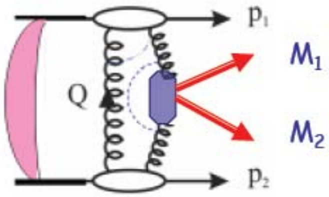
WORKSHOP ON QCD AND DIFFRACTION AT THE LHC:

CRACOW
POLAND
November 28-29-30 2011

Central Exclusive Meson Pair Production in the Perturbative Regime.

(KRYSTHAL collaboration)

V.A. Khoze (IPPP, Durham)

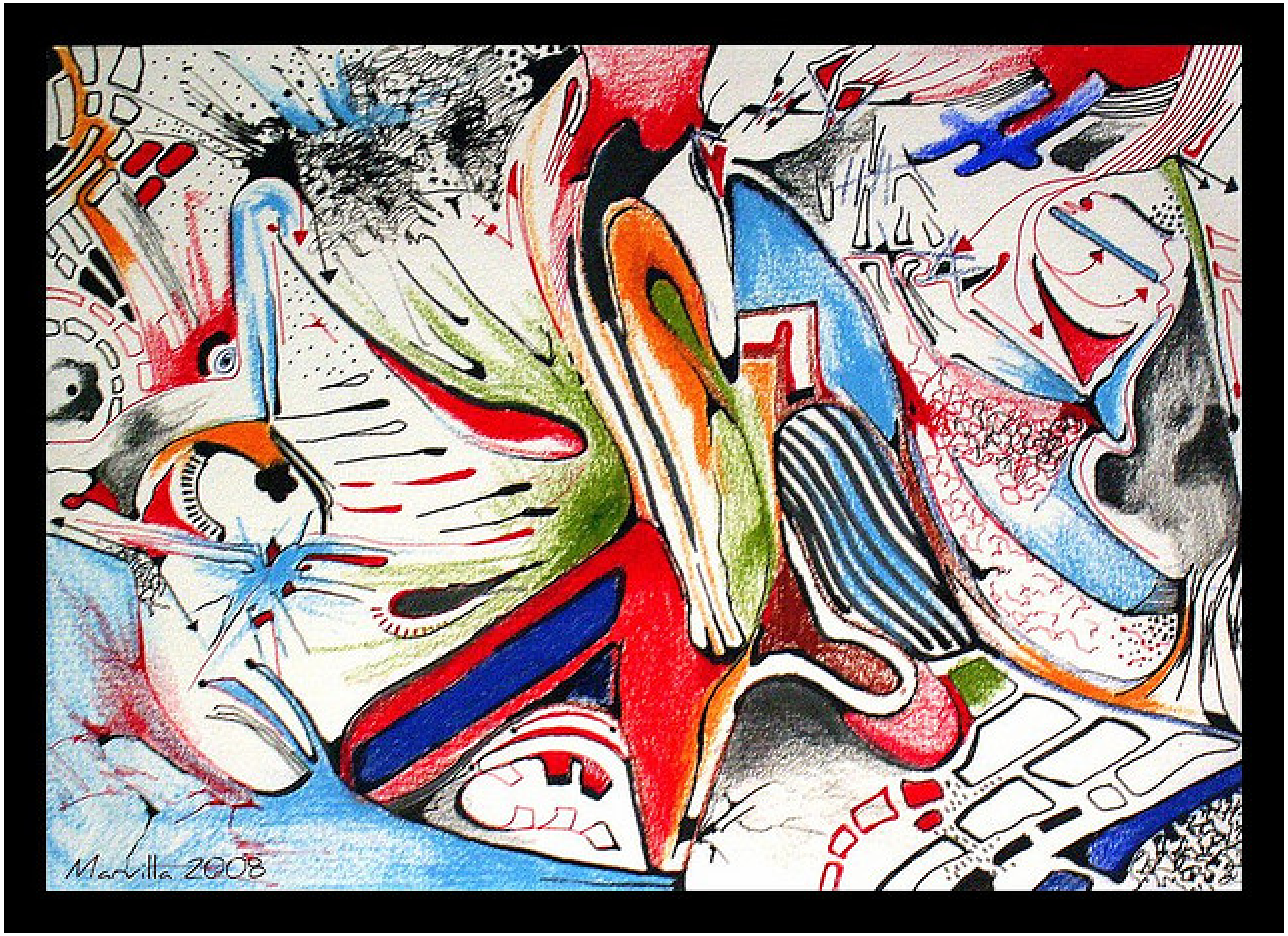


Based on work by V.A. Khoze, M.G. Ryskin, W.J. Stirling and L.A. Harland-Lang. (KHRYSTHAL collaboration)

For more details see arXiv:1005.0695, arXiv:1011.0680 and arXiv:1105.1626

On the same pasture:
activity by Cracow group Antoni Szczurek et al

This Workshop:
(talks by Piotr & Antoni)

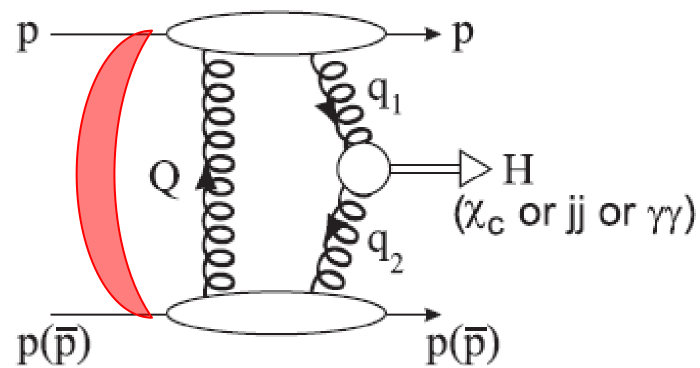


Encuentros y desencuentros (Agreements and disagreements)

(Fernando Marvilla, 2008)

Central Exclusive Production (CEP) : Durham model

- 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.



$M\overline{M}$

- The generic process $pp \to p + X + p$ is modeled perturbatively by the exchange of two t-channel gluons, with the use of pQCD justified by the presence of a hard scale $\sim M_X$.
- '$J_z = 0$ selection rule': production of states with non-$J_Z^P = 0^+$ quantum numbers is strongly suppressed by ~ 2 orders of magnitude.

CEP-spin-parity filter
(KMR-00,KKMR-03)

- χ_c, $\gamma\gamma$ CEP already observed by CDF and *jj* CEP observed by CDF & D0.
- NEW! χ_{cJ} CEP is reported by LHCb (DIS-11)
- NEW! new CDF $\gamma\gamma$CEP results (low x-11,DIS-11

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

Meson pair CEP

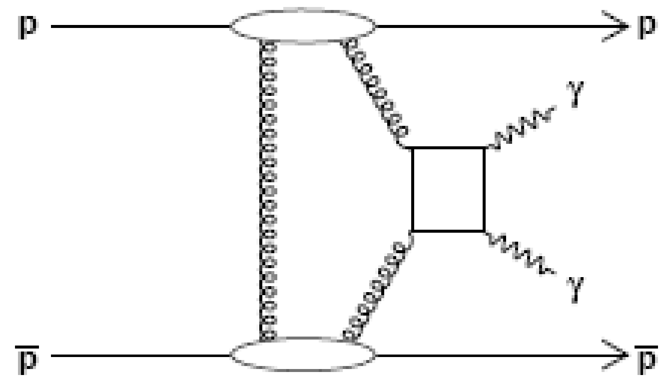
- CEP is a promising way to study new physics at the LHC, but we can also consider the CEP of lighter, established objects : χ_c, $\gamma\gamma$ and jj CEP already observed at the Tevatron.

