Standard Candles for Central Exclusive Processes at the Tevaron and LHC

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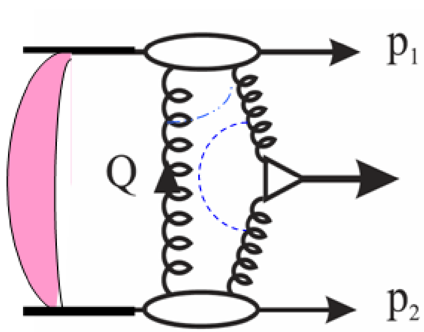
(In collaboration with L. Harland-Lang, M.Ryskin and W.J. Stirling)



$jj, \chi_c, \chi_b, \gamma\gamma$

Outline

(based on Eur.Phys.J.C65:433-448,2010)

1. Introduction.
2. Central exclusive production (CEP) of $\chi_{c0,1,2}$ states at the Tevatron and LHC.
   - Motivation.
   - CDF data.
   - Calculation of $\chi_{c1,2}$ rates.
   - Forward proton distributions.
   - Monte Carlo simulation: SuperCHIC.
3. Overview of $\gamma\gamma$ and χ_b CEP results and ongoing studies.
4. Conclusion.

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.
- χ_c, jj and $\gamma\gamma$ CEP has been observed by CDF.

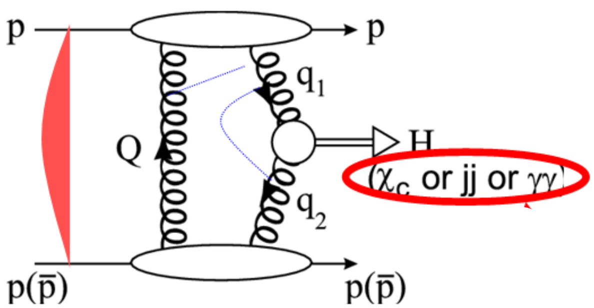
$\rightarrow$ Can serve as 'Standard Candle' processes, which allow us to check the theoretical predictions for central exclusive new physics signals at the LHC.

- $\chi_{c,b}$ 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 perhaps shed light on the various 'exotic' charmonium states observed recently.

Standard Candle Processes

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

(Confucius)

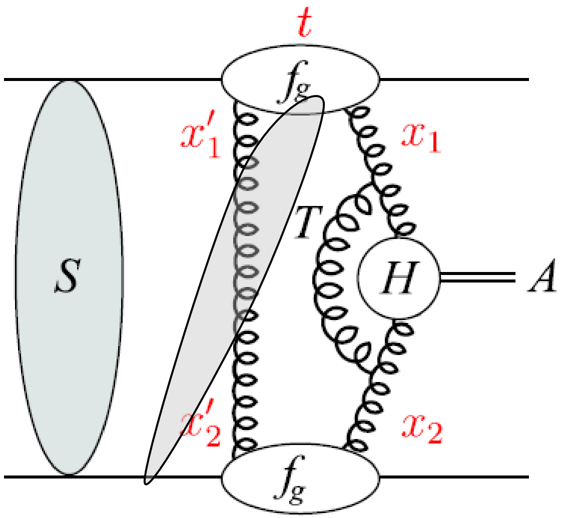


The process p-p→$\gamma\gamma$/χ_c/ χ_b/ j-j are standard candles for the exclusive Higgs

孔夫子

孔丘 *Kong Qiu*

Are the early LHC runs,
without proton taggers,
able to check estimates
for pp → p+A+p ?



KMR: 0802.0177

Possible checks of:

(i) survival factor S^2: W+gaps, Z+gaps

(ii) generalised gluon f_g : γp → Υp

(iii) Sudakov factor T : 3 central jets

(iv) **soft-hard factorisation**
(enhanced absorptive corr^n)

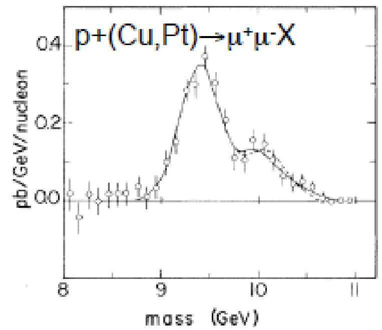
$$\frac{\#(\text{A+gap})\ \text{evts}}{\#(\text{inclusive A})\ \text{evts}}$$

