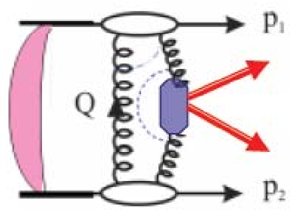
International Moscow Workshop on Phenomenology of Particle Physics devoted to the memory of Prof. Alexei Kaidalov

Central Exclusive Processes at Hadron Colliders: from dimesons to Higgs

V.A. Khoze (IPPP, Durham & PNPI)



(selected topics)

(Based on works with Aliosha Kaidalov, Lucian Harland-Lang, Alan Martin, Misha Ryskin, James Stirling and Marek Tasevsky)

A great privilege to work with Aliosha : 13 papers written in collaboration,
6 conference talks.
1973-first common paper, 2010-last common paper

always in close contact with the experimentalists

Volume 45B, number 5 PHYSICS LETTERS 20

ON DETERMINATION OF THE TRIPLE-POMERON COUPLING FROM THE ISR

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Received 30 May 1973

The inclusive hadron spectra in the high-energy pp collisions near the kinematic boundary are described wi
the framework of the triple-Regge model with scaling terms only.
The magnitude of the triple-Pomeron vertex is determined and the role of the latter in different approache
the description of strong interactions asymptotics is discussed.

The investigation of the hadron spectra pp → pX near the kinematic boundary $s \gg M^2 \gg m^2$, $-t \lesssim m^2$ within the framework of the triple-Regge (TR) model [e.g. 1–5] is of interest both from the point of view of scaling verification in the inclusive reactions (i.e. dependency only on $x = 2p_{\parallel}/\sqrt{s}$) and in connection with the possibility of extraction some information about the TR vertices. Of special interest is the triple-Pomeron (TR) vertex whose behaviour at small-t is of importance for the understanding of the strong interactions asymptotics [6–8].

It is shown in the present work that the recent experimental ISR data at s = 929.5, 940, 1995 GeV^2 [9, 10] can be successfully described on the basis of TR model taking into account two scaling terms PPP and RRP only (here P is Pomeranchuk pole, R secondary trajectories P′, ρ, ω, A_2 with $\alpha_R(0) = 0.5$).

In the preceding analyses the data at $s \sim 20 - 60$ GeV^2 [11, 12] and ISR data were described separately assuming the importance of the PPR and RRP contributions. It was shown in paper [13] that the simultaneous examination of these data leads to an absolutely different relation between these couplings, namely, the importance of the scaling terms PPP and RRP, the necessity of including of the RRR coupling; and the unimportance of the PPR at $s \sim 10^3$ GeV^2, $x < 0.98$. The non-scaling corrections are proved to be of about $\lesssim 20\%$ at energies $s \gtrsim 10^3$ GeV^2 and therefore we restrict ourselves only to the scaling terms in this energy region.

Then the inclusive cross section takes t

$$F\frac{d^3\sigma}{d^3p} = \frac{\beta_P(0)}{16\pi^2}\left[\frac{g_{PPP}(t)|\beta_P(t)\eta_P(t)|^2}{(1-x)1-2\alpha'_P|t|}\right.$$

$$\left. + g_{RRP}(t)|\beta_R(t)\eta_R(t)|^2(1-x)^{2\alpha'_R|t|}\right]$$

$$\equiv \frac{G_{PPP}(t)}{(1-x)^{1-2\alpha'_P|t|}} + G_{RRP}(t)(1-x)^{2\alpha'_R|t}$$

$$\equiv (PPP) + (RRP),$$

where $\beta_P(t)$, $\beta_R(t)$ are the couplings of Re
with p ($\sigma^{pp}_{tot} = \Sigma_i\beta_i^2(0)\,\mathrm{Im}\,\eta_i(s/s_0)^{\alpha_i(0)-1}$,
$\eta_P(t)$ and $\eta_R(t)$ are the corresponding sig
tors, $g_{PPP}(t)$ and $g_{RRP}(t)$ the TR vertices†
bution of the interference term PRP is ne
its consideration can result only in ~20%
to $g_{PPP}(t)$ [13]. The contributions of the
lying j-plane poles are also neglected.

Let us put an argument for the PPP exi
Namely, to subtract the P contribution we
late the spectrum at fixed M^2 and t to the
and represent it in the following form

$$\left(\frac{d\sigma}{dt\,dM^2}\right)_P = \frac{1}{16\pi}|\beta_P(t)\eta_P(t)|^2(1-x)^{2(1-\alpha}$$

$$\times \frac{1}{M^2}\sigma_{Pp}(M^2, t),$$

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** Yerevan Physical Institute.

† The vertices $g_{PPP}(t)$ and $g_{RRP}(t)$ in our norm
connected with $r(t)$, used in the ref. [8] in th
way $g_{PPP}(t) = \sqrt{8\pi}\,r(t)$.

(The results are still relevant)

Eur. Phys. J. C (2010) 66: 373–376
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THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

Factorisation breaking in diffractive dijet photoproduction at HERA

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Abstract We discuss the factorisation breaking observed in diffractive dijet photoproduction by the H1 and ZEUS collaborations at HERA. By considering the effects of rapidity gap survival, hadronisation, migration and NLO contributions, we find that the observed data are compatible with theoretical expectations.

1 Introduction

As is well known, in QCD the cross section for a 'hard' inclusive process *factorises* into universal parton densities and calculable hard subprocess cross sections. However, for diffractive processes the factorization into universal diffractive parton densities and the known subprocess cross sections may be *broken*, since the rapidity gaps associated with the diffractive process can be populated by secondary particles from 'soft' rescattering.

Here, we discuss factorization breaking of the diffractive photoproduction of dijets at HERA,[1] where each jet has large transverse momentum, E_T. That is, events with a large rapidity gap between the proton and the hadronic dijet system produced by a photon with virtuality $Q^2 \sim 0$ (see for example [1, 4]). The domains $x_P < 0.03$ and $x_P < 0.025$ were selected by the H1 and ZEUS collaborations, respectively. The comparison of these data with theory is not well understood. The situation may be summarised as follows. In general, there is a tendency for the observed cross sections to be smaller than those predicted [5–9] by NLO QCD. Indeed, for the H1 choice of jet cuts, $E_{Tjet1} > 5$ GeV ($E_{Tjet2} >$ 4 GeV), the ratio of data/theory is about 0.5–0.6 independent of the observed x_γ [1], indicating an overall suppression relative to the QCD prediction. On the other hand, with higher jet cuts, $E_{Tjet1} > 7.5$ GeV ($E_{Tjet2} > 6.5$ GeV), the data of the ZEUS collaboration [4] give a data/theory ratio of 0.9 if the diffractive PDFs of H1 fit B [10] are used, compatible with little or no overall suppression.[2] Moreover, in the latest H1 analysis [12, 13] the events have been selected using a similar set of cuts to those adopted by ZEUS, with, in fact, identical choices of the E_T and x_P cuts. In this case, the (preliminary) H1 results give, using the H1 'jets' diffractive PDFs [2],[3] a data/theory ratio consistent with an overall suppression of about 0.8 [12, 13], which, within the 20–30% experimental uncertainties, is not in contradiction with the findings of ZEUS.

There was an attempt to describe the factorization breaking by soft spectators from the photon interacting inelastically with the proton target and producing secondaries which populate the rapidity gap. For the hadron-like component of the photon wave function this would have produced a suppression by a factor of about 3, corresponding to a gap survival factor $S^2 = 0.34$ [14]. This idea was widely discussed and used, for example, in the studies of Klasen and Kramer [6–9]. Nevertheless, the absorption of the hadron-like component of the photon cannot explain the suppression of the dijet yield observed in the largest x_γ bin, close to $x_\gamma = 1$. When the dijet system carries away almost all of the incoming photon momentum, the 'direct $\gamma \to$ dijet' subprocess dominates and we anticipate that $S^2 \simeq 1$, since

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[1]The HERA data for the diffractive production of dijets in deep-inelastic scattering are consistent with NLO predictions [1–3]. That is, within the present uncertainties of the data and theory, no evidence of factorization breaking is observed.

[2]In a recent ZEUS paper [11] the data on diffractive dijet production in DIS have been included in a DGLAP analysis to better constrain the diffractive gluon densities. With these diffractive PDFs the dijet data are well described without factorization breaking, but see the comments in the concluding section.

[3]If H1 fit B diffractive PDFs are used then the ratio for the preliminary H1 data implies an overall suppression of about 0.6 [12, 13].

Springer

(Currently is tested in the H1 analysis)

Outline

- **Introduction** **(why we are interested in CEP processes?)** 
- **Standard Candle CEP reactions.**
- **CEP through the KRYSTHAL eyes (new results, selected topics).**
  - **Diphoton CEP.**
  - **Dimeson CEP.**

Khoze,Ryskin,Stirling,Harland-Lang-→ Krysthal Collab.

With a bit of personal flavour

- **CEP as a way to study old and new heavy resonances**
- **'Diffractive Higgs' revisited.**
- **Towards the Full Acceptance Detector at the LHC (bj-1992).**
- **Summary and Outlook.**

Introduction (why we are interested in CEP ?)

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

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

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

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

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

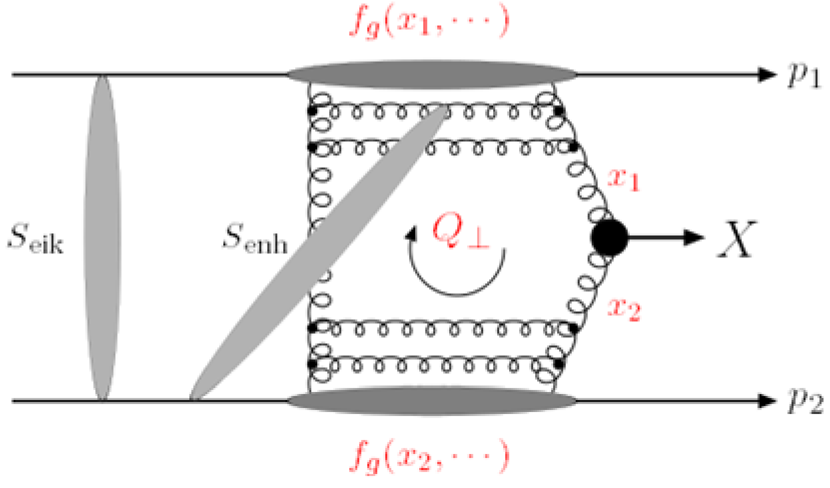
Spin-Parity Analyzer (KMR-00, KKMR-2003)

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

A.B.Kaidalov +KMR Central exclusive diffractive production as a spin-parity analyser: From Hadrons to Higgs,
Eur.Phys.J. C33 (2004) 261-271

‘Durham Model’ of central exclusive production

- The generic process $pp \to p + X + p$ is modeled perturbatively by the exchange of two t-channel gluons.
- The use of pQCD is justified by the presence of a hard scale $\sim M_X/2$. This ensures an infrared stable result via the Sudakov factor: the probability of no additional perturbative emission from the hard process.
- The possibility of additional soft rescatterings filling the rapidity gaps is encoded in the ‘eikonal’ and ‘enhanced’ survival factors, $S^2_{\rm eik}$ and $S^2_{\rm enh}$. (a lot of attention)
- In the limit that the outgoing protons scatter at zero angle, the centrally produced state X must have $J_Z^P = 0^+$ quantum numbers.



A.B. Kaidalov +KMR Probabilities of rapidity gaps in high-energy interactions ,
Eur.Phys.J. C21 (2001) 521-529

High price to pay for such a clean exclusive environment:

σ (CEP) ~ 10^{-4} $*$ σ(inclus.)

Rapidity Gaps should survive **hostile** hadronic *radiation damages* and *'partonic pile-up'*

symbolically $W = S^2 T^2$

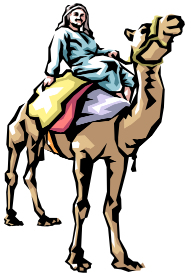
Colour charges of the 'digluon dipole' are screened only at $r_d \geq 1/(Q_t)_{ch}$

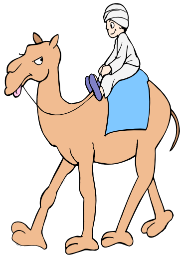
GAP Keepers (Survival Factors) , protecting RG against:

- the debris of QCD radiation with $1/Q_t \geq \lambda \geq 1/M$ **(T)**
- soft rescattering effects (necessitated by unitariy) **(S)** (Alan, Asher,Uri)

How would you explain this to your (grand) children ?

