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Selected New Results on Central Exclusive Production

(KRYSTHAL Collaboration)



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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 arXiv:1204.4803

Outline

- Introduction (why we are interested in CEP processes?)
- Oiffractive Higgs' revisited.
- Standard Candle CEP processes.
- CEP as a way to study old and new heavy resonances.
- CEP through the KRYSTHAL eyes (new results, selected topics).
 - **Diphoton CEP.** (Mike's and Wenbo's talks)
 - Dimeson CEP. (new CDF&CMS data to come) (Mike)
 - SuperCHIC MC.
 - Summary and Outlook.



Introduction (why we are interested in CEP ?)

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.
- χ_c , *jj* and $\gamma\gamma$ CEP has been observed by CDF.
- → 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:
 - Heavy quarkonium production can shed light on the physics of bound states (lattice, NRQCD···).
 - Potential to produce different J^P states, which exhibit characteristic features (e.g. angular distributions of forward protons).
 - Possibility to shed light on the various 'exotic' charmonium states observed recently (X,Y,Z) charmonium-like states.

Spin-Parity Analyzer

(KMR-00, KKMR-2003)

 Detailed tests of dynamics of soft diffraction (KMR-02)
 New CMS, CDF, LHCb dihadron CeX results (soon) to come. Alice dipion data. D0 jj- results. LHCb χ_c CMS, RHIC data expected



+ strong evidence from the Tevatron

Elusive particle found, looks like Higgs boson



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Rolf Heuer, Director-General of CERN, answers a journalist's question about the scientific seminar to deliver the latest update in the search for the Higgs boson in Meyrin near Geneva on Wednesday.

AP

'Diffractive Higgs' revisited



New leverage -proton momentum correlations (probes of QCD dynamics, CP- violation effects...)

(Christophe's talk)

mass, spin, couplings to fermions, invisible modes... \rightarrow for all these purposes the CeXP will be particularly handy ! SuperCHIC

(ExHuME-05) .

(Halfway)

Higgs Boson: cross section predictions



- Cross section ~ fbs, i.e. roughly 4 orders of mag. lower than inclusive case (price paid for exclusivity).
- CEP of a CP–odd Higgs suppressed by σ(0[−])/σ(0⁺) ~ 1/100 → with just a few signal events, the Higgs quantum numbers can be determined (does not rely on coupling to weak bosons).



THINGS TO DO !



- Account for the b-dependence of the survival factors
- NLO effects in the unintegrated parton densities
- A systematic account of self-energy insertions in the propagator of the screening gluon
- The dependence on the gluon PDF is amplified by the fact that the CEP cross section is essentially proportional to $(xg(x))^4$. KKMR-04; CLP-07.

CDF $\gamma\gamma$ data *may* suggest more 'LO–type' PDFs (\rightarrow more optimistic Higgs cross sections) are appropriate.



Current theoretical understanding:



Strong interaction of the 125 GeV boson with the ZZ/WW disfavours (but not conclusively excludes) pseudoscalar, but heavier Higgs-like particles ?

(GLM-new results)



 $S_{\rm enh}^2, S_{\rm eik}^2$



(M.Tasevsky+HKW-2012)

Needs (post July 4th) updatefurther shrinkage !

Available MSSM CEP x-sections

2012 results M.Tasevsky+ HKW



 M_h contours stay constant with M_A

Available MSSM CEP x-section stay constant with M_A (because R=MSSM/SM =1 in this region) reaching maximum of 1.8 fb

x-section of 1.5 fb reachable but in a tiny allowed phase-space region. Outside this region the x-section is very small

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Max -factor 5-10 enhancement.

a) LHC MSSM exclusion regions (red area)[HiggsBounds: P. Bechtle et al., Comput. Phys. Commun. 181 (2010) 138]b) One possible region of interest (green area): SM Higgs at M=125 GeV +- 1 GeV (exper.).If theory uncertainties added: 122 < M < 128 GeV</td>[S. Heinemeyer et al., arXiv:1112.3026[hep-ph]]



CEP as a way to study old and new heavy resonances.



