Central Exclusive Processes at Hadron Colliders
(Selected Topics)

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(in collaboration with Lucian Harland-Lang and Misha Ryskin)
Outline

- **Introduction** (why we are interested in collecting CEPs?)
- Standard Candle CEP reactions.
- CEP as a way to study old and new heavy resonances
  - CEP: general theory.
  - $\chi_c$ CEP:
  - Exotic states: $X(3872)$...
- Dimeson CEP
- Exclusive jet production (preliminary results).
- Summary and Outlook.
Introduction  (why we are interested in CEP ?)

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

- Driven by same mechanism as Higgs (or other new object) CEP at the LHC.

- $\chi_c$, $jj$ and $\gamma \gamma$ CEP has been observed (CDF, D0, LHCb, Totem-CMS).

- 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)
This is all about QCD with all its beauty and complexities

What are the problems with this? ..... 
....it is not at all evident to experimentalists, who nowadays tend to prefer mining gold to going fishing. 

in the CEP case: ..... mining gold to mushroom picking.
‘$J_z = 0$ selection rule’: production of non-$J_z^{PC} = 0^{++}$ states heavily suppressed, allowing a clean determination of the central object quantum numbers.

Higgs CEP: central exclusive $b\bar{b}$ background vanishes at LO (for massless quarks).

Outgoing proton momenta can be measured by Roman Pot (RP) detectors down the beam line:

- The proton energy loss is directly related to the central system mass $M_X^2 \approx \xi_1 \xi_2 s$, allowing a high resolution ‘missing mass’ measurement.
- Proton tagging can also provide spin and parity information about the central system as well as the structure of the proton and models of soft interactions.

FP420 R&D collaboration: proposed installation of RP detectors at 420m from ATLAS (AFP) and CMS (PPS) (arXiv:0806.0302)

RP detectors are already installed at RHIC, where data with $pp$ collisions are being taken for $\sqrt{s} \leq 500$ GeV.

Totem-CMS first measurements-2012, upgrade program. MoU (Valentina)
Calculating CEP: ingredients

- **Soft Survival probability:**
  - Non-perturbative object, must take a physical model of hadronic interactions, fitted to soft hadronic data. ‘State of the art’ models roughly consistent.

  Khoze, Martin Ryskin, Gotsman, Levin, Maor
  (S. Ostapchenko)

  G. Antchev et al. [TOTEM Collaboration], Europhys. Lett. 101 (2013) 21004 etc
  - Recent TOTEM data on total, elastic and diffractive cross sections has been important guide for LHC predictions.

  See arXiv:1306.2149 for latest KMR model, accounting for TOTEM

- **‘Skewed’ PDFs:**
  - Correspond to $gg$ coupling to proton for relevant kinematics
  - In the CEP regime can be calculated via usual global PDFs.

- **Sudakov factor:**
  - Resums higher order logs in $Q^2/M_X$, ensuring IR stable result and validity of perturbative treatment.

Important to include all factors correctly! **One step forward, two steps back (V.I. Lenin)**
‘Standard Candle’ processes

- CEP is a promising way to study new physics at the LHC (light Higgs CEP as well...), but we can also consider the CEP of lighter, established objects: $\chi_c$, $\gamma\gamma$, and $jj$. CEP already observed at the Tevatron, $\chi_c$ at the LHC, with more to come... LHCb, CMS, (Totem-CMS).

- 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$^2$.

Some examples are:

- $\chi_c$ ($\rightarrow J/\psi\gamma, \pi^+\pi^-, K^+K^-...$).
- Light meson pairs ($\pi\pi$, $KK$, $\eta(\prime)\eta(\prime)...$). (soon to come CMS, Totem-CMS, LHCb, RHIC)
- Diphotons $\gamma\gamma$. (CMS-limits)
- Dijets $jj$. (D0, Totem-CMS,...AFP/PPS).

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

Heavy Quarkonia

Zoo of charmonium -like XYZ states
\(\chi_{c1}\) and \(\chi_{c2}\): general considerations

- General considerations tell us that \(\chi_{c1}\) and \(\chi_{c2}\) CEP rates are strongly suppressed:
  - \(\chi_{c1}\): Landau-Yang theorem forbids decay of a \(J = 1\) particle into on-shell gluons.
  - \(\chi_{c2}\): Forbidden (in the non-relativistic quarkonium approximation) by \(J_z = 0\) selection rule that operates for forward \((p_\perp = 0)\) outgoing protons.

