DIFFRACTION 2010

International Workshop on Diffraction in High-Energy Physics

A.B. Kaidalov (1940-2010)

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Dedicated to the memory of Aliosha Kaidalov

Central Diffractive Processes at the Tevaron, RHIC and LHC.

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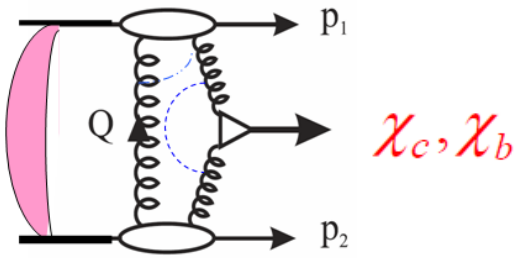
(In collaboration with L. Harland-Lang, M. Ryskin and W.J. Stirling)



For more details see arXiv:0909.4748 and arXiv:1005.0695

Outline

- Introduction.
- Central exclusive production (CEP) of $\chi_{c0,1,2}$ states at the **Tevatron, LHC and RHIC.**
- Overview of $\gamma\gamma$ and χ_b CEP results and ongoing studies.
- **Forward proton distributions and correlations.**
- **CDP@LHC with FSC** (Mike, Risto)
- Conclusion.

Introduction

Why are we interested in central exclusive χ_c (χ_b, $\gamma\gamma$, jj) production?

- Driven by same mechanism as Higgs (or other new object) CEP at the LHC. (Marek)
- χ_c, jj and $\gamma\gamma$ CEP has been observed by CDF. (Dino, Mike)

New D0 results(CR)
RHIC data expected (WG)

→ Can serve as 'Standard Candle' processes, which allow us to check the theoretical predictions for central exclusive new physics signals at the LHC.

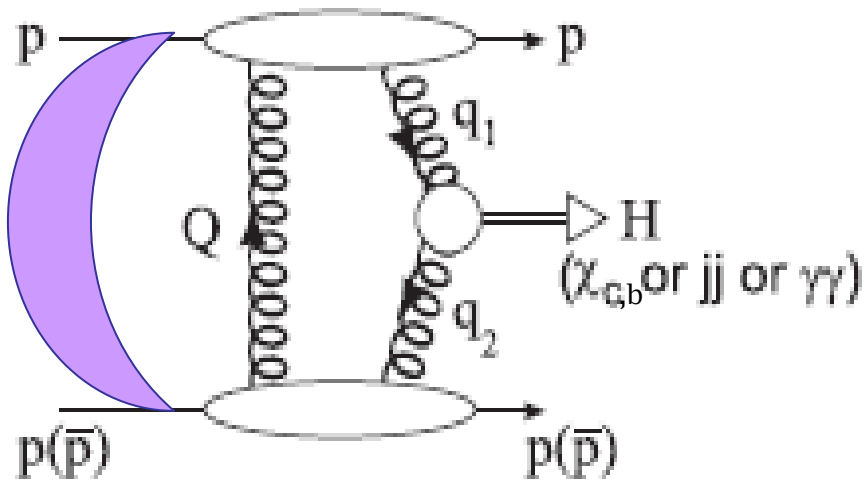
- $\chi_{c,b}$ production is of special interest: (star reactions!)
  - Heavy quarkonium production can shed light on the physics of bound states (lattice, NRQCD$\cdots$).
  - Potential to produce different J^P states, which exhibit characteristic features (e.g. angular distributions of forward protons).
  - Could perhaps shed light on the various 'exotic' charmonium states observed recently. (X,Y,Z) charmonium-like states.

Spin-Parity Analyzer (A.Kaidalov & KMR-2003)

- Detailed tests of dynamics of soft diffraction (KMR-02)

Central exclusive Production (CEP)

- Colliding protons interact via a colour singlet exchange and remain intact.
- A system of mass M_X is produced at the collision point, and *only* its decay products are present in the central detector region.

