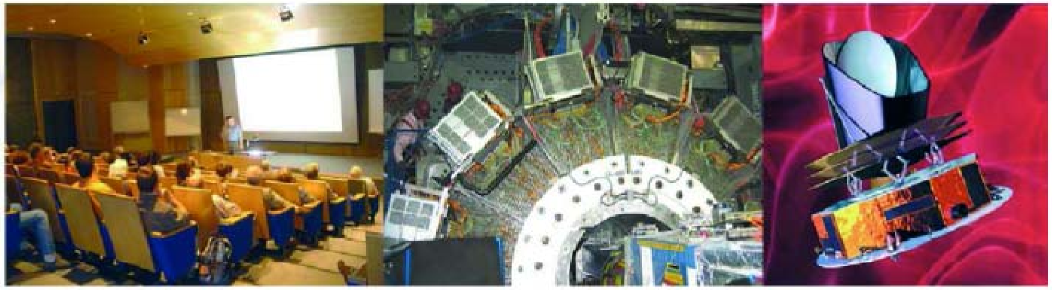
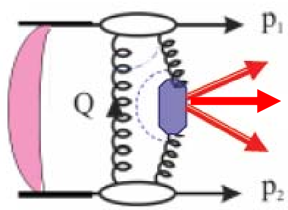


Séminaire du Laboratoire de l'Accélérateur Linéaire

Central Exclusive Production at Hadron Colliders

(KRYSTHAL Collaboration)

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)

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

NEW! **arXiv:1204.4803**

Outline

- **Introduction** **(why we are interested in CEP processes?)**
- **'Diffractive Higgs' revisited.**
- **Standard Candle CEP processes.**
- **CEP as a way to study old and new heavy resonances.**
- **CEP through the KRYSTHAL eyes (new results, selected topics).**
  - **Diphoton CEP.**
  - **Dimeson CEP.**
- **SuperCHIC MC.**
- **Summary and Outlook.**

With a bit of personal flavour

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)

Forward Proton Taggers @ 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 ...

(accounting for the LHC exclusion zones)

•Various aspects of Diffractive Physics (*soft & hard*).

•High intensity **Gluon Factory** (underrated gluons) (~20 mln quraks vs 417 'tagged' g at LEP)

QCD test reactions, dijet P-luminosity monitor

•Searches for new heavy gluophilic states and many other goodies...

FPT

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

σ(CDPE) ~ 10^{-4} * σ (incl)

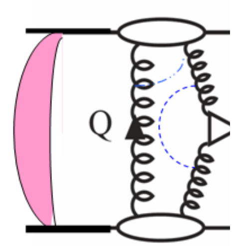
✵Higgs is only a part of the broad EW, BSM and diffractive program@LHC

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

'Diffractive Higgs' revisited

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

Higgs width (some BSM scenarios) ! ?

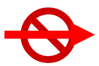


currently ATLAS FP-420
(STFC cutting rule)
CMS-HPS, Totem ?

- 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.

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

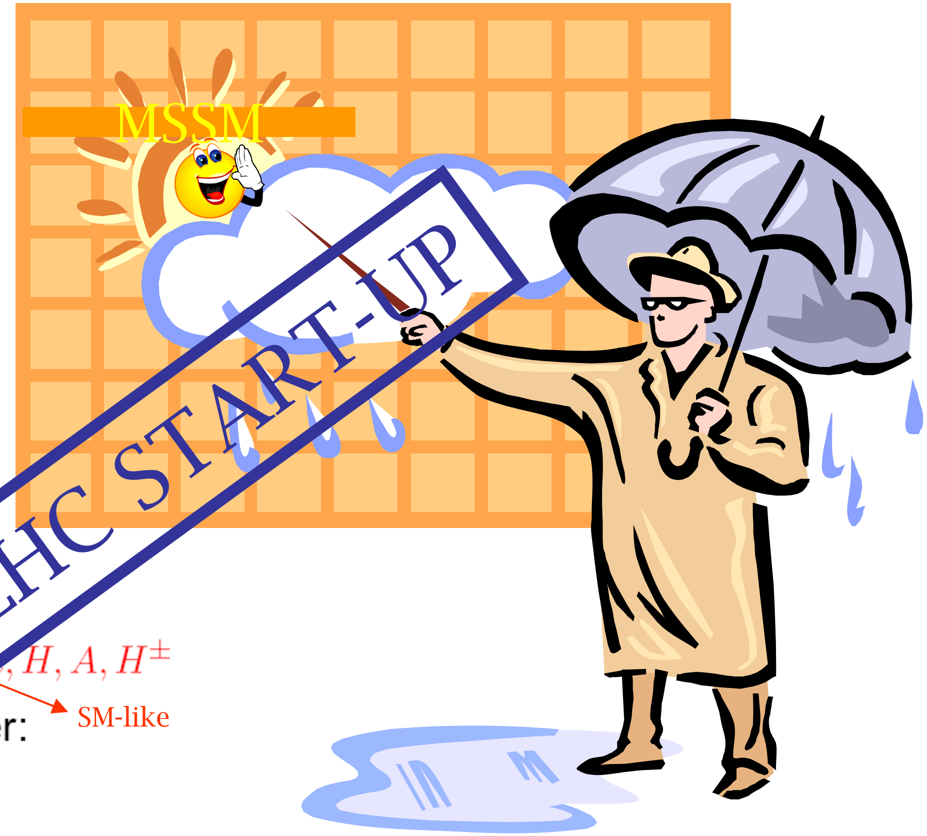
Higgs or technipion or ???

mass, spin, couplings to fermions and Gauge Bosons, invisible modes…

→ for all these purposes the CEP will be particularly handy !

without 'clever hardware':
for H(SM)→bb at 60fb-1 only
a handful of events due to
severe exp. cuts and low efficiencies,
though **S/B~1** .
But **H->WW** mode at M>135 GeV. (B.Cox et al-06)

enhanced trigger strategy & improved
timing detectors (FP420, TDR)



situation in the MSSM is **very different**
from the SM

- Higgs sector of the MSSM: physical states $h, H, A, H^{\pm}$ → SM-like

  Described by two parameters at lowest order:
  M_A, $\tan\beta \equiv v_2/v_1$

- Search for heavy MSSM Higgs bosons ($M_A, M_H > M_Z$):
  Decouple from gauge bosons
  ⇒ no HVV coupling
  ⇒ no Higgs production in weak boson fusion
  ⇒ no decay $H \to ZZ \to 4\mu$

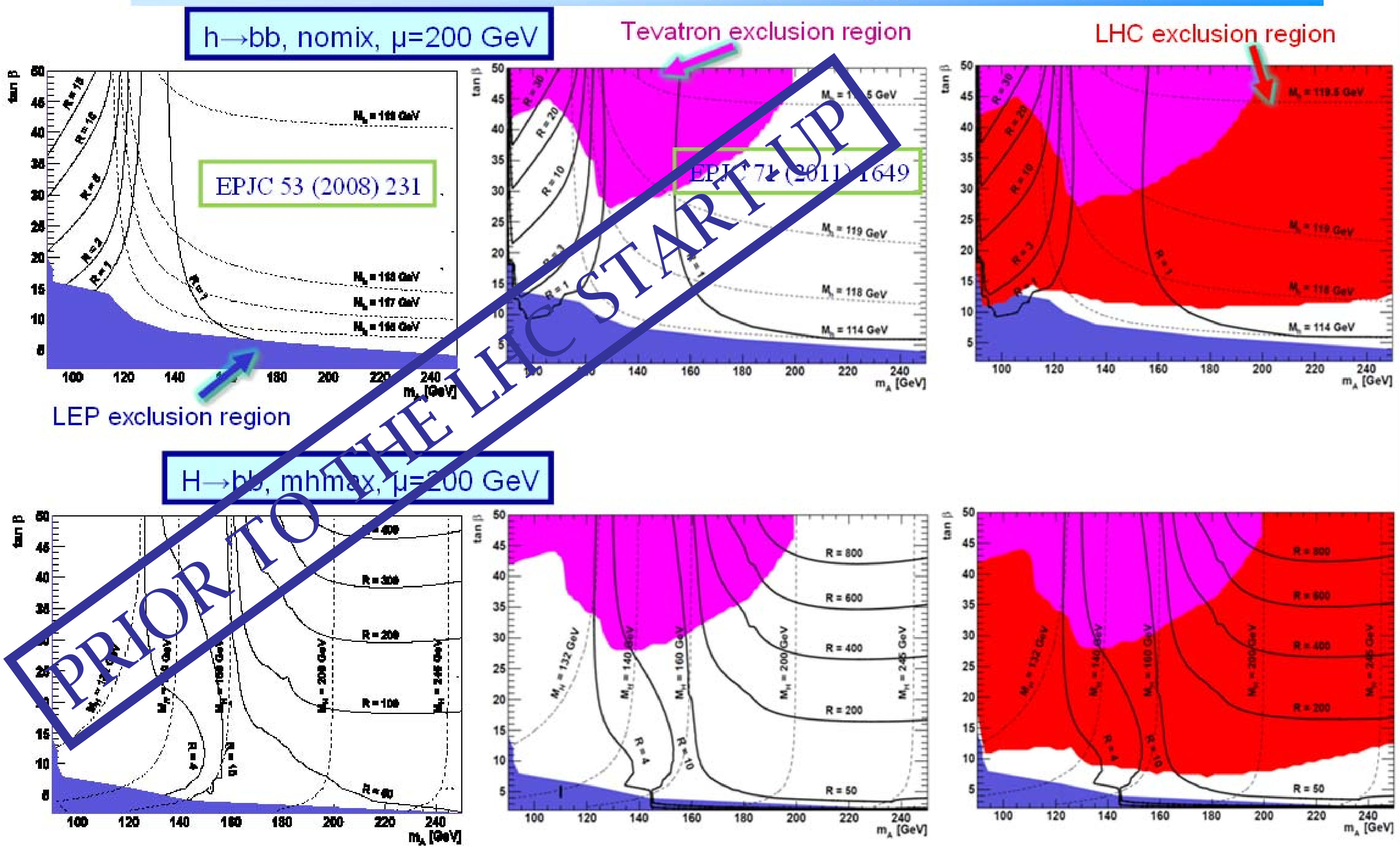
  Large enhancement of coupling to $b\bar{b}$ (and $\tau^+\tau^-$) in region of high $\tan\beta$

PRIOR TO THE LHC START-UP

Conventionally due to overwhelming QCD backgrounds, the direct measurement of Hbb is hopeless

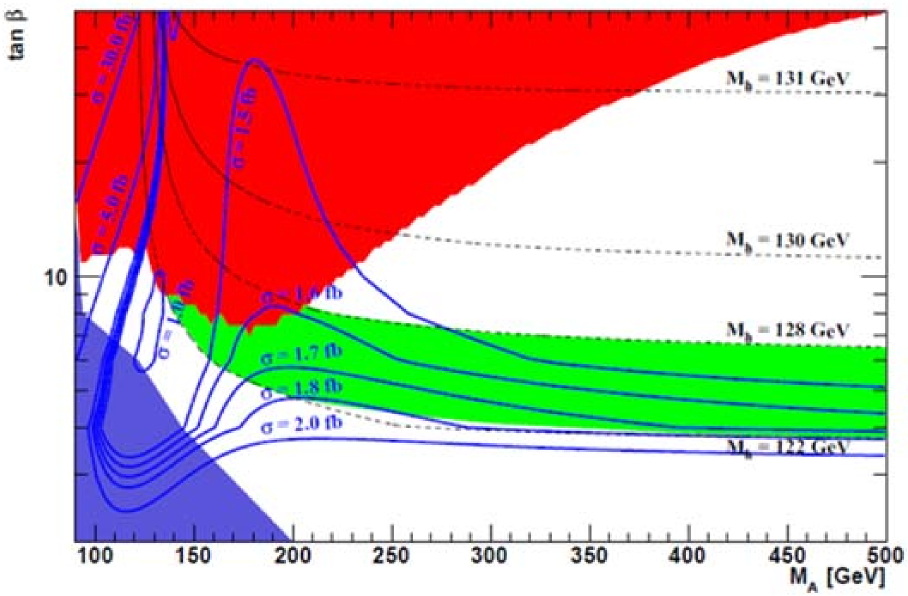
The backgrounds to the diffractive H bb mode are manageable!

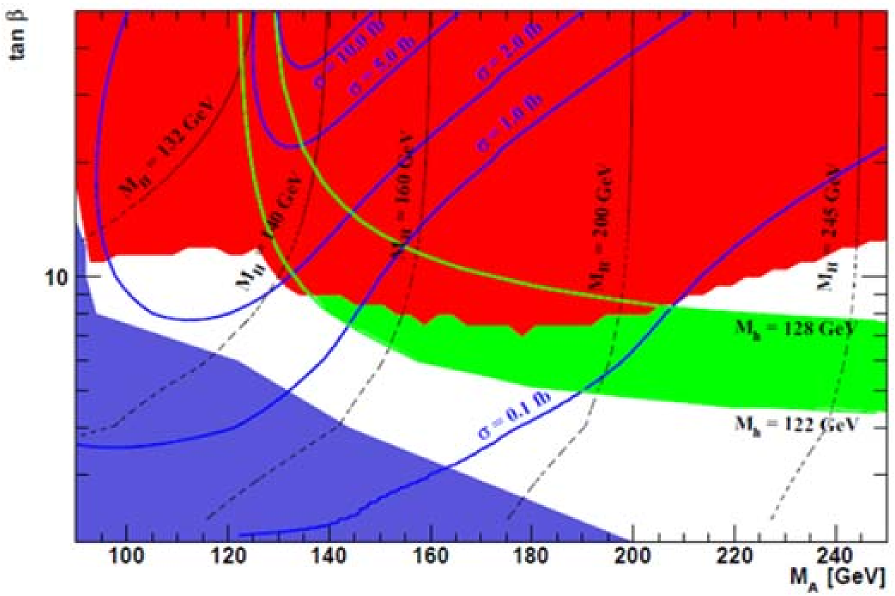
Ratios R=MSSM[M,tanβ] / SM[M]



Available MSSM CEP x-sections

2012 results M.Tasevsky+ HKW





M_h contours stay constant with M_A

Available MSSM CEP x-section stay constant with M_A (because R=MSSM/SM =1 in this region) reaching maximum of 1.8 fb

x-section of 1.5 fb reachable but in a tiny allowed phase-space region. Outside this region the x-section is very small

Max –factor 5-10 enhancement.

a) LHC MSSM exclusion regions (red area) [HiggsBounds: P. Bechtle et al., Comput. Phys. Commun. 181 (2010) 138]

b) One possible region of interest (green area): SM Higgs at **M=125 GeV +- 1 GeV (exper.)**.

If theory uncertainties added: **122 < M < 128 GeV** [S. Heinemeyer et al., arXiv:1112.3026[hep-ph]]

Summary

CED Higgs production in MSSM

- **The signal yields are potentially greatly enhanced**
- **Gives complementary information about Higgs sector**
- **Gives information about Yukawa Hbb coupling (which is difficult in standard searches)**
- **New CDM benchmark planes (consistent results with Mhmax and No-mixing scenarios)**

IN PARTICULAR

a few events are enough to establish the quantum numbers of a Higgs candidate. No need for coupling to vector bosons.

- **BUT high significances need high FD acceptances → all advantages of MSSM CED process can be useful only if forward detector upgrades (AFP, HPS) contain both, very forward (420 m) and forward (220 m) stations. This is not on the table at the moment: AFP and HPS defendable with ~220 m stations only**

New Ideas ?!

CED MSSM signal still survives the as yet provided LHC exclusion limits. In the allowed region 115.5 < M_h < 127 GeV even 5σ-significances may be achieved for the highest luminosity scenarios. Also: MSSM is in agreement with the tentative hints at M_h = 125 GeV. (although the allowed region may shrink further with time…)

CEP as a way to study old and new heavy resonances.

