Workshop soft diffraction, CERN June 25-26, 2009

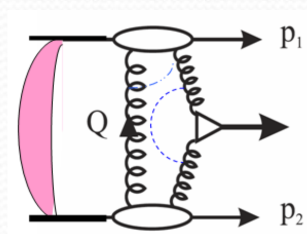
Heavy Quarkonia: as Seen through the Eyes of Central Exclusive Production at the Tevatron and LHC

June 26th 09

V.A. Khoze (IPPP, Durham)

(Based on collaboration with L. Harland-Lang, A..Martin, M.Ryskin and W.J. Stirling)

main aim: to demonstrate that CEP can open a new way to study the properties of heavy quarkonia , and, in particular, to serve as a spin-parity analyser



χ_c, χ_b

PLAN

1. Introduction

2. Central Exclusive Production as a heavy meson spin-parity analyser.

3. What is known from the general rules (Regge theory).

4. Expectations within the pQCD Durham approach.

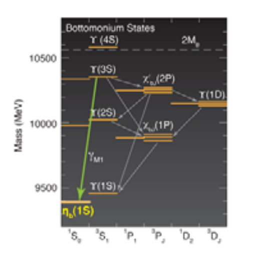
5. Interpretation of the CDF results on charmonium CEP.

6. New Run of Durham studies (still preliminary).

7. Prospective measurements.

8. A few remarks about the models for soft diffraction.

9. Conclusion.



INTRODUCTION

Why an interest to the CEP of χ_c, χ_b ?

- Testing ground for the formalism of CEP used to evaluate the New Physics signals (e.g. 'Diffractive Higgs')
- Open issues in Quarkonium Spectroscopy, such as χ_b quantum numbers. New way to address Quarkonium Physics..
- New Encouraging CDF results on CEP of the χ_c . . (Mike)

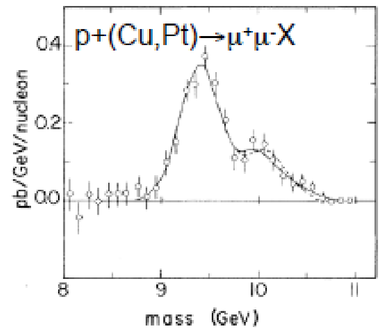
Heavy Quarkonia

Traditional testing ground for various aspects of QCD

- NRQCD, QCDME, Lattice QCD, QCD sum rules, potential models,...
- Large NLO..... PT corrections.
- P-states- sensitivity to the derivatives of the wave function, relativistic effects....

Bottomonium history started 30 years ago

(PRL 39, 242 (1977) and PRL 39,1240 (1977))



$M(\Upsilon)=9.40\pm0.013$

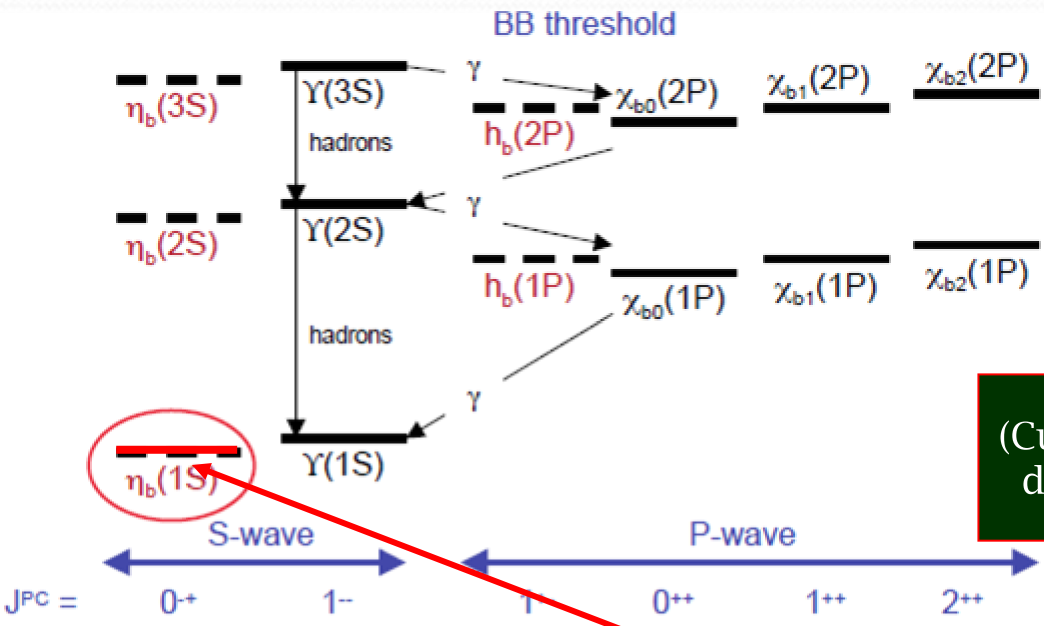
$M(\Upsilon')=10.00\pm0.04$

$M(\Upsilon'')=10.43\pm0.12$

FNAL, E288

30 years later….

(spins- still unconfirmed)



$\Upsilon(nS)$ confirmed and $\chi_{bJ}(1,2P)$ states observed

Below $B\bar{B}$, several states not yet observed: 3 S-wave (η_b), 2 P-wave (h_b), D-wave,etc…

(Currently no complete theor. description of onium properties.)

(BABAR (2008))

(Still some puzzles)

The heaviest and most compact quark-antiquark bound state in nature

PDG Summary Tables

Meson Summary Tables

in the 2008 Review of Particle Physics

$\chi_{b0}(1P)$ [d]

$I^G(J^{PC}) = 0^+(0^{++})$

J needs confirmation.

Mass $m = 9859.44 \pm 0.42 \pm 0.31$ MeV

$\chi_{b0}(1P)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\gamma\,\Upsilon(1S)$	<6 %	90%	391

$\chi_{b1}(1P)$ [d]

$I^G(J^{PC}) = 0^+(1^{++})$

J needs confirmation.

$\gamma\,\Upsilon(1S)$	(35 ± 8) %	423

$\chi_{b2}(1P)$ [d]

$I^G(J^{PC}) = 0^+(2^{++})$

J needs confirmation.

Mass $m = 9912.21 \pm 0.26 \pm 0.31$ MeV

$\chi_{b2}(1P)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\gamma\,\Upsilon(1S)$	(22 ± 4) %	442

The main advantages of the χ_c, χ_b -CEP

- Quantum number filter/analyser.

  (0++ dominance ; C,P-even),

- Clean few-particle final state,

- Favourable background conditions.
  (theoretical estimates, $\gamma\gamma$- data).