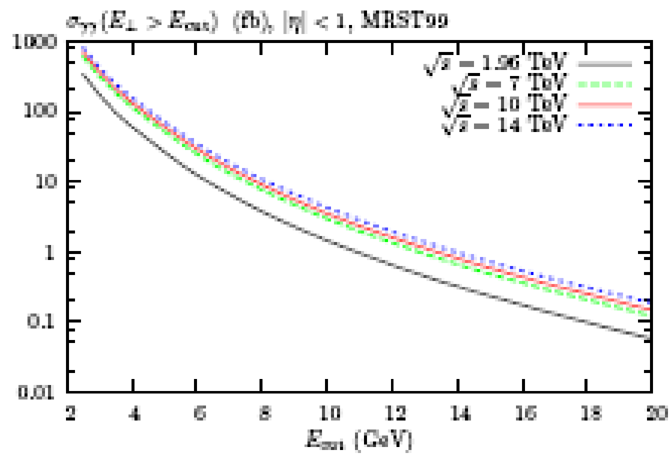
- Can serve as 'Standard Candle' processes, which allow us to check the theoretical predictions for central exclusive new physics signals at the LHC, as well as being of interest in their own right[1].
- This talk will focus on the CEP of light meson pairs, $M\overline{M}$, at sufficiently high invariant mass for perturbative formalism to be applicable:
  - Provides novel application/test of hard exclusive formalism, complementary to more standard photon-induced processes ($\gamma\gamma \to M\overline{M}$, $\gamma\gamma^{(*)} \to M$ etc[2]).
  - Demonstrates application of MHV formalism to simplify/check calculations.
  - $\pi^0\pi^0$ CEP a possible background to $\gamma\gamma$ CEP.
  - Could probe the $q\overline{q}$ and gg content of η, η' mesons?
  - An interesting potential observable @ RHIC, Tevatron and LHC: meson pair CEP data (at lower $p_\perp$) already being taken by ALICE and CDF.

[1] See LHL, V.A. Khoze, M.G. Ryskin, W.J. Stirling, arXiv:1005.0695 and arXiv:1011.0680 .
[2] For a recent review, see for example V. L. Chernyak, arXiv:0912.0623.

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 $E_{\perp_\gamma} < E_{\text{cut}}$ scale, but this decreases for higher scales.
- More CDF events allow us to probe scaling of σ with cut on photon $E_\perp$ ($\lesssim M_{\gamma\gamma}/2$): strong predicted fall-off with $M_{\gamma\gamma}$ driven by Sudakov factor (already seen in dijet data).





(KMRS-04)
(LKRS-10)

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

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

43 Events with no tracks in COT ($\gamma\gamma$ candidates: $\pi^0\pi^0$?)

(to be published in PRL soon)

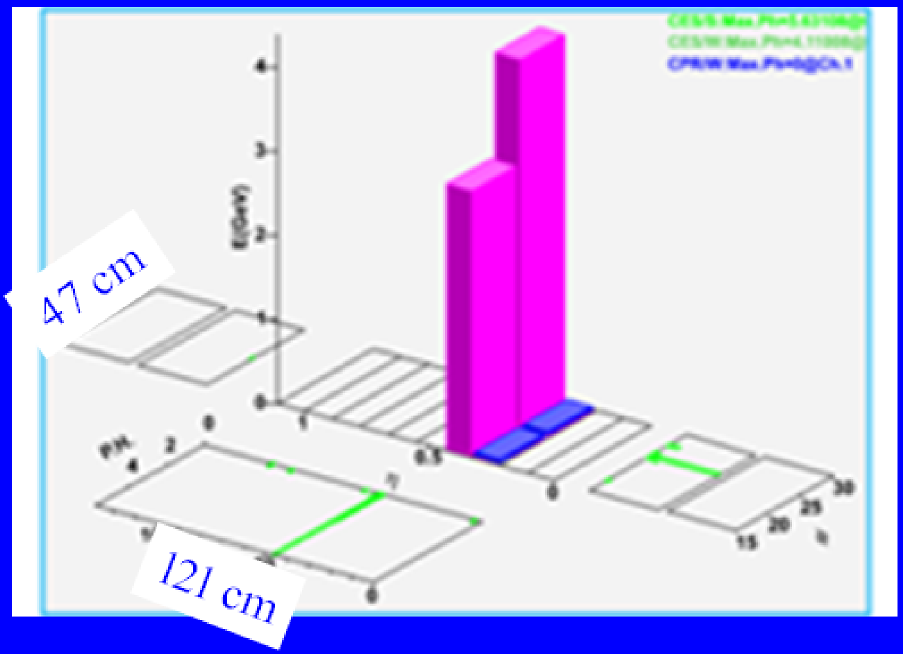
How do we know if they are $\gamma\gamma$ or $\pi^0\pi^0$?

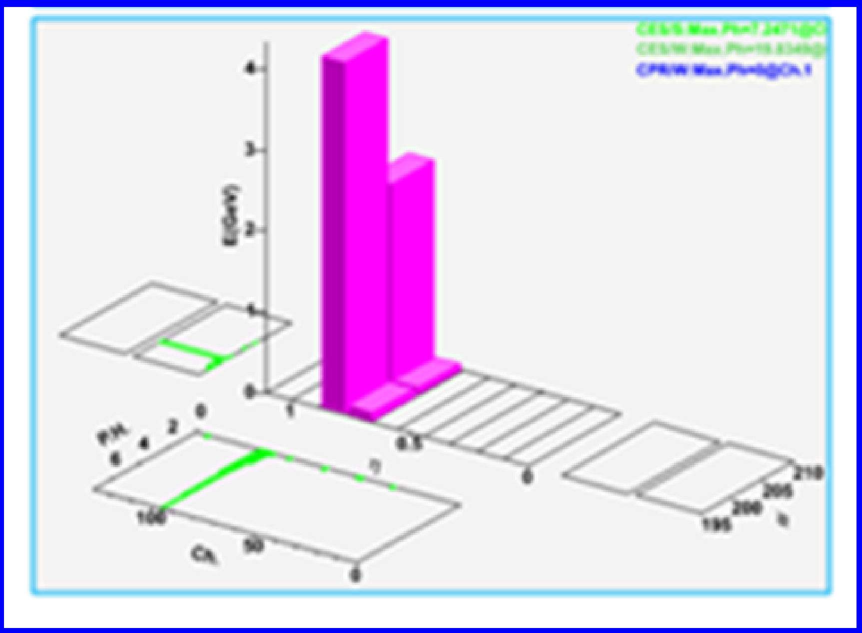
Note that exclusive **p + $\gamma\,\pi^0$ + p** is forbidden (e.g. **C-parity)**

Count showers in CES strip chambers. **Wires 1.45 cm, strips ~ 1.8 cm**

Two photons cannot merge:

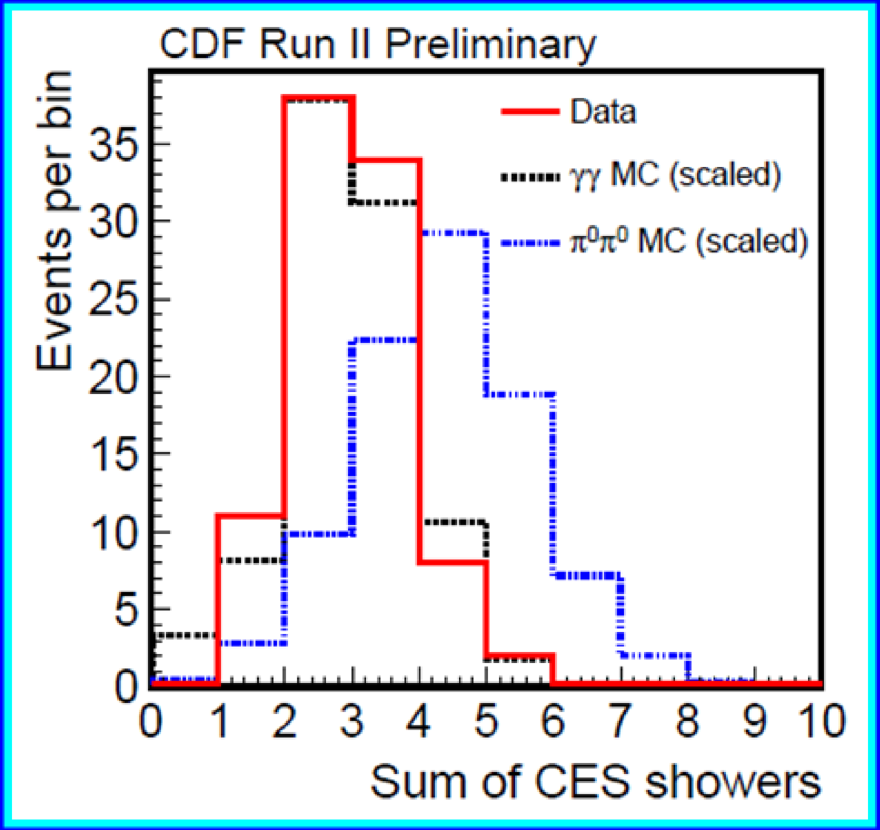
$$\theta(\gamma\gamma)_{min} = 2 \times \left(\frac{m_\pi}{p_\pi}\right) = 3.2^0 \text{ for } p_\pi = 5\,\text{GeV/c}$$
$$= 11.2 \text{ cm at } 2 \text{ m.}$$