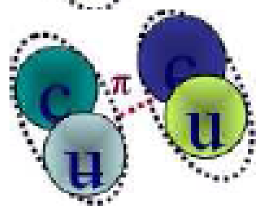
- **Heavy Quarkonia**

- **Zoo of charmonium –like XYZ states**

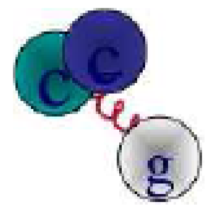
Zoo of charmonium –like XYZ states

Tetraquark:
four tightly bound quarks

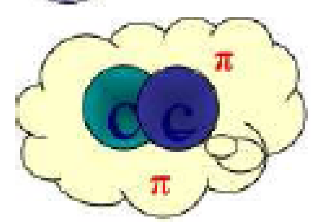
Molecular state:
two loosely bound mesons



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)

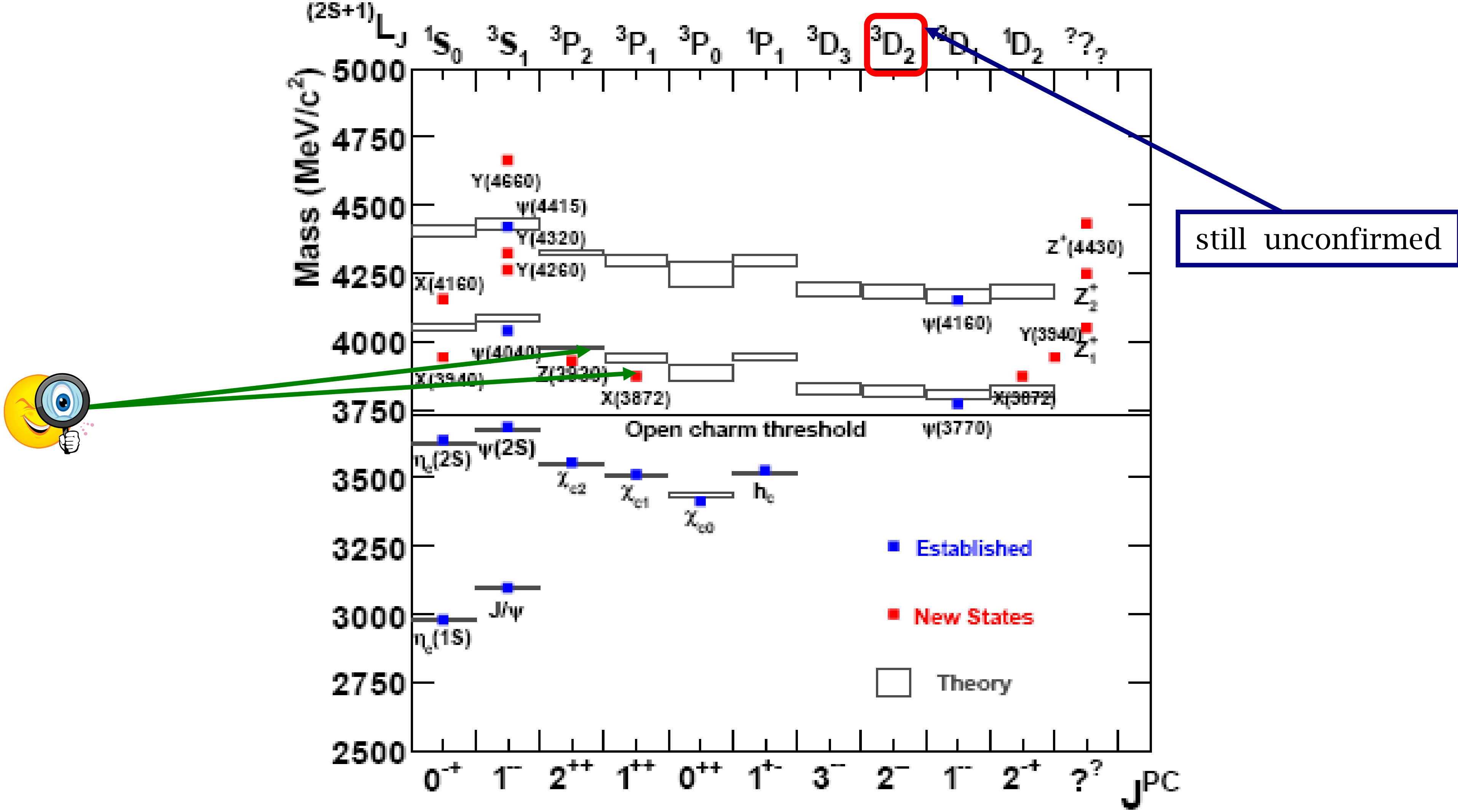


Figure 1: The mass versus the quantum numbers (J^{PC}) for the charmonium-like states. The boxes represent the predictions; blue boxes show the established states, and the red boxes indicate the new states discovered at the B-factories.

X(3872)

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

- Discovered by BELLE in 2003, confirmed by BaBar, CDF, D0, CMS, LHCb.
- 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 $\Gamma(\pi^+\pi^- J/\psi(1S))/\Gamma_{\text{total}}$ >2.6 % ; $\Gamma(\gamma\psi(2S))/\Gamma_{\text{total}}$ >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}

Triggering on J/ψ: M→ J/ψ+γ, J/ψ+ ρ….

Results & Conclusion

First evidence of narrow state at 3823 MeV in $\chi_{c1}\gamma$.

- Most probably the missing $\Psi_2(c\bar{c})$ state.

X(3872) as tetraquark

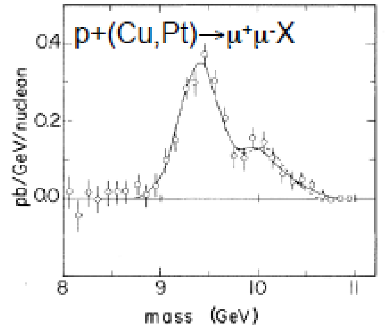
- No signal seen in tetraquark interpretation of X(3872) in $J/\Psi\eta$, $\chi_{c1}\gamma$.
- Most stringent upper limits are provided (0 width hypothesis).

X(3872) properties update.

- Precise X(3872) mass and best limit on width (<1.2 MeV @ 90%C.L)
- Precise branching fractions in B decays (B→X(3872)K)
- No charged partner found.
- J^{PC} (1^{++} or 2^{-+})

P-wave Bottomonia

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

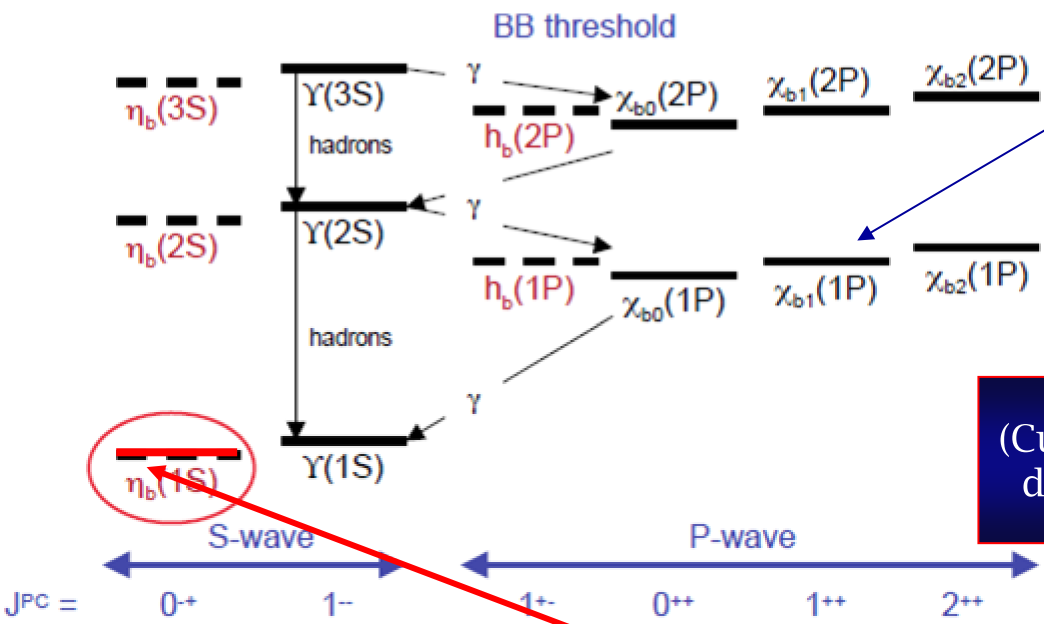


M(Υ)=9.40±0.013
M(Υ')=10.00±0.04
M(Υ'')=10.43±0.12

FNAL, E288

30 years later….

(spins- still unconfirmed)



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))

(Still some puzzles)

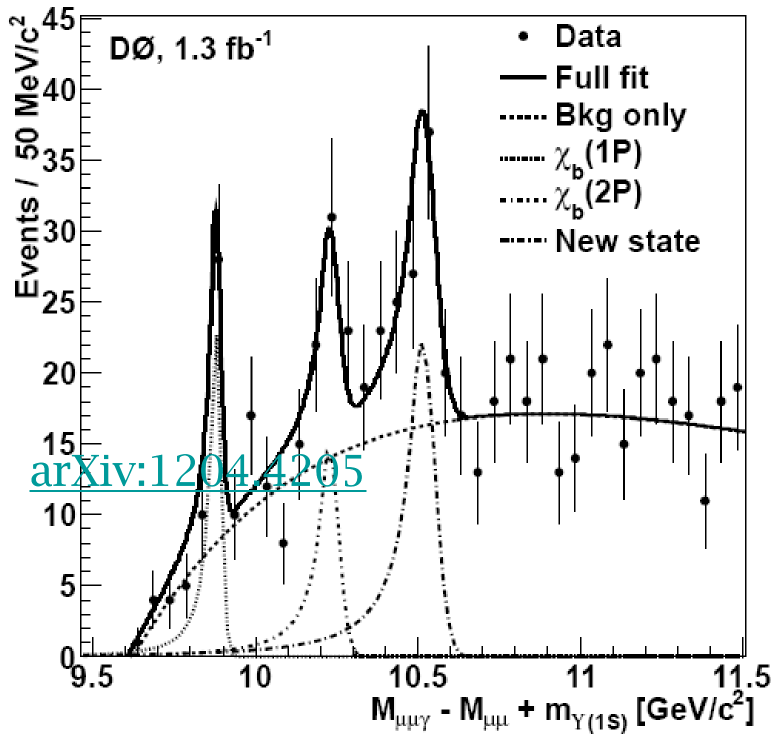
The heaviest and most compact quark-antiquark bound state in nature

FERMILAB-PUB-12-084-E

NEW!

Observation of a narrow mass state decaying into $\Upsilon(1S) + \gamma$ in $p\overline{p}$ collisions at $\sqrt{s} =$ 1.96 TeV

ATLAS-2011



arXiv:1204.4205

$\chi_b(3P)$?

Observation of $\eta_b(2S)$ in $\Upsilon(2S) \to \gamma\eta_b(2S)$, $\eta_b(2S) \to$ hadrons, and Confirmation of $\eta_b(1S)$

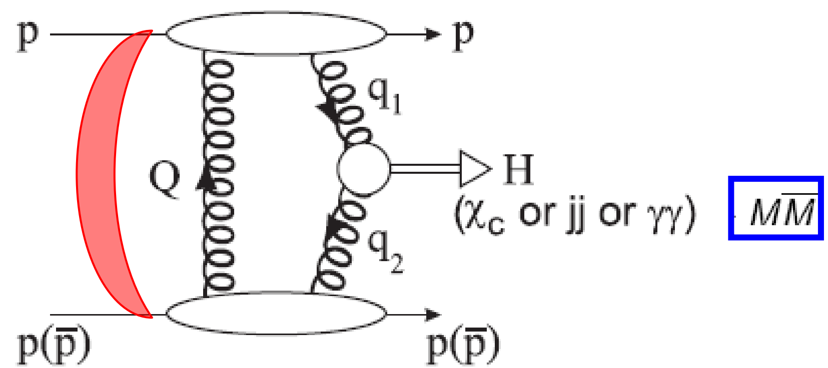
arXiv:1204.4205

$$M(\eta_b(2S)) = 9974.6 \pm 3.1 \text{ MeV}$$

CLEO III

CEP through the eyes of the KRYSTHAL (2008-2012)

- Colliding protons interact via a colour singlet exchange and remain intact: can be measured by adding detectors far down the beam-pipe. **(or LRGs)**
- A system X of mass M_X is produced at the collision point, and *only* its decay products are present in the central detector.



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

- χ_c, $\gamma\gamma$ CEP already observed by CDF and *jj* CEP observed by CDF & D0.
- NEW! χ_{cJ} CEP is reported by LHCb (DIS-11)
- NEW! new CDF $\gamma\gamma$CEP results (PRL-2012)

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

Special Attention

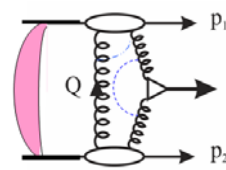
(CMS-2012-first studies)

Standard Candle Processes

How reliable are the calculations ?

Are they well tested experimentally ?

- How well we understand/model soft physics ?
- How well we understand hard diffraction ?
- Is 'hard-soft factorization' justified ?



✷ What else could/should be done in order to improve the accuracy of the calculations ?

So far the Tevatron and LHC diffractive data have been Durham-friendly)

clouds on the horizon ?

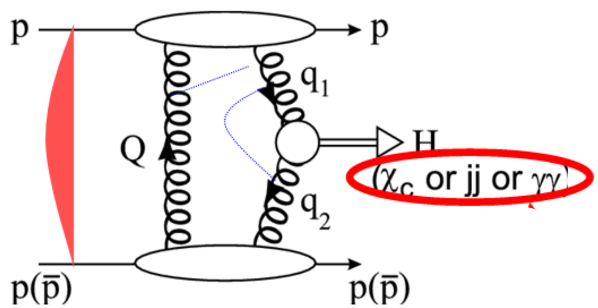
or

?

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

Standard Candle Processes

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

- Can serve as 'Standard Candle' processes, which allow us to check the theoretical predictions for central exclusive new physics signals at the LHC, as well as being of interest in their own right[1].
- This talk will focus on the CEP of $\gamma\gamma$ **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.

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

(2007-2009)

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

FSC@LHC

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

* $p+\bar{p} \rightarrow p+\chi_c+\bar{p}$

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

* $p+\bar{p} \rightarrow p+JJ+\bar{p}$

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!

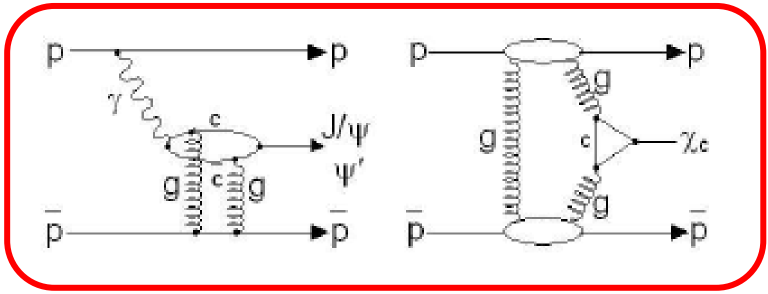
Prprospects !

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

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

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



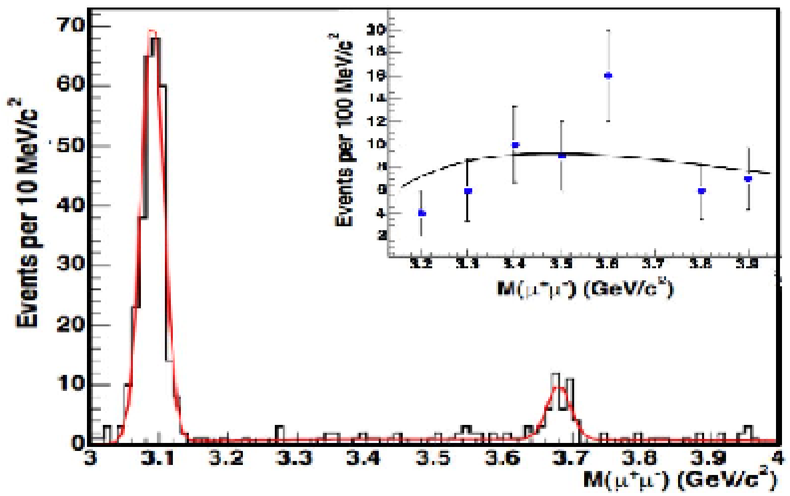


FIG. 2: Mass $M_{\mu\mu}$ distribution of 402 exclusive events, with no EM shower, (histogram) together with a fit to two Gaussians for the J/ψ and $\psi(2S)$, and a QED continuum. All three shapes are predetermined, with only the normalizations floating. Inset: Data above the J/ψ and excluding $3.65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

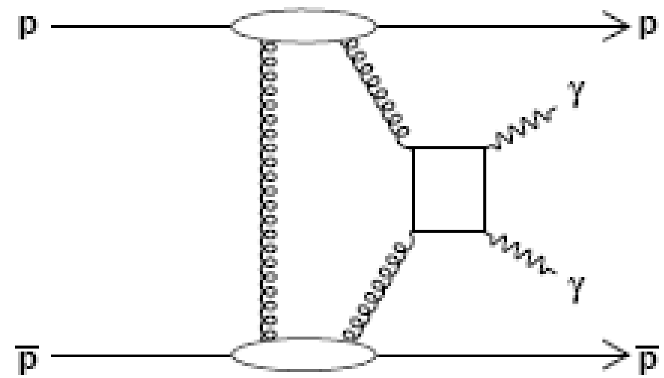
KMRS -2004: **130 nb →80 nb** (PDG-2008)

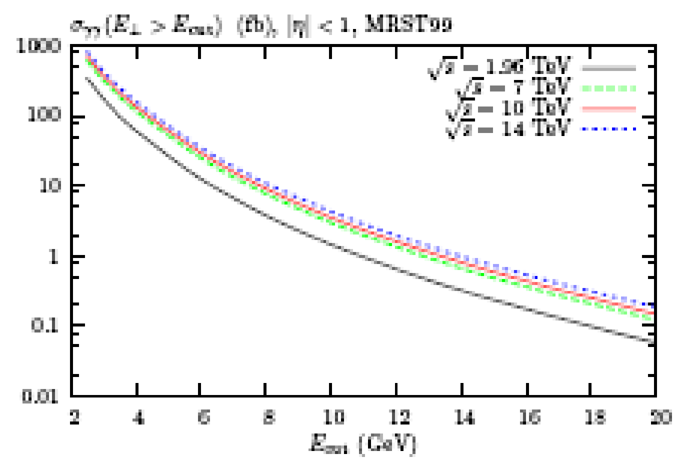
ππ/KK mode as a spin-parity analyzer

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

Dimeson CEP, motivation: $\gamma\gamma$ production

- 3 candidate events observed by CDF (arXiv:0707.237) **Now 43 events**
- Similar uncertainties to χ_c case for low $E_{\perp_\gamma} < E_{\rm cut}$ scale, but this decreases for higher scales.
- More CDF events allow us to probe scaling of σ with cut on photon $E_\perp$ ($\lesssim M_{\gamma\gamma}/2$): strong predicted fall-off with $M_{\gamma\gamma}$ driven by Sudakov factor (already seen in dijet data).