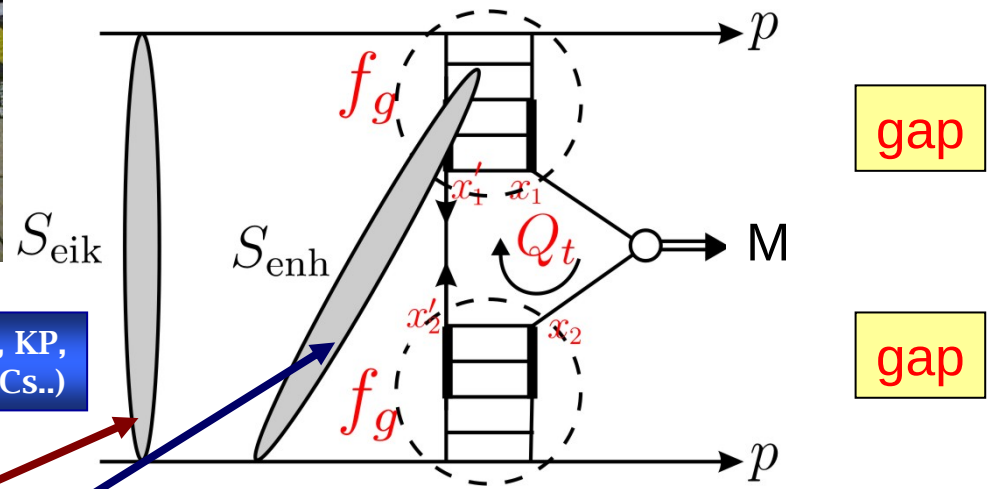


- The generic process $pp \to p + X + p$ is modeled perturbatively by the exchange of two t-channel gluons.
- The possibility of additional soft rescatterings filling the rapidity gaps is encoded in the 'eikonal' and 'enhanced' survival factors, $S^2_{\rm eik}$ and $S^2_{\rm enh}$.
- In the limit that the outgoing protons scatter at zero angle, the centrally produced state X must have $J^P_Z = 0^+$ state.

"soft" scattering can easily destroy the gaps

S^2 ➔ absorption effects -necessitated by unitarity

(Alan,Uri)



Everybody's ~ happy (KMR, GLMM, FHSW, KP, S.Ostapchenco. Petrov et al, BH, GGPS, MCs..)

eikonal rescatt: between protons ← soft-hard factoriz^n

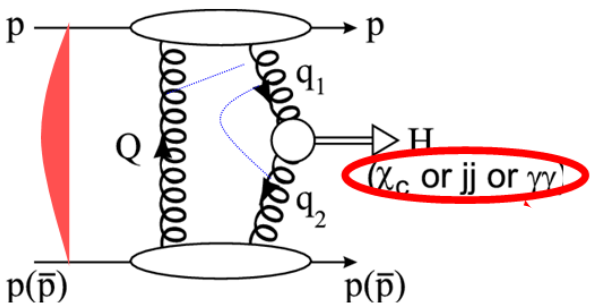
enhanced rescatt: involving intermediate partons ← conserved broken

Subject of hot discussions recently : S^2enh

Standard Candle Processes

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

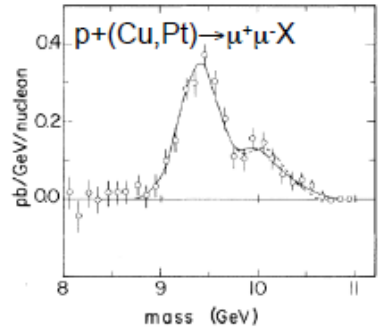
(Confucius)



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

Bottomonium history started 30 years ago

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



M(ϒ)=9.40±0.013

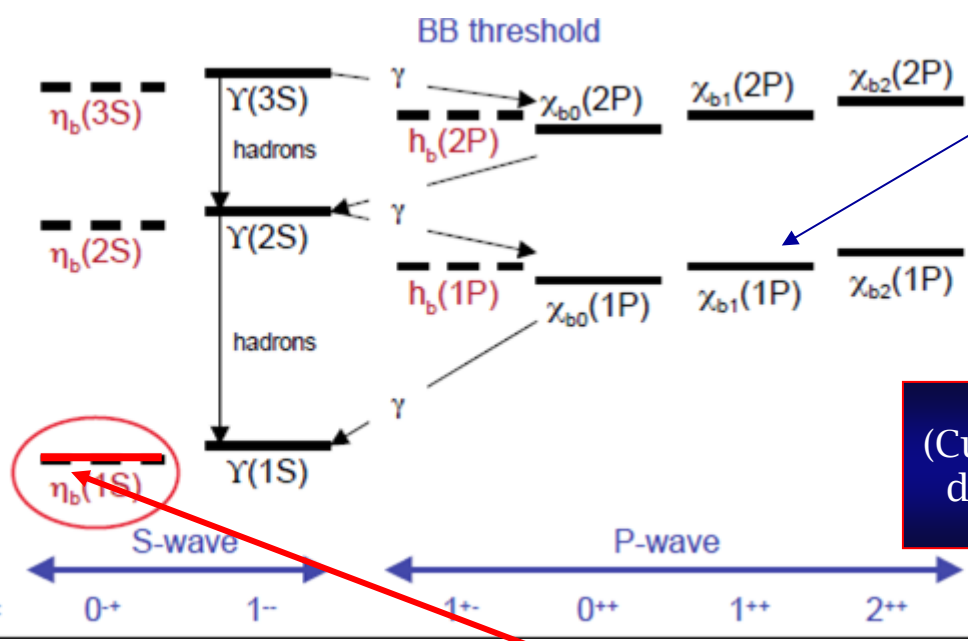
M(ϒ')=10.00±0.04

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 theoretical description of onium properties.)

(BABAR (2008))

(Still puzzles)

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

Currently -about a dozen new ('unwanted') charmonium-like states X, Y, Z….

