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

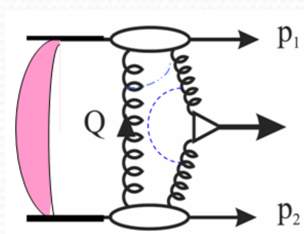
Durham University

V.A. Khoze (IPPP, Durham & AFO, HIP)

IP3

(Based on collaboration with L. Harland-Lang, 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

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.

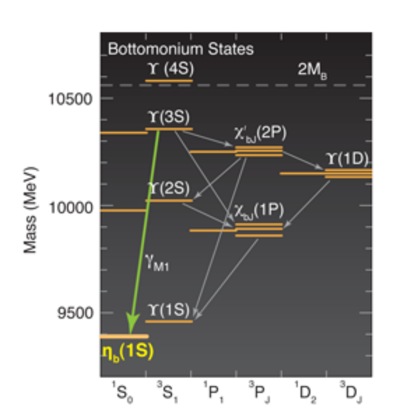
5. *A few remarks about the models for soft diffraction.*

6. *Interpretation of the CDF results on charmonium CEP.*

7. *New Run of Durham studies (ArXiv: 0909.4748)*

8. *Prospective measurements.*

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')

a 'standard candle '

- 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 .

Heavy Quarkonia

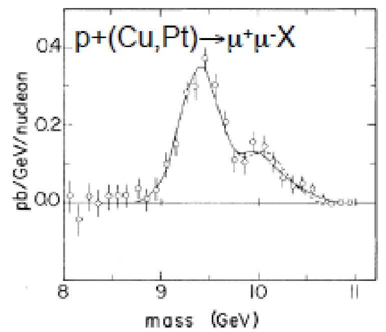
Traditional testing ground for various aspects of QCD

- 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....

long-standing issues

Bottomonium history started 30 years ago

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



M(Υ)=9.40±0.013

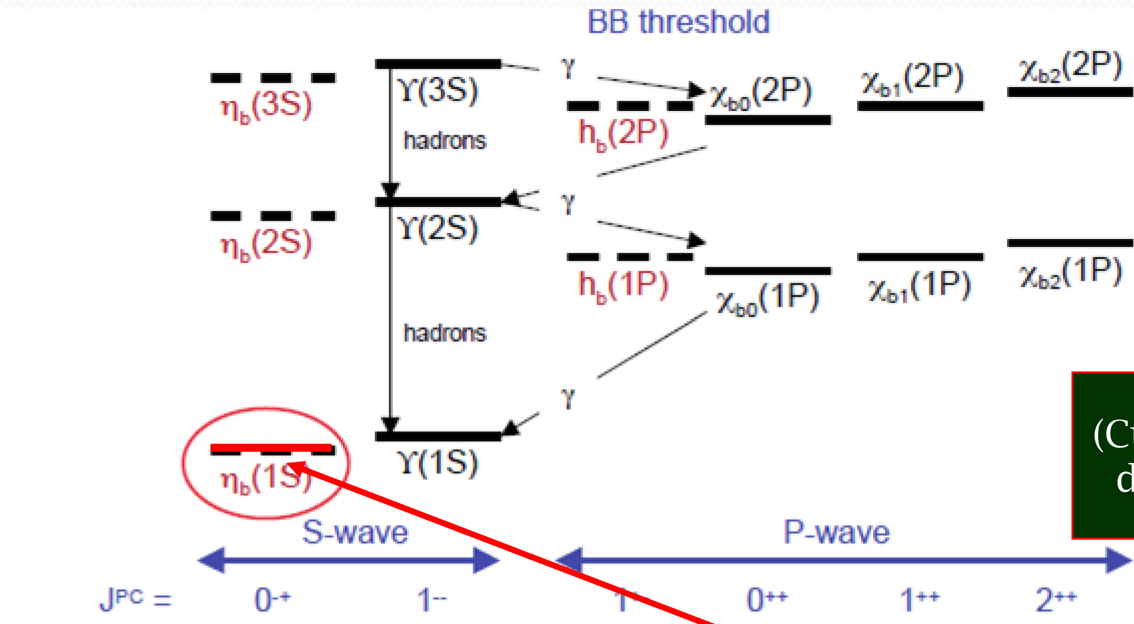
M(Υ')=10.00±0.04

M(Υ'')=10.43±0.12

FNAL, E288

30 years later….

(spins- still unconfirmed)



Υ(nS) confirmed and χ_{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 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

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

work in progress

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)

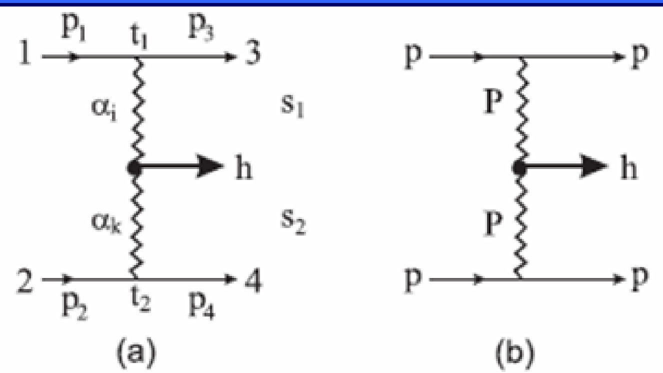


Figure 1: (a) The central production of a state h by double-Reggeon exchange. (b) The double-Pomeron exchange contribution to $pp \to p + h + p$, which dominates at high energies, where the + signs are used to indicate the presence of Pomeron-induced rapidity gaps.

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

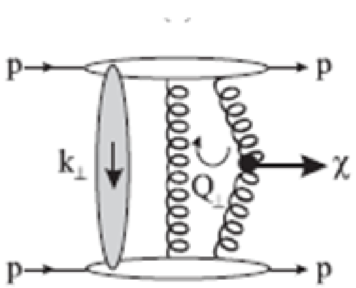
$J^P(h) = 1^+$ For small p_{it}

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

- Cross section tends to zero at low K_t
- 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



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

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

- **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.)

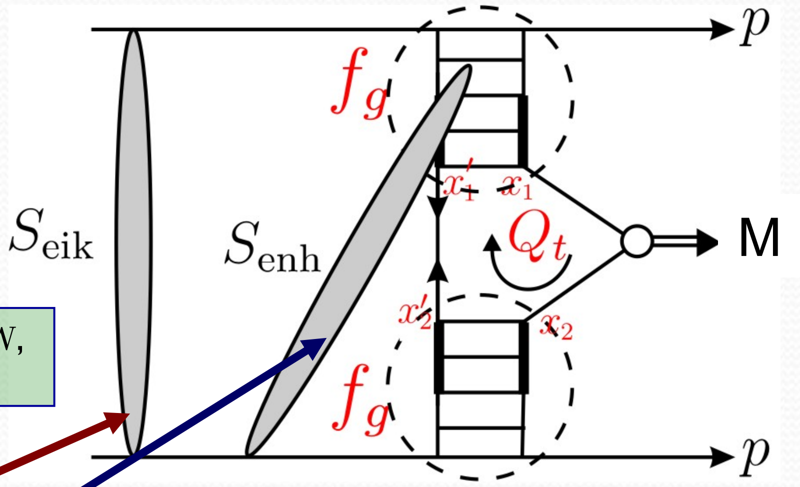
KMR-02, KKMR-03

- 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 factoriz^n

eikonal rescatt: between protons ← conserved

enhanced rescatt: involving intermediate partons ← broken

Subject of hot discussions : S^2enh

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

- 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))

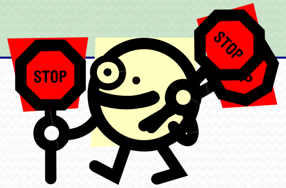
- describe all the existing experimental data on elastic scattering and SD ,DD and CED
  at the Tevatron energies and below (KMR; GLM(M))

- 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.
Tevatron data & program of Early LHC measurements (KMR)



LET THE DATA TALK !

