Latest Results on Standard Candle Central Exclusive Production within the Durham Model

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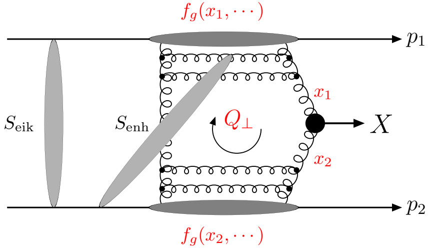
Exclusive and diffractive processes in high energy proton–proton and nucleon–nucleon collisions, ECT* Trento, Italy, Feb 27-March 2, 2012.

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

Central Exclusive Production (CEP)

- Colliding protons interact via a colour singlet exchange and remain intact- can then be measured by adding detectors far down the beam-pipe.



- A system of mass M_X is produced at the collision point, and *only* its decay products are present in the central detector region.
- The generic process $pp \to p + X + p$ is modeled perturbatively by the exchange of two t-channel gluons.
- 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 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 : χ_c, $\gamma\gamma$ and jj CEP already observed at the Tevatron, χ_c at the LHC, with more to come...
- 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[1].
- This talk will discuss three important examples:
  - χ_c ($\to J/\psi\gamma$, $\pi^+\pi^-$, K^+K^-...).
  - Proton dissociation.
  - Light meson pairs ($\pi\pi$, KK, $\eta(')\eta(')$...).
  - Diphotons $\gamma\gamma$.

[1] See LHL, V.A. Khoze, M.G. Ryskin, W.J. Stirling, arXiv:1005.0695 and arXiv:1011.0680.

χ_c CEP @ the LHC (1)

- Previous CDF data: encouraging agreement with theory (within sizeable theory uncertainties), but issues remain (i.e. $\chi_{(1,2)}$ contribution? Recall large $\mathrm{Br}(\chi_{c(1,2)} \to J/\psi\gamma)$).
- Although theory behind total cross prediction has large uncertainties, we can use agreement with CDF data to 'calibrate' predictions for the LHC, provided we understand the $\sqrt{s}$ dependence[2]
- Recent LHCb data[3]: select 'exclusive' $\chi_c \to J/\psi\gamma$ events by vetoing on additional activity in given η range.
- LHCb see:

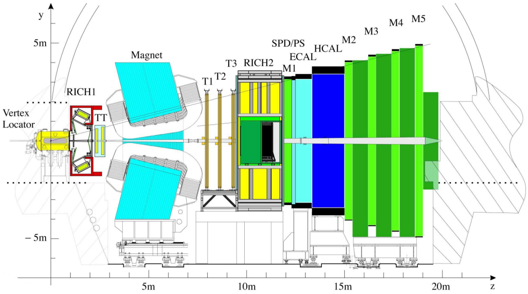
	$\sigma(pp \to pp(J/\psi + \gamma))$ LHCb (pb)	SuperCHIC prediction (pb)
χ_{c0}	9.3 ± 4.5	14
χ_{c1}	16.4 ± 7.1	10
χ_{c2}	28 ± 12.3	3

[2] See LHL, V. A. Khoze, M. G. Ryskin, W. J. Stirling, Eur. Phys. J. **C69** (2010) 179-199.
[3] LHCb-CONF-2011-022, Dermot Moran's talk.

χ_c CEP @ the LHC (2)

→ Good agreement for $\chi_{c(0,1)}$ states (recall theory uncertainty), but a significant excess of χ_{c2} events above theory prediction for CEP. Supports previous expectation that $\chi_{c(1,2)}$ states should contribute to CDF χ_c data.

- Are relativistic/non-perturbative corrections to χ_{c2} important?
- Is there a significant high mass proton dissociation $pp \to p + \chi + X$ background skewing the results?



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[4]: 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 $(1 + c)^2 \sim 1.4$.

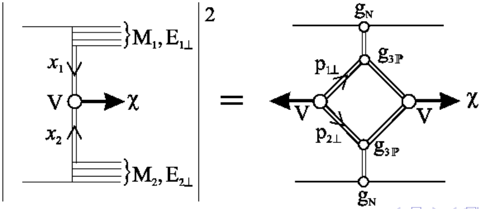
[4] F. Aaron et al., Eur.Phys.J. C71, 1578 (2011), 1010.1476.; S. Chekanov et al., Nucl.Phys. B816, 1 (2009), 0812.2003

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

$$\frac{\sigma(p \to M_Y)}{\sigma(\mathrm{CEP})} = \int \frac{\mathrm{d}M_Y^2}{M_Y^2} \frac{g_N(0) g_{3P}(t)}{\pi g_N^2(t)} , \tag{1}$$

- 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[5] $b_{3P} < 2\ \mathrm{GeV}^{-2}$.
  - 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. (1) 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...).
  - χ_c CEP: other decays ($\chi_{c(0,2)} \to \pi^+\pi^-, K^+K^-, pp, \Lambda\overline{\Lambda}$...).