- $X(3872)$ **mystery**

- Discovered by BELLE in 2003, confirmed by BaBar, CDF, D0
- Possible spin-parity assignment: 1^{++} or 2^{-+}
- May well be of exotic nature : loosely bound molecule, diquark-antidiquark, hybrid,….. but a conventional 2 P-wave charmonium interpretation is still on the table (recent renewal of interest).
- BaBar (2010) seems to favour 2^{-+} though various theory groups find this assignment highly problematic.
- According to PDG $\Gamma(\pi^+\pi^- J/\psi(1S))/\Gamma_{\text{total}}$ >2.6 % ; $\Gamma(\gamma\psi(2S))/\Gamma_{\text{total}}$ >3.0 %, Γ <2.3 MeV.

- CEP as a spin-parity analyzer could help to resolve the $X(3872)$ puzzle.

(Dino, Mike,Risto)

(Cannot detect p/pbar, down beam pipe, but BSC → η = 7.4 empty)

FSC@LHC

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

Cleanest (no S.I.) but smallest σ

KMR: 38 pb in our box). 2+1 candidates (more coming soon)

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

Clean, big σ: $\frac{d\sigma}{dy}(y=0) \sim 100\,\text{nb (KMRS)}$

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

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

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

More perturbative, smaller theory uncertainty
But σ ~ 1/500th χc. Also BR's not known!

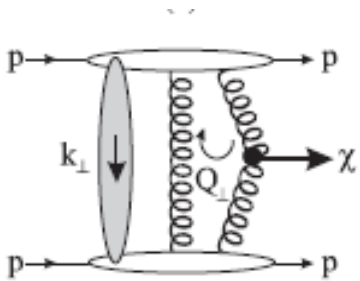
Prpospects !

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

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

What we expect within the framework of the Perturbative Durham formalism
(KMR-01, KKMR-03, KMRS-04, HKRS-10)

Example, O++ -case



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

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

- The $gg \to \chi_{cJ}$ vertex and can be calculated by a simple extension of the previous $\gamma\gamma \to \chi_c$ potential model results. These give the Lorentz structure of the vertices, while the normalisation is set by the derivative of the P-wave meson wavefunction at the origin $\phi_P'(0)$.

- **Strong sensitivity to the polarization structure of the vertex in the bare amplitude.** KMR-01

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

- χ_c, χ_b -production is especially sensitive to the effects of enhanced absorption KMR-02, KKMR-03, HKRS 09-10
  - larger available rapidity interval
  - lower scale ➔ larger dipole size ➔ larger absorption

  (Gap size for χ_c at the Tevatron is expected to exceed that for the Higgs at the LHC)

- **Forward proton distributions& correlations- possibility to test diffraction dynamics** KMR-02

CDF χ_c data

Phys.Rev.Lett.102:242001,2009

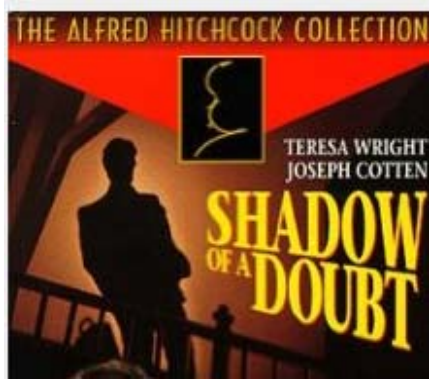
- 65 ± 10 signal χ_c events observed, but with a limited $M(J/\psi\gamma)$ resolution.
- Possible contribution from χ_{c1} and χ_{c2} states assumed, rather than observed, to be negligible.
- Assuming χ_{c0} dominance, CDF found:

$$\left.\frac{d\sigma(\chi_{c0})}{dy_\chi}\right|_{y=0} = (76 \pm 14)\,\mathrm{nb}\ ,$$

in good agreement with the previous KMRS value of 90 nb (arXiv:0403218).

Too good to be true ?!

- But can we be sure that χ_{c1} and χ_{c2} events to do not contribute?



SuperCHIC MC (HKRS-09,10)

- A new MC (available on HepForge) including:
  - Non-forward $p_\perp \neq 0$ protons via the 'effective' slope parameters $b_{\rm eff}$.
  - Full simulation of $\chi_{c(0,1,2)}$ CEP via the $\chi_c \to J/\psi\gamma \to \mu^+\mu^-\gamma$ decay chain.
  - $\chi_{b(0,1,2)}$ CEP via the equivalent $\chi_b \to \Upsilon\gamma \to \mu^+\mu^-\gamma$ decay chain.
- The angular distributions of the final state particles, modeled in the MC, might help us to distinguish between the different states...
- ...however the severity of current CDF experimental cuts for χ_c CEP ($p_\perp(\mu) > 1.4\,\mathrm{GeV/c}$, $|\eta_\mu| < 1$) appears to preclude this.
- Simulation of different CEP processes, including all spin correlations:
  - $\chi_{(b,c)J}$ and $\eta_{(b,c)}$ CEP via general two body decay channels
  - $\gamma\gamma$ CEP.
- More to come (dijets, open quark, Higgs...?).

