



4th International Conference on New Frontiers in  
Physics ICNFP2015 23-30 August 2015

## Central Exclusive Production at hadron colliders (selected topics)

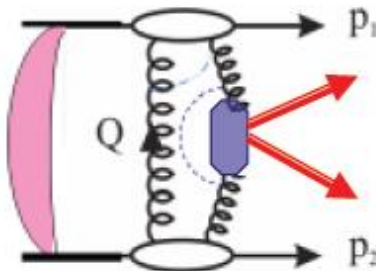


V.A. Khoze (IPPP, Durham and PINP)



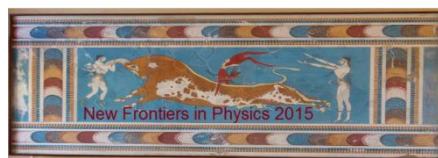
(in collaboration with Lucian Harland-Lang and Misha Ryskin)

CEP =  series





- Introduction (why we are interested in collecting CEPs ?)
- Standard Candle CEP reactions.
- CEP as a way to study old and new heavy resonances  
(e.g. zoo of 'exotic' X,Y,Z states).
- Diphoton and Dimeson **CEP**, gluonic component of  $\eta'$
- Exclusive jet production.
- Double  $J/\psi$  central production.
- SuperChic MC.
- Summary and Outlook.



# Introduction (why we are interested in CEP ?)

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

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

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

→ Can serve as 'Standard Candle' processes, which allow us to check the theoretical predictions for central exclusive new physics signals at the LHC. (dimeson CEP: CDF, RHIC, ALICE-new data)

- $\chi_{c,b}$  production is of special interest:

- Heavy quarkonium production can shed light on the physics of bound states (lattice, NRQCD. . . ).
- Potential to produce different  $J^P$  states, which exhibit characteristic features (e.g. angular distributions of forward protons).
- Possibility to shed light on the various 'exotic' charmonium states observed recently (X,Y,Z) charmonium-like states.

Spin-Parity Analyzer

KMR -00, A.B. Kaidalov +KMR-2003



Detailed tests of dynamics of soft diffraction (KMR-02)



## This is all about QCD with all its beauty and complexities

What are the problems with this? ....

...it is not at all evident to experimentalists, who nowadays tend to prefer mining gold to going fishing.

(J.D. Bjorken, Int.J.Mod.Phys. A7 (1992) 4189-4258)



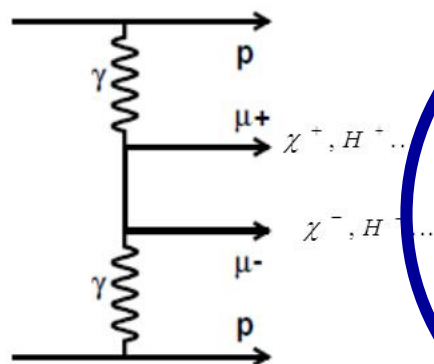
in the CEP case: ....**mining gold to mushroom picking.**

# CENTRAL EXCLUSIVE PRODUCTION PROCESSES

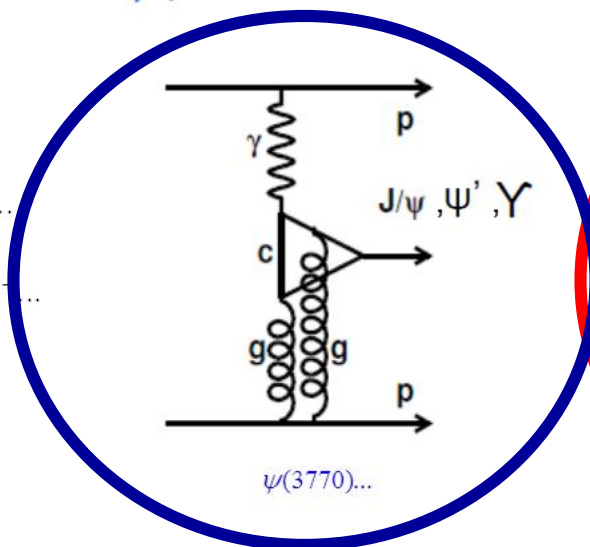


- Elastic process, intact protons continuing down beampipe
- Exchange of colourless objects (photon, pomeron)

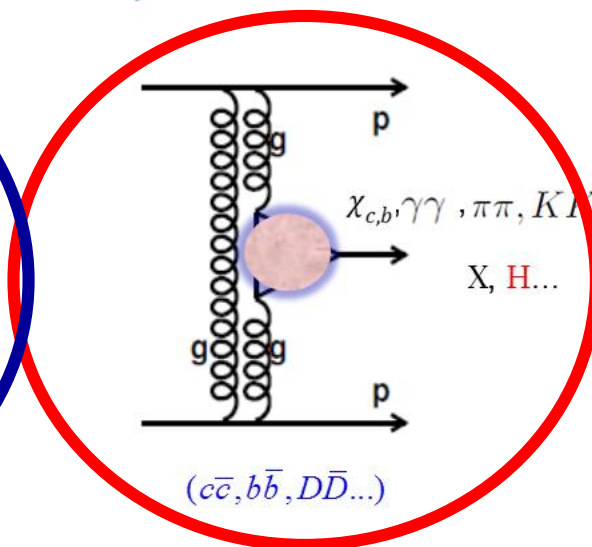
*diphoton fusion*



*γ-pomeron fusion*

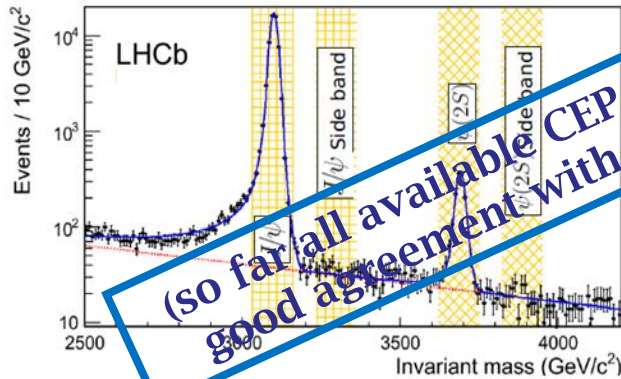


*dipomeron fusion*

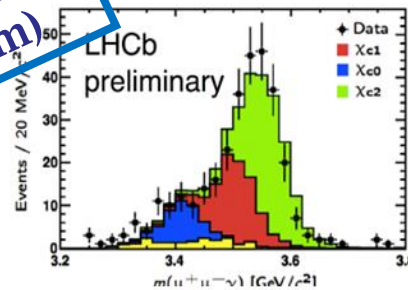


(also searches for odderon...)

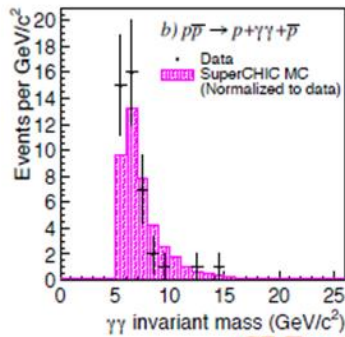
- **Theoretically:** a complementary and novel application of QCD.
  - **Experimentally:** very clean signal. Data already taken at the Tevatron (Jim Pinfeld) ( $jj, \gamma\gamma, l^+l^-, \chi_c, J/\psi, \pi^+\pi^- \dots$ ) and taken/looked for at the LHC. RHIC
- Many plans for future measurements, lot of potential channels....