$\chi_c \to \pi^+\pi^-$ CEP[7]

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

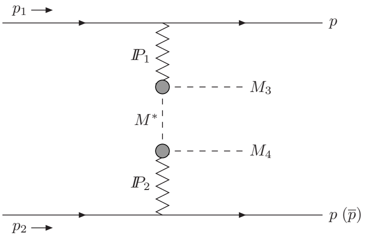
$\to$ χ_{c0} CEP via $\pi^+\pi^-$ channel expected to strongly dominate, with similar/bigger production cross sections to $J/\psi\gamma$ channel (similarly for K^+K^- channel).

- Ideally suited to, e.g., LHCb and STAR experiments (excellent PID and high momentum resolution), but also ALICE ($\pi^+\pi^-$ CEP at lower $M_{\pi\pi}$ already observed[6]), CMS, ATLAS...
- Continuum $\pi^+\pi^-$ CEP background under control?
  - Non-perturbative contribution (lower $M_{\pi\pi}/k_\perp(\pi)$), modeled using Regge theory.
  - Perturbative contribution (higher $M_{\pi\pi}/k_\perp(\pi)$), modeled using hard exclusive formalism.

[6] See e.g. R. Schicker, arXiv:1110.3693

[7] See Piotr Lebiedowicz's talk.

Meson pair CEP: non-perturbative production

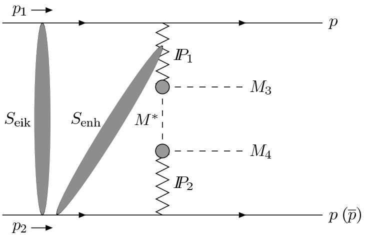


- For low values of meson $k_\perp$, expect non-perturbative double Pomeron/Reggeon exchange mechanism to contribute, mediated via an off-shell meson. The amplitude is given by $\mathcal{M} = \mathcal{M}_{\hat{t}} + \mathcal{M}_{\hat{u}}$, with

$$\mathcal{M}_{\hat{t}} = \frac{1}{M^2 - \hat{t}} F_p(p_{1\perp}^2) F_M(p_{2\perp}^2) F_M^2(k_\perp^2) \sigma_0^2 \left(\frac{s_{13}}{s_0}\right)^{\alpha(p_{1\perp}^2)} \left(\frac{s_{24}}{s_0}\right)^{\alpha(p_{2\perp}^2)},$$

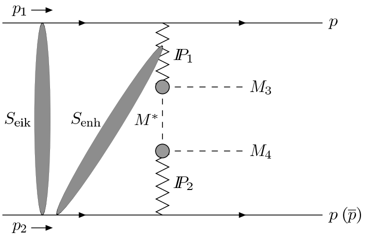
  - $F_M(k_\perp^2)$: meson form factor. Uncertainty in precise form for off-shell meson. However, expect 'soft' form $\sim \exp(-\vec{k}_\perp^2)$ (slope roughly fit to ISR data) $\to$ will strongly suppress higher values of meson $k_\perp$.

Non-perturbative production, screening (1)



- Need exclusive cross section $\rightarrow$ must also take into account probability not produce additional particles, i.e. include screening corrections, in Reggeon formalism described by exchange of one (or more) additional Pomerons:
  - Exchange between incoming protons $\rightarrow S_{\rm eik}$ ($\sim$ 0.05).
  - Exchange between the upper (lower) proton and the lower (upper) meson and Pomeron $\rightarrow S_{\rm enh}$ ($\sim$ 0.35 for $\pi^+\pi^-$ at $\sqrt{s} = 7$ TeV):
    - Do not include exchange between $p_1(p_2)$ and $M_3(M_4)$, as already included in effective Pomeron $P_1(P_2)$.
    - Main effect is expected to be from the secondary proton-meson interaction, due to smallness of triple Pomeron vertex.