- However the experimentally observed decay chain
  \(\chi_c \rightarrow J/\psi \gamma \rightarrow \mu^+ \mu^- \gamma\) strongly favours \(\chi_{c(1,2)}\) production, with:
  \[
  \text{Br}(\chi_{c0} \rightarrow J/\psi \gamma) = 1.1\% , \\
  \text{Br}(\chi_{c1} \rightarrow J/\psi \gamma) = 34\% , \\
  \text{Br}(\chi_{c2} \rightarrow J/\psi \gamma) = 19\% .
  \]

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

- The effects of non-zero \(p_T\) (especially for \(2^+\)).
LHCb 2010

2011-2012 dataset ~ 80 times more lumi

Move to 25 ns running doubles usable luminosity

HKRS: arXiv:0909.4748

<table>
<thead>
<tr>
<th>( \chi_{c0} )</th>
<th>( \chi_{c1} )</th>
<th>( \chi_{c2} )</th>
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<tbody>
<tr>
<td>( \sigma(pp \rightarrow pp(\mu^+ \mu^- + \gamma)) ) ( \frac{\text{Br}(J/\psi \rightarrow \mu^+ \mu^-) \text{Br}(\chi_{cJ} \rightarrow J/\psi \gamma)}{\text{LHCb (nb)}} )</td>
<td>( \text{LHCb (nb)} )</td>
<td>( \text{SuperCHIC (nb)} )</td>
</tr>
<tr>
<td>13 ± 6.5</td>
<td>0.80 ± 0.35</td>
<td>2.4 ± 1.1</td>
</tr>
<tr>
<td>20</td>
<td>0.49</td>
<td>0.26</td>
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- See clear suppression in \( \chi_c(1,2) \) states.
- Do not expect to see (or find) in inclusive production.

LHCb Collaboration, arXiv:1307.4285

Measurement of the relative rate of prompt \( \chi_{c0}, \chi_{c1}, \) and \( \chi_{c2} \) production at \( \sqrt{s} = 7 \text{ TeV} \)

\[
\frac{\sigma(\chi_{c0})}{\sigma(\chi_{c2})} = 1.19 \pm 0.27 \text{ (stat)} \pm 0.29 \text{ (syst)} \pm 0.16 \text{ (pT model)} \pm 0.09 \text{ (B)};
\]

\[
\frac{\sigma(\chi_{c2})}{\sigma(\chi_{c3})} = 0.787 \pm 0.014 \text{ (stat)} \pm 0.034 \text{ (syst)} \pm 0.051 \text{ (pT model)} \pm 0.047 \text{ (B)};
\]

- Good data/theory agreement for \( \chi_c(0,1) \) states (within quite large theory uncertainty), but significant \( \chi_{c2} \) excess...

Bad guys-diffractive dissociation 😳

FSCs- to veto proton dissociation-next run

Theory corrections?
X(3872) analysis: motivation

X(3872) is “a riddle, wrapped in a mystery, inside an enigma; but perhaps there is a key” ¹

What is it? LHCb J^PC=1^{++} determination leaves \( \chi_{c1}(2^3P_1) \) available as well as \( D^0 D^{*0} \) molecule, tetraquarks, \( ccg \) hybrids + combinations...

Observation of CEP X(3872) could lend weight to charmonium interpretation:

- Prediction possible for ratio of CEP cross sections \( \sigma(\chi_{c1}(2P))/\sigma(\chi_{c1}(1P)) \)
- Tetraquark/molecule interpretation requires additional quarks or D mesons - available to inclusive processes only
- If the X(3872) is a combination of these the proportion can be probed by the CEP cross-section measurement

Most likely interpretation:
- DD* molecule with admixture of \( \chi_{c1}(2P) \)
- Isospin violation
- Production at high energy

(if it is not \( \chi'_{c1} \), where is \( \chi'_{c1} \)?)