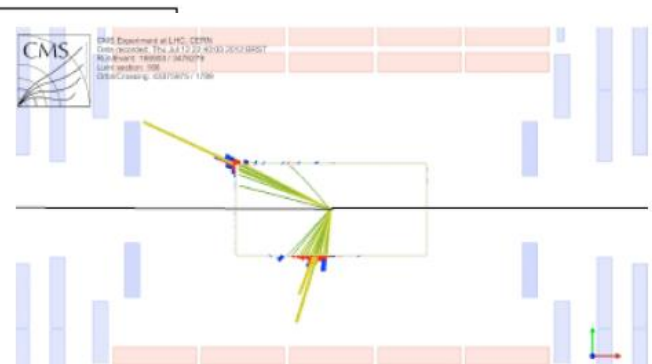
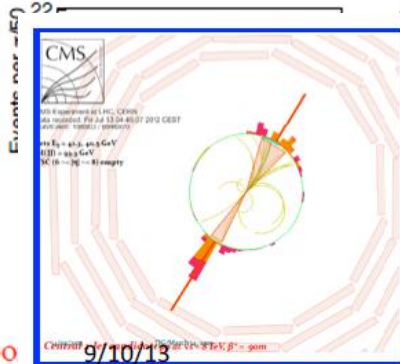
**(so far all available CEP data in a good agreement with Durham)**



arXiv:1301.7084



CDF collabo



(CMS+ TOTEM event display, Run I)



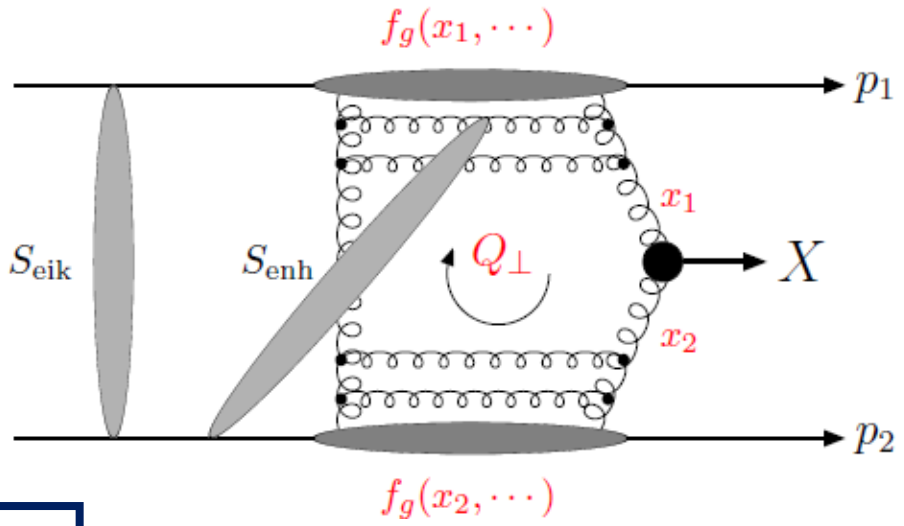
(QCD mediated)

# ‘Durham Model’ of Central Exclusive Production

- Model via diagram shown: two gluons exchange in the t-channel. Use of pQCD justified by hard scale  $\sim M_X$ . IR stable result due to Sudakov factor: probability of no additional hard radiation.
- However must also include probability of no additional soft secondary particle production, independent of hard process: the soft survival factor  $S^2$ , discussed before.

→ Both soft and hard QCD must be included.

- $J_z^{PC} = 0^{++}$  selection rule: these quantum numbers are dominantly preferred, i.e. only certain  $gg \rightarrow X$  helicity amplitudes contribute, not the usual inclusive sum.



# Calculating CEP : ingredients

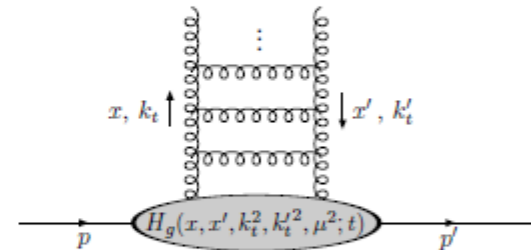


- **Soft Survival probability:**

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

Durham group, GLM, S. Ostapchenko, S-F.

- ▶ Recent TOTEM data on total, elastic and diffractive cross sections has been an important guide for LHC predictions.



- **‘Skewed’ PDFs:**

- ▶ Correspond to  $gg$  coupling to proton for relevant kinematics
- ▶ In the CEP regime can be calculated via usual global PDFs.

PRD 88, 034029 (2013) for latest results.

- **Sudakov factor:**

- ▶ Resums higher order logs in  $Q_{\perp}/M_X$ . ensuring IR stable result and validity of perturbative treatment.

Important to include all  factors correctly!

One step forward, two steps back (V.I. Lenin)

# $\chi_{c1}$ and $\chi_{c2}$ : general considerations

- General considerations tell us that  $\chi_{c1}$  and  $\chi_{c2}$  CEP rates are strongly suppressed:
  - $\chi_{c1}$ : Landau-Yang theorem forbids decay of a  $J = 1$  particle into on-shell gluons.
  - $\chi_{c2}$ : Forbidden (in the non-relativistic quarkonium approximation) by  $J_z = 0$  selection rule that operates for forward ( $p_{\perp} = 0$ ) outgoing protons. KMR-01 (A. Alekseev-1958-positronium)
- However the experimentally observed decay chain  $\chi_c \rightarrow J/\psi\gamma \rightarrow \mu^+\mu^-\gamma$  strongly favours  $\chi_{c(1,2)}$  production, with:  
$$\text{Br}(\chi_{c0} \rightarrow J/\psi\gamma) = 1.1\% ,$$
$$\text{Br}(\chi_{c1} \rightarrow J/\psi\gamma) = 34\% ,$$
$$\text{Br}(\chi_{c2} \rightarrow J/\psi\gamma) = 19\% .$$
- We should therefore seriously consider the possibility of  $\chi_{c(1,2)}$

(O.Teryaev et al; HKRS-2009)

□ The effects of non-zero  $p_T$  (especially for  $2^+$  ). ...and especially without proton detectors!

2011-2012 dataset ~ 80 times more lumi

Move to 25 ns running doubles usable luminosity

HKRS: arXiv:0909.4748

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

- See clear suppression in  $\chi_{c(1,2)}$  states.

Do not expect to see (or find) in inclusive production.

LHCb Collaboration, arXiv:1307.4285

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

$$\sigma(\chi_{c0})/\sigma(\chi_{c2}) = 1.19 \pm 0.27 \text{ (stat)} \pm 0.29 \text{ (syst)} \pm 0.16 \text{ (} p_T \text{ model)} \pm 0.09 \text{ (} \mathcal{B} \text{)},$$

$$\sigma(\chi_{c2})/\sigma(\chi_{c1}) = 0.787 \pm 0.014 \text{ (stat)} \pm 0.034 \text{ (syst)} \pm 0.051 \text{ (} p_T \text{ model)} \pm 0.047 \text{ (} \mathcal{B} \text{)}$$

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

- A clear way to resolve the issue of  $\chi_c$  spin-parity identification will be to search for the two-body decays: KMRS-2004

$Br(\chi_{c0} \rightarrow \pi\pi, K^+ K^-) = 1.3\%$       $\chi_{c1}, \eta_c \not\rightarrow \pi\pi, KK$       $Br(\chi_{c2} \rightarrow \pi\pi, K^+ K^-) = 0.3\%$   
 $Br(\chi_{c0} \rightarrow p\bar{p}) = 2 \cdot 10^{-4}$       $Br(\chi_{c1} \rightarrow p\bar{p}) = 6.6 \cdot 10^{-5}$       $Br(\chi_{c2} \rightarrow p\bar{p}) = 6.7 \cdot 10^{-5}$   
 $Br(\eta_c \rightarrow p\bar{p}) = 0.13\%$

- Tagged forward protons: spin-parity ID of old and new heavy meson states, detailed tests of absorption effects

First CDF limits - 2013

We previously observed [5] exclusive  $\chi_c^0$  production in the mode  $J/\psi(\rightarrow \mu^+ \mu^-) + \gamma$ , but could not distinguish the three  $\chi_c$  states. The  $\pi^+ \pi^-$  and  $K^+ K^-$  channels have larger branching fractions and enough resolution to separate the  $\chi_c$  states. We do not see significant signals in this data, and give upper limits (90% C.L.) on  $d\sigma/dy|_{y=0}(\chi_{c0}) = 21.4 \pm 4.2 \text{ (syst.) nb}$  (in  $\pi^+ \pi^-$ ) and  $18.9 \pm 3.8 \text{ (syst.) nb}$  (in  $K^+ K^-$ ). This implies that < 25% of the  $J/\psi + \gamma$  events were  $\chi_{c0}$  (3415). Even though the  $\chi_{c2}$  (3556) may have a much smaller production cross section its branching fraction is 17x larger.

