Exclusive quarkonium production: theory

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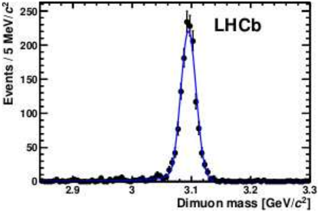
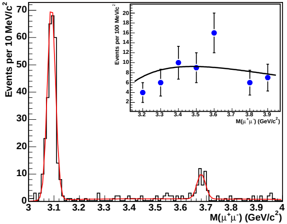
Based on work by V.A. Khoze, M.G. Ryskin, W.J. Stirling and L.A. Harland-Lang. (KHRYSTHAL collaboration)
For more details see arXiv:0909.4748, arXiv:1005.0695 and arXiv:1204.4803

Introduction

- What is Central Exclusive Production?
- CEP: general theory.
- χ_c CEP:
  - $\chi_{c(1,2)}$ suppression.
  - χ_c CEP with and without tagged protons.
  - $\chi_c \to \pi\pi, KK$ ...
- Don't forget: η_c, χ_b, η_b production...
- Exotic states: X(3872)...
- $J/\psi, \psi(2S), \Upsilon$... photoproduction.



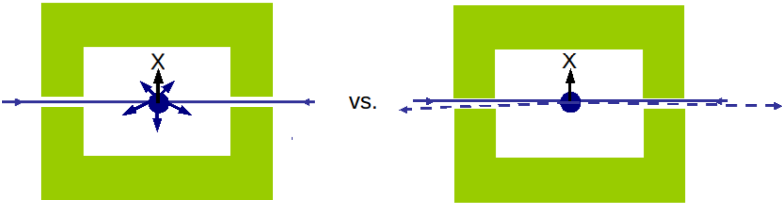


Central exclusive diffraction

Central exclusive diffraction, or central exclusive production (CEP) is the process

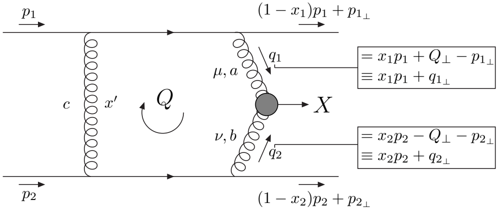
$$h(p_1)h(p_2) \to h(p_1') \, + \, X \, + \, h(p_2')$$

- Diffraction: colour singlet exchange between colliding hadrons, with large rapidity gaps ('$+$') in the final state.
- Exclusive: hadrons lose energy, but remain intact after collision and can in principal be measured by detectors positioned down the beam line.
- Central: a system of mass M_X is produced at the collision point, and *only* its decay products are present in the central detector region.



Theory: parton level amplitude

- The generic process $pp \to p + X + p$ is modeled perturbatively by the exchange of two t-channel gluons in a colour singlet state[1].



- Using the Cutkosky rules, and eikonal approximation for the qg vertices, we find

$$\frac{iA}{s} = \alpha_s^2 C_F^2 \int \frac{d^2 Q_\perp}{Q_\perp^2 q_{1_\perp}^2 q_{2_\perp}^2} \mathcal{M} \, ,$$

where $\mathcal{M}$ is the normalised, colour averaged subamplitude, written in terms of the $gg \to X$ vertex V as

$$\mathcal{M} \equiv \frac{2}{M_X^2} \frac{1}{N_C^2 - 1} \sum_{a,b} \delta^{ab} q_{1_\perp}^{\mu} q_{2_\perp}^{\nu} V_{\mu\nu}^{ab} \, .$$

[1]See V.A. Khoze, A.D. Martin and M.G. Ryskin, Eur. Phys. J.C 14, 525 (2000)

$J_z^{PC} = 0^{++}$ selection rule

- Quantum numbers of object X (= Higgs, $\gamma\gamma$...) determined by the unique dynamics of CEP process:
  - Fusing gluons in $gg \to X$ subprocess in a colour singlet state $\Rightarrow X$ is C–even.
  - The initial and final–state protons have $L_z = 0$, with no angular momentum transfer between them $\Rightarrow X$ must have $J_z = 0$.
  - The structure of the CEP amplitude correlates the polarizations of the fusing gluons ($gg \to X$) such that they must be in an even parity state.

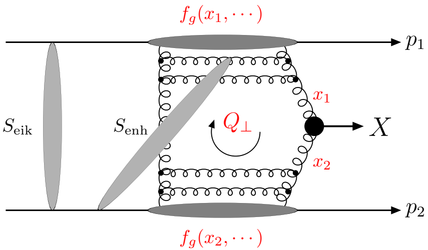
$\to$ In the limit that the outgoing protons scatter at zero angle (a good approx.), the object X obeys a $J_z^{PC} = 0^{++}$ selection rule. The CEP process acts a 'spin–parity analyzer'.