"The first thing we do, let's kill all the lawyers"

The line is from ***The Second Part of Henry VI****, act IV, scene ii, line 86; spoken by Dick the butcher*

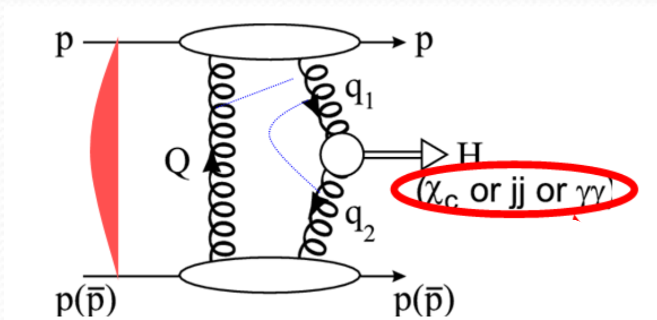
Shakespeare's Henry VI

Dick the Butcher, Henry VI, Act 4, Scene 2

Standard Candle Processes

'BETTER TO LIGHT A CANDLE THAN TO RANT AGAINST DARKNESS'

(Confucius)



The process p-p → $\gamma\gamma$/χ_c/ χ_b/ j-j are standard candles for the exclusive Higgs

孔夫子

孔丘 Kong Qiu

CDF, Helsinki Group

$$p+\bar{p} \rightarrow p+\gamma\gamma+\bar{p}$$

$$p+\bar{p} \rightarrow p+\chi_c+\bar{p}$$

$$p+\bar{p} \rightarrow p+\chi_b+\bar{p}$$

$$p+\bar{p} \rightarrow p+JJ+\bar{p}$$

Cleanest (no S.I.) but smallest σ

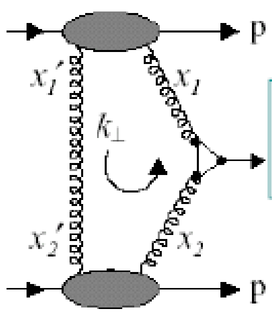
KMR: 36 pb in our box : . 2+1 candidates

Clean, big σ: $\frac{d\sigma}{dy}(y=0) \sim 90\,\text{nb (KMRS)}$

but M(c) small (non-pert) & hadron

More perturbative, smaller theory uncertainty
But σ ~ 1/500th χc. Also BR's not known!
May not be possible at Tevatron. ?

Accessible cross section, but least well defined (jets!) and largest background. ~ 100 pb for M(JJ) > 30 GeV



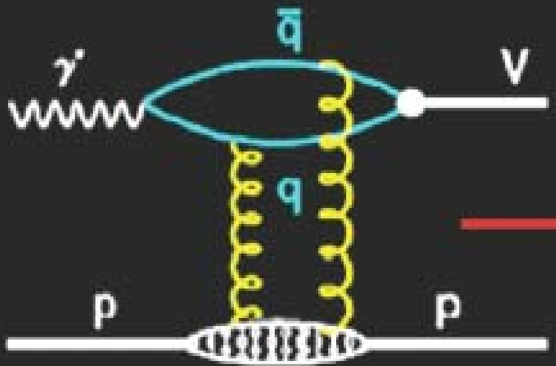
$\sigma(600), f_0(980)$
$\gamma\gamma, \chi_c, \chi_b$, JJ, H

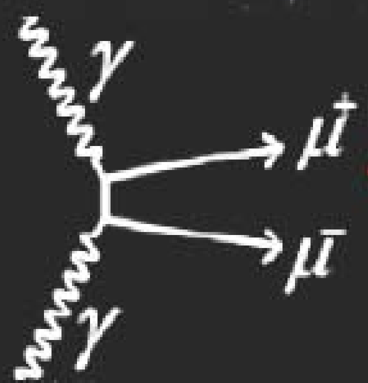
ISR did it

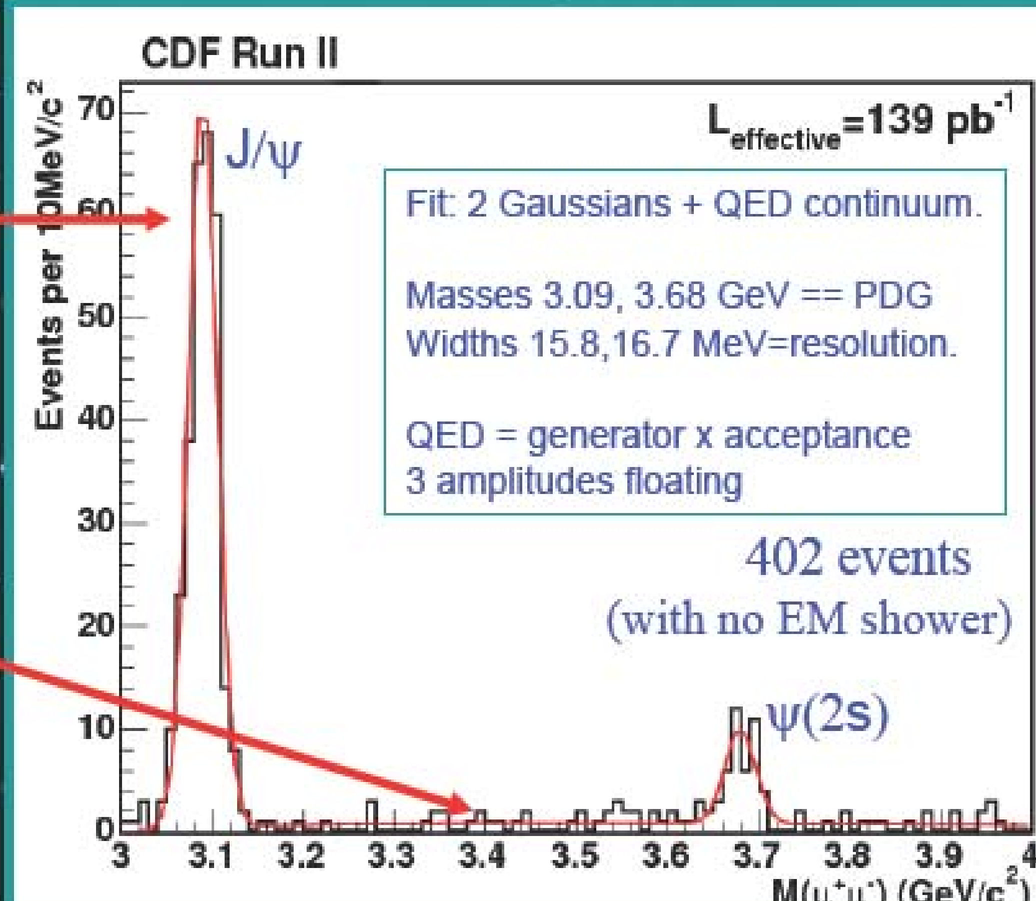
Our 3 measurements are all in good agreement (factor "few") with the Durham group predictions.

Exclusive $\mu^+\mu^-$ Production (4)

$$p + \bar{p} \rightarrow p + \mu^+\mu^- + \bar{p}$$







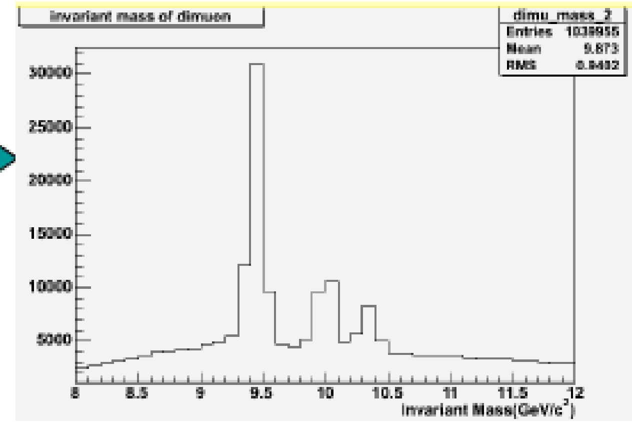
Dimuons: Upsilon Region

Trigger: μ+μ-
|η|<0.6 , pT(μ) > 4 GeV/c

Search for/measurement of photoproduction of Υ(1S),Υ(2S),Υ(3S) (not before seen in hadron-hadron)