Bad guys-diffractive dissociation

FSCs- to veto proton dissociation- run-2,  
HERSHEL@LHCb, ADA, ADC-ALICE

## Some CEP Samples

- CEP of **light meson pairs** ( $\pi\pi, KK, \eta(\prime)\eta(\prime)\dots$ ) : predict very different behaviour for singlet vs. non-singlet mesons. Can shed light on the component of the  $\eta', \eta$ . Interesting theoretical features of Durham + 'hard exclusive' formalism. Remarkable theory expectations.
- $\gamma\gamma$  CEP : experimentally clean signal. Further (differential) test of approach. Sensitive to gluon PDF, benchmark for Higgs production.
- The **Higgs boson**: suppression in  $gg \rightarrow b\bar{b}$  BG.  $J_z^{PC} = 0^{++}$  selection rule gives probe of CP violating effects.
- **Photoproduction** ( $J/\psi, \Upsilon, \psi(2S)$ ), **two-photon** collisions, **BSM** objects, **glueballs**...



## CEP of meson pairs

CEP via this mechanism can in general produce *any*  $C$ -even object which couples to gluons: Higgs, BSM objects...but also dijets, quarkonium states, [light meson pairs](#)...

i.e consider production of a pair of light mesons

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

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

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

[Lower  \$k\_{\perp}\$  region: use Regge-based model](#)

[Lebiedowicz, Pasechnik, Szczurek, PLB 701:434-444, 2011](#)

[HKRS: arXiv:1204.4803](#)

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

[HKRS: arXiv:1304.4262, 1302.2004, 1204.4803, 1105.1626](#)

# Flavour non-singlet mesons

HKRS: arXiv:1105.1626

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

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

$$T_{++} = T_{--} = 0 \quad (\text{MHV-technique})$$

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

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

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

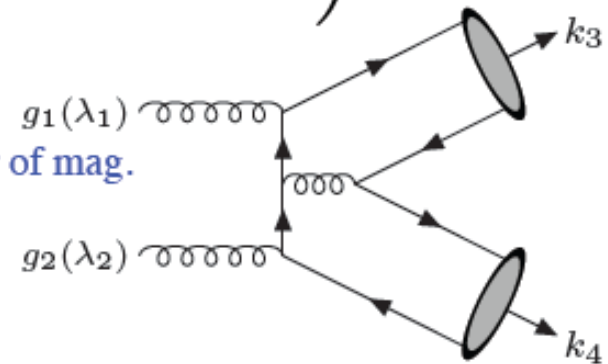
Further suppression from radiation zero in  $J_z = \pm 2$  amplitude.

T. Aaltonen et al., PRL 108, 081801 (2012), arXiv:1112.0858

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

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

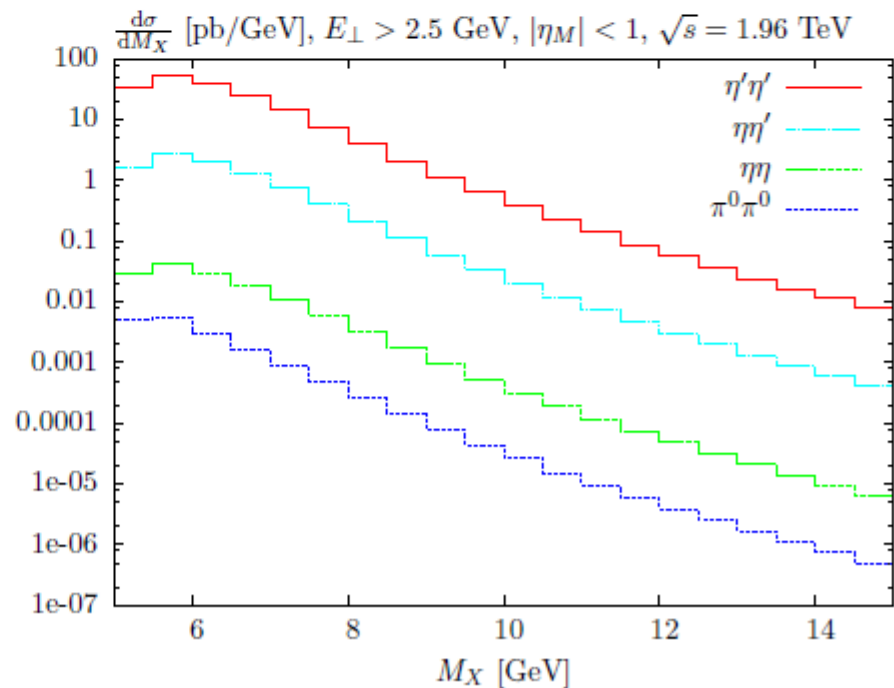
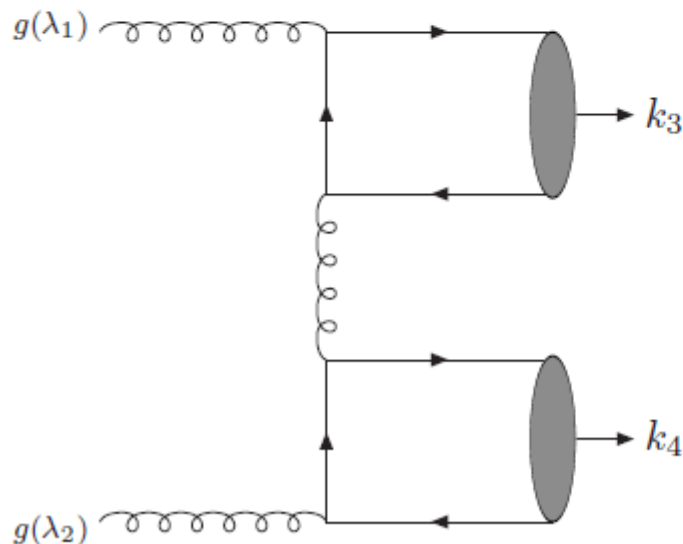
Theory:  $\sigma(\pi^0\pi^0)/\sigma(\gamma\gamma) \approx 1\%$