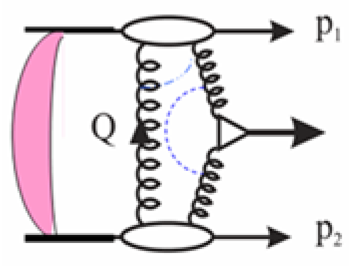
Forcing two camels to go through the eye of a needle





P → **H** ← **P**

The KKMR technology



(KKMR 1997-2009)

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

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

σ(CEP) ~ 10^{-4} σ (incl)

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

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

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

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

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

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

Tg + anom.dim. → IR filter

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

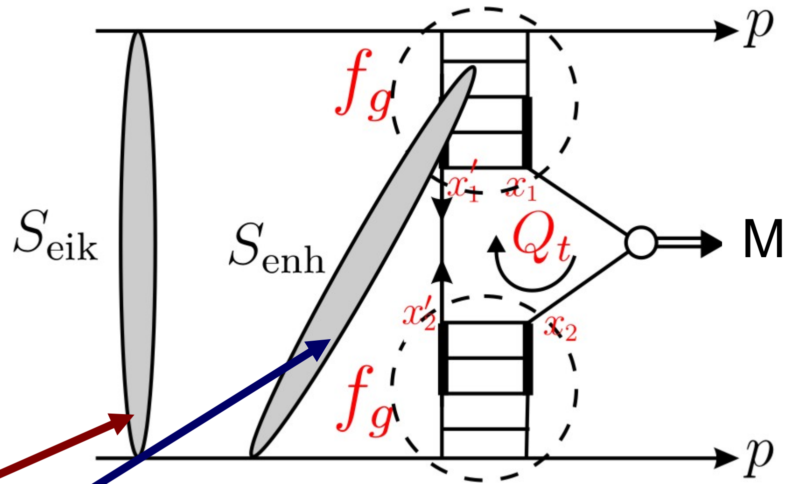
CDF results (dijets, γγ, χ_c), D0

(new LHCb & CMS results)

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

“soft” scattering can easily destroy the gaps

S² ➔ absorption effects -necessitated by unitarity



gap

gap

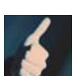
soft-hard factorizⁿ conserved brokenSErgei

Eikonal rescatt: between protons

Semi-enhanced rescatt: involving intermediate partons

(also Enhanced diagrams…GLM, S.Ostapchenko)

A subject of intensive theoretical discussions



Durham and Tel-Aviv group now - in a broad agreement

(Alan, Asher, Genya,Uri)

New Durham Studies

(known unknowns)

- Account for the b-dependence of the survival factors $S^2_{\rm enh}$, $S^2_{\rm eik}$ (GLM-new results)
- NLO effects in the unintegrated parton densities
  (N)NLO-effects in hard ME.

- A systematic account of self–energy insertions in the propagator of the screening gluon
- The dependence on the gluon PDF is amplified by the fact that the CEP cross section is essentially proportional to $(xg(x))^4$.

CDF $\gamma\gamma$ data *may* suggest more 'LO–type' PDFs ($\to$ more optimistic Higgs cross sections) are appropriate.

Improvements of models for soft diffraction: (Alan's talk)
- removing tensions with Totem data on $\sigma_{\rm el}$ and $\sigma_{\rm tot}$,
- agreement with the LHC results on low mass SD,
- agreement with the Tevatron/LHC data on CEP processes

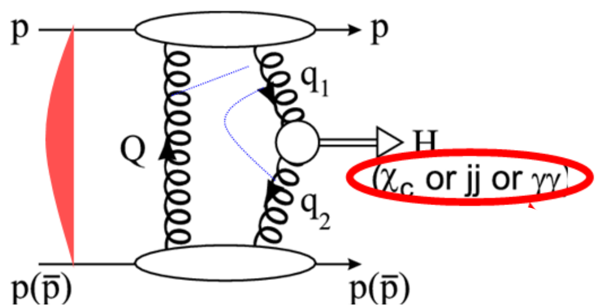
subprogram to SuperCHIC to calculate S^2 in SuperCHIC- progress KRH-L

Uncertainties within a factor of three or so

Standard Candle Processes

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

(Confucius)



The process p-p $\rightarrow \gamma\gamma / \chi_c / \chi_b /$ j-j are standard candles for the exclusive Higgs

孔夫子

孔丘 Kong Qiu

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

- Can serve as 'Standard Candle' processes, which allow us to check the theoretical predictions for central exclusive new physics signals at the LHC, as well as being of interest in their own right[1].

- the CEP of $\gamma\gamma$ **and light** meson pairs, $M\overline{M}$, at sufficiently high invariant mass for perturbative formalism to be applicable:
  - Provides novel application/test of hard exclusive formalism, complementary to more standard photon-induced processes ($\gamma\gamma \to M\overline{M}$, $\gamma\gamma^{(*)} \to M$ etc[2]).
  - Demonstrates application of MHV formalism to simplify/check calculations.
  - $\pi^0\pi^0$ CEP a possible background to $\gamma\gamma$ CEP.
  - Could probe the $q\overline{q}$ and gg content of η, η' mesons
  - An interesting potential observable @ RHIC, Tevatron and LHC: meson pair CEP data (at lower $p_\perp$) already being taken by ALICE and CDF.

(CMS, Totem+CMS- soon to come)

The SuperCHIC MC

A MC event generator including[8]:

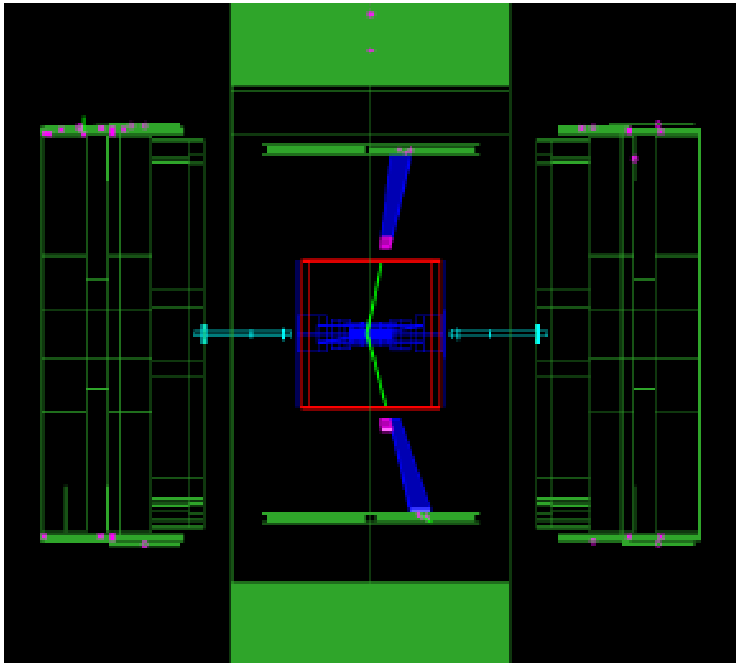
- Simulation of different CEP processes, including all spin correlations:
  - $\chi_{c(0,1,2)}$ CEP via the $\chi_c \to J/\psi\gamma \to \mu^+\mu^-\gamma$ decay chain.
  - $\chi_{b(0,1,2)}$ CEP via the equivalent $\chi_b \to \Upsilon\gamma \to \mu^+\mu^-\gamma$ decay chain.
  - $\chi_{(b,c)J}$ and $\eta_{(b,c)}$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

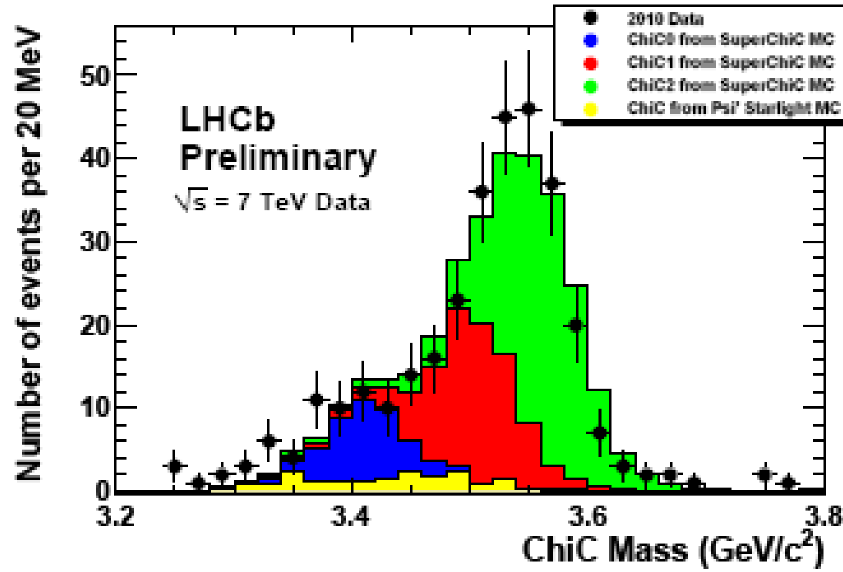
Plans to develop further: Herwig++, updated survival factors....

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

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

Data...



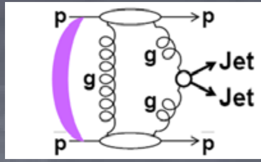


A wide range of central exclusive processes– $X = \mu^+\mu^-$, e^+e^- (QED), $\gamma\gamma$, jj, χ_c (CEP), J/ψ, $\psi(2S)$ (photoproduction)– have been observed by the CDF/D0 collaborations at the Tevatron, by selecting events with no additional activity in a large η range, and exclusive data at the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

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

(in a good agreement with the Durham expectations)

Comparison with KMR



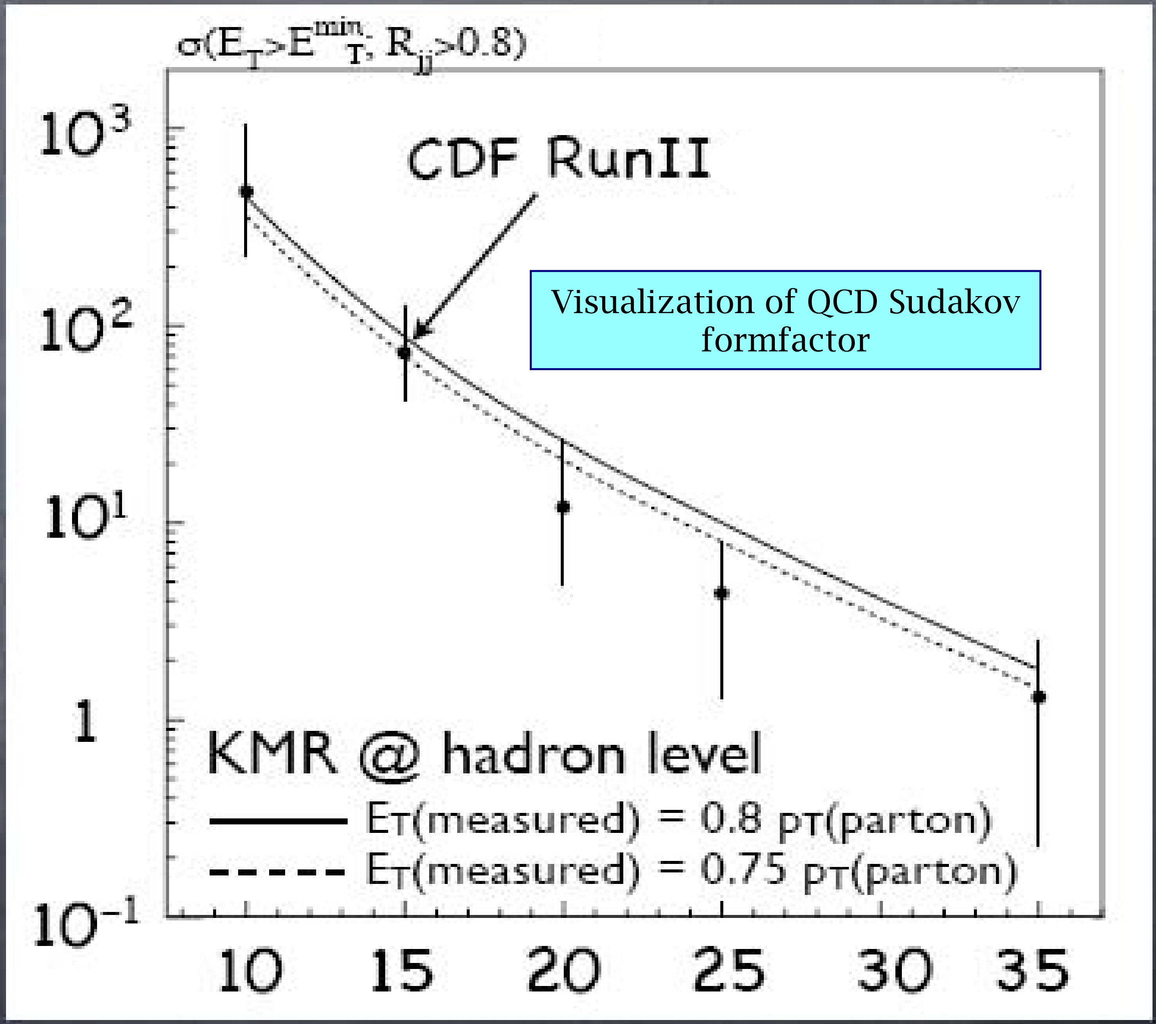
More direct comparison with KMR calculations including hadronization effects preferred

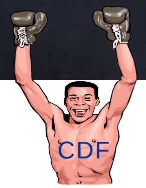
CDF out-of-cone energy measurement (cone R=0.7) :

- 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





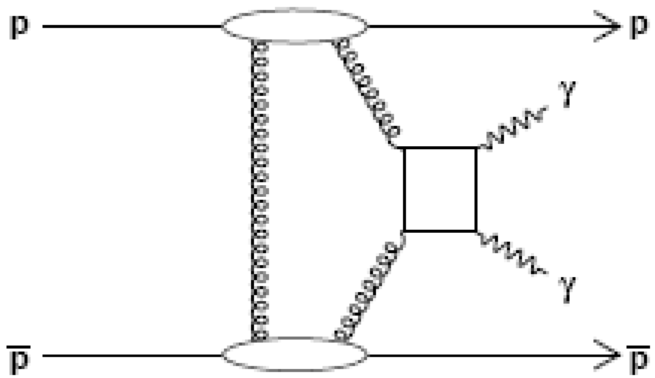
A killing blow to the wide range of theoretical models.