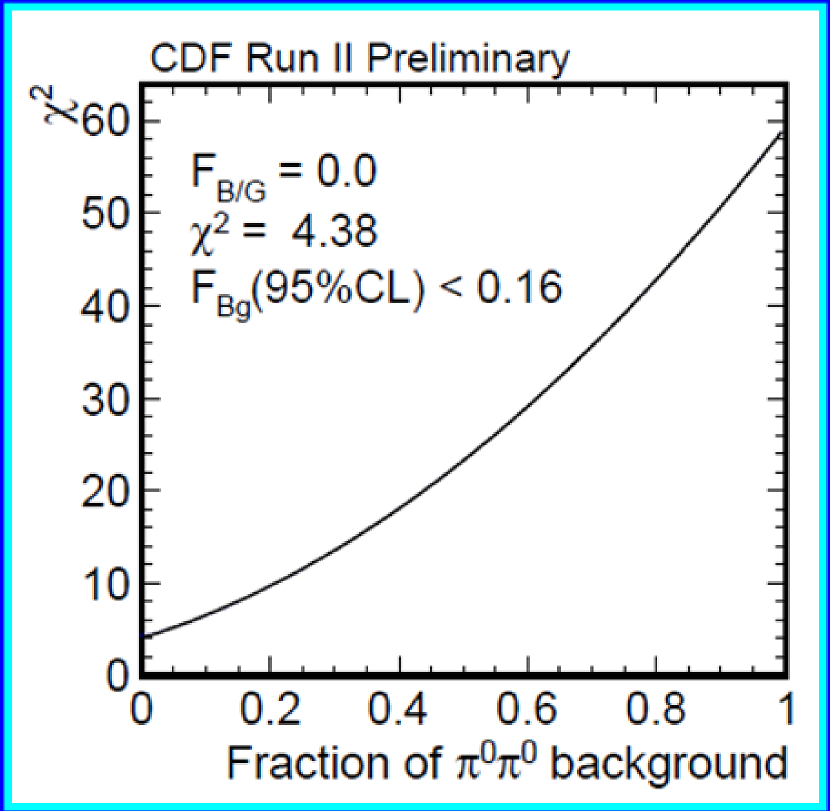




Are any events not $\gamma\gamma$ but $\pi^0\pi^0$?

Add # showers on both sides (there is no correlation)





Result: Best fit is with ZERO background from $\pi^0\pi^0 \rightarrow 4\gamma$

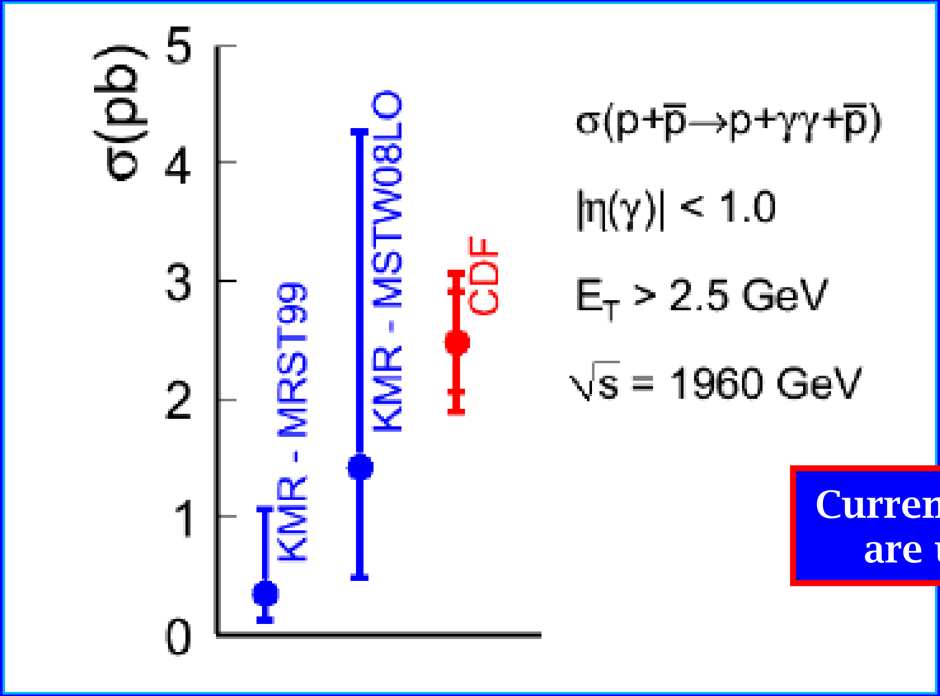
Pearson's χ^2 test: fraction of $\gamma\gamma$ events in sample < 16% (95% C.L.)

Final results on $p+\bar{p} \to p+\gamma\gamma+\bar{p}$ via IP + IP (QCD)

$$\sigma_{\gamma\gamma\,\mathrm{excl.}}^{|\eta|<1, E_T>2.5\mathrm{GeV}} = 2.48 \pm 0.42(\mathrm{stat}) \pm 0.41(\mathrm{sys})\ \mathrm{pb}$$

$$\sigma_{\mathrm{SuperCHIC\ (MSTW08LO)}}^{|\eta|<1, E_T>2.5\mathrm{GeV}} = 1.42^{\times 3}_{\div 3}\ \mathrm{pb}$$

$$\sigma_{\mathrm{SuperCHIC\ (MRST99)}}^{|\eta|<1, E_T>2.5\mathrm{GeV}} = 0.35^{\times 3}_{\div 3}\ \mathrm{pb}$$



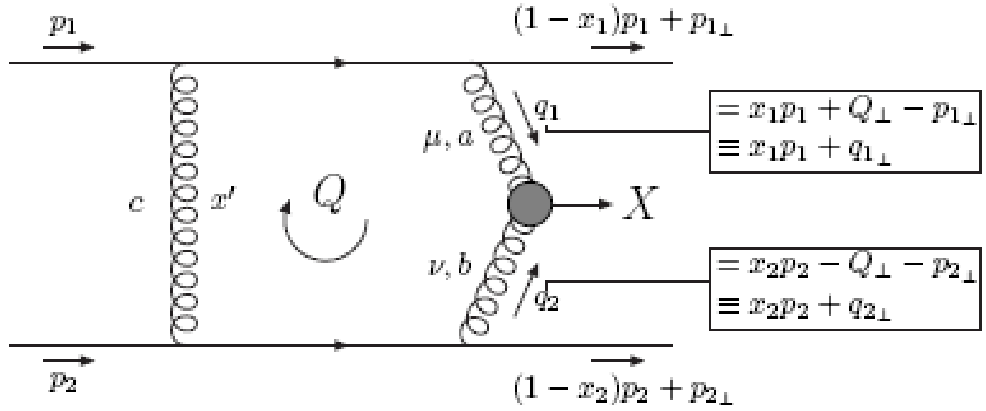
NEW! NLO effects- factor of 1.55

(HKRS in preparation)

Currently theoret. uncertainties are under further revision.

