,
particle identification.

Barrel ElectroMagnetic Calorimeter (BEMC):

electron identification,
fast triggering

Two new detectors since 2014:

Muon Telescope Detector (**MTD**)

Heavy Flavor Tracker (**HFT**)

Dataset and Trigger

Competition effect:

- High instantaneous luminosity
- Limited event recording rate of slow tracking detector (TPC)

Fast detectors select (or trigger on) interesting events.

Barrel ElectroMagnetic Calorimeter(BEMC) is a good choice.

Channel of interest: $J/\psi \rightarrow e^-e^+$

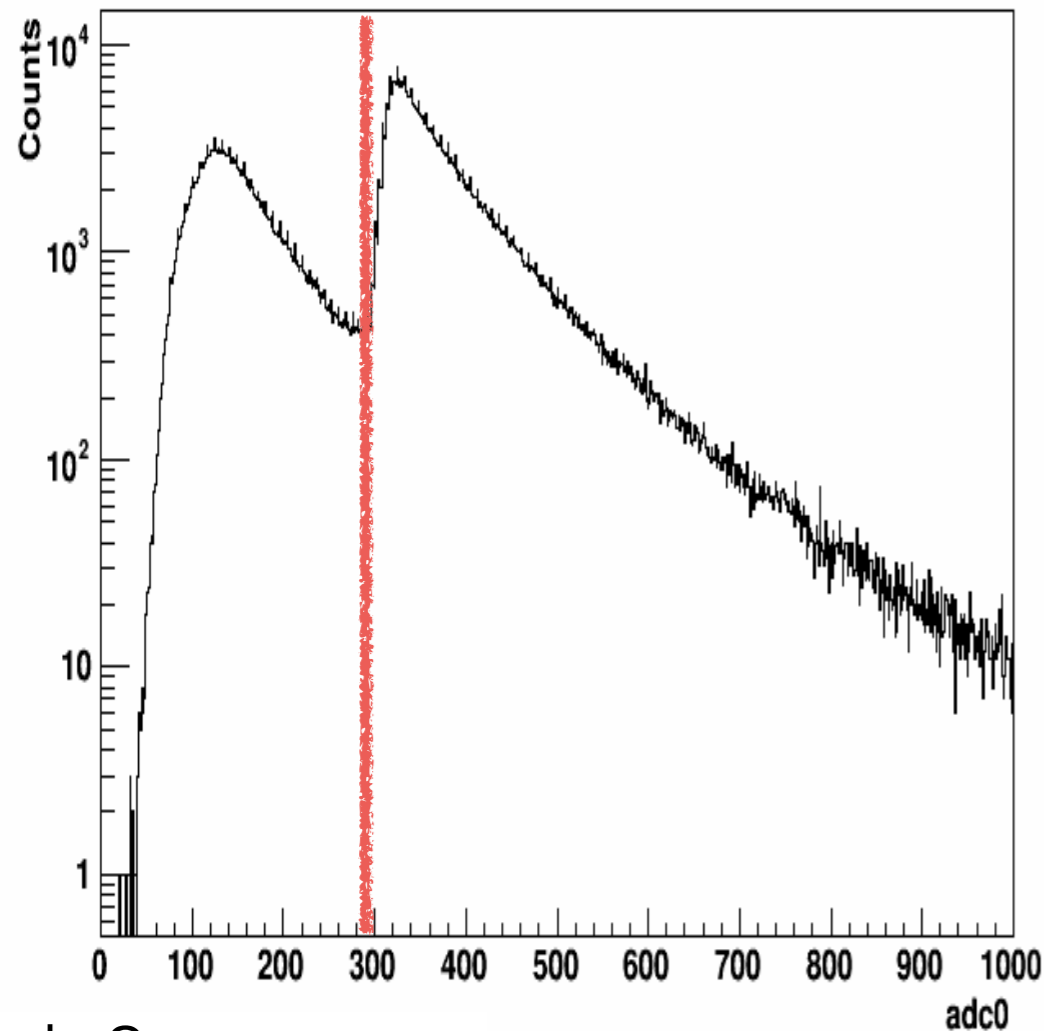
An event with an energy deposition in a single tower of the BEMC above a certain threshold was recorded.

Large BEMC triggered data samples in p+p collisions at $\sqrt{s} = 500$ GeV from 2011.

Trigger Name	Trigger Threshold	Number of Events	Sampled Luminosity
BHT1	$E_T > 3.5\text{GeV}$	170M	22 pb ⁻¹
VPDMB		106M	0.011pb ⁻¹

Electron Identification: Triggered electron

Triggered electron: BEMC($adc0$ and pc/E) and TPC(dE/dx)

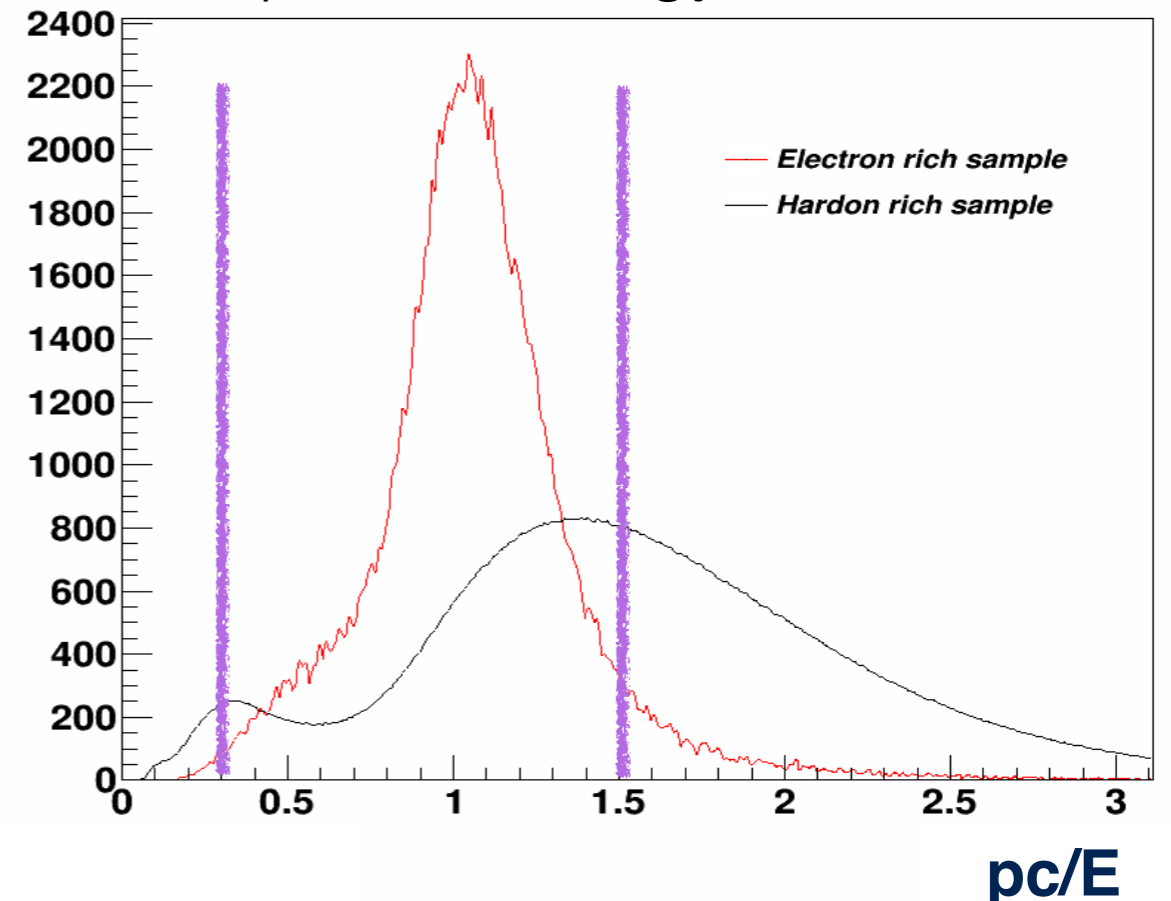


$Adc0$:

most energetic tower in a BEMC cluster.

- peak around 300 - electron firing the trigger

pc/E : ratio of particle momentum to its deposited energy in BEMC.