(KMRS-04)
(LKRS-10)

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

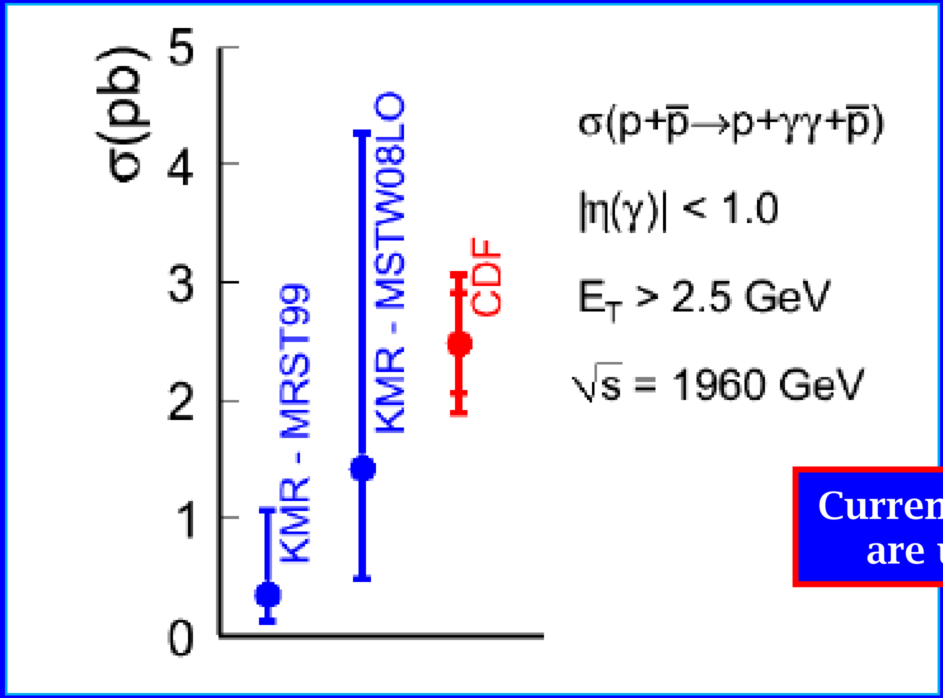
NEW! (now proved to be very small (CDF) in agreement with our expectations)

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

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

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

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



NEW! NLO effects- factor of 1.55

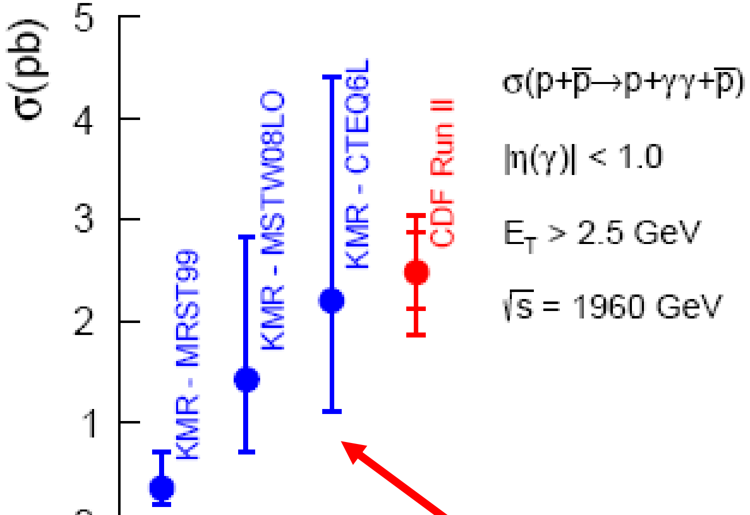
(HKRS in preparation)

Currently theoret. uncertainties are under further revision.

UNIVERSITAS HELSINGIENSIS

New Exclusive $\gamma\gamma$: Conclusions

Exclusive Photon-Pair Production	
Theoretical	$\sigma^{|\eta|<1,E_T>2.5\mathrm{GeV}}_{\mathrm{SuperCHIC}} = 0.35^{\times 3}_{\div 3}\mathrm{pb}$ (MRST99)
	$\sigma^{|\eta|<1,E_T>2.5\mathrm{GeV}}_{\mathrm{SuperCHIC}} = 1.42^{\times 3}_{\div 3}\mathrm{pb}$ (MSTW08LO)
Measured	$\sigma^{|\eta|<1,E_T>2.5\mathrm{GeV}}_{\gamma\gamma\,\mathrm{excl.}} = 2.48\,^{+0.40}_{-0.35}(\mathrm{stat})\,^{+0.40}_{-0.51}(\mathrm{syst})\,\mathrm{pb}$



- First observation of exclusive $\gamma\gamma$ in hadron-hadron collissions.
- Measurement of the cross section of the exclusive production of two high-E_T photons in hadron hadron collisions.
- This corresponds to 1 in 25 billion inelastic collisions.
- Constraint on central exclusive Higgs if existing (produced by same mechanism).
- Paper recently published: Phys. Rev. Lett. 108, 081801 (2012).

NEW! **NLO effects-factor of 1.55**

(HKRS in preparation)

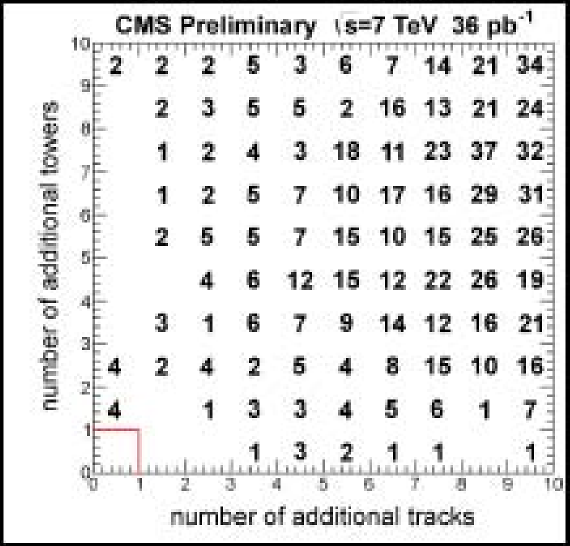
Currently theoret. uncertainties are under further revision.

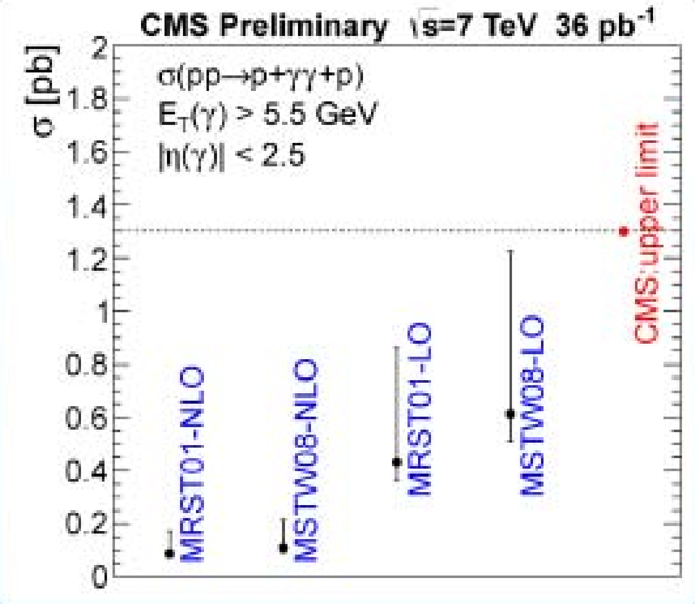
NEW!

Exclusive $\gamma\gamma$ results

- 0 events observed in the signal region
- Set a limit on exclusive + proton-dissociation production of $\gamma\gamma$ with $E_T(\gamma) > 5.5$ GeV, $|\eta(\gamma)| < 2.5$:

$\sigma < 1.30$ pb at 95% CL





- Results compared to several LO/NLO PDF sets with ExHume MC (also checked with SuperCHIC MC)
- Limit just above the highest predictions including uncertainties related to soft survival, Sudakov factors

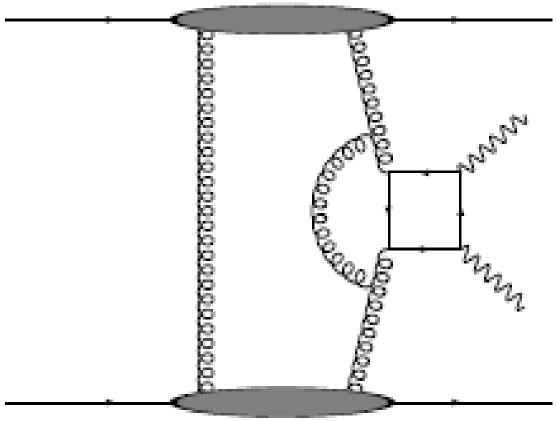
Factor of ~2 due to DD

CMS PAS FWD-11-005

$\gamma\gamma$ CEP: new results (2)

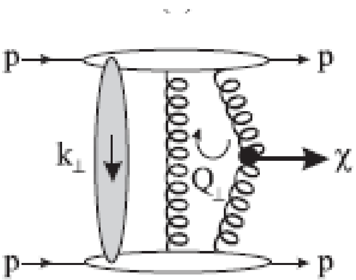
- Expect theory estimates to be somewhat conservative:
  - $S^2_{\rm enh}$ effect somewhat overestimated– latest number $\approx$ 20% bigger.
  - Small fraction of $\gamma\gamma$ events that are not truly exclusive ($\approx$ 10%).
  - NLO corrections could be numerically quite large (c.f. $\chi_{c0} \to gg$ and $H \to gg$, both receive infrared π^2 numerical enhancement). Including finite part of 1-loop corrections[14] to $gg \to \gamma\gamma$ get $K_{\rm nlo} \approx 1.6$, so a similar enhancement may be present. However: need full NLO calculation, divergences included in f_g's now cancel virtual IR divergences, and will get new finite contributions specific to CEP.

- Must also bear in mind reasonable theory uncertainties, but nevertheless some tension between theory (MRST99) and new data exists...



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

Example, O++ -case



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

$$A^2 = 8\pi\Gamma(\chi \to gg)/M_\chi^3 \quad {}^*K_{NLO} \qquad\qquad P(\chi(0^+)) = (\vec{Q}_\perp - \vec{p}_{1\perp}) \cdot (\vec{Q}_\perp + \vec{p}_{2\perp}).$$

- 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

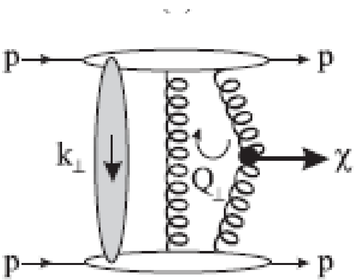
  (Gap size for χ_c at the Tevatron is expected to exceed that for the Higgs at the LHC) KMR-02

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

What we expect within the framework of the Perturbative Durham formalism

(KMR-01, KKMR-03, KMRS-04, HKRS-10)

Example, O++ -case



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

CDF χ_c data

Phys.Rev.Lett.102:242001,2009

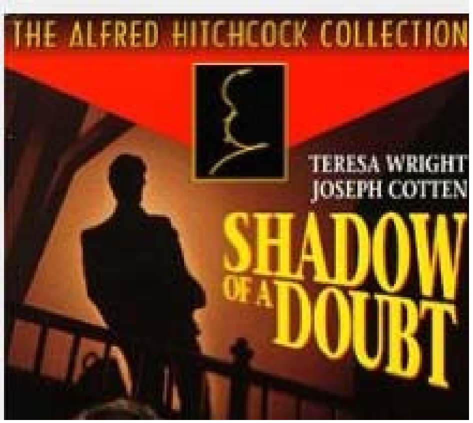
- 65 ± 10 signal χ_c events observed, but with a limited $M(J/\psi\gamma)$ resolution.
- Possible contribution from χ_{c1} and χ_{c2} states assumed, rather than observed, to be negligible.
- Assuming χ_{c0} dominance, CDF found:

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

  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!

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.

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 ($\sim \ln(s/m_\chi^2)$) 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

Prospects of $p\overline{p}$, $\Lambda\overline{\Lambda}$.

Modeling meson pair CEP perturbatively

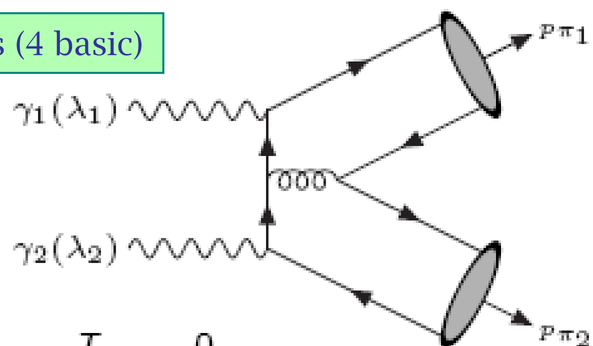
- Simpler exclusive process $\gamma\gamma \to M\overline{M}$ ($= \pi^0\pi^0, \pi^+\pi^-, K^+K^-$...) at large angles was calculated ~30 years ago[3].
- Total amplitude given by convolution of parton level $\gamma(\lambda_1)\gamma(\lambda_2) \to q\bar{q}q\bar{q}$ amplitude with non-perturbative pion wavefunction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

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

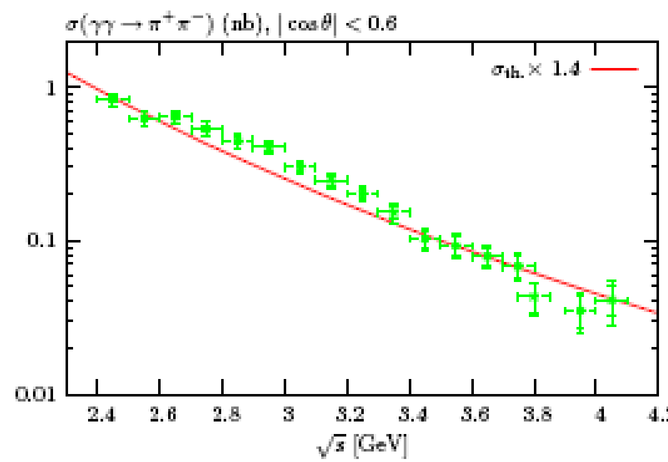
where helicity amplitudes $T_{\lambda_1\lambda_2}$ can be calculated perturbatively.

- With suitable choice of $\phi(x)$ shape, $\gamma\gamma \to M\overline{M}$ data are described quite well (see plot[4].).

40 diagrams (4 basic)



✳ $T_{++} = T_{--} = 0$



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

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

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

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

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

is this easy to understand ?

