Charming Mystery
- From November Revolution to NRQCD -

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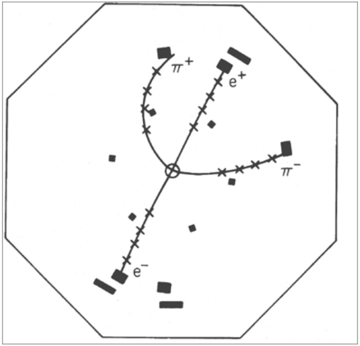
Prologue

November Revolution

- Discovery of J/ψ - SLAC and BNL independently on 11 November 1974
- 1976 Nobel Prize in Physics: Burton Richter and Samuel Ting



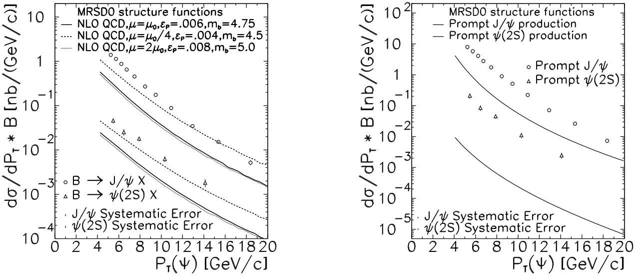
Charmonium

- Bound states of charm quark and anti-charm quark
- η_c (2.980 GeV/c^2), J/ψ (3.097 GeV/c^2), $\psi(2S)$ (3.686 GeV/c^2), *etc.*
- $\psi(2S)$ (or ψ') : the first excited state of J/ψ, negligible feed-down from higher states

Introduction

ψ Production in CDF Run I

- Extracted Prompt ψ Production using Silicon Vertex Detector
- Unexpectedly large J/ψ and $\psi(2S)$ prompt cross section
- $\psi(2S)$ anomaly - prompt cross section is higher than theoretical predictions based on the color-singlet model by a factor of ~ 50 (~ 6 for J/ψ)

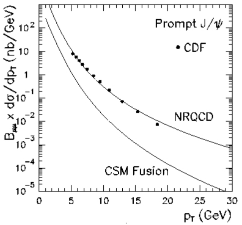


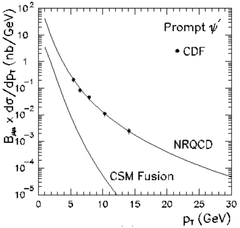
CDF Run I, J/ψ and $\psi(2S)$ Production Phys. Rev. Lett. 79, 572 (1997)

Introduction

NRQCD and ψ polarization

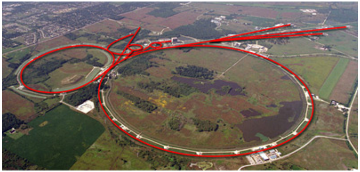
- CDF Run I measurement of J/ψ and $\psi(2S)$ production cross sections prompted the development of NRQCD models
- Non-Relativistic QCD (NRQCD) - An effective field theory
- Includes color-octet states
- Adjustable parameters (color-octet matrix elements) but still restrictive enough to have predictive power , *e.g.*, that all vector mesons should be transversely polarized at large p_T.





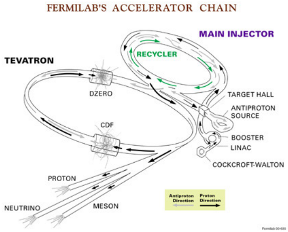
Prompt cross section at CDF Run I with NRQCD fit and color-singlet model prediction