Zoo of charmonium –like XYZ states





- Discovered by BELLE in 2003, confirmed by BaBar, CDF, D0, CMS, LHCb.
- 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 $\Gamma(\pi^+\pi^- J/\psi(1S))/\Gamma_{\text{total}} > 2.6\%$; $\Gamma(\gamma\psi(2S))/\Gamma_{\text{total}} > 3.0\%$, $\Gamma^{<1.2 \text{ MeV}}$ (maybe two different states X(3872), X(3875))

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

 $Z(3930) \equiv \chi_{c2}(2P)$

Indications for:

- $\chi_{c0}(2P), M = 3840 \ (3915) \ {
 m MeV}$
- Above DD threshold .
- Vertex detection at LHCb & RHIC→
- ; exclusive open charm: $D^+D^-, D^0\overline{D}^0$.
 - <u>Roughly</u> the same expectations for CEP as for $\chi_{c0,c2}$

Triggering on J/ψ : $M \rightarrow J/\psi + \gamma$, $J/\psi + \rho$

CEP through the eyes of the KRYSTHAL (2008-2012)

- Colliding protons interact via a colour singlet exchange and remain intact: can be measured by adding detectors far down the beam-pipe. (or LRGs)
- A system X of mass M_X is produced at the collision point, and only its decay products are present in the central detector.



- The generic process pp → p + X + p is modeled perturbatively by the exchange of two t-channel gluons, with the use of pQCD justified by the presence of a hard scale ~ M_X.
- 'J_z = 0 selection rule': production of states with non-J^P_Z = 0⁺ quantum numbers is strongly suppressed by ~ 2 orders of magnitude.
- χ_c , $\gamma\gamma$ CEP already observed by CDF and *jj* CEP observed by CDF & D0.



 χ_{cJ} CEP is reported by LHCb (DIS-11)



new CDF $\gamma\gamma$ CEP results (PRL-2012) (Mike's talk)

All measurements in agreement with Durham group (pre)dictions.

CMS-2012-first studies (Wenbo's talk) A MC event generator including⁸:

- 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.
 - γγ CEP.
 - Meson pair (ππ, KK, ηη...) 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.

⁸The SuperCHIC code and documentation are available at http://projects.hepforge.org/superchic/





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Standard Candle Processes

 CEP is a promising way to study new physics at the LHC, but we can also consider the CEP of lighter, established objects : χ_c, γγ and jj CEP

already observed at the Tevatron.



- 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 right¹.
- This talk will focus on the CEP of γγ and light meson pairs, MM, at sufficiently high invariant mass for perturbative formalism to be applicable:
 - Provides novel application/test of hard exclusive formalism, complementary to more standard photon-induced processes (γγ → MM, γγ^(*) → M etc²).
 - Demonstrates application of MHV formalism to simplify/check calculations.
 - $\pi^0 \pi^0$ CEP a possible background to $\gamma \gamma$ CEP.
 - Could probe the qq̄ and gg content of η, η' mesons?
 - An interesting potential observable @ RHIC, Tevatron and LHC: meson pair CEP data (at lower p_⊥) already being taken by ALICE and CDF.

¹See LHL, V.A. Khoze, M.G. Ryskin, W.J. Stirling, arXiv:1005.0695 and arXiv:1011.0680. ²For a recent review, see for example V. L. Chernyak, arXiv:0912.0623. □ ► < 클 ► < 클 ► < 클 ► < 클 ► < 클 ► < Ξ ► < S < ⊙

Standard Candle processes: χ_c CEP

- In arXiv:0902.1271 CDF reported 65 ± 10 signal χ_c events observed via the χ_c → J/ψγ → μ⁺μ⁻γ decay channel. This corresponds to dσ(χ_c)/dy_χ|_{y=0} = (76 ± 14) nb, in good agreement with Durham prediction of ~ 60 nb. (Krakow group)
- Recent LHCb data⁵: select 'exclusive' χ_c → J/ψγ events by vetoing on additional activity in given η range.
- LHCb see:

	$\sigma(pp \rightarrow pp(\chi_c \rightarrow \mu^+ \mu^- \gamma))$ LHCb (pb)	SuperCHIC (pb)
Xco	9.3 ± 4.5	14
Xcl	16.4 ± 7.1	10
Xc2	28 ± 12.3	3

→ Encouraging agreement between data and (Durham) theory, accounting for (large) theory uncertainties for χ_c case, and potential inclusive contamination at LHCb.