- In general protons can pick up some small non–zero $p_\perp$ (i.e. scatter at non–zero angle), but non–$J_z^P = 0^+$ quantum numbers are heavily suppressed (if $p_\perp$ transferred is too big, the protons will break up). This can be further suppressed by tagging and selecting protons with low $p_\perp$.

'Durham Model' of central exclusive production

- The generic process $pp \to p + X + p$ is modeled perturbatively by the exchange of two t-channel gluons.
- The use of pQCD is justified by the presence of a hard scale $\sim M_X/2$. This ensures an infrared stable result via the Sudakov factor: the probability of no additional perturbative emission from the hard process.

- 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 $J_z^P = 0^+$ quantum numbers.



Heavy quarkonium CEP

- CEP via the Durham model mechanism can in general produce *any* C–even object which couples to gluons: Higgs, BSM objects...but also dijets, light meson pairs, and quarkonium states.
- Quarkonium CEP provides a rich phenomenology:

$\rightarrow$ There are a wide range of conventional J^P states (χ_{qJ}, η_q...), each of which exhibits characteristic features in the exclusive mode, e.g.:

  - Different angular distributions of the forward protons.
  - Hierarchy in production cross sections.

$\rightarrow$ Could perhaps shed light on the various 'exotic' charmonium states observed recently, e.g. $Z(3930) = \chi_{c2}(2P)$ and $X(3872) =?$ (arXiv:1302.6269 $\rightarrow$ quantum numbers 1^{++}).

$\rightarrow$ Can also produce C–odd states via photoproduction $\gamma I\!P, OI\!P \rightarrow J/\psi, \Upsilon$...

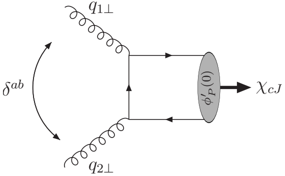
χ_{cJ} CEP

- Produced via $gg \to \chi_{cJ}$ subprocess: by demanding exclusivity, we are selecting χ_{cJ} state to be colour–singlet.
- Can use old potential model results to calculate coupling, giving for e.g. the χ_{c0}[2]

$$V(gg \to \chi_{c0}) \sim \phi'_P(0)(q_{1\perp} \cdot q_{2\perp}) \stackrel{p_\perp \to 0}{=} -\phi'_P(0)Q_\perp^2 \ , \qquad (1)$$

where $\phi'_P(0)$ is usual wavefunction derivative at the origin. Can be extracted from (potential models, Lattice...) fits, or approximately normalized to χ_{c0} total width. Cancels in cross sections ratios $(\sigma(\chi_{c0})/\sigma(\chi_{c1})...)$.

- Spin/parity of produced state determines form of vertex and behaviour in the forward proton ($p_\perp \to 0$) limit.



[2] See LHL, V.A. Khoze, M.G. Ryskin, W.J. Stirling Eur. Phys. J. C **65**, 433 (2010)

χ_{cJ} CEP: higher spins

- Considering case of $\chi_{c(1,2)}$ production: find that $V(gg \to \chi_{c(1,2)})$ vanishes in the forward ($p_\perp \to 0$) limit:

→ χ_{c2}: Coupling of χ_{c2} to gg is forbidden in the non-relativistic quarkonium approximation for $J_z = 0$ gluons. However, in the forward proton limit, the fusing gluons must be in such a helicity configuration: '$J_z = 0$ selection rule'.

→ χ_{c1}: Landau-Yang theorem forbids decay of a $J = 1$ particle into two on-shell gluons. In CEP gluons are almost on–shell, up to corrections of order $O(q_{i\perp}^2/M_\chi^2)$ → will expect suppression. In fact find that for case $q_{1\perp} = -q_{2\perp} = Q_\perp$, amplitude vanishes.

- Find that we expect the following approximate scaling

$$|V_{0^+}|^2 : |V_{1^+}|^2 : |V_{2^+}|^2 \sim 1 : \frac{\langle \mathbf{p}_\perp^2 \rangle}{M_\chi^2} : \frac{\langle \mathbf{p}_\perp^2 \rangle^2}{\langle \mathbf{Q}_\perp^2 \rangle^2} \sim 1 : \frac{1}{40} : \frac{1}{36}$$

taking e.g. $\mathbf{Q}_\perp^2 \approx 1.5\,\mathrm{GeV}^2$, $M_{\chi_c}^2 \approx 10\,\mathrm{GeV}^2$, and $\langle \mathbf{p}_\perp^2 \rangle \approx 0.25\,\mathrm{GeV}^2$ from integration over proton form factor.

→ Expect strong suppression in $\chi_{c(1,2)}$ CEP.