More results are expected to come

# Flavour singlet mesons

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

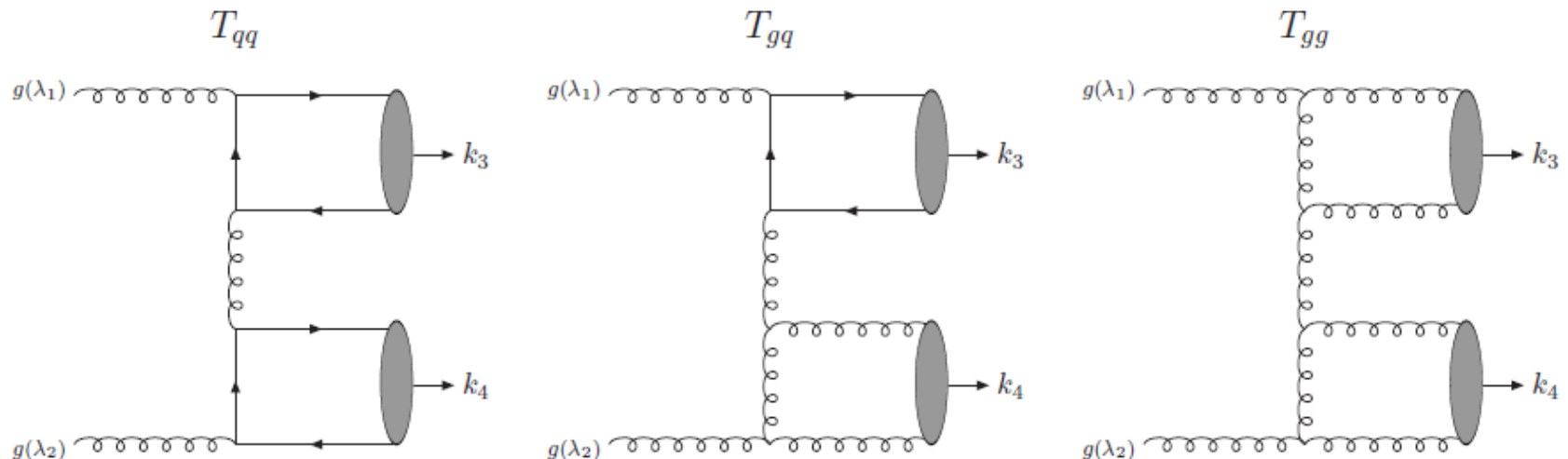


# The gluonic component of the $\eta'(\eta)$

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

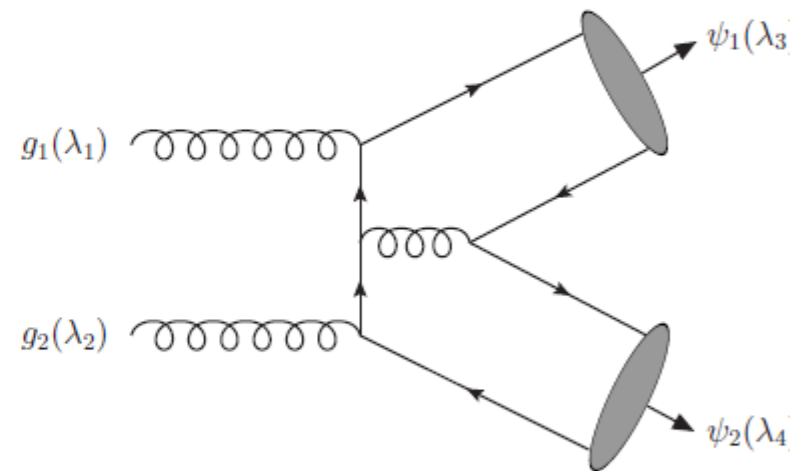
→ The  $gg \rightarrow \eta'(\eta)\eta'(\eta)$  process will receive a contribution from the  $gg \rightarrow ggq\bar{q}$  and  $gg \rightarrow gggg$  parton level diagrams.

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



## Example: exclusive $J/\psi J/\psi$ production

- Heavy quark mass ensures this is perturbative. Highly topical as a probe of (inclusive) double parton scattering, as well as tetraquark decays...
  - Generically we write the CEP process in terms of the  $gg \rightarrow X$  helicity amplitudes, in this case  $gg \rightarrow J/\psi J/\psi$ .
  - In high subprocess energy ( $\hat{s} \gg M_\psi^2$ ) limit find that amplitudes with initial-state gluons in  $J_z = 0$  config. vanish, while numerically suppressed away from this limit.
- Expect  $J/\psi J/\psi$  CEP cross section to be suppressed below naive estimates. Specific result of exclusive channel, relies upon selection rule.



Recently LHCb have released the first exclusive measurement:



## Observation of charmonium pairs produced exclusively in $pp$ collisions

J. Phys. G41 (2014) 11, 115002

The LHCb collaboration<sup>†</sup>

### Abstract

A search is performed for the central exclusive production of pairs of charmonia produced in proton-proton collisions. Using data corresponding to an integrated luminosity of  $3 \text{ fb}^{-1}$  collected at centre-of-mass energies of 7 and 8 TeV,  $J/\psi J/\psi$  and  $J/\psi \psi(2S)$  pairs are observed, which have been produced in the absence of any other activity inside the LHCb acceptance that is sensitive to charged particles in the pseudorapidity ranges  $(-3.5, -1.5)$  and  $(1.5, 5.0)$ . Searches are also performed for pairs of P-wave charmonia and limits are set on their production. The cross-sections for these processes, where the dimeson system has a rapidity between 2.0 and 4.5, are measured to be

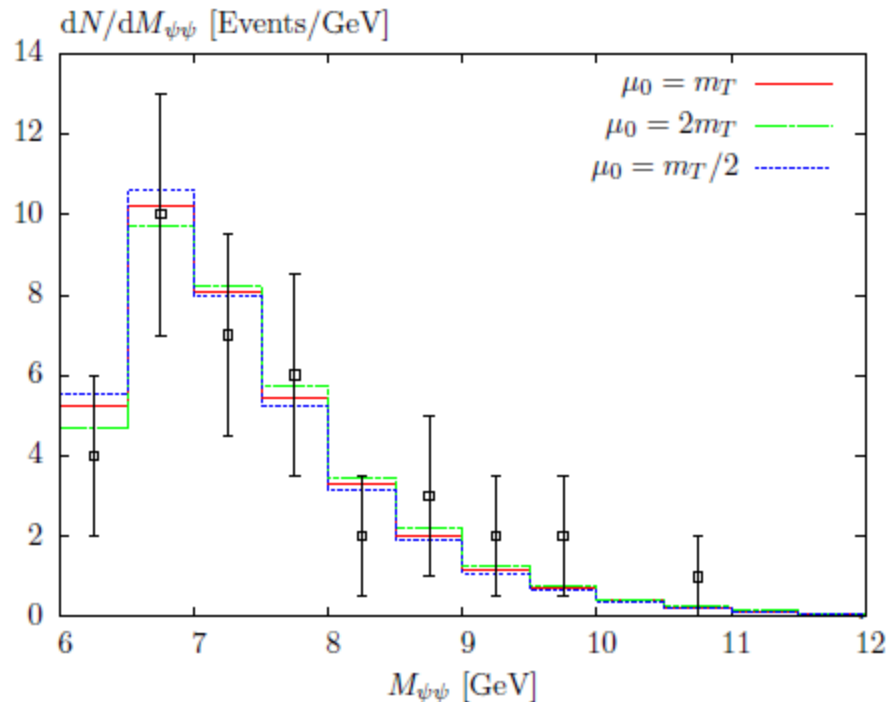
$$\begin{aligned}\sigma^{J/\psi J/\psi} &= 58 \pm 10(\text{stat}) \pm 6(\text{syst}) \text{ pb}, \\ \sigma^{J/\psi \psi(2S)} &= 63^{+27}_{-18}(\text{stat}) \pm 10(\text{syst}) \text{ pb}, \\ \sigma^{\psi(2S)\psi(2S)} &< 237 \text{ pb}, \\ \sigma^{\chi_{c0}\chi_{c0}} &< 69 \text{ nb}, \\ \sigma^{\chi_{c1}\chi_{c1}} &< 45 \text{ pb}, \\ \sigma^{\chi_{c2}\chi_{c2}} &< 141 \text{ pb},\end{aligned}$$

where the upper limits are set at the 90% confidence level. The measured  $J/\psi J/\psi$  and  $J/\psi \psi(2S)$  cross-sections are consistent with theoretical expectations.

→ Larger (MSTW/GJR) cross sections in fair agreement, within (reasonably large) theoretical and experimental uncertainties, but interesting possibility that predicted cross section are a little low.

- Can compare  $J/\psi J/\psi$  invariant mass distribution to LHCb measurement

Normalized  
to data



→ Encouraging agreement, within experimental uncertainties. But absolute cross section perhaps a bit higher in data.

- Outlook: during Run II we can anticipate (hope for) further, higher statistics, measurements of this from LHCb (defocused beams + HERSCHEL):  $J/\psi J/\psi, \psi(2S)\psi(2S), \chi_c\chi_c(?) \dots$



# X(3872) analysis: motivation

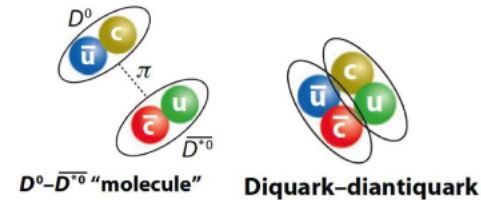


X(3872) is “a riddle, wrapped in a mystery, inside an enigma; but perhaps there is a key” <sup>1</sup>

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

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

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



Most likely interpretation:  
 $DD^*$  molecule with admixture of  $\chi_{c1}(2P)$   
 isospin violation      production at high energy