¹ Winston Churchill, 1939
Extreme Interpretations

A compact ‘tetraquark’ e.g. dq-dq*
Maiani, Piccinini, Polosa, Riquer ’2005
Terasaki; Ali; Ebert; Vijande; Nielsen & collab. ...
Approach based on symmetry

A loosely bound molecule
Tornqvist; Braaten, Kusinoki; Voloshin; Barnes;
Swanson; Close; Mehen, Fleming; Hanhart, Guo, Meissner
very long list...’2005 —
Based on strong hadron dynamics

Mixed Charmonium/Molecular interpretations
X at LHCb

Very recent arXiv:1404.0275

\[
\frac{B(X(3872) \rightarrow \psi(2S) \gamma)}{B(X(3872) \rightarrow J/\psi \gamma)} = 3.4 \pm 1.4
\]

“...The measured value agrees with expectations for a pure charmonium interpretation of the X(3872) state and a mixture of charmonium and molecular interpretations. However, it does not support a pure DD* molecular interpretation of the X(3872) state ...”

yet I would continue, citing Eichten, Lane & Quigg hep-ph/0511179

“...but the mass of X (3872) is too low to be gracefully identified with the \(2^3P_1\) charmonium state, especially if \(Z(3931)\) is to be identified as the \(2^3P_2\) level...”

- Loosely bound molecules promptly produced at high energy hadron colliders require a miracle in final state interactions. Close-to-threshold-hadrocharmonia should also be very unlikely formed in such collisions.

AD Polosa

(CERN seminar, 08/04-2014)
In CEP the state $X$ is produced directly, i.e.
short distances: 
$gg \rightarrow X(3872)$ and nothing else. \rightarrow 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.

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 $D\bar{D}$, $D^+D^-$ and $D^0\bar{D}^0$ seen.
- With vertex detection at LHCb and RHIC \rightarrow exclusive open charm ($D\bar{D}...$) production.
- Theory: roughly the same cross section and distributions as $\chi_{c2}(1P)$.

Good Luck to LHCb
CEP of meson pairs

CEP via this mechanism can in general produce any $C$–even object which couples to gluons: Higgs, BSM objects...but also dijets, quarkonium states, light meson pairs...

i.e consider production of a pair of light mesons

$$h(p_1)h(p_2) \rightarrow h(p'_1) + M_1M_2 + h(p'_2)$$

Where $M = \pi, K, \rho, \eta, \eta' ...$

For reasonable values of the pair invariant mass/transverse momentum, we can try to model this process using the pQCD-based Durham model.

Lower $k_\perp$ region: use Regge-based model

Lebiedowicz, Pasechnik, Szczurek, PLB 701:434-444, 2011  
HKRS: arXiv:1204.4803

→ Represents a novel application of QCD, with many interesting theoretical and phenomenological features...

Flavour non-singlet mesons

- The allowed parton-level diagrams depend on the meson quantum numbers. Leads to interesting predictions.....

**Flavour non-singlets** ($\pi^+\pi^-, \pi^0\pi^0, K^+K^-, \rho^0\rho^0,...$): (31 diagrams)

\[
T_{++} = T_{--} = 0
\]

\[
T_{--} = T_{++} \propto \frac{\alpha_s^2}{a^2 - b^2 \cos^2 \theta} \left( \frac{N_c}{2} \cos^2 \theta - C_F a \right)
\]

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

\( \rightarrow J_z = 0 \) amplitudes vanish. Strong \( \sim 2 \) order of mag. suppression in CEP cross section expected.

Further suppression from radiation zero
in \( J_z = \pm 2 \) amplitude.


Seen in CDF $\gamma\gamma$ data ($E_\perp(\gamma) > 2.5$ GeV, $|\eta| < 1$)

**Experiment:** $N(\pi^0\pi^0)/N(\gamma\gamma) < 0.35$ @ 95% confidence

**Theory:** $\sigma(\pi^0\pi^0)/\sigma(\gamma\gamma) \approx 1\%$

More results are expected to come from CDF
Flavour singlet mesons

- For flavour singlet mesons a second set of diagrams can contribute, where $q\bar{q}$ pair is connected by a quark line.
- For flavour non-singlets vanishes from isospin conservation ($\pi^\pm$ is clear, for $\pi^0$ the $u\bar{u}$ and $d\bar{d}$ Fock components interfere destructively).
- In this case the $J_z = 0$ amplitude does not vanish $\Rightarrow$ expect strong enhancement in $\eta'\eta'$ CEP and (through $\eta - \eta'$ mixing) some $\eta\eta$ enhancement. The $\eta'\eta'$ rate is predicted to be large!
The gluonic component of the $\eta'(\eta)$

- The flavour singlet $\eta'$ (and, through mixing $\eta$) should contain a $gg$ component. But no firm consensus about its size. Thomas, arXiv: 0705.1500...

