LOW X MEETING

ISCHIA ISLAND, ITALY

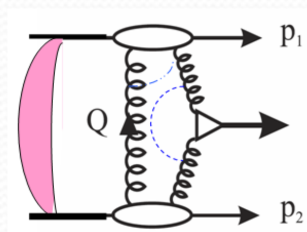
September 8-13, 2009

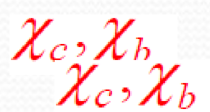
Heavy Quarkonia: as Seen through the Eyes of Central Exclusive Production at the Tevatron and LHC

V.A. Khoze (IPPP, Durham, PNPI)

(Based on works 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





PLAN

1. Introduction

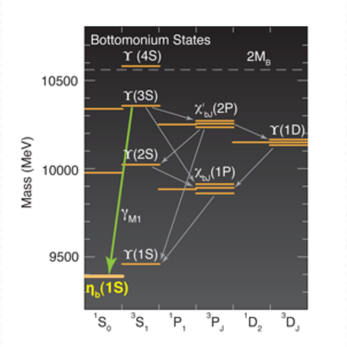
2. Central Exclusive Production as a heavy meson spin-parity analyser.

3. *Interpretation of the CDF results on charmonium CEP.* (Mike, Jim)

4. New Run of Durham studies.

5. Remarks about the models for soft diffraction. *(Alan, Asher)*

6. 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 (numerous new exotic charmonium like states).
- New Encouraging CDF results on CEP of the χ_c . (Mike, Jim)

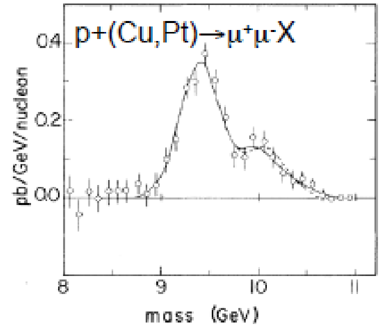
Heavy Quarkonia

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….
- Nature of the new states around 4 GeV; X, Y, Z, other applications of the CEP…

Bottomonium history started 30 years ago

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



M(Υ)=9.40±0.013

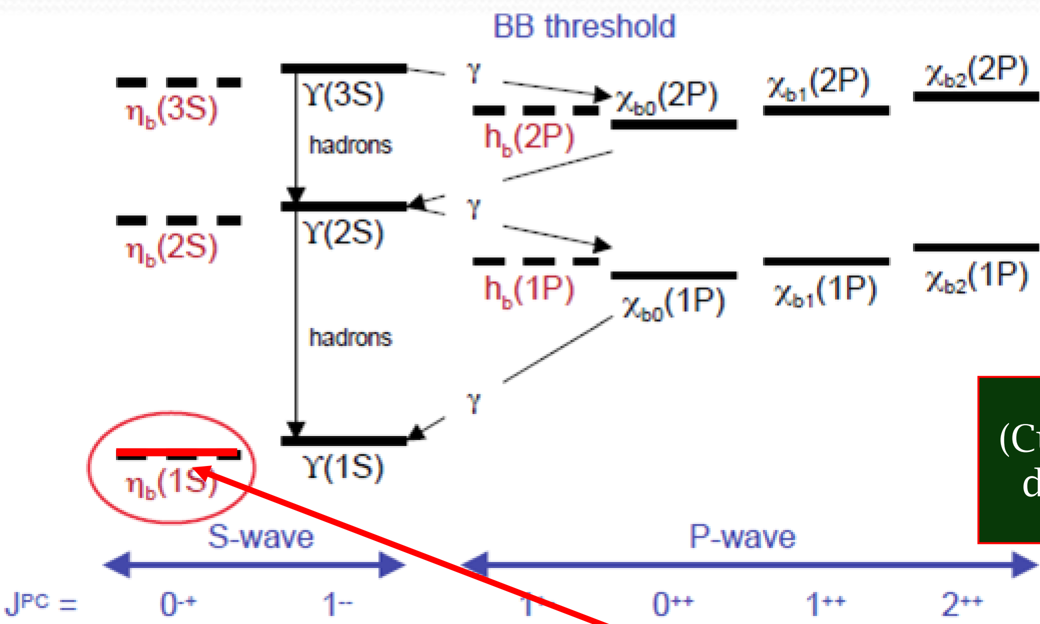
M(Υ')=10.00±0.04

M(Υ'')=10.43±0.12

FNAL, E288

30 years later….