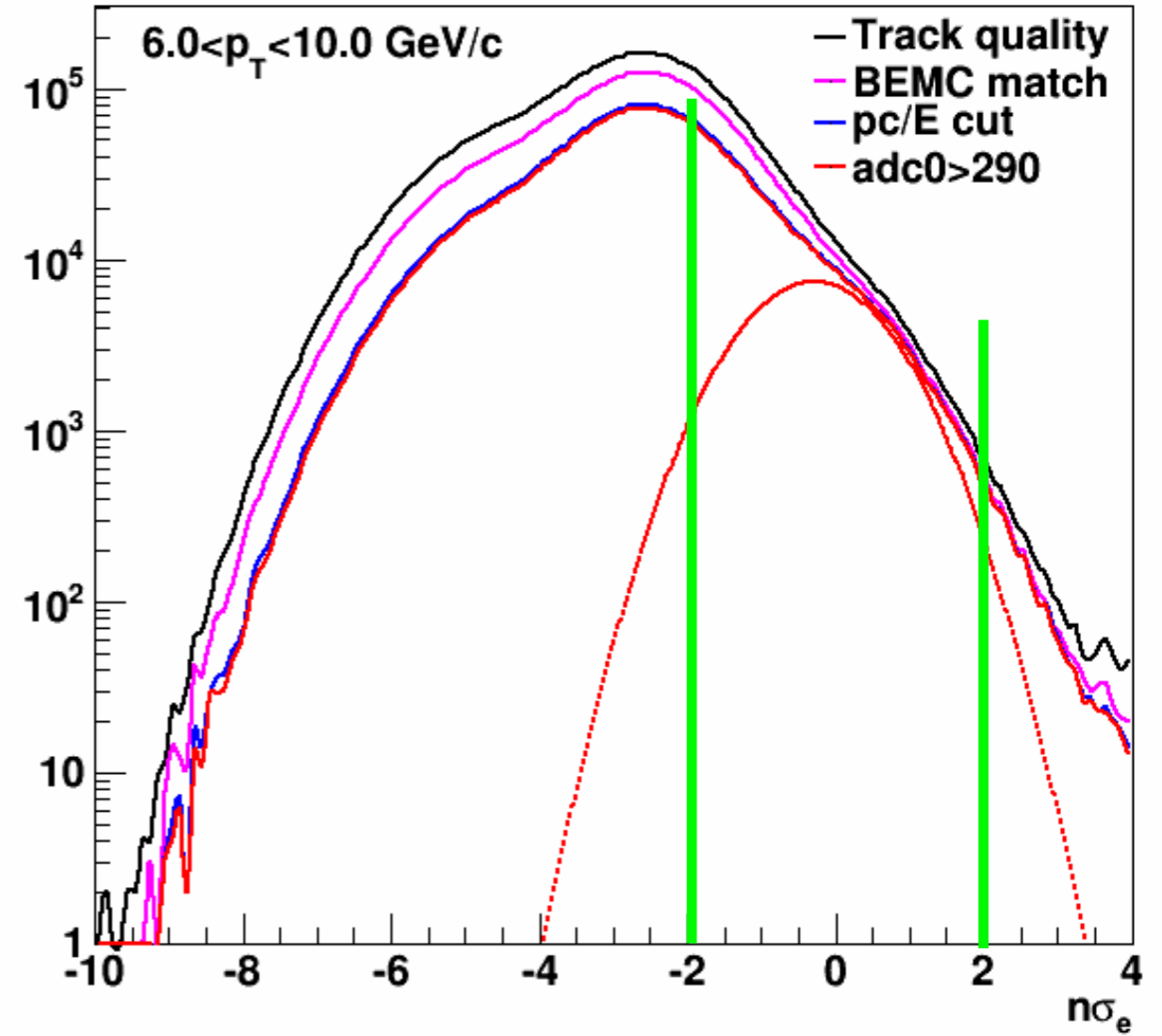
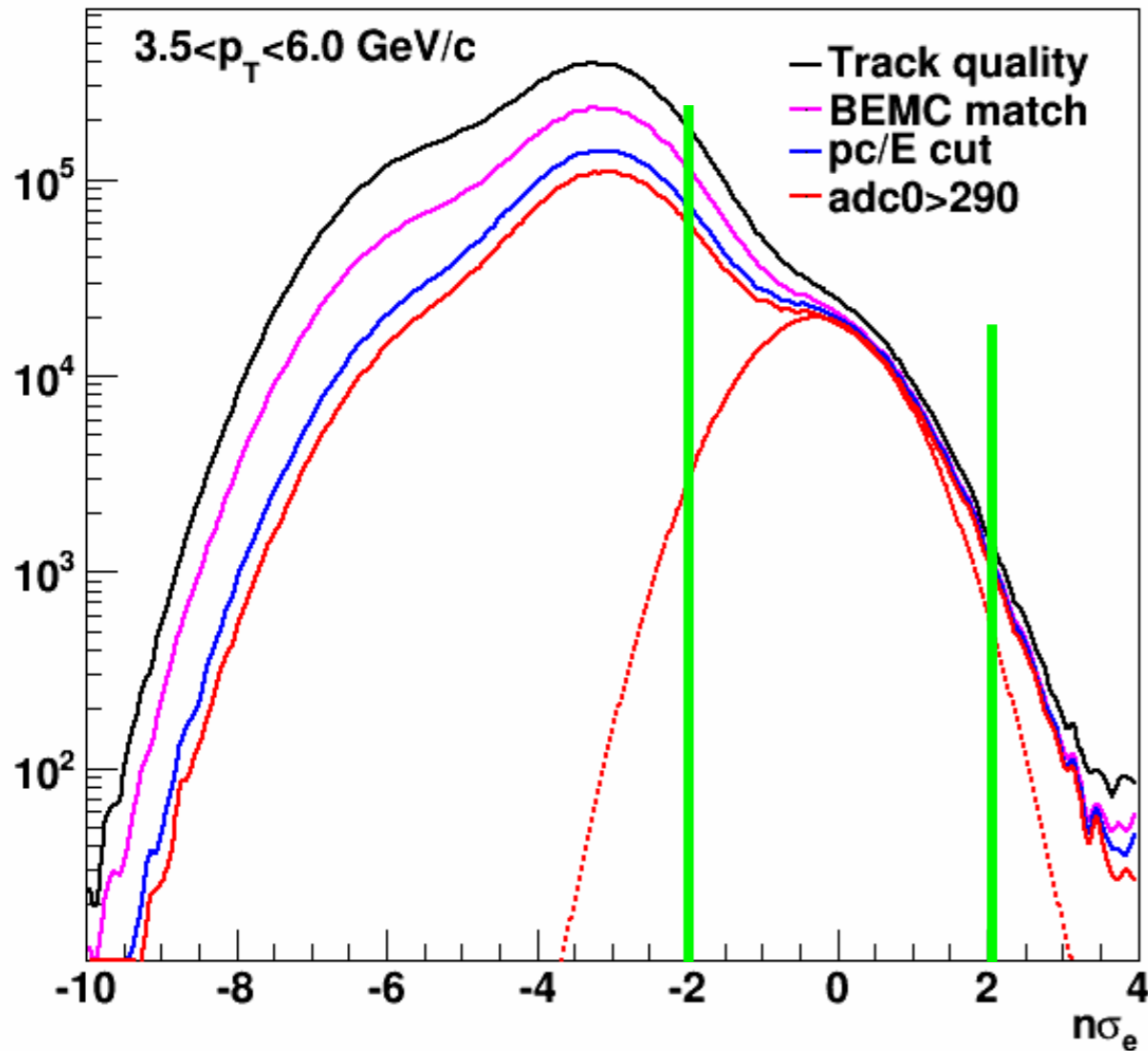


Hadrons: deposit part of its energy in BEMC.

Electron: deposit almost all energy in BEMC

Electron Identification: Triggered electron

$$n\sigma_e = \frac{1}{R} \log \frac{dE/dx_{measured}}{\langle dE/dx \rangle}$$

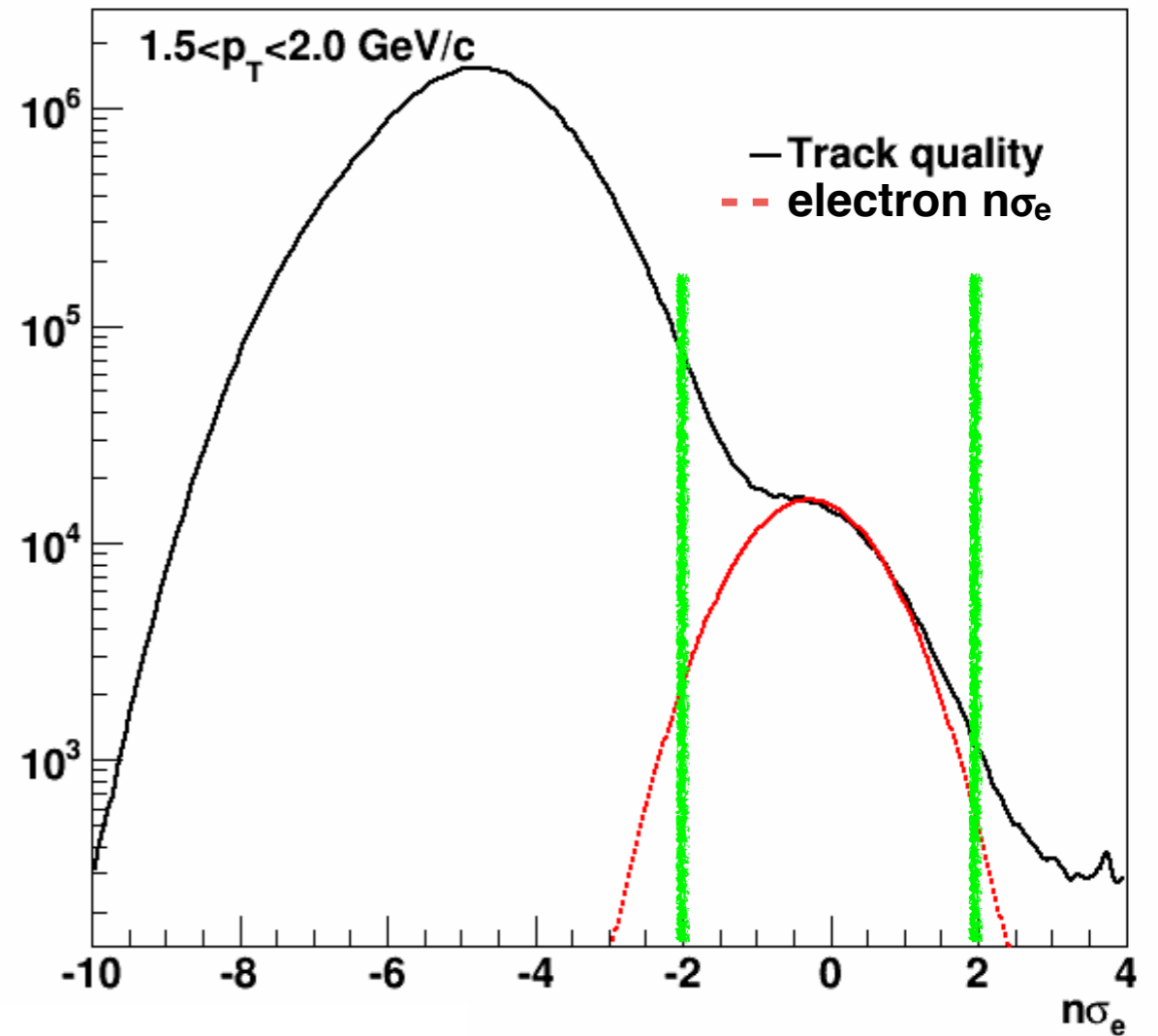
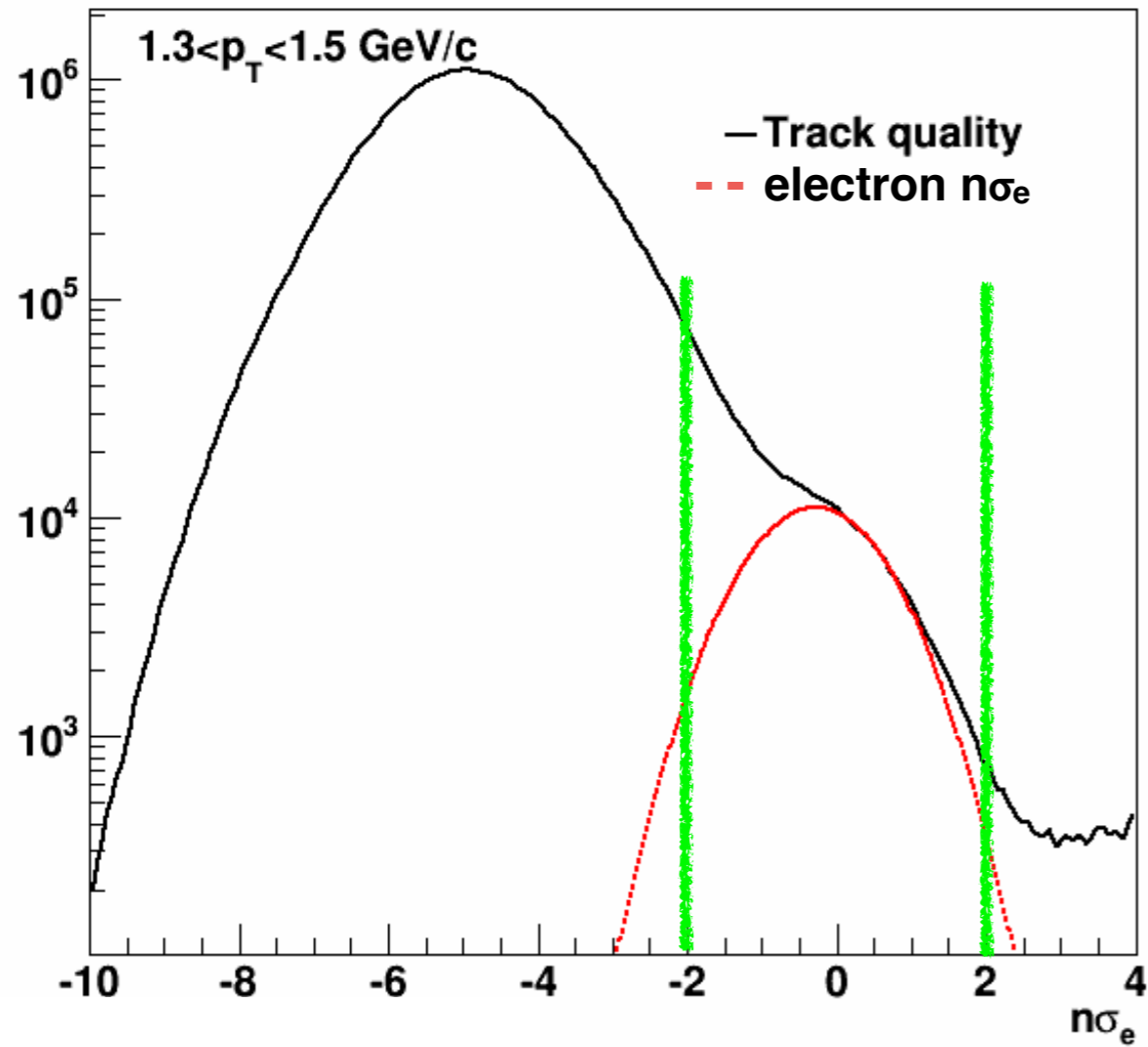