Non-perturbative production, screening (2)

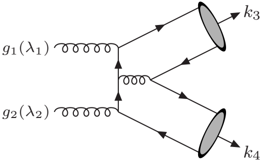


- Need no emission of secondaries in $I\!PI\!P \to M_3M_4$ process, but treatment in terms of Regge exchanges between mesons contradicts causality at high meson energy, E:
  - Lab time taken to form Reggeon $\propto E$ but meson pair production time is almost instant $\propto 1/E \to$ at high $s_{\pi\pi}$ outgoing mesons cannot talk to each other (c.f. $q\overline{q} \to$ meson formation...).
  - Should instead include Reggeization of M^* exchange (t–channel meson has its own size), but we choose a simple phenomenological form to account for Poisson probability not to emit secondaries in the initial meson pair production state, $\sim \exp(-\langle n \rangle)$ (~ 0.2 for $\sqrt{\hat{s}} \sim M_\chi$).

$\to$ Screening effects tend to suppress non-perturbative CEP cross section, in particular as $\sqrt{\hat{s}}$ is increased (also $F_M(k_\perp^2)$ as $k_\perp \uparrow$).

Meson pair CEP: perturbative contribution (1)

- As $M_{\pi\pi}(k_\perp)$ is increased, expect to describe process in terms of pQCD (within Durham CEP model).
- $gg \to M\overline{M}$ modeled by generalisation of 'hard exclusive' formalism[8] to the case of $gg \to \pi^+\pi^-$.



- Total amplitude given by convolution of parton level $g(\lambda_1)g(\lambda_2) \to q\overline{q}q\overline{q}$ amplitude with non-perturbative meson wavefunction $\phi(x)$

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

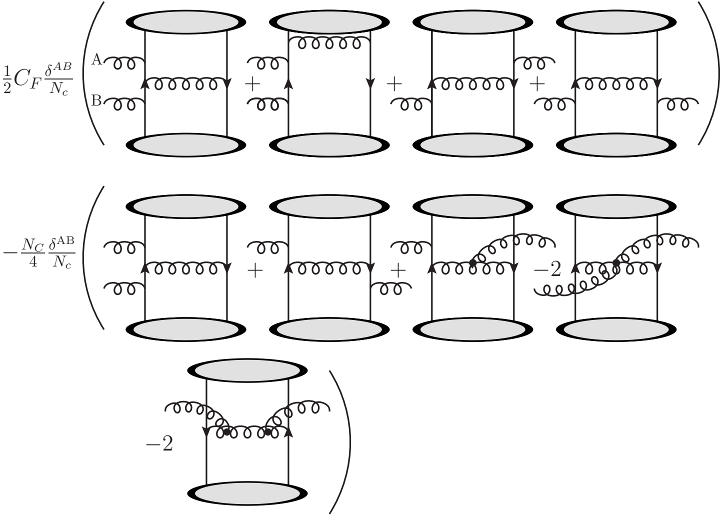
where helicity amplitudes $T_{\lambda_1\lambda_2}$ can be calculated perturbatively.

- Generically, meson pair CEP cross section will be suppressed by a factor $(f_M/k_\perp)^4$ (where $f_M \sim \int \phi(x)$) is meson decay constant): small probability for $q\overline{q}$ pairs to form mesons[9].

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

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

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



Meson pair CEP: perturbative contribution (2)

- Simplest case: production of flavour non-singlet scalar mesons (e.g. $\pi^0\pi^0$, $\pi^+\pi^-$...).
- Can calculate the LO $gg \to M\overline{M}(= q\bar{q}q\bar{q})$ amplitudes to give[10]

$$T_{++} = T_{--} = 0\,,$$
$$T_{-+} = T_{+-} \propto \frac{\alpha_S^2}{a^2 - b^2\cos^2\theta}\left(\frac{N_c}{2}\cos^2\theta - C_F a\right)\,,$$

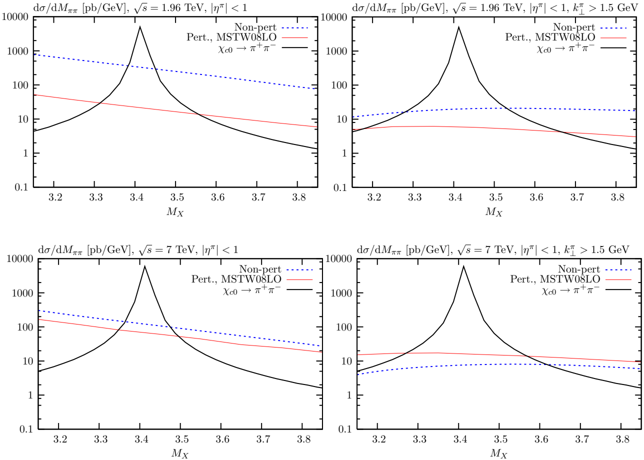
where $a, b = (1-x)(1-y) \pm xy$.