Theory: parton level amplitude

- The generic process $pp \to p \ + \ X \ + \ p$ is modeled perturbatively by the exchange of two t-channel gluons in a colour singlet state[1].



- Using the Cutkosky rules, and eikonal approximation for the qg vertices, we find

$$\frac{iA}{s} = \alpha_S^2 C_F^2 \int \frac{d^2 Q_\perp}{Q_\perp^2 q_{1_\perp}^2 q_{2_\perp}^2} \mathcal{M} \, ,$$

where $\mathcal{M}$ is the normalised, colour averaged subamplitude, written in terms of the $gg \to X$ vertex V as

$$\mathcal{M} \equiv \frac{2}{M_X^2} \frac{1}{N_C^2 - 1} \sum_{a,b} \delta^{ab} q_{1_\perp}^{\mu} q_{2_\perp}^{\nu} V_{\mu\nu}^{ab} \, .$$

[1] See V.A. Khoze, A.D. Martin and M.G. Ryskin, Eur. Phys. J.C 14, 525 (2000)

$J_z^P = 0^+$ selection rule

- Consider the limit $p_{1_\perp} = p_{2_\perp} = 0$, i.e. exactly forward scattering. Have

$$q_{1_\perp} = -q_{2_\perp} = Q_\perp \;,$$
$$\epsilon_1 = -\epsilon_2 \;,$$

  i.e. $gg \to X$ subamplitude is given by

$$\mathcal{M} \sim Q_\perp^i Q_\perp^j V_{ij} \qquad (i/j = 1,2)$$
$$\to \frac{1}{2} Q_\perp^2 (V_{++} + V_{--})$$

  i.e. fusing gluons have equal (transverse) polarisations $\lambda_1 = \lambda_2 = \pm$.

$\to$ In exact forward limit, fusing gluons are in a $J_z = 0$ state along beam axis.

- For general proton $p_\perp \neq 0$, non-$J_z^P = 0^+$ states contribute, but these will be sub-leading (as $p_\perp \approx 0$ in general) and can be efficiently suppressed with proton tagging.

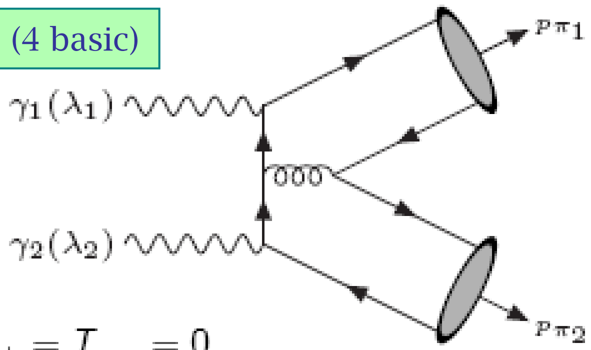
Modeling meson pair CEP perturbatively

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

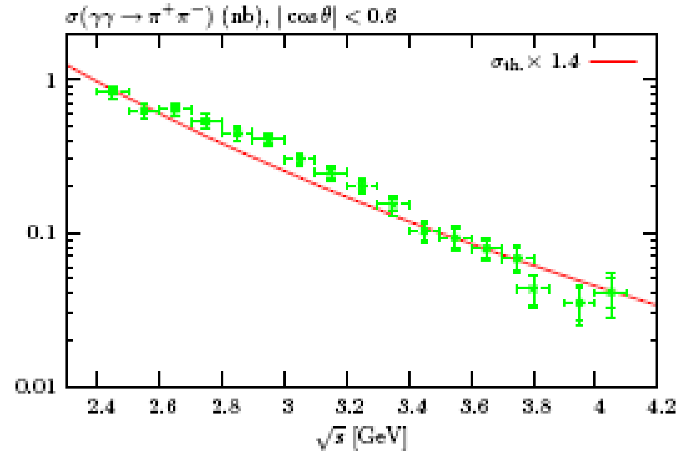
$$\mathcal{M}_{\lambda_1\lambda_2}(s,t) = \int_0^1 dx\, dy\, \phi(x)\phi(y) T_{\lambda_1\lambda_2}(x,y;s,t)$$

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

40 diagrams (4 basic)



✵ $T_{++} = T_{--} = 0$



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

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

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

- 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

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

is this easy to understand ?

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

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

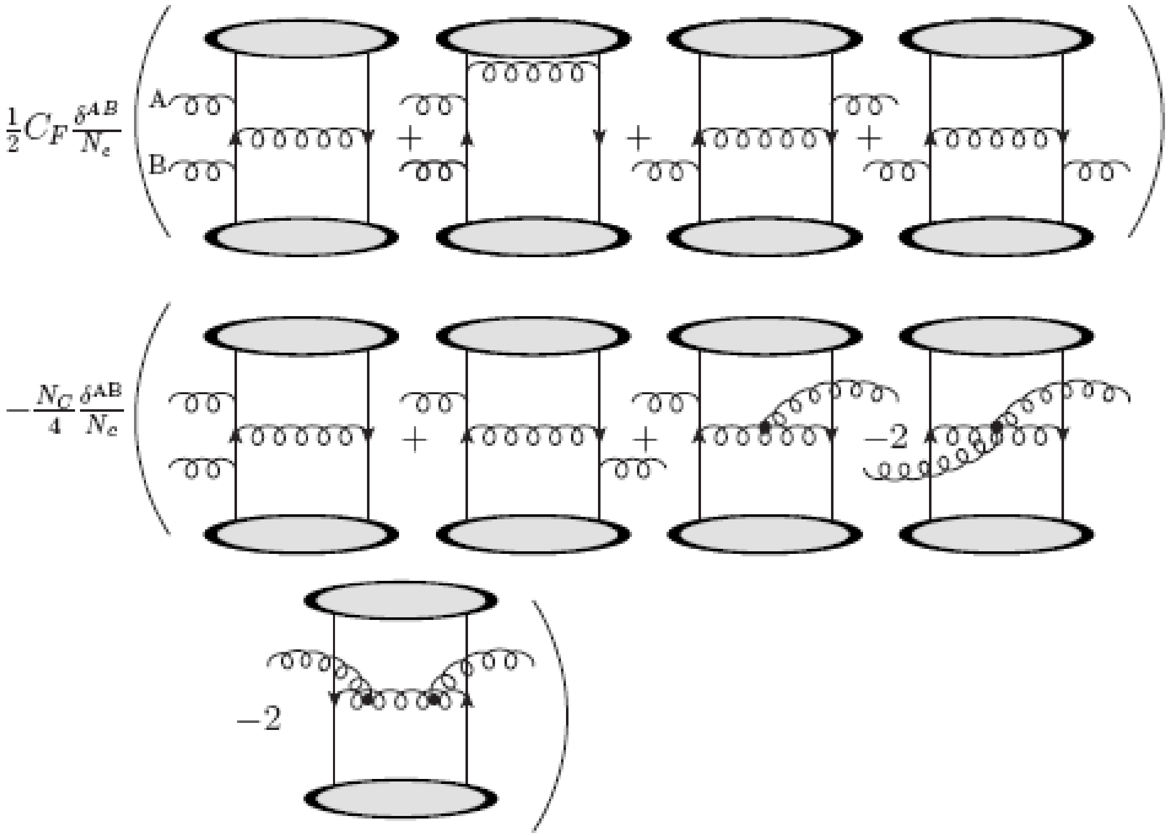
→ $J_z = 0$ amplitudes vanish, as in $\gamma\gamma \to M\overline{M}$ for neutral mesons. We therefore expect a strong suppression in flavour non-singlet $M\overline{M}$ CEP due to $J_z = 0$ selection rule.

→ $J_z = 2$ 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. 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.

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

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

is this easy to understand ?