Triggered electron

- a) adc0 > 290
- c) 0.3 < pc/E < 1.5
- d) dE/dx cut (-2 < nσ_e < 2)

Electron Identification: Non-triggered electron

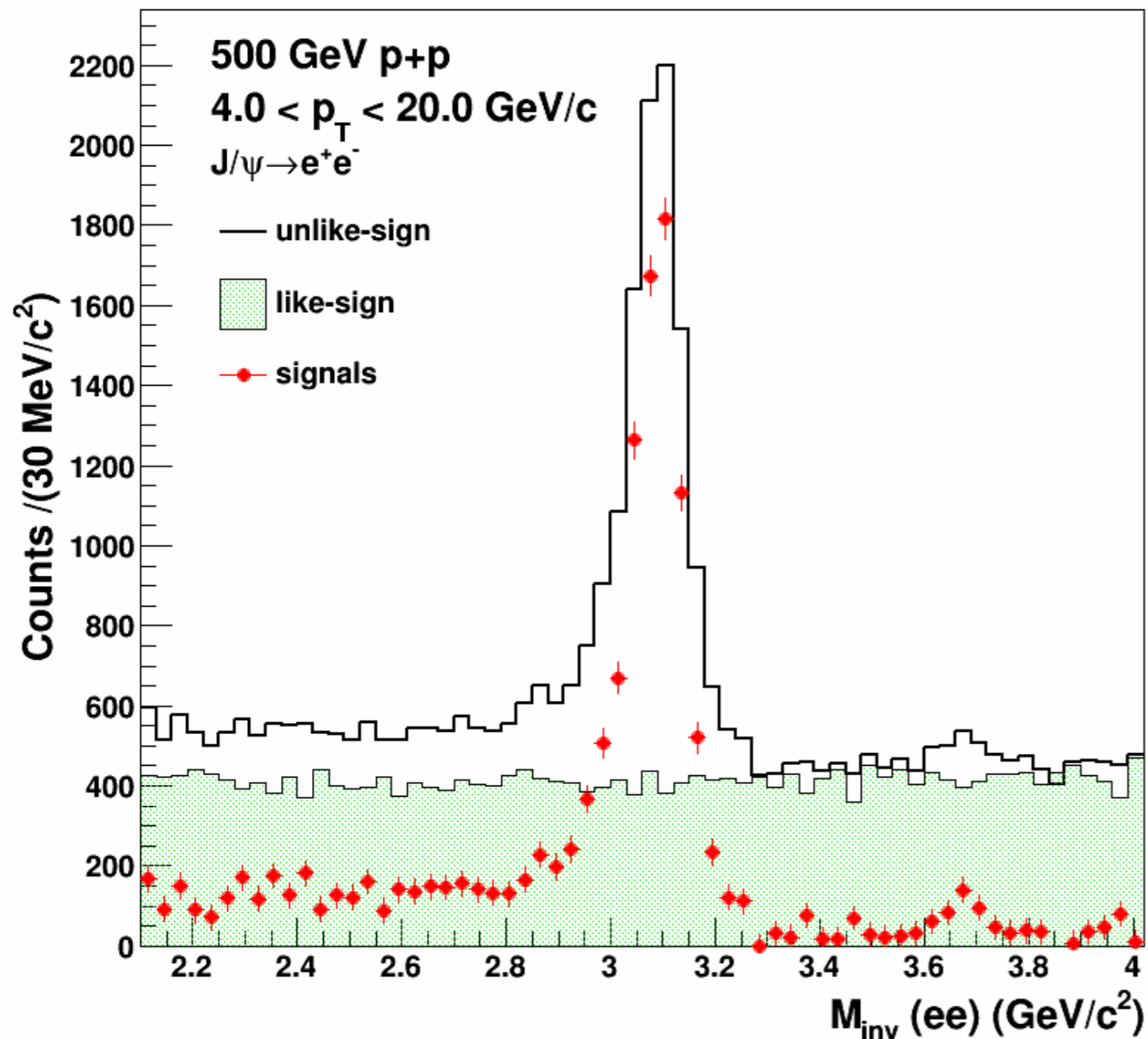
- dE/dx cut ($-2 < n\sigma_e < 2$)



- dE/dx is sufficient for low p_T electron identification.

J/ ψ and $\psi(2s)$ Reconstruction

Invariant mass distribution of e^-e^+ pairs



- Reconstruction method:
 - “triggered electron” : identified using TPC and BEMC
 - “non-trigger electron”: identified using TPC only
 - “triggered electron” + “non-triggered electron” (and “triggered” + “triggered electron”)
- Background reconstruction:
 - Like-sign technique($e^+e^+ + e^-e^-$)

