Exclusive Quarkonium Production in pp Collisions

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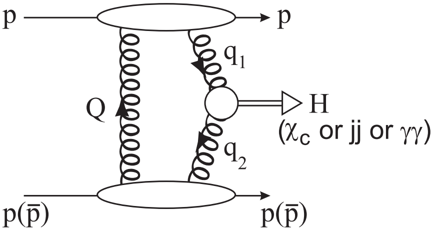
Based on work by V.A. Khoze, M.G. Ryskin, W.J. Stirling and L.A. Harland-Lang. (KHRYSTHAL collaboration)
For more details see arXiv:1005.0695, arXiv:1011.0680 and arXiv:1105.1626

Central Exclusive Production (CEP)

- Colliding protons interact via a colour singlet exchange and remain intact- can then be measured by adding detectors far down the beam-pipe.
- 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.
- In the limit that the outgoing protons scatter at zero angle, the centrally produced state X must have $J_Z^P = 0^+$ quantum numbers.

Heavy quarkonium CEP

- CEP of low mass objects (χ_c, χ_b, $\gamma\gamma$ and jj) driven by the same mechanism as Higgs (or other new object which couples to gluons) CEP at the LHC, but will have larger cross sections.
- χ_c, $\gamma\gamma$ and jj CEP already observed by CDF (LHCb).

$\rightarrow$ Can serve as 'Standard Candle' processes, which allow us to check the theoretical predictions for central exclusive new physics signals at the LHC, as well as being of interest in their own right.

- Quarkonium production is of special interest as a Standard Candle process:
  - χ_c CEP observation is CDF 'star reaction'– experimentally clean signal.
  - CEP probes the form of the purely colour singlet $gg \to X(= c\overline{c}/b\overline{b})$ coupling.
  - Potential to produce different J^P states (χ_{qJ}, η_q...) which exhibit characteristic features (e.g. angular distributions of forward protons).
  - Could shed light on the various 'exotic' charmonium states observed recently, e.g. $X(3872)$, and the wide range of other (X,Y,Z) charmonium-like states.

CDF χ_c data vs theory

- 65 ± 10 signal χ_c events observed via the $\chi_c \to J/\psi\gamma \to \mu^+\mu^-\gamma$ decay channel, but with a limited $M(J/\psi\gamma)$ resolution. (CDF Collaboration, arXiv:0902.1271). Assuming χ_{c0} dominance, CDF found:

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

- Within CEP formalism the χ_{c1} and χ_{c2} CEP rates are strongly suppressed (by $\sim$ 2 orders of mag.), but the experimentally observed decay chain $\chi_c \to J/\psi\gamma \to \mu^+\mu^-\gamma$ strongly favours $\chi_{c(1,2)}$ production.
- An explicit calculation then shows that we indeed expect a non-negligible contribution from the $\chi_{c(1,2)}$ states ($\sigma_{\chi_0} \approx \sigma_{(\chi_1+\chi_2)}$), and we can then use the relevant χ_{cJ} branching ratios to convert our result to a total predicted χ_c cross section at the Tevatron:

$$\left.\frac{\mathrm{d}\sigma^{\mathrm{tot}}_{\chi_c}}{\mathrm{d}y_x}\right|_{y_\chi=0} \approx 60\,\mathrm{nb}\;.$$

- Note this carries very large uncertainties ($\sim\overset{\times}{\div}$ 5) but is nonetheless in good agreement with the experimental value.

Cross section results for the LHC

- Although theory behind total cross prediction has large uncertainties, we can use agreement with CDF data to 'calibrate' predictions for the LHC, provided we understand the $\sqrt{s}$ dependence.
- As the cms energy increases we have:
  - Larger gluon density at smaller x values.
  - Smaller $S^2_{\rm eik}$, $S^2_{\rm enh}$ survival factors- probability that extra soft emission from underlying event does not spoil the exclusive final state.

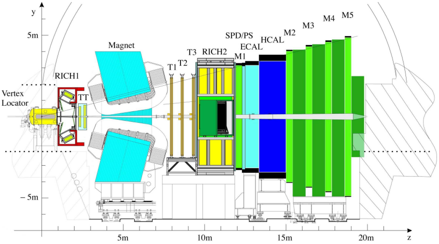
→ The combined result of these different effects is that the χ_c CEP rate is expected to have a weak energy dependence going from the Tevatron to the LHC.