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

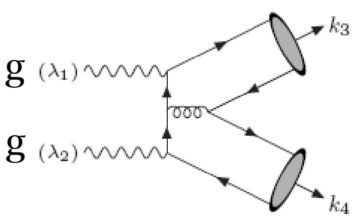
$gg \to M\overline{M}$ amplitude: MHV calculation (1)

- $g(+)g(+) \to q(\pm)\overline{q}(\mp)q(\pm)\overline{q}(\mp)$ 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 amplitude[5]

$$M_n \propto \sum_\sigma \frac{\langle k_p\, k_{\overline{q}}\rangle}{\langle k_p\, a_1\rangle \cdots \langle a_l\, k_{\overline{q}}\rangle} \frac{\langle k_q\, k_{\overline{p}}\rangle}{\langle k_q\, b_1\rangle \cdots \langle b_{l'}\, k_{\overline{p}}\rangle} (\lambda^{a_1} \cdots \lambda^{a_l})_{i_1 j_2} (\lambda^{b_1} \cdots \lambda^{b_{l'}})_{i_2 j_1}$$
$$- \frac{1}{N_c} \frac{\langle k_p\, k_{\overline{p}}\rangle}{\langle k_p\, a_1\rangle \cdots \langle a_l\, k_{\overline{p}}\rangle} \frac{\langle k_q\, k_{\overline{q}}\rangle}{\langle k_q\, b_1\rangle \cdots \langle b_{l'}\, k_{\overline{q}}\rangle} (\lambda^{a_1} \cdots \lambda^{a_l})_{i_1 j_1} (\lambda^{b_1} \cdots \lambda^{b_{l'}})_{i_2 j_2} \; .$$

- Making colour singlet identification ($i_1 = j_2$, $i_2 = j_1$) and identifying $q\overline{q}$, $p\overline{p}$ with collinear quarks within mesons

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



then amplitude reduces to

$$M \propto \langle k_3\, k_2\rangle\langle k_1\, k_4\rangle + \langle k_1\, k_3\rangle\langle k_2\, k_4\rangle - \langle k_3\, k_4\rangle\langle k_1\, k_2\rangle = 0 \; ,$$

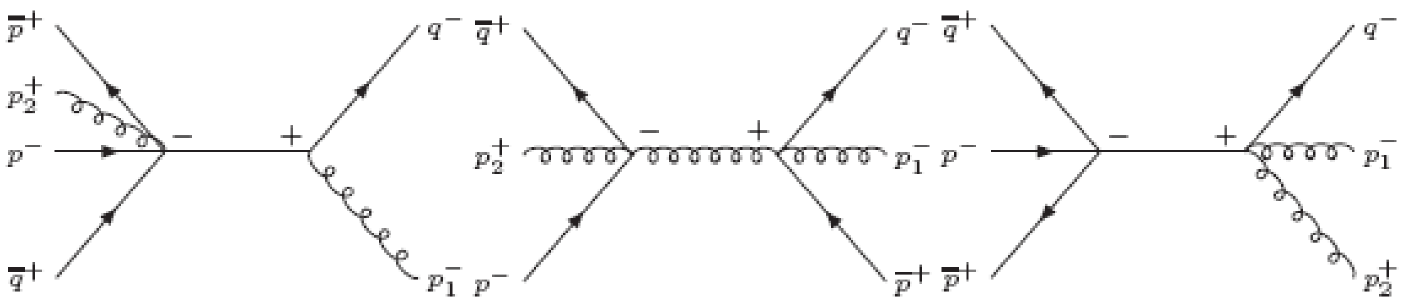
which vanishes from the Schouten identity.

[5] M. 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 '$\langle k, l\rangle$'

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

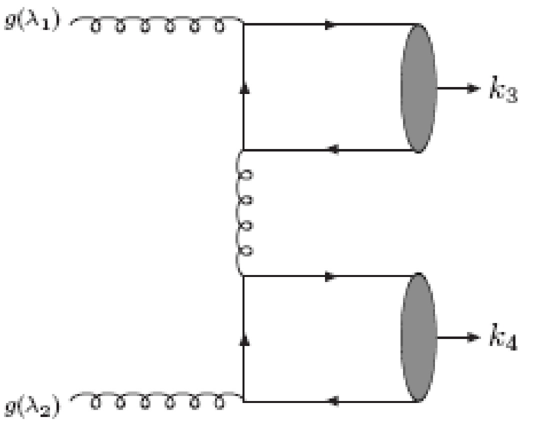
- The vanishing of the $gg \to M\overline{M}$ $J_Z = 0$ amplitudes follow directly from the corresponding 6-particle MHV amplitude. This result depends crucially on the colour singlet projection and collinearity of the $q\overline{q}$ pairs, and only occurs for non-flavour singlet mesons
- The MHV formalism 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-shell[6]. 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.



[6] see 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 $q\overline{q}$ 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[7] and (through η-η' mixing), some enhancement to $\eta\eta$ rate. $\eta\eta'$ CEP can also occur via this mechanism.
- Also: 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.

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

SuperCHIC MC (KRYSTHAL coll.- 09-11)

A MC event generator including[9]:

- Simulation of different CEP processes, including all spin correlations:
  - $\chi_{c(0,1,2)}$ CEP via the $\chi_c \to J/\psi\gamma \to \mu^+\mu^-\gamma$ decay chain.
  - $\chi_{b(0,1,2)}$ CEP via the equivalent $\chi_b \to \Upsilon\gamma \to \mu^+\mu^-\gamma$ decay chain.
  - $\chi_{(b,c)J}$ and $\eta_{(b,c)}$ CEP via general two body decay channels
  - Physical proton kinematics + survival effects for quarkonium CEP at RHIC.
  - $\gamma\gamma$ CEP.
  - Exclusive J/ψ and Υ photoproduction.
- Meson pair CEP r ($\pi\pi$, KK, $\eta\eta$...)
- More to come (dijets, open quark, Higgs...?).

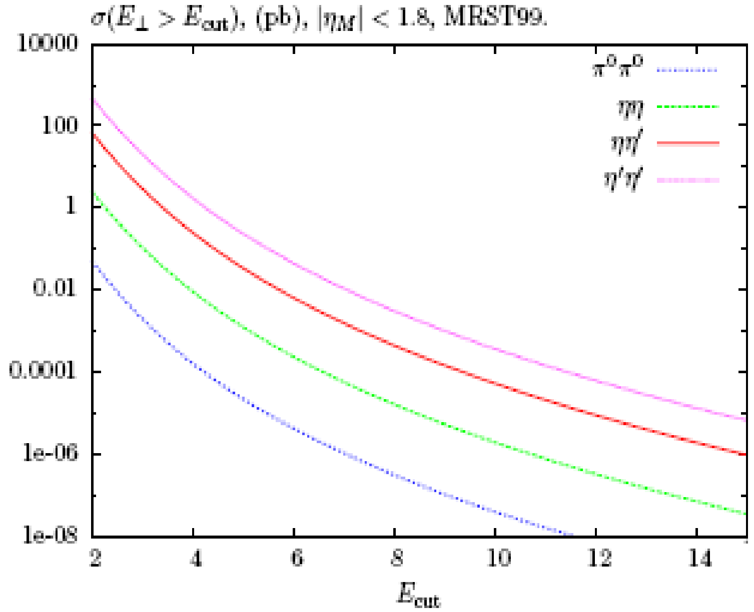
→ Via close collaboration with CDF, STAR and LHC groups, in both proposals for new measurements and applications of SuperCHIC, it is becoming an important tool for current and future CEP studies.

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

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 $\eta - \eta'$ mixing angle.
- CEP cross sections for vector mesons ($\rho\rho$, $\omega\omega$, $\phi\phi$) can be calculated in the same way.