- New leverage –proton momentum correlations

Potential (theoretical) problems

- Higher sensitivity to low scales- **'usual suspects'**

- Stronger dependence on Enhanced Screening effects

  (larger s/M_χ^2)

What we know from Regge theory (KKMR-2003)

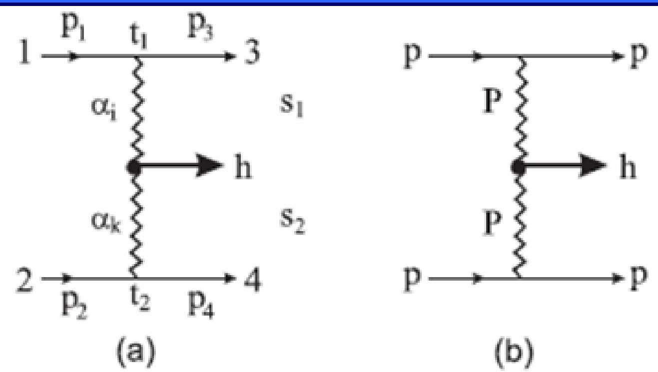


Figure 1: (a) The central production of a state h by double-Reggeon exchange. (b) The double-Pomeron exchange contribution to $pp \to p + h + p$, which dominates at high energies, where the + signs are used to indicate the presence of Pomeron-induced rapidity gaps.

$J^P(h) = 0^+$ Vertex Coupling $g^h_{ik} = f_{0^+}(p^2_{3\perp}, p^2_{4\perp}, \vec{p}_{3\perp}\cdot\vec{p}_{4\perp})$ depends on dynamics

$J^P(h) = 0^-$ $\sigma \sim |t_1||t_2| \sin^2\phi$ observed for η,η' by WA102 Group (450 GeV, pp CERN Omega Spectrometer.)

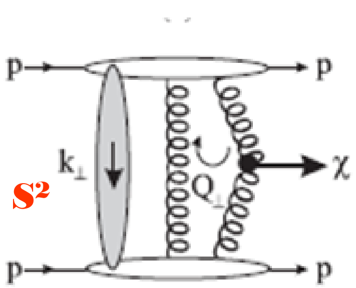
$J^P(h) = 1^+$ For small p_{it}

$$g_{PP} = a_{\lambda=0}(p^2_{3t} - p^2_{4t})/M^2(\vec{p}_{3t}\times\vec{p}_{4t})\vec{e} + f_{\lambda=1}(\vec{K}\times\vec{n})\vec{e}/M\ , \quad \vec{K} = (\vec{p}_3 - \vec{p}_4)$$

- Cross section tends to zero at low K_t (also Petrov et al-04, Szczurek et al)
- Dominantly produced in the helicity-one state
- Coincide with the NCVC model expectation by F. Close et al (1999)
- Agree with the WA102 data on f_1 (1420) and f_1(1285)

What we expect within the framework of the Perturbative Durham formalism
(KMR-01, KKMR-03, KMRS-04)

O++ -case



$$T = A\pi^2 \int \frac{d^2Q_\perp \, P(\chi(0^+))}{Q_\perp^2 (\vec{Q}_\perp - \vec{p}_{1\perp})^2 (\vec{Q}_\perp + \vec{p}_{2\perp})^2} f_g(x_1, x_1', Q_1^2, \mu^2; t_1) f_g(x_2, x_2', Q_2^2, \mu^2; t_2),$$

$$A^2 = 8\pi\Gamma(\chi \to gg)/M_\chi^3 \quad {}^*K_{NLO} \qquad P(\chi(0^+)) = (\vec{Q}_\perp - \vec{p}_{1\perp}) \cdot (\vec{Q}_\perp + \vec{p}_{2\perp}).$$

- **Strong sensitivity to the polarization structure of the vertex in the bare amplitude.**
- In the on-shell-gluon approximation spin -1 is excluded by Landau-Yang theorem. Should lead to a strong suppression.
- For forward going protons in the non-relativistic quarkonium approximation, CEP of the spin-2 meson is strongly suppressed (Jz = 0 selection rule) — KMR-01

(A. Alekseev-1958-positronium)

- **Absorption is sizeably distorted by the polarization structure** (affects the b-space distr.)

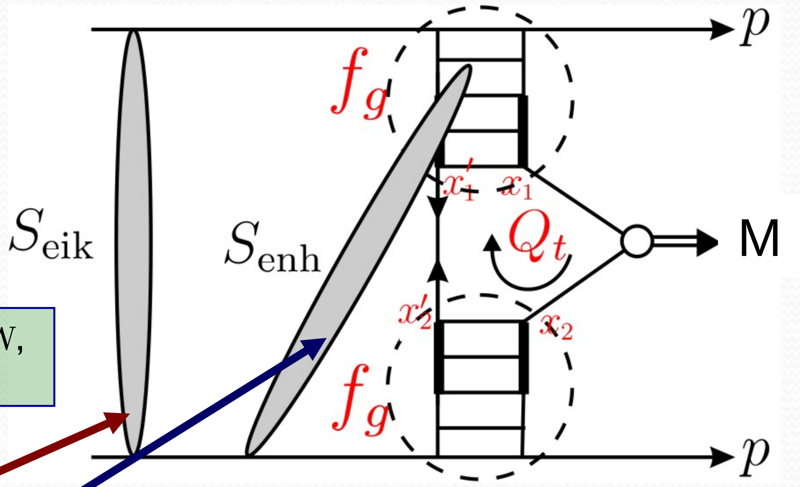
KMR-02, KKMR-03

- χ_c, χ_b -production is especially sensitive to the effects of enhanced absorption
- larger available rapidity interval
- lower scale → larger dipole size → larger absorption

(S^2enh for χ_c at the Tevatron is expected to exceed that for the Higgs at the LHC)

"soft" scattering can easily destroy the gaps

S^2 → absorption effects -necessitated by unitarity



gap

gap

Everybody's happy (KMR, GLM, FHSW, Petrov et al, BH, GGPS, Luna...MCs)

soft-hard factorizn

eikonal rescatt: between protons ← conserved

enhanced rescatt: involving intermediate partons ← broken

Subject of hot discussions : S^2enh

Interpretation of CDF results

(CDF Collaboration, arXiv:0902.1271 [hep-ex], PRL in press)

(Mike)

Assuming that all events are originated from CEP of $\chi_c(0^+)$ (limited acceptance)
(used CHIC MC- Durham based)

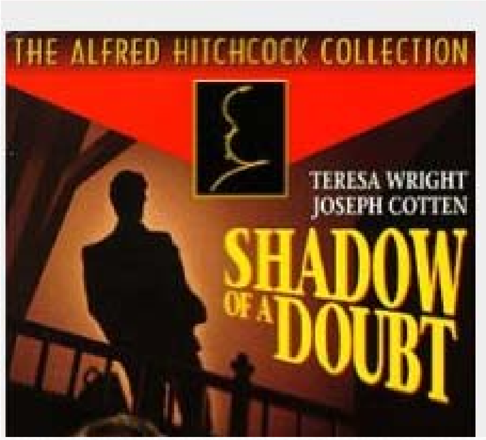
CDF $\left.\frac{d\sigma(\chi_c)}{dy}\right|_{y=0} = (76 \pm 14)$ nb

KMRS -2004: 130 nb → 90 nb (PDG-2008)

Signal based on: $\chi_c \to J/\psi + \gamma$

A certain preference to 0^+ in the $(J/\psi + \gamma)$ mass distribution

Too good to be true ?!