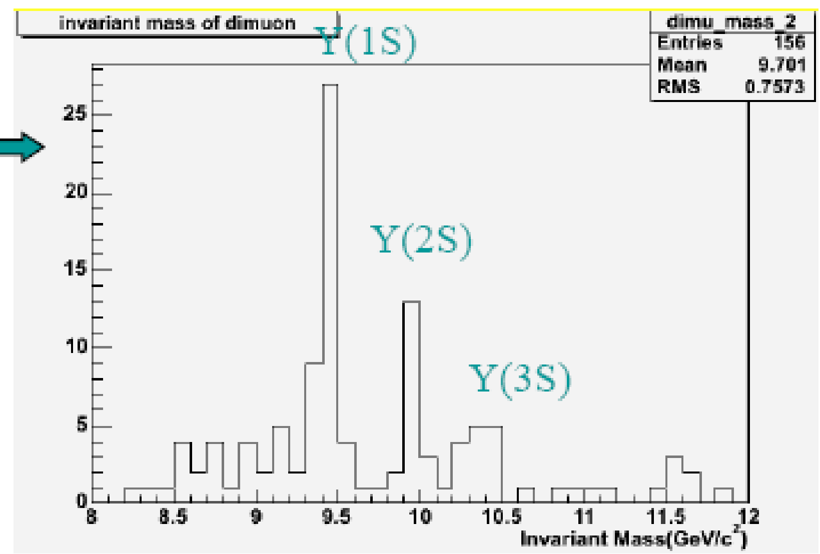
Inclusive →

CDF Run II Preliminary



Invariant Mass
0 associated tracks
pT(μμ) < 1.5 GeV/c →

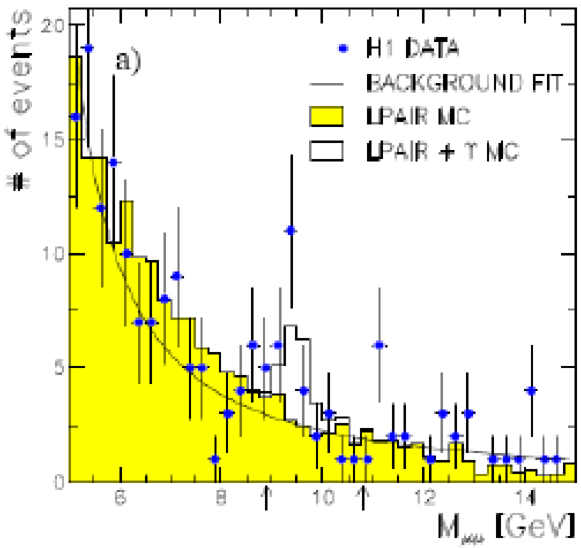
CDF Run II Preliminary



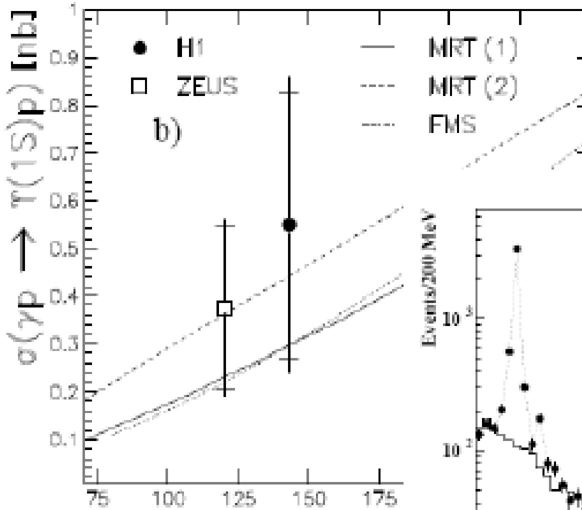
Status:
analysis in progress.
QED continuum check
Υ : cf HERA (we resolve states)
Can we see $\chi_b \rightarrow \Upsilon + \gamma$?

HERA: e + p

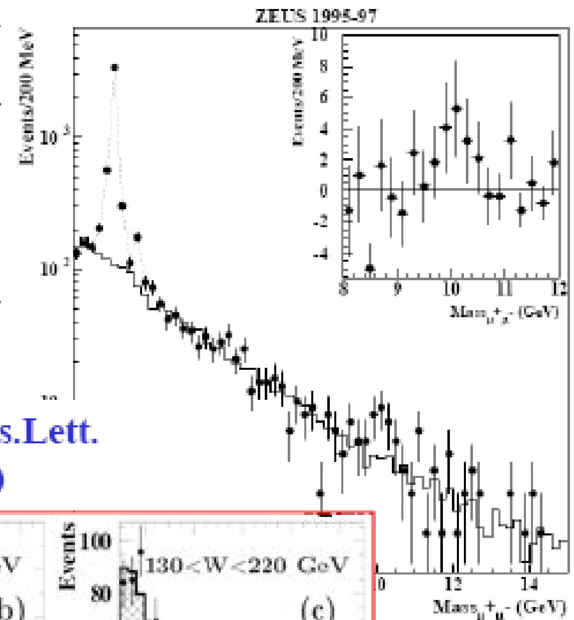
H1



Phys.Lett.B483:23-35 (2000)



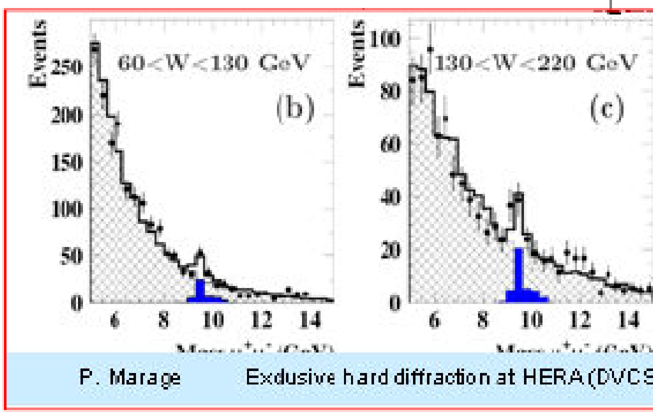
ZEUS



J.Breitweg et al.,Phys.Lett. B437: 432-444 (1998)

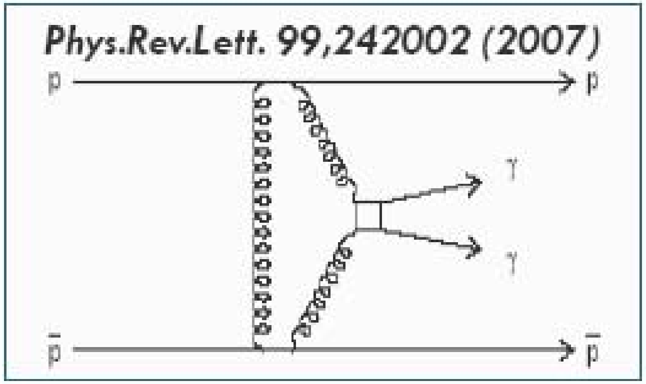
Y(1),Y(2),Y(3) signals in CDF cleaner than at HERA!
Better mass resolution, less γγ→μμ background.
BUT χ_b → Y+γ background absent at HERA!

Just saw in Marage talk



ZEUS

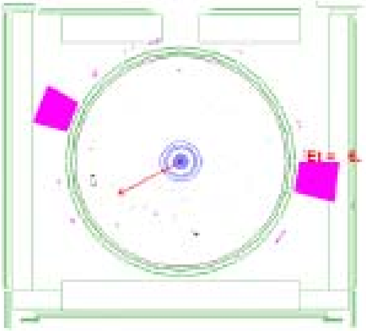
Exclusive γγ Production



3 candidates observed:

2 events are good γγ candidates

1 event is good $\pi^0\pi^0$ candidate



$E_T(\gamma) > 5$ GeV

$|\eta(\gamma)| < 1.0$

Theoretical Prediction:

V.A.Khoze et al. Eur. Phys. J C38, 475 (2005)

σ (with our cuts) = (36 +72 – 24) fb

= 0.8 +1.6 –0.5 events.

Cannot yet claim "discovery" as b/g study *a posteriori*,

2 events correspond to σ ~ 90 fb, agreeing with Khoze *et al.*

New data. Lower threshold, possible "observation"

(M.Albrow, EDS-09)

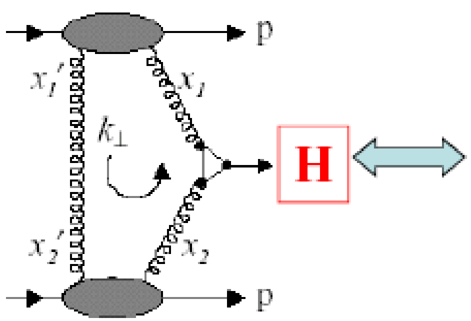
Erik, Risto

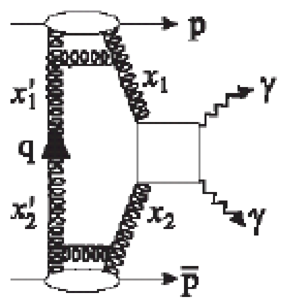
PRL 99, 242002 (2007) PHYSICAL REVIEW LETTERS week ending 14 DECEMBER 2007

Search for Exclusive $\gamma\gamma$ Production in Hadron-Hadron Collisions

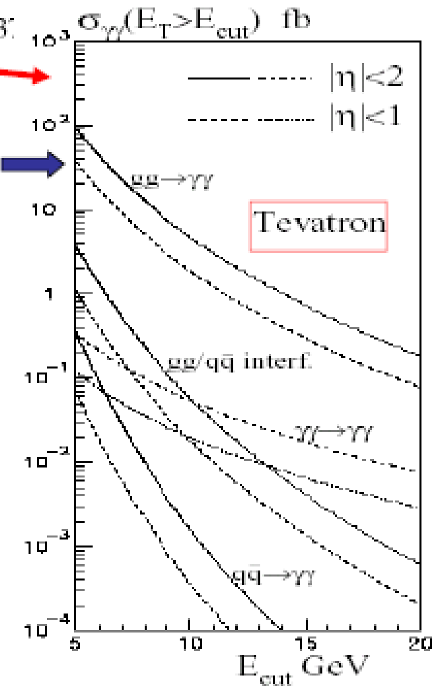
Khoze, Martin and Ryskin, Eur.Phys.J. C23: 311 (2002) ; KMR+Stirling hep-ph/040903?