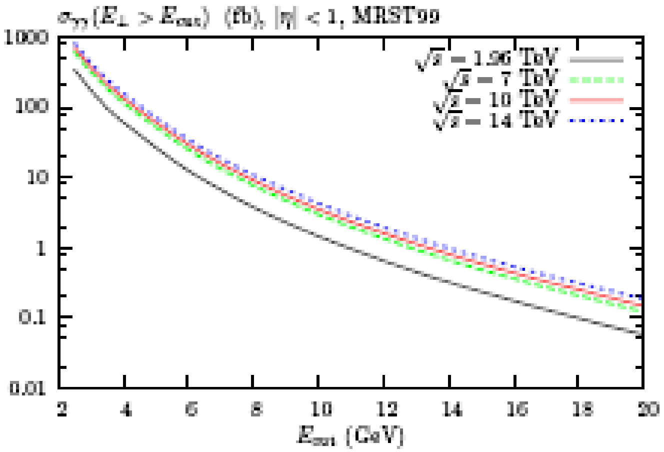
CDF
PRD-2008

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).





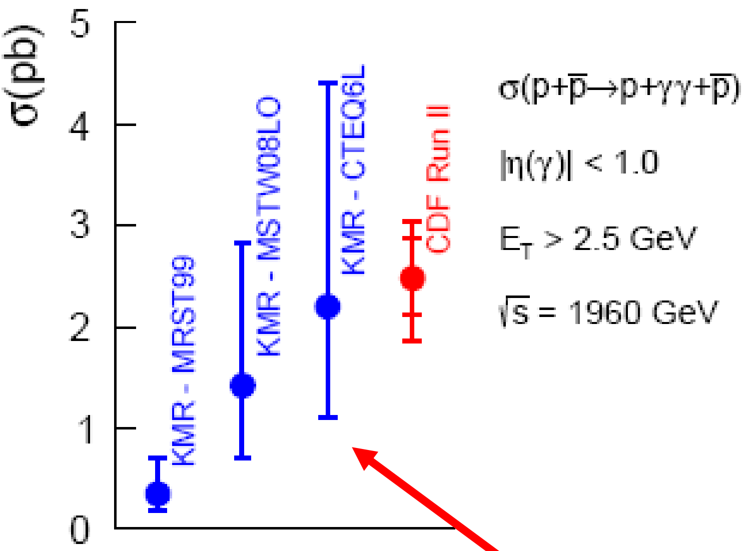
(KMRS-04)
(HKRS-10)

- **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 the Durham expectations)

New Exclusive $\gamma\gamma$: Conclusions

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



NEW! NLO effects-factor of 1.55

Currently theoret. uncertainties are under further revision.

- 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).

CEP of meson pairs

CEP via this mechanism can in general produce *any* C–even object which couples to gluons: Higgs, BSM objects...but also dijets, quarkonium states, light meson pairs...

i.e consider production of a pair of light mesons

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

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

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

Lower $k_\perp$ region: use Regge-based model

Lebiedowicz, Pasechnik, Szczurek, PLB 701:434-444, 2011 HKRS: arXiv:1204.4803

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

HKRS: arXiv:1304.4262, 1302.2004, 1204.4803, 1105.1626

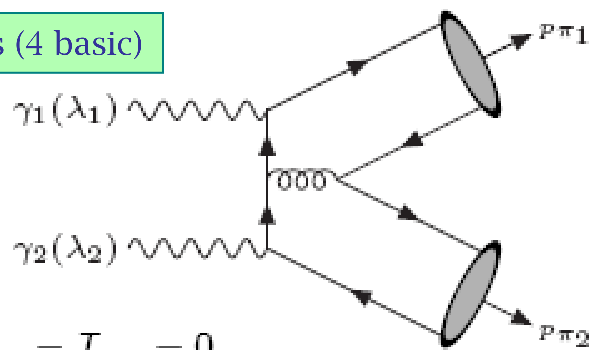
Modeling meson pair CEP perturbatively

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

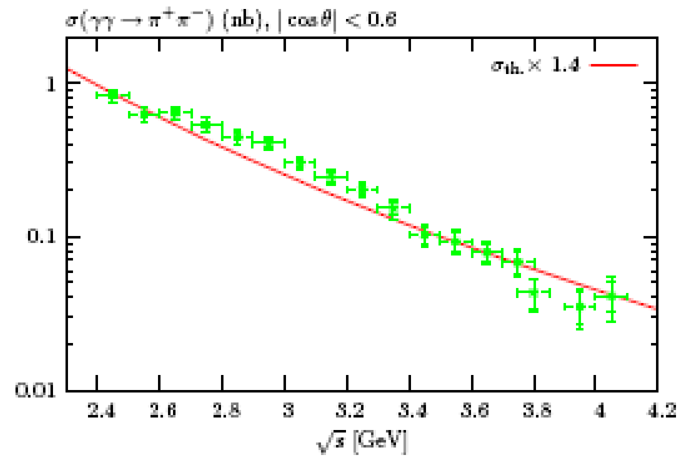
$$\mathcal{M}_{\lambda_1\lambda_2}(s,t) = \int_0^1 \mathrm{d}x\, \mathrm{d}y\, \phi(x)\phi(y) T_{\lambda_1\lambda_2}(x,y;s,t)$$

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

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

Flavour non-singlet mesons

HKRS: arXiv:1105.1626

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

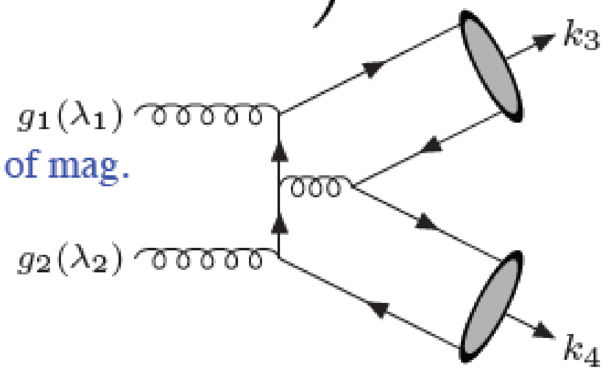
Flavour non-singlets $(\pi^+\pi^-, \pi^0\pi^0, K^+K^-, \rho^0\rho^0 ...)$: (31 diagrams)

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

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

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

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



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

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

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

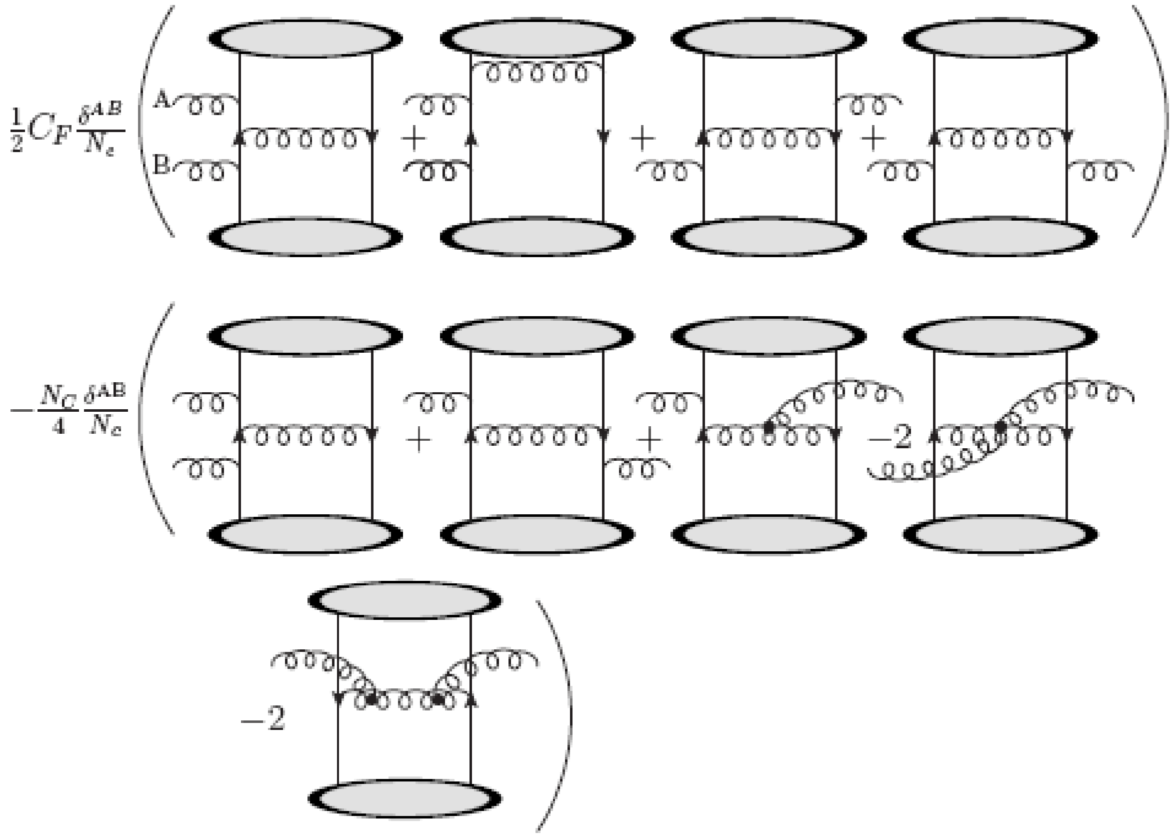
Experiment: $N(\pi^0\pi^0)/N(\gamma\gamma) < 0.35$ @ 95% confidence

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

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

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

is this easy to understand ?

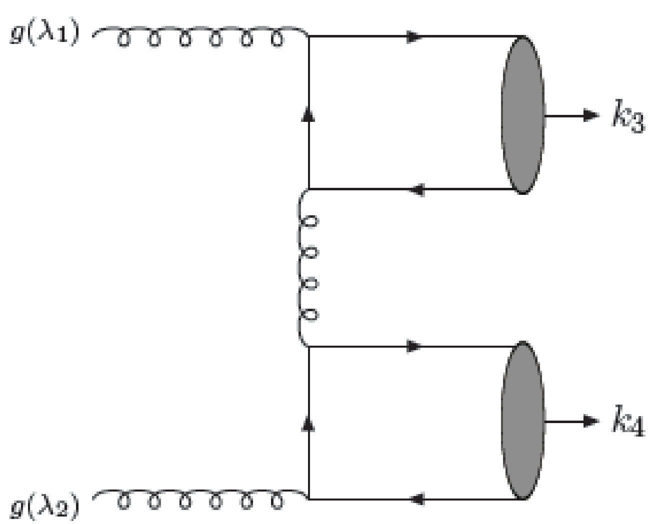


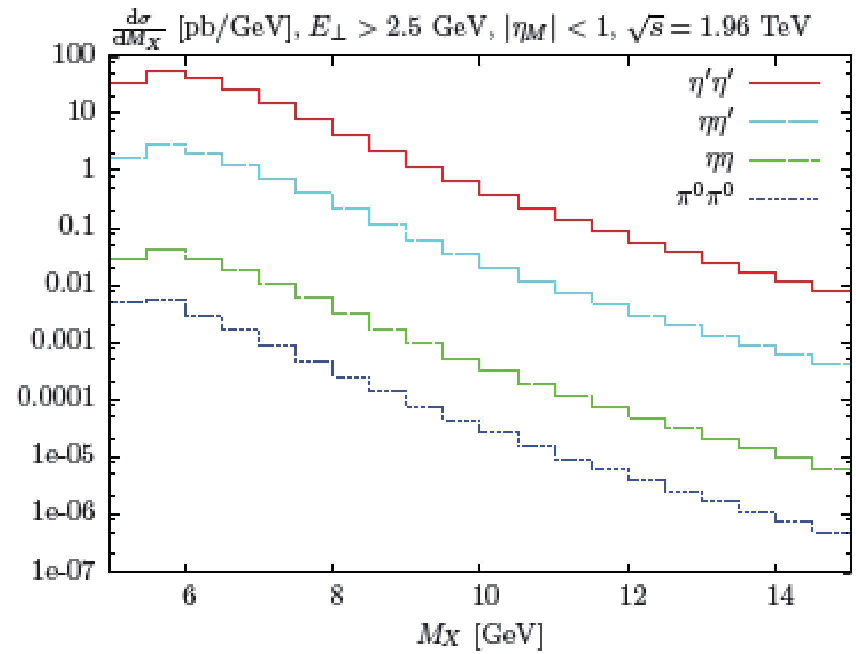
currently popular (among the more formal community) MHV- technique

Flavour singlet mesons

HKRS: arXiv:1105.1626

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





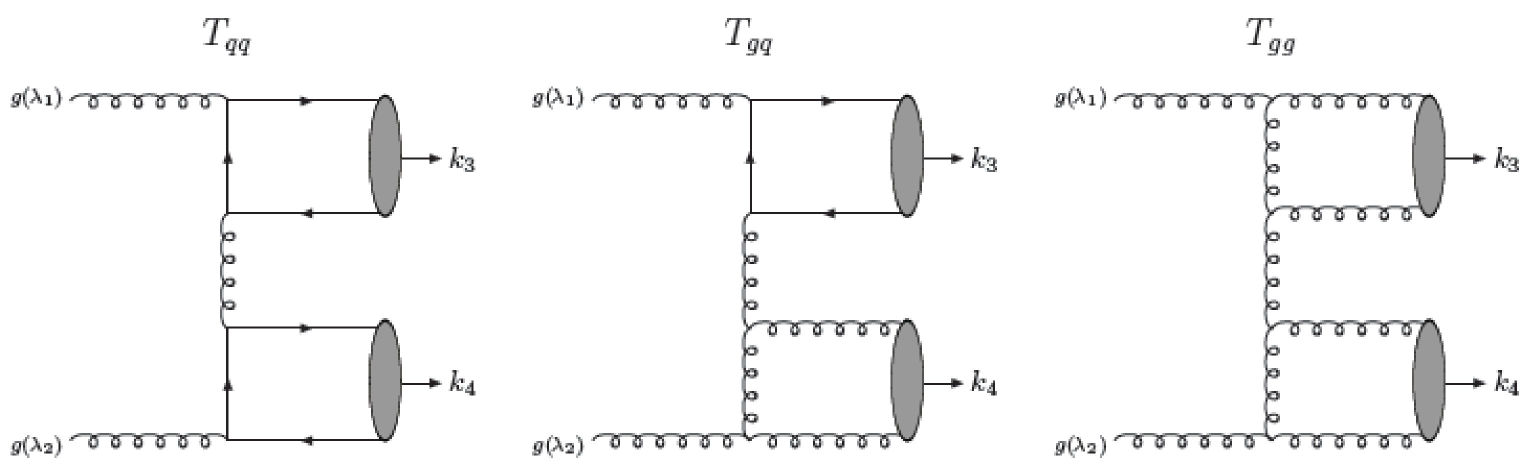
The gluonic component of the $\eta'(\eta)$

