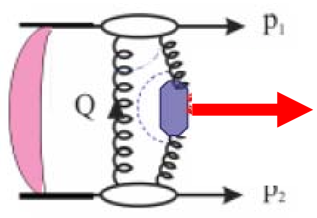
Central exclusive production of heavy quarkonia and charmonium-like states

V.A. Khoze (IPPP, Durham)



(selected topics)

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

Outline

- **Introduction** **(why we are interested in CEP processes?)** 
- **Standard Candle CEP reactions.** **(for new physics)**
- **CEP as a way to study old and new heavy resonances**
  - CEP: general theory.
  - χ_c CEP:
    - $\chi_{c(1,2)}$ suppression.
    - χ_c CEP with and without tagged protons.
    - $\chi_c \to \pi\pi, KK \ldots$
  - Don't forget: η_c, χ_b, η_b production...
  - Exotic states: X(3872)...
- **Towards the Full Acceptance Detector at the LHC (bj-1992).**
- **Summary and Outlook.**

Introduction (why we are interested in CEP ?)

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

- Driven by same mechanism as Higgs (or other new object) CEP at the LHC.
- χ_c, jj and $\gamma\gamma$ CEP has been observed by CDF.

D0 jj- results. LHCb χ_c
CMS, RHIC data expected

→ Can serve as 'Standard Candle' processes, which allow us to check the theoretical predictions for central exclusive new physics signals at the LHC.

- $\chi_{c,b}$ production is of special interest:
  - Heavy quarkonium production can shed light on the physics of bound states (lattice, NRQCD$\cdots$).
  - 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.

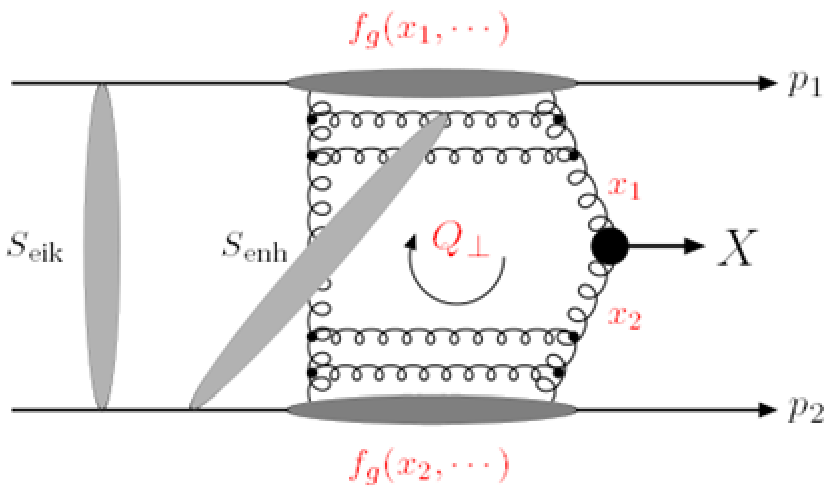
Spin-Parity Analyzer (KMR-00, KKMR-2003)

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

'Durham Model' of central exclusive production

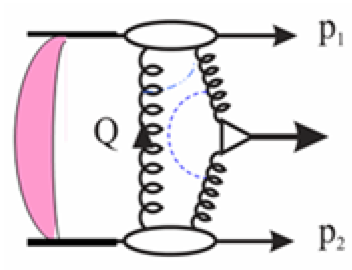
- The generic process $pp \to p + X + p$ is modeled perturbatively by the exchange of two t-channel gluons.
- The use of pQCD is justified by the presence of a hard scale $\sim M_X/2$. This ensures an infrared stable result via the Sudakov factor: the probability of no additional perturbative emission 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 $S^2_{\rm enh}$. (a lot of attention)
- In the limit that the outgoing protons scatter at zero angle, the centrally produced state X must have $J_Z^P = 0^+$ quantum numbers.



(KMR-2000)

The Durham technology



(1997-2013)

$$\sigma_{pp}(M^2,\ldots) = L_{eff}(M^2,y) * \sigma_{hard}(M^2,\ldots)$$

$$\frac{\partial^2 L_{eff}}{\partial y \partial M^2} M^2 = S^2 * L(M^2)$$

$\sigma_H(CEP) \sim 10^{-4}\ \sigma_H$ (incl)

focus on $\sigma^{bgd}{}_{hard}(M^2,\ldots)$

$L_{eff}(M^2,y)$ → the same for Signal and Bgds

$$L_{eff} \sim \frac{\hat{S}^2}{b^2} \left| N \int \frac{dQ_t^2}{Q_t^4} f_g(x_1, x_1', Q_t^2, \mu^2) f_g(x_2, x_2', Q_t^2, \mu^2) \right|^2$$

contain Sudakov factor T_g which exponentially suppresses infrared Q_t region → pQCD

$$< Q_t >_{SP} \simeq M / 2 * \exp(-1/\bar{\alpha}_s) \approx 2 GeV \gg \Lambda_{QCD},$$

$$\bar{\alpha}_S \simeq (N_C/\pi) * \alpha_S(M) * C_\gamma$$

Tg + anom.dim. → *IR filter*

S^2 is the prob. that the rapidity gaps survive population by secondary hadrons → soft physics

CDF results (dijets, $\gamma\gamma$, χ_c), D0

(new LHCb & CMS results)

not so long ago: between Scylla and Charibdis:
Many orders of magnitude differences in the theoretical predictions are now an ancient history

$J_z^{PC} = 0^{++}$ selection rule (KMR-2000)

- Quantum numbers of object X (= Higgs, χ_c ..) determined by the unique dynamics of CEP process:
  - Fusing gluons in $gg \to X$ subprocess in a colour singlet state $\Rightarrow X$ is C–even.
  - The initial and final–state protons have $L_z = 0$, with no angular momentum transfer between them $\Rightarrow X$ must have $J_z = 0$.
  - The structure of the CEP amplitude correlates the polarizations of the fusing gluons ($gg \to X$) such that they must be in an even parity state.

$\to$ In the limit that the outgoing protons scatter at zero angle (a good approx.), the object X obeys a $J_z^{PC} = 0^{++}$ selection rule. The CEP process acts a 'spin–parity analyzer'.

- In general protons can pick up some small non–zero $p_\perp$ (i.e. scatter at non–zero angle), but non–$J_z^P = 0^+$ quantum numbers are heavily suppressed (if $p_\perp$ transferred is too big, the protons will break up). This can be further suppressed by tagging and selecting protons with low $p_\perp$.

Heavy quarkonium CEP

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

$\rightarrow$ There are a wide range of conventional J^P states ($\chi_{qJ}, \eta_q \ldots$), each of which exhibits characteristic features in the exclusive mode, e.g.:

- Different angular distributions of the forward protons.
- Hierarchy in production cross sections.

$\rightarrow$ **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^{++}).

$\rightarrow$ Can also produce C–odd states via photoproduction $\gamma I\!P, OI\!P \rightarrow J/\psi, \Upsilon$..

χ_c CEP : subprocess

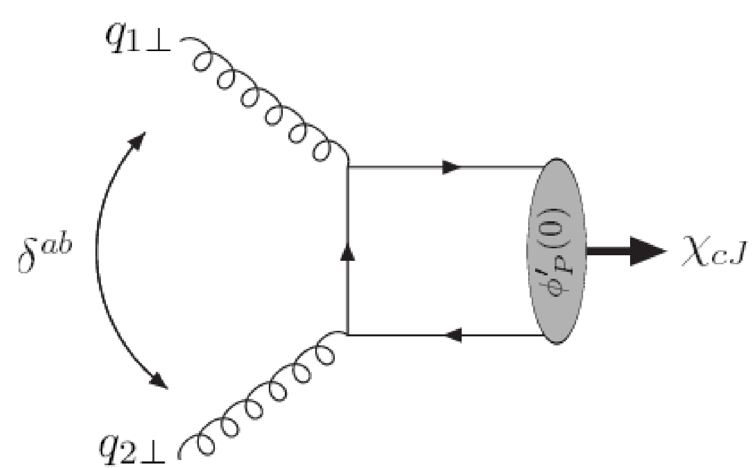
χ_{cJ} : $L=1, S=1, J^{PC}=(0,1,2)^{++}$ $c\bar{c}$ meson states, $M_{\chi_c} \approx 3.5$ GeV.

- Produced via $gg \to \chi_c$ subprocess: by demanding exclusivity, we are selecting state to be colour singlet.
- Can use old potential model results to calculate coupling, giving e.g.

$$\mathcal{M}(gg \to \chi_{c0}) \sim \phi'_P(0)(q_{1\perp} \cdot q_{2\perp}) \stackrel{p_\perp \to 0}{=} \phi'_P(0) Q_\perp^2$$

where $\phi'_P(0)$ is the wavefunction derivative at the origin. Can be extracted from (potential model, lattice...) fits, or approximately normalized to χ_{c0} total width. Cancels in cross section ratios.

- Spin of produced state determines form of vertex and behaviour in the forward proton ($p_\perp \to 0$) limit.



$q_{1\perp} = Q_\perp - p_{1\perp}$

$q_{2\perp} = -Q_\perp - p_{2\perp}$

χ_{cJ} : higher spins

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

• Considering case of χ_{c1} production, find that $V(gg \to \chi_{c1})$ vanishes in the forward limit. Have:

$$\mathcal{M}_1 \sim p_{1,\nu} p_{2,\alpha} \left((q_{2\perp})_\mu q_{1\perp}^2 - (q_{1\perp})_\mu q_{2\perp}^2 \right) \epsilon^{\mu\nu\alpha\beta} \epsilon_\beta^{*\chi}$$

which vanishes for $q_{i\perp}^2 = 0$.

$\longrightarrow$ Due to Landau-Yang theorem: forbids decay of $J = 1$ particle into two on-shell gluons ($q_{i\perp}^2 = 0$). In fact, for forward protons ($p_\perp = 0$) we have

$$\mathcal{M}_1 \sim p_{1,\nu} p_{2,\alpha} Q_\perp^2 Q_{\perp\mu} \epsilon^{\mu\nu\alpha\beta} \epsilon_\beta^{*\chi} \qquad \text{Odd in } Q_\perp$$

which vanishes after $Q_\perp$ integration. So gluon 'off-shellness' must be provided by non-zero proton $p_\perp$. $\sim \langle p_\perp^2 \rangle / M_\chi^2 \to$ small!