$\rightarrow$ The $gg \rightarrow \eta'(\eta')\eta'(\eta')$ process will receive a contribution from the $gg \rightarrow gggq$ and $gg \rightarrow gggg$ parton level diagrams.

$\rightarrow$ Use $\eta'(\eta')\eta'(\eta')$ CEP as a probe of the size of this $gg$ component.

Theoretically: two different processes will in general contribute to signal.

Exclusively jet production: theory

- We are interested in the exclusive signal, in which case we have

(Note does not include survival factor)

- The parton-level dijet amplitude is given by the usual Durham expression:

\[
T = \pi^2 \int \frac{d^2Q_\perp}{Q_\perp(Q_\perp - p_{1\perp})^2(Q_\perp + p_{2\perp})^2} \mathcal{M}(gg \rightarrow X) f_g(x_1, x'_1, Q_1^2, \mu^2; t_1) f_g(x_2, x'_2, Q_2^2, \mu^2; t_2)
\]

Where \( X = gg, q\bar{q} \)
Production subprocess

- If we consider the exclusive cross section ratio, we find

\[
\frac{d\sigma(q\bar{q})/dt}{d\sigma(gg)/dt} \approx \frac{N_c^2 - 1}{4N_c^3} \frac{m_q^2}{M_X^2} = \frac{2}{27} \frac{m_q^2}{M_X^2}
\]

Additional suppression from colour and spin 1/2 quarks

- Taking e.g. \( m_b = 4.5 \text{ GeV} \) and \( M_X = 40 \text{ GeV} \) we then get

\[
\frac{d\sigma(b\bar{b})/dt}{d\sigma(gg)/dt} \approx 10^{-3}
\]

\[\rightarrow\] Huge suppression in b quark jets (increasing with \( M_X \)). Completely unlike inclusive case. See also: \( H \rightarrow b\bar{b} \)

\[
\frac{\sigma(|J_z| = 2)}{\sigma(J_z = 0)} \sim \frac{\langle p_{\perp}^2 \rangle^2}{\langle Q_{\perp}^2 \rangle^2} \sim 10^{-2}
\]

Average outgoing proton transverse momentum (sub-GeV\(^2\))

Average gluon transverse momentum in loop = several GeV\(^2\)

\[
\frac{d\sigma^{J_z=\pm 2}(q\bar{q})/dt}{d\sigma(gg)/dt} \approx \frac{N_c^2 - 1}{16N_c^3} \frac{\langle p_{\perp}^2 \rangle^2}{\langle Q_{\perp}^2 \rangle^2} \sim 10^{-4}
\]

For one flavour
\[\Rightarrow\] multiply by \( n_f = 4 \)

\[\rightarrow\] Huge suppression in light quark jets
Gluon jet dominance

From the above considerations, we expect dijet events to be almost entirely (colour singlet) $gg$.

CEP of dijets offers the possibility of observing the isolated production of gluon jets at the LHC.

These dijet and trijet events are the cleanest ever seen at a hadron collider, and remind one of LEP events. But these dijets are nearly all $gg$, while at LEP there were all $q\bar{q}$.

Clean probe of properties of gluons jets (multiplicity, particle correlations...)

Dijet CEP as a gluon factory
Trijet production

• Consider three-jet production, proceeds via $gg \rightarrow ggg$ and $gg \rightarrow q\bar{q}g$

• $q\bar{q}g$: configuration with $g$ becoming soft/collinear to $q/\bar{q}$ driven by two-jet $q\bar{q}$ amplitude, which vanishes for $J_z = 0$ gluons and $m_q = 0$.

• More precisely, according to ‘Low-Burnett-Kroll’ theorem, the radiative amplitude $M_{q\bar{q}g}$ can be expanded in powers of $x_g = \frac{2E_g}{\sqrt{s}}$ as

$$M_{q\bar{q}g} = \frac{1}{x_g} \sum_{n=0}^{\infty} C_n x_g^n$$

where $C_0$ and $C_1$ are given in terms of the Born-level amplitude $M_{q\bar{q}}$

⇒ First non-vanishing term is $n = 2$ giving

$$\frac{d\sigma^{q\bar{q}g}}{dE_g} \sim E_g^3$$

while

$$\frac{d\sigma^{ggg}}{dE_g} \sim \frac{1}{E_g}$$

For $J_z = 0$ incoming gluons

Usual (singular) IR behaviour

New Monte Carlo implementation

Boonekamp et al. arXiv:1102.2531

• Dijet production previously implemented in Exhume and FPMC

• However, there have been a number of theoretical developments:

  ‣ Correct inclusion of Sudakov factor
  ‣ Consistent treatment of ‘skewed’ gluon PDFs
  ‣ Latest model of soft survival effects

Most importantly, neither of these include survival effects in a complete way:

\[
\frac{d\sigma}{dy}\propto \int d^2p_{1\perp} d^2p_{2\perp} |T(p_{1\perp}, p_{2\perp})|^2 S_{\text{elk}}(p_{1\perp}, p_{2\perp})
\]

• Survival factor is not constant, but depends on (and effects) the distribution of the outgoing proton \(P_{\perp}\) vectors.

  Expected suppression will depend on specific process, and soft survival factors can have a dramatic effect on the predicted distributions

(Recent KHARYS papers (2013-2014))

New MC (under development) includes all of these updates and a full treatment of soft survival effects.
SuperCHIC 2

New MC for CEP under development. Based on original SuperCHIC, but with significant extensions.

- Theoretical developments:
  - Correct inclusion of Sudakov factor
  - Consistent treatment of ‘skewed’ gluon PDFs
  - Full (differential) treatment of soft survival effects

- LHAPDF interface.
- Complete calculation performed ‘on-line’, and structured so that additional processes can be easily added.

- Processes include: $\chi_{c,b}$, $\gamma\gamma$, meson pairs ($\pi\pi$, $\rho\rho$, $\eta(')\eta(')$...), Higgs, jets... and photoproduction ($J/\psi$, $\Upsilon$...) as in original SuperCHIC

  Dijets ($gg \to gg, q\bar{q}$) and trijets ($gg \to ggg, gq\bar{q}$) included
Tevatron cross sections

- Can compare results of the MC with the CDF measurement.
- See clearly how both soft survival effects and Sudakov factor (non-pert. and pert. physics) are crucial to describe data.

\[
\frac{d\sigma}{dM_{jj}} \text{[pb/GeV]}, \sqrt{s} = 1.96 \text{ TeV, parton level}
\]

- Probability to produce colour singlet dijet state drops strongly with \( M_{jj} \)
- All predictions made with MSTW08LO PDFs, parton level

Made with particular choice of \( S^2 \) model and PDFs \( \Rightarrow \) more measurements (different \( \sqrt{s} \)... ) needed to test theory further...

Also, caveat: only parton level!
LHC Cross Sections

- Consider two scenarios for observing exclusive jets at the LHC:
  - Low luminosity (CMS + TOTEM), special runs, lower $M_X$
  - High luminosity (ALFA, PPS), no need for special runs, but $M_X$ must be larger ($\xi$ acceptance of proton taggers)

Dijet predictions for both scenarios: $|\eta_j| < 2.5$ \ $|p_{\perp,j}| > 20$ GeV \ $\sqrt{s} = 13$ TeV

<table>
<thead>
<tr>
<th>$M_X$ (min) [GeV]</th>
<th>$gg$</th>
<th>$q = b$</th>
<th>$q = c, s, u, d$</th>
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<tr>
<td>50</td>
<td>620</td>
<td>1.1</td>
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<tr>
<td>250</td>
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<td>$1.1 \times 10^{-4}$</td>
<td>$4.0 \times 10^{-4}$</td>
</tr>
<tr>
<td>500</td>
<td>$1.9 \times 10^{-3}$</td>
<td>$8.6 \times 10^{-7}$</td>
<td>$3.3 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

\[ \sigma [pb] \, \quad \frac{q\bar{q}}{n_f = 4} \, \text{Preliminary} \]
Low luminosity CMS + TOTEM, event selection:
Central: $|\eta_j| < 4.4$, $|p_{Tj}| > 30$ GeV  
Protons: $|p_{T1}| > 0.1$ GeV, $p_{T1}^y * p_{T2}^y > 0$

$\Rightarrow \sigma(gg) \approx 100$ pb

High luminosity CMS + TOTEM (‘CT PPS’) event selection:
Central: $|p_{Tj}| > 120$ GeV, $|\eta_j| < 2.5$
Protons: $\xi > 0.03$

$\Rightarrow \sigma(gg) \approx 0.5$ fb

$\sqrt{s} = 13$ TeV

$M_X > 390$ GeV

CMS + TOTEM event displays (2012)
• The observation of exclusive jets (and other processes) with tagged protons also provides additional information....