with A = W, dijet, Υ…

Divide et Impera

Bottomonium history started 30 years ago

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



M(ϒ)=9.40±0.013

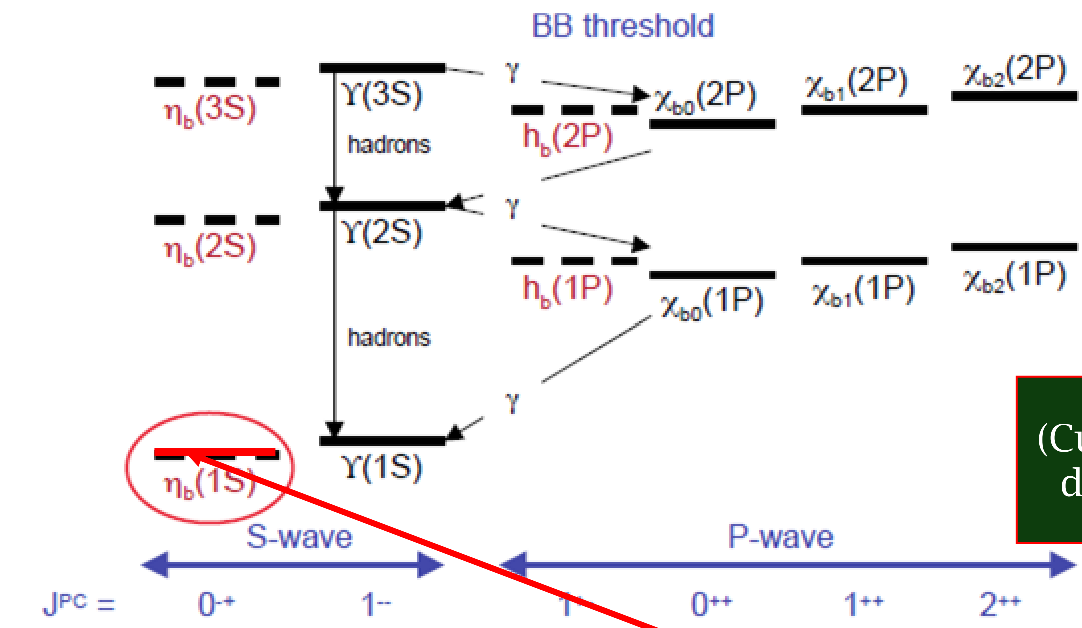
M(ϒ')=10.00±0.04

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 puzzles)

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

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

FSC@LHC

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

Cleanest (no S.I.) but smallest σ

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

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

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

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

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

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

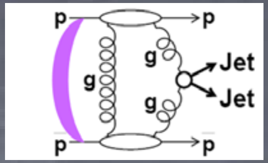
* $p+\bar{p} \rightarrow p+JJ+\bar{p}$

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

Prpospects !