• Find similar vanishing for χ_{c2} : coupling to gg is forbidden in non-relativistic quaronium approximation, for $J_z = 0$ gluons. However, in $p_\perp = 0$ limit, fusing gluons must be in such a configuration ($J_z = 0$ selection rule).

First CEP measurements

(Cannot detect p/pbar, down beam pipe, but BSC → η = 7.4 empty)

FSC@LHC *

* $p+\bar{p} \rightarrow p+\gamma\gamma+\bar{p}$ ← Cleanest (no S.I.) but smallest σ
KMR: 38 pb in our box). 2+1 candidates (more coming soon)

* $p+\bar{p} \rightarrow p+\chi_c+\bar{p}$ ← Clean, big σ: $\frac{d\sigma}{dy}(y=0) \sim 80$ nb (KMRS)
but M(c) small (non-pert) & hadron

$p+\bar{p} \rightarrow p+\chi_b+\bar{p}$ ← More perturbative, smaller theory uncertainty

* $p+\bar{p} \rightarrow p+JJ+\bar{p}$ ← Big cross section, but least well defined (jets!) and largest background. ~ 100 pb for M(JJ) > 30 GeV

Prpospects !

Tevatron observations:
CDF and D0 each have exclusive JJ events > 100 GeV

All 3 measurements are all in good agreement (factor "few") with the Durham group predictions.

CDF χ_c data

Phys.Rev.Lett.102:242001,2009

- 65 ± 10 signal χ_c events observed, but with a limited $M(J/\psi\gamma)$ resolution.
- Possible contribution from χ_{c1} and χ_{c2} states assumed, rather than observed, to be negligible.
- Assuming χ_{c0} dominance, CDF found:

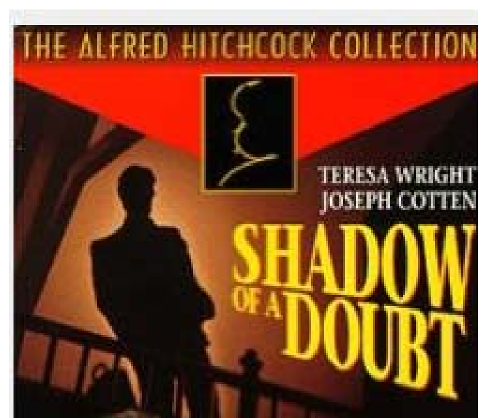
$$\left.\frac{\mathrm{d}\sigma(\chi_{c0})}{\mathrm{d}y_{\chi}}\right|_{y=0} = (76 \pm 14)\,\mathrm{nb}\ ,$$

in good agreement with the previous KMRS value of 80 nb (arXiv:0403218).

Too good to be true ?!

- But can we be sure that χ_{c1} and χ_{c2} events to do not contribute?

(LHCb-first inclusive χ_{c0} mid-July 2013)



χ_{c1} and χ_{c2}: general considerations

- General considerations tell us that χ_{c1} and χ_{c2} CEP rates are strongly suppressed:
  - χ_{c1}: Landau-Yang theorem forbids decay of a $J = 1$ particle into on-shell gluons.
  - χ_{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 $\chi_c \to J/\psi\gamma \to \mu^+\mu^-\gamma$ strongly favours $\chi_{c(1,2)}$ production, with:

$$\mathrm{Br}(\chi_{c0} \to J/\psi\gamma) = 1.1\% \ ,$$
$$\mathrm{Br}(\chi_{c1} \to J/\psi\gamma) = 34\% \ ,$$
$$\mathrm{Br}(\chi_{c2} \to J/\psi\gamma) = 19\% \ .$$

- We should therefore seriously consider the possibility of $\chi_{c(1,2)}$

❑ The effects of non-zero p_T (especially for 2^+). 

…and especially without proton detectors!

Cross section results (1)

- We find the following approximate hierarchy for the spin-summed amplitudes squared (assuming an exponential proton form factor $e^{-b\mathbf{p}_\perp^2}$):

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

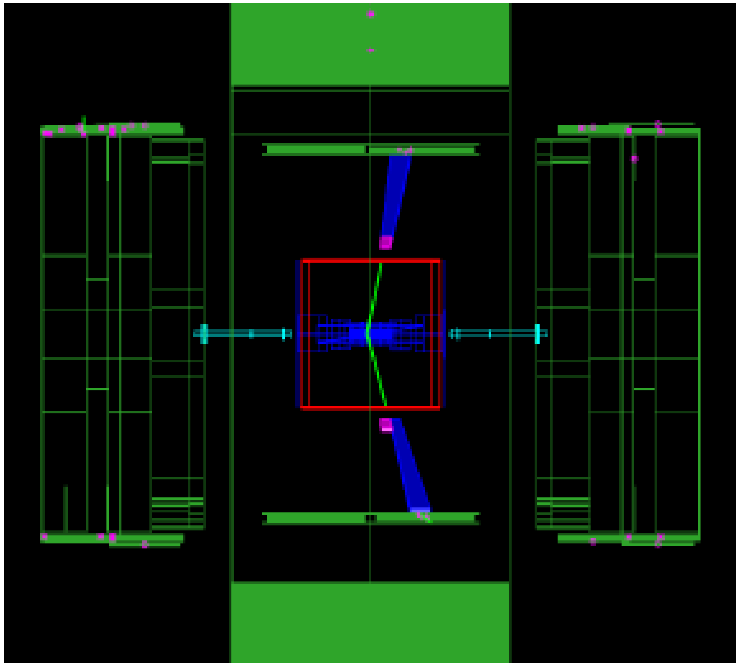
- This $\sim 1/40$ suppression for the $\chi_{c1,2}$ states will be compensated by the larger $\chi_c \to J/\psi\gamma$ branching ratios, as well as by the larger survival factors $S_{\rm eik}^2$ for the more peripheral reactions.
- An explicit calculation gives (for the perturbative contribution):

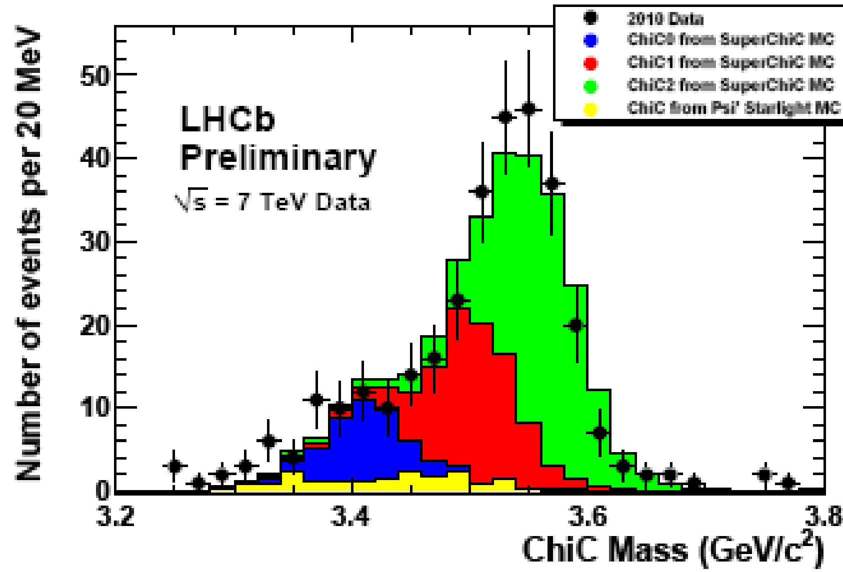
$$\frac{\Gamma^{\chi_0}_{J/\psi+\gamma}}{\Gamma^{\chi_0}_{\rm tot}}\frac{{\rm d}\sigma^{\rm pert}_{\chi_{c0}}}{{\rm d}y} : \frac{\Gamma^{\chi_1}_{J/\psi+\gamma}}{\Gamma^{\chi_1}_{\rm tot}}\frac{{\rm d}\sigma^{\rm pert}_{\chi_{c1}}}{{\rm d}y} : \frac{\Gamma^{\chi_2}_{J/\psi+\gamma}}{\Gamma^{\chi_2}_{\rm tot}}\frac{{\rm d}\sigma^{\rm pert}_{\chi_{c2}}}{{\rm d}y} \approx \mathbf{1 : 0.6 : 0.22}$$

- Note: these approximate values carry a factor of $\sim \stackrel{\times}{\div} 2$ uncertainty.

- First 'exclusive' events now being seen at LHCb. Results suggestive of a sizeable χ_{c2} contribution.

Data...





A wide range of central exclusive processes– $X = \mu^+\mu^-$, e^+e^- (QED), $\gamma\gamma$, jj, χ_c (CEP), J/ψ, $\psi(2S)$ (photoproduction)– have been observed by the CDF/D0 collaborations at the Tevatron, by selecting events with no additional activity in a large η range, and exclusive data at the LHC is being taken.

arXiv:0712.0604,0902.1271,1112.0858,1301.7084,CERN-LHCb-CONF-2011-022,CMS-PAS-FWD-11-004...

(in a good agreement with the Durham expectations)

χ_c CEP: data

- In arXiv:0902.1271 CDF reported 65 ± 10 signal χ_c events observed via the $\chi_c \to J/\psi\gamma \to \mu^+\mu^-\gamma$ decay channel. This corresponds to $\mathrm{d}\sigma(\chi_c)/\mathrm{d}y_\chi|_{y=0} = (76 \pm 14)\,\mathrm{nb}$, in good agreement with Durham prediction of ~ 60 nb.
- Recent LHCb data[3]: select 'exclusive' $\chi_c \to J/\psi\gamma$ events by vetoing on additional activity in given η range.
- LHCb see:

	$\frac{\sigma(pp\to pp(\mu^+\mu^-+\gamma))}{\mathrm{Br}(J/\psi\to\mu^+\mu^-)\mathrm{Br}(\chi_{cJ}\to J/\psi\gamma)}$ 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.