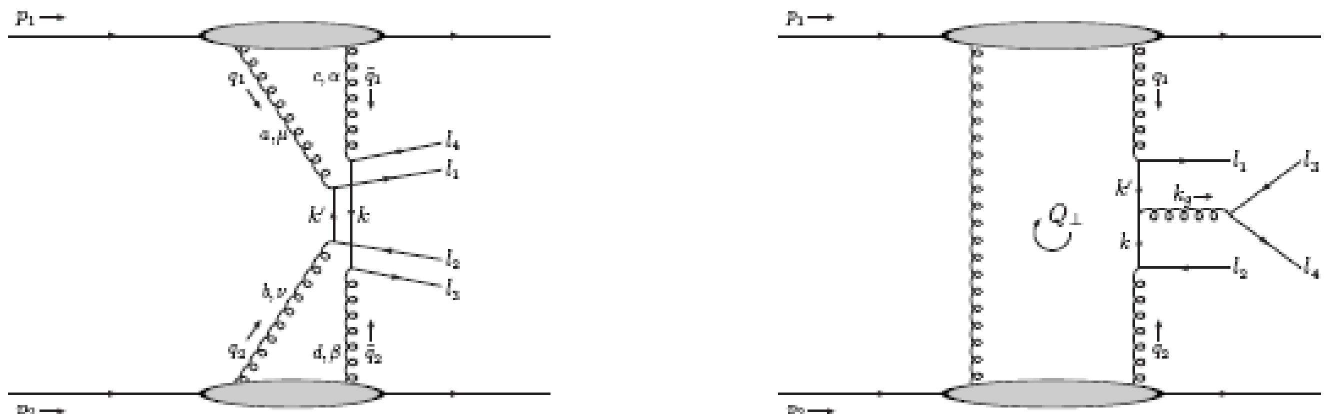


- $\pi^0\pi^0$ CEP can in principle be an important background to $\gamma\gamma$ CEP, but we find this not to be the case. This depends crucially on vanishing of the $gg \to \pi^0\pi^0$ amplitude for $J_z = 0$ initial-state gluons.
- However: possible $J_Z = 0$ contribution from higher twist effects, NNLO corrections... could increase flavour non-singlet rate by a factor 'a few'. Also, possible non-perturbative contribution at lower $p_\perp$?

(K-factor,..)

New CDF data nicely confirm this !)

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



(b) (a)

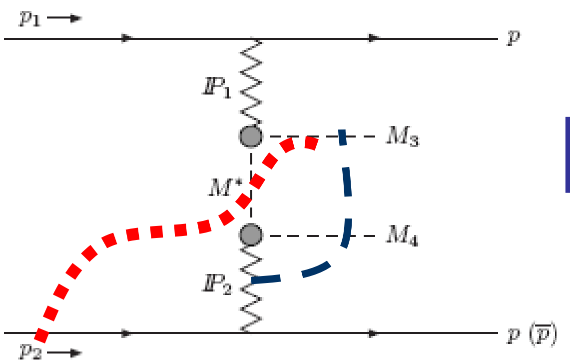
- As well as the standard CEP diagram (a), we must in principle consider the process shown in diagram (b)[8].
- It is formally subleading, as the amplitude has an extra power of the pion transverse momentum squared, $k_\perp^2$, in the denominator.
- However: we have seen that CEP $\pi^0\pi^0$ process is strongly suppressed by the $J_Z = 0$ selection rule, so this diagram may be important.
- Preliminary numerical estimates suggest this *may* be the case at lower $p_\perp$.

$$\frac{A_{\rm sym}}{A_{\rm skew}} \sim \frac{\langle Q_\perp^2 \rangle}{k_\perp^2}$$

large $k_\perp$ tail of the non-perturbative amplitude.

$M\overline{M}$ non-perturbative production

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



(currently under study)

- Uncertainty in what to take for form factor of off-shell pion ('soft' vs 'hard' fit), which suppresses high values of final state pion $p_\perp$, leads to quite large uncertainty in expected rate.
- Expect smooth transition with increasing $p_\perp$ between non-perturbative (dominantly real amplitude) and perturbative (dominantly imaginary amplitude) dominance.
- Measurement of $\pi^0\pi^0/\pi^+\pi^-$ CEP in low $p_\perp$ region would help constrain off-shell pion form factor.

Y. I. Azimov, V. A. Khoze, E. M. Levin *et al.*, Sov. J. Nucl. Phys. **21** (1975) 215.

B. R. Desai, B. C. Shen and M. Jacob, Nucl. Phys. B **142**, 258 (1978).

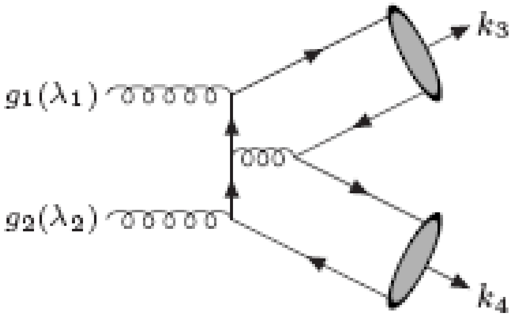
P. Lebiedowicz and A. Szczurek, Phys. Rev. **D81**, 036003 (2010) [arXiv:0912.0190 [hep-ph]]. arXiv:1110.4787

P. Lebiedowicz, R. Pasechnik, A. Szczurek, [arXiv:1103.5642 [hep-ph]].

R..Staszewski et al, Acta Phys.Polon.B42:1961,2011

$\chi_c \to \pi^+\pi^-$ CEP (2)

- Perturbative contribution (higher $M_{\pi\pi}$), modeled using standard pQCD framework, with 'hard exclusive' formalism[2] used to calculate $gg \to \pi^+\pi^-$ amplitude



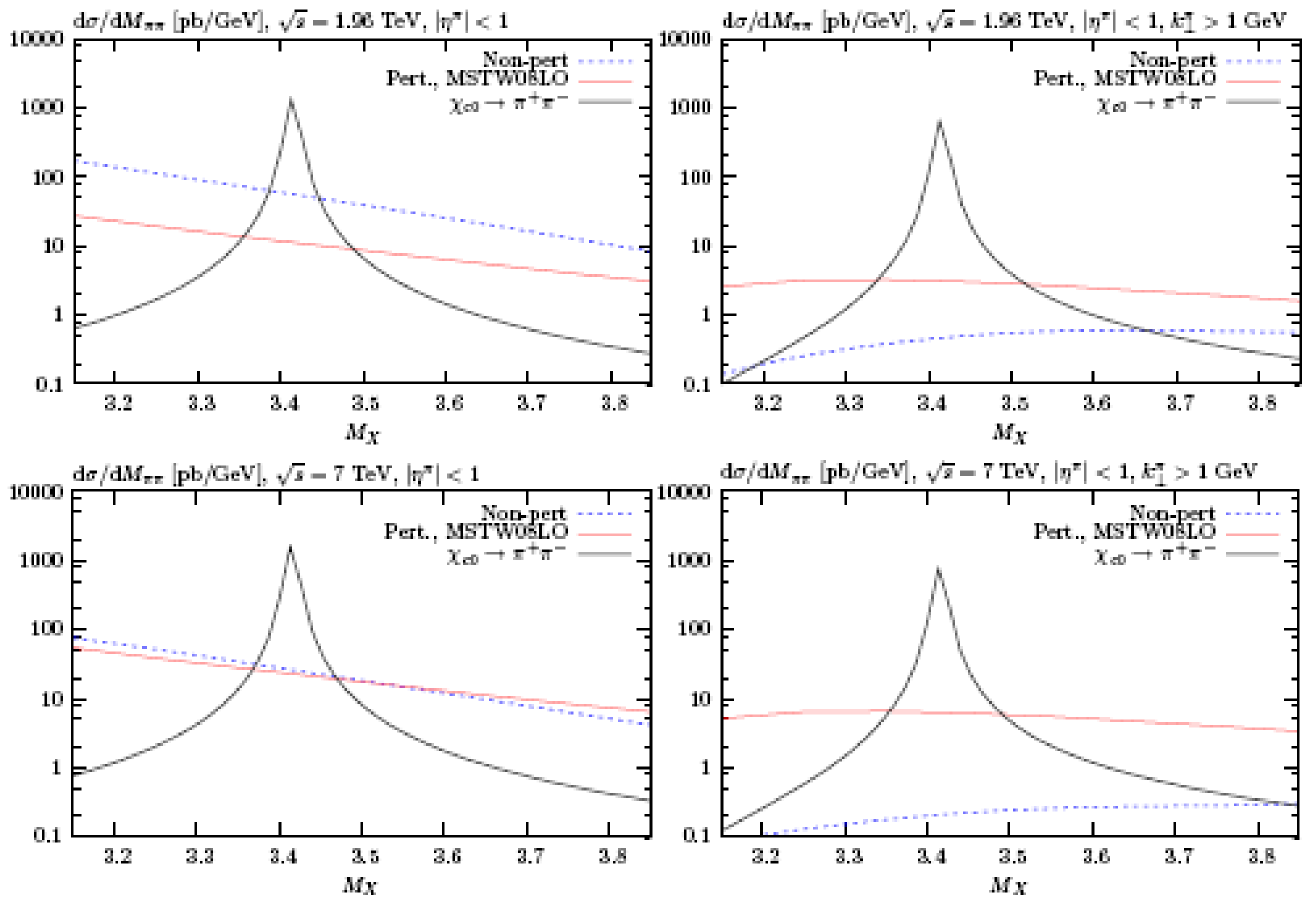
  - Expected to be numerically suppressed by a factor $(f_\pi/p_\perp(\pi))^4$ and also by $J_Z = 0$ selection rule[3] (as in χ_{c2} CEP).

