479.WE-Heraeus-Seminar

Physics at LHCb

26. - 29. April 2011, Bad Honnef, Germany

Wilhelm und Else Heraeus Stiftung

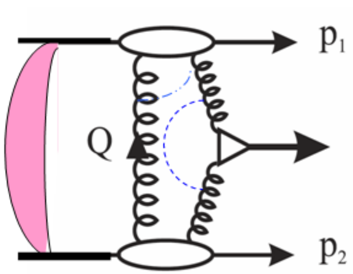
Central Diffractive Production of Heavy Quarkonia.

(KRYSTHAL collaboration)

V.A. Khoze, IPPP, Durham

(Manchester, St. Petersburg, Helsinki & Rockefeller)

(based on works by V.Khoze, M. RYskin and W.J. STirling and L. HArland-Lang)



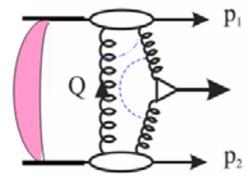
χ_c, χ_b

For more details see arXiv:0909.4748 ; arXiv:1005.0695 and arXiv: 01011.0680

Outline

- Introduction

  (topical examples)



- Central exclusive production (CEP) of $\chi_{c0,1,2}$ states at the **Tevatron, RHIC and LHC**
- η_c, χ_b CEP results and ongoing studies.
- **Forward proton distributions and correlations.**
- **High- p_T meson pair CEP**
- **CDP@LHC with FSC**
- Conclusion.

With a bit of personal flavour

Introduction

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.

LHCb- quarkonim- news!
(Dermont Moran)

- χ_c, jj and $\gamma\gamma$ CEP has been observed by CDF. **CEP dijets @D0.**

→ 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: **(star reactions!)**
  - 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).
  - **Could shed light on the nature of** the various 'exotic' charmonium states observed recently. (X,Y,Z) charmonium-like states. (Joel Bressieux)

Spin-Parity Analyzer (KKMR-2003)

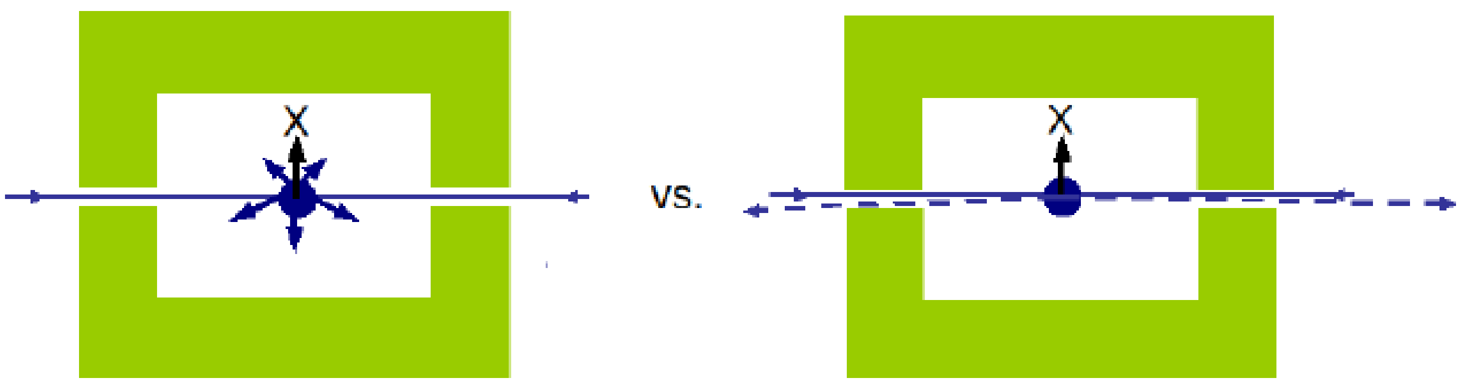
- Detailed tests of dynamics of soft diffraction (KMR-02)

Central exclusive diffraction

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

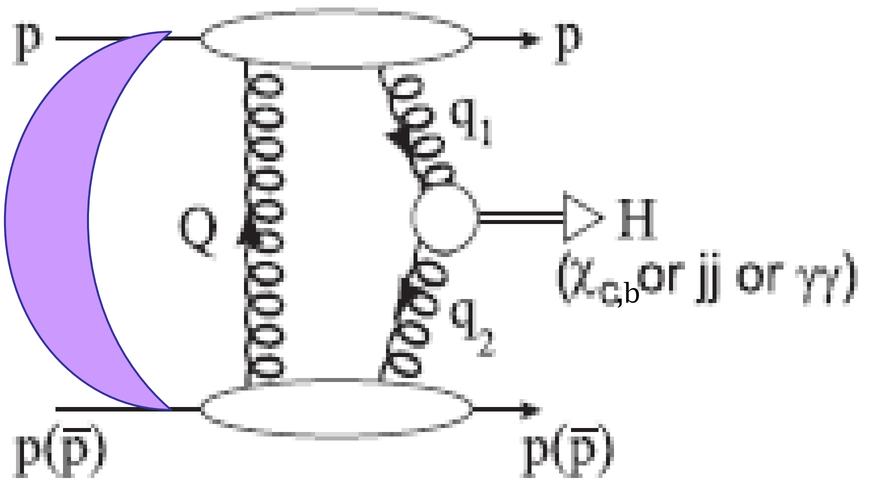
$$h(p_1)h(p_2) \to h(p_1') \;+\; X \;+\; h(p_2')$$

- Diffraction: colour singlet exchange (pomeron, photon...) 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.



Central exclusive Production (CEP)

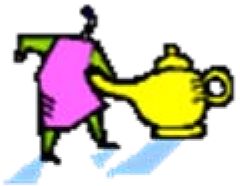
- Colliding protons interact via a colour singlet exchange and remain intact.
- A system of mass M_X is produced at the collision point, and *only* its decay products are present in the central detector region.



- The generic process $pp \to p + X + p$ is modeled perturbatively by the exchange of two t-channel gluons.
- The possibility of additional soft rescatterings filling the rapidity gaps is encoded in the 'eikonal' and 'enhanced' survival factors, S^2_{eik} and S^2_{enh}.
- In the limit that the outgoing protons scatter at zero angle, the centrally produced state X must have $J_z^P = 0^+$ state.

Forward Proton Tagging at the LHC as a gluonic Aladdin's Lamp

(Old and New Physics menu)



- Higgs Hunting (the LHC *'core business'*)
- Photon-Photon, Photon - Hadron Physics
- **'Threshold Scan'**: 'Light' SUSY ... Extra dimensions...
- Various aspects of Diffractive Physics (*soft & hard*).

High intensity **Gluon Factory** *(underrated gluons)* KMR-00, KMR-01

QCD test reactions, dijet luminosity monitor

- Searches for new heavy gluophilic states

FPT

✱Would provide a unique additional tool to complement the conventional strategies at the LHC and ILC.

FPT ▶ will open up an additional rich physics menu ILC@LHC

✱Higgs is only a part of the broad EW, BSM and diffractive program@LHC

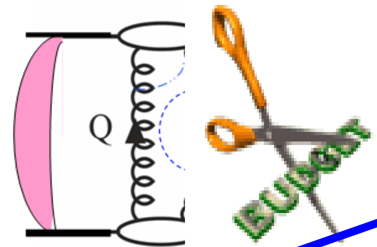
wealth of QCD studies, glue-glue collider, photon-hadron, photon-photon interactions…

CED Higgs production at the LHC

- Prospects for high accuracy (~1%) mass measurements (irrespectively of the decay mode).

- Quantum number filter/analyser.
  (0++ dominance ;C,P-even)

- H ->bb opens up (Hbb- coupl.)
  (gg)$_{CED}$ ↛ bb in LO ; NLO,NNLO, b- mass effects - controllable.



currently ATLAS FP-420
(STFC cutting rule) ?
CMS-HPS

- For some areas of the MSSM param. space **CEDP** may become *a* **discovery channel !**
- **H →WW*/WW - an added value** (less challenging experimentally + small bgds., better PU cond.)

- New leverage –proton momentum correlations (probes of QCD dynamics , CP- violation effects…)

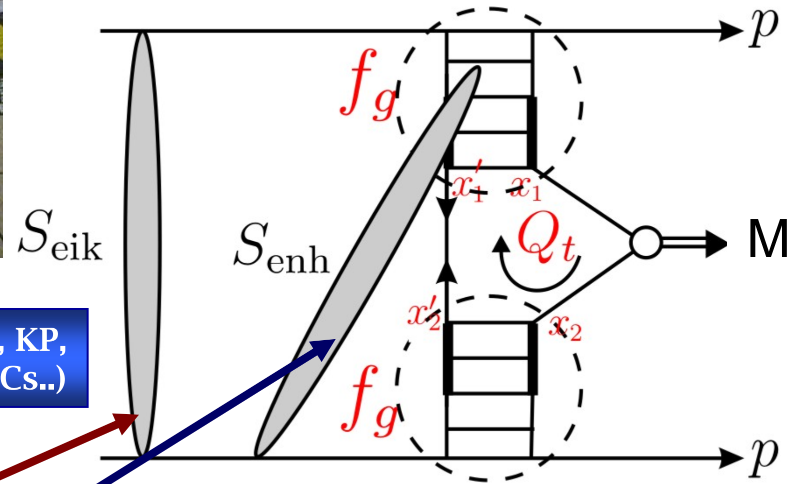
✶ LHC : 'after discovery stage', Higgs **ID**......