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

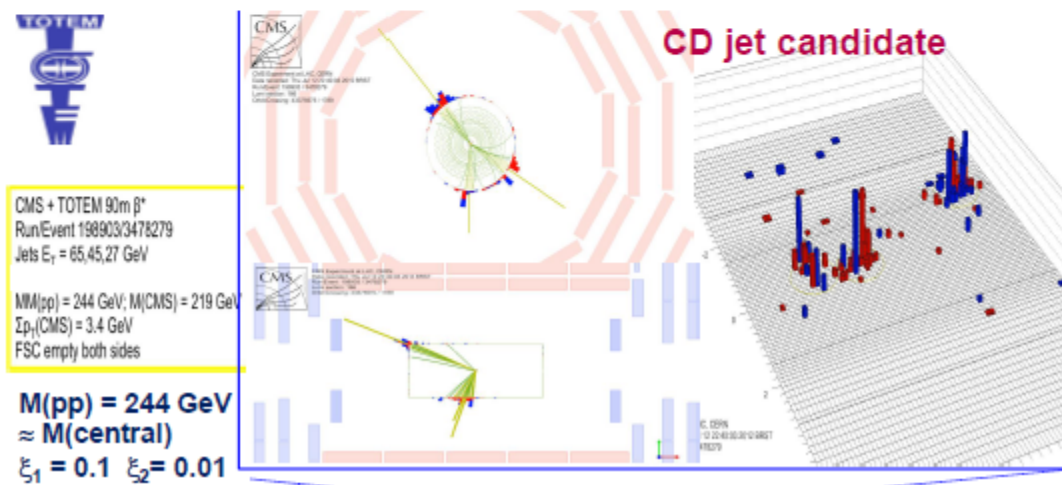
# Insight from CEP

- In CEP the state  $X$  is produced directly, i.e. at short distances:  
 $gg \rightarrow X(3872)$  and nothing else.  $\rightarrow$  would be clear evidence of a direct production mode.
  - In an inclusive environment, for which additional soft quarks, D-mesons etc can be present/emitted it *may* be easier to form molecular or 4-quark states.
- $\rightarrow$  Can shed further light by comparing to the rate of  $\chi_{c1}(1^3P_1)$  production, as seen by LHCb. Up to mass effects, cross section ratio should be given by ratio of squared wavefunction derivatives at the origin  $|\phi'_P(0)|^2$ .
- ▶ Also, can consider e.g. the  $Z(3930) \equiv \chi_{c2}(2P)$ :
    - Above threshold: decays to  $D\bar{D}$ ,  $D^+D^-$  and  $D^0\bar{D}^0$  seen.
    - With vertex detection at LHCb and RHIC  $\rightarrow$  exclusive open charm ( $D\bar{D}\dots$ ) production.
    - Theory: roughly the same cross section and distributions as  $\chi_{c2}(1P)$ .

Good Luck to LHCb

# Other processes: jet production

- ▶ Large cross sections, expect strong  $gg$  dominance, i.e. isolated gluon jets at the LHC.  $\rightarrow$  possible clean probe of properties of gluon jets.
- ▶ 3-jet events: expect enhancement in ‘Mercedes’ configurations in  $q\bar{q}g$  case and potential for (first) observation of QCD ‘radiation zeros’ in  $ggg/q\bar{q}g$  channels.  
*LHL, JHEP 1505 (2015) 146*
- ▶ Proposals for measurements during Run II with tagged protons, both during low lumi. running with CMS-TOTEM, ATLAS+ALFA (can expect  $\sim 10000$  events for  $100 \text{ pb}^{-1}$ ) and during normal running with CT-PPS and AFP (detailed studies have been performed and S/B found to be viable).



# Dijet production

- We need the amplitudes for

$$gg \rightarrow gg \quad \text{and} \quad gg \rightarrow q\bar{q}$$

For colour singlet gluons.  $J_z = 0$  selection rule  $\Rightarrow$  dominant contribution will come from amplitude for incoming gluons with  $(++, --)$  helicities. These are given by

$$\mathcal{M}(g(\pm)g(\pm) \rightarrow g(\pm)g(\pm)) = \delta^{CD} \frac{N_c}{N_c^2 - 1} \frac{32\pi\alpha_s}{(1 - \cos^2 \theta)}$$

Other final state helicities give vanishing amplitudes

$$\mathcal{M}(g(\pm)g(\pm) \rightarrow q_h\bar{q}_{\bar{h}}) = \frac{\delta^{cd}}{2N_c} \frac{16\pi\alpha_s}{(1 - \beta^2 \cos^2 \theta)} \frac{m_q}{M_X} (\beta h \pm 1) \delta_{h,\bar{h}}$$

For massless quarks this vanishes!

Helicity non-conservation along quark line

$\rightarrow$  Quark jets dynamically suppressed by selection rule

**MHV-rule**

Dijet CEP as a gluon factory

# Production subprocess

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

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

↑  
Additional suppression from colour and spin 1/2 quarks

- Taking e.g.  $m_b = 4.5$  GeV and  $M_X = 40$  GeV we then get

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

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

CDF-2008

$\frac{\sigma( J_z  = 2)}{\sigma(J_z = 0)} \sim \frac{\langle p_{\perp}^2 \rangle^2}{\langle Q_{\perp}^2 \rangle^2} \sim 10^{-2}$	<p style="font-size: small; color: blue;">Average outgoing proton transverse momentum (sub-GeV<sup>2</sup>)</p> <p style="font-size: small; color: blue;">Average gluon transverse momentum in loop <math>\propto</math> several GeV<sup>2</sup></p>
---	--

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

For one flavour  
⇒ multiply by  $n_f = 4$

→ Huge suppression in light quark jets

# Trijet production

- Consider three-jet production, proceeds via  $gg \rightarrow ggg$  and  $gg \rightarrow q\bar{q}g$
- $q\bar{q}g$  : configuration with  $g$  becoming soft/collinear to  $q/\bar{q}$  driven by two-jet  $q\bar{q}$  amplitude, which vanishes for  $J_z = 0$  gluons and  $m_q = 0$ .
- More precisely, according to ‘Low-Burnett-Kroll’ theorem, the radiative amplitude  $M_{q\bar{q}g}$  can be expanded in powers of  $x_g = \frac{2E_g}{\sqrt{\hat{s}}}$  as

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

Vanishes ↙

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

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

$$\frac{d\sigma^{q\bar{q}g}}{dE_g} \sim E_g^3 \quad \text{while} \quad \frac{d\sigma^{ggg}}{dE_g} \sim \frac{1}{E_g}$$

For  $J_z = 0$  incoming gluons

Usual (singular) IR behaviour ↗

See also V.A. Khoze, M.G. Ryskin, W.J. Stirling, Eur.Phys.J. C48 (2006) 477-488, hep-ph/0607134

# SuperChic v1



EDS Blois 2013

A MC event generator including<sup>8</sup>:

- Simulation of different CEP processes, including all spin correlations:
  - $\chi_{c(0,1,2)}$  CEP via the  $\chi_c \rightarrow J/\psi\gamma \rightarrow \mu^+\mu^-\gamma$  decay chain.
  - $\chi_{b(0,1,2)}$  CEP via the equivalent  $\chi_b \rightarrow \Upsilon\gamma \rightarrow \mu^+\mu^-\gamma$  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  $J/\psi$  and  $\Upsilon$  photoproduction. +  $\psi(2S)$
  - $\gamma\gamma$  CEP.
  - Meson pair ( $\pi\pi$ ,  $KK$ ,  $\eta\eta\dots$ ) CEP.

→ Additional processes to add, but also theoretical improvements to be included.

## Survival factor

- Survival factor,  $S_{\text{eik}}^2$ : probability of no additional soft proton-proton interactions, spoiling exclusivity of final-state.
  - **Not** a constant: depends sensitively on the outgoing proton  $\mathbf{p}_\perp$  vectors. Physically- survival probability will depend on impact parameter of colliding protons. Further apart  $\rightarrow$  less interaction, and  $S_{\text{eik}}^2 \rightarrow 1$ .  
 $b_t$  and  $p_\perp$  : Fourier conjugates.
- $\rightarrow$  Need to include survival factor differentially in MC.

# SuperChic v2

New MC for CEP close to release. Based on original SuperCHIC, but with significant extensions.

- Theoretical developments:
  - ▶ Correct inclusion of Sudakov factor [T.D. Coughlin and J.R. Forshaw, JHEP 1001 \(2010\) 121](#)
  - ▶ Consistent treatment of ‘skewed’ gluon PDFs [LHL, Phys. Rev. D88 \(2013\) 3, 034029](#)
  - ▶ **Full** (differential) treatment of soft survival effects
- LHAPDF interface.
- Complete calculation performed ‘on-line’, and structured so that additional processes can be easily added.

