Central exclusive quarkonium and diphoton production

Lucian Harland-Lang

Cavendish Laboratory, University of Cambridge

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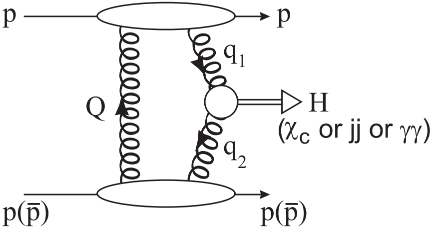
Based on work by V.A. Khoze, M.G. Ryskin, W.J. Stirling and L.A. Harland-Lang. (KHRYSTHAL collaboration)
For more details see arXiv:1005.0695 and arXiv:1011.0680

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.
- 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.

‘Standard Candle’ processes

- CEP of low mass objects (χ_c, χ_b, $\gamma\gamma$ and *jj*) driven by the same mechanism as Higgs (or other new object) CEP at the LHC, but will have larger cross sections.
- χ_c, $\gamma\gamma$ CEP already observed by CDF and *jj* CEP observed by CDF & D0.

→ 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.

- In this talk I will focus on:
  - Quarkonium production: χ_c, χ_b, XYZ charmonia, proton correlations...
  - Diphoton/Dimeson production: $\pi^0\pi^0$ as a background to $\gamma\gamma$ CEP.

CDF χ_c data vs theory

χ_{cJ} : $L = 1, S = 1, J^{PC} = (0,1,2)^{++}$ $c\bar{c}$ meson states, $M_{\chi_c} \approx 3.5$ GeV.

- 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:

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

- General considerations tell us that χ_{c1} and χ_{c2} CEP rates are strongly suppressed, 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 ($\sim \stackrel{\times}{\div} 5$) 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, 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.

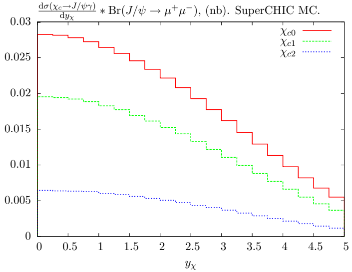
$\rightarrow$ The combined result of these different effects is that the χ_c CEP rate is expected to have a weak energy dependence going from the Tevatron to the LHC.

- An explicit calculation gives the results (for $y_\chi = 0$):

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

χ_c CEP @ LHCb (ALICE)

- 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.



- 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 $pp \to p + \chi + X$, can be of similar size to exclusive rate (depends on cuts and event selection).
  - Fully inclusive $pp \to \chi + X$ with fluctuation due to hadronisation creating gap(s)– probability exponentially supressed $\sim e^{-\Delta\eta}$, but inclusive rate ~ 4 orders of mag. higher.
- Average $p_\perp(\chi_c)$ lower in exclusive case.
- Foward shower counters @ LHC: can veto on greatly extended η region, will reduce inclusive contamination.
- Other decays ($\chi_{c(0,2)} \to \pi^+\pi^-, K^+K^-$...) $\to$ should dominantly see χ_{c0}'s.

χ_b CEP

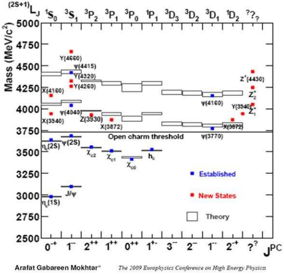
- Higher χ_b mass means cross section is more perturbative and so is better test of theory, although rate is $\sim$ 3 orders of magnitude smaller than χ_c.
- J assignment of χ_b states still experimentally undetermined: CEP could shed light on this.
- New data: CLEO measurement gives $\mathrm{Br}(\chi_{b0} \to \Upsilon\gamma) = (1.73 \pm 0.35)\%$ (arXiv:1012.0589), lower than our previous default value of 3%.
- $\Gamma(\chi_{b0} \to \Upsilon\gamma)$ (E1) transition width under good control theoretically $\Rightarrow$ measurement indicates that $\Gamma_{\rm tot}(\chi_{b0}) \approx 1.2$ MeV (0.8 MeV previously).
  - Predicted χ_{b0} cross section is higher by a factor $\sim 3/1.73$.
  - χ_{b0} cross section via $\Upsilon\gamma$ decay unchanged (only depends on $\Gamma(\chi_{b0} \to \Upsilon\gamma)$).
  - Suppression of χ_{b1} and χ_{b2} rates relative to χ_{b0} is expected to be less strong (by a factor $\sim 3/1.73$) than previously estimated.
- Updated 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