How do we know what we've found?

mass, spin, couplings to fermions and Gauge Bosons, invisible modes…
→ for all these purposes the CEDP will be particularly handy !

“soft” scattering can easily destroy the gaps

S^2 → absorption effects -necessitated by unitarity



gap

gap

Everybody’s ~ happy (KMR, GLMM, FHSW, KP, S.Ostapchenco. Petrov et al, BH, GGPS, MCs..)

soft-hard factoriz^n

eikonal rescatt: between protons ← conserved

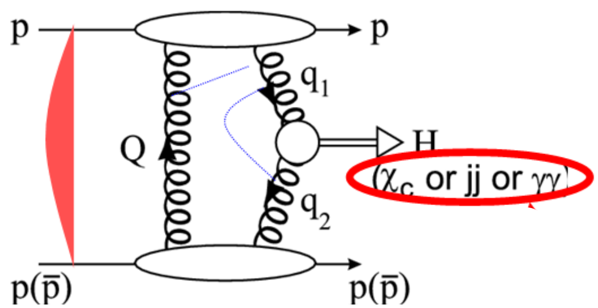
enhanced rescatt: involving intermediate partons ← broken

Subject of hot discussions recently : S^2enh

Standard Candle Processes

'BETTER TO LIGHT A CANDLE THAN TO RANT AGAINST DARKNESS'

(Confucius)



The process p-p→$\gamma\gamma$/χ_c/ χ_b/ j-j are standard candles for the exclusive Higgs

孔夫子

孔丘 *Kong Qiu*

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

FSC@LHC

* $p+\bar{p} \to p+\gamma\gamma+\bar{p}$
* $p+\bar{p} \to p+\chi_c+\bar{p}$
$p+\bar{p} \to p+\chi_b+\bar{p}$
* $p+\bar{p} \to p+JJ+\bar{p}$

Cleanest (no S.I.) but smallest σ

KMR: 38 pb in our box). 2+1 candidates (more coming soon)

Clean, big σ: $\frac{d\sigma}{dy}(y=0) \sim 100$ nb (KMRS)

but M(c) small (non-pert) & hadron

More perturbative, smaller theory uncertainty
But σ ~ 1/500th χc. Also BR's not known!

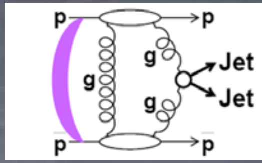
Prpospects !

Big cross section, but least well defined (jets!)
and largest background. ~ 100 pb for M(JJ) > 30 GeV

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

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

Comparison with KMR



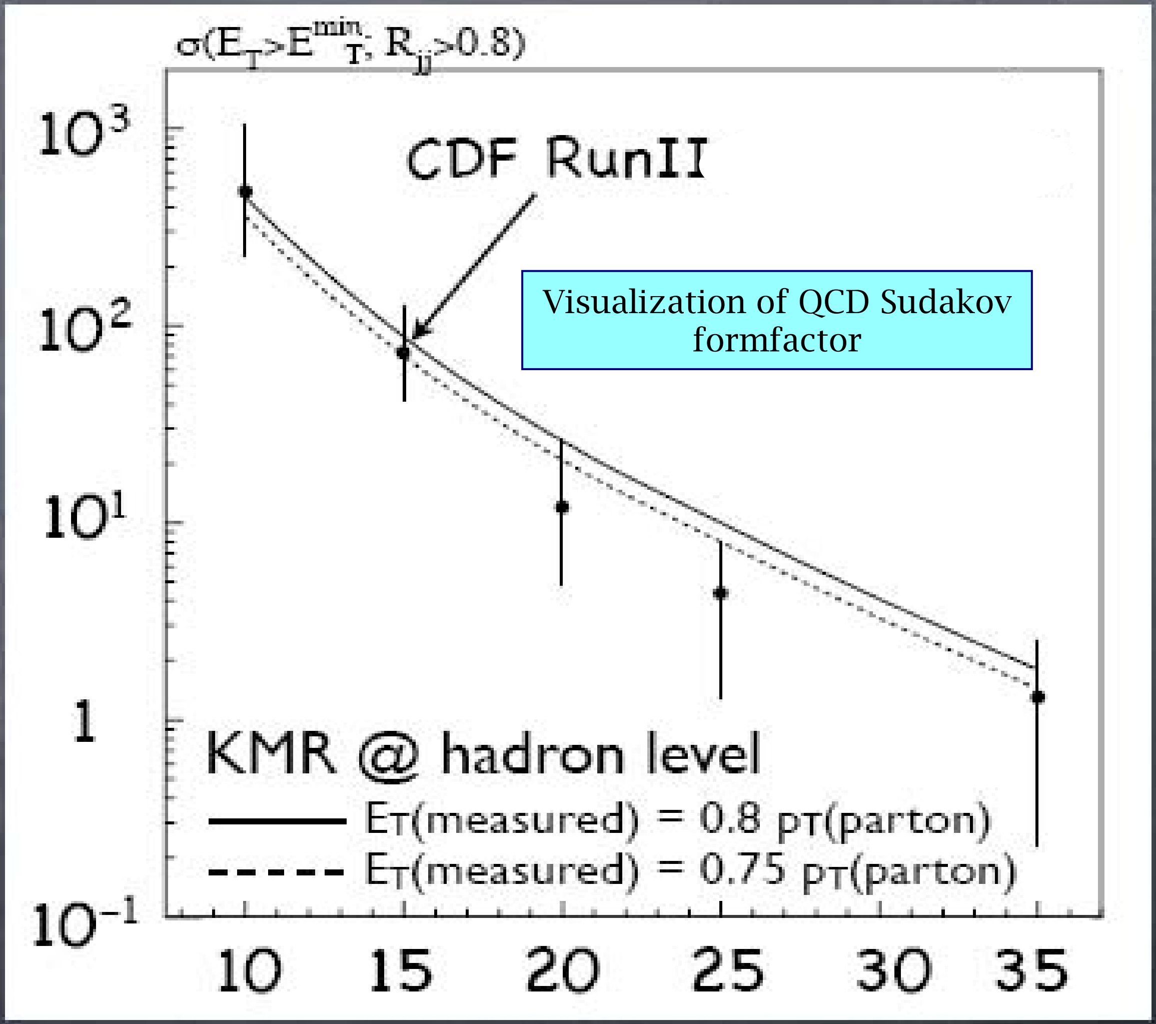
More direct comparison with KMR calculations including hadronization effects preferred

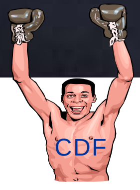
CDF out-of-cone energy measurement (cone R=0.7) :

- 20–25% at E_T^{jet}=10–20 GeV
- 10–15% at E_T^{jet}=25–35 GeV

Koji Terashi

Good agreement with data found by rescaling parton p_T to hadron jet E_T





A killing blow to the wide range of theoretical models.

CDF PRD-2008

D0-2010

Observation of Exclusive Charmonium Production and $\gamma\gamma \to \mu^+\mu^-$ in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

CDF Collaboration, arXiv:0902.1271 [hep-ex], PRL

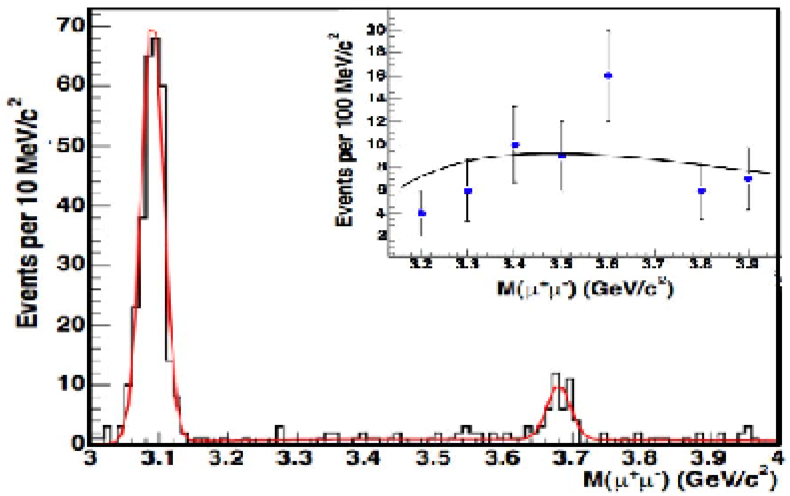


FIG. 2: Mass $M_{\mu\mu}$ distribution of 402 exclusive events, with no EM shower, (histogram) together with a fit to two Gaussians for the J/ψ and $\psi(2S)$, and a QED continuum. All three shapes are predetermined, with only the normalizations floating. Inset: Data above the J/ψ and excluding $3.65 < M_{\mu\mu} < 3.75$ GeV/c^2 ($\psi(2S)$) with the fit to the QED spectrum times acceptance (statistical uncertainties only).