Claim factor ~ 3 uncertainty ; Correlated to p+H+p

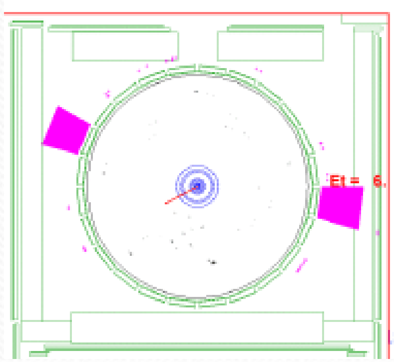




36 fb



$\gamma\gamma \to \gamma\gamma$ & $q\bar{q} \to \gamma\gamma$ much smaller



$E_T(\gamma) > 5\,\mathrm{GeV}; |\eta(\gamma)| < 1.0$

3 candidates, 2 golden, 1 ? $\pi^0\pi^0$?

36 fb → 0.8 events

$$\text{Note}: \sigma_{MEAS} \approx 2\times10^{-12}\,\sigma_{INEL}\,!$$

New data, Lower threshold, possible "observation"

sive production in CDF: M > 8 GeV Low-x Ischia 2009

Erik,Risto, Mike

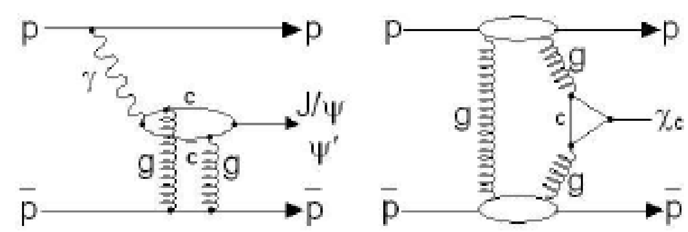
Next steps:

Finish acceptance x efficiency → QED cross section (Good?)
+ other triggers + ~ 2 x more data
Y cross section or upper limit (large non-exclusive B/G)
Select no-pile-up events, allowing EM showers.
Any $\chi c \rightarrow Y + \gamma$ candidates? Cross section x BR or limit

Parallel analysis on e+e- (Erik Brucken, Risto Orava, MA) No-PU
Any Y signal? Compare results
Especially look for more exclusive $\gamma\ \gamma$ events

Observation of Exclusive Charmonium Production and $\gamma\gamma \to \mu^+\mu^-$ in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

CDF Collaboration, arXiv:0902.1271 [hep-ex]



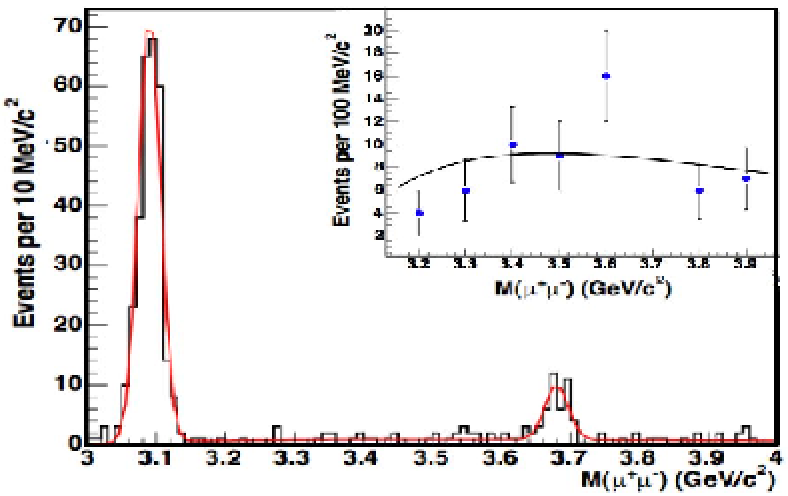


FIG. 2: Mass $M_{\mu\mu}$ distribution of 402 exclusive events, with no EM shower, (histogram) together with a fit to two Gaussians for the J/ψ and $\psi(2S)$, and a QED continuum. All three shapes are predetermined, with only the normalizations floating. Inset: Data above the J/ψ and excluding $3.65 < M_{\mu\mu} < 3.75$ GeV/c^2 ($\psi(2S)$) with the fit to the QED spectrum times acceptance (statistical uncertainties only).

TABLE I: Numbers of events fitted to classes $J/\psi, \psi(2S)$, QED and χ_{c0}. Backgrounds are given as percentages of the fit events, and efficiencies are to be applied to the events without background. The stated branching fraction $\mathcal{B}$ for the χ_{c0} is the product of the $\chi_{c0} \to J/\psi + \gamma$ and $J/\psi \to \mu^+\mu^-$ branching fractions [11]. The cross sections include a 6% luminosity uncertainty.

Class	J/ψ	$\psi(2S)$	$\gamma\gamma \to \mu^+\mu^-$	$\chi_{c0}(1P)$
Acceptances:				
Detector(%)	18.8±2.0	54±3	41.8±1.5	19±2
Efficiencies:				
μ-quality(%)	33.4±1.7	45±6	41.8±2.3	33±2
Photon(%)	-	-	-	83±4
Events(fit)	286±17	39±7	77±10	65±8
Backgrounds:				
Dissoc.(%)	9±2	9±2	8±2	11±2
Non-excl.(%)	3±3	3±3	9±5	3±3
χ_{c0}(%)	4.0±1.6	-	-	-
Events(corr.)	243±21	34±7	65±10	56±8
$\mathcal{B}.\sigma_{FKR}$(pb)	28.4±4.5	1.02±0.26	2.7±0.5	8.0±1.3
$\mathcal{B} \to \mu^+\mu^-$(%)	5.93±0.06	0.75±0.08	-	0.076 ±0.007
$\frac{d\sigma}{dy}\|_{y=0}$(nb)	3.92±0.62	0.53±0.14	-	76±14

KMRS -2004: **130 nb** → 80 nb (PDG-2008)

ππ/KK mode as a spin-parity analyzer

Prospects of χ(b)-spectroscopy , FSC@CMS

Interpretation of CDF results

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

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

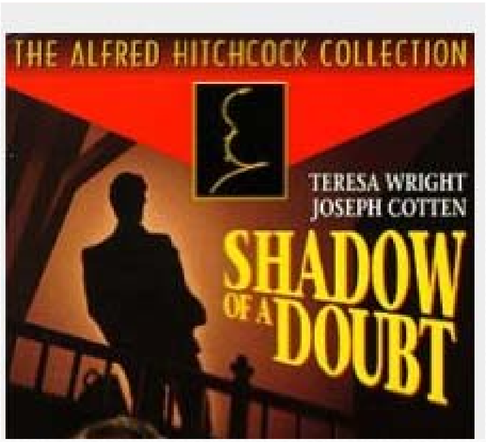
CDF $\left.\frac{d\sigma(\chi_c)}{dy}\right|_{y=0} = (76 \pm 14)$ nb

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

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

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

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

- 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.

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

SUPERCHIC MC

- 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.

- 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: $\pi\pi, KK, p\bar{p}$ or outgoing proton momentum correlations KMRS-04

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

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 ± 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 $(p_{3,4})_t$