→ Good data/theory agreement for $\chi_{c(0,1)}$ states (within quite large theory uncertainty), but a significant excess of χ_{c2} events above theory prediction for CEP.

[3] LHCb-CONF-2011-022

Cross section results for RHIC and the LHC

- As the cms energy increases we have:
  - Larger gluon density at smaller x values.
  - Smaller $S^2_{\rm eik}$ survival factor.
  - Smaller $S^2_{\rm enh}$ due to increase in size of rapidity gaps ($\sim \ln(s/m^2_\chi)$) available for 'enhanced' absorptive effects.

$\rightarrow$ The combined result of these different effects is that the χ_c CEP rate has only a very weak energy dependence going from the Tevatron to the LHC.

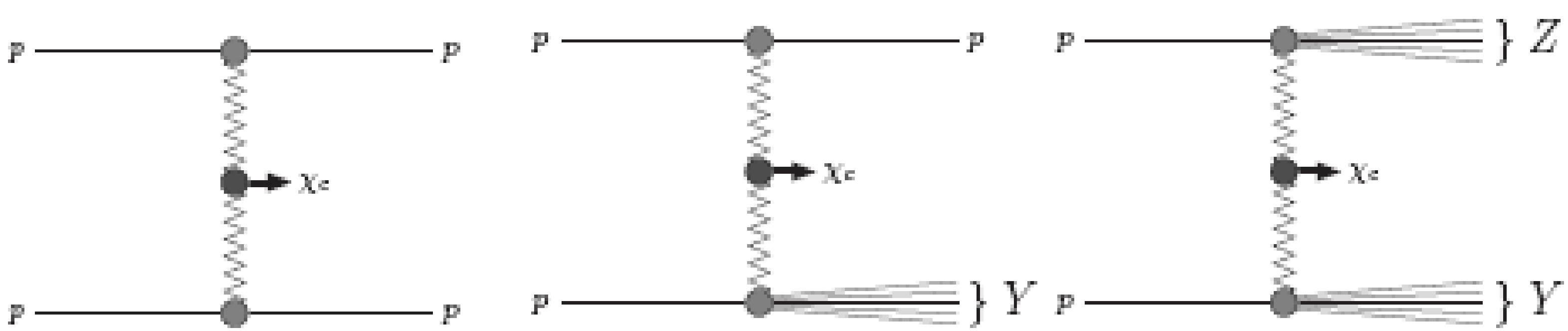
- An explicit calculation gives the results:

$\sqrt{s}$ (TeV)	$d\sigma/dy_\chi(pp \to pp(J/\psi + \gamma))$ (nb)
0.5	0.57
1.96	0.73
7	0.89
10	0.94
14	1.0

$\chi_c \to \pi\pi$, $\chi_c \to K\overline{K}$ Spin-parity Analyzer

χ_c CEP without tagged protons

- Are relativistic/non-perturbative corrections to χ_{c2} important (suppression of χ_{c1} expected by general considerations)?
- Is there a significant high mass proton dissociation $pp \to p + \chi + X$ background skewing the results?
  - Higher–mass dissociation $p \to N^*(M_Y \gtrsim 2$ GeV): allows a higher $p_\perp$ transfer to the protons and so an increasing violation of the $J_z = 0$ selection rule (recall χ_{c2} contribution is $\propto \langle p_\perp^2 \rangle^2$).
  - Such contamination should enhance in particular the χ_{c2} cross section preferentially: to consider when subtracting the proton dissociative background (always necessary to some extent without tagged protons).
  - Look at $p_\perp(\chi_c)$ dependence of cross section ratios to shed further light on this.



Measuring forward proton angular distributions

SPIN-PARITY ANALYSER

KKMR-03

$\bar{p}_\perp^2 \ll Q_\perp^2$

- For low proton transverse momenta $p_{1,2_\perp}$ we have:

$$d\sigma(0^+)/d\phi \approx \text{const.}\ ,$$

$$d\sigma(1^+)/d\phi \approx (p_{1_\perp} - p_{2_\perp})^2\ ,$$

$$d\sigma(0^-)/d\phi \approx p_{1\perp}^2 p_{2\perp}^2 \sin^2\phi\ ,$$

while there does not exist a simple closed form for the χ_2 case

- Note these will receive corrections of $O(p_\perp^2/\langle Q_\perp^2\rangle)$.
- These distributions are strongly affected by absorptive corrections, through their dependence on the proton distribution in impact parameter *b* space.
- Forward proton detection would allow a clear discrimination between the different *J* states.

- Very topical for STAR@RHIC forthcoming measurements with tagged forward protons.
- Hopefully, LHCb one day if/when RPs are installed.

Forward proton angular distributions (2)

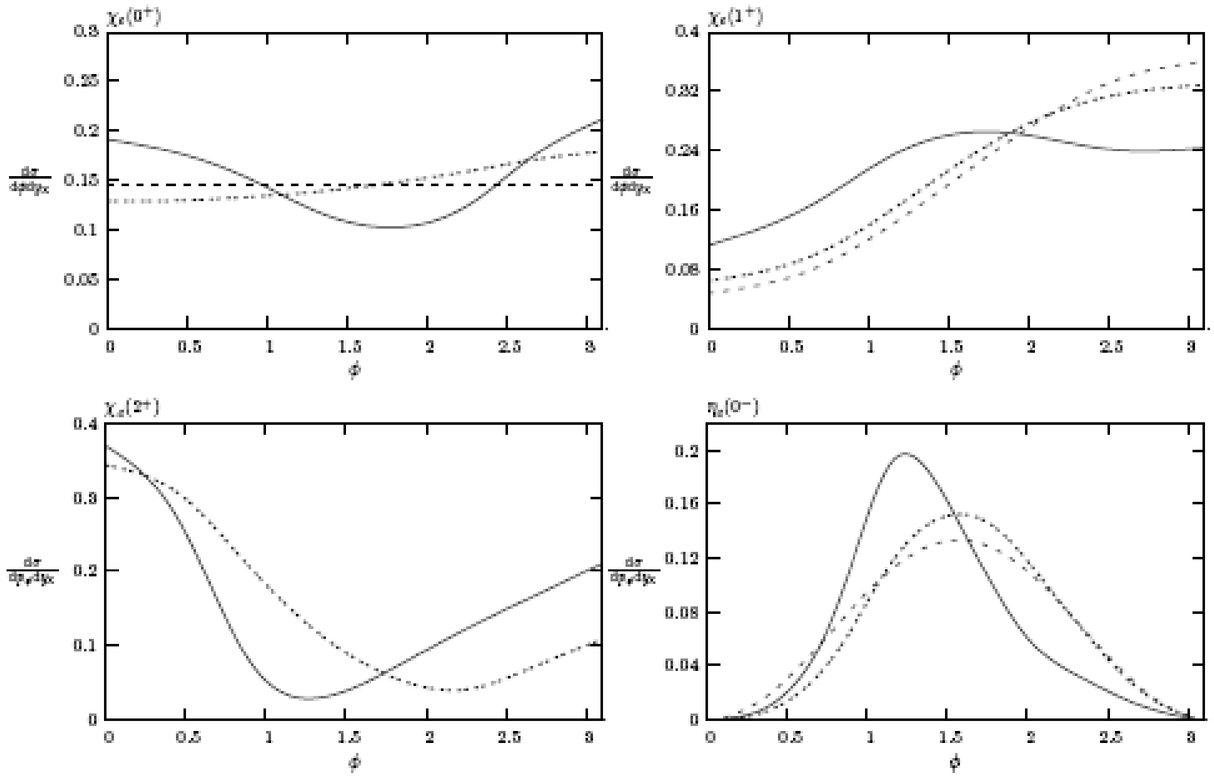


Figure: distribution (in arbitrary units) within the perturbative framework of the difference in azimuthal angle of the outgoing protons for the CEP of different J^P $c\overline{c}$ states at $\sqrt{s} = 14$ TeV. The solid (dotted) line shows the distribution including (excluding) the survival factor,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

PROSPECTIVE MEASUREMENTS

- A clear way to resolve the issue of χ_c spin-parity identification will be be to search for the two-body decays:

$$Br(\chi_{co} \to \pi\pi, K^+K^-) \simeq 1.3\% \qquad \chi_{c1}, \eta_c \not\to \pi\pi, KK \qquad Br(\chi_{c2} \to \pi\pi, K^+K^-) \simeq 0.3\%$$

$$Br(\chi_{c0} \to p\bar{p}) \simeq 2 * 10^{-4} \qquad Br(\chi_{c1} \to p\bar{p}) \simeq 6.6 * 10^{-5} \qquad Br(\chi_{c2} \to p\bar{p}) \simeq 6.7 * 10^{-5}$$

$$Br(\eta_c \to p\bar{p}) \simeq 0.13\%$$

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

- With sufficient statistics of $\gamma\gamma$ CEP, the measurement of the ratio

$$\sigma(\chi_b) / \sigma(\gamma\gamma)$$

can be quite instructive (the same mass range, various uncertainties cancel).

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.