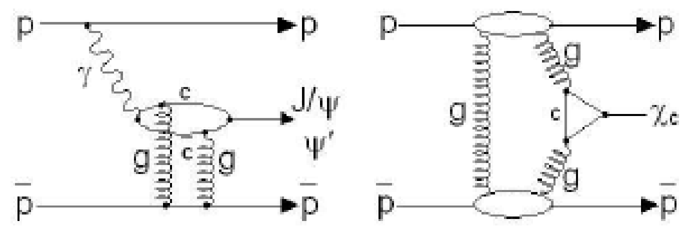


TABLE I: Numbers of events fitted to classes $J/\psi, \psi(2S)$, QED and χ_{c0}. Backgrounds are given as percentages of the fit events, and efficiencies are to be applied to the events without background. The stated branching fraction $\mathcal{B}$ for the χ_{c0} is the product of the $\chi_{c0} \to J/\psi + \gamma$ and $J/\psi \to \mu^+\mu^-$ branching fractions [11]. The cross sections include a 6% luminosity uncertainty.

Class	J/ψ	$\psi(2S)$	$\gamma\gamma \to \mu^+\mu^-$	$\chi_{c0}(1P)$
Acceptances:				
Detector(%)	18.8±2.0	54±3	41.8±1.5	19±2
Efficiencies:				
μ-quality(%)	33.4±1.7	45±6	41.8±2.3	33±2
Photon(%)	-	-	-	83±4
Events(fit)	286±17	39±7	77±10	65±8
Backgrounds:				
Dissoc.(%)	9±2	9±2	8±2	11±2
Non-excl.(%)	3±3	3±3	9±5	3±3
χ_{c0}(%)	4.0±1.6	-	-	-
Events(corr.)	243±21	34±7	65±10	56±8
$\mathcal{B}.\sigma_{FKR}$(pb)	28.4±4.5	1.02±0.26	2.7±0.5	8.0±1.3
$\mathcal{B} \to \mu^+\mu^-$(%)	5.93±0.06	0.75±0.08	-	0.076 ±0.007
$\frac{d\sigma}{dy}\|_{y=0}$(nb)	3.92±0.62	0.53±0.14	-	76±14

KMRS -2004: **130 nb →80 nb** (PDG-2008)

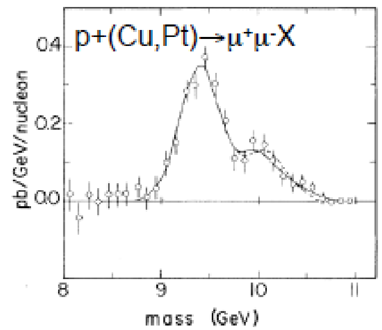
$\pi\pi$/KK mode as a spin-parity analyzer

Prospects of χ(b)-spectroscopy , FSC@CMS

P-wave Bottomonia

Bottomonium history started 30 years ago

(PRL 39, 242 (1977) and PRL 39,1240 (1977))



M(ϒ)=9.40±0.013

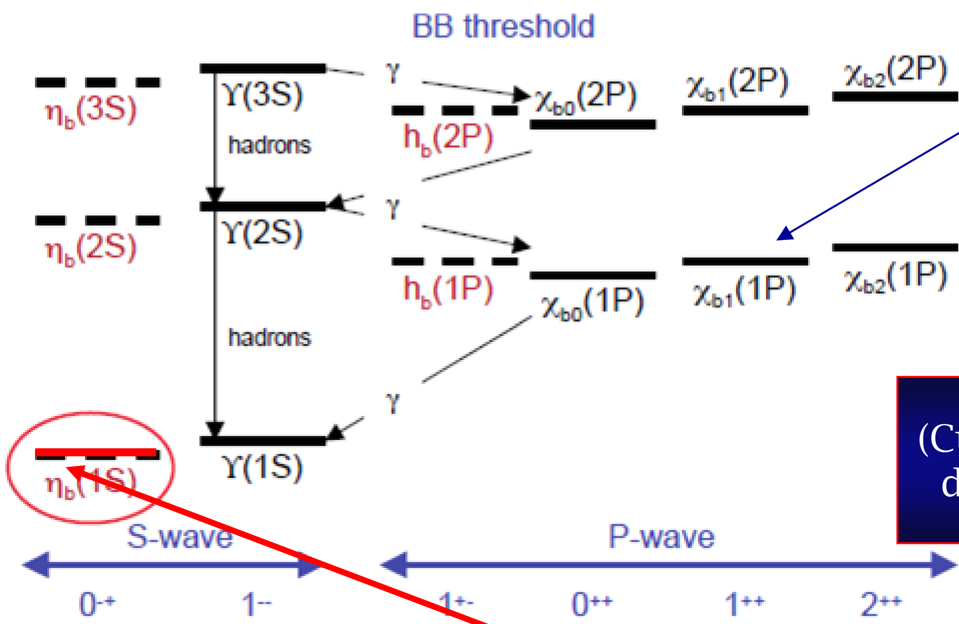
M(ϒ')=10.00±0.04

M(ϒ'')=10.43±0.12

FNAL, E288

(spins- still unconfirmed)

30 years later….



$\Upsilon(nS)$ confirmed and $\chi_{bJ}(1,2P)$ states observed

Below BB̄, 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))

(Still some puzzles)

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

PDG Summary Tables

$\chi_{b0}(1P)$ [d]

$I^G(J^{PC}) = 0^+(0^{++})$

J needs confirmation.

Mass $m = 9859.44 \pm 0.42 \pm 0.31$ MeV

$\chi_{b0}(1P)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\gamma \Upsilon(1S)$	<6 %	90%	391

$(1.73 \pm 0.35)\%$
CLEO-2011

(Crystal Ball-1986)

$\chi_{b1}(1P)$ [d]

$I^G(J^{PC}) = 0^+(1^{++})$

J needs confirmation.

$\gamma \Upsilon(1S)$	(35 ± 8) %	423

$\chi_{b2}(1P)$ [d]

$I^G(J^{PC}) = 0^+(2^{++})$

J needs confirmation.

Mass $m = 9912.21 \pm 0.26 \pm 0.31$ MeV

$\chi_{b2}(1P)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\gamma \Upsilon(1S)$	(22 ± 4) %	442

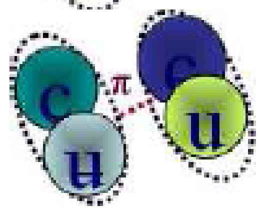
Zoo of charmonium –like XYZ states

(Joel Bressieux)

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

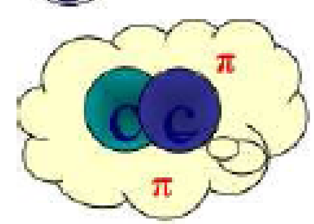
Tetraquark:
four tightly bound quarks

Molecular state:
two loosely bound mesons



Hybrid: states with
excited gluonic degrees of freedom

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



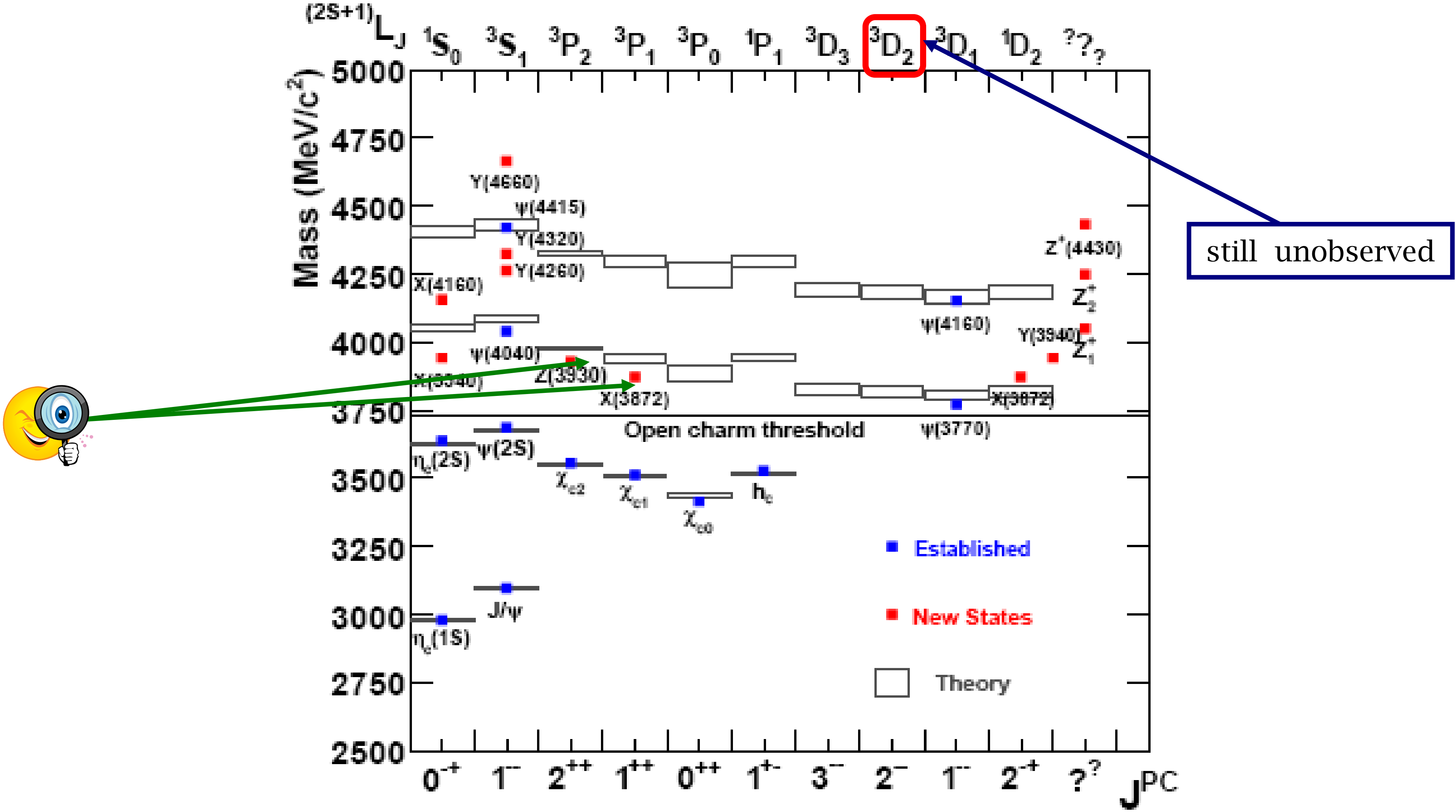


Figure 1: The mass versus the quantum numbers (J^{PC}) for the charmonium-like states. The boxes represent the predictions; blue boxes show the established states, and the red boxes indicate the new states discovered at the B-factories.