χ_c CEP: data

- In arXiv:0902.1271 CDF reported 65 ± 10 signal χ_c events observed via the $\chi_c \to J/\psi\gamma \to \mu^+\mu^-\gamma$ decay channel. This corresponds to $\mathrm{d}\sigma(\chi_c)/\mathrm{d}y_\chi|_{y=0} = (76 \pm 14)\,\mathrm{nb}$, in good agreement with Durham prediction of $\sim$ 60 nb.
- Recent LHCb data[3]: select 'exclusive' $\chi_c \to J/\psi\gamma$ events by vetoing on additional activity in given η range.
- LHCb see:

	$\frac{\sigma(pp\to pp(\mu^+\mu^-+\gamma))}{\mathrm{Br}(J/\psi\to\mu^+\mu^-)\mathrm{Br}(\chi_{cJ}\to J/\psi\gamma)}$ LHCb (nb)	SuperCHIC (nb)
χ_{c0}	13 ± 6.5	20
χ_{c1}	0.80 ± 0.35	0.49
χ_{c2}	2.4 ± 1.1	0.26

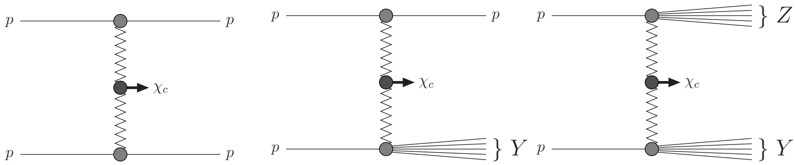
$\to$ See clear suppression in $\chi_{c(1,2)}$ states.

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

[3] LHCb-CONF-2011-022

χ_c CEP without tagged protons

- Are relativistic/non-perturbative corrections to χ_{c2} important (suppression of χ_{c1} expected by general considerations)?
- Is there a significant high mass proton dissociation $pp \to p + \chi + X$ background skewing the results?
  - Higher–mass dissociation $p \to N^*(M_Y \gtrsim 2\ \mathrm{GeV})$: allows a higher $p_\perp$ transfer to the protons and so an increasing violation of the $J_z = 0$ selection rule (recall χ_{c2} contribution is $\propto \langle p_\perp^2 \rangle^2$).
  - Such contamination should enhance in particular the χ_{c2} cross section preferentially: to consider when subtracting the proton dissociative background (always necessary to some extent without tagged protons).
  - Look at $p_\perp(\chi_c)$ dependence of cross section ratios to shed further light on this.



Quarkonium CEP with tagged protons

- For low proton transverse momenta $p_{1,2_\perp}$ we have

$$\begin{aligned} \mathrm{d}\sigma(0^+)/\mathrm{d}\phi &\approx \text{const.}\;, \\ \mathrm{d}\sigma(1^+)/\mathrm{d}\phi &\approx (p_{1_\perp} - p_{2_\perp})^2\;, \\ \mathrm{d}\sigma(0^-)/\mathrm{d}\phi &\approx p_{1_\perp}^2 p_{2_\perp}^2 \sin^2(\phi)\;. \end{aligned}$$

- Note these will receive corrections of $O(p_\perp^2/\langle Q_\perp^2\rangle)$, while the χ_2 distribution cannot be written in a simple form.
- These distributions are affected in a model dependent way by absorptive corrections, through their dependence on the proton distribution in impact parameter **b** space, although the above qualitative features remain. The full cross section is then given by:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}y_X} \propto \int \mathrm{d}^2\mathbf{p}_{1_\perp}\mathrm{d}^2\mathbf{p}_{2_\perp}|T(\mathbf{p}_{1_\perp},\mathbf{p}_{2_\perp}))|^2 S_{\mathrm{eik}}^2(\mathbf{p}_{1_\perp},\mathbf{p}_{2_\perp})\;, \qquad (2)$$

where T is the CEP amplitude excluding the soft survival factor. The corresponding proton $p_\perp$ and ϕ are then extracted from (2).

Forward proton angular distributions

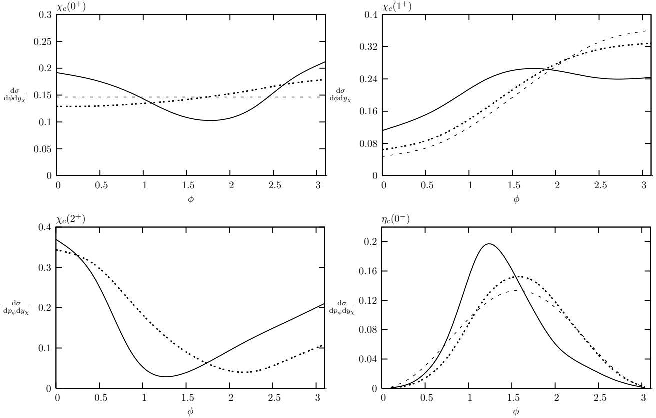


Figure: distribution (in arbitrary units) within the perturbative framework of the difference in azimuthal angle of the outgoing protons for the CEP of different J^P $c\bar{c}$ states at $\sqrt{s} = 14$ TeV. The solid (dotted) line shows the distribution including (excluding) the survival factor, while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