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

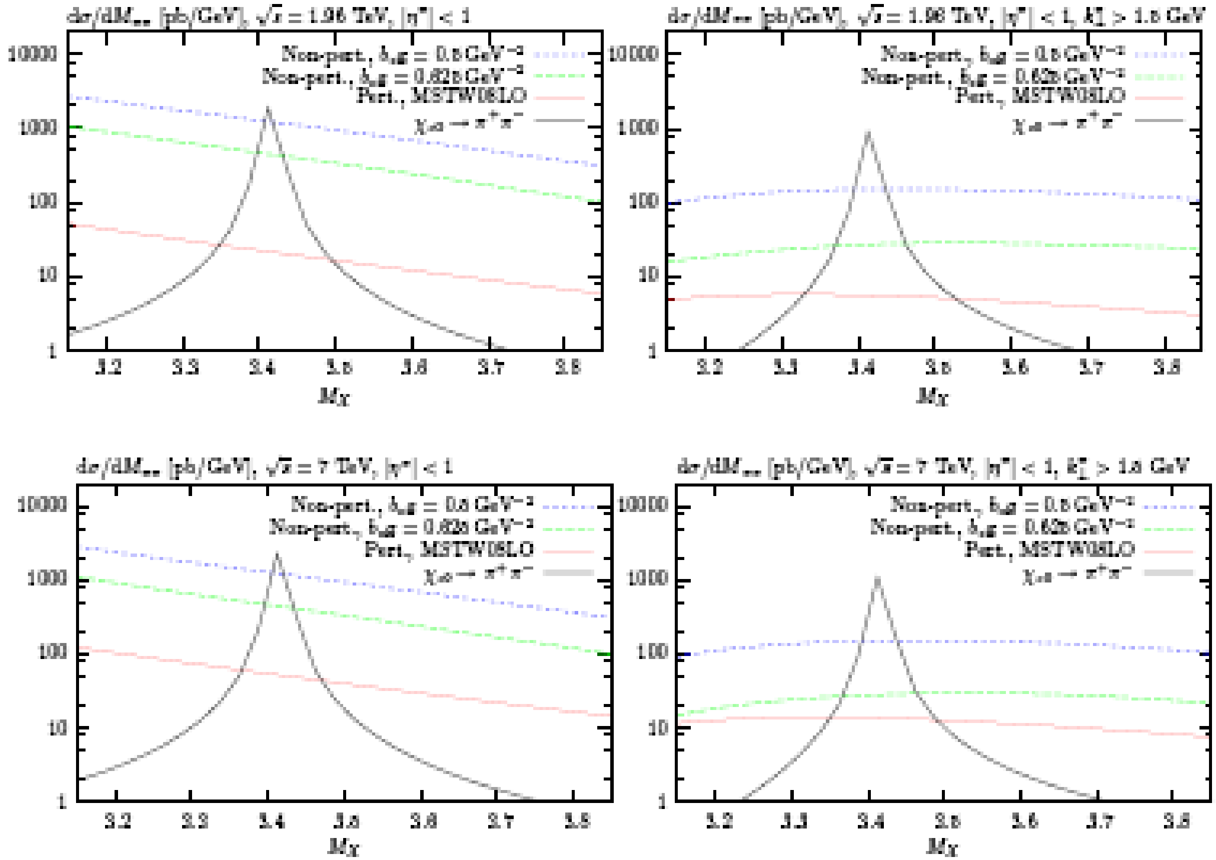
- CEP is a promising way to study new physics at the LHC, but we can also consider the CEP of lighter, established objects : χ_c, $\gamma\gamma$ and *jj* CEP already observed at the Tevatron.

- 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].

- the CEP of $\gamma\gamma$ **and 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.

(CMS, Totem+CMS- soon to come)

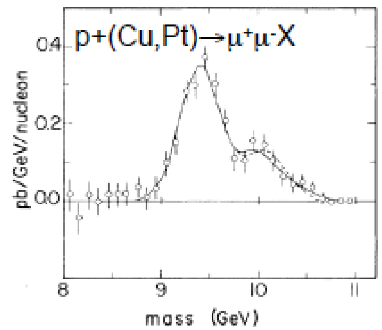
$\chi_c \to \pi^+\pi^-, KK$ CEP



- (Exclusive) continuum $\pi^+\pi^-$ background expected to be under control, at least once reasonable cuts ($k_\perp > 1.5$ GeV, $|\eta| < 1$) have been imposed $\Rightarrow$ $\chi_{c0} \to \pi^+\pi^-$ (and K^+K^-) channel should give a clean χ_{c0} CEP signal[4].

P-wave Bottomonia

Bottomonium history started 30 years ago
(PRL 39, 242 (1977) and PRL 39,1240 (1977))

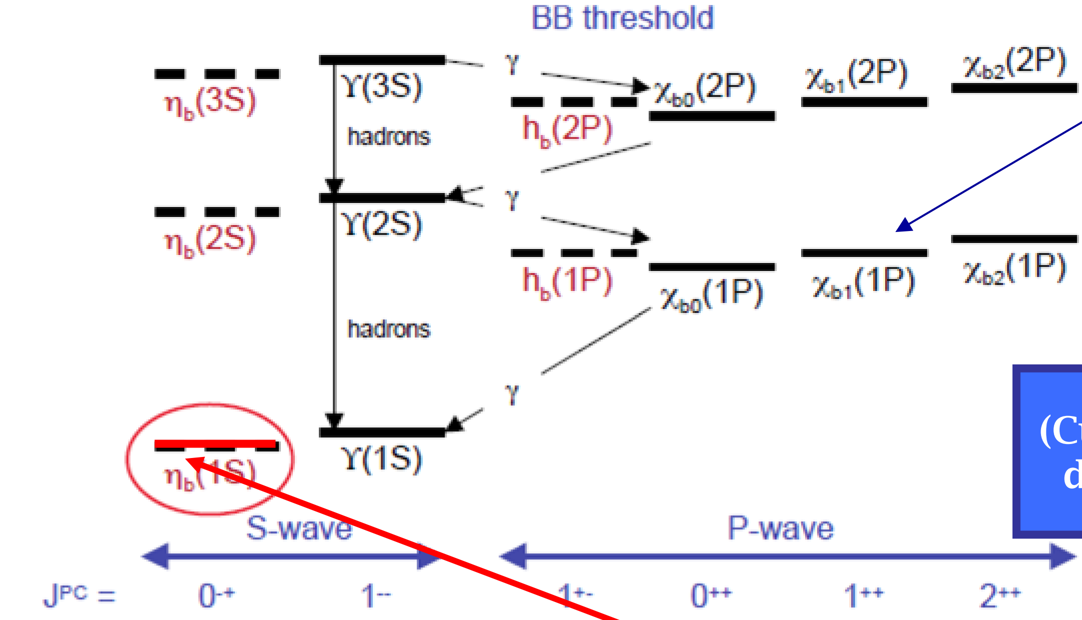


FNAL, E288

M(Υ)=9.40±0.013
M(Υ')=10.00±0.04
M(Υ'')=10.43±0.12

(spins- still unconfirmed)

30 years later….



Υ(nS) confirmed and χ_{bJ}(1,2P) states observed

Below $B\bar{B}$, several states not yet observed: 3 S-wave (η_b), 2 P-wave (h_b), D-wave,etc…

(Currently no complete theoretical description of onium properties.)

(BABAR (2008))

The heaviest and most compact quark-antiquark bound state in nature

χ_b production

- 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 for χ_c .
- J assignment of χ_{bJ} states still experimentally undetermined: CEP can shed light on this.
- Calculation very similar to χ_c case

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

$\chi_b(nP) \to DX$ (about 0.25 of all hadronic decays (CLEO-2009))

$\chi_{b1} \to c\bar{c}X$ (Barbieri et al (1979), NRQCD)

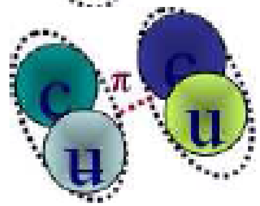
- Measurement of ratio of χ_b to $\gamma\gamma$ CEP rates in same mass region would eliminate certain theory uncertainties (survival factors....).
- Predictions for χ_b CEP via $\Upsilon\gamma$ decay (at $y_\chi = 0$):

$\sqrt{s}$ (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

Zoo of charmonium –like XYZ states

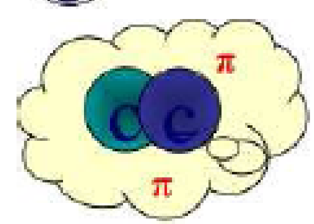
Tetraquark:
four tightly bound quarks

Molecular state:
two loosely bound mesons



Hybrid: states with
excited gluonic degrees of freedom

Hadrocharmonium: charmonium state,
"coated" by excited light-hadron matter



- X(3872) –
- XYZ(3940) & X(3915) –
- Y(4140)/Y(4280) & X(4350)