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

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

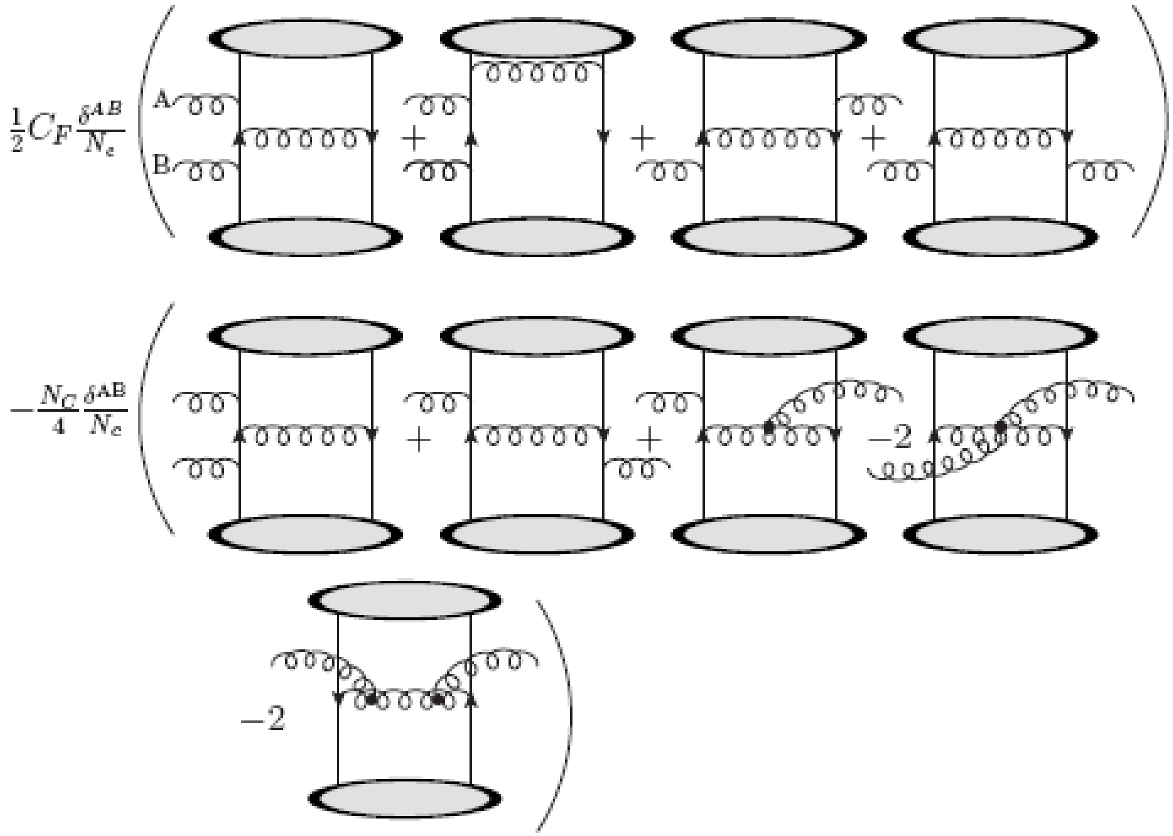
→ $J_z = 0$ amplitudes vanish, as in $\gamma\gamma \to M\overline{M}$ for neutral mesons. We therefore expect a strong suppression in flavour non-singlet $M\overline{M}$ CEP due to $J_z = 0$ selection rule.

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

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

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

is this easy to understand ?



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

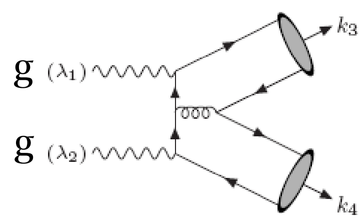
$gg \to M\overline{M}$ amplitude: MHV calculation (1)

- $g(+)g(+) \to q(\pm)\overline{q}(\mp)q(\pm)\overline{q}(\mp)$ amplitude is MHV: maximum $(n-2)$ number of particles have same helicity.
- Such amplitudes known to have remarkably simple forms, and corresponding 'spinor helicity' formalism can greatly simplify calculation.
- T_{++}, T_{--} can be calculated from known Parke-Taylor amplitude[5]

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

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

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



then amplitude reduces to

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

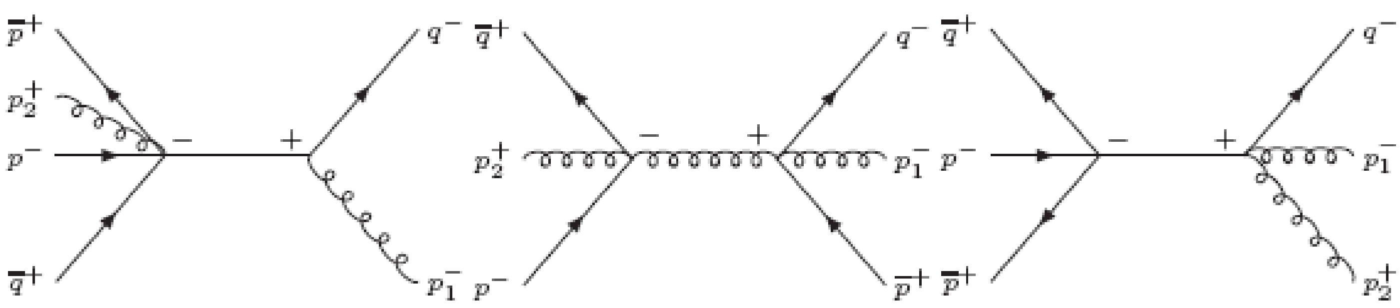
which vanishes from the Schouten identity.

[5] M. L. Mangano, S. J. Parke, Phys. Rept. 200 (1991) 301-367

Here the indices $r(\overline{r})$ and $s(\overline{s})$ refer to the quarks (antiquarks) with colour indices $i_1(j_1)$ and $i_2(j_2)$, respectively, and the labels a_i, b_i refer to the gluons, while the standard spinor contraction '$\langle k, l\rangle$'

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

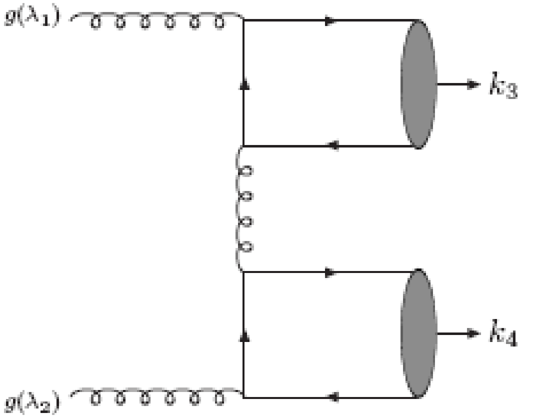
- The vanishing of the $gg \to M\overline{M}$ $J_Z = 0$ amplitudes follow directly from the corresponding 6-particle MHV amplitude. This result depends crucially on the colour singlet projection and collinearity of the $q\overline{q}$ pairs, and only occurs for non-flavour singlet mesons
- The MHV formalism can be extended to include the non-MHV $|J_Z| = 2$ amplitude: contributing amplitudes given by tree graphs in which the vertices are the usual tree-level MHV scattering amplitudes continued off-shell[6]. F. Cachazo, P. Svrcek, E. Witten, JHEP 0409 (2004) 006 [hep-th/0403047].
- More complicated than $J_Z = 0$ case, but an explicit calculation within this framework confirms our result.



[6] see e.g. G. Georgiou, V. V. Khoze, JHEP 0405 (2004) 070.

Flavour singlet meson production

- A second set of diagrams can in general contribute, where the $q\overline{q}$ forming the mesons connected by a quark line (no equivalent diagram in $\gamma\gamma \to M\overline{M}$ process).
- Only relevant for flavour singlet states (e.g. for $gg \to \pi^0\pi^0$, $|u\overline{u}\rangle$ and $|d\overline{d}\rangle$ Fock components interfere destructively).



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

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

Backgrounds for the diphoton CEP @ CMS ?

$pp, \Lambda\overline{\Lambda}$

very promising channels

LAL-12-07

Investigating charmonium production at LHC with the $p\bar{p}$ final state

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(Dated: February 13, 2012)

We propose to investigate various charmonium states using their common decay channel to $p\bar{p}$ at LHC. Having the branching ratios for charmonium decaying into the $p\bar{p}$ final state measured or calculated, we propose to measure the charmonium production rate for both hadroproduction including soft-diffraction and inclusive production from b-hadron decays. We discuss the theoretical impacts in QCD of measuring different charmonium production rates and also the experimental prospects at LHCb, in particular, those for yet unmeasured η_c and h_c.

PACS numbers: 14.40.Pq, 13.25.Gv

I. INTRODUCTION

The quarkonium, the bound state of heavy quarks, has been playing an important role in understanding the nature of the strong interaction. The recent discoveries of the new type of heavy quark bound states, the so-called XYZ particles, are further enriching the quarkonium physics (see [1] for a recent review). The theoretical predictions for charmonium decay and production have been a great challenge of the Quantum Chromo-Dynamics (QCD). An important progress has been made by the effective field theory approach, called the Non-Relativistic QCD (NRQCD) [2]. The NRQCD approach allows to systematically improve theoretical predictions by computing higher order terms in the expansion of α_s as well as of the velocity v. While substantial theoretical efforts have been made, comparison of the NRQCD predictions to the experimental data still leaves open questions (see e.g. [1, 3, 4]). In this article, we propose to further investigate charmonium production as well as decay mechanisms at Large Hadron Collider (LHC) at CERN through a simultaneous measurement of various charmonium states using their decays into the $p\bar{p}$ final state.

The LHC produces huge samples of primary and secondary charmonium, thanks to its extremely high luminosity as well as the large $c\bar{c}$ and $b\bar{b}$ production cross sections of approximately 6 mb and 0.3 mb at $\sqrt{s} = 7$ GeV energy, respectively [5]. The LHCb experiment is the main actor at heavy flavour studies at the LHC due to its precise vertex and track reconstruction, powerful particle identification and flexible trigger [6]. Within the LHCb acceptance, roughly 10^{12} $c\bar{c}$ pairs are produced and a 10^8 J/ψ reconstructed through its $\mu^+\mu^-$ decay per 1 fb^{-1} of data.

The transverse momentum dependence of the production cross section as well as the angular distribution of the $J/\psi \to \mu^+\mu^-$ decay are known to carry important information to probe the NRQCD picture. Some discrepancies reported by the previous measurements of these observables at Tevatron [7–9] motivate a further investigation at LHC. LHC brings a new information by measuring the production at a higher energy. In particular, the LHCb unique acceptance of $1.9 < \eta < 4.9$ fully instrumented coverage gives access to the QCD studies at the forward region [5]. Furthermore, powerful particle identification of LHCb makes it possible to measure the production rates of different charmonium states.

So far, charmonium study at LHC has been limited to using the $\mu^+\mu^-$ final state, thus mainly focused on J/ψ, $\psi(2S)$ or radiative transitions of $\chi_{c0,1,2}$ to J/ψ. The $p\bar{p}$ final state is more convenient since most of the charmonium states can decay into it. We propose to investigate charmonium prompt production as well as inclusive charmonium yield from b-hadron decays using the $p\bar{p}$ final state, which may allow us to study all the charmonium states below the $D\overline{D}$ threshold, $J/\psi, \eta_c, \chi_{cJ}, h_c, \psi(2S), \eta(2S)$. We also suggest to test the potential $X(3872) \to p\bar{p}$ decay. Prompt production assumes hadroproduction including soft-diffraction, although we do not consider the latter in this article.

While experimental measurements can provide only the information of the product of the cross section and the branching ratio, the branching ratios for the $p\bar{p}$ final state for many charmonia are rather well measured. Using these measured values, we can extract the information of the production cross section. For h_c, the branching ratio for the $p\bar{p}$ final state is not known, and we estimate it theoretically below.

In the next section, we propose the simultaneous measurement of various charmonium states with the $p\bar{p}$ final state at LHCb. We also discuss what new information in terms of testing the NRQCD can be obtained through this study. In section 3, we attempt to evaluate the branching ratio of $h_c \to p\bar{p}$ process. In section 4, we discuss other final states which could be used, and our conclusion is given in section 5.

II. INVESTIGATING VARIOUS CHARMONIUM STATES USING THE COMMON DECAY MODE INTO $p\bar{p}$

If a given charmonium state has a significant branching ratio for the $p\bar{p}$ decay channel, a simultaneous reconstruction of this charmonium state and the well-measured J/ψ state via decay to $p\bar{p}$ is experimentally advantageous: in the ratio of topologically identical channels, systematic uncertainty partially cancels. In particular, relative prompt production and inclusive yield of charmonium

SuperCHIC MC (KRYSTHAL coll.- 08-12)

A MC event generator including[15]:

- 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...?).

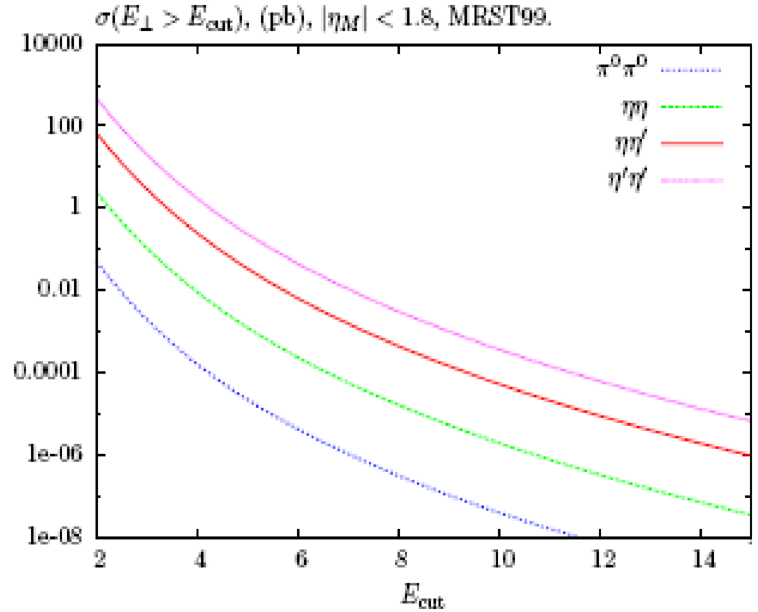
$\rightarrow$ Via close collaboration with CDF, STAR and LHC collaborations, in both proposals for new measurements and applications of SuperCHIC, it is becoming an important tool for current and future CEP studies.

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

Numerical Results

(our new results will be available soon)

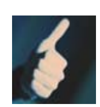
- Strong enhancement in flavour singlet states clear, with precise η'/η hierarchy given by choice of $\eta - \eta'$ mixing angle.
- CEP cross sections for vector mesons ($\rho\rho$, $\omega\omega$, $\phi\phi$) can be calculated in the same way.



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

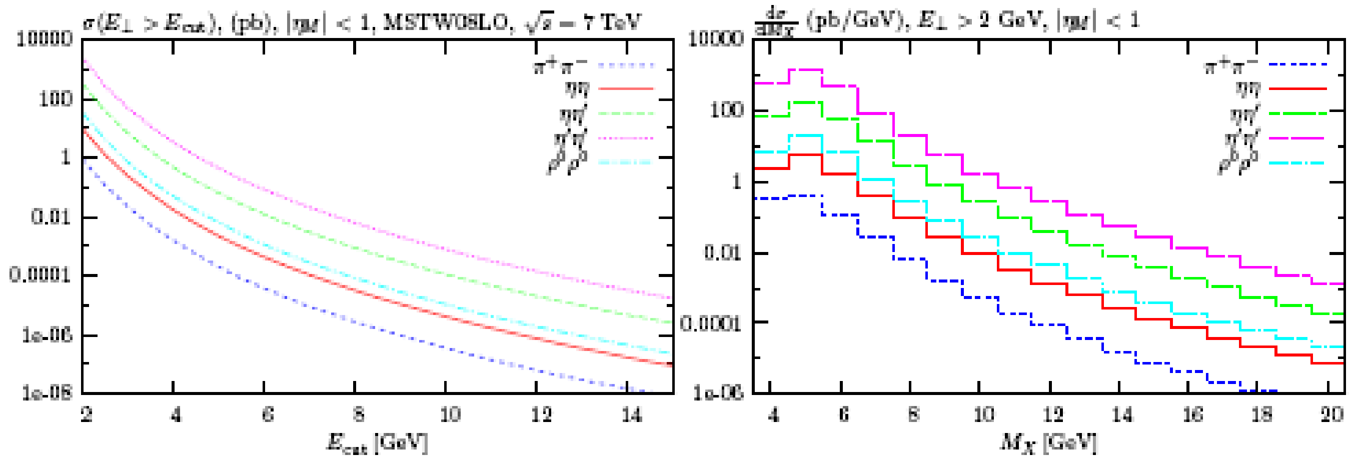
(K-factor,..)

New CDF data nicely confirm this !



Prospects of further measurements

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 could in principle be an important background to $\gamma\gamma$ CEP, but we find this not to be the case. (However: possible $J_Z = 0$ contribution from higher twist effects, NNLO corrections... could increase flavour non-singlet rate by a factor 'a few'.)
- New CDF $\gamma\gamma$ data (arXiv:1112.0858): $N(\pi^0\pi^0)/N(\gamma\gamma) < 0.35$ @ 95% confidence $\rightarrow$ supports our result (Theory: $\sigma(\pi^0\pi^0)/\sigma(\gamma\gamma) \approx 0.01$).

$\gamma\gamma$ CEP: new results (2)

- Expect theory estimates to be somewhat conservative:
  - $S^2_{\rm enh}$ effect somewhat overestimated– latest number $\approx$ 20% bigger.
  - Small fraction of $\gamma\gamma$ events that are not truly exclusive ($\approx$ 10%).
  - NLO corrections could be numerically quite large (c.f. $\chi_{c0} \to gg$ and $H \to gg$, both receive infrared π^2 numerical enhancement). Including finite part of 1-loop corrections[10] to $gg \to \gamma\gamma$ get $K_{\rm nlo} \approx 1.6$, so a similar enhancement may be present. However: need full NLO calculation, divergences included in f_g's now cancel virtual IR divergences, and will get new finite contributions specific to CEP.
- Must also bear in mind reasonable theory uncertainties, but nevertheless some tension between theory (MRST99) and new data exists.

