**main aim:** to highlight recent development in the theory and phenomenology of the CED Higgs production
PLAN

1. Introduction (gluonic Aladdin’s lamp)

2. Central Exclusive Diffractive Production (only a taste).


4. Other BSM scenarios.

5. Conclusion.

"The World's Most Wanted"

Fugitives: Higgs boson
The main advantages of CED Higgs production

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

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

• $H \rightarrow bb$ opens up ($H_{bb}$- coupl.)
  \[ (gg)^{CED} \not\rightarrow bb \text{ in LO ; NLO,NNLO, } b- \text{ mass effects – controllable.} \]

• For some areas of the MSSM param. space CEDP may become a discovery channel!

• $H \rightarrow WW^*, \tau\tau$ (less challenging experimentally + smaller bgds., better PU cond.)

• 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…)

  LHC: ‘after discovery stage’, Higgs ID…….

  How do we know what we’ve found? 😐

  mass, spin, couplings to fermions and Gauge Bosons, invisible modes…
  → for all these purposes the CEDP will be particularly handy!
New CDF results (dijets, $\gamma\gamma$, $\chi_c$) (Christina, Jim) not so long ago: between Scylla and Charibdis: orders of magnitude differences in the theoretical predictions are now a history.

KMR technology (implemented in ExHume MC)

\[ \sigma_{pp}(M^2,\ldots) = L_{eff}(M^2,y) \ast \sigma_{hard}(M^2,\ldots) \]

\[ \frac{\partial^2 L_{eff}}{\partial y \partial M^2} = S^2 \ast L(M^2) \]

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

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

\[ L_{eff} \sim \left( \frac{S^2}{b^2} \right)^2 \left| N \int \frac{dQ_t^2}{Q_t^4} f_g(x_1, x'_1, Q_t^2, \mu^2) f_g(x_2, x'_2, Q_t^2, \mu^2) \right|^2 \]

contain Sudakov factor $T_g$ which exponentially suppresses infrared $Q_t$ region $\Rightarrow pQCD$

\[ < Q_t >_{\perp} G^2 = M / 2 \ast \exp \left( -1 / \bar{\alpha}_s \right) \approx 2 GeV \Rightarrow A_{GCD}, \]

\[ \bar{\alpha}_s = (N_c / \pi) \ast \alpha_s(M) \ast C_y \]

$T_g +$ anom. dim. $\Rightarrow$ IR filter

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

$\sigma$(CDPE) $\sim 10^{-4}$ (incl)
“soft” scattering can easily destroy the gaps

Subject of hot discussions: $S^2$

- Eikonal rescatt: between protons
- Enhanced rescatt: involving intermediate partons

$S^2 \rightarrow$ absorption effects - necessitated by unitarity

(KMR-01; BBKM-06; RMK-07-09, ...FHSW-07-09;GLMM-07-09 ...)
‘Well, it is a possible supposition.’
‘You think so, too?’
‘I did not say a probable one.’
Up to now the diffractive production data are consistent with \( K(KMR)S \) results
Still more work to be done to constrain the uncertainties.

- **Exclusive** high-E\( _{t} \) dijets
  - **CDF**: data up to (E\( _{t} \))\( _{\text{min}} \)>35 GeV (PRD-2008) (Christina)

  - 'Factorization breaking' between the effective diffractive structure functions measured at the Tevatron and HERA.
  - The ratio of high Et dijets in production with one and two rapidity gaps
  - **CDF** results on exclusive charmonium CEDP, (CDF, PRL) (Jim)
  - Energy dependence of the RG survival (D0, CDF).

- **Central Diffractive Production** of \( \gamma \gamma (\ldots \pi \pi, \eta \eta) \) (CDF, PRL-07) (Jim)
  (in line with the KMRS calculations) (3 candidates & 2 more candidates in the new data)

- Leading neutrons at HERA

*LET THE DATA TALK!*

Only a large data set would allow to impose a **restriction order** on the theoretical models
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 $E_T^{\text{Jet}}=10–20$ GeV
- 10–15% at $E_T^{\text{Jet}}=25–35$ GeV

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

Visualization of QCD Sudakov formfactor

A killing blow to the wide range of theoretical models.
Observation of Exclusive Charmonium Production and $\gamma\gamma \rightarrow \mu^+\mu^-$ in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV


![Graph showing mass distribution](image)

**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 $J/\psi$ and $\psi(2S)$, and a QED continuum. All three shapes are predetermined, with only the normalizations floating. Insert: Data above the $J/\psi$ and excluding $3.69 < M_{\mu\mu} < 3.75$ 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 $\chi_{c0}$. Backgrounds are given as percentages of the fit events, and efficiencies are to be applied to the events without background. The stated branching fraction $B$ for the $\chi_{c0}$ is the product of the $\chi_{c0} \rightarrow J/\psi + \gamma$ and $J/\psi \rightarrow \mu^+\mu^-$ branching fractions [11]. The cross sections include a 6% luminosity uncertainty.