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

Comparison with KMR

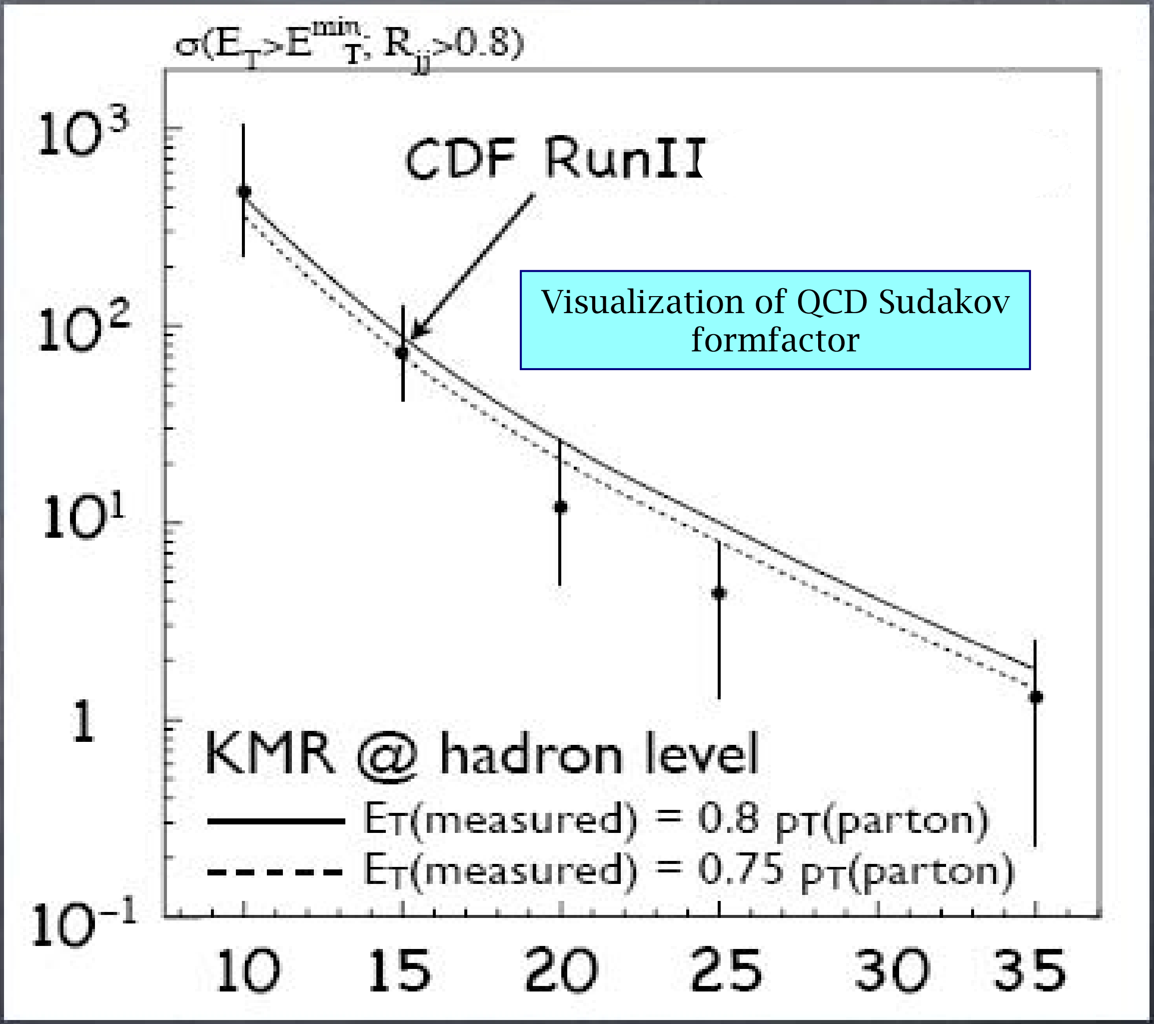


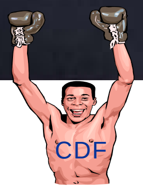
More direct comparison with KMR calculations including hadronization effects preferred

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.

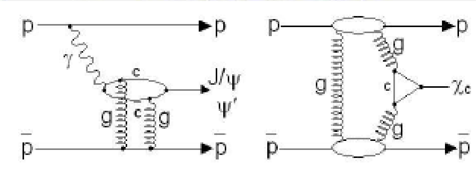
CDF
PRD-2008

D0-2010

Summary of Results

$$p+\bar{p}\rightarrow p+\mu^{+}\mu^{-}+\bar{p}$$
$$p+\bar{p}\rightarrow p+\mu^{+}\mu^{-}\gamma+\bar{p}$$

M = 3-4 GeV/c2

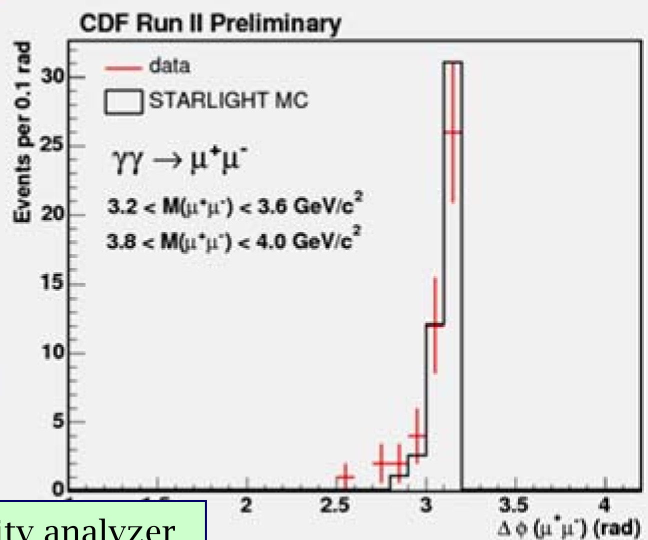


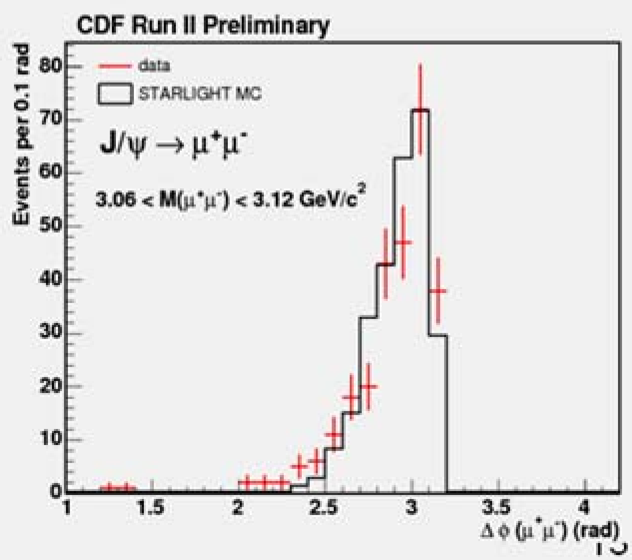
Quantity	This analysis	Theory
$\frac{d\sigma}{dy}(y=0)J/\psi$ (nb)	3.92 ± 0.62	3.0 ± 0.3
$\frac{d\sigma}{dy}(y=0)\psi(2S)$ (nb)	0.53 ± 0.14	$0.46^{+0.11}_{-0.04}$
$\frac{d\sigma}{dy}(y=0)\chi_c^{\circ}$ (nb)	76 ± 14	$130\pm\approx50$
$\sigma(box, QED, pb)$	2.7 ± 0.5	2.18 ± 0.02
$\frac{d\sigma}{dy}(y=0)O\mathbb{P}\rightarrow J/\psi$	<2.3 nb (95% C.L.)	
$\frac{J/\psi}{\chi_c}$	0.052 ± 0.015	No Prediction