(spins- still unconfirmed)



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

Below BB̄, several states not yet observed: 3 S-wave (η_b), 2 P-wave (h_b), D-wave,etc…

(Currently no complete theoretical description of onium properties.)

(BABAR (2008)

(Still puzzles)

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

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

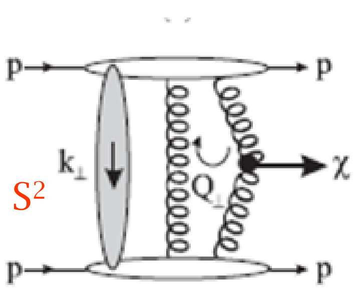
Potential (theoretical) problems

- Higher sensitivity to low scales- **'usual suspects'**
- Stronger dependence on Enhanced Screening effects

  (larger s / M_{χ}^{2} **)**

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

0++ -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. (R. Pasechnik)
  - For forward going protons in the non-relativistic quarkonium approximation, CEP of the spin-2 meson is strongly suppressed ($J_z = 0$ selection rule) KMR-01

    (A. Alekseev-1958-positronium)

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

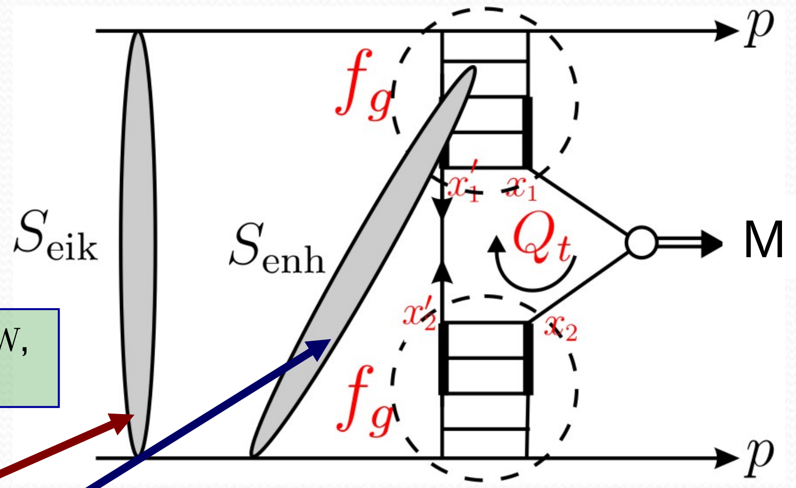
KMR-02, KKMR-03

- 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) (KMR-08)

"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 factoriz^n

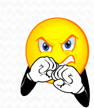
eikonal rescatt: between protons ← conserved

enhanced rescatt: involving intermediate partons ← broken

(BBKM-06)

(Alan,Asher)

Subject of hot discussions : S^2enh



Interpretation of CDF results

(CDF Collaboration, arXiv:0902.1271, PRL-09)

(Mike, Jim)

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

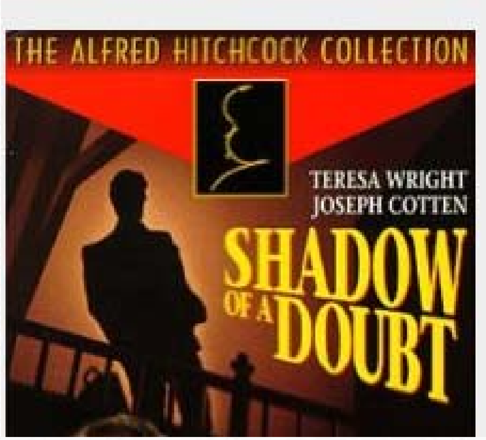
CDF $\left.\frac{d\sigma(\chi_c)}{dy}\right|_{y=0} = (76 \pm 14)$ nb

KMRS -2004: 130 nb → 80 nb (PDG-2008)

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

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 (KMRS-04)

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

$$Br(\chi_c(0^+) \to J/\Psi + \gamma) = (1.14 \pm 0.11)\%$$
$$Br(\chi_c(1^+) \to J/\Psi + \gamma) = (34.1 \pm 1.5)\%$$
$$Br(\chi_c(2^+) \to J/\Psi + \gamma) = (19.4 \pm 0.8)\%$$

- 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 **SUPERCHIC** 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.