• Consider, e.g. $\pi^+\pi^-$ production, with tagged protons. TOTEM, ALFA
R. Staszewski et al., arXiv:1104.3568

Proton $\phi$ distributions for low mass $\pi^+\pi^-$ CEP, using Dime MC

• Distributions in angle $\phi$ between outgoing protons strongly affected by soft survival effects, in model dependent way.

• This is in particular true when larger values of $p_\perp$ are selected. Cancellation between screened and unscreened amplitudes results in characteristic ‘diffractive dip’ structure. V.A. Khoze, A.D. Martin and M.G. Ryskin, hep-ph/0203122

Plots for $\pi^+\pi^-$ but similar effect seen in dijet production
Other observables

- $\chi b$ production: also for $J = 1,2$ 
  ‣ Smaller cross sections ($\sim$ pb)...
  ‣ ...but smaller theoretical uncertainty (higher $M_X$)

- $\eta_{c,b}$ production:
  ‣ Odd parity $\Rightarrow$ suppressed
  ‣ $\eta_c \sim 0.1$ nb, $\eta_b \sim 0.1$ pb

- CEP with tagged protons: distributions of outgoing protons sensitive to spin/parity of production state.
Strong motivation for programme of CEP measurements, with tagged protons at the LHC, both at low (TOTEM+CMS, ALFA+ATLAS) and high (PPS, AFP...) luminosity.  

(Valentina, Rafal)

- Work underway on SuperCHIC 2, new MC for CEP, including exclusive two and three jet production.
Summary and Outlook

- CEP 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 low-luminosity LHC can serve as ‘standard candles’ for Higgs (and other physics) CEP at the LHC.
- The data are in good overall agreement with the Durham theory supports predictions for e.g. Higgs (and new physics) CEP.
- The CEP of mesons pairs at high invariant masses ($l/k_\perp$) is an interesting process, representing a novel application of pQCD framework for describing exclusive processes.
- Exclusive jet production at the LHC presents an interesting and potentially unique probe of QCD.

- The Durham perturbative approach (already supported by Tevatron measurements) makes very clear predictions, which are quite different from ‘standard’ inclusive case:
  - Isolated $gg$ dominance (LO $gg \rightarrow q\bar{q}$ vanishes for massless quarks and $J_z = 0$ gluons). See also: $H \rightarrow b\bar{b}$
  - ‘Mercedes’ configuration for $gq\bar{q}$ favoured. $ggg$ vs $gq\bar{q}$ topologies
- Correlations between outgoing proton momenta sensitive to model of soft proton-proton interactions.
We are looking forward to new exciting adventures in Exclusiveland
BACKUP
The generic process $pp \rightarrow p + X + p$ 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, $S_{eik}^2$ and $S_{enhl}^2$.

In the limit that the outgoing protons scatter at zero angle, the centrally produced state $X$ must have $J^{P} = 0^+$ quantum numbers.
• Clean probe of theory: ideal ‘Standard Candle’ for higher mass CEP.
• Highly sensitive probe of gluon density at low $x$ and $Q^2$.
• Measured by CDF: $\sigma_{\gamma\gamma} = 2.48^{+0.40}_{-0.35} \text{ (stat)} \pm 0.40 \text{ (syst)} \text{ pb}$ for $E_\perp > 2.5 \text{ GeV}, |\eta_\gamma| < 1$
• In good agreement with Durham predictions:

| $\sqrt{s} = 1.96 \text{ TeV (}|\eta| < 1)$ | MSTW08LO | CTEQ6L | GJR08LO |
|-----------------------------------------|-----------|--------|---------|
| 1.4                                     | 2.2       | 3.6    |

• CMS have set limits close to Durham LHC predictions.

\Rightarrow No room for much larger $S^2$ at the LHC
The $gg \rightarrow q\bar{q}g, ggg$ amplitudes for a given helicity config. are known, and have (relatively) simple forms (can be written down in $\sim 3 - 4$ lines) MHV.

Consider amplitudes for $J_z = 0$ colour-singlet gluons (and massless quarks for simplicity)...  

$$|y_i| < 5 \quad \sqrt{s} = 200 \text{ GeV}$$  

$q\bar{q}g, ggg$ normalised to each other.