The SuperCHIC code and documentation are available at http://projects.hepforge.org/superchic/

χ_{c1} and χ_{c2}: general considerations

- General considerations tell us that χ_{c1} and χ_{c2} CEP rates are strongly suppressed:
  - χ_{c1}: Landau-Yang theorem forbids decay of a $J = 1$ particle into on-shell gluons.
  - χ_{c2}: Forbidden (in the non-relativistic quarkonium approximation) by $J_z = 0$ selection rule that operates for forward ($p_\perp$=0) outgoing protons. KMR-01 (A. Alekseev-1958-positronium)
- However the experimentally observed decay chain $\chi_c \to J/\psi\gamma \to \mu^+\mu^-\gamma$ strongly favours $\chi_{c(1,2)}$ production, with:

$$\mathrm{Br}(\chi_{c0} \to J/\psi\gamma) = 1.1\% \ ,$$
$$\mathrm{Br}(\chi_{c1} \to J/\psi\gamma) = 34\% \ ,$$
$$\mathrm{Br}(\chi_{c2} \to J/\psi\gamma) = 19\% \ .$$

- We should therefore seriously consider the possibility of $\chi_{c(1,2)}$

(R.Pasechnik et al, Phys.Lett.B680:62-71,2009; HKRS, Eur.Phys.J.C65:433-448,2010)

Cross section results (1)

- We find the following approximate hierarchy for the spin-summed amplitudes squared (assuming an exponential proton form factor $e^{-b\mathbf{p}_\perp^2}$):

$$|V_0|^2 : |V_1|^2 : |V_2|^2 \sim 1 : \frac{\langle \mathbf{p}_\perp^2 \rangle}{M_\chi^2} : \frac{\langle \mathbf{p}_\perp^2 \rangle^2}{\langle \mathbf{Q}_\perp^2 \rangle^2} \,. \qquad (2)$$

- This $\sim 1/40$ suppression for the $\chi_{c1,2}$ states will be compensated by the larger $\chi_c \to J/\psi\gamma$ branching ratios, as well as by the larger survival factors $S^2_{\rm eik}$ for the more peripheral reactions.
- An explicit calculation gives (for the perturbative contribution):

$$\frac{\Gamma^{\chi_0}_{J/\psi+\gamma}}{\Gamma^{\chi_0}_{\rm tot}} \frac{{\rm d}\sigma^{\rm pert}_{\chi_{c0}}}{{\rm d}y} : \frac{\Gamma^{\chi_1}_{J/\psi+\gamma}}{\Gamma^{\chi_1}_{\rm tot}} \frac{{\rm d}\sigma^{\rm pert}_{\chi_{c1}}}{{\rm d}y} : \frac{\Gamma^{\chi_2}_{J/\psi+\gamma}}{\Gamma^{\chi_2}_{\rm tot}} \frac{{\rm d}\sigma^{\rm pert}_{\chi_{c2}}}{{\rm d}y} \approx \quad 1 : \ 0.6 \ : 0.22$$

- Note: these approximate values carry a factor of $\sim \times \div$ 2 uncertainty.

Cross section results for RHIC and the LHC

- As the cms energy increases we have:
  - Larger gluon density at smaller x values.
  - Smaller $S^2_{\rm eik}$ survival factor.
  - Smaller $S^2_{\rm enh}$ due to increase in size of rapidity gaps ($\sim \ln(s/m_\chi^2)$) available for 'enhanced' absorptive effects.

→ The combined result of these different effects is that the χ_c CEP rate has only a very weak energy dependence going from the Tevatron to the LHC.

- An explicit calculation gives the results:

$\sqrt{s}$ (TeV)	$d\sigma/dy_\chi(pp \to pp(J/\psi + \gamma))$ (nb)
0.5	0.57
1.96	0.73
7	0.89
10	0.94
14	1.0

$\chi_c \to \pi\pi$, $\chi_c \to K\overline{K}$ Spin-parity Analyzer

Central Diffractive Production of χ_b

- Higher χ_b mass means cross section is more perturbative (c.f. Sudakov factor) and so is better test of theory, although rate is $\sim$ 3 orders of magnitude smaller than χ_c.
- J assignment of χ_b states still experimentally undetermined: CEP could shed light on this.

- Calculation exactly analagous to χ_c case with same hierarchy : However we have a stronger supression in the χ_{b1} and χ_{b2} rates than for the χ_c case.
- Larger $\langle Q_\perp^2 \rangle$ scale gives smaller $b_{\rm eff}$ values, i.e. non-forward effects are less strong, but still important.
- Significant uncertainties in input parameters:
  - Only have $\mathrm{Br}(\chi_{b0} \to \Upsilon\gamma) < 6\%$ from experiment
  - $\Gamma_{\rm tot}(\chi_{b0})$ experimentally undetermined.

$\mathrm{BR}(\chi_{b1} \to \Upsilon\gamma) = (35 \pm 8)\%$
$\mathrm{BR}(\chi_{b2} \to \Upsilon\gamma) = (22 \pm 4)\%$

(Crystal Bal -1986)

- Consistently with the results of NRQCD, as well as the existing experimental data, we can take the values[3] $\Gamma(\chi_{b0} \to gg) = 0.8$ MeV and $\mathrm{Br}(\chi_{b0} \to \Upsilon\gamma) =$ 3 % .

