Exclusive production at the LHC: quarkonium, meson pairs and beyond

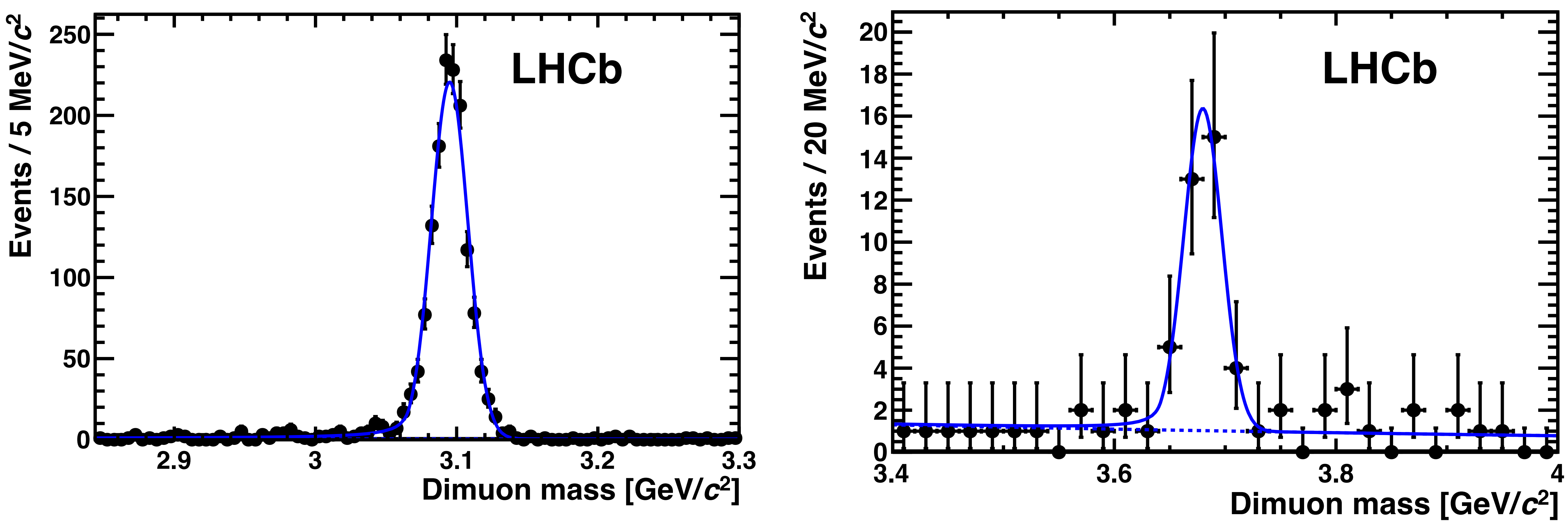
LHC WG on Forward Physics and diffraction, May 15, 2013

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

Outline

- Introduction: central exclusive production, the Durham model...
- Production of lower mass objects, some processes of interest:
  - Exclusive production of heavy quarkonium: $\chi_c, \chi_b \cdots$
  - Exotic quarkonium like-states: the X(3872)
  - Exclusive production of meson pairs: $\pi\pi, KK, \eta(')\eta(')...$
  - Exclusive photoproduction: $J/\psi, \Upsilon...$

low/mid lumi
(brief reviews)



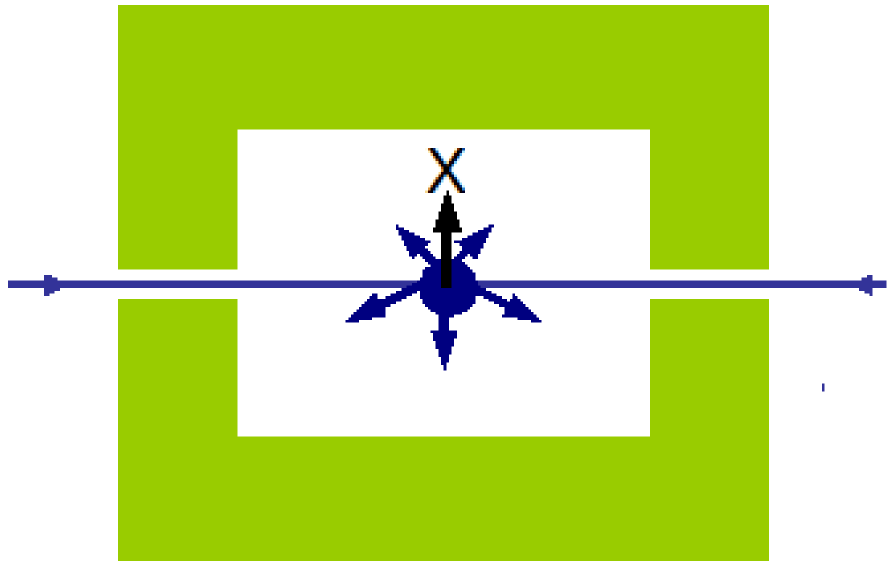
arXiv:1301.7084

Central Exclusive Diffraction

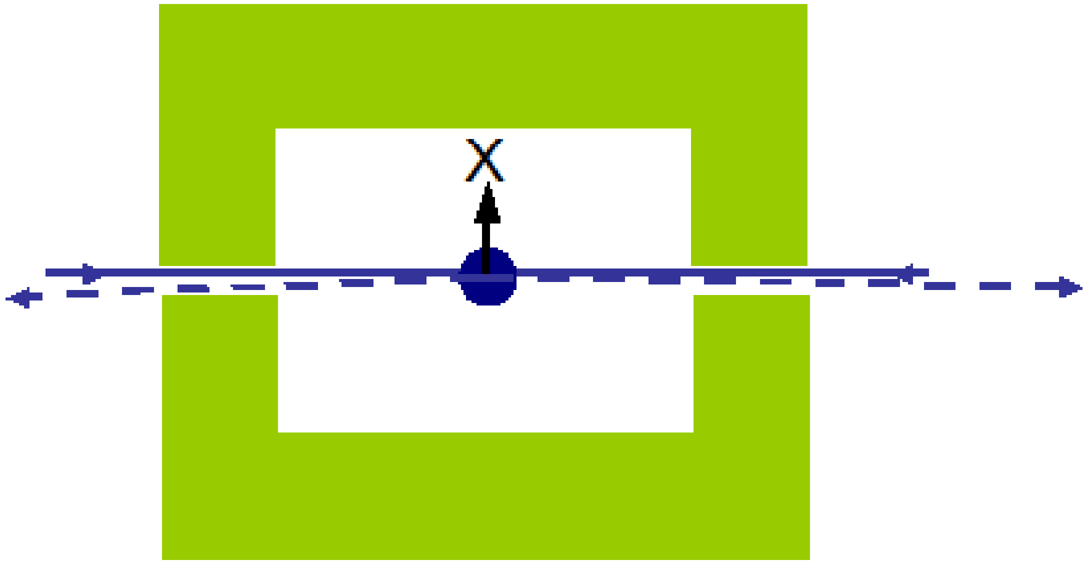
Central exclusive diffraction, or central exclusive production (CEP) is the process

$$h(p_1)h(p_2) \to h(p_1') \; + \; X \; + \; h(p_2')$$

- Diffraction: colour singlet exchange between colliding hadrons, with large rapidity gaps ('$+$') in the final state.
- Exclusive: hadrons lose energy, but remain intact after collision and can in principal be measured by detectors positioned down the beam line.
- Central: a system of mass M_X is produced at the collision point, and *only* its decay products are present in the central detector region.

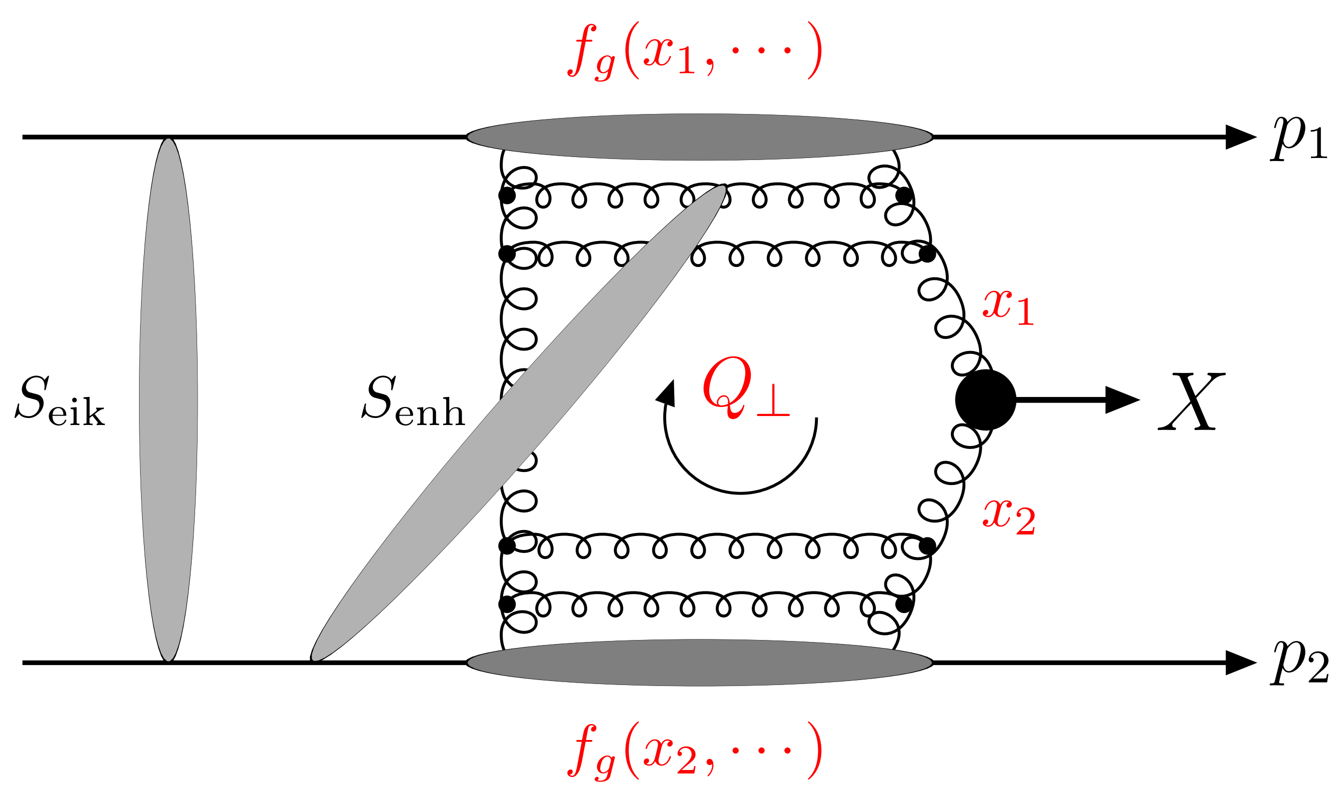


vs.



‘Durham Model’ of Central Exclusive Production

- The generic process $pp \to p + X + p$ 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, $S^2_{\rm eik}$ 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.



$J_z = gg$ axis $\approx$ beam axis

- Protons can have some small $p_\perp$ (scatter at non-zero angle), but if this is too big, they break up $\longrightarrow$ strong suppression in non $J_z^P = 0^+$ configuration.

Heavy quarkonium CEP

- CEP via this mechanism can in general produce *any* C–even object which couples to gluons: Higgs, BSM objects...but also dijets, light meson pairs, quarkonium states...
- Quarkonium CEP provides a rich phenomenology:

$\longrightarrow$ There are a wide range of conventional states, each of which exhibits characteristic features in the exclusive mode, e.g.:

- Different angular distributions of the forward protons.
- Hierarchy in production cross sections of different J^{PC} states.