Proton dissociation conribution

· · · · · · · · ·

⁵LHCb-CONF-2011-022.

Saa

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

- 3 candidate events observed by CDF (arXiv:0707.237) Now 43 events
- Similar uncertainties to χ_c case for low E_{⊥_γ} < E_{cut} scale, but this decreases for higher scales.
- More CDF events allow us to probe scaling of σ with cut on photon E_{\perp} ($\leq M_{\gamma\gamma}/2$): strong predicted fall-off with $M_{\gamma\gamma}$ driven by Sudakov factor (already seen in dijet data).



 However: π⁰π⁰(ηη) production, with one photon from each decay either undetected or two photons merging, is a potentially important background (pure QCD process).



(now proved to be very small (CDF) in agreement with our expectations)





Standard Candle processes: $\gamma\gamma$ CEP

- γγ CEP: represents clean signal, with less of the theory issues related to, e.g. χ_c CEP. → ideal 'standard candle'.
- New CDF $\gamma\gamma$ data⁶ for $E_{\perp}(\gamma) > 2.5$ GeV, $|\eta(\gamma)| < 1$. They find $\sigma_{\gamma\gamma} = 2.48^{+0.40}_{-0.35}$ (stat) $^{+0.40}_{-0.51}$ (syst) pb,
- Theory predictions: 1.42 pb (MSTW08LO) and 0.35 pb (MRST99), with approx. uncertainties (additional to PDFs) ~ [×]/_÷2.
- $\pi^0 \pi^0$ BG observed to be small, in agreement with non-trivial Durham prediction (follows from $J_z = 0$ selection rule).
- New CMS $\gamma\gamma$ search for $E_{\perp}(\gamma) > 5 \text{ GeV}^7$: $\sigma_{\gamma\gamma} < 1.3 \text{ pb} @ 95\%$ (Wenbo's talk) confidence.





New Exclusive $\gamma\gamma$: Conclusions

Exclusive Photon-Pair Production							
Theoretical	$\sigma_{\text{SuperCHIC}}^{ \eta <1,E_{\text{T}}>2.5\text{GeV}} = 0.35^{\times 3}_{\div 3}\text{pb} \text{ (MRST99)}$						
	$\sigma_{\text{SuperCHIC}}^{ \eta < 1, E_T > 2.5 \text{GeV}} = 1.42 \stackrel{\times 3}{\cdot 3} \text{pb} \text{ (MSTW08LO)}$						
Measured	$\sigma_{\gamma\gamma \text{excl.}}^{ \eta < 1, E_T > 2.5 \text{GeV}} = 2.48 \substack{+0.40 \\ -0.35} (\text{stat}) \substack{+0.40 \\ -0.51} (\text{syst}) \text{ pb}$						

(Mike's talk)



- First observation of exclusive γγ in hadron-hadron collissions.
- Measurement of the cross section of the exclusive production of two high-E_T photons in hadron hadron collisions.
- This corresponds to 1 in 25 billion inelastic collisions.
- Constraint on central exclusive Higgs if existing (produced by same mechanism).
- Paper recently published: (Mike's talk)
 Phys. Rev. Lett. 108, 081801 (2012).

Currently theoret. uncertainties are under further revision.

Modeling meson pair CEP perturbatively

- Simpler exclusive process γγ → MM (= π⁰π⁰, π⁺π⁻, K⁺K⁻...) at large angles was calculated ~30 years ago³.
- Total amplitude given by convolution of parton level γ(λ₁)γ(λ₂) → qqqq amplitude with non-perturbative pion wavefunction φ(x)

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

where helicity amplitudes $T_{\lambda_1\lambda_2}$ can be calculated perturbatively.

 With suitable choice of φ(x) shape, γγ → MM data are described quite well (see plot⁴.).