HKRS: arXiv:1302.2004

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

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

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



• As in the case of flavour non-singlet mesons, the $J_z = 0$ amplitudes have very simple forms. After lengthy calculation, finally get

(8 diagrams)

$$T^{qq\cdot}_{++} = T^{qq\cdot}_{--} = -\frac{\delta^{ab}}{N_C}\frac{64\pi^2\alpha_S^2}{\hat{s}xy(1-x)(1-y)}\frac{(1+\cos^2\theta)}{(1-\cos^2\theta)^2}$$

(72 diagrams)

$$T^{gq\cdot}_{++} = T^{gq\cdot}_{--} = 2\,T^{qq\cdot}_{++}\frac{N_c^2}{\sqrt{N_c(N_c^2-1)}}(2x-1)$$

(130 diagrams)

$$T^{gg\cdot}_{++} = T^{gg\cdot}_{--} = 4\,T^{qq\cdot}_{++}\frac{N_c^3}{N_c^2-1}(2x-1)(2y-1)$$

Not just diagrams of 'ladder type'

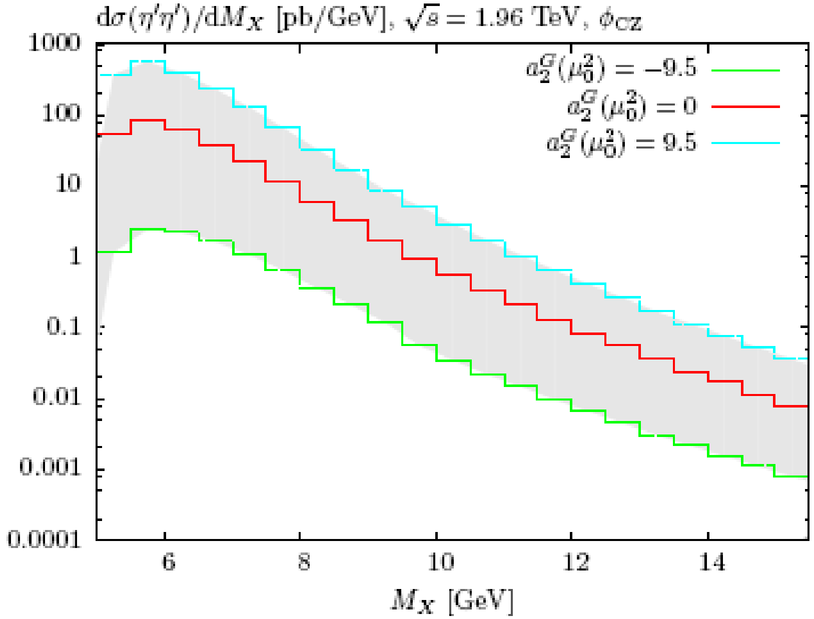
Simple, and identical in form, up to overall colour and normalization factors. Feynman diagrams complete distinct and apparently unrelated.

$\longrightarrow$ Unexpected result, but MHV can shed light

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

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

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



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

HKRS: arXiv:1302.2004

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

- **Heavy Quarkonia**

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

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!

χ_c CEP

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

- Considering case of $\chi_{c(1,2)}$ production: find that $V(gg \to \chi_{c(1,2)})$ vanishes in the forward ($p_\perp \to 0$) limit[5]:

→ χ_{c2}: Coupling of χ_{c2} to gg is forbidden in the non-relativistic quarkonium approximation for $J_z = 0$ gluons. However, in the forward proton limit, the fusing gluons must be in such a helicity configuration: '$J_z = 0$ selection rule'.

→ χ_{c1}: Landau-Yang theorem forbids decay of a $J = 1$ particle into two on-shell gluons. In CEP gluons are almost on–shell, up to corrections of order $O(q_{i\perp}^2/M_\chi^2)$ → will expect suppression. In fact find that for case $q_{1\perp} = -q_{2\perp} = Q_\perp$, amplitude vanishes.

- In arXiv:0902.1271 CDF reported 65 ± 10 signal χ_{cJ} ($= {}^3P_J$ $c\bar{c}$ states) events observed via the $\chi_c \to J/\psi\gamma \to \mu^+\mu^-\gamma$ decay channel. This corresponds to $\mathrm{d}\sigma(\chi_c)/\mathrm{d}y_\chi|_{y=0} = (76 \pm 14)\,\mathrm{nb}$, in good agreement with Durham prediction of ~ 60 nb.

- However, couldn't distinguish between different χ_{cJ} states...

[5] For more details see LHL, V.A.Khoze, M.G. Rysin, W.J. Stirling, Eur.Phys.J.C65:433-448,2010,

Cross section results (1)

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

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

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

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

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

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

(better Rap Gap veto coverage needed- FSCs can be quite useful)

Forward proton angular distributions (2)

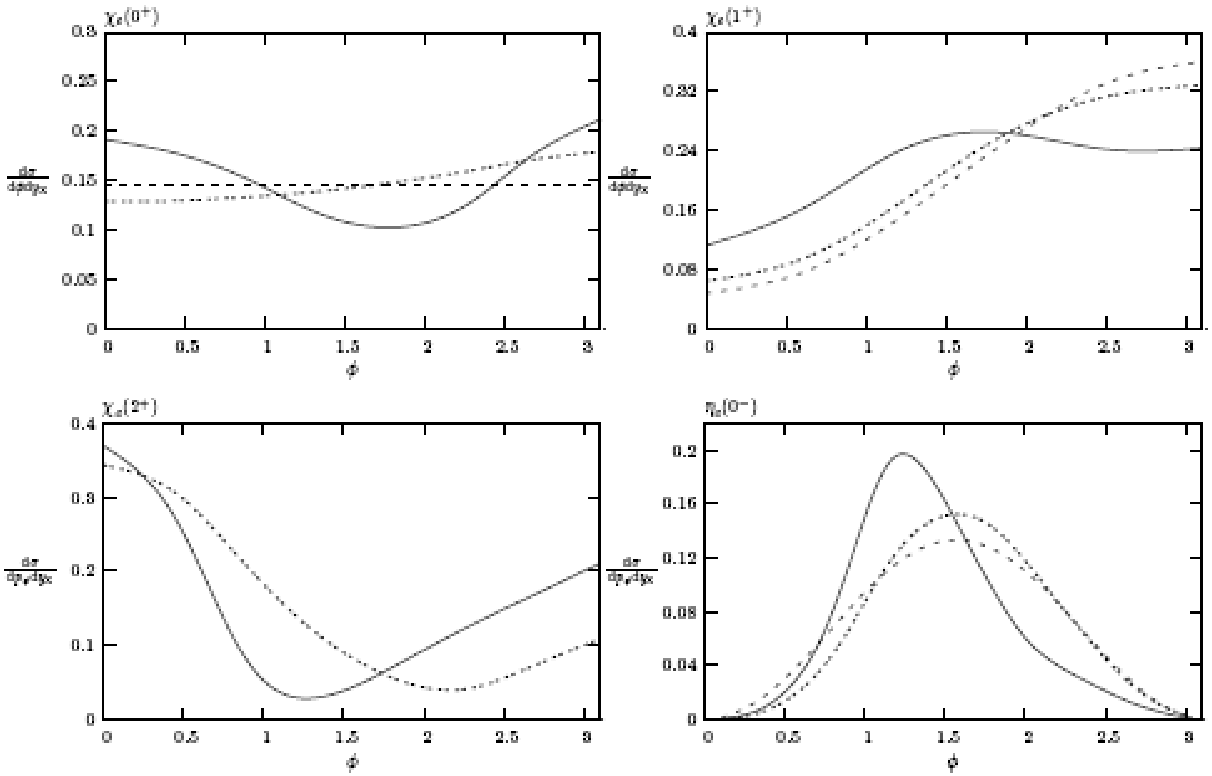


Figure: distribution (in arbitrary units) within the perturbative framework of the difference in azimuthal angle of the outgoing protons for the CEP of different J^P $c\bar{c}$ states at $\sqrt{s} = 14$ TeV. The solid (dotted) line shows the distribution including (excluding) the survival factor, while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

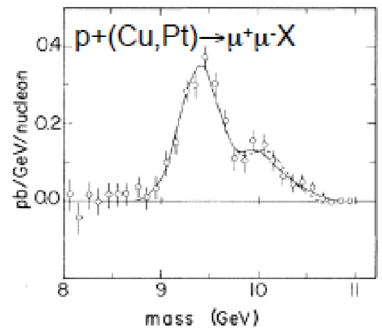
→ Measurement of azimuthal angle, ϕ, between outgoing protons and proton $p_\perp$ distributions via forward proton taggers would allow a clear discrimination between the different J states, as well as possibly probing different models of soft diffraction (which will predict in general different distributions).

A.B.Kaidalov +KMR Central exclusive diffractive production as a spin-parity analyser: From Hadrons to Higgs,, Eur.Phys.J. C33 (2004) 261-271

P-wave Bottomonia

Bottomonium history started 30 years ago

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



FNAL, E288

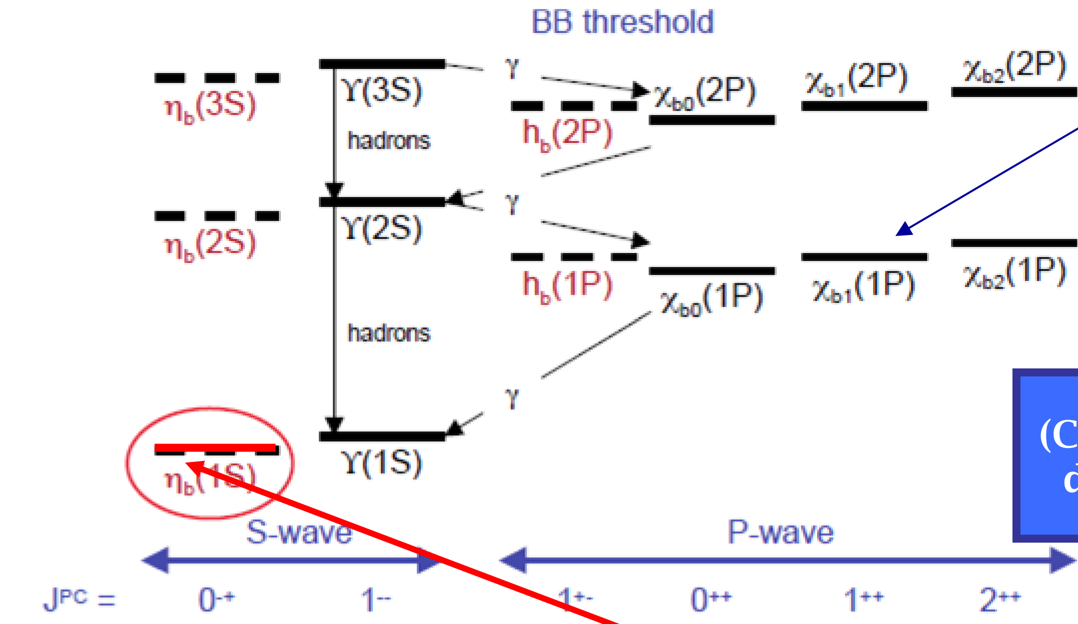
$M(\Upsilon)=9.40\pm0.013$

$M(\Upsilon')=10.00\pm0.04$

$M(\Upsilon'')=10.43\pm0.12$

(spins- still unconfirmed)

30 years later….



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

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

(Currently no complete theoretical description of onium properties.)