90 nb
(χ width)
Durham

No **strong** evidence for odderon

$$\langle p_T(\gamma\gamma)\rangle < \langle p_T(IP)\rangle$$





ππ/KK mode as a spin-parity analyzer

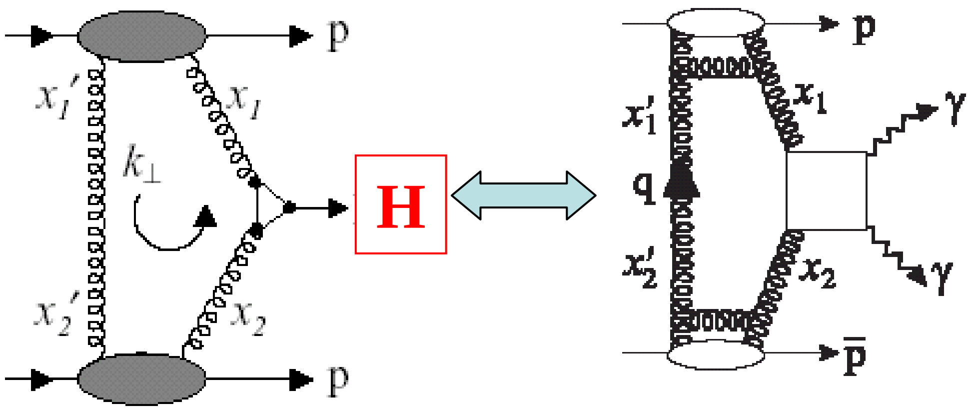
PRL 99, 242002 (2007) PHYSICAL REVIEW LETTERS week ending 14 DECEMBER 2007

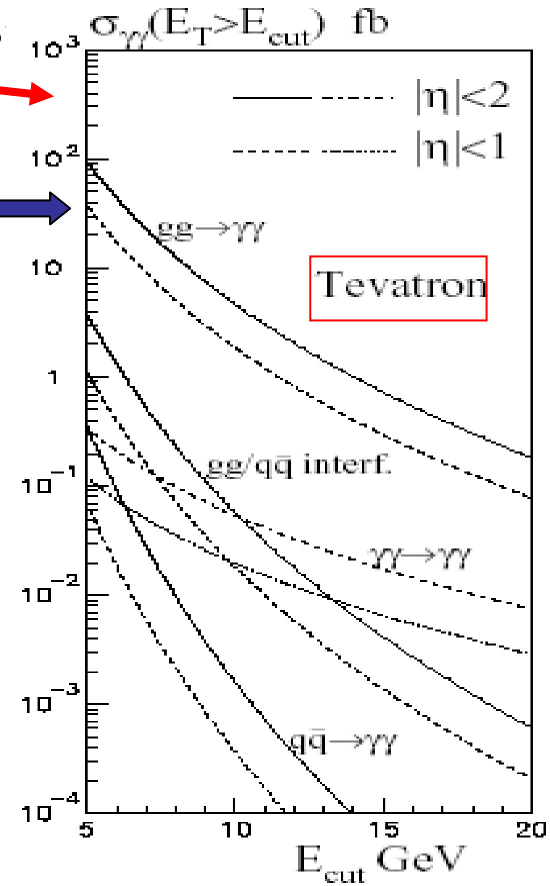
Search for Exclusive $\gamma\gamma$ Production in Hadron-Hadron Collisions

Khoze, Martin and Ryskin, Eur.Phys.J. C23: 311 (2002) ; KMR+Stirling hep-ph/040903

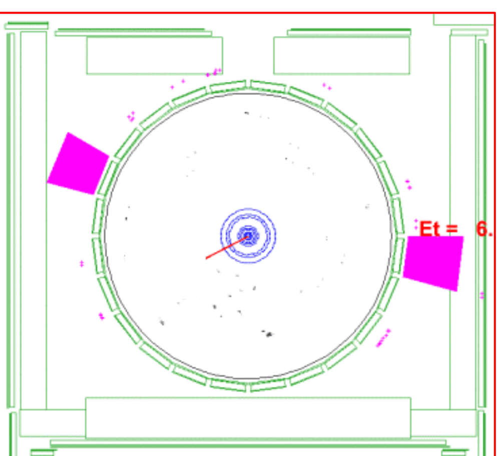
Claim factor ~ 3 uncertainty ; Correlated to p+H+p

36 fb





$\gamma\gamma \to \gamma\gamma$ & $q\bar{q} \to \gamma\gamma$ much smaller



$E_T(\gamma) > 5$ GeV; $|\eta(\gamma)| < 1.0$

3 candidates, 2 golden, 1 ? $\pi^0\pi^0$?