- An explicit calculation gives for $d\sigma/dy_\chi(pp \to pp(J/\psi + \gamma))$ (nb) (at $y_\chi = 0$):

$\sqrt{s}$ (TeV)	1.96	7	14
χ_{c0}	0.40	0.46	0.52
χ_{c1}	0.24	0.32	0.37
χ_{c2}	0.09	0.11	0.12

χ_c CEP @ LHCb (1)

- Select 'exclusive' events by vetoing on additional activity in given η range– $\chi_c \to J/\psi\gamma$ events seen by LHCb.
- Expect $\sigma_{\chi_0} \approx \sigma_{(\chi_1+\chi_2)} \to$ recalling $\mathrm{Br}(\chi_{c0} \to J/\psi\gamma)$ suppression, observation of χ_{c0} events strongly favours exclusivity.



- LHCb see[1]:

	$\sigma(pp \to pp(J/\psi+\gamma))$ LHCb (pb)	SuperChic prediction (pb)
χ_{c0}	9.3 ± 4.5	14
χ_{c1}	16.4 ± 7.1	10
χ_{c2}	28 ± 12.3	3

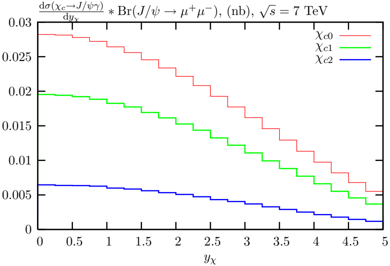
$\to$ Good agreement for $\chi_{c(0,1)}$ states (recall large theory uncertainty), but a significant excess of χ_{c2} events above theory prediction.

[1] Preliminary data– LHCb-CONF-2011-022

χ_c CEP @ LHCb (2)

- Excess of χ_{c2} events: $J_z = 0$ suppression of χ_{c2} state only exact in non-relativistic limit $\rightarrow$ relativistic corrections important? Or non-perturbative corrections?
- However: possibility of inclusive contamination (no $J_z = 0$ selection rule $\Rightarrow$ will increase observed $\chi_{c(1,2)}$ yield):
  - Single high mass proton dissociation $pp \rightarrow p + \chi + X$, can be of similar size to exclusive rate (depends on cuts and event selection).
  - Fully inclusive $pp \rightarrow \chi + X$ with fluctuation due to hadronisation creating gap(s)– probability exponentially suppressed $\sim e^{-\Delta\eta}$, but inclusive rate ~ 4 orders of mag. higher.

- $\langle p_\perp(\chi_c)\rangle$ lower in exclusive case.
- Forward shower counters @ LHC: can veto on greatly extended η region, will reduce inclusive contamination.
- Other decays ($\chi_{c(0,2)} \rightarrow \pi^+\pi^-, K^+K^-$...): should dominantly see χ_{c0}'s.



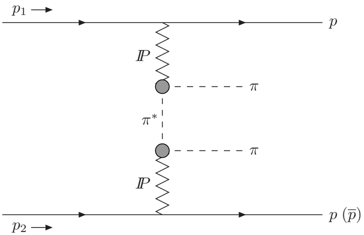
$\chi_c \to \pi^+\pi^-$ CEP (1)

- $\text{Br}(\chi_{c0} \to \pi^+\pi^-) = (0.56 \pm 0.03)\%$ and $\text{Br}(\chi_{c2} \to \pi^+\pi^-) = (0.16 \pm 0.01)\%$, while $\chi_{c1} \to \pi^+\pi^-$ does not occur.

$\to$ χ_{c0} CEP via $\pi^+\pi^-$ channel expected to strongly dominate, with similar/bigger production cross sections to $J/\psi\gamma$ channel (similarly for K^+K^- channel).

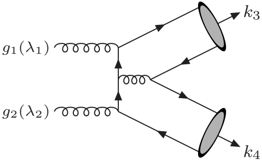
- Ideally suited to, e.g., LHCb and STAR experiments (excellent PID and high momentum resolution).
- Continuum $\pi^+\pi^-$ CEP background under control?