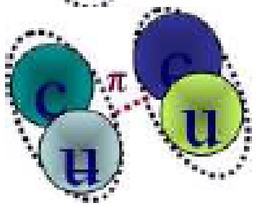
(BABAR (2008))

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

Zoo of charmonium –like XYZ states

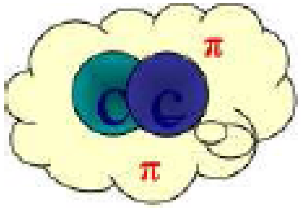
Tetraquark:
four tightly bound quarks

Molecular state:
two loosely bound mesons



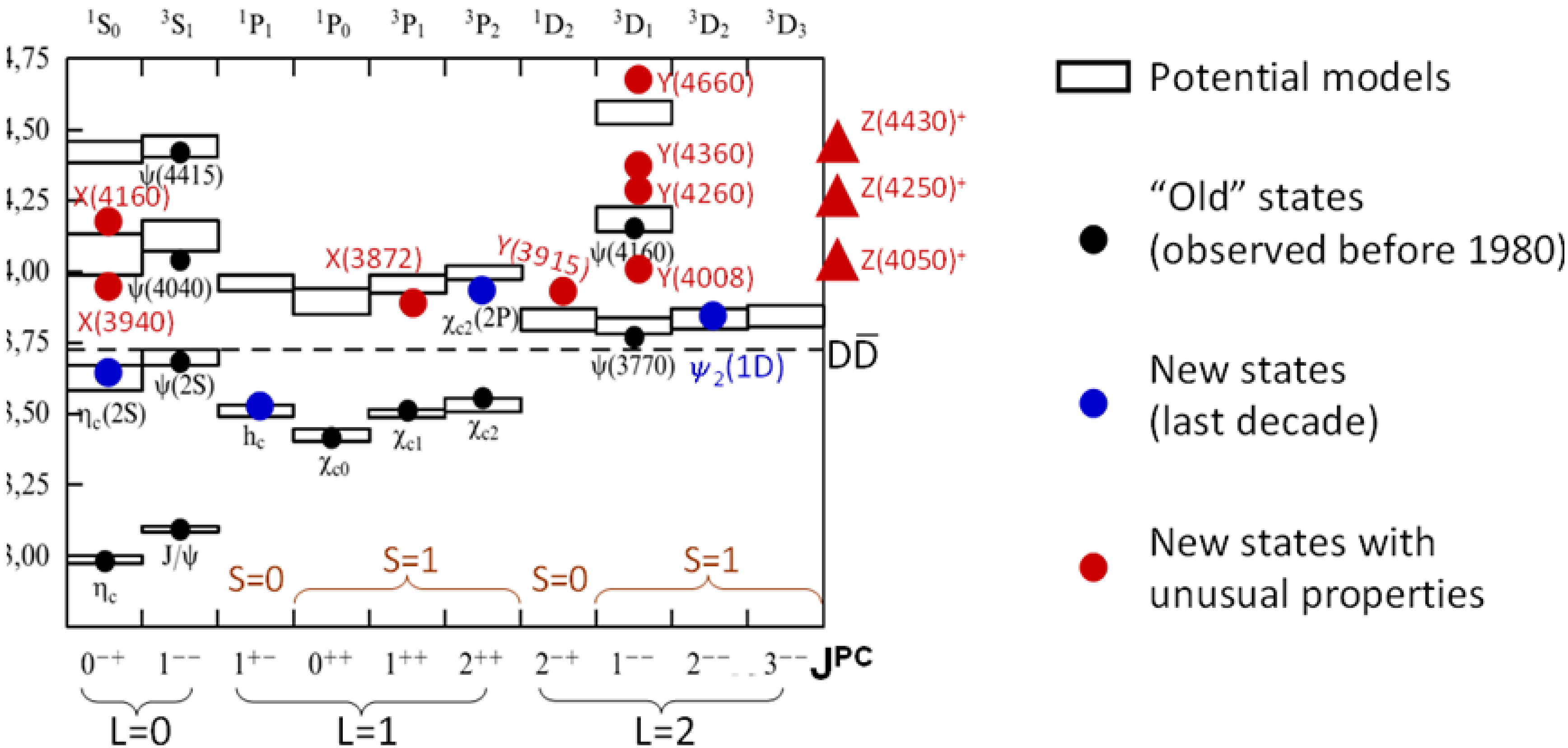
Hybrid: states with
excited gluonic degrees of freedom

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



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

Charmonium table

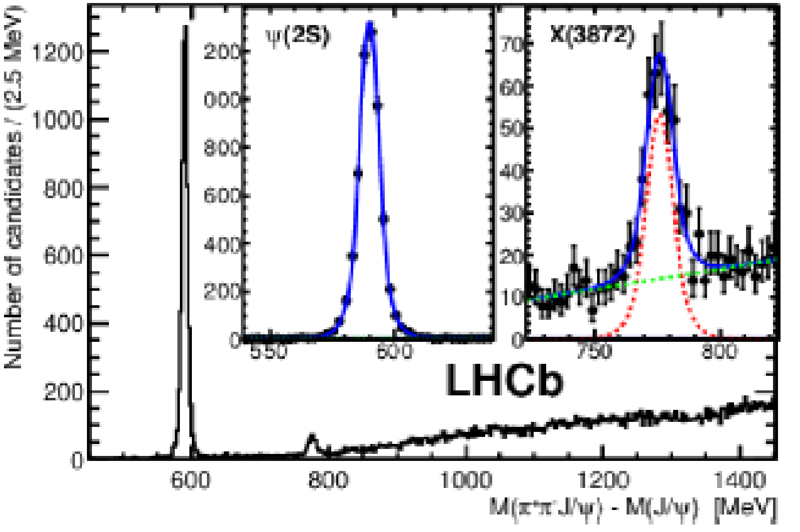


States below DD̄ threshold are narrow (annihilation or → other charmonia)

States above DD̄ threshold are broad (→ DD̄, DD̄*, ...)

The future (?): X(3872)

- Discovered by Belle in 2003, confirmed by Babar, at the Tevatron and the LHC.
- Could be of exotic nature: loosely bound hadronic molecule, diquark-antidiquark ('tetraquark') and hybrid ($\bar{c}cg \cdots$). However, conventional $c\bar{c}$ interpretation is still possible.



- Possible J^{PC} assignments were 1^{++} or 2^{-+}.
- New LHCb data (arXiv:1302.6269) rejects 2^{-+} at 8 sigma level $\rightarrow \eta_{c2}(1^1D_2)$ ruled out.
- Exotic interpretations still possible or conventional $\chi_{c1}(2^3P_1)$ charmonium? Or admixture?

PDG'12

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

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

isospin violation

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

Most likely interpretation:

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

isospin violation

production at high energy

Fractions of admixtures? Bound or virtual? Dynamical model?

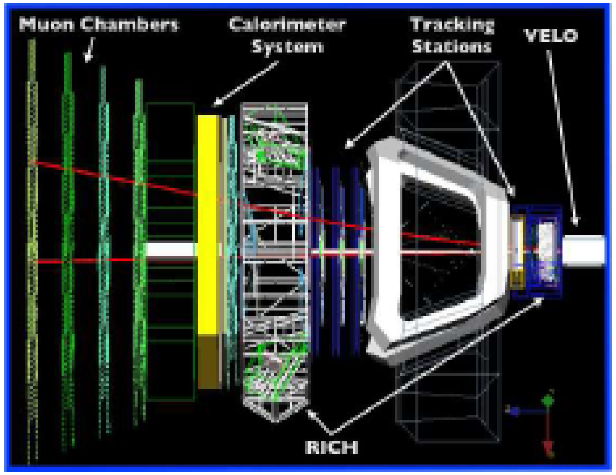
Experimental issues:

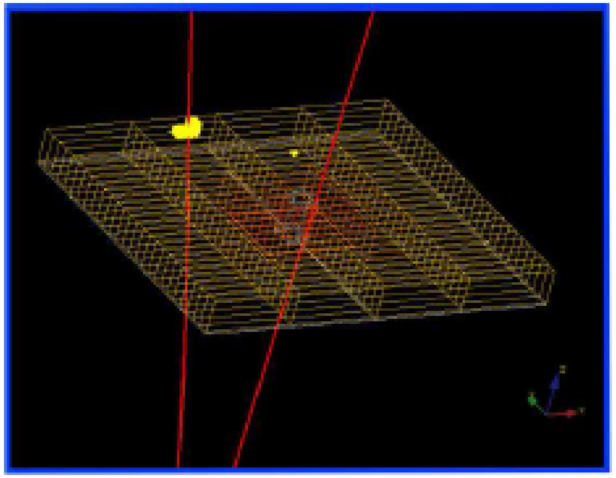
- δM (D^0 mass uncertainty dominates)
- $\psi(2S)\,\gamma$ (Belle/BaBar controversy)
- line-shape in $D\bar{D}^*$ (statistics limited)
- absolute BF (inelastic channels?)

Insight from CEP

- In CEP the state X is produced directly, i.e. at short distances: $gg \to X(3872)$ and nothing else. $\to$ would be clear evidence of a direct production mode.
- In an inclusive environment, for which additional soft quarks, D–mesons etc can be present/emitted it should be easier to form molecular state. Will expect additional suppression in exclusive case.

$\to$ Can shed further light by comparing to the rate of $\chi_{c1}(1^3P_1)$ production, as seen by LHCb. Up to mass effects, cross section ratio should be given by ratio of squared wavefunction derivatives at the origin $|\phi'_P(0)|^2$.

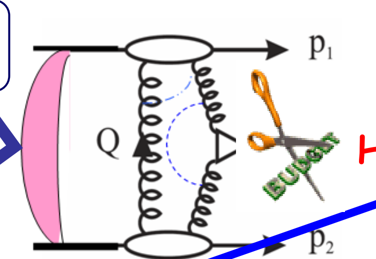




Good Luck to LHCb

Main Goal: Keep The Ball Rolling

The main advantages of CEP Higgs production



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

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

- H ->bb opens up (Hbb Yukawa coupl.) ☺

(gg)CED → bb in LO ; NLO,NNLO, b- mass effects – controllable.

- For some BSM scenarios CEP may become *a* discovery channel 😐

PRIOR TO THE LHC START-UP

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

  - A handle on the overlap backgrounds- Fast Timing Detectors (10 ps timing or better).

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

Triple product correlation: $\vec{n}_0 \cdot (\vec{p}_{1\perp} \times \vec{p}_{2\perp}) \sim \sin\varphi$,

Integrated counting asymmetry (~10%)

$$A = \frac{\sigma(\varphi < \pi) - \sigma(\varphi > \pi)}{\sigma(\varphi < \pi) + \sigma(\varphi > \pi)} ,$$

+ strong evidence from the Tevatron

Elusive particle found, looks like Higgs boson

4 July 2012

SHARE · COMMENT (40) · PRINT

Rolf Heuer, Director-General of CERN, answers a journalist's question about the scientific seminar to deliver the latest update in the search for the Higgs boson in Meyrin near Geneva on Wednesday. AP

(Sergei, Ilya)

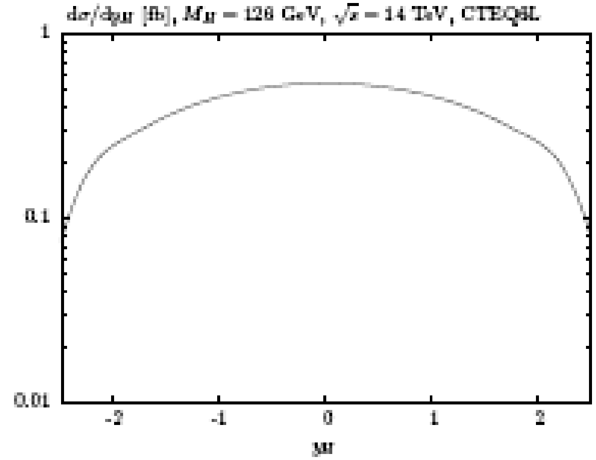
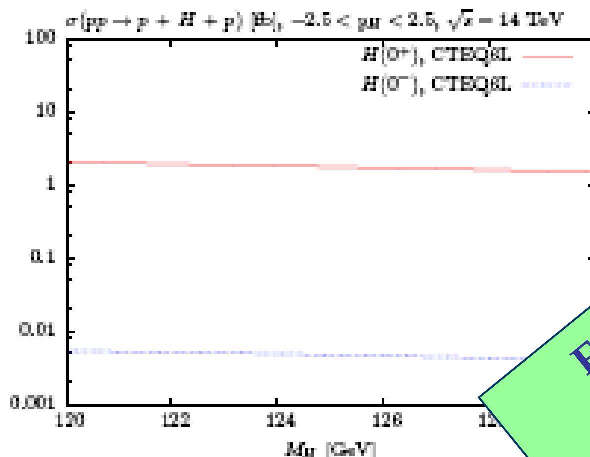


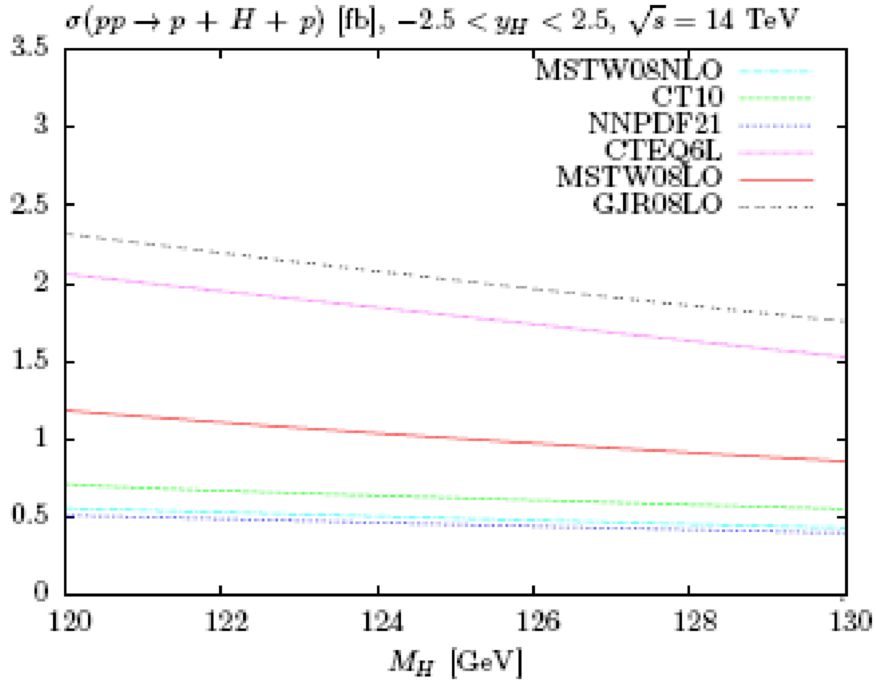
Figure 5: Rapidity distribution $d\sigma/dy_H$ for a $M_H = 126$ GeV SM Higgs boson, using CTEQ6L PDFs.