X(3872) first and most puzzling state (observed in 2003 at Belle)

- Discovered by BELLE in 2003, confirmed by BaBar, CDF, D0
- Possible spin-parity assignment: 1^{++} or 2^{-+}
- May well be of exotic nature : loosely bound molecule, diquark-antidiquark, hybrid,….. but a conventional 2 P-wave charmonium interpretation is still on the table (recent renewal of interest).
- BaBar (2010) seems to favour 2^{-+} though various theory groups find this assignment highly problematic.
- According to PDG $\Gamma(\pi^+\pi^- J/\psi(1S))/\Gamma_{total}$ >2.6 % ; $\Gamma(\gamma\psi(2S))/\Gamma_{total}$ >3.0 %, Γ <2.3 MeV.

  (maybe two different states X(3872), X(3875))

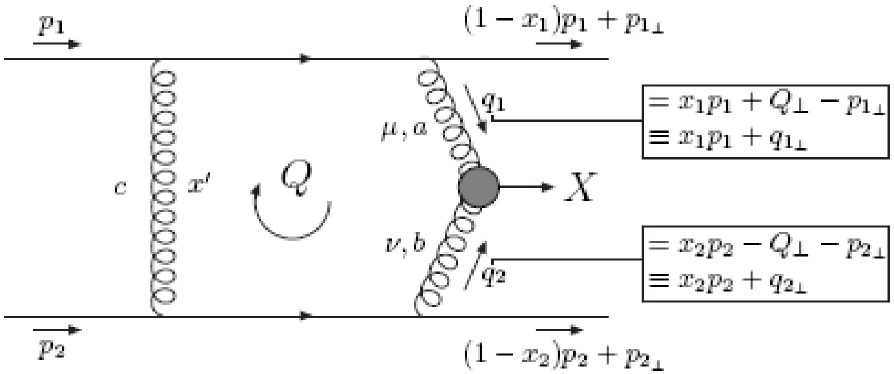
CEP as a spin-parity analyzer could help to resolve the $X(3872)$ puzzle.

$Z(3930) \equiv \chi_{c2}(2P)$?

- Above DD threshold .
- Vertex detection at LHCb & RHIC→ exclusive open charm: $D^+D^-, D^0\bar{D}^0$,
- Roughly the same expectations for CEP as for χ_{c2}

Theory: parton level amplitude

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



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

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

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

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

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

$J_z^P = 0^+$ selection rule

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

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

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

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

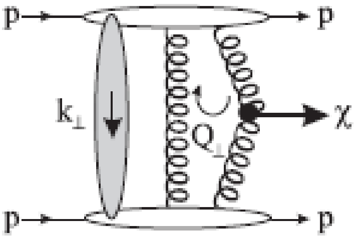
i.e. fusing gluons have equal (transverse) polarisations $\lambda_1 = \lambda_2 = \pm$.

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

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

What we expect within the framework of the Perturbative Durham formalism
(KMR-01, KKMR-03, KMRS-04, HKRS-10)

Example, O++ -case



$$T = A\pi^2 \int \frac{d^2Q_\perp \, P(\chi(0^+))}{Q_\perp^4 (\vec{Q}_\perp - \vec{p}_{1\perp})^2 (\vec{Q}_\perp + \vec{p}_{2\perp})^2} f_g(x_1, x_1', Q_1^2, \mu^2; t_1) f_g(x_2, x_2', Q_2^2, \mu^2; t_2),$$

$A^2 = 8\pi\Gamma(\chi \to gg)/M_\chi^3$ $*K_{NLO}$

$P(\chi(0^+)) = (\vec{Q}_\perp - \vec{p}_{1\perp}) \cdot (\vec{Q}_\perp + \vec{p}_{2\perp}).$

- The $gg \to \chi_{cJ}$ vertex and can be calculated by a simple extension of the previous $\gamma\gamma \to \chi_c$ potential model results. These give the Lorentz structure of the vertices, while the normalisation is set by the derivative of the P-wave meson wavefunction at the origin $\phi'_P(0)$.

- **Strong sensitivity to the polarization structure of the vertex in the bare amplitude.** KMR-01

  Absorption is sizeably distorted by the polarization structure (affects the b-space distr.)

- χ_c, χ_b -production is especially sensitive to the effects of enhanced absorption KMR-02, KKMR-03, HKRS 09-10
  - larger available rapidity interval
  - lower scale → larger dipole size → larger absorption

  (Gap size for χ_c at the Tevatron is expected to exceed that for the Higgs at the LHC) KMR-02

- **Forward proton distributions& correlations- possibility to test diffraction dynamics**

CDF χ_c data

Phys.Rev.Lett.102:242001,2009

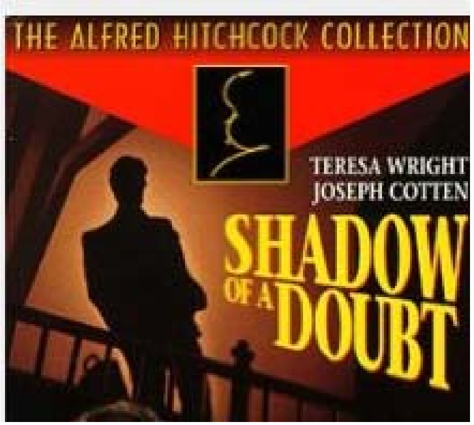
- 65 ± 10 signal χ_c events observed, but with a limited $M(J/\psi\gamma)$ resolution.
- Possible contribution from χ_{c1} and χ_{c2} states assumed, rather than observed, to be negligible.
- Assuming χ_{c0} dominance, CDF found:

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

  in good agreement with the previous KMRS value of 90 nb (arXiv:0403218).

Too good to be true ?!

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



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 $\chi_{c(1,2)}$

(R.Pasechnik et al, Phys.Lett.B680:62-71,2009; HKRS, Eur.Phys.J.C65:433-448,2010)

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

…and especially without proton detectors!

SuperCHIC MC (KRYSTHAL coll.- 09-11)

A MC event generator including[9]:

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

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

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

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 $S^2_{\rm eik}$ for the more peripheral reactions.
- An explicit calculation gives (for the perturbative contribution):

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

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

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

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.

→ 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_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, but we have a stronger suppression in the χ_{b1} and χ_{b2} rates than for the χ_c case.
- 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).
- Previous uncertainties in input parameters $\mathrm{Br}(\chi_{b0} \to \Upsilon\gamma)$ and $\Gamma_{\mathrm{tot}}(\chi_{b0})$ greatly reduced by new CLEO data (arXiv:1012.0589).
- Updated predictions for χ_b CEP via the $\Upsilon\gamma$ decay chain (at $y_\chi = 0$):

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

- $\chi_b(nP) \to DX$ (about 0.25 of all hadronic decays (CLEO-2009))
  $\chi_{b1} \to c\bar{c}X$ (Barbieri et al (1979), NRQCD)
  Suppressed non-resonant background $\sim m_c^2/M_{\chi_b}^2$