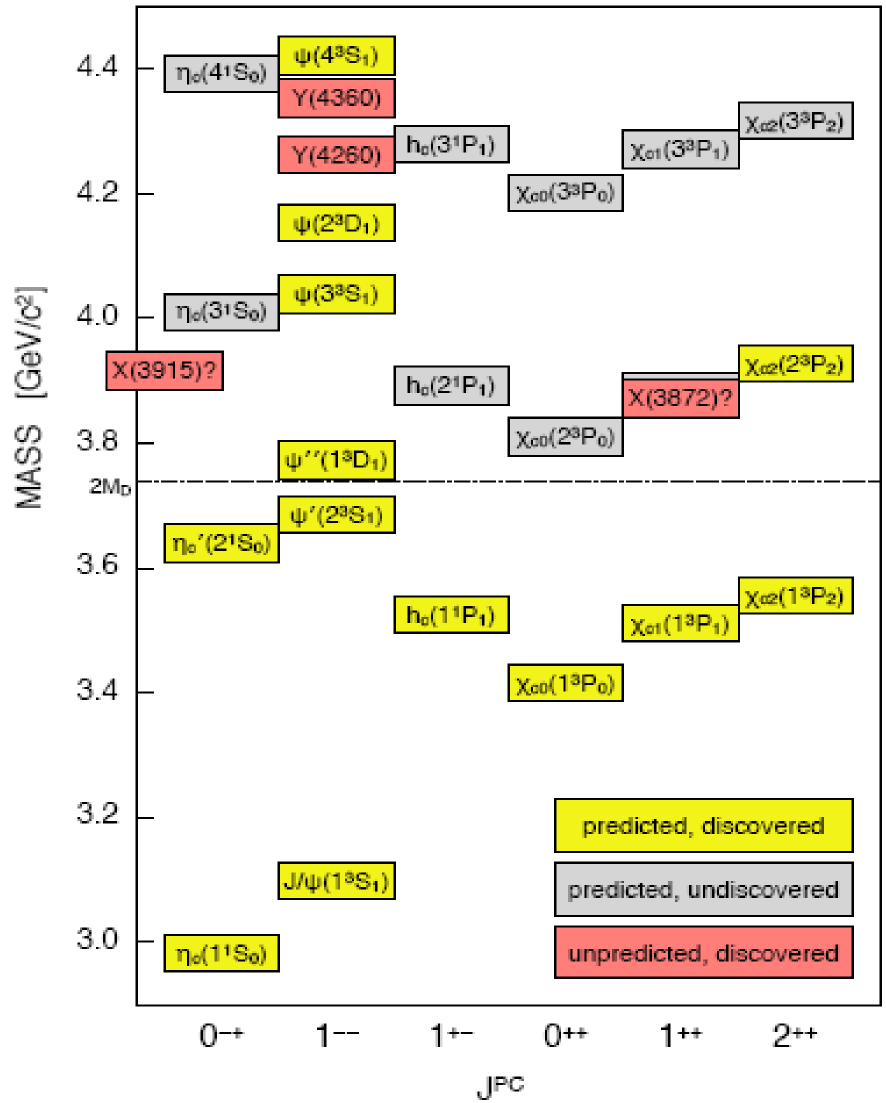
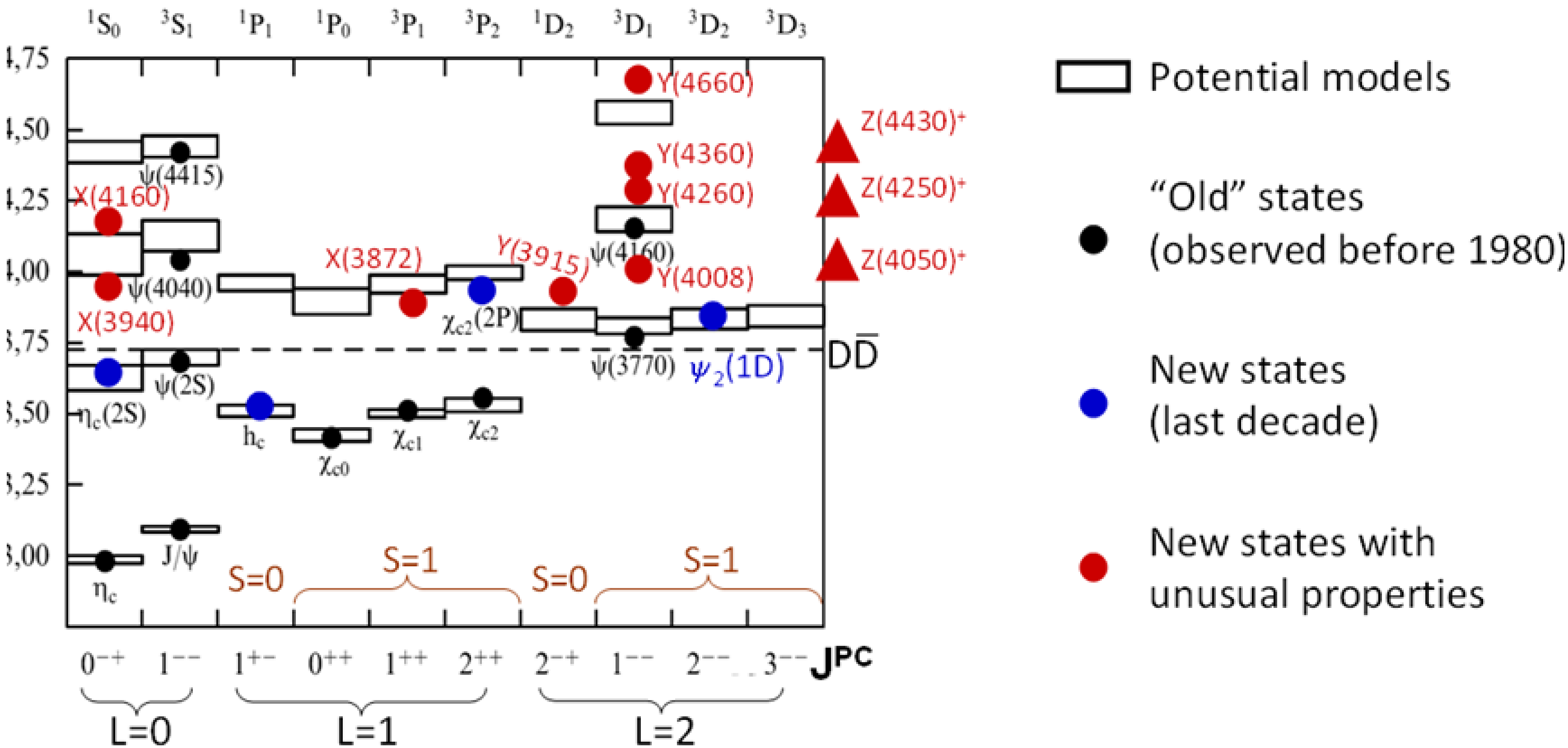


Figure 2: The mass spectrum of charmonium(-like) states in the energy interval available in BESIII and as a function of their spin-parity, J^{PC}. The yellow boxes represent charmonium states predicted by theory and confirmed by experiment. The grey boxes are those charmonium states that are predicted but not yet discovered. The red boxes are discovered charmonium-like states which nature is still mysterious. The dashed line indicates the open-charm ($D\bar{D}$) threshold. The figure is taken from a presentation by R. Mitchell.

Charmonium table



States below $D\bar{D}$ threshold are narrow (annihilation or → other charmonia)

States above $D\bar{D}$ threshold are broad (→ $D\bar{D}$, $D\bar{D}^*$, ...)

PDG'12

$$M_{X(3872)} - (M_{D^0} + M_{D^{*0}}) = -0.16 \pm 0.32 \text{ MeV}$$

	Relative BF
$J/\psi\,\rho$	1
$J/\psi\,\omega$	0.8 ± 0.3
$J/\psi\,\gamma$	0.21 ± 0.06
$D^0\bar{D}^{*0}$	~ 10

isospin violation

$J^{PC} = 1^{++}$

Most likely interpretation:

DD^* molecule with admixture of $\chi_{c1}(2P)$

isospin violation

production at high energy

Fractions of admixtures? Bound or virtual

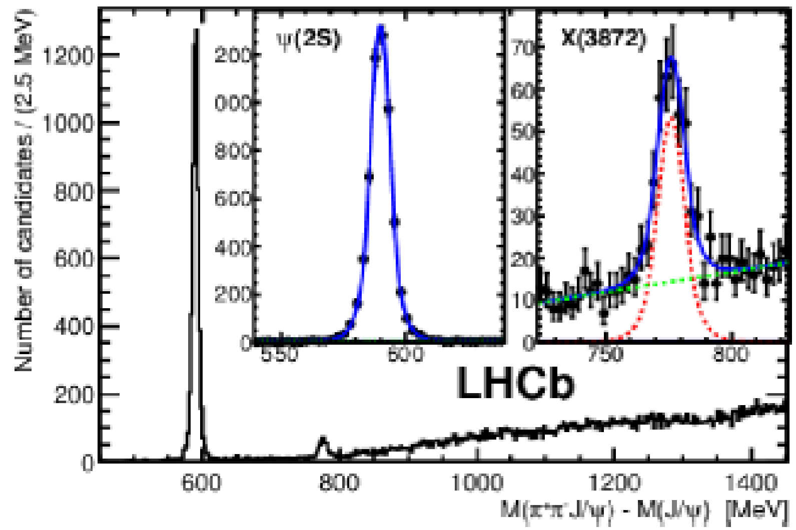
Dynamical model?

Experimental issues:

- δM (D^0 mass uncertainty dominates)
- $\psi(2S)\,\gamma$ (Belle/BaBar controversy)
- line-shape in $D\bar{D}^*$ (statistics limited)
- absolute BF (inelastic channels?)

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? Or admixture?

(if it is not χ'_{c1}, where is χ'_{c1}?[10])

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 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.

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

- Also, can consider e.g. the $Z(3930) \equiv \chi_{c2}(2P)$:
  - Above threshold: decays to $D\overline{D}$, D^+D^- and $D^0\overline{D^0}$ seen.
  - With vertex detection at LHCb and RHIC $\to$ exclusive open charm ($D\overline{D}$...) production.
  - Theory: roughly the same cross section and distributions as $\chi_{c2}(1P)$.

Good Luck to LHCb

Towards Full Acceptance Detector (bj- 1992)

CMS (& ATLAS) currently blind between η = 6.4 (CASTOR) and beam rapidity (y_p = 8.9 @ 7 TeV) except ZDC (neutrals). Cannot distinguish most diffractive/non-diffractive events.

IS THERE A WAY OUT ?

Yes, an addition of Forward Shower Counters around beam pipes- low PU runs

NEW!

first results of combined CMS+ TOTEM measurements with the FSCs on (see showers from particles with $|\eta|$ = 7-9)

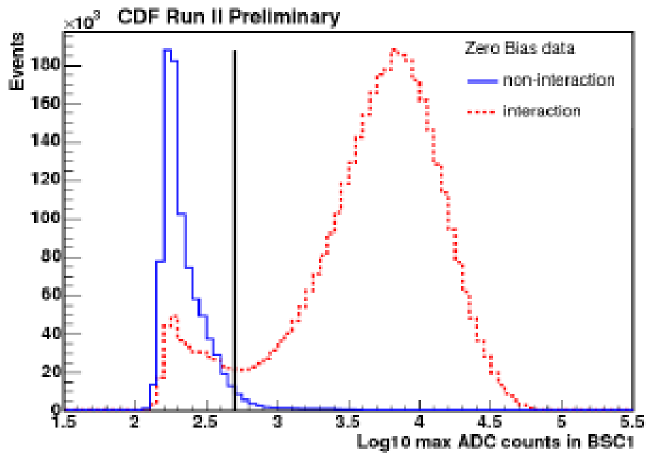
(Alice is installing such counters, ongoing studies for LHCb)

BSC very important as rap gap detectors.
All LHC experiments should have them!