- ▸ $J_z = 0$ amplitudes vanish, as in $\gamma\gamma \to M\overline{M}$ for neutral mesons. We therefore expect a strong suppression of flavour non-singlet $M\overline{M}$ CEP due to $J_z = 0$ selection rule.
- ▸ $J_z = 2$ amplitudes contain 'radiation zero', vanishing for a physical value of $\cos^2\theta$. Well known effect in all gauge theories (e.g. $u\bar{d} \to W^+\gamma$), but usually washed out in QCD by colour averaging.

$\to$ $\pi^+\pi^-$ CEP strongly suppressed (by $\sim 1/100$) by $J_z = 0$ selection rule, and further by suppression by $|J_z| = 2$ radiation zero.

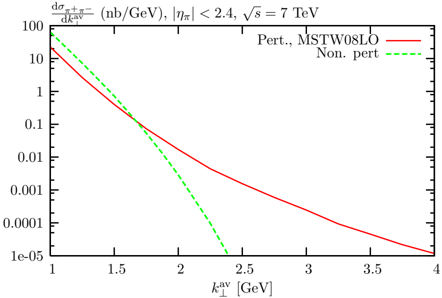
[10] Also true in Handbag fact. as $T_{++/--}(gg \to q\bar{q}) = 0$ for massless quarks.

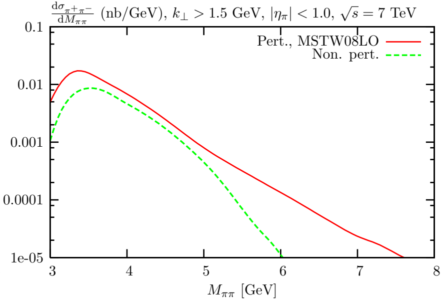
$\chi_c \to \pi^+\pi^-$ CEP: preliminary results.



- Pert. and Non Pert. continuum $\pi^+\pi^-$ background expected to be small, at least once reasonable $k_\perp$ cuts have been imposed $\Rightarrow$ $\chi_{c0} \to \pi^+\pi^-$ (and K^+K^-) channel should give a clean χ_{c0} CEP signal
- However: large theory uncertainties, in pert. ($J_z = 0$...) and non-pert. contribution ($F_M(k_\perp^2)$, screening...) $\to$ measurement of $\pi\pi(KK)$ CEP in lower $k_\perp$ region useful.

Meson pair CEP: pert. vs. non-pert.

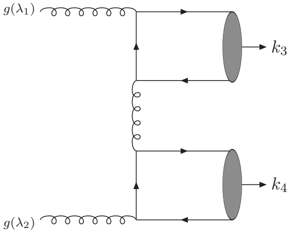




$\rightarrow$ By cutting on meson $k_\perp$ (and η), can potentially isolate perturbative contribution, although in region where statistics may be an issue for $\pi^+\pi^-$(K^+K^-?). Can also consider other observables...

Flavour singlet meson production

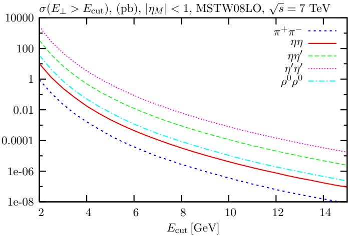
- A second set of diagrams can now contribute, where the $q\overline{q}$ forming the mesons connected by a quark line (no equivalent diagram in $\gamma\gamma \to M\overline{M}$ process).
- Only relevant for flavour singlet states (e.g. for $gg \to \pi^0\pi^0$, $|u\overline{u}\rangle$ and $|d\overline{d}\rangle$ Fock components interfere destructively).