Measuring forward proton angular distributions

KKMR-03

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

$\mathrm{p}_\perp^2 \ll \mathrm{Q}_\perp^2$

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

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

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

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

KRYSTHAL coll. **arXiv: 01011.0680**

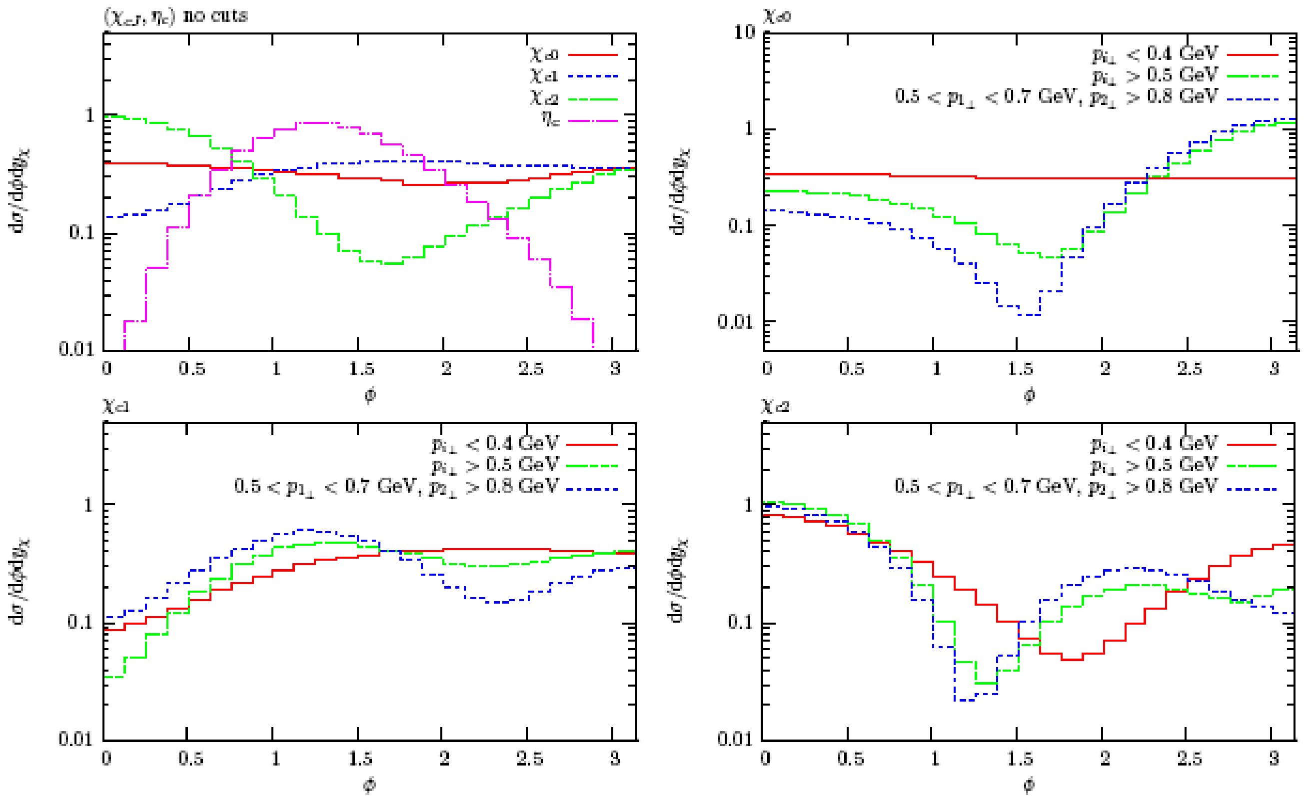
χ_c CEP at RHIC

(or LHCb/ALICE with proton taggers)

KHRYSTHAL-2010

- Roman pot (RP) forward proton detectors with acceptance for χ_{cJ} masses installed at STAR, with upgrade planned for 2012.
- Can observe χ_{cJ} production via $\chi_{cJ} \to J/\psi\gamma$ decay.
- Can also consider χ CEP via two and four-body decays (e.g. $\chi_{c0} \to \pi\pi, p\overline{p}$ and $\chi_{c0} \to 2(\pi^+\pi^-)$), for which χ_{c0} states will dominate:
  - Estimate of $gg \to \pi\pi$ QCD background work in progress
  - Excellent mass resolution ($\sim$ a few MeV) of central TPC detector will greatly increase S/B.
- RPs will be able to measure proton ϕ and $p_\perp$ distributions over a broad range, in principle giving spin information about the centrally produced χ_c state as well as probing soft survival effects...

CEP with proton taggers



→ ϕ distributions (SuperCHIC) depend on central particle spin, but are also strongly affected by soft survival effects, in particular for larger values of proton $p_\perp$ (RHIC II), where cancellation between screened and unscreened amplitudes results in characteristic 'diffractive dip' structure.[3]

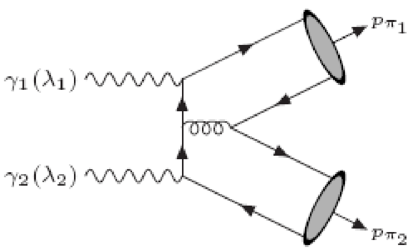
[3] V. A. Khoze, A. D. Martin and M. G. Ryskin, Eur. Phys. J. C 24, 581 (2002) [arXiv:hep-ph/0203122].

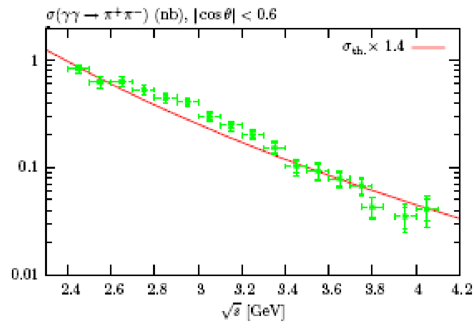
Meson pair CEP

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

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

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





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

Dimeson CEP

- 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.

$gg \to M\overline{M}$ calculation

- Simplest case: production of flavour non-singlet scalar mesons (e.g. $\pi^0\pi^0$, $\pi^+\pi^-$ ...).
- Can calculate the LO $gg \to M\overline{M}(= q\overline{q}q\overline{q})$ amplitudes to give

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

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

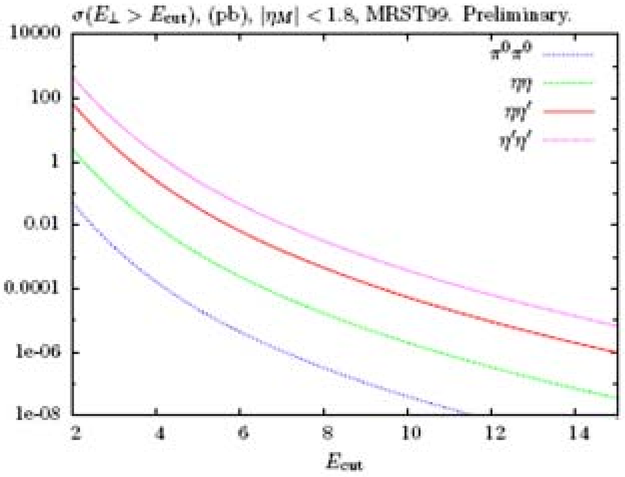
where $a, b = (1-x)(1-y) \pm xy$.

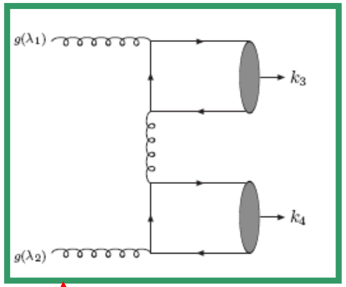
→ $J_Z = 0$ amplitudes vanish, as in $\gamma\gamma \to M\overline{M}$ for neutral mesons. We therefore expect a strong suppression in flavour non-singlet $M\overline{M}$ CEP due to $J_z = 0$ selection rule.

→ $J_Z = 2$ amplitudes contain 'radiation zero', vanishing for a physical value of $\cos^2\theta$. Well known effect in all gauge theories (e.g. $u\overline{d} \to W^+\gamma$), but usually washed out in QCD by colour averaging. Here, position of zero depends on the choice of $\phi(x)$, and we find that there is always a zero in the physical region for any choice of $\phi(x)$ and general N_c.

Numerical Results

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





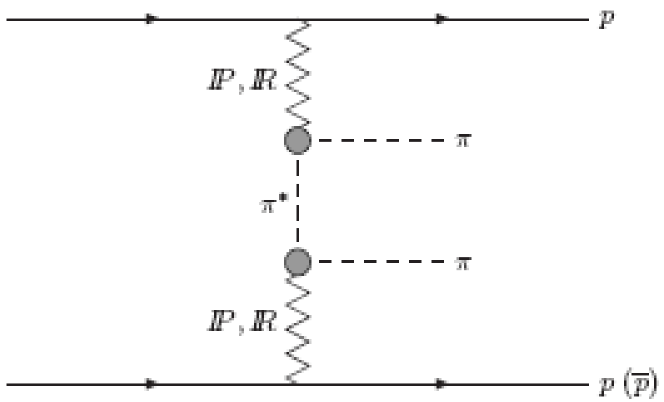
- $\pi^0\pi^0$ CEP can in principle be an important background to $\gamma\gamma$ CEP, but we find this not to be the case. This depends crucially on vanishing of the $gg \to \pi^0\pi^0$ amplitude for $J_z = 0$ initial-state gluons.
- However: possible $J_Z = 0$ contribution from higher twist effects,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

- In this case the $J_z = 0$ amplitude does not vanish $\to$ Expect strong enhancement in $\eta'\eta'$ CEP rate[7] and (through η-η' mixing), some enhancement to $\eta\eta$ rate. $\eta\eta'$ CEP can also occur via this mechanism.
- Also: any sizable gg component to flavour singlet states, contributing through $gg \to 4g$ and $gg \to q\bar{q}gg$ processes, may in principle strongly enhance the CEP cross section (again $J_z = 0$ amplitudes do not vanish). A significant 'excess' in future CEP data could be evidence for this.

$\gamma\gamma$ CEP: $\pi^0\pi^0$ background (2)

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

(theory studies since mid- seventies, AKLR-1974…..)



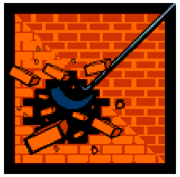
- Uncertainty in what to take for form factor of off-shell pion ('soft' vs 'hard' fit), which suppresses high values of final state pion $p_\perp$, leads to quite large uncertainty in expected rate.
- Expect smooth transition with increasing $p_\perp$ between non-perturbative ($\sim$ real amplitude) and perturbative ($\sim$ imaginary amplitude) dominance.
- Measurement of $\pi_0\pi_0/\pi^+\pi^-$ CEP in low $p_\perp$ region would help constrain off-shell pion form factor.