$\rightarrow$ 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_b CEP

- Higher χ_b mass means cross section is more perturbative 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 analogous to χ_c case

$$|V_{0^+}|^2 : |V_{1^+}|^2 : |V_{2^+}|^2 \sim 1 : \frac{\langle \mathbf{p}_\perp^2 \rangle}{M_\chi^2} : \frac{\langle \mathbf{p}_\perp^2 \rangle^2}{\langle \mathbf{Q}_\perp^2 \rangle^2} \sim 1 : \frac{1}{400} : \frac{1}{36}$$

$\rightarrow$ Do not expect to see χ_{b1}, which is strongly suppressed by χ_b mass.

- Measurement of ratio of χ_b to $\gamma\gamma$ ($E_\perp = 5$ GeV) CEP rates would eliminate certain uncertainties (i.e. dependence on survival factors).
- Predictions for χ_b CEP via the $\Upsilon\gamma$ decay chain (at $y_\chi = 0$):

$\sqrt{s}$ (TeV)	1.96	7	10	14
$\frac{d\sigma}{dy_{\chi_b}}(pp \to pp(\Upsilon + \gamma))$ (pb)	0.60	0.75	0.78	0.79
$\frac{d\sigma(1^+)}{d\sigma(0^+)}$	0.050	0.055	0.055	0.059
$\frac{d\sigma(2^+)}{d\sigma(0^+)}$	0.13	0.14	0.14	0.14

$\eta_{c,b}$ production

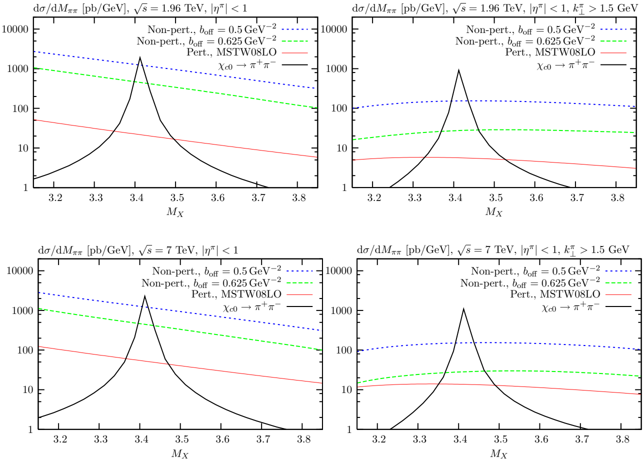
- $gg \to \eta$ vertex calculated as in χ case, but normalisation set in terms of S-wave meson wavefunction at the origin $\phi_S(0)$, which can be related to $\Gamma_{\rm tot}(\eta_c)$ and $\Gamma(\Upsilon(1S) \to \mu^+\mu^-)$ widths.
- Amplitude squared has Lorentz structure

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

  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

$\chi_c \to \pi^+\pi^-, KK$ CEP



- (Exclusive) continuum $\pi^+\pi^-$ background expected to be under control, at least once reasonable cuts ($k_\perp > 1.5$ GeV, $|\eta| < 1$) have been imposed $\Rightarrow$ $\chi_{c0} \to \pi^+\pi^-$ (and K^+K^-) channel should give a clean χ_{c0} CEP signal[4].

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[4] LHL, V.A. Khoze, M.G. Ryskin, W.J. Stirling, Eur. Phys. J. C **72** (2012) 2110.
P. Lebiedowicz, R. Pasechnik and A. Szczurek, Phys. Lett. B **701** (2011) 434.

‘Exotic’ charmonium-like states

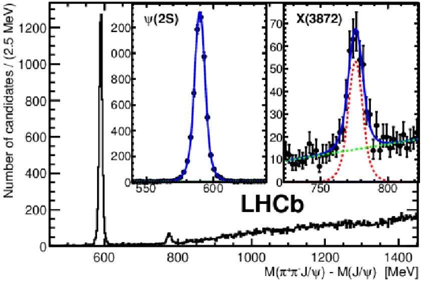
- A ‘zoology’ of XYZ charmonium-like states above the open charm threshold has recently been observed at Belle, Babar, the Tevatron and LHC (arXiv:1010.5827– table).
- Many interpretations (molecular states, tetraquarks, $c\bar{c}g$ hybrids, conventional charmonium...) on the market and many quantum numbers still unassigned.