$\longrightarrow$ Could shed light on the various 'exotic' charmonium states observed recently, e.g. $Z(3930) = \chi_{c2}(2P)$ and $X(3872)$ =? (arXiv:1302.6269 $\rightarrow$ quantum numbers 1^{++}).

$\longrightarrow$ Can also produce C–odd states via photoproduction: $\gamma I\!P, O I\!P \to J/\psi, \Upsilon$...

χ_c CEP

χ_{cJ} : $L=1, S=1, J^{PC}=(0,1,2)^{++}$ $c\bar{c}$ meson states, $M_{\chi_c} \approx 3.5$ GeV.

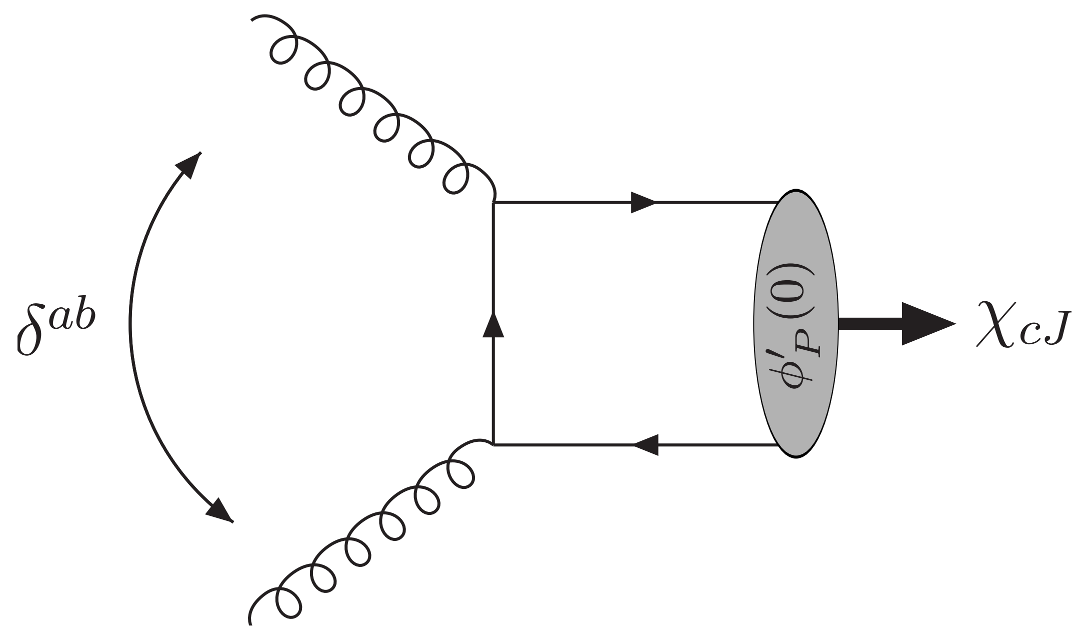
- Production cross sections determined by unique CEP kinematics:

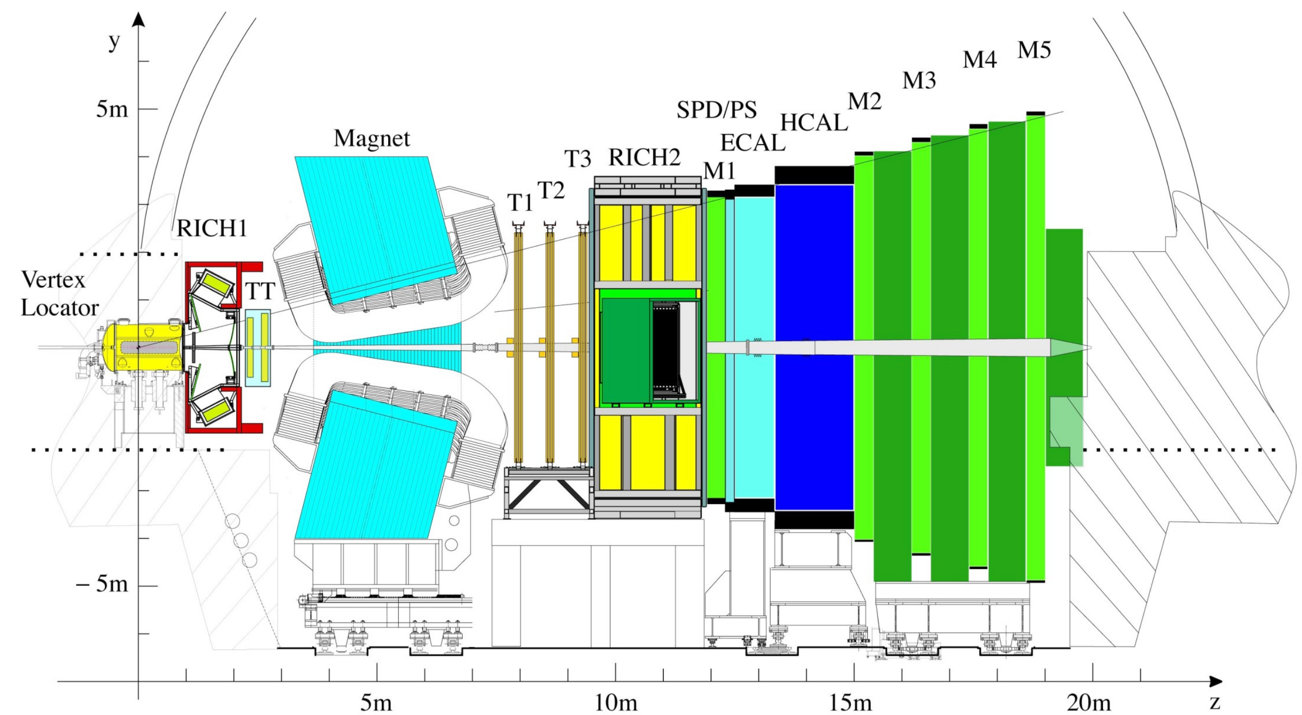
‣ χ_{c2} : in the non-relativistic quarkonium approximation coupling to gg in a $J_z = 0$ state vanishes (dominant configuration for CEP).

‣ χ_{c1} : Landau-Yang theorem forbids coupling of a $J=1$ particle to on-shell gluons (true to good approximation in CEP). Additionally suppressed by specific form of vertex.

(Ronan's talk)

- Measurements made by CDF and LHCb, by vetoing on additional activity in given η range in the $\chi_c \to J/\psi\gamma$ channel (favours $\chi_{c(1,2)}$).