$d\sigma/d\theta$ (for $ggg$ between arbitrary gluons)

$M(q\bar{q}g) \sim M(q\bar{q}) \cdot P_{gq}$

$\sim \frac{1}{x_g}$

$\sim x_g^3$

Preliminary
Zoo of charmonium -like XYZ states

Tetraquark:
four tightly bound quarks

Molecular state:
two loosely bound mesons

Hybrid: states with
excited gluonic degrees of freedom

Hadrocharmonium: charmonium state,
“coated” by excited light-hadron matter

- X(3872)
- XYZ(3940) & X(3915)
- Y(4140)/Y(4280) & X(4350)
X captured attention...

Top Cited Articles of All Time (2013 edition) in hep-ex
The 100 most highly cited papers of All Time (2013 edition) in the hep-ex archive

22. 844 citations up to the end of 2013
Observation of a narrow charmonium - like state in exclusive $B^{++} \rightarrow K^+ \pi^+ \pi^- J/\psi$ decays
Published in Phys.Rev.Lett. 91 (2003) 262001
DOI: 10.1103/PhysRevLett.91.262001

61. 506 citations up to the end of 2013
Observation of the narrow state $X(3872) \rightarrow J/\psi \pi^+ \pi^-$ in $\bar{p}p$ collisions at $\sqrt{s} = 1.96$ TeV
FERMILAB-PUB-03-395-E

Also its vector cousin got much attention

64. 495 citations up to the end of 2013
Observation of a broad structure in the $\pi^+ \pi^- J/\psi$ mass spectrum around 4.26-GeV/c$^2$ $2\pi$
Published in Phys.Rev.Lett. 95 (2005) 142001
BABAR-PUB-05-29, SLAC-PUB-11320
DOI: 10.1103/PhysRevLett.95.142001
Taking this envelope of values, we find a \( \sim \) order of magnitude variation in the \( \eta(\prime)\eta(\prime) \) cross section!

\( gg \) contribution enters at same (LO) order as \( q\bar{q} \), and is not dynamically \( (J_z = 0) \) or colour suppressed.

\( \rightarrow \) CEP provides a potentially sensitive probe of the \( gg \) component of the \( \eta, \eta' \) mesons. Cross section ratios can pin this down further/reduce uncertainties.

<table>
<thead>
<tr>
<th>( a_2^G(\mu_0^2) )</th>
<th>( 9.5 )</th>
<th>( 0 )</th>
<th>( 9.5 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma(\eta\eta) / \sigma(\pi^0\pi^0) )</td>
<td>( 2.7 )</td>
<td>( 12 )</td>
<td>( 66 )</td>
</tr>
<tr>
<td>( \sigma(\eta'\eta') / \sigma(\pi^0\pi^0) )</td>
<td>( 570 )</td>
<td>( 16000 )</td>
<td>( 100000 )</td>
</tr>
<tr>
<td>( \sigma(\eta'\eta') / \sigma(\gamma\gamma) )</td>
<td>( 3.5 )</td>
<td>( 100 )</td>
<td>( 660 )</td>
</tr>
<tr>
<td>( \sigma(\eta\eta \rightarrow 4\gamma) / \sigma(\gamma\gamma) )</td>
<td>( 0.0017 )</td>
<td>( 0.049 )</td>
<td>( 0.33 )</td>
</tr>
<tr>
<td>( \sigma(\eta\eta \rightarrow 4\gamma) / \sigma(\gamma\gamma) )</td>
<td>( 0.0025 )</td>
<td>( 0.012 )</td>
<td>( 0.066 )</td>
</tr>
</tbody>
</table>


(CDF, TOTEM-CMS –prospects)
Higher $\chi_b$ mass means cross section is more perturbative, and so is better test of theory, although rate is $\sim 3$ orders of magnitude smaller than for $\chi_c$.
• $J$ assignment of $\chi_b J$ states still experimentally undetermined: CEP can shed light on this.
• Calculation very similar to $\chi_c$ case

$$|V_{0+}|^2 : |V_{1+}|^2 : |V_{2+}|^2 \sim 1 : \frac{\langle P_1^2 \rangle}{M_X^2} : \frac{\langle P_1^2 \rangle^2}{\langle Q_1^2 \rangle^2} \sim 1 : \frac{1}{400} : \frac{1}{100}$$