- Non-perturbative contribution (lower $M_{\pi\pi}$), modeled using Regge theory.
  - ▶ Expected to be numerically small once reasonable $p_\perp(\pi)$ cuts are imposed



$\chi_c \to \pi^+\pi^-$ CEP (2)

- Perturbative contribution (higher $M_{\pi\pi}$), modeled using standard pQCD framework, with 'hard exclusive' formalism[2] used to calculate $gg \to \pi^+\pi^-$ amplitude



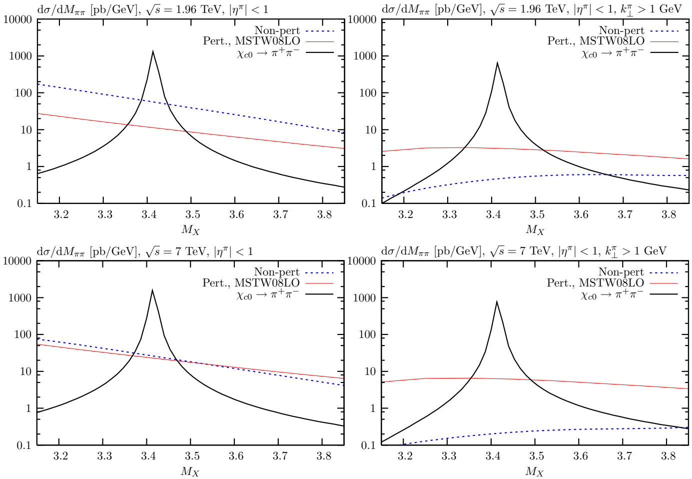
  - Expected to be numerically suppressed by a factor $(f_\pi/p_\perp(\pi))^4$ and also by $J_z = 0$ selection rule[3] (as in χ_{c2} CEP).

- In χ_c mass region, both these mechanisms are expected to contribute to $\pi^+\pi^-$ continuum background...

[2] S. J. Brodsky and G. P. Lepage, Phys. Rev. D 24 (1981) 1808.

[3] See arXiv:1105.1626 for more details of calculation and of perturbative and non-perturbative models.

$\chi_c \to \pi^+\pi^-$ CEP (3)



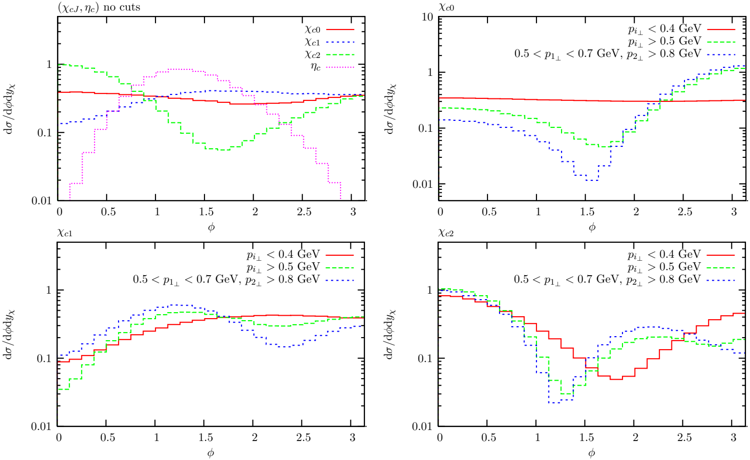
- Continuum $\pi^+\pi^-$ background expected to be very small, in particular once reasonable $p_\perp$ cuts have been imposed $\Rightarrow \chi_{c0} \to \pi^+\pi^-$ (and K^+K^-) channel should give a clean χ_{c0} CEP signal (similarly at RHIC- see backup slide), provided exclusive events can be effectively selected.

χ_c CEP at RHIC

(see arXiv:1011.0680 for more details)

- 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:
  - Continuum $\pi^+\pi^-$ background expected to be low.
  - 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 state as well as probing soft survival effects...

CEP with proton taggers



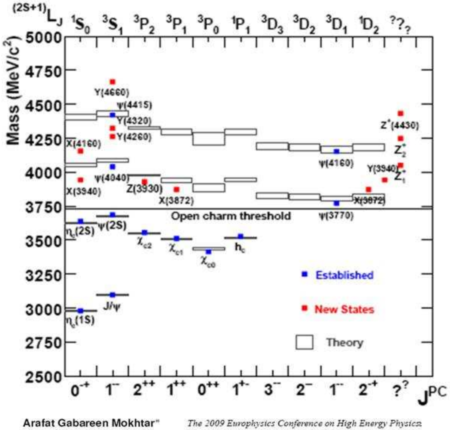
→ ϕ distributions (SuperCHIC) depend on central particle spin, but are also strongly affected by soft survival effects, in particular for larger values of proton $p_\perp$ (RHIC II), where cancellation between screened and unscreened amplitudes results in characteristic 'diffractive dip' structure.[4]

[4] V. A. Khoze, A. D. Martin and M. G. Ryskin, Eur. Phys. J. C 24, 581 (2002) [arXiv:hep-ph/0203122].