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

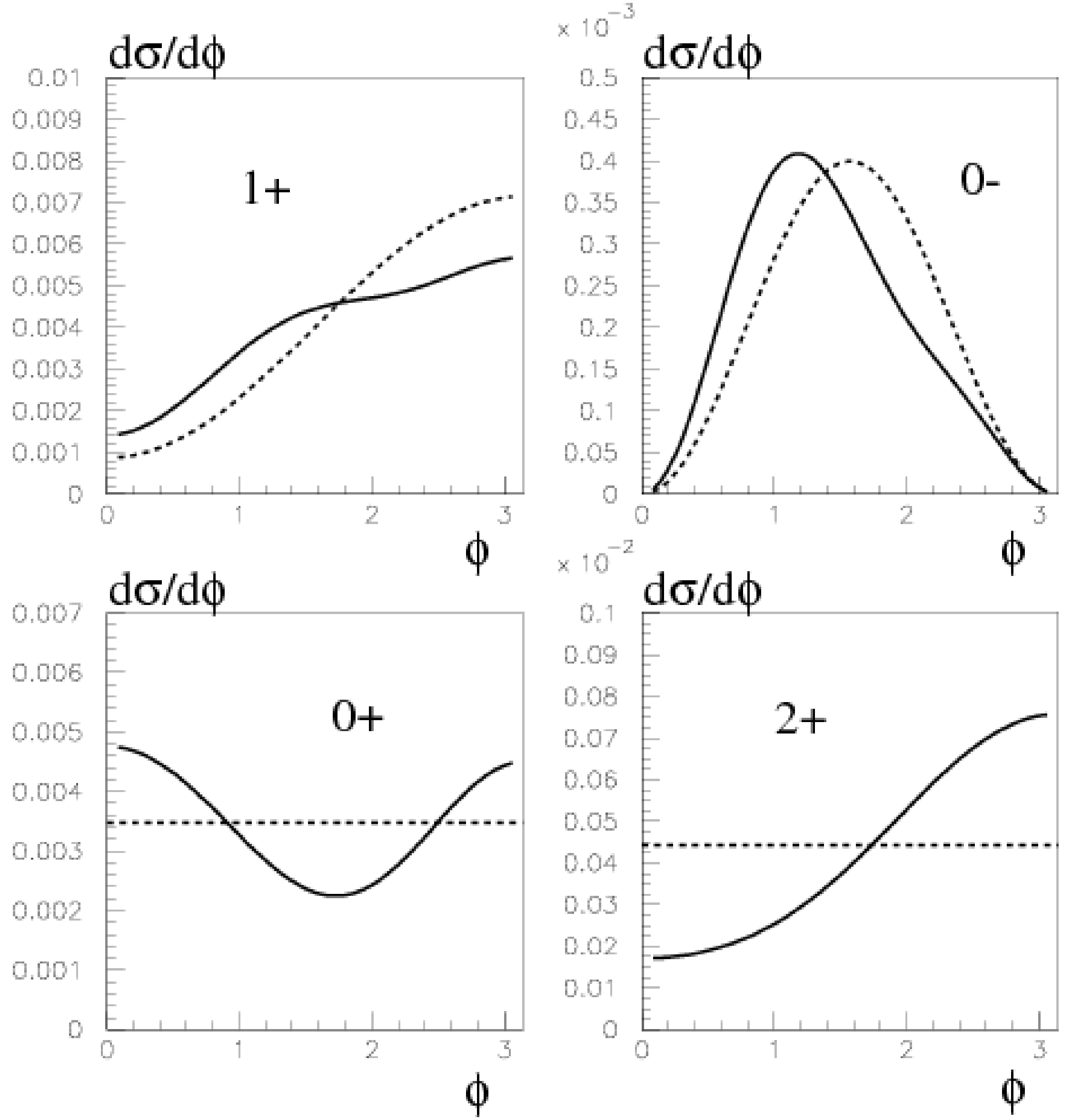
$$d\sigma(0^-)/d\phi \simeq \sin^2\phi;$$

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

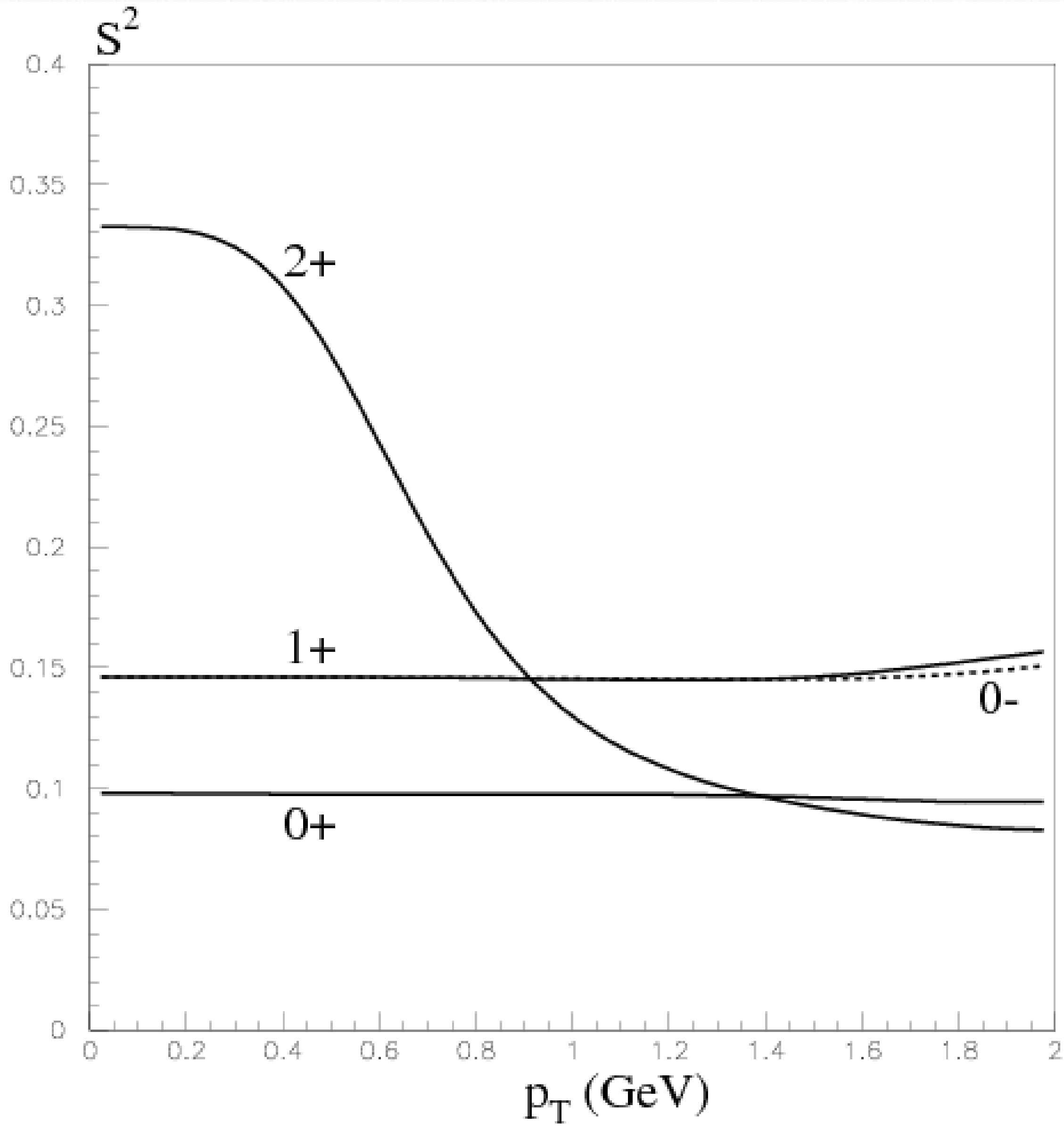
$$d\sigma(2^+)/d\phi \simeq const;$$

- 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 $\vec{b}$)