- Processes generated:

New ▶ SM Higgs boson

New ▶ Jets:  $gg$ , heavy/massless  $q\bar{q}$ ,  $ggg$ , massless  $gq\bar{q}$

New ▶ Double quarkonia:  $J/\psi J/\psi$ ,  $J/\psi\psi(2S)$  and  $\psi(2S)\psi(2S)$

▶ Light meson pairs:  $\pi\pi$ ,  $KK$ ,  $\rho\rho$ ,  $\eta(\prime)\eta(\prime)$ ,  $\phi\phi$

▶  $\chi_{c,b}$ : two body and  $J/\psi$ ,  $\Upsilon + \gamma$  channels

▶  $\eta_{c,b}$

▶ Photoproduction:  $J/\psi$ ,  $\psi(2S)$  and  $\Upsilon$  **HERA fit**

New ▶ Two-photon interactions:  $W^+W^-$ ,  $\mu^+\mu^-$  and  $e^+e^-$

- Averaged survival factor given by (in impact parameter space)

Opacity, relates to prob. of no inelastic scattering

$$\langle S_{\text{eik}}^2 \rangle = \frac{\int d^2 b_{1t} d^2 b_{2t} |T(s, b_{1t}, b_{2t})|^2 \exp(-\Omega(s, b_t))}{\int d^2 b_{1t} d^2 b_{2t} |T(s, b_{1t}, b_{2t})|^2}$$

One-channel for illustration

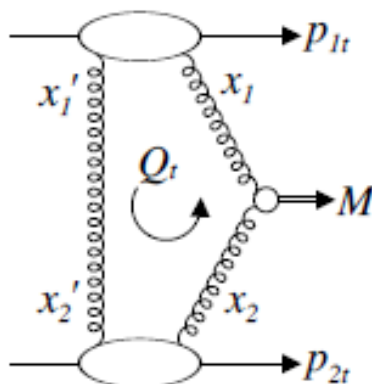
in  $p_{\perp}$  space this is equivalent to

'Bare' amplitude

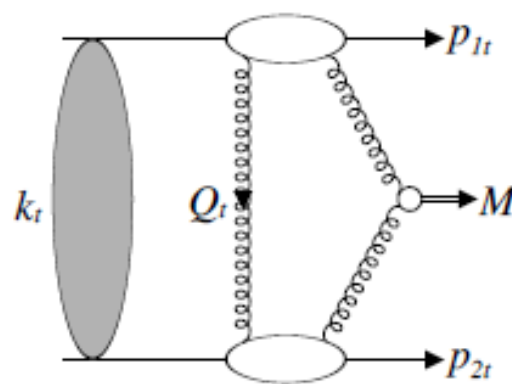
$$\langle S_{\text{eik}}^2 \rangle = \frac{\int d^2 p_{1\perp} d^2 p_{2\perp} |T(s, p_{1\perp}, p_{2\perp}) + T^{\text{res}}(s, p_{1\perp}, p_{2\perp})|^2}{\int d^2 p_{1\perp} d^2 p_{2\perp} |T(s, p_{1\perp}, p_{2\perp})|^2}$$

where 'screened' amplitude is given by

$$T^{\text{res}}(s, p_{1\perp}, p_{2\perp}) = \frac{i}{s} \int \frac{d^2 k_{\perp}}{8\pi^2} T_{\text{el}}(s, k_{\perp}^2) T(s, p'_{1\perp}, p'_{2\perp})$$

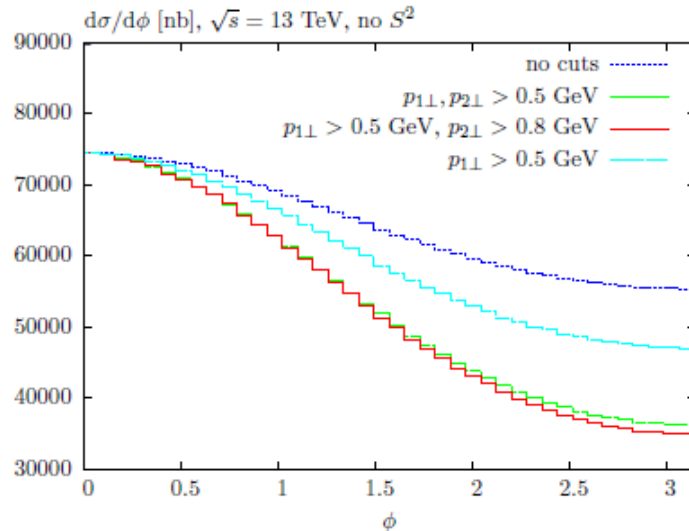
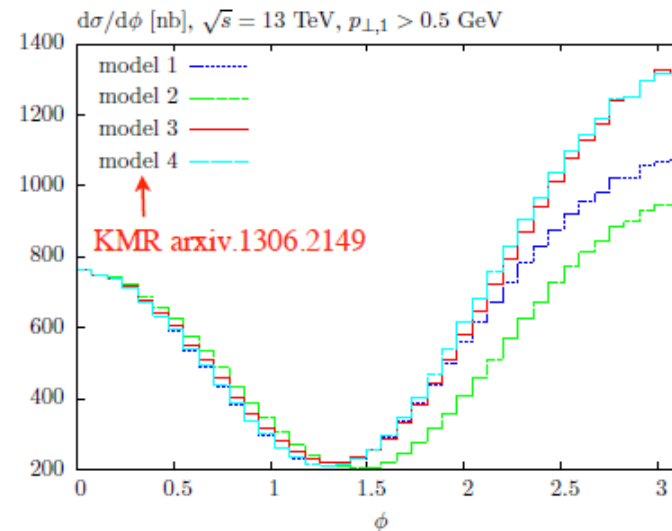


'Bare' amplitude



'Screened amplitude'

- The observation of such a process with tagged protons also provides additional information about survival factors...

 $S^2$  off $S^2$  on

LHL, V.A. Khoze and M.G. Ryskin, arXiv:1312.4553

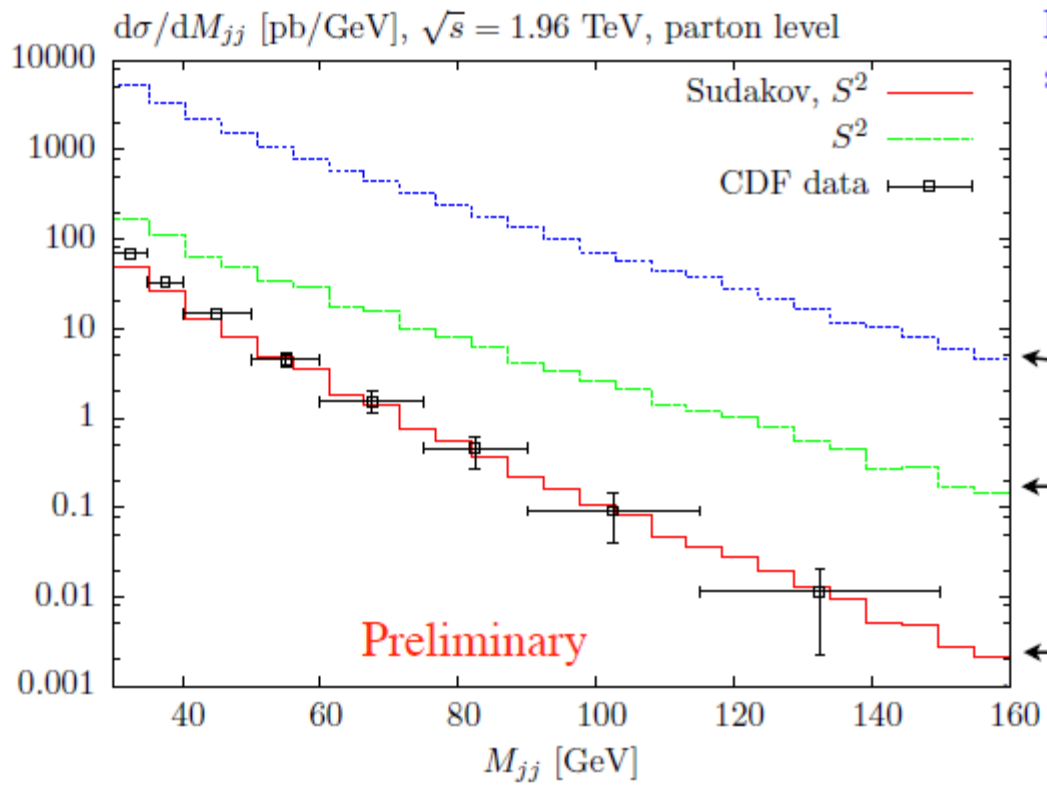
- Distribution in angle  $\phi$  between outgoing protons strongly effected, in model dependent way.
- In particular true when larger values of proton  $p_{\perp}$  are selected. Cancellation between screened and unscreened amplitudes leads to characteristic 'diffractive dip' structure
- Largely independent of production subprocess in central region.