<table>
<thead>
<tr>
<th>Class</th>
<th>$J/\psi$</th>
<th>$\psi(2S)$</th>
<th>$\gamma\gamma \rightarrow \mu^+\mu^-$</th>
<th>$\chi_{c0}(1P)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptances</td>
<td>$18.8\pm2.0$</td>
<td>$54\pm3$</td>
<td>$41.8\pm1.5$</td>
<td>$19\pm2$</td>
</tr>
<tr>
<td>Efficiencies</td>
<td>$33.4\pm1.7$</td>
<td>$45\pm6$</td>
<td>$41.8\pm2.3$</td>
<td>$33\pm2$</td>
</tr>
<tr>
<td>$\mu$-quality</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Photon (%)</td>
<td>$83\pm4$</td>
<td>$77\pm10$</td>
<td>$65\pm8$</td>
<td></td>
</tr>
<tr>
<td>Events (fit)</td>
<td>$286\pm17$</td>
<td>$39\pm7$</td>
<td>$77\pm10$</td>
<td>$65\pm8$</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>$9\pm2$</td>
<td>$9\pm2$</td>
<td>$8\pm2$</td>
<td>$11\pm2$</td>
</tr>
<tr>
<td>Dissoc. (%)</td>
<td>$3\pm3$</td>
<td>$3\pm3$</td>
<td>$9\pm5$</td>
<td>$3\pm3$</td>
</tr>
<tr>
<td>Non-excl. (%)</td>
<td>$4.0\pm1.6$</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\chi_{c0}$ (%)</td>
<td>$24.3\pm21$</td>
<td>$34\pm7$</td>
<td>$65\pm10$</td>
<td>$56\pm8$</td>
</tr>
<tr>
<td>$\mathcal{B} \rightarrow \mu^+\mu^-$ (pb)</td>
<td>$28.4\pm4.5$</td>
<td>$1.02\pm0.26$</td>
<td>$2.7\pm0.5$</td>
<td>$8.0\pm1.3$</td>
</tr>
<tr>
<td>$\mathcal{B}$ (ratio)</td>
<td>$5.96\pm0.66$</td>
<td>$0.75\pm0.08$</td>
<td>-</td>
<td>$0.076$</td>
</tr>
<tr>
<td>$d\sigma /dy</td>
<td>_{B=0}$ (nb)</td>
<td>$3.92\pm0.62$</td>
<td>$0.53\pm0.14$</td>
<td>-</td>
</tr>
</tbody>
</table>

**KMRS -2004: 130 nb → 90 nb (PDG-2008)**

(role of higher spin states, NLO-effects, DD..... need further detailed studies)

**ππ/KK mode as a spin-parity analyzer**
Are the early LHC runs, without proton taggers, able to check estimates for $pp \to p+A+p$?

Possible checks of:

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

(ii) generalised gluon $f_g$: $γp \to Υp$

(iii) Sudakov factor $T$: 3 central jets

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

$\frac{\#(A+gap) \text{ evts}}{\#(inclusive A) \text{ evts}}$ with $A = W, \text{ dijet, } Υ…$
without ‘clever hardware’:
for $H(\text{SM}) \rightarrow bb$ at 60fb-1 only
a handful of events due to
severe exp. cuts and low efficiencies,
though $S/B \sim 1$.