³S. J. Brodsky and G. P. Lepage, Phys. Rev. D 24 (1981) 1808.
⁴Data taken from Belle Collaboration, Phys. Lett. B615 (2005) 39

(M.Benayoun, V.Chernyak, -1990)

 $gg \rightarrow M\overline{M}$ calculation (explicit calculation)

- Simplest case: production of flavour non-singlet scalar mesons (e.g. π⁰π⁰, π⁺π⁻...).
- Can calculate the LO $gg \rightarrow M\overline{M}(=q\overline{q}q\overline{q})$ amplitudes to give

$$T_{++} = T_{--} = 0, \qquad \text{is this easy to understand ?} \qquad (?)$$
$$T_{-+} = T_{+-} \propto \frac{\alpha_{\rm S}^2}{a^2 - b^2 \cos^2 \theta} \left(\frac{N_c}{2} \cos^2 \theta - C_F a \right),$$

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

- → $J_Z = 0$ amplitudes vanish, as in $\gamma\gamma \rightarrow MM$ for neutral mesons. We therefore expect a strong suppression in flavour non-singlet $M\overline{M}$ CEP due to $J_Z = 0$ selection rule.
- $\rightarrow J_Z = 2$ amplitudes contain 'radiation zero', vanishing for a physical value of cos² θ . Well known effect in all gauge theories (e.g. $ud \rightarrow W^+\gamma$), but usually washed out in QCD by colour averaging. Here, position of zero depends on the choice of $\phi(x)$, and we find that there is always a zero in the physical region for any choice of $\phi(x)$ and general N_c .

$gg \rightarrow M\overline{M}$ amplitude: Feynman diagrams

Vanishing of T_{++}, T_{--} follows after calculating:

is this easy to understand ?



currently popular (among the more formal community) MHV- technique



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$gg \rightarrow M\overline{M}$ amplitude: MHV calculation (1)

- g(+)g(+) → q(±)q(∓)q(±)q(∓) amplitude is MHV: maximum (n 2) number of particles have same helicity.
- Such amplitudes known to have remarkably simple forms, and corresponding 'spinor helicity' formalism can greatly simplify calculation.
- T₊₊, T₋₋ can be calculated from known Parke-Taylor amplitude⁵

$$M_{n} \propto \sum_{\sigma} \frac{\langle k_{p} \, k_{\overline{q}} \rangle}{\langle k_{p} \, a_{1} \rangle \cdots \langle a_{l} \, k_{\overline{q}} \rangle} \frac{\langle k_{q} \, k_{\overline{p}} \rangle}{\langle k_{q} \, b_{1} \rangle \cdots \langle b_{l'} \, k_{\overline{p}} \rangle} (\lambda^{a_{1}} \cdots \lambda^{a_{l}})_{i_{1} j_{2}} (\lambda^{b_{1}} \cdots \lambda^{b_{l'}})_{i_{2} j_{1}} - \frac{1}{N_{c}} \frac{\langle k_{p} \, k_{\overline{p}} \rangle}{\langle k_{p} \, a_{1} \rangle \cdots \langle a_{l} \, k_{\overline{p}} \rangle} \frac{\langle k_{q} \, k_{\overline{q}} \rangle}{\langle k_{q} \, b_{1} \rangle \cdots \langle b_{l'} \, k_{\overline{q}} \rangle} (\lambda^{a_{1}} \cdots \lambda^{a_{l}})_{i_{1} j_{1}} (\lambda^{b_{1}} \cdots \lambda^{b_{l'}})_{i_{2} j_{2}} .$$

Making colour singlet identification (*i*₁ = *j*₂, *i*₂ = *j*₁) and identifying *qq*, *pp* with collinear quarks within mesons

$$k_q = xk_3$$
 $k_{\overline{q}} = (1 - y)k_4$ $k_p = yk_4$ $k_{\overline{p}} = (1 - x)k_3$,

then amplitude reduces to

$$M \propto \langle k_3 \, k_2 \rangle \langle k_1 \, k_4 \rangle + \langle k_1 \, k_3 \rangle \langle k_2 \, k_4 \rangle - \langle k_3 \, k_4 \rangle \langle k_1 \, k_2 \rangle = \mathbf{0} ,$$



which vanishes from the Schouten identity.