- $\chi_b(nP) \to DX$ (about 0.25 of all hadronic decays (CLEO-2009)
  $\chi_{b1} \to c\bar{c}X$ (Barbieri et al (1979), NRQCD)

FSC@LHCb ?

Suppressed non-resonant background $\sim m_c^2/M_{\chi_b}^2$

χ_b CEP (2)

$$\frac{\Gamma^{\chi_0}_{\Upsilon+\gamma}}{\Gamma^{\chi_0}_{\rm tot}}\frac{d\sigma^{\rm pert}_{\chi_{b0}}}{dy} : \frac{\Gamma^{\chi_1}_{\Upsilon+\gamma}}{\Gamma^{\chi_1}_{\rm tot}}\frac{d\sigma^{\rm pert}_{\chi_{b1}}}{dy} : \frac{\Gamma^{\chi_2}_{\Upsilon+\gamma}}{\Gamma^{\chi_2}_{\rm tot}}\frac{d\sigma^{\rm pert}_{\chi_{b2}}}{dy} \approx$$

1 : 0.03 : 0.08

$\sqrt{s}$ (TeV)	0.5	1.96	7	10	14
$\frac{d\sigma}{dy_\chi}(\chi_{c0})$	27	35	42	43	45
$\frac{d\sigma}{dy_\chi}(\chi_{b0})$	–	0.017	0.021	0.022	0.022

Differential cross section (in nb) at rapidity $y_\chi = 0$ for central exclusive $\chi_{(b,c)0}$ production at RHIC, Tevatron and LHC energies, and calculated using GRV94HO partons,

expected χ_b CEP rates via the $\Upsilon\gamma$ decay chain

$\sqrt{s}$ (TeV)	$d\sigma/dy_\chi(pp \to pp(\Upsilon+\gamma))$ (pb)
1.96	0.68
7	0.70
14	0.74

Measuring forward proton angular distributions

KKMR-03

- For low proton transverse momenta $p_{1,2_\perp}$ we have: $\boxed{\bar{p}_\perp^2 \ll Q}$

$$d\sigma(0^+)/d\phi \approx \text{const.} \,,$$

$$d\sigma(1^+)/d\phi \approx (p_{1_\perp} - p_{2_\perp})^2 \,,$$

$$d\sigma(0^-)/d\phi \approx \mathbf{p}_{1\perp}^2 \mathbf{p}_{2\perp}^2 \sin^2\phi \,,$$

while there does not exist a simple closed form for the χ_2 case

- Note these will receive corrections of $O(p_\perp^2/\langle Q_\perp^2\rangle)$.
- These distributions are strongly affected by absorptive corrections, through their dependence on the proton distribution in impact parameter b space.
- Forward proton detection would allow a clear discrimination between the different J states.

- Very topical for STAR@RHIC forthcoming measurements with tagged forward protons (Wlodek)
(new HKRS results soon to come).