TABLE 9: As in Table 4, but for new *unconventional* states in the $c\bar{c}$ and $b\bar{b}$ regions, ordered by mass. For $X(3872)$, the values given are based only upon decays to $\pi^+\pi^- J/\psi$. $X(3945)$ and $Y(3940)$ have been subsumed under $X(3915)$ due to compatible properties. The state known as $Z(3930)$ appears as the $\chi_{c2}(2P)$ in Table 4. See also the reviews in [81–84]

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$X(3872)$	3871.52±0.20	1.3±0.6	$1^{++}/2^{-+}$	$B \to K(\pi^+\pi^- J/\psi)$	Belle [85, 86] (12.8), BABAR [87] (8.6)	2003	OK
		(<2.2)		$p\bar{p} \to (\pi^+\pi^- J/\psi) + ...$	CDF [88–90] (np), DØ [91] (5.2)		
				$B \to K(\omega J/\psi)$	Belle [92] (4.3), BABAR [93] (4.0)		
				$B \to K(D^{*0}\bar{D}^0)$	Belle [94, 95] (6.4), BABAR [96] (4.9)		
				$B \to K(\gamma J/\psi)$	Belle [92] (4.0), BABAR [97, 98] (3.6)		
				$B \to K(\gamma\psi(2S))$	BABAR [98] (3.5), Belle [99] (0.4)		
$X(3915)$	3915.6 ± 3.1	28±10	$0/2^{?+}$	$B \to K(\omega J/\psi)$	Belle [100] (8.1), BABAR [101] (19)	2004	OK
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle [102] (7.7)		
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle [103] (6.0)	2007	NC!
				$e^+e^- \to J/\psi$ (...)	Belle [54] (5.0)		
$G(3900)$	3943 ± 21	52±11	1^{--}	$e^+e^- \to \gamma(D\bar{D})$	BABAR [27] (np), Belle [21] (np)	2007	OK
$Y(4008)$	4008^{+121}_{-49}	226±97	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	Belle [104] (7.4)	2007	NC!
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [105] (5.0)	2008	NC!
$Y(4140)$	4143.4 ± 3.0	15^{+11}_{-7}	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF [106, 107] (5.0)	2009	NC!
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle [103] (5.5)	2007	NC!
$Z_2(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [105] (5.0)	2008	NC!
$Y(4260)$	4263 ± 5	108±14	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	BABAR [108, 109] (8.0)	2005	OK
					CLEO [110] (5.4)		
					Belle [104] (15)		
				$e^+e^- \to (\pi^+\pi^- J/\psi)$	CLEO [111] (11)		
				$e^+e^- \to (\pi^0\pi^0 J/\psi)$	CLEO [111] (5.1)		
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF [107] (3.1)	2010	NC!
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0,2^{++}$	$e^+e^- \to e^+e^-(\phi J/\psi)$	Belle [112] (3.2)	2009	NC!
$Y(4360)$	4353 ± 11	96±42	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$	BABAR [113] (np), Belle [114] (8.0)	2007	OK
$Z(4430)^+$	4443^{+24}_{-18}	107^{+113}_{-71}	?	$B \to K(\pi^+\psi(2S))$	Belle [115, 116] (6.4)	2007	NC!
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$	Belle [25] (8.2)	2007	NC!
$Y(4660)$	4664±12	48±15	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$	Belle [114] (5.8)	2007	NC!
$Y_b(10888)$	10888.4±3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\pi^+\pi^-\Upsilon(nS))$	Belle [37, 117] (3.2)	2010	NC!

X(3872)

- Discovered by Belle in 2003, confirmed by Babar, at the Tevatron and the LHC.
- Could be of exotic nature: loosely bound hadronic molecule, diquark-antidiquark ('tetraquark') and hybrid ($\bar{c}cg\cdots$). However, conventional $c\bar{c}$ interpretation is still possible.



- Possible J^{PC} assignments were 1^{++} or 2^{-+}.
- New LHCb data (arXiv:1302.6269) rejects 2^{-+} at 8 sigma level $\rightarrow \eta_{c2}(1^1D_2)$ ruled out.
- Exotic interpretations still possible or conventional $\chi_{c1}(2^3P_1)$ charmonium?

Insight from CEP

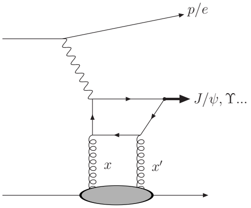
- In CEP the state X is produced directly, i.e. at short distances: $gg \to X(3872)$ and nothing else. $\to$ would be clear evidence of a direct production mode.
- In an inclusive environment, for which additional soft quarks, D–mesons etc can be present/emitted it *may* be easier to form molecular or 4–quark states.

$\to$ Can shed further light by comparing to the rate of $\chi_{c1}(1^3P_1)$ production, as seen by LHCb. Up to mass effects, cross section ratio should be given by ratio of squared wavefunction derivatives at the origin $|\phi'_P(0)|^2$.