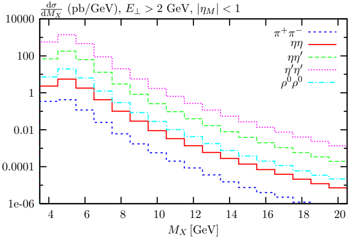


- In this case the $J_z = 0$ amplitude does not vanish $\to$ Expect strong enhancement in $\eta'\eta'$ CEP rate[11] and (through η-η' mixing), some enhancement to $\eta\eta$ rate. $\eta\eta'$ CEP can also occur via this mechanism.
- Any sizable gg component to flavour singlet states, contributing through $gg \to 4g$ and $gg \to q\overline{q}gg$ 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.

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

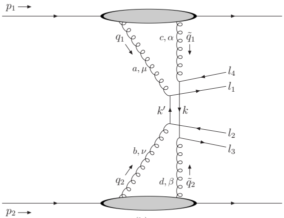
Numerical results. (see arXiv:1105.1626)



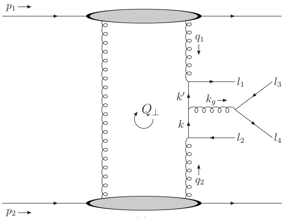


- Strong enhancement in flavour singlet states clear, with precise η'/η hierarchy given by choice of $\eta - \eta'$ mixing angle.
- CEP cross sections for vector mesons ($\rho\rho$, $\omega\omega$, $\phi\phi$) can be calculated in the same way.
- $\pi^0\pi^0$ CEP could in principle be an important background to $\gamma\gamma$ CEP, but we find this not to be the case. (However: possible $J_Z = 0$ contribution from higher twist effects, NNLO corrections... could increase flavour non-singlet rate by a factor 'a few'.)
- New CDF $\gamma\gamma$ data (arXiv:1112.0858): $N(\pi^0\pi^0)/N(\gamma\gamma) < 0.35$ @ 95% confidence $\rightarrow$ supports our result (Theory: $\sigma(\pi^0\pi^0)/\sigma(\gamma\gamma) \approx 0.01$).

$M\overline{M}$ CEP: secondary mechanism (1)



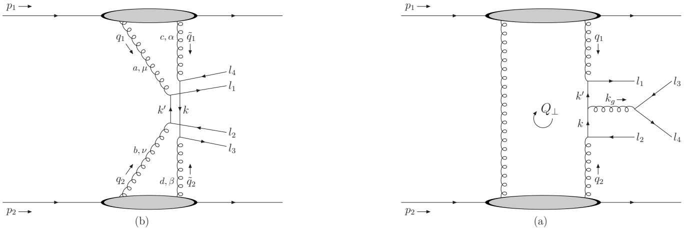
(b)



(a)

- As well as the standard CEP diagram (a), we must in principle consider the process shown in diagram (b)[12].
- This represents the perturbative tail to the non-perturbative process, ‘resolving’ 2-gluon structure of exchanged Pomerons.
- It is formally subleading, as the amplitude has an extra power of the meson transverse momentum squared, $k_\perp^2$, in the denominator.
- However: we have seen that flavour non–singlet meson pair ($\pi\pi$, KK ...) CEP process is strongly suppressed by the $J_z = 0$ selection rule, so this diagram may be important...

[12] ackn. to Jeff Forshaw for pointing this out.



- CEP amplitude given by (assume forward protons for simplicity)

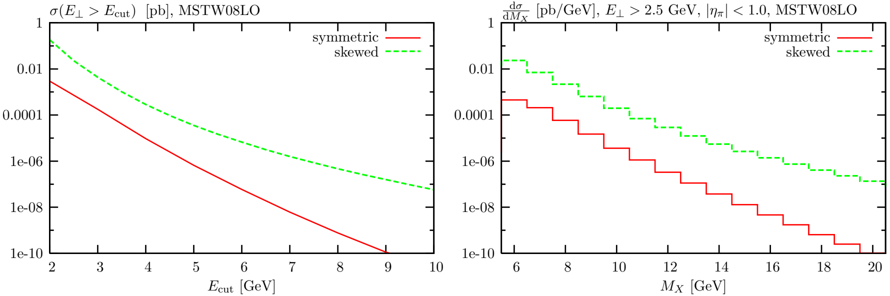
$$T_{\rm sym.} = \pi^2 \int \frac{d^2 q_{1\perp}}{q_{1\perp}^4 q_{2\perp}^4} \mathcal{M}_{\rm sym.} f_g(x_1, \tilde{x}_1, q_{1_\perp}^2, \mu^2; t_1) f_g(x_2, \tilde{x}_2, q_{2_\perp}^2, \mu^2; t_2) \; ,$$

with

$$\mathcal{M}_{\rm sym.} = \frac{4}{M_X^4} \frac{1}{N_C^2 - 1} \delta^{ac} \delta^{bd} q_{1\perp}^\mu q_{2\perp}^\nu q_{1\perp}^\alpha q_{2\perp}^\beta V_{\mu\nu\alpha\beta}^{abcd} \; .$$

f_g's unknown for these kinematics $\rightarrow$ set only upper limit using Schwarz inequality $f_g(x, x', Q^2 ...) < (f_g(x, -x, Q^2 ...) + f_g(x', -x', Q^2, ...))/2$.