Devil's Advocate Questions

1. How do we know which particular P- state has been found ?

   (P-states are not clearly separated experimentally)

2. Is reconstruction based on CHIC MC still acceptable, what if not $J^{PC} = 0^{++}$?

3. Are we close to the CEP prescription (role of low mass SD and DD)

Yes, due to the record CDF gap coverage (7.4) (KMRS-04)

$\chi_c(0^+)$ dominates CEP, but

$$Br(\chi_c(0^+) \to J/\psi + \gamma) = (1.28 \pm 0.11)\%$$

$$Br(\chi_c(1^+) \to J/\psi + \gamma) = (36.0 \pm 1.9)\%$$

$$Br(\chi_c(2^+) \to J/\psi + \gamma) = (20.0 \pm 1.0)\%$$

- On-mass-shell 1^+ production is forbidden due to Landau-Yang theorem, but what about off-mass-shall effects ?
  Recently- renewal of interest (R.Pasechnik, A. Szczurek, O.Teryaev-09)

Still numerically small

- Within the non-relativistic framework for forward going protons 2^+ is strongly suppressed, but what about non-forward protons and relativistic effects ?

Important phenomenon- absorptive corrections are quite sensitive to the meson spin-parity
(studied before in the context of scalar/pseudoscalar Higgs-KKMR04,)

New Run of Durham Studies

Issues addressed:

- New CHIC MC for all $c\bar{c}$ **P** -states.
- Absorption effects for **CEP** of the $0^+, 1^+, 2^+, 0^-$ $c\bar{c}$ - states revisited
- Proton angular correlations for different $0^+, 1^+, 2^+, 0^-$ $c\bar{c}$ -states.
- Expectations for the CEP of the $0^+, 1^+, 2^+, 0^-$ $b\bar{b}$ -states.

PRELIMINARY

As compared to the previous K(KMR)S studies:

- More comprehensive calculation of the absorption effects using the new KMR-07/08 model for soft diffraction (including the enhanced screening).
- New calculational routine for implementing polarization structure in the b-space.
- New experimental/theoretical results for the parameters of heavy quarkonia, in particular $\Gamma(\chi \to gg)$.

CHARMONIUM

- The final state (muon) distributions in the $(J/\psi+\gamma)$ system are sensitive to the meson spin, but after imposing the CDF cuts this dependence is strongly reduced. (L. Harland-Lang, W.J. Stirling).

- Cross-section 'reconstruction' is safe
- Spin is not discriminated via the $(J/\psi+\gamma)$ decay products
- We need to measure better spin-parity analysing final state: $\pi\pi, KK, p\bar{p}$ KMRS-04
  or outgoing proton momentum correlations

For normalization purposes- scalar case at the Tevatron

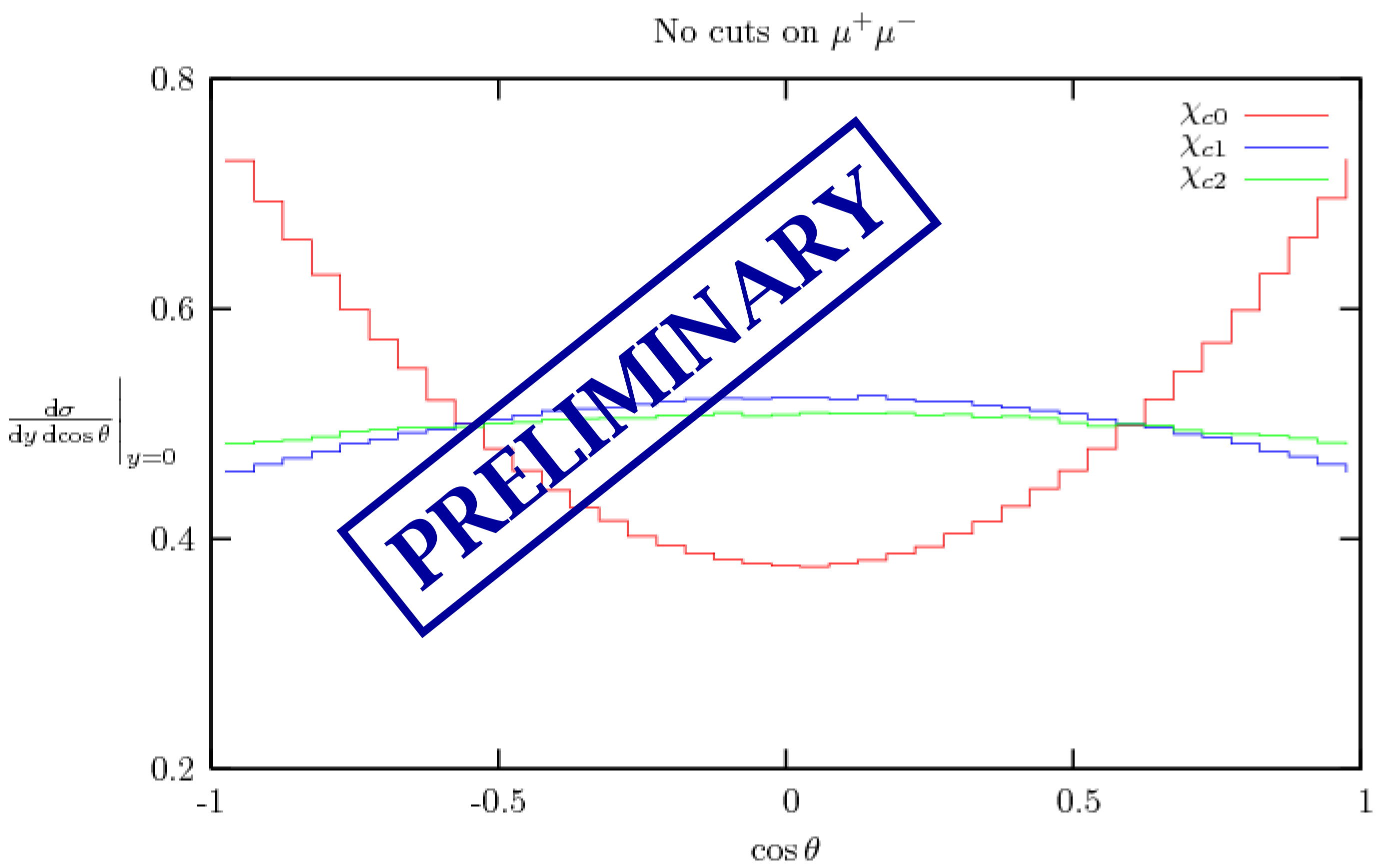
$$<S^2_{eik}(0^+)>\approx 0.06 \qquad <S^2_{eff}(0^+)>\approx 0.02$$