Published in JINST-2009

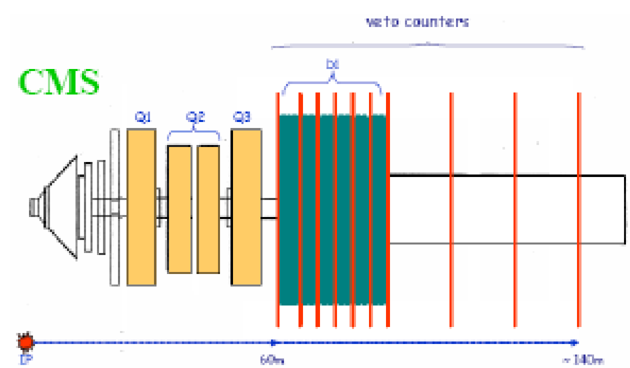
FORWARD PHYSICS WITH RAPIDITY GAPS AT THE LHC

Michael Albrow[1], Albert De Roeck[2], Valery Khoze[3], Jerry Lämsä[4,5], E. Norbeck[6],
Y. Onel[6], Risto Orava[5], and M.G. Ryskin[7]
Sunday, November 09, 2008

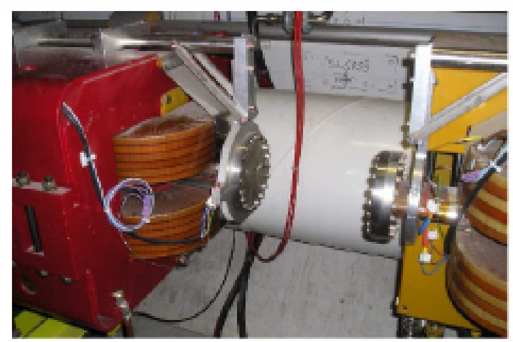


Warm accessible vacuum pipe (circular – elliptical)

Do not see primary particles, but showers in pipe ++
Simple scintillator paddles: **Gap detectors in no P-U events**



Take 0-bias events (Essential!)
{1} = prob no interaction
{2} = prob >= 1 interaction
Take hottest PMT of 8 BSC1
Plot log max ADC for {1} and {2}
Separates empty / not empty
Repeat for all detectors



4

(Installed in 2011 at the CMS)

Forward Shower Counters (FSC): extending the CMS η-coverage.

- CMS, as most collider detectors, has excellent hermeticity at low η
- In the forward direction the CMS coverage is extended with different additional detectors: HF + Castor + ZDC (+ TOTEM)
- There may be gaps in the coverage of the forward region (high η)
- The Forward Shower Counters (FSC) system is made of scintillators installed near the LHC beam pipe at 59, 85 and 114 m from IP5, on both sides of CMS
- These counters detect showers produced by very forward hadrons hitting the beam pipe and surrounding materials.

Forward Physics at LHC
Reggio Calabria (15-18 July 2013)

Aldo Penzo (INFN-Trieste)
for the CMS Collaboration
and the FSC Team

Towards Full Acceptance

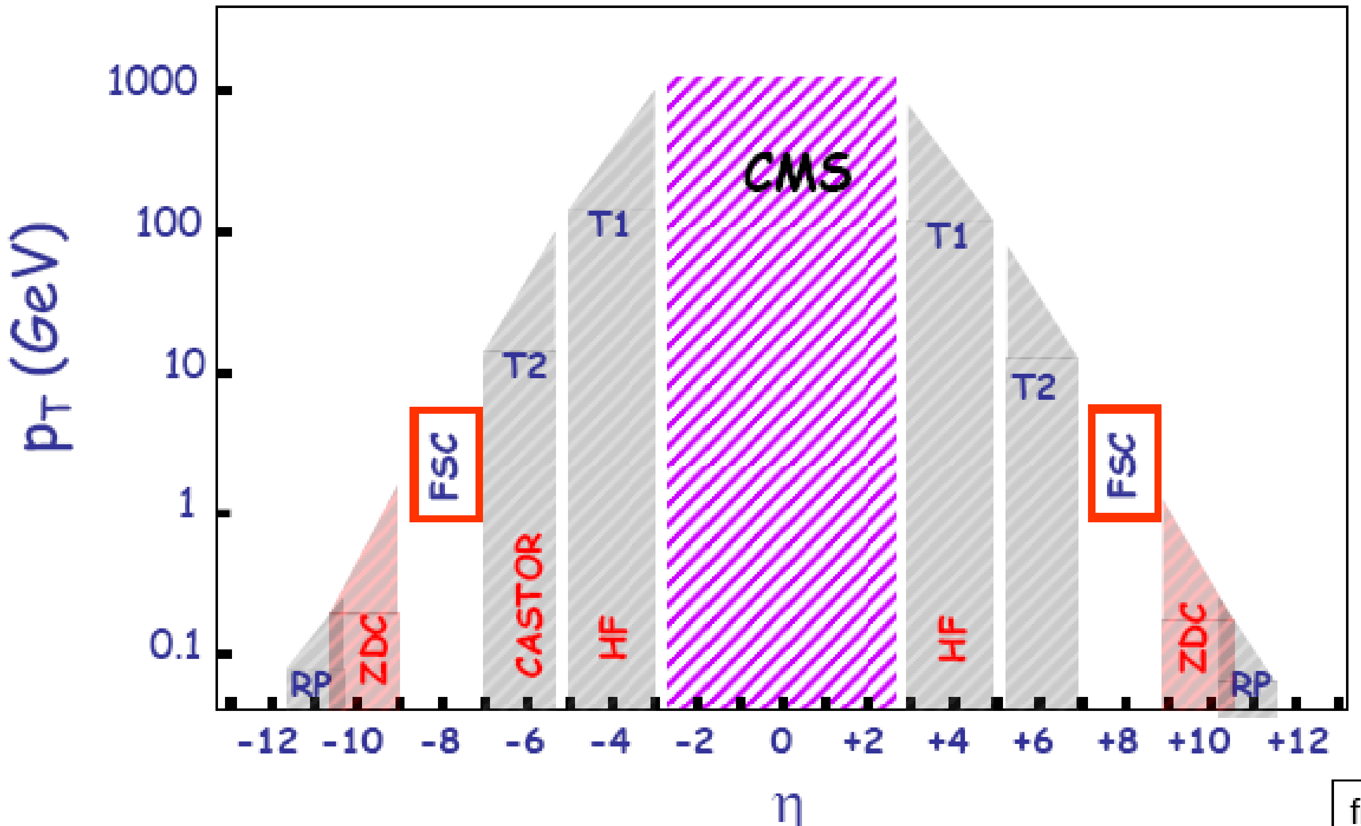


figure adapted from Risto Orava (Diffraction 2006)

FSC covers a gap in η between the forward calorimeters (HF, CASTOR) and the very forward (ZDC, TOTEM RP)

FSC Team

CMS FSC Team:

Fermilab: M.G.Albrow, S. Popescu, Y. Guo, N. Mokhov, I. Rakhno
IHEP-Protvino: R.Ryutin, V. Samoylenko, A. Sobol
INFN-Trieste: A. Penzo + …
*U. Iowa: P. Debbins, D. Ingram, **E. Norbeck**†, Y. Onel, S. Sen*
IPM-Teheran: M. Khakzad, F. Rezaei Hosseinabadi
U. Kansas: O. Grachov, P.Kenny, M. Murray, Q. Wang, C. Bruner, Z.Tu

Other Institutions:

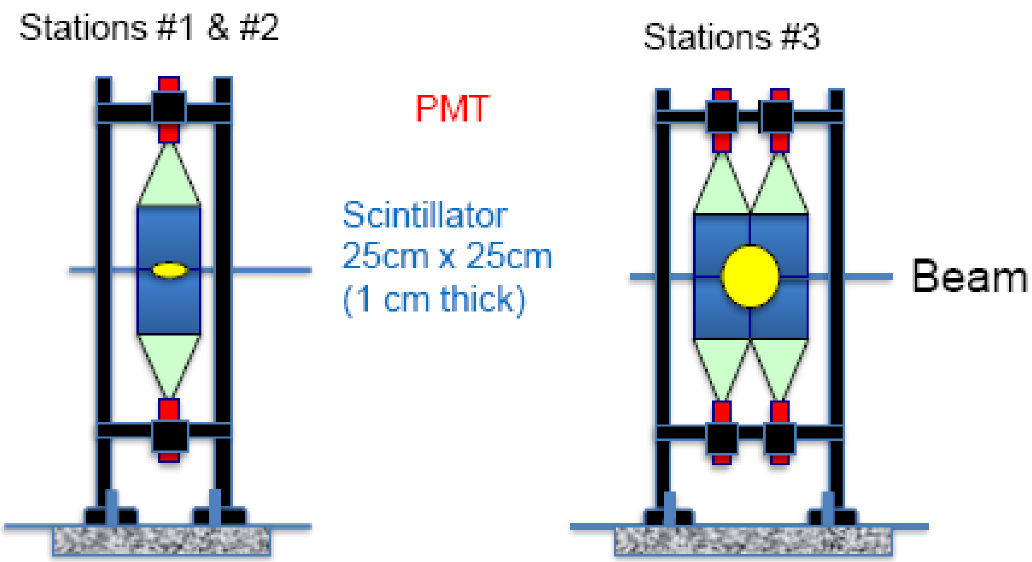
U. Durham: V. Khoze +…
U. Helsinki: J. Lamsa, R. Orava +…
U. Messina: A. Lamberto, G.F. Rappazzo

In collaboration with **CMS FSQ:**

Conveners: D. d'Enterria, J. Hollar, A. Vilela

Not only CMS…

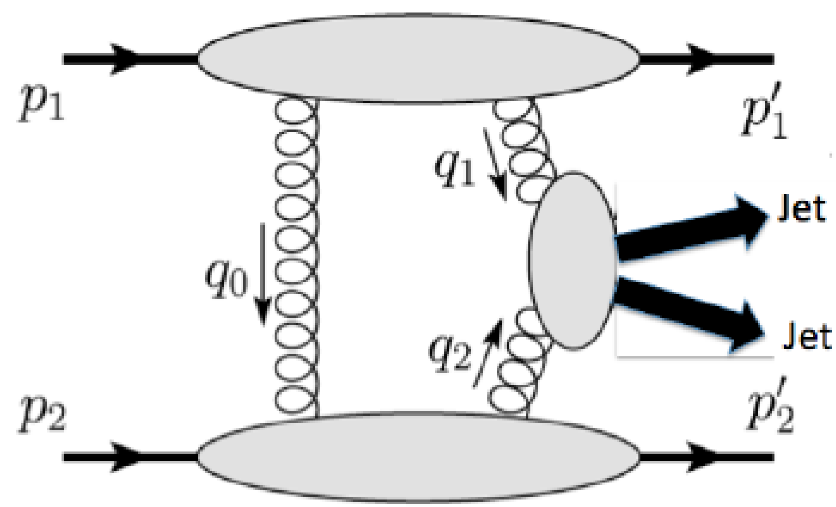
- ***Most LHC experiments*** *plan to use* ***"patch"*** *detectors to bridge their gaps in η-coverage (see Paula Collins' LHCb talk here)*
- *CMS has installed* ***FSC counters*** *since 2011 (used throughout 2012)*