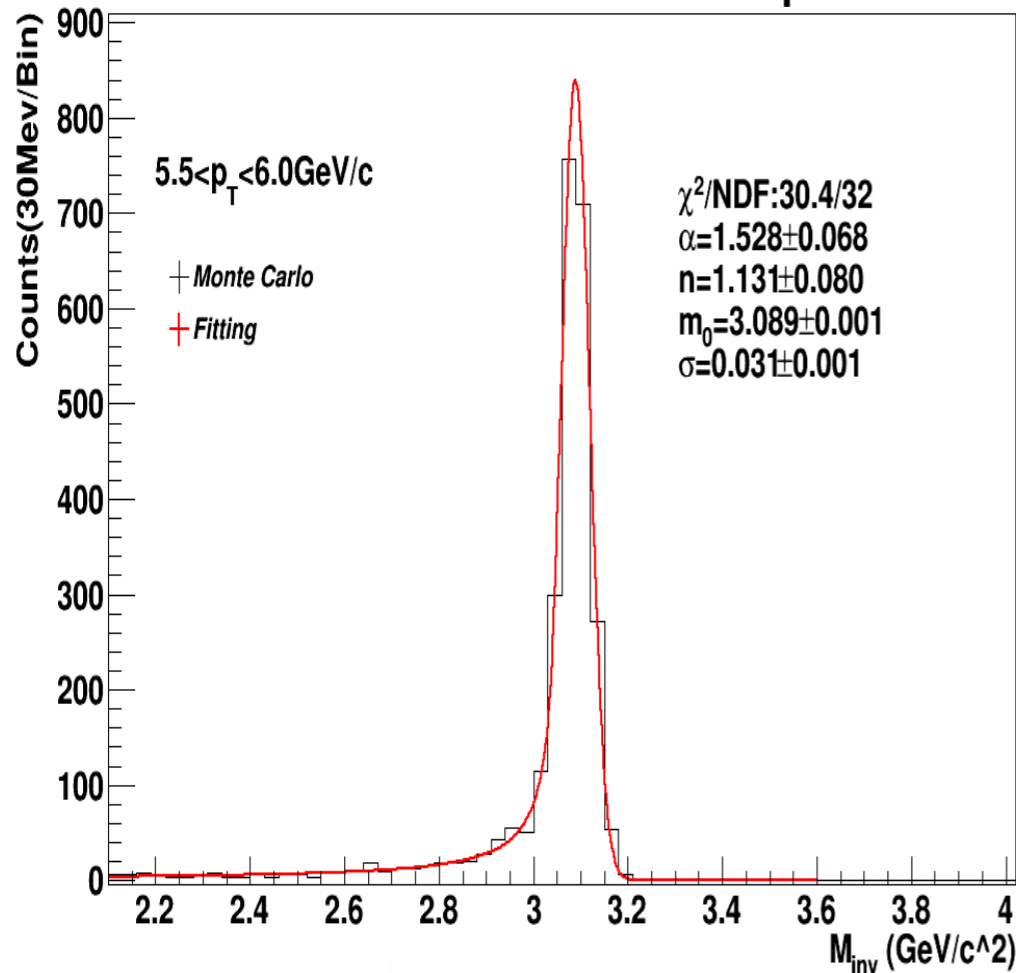
Extract J/ψ line shape from Monte Carlo

bremsstrahlung–tail at low mass range

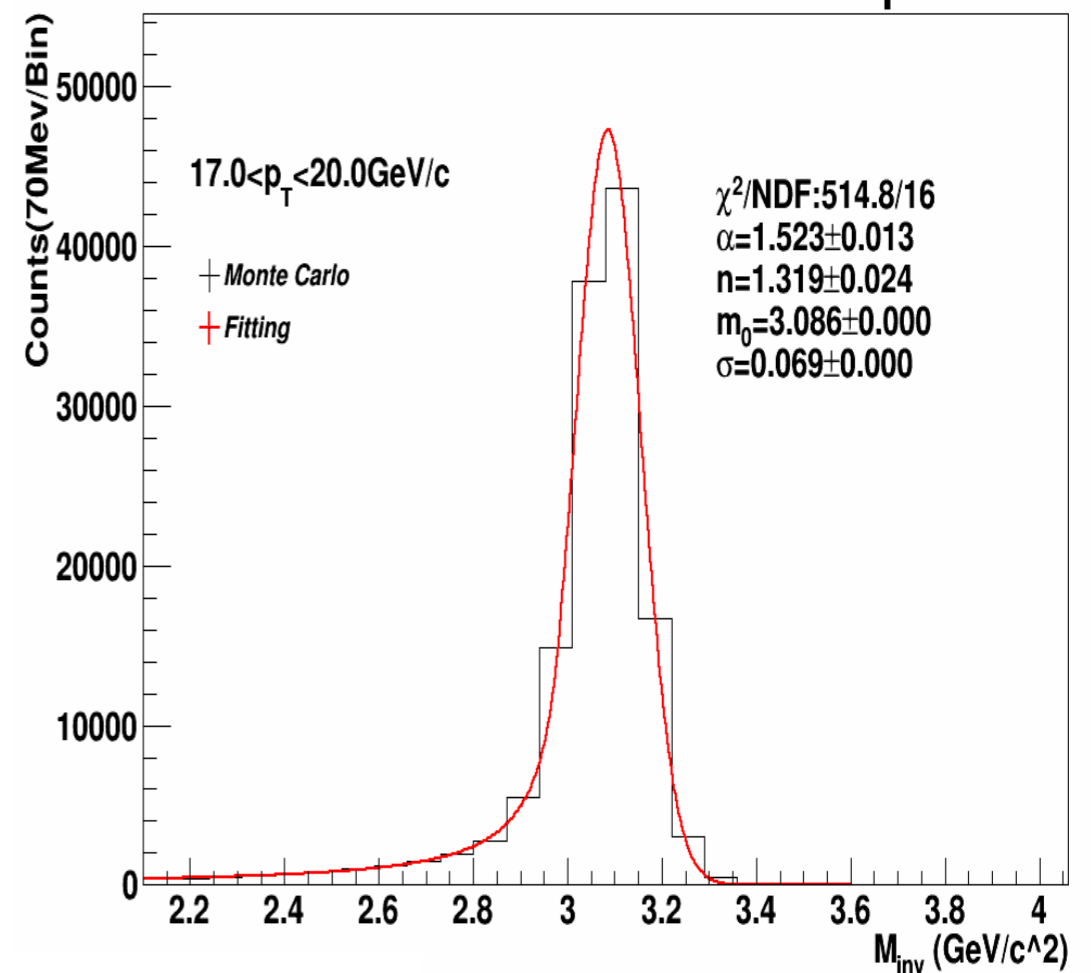
To account for electron energy loss in detector, Crystal Ball function was used to describe the line shape of J/ψ signal.

$$f_{CB}(m) = \begin{cases} \frac{N}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(m-m_0)^2}{2\sigma^2}\right), & \text{for } \frac{m-m_0}{\sigma} > -\alpha; \\ \frac{N}{\sqrt{2\pi}\sigma} \left(\frac{n}{|\alpha|}\right)^n \exp\left(-\frac{|\alpha|^2}{2}\right) \left(\frac{n}{|\alpha|} - |\alpha| - \frac{m-m_0}{\sigma}\right)^{-n}, & \text{for } \frac{m-m_0}{\sigma} \leq -\alpha. \end{cases}$$

Monte Carlo line shape



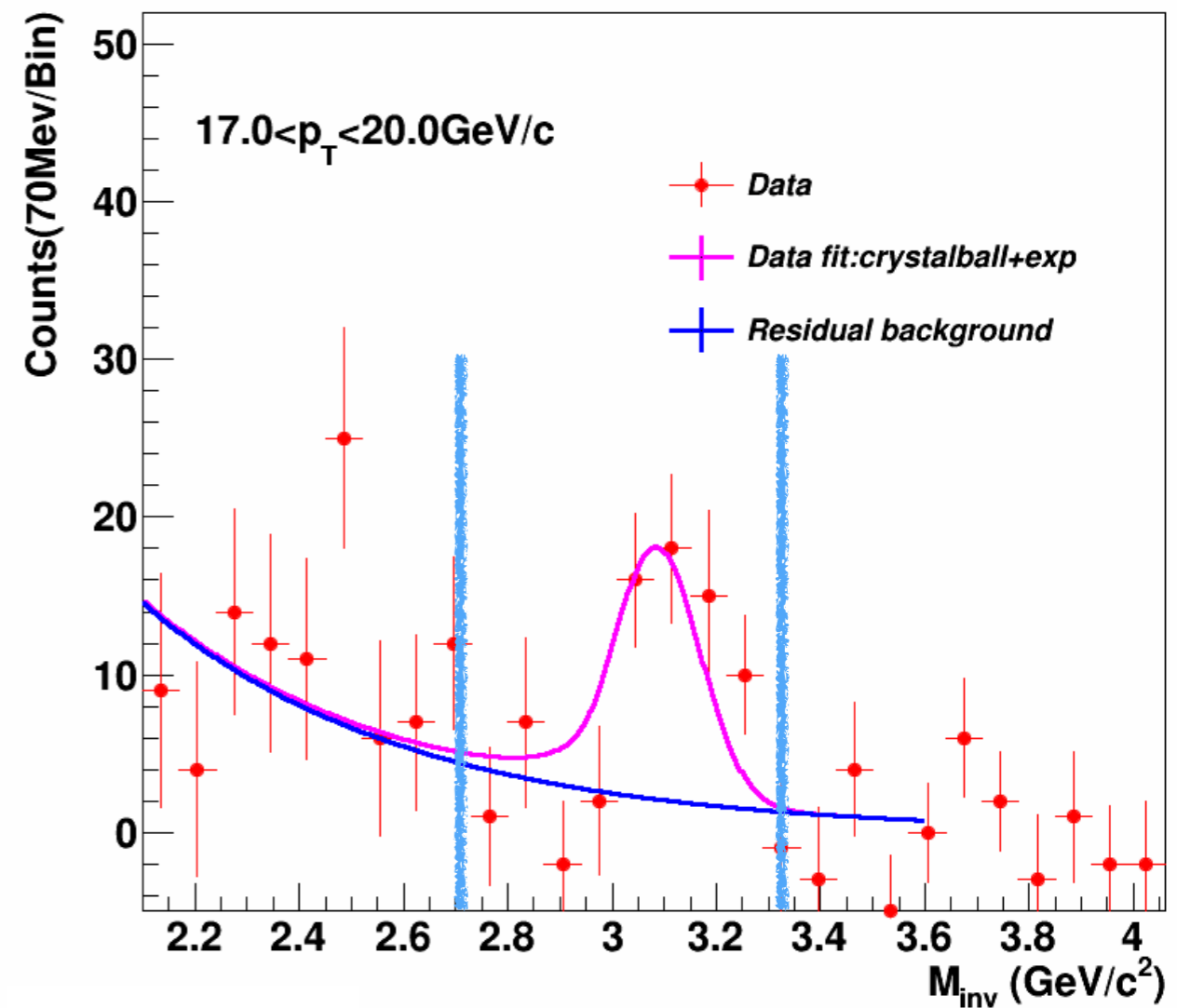
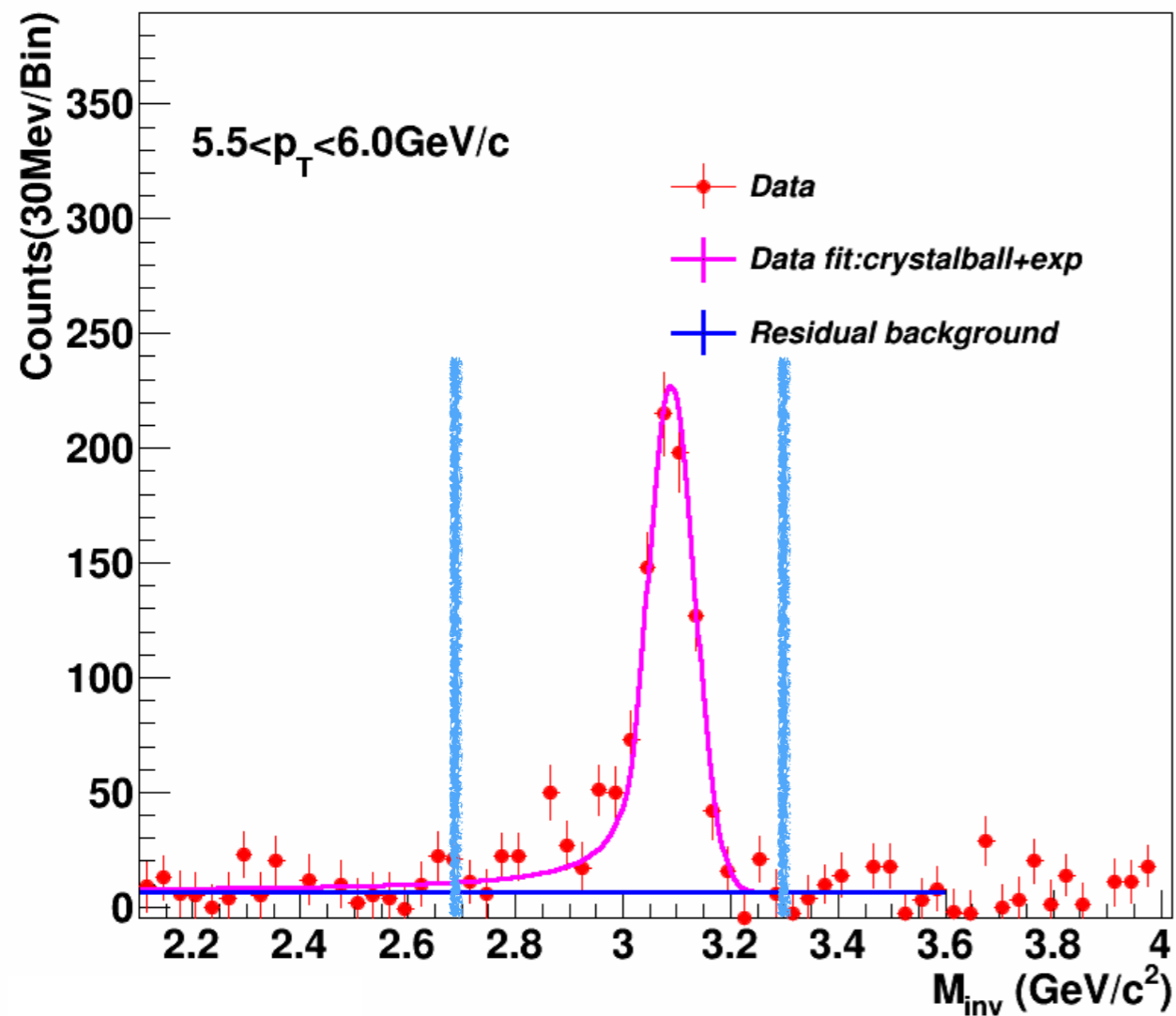
Monte Carlo line shape