→ More theory work needed.

→ More data @ the LHC would be very useful in further constraining these issues...

[10] Z. Bern, A. De Freitas, L. J. Dixon, JHEP **0109** (2001) 037.

$\gamma\gamma$ CEP: PDF comparison (2)

- The gluon density is not sufficiently well described by fixed order, twist = 2 DGLAP at low x and Q^2.
- There is some indication from, e.g. diffractive J/ψ production that the $g(x, Q^2)$ is larger than the current NLO PDFs[15].

→ Can also use, e.g. $\gamma\gamma$ CEP to shed light on the gluon density, with the LO and NLO gluons giving approx. upper and lower bounds on the CEP cross section due to the (large) PDF uncertainty.

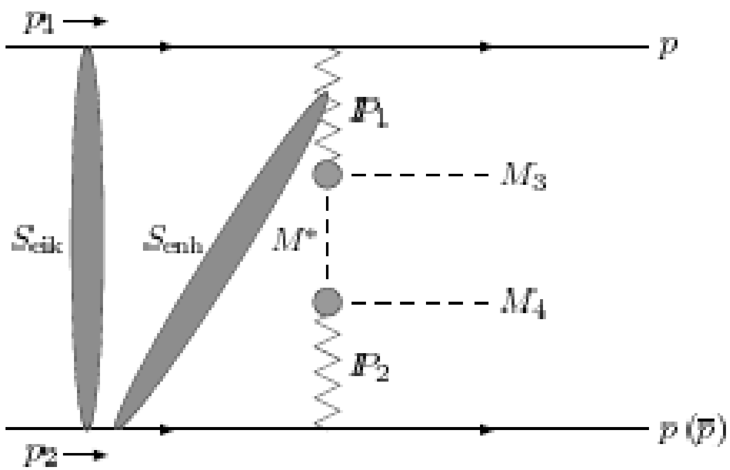
- Use an updated model[16] for $S^2_{\rm eik}$, which includes the new TOTEM elastic data (requires $\Omega(b_t)\uparrow$ in particular at lower b_t, and therefore $S^2_{\rm eik}\downarrow$), and for $S^2_{\rm enh}$ (somewhat higher than previously), gives factor ~ 2 decrease in σ @ 7 TeV. The $\gamma\gamma$ CEP cross sections (in pb) are predicted to be (for $E_\perp > 2.5$ GeV):

	MSTW08LO	CTEQ6L	MRST99	CT10	NNPDF2.1
$\sqrt{s} = 1.96$ TeV ($\lvert\eta\rvert < 1$)	1.4	2.2	0.35	0.47	0.29
$\sqrt{s} = 7$ TeV ($\lvert\eta\rvert < 1$)	2.1	2.0	0.32	0.29	0.16
$\sqrt{s} = 7$ TeV ($\lvert\eta\rvert < 2.4$)	6.2	6.2	0.94	0.91	0.50

[15] A. Martin, C. Nockles, M. G. Ryskin, and T. Teubner, Phys.Lett. B662, 252 (2008), 0709.4406.

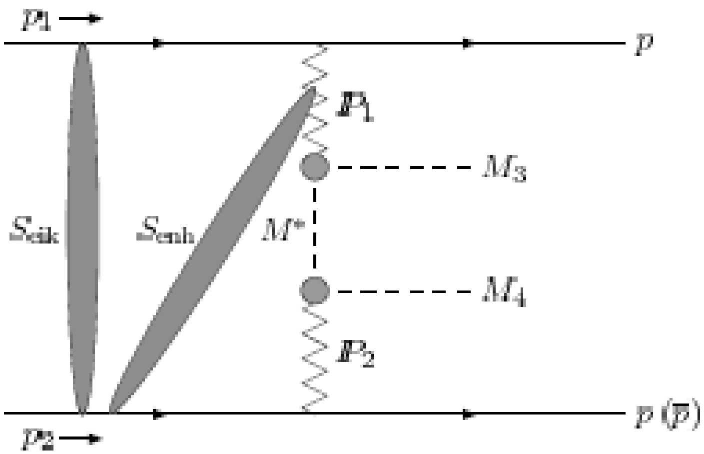
[16] M. Ryskin, A. Martin, and V. Khoze, (2012), 1201.6298.

Non-perturbative production, screening (1)



- Need exclusive cross section $\rightarrow$ must also take into account probability not produce additional particles, i.e. include screening corrections, in Reggeon formalism described by exchange of one (or more) additional Pomerons:
  - Exchange between incoming protons $\rightarrow S_{\rm eik}$ ($\sim$ 0.05).
  - Exchange between the upper (lower) proton and the lower (upper) meson and Pomeron $\rightarrow S_{\rm enh}$ ($\sim$ 0.35 for $\pi^+\pi^-$):
    - Do not include exchange between $p_1(p_2)$ and $M_3(M_4)$, as already included in effective Pomeron $P_1(P_2)$.
    - Main effect is expected to be from the secondary proton-meson interaction, due to smallness of triple Pomeron vertex.

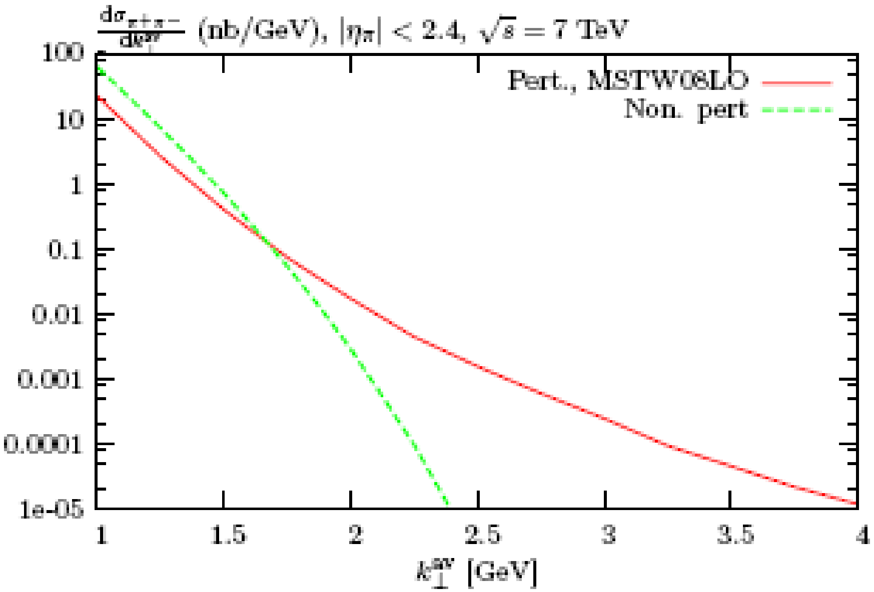
Non-perturbative production, screening (2)

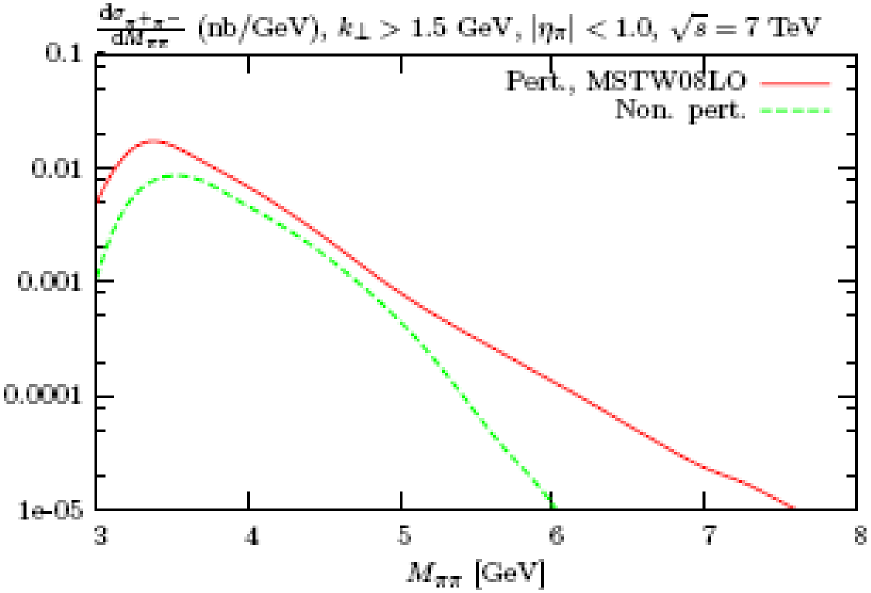


- Need no emission of secondaries in $I\!PI\!P \to M_3M_4$ process, but treatment in terms of Regge exchanges between mesons contradicts causality:
  - Lab time taken to form Reggeon $\propto E$ but meson pair production time is almost instant $\propto 1/E \to$ at high $s_{\pi\pi}$ outgoing mesons cannot talk to each other (c.f. final state Coulomb interaction, $q\overline{q} \to$ meson formation...).
  - Should instead include Reggeization of M^* exchange (t–channel meson has its own size), but we choose a simple phenomenological form to account for Poisson probability not to emit secondaries in the initial meson pair production state, $\sim \exp(-\langle n \rangle)$ (~ 0.2 for $\sqrt{\hat{s}} \sim M_X$).

$\to$ Screening effects tend to suppress non-perturbative CEP cross section, in particular as $\sqrt{\hat{s}}$ is increased (also $F_M(k_\perp^2)$ as $k_\perp \uparrow$).

Meson pair CEP: pert. vs. non-pert.





$\rightarrow$ By cutting on meson $k_\perp$ (and η), can potentially isolate perturbative contribution, although in region where statistics may be an issue for $\pi^+\pi^-(K^+K^-)$. Can also consider other observables...

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

pp, $\Lambda\overline{\Lambda}$.

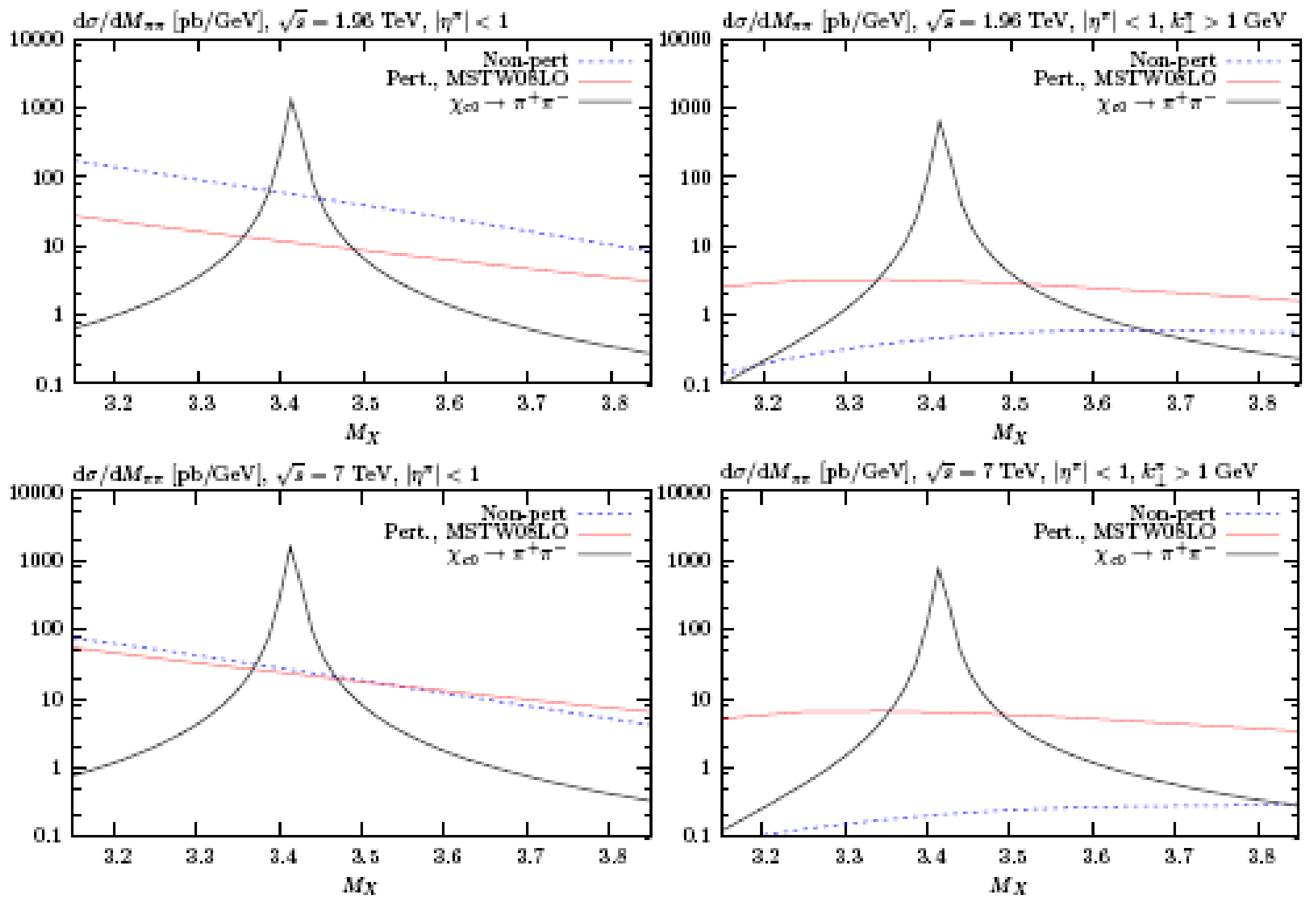
- $\mathrm{Br}(\chi_{c0} \to \pi^+\pi^-) = (0.56 \pm 0.03)\%$ and $\mathrm{Br}(\chi_{c2} \to \pi^+\pi^-) = (0.16 \pm 0.01)\%$, while $\chi_{c1} \to \pi^+\pi^-$ does not occur.

$\to$ χ_{c0} CEP via $\pi^+\pi^-$ channel expected to strongly dominate, with similar/bigger production cross sections to $J/\psi\gamma$ channel (similarly for K^+K^- channel).

- Ideally suited to, e.g., LHCb and STAR experiments (excellent PID and high momentum resolution), but also ALICE ($\pi^+\pi^-$ CEP at lower $M_{\pi\pi}$ already observed[6]), CMS, ATLAS...
- Continuum $\pi^+\pi^-$ CEP background under control?
  - Non-perturbative contribution (lower $M_{\pi\pi}/k_\perp(\pi)$), modeled using Regge theory.
  - Perturbative contribution (higher $M_{\pi\pi}/k_\perp(\pi)$), modeled using hard exclusive formalism.