- Also, can consider e.g. the $Z(3930) \equiv \chi_{c2}(2P)$:
  - 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 $\chi_{c2}(1P)$.

Exclusive ($J/\psi, \psi(2S), \Upsilon$,...) production

- Can also produce C–odd states exclusively, via $\gamma gg \to X$.
- Strong coupling part of diagram can be modelled in QCD, mediated by 2–gluon exchange.



- Gives

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

where $Q^2 = M^2/4$, $x = M/\sqrt{s}\exp(-y)$, and $\Gamma_{ee} = \Gamma(... \to e^+e^-)$.

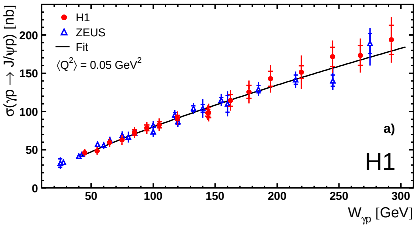
$\to$ At forwards rapidities, exclusive $J/\psi(\Upsilon)$ production cross section is sensitive to gluon pdf in low x region.

- Low–$p_\perp$ (large distance) photon exchange: $S^2 \sim 85\%$ close to 1.
- However: other corrections may give some correction to this simple formula, and should be considered[5]. For e.g. J/ψ: relativistic corrections ($\sim -10\%$), $M_\psi \neq 2m_c$ effect ($\lesssim +50\%$), real part of amplitude ($\sim +50\%$), gluon $k_\perp$ ($\lesssim -30\%$), $x' \neq 0$ ($\sim +10\%$), full NLO treatment...

[5] See e.g. A.D. Martin, M.G. Ryskin, T. Teubner, Phys.Lett. B454 (1999) 339-345

Exclusive ($J/\psi, \psi(2S), \Upsilon$...) production (2)

- Can also occur in *ep* collisions: $\gamma p \to J/\psi(\Upsilon)p$ measured at HERA.
- This can trivially be translated into a cross section in *pp* collisions: only difference is in *e* v.s. *p* EM form factor.



- This can be fit well using a simple parameterization (expected from Regge)

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

- Measured for energies up to $W_{\gamma p} \approx 300$ GeV, i.e. $|y_\psi| < 1.4$ at $\sqrt{s} = 7$ TeV.

$\rightarrow$ LHC can probe new energies at forward rapidities, but these fits should give reliable predictions for these (seen by LHCb arXiv:1301.7084) .

SuperCHIC MC

A MC event generator including[6]:

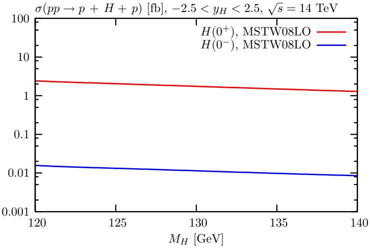
- Simulation of different CEP processes, including all spin correlations:
  - $\chi_{c(0,1,2)}$ CEP via the $\chi_c \to J/\psi\gamma \to \mu^+\mu^-\gamma$ decay chain.
  - $\chi_{b(0,1,2)}$ CEP via the equivalent $\chi_b \to \Upsilon\gamma \to \mu^+\mu^-\gamma$ decay chain.
  - $\chi_{(b,c)J}$ and $\eta_{(b,c)}$ 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 heavy quark, Higgs...?).

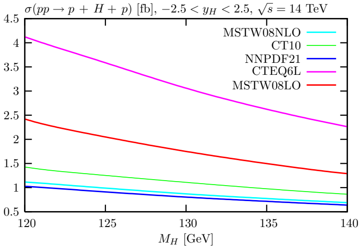
→ Via close collaboration with CDF, STAR and LHC collaborations, in both proposals for new measurements and applications of SuperCHIC, it is becoming an important tool for current and future CEP studies.

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

The future(?) Higgs Boson CEP

- Higgs Boson CEP $pp \to p + H + p$ via $gg \to H$ is a very promising observable[7].
- The observation of Higgs Boson CEP provides an additional way to determine its spin and CP properties and to precisely measure its mass, (in some cases) width and couplings (Hbb Yukawa...). However, this requires the addition of forward proton taggers at 420m from the CMS/ATLAS interaction point. Currently only the 220m detectors are on the table.





[7] See e.g. LHL, V.A. Khoze, M.G. Ryskin, W.J. Stirling, arXiv:1301.2552, and references therein.

Summary and Outlook

- CEP in hadron collisions offers a promising and complementary framework within which to study the quarkonium sector.
- Specific dynamics of exclusive production mode offers new insight:
  - Can act as quantum number filter, through $J_z^P C = 0^{++}$ selection rule $\to$ gives a strong hierarchy in cross sections.
  - Distinct proton angular distributions depending on the central object quantum numbers.
- Exclusive χ_{cJ} production already observed at the LHC and Tevatron, in reasonable agreement with theory.
- χ_{bJ} and $\eta_{c,b}$ represent other interesting observables.
- The CEP process may shed light on the exotic charm sector ($X(3872)$...).
- Exclusive photoprouction of C–odd ($J/\psi, \Upsilon$...) a further interesting process, for which LHC data now exists.