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

$$< S^2_{eik}(0^+) > \approx 0.065 \qquad < S^2_{eff}(0^+) > \approx 0.02 \qquad (\Delta=2.3)$$

$$d\sigma(0^+)/dy|_{y=0} \simeq 80 \text{ nb} \qquad d\sigma(0^+)/dy|_{y=0} \simeq 30 \text{ nb}$$

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

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

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.

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

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

- $\sigma(0^+ \to J/\psi + \gamma) : \sigma(1^+ \to J/\psi + \gamma) : \sigma(2^+ \to J/\psi + \gamma) = 1 : 1.3 : 0.8$

  Then $d\sigma(0^+, 1^+, 2^+)/dy \simeq 95$ 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.

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

- 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 $(p_{3,4})_t$ (KKMR03)

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

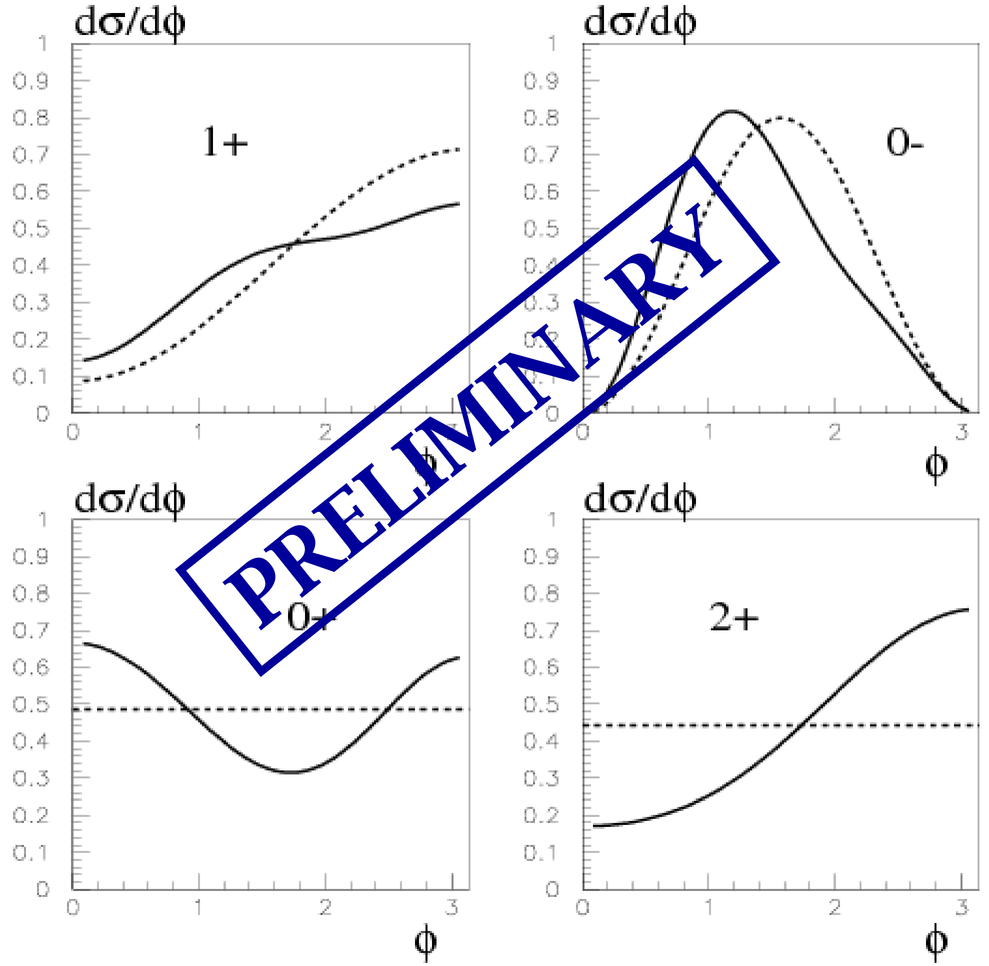
$$d\sigma(0^-)/d\phi \simeq \sin^2\phi;$$