[6] See e.g. R. Schicker, arXiv:1110.3693

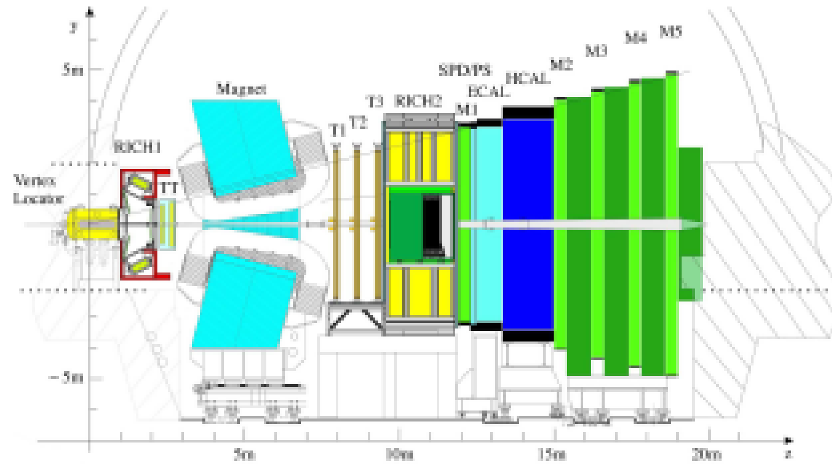
$\chi_c \to \pi^+\pi^-$ CEP (3) (preliminary)



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

χ_c CEP @ LHCb (1)

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



- LHCb see[1]:

Proton dissociation conribution

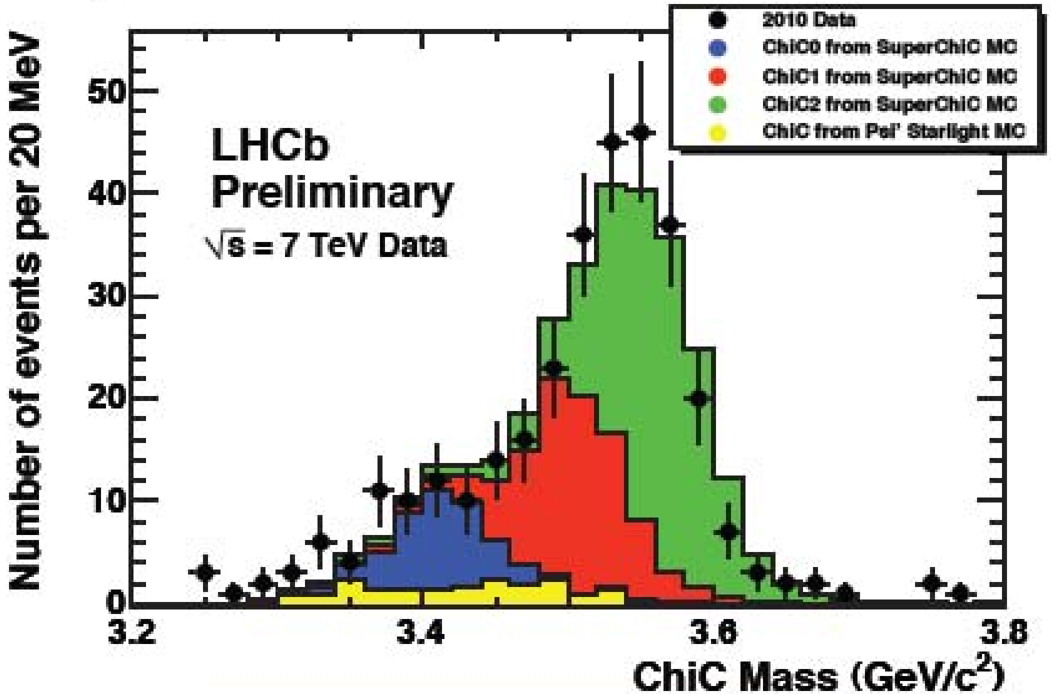
	$\sigma(pp \to pp(J/\psi + \gamma))$ LHCb (pb)	SuperChic prediction (pb)
χ_{c0}	9.3 ± 4.5	14
χ_{c1}	16.4 ± 7.1	10
χ_{c2}	28 ± 12.3	3

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

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

J/Ψ + Photon Mass

- X_{c0}:X_{c1}:X_{c2} ratio determined from fit to mass spectrum
- Ψ(2S) background



25 X_{c0} Candidates

56 X_{c1} Candidates

99 X_{c2} Candidates

Future Plans

- In 2011 LHCb collected ~ 1 fb^{-1}
- Average μ ~ 1.5
- x 30 Increase in Stats!!

→ Odderon? Low x gluon behavior?

→ χ_b ? More perturbative better test of CEP

→ Luminosity measurement with γγ Dimuons

- Low Mult DiHadron Trigger

→ Exclusive $\pi^+\pi^-$, K^+K^-

→ $\chi_c \rightarrow \pi^+\pi^-, K^+K^-$ (0,1,2 Separation)

→ MisId determination for γγ Dimuons

- Low Mult DiPhoton Trigger

→ Exclusive γγ

Dermot Moran (University of Manchester)
On behalf of the LHCb Collaboration

UNIVERSITAS HELSINGIENSIS

Summary and What's Next?

CDF II results on CEP

- ✓ Observation of Exclusive Dijet events $\rightarrow$ PRD 77, 052004 (2008).
- ✓ Observation of Exclusive e^+e^- $\rightarrow$ PRL 98, 112011 (2007).
- ✓ Observation of Exclusive Charmonium and Dimuon $\rightarrow$ PRL 102, 242001 (2009).
- ✓ Search for Exclusive Z & High Mass Dilepton $\rightarrow$ PRL 102, 222002 (2009).
- ✓ New: Observation of Exclusive Diphoton $\rightarrow$ PRL 99, 242002 (2007) & PRL 108, 081801 (2012).

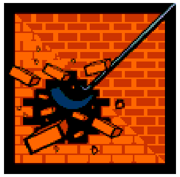
What next?

- Gap-X-Gap study: X being $\geqslant$ 2hadrons, and $\chi_c \rightarrow \pi^+\pi^-$, K^+K^-.
- More on exclusive $\gamma\gamma$ and $\pi^0\pi^0$ (limit?).
- Analysis of low s scan data (300 and 900 GeV).

Towards a 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 ?

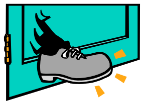


Yes, an addition of Forward Shower Counters around beam pipes at CMS!

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

(Alice is installing such counters, discussions at the LHCb)

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



Diffraction with Forward Shower Counters FSC

Mike Albrow,

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

What: We propose to install a set of scintillation counters around both outgoing beam pipes at CMS, ~ 60m – 100 m

Why:

(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

(f) To monitor beam conditions on incoming and outgoing beams.

(g) To test forward flux simulations (MARS etc.)

(h) Additional Luminosity monitor.

Also: They may provide valuable tests of radiation environment to be expected for HPS = High Precision Spectrometers

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Forward physics with rapidity gaps at the LHC

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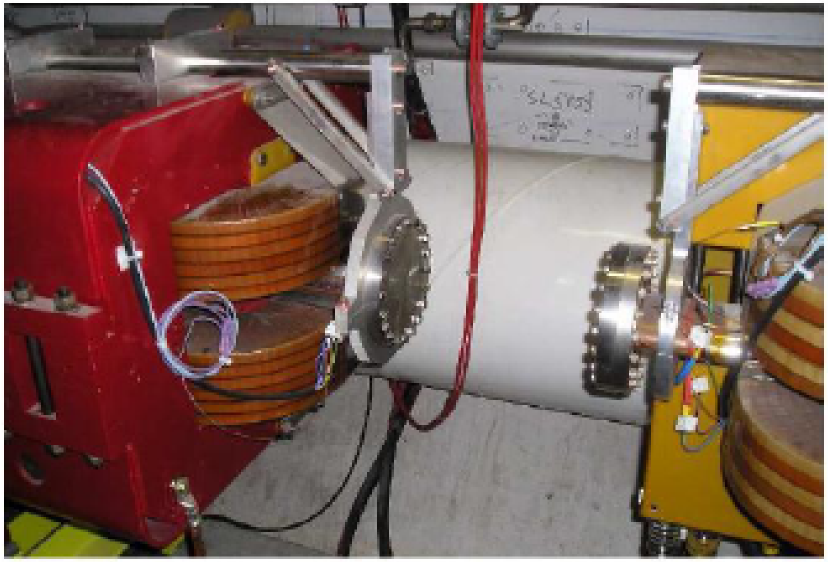
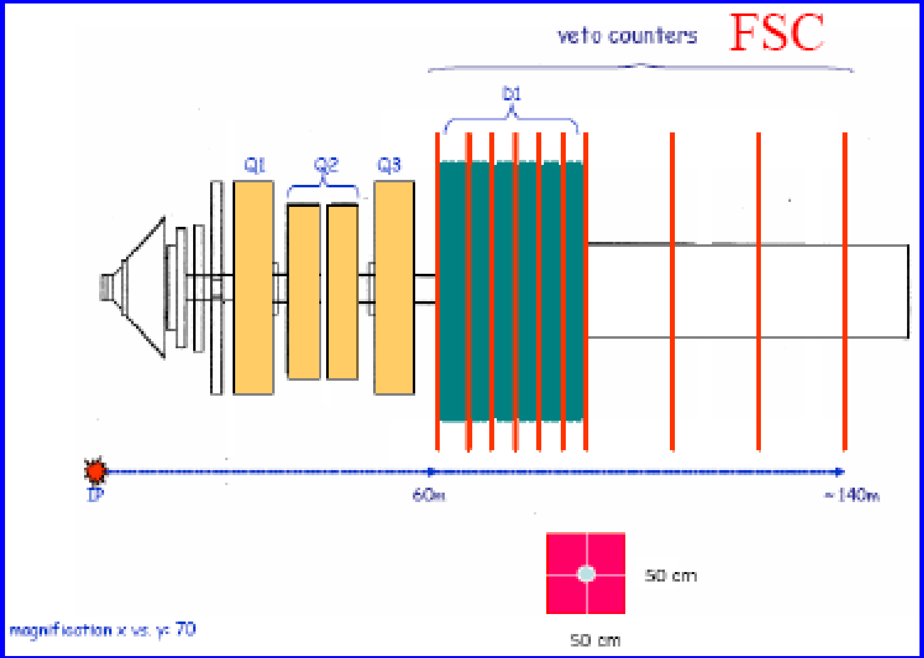


Accessible warm beam pipe between BMX magnets



Can put scintillators at several z-locations
FSC = Forward Shower Counters

Do not see primary particles, but showers in pipe and other material.

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

Station 3 (114m) Installed on both sides.

March Technical Stop (28-31.03.11).

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 $\langle n/x \rangle < \sim 5$
(Do not expect to use > 2012)

The FSC- these are for real !

Main concern- lumi per bunch crossing might be too high.

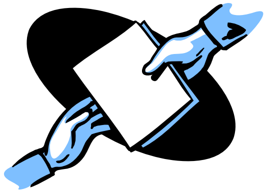
What about a precise measurement of SD? This certainly needs all the counters and some low lumi run, or at least bunches.

Both CMS &ATLAS requested a special low-PU run in 2012 with lumi about 100 pb^{-1}.

Summary and Outlook

- CEP processes observed at the Tevatron, RHIC and early LHC can serve as 'standard candles' for new physics CEP at the LHC.
- New LHCb $\chi_c \to J/\psi$ data, support: previous suggestion that $\chi_{c(1,2)}$ contribute to CDF χ_c data.
- First estimates of dissociative background given.
- χ_{c0} CEP via two-body decays ($\pi^+\pi^+$, K^+K^-...) interesting and realistic channels, with continuum background expected to be low. Other decay channels (e.g. $p\overline{p}$, $\Lambda\overline{\Lambda}$, $2(\pi^+\pi^-)$...) also possible.
- The CEP of mesons pairs at high invariant masses ($/k_\perp$) is an interesting process, representing a novel application of pQCD framework for describing exclusive processes.
- Measurement of $\pi\pi$ (KK...) CEP at lower mass/$k_\perp$ values would help constrain non-perturbative models.
- CEP could help probe the gluonic structure of η, η' mesons.
- Perturbative calculation predicts that $\pi^0\pi^0$ BG to $\gamma\gamma$ CEP is suppressed.
- New CDF $\gamma\gamma$ data gives encouraging results! Could shed light on the gluon density...
- More CEP results to come from RHIC, the Tevatron and LHC in the future.

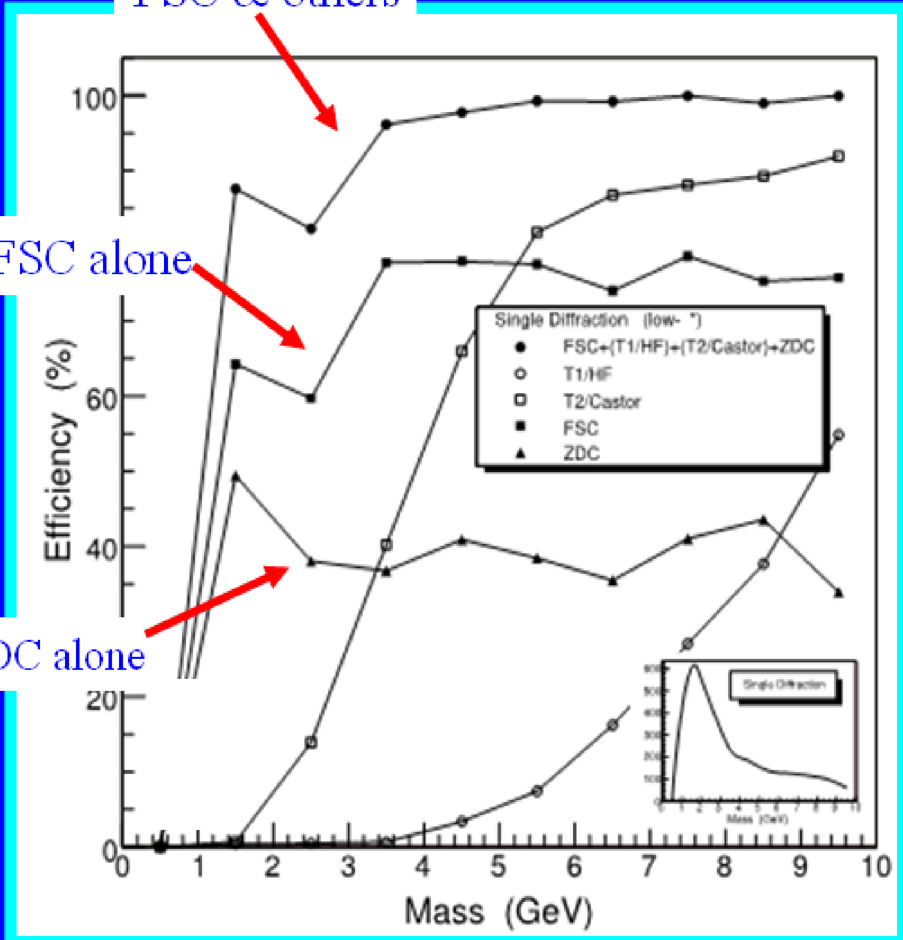
Productive cooperation between the theorists and experimentalists.
Welcome to the Exclusive CEP club!

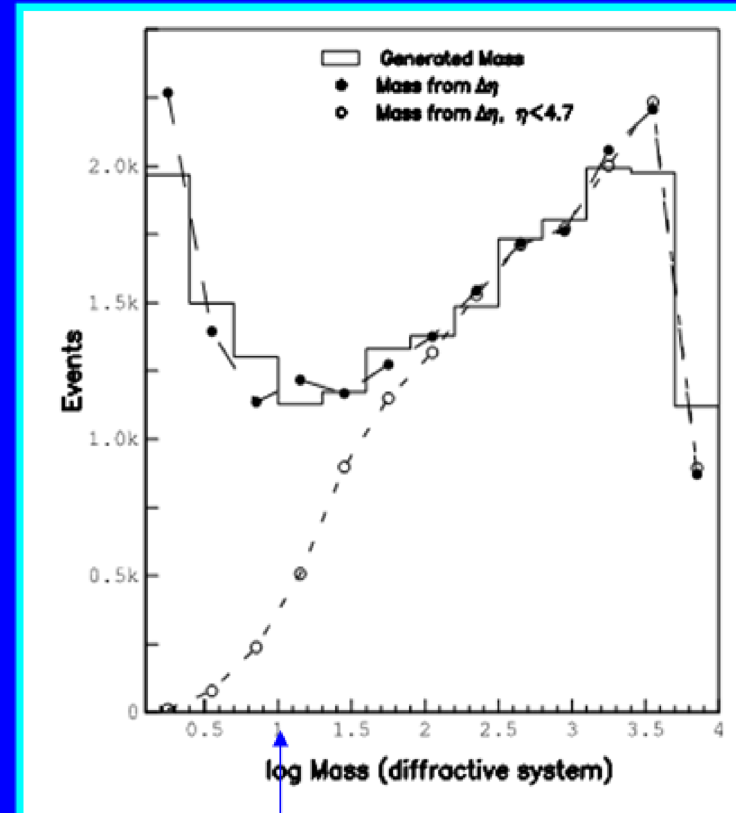



THANK YOU


QUESTIONS?