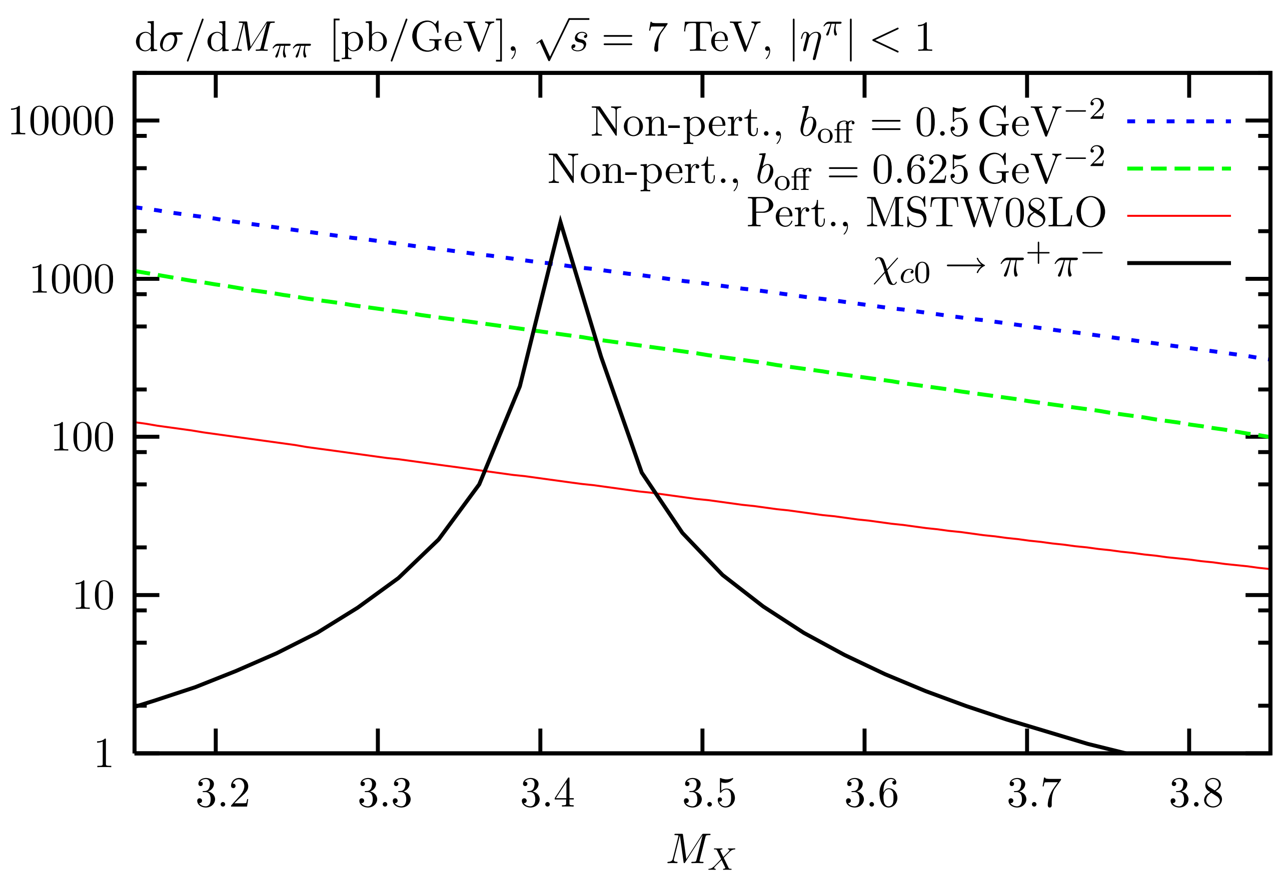
χ_c CEP : comparison to data

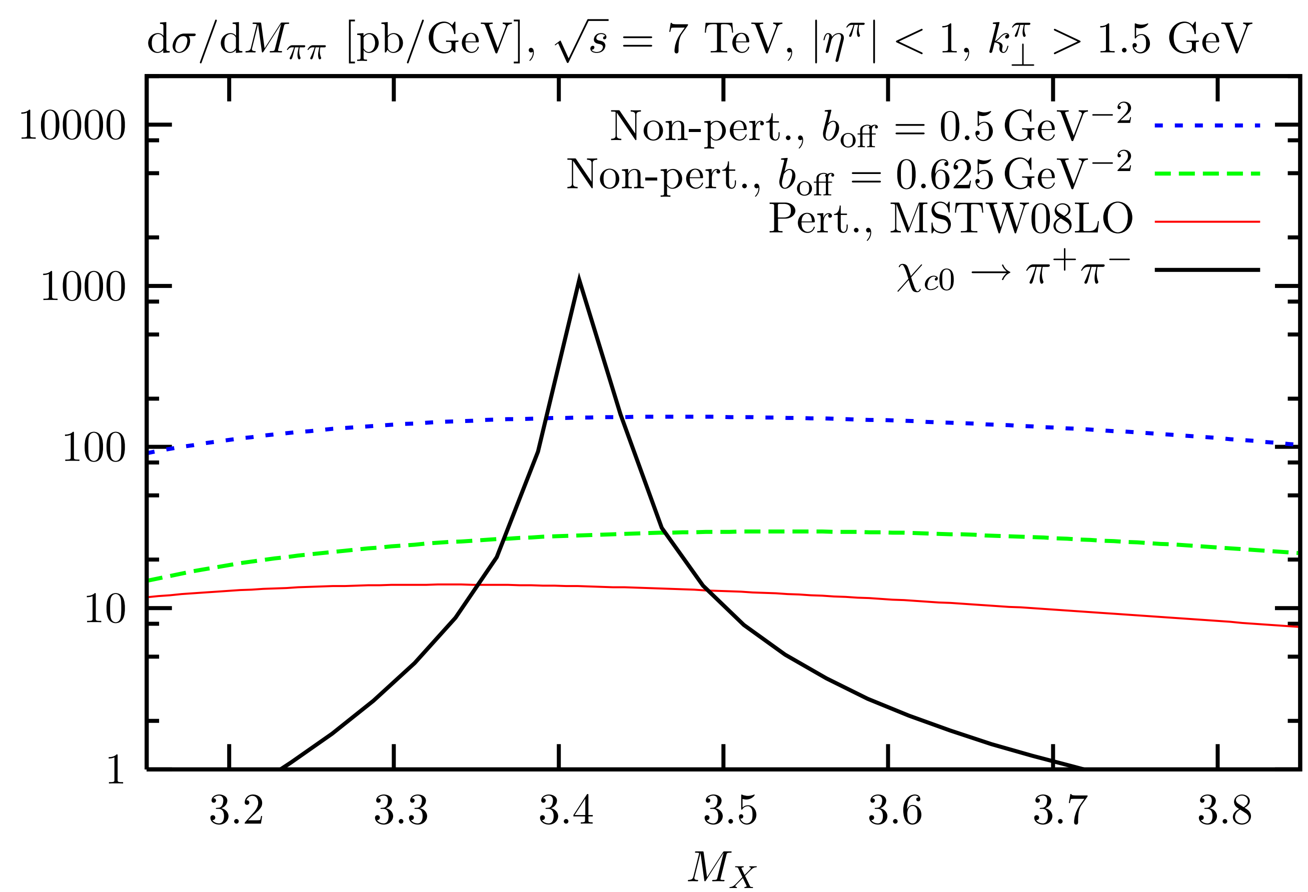
- LHCb see: CERN-LHCb-CONF-2011-022 HKRS: arXiv:0909.4748

	$\frac{\sigma(pp \to pp(\mu^+\mu^-+\gamma))}{\text{Br}(J/\psi \to \mu^+\mu^-)\text{Br}(\chi_{cJ} \to J/\psi\gamma)}$ LHCb (nb)	SuperCHIC (nb)
χ_{c0}	13 ± 6.5	20
χ_{c1}	0.80 ± 0.35	0.49
χ_{c2}	2.4 ± 1.1	0.26

- See clear suppression in $\chi_{c(1,2)}$ states. Do not expect to see (or find) in inclusive production.
- Good data/theory agreement for $\chi_{c(0,1)}$ states (within quite large theory uncertainty), but significant χ_{c2} excess:
  - Theory: relativistic corrections? Sensitivity to low gluon $Q_\perp$ (is the χ_c mass large enough to justify full pQCD treatment: 'non-perturbative' corrections. HKRS: arXiv:0909.4748 Pasechnik, Szczurek, Teryaev: arXiv:0912.4251
  - Experiment: inclusive contamination could favour χ_{c2} . Closer study of cross section ratios as a function of meson $p_\perp$ will clarify situation. HKRS: arXiv:1204.4803

χ_c CEP : two-body decays





Consider decays: $\chi_c \to \pi\pi,\ KK,\ \Lambda\overline{\Lambda}, p\overline{p}...$

HKRS: arXiv:1204.4803, Lebiedowicz, Pasechnik, Szczurek: arXiv:1108.2522

- χ_{c1} decay cannot occur, while $\chi_{c(0,2)}$ branchings are of similar size $\Rightarrow$ expect χ_{c0} dominance.
- (Exclusive) continuum background expected to be under control, at least once reasonable cuts have been imposed.

$\Rightarrow \chi_{c(0,2)} \to \pi^+\pi^-\ (K^+K^-)$ could give clean exclusive signal

Exotic charmonium-like states

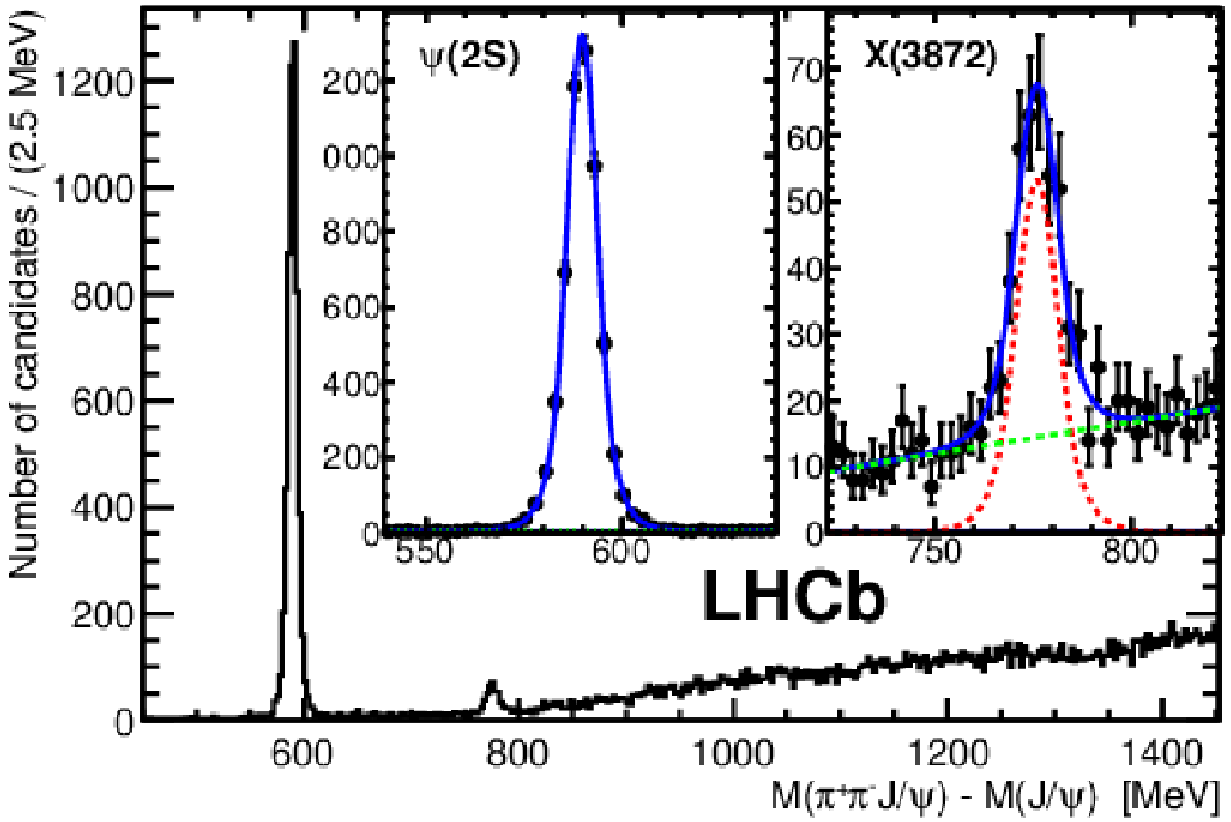
- A 'zoology' of XYZ charmonium-like states above the open charm threshold has recently been observed at Belle, Babar, the Tevatron and LHC (arXiv:1010.5827-table).
- Many interpretations (molecular states, tetraquarks, hybrids, conventional...) on the market, and many quantum numbers still unassigned.

TABLE 9: As in Table 4, but for new *unconventional* states in the $c\bar{c}$ and $b\bar{b}$ regions, ordered by mass. For $X(3872)$, the values given are based only upon decays to $\pi^+\pi^- J/\psi$. $X(3945)$ and $Y(3940)$ have been subsumed under $X(3915)$ due to compatible properties. The state known as $Z(3930)$ appears as the $\chi_{c2}(2P)$ in Table 4. See also the reviews in [81–84]

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$X(3872)$	3871.52±0.20	1.3±0.6	$1^{++}/2^{-+}$	$B \to K(\pi^+\pi^- J/\psi)$	Belle [85, 86] (12.8), *BABAR* [87] (8.6)	2003	OK
		(<2.2)		$p\bar{p} \to (\pi^+\pi^- J/\psi) + ...$	CDF [88–90] (np), DØ [91] (5.2)		
				$B \to K(\omega J/\psi)$	Belle [92] (4.3), *BABAR* [93] (4.0)		
				$B \to K(D^{*0}\bar{D}^0)$	Belle [94, 95] (6.4), *BABAR* [96] (4.9)		
				$B \to K(\gamma J/\psi)$	Belle [92] (4.0), *BABAR* [97, 98] (3.6)		
				$B \to K(\gamma\psi(2S))$	*BABAR* [98] (3.5), Belle [99] (0.4)		
$X(3915)$	3915.6 ± 3.1	28±10	$0/2^{?+}$	$B \to K(\omega J/\psi)$	Belle [100] (8.1), *BABAR* [101] (19)	2004	OK
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle [102] (7.7)		
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle [103] (6.0)	2007	NC!
				$e^+e^- \to J/\psi\ (...)$	Belle [54] (5.0)		
$G(3900)$	3943 ± 21	52±11	1^{--}	$e^+e^- \to \gamma(D\bar{D})$	*BABAR* [27] (np), Belle [21] (np)	2007	OK
$Y(4008)$	4008^{+121}_{-49}	226±97	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	Belle [104] (7.4)	2007	NC!
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [105] (5.0)	2008	NC!
$Y(4140)$	4143.4 ± 3.0	15^{+11}_{-7}	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF [106, 107] (5.0)	2009	NC!
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle [103] (5.5)	2007	NC!
$Z_2(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [105] (5.0)	2008	NC!
$Y(4260)$	4263 ± 5	108±14	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	*BABAR* [108, 109] (8.0)	2005	OK
					CLEO [110] (5.4)		
					Belle [104] (15)		
				$e^+e^- \to (\pi^+\pi^- J/\psi)$	CLEO [111] (11)		
				$e^+e^- \to (\pi^0\pi^0 J/\psi)$	CLEO [111] (5.1)		
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF [107] (3.1)	2010	NC!
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0,2^{++}$	$e^+e^- \to e^+e^-(\phi J/\psi)$	Belle [112] (3.2)	2009	NC!
$Y(4360)$	4353 ± 11	96±42	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$	*BABAR* [113] (np), Belle [114] (8.0)	2007	OK
$Z(4430)^+$	4443^{+24}_{-18}	107^{+113}_{-71}	?	$B \to K(\pi^+\psi(2S))$	Belle [115, 116] (6.4)	2007	NC!
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$	Belle [25] (8.2)	2007	NC!
$Y(4660)$	4664±12	48±15	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$	Belle [114] (5.8)	2007	NC!
$Y_b(10888)$	10888.4±3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\pi^+\pi^-\Upsilon(nS))$	Belle [37, 117] (3.2)	2010	NC!

The X(3872)

- Discovered by Belle in 2003, confirmed by Babar, at the Tevatron and the LHC.
- Could be of exotic nature: loosely bound hadronic molecule, diquark-antidiquark ('tetraquark') and hybrid ($\bar{c}cg\cdots$). However, conventional $c\bar{c}$ interpretation is still possible.