Towards Full Acceptance Detector (bj- 1992)

CMS (& ATLAS) currently blind between $\eta = 6.4$ (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 ?

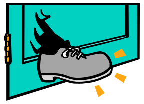
Yes, an addition of Forward Shower Counters around beam pipes at CMS!

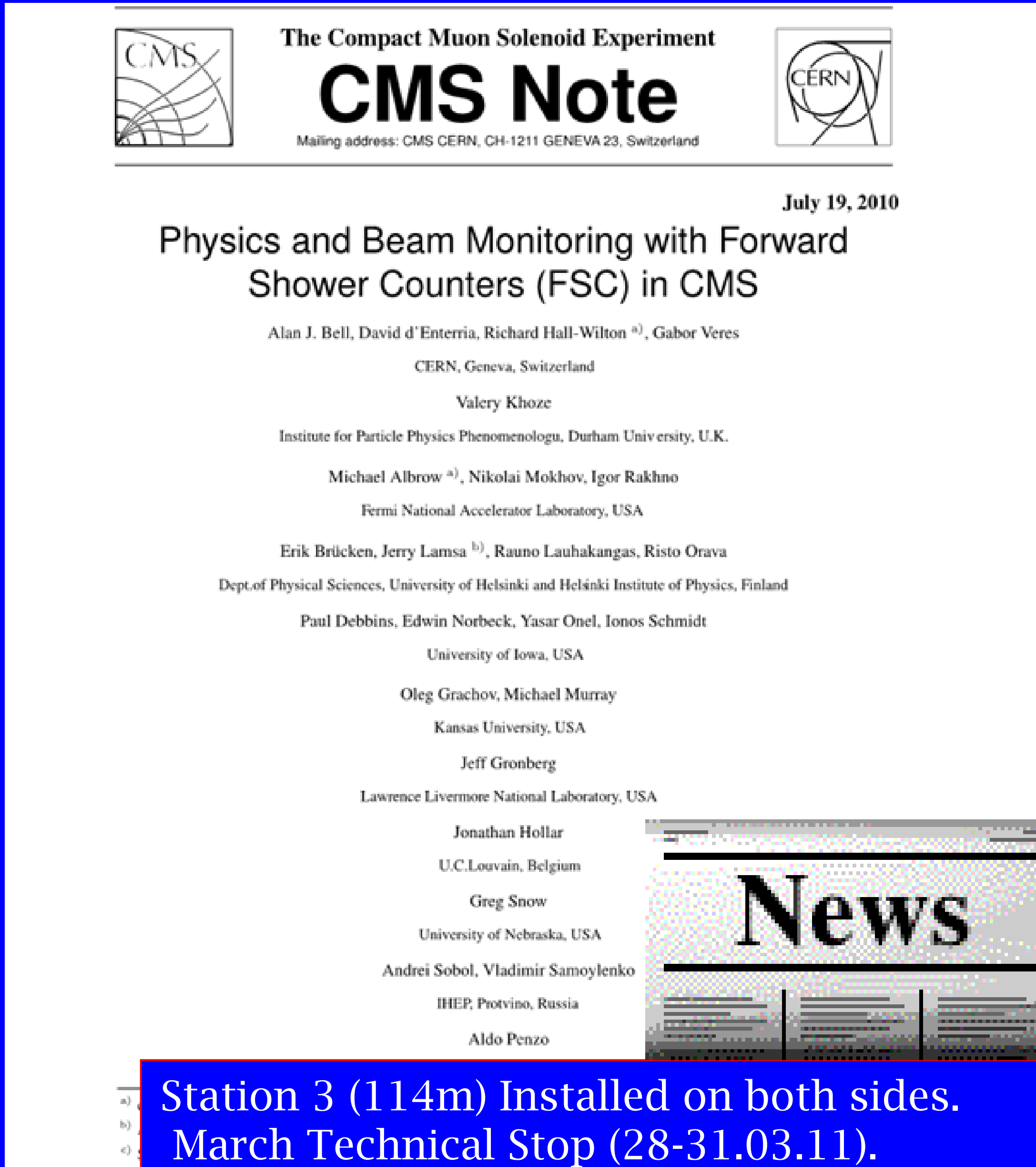


(8 FSC per side see showers from particles with $|\eta| = 7$-9)

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

(**FSC**→ at least a good foot in the door)





The Compact Muon Solenoid Experiment

CMS Note

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

July 19, 2010

Physics and Beam Monitoring with Forward Shower Counters (FSC) in CMS

Alan J. Bell, David d'Enterria, Richard Hall-Wilton [a], Gabor Veres

CERN, Geneva, Switzerland

Valery Khoze

Institute for Particle Physics Phenomenologu, Durham University, U.K.

Michael Albrow [a], Nikolai Mokhov, Igor Rakhno

Fermi National Accelerator Laboratory, USA

Erik Brücken, Jerry Lamsa [b], Rauno Lauhakangas, Risto Orava

Dept.of Physical Sciences, University of Helsinki and Helsinki Institute of Physics, Finland

Paul Debbins, Edwin Norbeck, Yasar Onel, Ionos Schmidt

University of Iowa, USA

Oleg Grachov, Michael Murray

Kansas University, USA

Jeff Gronberg

Lawrence Livermore National Laboratory, USA

Jonathan Hollar

U.C.Louvain, Belgium

Greg Snow

University of Nebraska, USA

Andrei Sobol, Vladimir Samoylenko

IHEP, Protvino, Russia

Aldo Penzo

Station 3 (114m) Installed on both sides.
March Technical Stop (28-31.03.11).
Stations 1&2- to be installed in May
(next Tech. stop)

CMS NOTE-2010/015

Approved by CMS MB
for Jan-Feb 2011 installation.

“Limited approval” :
Go ahead without detracting from necessary shutdown work.

Most value is 2011 running
& when <n/x> < ~ 5
(Do not expect to use > 2012)

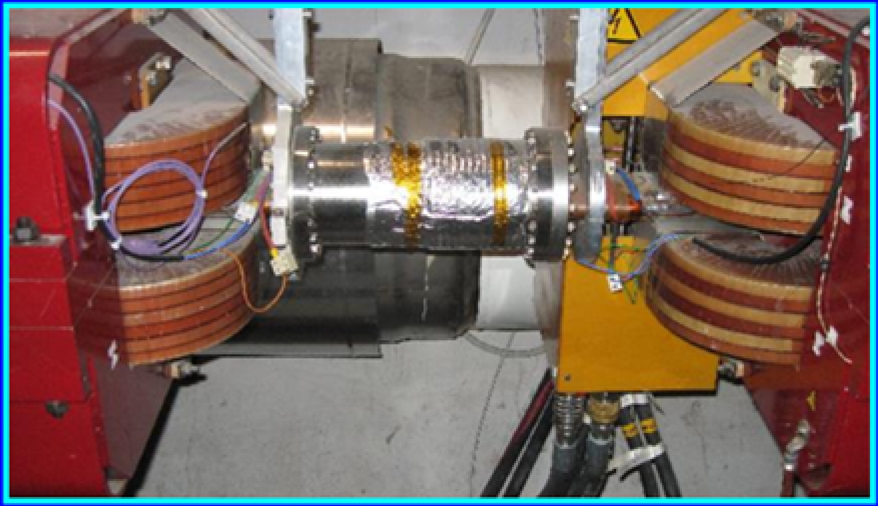
Proposal to add Forward Shower Counters FSC to CMS

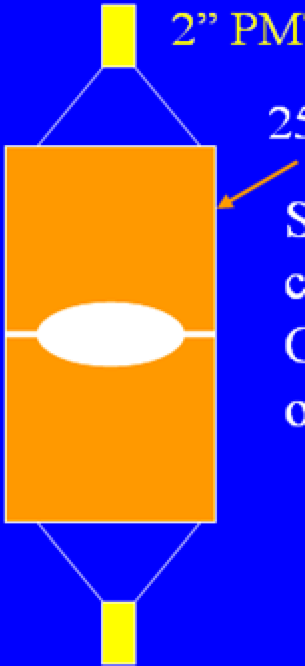
What: We propose to install a set of scintillation counters around both outgoing warm, accessible beam pipes at CMS, ~ 60m – 125 m