$\chi_b(nP) \rightarrow dX$

(about 0.25 of all hadronic decays (CLEO-2009))

$\chi_b(1^+) \rightarrow \bar{c}\bar{c}X$

(Barbieri et al (1979), NROCD)

• Measurement of ratio of $\chi_b$ to $\gamma\gamma$ CEP rates in same mass region would eliminate certain theory uncertainties (survival factors...).
• Predictions for $\chi_b$ CEP via $\gamma\gamma$ decay (at $y_X = 0$):

<table>
<thead>
<tr>
<th>$\sqrt{s}$ (TeV)</th>
<th>1.96</th>
<th>7</th>
<th>10</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{d\sigma}{dy_{\chi_b}} (pp \rightarrow pp(\gamma + \gamma))$ (pb)</td>
<td>0.60</td>
<td>0.75</td>
<td>0.78</td>
<td>0.79</td>
</tr>
<tr>
<td>$\frac{d\sigma(1^+)}{d\sigma(0^+)}$</td>
<td>0.050</td>
<td>0.055</td>
<td>0.055</td>
<td>0.059</td>
</tr>
<tr>
<td>$\frac{d\sigma(2^+)}{d\sigma(0^+)}$</td>
<td>0.13</td>
<td>0.14</td>
<td>0.14</td>
<td>0.14</td>
</tr>
</tbody>
</table>
**Trijet cross sections:** $|\eta_j| < 2.5$  
anti-$k_t$, $\Delta R=0.6$

<table>
<thead>
<tr>
<th>$M_X$ (min) [GeV]</th>
<th>For comparison</th>
<th>$gg$</th>
<th>$ggg$</th>
<th>$q\bar{q}g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>75</td>
<td>120</td>
<td>3.1</td>
<td>0.30</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>30</td>
<td>2.1</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>150</td>
<td>4.1</td>
<td>0.56</td>
<td>0.054</td>
<td></td>
</tr>
<tr>
<td>150</td>
<td>1.9</td>
<td>0.046</td>
<td>$2.5 \times 10^{-3}$</td>
<td></td>
</tr>
<tr>
<td>250</td>
<td>0.14</td>
<td>0.013</td>
<td>$8.8 \times 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>250</td>
<td>0.082</td>
<td>$2.0 \times 10^{-3}$</td>
<td>$1.7 \times 10^{-4}$</td>
<td></td>
</tr>
</tbody>
</table>

**Inclusive $\bar{b}b$g:**

$|p_{\perp,j}| > 20$ GeV

$|p_{\perp,j}| > 40$ GeV

$|p_{\perp,j}| > 60$ GeV

$\sum q = e, s, u, d$ Preliminary

CMS = TOTEM 90a (1) Run
Run/Event 1989933/34714799
Leading three jets $E_T = 65, 45, 27$ GeV
proton $\Delta y = 0.04$ (2)
proton $\Delta y = 0.1$ (2)
Max $E_T =$ 24 GeV
Max $E_T =$ 20 GeV
$E_T$ (CMS) = 1.4 GeV
FSC empty in both sides
ECAL/HCAL $E_T > 200$ MeV
Track $p_T > 1$ GeV
CMS + TOTEM event
Date recorded: 13.07.2012
Run/Event: 198903/10105843
Central Di-jet with leading protons

pp at \(\sqrt{s} = 8\) TeV, \(\beta^* = 90\) m
All tracks shown, & Calorimeter towers \(E_T > 200\) MeV

\[ E_T = 46.2\text{ GeV} \]
\[ E_T = 49.3\text{ GeV} \]
\[ M(JJ) = 132.5\text{ GeV} \]

Proton track in \(+z\) and \(-z\) TOTEM Roman pots
Rapidity gap in \(+z\) and \(-z\) Forward Shower Counters

Run, event: 198903, 10105843
CMS + TOTEM event

Date recorded: 13.07.2012
Run/Event: 198903/9476393

Central Tri-jet with leading protons

pp at $\sqrt{s} = 8$ TeV, $\beta^* = 90m$

All tracks shown, & Calorimeter towers $E_T > 200$ MeV

$E_T = 20.6$ GeV

$E_T = 32.0$ GeV

$E_T = 27.4$ GeV

Proton track in +z and -z TOTEM Roman pots
Rapidity gap in +z and -z Forward Shower Counters

$\eta(jets) = -1.38, -1.95, -2.20$