‘Exotic’ charmonium-like states

A ‘zoology’ of charmonium-like XYZ 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): charmonium?
- 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 and D0.
  - 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 (recent renewal of interest).
  - Possible J^{PC} assignments are 1^{++} or 2^{-+}.
  - Recent Belle $X(3872) \to J/\psi\omega$ data seems to favour[1] 2^{-+} although many theory groups find conventional $^2D_1$ $c\bar{c}$ 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 $\rightarrow$ exclusive open charm ($D\overline{D}$...) production.
  - Theory: roughly the same cross section and distributions as $\chi_{c2}(1P)$.

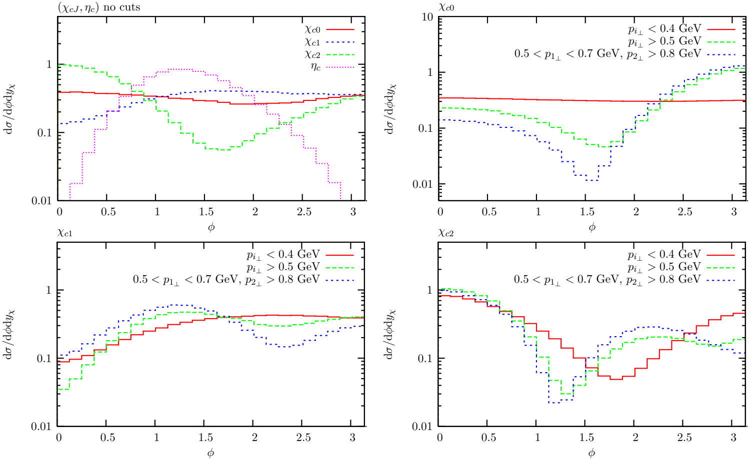
[1] S-wave fit– $P(\chi^2, \mathrm{NDF}) = 7.1\%$; P-wave fit– $P(\chi^2, \mathrm{NDF}) = 61.9\%$

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:
  - Direct $gg \to \pi\pi$ background expected to be low (see later in talk).
  - 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

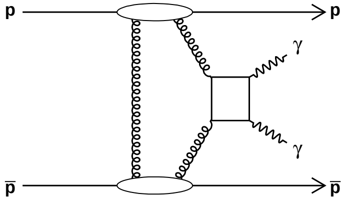


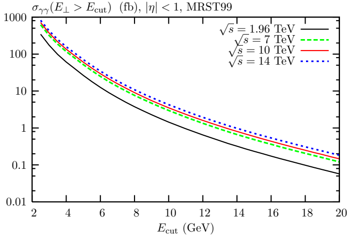
$\rightarrow$ ϕ distributions depend on central particle spin, but are also strongly affected by soft survival effects, in particular for larger values of proton $p_\perp$ (RHIC II), where cancellation between screened and unscreened amplitudes results in characteristic 'diffractive dip' structure.[2]

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

Dimeson CEP, motivation: $\gamma\gamma$ production

- 3 candidate events observed by CDF (arXiv:0707.237), with more to come very soon.
- Similar uncertainties to χ_c case for low $E_{\perp_\gamma} < E_{\rm cut}$ scale, but this decreases for higher scales.
- More CDF events will allow us to probe scaling of σ with cut on photon $E_\perp$ ($\lesssim M_{\gamma\gamma}/2$): strong predicted fall-off with $M_{\gamma\gamma}$ comes from Sudakov factor (already seen in dijet data).





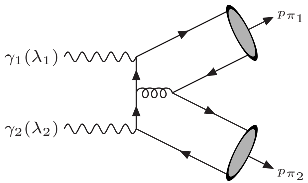
- **However**: $\pi^0\pi^0(\eta\eta)$ production, with one photon from each decay either undetected or two photons merging, is a potentially important background (pure QCD process).