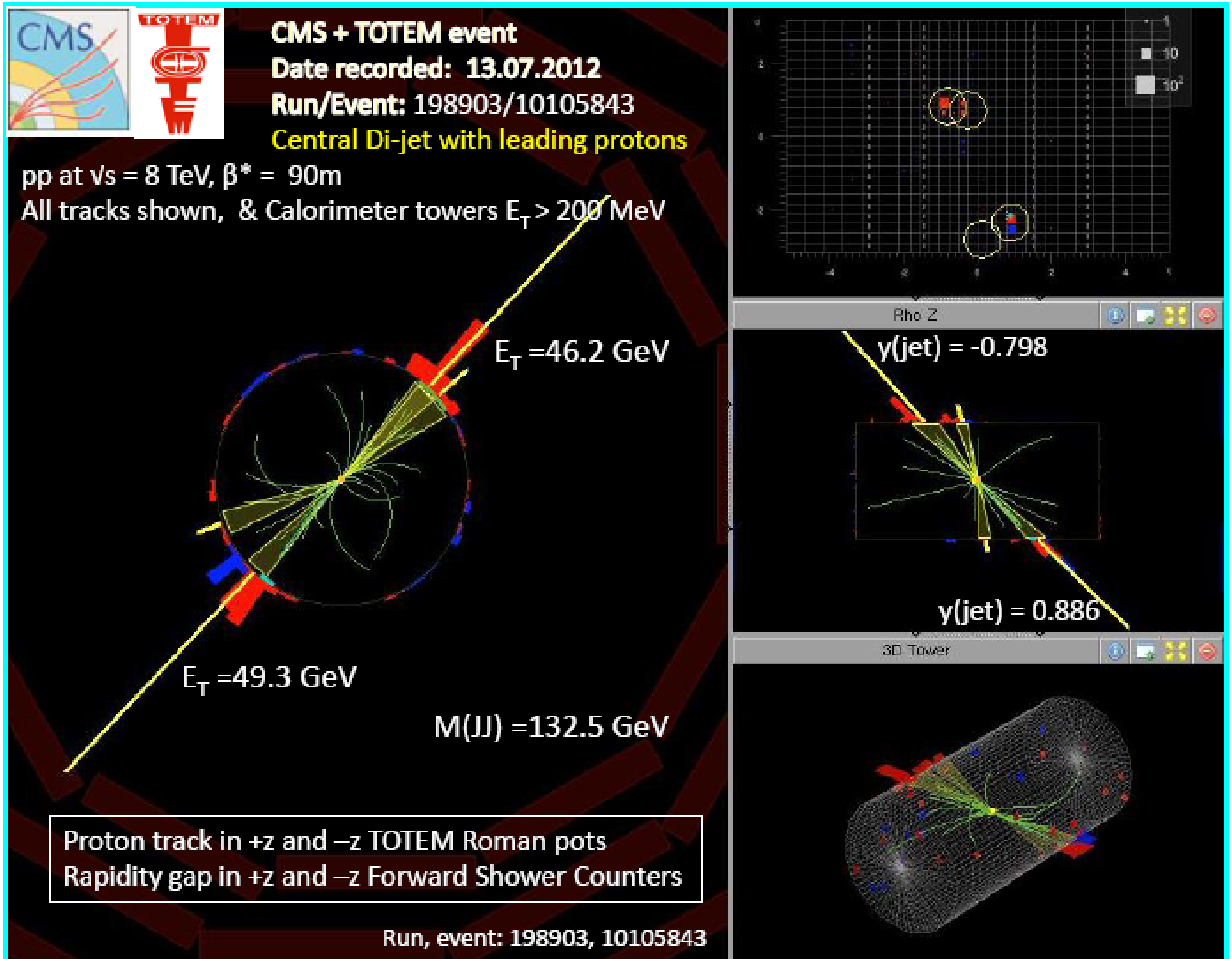
Sector 4-5 Station3

Results from Low PU Runs

- *Data collected during* ***low PU (β^* = 90 m) pp at 8 TeV*** *runs in July 2012, with CMS and TOTEM operating with* ***common triggers****, show events consistent with central production of high-pT jets accompanied by two leading protons.*
- *FSC detectors, covering the very forward pseudo-rapidity $6 < |\eta| < 8$, were* ***required to be empty****.*
- *The leading protons were detected as tracks in the TOTEM Roman Pot (RP) stations around the CMS interaction point.*
- *Preliminary results shown in:*
- ***CMS DP -2013/004:*** *CMS-TOTEM events: high-pT jets with two leading protons*
- ***CMS DP -2013/006:*** *Central high-pT jet production during low pile-up, β^* = 90m, 8 TeV pp run*



Dipion CEP- coming soon


CMS
TOTEM
CMS + TOTEM event
Date recorded: 13.07.2012
Run/Event: 198903/10105843
Central Di-jet with leading protons
pp at √s = 8 TeV, β* = 90m
All tracks shown, & Calorimeter towers E_T > 200 MeV
E_T =46.2 GeV
E_T =49.3 GeV
M(JJ) =132.5 GeV
Proton track in +z and –z TOTEM Roman pots
Rapidity gap in +z and –z Forward Shower Counters
Run, event: 198903, 10105843
Rho Z
y(jet) = -0.798
y(jet) = 0.886
3D Tower

Potentially rich program of CDP studies with the LHCb

CENTRAL DIFFRACTION AT THE LHCb

LHCb IS IDEAL FOR DETECTING AND ANALYSING LOW MASS CENTRAL DIFFRACTIVE PRODUCTION OF EXCLUSIVE $\pi^+\pi^-/K^+K^-$ STATES IN:

$$pp \rightarrow p + M + p$$

glueballs, hybrids, heavy quarkonia: χ_c, χ_b
exotic states….

$\pi^+\pi^-/K^+K^-$ STATES AS SPIN-PARITY ANALYZERs.

HOW TO FACILITATE THIS?

LHCb
Excellent particle ID (pion/Kaon separation), vertex and proper time resolution

Jerry W. Lämsä and Risto Orava **JINST 4:P11019,2009.**

Hershel Project:
High Rapidity Shower Counters for LHCb

Expect greater CEP yield with move to 25 ns running (20%→40% useable luminosity)

LHCb is actively investigating the possibility of expanding the programme with the installation of scintillator counters

A series of stations upstream and downstream of the experiment can be used to veto CEP background

Information will be used at analysis stage and also in L0 trigger, helping to suppress background and increase signal rate

Summary and Outlook

- CEP in hadron collisions offers a promising and complementary framework within which to study the quarkonium sector.
- Specific dynamics of exclusive production mode offers new insight:
  - Can act as quantum number filter, through $J_z^P C = 0^{++}$ selection rule $\rightarrow$ gives a strong hierarchy in cross sections.
  - Distinct proton angular distributions depending on the central object quantum numbers.
- Exclusive χ_{cJ} production already observed at the LHC and Tevatron, in reasonable agreement with theory.
- χ_{bJ} and $\eta_{c,b}$ represent other interesting observables.
- The CEP process may shed light on the exotic charm sector ($X(3872)$...).
- Exclusive photoprouction of C–odd ($J/\psi, \Upsilon$...) a further interesting process, for which LHC data now exists.

- An installation of the FSCs and RPs at the LHCb could strongly enhance physics potential for the CEP measurements.
- Currently active studies are in progress, both on the experimental and theory sides.



We are looking forward to new exciting adventures in Exclusiveland


THANK YOU


QUESTIONS?

BACKUP

$\eta_{c,b}$ production

$\eta_{(c,b)}$: $L = 0, S = 0, J^{PC} = 0^{-+}$ pseudoscalar $c\bar{c}/b\bar{b}$ meson states.

- $gg \to \eta$ 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

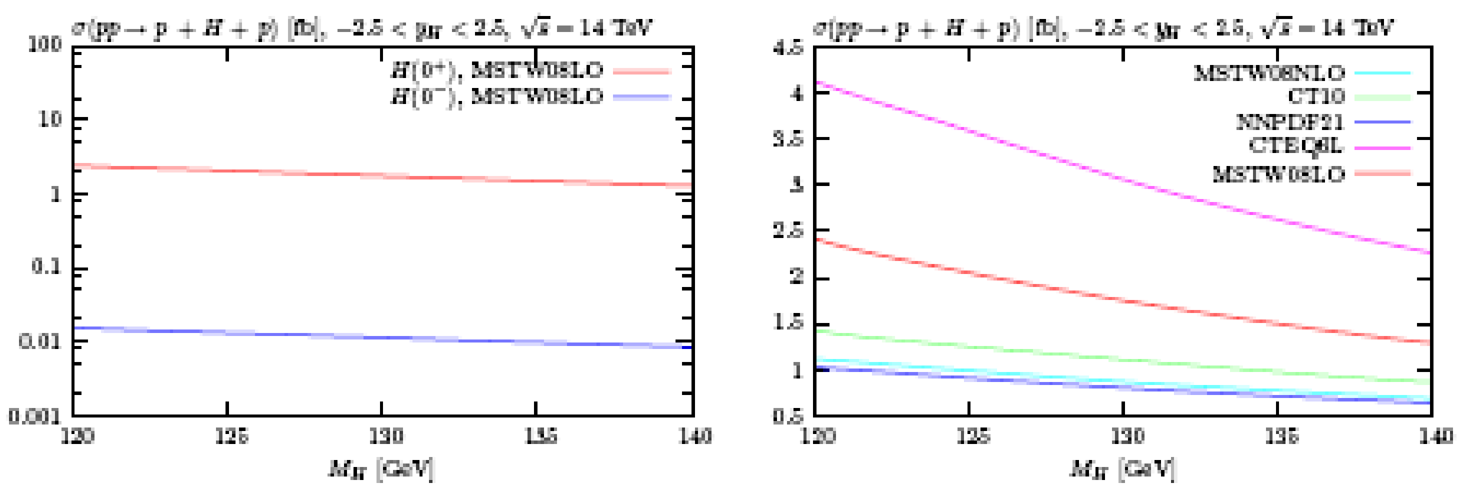
$$|V_{0-}|^2 \propto p_{1\perp}^2 p_{2\perp}^2 \sin^2(\phi) \,,$$

  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

The future(?) Higgs Boson CEP

- Higgs Boson CEP $pp \to p + H + p$ via $gg \to H$ is a very promising observable[7].
- The observation of Higgs Boson CEP provides an additional way to determine its spin and CP properties and to precisely measure its mass, (in some cases) width and couplings (Hbb Yukawa...). However, this requires the addition of forward proton taggers at 420m from the CMS/ATLAS interaction point. Currently only the 220m detectors are on the table.