- In χ_c mass region, both these mechanisms are expected to contribute to $\pi^+\pi^-$ continuum background...

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

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

$\chi_c \to \pi^+\pi^-$ CEP (3) (preliminary)



- Continuum $\pi^+\pi^-$ background expected to be very small, in particular once reasonable $p_\perp$ cuts have been imposed $\Rightarrow \chi_{c0} \to \pi^+\pi^-$ (and K^+K^-) channel should give a clean χ_{c0} CEP signal (similarly at RHIC- see backup slide), provided exclusive events can be effectively selected.

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.
- The CEP of mesons pairs at high invariant masses is an interesting process, representing a novel application of pQCD framework for describing exclusive processes
- MHV formalism can be readily applied to these processes, and can simplify calculations.
- 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.
- More CEP results to come from RHIC, the Tevatron and LHC in the future.

- New CDF data confirm both Durham predictions for $\gamma\gamma$ CEP and strong suppression of the $\pi^0\pi^0$ BG to $\gamma\gamma$ CEP


THANK YOU


QUESTIONS?

BACKUP

Executive Summary (Repeat)

We have observed (43 events, >> 5 σ) the new clean process:

$$p + \bar{p} \rightarrow p + \gamma\gamma + \bar{p}$$

We needed:

A good level 1 trigger (EM showers + Forward gap-seeds with BSC-1)

Extended rapidity coverage of CDF to $\eta = \pm 7.4$

Understood noise levels in all calorimeters and counters.

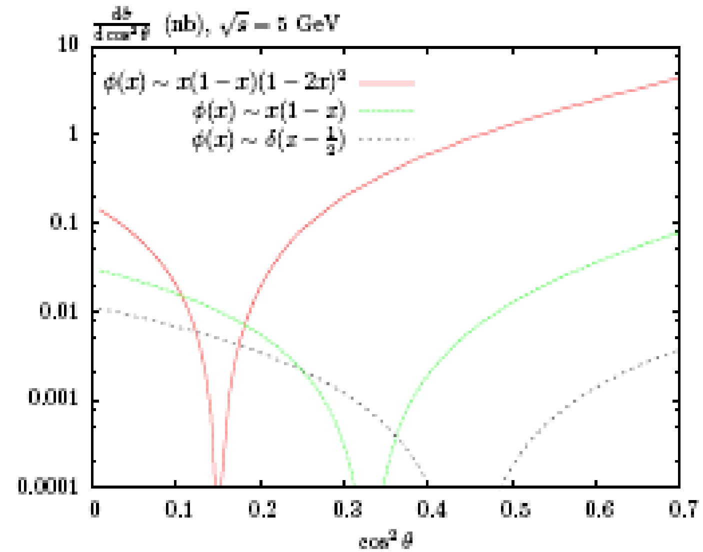
Demonstrated understanding of "empty events" (non-interaction in 0-bias)

Used $p + \bar{p} \rightarrow p + e^{+}e^{-} + \bar{p}$ via γγ (QED) as a control (σ known)

Showed that EM showers are from γ and not π^0 as theoretically expected

Backup 1: radiation zeros

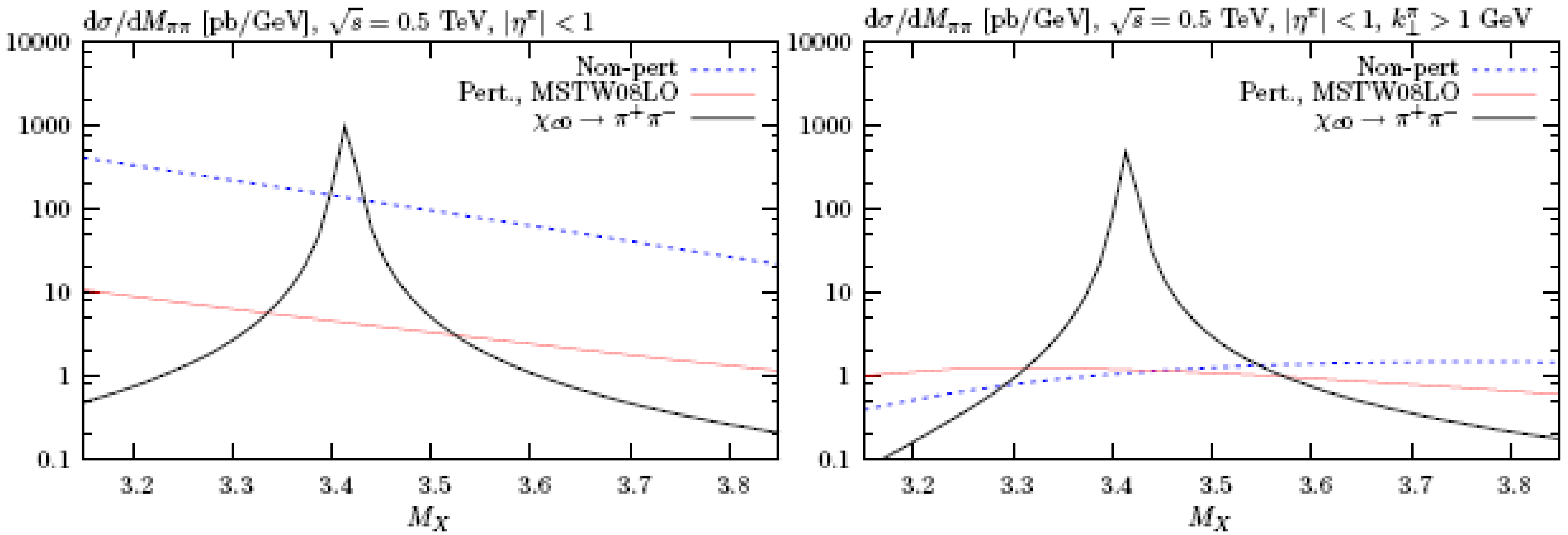
- Complete destructive interference of radiation patterns, resulting in vanishing amplitude for certain configuration of final state particles.
- Occurs in most Born amplitudes for radiation of massless gauge bosons, first seen in $u\overline{d} \to W^+\gamma$ amplitude.



- General conditions for zeros are known[10]: 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.