Tevatron - Fermi National Accelerator Laboratory

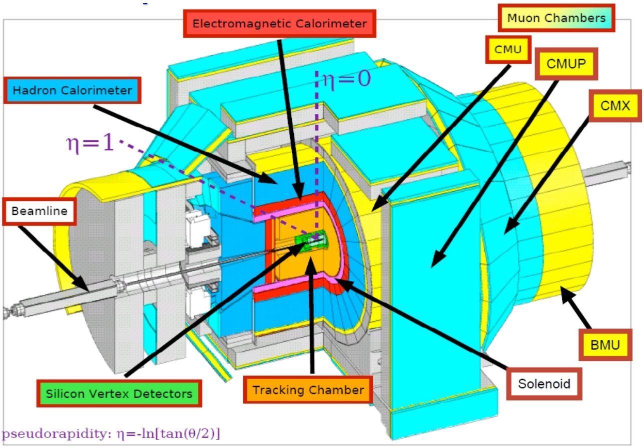


- The Energy Frontier
- 1000 superconducting magnets at -268 °C
- Proton-Antiproton: 1 TeV, 0.9999999954 c
- Collision at 2 TeV
- Discoveries: the bottom quark(1977), the top quark(1995), and the tau neutrino (2000)

- Accelerator Chain
- Linear Accelerator: $\sim$ 500 feet, up to 400 MeV
- Booster: circular accelerator, up to 8 GeV
- Main Injector
- Antiproton Source: proton beams on nickel
- Fixed Target Area, CDF, DZero Detector

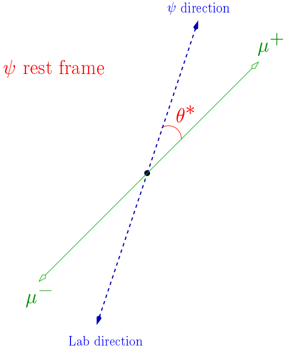


Collider Detector at Fermilab II



- A general purpose forward-backward symmetric detector

Polarization Measurement in $\psi(2S) \to \mu^+\mu^-$



Decay angle distribution

- The angle between the μ^+ direction in the $\psi(2S)$ rest frame and the $\psi(2S)$ direction in the lab frame.

$$\frac{d\,\Gamma}{d\cos\theta^*} \propto \frac{3}{2\,(\alpha+3)}\left(\,1+\alpha\cos^2\theta^*\right)$$

- The polarization parameter α
  - $\alpha = +1$: helicity ± 1 or fully transverse.
  - $\alpha = -1$: helicity 0 or fully longitudinal.

Polarization Measurement in $\psi(2S) \to \mu^+\mu^-$

Template method

Main idea: Compare the observed $\cos\theta^*$ distribution with fully polarized(transverse/longitudinal) $\cos\theta^*$ distribution from Monte Carlo samples.

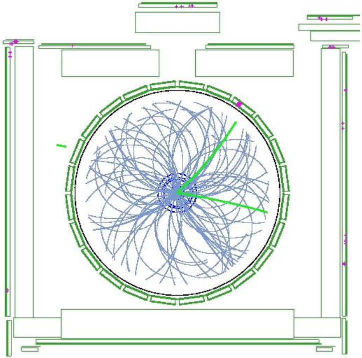
- Realistic MC samples are corrected for the detector acceptance, efficiency, and the trigger efficiencies.
- The polarization is obtained using a χ^2 fit of the data to a weighted sum of T & L templates.

Polarization fit

- The data events are histogrammed in $\cos\theta^*$, with bin widths of 0.1
- The Poisson likelihood χ^2: $\chi^2 = -2\ln\lambda$, where λ is the likelihood ratio
- Pearson's χ^2 following Gaussian distribution: $\chi^2 = \sum_i (n_i - y_i)^2/y_i$, where n_i is the number of events in the i th bin and y_i is the number of events predicted by the model to be in the i th bin

Event Selection

- 800pb^{-1} CDF Run II data collected by the track based dimuon trigger.
- $\psi(2S) \rightarrow \mu^+\mu^-$, $5 \leq p_T(\mu^+\mu^-) < 30$ GeV/c, $|y| < 0.6$.



- Muon candidates reconstructed in the Central Outer Tracker(COT) and Central Muon detectors(CMU,CMUP). Additionally, the Silicon Vertex Detector(SVX II) information is used.