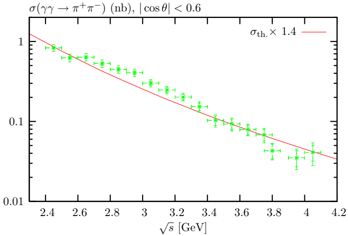
Modelling dimeson CEP perturbatively

- Simpler exclusive process $\gamma\gamma \to M\overline{M}$ $(= \pi^0\pi^0, \eta\eta, \pi^+\pi^- ...)$ at large angles was calculated ∼30 years ago[3].
- Total amplitude given by convolution of parton level $\gamma(\lambda_1)\gamma(\lambda_2) \to q\bar{q}q\bar{q}$ amplitude with non-perturbative pion wavefunction $\phi(x)$

$$\mathcal{M}_{\lambda_1\lambda_2}(s,t) = \int_0^1 \mathrm{d}x\,\mathrm{d}y\,\phi(x)\phi(y)T_{\lambda_1\lambda_2}(x,y;s,t)$$

where helicity amplitudes $T_{\lambda_1\lambda_2}$ can be calculated perturbatively.
- With suitable choice of $\phi(x)$, $\gamma\gamma \to M\overline{M}$ data is described quite well (see plot[4].).





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

[4] Data taken from Belle Collaboration, Phys. Lett. B615 (2005) 39

$gg \to M\overline{M}$ calculation (preliminary)

- Can calculate the LO $gg \to M\overline{M}$ amplitudes in same way to give

$$T_{++} = T_{--} = 0\,,$$

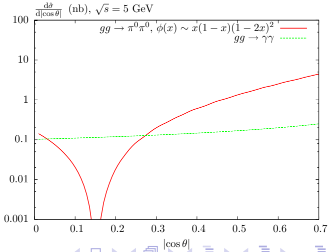
$$T_{-+} = T_{+-} \propto \frac{\alpha_S^2}{a^2 - b^2\cos^2\theta}\left(\frac{N_c}{2}\cos^2\theta - C_F a\right)\,,$$

where $a, b = (1-x)(1-y) \pm xy$.

$\rightarrow$ $J_z = 0$ amplitudes vanish, as in $\gamma\gamma \to M\overline{M}$ for neutral mesons.

$\rightarrow$ $J_z = 2$ amplitudes contain 'radiation zero'[5]: vanish for a physical value of $\cos\theta$. Well known effect in all gauge theories (e.g. $u\overline{d} \to W^+\gamma$), but usually washed out in QCD by colour averaging.

- $\hat{\sigma}(gg \to \pi^0\pi^0)$ enhanced relative to $\hat{\sigma}(gg \to \gamma\gamma)$ by $\sim (\alpha_S/\alpha)^2$.
- Normalisation of $\phi(x)$ introduces a factor $f_\pi/\hat{s}^{1/2} \sim$ prob. amp. for $q\overline{q}$ to form pion $\Rightarrow$ cross section suppressed by $\sim (f_\pi/\hat{s}^{1/2})^4$.



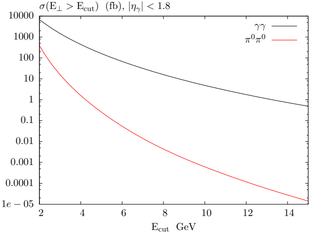
[5] See for example R.W. Brown, arXiv:hep-th/9506018

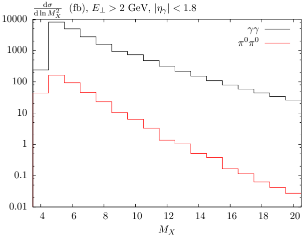
$\pi^0\pi^0(\eta\eta)$ CEP (preliminary)

- The $J_z = 0$ $gg \to \pi^0\pi^0$ amplitude vanishes and so fusing gluons will principally be in a $|J_z| = 2$ state, but this is heavily suppressed by $J_Z = 0$ selection rule:

$$\frac{\sigma_{\rm CEP}(\pi^0\pi^0)}{\sigma_{\rm CEP}(\gamma\gamma)} \approx \frac{\hat{\sigma}(\pi^0\pi^0)}{\hat{\sigma}(\gamma\gamma)} \frac{\langle p_\perp^2\rangle^2}{\langle Q_\perp^2\rangle^2}$$

- $\pi^0\pi^0$ contribution to diphoton signal expected to be small, and strongly decreasing with mass $\sigma(\pi^0\pi^0)/\sigma(\gamma\gamma) \sim M_X^{-4}$. This also applies to $\eta\eta$ CEP.