Extract J/ ψ yield

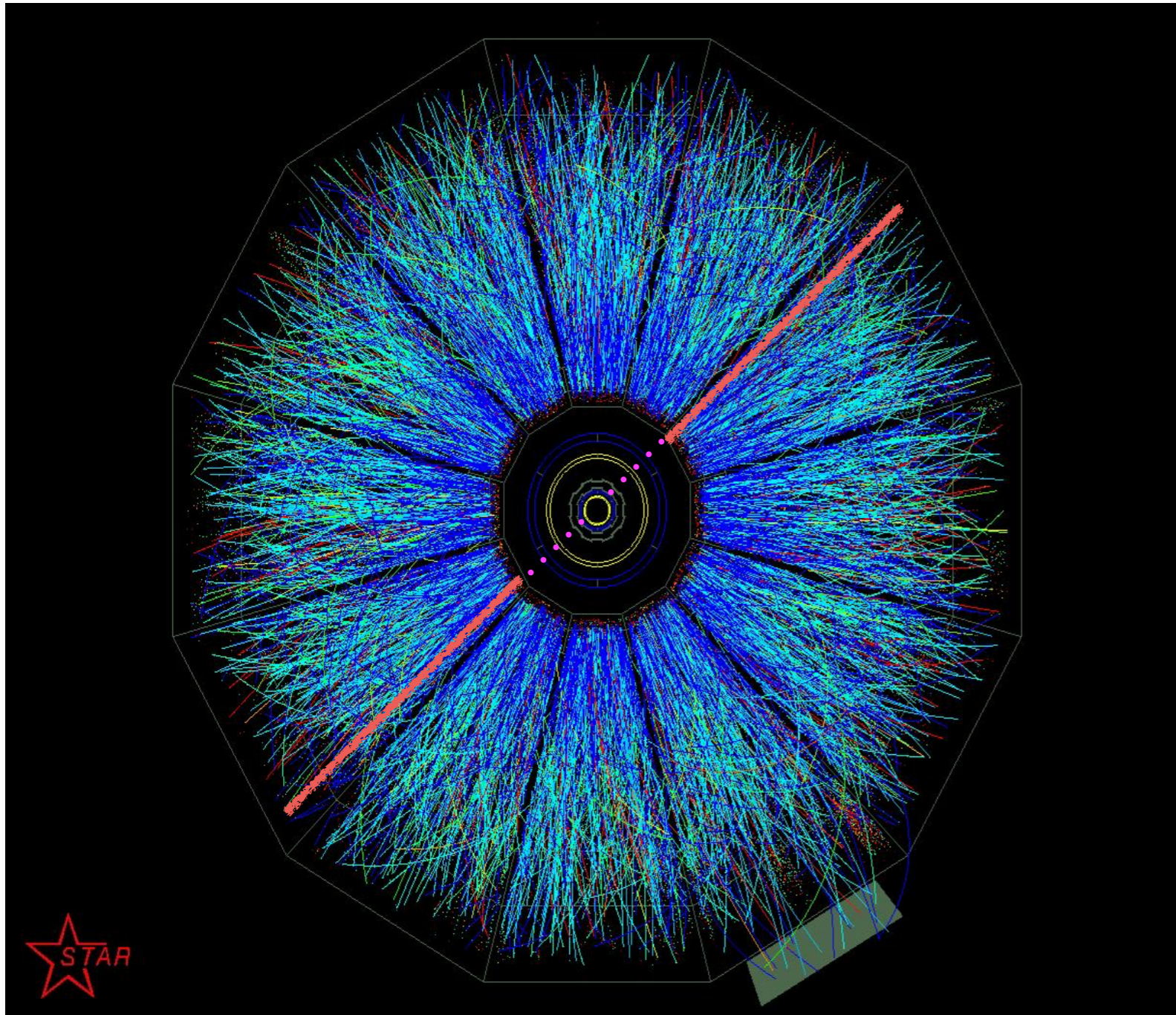
J/ ψ line shape is extracted from Monte Carlo (fixed m_0 , α and n).

- Crystal ball function and exponential function are used to describe J/ ψ signal and residual background.



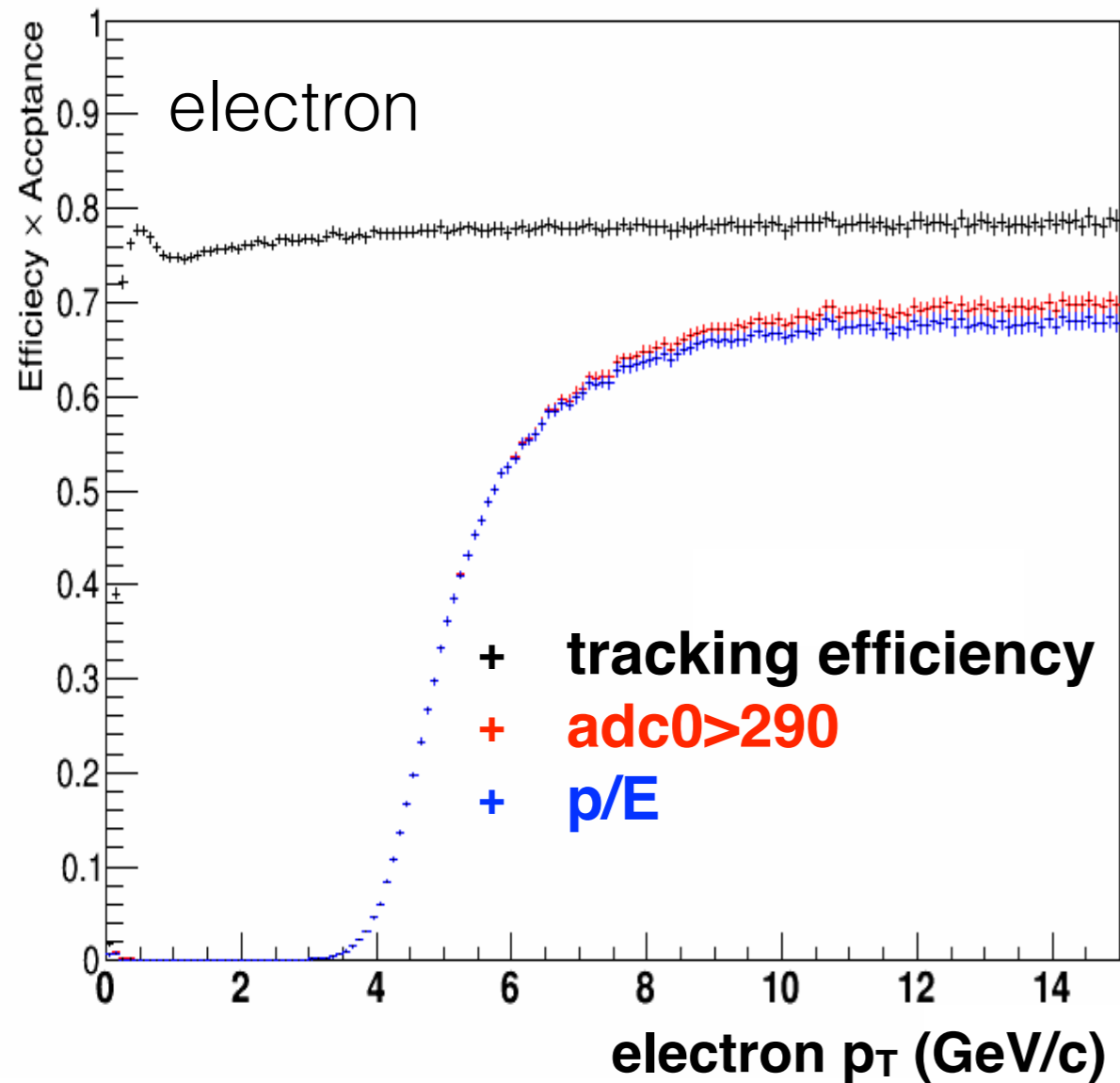
Residual background: $D\bar{D}$ and $B\bar{B}$ decays as well as Drell-Yan process.

J/ ψ efficiency—embedding technique

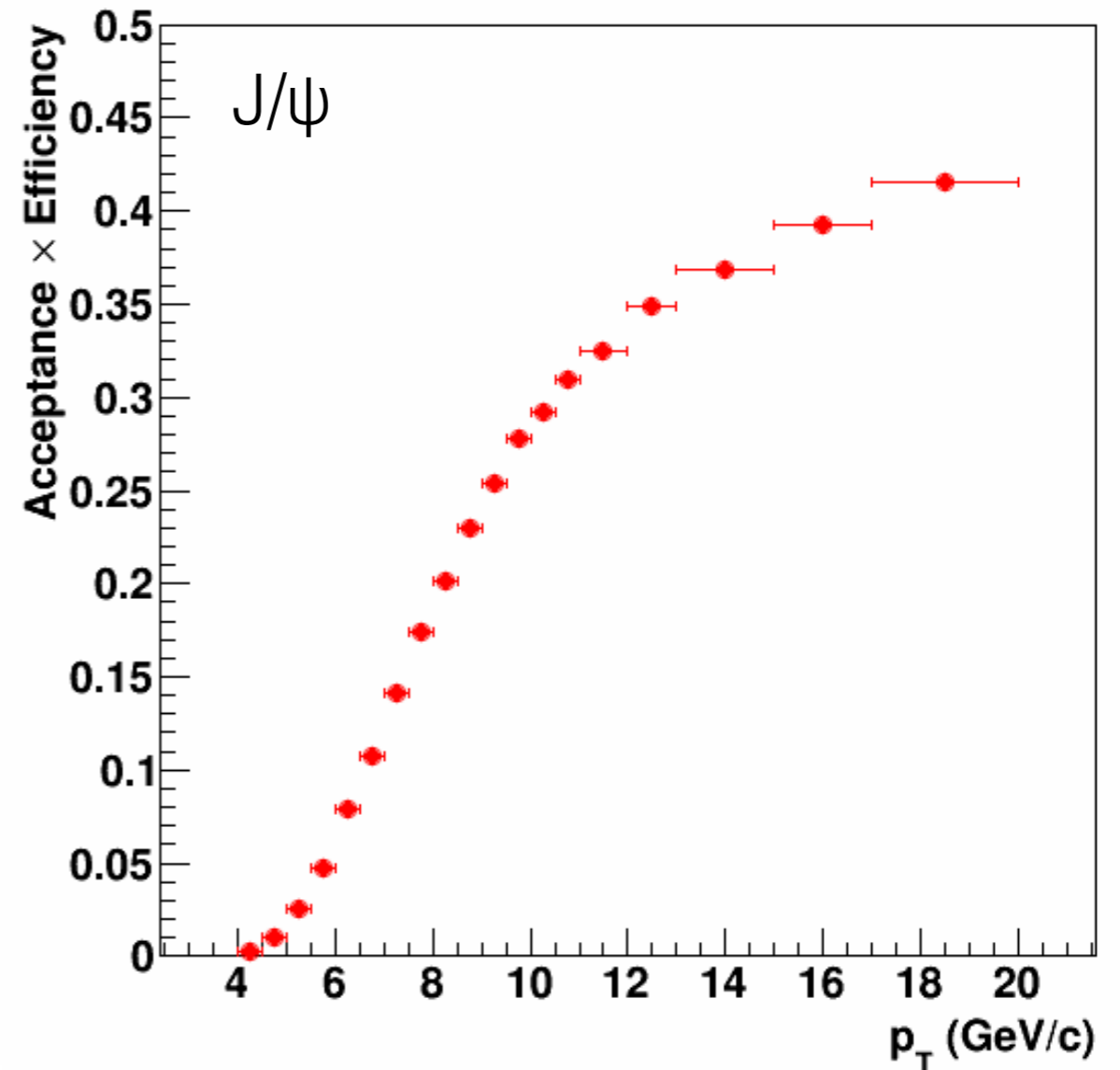


1. Simulated tracks are embedded into real events at the **raw data level**.
2. Mixed events are processed through **the full reconstruction chain**.
3. An **association map** is created between the input MC tracks and the reconstructed tracks.