- Minimum $p_T(\mu)$ 1.75 GeV/c to avoid trigger turn-on.

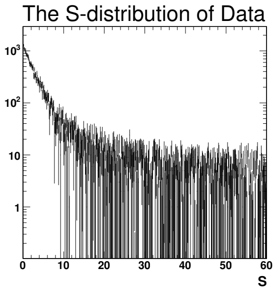
Prompt Vs. B-decay

Impact parameter significance cut

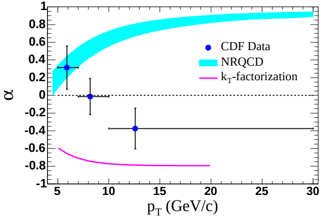
- $\psi(2S)$ from decays of B-hadrons have a different average polarization than prompt V mesons.
- The long B lifetime $\Rightarrow$ $\psi(2S)$ from B decay lead to muons that don't point to the primary vertex and can be separated by an impact parameter significance cut.

$$S = \left(\frac{d_0(\mu^-)}{\sigma_{d_0(\mu^-)}}\right)^2 + \left(\frac{d_0(\mu^+)}{\sigma_{d_0(\mu^+)}}\right)^2$$

- $S \leq 8$ for the prompt and $S > 16$ for the B-decay: based on the S - distribution of the data and a Monte Carlo sample.



Result - $\psi(2S)$ Polarization



$$\eta_B = 0.19 \pm 0.09 \pm 0.01 \text{ or } \alpha_B = 0.36 \pm 0.25 \pm 0.03$$

p_T[GeV/c]	$< p_T >$ [GeV/c]	η_{prompt}	α_{prompt}	χ^2/d.o.f
5 - 7	6.2	$0.210 \pm 0.086 \pm 0.01$	$+0.306 \pm 0.235 \pm 0.027$	14.4/12
7 - 10	7.9	$0.327 \pm 0.089 \pm 0.01$	$+0.014 \pm 0.202 \pm 0.023$	18.7/14
10 - 30	11.6	$0.558 \pm 0.136 \pm 0.01$	$-0.433 \pm 0.224 \pm 0.016$	26.8/16

Prompt $\psi(2S)$ polarization

- Contradictory to the prediction of NRQCD factorization

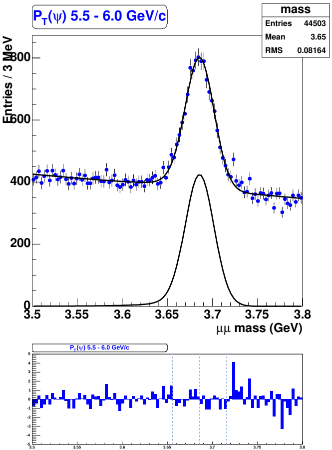
$\psi(2S)$ Production Cross Section

p_T dependent differential cross section

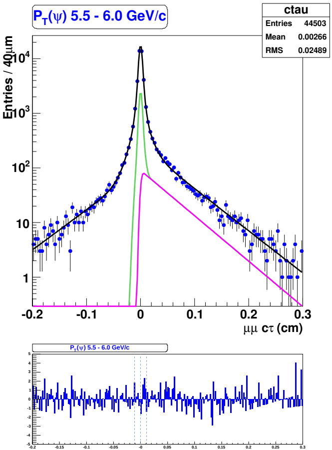
$$\frac{d\sigma(\psi(2S))}{dp_T} = \frac{N(\psi(2S))}{A \cdot \epsilon \cdot \int \mathcal{L}dt \cdot \Delta P_T}$$

- $\psi(2S) \rightarrow \mu^+\mu^-$ decays are reconstructed by selecting events with two oppositely charged muon candidates
- 1.1 fb^{-1} of data corresponding to an effective integrated luminosity of 954.1pb^{-1}
- Simultaneous unbinned maximum likelihood fit in mass and proper decay length is performed to extract the $\psi(2S)$ events from the background and separate the prompt and B-decay $\psi(2S)$ yield