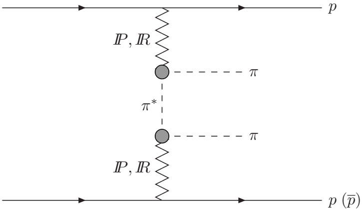


- However: possible $J_Z = 0$ contribution from higher twist effects (c.f. $\sigma(\pi^+\pi^-)/\sigma(\pi^0\pi^0)$ data[6]), NLO corrections... could increase rate by a factor 'a few'. Also, possible non-perturbative contribution at lower $p_\perp$?

[6] Belle colaboration, Phys. Rev. D78 (2008) 052004.

$\pi^0\pi^0$ non-perturbative production

- For low values of pion $p_\perp$, expect non-perturbative double Pomeron/Reggeon exchange mechanism to contribute, mediated via an off-shell pion.



- Uncertainty in what to take for form factor of off-shell pion ('soft' vs 'hard' fit), which suppresses high values of final state pion $p_\perp$, leads to quite large uncertainty in expected rate.
- Expect smooth transition with increasing $p_\perp$ between non-perturbative ($\sim$ real amplitude) and perturbative ($\sim$ imaginary amplitude) dominance.
- Measurement of $\pi_0\pi_0/\pi^+\pi^-$ CEP in low $p_\perp$ region would help constrain off-shell pion form factor.

SuperCHIC MC

A MC event generator including[7]:

- 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.
  - $\gamma\gamma$ CEP.
  - Exclusive J/ψ and Υ photoproduction.
- More to come (dimeson, dijets, open quark, Higgs...?).

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

Conclusion

- 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.
- Possibility that χ_{c1} and χ_{c2} CEP may contribute to CDF χ_c events-measurement of relative χ_{cJ} contributions at LHC would be very interesting.
- χ_b, η_b and η_c CEP potential observables at the LHC.
- CEP with proton tagging already possible at RHIC.
- CEP is possible tool in establishing nature of the various X,Y,Z charmonium-like states.
- J/ψ (Υ) exclusive photoproduction included in SuperCHIC.
- Perturbative calculation predicts that $\pi^0\pi^0$ (and $\eta\eta$) BG to $\gamma\gamma$ CEP to be supressed– publication to follow.
- Future work: dimeson CEP of interest in its own right, e.g. $\eta'\eta'$ production, expected to be enhanced relative to $\pi\pi$...

Backup 1: $\eta_{c,b}$ 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

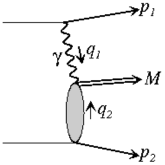
$$|V_{0^-}|^2 \propto p_{1_\perp}^2 p_{2_\perp}^2 \sin^2(\phi) \ ,$$

  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 2: 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 3: CEP with proton taggers (2)

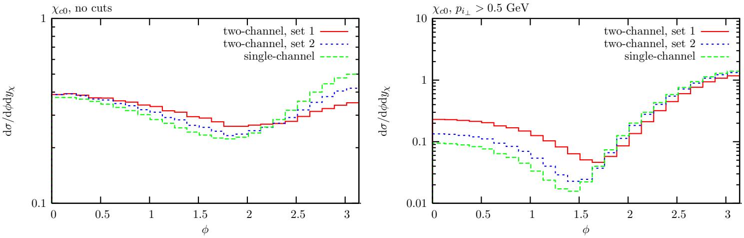


Figure: Normalised distributions (in arbitrary units) of the difference in azimuthal angle between the outgoing protons for χ_{c0} CEP, with the survival factor $S^2_{\rm eik}(b_t)$ calculated using a two-channel eikonal model, with two different choices of model parameters. Parameter set 1 accounts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