J/ ψ efficiency and acceptance

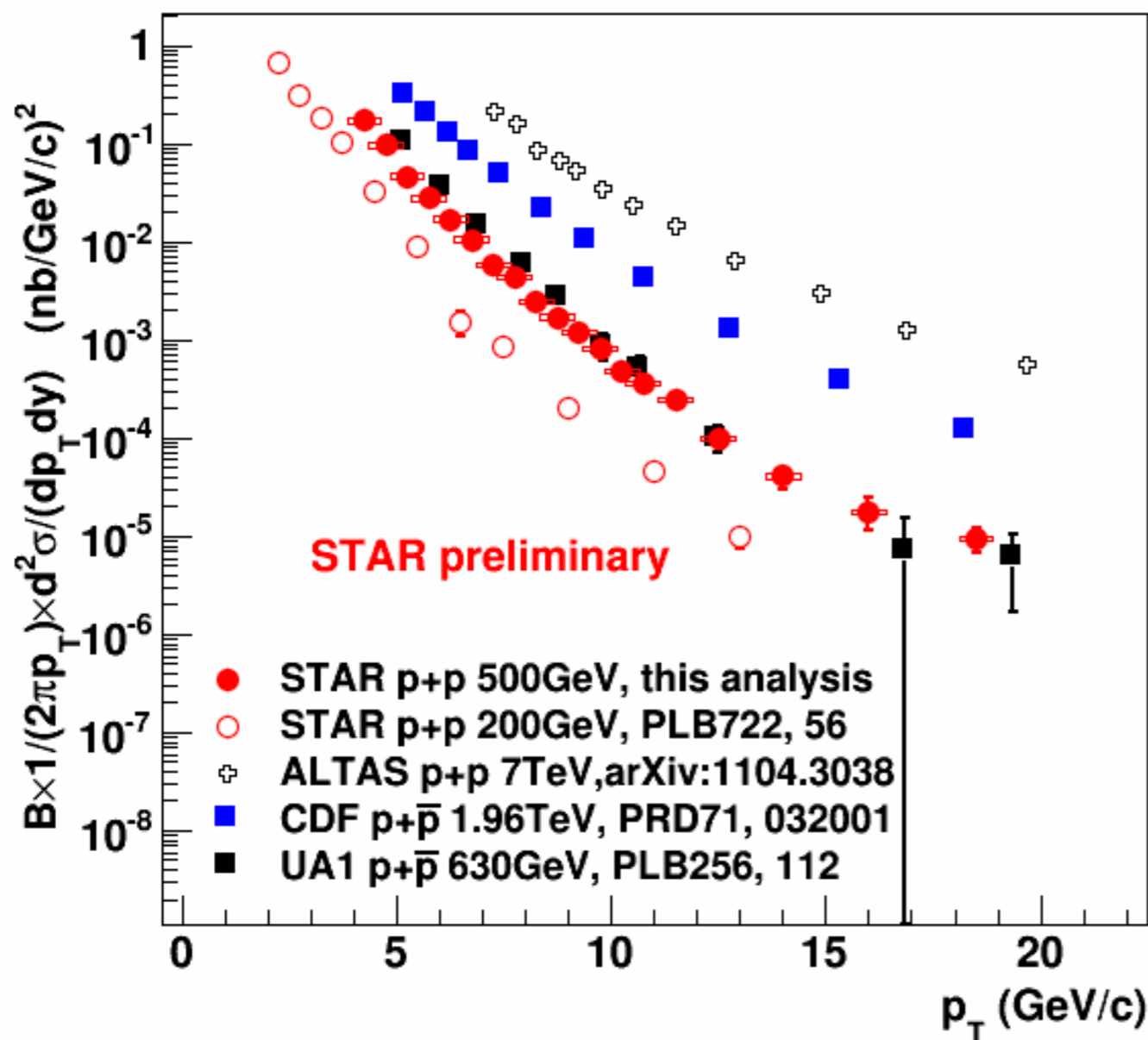


- ~75% tracking efficiency.
- Trigger efficiency turns on 3.5 GeV/c.
- High p/E cut efficiency.



- High efficiency at high p_T
- Gentle efficiency slope

J/ψ invariant cross section



	Systematic uncertainty
yield extraction	1.3%
p_T cut	4.5%
dca	3.0%
p/E	3.0%
adc0	1.0%
$n\sigma_e$	1.0%
total	6.0%

Precise measurements of J/ψ in $4 < p_T < 20$ GeV/c at p+p 500GeV

Theoretical calculation is very welcome!!

x_T scaling

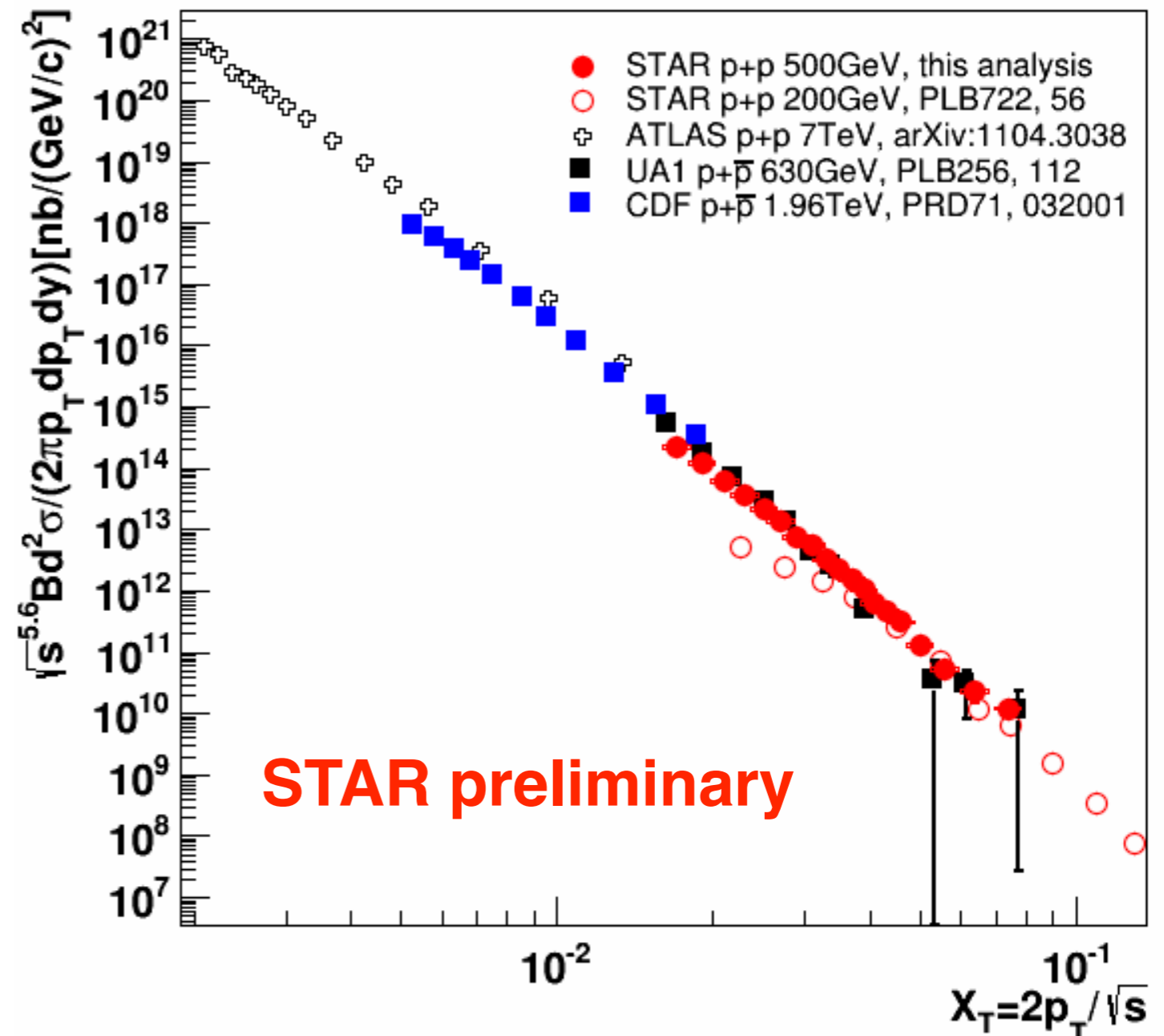
Proton and pion inclusive production cross sections in high energy p+p collisions have been found to follow x_T scaling:

$$E \frac{d^3\sigma}{dp^3} = g(x_T) \frac{1}{s^{\frac{n}{2}}}$$

In the parton model, n reflects the number of **constituents taking an active role in hadron production**.