‘Exotic’ charmonium-like states

A ‘zoology’ of XYZ charmonium-like states above the open charm threshold has recently been observed at Belle, Babar and the Tevatron:

- X(3972) ($^1D_2$ charmonium? $D^{*0}\overline{D^0}$ molecular state?).
- X(3940) ($\eta_c(3S)$?), Y(3940) ($c\bar{c}g$?), Z(3940) ($2\ ^3P_2$) & X(4350).
- Y(4140)/Y(4280) & X(4350) (tetraquark states?).
- Y states and excited ψ’s (hybrids?)



Insight from CEP

- X(3872):
  - Discovered by Belle in 2003, confirmed by Babar, CDF, D0 and LHCb.
  - Could be of exotic nature: loosely bound hadronic molecule, diquark-antidiquark ('tetraquark') and hybrid ($\overline{c}cg\cdots$). However, conventional $c\overline{c}$ interpretation is still possible (recent renewal of interest).
  - Possible J^{PC} assignments are 1^{++} or 2^{-+}.
  - Recent Babar $X(3872) \to J/\psi\omega$ data seems to favour[5] 2^{-+} although many theory groups find conventional $^2D_1$ $c\overline{c}$ interpretation problematic (mass and production cross section predictions disagree with data).

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

- $Z(3930) \equiv \chi_{c2}(2P)$:
  - Above threshold: decays to $D\overline{D}$, D^+D^- and $D^0\overline{D^0}$ seen.
  - With vertex detection at LHCb and RHIC $\to$ exclusive open charm ($D\overline{D}$...) production.
  - Theory: roughly the same cross section and distributions as $\chi_{c2}(1P)$.

[5] S-wave fit– $P(\chi^2, \mathrm{NDF}) = 7.1\%$; P-wave fit– $P(\chi^2, \mathrm{NDF}) = 61.9\%$

SuperCHIC MC

A MC event generator including[6]:

- Simulation of different CEP processes, including all spin correlations:
  - $\chi_{c(0,1,2)}$ 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.
  - $\chi_{(b,c)J}$ and $\eta_{(b,c)}$ CEP via general two body decay channels
  - Physical proton kinematics + survival effects for quarkonium CEP at RHIC.
  - Exclusive J/ψ and Υ photoproduction.
  - $\gamma\gamma$ CEP.
  - Meson pair ($\pi\pi$, KK, $\eta\eta$...) CEP.
- More to come (dijets, open quark, Higgs...?).

$\to$ Via close collaboration with CDF, STAR and LHC groups, in both proposals for new measurements and applications of SuperCHIC, it is becoming an important tool for current and future CEP studies.

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

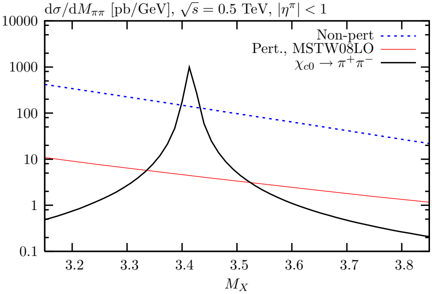
Summary and Outlook

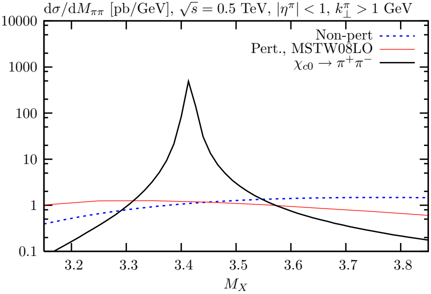
- Central exclusive production in hadron collisions offers a promising framework within which to study novel aspects of QCD and new physics signals.
- CEP processes observed at the Tevatron, RHIC and early LHC can serve as 'standard candles' for new physics CEP at the LHC, with CDF χ_c as 'star reaction'.
- Possibility that χ_{c1} and χ_{c2} CEP may contribute to CDF χ_c events.