(Δ=2.3)

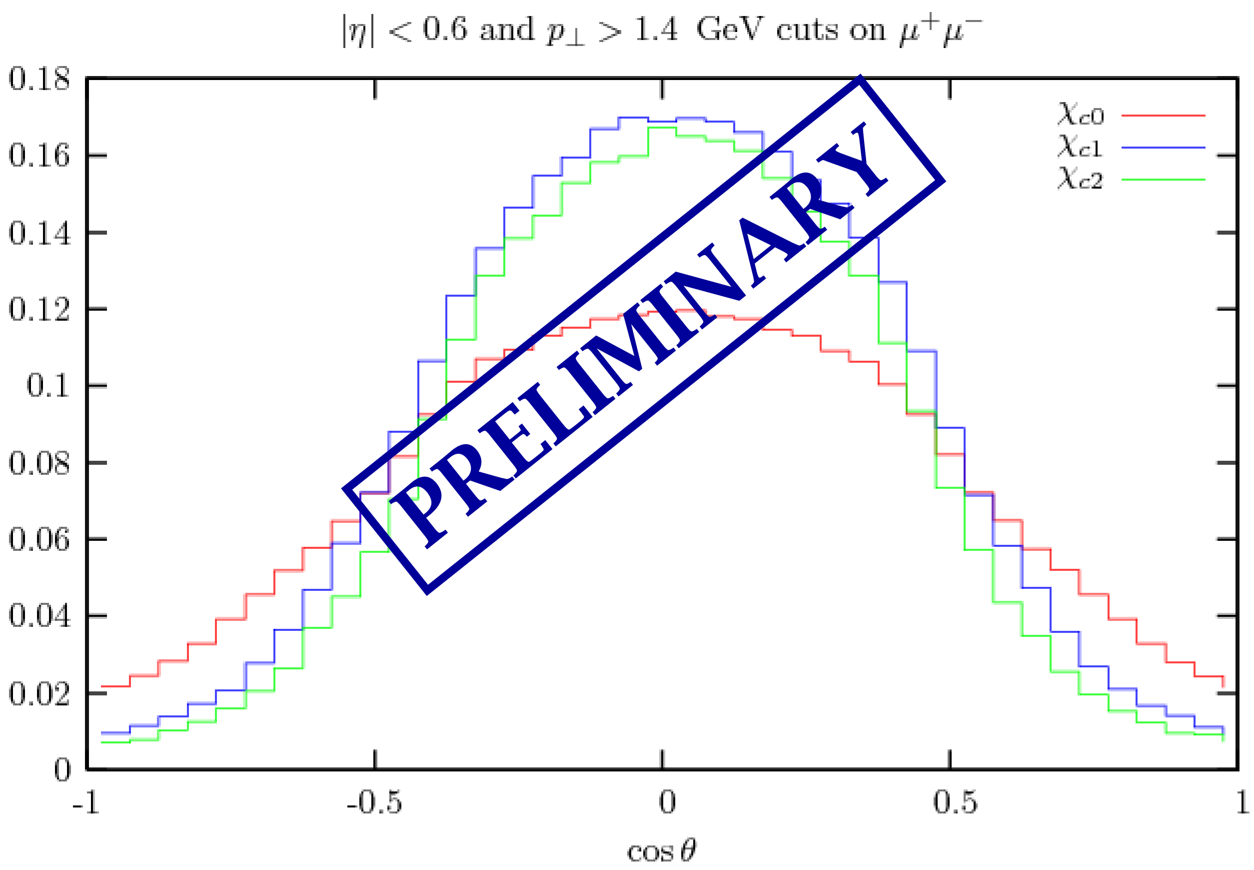
$$d\sigma(0^+)/dy|_{y=0}\simeq 90 \text{ nb} \qquad d\sigma(0^+)/dy|_{y=0}\simeq 35 \text{ nb}$$

- Still within Durham approach-uncertainties, recall, in particular $(f_g)^4$- effect

  Reasons to believe that enhanced absorption is overestimated- KMR-09



No cuts on $\mu^+\mu^-$
0.8
0.6
0.4
0.2
$\left.\frac{d\sigma}{dy\, d\cos\theta}\right|_{y=0}$
-1
-0.5
0
0.5
1
$\cos\theta$
χ_{c0}
χ_{c1}
χ_{c2}
PRELIMINARY



$|\eta| < 0.6$ and $p_\perp > 1.4$ GeV cuts on $\mu^+\mu^-$
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
-1
-0.5
0
0.5
1
$\cos\theta$
χ_{c0}
χ_{c1}
χ_{c2}
PRELIMINARY

Some of the 'typical' uncertainties cancel in the ratios

- $$\sigma(1^+)/\sigma(0^+) \simeq \langle p_t^2 \rangle / M_\chi^2 * \langle S^2_{eik}(1) \rangle / \langle S^2_{eik}(0) \rangle * R^1_{NLO} \simeq 0.05$$

- $\langle S^2_{enh}(J) \rangle$ - the same for all J within ~20% accuracy,

- $\langle S^2_{eik}(1,2) \rangle / \langle S^2_{eik}(0) \rangle \simeq 2.5$; $\langle p_t \rangle \simeq 0.5$ GeV .

Production is more peripheral: zero at $\vec{b} = 0$, where the absorption is largest
at larger $\vec{b}$ absorption is small anyway.

- $$\sigma(2^+)/\sigma(0^+) \simeq (\langle p_t^2 \rangle / Q_t^2)^2 * \langle S^2_{eik}(2) \rangle / \langle S^2_{eik}(0) \rangle * R^2_{NLO} \simeq 0.05$$

($\langle Q_t \rangle \simeq 1 GeV$)

- $$\sigma(0^+ \to J/\psi + \gamma) : \sigma(1^+ \to J/\psi + \gamma) : \sigma(2^+ \to J/\psi + \gamma) = 1 : 1.4 : 0.77$$

Then $d\sigma(0^+, 1^+, 2^+)/dy \simeq 110$ nb, as compared to experiment: (76 $\pm$ 14) nb

After all , keeping in mind all uncertainties

Energy Dependence

- Expected to be weak, since the rise of the gluon density at low x is compensated by stronger enhanced screening.