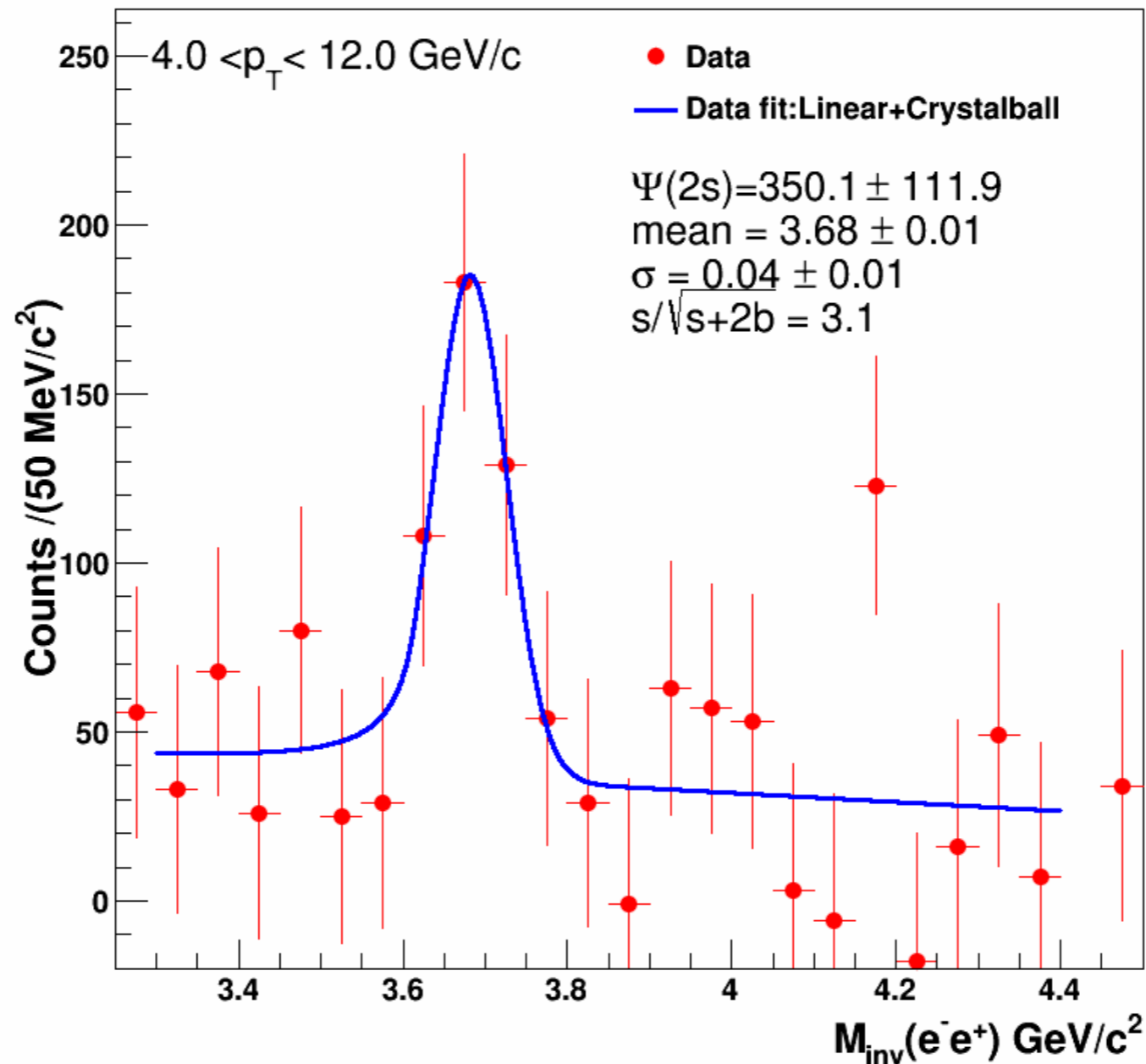
J/ ψ is also found to follow x_T scaling ($n=5.6\pm 0.2$).

NRQCD prediction $n\approx 6$



- J/ ψ follows x_T scaling at $p_T > 4$ GeV/c.

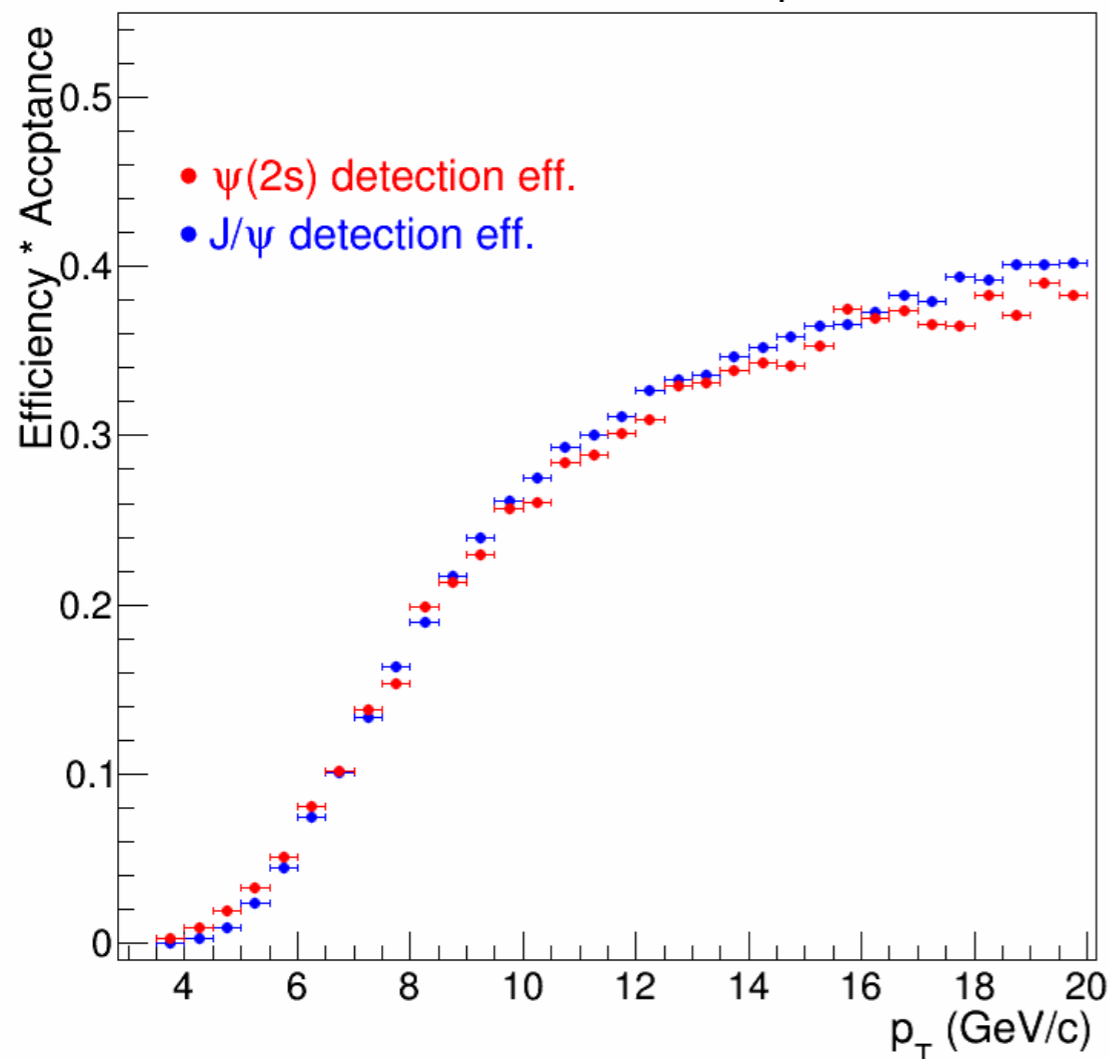
Extract $\psi(2s)$ yield



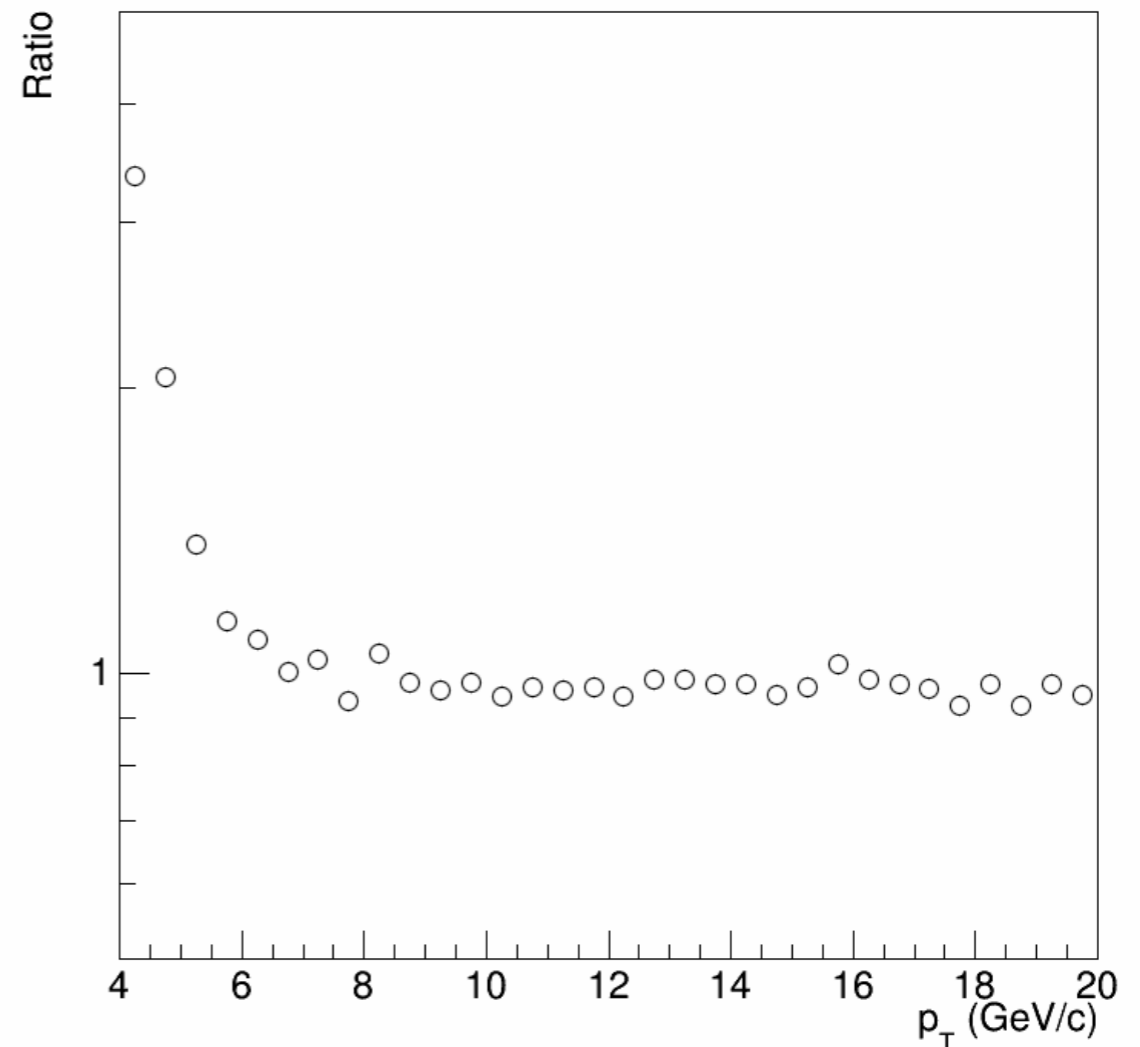
- **Crystal ball function** and linear function are used to describe $\psi(2s)$ signal and residual background.

