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

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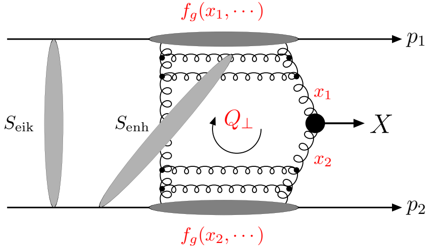
Based on work by V.A. Khoze, M.G. Ryskin, W.J. Stirling and L.A. Harland-Lang. (KHRYSTHAL collaboration)
For more details see arXiv:1005.0695, arXiv:1011.0680 and arXiv:1105.1626

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^-...).
  - 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

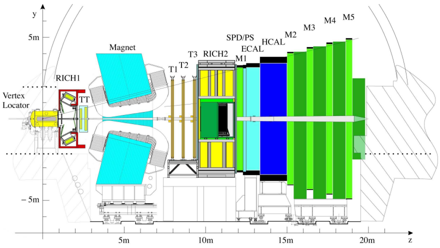
χ_c CEP @ the LHC (2)

→ 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?

Possible ways to shed some light on this issue:

- Forward shower counters @ LHC: can veto on greatly extended η region, will reduce inclusive contamination.
- Other decays ($\chi_{c(0,2)} \to \pi^+\pi^-, K^+K^-$...): should dominantly see χ_{c0}'s.



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

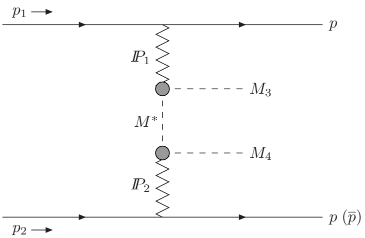
- $\text{Br}(\chi_{c0} \to \pi^+\pi^-) = (0.56 \pm 0.03)\%$ and
  $\text{Br}(\chi_{c2} \to \pi^+\pi^-) = (0.16 \pm 0.01)\%$, while $\chi_{c1} \to \pi^+\pi^-$ does not occur.

$\to$ 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[4]), 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.

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

Meson pair CEP: non-perturbative production



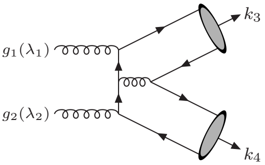
- For low values of meson $k_\perp$, expect non-perturbative double Pomeron/Reggeon exchange mechanism to contribute, mediated via an off-shell meson. The amplitude is given by $\mathcal{M} = \mathcal{M}_{\hat{t}} + \mathcal{M}_{\hat{u}}$, with

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

  - $F_M(k_\perp^2)$: meson form factor. Uncertainty in precise form for off-shell meson. However, typically expect 'soft' form $\sim \exp(-\vec{k}_\perp^2) \to$ will strongly suppress higher values of meson $k_\perp$. $p\pi$ (and pp) rescattering and no emission prob. in Pom+Pom $\to M_3 M_4$ process will further suppress rate.

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[5] to the case of $gg \to \pi^+\pi^-$.



- Total amplitude given by convolution of parton level $g(\lambda_1)g(\lambda_2) \to q\bar{q}q\bar{q}$ 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.

- 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 $q\bar{q}$ pairs to form pions[6].

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

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

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 $gg \to M\overline{M}(= q\overline{q}q\overline{q})$ amplitudes to give

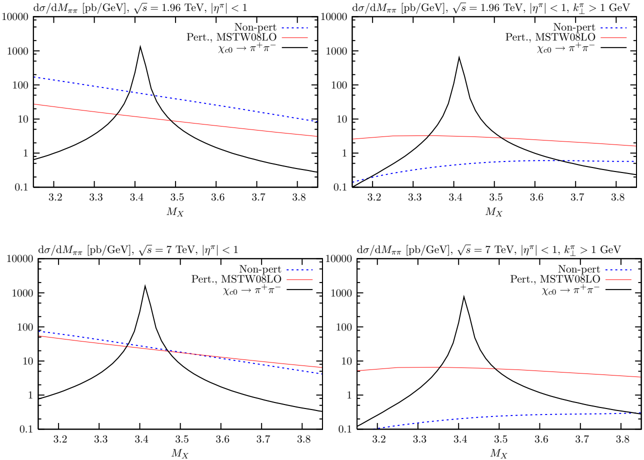
$$T_{++} = T_{--} = 0\,,$$
$$T_{-+} = T_{+-} \propto \frac{\alpha_S^2}{a^2 - b^2\cos^2\theta}\left(\frac{N_c}{2}\cos^2\theta - C_F a\right)\,,$$

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

- ▸ $J_z = 0$ 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. $u\overline{d} \to W^+\gamma$), but usually washed out in QCD by colour averaging.