$H \rightarrow WW$ mode at $M > 135$ GeV. (B.Cox et al-06)

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

- **Higgs sector of the MSSM**: physical states $h, H, A, H^\pm$
  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
  $\Rightarrow$ no $HVV$ coupling
  $\Rightarrow$ no Higgs production in weak boson fusion
  $\Rightarrow$ no decay $H \rightarrow ZZ \rightarrow 4\mu$

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

- Conventionally due to overwhelming QCD backgrounds, the direct measurement of $H bb$ is hopeless

The backgrounds to the diffractive $H bb$ mode are manageable!
some regions of the MSSM parameter space are especially \textit{proton tagging friendly} (at large \(\tan \beta\) and \(M \leq 250\), \(S/B \geq 20\))

\textbf{Myths}

For the \(b\bar{b}\) channel \(bgds\) are well known and incorporated in the MCs:

Exclusive LO - \(b\bar{b}\) production (mass-suppressed) + \(gg\) misident+ soft & hard PP collisions.

\textbf{Reality}

The background calculations are still in progress:

(\textit{uncomfortably & unusually} large high-order QCD and b-quark mass effects).

About a dozen various sources (studied by Durham group)

1 admixture of \(|Jz|=2\) production.
2 NLO radiative contributions (hard blob and screened gluons)
3 NNLO one-loop box diagram (mass- unsuppressed, cut-non-reconstructible)
4 'Central inelastic' backgrounds (soft and hard Pomerons)
5 b-quark mass effects in dijet events
The MSSM and more ‘exotic’ scenarios

\[ pp \rightarrow p + \phi + p \]

If the coupling of the Higgs-like object to gluons is large, double proton tagging becomes very attractive.

- The intense coupling regime of the MSSM (E. Boos et al., 02-03)
- CP-violating MSSM Higgs physics (B. Cox et al. 03, KMR-03, J. Ellis et al. -05)
- Potentially of great importance for electroweak baryogenesis
- Triplet Higgs bosons (CHHKP-2009)
- Fourth Generation Higgs
- NMSSM (J. Gunion, et al.)
- Invisible’ Higgs (BKM-04)

There is NO experimental preference for a SM Higgs. Any Higgs-like boson is very welcome! 😊
Extended Higgs sectors: “typical” features

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

Large enhancement of coupling to $b\bar{b}, \tau^+\tau^-$ for high $\tan \beta$
- Decays into $b\bar{b}$ and $\tau^+\tau^-$ play a crucial role

“Typical” features of models with an extended Higgs sector:
- A light Higgs with SM-like properties, couples with about SM-strength to gauge bosons
- Heavy Higgs states that decouple from the gauge bosons
Four integrated luminosity scenarios
(S. Heinemeyer, VAK, M. Ryskin, W. J. Stirling, M. Tasevsky and G. Weiglein-07,08)

(bb, WW, \(\tau\tau\)- modes studied)

1. \(L = 60\text{fb}^{-1}\): 30 (ATLAS) + 30 (CMS): 3 yrs with \(L=10^{33}\text{cm}^{-2}\text{s}^{-1}\)

2. \(L = 60\text{fb}^{-1}, \text{effx2}\): as 1, but assuming doubled exper.(theor.) eff.

3. \(L = 600\text{fb}^{-1}\): 300 (ATLAS) + 300 (CMS): 3 yrs with \(L=10^{34}\text{cm}^{-2}\text{s}^{-1}\)

4. \(L = 600\text{fb}^{-1}, \text{effx2}\): as 3, but assuming doubled exper.(theor.) eff.

We have to be open-minded about the theoretical uncertainties. Should be constrained by the early LHC measurements (KMR-08)
Ratio of signal rate for the light MSSM Higgs boson over the SM rate in the $h \rightarrow b \bar{b}$ channel

$m_{h_{\text{max}}}^{\text{max}}$ benchmark scenario:

New Tevatron data still pouring

$\Rightarrow$ Large enhancement possible for relatively small $M_A$ and large $\tan \beta$
Ratio of signal rate for the heavy $CP$-even MSSM Higgs boson over the SM rate, $H \rightarrow b\bar{b}$ channel

$m_h^{\text{max}}$ benchmark scenario:

$\Rightarrow$ Huge enhancement compared to SM case, up to factor 400
NEW DEVELOPMENT

- Current Tevatron limits implemented.
- CDM scenarios analysed
- 4 Generation scenarios
  (S. Heinemeyer, VA K, M. Ryskin, W. J. Stirling, M. Tasevsky and G. Weiglein 07-08)
- bb backgrounds revisited (Shuvaev + KMR)
- Neutral Higgs in the triplet model (CHHKP-09)

Still to come

- $\tau\tau$ -mode, in particular, trigger strategy
- Charged Higgs bosons in MSSM and triplet models
“600 x 2” scenario covers nearly the whole allowed region for the light Higgs.