BACKUP





>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:

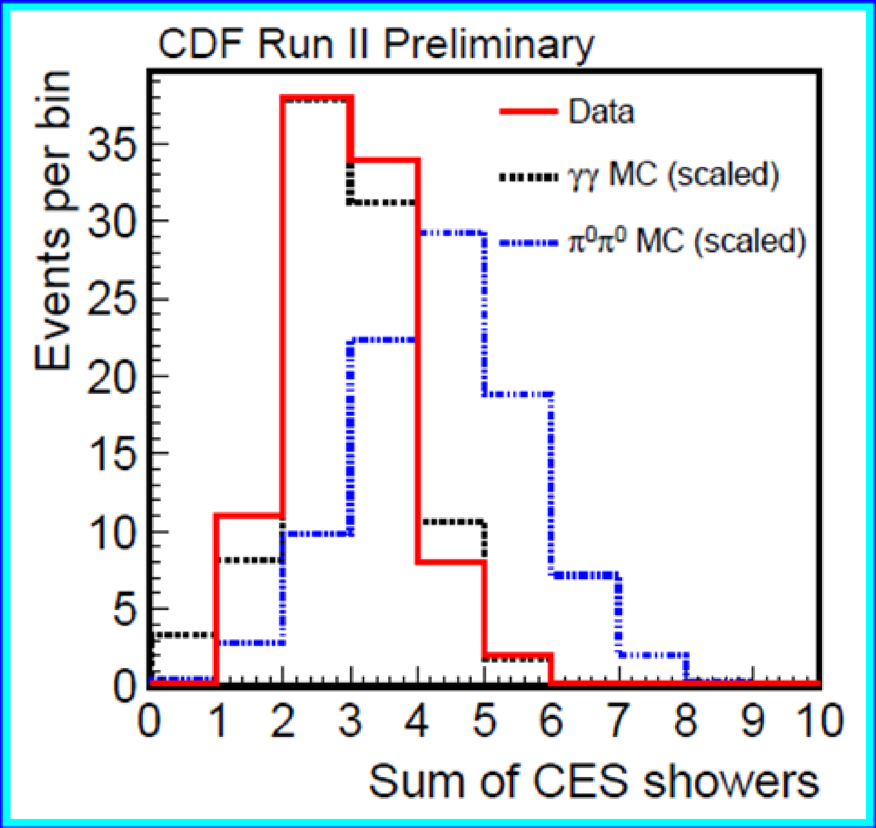
(a) full η coverage

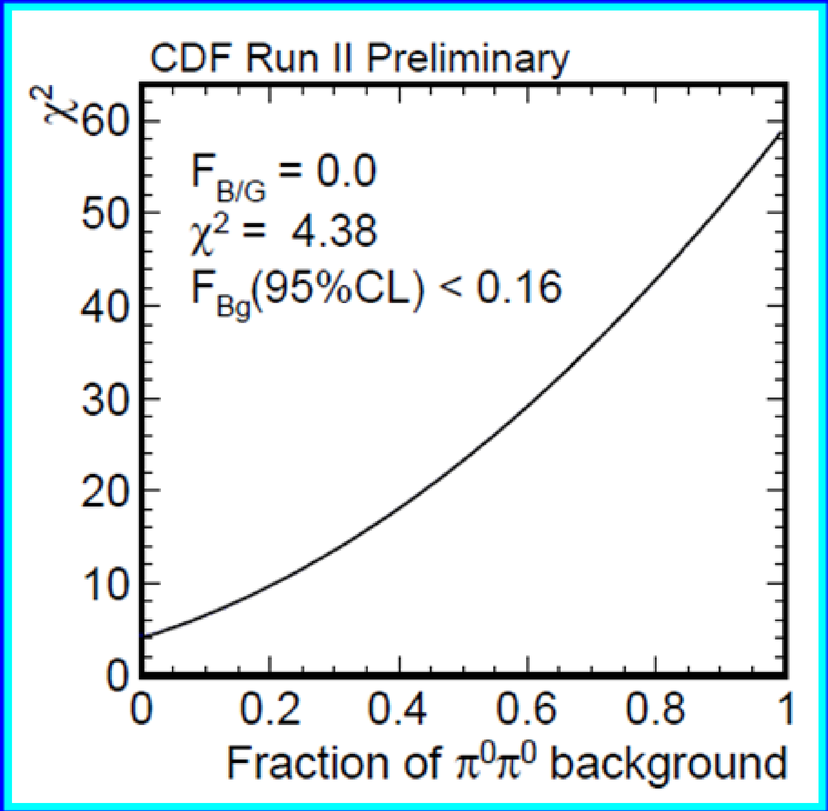
(b) $\eta < 4.7$ (no FSC)

Below 10 GeV/c² FSC contain most particles

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

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



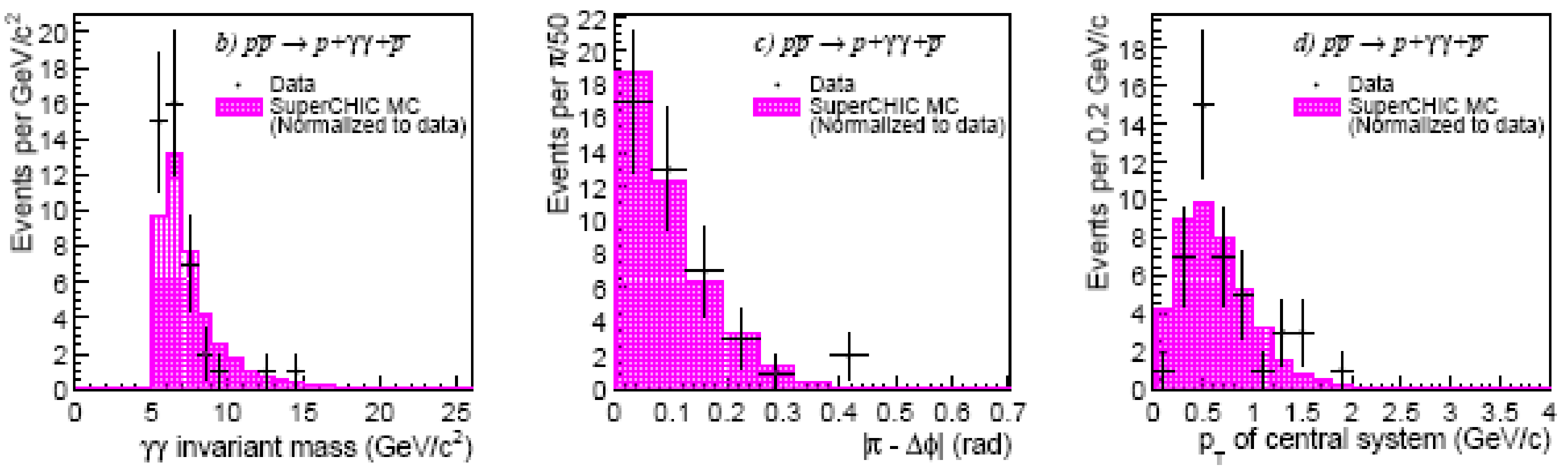


Result: Best fit is with ZERO background from $\pi^0\pi^0 \rightarrow 4\ \gamma$

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

$\gamma\gamma$ CEP: new results (1)

- $\gamma\gamma$ CEP: represents clean signal, with less of the theory issues related to, e.g. χ_c CEP. $\to$ ideal 'standard candle'.
- New CDF $\gamma\gamma$ data[11] for $E_\perp(\gamma) > 2.5$ GeV, $|\eta(\gamma)| < 1$. They find $\sigma_{\gamma\gamma} = 2.48^{+0.40}_{-0.35}$ (stat) ${}^{+0.40}_{-0.51}$ (syst) pb,
- Theory predictions: 1.42 pb (MSTW08LO) and 0.35 pb (MRST99), with approx. uncertainties $\sim \stackrel{\times}{\div} 2$.

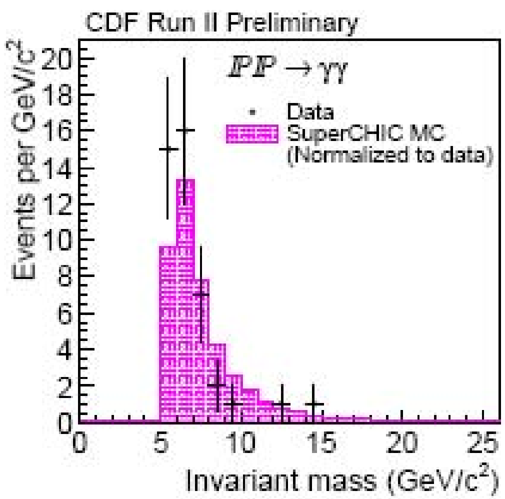


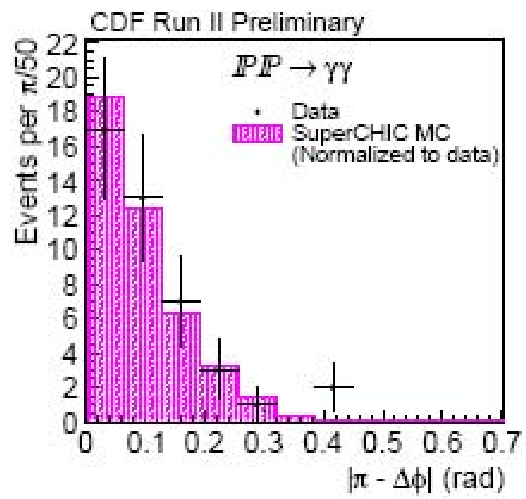
[11] CDF Collaboration, T. Aaltonen et al., Phys. Rev. Lett. 108, 081801 (2012) 1112.0858. (plots taken from here)

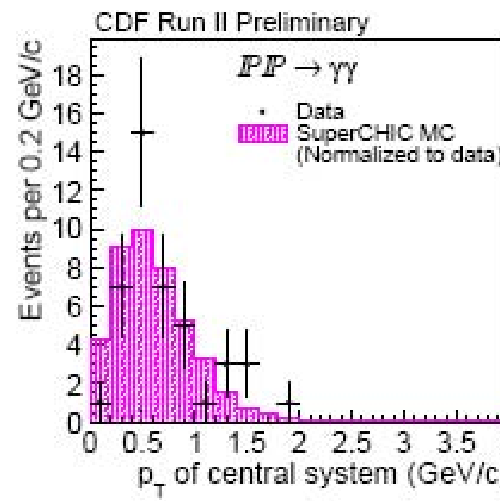
New Exclusive $\gamma\gamma$: Numbers and Kinematics

- No tracks in event.
- No conversion allowed.
- SuperCHIC signal MC
  (KMR, Harland-Lang, Eur.Phys.J. C69 (2010) 179).

Exclusive $\gamma\gamma$ (events)	43
$\mathcal{L}_{\text{int}}$	1.11 ± 0.07 fb^{-1}
Photon pair eff.	0.40 ± 0.02 (stat)± 0.03 (syst)
Exclusive eff.	0.0680 ± 0.004 (syst)
Conversion acceptance	0.57 ± 0.06 (syst)
$\pi^0\pi^0$ background (events)	0.0, $<$ 15 (95% C.L.)
Dissoc. backg. (events)	0.14 ± 0.14 (syst)



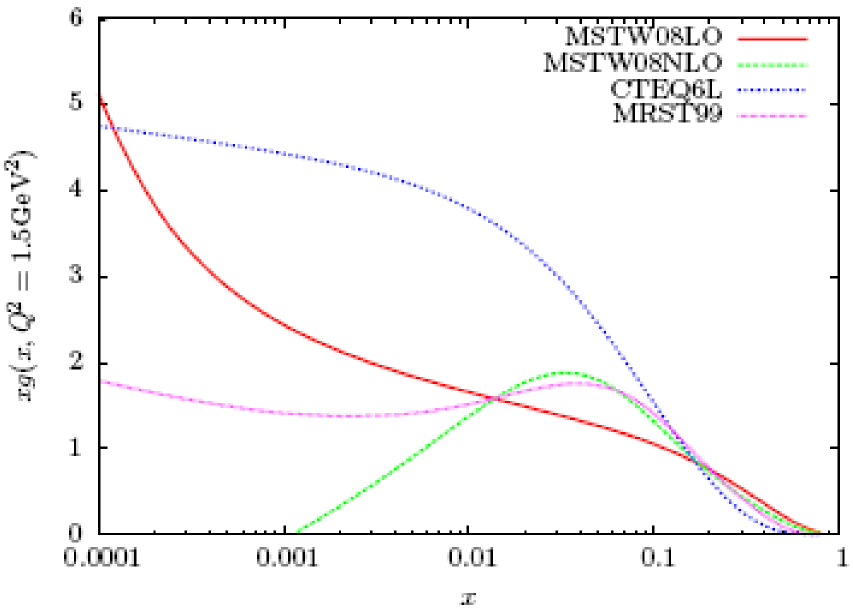




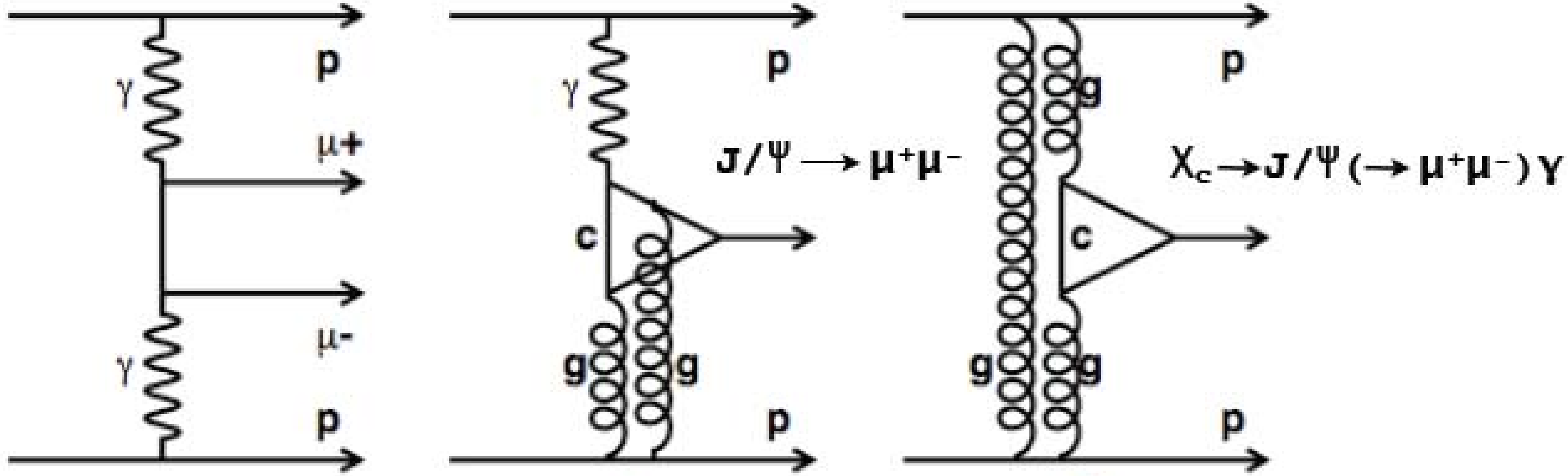
Note: Normalized to data. No overflow! Could be $\gamma\gamma$ or $\pi^0\pi^0$ ($\gamma\pi^0$ forbidden by C-parity).

$\gamma\gamma$ CEP: PDF comparison (1)

- At the low-x, Q^2 values relevant for the CEP of low mass objects there is a large PDF uncertainty (recall $\sigma_{\rm CEP} \sim (xg)^4$).
- The fitted gluon at low x comes almost entirely from the DGLAP evolution, $\mathrm{d}F_2(x,Q^2)/\mathrm{d}\ln Q^2$, and depends on the approximations of this, i.e. smallness of higher order and power effects. At lower scales these are not negligible.
- LO and NLO gluons at low x, Q^2 have completely different behaviours:
  - LO: steep x dep. (compensating for lack of 1/z singularity in LO $P_{qg}(z)$), gives only fair description of HERA F_2 data.
  - NLO: much flatter, with modern fits preferring a negative gluon for $x \lesssim 10^{-2}$, $Q^2 \sim Q_0^2$ (screening corrections not included in linear DGLAP, possible $1/z$ resummation required...), which clearly cannot be trusted for CEP.



Exclusive Dimuons



Ideal for luminosity measurement

Allows Odderon search

Allows test of CEP theory (Higgs predictions)

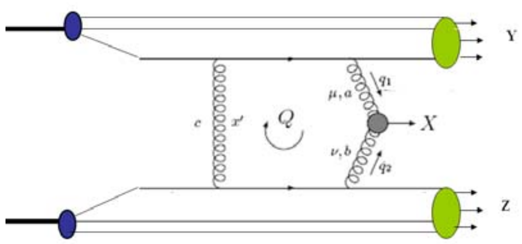
Probe of gluon density at low x

- Protons go down beam pipe and are undetected
- Signal in detector is 2 Muons or 2 Muons and a Photon with large rapidity gaps

PT expectations if no proton tagging

Violation of '$J_z = 0$ selection rule'

pp→Y+X+Z



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

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

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

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

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

for CEP (KMRS-04)

Spin-2 quarkonium suppression is easier to violate!

Low mass dissociation

- Dissociation into low mass nucleon excitations ($p \to N^* + ...$) with $M_Y \lesssim 2$ GeV.
- Situation is not too different from pure elastic $p \to p$ transition relevant to CEP, so it is reasonable to assume same x, Q^2, μ and t behaviour for f_g's.

$\to$ Can incorporate low mass dissociation by simply multiplying CEP result by some factor $1 + c$, where c is the probability of the $p \to N^*$ transition.

- Value of c can be calculated in two ways:
  - Measured at lower (fixed target and CERN-ISR) energies, can be extrapolated to the LHC by accounting for the stronger absorptive effects at higher $\sqrt{s}$.
  - Diffractive DIS @ HERA[4]: by comparing size of the measured cross section using the leading proton spectrometer and with the LRG requirement.
- In both case we find $c \approx 0.2 \Rightarrow$ CEP prediction should be enlarged by a factor $(1 + c)^2 \sim 1.4$.