36 fb → 0.8 events

$$\text{Note}: \sigma_{MEAS} \approx 2\times10^{-12}\sigma_{INEL}\,!$$

New data, Lower threshold, **possible "observation" to come**
& **SuperCHIC !** (HKRS-09)

CDF χ_c data

Phys.Rev.Lett.102:242001,2009

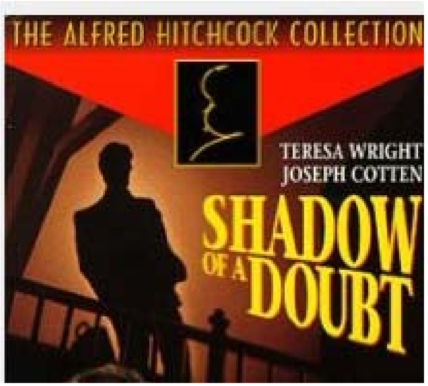
- 65 ± 10 signal χ_c events observed, but with a limited $M(J/\psi\gamma)$ resolution.
- Possible contribution from χ_{c1} and χ_{c2} states assumed, rather than observed, to be negligible.
- Assuming χ_{c0} dominance, CDF found:

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

  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:

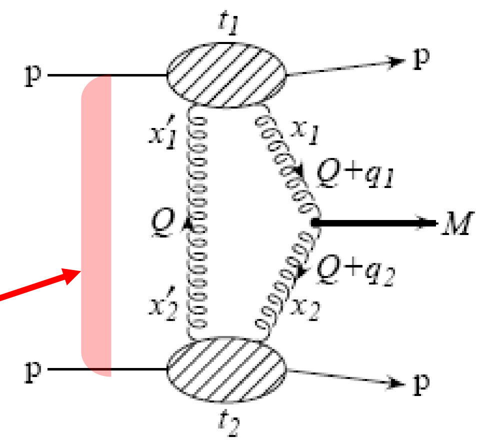
$$
\begin{aligned}
\mathrm{Br}(\chi_{c0} \to J/\psi\gamma) &= 1.1\% \, , \\
\mathrm{Br}(\chi_{c1} \to J/\psi\gamma) &= 34\% \, , \\
\mathrm{Br}(\chi_{c2} \to J/\psi\gamma) &= 19\% \, .
\end{aligned}
$$

- 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)

Non-forward effects

- While the $\chi_{c(1,2)}$ CEP amplitudes vanish in the limit of forward outgoing protons, we expect some violation of this from the effect of non-zero proton $p_\perp$.



Important role of absorption effects

- To achieve this we write our amplitude as:

$$T = \pi^2 \int \frac{d^2\mathbf{Q}_\perp\, V_J}{\mathbf{Q}_\perp^2(\mathbf{Q}_\perp - \mathbf{p}_{1_\perp})^2(\mathbf{Q}_\perp + \mathbf{p}_{2_\perp})^2} f_g(Q_1^2,\cdots)f_g(Q_2^2,\cdots)\,. \qquad (1)$$

- V_J represents the $gg \to \chi_{cJ}$ vertex and can be calculated by a simple extension of the previous $\gamma\gamma \to \chi_c$ results.

Cross section results (1)

- We find the following approximate hierarchy for the spin-summed amplitudes squared

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

- 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):

$$\frac{\Gamma^{\chi_0}_{J/\psi+\gamma}}{\Gamma^{\chi_0}_{\rm tot}} \frac{{\rm d}\sigma^{\rm pert}_{\chi_{c0}}}{{\rm d}y} : \frac{\Gamma^{\chi_1}_{J/\psi+\gamma}}{\Gamma^{\chi_1}_{\rm tot}} \frac{{\rm d}\sigma^{\rm pert}_{\chi_{c1}}}{{\rm d}y} : \frac{\Gamma^{\chi_2}_{J/\psi+\gamma}}{\Gamma^{\chi_2}_{\rm tot}} \frac{{\rm d}\sigma^{\rm pert}_{\chi_{c2}}}{{\rm d}y} \approx 1 : 0.8 : 0.6 .$$

- Note: these approximate values carry a factor of $\sim \stackrel{\times}{\div} 1.5 - 2$ uncertainty.

Cross section results (2)

- Finally, we must include the factorization breaking 'enhanced' absorptive effects, which we can roughly account for (in the χ_c case) by the introduction of a simple multiplicative 'effective' survival factor:

$$\langle S^2_{\rm eff}\rangle \approx \langle S^2_{\rm enh}\rangle \times \langle S^2_{\rm eik}\rangle \approx \frac{1}{3}\,\langle S^2_{\rm eik}\rangle \;,$$

- NB: This value carries large uncertainties ($\sim \pm 50\%$) may change with more exact calculations (work in progress).
- We can then use the relevant χ_{c0} branching ratios to convert our result to a total predicted χ_c cross section at the Tevatron:

$$\left.\frac{{\rm d}\sigma^{\rm tot}_{\chi_c}}{{\rm d}y_\chi}\right|_{y_\chi=0} \approx 60\,{\rm nb}\;.$$

- Note this carries large uncertainties ($\sim\overset{\times}{\div}$ 5) but is nonetheless in good agreement with the experimental value.