Example - Fit Projection



$\chi^2/ndf = 71.4/100$, χ^2-prob.$= 0.99$



$\chi^2/ndf = 120.0/121$, χ^2-prob.$= 0.51$

Acceptance, Efficiencies, and Luminosity

Acceptance

- Acceptance is sensitive to the $\psi(2S)$ polarization parameter α.
- For prompt decay, averaged $\alpha = 0.01 \pm 0.13$ is used to determine the acceptance.
- For B-decay, the measured B-decay polarization $\alpha_{eff} = 0.36 \pm 0.25 \pm 0.03$ is used.

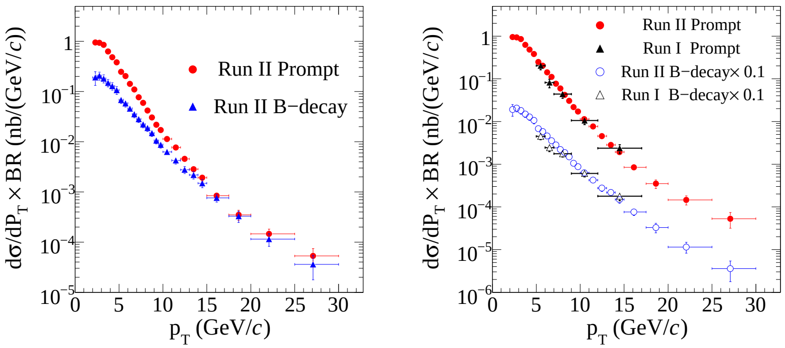
Efficiencies

- Trigger efficiency - the data based trigger efficiencies, CDF 7314
- Reconstruction efficiency - Product of tracking and muon selection efficiencies measured in CDF data, $\varepsilon_{reco} = 0.798 \pm 0.025$.

Luminosity

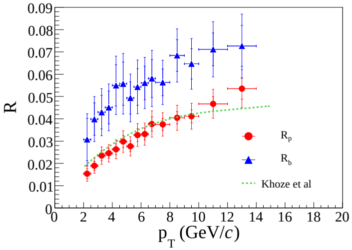
- 1.1 fb^{-1} data set of the dimuon trigger path (`JPSI_CMUCMU1.5` or `JPSI_CMUCMU1.5_DPS`).
- The luminosity for the dynamically prescaled trigger path is calculated using DPS Accounting tool.
- The effective luminosity: 954 pb^{-1}.

Result - Prompt and B-decay $\psi(2S)$ Cross Section



- Left: Prompt and B-decay production cross section distribution versus p_T.
- Right: The same data with the Run I points included.

Cross section Ratio of $\psi(2S)$ to J/ψ



- The differential cross section ratio of $\psi(2S)$ to J/ψ as a function of p_T for prompt (R_p) and B-decay events (R_b).
- Prompt $\psi(2S)$ production has a harder p_T spectrum than that for J/ψ production.
- The increase in the ratio at larger p_T reflects the slope difference.
- The ratio of B-decay to prompt ratios R_b/R_p is independent of p_T (χ^2/n.d.f. = 13/14).

Conclusion

The $\psi(2S)$ production cross section and the polarization have been measured with 1 fb^{-1} data

$\psi(2S)$ Polarization

- Improved with an order of magnitude higher statistics
- Consistent with being zero in the p_T region
- Contradictory to the prediction of NRQCD factorization

$\psi(2S)$ Production Cross Section

- Extended with good statistics out to 30 GeV/c
- The increase in the integrated cross section from Run I can be explained by the changes in the PDF at higher collision energy
- Important input for an update of the matrix elements in NRQCD

A successful description of the cross section in the perturbative p_T region with matching the polarization measurement would demonstrate a good understanding of the charmonium hadroproduction mechanisms