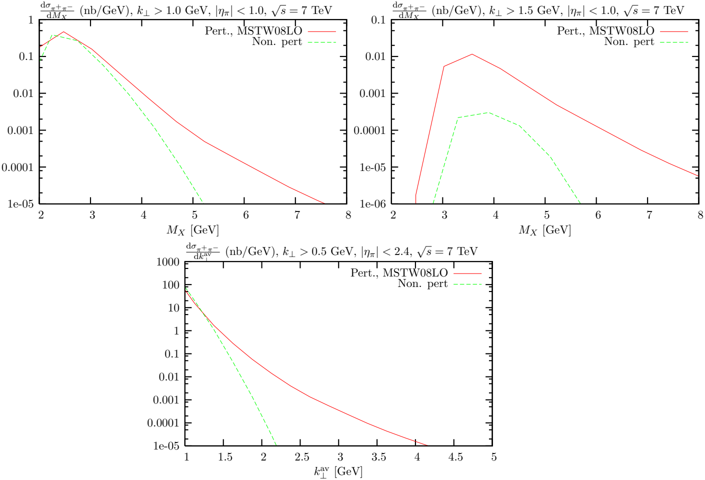
$\to$ $\pi^+\pi^-$ CEP strongly suppressed (by $\sim 1/100$) by $J_z = 0$ selection rule, and further by suppression by $|J_z| = 2$ radiation zero.

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



- Continuum $\pi^+\pi^-$ background expected to be very small, in particular 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 particular in non-pert. contribution (F_M, screening...) $\to$ measurement of $\pi\pi(KK)$ CEP in lower $k_\perp$ region useful.

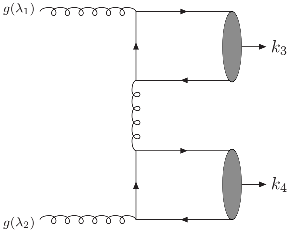
Meson pair CEP: pert. vs. non-pert.



$\rightarrow$ By cutting on meson $k_\perp$ (and η), can effectively 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

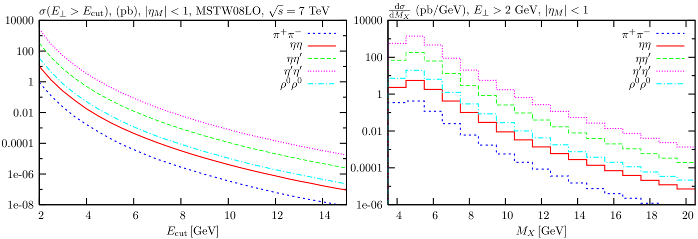
- A second set of diagrams can now contribute, where the $q\bar{q}$ forming the mesons connected by a quark line (no equivalent diagram in $\gamma\gamma \to M\overline{M}$ process).
- Only relevant for flavour singlet states (e.g. for $gg \to \pi^0\pi^0$, $|u\bar{u}\rangle$ and $|d\bar{d}\rangle$ Fock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



- In this case the $J_z = 0$ amplitude does not vanish $\to$ Expect strong enhancement in $\eta'\eta'$ CEP rate[7] 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 $gg \to q\bar{q}gg$ 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.

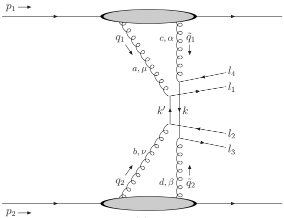
[7] Recall quark content of $|\eta'\rangle$ is dominantly $\sim |u\bar{u} + d\bar{d} + s\bar{s}\rangle$

Numerical results.

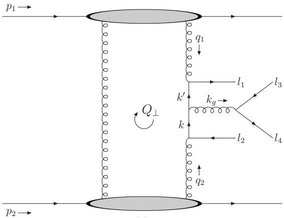


- Strong enhancement in flavour singlet states clear, with precise η'/η hierarchy given by choice of $\eta - \eta'$ mixing angle.
- CEP cross sections for vector mesons ($\rho\rho$, $\omega\omega$, $\phi\phi$) can be calculated in the same way.
- $\pi^0\pi^0$ CEP could in principle be an important background 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)

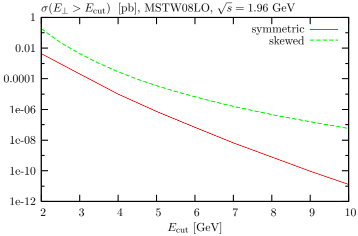


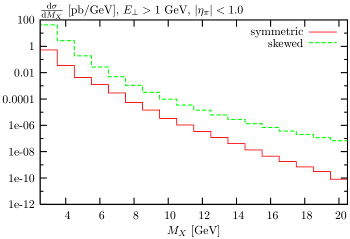
(a)

- As well as the standard CEP diagram (a), we must in principle consider the process shown in diagram (b)[8].
- 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...