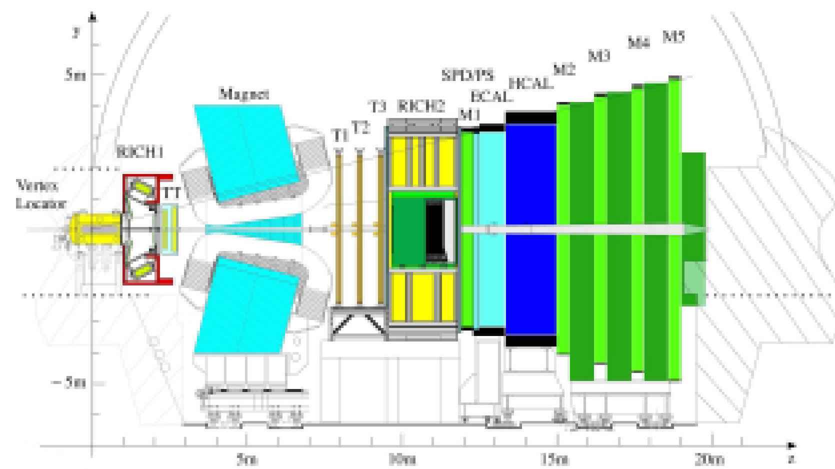
[10]S.J. Brodsky and R.W. Brown, Phys. Rev. Lett. 49, 966 (1982)

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



χ_c CEP @ LHCb (1)

- Select 'exclusive' events by vetoing on additional activity in given η range– $\chi_c \to J/\psi\gamma$ events seen by LHCb.
- Expect $\sigma_{\chi_0} \approx \sigma_{(\chi_1+\chi_2)}$ $\to$ recalling $\mathrm{Br}(\chi_{c0} \to J/\psi\gamma)$ suppression, observation of χ_{c0} events strongly favours exclusivity.



- LHCb see[1]:

	$\sigma(pp \to pp(J/\psi + \gamma))$ 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

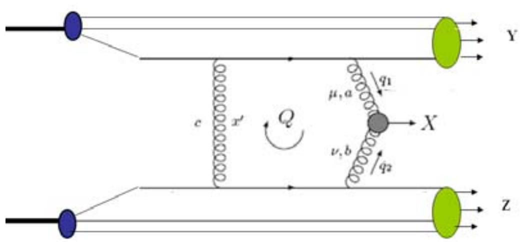
$\to$ Good agreement for $\chi_{c(0,1)}$ states (recall large theory uncertainty), but a significant excess of χ_{c2} events above theory prediction.

[1] Preliminary data– LHCb-CONF-2011-022

PT expectations if no proton tagging

Violation of ‘$J_z = 0$ selection rule’

pp→Y+X+Z



- $$\frac{|T(|J_z|=2)|^2}{|T(J_z=0)|^2} \sim \frac{\langle p_\perp^2\rangle^2}{\langle Q_\perp^2\rangle^2},$$

- $$|V_0|^2 : |V_1|^2 : |V_2|^2 \sim 1 : \frac{\langle \mathbf{p}_\perp^2\rangle}{M_\chi^2} : \frac{\langle \mathbf{p}_\perp^2\rangle^2}{\langle \mathbf{Q}_\perp^2\rangle^2}.$$

$p_{1,2_\perp}$ -momentum transfer through the ‘digluon Pomeron’

$$q_{1_\perp} = Q_\perp - p_{1_\perp}, \qquad q_{2_\perp} = -Q_\perp - p_{2_\perp},$$

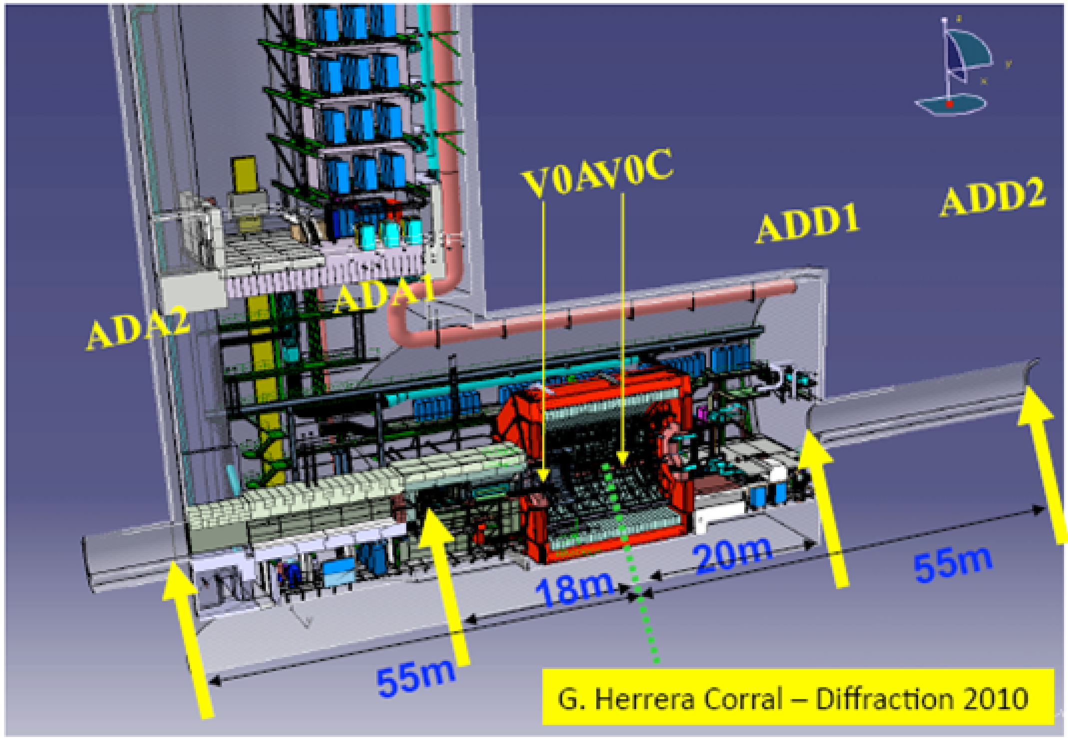
- In the low $M_{Y,Z}$ mass region: $(p_\perp^2 / \langle Q_\perp^2\rangle)$ is small.
- Non-relativistic effects for spin 2.
- Non-PT contribution (for spin 1, still ~ $\langle \mathbf{p}_\perp^2\rangle$).

for CEP (KMRS-04)

Spin-2 quarkonium suppression is easier to violate!

ALICE upgrade

- Discussions in the collabortion of possible addition of counters to extend the pseudorapidity coverage



ADA $5.5 \leq \eta \leq 7.5$

ADD $-7.5 \leq \eta \leq -5.5$

Would cover 15 units of pseudorapidity

Future Measurements

With Current Trigger (More Stats required)

- Exclusive Upsilon, Phi (-> $\mu^+\mu^-$) ← **Already some evidence**
- Exclusive Z (-> $\mu^+\mu^-$)
- Exclusive X_b (-> $\mu^+\mu^-\gamma$)

CS predictions are relatively small, yet to be observed

With New Triggers (To be implemented)

- Exclusive $\gamma\gamma$ production
- Exclusive e^+e^- production
- Exclusive $\pi^+\pi^-/k^+k^-$ production

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 $u_{+}(k) = \begin{pmatrix} \sqrt{k_{+}} \\ \sqrt{k_{-}}e^{i\phi_k} \end{pmatrix}, \qquad u_{-}(k) = \begin{pmatrix} \sqrt{k_{-}}e^{-i\phi_k} \\ -\sqrt{k_{+}} \end{pmatrix}$

$$e^{\pm i\phi_k} \equiv \frac{k^1 \pm ik^2}{\sqrt{k_{+}k_{-}}}, \qquad k_{\pm} = k^0 \pm k^3$$

We then obtain the explicit formulæ

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

$$[i\,j] = \langle j\,i\rangle^* = \sqrt{k_{i+}k_{j-}}e^{-i\phi_{k_j}} - \sqrt{k_{i-}k_{j+}}e^{-i\phi_{k_i}} \qquad (k^0_{i,j} > 0)$$

otherwise $[j\,i] = \text{sign}(k^0_i k^0_j)\,\langle i\,j\rangle^*$

so that the identity $\langle i\,j\rangle\,[j\,i] = 2k_i \cdot k_j$ always holds

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