Forward proton angular distributions

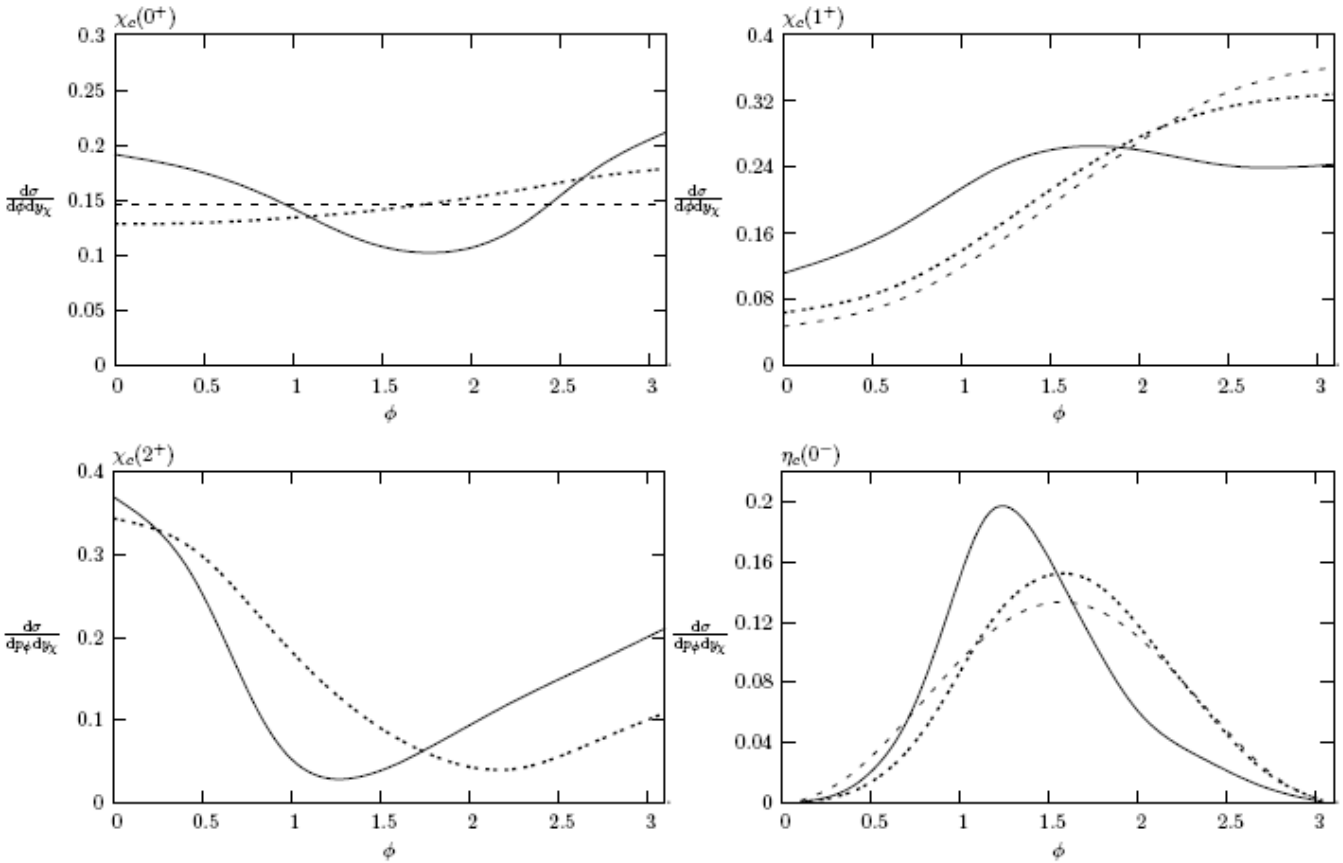
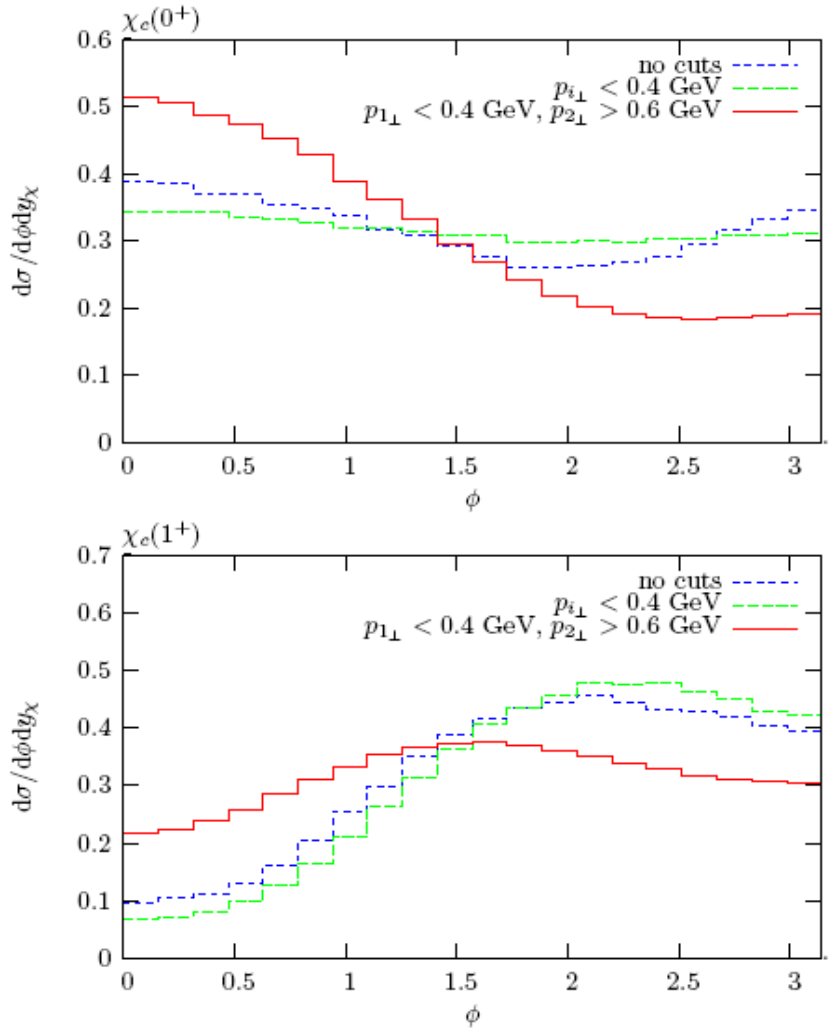


Figure: distribution (in arbitrary units) within the perturbative framework of the difference in azimuthal angle of the outgoing protons for the CEP of different J^P $c\bar{c}$ states at $\sqrt{s} = 14$ TeV. The solid (dotted) line shows the distribution including (excluding) the survival factor, while the dashed line shows the distribution in the small $p_\perp$ limit excluding the survival factor.

→ Measurement of azimuthal angle, ϕ, between outgoing protons and proton $p_\perp$ distributions via forward proton taggers would allow a clear discrimination between the different J states, as well as possibly probing different models of soft diffraction (which will predict in general different distributions).