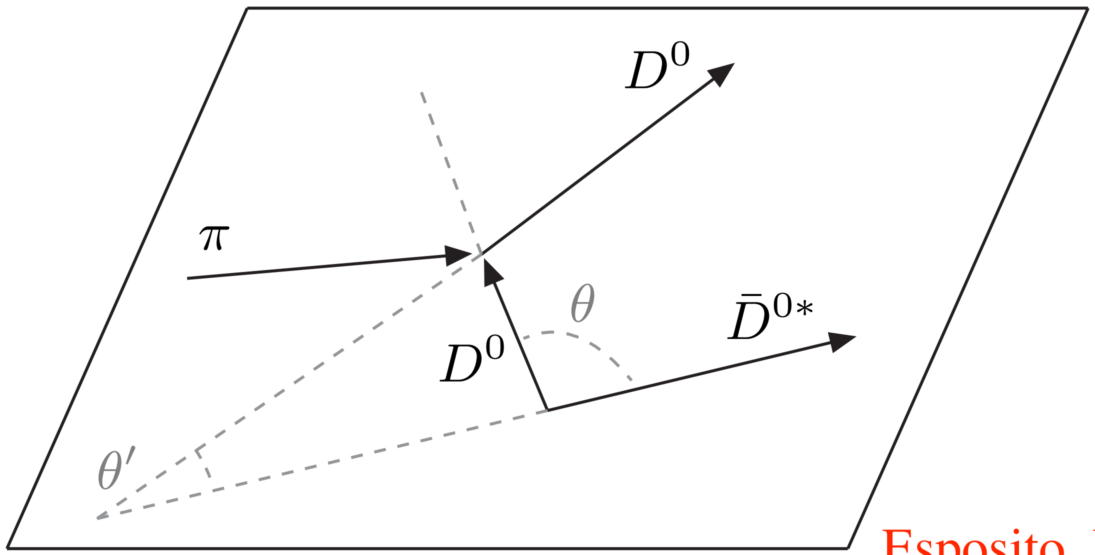


- Possible J^{PC} assignments were 1^{++} or 2^{-+}.
- New LHCb data (arXiv:1302.6269) rejects 2^{-+} at 8 sigma level $\rightarrow \eta_{c2}(1^1D_2)$ ruled out.
- Exotic interpretations still possible or conventional $\chi_{c1}(2^3P_1)$ charmonium?

Insight from CEP

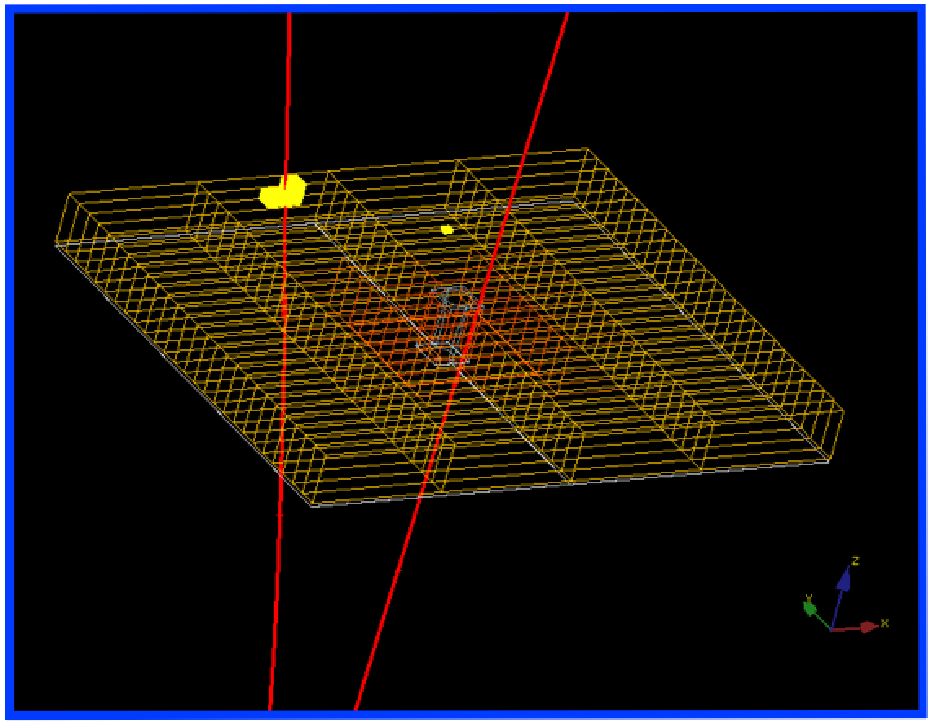
- In CEP the state X is produced directly, i.e. at short distances: $gg \to X(3872)$ and nothing else. $\to$ would be clear evidence of a direction production mode.
- In an inclusive environment, for which additional soft quarks, D-mesons etc can be present/emitted it should be easier to form molecular state (arXiv:1305.0527, 1008.2868, 0911.2016...). Will expect additional suppression in exclusive case.

$\to$ 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 $|\phi'_P(0)|^2$.



$k_0 < 50$ MeV	0π	1π	3π
Herwig	10	19	802
Pythia	3	21	814

Esposito, Piccinini, Pilloni, Polosa: arXiv:1305.0527



C odd states : $J/\psi, \psi(2S), \Upsilon, ...$

- Can also produce C-odd states exclusively, via $\gamma I\!P \to V$. Can model using pQCD framework:

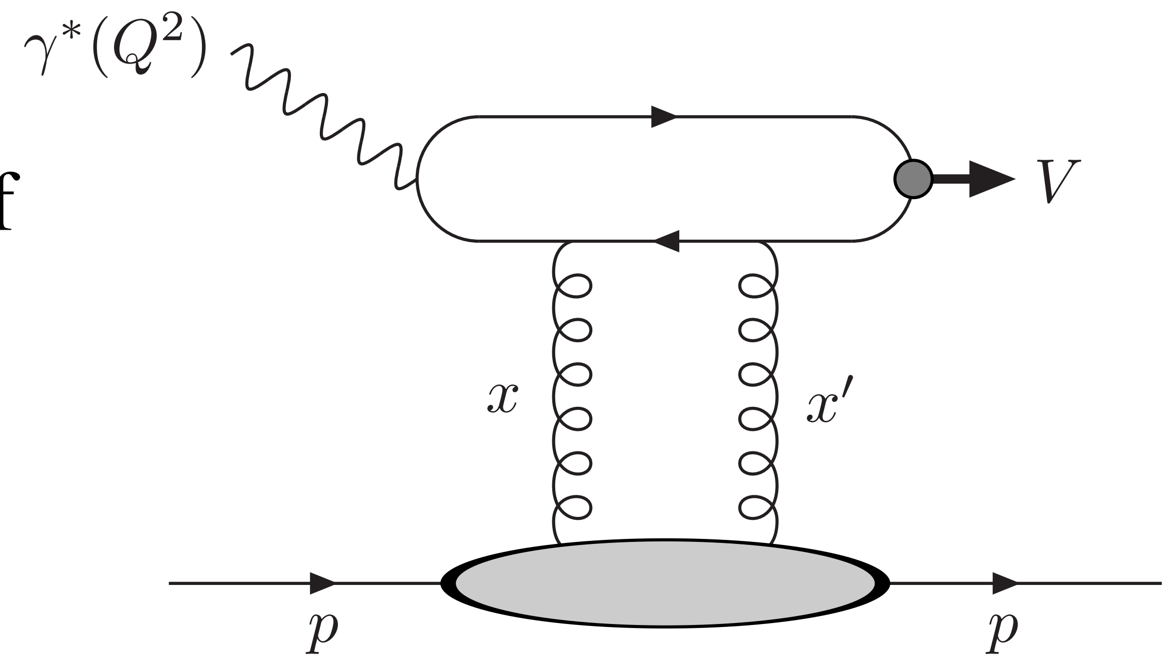
Simplified formula $\to$ $$\frac{\mathrm{d}\sigma(\gamma p \to Vp)}{\mathrm{d}\mathbf{p}_\perp^2} \approx \frac{16\Gamma_{ee}\pi^3\alpha_s(Q^2)}{3\alpha M^5}[xg(x,Q^2)]^2 e^{-b\mathbf{p}_\perp^2} ,$$

where $Q^2 = M^2/4$, $x = M/\sqrt{s}\exp(-y)$, and $\Gamma_{ee} = \Gamma(... \to e^+e^-)$.

$\longrightarrow$ Sensitive to gluon at low x

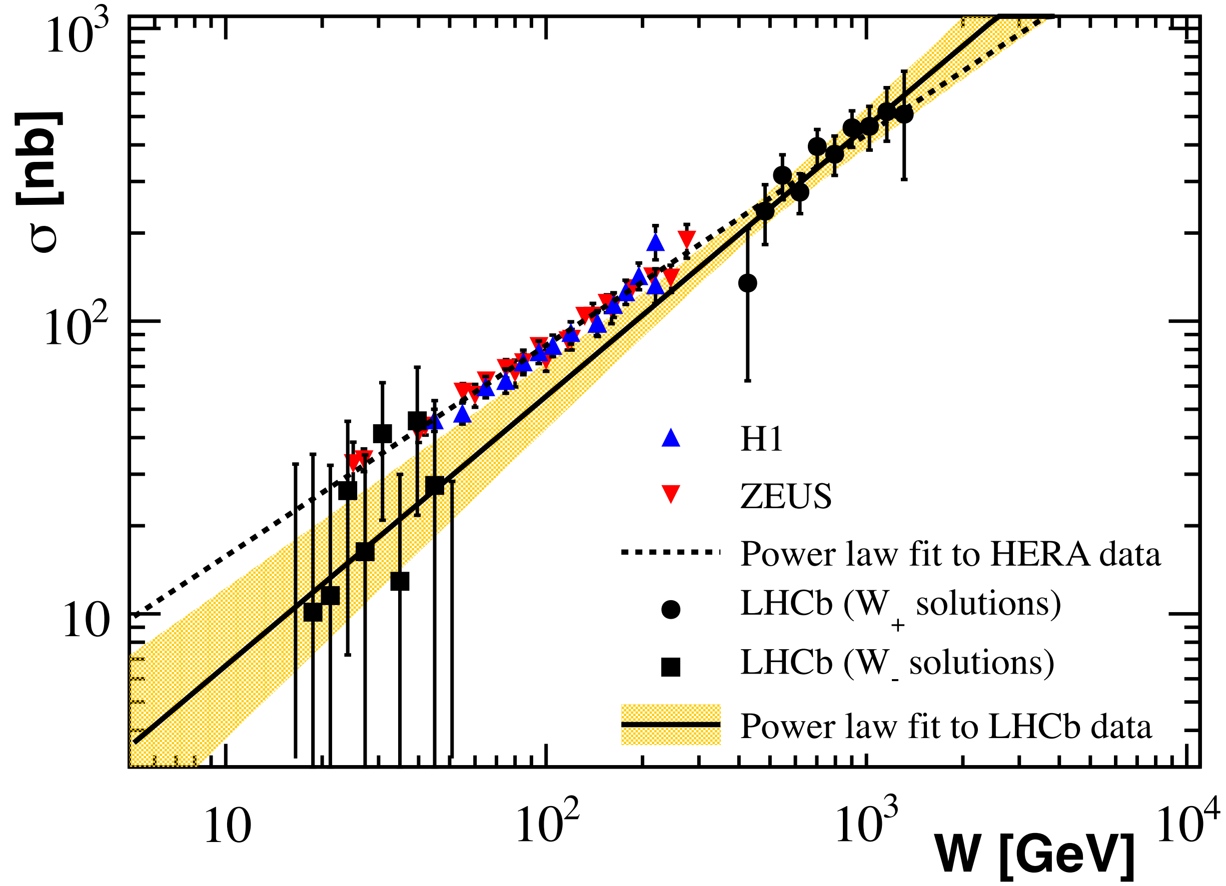
Martin, Nockles, Ryskin, Teubner: arXiv:0709.4406....