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

$$h(p_1)h(p_2) \to h(p_1') \ + \ M_1 M_2 \ + \ h(p_2')$$

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

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

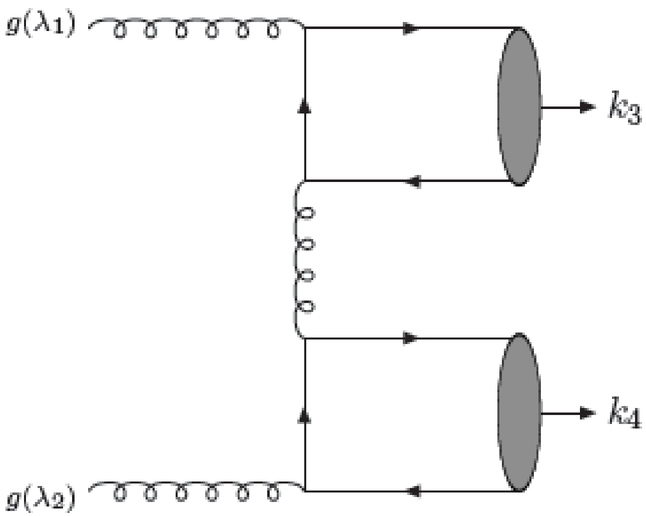
$\longrightarrow$ Represents a novel application of QCD, with many interesting theoretical and phenomenological features...

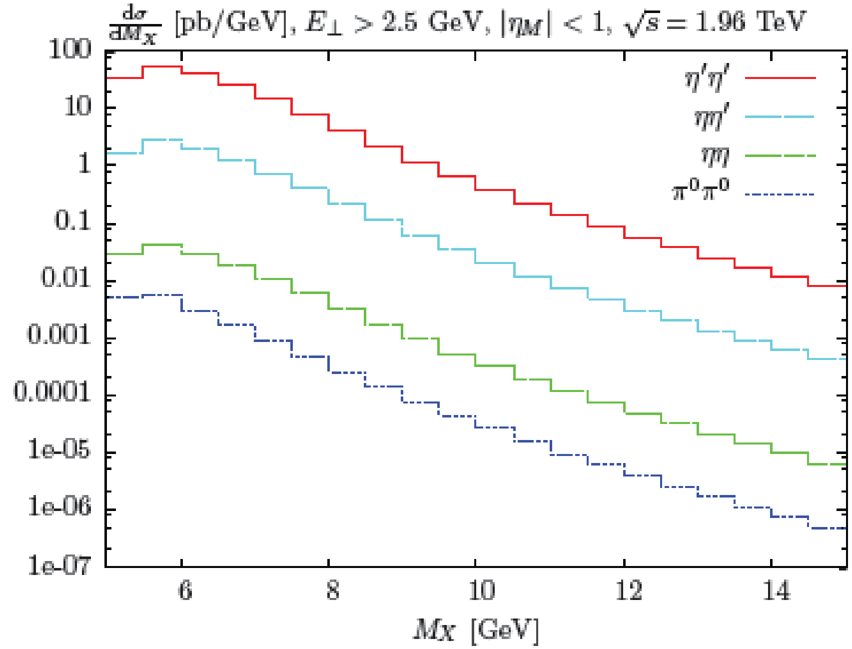
HKRS: arXiv:1304.4262, 1302.2004, 1204.4803, 1105.1626

Flavour singlet mesons

HKRS: arXiv:1105.1626

- 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 (see later) $\Rightarrow$ expect strong enhancement in $\eta'\eta'$ CEP and (through $\eta - \eta'$ mixing) some enhancement to $\eta\eta'$, $\eta\eta$ CEP. The $\eta'\eta'$ rate is predicted to be large!





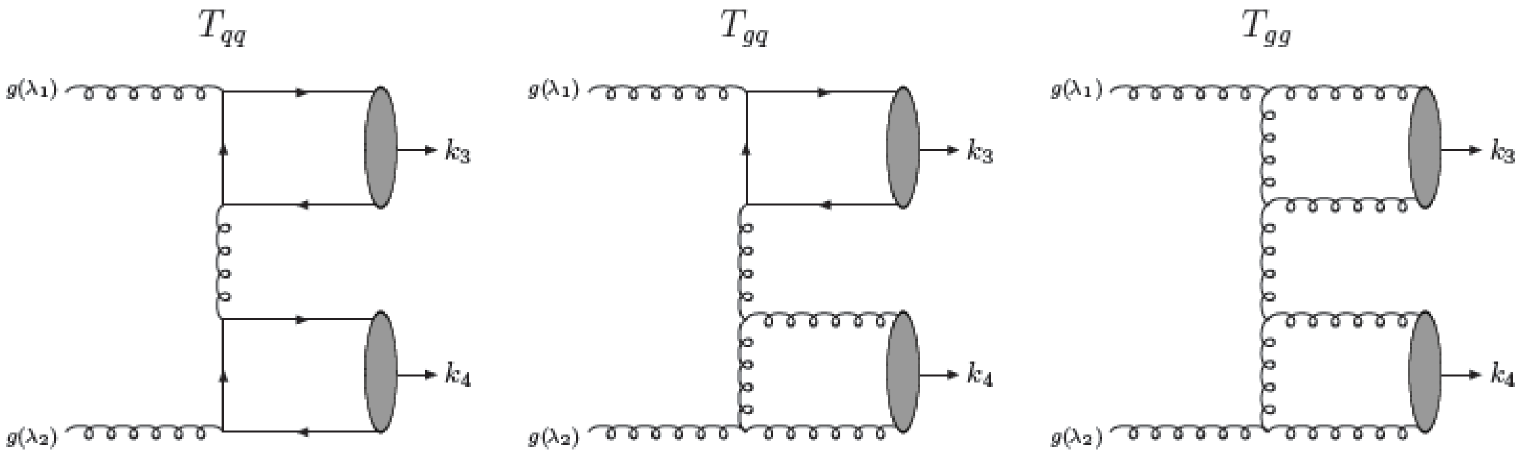
The gluonic component of the $\eta'(\eta)$

HKRS: arXiv:1302.2004

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

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

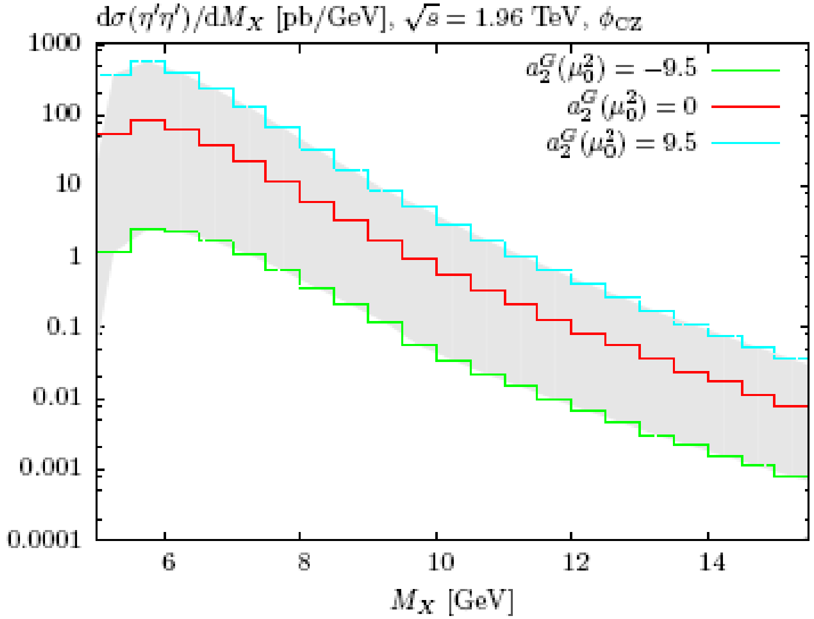
$\longrightarrow$ Use $\eta(')\eta(')$ CEP as a probe of the size of this gg component.



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

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

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



$a_2^G(\mu_0^2)$	-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
$\sigma(\eta'\eta'\to 4\gamma)/\sigma(\gamma\gamma)$	0.0017	0.049	0.33
$\sigma(\eta\eta\to 4\gamma)/\sigma(\gamma\gamma)$	0.0025	0.012	0.066

HKRS: arXiv:1302.2004

UNCERTAINTIES

Known Unknowns

- N(N)LO- radiative effects (K-factors etc..)
  '…possible inadequancy of PT theory in α_s …' R.Barbieri et al-1980
- ' 'Right' choice of gluon densities, in particular at so low scales as in the χ_c case
  (potentiality of a factor of ~3 rise for the H-case) .
- Complete model for calculation of enhanced absorption.

Unknown Unknowns

- Non- pQCD effects in the meson characteristics.
  Currently no complete description of heavy quarkonium characteristics.
  'Two gluon width does not tell the whole story.'
- Gluons at so low scales, surprises are not excluded at all.

Could be Factor of 5 up or down