For large tan β heavy Higgs reach goes beyond 235 GeV.

For the H-boson the area reachable in the “60”-scenario is to large extent ruled out by the Tevatron data.

• Tevatron limits shown.
• Updated theory calculations
• New bb-backgrounds
• Updated theory calculation for signal & background

\[ H \rightarrow b\bar{b} \]

Abundance of the lightest neutralino in the early universe compatible with the CDM constraints as measured by WMAP.
The \( M_\Delta - \tan \beta \) planes are in agreement with the EW and B-physics constraints.
$H \rightarrow b\bar{b}$

5$\sigma$ -discovery, 
P3- NUHM scenario

3$\sigma$ -contours, 
P4- NUHM scenario
MSSM SUMMARY

- Detailed analysis of prospects for CED production of \( \mathcal{CP} \)-even MSSM Higgs bosons, \( pp \to p \oplus h, H \oplus p \)

- Light MSSM Higgs boson, \( h \to b \bar{b} \) channel: almost complete coverage of \( M_A - \tan \beta \) plane (and case of light SM Higgs) at the 3\( \sigma \) level with 600 fb\(^{-1} \times 2 \)
  \( \Rightarrow \) CED channel may yield crucial information on bottom Yukawa coupling and \( \mathcal{CP} \) properties

- Heavy \( \mathcal{CP} \)-even Higgs boson, \( H \to b \bar{b} \) channel: discovery of a 140 GeV Higgs for all values of \( \tan \beta \) with 600 fb\(^{-1} \times 2 \)
  In high \( \tan \beta \) region: discovery reach beyond \( M_H \approx 200 \) GeV also for lower luminosities

- ‘Semi-exclusive’ production of \( A \) looks challenging
  \( \Rightarrow \) Interesting physics potential for probing MSSM Higgs sector; further experimental + theoretical efforts desirable
M. Chaichian, P.Hoyer, K.Huitu, VAK, A.Pilkington, JHEP (in print)

Higgs bosons in a triplet model

- Extend SM by addition of higher representations of Higgs sector in addition to the doublet.
  - One real and one complex triplet chosen à la Georgi and Machacek.
- 4 neutral scalar Higgs’ bosons, charged and doubly charged Higgs also.
- Enhancement of Higgs-fermion-antifermion coupling by $1/c_H^2$ where $c_H$ is a doublet-triplet mixing parameter.
- Large enhancement in CEP production cross section for $c_H < 1$ (top-loop).
- LEP constraints on Higgs mass weaker as coupling to weak bosons reduced by $c_H^2$.
- Tevatron will be able to access $c_H = 0.2$ in tau-tau decay channel in near future.

An additional bonus: **doubly charged Higgs in photon-photon collisions** $\uparrow$ factor of 16 enhancement
Results: Triplet Higgs production

Expected mass distributions given 60 fb-1 of data.
Beyond the 3SM generation at the LHC era

4-5 September 2008

http://indico.cern.ch/conferenceDisplay.py?confId=33285

Enhancement of $\Gamma(H\to gg)$

$B(H\to \gamma\gamma)$ is suppressed

- at 220 GeV: CED ($H\to WW/ZZ$) rate - factor of $\sim 9$;
  at 120 GeV: CED ($H\to bb$) rate - factor of $\sim 5$.

$H\to ZZ$ - especially beneficial at $M=200-250$ GeV
At 60 fb⁻¹: for M=120 GeV, ~25 bb ev; for M=220 GeV, ~50 WW ev; favourable bgs

<table>
<thead>
<tr>
<th>L (fb⁻¹)</th>
<th>Stat. Sign.</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>3.7</td>
</tr>
<tr>
<td>60*2</td>
<td>5.2</td>
</tr>
<tr>
<td>600</td>
<td>11.1</td>
</tr>
<tr>
<td>600*2</td>
<td>15.7</td>
</tr>
</tbody>
</table>
CONCLUSION

Strongly suppressed QCD backgrounds in the forward proton mode provide a potential for direct determination of the Hbb Yukawa coupling, for probing CP properties and for measuring Higgs mass and width.

Forward Proton Tagging would significantly extend the physics reach of the ATLAS and CMS detectors by giving access to a wide range of exciting new physics channels.

FPT has the potential to make measurements which are unique at LHC and challenging even at a ILC.

For certain BSM scenarios the FPT may be the Higgs discovery channel.