Find a CEP resonance and you have confirmed its quantum numbers!

Figure 6: Cross sections for the CEP of scalar $J^P = 0^+$ and pseudoscalar $J^P = 0^-$ particles of the Higgs sector as a function of the Higgs mass, M_H, integrated over the rapidity interval $-2.5 < y_H < 2.5$.

Higgs Boson: cross section predictions



SuperCHIC

- Cross section $\sim$ fbs, i.e. roughly 4 orders of mag. lower than inclusive case (price paid for exclusivity).
- Uncertainties (Survival factors, higher–order corrections, PDFs) exist in theoretical calculation. But $\gamma\gamma$ CEP cross section tends to lie a little above theory estimates $\to$ favours the higher predictions shown.

SM Higgs, 125 GeV

Signal-to-Background Ratio (a brief reminder)

$H \to b\bar{b}$

- The largest signal, but large background and (most) difficult trigger

  (other channels –too low rate).

- Major theor. uncertainties cancel in the ratio, in particular survival factors, PDFs,..
- Experimental efficiencies (trigger, b-tagging..) cancel.

Dominant non-PU backgrounds:

[DeRoeck, Orava+KMR, EPJC 25 (2002) 392, EPJC 53 (2008) 231]

1) Admixture of |Jz|=2 production

2) NLO gg→bbg, large-angle hard gluon emission

3) LO gg→gg, g can be misidentified as b

4) b-quark mass effects in dijet processes, HO radiative corrections

Main characteristics:
2007 (HKRTSW) values

Mass window	ΔM	~4 GeV.
g-b misID	$P(g/b)$	~ 1.3%
cone size	ΔR	~0.5.

S/B ≈1

(420+420)

Could be improved by a factor of 2 or so.

A.B. Kaidalov+ KMR Extending the study of the Higgs sector at the LHC by proton tagging ,
Eur.Phys.J. C33 (2004) 261-271

News on Exclusive Production of the BSM Higgs bosons

Marek Taševský

(in collaboration with S. Heinemeyer, V. Khoze and G. Weiglein)

Low-x workshop 2013, Eilat, Israel - 02/06 2013

LHC Higgs observation and MSSM exclusion bounds from all LHC data

New MSSM benchmark scenarios

New MSSM benchmark scenarios

- **M. Carena, S. Heinemeyer, O. Stal, C. Wagner, G. Weiglein: 1302.7033**

New low-energy MSSM scenarios that are compatible with the mass and production rates of the observed Higgs boson signal at ~ 125.5 GeV:

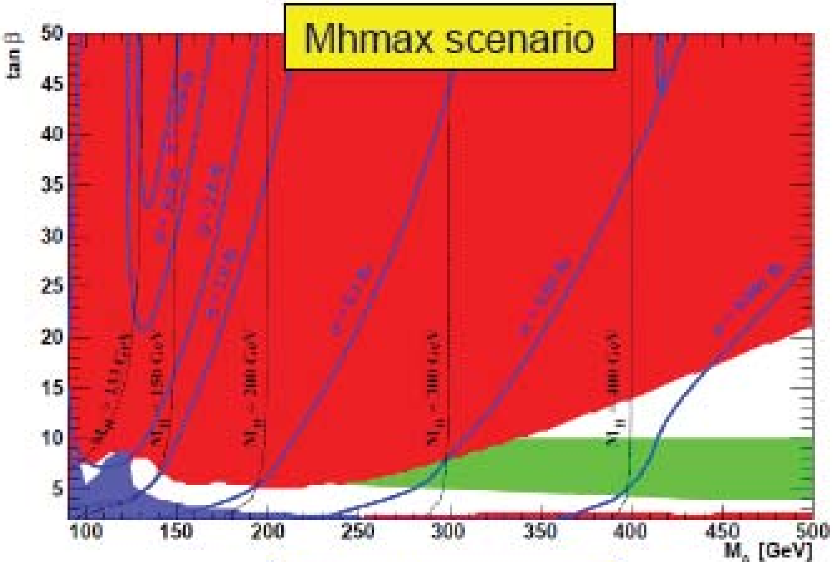
1. Mhmax: mass of the light CP-even Higgs boson is maximized for fixed $\tan\beta$ and large M_A
2. Mhmod+: modified Mhmax: reduces the mixing in the stop sector compared to the value that maximizes M_h
3. Mhmod-: similar to Mhmod+
4. Lightstop: suppression of the lightest CP-even Higgs gluon fusion rate
5. Lightstau: enhanced decay rate of $h \to \gamma\gamma$ at large $\tan\beta$
6. Tauphobic: the lightest Higgs has suppressed couplings to down-type fermions
7. LowMh: fixes the value of M_A (=110 GeV) and varies μ

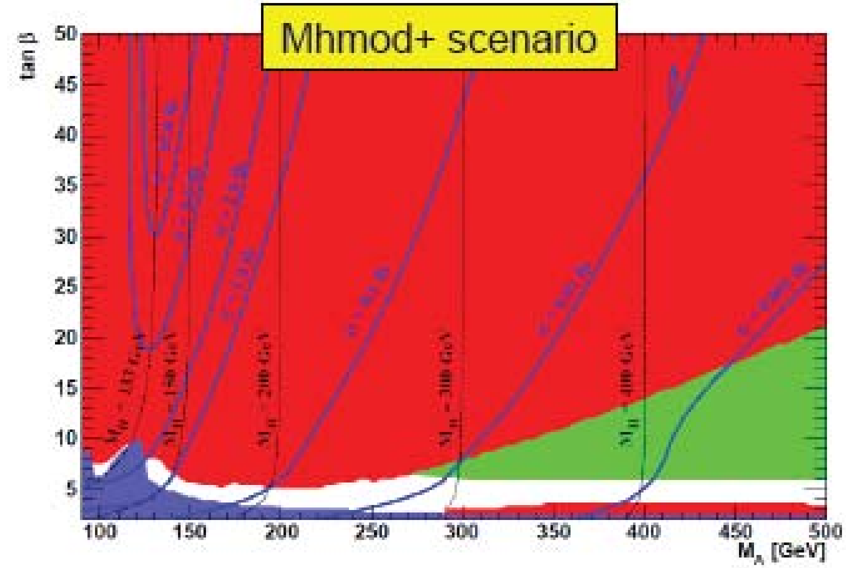
light Higgs~SM-like

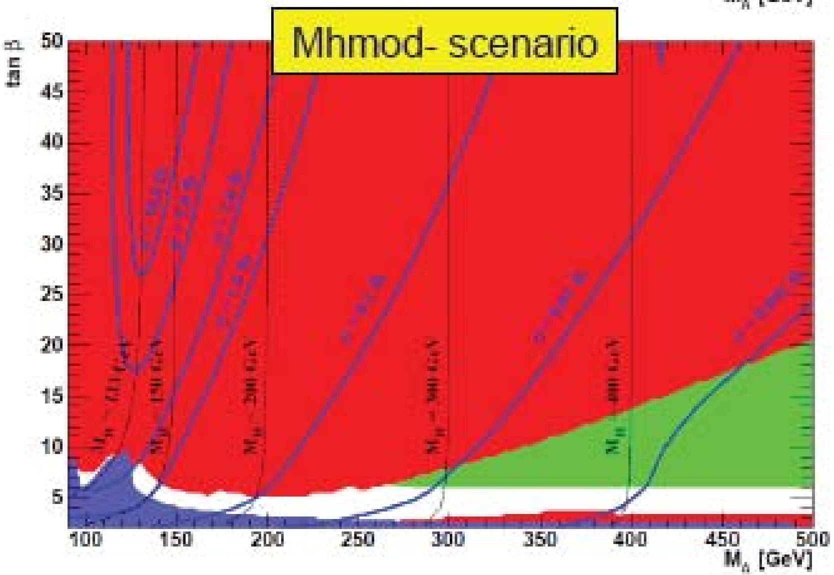
1-6: the discovered Higgs is the CP-even lightest Higgs; look for the heavy partner
7: the discovered Higgs is the CP-even heavy Higgs; look for the lighter partner

The LHC exclusion regions inferred from analyses searching for MSSM Higgs bosons:
[φ=h,H,A]: 1) $pp \to \varphi \to \tau^+\tau^-$ (inclusive); $b\bar{b}\varphi$, $\varphi \to \tau^+\tau^-$ (with b-tag); 2) $b\bar{b}\varphi$, $\varphi \to b\bar{b}$(with b-tag),
$pp \to t\bar{t} \to H^{\pm}W^{\mp}b\bar{b}$, $H^{\pm} \to \tau\nu_\tau$, $gb \to H^-t$ or $g\bar{b} \to H^+\bar{t}$, $H^{\pm} \to \tau\nu_\tau$

CED H→bb signal x-sections







$122.5 < M_h < 128.5$ GeV

LHC exclusion regions

LEP exclusion regions

X-sections come from KMR calculations.
They still need to be multiplied by experim. efficiencies (~10%) to get significances.
Signal yields in the allowed region are tiny.

similar unpromising situation with the CEP rates for heavier H- boson in other MSSM scenarios

Low M_H MSSM scenario

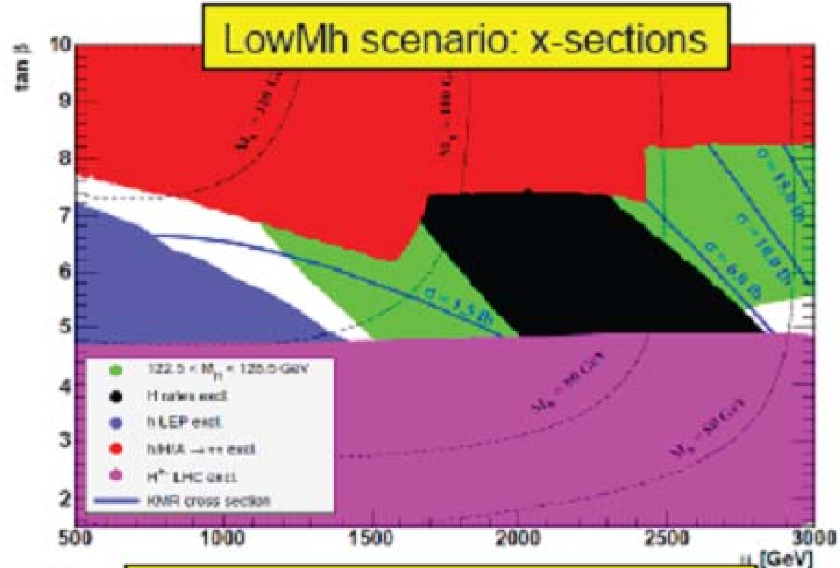
(see for instance arXiv: 1302.7033, also NMSSM)

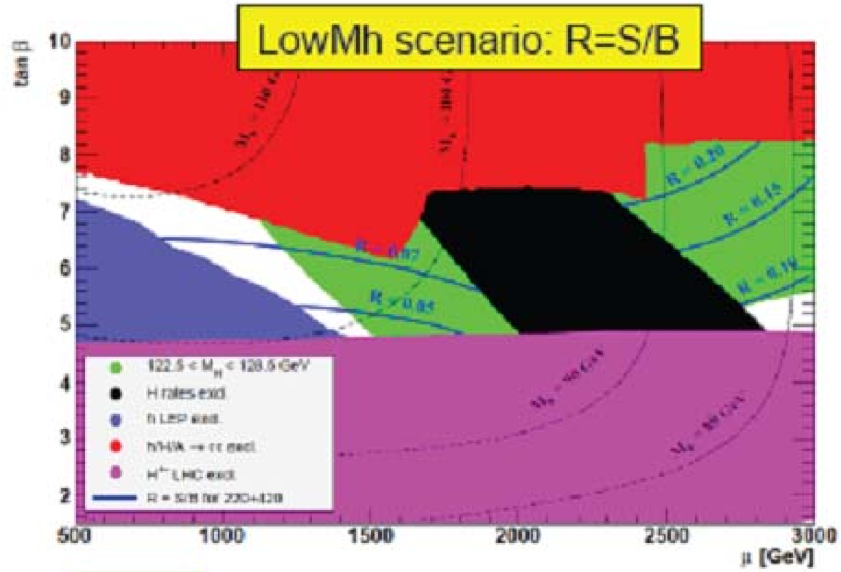
- The LHC signal corresponds to the heavy CP-even Higgs boson.- SM like.
- Light CP-even Higgs – heavily suppressed couplings to the gauge bosons.
- The available parameter space is already affected by the current limits.
- All 5 Higgs states have masses have masses of order 100 GeV
- Rich phenomenology- but might be excluded by the standard search channels at the LHC comparatively soon. 
- Recall also that the background is increasing with mass decreasing 