Supplementary Slides

$J_z^{PC} = 0^{++}$ selection rule

- Consider the limit $p_{1_\perp} = p_{2_\perp} = 0$, i.e. exactly forward scattering. Have

$$q_{1_\perp} = -q_{2_\perp} = Q_\perp \; ,$$
$$\epsilon_1 = -\epsilon_2 \; ,$$

i.e. $gg \to X$ subamplitude is given by

$$\mathcal{M} \sim Q_\perp^i Q_\perp^j V_{ij} \qquad (i/j = 1,2)$$
$$\to \frac{1}{2} Q_\perp^2 (V_{++} + V_{--})$$

i.e. fusing gluons have equal (transverse) polarisations $\lambda_1 = \lambda_2 = \pm$, and are even under the interchange $+ \pm -$ of the gluon polarizations.

$\to$ In exact forward limit, fusing gluons are in a $J_z^P = 0^+$ state along beam axis.

χ_c CEP: uncertainties

- Principle sources of uncertainty are:
  - Due to choice of PDFs at low–x, Q^2: $\sim \stackrel{\times}{\div} 2-3$
  - Higher–order corrections (in particular for $\chi_{c(1,2)}$): $\sim \stackrel{\times}{\div} 2$.
  - Non-perturbative corrections, harder to quantify, but roughly expect $\sim \stackrel{\times}{\div} 2-3$.
  - Survival factors: $\sim \stackrel{\times}{\div} 1.5$.

$\rightarrow$ Expect about a $\sim \stackrel{\times}{\div} 5$ uncertainty in the *total* χ_c cross section. However:
  - This is expected to be much less ($\sim \stackrel{\times}{\div} 2$) when considering the ratio of χ_{cJ} cross sections, as PDF and survival factors (almost) completely cancel, with some cancellation for other uncertainties.
  - Can 'calibrate' theory prediction to Tevatron data, so that uncertainty at the LHC is much less.

$\chi_{c(1,2)}$ CEP: vertices

- $gg \to \chi_{c(1,2)}$ vertices given by

$$V_1 = -\frac{2ic}{s} p_{1,\nu} p_{2,\alpha} ((q_{2_\perp})_\mu (q_{1_\perp})^2 - (q_{1_\perp})_\mu (q_{2_\perp})^2) \epsilon^{\mu\nu\alpha\beta} \epsilon^{*\chi}_\beta \,, \tag{3}$$

$$V_2 = \frac{\sqrt{2} c M_\chi}{s} (s (q_{1_\perp})_\mu (q_{2_\perp})_\alpha + 2 (q_{1_\perp} q_{2_\perp}) p_{1\mu} p_{2\alpha}) \epsilon_\chi^{*\mu\alpha} \,, \tag{4}$$

where $c \propto \phi'_P(0)$. In $p_\perp \to 0$ limit these reduce to

$$V_1 \to \frac{4ic}{s} Q_\perp^2 p_{1,\nu} p_{2,\alpha} Q_{\perp\mu} \epsilon^{\mu\nu\alpha\beta} \epsilon^{*\chi}_\beta \,, \tag{5}$$

$$V_2 \to -\frac{\sqrt{2} c M}{s} (s Q_{\perp\mu} Q_{\perp\alpha} + 2 Q_\perp^2 p_{1\mu} p_{2\alpha}) \epsilon_\chi^{*\mu\alpha} \,. \tag{6}$$

$\to$ V_1 vanishes due to antisymmetry of $\epsilon^{\mu\nu\alpha\beta}$.

$\to$ V_2 vanishes after performing the azimuthal integral in $\mathrm{d}^2 Q_\perp$:

$$\int d^2 Q_\perp Q_{\perp\mu} Q_{\perp\sigma} = \frac{\pi}{2} \int dQ_\perp^2 Q_\perp^2 g^T_{\mu\sigma} \,, \tag{7}$$

where $g^T_{\mu\sigma}$ is the tranverse metric, and we need that $\epsilon^{*\mu}_{\chi,\mu} = 0$.