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

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

- 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+
ϕ
dσ/dϕ
0-
ϕ
dσ/dϕ
0+
ϕ
dσ/dϕ
2+
ϕ
PRELIMINARY

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

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)

S^2

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

‘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)

- 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.

with a bit of personal flavour

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

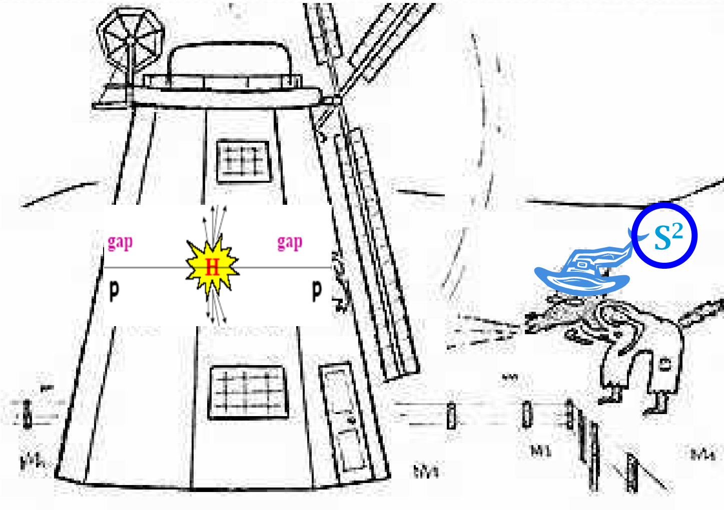
So far (only) Durham model has passed these tests.

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).

  Overlap background ☛ psec (not lifetime of theor. pred^{ns}, but **FTD** resol^{n})

- Main reduction of the signal (factor of ~50) comes from the experimental requirements (cuts and efficiencies...) which are currently known mainly 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).

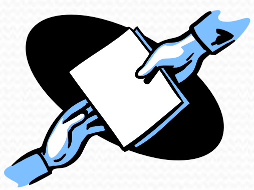
- Durham selection of the UPDF is quite conservative.
  Due to the $(f_g)^4$ behaviour- rise up to a factor of 3 (Cox et al, KMR).
  New studies underway.

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

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

CONCLUSION

- CDF data on CEP of the χ_c are in a broad agreement with the Durham predictions.
- 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 (exotic) 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

PDG particle data group 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

What we know from Regge theory (KKMR-2003)

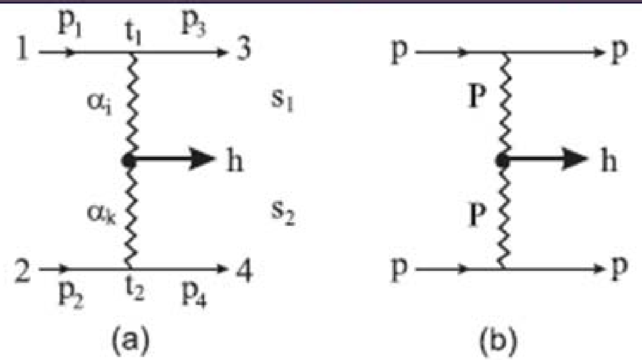


Figure 1: (a) The central production of a state h by double-Reggeon exchange. (b) The double-Pomeron exchange contribution to $pp \to p + h + p$, which dominates at high energies, where the + signs are used to indicate the presence of Pomeron-induced rapidity gaps.

$J^P(h) = 0^+$ 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
- 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)

for completeness

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

1.5 nb at the LHC

note: some decay modes are quite sizeable ($\rho\rho$, $KK\pi$, $\eta\pi\pi$.. 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+}

$X(3940) \rightarrow \chi_{c1}(2P)$ or $\eta_c(3S)$ or ?

$Z(3930) \rightarrow \chi_{c2}(2P)$

$X(3872)$, $Y(3940)$ $Y(4260)$ $\rightarrow J/\psi$