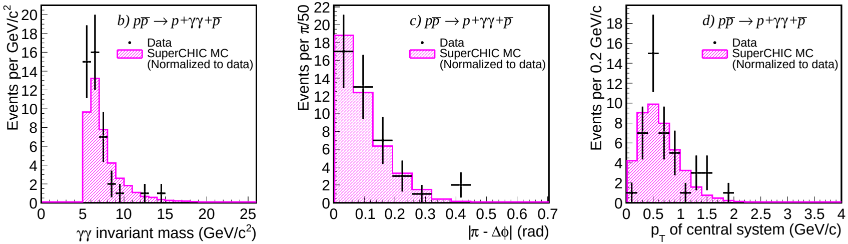
$M\overline{M}$ CEP: secondary mechanism (3)



- After explicit calculation, find 'symmetric' mechanism is subleading, even for, e.g., $\pi^+\pi^-$ CEP (plots, $\sqrt{s} = 7$ TeV).
- A similar type of 'symmetric' diagram can also occur in, e.g., exclusive dijet production (*gg* final state). Following same argument as above, will give a small contribution, in particular as the jet $k_\perp$ is increased.

$\gamma\gamma$ CEP: new results (1)

- $\gamma\gamma$ CEP: represents clean signal, with less of the theory issues related to, e.g. χ_c CEP. $\rightarrow$ ideal 'standard candle'.
- New CDF $\gamma\gamma$ data[13] 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 $\sim \stackrel{\times}{\div} 2$.

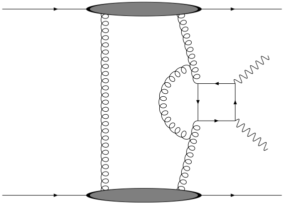


[13] CDF Collaboration, T. Aaltonen et al., Phys. Rev. Lett. 108, 081801 (2012) 1112.0858. (plots taken from here)

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

- Expect theory estimates to be somewhat conservative:
  - $S^2_{\rm enh}$ effect somewhat overestimated– latest number $\approx$ 20% bigger.
  - Small fraction of $\gamma\gamma$ events that are not truly exclusive ($\approx$ 10%).
  - NLO corrections could be numerically quite large (c.f. $\chi_{c0} \to gg$ and $H \to gg$, both receive infrared π^2 numerical enhancement). Including finite part of 1-loop corrections[14] to $gg \to \gamma\gamma$ get $K_{\rm nlo} \approx 1.6$, 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...

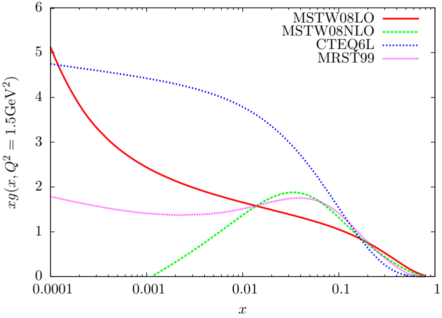


[14] Z. Bern, A. De Freitas, L. J. Dixon, JHEP **0109** (2001) 037.

$\gamma\gamma$ CEP: PDF comparison (1)

- At the low-x,Q^2 values relevant for the CEP of low mass objects there is a large PDF uncertainty (recall $\sigma_{\rm CEP} \sim (xg)^4$).
- The fitted gluon at low x comes almost entirely from the DGLAP evolution, ${\rm d}F_2(x,Q^2)/{\rm d}\ln Q^2$, and depends on the approximations of this, i.e. smallness of higher order and power effects. At lower scales these are not negligible.
- LO and NLO gluons at low x, Q^2 have completely different behaviours:

  - LO: steep x dep. (compensating for lack of 1/z singularity in LO $P_{qg}(z)$), gives only fair description of HERA F_2 data.
  - NLO: much flatter, with modern fits preferring a negative gluon for $x \lesssim 10^{-2}$, $Q^2 \sim Q_0^2$ (screening corrections not included in linear DGLAP, possible $1/z$ resummation required...), which clearly cannot be trusted for CEP.