- However, other corrections to consider: relativistic effects, $M_V \neq 2m_q$, real part of amplitude, gluon $k_\perp$, $x' \neq 0$, NLO....
- Also: 'b-sat' models for scattering of $q\bar{q}$ dipole off proton, may be more appropriate for this elastic process.



Motyka, Watt: arXiv:0805.2113, Kowalski, M, W: hep-ph/0606272....

- Can also occur in *ep* collisions: $\gamma p \to J/\psi(\Upsilon) p$ measured at HERA.
- This can trivially be translated into a cross section in *pp* collisions: only difference is in *e* v.s. *p* EM form factor.



- This can be fit well using a simple parameterization (expected from Regge)

$$\frac{\mathrm{d}\sigma(\gamma p \to J/\psi(\Upsilon) + p)}{\mathrm{d}\mathbf{p}_\perp^2} \propto W_{\gamma p}^{\delta} e^{-bW_{\gamma p}\mathbf{p}_\perp^2} ,$$

- Measured for energies up to $W_{\gamma p} \approx 300$ GeV, i.e. $|y_\psi| < 1.4$ at $\sqrt{s} = 7$ TeV.

$\to$ LHC can probe new energies at forward rapidities, but these fits should give reliable predictions for these (seen by LHCb arXiv:1301.7084) .

CEP of meson pairs

Consider production of a pair of light mesons

$$h(p_1)h(p_2) \to h(p_1') \ + \ M\overline{M} \ + \ h(p_2')$$

- At reasonable meson $k_\perp$ a pQCD treatment can be used, using the 'hard exclusive' formalism to model $gg \to M\overline{M}$ subprocess. Theory: relevant amplitudes display many interesting features.
- At lower $k_\perp$ enter the soft regime, and must use Regge theory double Pomeron exchange.

$\longrightarrow$ Experimentally can probe transition between theses regimes.

- $\eta(')\eta(')$ CEP : sensitive to gluonic component of
- $\pi\pi(KK...)$ CEP : background to $\chi_c \to \pi\pi(KK)$

HKRS: arXiv:1304.4262, 1302.2004, 1204.4803, 1105.1626

Perturbative regime

- For reasonable meson $k_\perp$ model $gg \to M\overline{M}$ process using 'hard exclusive' formalism. Amplitude is written as

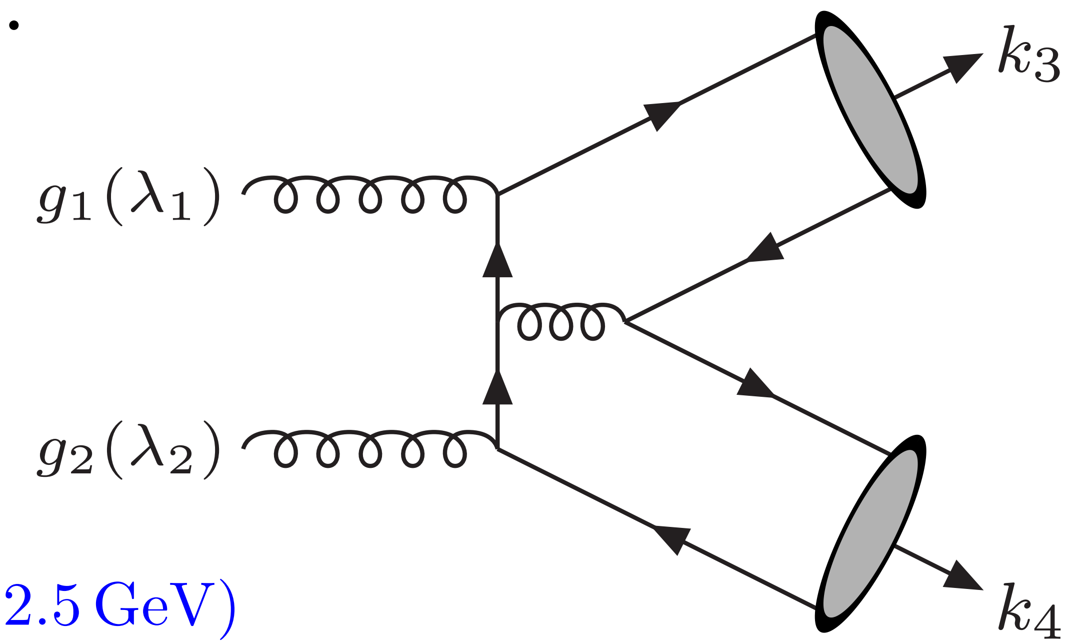
Brodsky, Lepage: Phys.Rev. D24 (1981) 1808....

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

where $T_{\lambda_1\lambda_2}$ is (pert.) parton level amplitude and $\phi(x)$ is (non pert.) wavefunction for collinear partons to form parent meson.

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

- For flavour non-singlet mesons ($\pi\pi, KK\ldots$) diagrams of type shown contribute. Vanish for $J_z = 0$ gluons. $\Rightarrow$ Strong suppression in CEP cross sections expected.



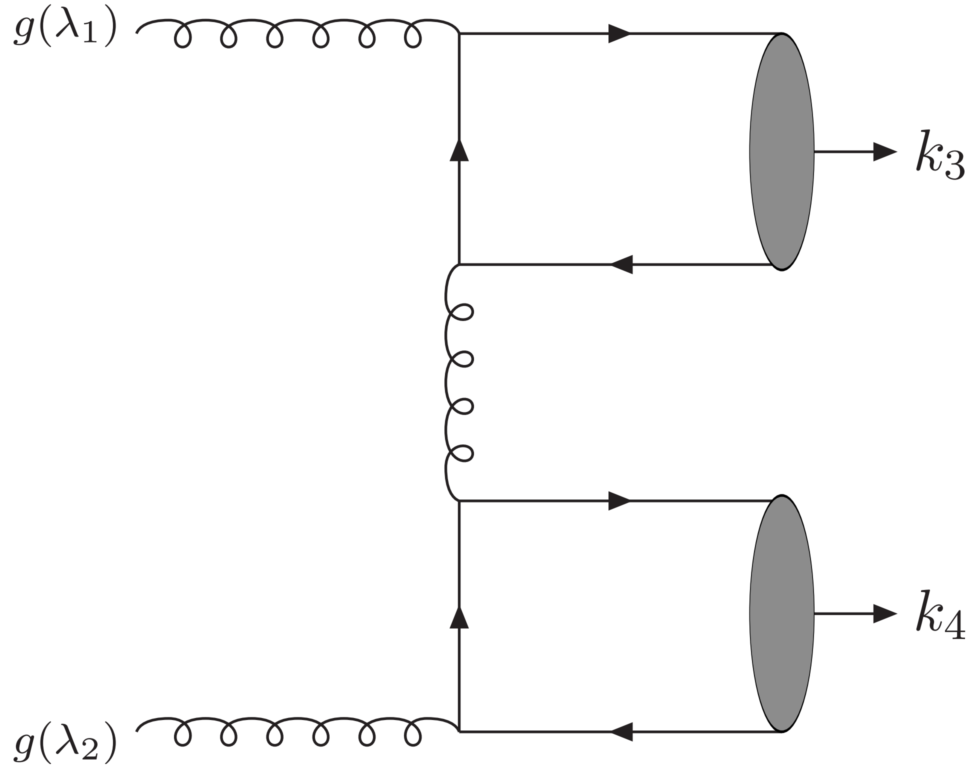
$(E_\perp(\gamma) > 2.5\,\mathrm{GeV})$

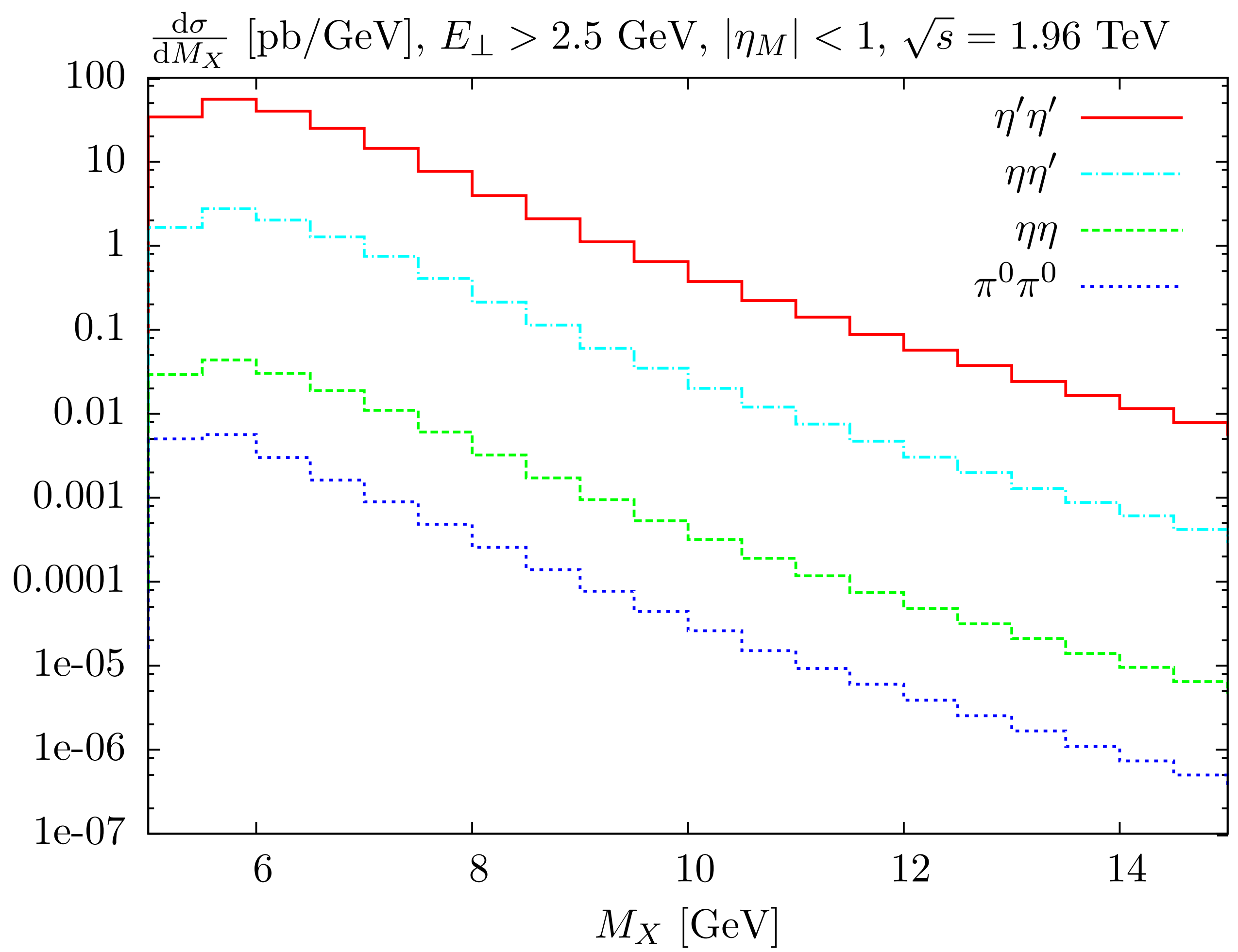
Seen in CDF $\gamma\gamma$ data (arXiv:1112.0858): $N(\pi^0\pi^0) < 0.35$ @ 95 % confidence

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

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 π^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 enhancement to. $\eta'\eta'$ rate is predicted to be large!