Cross section results for the LHC

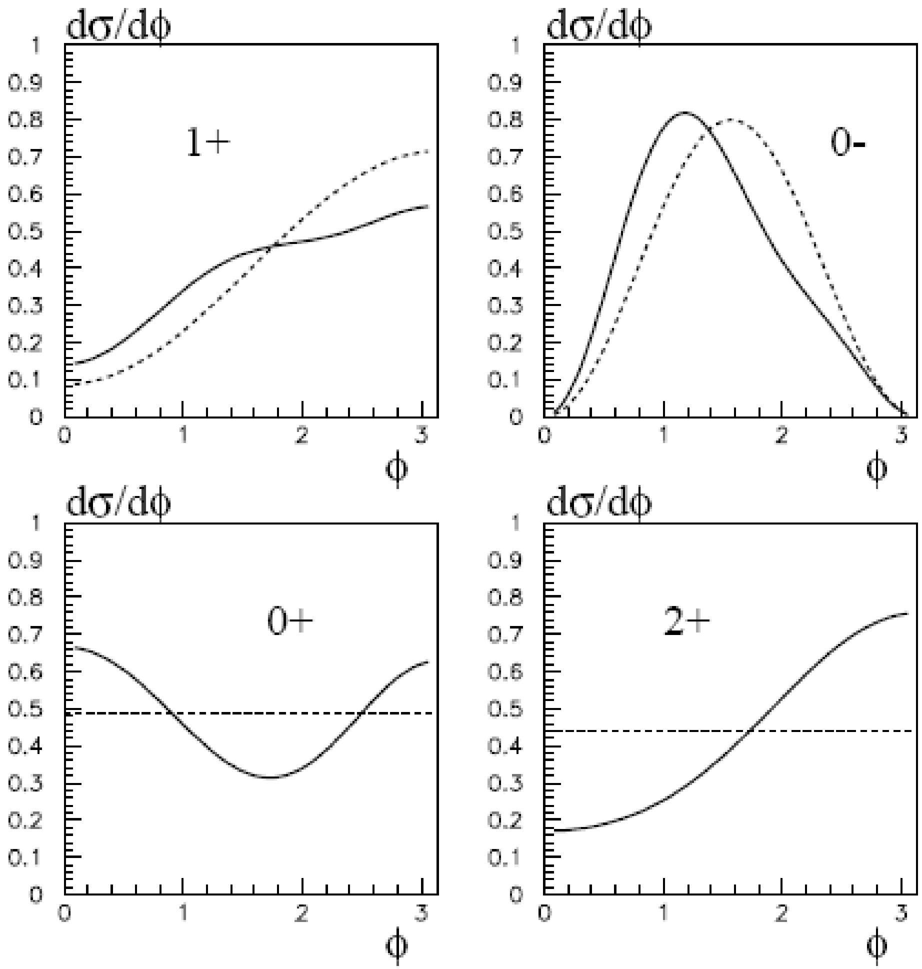
- As the cms energy increases we have:
  - Larger gluon density at smaller x values.
  - Smaller $S^2_{\rm eik}$ survival factor.
  - Smaller $S^2_{\rm enh}$ due to increase in size of rapidity gaps ($\sim s/m^2_\chi$) available for 'enhanced' absorptive effects.

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

- An explicit calculation gives the (**preliminary**) results:

$\sqrt{s}$ (TeV)	$d\sigma/dy_\chi(pp \to pp(J/\psi + \gamma))$ (nb)
1.96	0.70
7	0.85
10	0.86
14	0.90

Measuring forward proton angular distributions



- Forward proton detection would allow a clear discrimination between the different *J* states.

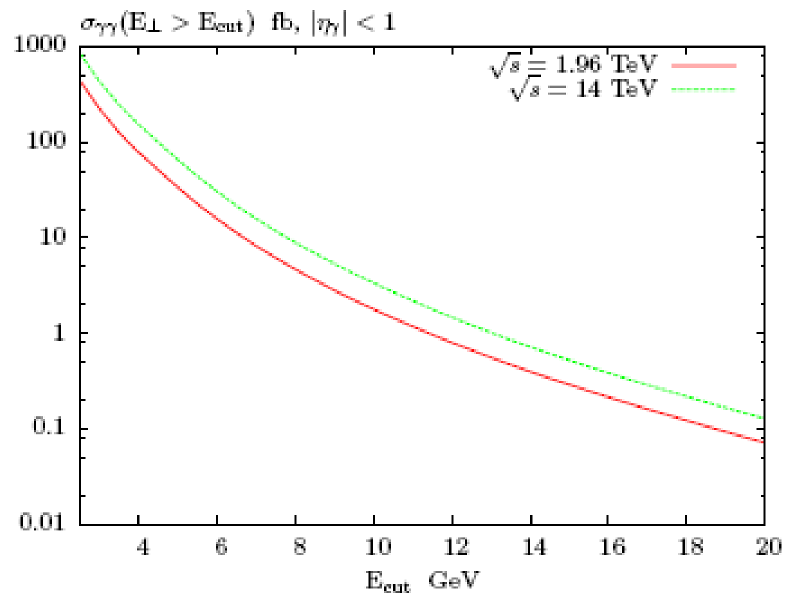
SuperCHIC MC

- A new MC (available on HepForge) including:
  - Non-forward $p_\perp \neq 0$ protons via the 'effective' slope parameters $b_{\rm eff}$.
  - Full simulation of $\chi_{c(0,1,2)}$ 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.
  - More to come...
- The angular distributions of the final state particles, modeled in the MC, might help us to distinguish between the different states...
- ...however the severity of current CDF experimental cuts for χ_c CEP ($p_\perp(\mu) > 1.4\,\mathrm{GeV/c}$, $|\eta_\mu| < 1$) appears to preclude this.