  $d\sigma(\chi_{c0})/dy \simeq 50$ nb at the LHC

- Test of the enhanced absorption (less model dependent):

  $\sigma(\chi, LHC)/\sigma(\chi, Tevatron)$

  various uncertainties cancel (NLO effects, width,…)

- $\sigma(\chi_{c2})/\sigma(\chi_{c0})$ decreasing with energy ($< Q_t >$ increasing)

Momentum correlations between outgoing protons

- Separation of different meson states (irrespectively of the final state), seen in the CEP of light mesons (WA102 Collab).

  Recall the results of Regge theory at low transverse momenta $(p_{3,4})_t$

$$d\sigma(0^+)/d\phi \simeq const; \quad ;$$

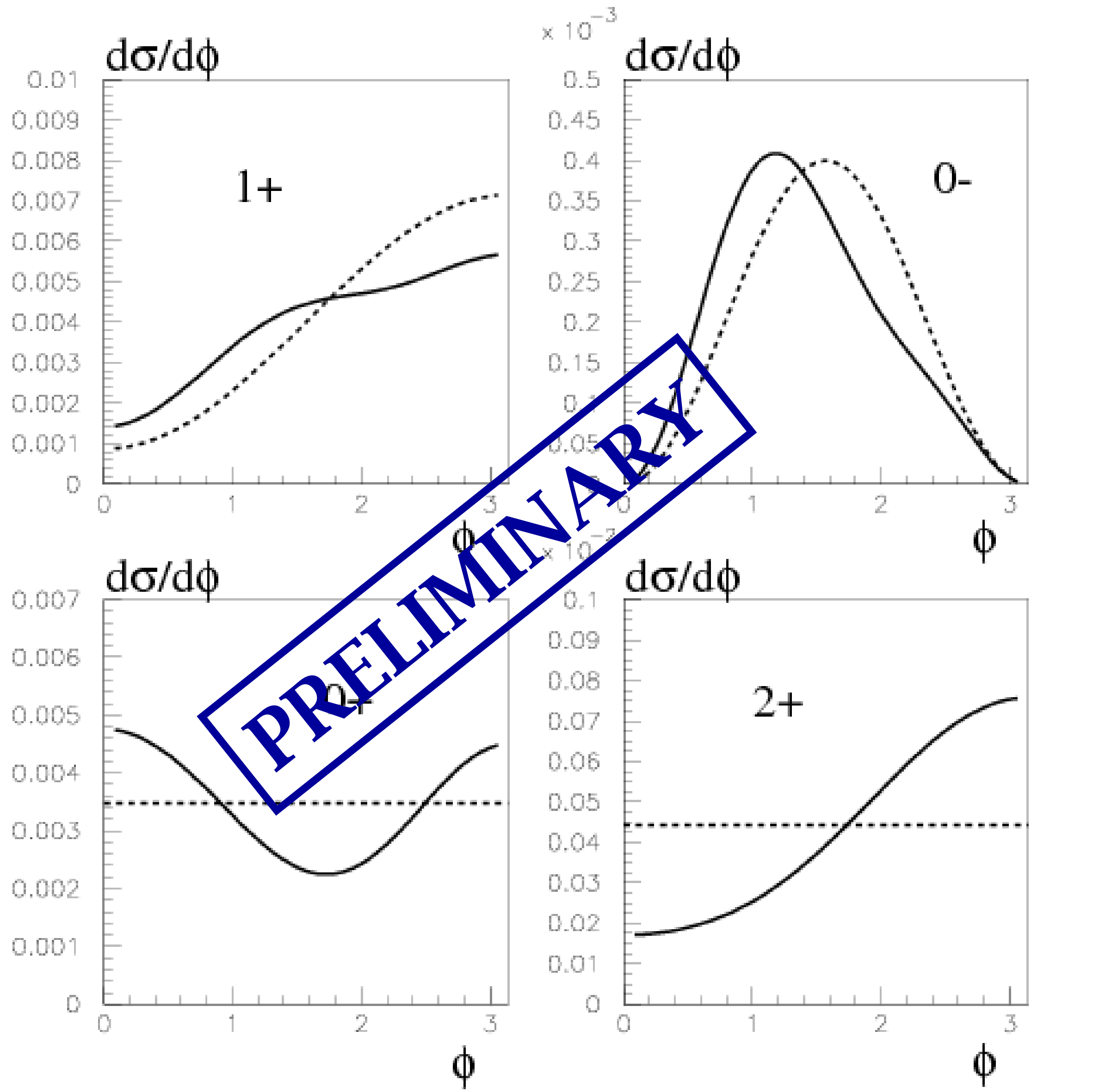
$$d\sigma(0^-)/d\phi \simeq \sin^2\phi;$$