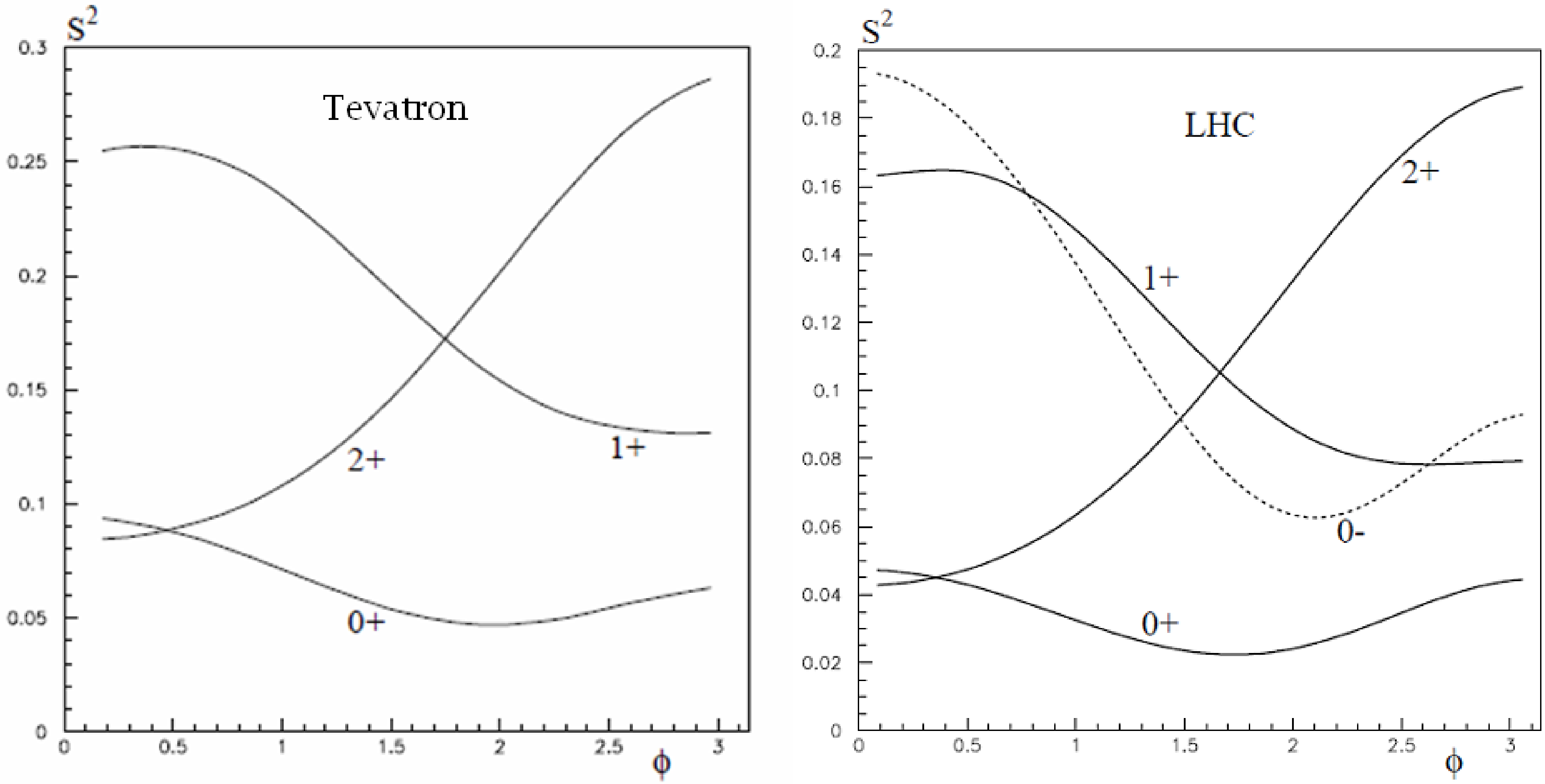


dσ/dϕ
1+
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
0
1
2
3
ϕ
× 10^-3
dσ/dϕ
0-
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
1
2
3
ϕ
dσ/dϕ
0+
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
0
1
2
3
ϕ
× 10^-2
dσ/dϕ
2+
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
1
2
3
ϕ



S²
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
2+
1+
0-
0+
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
p_T (GeV)

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

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

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+}

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

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)

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

$$Br(\eta_b \to \gamma\gamma) = 3.4 * 10^{-5}$$ (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:

$$Br(\chi_{c0} \to \pi\pi, K^+K^-) \simeq 1.3\%$$

$$\chi_{c1}, \eta_c \not\to \pi\pi, KK$$

$$Br(\chi_{c2} \to \pi\pi, K^+K^-) \simeq 0.3\%$$

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

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

Risto, Jerry

- 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..)
- ' '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
- Gluons at so low scales, surprises are not excluded at all.

Factor of 5 up or down (at best)

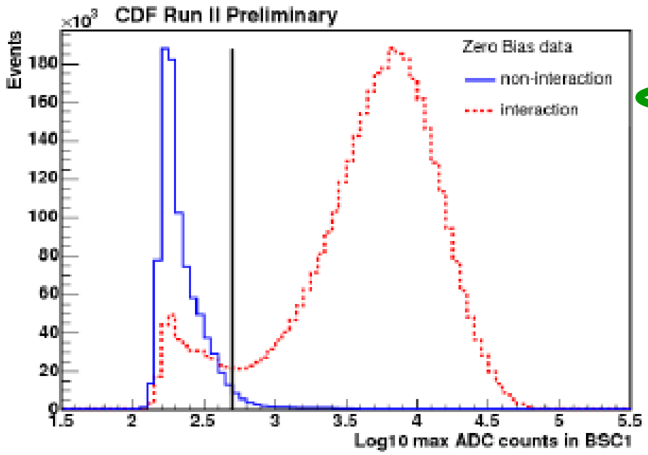
BSC very important as rap gap detectors.
All LHC experiments should have them!

FORWARD PHYSICS WITH RAPIDITY GAPS AT THE LHC

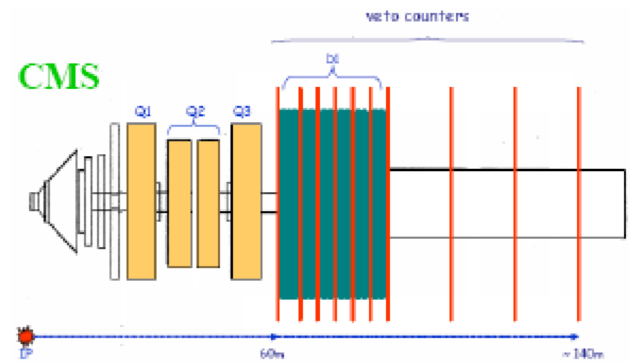
arXiv:0811.0120

Michael Albrow[1], Albert De Roeck[2], Valery Khoze[3], Jerry Lämsä[4,5], E. Norbeck[6], Y. Onel[6], Risto Orava[5], and M.G. Ryskin[7]
Sunday, November 09, 2008

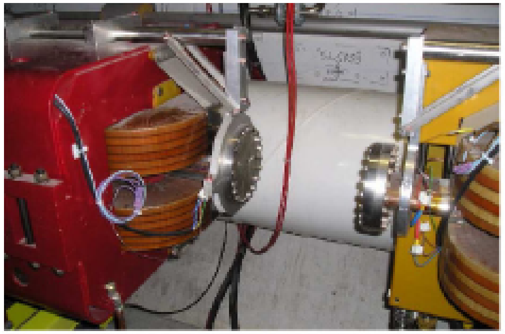
JINST in press



Warm accessible vacuum pipe (circular – elliptical)
~~Do not see primary particles, but showers in pipe ++~~
Simple scintillator paddles: **Gap detectors in no P-U events**



Take 0-bias events (Essential!)
{1} = prob no interaction
{2} = prob >= 1 interaction
Take hottest PMT of 8 BSC1
Plot log max ADC for {1} and {2}
Separates empty / not empty
Repeat for all detectors



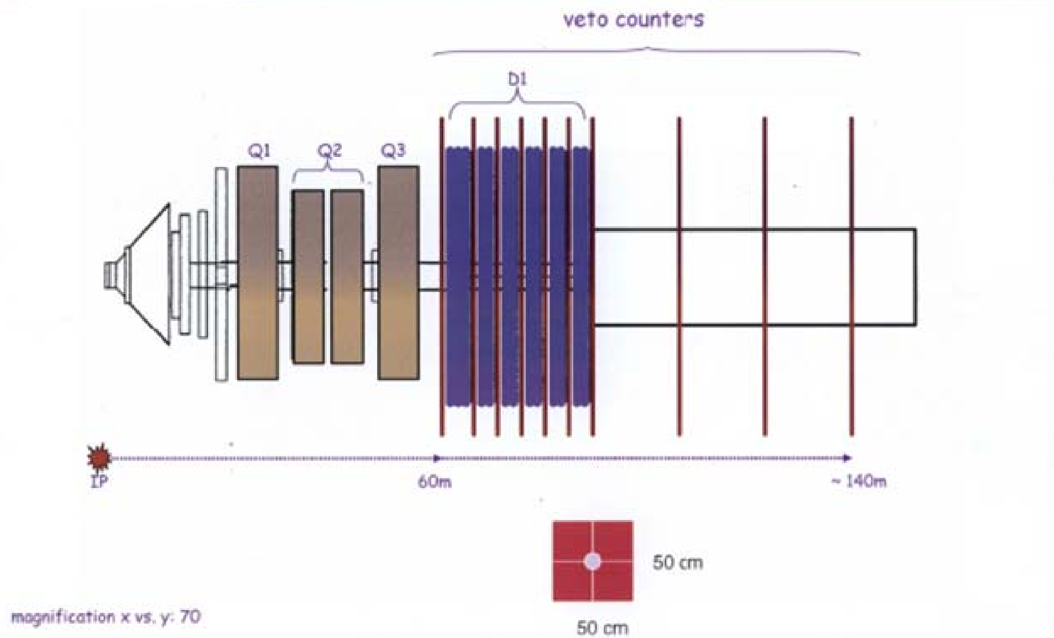


Figure 1. The proposed layout of the FSC counters on both sides of the CMS intersection region from $z = \pm 60$m to $z = \pm 140$m. The vertical lines indicate the locations of the proposed counters.

The FSC do not detect particles directly from the collisions, but they detect showers from forward particles that interact in the beam pipe and surrounding material. These detectors can be used to make measurements of rapidity gaps for events without pile-up, in the early days of LHC running.

Scintillation counters can be added closely surrounding the beam pipes, with 60 m $< |z| <$ 85 m (z is the coordinate along the beam direction), and at further locations out to $z = \pm 140$ m on both sides of the interaction point (IP5), see Figure 1. At these locations the beam pipes are accessible, and not in a cryogenic region.