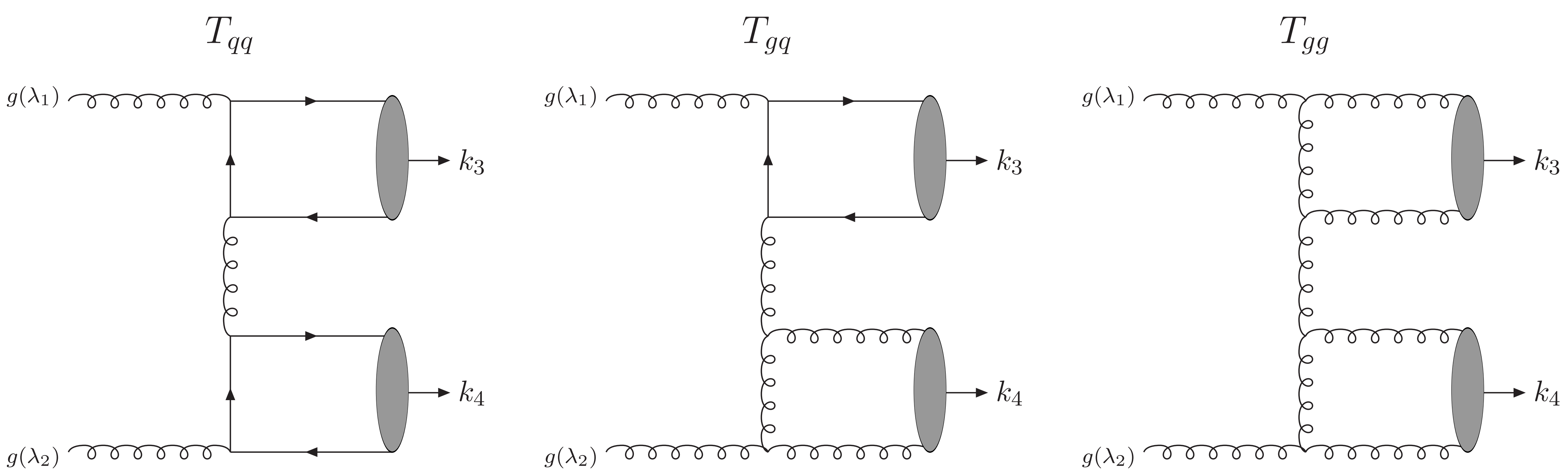


The gluonic component of the $\eta'(\eta)$

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

$\longrightarrow$ The $gg \to \eta(')\eta(')$ process will receive a contribution from the $gg \to ggq\overline{q}$ and $gg \to gggg$ parton level diagrams.

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



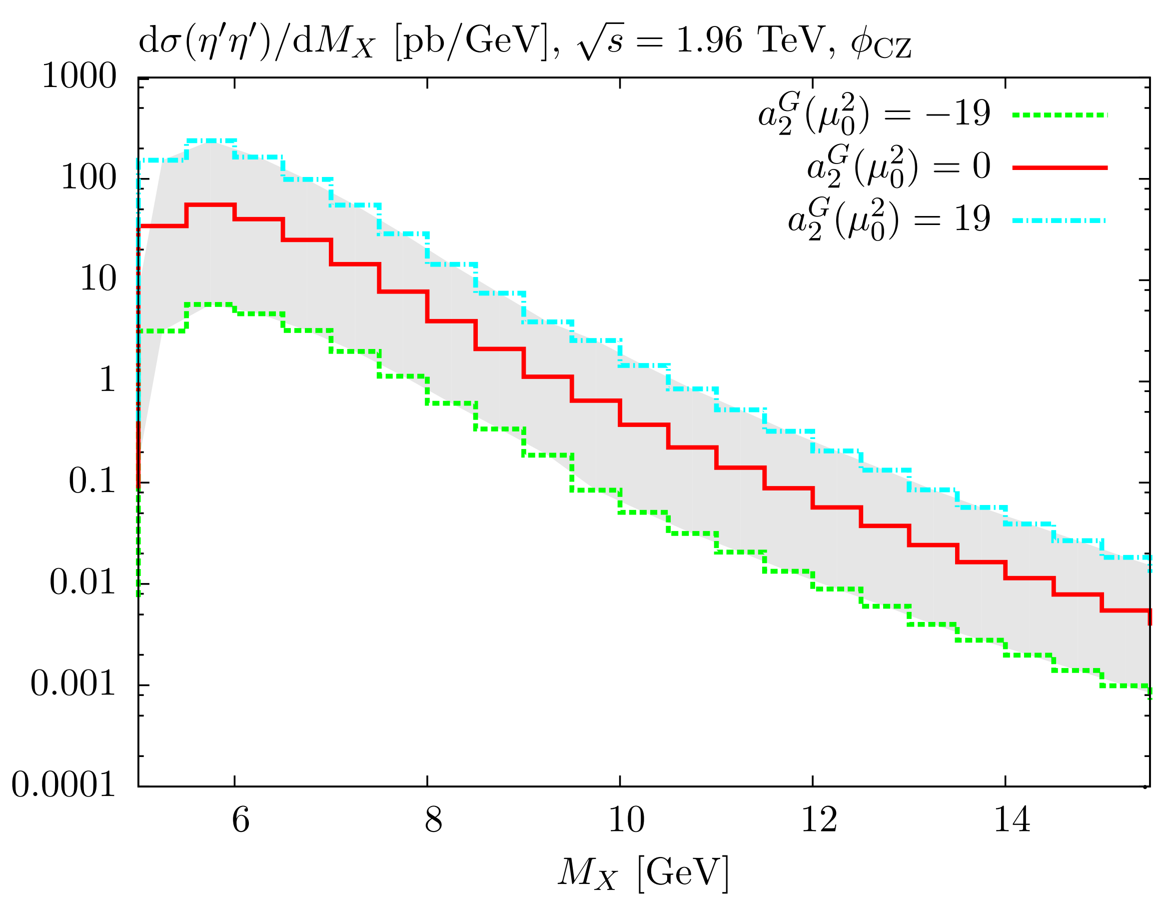
• Find that the relevant $gg \to gg q\overline{q}(gg)$ amplitudes do not vanish for $J_z = 0$ incoming gluons $\Rightarrow$ no suppression present. Enter at same (leading) order to $q\overline{q}$ component.

Kroll, Passek-Kumericki

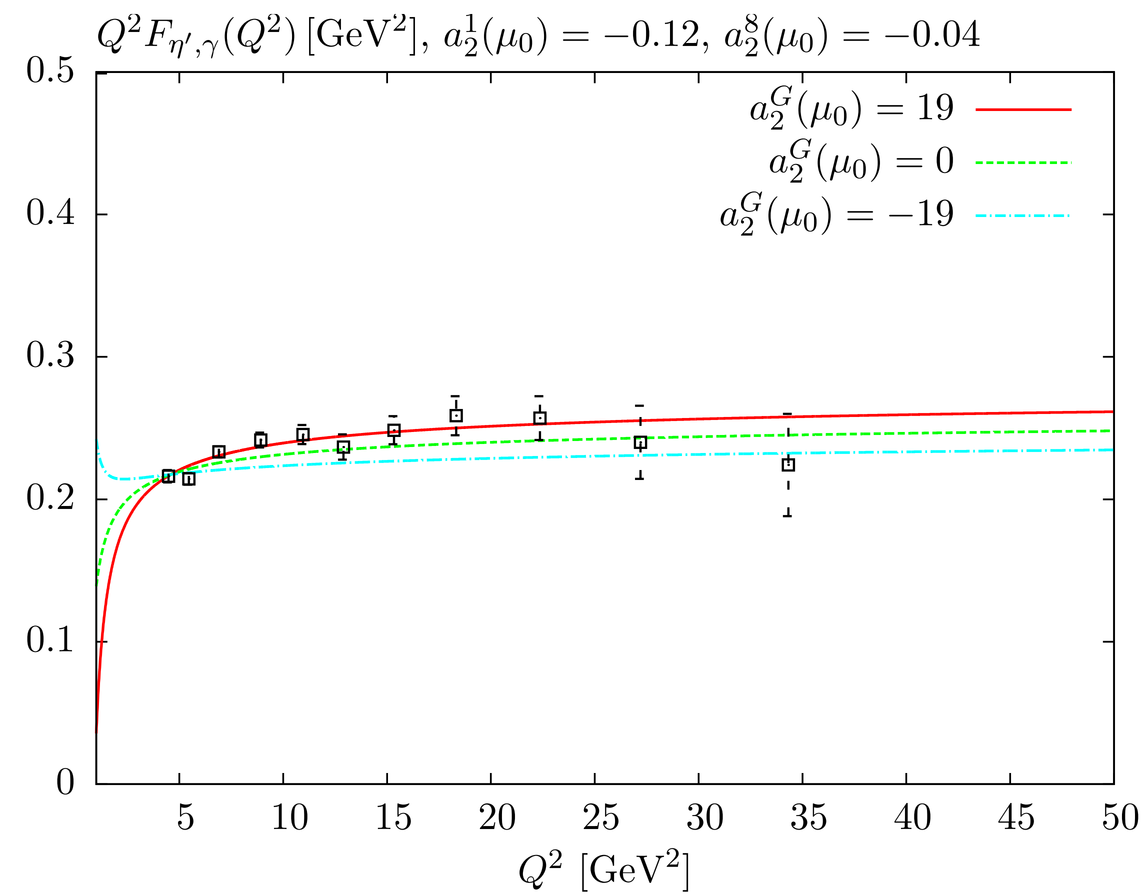
• Taking the central fit of arXiv:1206.4870, we would expect a ~ order of magnitude increase in the $\eta(')\eta(')$ cross section!

$\longrightarrow$ CEP provides a potentially sensitive probe of the gg component of the η, η' mesons. Cross section ratios can pin this down further.