χ_c CEP at RHIC

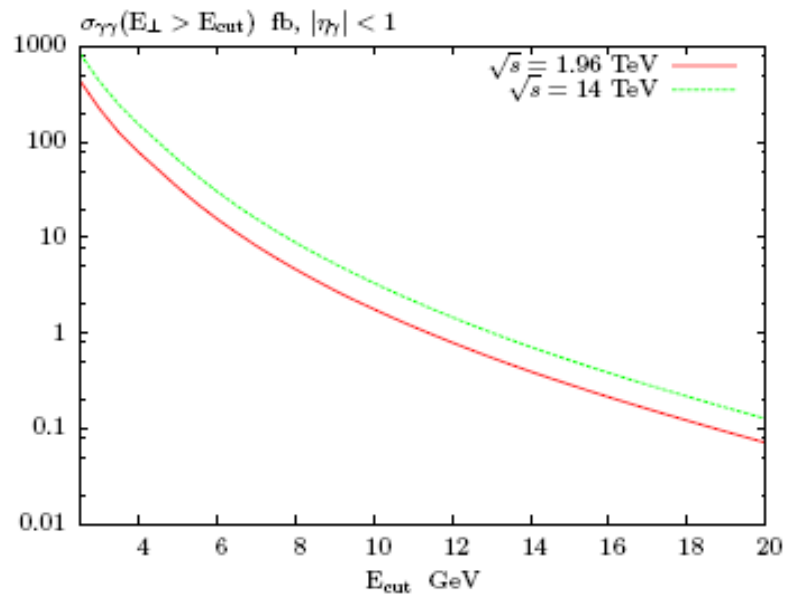
- Roman pot (RP) forward proton detectors with acceptance for χ_{cJ} masses installed at STAR, with upgrade planned for 2012. (Wlodek)
- RPs will be able to measure proton ϕ and $p_\perp$ distributions over a broad range, in principle giving spin information about the centrally produced χ state.
- 'Missing mass' measurement also possible method for discriminating χ states.
- Can also consider χ CEP via two and four-body decays (e.g. $\chi_{c0} \to \pi\pi$ and $\chi_{c0} \to 2(\pi^+\pi^-)$), for which χ_{c0} states will dominate



$\gamma\gamma$ CEP

(KMRS, arXiv:0409037)

- 3 candidate events observed by CDF (arXiv:0707.237), with more to come.
- More events would allow us to probe scaling of σ with $E_{\rm cut}$.
- Similar uncertainties to χ_c case for low $E_{\rm cut}$ scale.
- Potential $|J_z| = 2$ contribution found to be unimportant.
- New encouraging results for $gg \to \pi^0\pi^0$ background.
- $\gamma\gamma$ CEP now included in SuperCHIC.



(HKRS-2010)

(Leading term QCD expectations)

- HKRS-results at different energies, $E_\perp$ and η_γ cuts are now available.

Conclusion

- CEP processes observed at the Tevatron can serve as 'standard candles' for new physics CEP at the LHC.
- Possibility that χ_{c1} and χ_{c2} CEP may contribute to CDF χ_c events.
- Cannot currently distinguish states, but may be possible with:
  - More detailed analysis and/or higher statistics.
  - Forward proton detection.
  - Different decay modes, $\chi_c \to \pi\pi$, KK,$\overline{p}p$,$\Lambda\overline{\Lambda}$.

- χ_b , dijet, diphton CEP- rich program of studies at the LHC; promising potential of LHCb.
- New STAR@RHIC results on CEP with tagged forward protons soon to come.

Prospects of CDP studies at ALICE & LHCb

Currently active studies are in progress (both in theory and experiment).

Thank You

BACKUP

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.