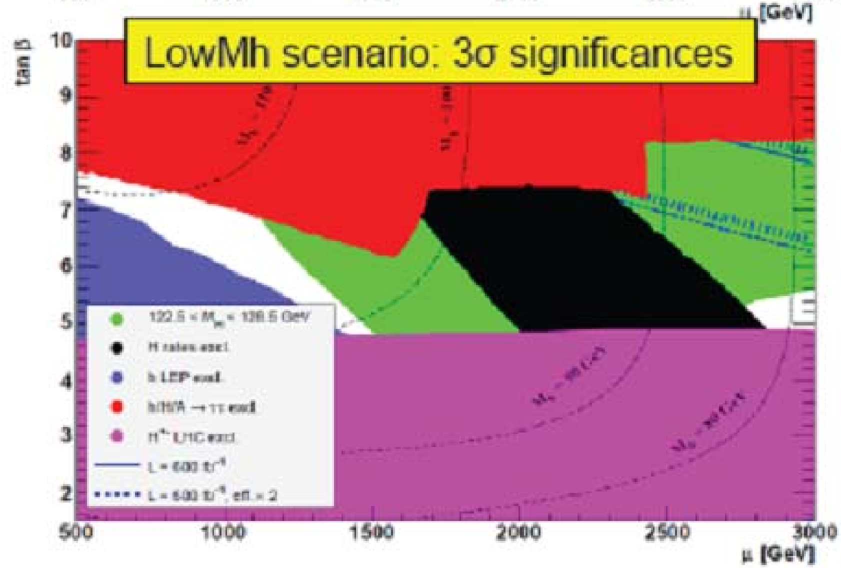
$$S / B \sim \Delta M / M^3$$

(New studies in progress by M.Tasevsky, S.Heinemeyer, G.Weiglein and VAK)

CED H→bb at LowMh scenario







122.5 < M_h < 128.5 GeV

H → ZZ,WW rates exclusion

h LEP exclusion

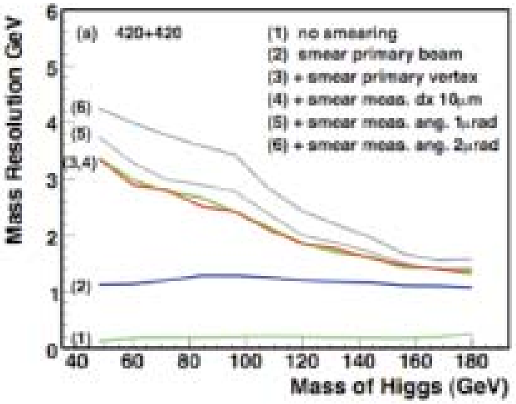
h/H/A → ττ exclusion

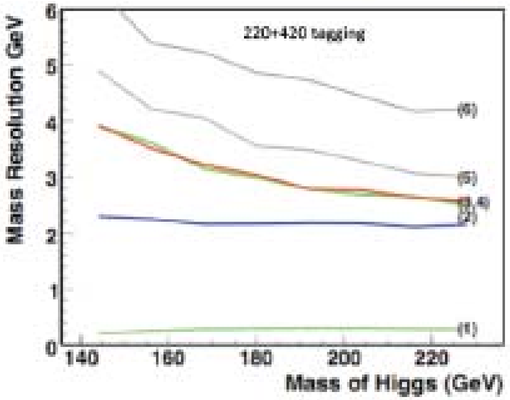
H^{+-} LHC exclusion

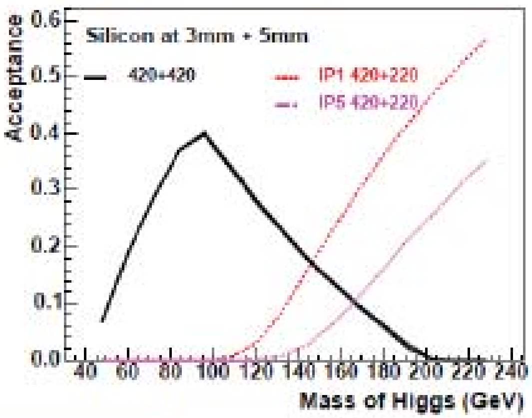
Ratios and significances include the experim. efficiencies

LowMh considerations

- Ratios S/B and 3σ-significances include the experimental efficiencies.
- 3σ is reachable only for large integrated luminosity (~1000 fb^{-1}). This means we need to combine data from both CMS and ATLAS.
- In this scenario, the Higgs boson found at M_H ~ 125.5 GeV is the heavy one; we need to search for the lighter one → picture shows the region of interest M_h ~ 80-90 GeV.
- The region of interest M_h ~ 80-90 GeV is experimentally difficult:
  1. Only 420+420 configuration relevant
  2. 420m station can hardly be put into L1 trigger (at least in ATLAS)
  3. Slightly worse missing mass resolution than for higher masses
  4. Worse situation also in the central detector (L1 triggers highly prescaled, Pile-up issue)







FP420 R&D Report JINST 4 (2009) T10001

Towards Full Acceptance Detector (bj- 1992)

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

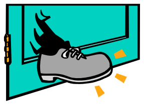
IS THERE A WAY OUT ?

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

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

(Alice is installing such counters, ongoing studies for 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.

! ?

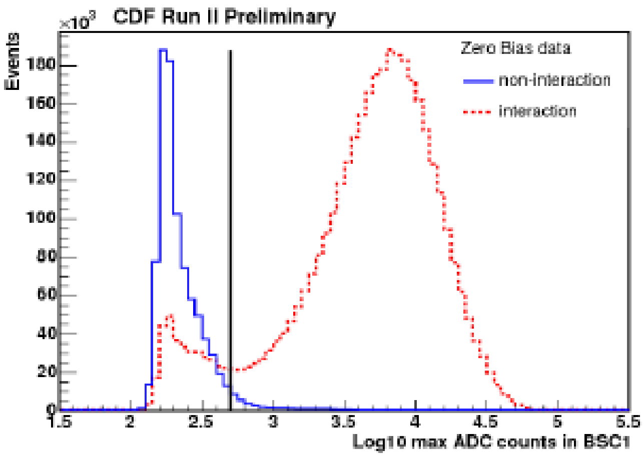
Also: They may provide valuable tests of radiation environment to be expected for HPS = High Precision Spectrometers

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

FORWARD PHYSICS WITH RAPIDITY GAPS AT THE LHC

Published in JINST-2009

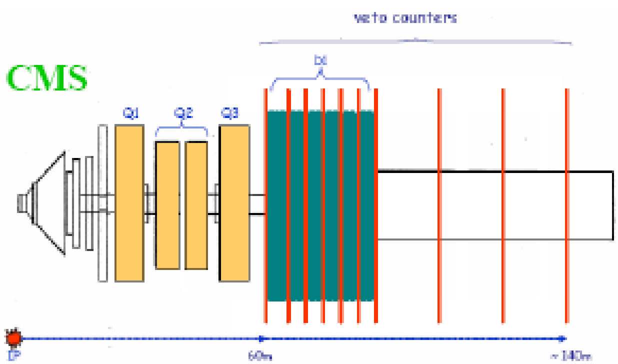
Michael Albrow[1], Albert De Roeck[2], Valery Khoze[3], Jerry Lämsä[4,5], E. Norbeck[6],
Y. Onel[6], Risto Orava[5], and M.G. Ryskin[7]
Sunday, November 09, 2008



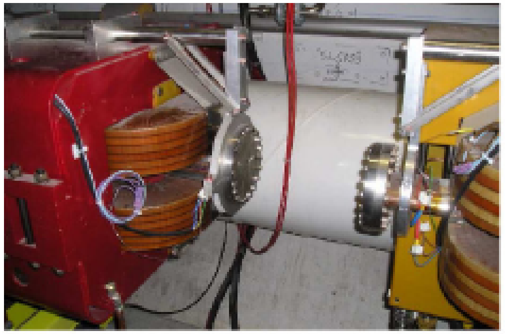
Warm accessible vacuum pipe (circular – elliptical)

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

CMS



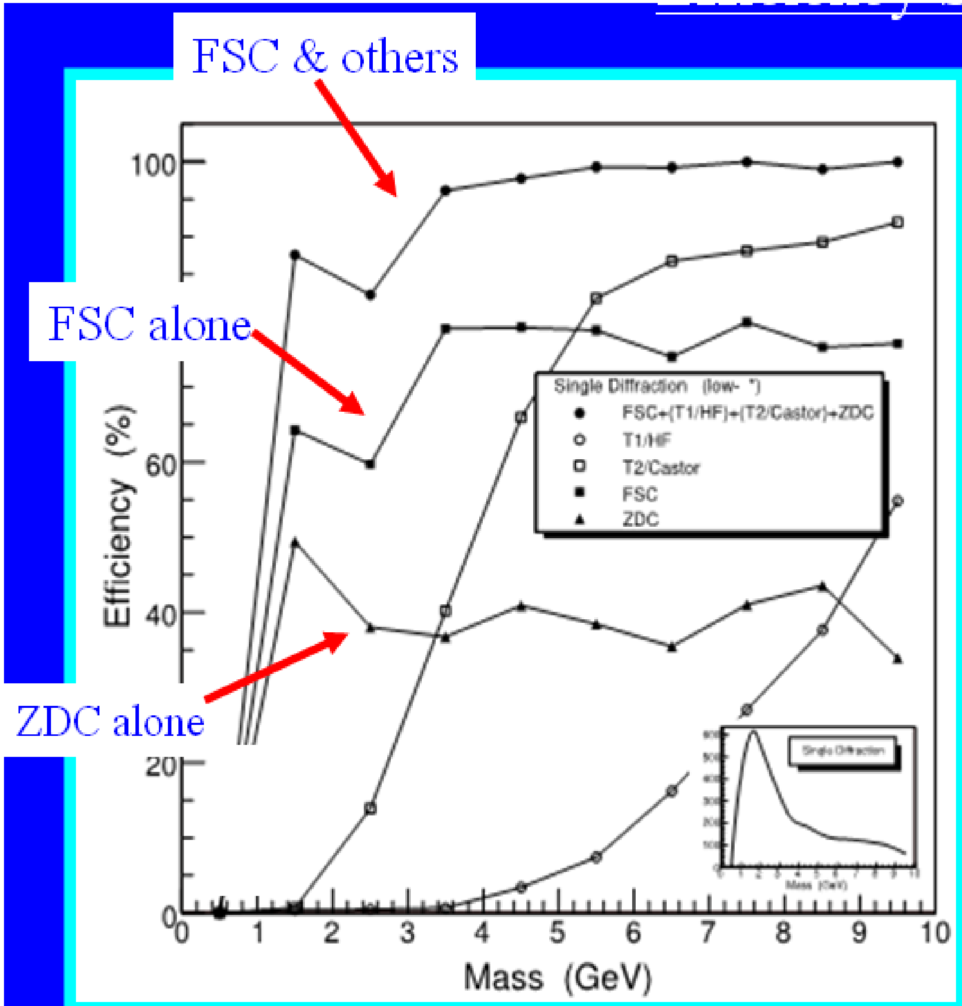
Take 0-bias events (Essential!)
{1} = prob no interaction
{2} = prob >= 1 interaction
Take hottest PMT of 8 BSC1
Plot log max ADC for {1} and {2}
Separates empty / not empty
Repeat for all detectors

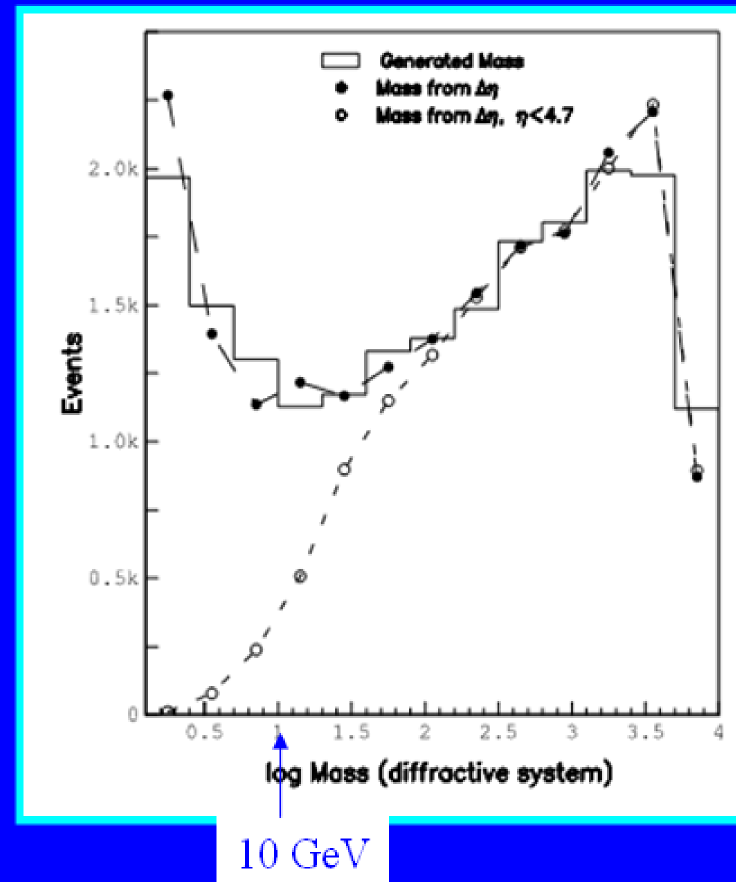


4

Mike Albrow   Exclusive production in CDF: high mass   Blois 2009 CERN

(Installed in 2011 at the CMS)





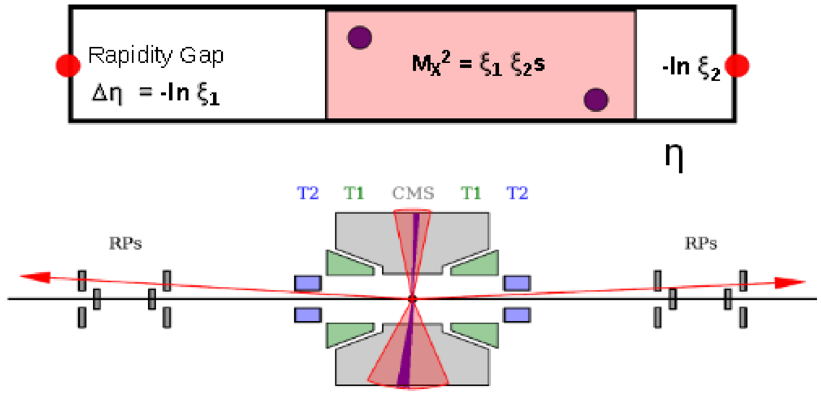
>4 hits in FSC or > 1 track in HF
or CASTOR or ZDC(min)