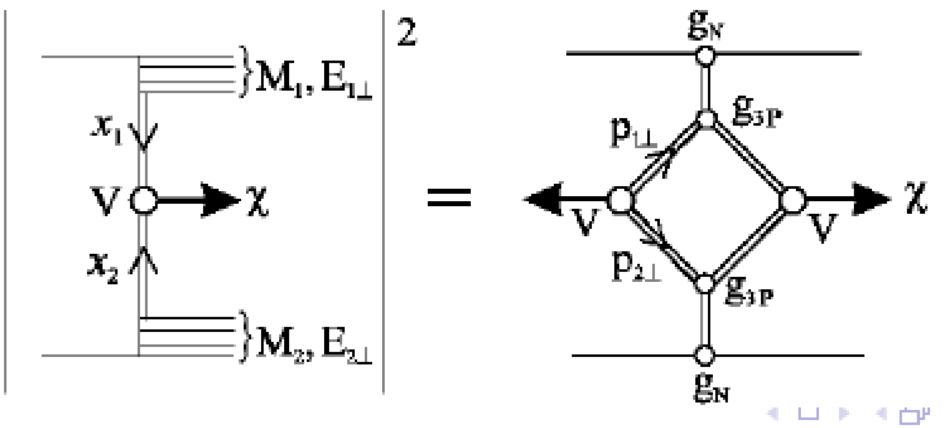
[4] F. Aaron et al., Eur.Phys.J. C71, 1578 (2011), 1010.1476.; S. Chekanov et al., Nucl.Phys. B816, 1 (2009),

High mass dissociation

- Dissociation into higher mass states ($M_Y \gtrsim 2$ GeV) described by triple–Pomeron diagrams. For fixed momentum transfered through the Pomeron, t, we have

$$\frac{\sigma(p \to M_Y)}{\sigma(\mathrm{CEP})} = \int \frac{\mathrm{d}M_Y^2}{M_Y^2} \frac{g_N(0) g_{3P}(t)}{\pi g_N^2(t)} , \quad (1)$$

- Triple–Pomeron vertex, g_{3P} can be extracted from lower energy data (CERN-ISR, Tevatron) to give $g_{3P}(0) = 0.2 g_N(0)$.
- However: the t–slope, b_{3P} of the 'bare' $g_{3P} \propto \exp(b_{3P} t)$ vertex is poorly known, and may even be consistent with zero, with[5] $b_{3P} < 2\ \mathrm{GeV}^{-2}$.
  - Absorptive effects strongly depend on shape of amplitude in impact parameter, b_t, space $\Rightarrow$ size of S^2 uncertain.



High mass dissociation (2)

- From Eq. (1) the proton $p_\perp^2 \sim 1/b_{3P}$ can be large:
  - Cannot justify factorization $f_g(x_i, ...\mu^2; t; M_Y^2) = G(t) f_g(x_i, ..., \mu^2; M_Y^2)$, with unreasonably large dissociation probability.
  - Larger $p_\perp$ allows an increasing violation of the $J_z = 0$ selection rule ($|J_z| = 2$ contribution is $\propto \langle p_\perp^2 \rangle^2$). Recall that χ_{c2} (also $\pi\pi$) $J_z = 0$ CEP are strongly suppressed $\rightarrow$ could play an important role in LHCb data.
- Taking $b_{3P} = 1\mathrm{GeV}^{-2}$ we can roughly estimate the admixture, C, of high mass dissociation in LHC 'exclusive' events by integrating over uninstrumented Δy.
- We find $C \approx 30 - 40\%$ for the CMS (ATLAS) experiment and $C \approx 50\%$ for LHCb. However we should recall large uncertainties in these estimates (MC + detector simulation etc also needed).
- Possible ways to shed light on this issue:
  - Forward shower counters (and ZDC) @ LHC in low luminosity runs: can veto on greatly extended η region, will reduce inclusive contamination (installed at CMS).
  - Select events with low $p_\perp$ in central system (e.g. coplanarity $\Delta\phi$ cuts for $\gamma\gamma$, $\pi\pi$ CEP...).
  - χ_c CEP: other decays ($\chi_{c(0,2)} \rightarrow \pi^+\pi^-, K^+K^-, pp, \Lambda\overline{\Lambda}$...).

χ_b CEP

- Higher χ_b mass means cross section is more perturbative and so is better test of theory, although rate is $\sim$ 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 $y_\chi = 0$):

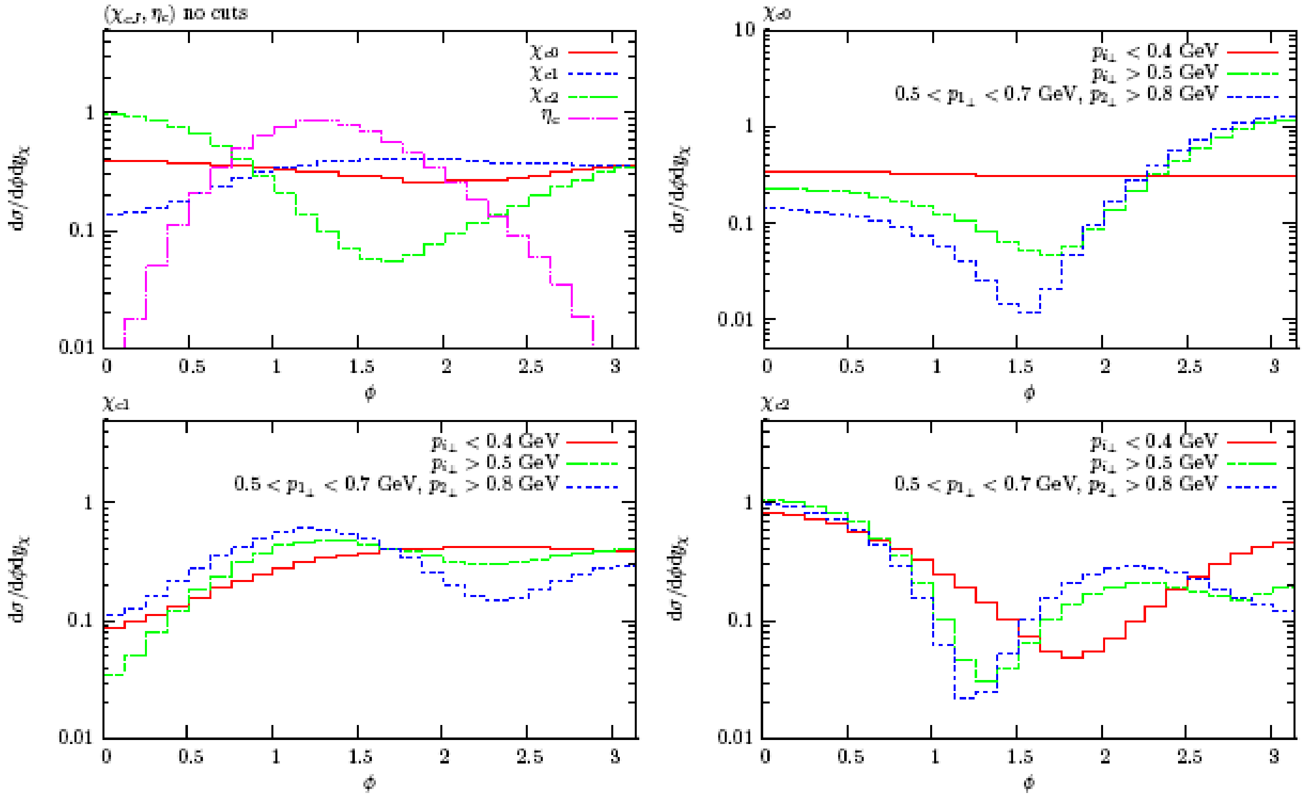
$\sqrt{s}$ (TeV)	1.96	7	10	14
$\frac{\mathrm{d}\sigma}{\mathrm{d}y_{\chi_b}}(pp \to pp(\Upsilon + \gamma))$ (pb)	0.60	0.75	0.78	0.79
$\frac{\mathrm{d}\sigma(1^+)}{\mathrm{d}\sigma(0^+)}$	0.050	0.055	0.055	0.059
$\frac{\mathrm{d}\sigma(2^+)}{\mathrm{d}\sigma(0^+)}$	0.13	0.14	0.14	0.14

- $\chi_b(nP) \to DX$ (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 $\sim m_c^2/M_{\chi_b}^2$

CEP with proton taggers

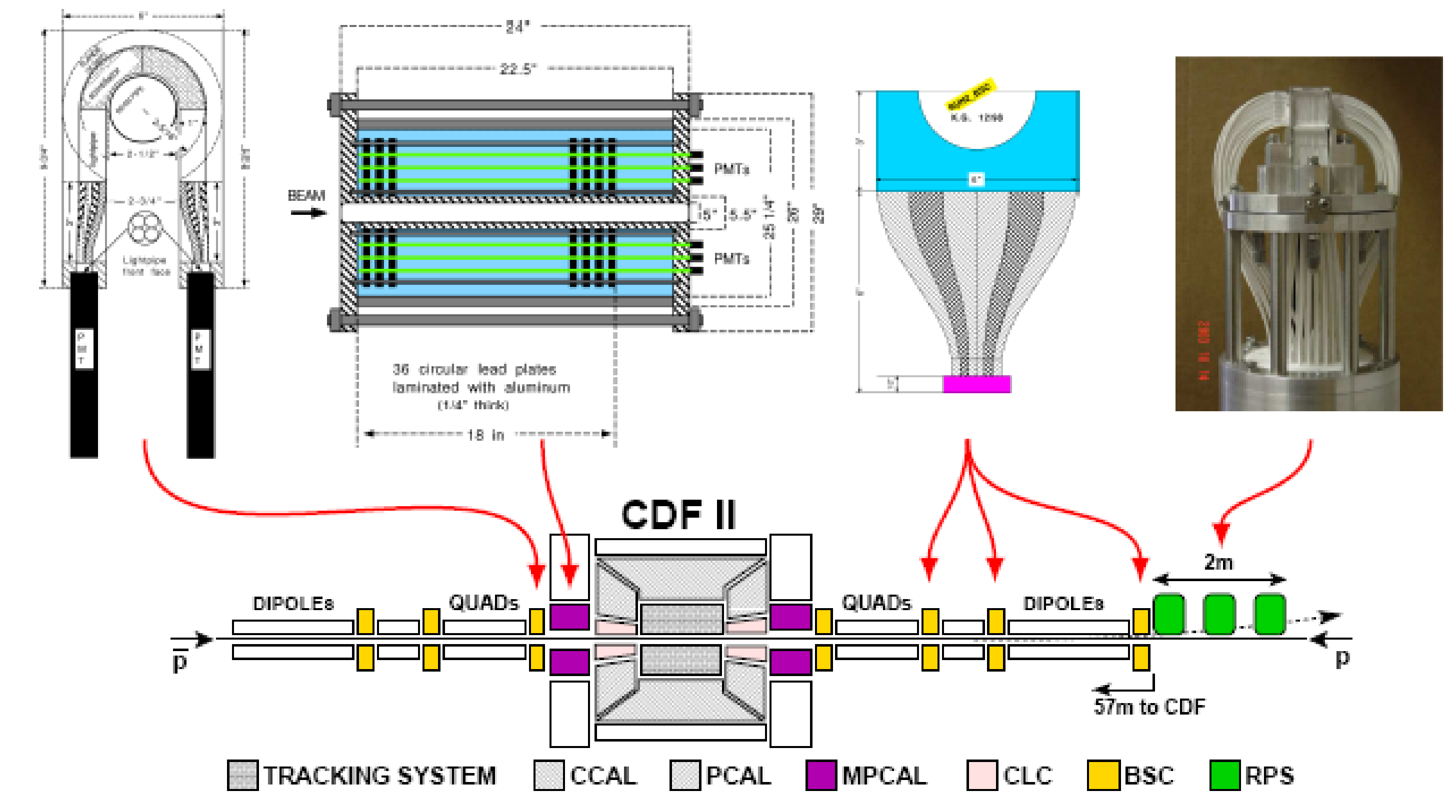


$\rightarrow$ ϕ distributions (SuperCHIC) depend on central particle spin, but are also strongly affected by soft survival effects, in particular for larger values of proton $p_\perp$ (RHIC II), where cancellation between screened and unscreened amplitudes results in characteristic 'diffractive dip'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

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

CDF Forward Coverage

BSC-1	Miniplug	BSC-2/3	RPS
$5.4 < \lvert\eta\rvert < 5.9$	$3.6 < \lvert\eta\rvert < 5.2$	$6.4 < \lvert\eta\rvert < 7.4(8.0)$	$0.02 < \xi < 0.1$

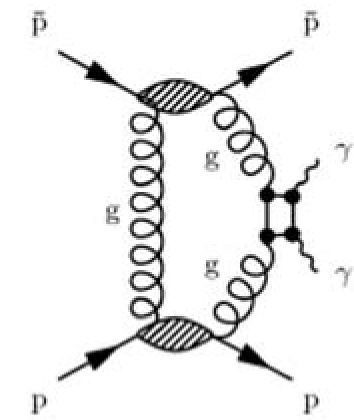


Overview of CEP Analyses done at CDF

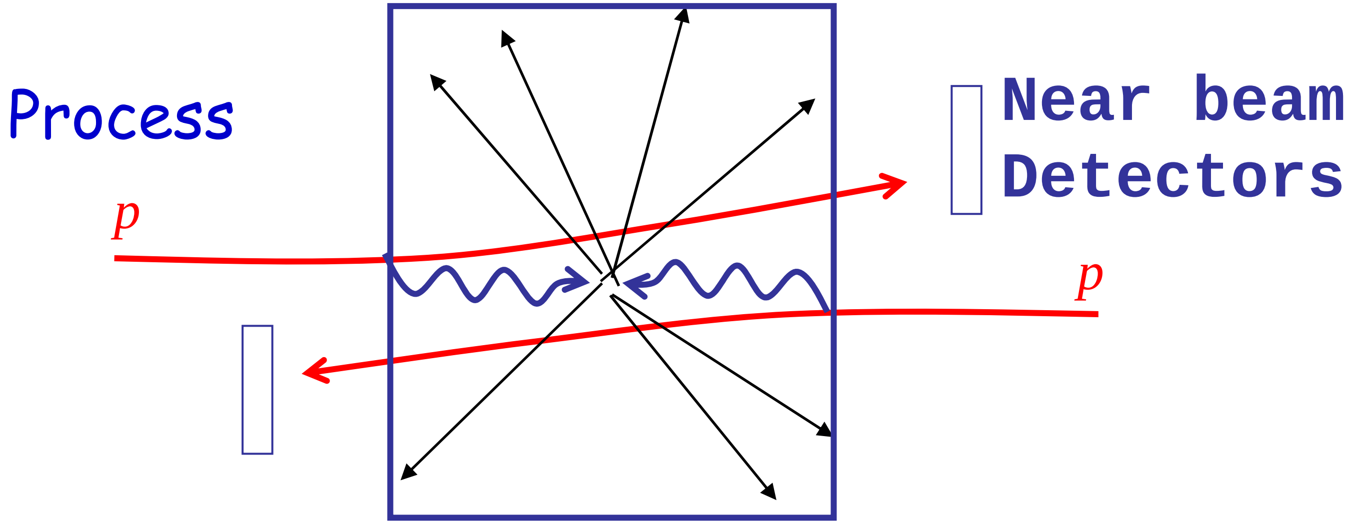
- **QED Production**
  - ★ Exclusive e^+e^- Production
  - ★ Exclusive $\mu^+\mu^-$ Production
- **Photoproduction**
  - ★ Exclusive Charmonium and J/Ψ Production
  - ★ Search for Exclusive Z Production
- **Double Pomeron Exchange**
  - ★ Exclusive Dijet Production
  - ★ Exclusive χ_c Production
  - ★ Exclusive $\gamma\gamma$ Production

New Exclusive $\gamma\gamma$: Trigger, Data and Selection

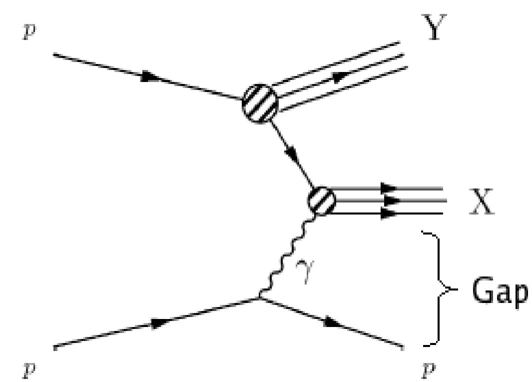
- Recorded data of 1.11fb^{-1} integrated luminosity, triggered on 2 EM showers > 2 GeV and BSC-1 veto.
- Selection of EM object pairs plus nothing.
- EMO with $|\eta| < 1.0$ and $E_T > 2.5$ GeV.
- Filter for exclusivity (rapidity gap selection).
- Quality cuts and tracking cut.
- 2 samples:
  1. 2 EMO with good tracks $\Rightarrow$ 34 e^+e^- candidates.
  2. 2 EMO without any tracks $\Rightarrow$ 43 $\gamma\gamma$ candidates.



LHC as a High Energy photon-photon Collider



...and γp



Extensive Program

- $\gamma\,\gamma \rightarrow \mu\mu$, ee QED processes
- $\gamma\,\gamma \rightarrow$ QCD (jets..)
- $\gamma\,\gamma \rightarrow$ WW anomalous couplings
- $\gamma\,\gamma \rightarrow$ squark, top… pairs
- $\gamma\,\gamma \rightarrow$ BSM Higgs
- $\gamma\,\gamma \rightarrow$ Charginos
- …

(accounting for the LHC exclusion zones)

Maybe photon-proton collider @ LHC