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

- The gluon density is not sufficiently well described by fixed order, twist = 2 DGLAP at low x and Q^2.
- There is some indication from, e.g. diffractive J/ψ production that the $g(x, Q^2)$ is larger than the current NLO PDFs[15].

→ Can also use, e.g. $\gamma\gamma$ 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 model[16] for $S^2_{\rm eik}$, which includes the new TOTEM elastic data (requires $\Omega(b_t)\uparrow$ in particular at lower b_t, and therefore $S^2_{\rm eik}\downarrow$), and for $S^2_{\rm enh}$ (somewhat higher than previously), gives factor ~ 2 decrease in σ @ 7 TeV. The $\gamma\gamma$ CEP cross sections (in pb) are predicted to be (for $E_\perp > 2.5$ GeV):

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

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

SuperCHIC MC

A MC event generator including[17]:

- 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...?).

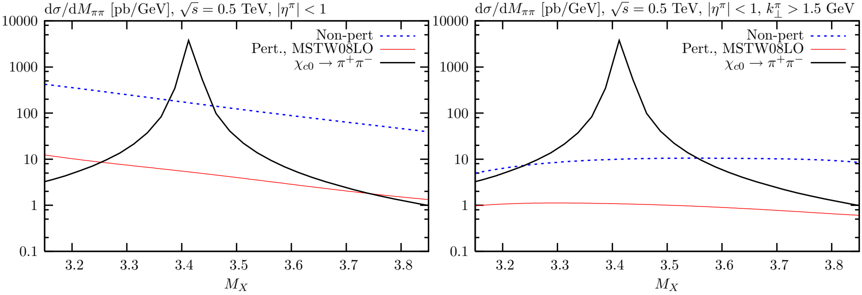
$\rightarrow$ Via close collaboration with CDF, STAR and LHC collaborations, in both proposals for new measurements and applications of SuperCHIC, it is becoming an important tool for current and future CEP studies.

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

Summary and Outlook

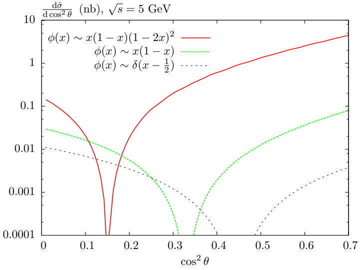
- CEP processes observed at the Tevatron, RHIC and early LHC can serve as 'standard candles' for new physics CEP at the LHC.
- New LHCb $\chi_c \to J/\psi$ data, supports previous suggestion that $\chi_{c(1,2)}$ contribute to CDF χ_c data.
- First estimates of dissociative background given.
- χ_{c0} CEP via two-body decays ($\pi^+\pi^+$, K^+K^-...) interesting and realistic channels, with continuum background expected to be low. Other decay channels (e.g. $p\overline{p}$, $\Lambda\overline{\Lambda}$, $2(\pi^+\pi^-)$...) also possible.
- The CEP of mesons pairs at high invariant masses ($/k_\perp$) is an interesting process, representing a novel application of pQCD framework for describing exclusive processes.
- Measurement of $\pi\pi$ (KK...) CEP at lower mass$/k_\perp$ 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 $\gamma\gamma$ data gives encouraging results! Could shed light on the gluon density...awaiting CMS results.
- More CEP results to come from RHIC, the Tevatron data analysis and LHC in the future.

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



Backup 2: radiation zeros

- Complete destructive interference of radiation patterns, resulting in vanishing amplitude for certain configuration of final state particles.
- Occurs in most Born amplitudes for radiation of massless gauge bosons, first seen in $u\overline{d} \to W^+\gamma$ amplitude.



- General conditions for zeros are known[18]: often zeros do not occur in physical region.
- Occurs in QCD, but zeros are usually neutralised along with colour by averaging of hadronisation $\to$ pure colour singlet CEP process *in principle* uniquely positioned to observe zeros.
- However: zero only occurs at LO in subleading $|J_z| = 2$ amplitude. We may reasonably expect higher order ($J_z = 0$) corrections to fill in the zero.

[18] S.J. Brodsky and R.W. Brown, Phys. Rev. Lett. 49, 966 (1982)