$\rightarrow$ Supported by new LHCb $\chi_c \rightarrow J/\psi$ data (although question of exclusivity).

- χ_{c0} CEP via two-body decays ($\pi^+\pi^+$, K^+K^-...) interesting and realistic channels, with continuum background expected to be low. Other decay channels (e.g. $p\overline{p}$, $\Lambda\overline{\Lambda}$, $2(\pi^+\pi^-)$...) also possible.
- χ_b, η_b and η_c CEP potential observables at the LHC.
- Heavy quarkonium CEP with proton tagging already possible at RHIC.
- CEP is potentially powerful tool in establishing nature of the various X,Y,Z charmonium-like states.
- Theory work is ongoing, and the future there will hopefully be many more exclusive quarkonia results from the LHC, RHIC and the Tevatron to look out for.

Backup 1: $\chi_c \to \pi^+\pi^-$ @ RHIC





Backup 2: $\eta_{c,b}$ production

$\eta_{(c,b)}$: $L=0, S=0, J^{PC}=0^{-+}$ pseudoscalar $c\bar{c}/b\bar{b}$ meson states.

- $gg \to \eta$ 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

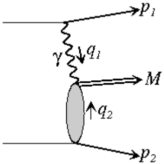
$$|V_{0^-}|^2 \propto p_{1_\perp}^2 p_{2_\perp}^2 \sin^2(\phi) \;,$$

  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.
- Possible decays: $K\overline{K}\pi$, $4(\pi^+\pi^-)$...
- An explicit calculation gives (for $y_\eta = 0$):

$\sqrt{s}$ (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

Backup 3: Exclusive $J/\psi(\Upsilon)$ production

- Proceeds via elastic photoproduction subprocess $\gamma p \to J/\psi(\Upsilon) + p$.
- Measured at HERA at energies upto $W_{\gamma p} \approx 300$ GeV, i.e. $|y_\psi| < 1.4$ at $\sqrt{s} = 7$ TeV.



- SuperCHIC uses fit to HERA data

$$\frac{\mathrm{d}\sigma(\gamma p \to J/\psi(\Upsilon) + p)}{\mathrm{d}\mathbf{p}_\perp^2} \propto W_{\gamma p}^\delta e^{-b\mathbf{p}_\perp^2} ,$$

or LO pQCD result

$$\frac{\mathrm{d}\sigma(\gamma p \to J/\psi(\Upsilon) + p)}{\mathrm{d}\mathbf{p}_\perp^2} \approx \frac{16\Gamma_{ee}\pi^3\alpha_s(Q^2)}{3\alpha M_\psi^5}[xg(x, Q^2)]^2 e^{-b\mathbf{p}_\perp^2} ,$$

where $Q^2 = M_\psi^2/4$.

- At forwards rapidities, exclusive $J/\psi(\Upsilon)$ production cross section is sensitive to gluon pdf in low x region.

Backup 4: CEP with proton taggers (2)

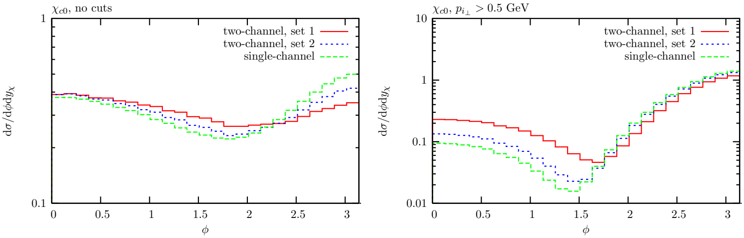


Figure: Normalised distributions (in arbitrary units) of the difference in azimuthal angle between the outgoing protons for χ_{c0} CEP, with the survival factor $S^2_{\rm eik}(b_t)$ calculated using a two-channel eikonal model, with two different choices of model parameters. Parameter set 1 accounts for the first N* resonance excitation in low mass ($p \to N^*$) proton dissociation, while set 2 includes excitations up to a larger $M^2 \sim 6\ \mathrm{GeV}^2$. Also shown is the result of using the simplified single channel eikonal approach.

- Proton distributions depend on choice of model parameters and model used to calculated survival effects

$\rightarrow$ Proton tagging can in principle be used to probe different models of soft diffraction.