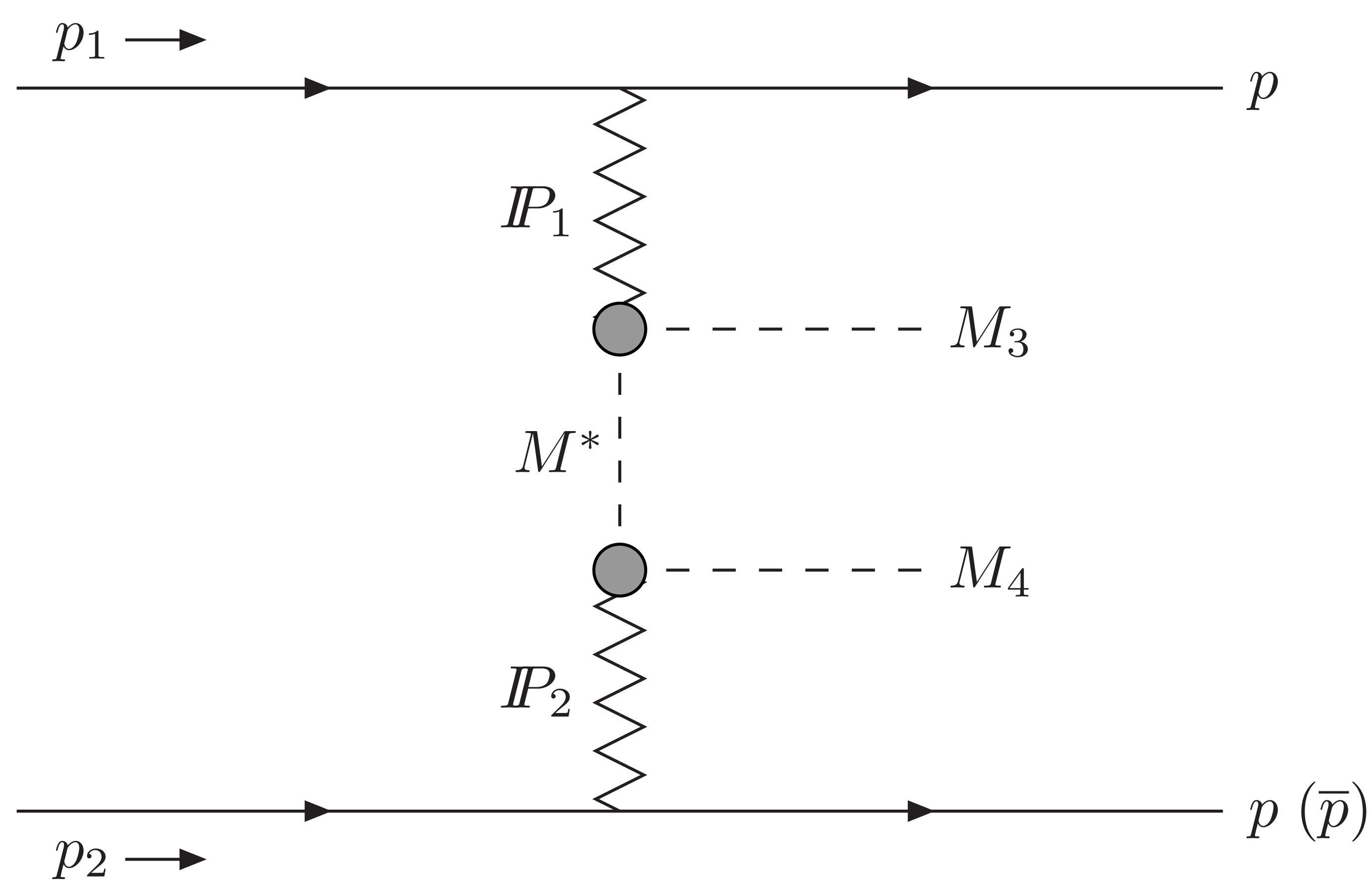
HKRS: arXiv:1302.2004



NLO contribution to $\gamma^*\gamma \to \eta(')$



The low $k_\perp$ region....



- The scale of the meson pair production process is set by the meson $k_\perp$.
- As this decreases (and cross section increases!), a perturbative treatment cannot be trusted.
- Can model process in this regimes using Regge theory: double Pomeron exchange picture.
- Important theoretical uncertainties in such a model ($I\!P \to MM^*$ form factor, 'rescattering' corrections, additional exchanges in the t-channel...).
- Data can test these non-perturbative models, and could probe the transition to the perturbative region...

The SuperCHIC MC

A MC event generator including[8]:

- 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...?).

Plans to develop further: Herwig++, updated survival factors....

$\longrightarrow$ Via close collaboration with experimental collaborations, in both proposals for new measurements and applications of SuperCHIC, it is becoming an important tool for current and future CEP studies at the LHC. Suggestions for additional modes etc to include/study are welcome!

Summary and Outlook

- CEP in hadron collisions offers a promising and complementary framework within which to study Standard Model and new physics signals.
- Exclusive processes during low pile-up/luminosity LHC (selected with rapidity vetoes) can serve as 'standard candles' for the exclusive Higgs, and other new physics, but are of interest in their own right.
- Many observables to look at/work on:
  - C - even quarkonia (χ_c, χ_b, $\eta_{c,b}$...)
  - Photoproduction of C - odd states (J/ψ, Υ, $Z(?)$, ...)
  - Exotic bound states
  - Light meson pairs
  - Diphotons
  - Dijets
  - Lepton pairs
  - ...
- Hopefully many more CEP results to come in the future!

Back up

χ_b CEP

- Higher χ_b mass means cross section is more perturbative and so is better test of theory, although rate is ~ 3 orders of magnitude smaller than χ_c.
- J assignment of χ_b states still experimentally undetermined: CEP could shed light on this.
- Calculation exactly analogous to χ_c case

$$|V_{0^+}|^2 : |V_{1^+}|^2 : |V_{2^+}|^2 \sim 1 : \frac{\langle \mathbf{p}_\perp^2 \rangle}{M_\chi^2} : \frac{\langle \mathbf{p}_\perp^2 \rangle^2}{\langle \mathbf{Q}_\perp^2 \rangle^2} \sim 1 : \frac{1}{400} : \frac{1}{36}$$

$\rightarrow$ Do not expect to see χ_{b1}, which is strongly suppressed by χ_b mass.

- Measurement of ratio of χ_b to $\gamma\gamma$ ($E_\perp = 5$ GeV) CEP rates would eliminate certain uncertainties (i.e. dependence on survival factors).
- Predictions for χ_b CEP via the $\Upsilon\gamma$ decay chain (at $y_\chi = 0$):

$\sqrt{s}$ (TeV)	1.96	7	10	14
$\frac{d\sigma}{dy_{\chi_b}}(pp \to pp(\Upsilon + \gamma))$ (pb)	0.60	0.75	0.78	0.79
$\frac{d\sigma(1^+)}{d\sigma(0^+)}$	0.050	0.055	0.055	0.059
$\frac{d\sigma(2^+)}{d\sigma(0^+)}$	0.13	0.14	0.14	0.14

$\eta_{c,b}$ production

- $gg \to \eta$ vertex calculated as in χ case, but normalisation set in terms of S-wave meson wavefunction at the origin $\phi_S(0)$, which can be related to $\Gamma_{\rm tot}(\eta_c)$ and $\Gamma(\Upsilon(1S) \to \mu^+\mu^-)$ widths.
- Amplitude squared has Lorentz structure

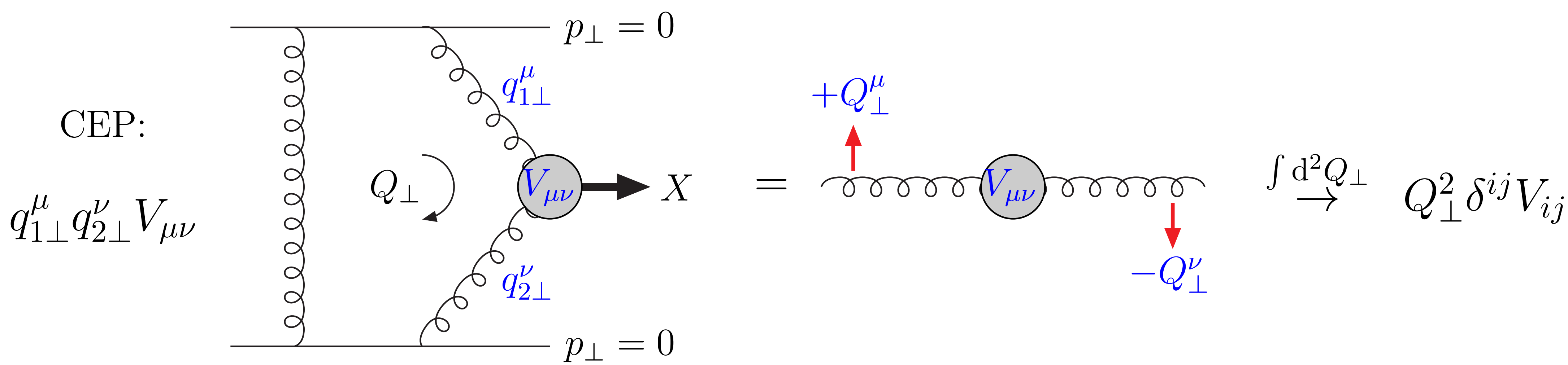
$$|V_{0^-}|^2 \propto p_{1_\perp}^2 p_{2_\perp}^2 \sin^2(\phi) ,$$

i.e. it is suppressed relative to χ_0 rate by a factor $\sim \langle \mathbf{p}_\perp^2 \rangle^2 / 2 \langle \mathbf{Q}_\perp^2 \rangle^2$, with a characteristic azimuthal angular distribution of the outgoing protons.
- An explicit calculation gives:

$\sqrt{s}$ (TeV)	$d\sigma/dy_\eta(\eta_c)$ (pb)	$d\sigma/dy_\eta(\eta_b)$ (pb)
1.96	200	0.15
7	200	0.14
14	190	0.12

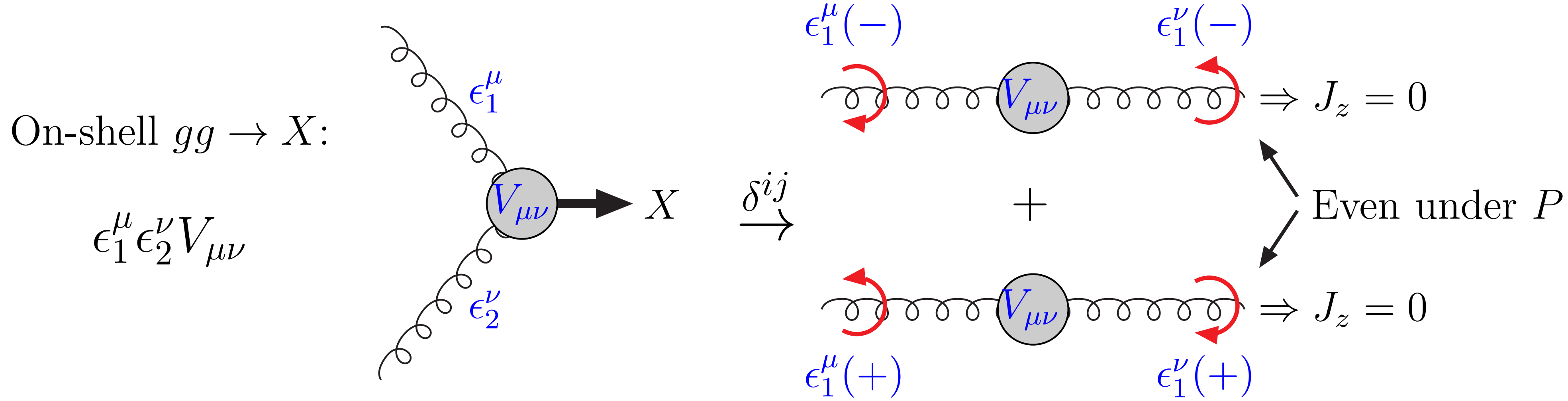
$J_z^P = 0^+$ selection rule (2)

- In the limit of forward protons ($p_\perp = 0$), the CEP subamplitude becomes



- If we consider the on–shell $gg \to X$ vertex $V_{\mu\nu}$, then we have the equality

$$\delta^{ij} V_{ij} = V_{xx} + V_{yy} = (\epsilon_1^\mu(+)\epsilon_2^\nu(+) + \epsilon_1^\mu(-)\epsilon_2^\nu(-))V_{\mu\nu} \equiv V_{++} + V_{--} \ ,$$



$\rightarrow$ Fusing gluons/object X have zero J_z along gg axis, and are in an even parity state. Only $J_z = 0$ on–shell helicity amplitudes V_{++}, V_{--} will contribute (up to small $O(Q_\perp^2/M_X^2)$ corrrections fusing gluons are on–shell).