The role of proton dissociation

- The LHC cannot currently exclude the contribution from the central diffractive process
$$pp \to Y + X + Z ,$$
to pure CEP
$$pp \to p + X + p .$$
- How should we include this? Recall the (bare) CEP amplitude is given by

$$T = \pi^2 \int \frac{d^2\mathbf{Q}_\perp \mathcal{M}(gg \to X)}{\mathbf{Q}_\perp^2(\mathbf{Q}_\perp - \mathbf{p}_{1_\perp})^2(\mathbf{Q}_\perp + \mathbf{p}_{2_\perp})^2} f_g(x_1, x_1', Q_1^2, \mu^2; t_1) f_g(x_2, x_2', Q_2^2, \mu^2; t_2)$$

- For dissociation into a state with mass M_Y we must 'simply' replace the unintegrated gluon density $f_g(x_i, ...\mu^2; t) \to f_g(x_i, ...; t; M_Y^2)$. But the form of this function is almost unknown $\Rightarrow$ try to make plausible assumptions about its behaviour.
- Two regimes to consider:
  - Low mass dissociation ($M_Y \lesssim 2$ GeV).
  - High mass dissociation ($M_Y \gtrsim 2$ GeV).

Low mass dissociation

- Dissociation into low mass nucleon excitations ($p \to N^* + ...$) with $M_Y \lesssim 2$ GeV.
- Situation is not too different from pure elastic $p \to p$ transition relevant to CEP, so it is reasonable to assume same x, Q^2, μ and t behaviour for f_g's.

$\to$ Can incorporate low mass dissociation by simply multiplying CEP result by some factor $1 + c$, where c is the probability of the $p \to N^*$ transition.

- Value of c can be calculated in two ways:
  - Measured at lower (fixed target and CERN-ISR) energies, can be extrapolated to the LHC by accounting for the stronger absorptive effects at higher $\sqrt{s}$.
  - Diffractive DIS @ HERA[8]: by comparing size of the measured cross section using the leading proton spectrometer and with the LRG requirement.
- In both case we find $c \approx 0.2 \Rightarrow$ CEP prediction should be enlarged by a factor $(1 + c)^2 \sim 1.4$.

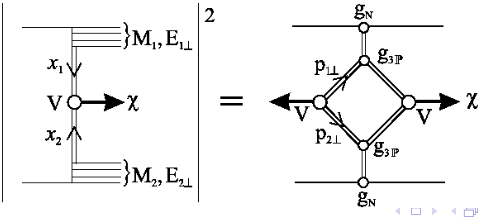
[8] F. Aaron et al., Eur.Phys.J. C71, 1578 (2011), 1010.1476.; S. Chekanov et al., Nucl.Phys. B816, 1 (2009), 0812.2003

High mass dissociation

- Dissociation into higher mass states ($M_Y \gtrsim 2$ GeV) described by triple–Pomeron diagrams. For fixed momentum transfered through the Pomeron, t, we have

$$\frac{\sigma(p \to M_Y)}{\sigma(\mathrm{CEP})} = \int \frac{\mathrm{d}M_Y^2}{M_Y^2} \frac{g_N(0) g_{3P}(t)}{\pi g_N^2(t)} \,, \tag{8}$$

- Triple–Pomeron vertex, g_{3P} can be extracted from lower energy data (CERN-ISR, Tevatron) to give $g_{3P}(0) = 0.2 g_N(0)$.
- However: the t–slope, b_{3P} of the 'bare' $g_{3P} \propto \exp(b_{3P} t)$ vertex is poorly known, and may even be consistent with zero, with[9] $b_{3P} < 2\ \mathrm{GeV}^{-2}$.
  - Absorptive effects strongly depend on shape of amplitude in impact parameter, b_t, space $\Rightarrow$ size of S^2 uncertain.



High mass dissociation (2)

- From Eq. (8) the proton $p_\perp^2 \sim 1/b_{3P}$ can be large:
  - Cannot justify factorization $f_g(x_i, ...\mu^2; t; M_Y^2) = G(t) f_g(x_i, ..., \mu^2; M_Y^2)$, with unreasonably large dissociation probability.
  - Larger $p_\perp$ allows an increasing violation of the $J_z = 0$ selection rule ($|J_z| = 2$ contribution is $\propto \langle p_\perp^2 \rangle^2$). Recall that χ_{c2} (also $\pi\pi$) $J_z = 0$ CEP are strongly suppressed $\to$ could play an important role in LHCb data.
- Taking $b_{3P} = 1\mathrm{GeV}^{-2}$ we can roughly estimate the admixture, C, of high mass dissociation in LHC 'exclusive' events by integrating over uninstrumented Δy.
- We find $C \approx 30 - 40\%$ for the CMS (ATLAS) experiment and $C \approx 50\%$ for LHCb. However we should recall large uncertainties in these estimates (MC + detector simulation etc also needed).
- Possible ways to shed light on this issue:
  - Forward shower counters (and ZDC) @ LHC in low luminosity runs: can veto on greatly extended η region, will reduce inclusive contamination (installed at CMS).
  - Select events with low $p_\perp$ in central system (e.g. coplanarity $\Delta\phi$ cuts for $\gamma\gamma$, $\pi\pi$ CEP...).