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

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

Below 10 GeV/c² FSC contain most particles

Central diffraction (aka DPE): TOTEM + CMS



Large η-coverage:

- CMS: $-5.5<\eta<5.5$
- T1: $3.1 < |\eta| < 4.7$
- T2: $5.3 < |\eta| < 6.5$
- FSC: $6 < |\eta| < 8$

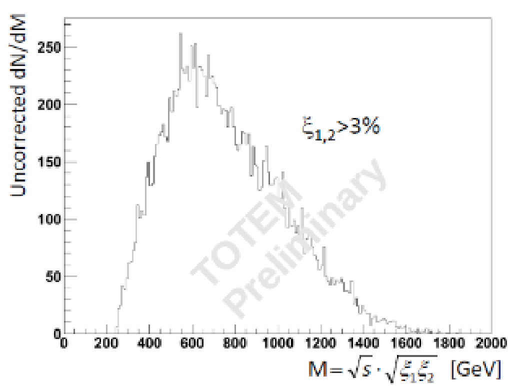
Double-arm proton detection

Prediction of mass to be seen in CMS from reconstructed protons: $M^2 = s\, \xi_1 \xi_2$

Initial vs. final state comparison: M_{TOTEM} (pp) =? M_{CMS}

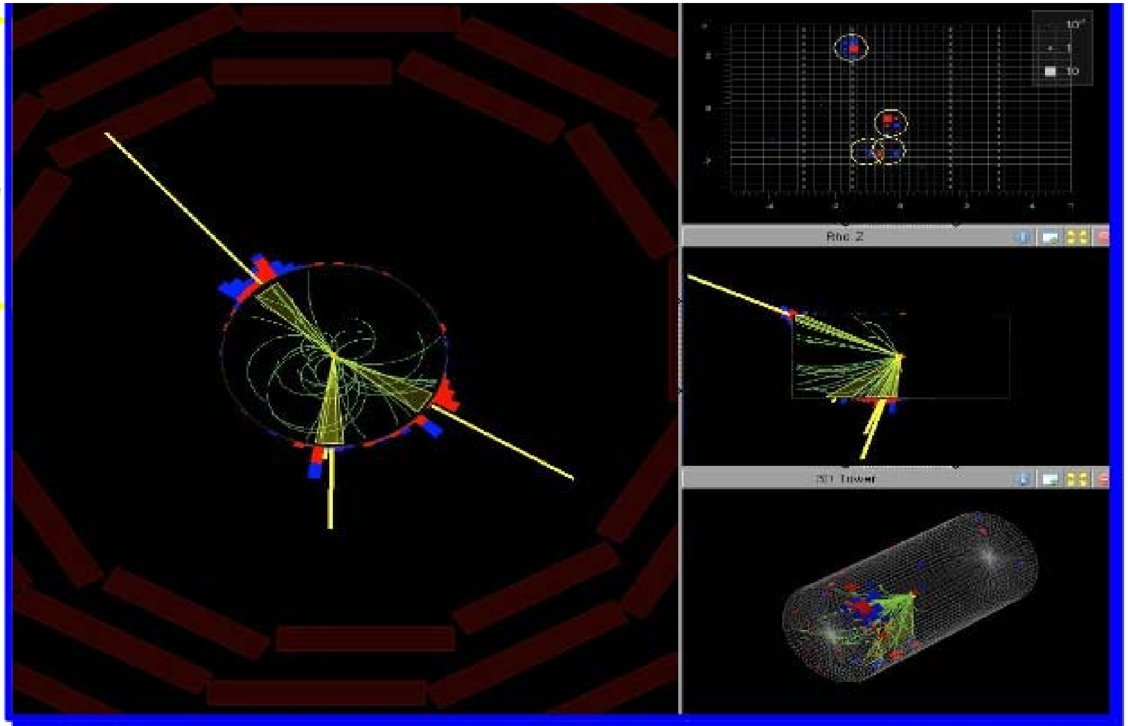
Prediction of central particle flow topology from proton ξэσ (rapidity gaps): $\Delta\eta_{1,2} = -\ln\xi_{1,2}$

Masses up to 1.8 TeV with pp survival!

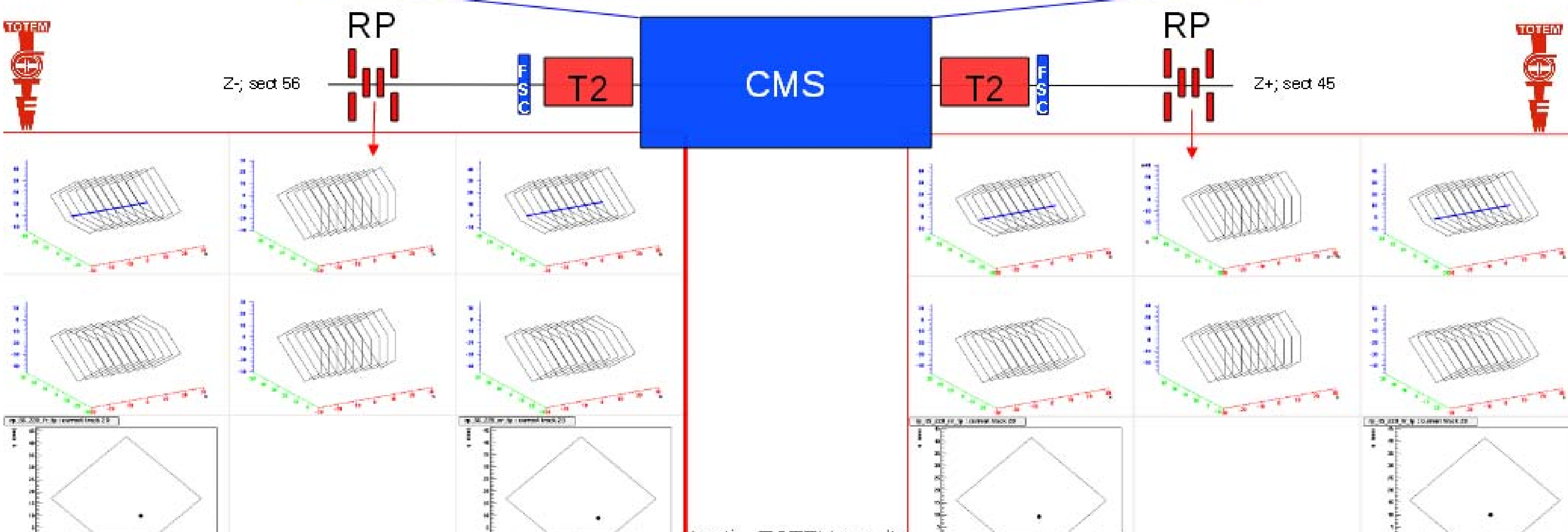


Analysis on going. Good statistic for soft diffraction; limited for hard diffraction

CMS + TOTEM 90m β^*
Run/Event 198903/3478279
Jets E_T = 65,45,27 GeV
[redacted]
MM(pp) = 244 GeV; M(CMS) = 219 GeV
Σp_T(CMS) = 3.4 GeV
FSC empty both sides



M(pp)= 244 GeV
ξ^-= -0.1 ξ^+= -0.01



Summary and Outlook

- CEP in hadron collisions offers a promising framework within which to study novel aspects of QCD and new physics signals.
- CEP processes observed at the Tevatron, RHIC and low–luminosity LHC can serve as 'standard candles' for Higgs (and other physics) CEP at the LHC.
- The data are in good overall agreement with the Durham theory $\to$ supports predictions for e.g. Higgs (and new physics) CEP.
- 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. Could help probe the gluonic structure of η, η' mesons.
- 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...awaiting CMS results.
- CEP could shed light on the nature of exotic charmonium–like states.
- More CEP results to come from RHIC, Tevatron data analysis and the LHC in the future.

- **'Diffractive Higgs' and new physics CEP (AFP, HPS) -jury is still out.**

We are looking forward to new exciting adventures in Exclusiveland


THANK YOU


QUESTIONS?

BACKUP

Forward Proton Taggers @ LHC as a gluonic Aladdin's Lamp

· **Higgs Studies**

- Photon-Photon, Photon - Hadron Physics.
- **'Threshold Scan'**: 'Light' New Physics ...
- 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 PP-luminosity monitor

PRIOR TO THE LHC START-UP

FPT

✴ Could provide a unique additional tool to complement the conventional strategies at the LHC.

σ(CDPE) ~ 10^{-4} * σ (incl)

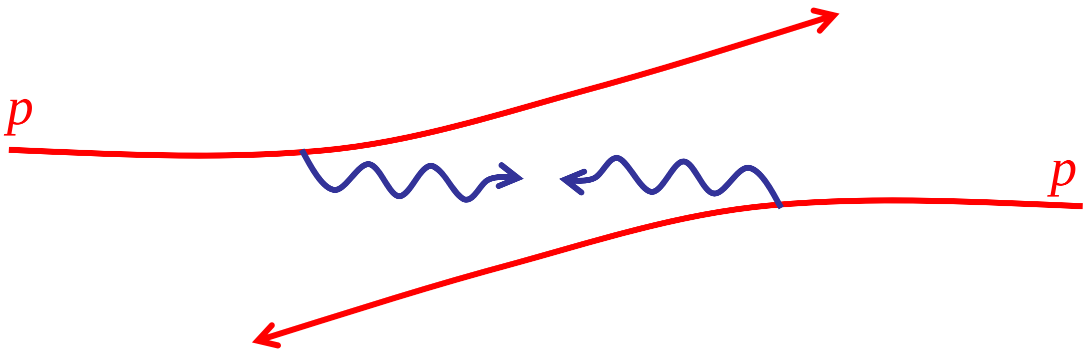
✴ Higgs is only a part of the broad EW, BSM and diffractive program@LHC

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

LHC as a High Energy $\gamma\gamma$ Collider

K. Piotrzkowski, Phys. Rev. **D63** (2001) 071502(R)
J.Ohnemus, T.Walsh & P .Zerwas -94;

KMR-02



<u>Highlights</u>:

• **$\gamma\gamma$ CM energy *W* up to/beyond 1 TeV (and under control)**

• **Large photon flux *F* therefore significant $\gamma\gamma$ luminosity**

• **Complementary (and clean) physics to *pp* interactions, eg studies of** *exclusive* **production of heavy particles might be possible ➡ opens new field of studying very high energy $\gamma\gamma$ (and γp) physics**

Very rich Physics Menu

MHV approach

= Maximally Helicity Violating $\qquad gg \to q\bar{q}q\bar{q}, ggq\bar{q}, gggg...$

- For meson pair production interested in 6 parton helicity amplitudes.
- Scalar mesons: outgoing partons have $+-$ helicity. Representative helicity configuration for $J_z = 0$ gluons:

$$\underset{1}{g(+)}\,\underset{2}{g(+)} \to \underset{3}{q(+)}\,\underset{1}{\overline{q}(-)}\,\underset{4}{q(+)}\,\underset{2}{\overline{q}(-)}$$

These LO amplitudes are MHV: maximum ($n-2=4$) number of partons have same helicity. Known to have very simple form: n-parton MHV amplitude can be written down analytically, often in one line.

$\Rightarrow$ Not suprising that previous $J_z = 0$ amplitudes are so simple

Meson pair production amplitudes represent a novel application of MHV formalism. Take general MHV expressions for n-parton amplitudes, and consider specific (6-parton) kinematics... Colour singlet Collinear

$$\underbrace{\mathcal{M}_n(\{p_i, h_i, c_i\})}_{\text{Total}} = \sum_\sigma \underbrace{T_n(\{c_{\sigma(i)}\})}_{\text{colour}} \underbrace{A_n(\{k_{\sigma(i)}, h_{\sigma(i)}\})}_{\text{kinematic}}$$

one for each non-cyclic ordering

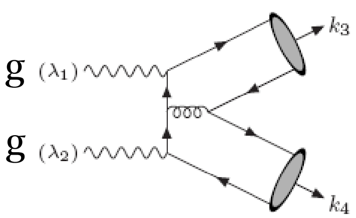
$gg \to M\overline{M}$ amplitude: MHV calculation (1)

- $g(+)g(+) \to q(\pm)\overline{q}(\mp)q(\pm)\overline{q}(\mp)$ 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 ‘$\langle k, l\rangle$’

χ_b CEP

- Higher χ_b mass means cross section is more perturbative and so is better test of theory, although rate is ~ 3 orders of magnitude smaller than χ_c.
- J assignment of χ_b states still experimentally undetermined: CEP could shed light on this.
- Calculation exactly analogous to χ_c case, but we have a stronger suppression in the χ_{b1} and χ_{b2} rates than for the χ_c case.
- Measurement of ratio of χ_b to $\gamma\gamma$ ($E_\perp = 5$ GeV) CEP rates would eliminate certain uncertainties (i.e. dependence on survival factors).
- Previous uncertainties in input parameters $\mathrm{Br}(\chi_{b0} \to \Upsilon\gamma)$ and $\Gamma_{\mathrm{tot}}(\chi_{b0})$ greatly reduced by new CLEO data (arXiv:1012.0589).
- Updated predictions for χ_b CEP via the $\Upsilon\gamma$ decay chain (at $y_\chi = 0$):

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

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

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

  Suppressed non-resonant background $\sim m_c^2/M_{\chi_b}^2$