⁵M. L. Mangano, S. J. Parke, Phys. Rept. 200 (1991) 301-367

Here the indices $r(\overline{r})$ and $s(\overline{s})$ refer to the quarks (antiquarks) with colour indices $i_1(j_1)$ and $i_2(j_2)$, respectively, and the labels a_i , b_i refer to the gluons, while the standard spinor contraction ' $\langle k, l \rangle$ '

$gg \rightarrow M\overline{M}$ amplitude: MHV calculation (2)

- The vanishing of the gg → MM J_Z = 0 amplitudes follow directly from the corresponding 6-particle MHV amplitude. This result depends crucially on the colour singlet projection and collinearity of the qq pairs, and only occurs for non-flavour singlet mesons
- The MHV formalism can be extended to include the non-MHV |J_Z| = 2 amplitude: contributing amplitudes given by tree graphs in which the vertices are the usual tree-level MHV scattering amplitudes continued off-shell⁶.
 F. Cachazo, P. Svrcek, E. Witten, JHEP 0409 (2004) 006 [hep-th/0403047].
- More complicated than J_Z = 0 case, but an explicit calculation within this framework confirms our result.



⁶see e.g. G. Georgiou, V. V. Khoze, JHEP 0405 (2004) 070.

Flavour singlet meson production

- A second set of diagrams can in general contribute, where the qq̄ forming the mesons connected by a quark line (no equivalent diagram in γγ → MM̄ process).
- Only relevant for flavour singlet states (e.g. for gg → π⁰π⁰, |uū) and |dd̄) Fock components interfere destructively).



- In this case the J_z = 0 amplitude does not vanish → Expect strong enhancement in η'η' CEP rate⁷ and (through η-η' mixing), some enhancement to ηη rate. ηη' CEP can also occur via this mechanism.
- Also: any sizable gg component to flavour singlet states, contributing through gg → 4g and gg → qqgg processes, may in principle strongly enhance the CEP cross section (again J_z = 0 amplitudes do not vanish). A significant 'excess' in future CEP data could be evidence for this.

Backgrounds for the diphoton CEP @ CMS ?



⁷Recall quark content of $|\eta'\rangle$ is dominantly $\sim |u\overline{u} + d\overline{d} + s\overline{s}\rangle$

Numerical Results

(our new results will be available soon)

- Strong enhancement in flavour singlet states clear, with precise η'/η hierarchy given by choice of η - η' mixing angle.
- CEP cross sections for vector mesons (ρρ, ωω, φφ) can be calculated in the same way.



π⁰π⁰ CEP can in principle be an important background to γγ CEP, but we find this not to be the case. This depends crucially on vanishing of the gg → π⁰π⁰ amplitude for J_z = 0 initial-state gluons.

However: possible J_Z = 0 contribution from higher twist effects, NNLO corrections... could increase flavour non-singlet rate by a factor 'a few'.
 Also, possible non-perturbative contribution at lower p_⊥? (K-factor,..)

New CDF data nicely confirm this !





- Dependence on gluon PDFs
- Role of diffractive dissociation in the real-life data needs evalⁿ (900 GeV CDF data could shed light)



Summary and Outlook

- CEP processes observed at the Tevatron, RHIC and early LHC can serve as 'standard candles' for new physics CEP at the LHC.
- New LHCb χ_c → J/ψ data, support: previous suggestion that χ_{c(1,2)} contribute to CDF χ_c data.
- First estimates of dissociative background given.
- χ_{c0} CEP via two-body decays (π⁺π⁺, K⁺K⁻...) interesting and realistic channels, with continuum background expected to be low. Other decay channels (e.g. pp, ΛΛ, 2(π⁺π⁻)...) also possible.
- The CEP of mesons pairs at high invariant masses (/k_⊥) is an interesting process, representing a novel application of pQCD framework for describing exclusive processes.
- Measurement of ππ (KK...) CEP at lower mass/k_⊥ values would help constrain non-perturbative models.
- CEP could help probe the gluonic structure of η , η' mesons.
- Perturbative calculation predicts that $\pi^0 \pi^0$ BG to $\gamma \gamma$ CEP is suppressed.
- New CDF γγ data gives encouraging results! Could shed light on the gluon density...
- More CEP results to come from RHIC, the Tevatron and LHC in the future.