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

Backup 4: $M\overline{M}$ CEP: secondary mechanism (2)



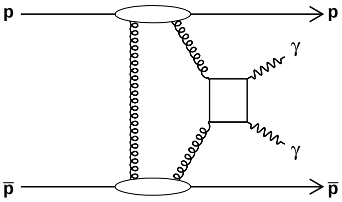


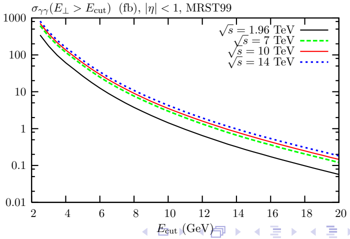
- After explicit calculation, find 'symmetric' mechanism is subleading, even for, e.g., $\pi\pi$ CEP[9].
- A similar type of 'symmetric' diagram can also occur in, e.g., exclusive dijet production (*gg* final state). Following same argument as above, will give a small contribution, in particular as the jet $k_\perp$ is increased.

[9] See arXiv:1105.1626 and future work for more details.

$\gamma\gamma$ 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 (arXiv:1112.0858) 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 estimates: 1.42 pb (MSTW08LO) and 0.35 pb (MRST99), with approx. uncertainties $\sim \stackrel{\times}{\div} 3$.
- At these low-x,Q^2 values there is a large PDF uncertainty (recall $\sigma_{\rm CEP} \sim (xg)^4$), with LO (steep x dep. – no 1/z singularity in LO $P_{qq}(z)$) and NLO (often negative – screening corrections not included in linear DGLAP). Data *might* show preference for more 'LO' type behaviour. However, other things to bear in mind...





$\gamma\gamma$ 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[10] 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.

$\to$ More theory work needed.

$\to$ More data @ the LHC would be very useful in further constraining these issues...

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

SuperCHIC MC

A MC event generator including[11]:

- 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...?).

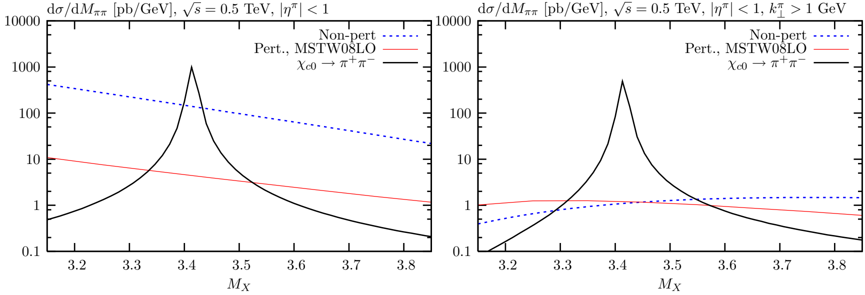
$\rightarrow$ Via close collaboration with CDF, STAR and LHC collaborations, in both proposals for new measurements and applications of SuperCHIC, it is becoming an important tool for current and future CEP studies.

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

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 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.
- 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 is an interesting process, representing a novel application of pQCD framework for describing exclusive processes.
- 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! Some tension with MRST99 PDFs...
- More CEP results to come from RHIC, the Tevatron and LHC in the future.

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

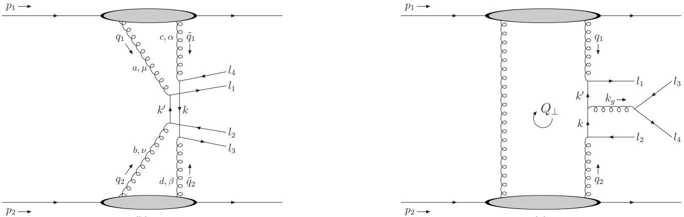


Backup 2: Meson pair CEP: non-perturbative production, screening

- Need exclusive cross section $\to$ 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 $\to S_{\rm eik}$ ($\sim$ 0.05).
  - Exchange between the upper (lower) proton and the lower (upper) meson and Pomeron $\to S_{\rm enh}$ ($\sim$ 0.35 for $\pi^+\pi^-$):
    - 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.
  - No emission of other secondaries in the Pom+Pom $\to M_3M_4$ process, take simple Poisson probability $\sim \exp(-\langle n\rangle)$ ($\sim$ 0.2 for $\sqrt{\hat{s}} \sim M_\chi$)

$\to$ All tend to suppress non-perturbative CEP cross section, in particular as $\sqrt{\hat{s}}$ is increased ($F_M(k_\perp^2)$, $\exp(-\langle n\rangle)$).

Backup 3: $M\overline{M}$ CEP: secondary mechanism



(b) (a)

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

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

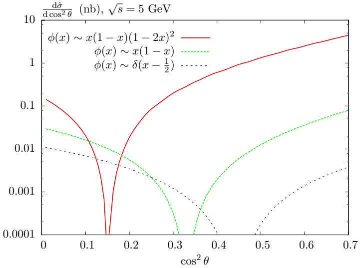
with

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

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

Backup 4: 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[12]: 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.

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