Novel probe of the models  
of soft interaction

V. A. Khoze, A.D. Martin and M.G. Ryskin, hep-ph/0203122  
LHL, V.A. Khoze, M.G. Ryskin and W.J. Stirling, arXiv:1011

# Tevatron cross sections

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



Probability to produce colour singlet dijet state drops strongly with  $M_{jj}$

All predictions made with MSTW08LO PDFs, parton level

Soft survival not included, scale of Sudakov factor frozen

Soft survival included, scale of Sudakov factor frozen

Soft survival included, scale of Sudakov factor

$\sim M_{jj}$

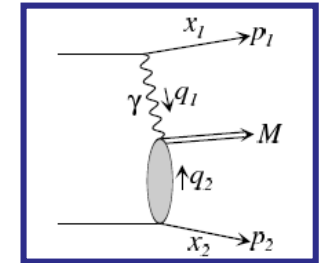
Made with particular choice of  $S^2$  model and PDFs  $\Rightarrow$  more measurements (different  $\sqrt{s}$ ...) needed to test theory further...

# $J/\psi$ photoproduction: results

- We find:

LHCb acceptance,  $\mu^+\mu^-$  decay including spin corr.

	$2 < \eta^\mu < 4.5$	
	$\sqrt{s} = 7 \text{ TeV}$	$\sqrt{s} = 13 \text{ TeV}$
$\sigma_{\text{bare}}^\psi$	<u>360</u>	512
$\sigma_{\text{sc.}}^\psi$	<u>278</u>	405
$\langle S_{\text{eik}}^2 \rangle$	0.77	0.79



- LHCb measure:

$$\sigma^{J/\psi \rightarrow \mu^+\mu^-} (2 < \eta^\mu < 4.5) = 291 \pm 7 \pm 19 \text{ pb}$$

recall these predictions are (roughly) the lowest values in good agreement with the H1 fit (can be up to  $\sim 40\%$  higher).

→ Predictions with screening effects favoured.

- Photon virtuality has kinematic minimum  $Q_{1,\text{min}}^2 = \frac{\xi_1^2 m_p^2}{1 - \xi_1}$



- Central exclusive production: ‘hard diffractive’ process, requiring non-trivial combination of soft and hard QCD. Can produce in principle any object that couples to gluons  $\rightarrow$  wide menu of processes to study
- LHC Run II has the potential to greatly increase our understanding of these processes. Please see the Forward Physics and Diffraction yellow report for status and prospects!
- new ‘SuperChic 2’ MC. Builds on previous MC, but with significant changes/extensions  $\rightarrow$  just released ([hep-ph 1508.02718](#))
- Currently active studies are in progress, both on the experimental and theory sides.



**EXCLUSIVE LAND AVAILABLE**

Complete this form for more information

Carindale William City Settlers Club Newland Anlecton Stone Wood Vale

**We are looking forward to new LHC Run II exciting adventures in Exclusiveland**



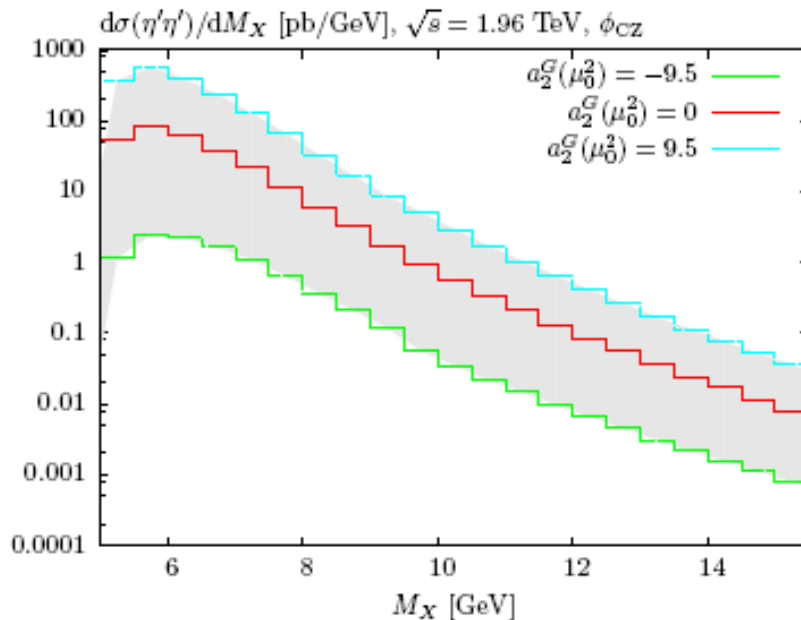
*BACKUP*

Taking this envelope of values, we find a  $\sim$  **order of magnitude** variation in the  $\eta(\prime)\eta(\prime)$  cross section!

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

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

(Peter Kroll, Kornelija Passek-Kumericki 2012)



$a_2^G(\mu_0^2)$	-9.5	0	9.5
$\sigma(\eta\eta)/\sigma(\pi^0\pi^0)$	2.7	12	66
$\sigma(\eta'\eta')/\sigma(\pi^0\pi^0)$	570	16000	100000
$\sigma(\eta'\eta')/\sigma(\gamma\gamma)$	3.5	100	660
$\sigma(\eta'\eta' \rightarrow 4\gamma)/\sigma(\gamma\gamma)$	0.0017	0.049	0.33
$\sigma(\eta\eta \rightarrow 4\gamma)/\sigma(\gamma\gamma)$	0.0025	0.012	0.066

HKRS: arXiv:1302.2004

(CDF, TOTEM-CMS, LHCb -prospects)

# χ<sub>b</sub> production

- Higher χ<sub>b</sub> mass means cross section is more perturbative, and so is better test of theory, although rate is ~ 3 orders of magnitude smaller than for χ<sub>c</sub>.
- *J* assignment of χ<sub>b*J*</sub> states still experimentally undetermined: CEP can shed light on this.
- Calculation very similar to χ<sub>c</sub> case

$$|V_{0+}|^2 : |V_{1+}|^2 : |V_{2+}|^2 \sim 1 : \frac{\langle \mathbf{p}_\perp^2 \rangle}{M_\chi^2} : \frac{\langle \mathbf{p}_\perp^2 \rangle^2}{\langle \mathbf{Q}_\perp^2 \rangle^2} \sim 1 : \frac{1}{400} : \frac{1}{100}$$

★ χ<sub>b</sub>(*nP*) → *DX* (about 0.25 of all hadronic decays (CLEO-2009))  
 χ<sub>b1</sub> → *cēX* (Barbieri et al (1979), NROCD)

- Measurement of ratio of χ<sub>b</sub> to γγ CEP rates in same mass region would eliminate certain theory uncertainties (survival factors....).
- Predictions for χ<sub>b</sub> CEP via Υγ decay (at *y*<sub>χ</sub> = 0):

√ <i>s</i> (TeV)	1.96	7	10	14
$\frac{d\sigma}{dy_{\chi_b}}(pp \rightarrow pp(\Upsilon + \gamma))$ (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

# X at LHCb

Very recent arXiv:1404.0275

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

“...The measured value agrees with expectations for a pure charmonium interpretation of the X(3872) state and a mixture of charmonium and molecular interpretations.

However, it does not support a pure DD\* molecular interpretation of the X(3872) state ...”