$\gamma\gamma$ CEP

(KMRS, arXiv:0409037)

- 3 candidate events observed by CDF (arXiv:0707.237), with more to come.
- More events would allow us to probe scaling of σ with E_{cut}.
- Similar uncertainties to χ_c case for low E_{cut} scale.
- Potential $|J_z| = 2$ contribution found to be unimportant.
- Initial encouraging results for $gg \to \pi^0\pi^0$ background.
- $\gamma\gamma$ CEP now included in SuperCHIC.



χ_b CEP (1)

- Calculation exactly analogous to χ_c case with same hierarchy as (2). However we have a stronger suppression in the χ_{b1} and χ_{b2} rates than for the χ_c case.
- Larger $\langle Q_\perp^2 \rangle$ scale gives smaller $b_{\rm eff}$ values, i.e. non-forward effects are less strong, but still important.
- 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).
- Significant uncertainties in input parameters:
    - Only have ${\rm Br}(\chi_{b0} \to \Upsilon\gamma) < 6\%$ from experiment (PDG 2009).
    - $\Gamma_{\rm tot}(\chi_{b0})$ experimentally undetermined.

  $\longrightarrow$ Must use, e.g., potential model estimates.
- Consistently with the results of NRQCD, as well as the existing experimental data, we can take the values[3] $\Gamma(\chi_{b0} \to gg) = 0.8$ MeV and ${\rm Br}(\chi_{b0} \to \Upsilon\gamma) = 3.2\%$.

[3] W. Kwong and J. L. Rosner, Phys. Rev. D 38, 279 (1988)

χ_b CEP (2)

- Performing the same explicit calculation as for the χ_c case, we find the following (**preliminary**) results:

$$\frac{\Gamma^{\chi 0}_{\Upsilon+\gamma}}{\Gamma^{\chi 0}_{\rm tot}}\frac{{\rm d}\sigma^{\rm pert}_{\chi_{b0}}}{{\rm d}y} : \frac{\Gamma^{\chi 1}_{\Upsilon+\gamma}}{\Gamma^{\chi 1}_{\rm tot}}\frac{{\rm d}\sigma^{\rm pert}_{\chi_{b1}}}{{\rm d}y} : \frac{\Gamma^{\chi 2}_{\Upsilon+\gamma}}{\Gamma^{\chi 2}_{\rm tot}}\frac{{\rm d}\sigma^{\rm pert}_{\chi_{b2}}}{{\rm d}y} \approx 1 : 0.03 : 0.2$$

- Note: these ratios depend on the value taken for ${\rm Br}(\chi_{b0} \to \Upsilon\gamma)$.
- Using these values we can evaluate the expected χ_b CEP rates via the $\Upsilon\gamma$ decay chain, which are largely independent on the choice of $\Gamma(\chi_{b0} \to gg)$:

$\sqrt{s}$ (TeV)	$d\sigma/dy_\chi(pp \to pp(\Upsilon+\gamma))$ (pb)
1.96	0.68
7	0.72
10	0.72
14	0.72

Conclusion

- CEP processes observed at the Tevatron and early LHC can serve as ‘standard candles’ for new physics CEP at the LHC.
- Possibility that χ_{c1} and χ_{c2} CEP may contribute to CDF χ_c events.
- Cannot currently distinguish different J states, but may be possible with:
  - More detailed analysis and/or higher statistics.
  - Forward proton detection.
  - Different decay modes, e.g. $\chi_c \to \pi\pi$, $\chi_c \to K\overline{K}$.
- $\gamma\gamma$ CEP of interest- variable $M_{\gamma\gamma}$ of central system allows a wider range of studies.
- χ_b CEP a potential observable at the LHC (ongoing study).
- CEP of higher excitation χ_{nP} states?
- More complete treatment of proton correlations possible future work.

Currently active studies are in progress (both in theory and experiment).

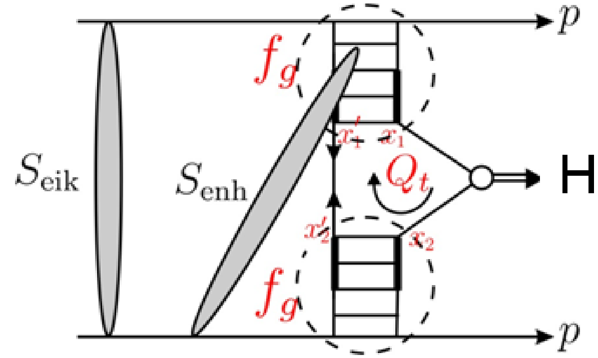
Thank You

BACKUP

pp → p+H+p

Base value: σ = 2.5 fb { SM M_H=120 GeV
LHC=14 TeV
eikonal screening

A. Martin, 12.12.09, Manchester



-45% adjust c in upper limit $1 - k_t/(cM_H+k_t)$ of z integration of Sudakov factor to reproduce one-loop result. Find c=1 (Forshaw-Coughlin, KMR09), and not 0.62 (KKMR04)

-25% if enhanced screening included (KMR-0812.2413)

+20% due to NLO unintegrated gluon (MRWatt-0909.5529)

+20% connected with self-energy insertions in propagator of screening gluon (Ryskin et al.)