$$d\sigma(1^+)/d\phi \simeq (\vec{p}_3 - \vec{p}_4)^2{}_t;$$

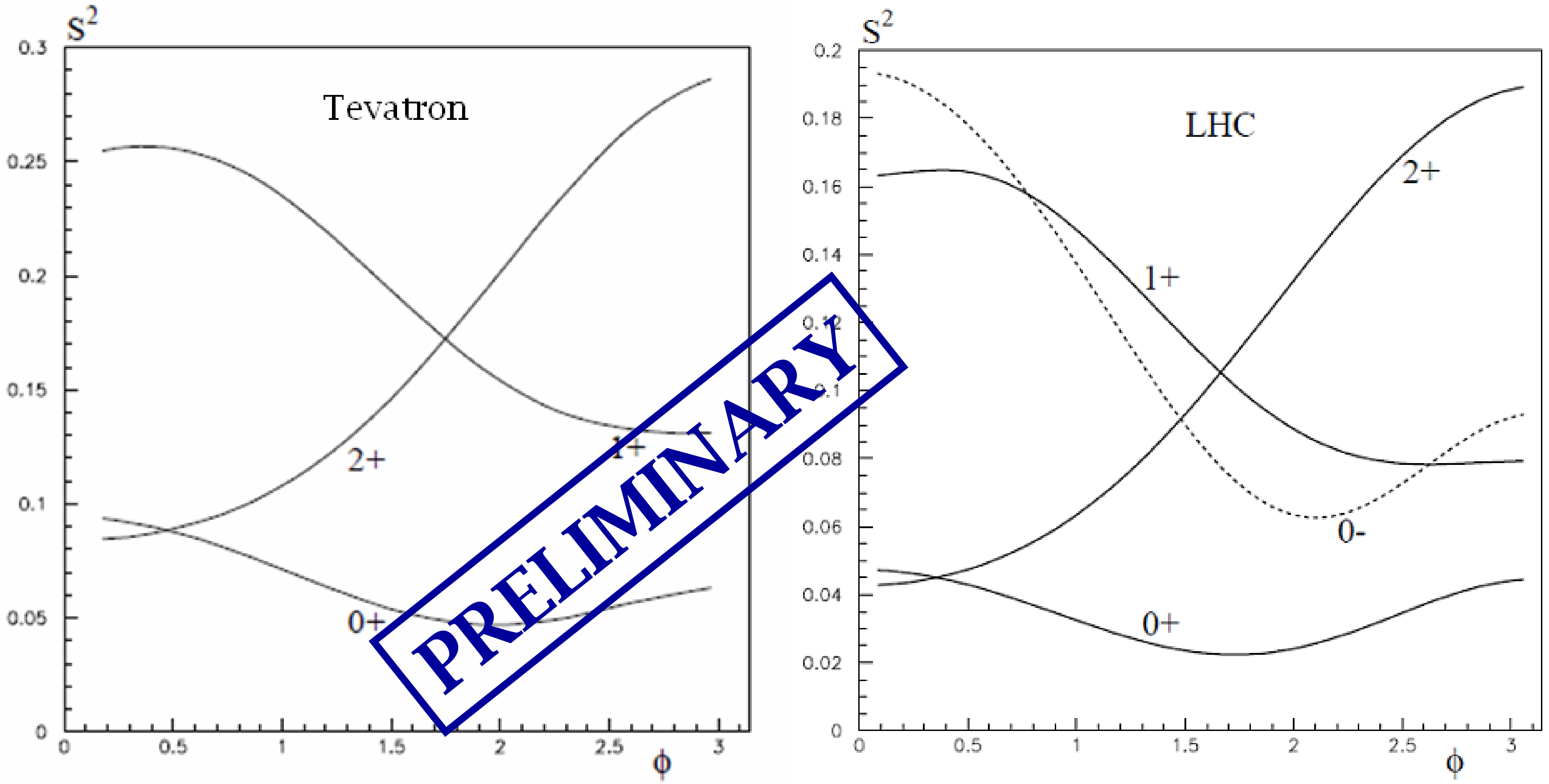
$$d\sigma(2^+)/d\phi \simeq const;$$

- Some dependence on the choice of unintegrated gluon densities (KMR-02, KKMR-03)

- Serious modification by the absorption effects (amount of suppression strongly depends on the impact parameter $\vec{b}$)


dσ/dφ
1+
dσ/dφ
× 10^-3
0-
dσ/dφ
dσ/dφ
2+
φ
φ
φ
PRELIMINARY

ϕ- dependence of S^2_{eik}



- More peripheral nature of $0^-, 1^+, 2^+$ production.
- Manifestations of the diffractive dip.
- Dependence on the p_t -cuts studied in KMR02, KKMR-03 for the H-case.
- $S^2 enh$ weakly depends on ϕ.

for completeness

$d\sigma(\eta_c)/dy|_{y=0} = 0.5$ nb at the Tevatron

1.5 nb at the LHC

note: some decay modes are quite sizeable (ρρ, KKπ, ηππ.. a few % level)

Spin-parity is not confirmed (yet) for some new mesons

- X(3872) : 1^{++} *or* 2^{-+} ?
- Y(4140) (decay $J/\Psi\phi$) **(molecule or tetra-quark or..?)**
- $X(3940)$, $Y(3940)$ and $Z(3930)$ J^{P+}

$\chi_{c1}(2P)$ $\chi_{c2}(2P)$

or

$\eta_c(3S)$ or ?

$X(3872)$, $Y(3940)$ $Y(4260)$

J/ψ

BOTTOMONIUM

Recall , the decay $\chi_{b0}(1P) \to Y(1S)\gamma$ has not been seen (yet)

but $Br(\chi_{b0}(2P) \to Y(2S)\gamma = (4.6 \pm 2.1)\%$

According to evaluation by J.T. Laverty et al (2009)

$\Gamma(\chi_{b0} \to gg) = 3.7 MeV$,

$Br(\eta_b \to \gamma\gamma) = 3.4 * 10^{-5}$ (Exp. $Br(\eta_{c0} \to \gamma\gamma) \simeq 2 * 10^{-4}$).

.

χ_b Higher scale ➔ better PT description

Smaller role of relativistic effects, better knowledge of gluon densities

- 1^{+}-is practically filtered out (strong M^2 -suppression)
- 2^{+} weak- $< Q_t >^2$ dependence
- Enhanced absorption- weaker (~ 2 times)

Expectations for χ_b, η_b

$d\sigma / dy |_{y=0}$ (in pb)

	χ_{b0}	χ_{b1}	χ_{b2}	η_b
Tevatron	400	3	10	5
LHC	700	7	20	15

$\rightarrow D^0$ -modes (small background)

(significant production of D^0 mesons from both the $\chi_{b1}(1P)$ and $\chi_{b1}(2P)$

NRQCD **CLEO III- 2008**)

PROSPECTIVE MEASUREMENTS

- A clear way to resolve the issue of χ_c spin-parity identification will be be to search for the two-body decays:

$$Br(\chi_{co} \to \pi\pi, K^+K^-) \simeq 1.3\% \qquad \chi_{c1}, \eta_c \not\to \pi\pi, KK \qquad Br(\chi_{c2} \to \pi\pi, K^+K^-) \simeq 0.3\%$$

$$Br(\chi_{c0} \to p\bar{p}) \simeq 2*10^{-4} \qquad Br(\chi_{c1} \to p\bar{p}) \simeq 6.6*10^{-5} \qquad Br(\chi_{c2} \to p\bar{p}) \simeq 6.7*10^{-5}$$

$$Br(\eta_c \to p\bar{p}) \simeq 0.13\%$$

- Tagged forward protons: spin-parity ID of old and new heavy meson states, detailed tests of absorption effects

- With sufficient statistics of $\gamma\gamma$ CEP, the measurement of the ratio

$$\sigma(\chi_b)/\sigma(\gamma\gamma)$$

can be quite instructive (the same mass range, various uncertainties cancel).

UNCERTAINTIES

Known Unknowns

- N(N)LO- radiative effects (K-factors etc..)
  '…possible inadequancy of PT theory in α_s …' R.Barbieri et al-1980
- ' 'Right' choice of gluon densities, in particular at so low scales as in the χ_c case (potentiality of a factor of ~3 rise for the H-case) .
- Complete model for calculation of enhanced absorption.
- χ_b -experimental widths, decays…

Unknown Unknowns

- Non- pQCD effects in the meson characteristics.
  Currently no complete description of heavy quarkonium characteristics.
  'Two gluon width does not tell the whole story.'
- Gluons at so low scales, surprises are not excluded at all.