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

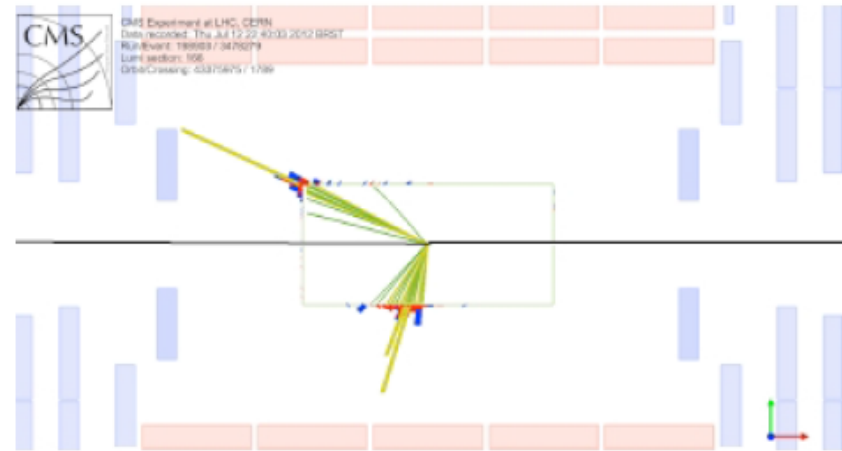
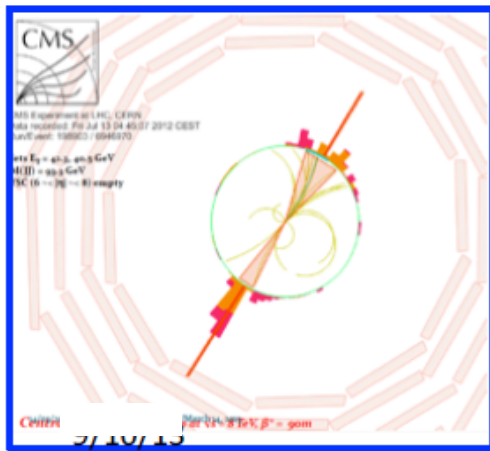
“...but the mass of X (3872) is too low to be gracefully identified with the  $2^3P_1$  charmonium state, especially if Z(3931) is to be identified as the  $2^3P_2$  level...”

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

# Gluon jet dominance

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

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



CMS + TOTEM event displays (2012)

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

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

**Dijet CEP as a gluon factory**

The  $gg \rightarrow q\bar{q}g, ggg$  amplitudes for a given helicity config. are known, and have (relatively) simple forms (can be written down in  $\sim 3 - 4$  lines) **MHV**

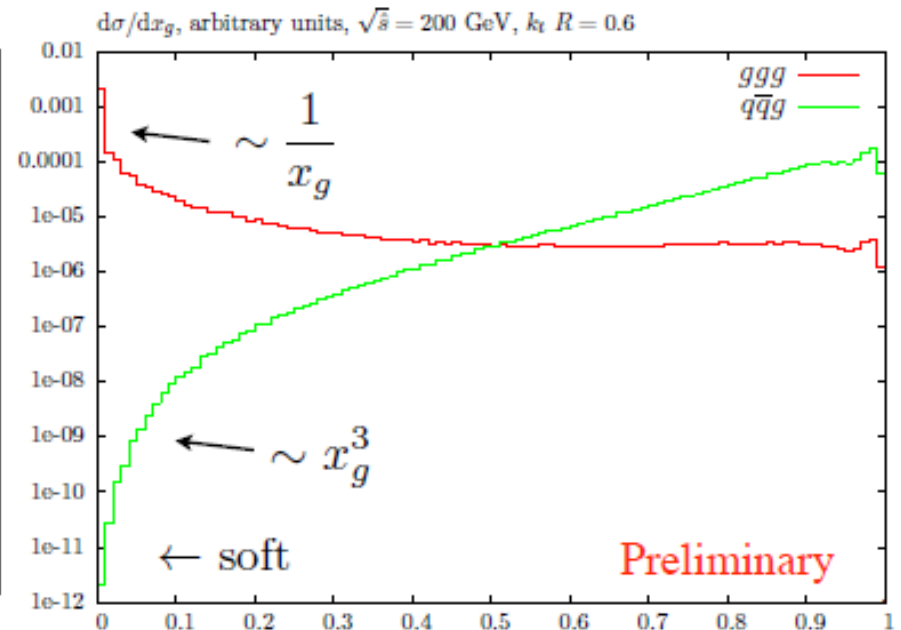
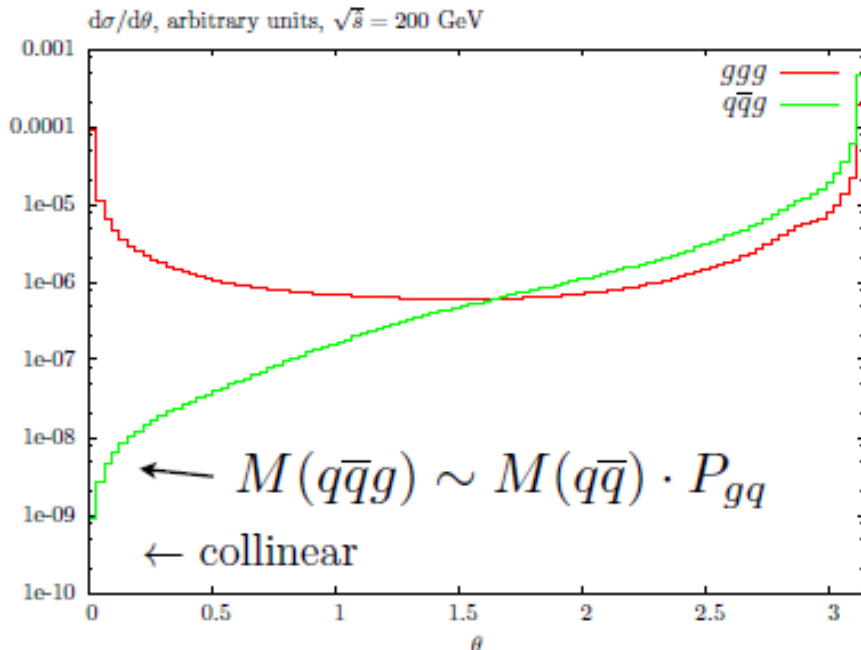
Consider amplitudes for  $J_z = 0$  colour-singlet gluons (and massless quarks for simplicity)...

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

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

$\theta$ :  $g$ - $b$  quark angle  
 $d\sigma/d\theta$  (for  $ggg$  between arbitrary gluons)

$d\sigma/dx_g$



# Theoretical improvements

- Sudakov factor:

$$T(Q_{\perp}, \mu) = \exp \left( - \int_{Q_{\perp}^2}^{\hat{s}/4} \frac{dk_{\perp}^2}{k_{\perp}^2} \frac{\alpha_s(k_{\perp}^2)}{2\pi} \int_0^{1-\Delta} dz \left[ z P_{gg}(z) + \sum_q P_{qg}(z) \right] \right)$$

with  $\Delta = k_{\perp}/M_X$  T.D. Coughlin and J.R. Forshaw, JHEP 1001 (2010) 121 HKRS-2010

Different value taken in Durham results before the CF paper, but this correct prescription used after. Accounted for in MC.

- Skewed gluon PDF often related to standard unintegrated gluon by

$$f_g(x, x', Q_{\perp}^2, \mu^2) \approx \tilde{R}_g \frac{\partial}{\partial \ln(Q_{\perp}^2)} \left[ xg(x, Q_{\perp}^2) \sqrt{T(Q_{\perp}, \mu^2)} \right]$$

with ‘skewness factor’  $\tilde{R}_g$ . However more exact form can be readily implemented in MC: LHL, Phys. Rev. D88 (2013) 3, 034029

$$f_g(x, x', Q_{\perp}^2, \mu^2) = \frac{\partial}{\partial \ln(Q_{\perp}^2)} \left[ H_g \left( \frac{x}{2}, \frac{x}{2}; Q_{\perp}^2 \right) \sqrt{T(Q_{\perp}, \mu^2)} \right]$$

$$\text{with } H_g \left( \frac{x}{2}, \frac{x}{2}, Q^2 \right) = \frac{4x}{\pi} \int_{x/4}^1 dy y^{1/2} (1-y)^{1/2} g \left( \frac{x}{4y}, Q^2 \right)$$