Signal and Background calculation

Take the experimental efficiencies $\boldsymbol{\epsilon}$ and calculate

Signal processes: use approximate formula

$$\sigma^{\text{excl}} = 3\text{fb} * \left(\frac{136}{16+m}\right)^{3.3} \left(\frac{120}{m}\right)^3 \cdot \frac{\Gamma(h/H \to gg)}{0.25 \,\text{MeV}} \cdot \frac{\text{BR}^{\text{MSSM}}}{\text{BR}^{\text{SM}}} \star \mathbf{\epsilon}$$

 $\Gamma(h/H \rightarrow gg)$, BR^{MSSM}, BRSM evaluated with *FeynHiggs*

[T. Hahn, S. Heinemeyer, W. Hollik, H. Rzeh G. Weiglein] (1998-2010)

Background for $h, H \rightarrow b\bar{b}$ obtained from

$$\sigma_{\rm B} \approx 2 \text{fb} \left[\frac{3}{4} \frac{\Delta M}{(4 \text{ GeV})} \left(\frac{120}{M} \right)^6 + \frac{1}{4} \frac{\Delta M}{(4 \text{ GeV})} \left(\frac{120}{M} \right)^8 \boldsymbol{\mathcal{C}_{NLO}} \right] \star \boldsymbol{\mathcal{E}}$$

[DeRoeck, Orava+KMR, EPJC 25 (2002) 392, EPJC 53 (2008) 231]

1) Admixture of |Jz|=2 production

2) NLO gg→bbg, large-angle hard gluon emission

3) LO $gg \rightarrow gg$, g can be misidentified as b

4) b-quark mass effects in dijet processes, HO radiative corrections

b-jet angular cut applied: $60^{\circ} \le \theta \le 120^{\circ} (|\Delta \eta_{jet}| \le 1.1)$ P(g/b)~1.3%(ATLAS) Four major bg sources: ~(1/4+1/4+1.3²/4 +1/4) fb at M_h=120 GeV, ΔM =4 GeV arXiv:0806.1447]

Pile-up background is heavily reduced after applying stringent cuts. Remaining Pile-up bg considered to be negligible.

Needs further update!



The mass dependence of the ration of the NLi exclusive $b\overline{b}$ cross section to that calculated in Bor approximation.

Good agreement with ExHuME and SuperCHIC MCs

$\gamma\gamma$ CEP: new results (2)

- Expect theory estimates to be somewhat conservative:
- S²_{enh} effect somewhat overestimated– latest number ≈ 20% bigger.
- Small fraction of $\gamma\gamma$ events that are not truly exclusive (\approx 10%).
- NLO corrections could be numerically quite large (c.f. χ_{c0} → gg and H → gg, both receive infrared π² numerical enhancement). Including finite part of 1-loop corrections¹⁴ to gg → γγ get K_{nlo} ≈ 1.6, so a similar enhancement may be present. However: need full NLO calculation, divergences included in f_g's now cancel virtual IR divergences, and will get new finite contributions specific to CEP.
- Must also bear in mind reasonable theory uncertainties, but nevertheless some tension between theory (MRST99) and new data exists...



Data/Durham theory comparison

- χ_c, γγ and jj CEP already observed at the Tevatron, χ_c at the LHC, with more to come...
- So far, data has been in overall good agreement with the Durham theory, giving confidence in the Higgs predictions, up to a ~ × 2 uncertainty.
- CDF γγ data may suggest more 'LO–type' PDFs (→ more optimistic Higgs cross sections) are appropriate.
- Studies are ongoing, and other observables (e.g. CEP of meson pairs, π⁺π⁻, η^(')η^(')...) are being explored theoretically and experimentally.