CENTRAL DIFFRACTION AT THE LHCb

LHCb IS IDEAL FOR DETECTING AND ANALYSING LOW MASS CENTRAL DIFFRACTIVE PRODUCTION OF EXCLUSIVE $\pi^+\pi^-/K^+K^-$ STATES IN:

$$pp \rightarrow p + M + p$$

glueballs, hybrids, heavy quarkonia: χ_c, χ_b

$\pi^+\pi^-/K^+K^-$ STATES AS SPIN-PARITY ANALYZERs.

HOW TO FACILITATE THIS?

Jerry W. Lämsä and Risto Orava

THE PROPOSED LHCb FSC LAY-OUT

ADD FSCs AT **20 – 100 METERS** ON BOTH SIDES OF IP8 – THE FSCs DETECT SHOWERS FROM THE VERY FORWARD PARTICLES.

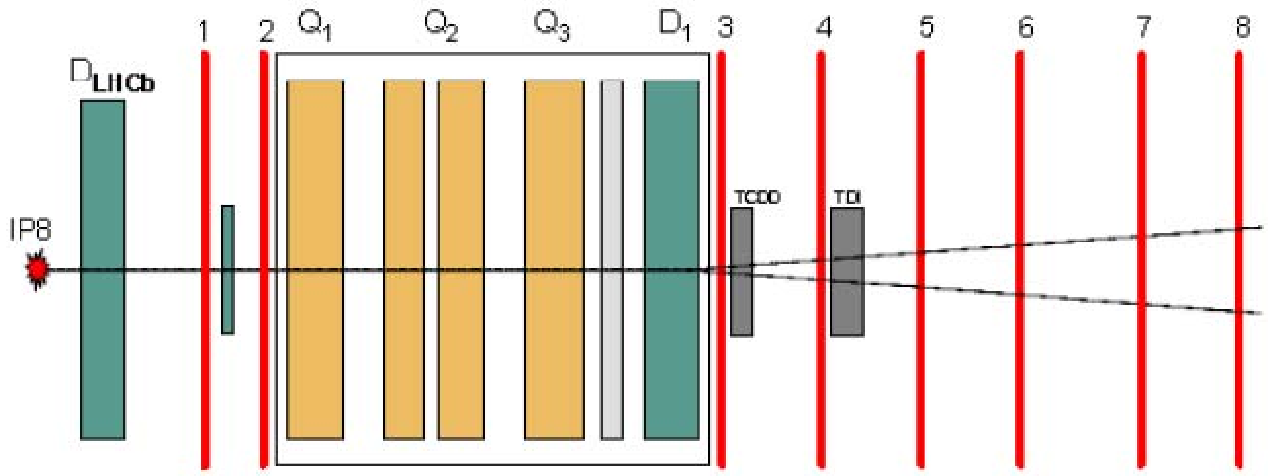


Figure 1. *The layout of LHCb detectors at the LHC Interaction Point (IP8). The proposed Forward Shower Counters (FSCs) are shown as vertical lines (1 to 8). The locations of the dipole (D) and quadrupole (Q) magnet elements are shown as green (dark) and yellow (light) boxes.*

TRIGGER FOR LOW CHARGED MULTIPLICITIES IN THE SPD, RESTRICT NO. OF CHARGED TRACKS IN VELO AND ABSENCE OF A SIGNAL IN FSCs

- TO DETECT A LOW MULTIPLICITY DECAY, A SMALL NUMBER OF CHARGED TRACKS ARE REQUIRED TO STRIKE THE SCINTILLATOR PAD DETECTOR (SPD).

- THE LHCb VErtex LOcator (VELO) IS REQUIRED TO HAVE NO CHARGED TRACKS (CENTRAL ANGLE VETO) WITHIN 10 – 170 deg.

- SIMULATION USES A COMBINATION OF PHOJET+PYTHIA & GEANT.

- ANGULAR ACCEPTANCE OF THE SPECTROMETER: < 250 mrad (vertical), < 300 mrad (horizontal)

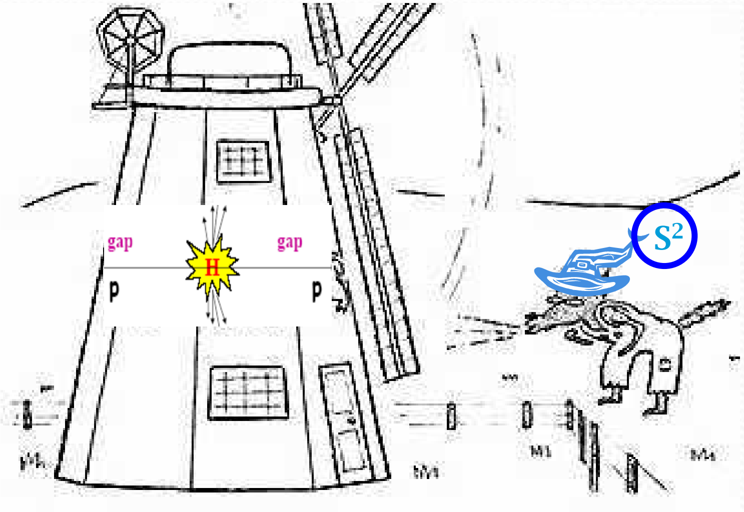
- NOTE: IN LOW LUMINOSITY LHCb RUNS, ONLY A SINGLE INTERACTION PER BX IS EXPECTED.

Jerry W. Lämsä and Risto Orava

Feasibility studies of the exclusive diffractive processes for the LHCb experiment have been carried out.

With a simple addition of Forward Shower Counters (FSCs), the experiment is shown to be ideally suited for detailed QCD studies and searches for exotic mesons states, such as glueballs, hybrids, and heavy quarkonia.

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 (including the NLO effects) are 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 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).

Helsinki-CERN-FNAL

Durham

Thank You

BACKUP

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

CURRENT EXPERIMENTAL CHECKS

Up to now the diffractive production data are consistent with K(KMR)S results

Still more work to be done to constrain the uncertainties.

- Exclusive high-Et dijets
  CDF: data up to $(Et)_{min} > 35$ GeV (PRD-2008)

- 'Factorization breaking' between the effective diffractive structure functions measured at the Tevatron and HERA. CDF

- The ratio of high Et dijets in production with one and two rapidity gaps. CDF

- CDF results on exclusive charmonium CEP, (CDF, PRL-09)

- Energy dependence of the RG survival (D0, CDF).

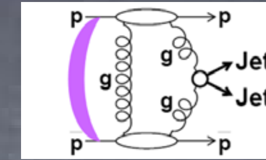
- Central Diffractive Production of γγ (….ππ,ηη) (CDF, PRL-07)
  (in line with the KMRS calculations) (3 candidates & ? more candidates in the new data)

Erick, Risto, MIke

- Leading neutrons at HERA

Only a large data set would allow to impose a restriction order on the theoretical models