$\psi(2s)$ and J/ψ efficiency difference

J/ψ and $\psi(2s)$ detection efficiency as a function of p_T

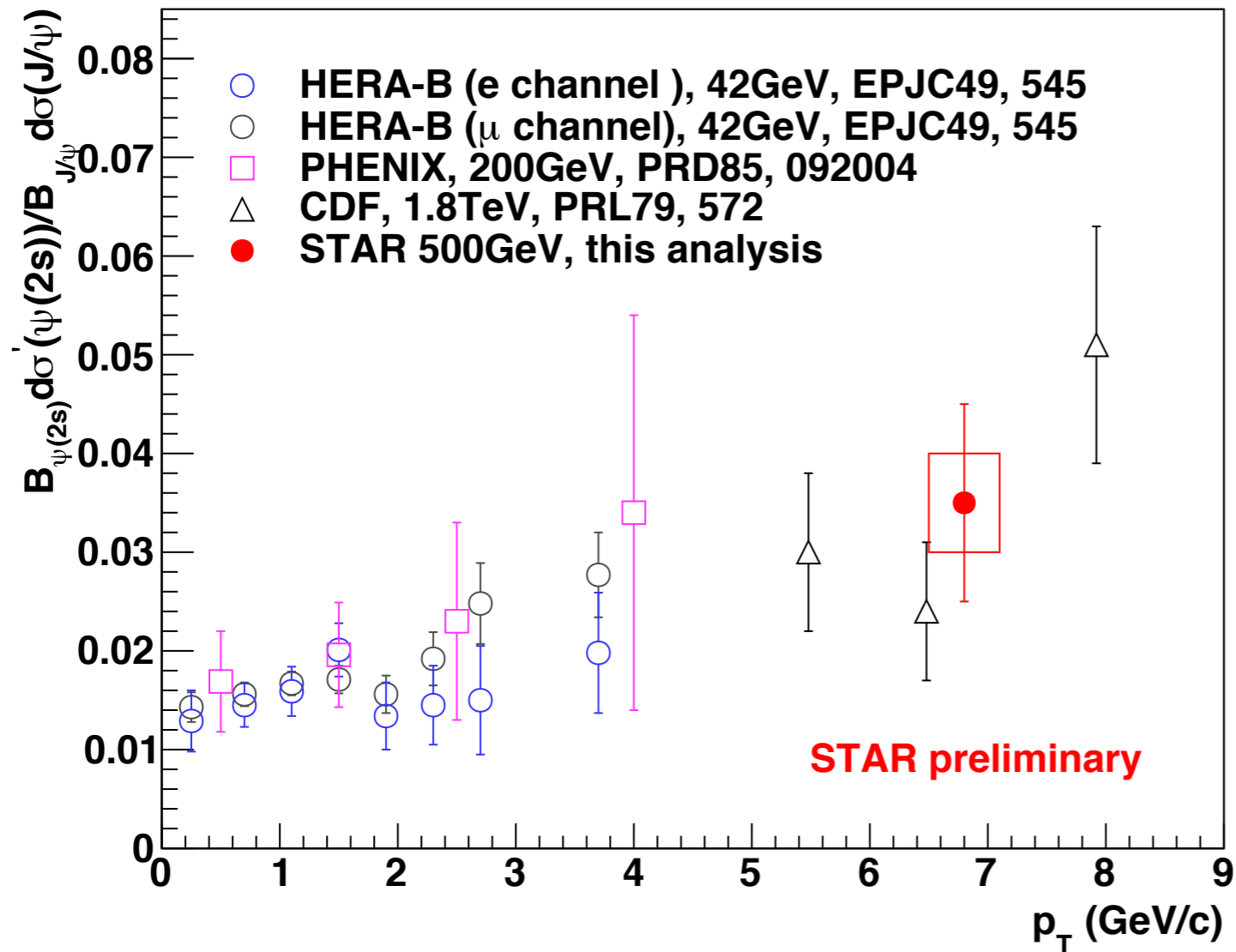


The ratio of $\psi(2s)$ to J/ψ detection efficiency



- At low p_T , **larger mass** of $\psi(2s)$ boosts the p_T of the decay electrons, thus enhancing the trigger efficiency.
- At high p_T , the **larger opening angle** between electron and positron from $\psi(2s)$ results in a smaller acceptance.

$\psi(2s)$ to J/ψ ratio



	Systematic uncertainty
yield extraction	15.1%
p_T cut	6.0%
dca	5.0%
p/E	6.0%
adc0	3.0%
total	18.1%

- STAR results consistent with world data trend with p_T .
- No collision energy dependence is seen with current precision.

Summary

- J/ψ production in the p_T range of 4-20 GeV/c in p+p collisions at $\sqrt{s} = 500$ GeV is measured.
- J/ψ inclusive production cross section follows x_T scaling for p_T larger than 4 GeV/c.
- The measured ratio of $\psi(2s)$ to J/ψ is consistent with previous measurements, and no energy dependence is seen.

Outlook

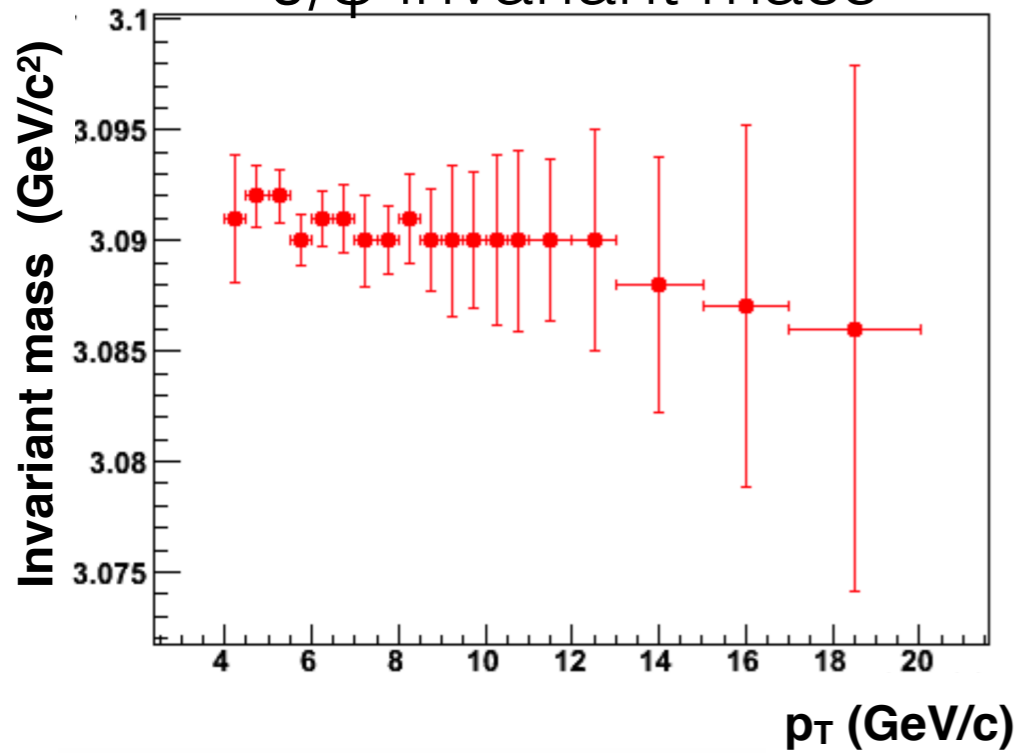
- Data analysis to extract J/ψ polarization is on-going, and the effect on the measured cross-section due to J/ψ polarization is under study.
- Comparison to theoretical calculations is under way. Input is very welcome.
- Low p_T J/ψ using MTD for p+p 500 GeV is ongoing, which is complementary to this analysis. Different kinematic sensitivity, different decay channel, different systematics.

Thank you!

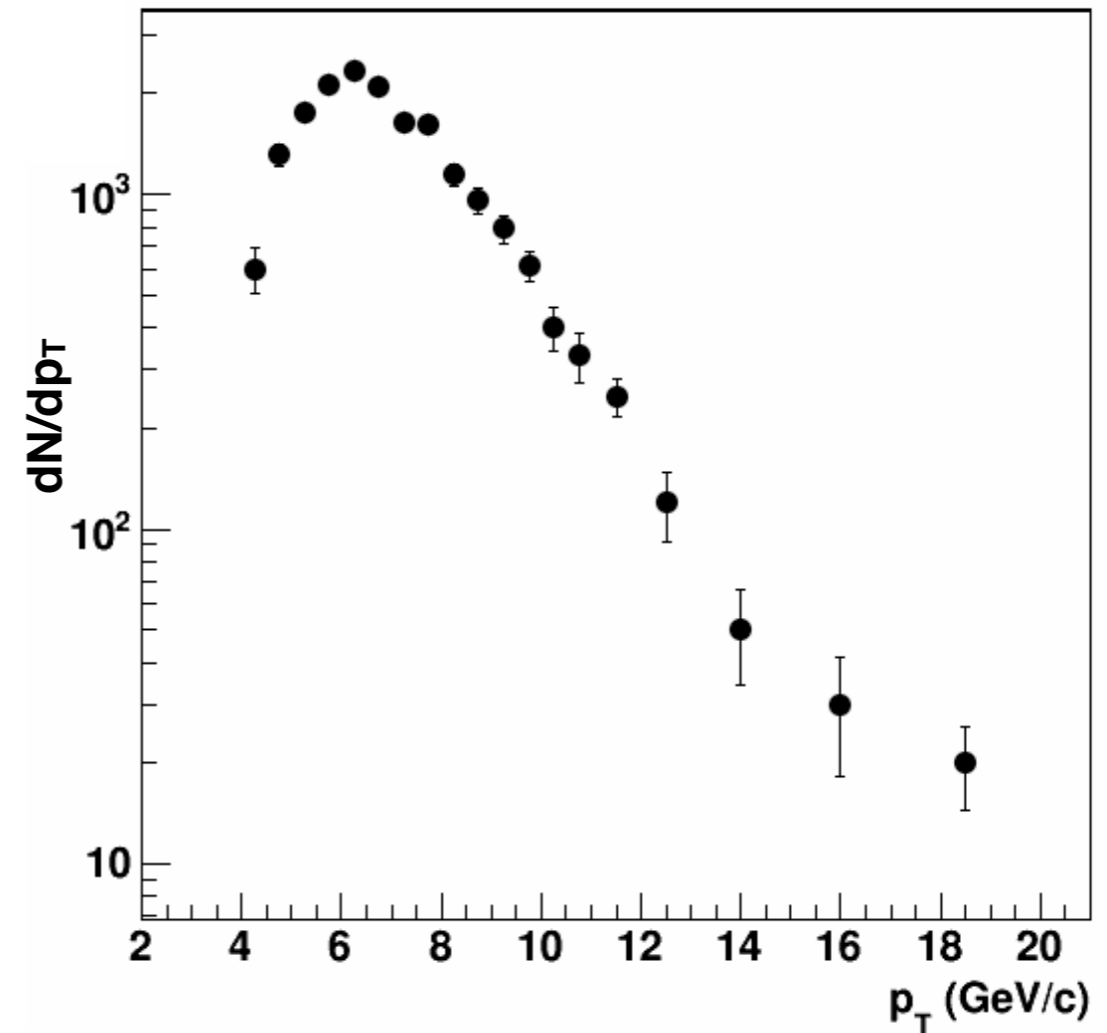
Backup

J/ψ invariant mass, signal width and its raw spectrum

J/ψ invariant mass



J/ψ raw spectrum



Width of J/ψ mass peak