$\gamma\gamma$ CEP: PDF comparison (2)

- The gluon density is not sufficiently well described by fixed order, twist = 2 DGLAP at low x and Q².
- There is some indication from, e.g. diffractive J/ψ production that the g(x, Q²) is larger than the current NLO PDFs¹⁵.
- → Can also use, e.g. γγ CEP to shed light on the gluon density, with the LO and NLO gluons giving approx. upper and lower bounds on the CEP cross section due to the (large) PDF uncertainty.
- Use an updated model¹⁶ for S²_{eik}, which includes the new TOTEM elastic data (requires Ω(b_t) ↑ in particular at lower b_t, and therefore S²_{eik} ↓), and for S²_{enh} (somewhat higher than previously), gives factor ~ 2 decrease in σ
 @ 7 TeV. The γγ CEP cross sections (in pb) are predicted to be (for E_⊥ > 2.5 GeV):

	MSTW08LO	CTEQ6L	MRST99	CT10	NNPDF2.1
$\sqrt{s}=1.96$ TeV ($ \eta <1)$	1.4	2.2	0.35	0.47	0.29
$\sqrt{s}=7\;TeV\;(\eta <1)$	2.1	2.0	0.32	0.29	0.16
$\sqrt{s}=$ 7 TeV ($ \eta <$ 2.4)	6.2	6.2	0.94	0.91	0.50

¹⁵A. Martin, C. Nockles, M. G. Ryskin, and T. Teubner, Phys.Lett. B662, 252 (2008), 0709.4406.
 ¹⁶M. Ryskin, A. Martin, and V. Khoze, (2012), 1201.6298.

χ_{c} CEP @ LHCb (1)

- Select 'exclusive' events by vetoing on additional activity in given η range- χ_c → J/ψγ events seen by LHCb.
- Expect σ_{χ0} ≈ σ_(χ1+χ2) → recalling Br(χ_{c0} → J/ψγ) suppression, observation of χ_{c0} events strongly favours exclusivity.





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

J/Ψ + Photon Mass

- X_{c0}:X_{c1}:X_{c2} ratio determined from fit to mass spectrum
- ¥(2S) background





On behalf of the LHCb Collaboration

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Exclusive and diffractive processes in high energy collisions - Trento - 27th Feb-2nd Mar 2012

Spinor Helicity

Spinor wavefunctions

$$|j^{\pm}\rangle \equiv u_{\pm}(k_j), \qquad \langle j^{\pm}| \equiv \overline{u_{\pm}}(k_j) .$$

Introduce spinor products

$$\langle i j \rangle \equiv \langle i^- | j^+ \rangle = \overline{u_-}(k_i)u_+(k_j) ,$$
$$[i j] \equiv \langle i^+ | j^- \rangle = \overline{u_+}(k_i)u_-(k_j)$$

Explicit representation

where
$$u_{\pm}(k) = \begin{pmatrix} \sqrt{k_{\pm}} \\ \sqrt{k_{\pm}}e^{i\phi_k} \end{pmatrix}$$
, $u_{\pm}(k) = \begin{pmatrix} \sqrt{k_{\pm}}e^{-i\phi_k} \\ -\sqrt{k_{\pm}} \end{pmatrix}$
$$e^{\pm i\phi_k} = \frac{k^1 \pm ik^2}{\sqrt{k_{\pm}k_{\pm}}}, \qquad k_{\pm} = k^0 \pm k^3$$

We then obtain the explicit formulæ

$$\langle i j \rangle = \sqrt{k_{i-}k_{j+}}e^{i\phi_{k_i}} - \sqrt{k_{i+}k_{j-}}e^{i\phi_{k_j}},$$

 $[i j] = \langle j i \rangle^* = \sqrt{k_{i+}k_{j-}}e^{-i\phi_{k_j}} - \sqrt{k_{i-}k_{j+}}e^{-i\phi_{k_i}} \quad (k_{i,j}^0 > 0)$
otherwise $[j i] = \operatorname{sign}(k_i^0 k_j^0) \langle i j \rangle^*$
so that the identity $\langle i i \rangle [i i] = 2k_i \cdot k_i$ always holds

• Schouten identity $\langle i\,j\rangle\,\langle p\,q\rangle = \langle i\,q\rangle\,\langle p\,j\rangle + \langle i\,p\rangle\,\langle j\,q\rangle$.