Comparison with KMR

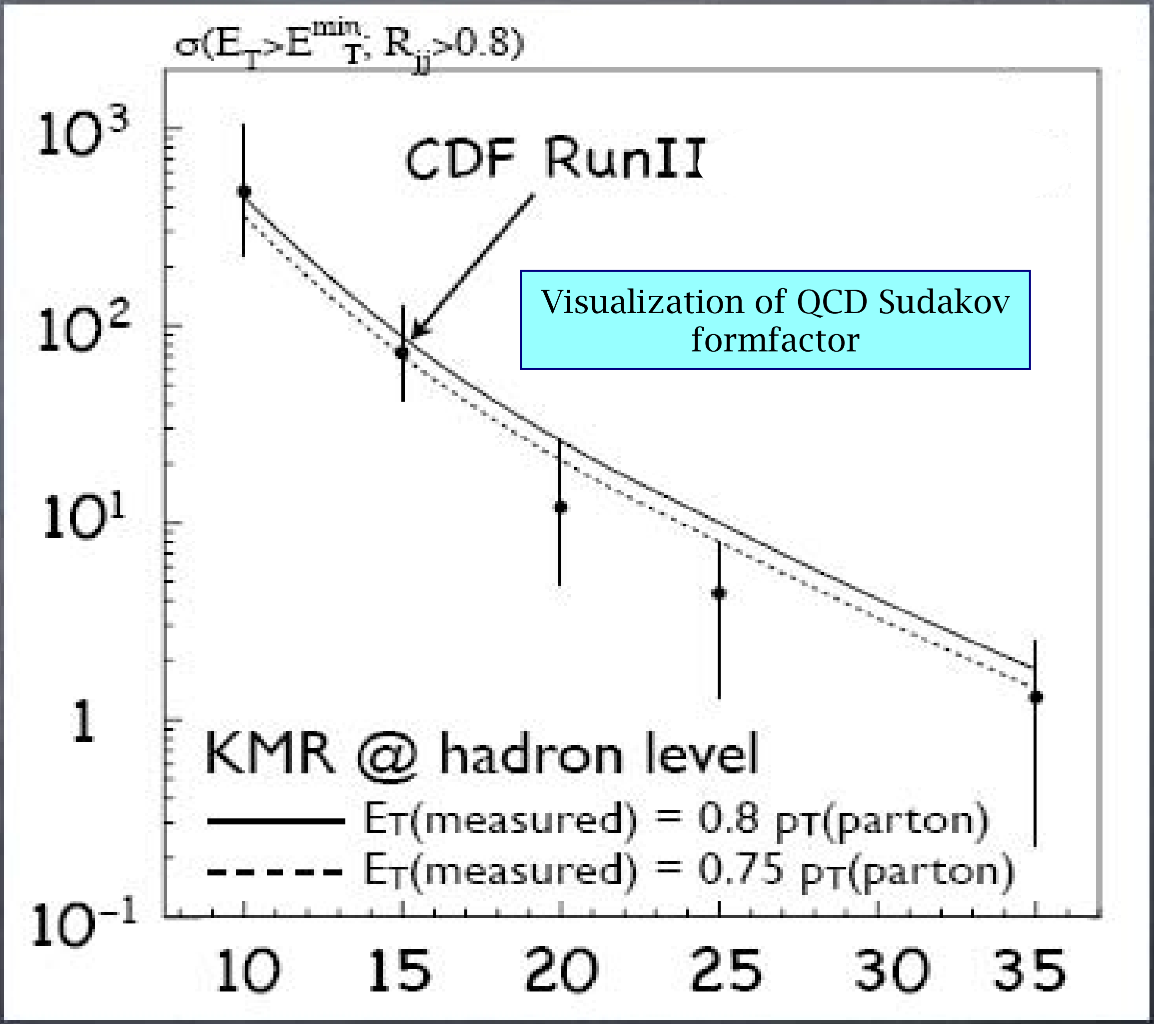


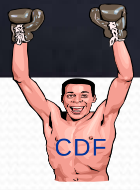
More direct comparison with KMR calculations including hadronization effects preferred

CDF out-of-cone energy measurement (cone R=0.7) :
- 20-25% at E_T^{jet}=10-20 GeV
- 10-15% at E_T^{jet}=25-35 GeV

Koji Terashi

Good agreement with data found by rescaling parton p_T to hadron jet E_T



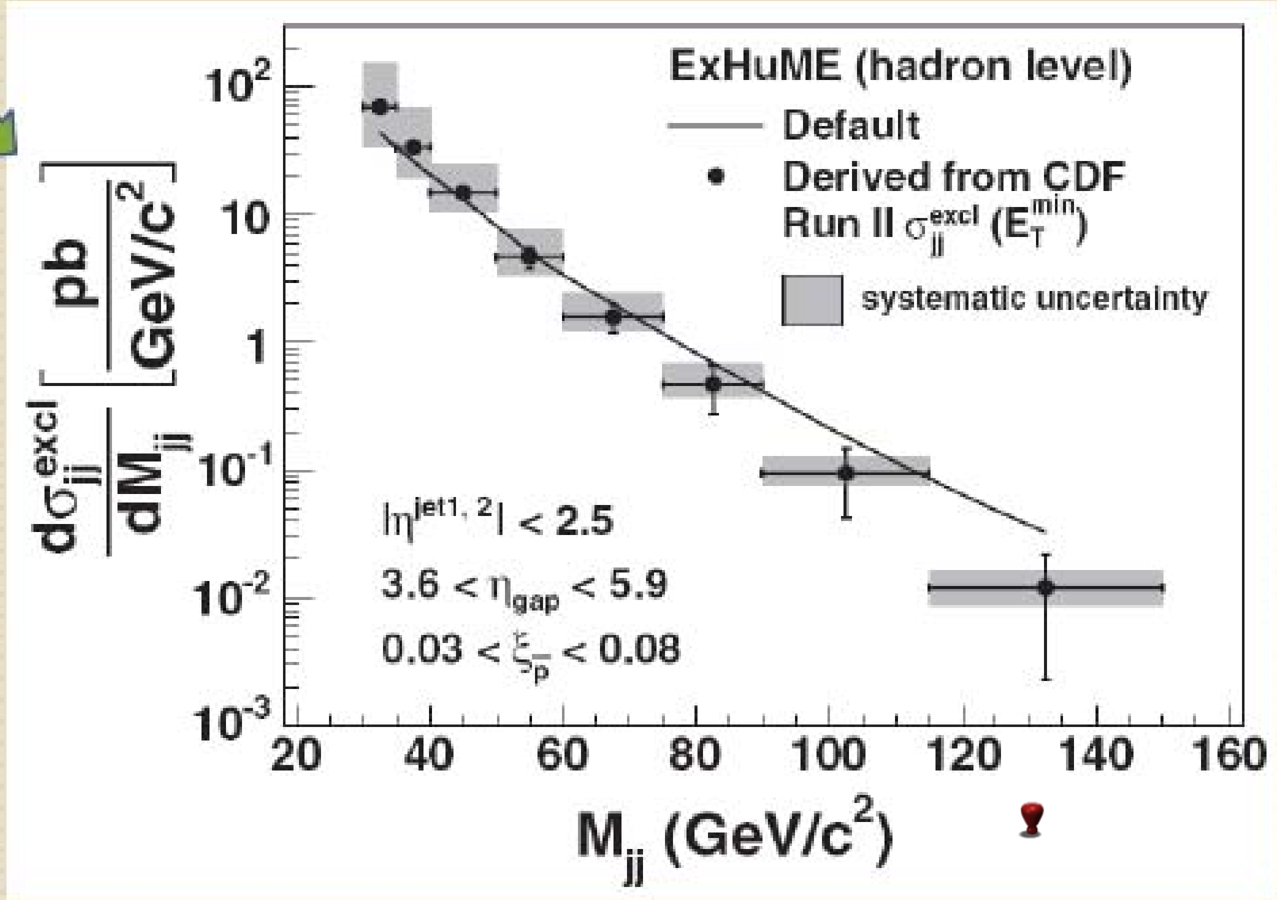


A killing blow to the wide range of theoretical models.

CDF
PRD-2008

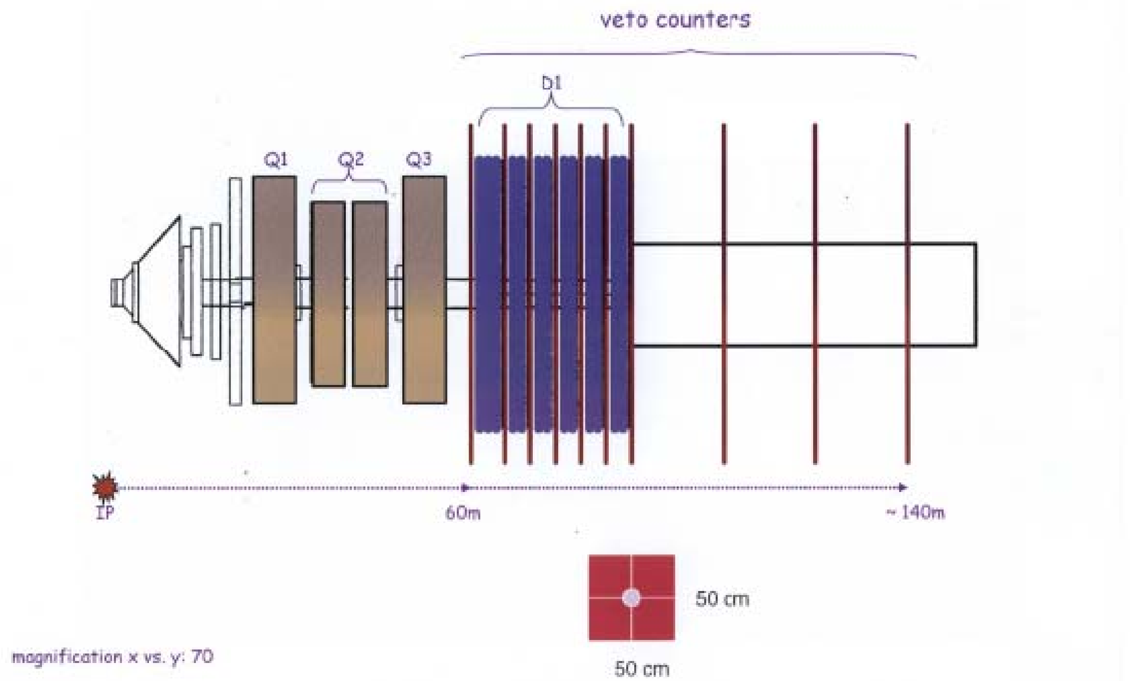
(Jim)

derived from CDF excl. dijet x-sections using ExHuME



29 Excl. Cross Section vs Dijet Mass

Stat. and syst. errors are propagated from measured cross section uncertainties using M_{jj} distribution shapes of ExHuME generated data.



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