They detect showers produced by v. forward particles in pipe +

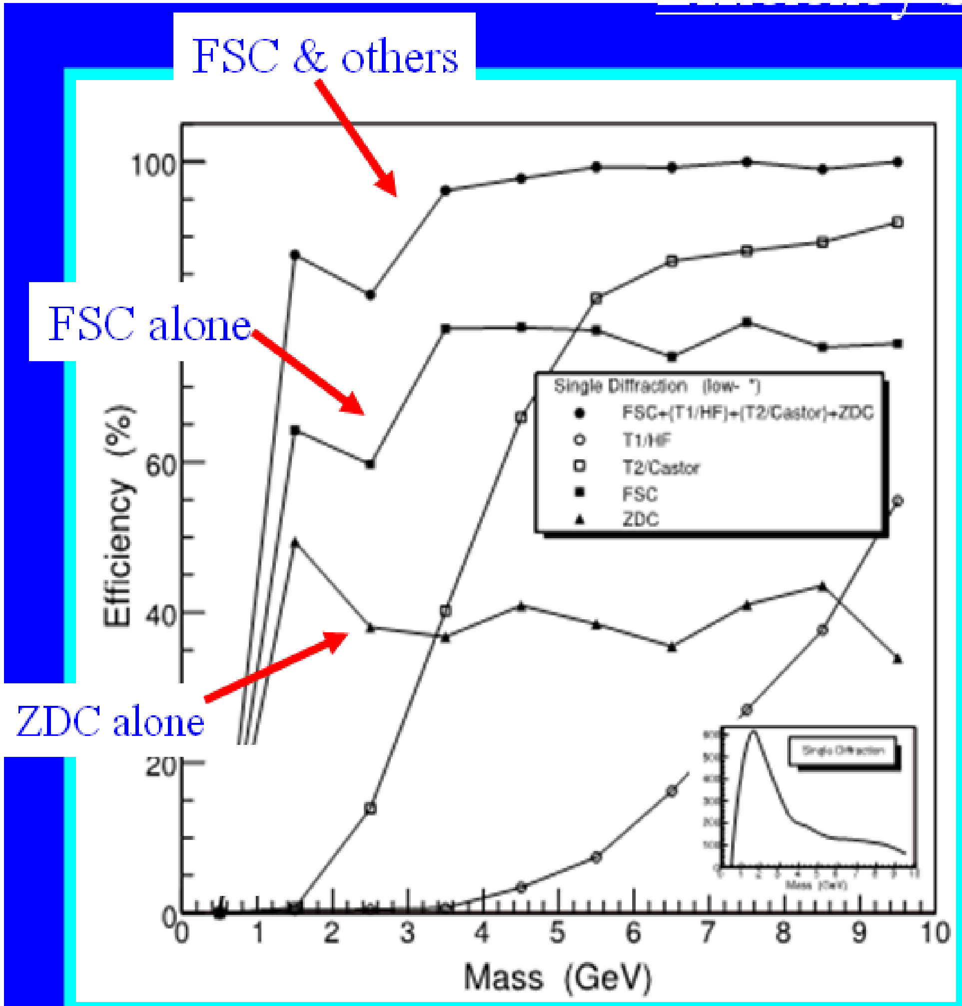
Very simple, low tech: 8 PMTs on each side in 4 pairs.

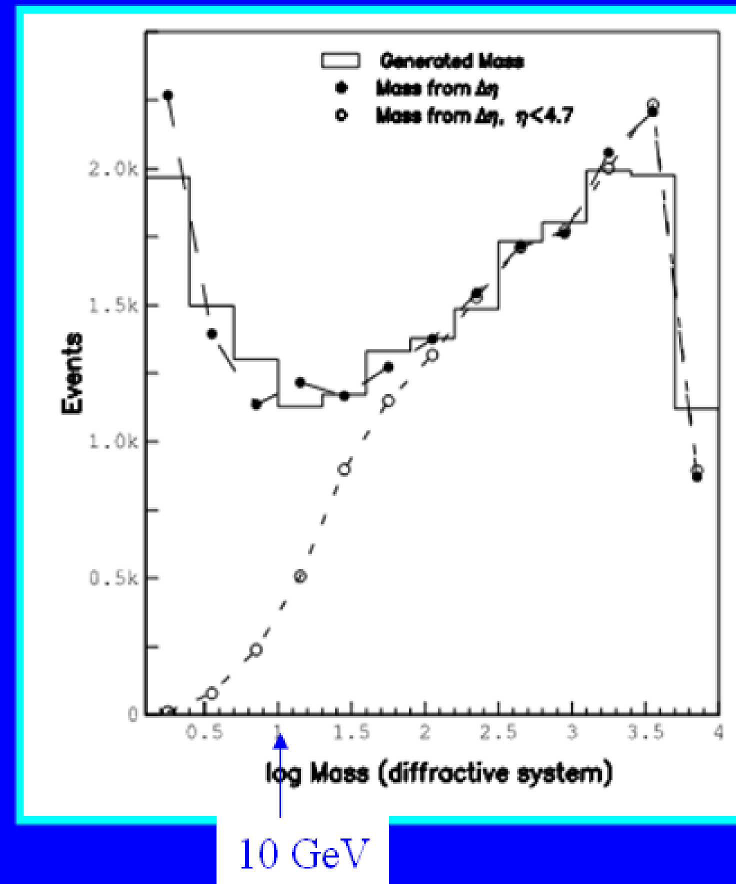
Between 2 MBX magnets





Four locations: z (m) = 59.2, 79.1, 88.5 and ~ 125 m (to be optimized)





>4 hits in FSC or > 1 track in HF
or CASTOR or ZDC(min)

M. Albrow et al, JINST 4:P10001,2009.

Generated diffractive mass (PYTHIA/PHOJET)
as log(M_X), M_X in GeV/c2,
cf to calculated from rapidity gap edge:
(a) full η coverage
(b) η < 4.7 (no FSC)

Below 10 GeV/c^2 FSC contain most particles

The FSC- these are for real !

- The installation and commissioning phase of FSC during the March Technical Stop.
- Main concern- lumi per bunch crossing might be too high.

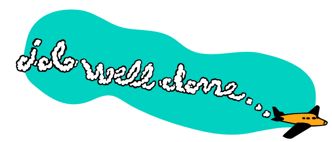
What about precise measurement of SD?

Don't hold your breath, Valery.
This certainly needs all the counters and some low lumi run, or at least bunches. (Mike Albrow)

Summary and Outlook

- CEP in hadron collisions offers a promising framework within which to study novel aspects of QCD and new physics signals.
- CEP processes observed at the Tevatron, RHIC and early LHC can serve as ‘standard candles’ for new physics CEP at the LHC.
- The CEP of mesons pairs at high invariant masses is an interesting process, representing a novel application of pQCD framework for describing exclusive processes (publication in preparation).

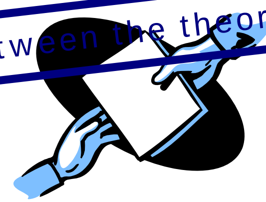
- **Very promising news from LHCb on χ_c CEP.**



- **Prospects of CDP studies at ALICE.**
- χ_b, η_b and η_c CEP a potential observable at the LHC.

- **New STAR@RHIC results on CEP with tagged forward protons soon to come.**

Productive cooperation between the theorists and experimentalists




THANK YOU


QUESTIONS?

BACKUP

$\eta_{c,b}$ production

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

Overview of exotic/charmonium spectroscopy (2)

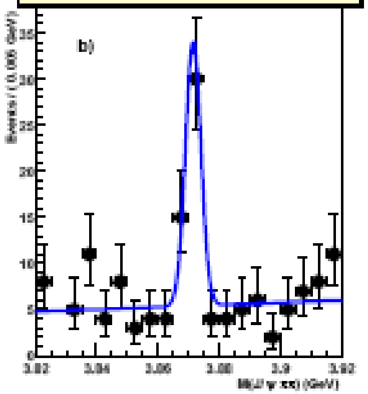
State	M, MeV	Γ, MeV	J^{PC}	Process
$X(3872)$	3871.52 ± 0.20	1.3 ± 0.6	$1^{++}/2^{-+}$	$B \to K(\pi^+\pi^- J/\psi)$
		(< 2.2)		$p\bar{p} \to (\pi^+\pi^- J/\psi) + \ldots$
				$B \to K(\omega J/\psi)$
				$B \to K(D^{*0} D^0)$
				$B \to K(\gamma J/\psi)$
				$B \to K(\gamma\psi(2S))$
$X(3915)$	3915.6 ± 3.1	28 ± 10	$0/2^{?+}$	$B \to K(\omega J/\psi)$
				$\gamma\gamma \to (\omega J/\psi)$
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$
				$e^+e^- \to J/\psi\ (\ldots)$
$Y(4008)$	4008^{+121}_{-49}	226 ± 97	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B \to K(\pi^+\chi_{c1}(1P))$
$Y(4140)$	4143.4 ± 3.0	15^{+11}_{-7}	$?^{?+}$	$B \to K(\phi J/\psi)$
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$
$Z_2(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	?	$B \to K(\pi^+\chi_{c1}(1P))$
$Y(4260)$	4263 ± 5	108 ± 14	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$
				$e^+e^- \to (\pi^+\pi^- J/\psi)$
				$e^+e^- \to (\pi^0\pi^0 J/\psi)$
$Y(4360)$	4353 ± 11	96 ± 42	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- \psi')$
$Z(4430)^+$	4443^{+24}_{-18}	107^{+113}_{-71}	?	$B \to K(\pi^+\psi(2S))$
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- \psi(2S))$

$X(3872)$ properties

Discovered by Belle in $B^\pm \to J/\psi\pi^+\pi^- K^\pm$ decays. Confirmed by D0, CDF, BaBar. What do we know about it?

~ 152 M $B\bar{B}$ pairs

Belle, PRL 91, 262001 (2003)



$M(X) - (m_{D^0} + m_{D^{*0}}) = -0.32 \pm 0.35$ MeV

$X(3872) \to \pi^+\pi^- J/\psi$

$M(\pi^+\pi^-)$ is consistent with $\rho \Rightarrow$

large isospin violation;

$C = +1$.

$X(3872) \to \pi^+\pi^-\pi^0 J/\psi \Rightarrow$

$M(\pi^+\pi^-\pi^0)$ is consistent with ω, different isospin then $\rho J/\psi$.

Angular analysis: $J^{PC} = 1^{++}$ or 2^{-+}

S-wave $D^0\bar{D}^{*0}$ molecular state?