Factor of 5 up or down (at best)

S²

Far more theoretical papers than the expected number of the CED produced Higgs events

(Laslo)

‘Well, it is a possible supposition
‘You think so, too ?’
‘I did not say a probable one’

Selection Criteria for the Models of Soft Diffraction

(Aliosha, Asher, Uri, Sergey)

with a bit of personal flavour

- We have to be open-eyed when the soft physics is involved.
  Theoretical models in the strong coupling regime contain various assumptions and parameters.

- Available data on soft diffraction at high energies are still fragmentary,
  especially concerning the (low mass) diffractive dissociation.

A viable model should:

- incorporate the inelastic diffraction : SD, DD
  (for instance 2-3 channel eikonal of KMR or GLM(M))

- describe all the existing experimental data on elastic scattering and SD ,DD and **CED**
  at the Tevatron energies and below (KMR; GLM(M))

- be able to explain the existing CDF data on the HERA-Tevatron factorization breaking
  and on the CED production of the di-jets, di-photons, χ, J/ψ, Υ.., lead. neutrons at HERA

- provide testable **pre-dictions** or at least **post-dictions** for the Tevatron and HERA

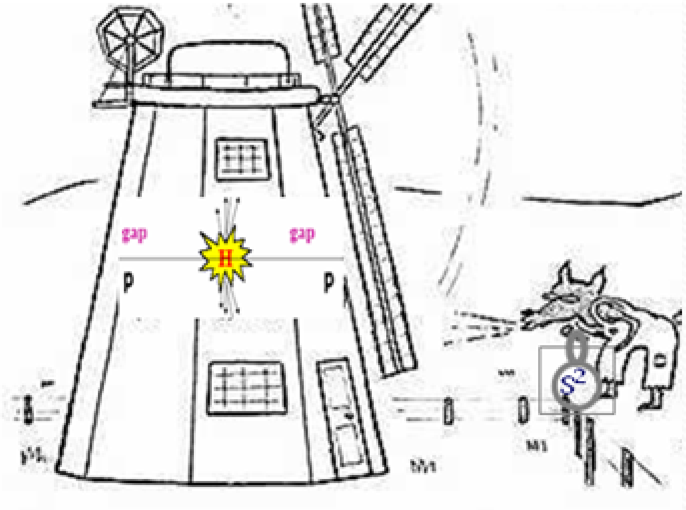
So far (only) **Durham** model has passed these tests.

Only a large enough data set would impose the restriction order on the theoretical models and to create a confidence in the determination of S^2.

Program of Early LHC measurements (KMR)

LET THE DATA TALK !

Who's Afraid of the Big, Bad Wolf?



- S^2 does not affect the signal-to-background ratio- for all irreducible backgrounds (signal evidence is much less affected)
- Main reduction of the signal (factor of ~50) comes from the experimental requirements (cuts and efficiences...) which are currently known for the inclusive environment. Further progress with hard/soft -ware for the CEP processes can be expected.
  More experimental work needed
- Experimentally we have not seen (at least so far) any evidence in favour of large enhanced absorption (KKMR, KMR- 2001-2009).
- Durham selection of the UPDF is quite conservative. Due to the $(fg)^4$ behaviour- rise up to a factor of 3 (Cox et al, KMR). New studies underway.

Up to two orders of magnitude rise in the popular BSM Higgs models.

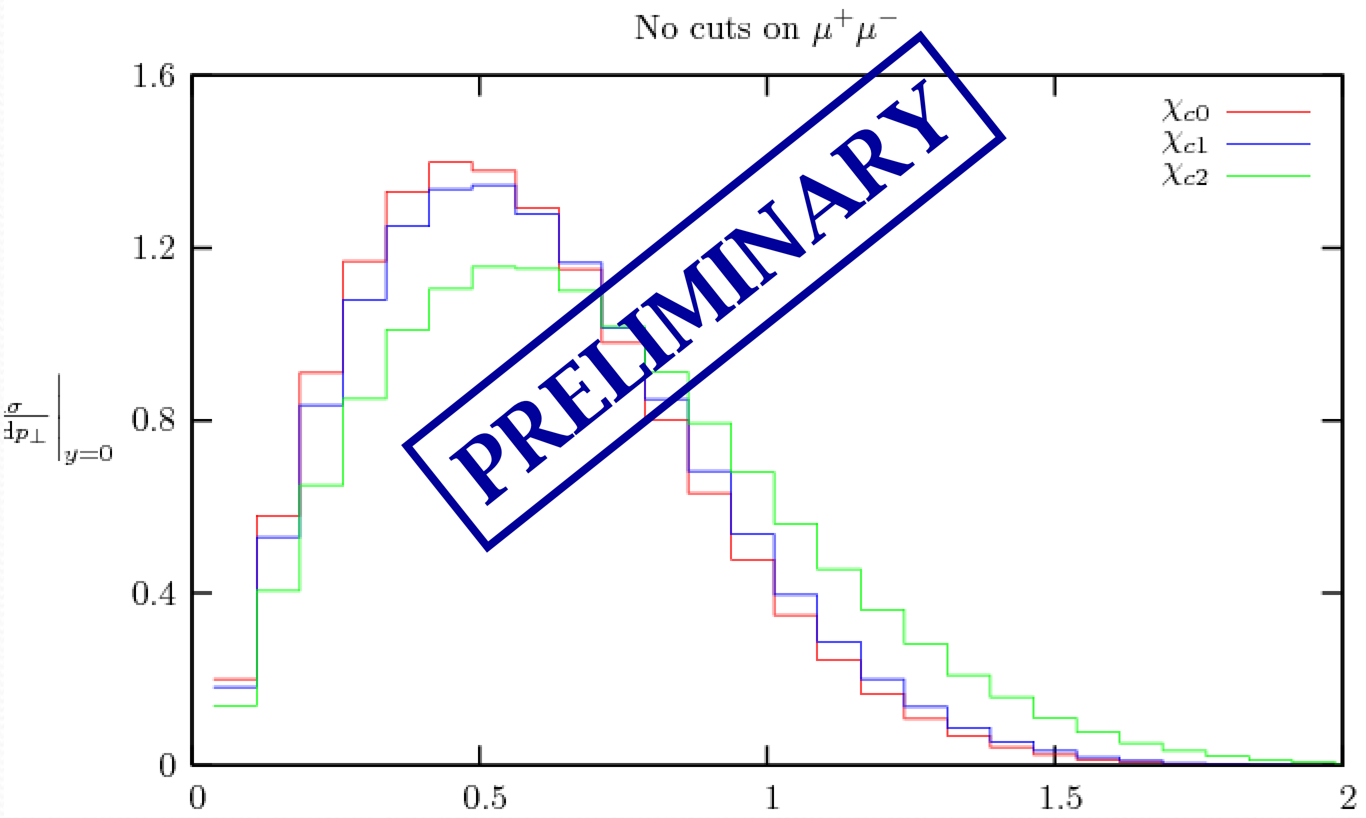
- We should be careful with relaying on the NLO corrections (e.g. BBKM-06). Can be misleading when large parameters are involved. (textbook example: non-relativistic Coulomb correction)