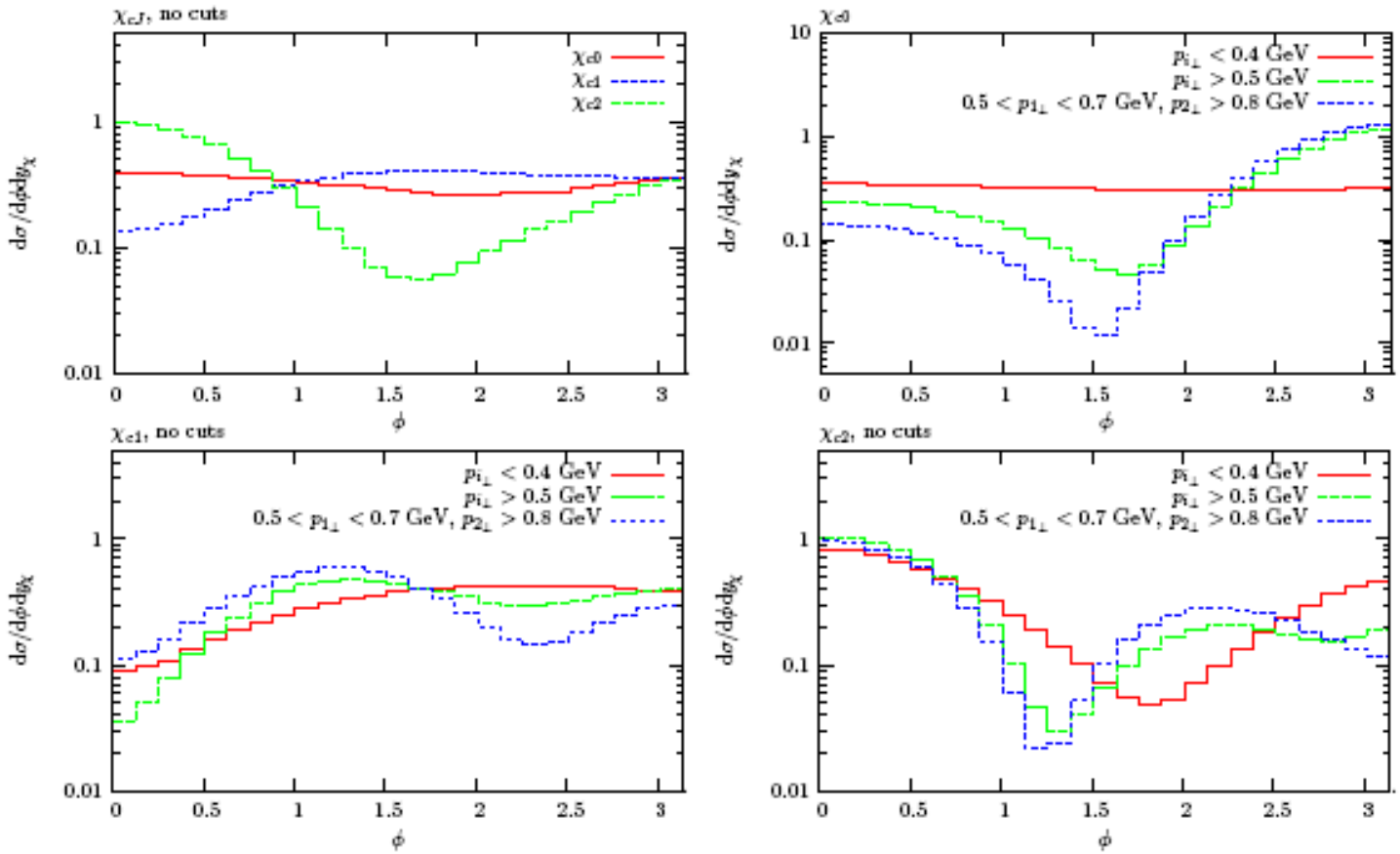
Factor of 5 up or down (at best)

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

χ_c CEP at RHIC (publication in progress)

- Roman pot (RP) forward proton detectors with acceptance for χ_{cJ} masses installed at STAR, with upgrade planned for 2012.
- Can observe χ_{cJ} production via $\chi_{cJ} \to J/\psi\gamma$ decay.
- Can also consider χ CEP via two and four-body decays (e.g. $\chi_{c0} \to \pi\pi, p\overline{p}$ and $\chi_{c0} \to 2(\pi^+\pi^-)$), for which χ_{c0} states will dominate:
  - Estimate of $gg \to \pi\pi$ QCD background work in progress (see $\gamma\gamma$ section).
  - Excellent mass resolution ($\sim$ a few MeV) of central TPC detector will greatly increase S/B.
- RPs will be able to measure proton ϕ and $p_\perp$ distributions over a broad range, in principle giving spin information about the centrally produced χ_c state as well as probing soft survival effects...

CEP at RHIC: proton distributions (1)- Preliminary



→ ϕ distributions depend on central particle spin, but are also strongly affected by soft survival effects, in particular for larger values of proton $p_\perp$ (RHIC II), where cancellation between screened and unscreened amplitudes results in characteristic 'diffractive dip' structure.

Potentially rich program of CDP studies with the LHCb

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
exotic states….

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

HOW TO FACILITATE THIS?

LHCb
Excellent particle ID (pion/Kaon separation), vertex and proper time resolution

Jerry W. Lämsä and Risto Orava

JINST 4:P11019,2009.

$\eta_{c,b}$ production

- $gg \to \eta$ vertex calculated as in χ case, but normalisation set in terms of S-wave meson wavefunction at the origin $\phi_S(0)$, which can be related to $\Gamma_{\rm tot}(\eta_c)$ and $\Gamma(\Upsilon(1S) \to \mu^+\mu^-)$ widths.
- Amplitude squared has Lorentz structure

$$|V_{0^-}|^2 \propto p_{1_\perp}^2 p_{2_\perp}^2 \sin^2(\phi) \ ,$$

  i.e. it is suppressed relative to χ_0 rate by a factor $\sim \langle \mathbf{p}_\perp^2 \rangle^2 / 2 \langle \mathbf{Q}_\perp^2 \rangle^2$, with a characteristic azimuthal angular distribution of the outgoing protons.
- An explicit calculation gives:

$\sqrt{s}$ (TeV)	$d\sigma/dy_\eta(\eta_c)$ (pb)	$d\sigma/dy_\eta(\eta_b)$ (pb)
1.96	200	0.15
7	200	0.14
14	190	0.12