PS Recall factor 3 uncertainty

PPS Remember SUSY Higgs can be greatly enhanced

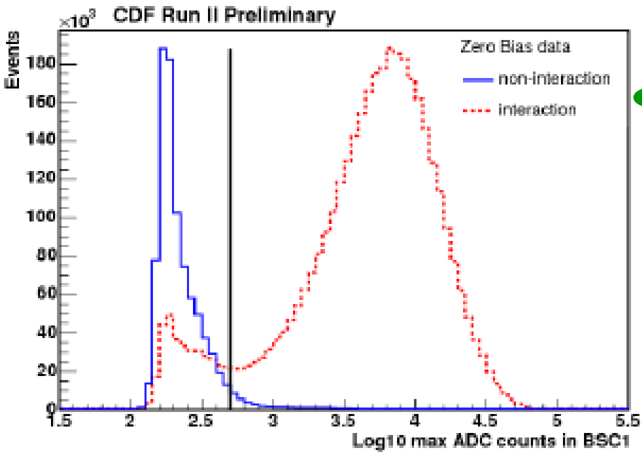
BSC very important as rap gap detectors.
All LHC experiments should have them!

FORWARD PHYSICS WITH RAPIDITY GAPS AT THE LHC

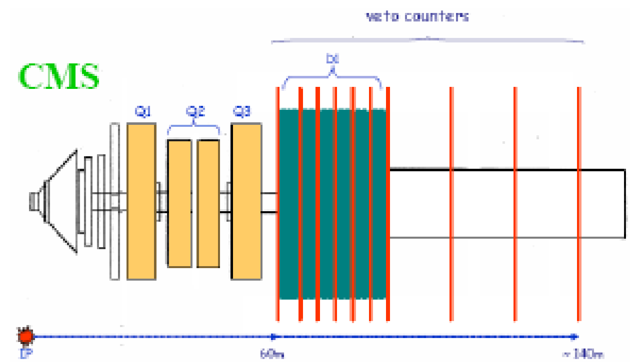
arXiv:0811.0120

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

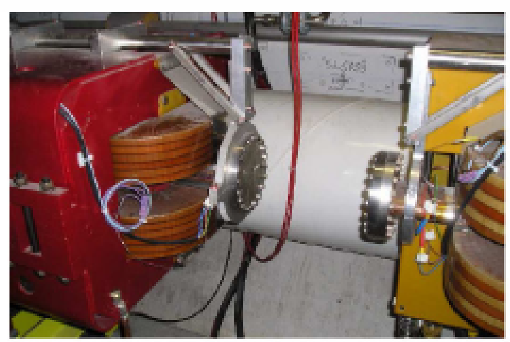
JINST



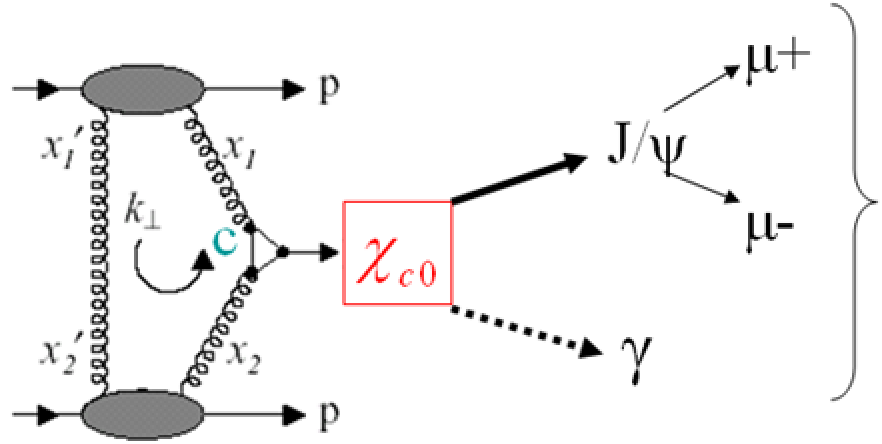
Warm accessible vacuum pipe (circular – elliptical)
Do not see primary particles, but showers in pipe ++
Simple scintillator paddles: **Gap detectors in no P-U events**



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



We set out to measure exclusive $\chi_c \to J/\psi + \gamma \to \mu{+}\mu{-}\ \gamma$



& nothing else
in all CDF
$-7.4 < |\eta| < +7.4$

Beam Shower Counters BSC: $5.2 < |\eta| < 7.4$

If these are all empty, p and $\overline{\text{p}}$ did not dissociate
(or BSC inefficient, estimated from data)
but went down beam pipe with small (<~ 1 GeV/c) transverse momentum.

Plan to put these (FSC) with CMS