Forward proton angular distributions

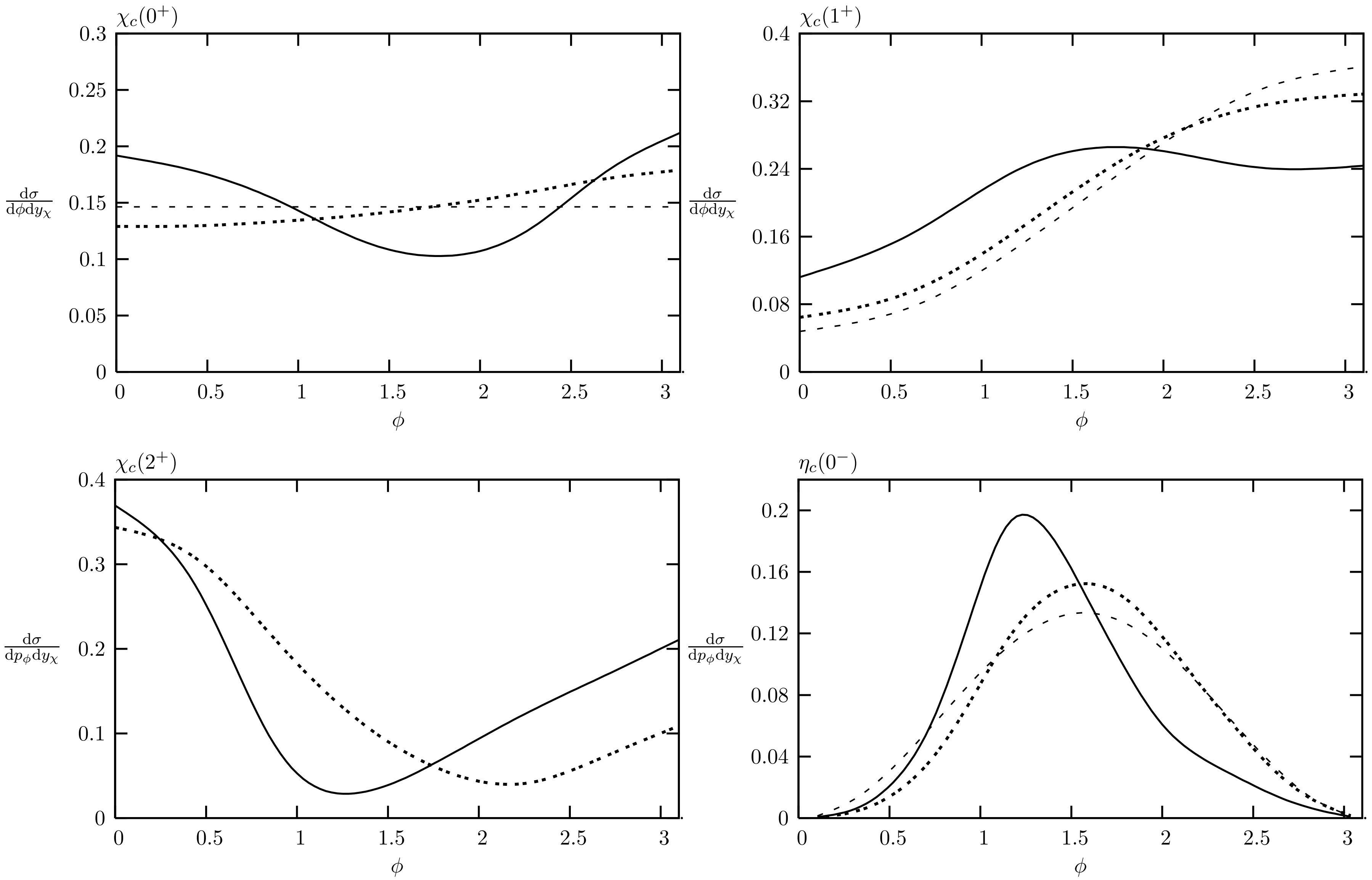
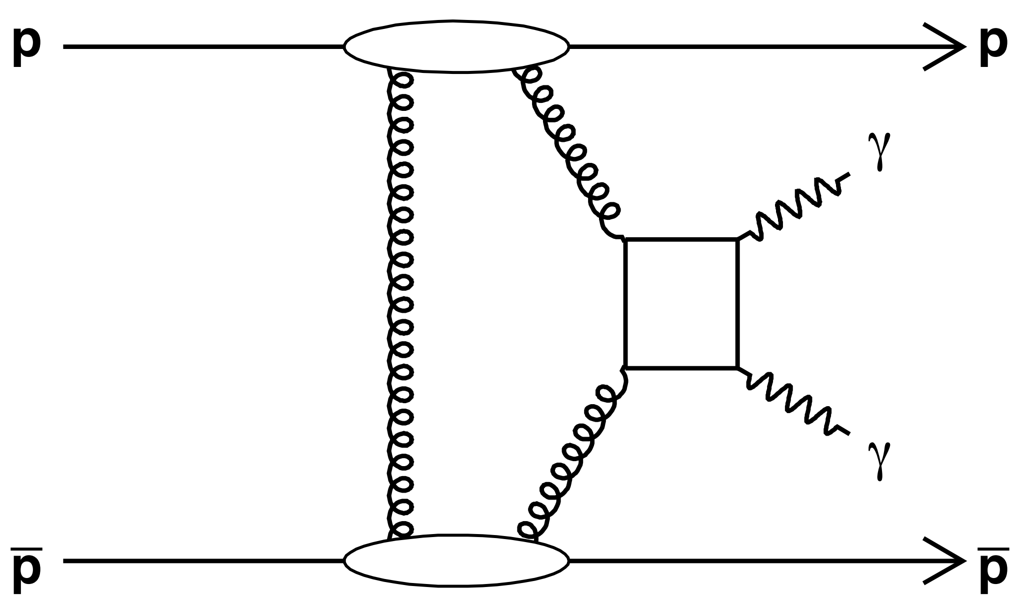


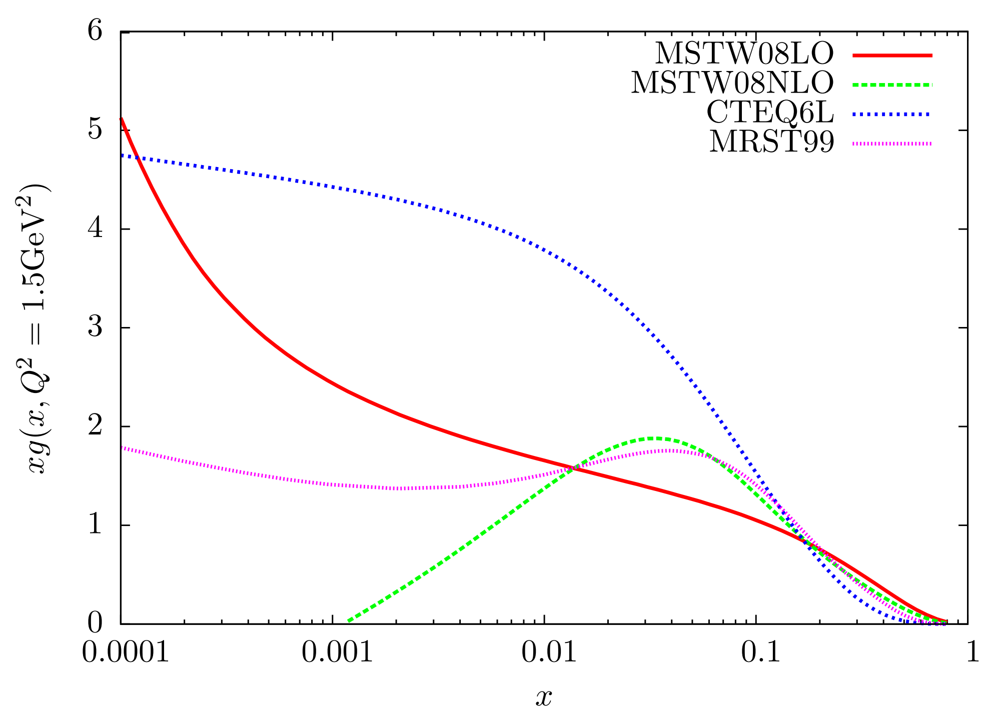
Figure: distribution (in arbitrary units) within the perturbative framework of the difference in azimuthal angle of the outgoing protons for the CEP of different J^P $c\bar{c}$ states at $\sqrt{s} = 14$ TeV. The solid (dotted) line shows the distribution including (excluding) the survival factor, while the dashed line shows the distribution in the small $p_\perp$ limit excluding the survival factor.

→ Measurement of azimuthal angle, ϕ, between outgoing protons and proton $p_\perp$ distributions via forward proton taggers would allow a clear discrimination between the different J states, as well as possibly probing different models of soft diffraction (which will predict in general different distributions).

$\gamma\gamma$ CEP

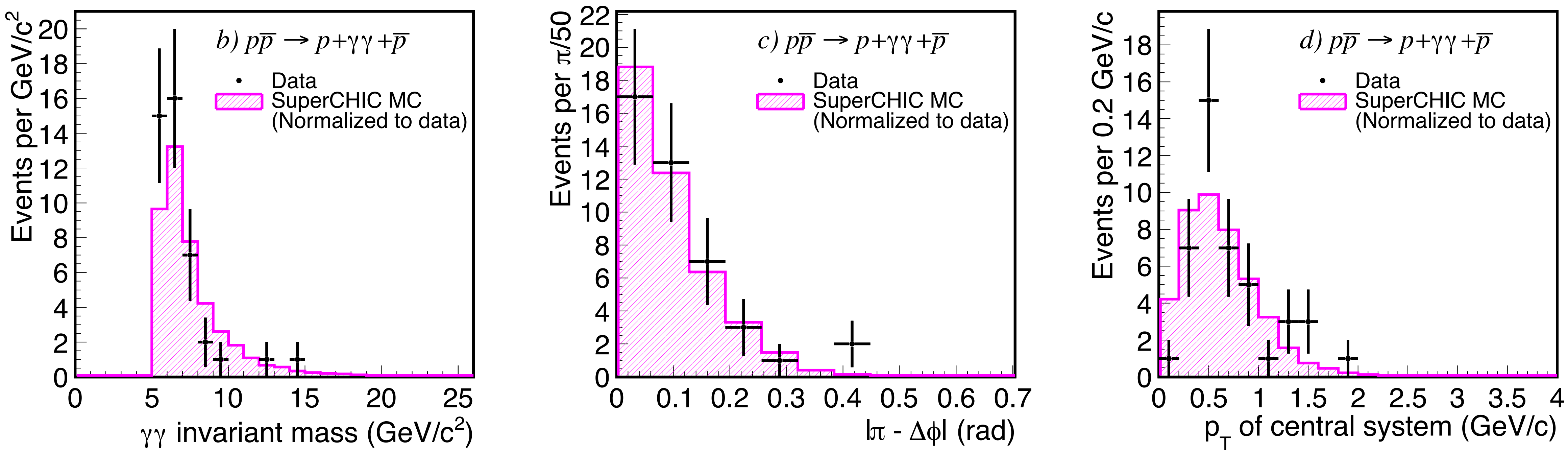
- $\gamma\gamma$ CEP: represents clean signal, with less of the theory issues related to, e.g. χ_c CEP. $\rightarrow$ ideal 'standard candle'.
- Sensitive to gluon PDF in the low-x,Q^2 region, where there is a large uncertainty (recall $\sigma_{\rm CEP} \sim (xg)^4$).





$\gamma\gamma$ CEP: comparison with data

- CDF $\gamma\gamma$ data[7] 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: 2.2 pb (CTEQ6L), 1.42 pb (MSTW08LO) and 0.35 pb (MRST99), with approx. uncertainties $\sim \stackrel{\times}{\div} 2$.
- $\pi^0\pi^0$ BG observed to be small, in agreement with non–trivial Durham prediction (follows from $J_z = 0$ selection rule): $N(\pi^0\pi^0)/N(\gamma\gamma) < 0.35$ @ 95% confidence $\rightarrow$ supports our result (Theory: $\sigma(\pi^0\pi^0)/\sigma(\gamma\gamma) \approx 0.01$).



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