E.S.Swanson, PLB 588, 189 (2004)

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

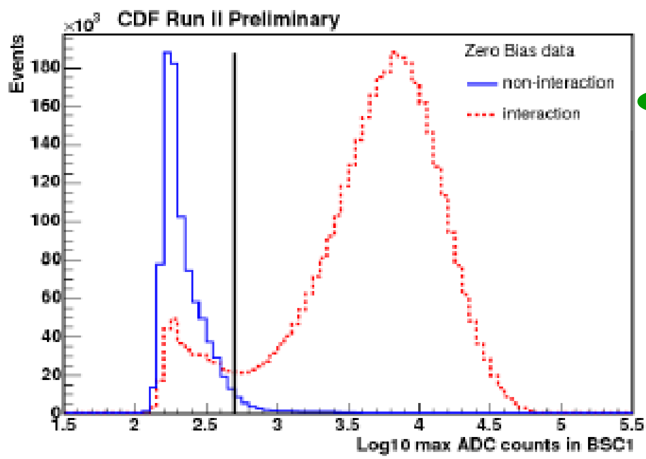
FORWARD PHYSICS WITH RAPIDITY GAPS AT THE LHC

arXiv:0811.0120

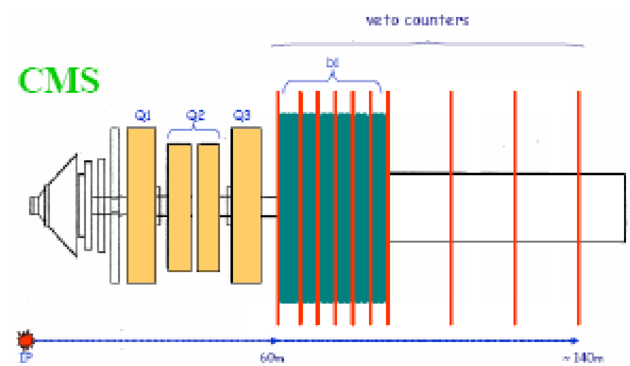
Michael Albrow[1], Albert De Roeck[2], Valery Khoze[3], Jerry Lämsä[4,5], E. Norbeck[6],
Y. Onel[6], Risto Orava[5], and M.G. Ryskin[7]

Sunday, November 09, 2008

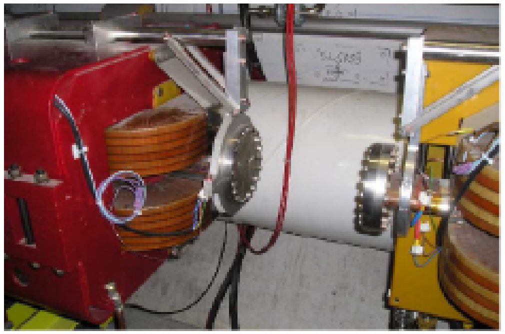
JINST-09



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



Physics, especially diffractive in no-PileUp interactions

(from Mike Albrow)

(a) As veto in Level 1 diff. triggers to reduce useless pile-up events.
(b) To detect rapidity gaps in diffractive events (p or no-p).
(c) Measure low mass diffraction and double pomeron exchange.
(d) Measure σ_{INEL} (if luminosity known, e.g. by Van der Meer)
(e) Help establish exclusivity in central exclusive channels

Beam monitoring etc, parallel uses:

(f) To monitor beam halo on incoming and outgoing beams.
(g) To test forward flux simulations (MARS etc.)
(h) Additional Luminosity monitor.
(i) Info on radiation environment for future (?) proton spectrometers

MORE PHYSICS

LOW COST

ZERO RISK*

*Subject to support approval by LHC

24

Mike's priority now - gap+X+gap triggers.
SD measurement requires all counters + low lumi run

UNCERTAINTIES

Known Unknowns

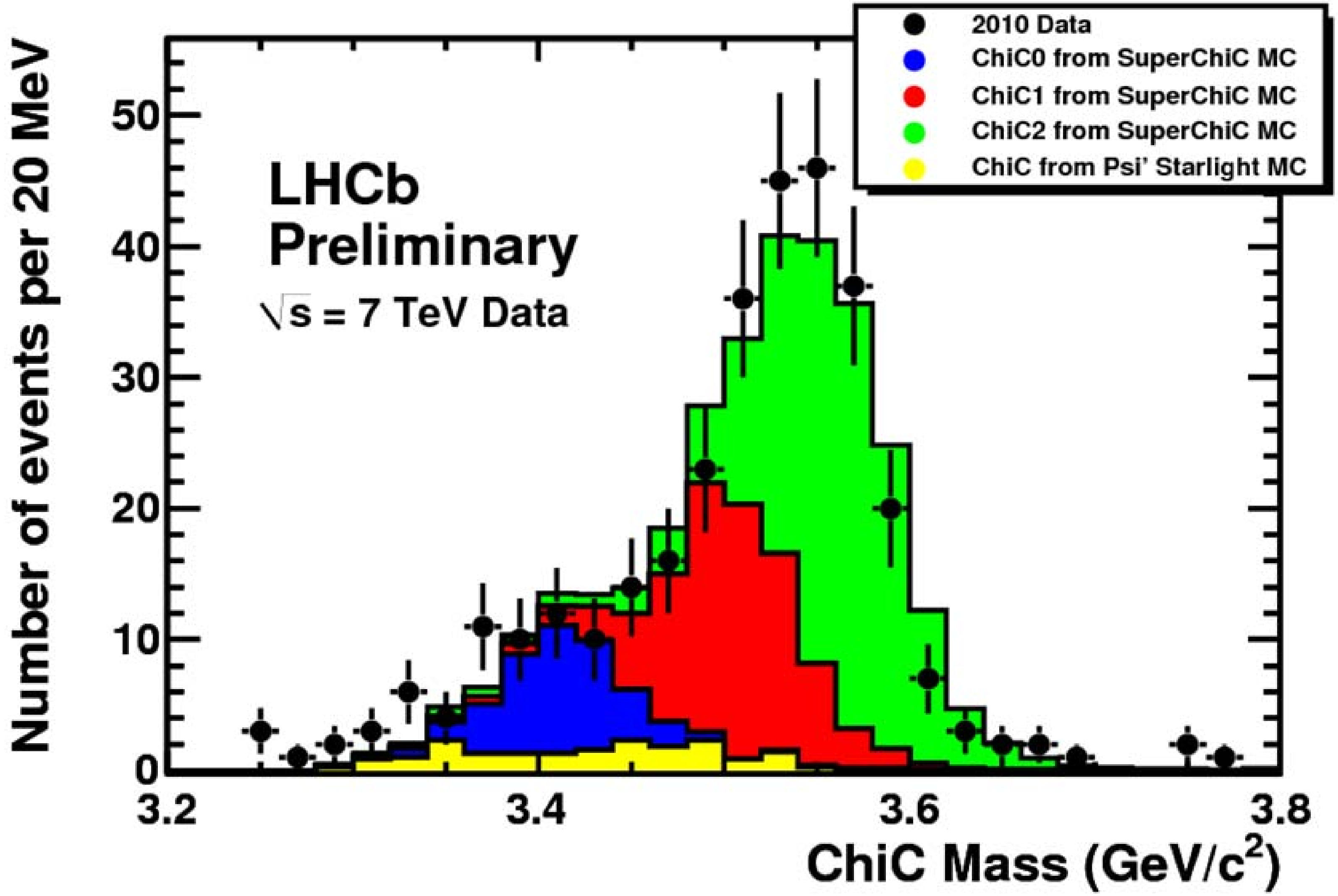
- N(N)LO- radiative effects (K-factors etc..)
  '…possible inadequancy of PT theory in α_s …' R.Barbieri et al-1980
- ' 'Right' choice of gluon densities, in particular at so low scales as in the χ_c case (potentiality of a factor of ~3 rise for the H-case) .
- Complete model for calculation of enhanced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

χ_c: DiMuon+Photon Invariant Mass

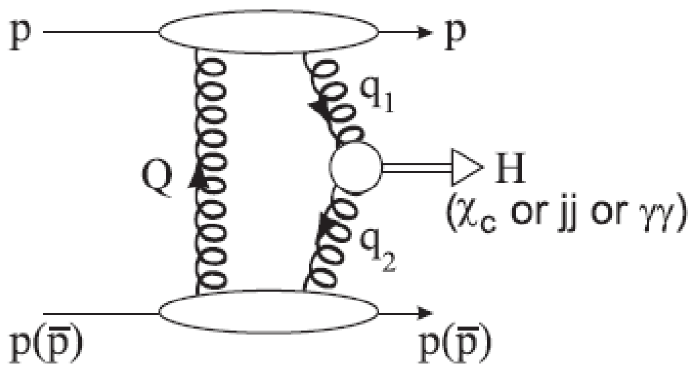


(Caveat: Inelastic contribution appears to be much larger than for J/ψ)

	χ_0	χ_1	χ_2
	χ_0: 9.3 +- 4.5 pb	χ_1: 16.4 +- 7.1 pb	χ_2: 28.0 +-12.3 pb
SuperChic:	14 pb	10 pb	3 pb

Durham model of CEP

- 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 $\sim M_X/2$, which ensures an infrared stable result.



- The possibility of additional soft rescatterings filling the rapidity gaps is encoded in the 'eikonal' and 'enhanced' survival factors, S^2_{eik} and S^2_{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. (or 2^+)