CONCLUSION

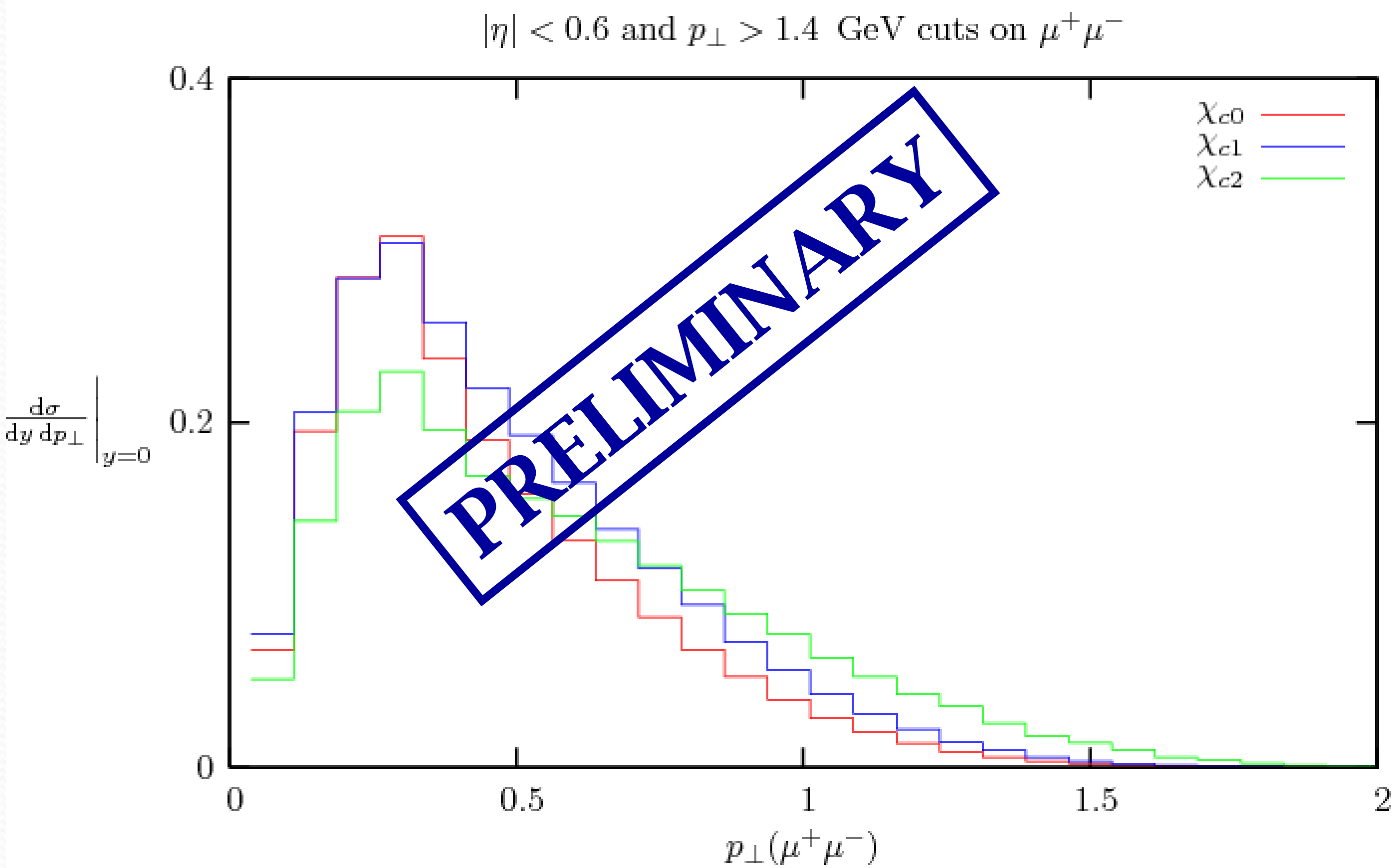
- CDF data on CEP of the χ_c are in a broad agreement with the Durham results.
- CEP of heavy mesons - a new way to study quarkonium spectroscopy as well as to address the physics of absorption;

  can help to establish the nature of newly discovered heavy states.
- Promising prospects of studying heavy meson CEP, especially with tagged forward protons.
- Currently active studies are still in progress (both in theory and experiment).

Backup



No cuts on $\mu^+\mu^-$
PRELIMINARY
χ_{c0}
χ_{c1}
χ_{c2}
1.6
1.2
0.8
0.4
0
0.5
1
1.5
2


$|\eta| < 0.6$ and $p_\perp > 1.4$ GeV cuts on $\mu^+\mu^-$
0.4
0.2
0
$\frac{d\sigma}{dy\,dp_\perp}\Big|_{y=0}$
0
0.5
1
1.5
2
$p_\perp(\mu^+\mu^-)$
χ_{c0}
χ_{c1}
χ_{c2}
PRELIMINARY

$\chi_{b1}(2P)$ [d]

$I^G(J^{PC}) = 0^+(1^{++})$
J needs confirmation.

Mass $m = 10.25546 \pm 0.00022 \pm 0.00050$ GeV
$m_{\chi_{b1}(2P)} - m_{\chi_{b0}(2P)} = 23.5 \pm 1.0$ MeV

$\chi_{b1}(2P)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor	p (MeV/c)
$\omega\,\Upsilon(1S)$	$(1.63^{+0.38}_{-0.34})$ %		135
$\gamma\,\Upsilon(2S)$	(21 ± 4) %	1.5	230
$\gamma\,\Upsilon(1S)$	(8.5 ± 1.3) %	1.3	764
$\pi\pi\chi_{b1}(1P)$	$(8.6 \pm 3.1) \times 10^{-3}$		238

$\chi_{b2}(2P)$ [d]

$I^G(J^{PC}) = 0^+(2^{++})$
J needs confirmation.

Mass $m = 10.26865 \pm 0.00022 \pm 0.00050$ GeV
$m_{\chi_{b2}(2P)} - m_{\chi_{b1}(2P)} = 13.5 \pm 0.6$ MeV

$\chi_{b2}(2P)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\omega\,\Upsilon(1S)$	$(1.10^{+0.34}_{-0.30})$ %	194
$\gamma\,\Upsilon(2S)$	(16.2 ± 2.4) %	242
$\gamma\,\Upsilon(1S)$	(7.1 ± 1.0) %	777
$\pi\pi\chi_{b2}(1P)$	$(6.0 \pm 2.1) \times 10^{-3}$	229