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# Higgs Search at the Tevatron

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# HIGGS SEARCH AT THE TEVATRON

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Searches for the Higgs boson at the Fermilab Tevatron Collider are described. Results are reported from both the CDF and DØ experiments, based on the data collected in the Run I period. Higss boson searched include Standard Model, MSSM Higgs, as well as bosonic Higgs. No signal is observed and limits are set for production cross sections for several channels.

## 1 Introduction

One of the triumphs of the Standard Model is the unification of the long range electromagnetic interaction with the short range weak interaction in the SU(1)×SU(2) gauge theory. The difficulty of gauge non-invariance caused by the short range, thus massive gauge boson, nature of the weak interaction is avoided by the gauge symmetry breaking mechanism, whereby massless weak bosons acquire masses through either a new strong force at higher energy scale, or through interactions with a scalar field that is non-zero in the ground state (vacuum). These are the so-called dynamic symmetry breaking and spontaneous symmetry breaking mechanisms.

The gauge symmetry breaking is well established experimentally by the discoveries of the neutral current, the W/Z bosons and many precise measurements of electroweak parameters. However the exact symmetry breaking mechanism remains a mystery.

If the electroweak symmetry is broken spontaneously, then there must exist a neutral scalar particle, the Higgs boson. Thus the search for the Higgs boson is one of the most important tasks of experimental particle physics today. Although the mass of the Higgs boson is not predicted by the theory, constraints can be obtained by measurements of higher order electroweak effects that are related to the Higgs mass. One recent analysis[1] gives a result of $m_H = 76^{+85}_{-47}$ GeV/$c^2$. The current best direct search limit comes from LEP, where the existence of the SM Higgs lighter than ~95 GeV/$c^2$ is excluded[2].

## 2 Search for SM Higgs

At the Tevatron, SM Higgs can be produced via the following channels: *a*) gluon fusion via a heavy quark loop; *b*) associate production with vector bosons W and Z; *c*) vector boson fusion and *d*) radiation off a heavy quark. Among these, process *a*) has the highest cross section but suffers a large QCD background in a hadron collider environment (see below). Process *b*) is most promising since the presence of a vector boson provides a handle to suppress effectively the background. The SM prediction of the total production cross section at the Tevatron energy for a Higgs around 100 GeV/$c^2$ is about 1 pb. Given the total integrated luminosity of each experiment from Run I is in the order of 100 pb$^{-1}$, the expected signal is very small, after the trigger and detection efficiencies have been taken into account. However one should be open to surprises. Given the importance of the Higgs particle, both experiment have conducted elaborate searches in various channels. Moreover, Run II of the Tevatron will increase the total integrated luminosity by at least 20 times. Therefore the experience gained from the searches with Run I data is extremely valuable for setting up trigger and analyses strategies for Run II.

For a Higgs lighter than 140 GeV/$c^2$, the dominant decay channel is $H^0 \to b\bar{b}$ ($\sim$80% for $m_H$ of 100 GeV/$c^2$), because of the coupling of Higgs to fermions is proportional to the square of the fermion mass. Therefore the identification of b-jets is fundamental in searching for the Higgs in this mass range. Experimentally, two b-tagging technics have been developed and demonstrated successfully in the discovery of the top quark by CDF and DØ. One method is the so called '*soft lepton tagging*' which exploits the fact that $\sim$20% of B hadrons decay semileptonically. Therefore a low $p_T$ lepton inside a hadonic jet is a good indication that this jet is from a b quark fragmentation. This method is used by both CDF and DØ. The second method exploit the relative long lifetime ($\sim$1.6 ps) of B hadrons that results in a displacement of the decay vertex from the interaction point. This method requires a precise vertex detector. During Run I only CDF has been equipped with such a detector (SVX).

As mentioned above, although the process $gg \to H^0$ has the largest cross section, it is very difficult to isolate a $H^0 \to b\bar{b}$ signal from the overwhelming QCD $b\bar{b}$ production. On the other hand, the process $q\bar{q} \to H^0W, H^0Z$ gives a distinct final state consisting of a vector boson and two b-jets. So far searches at the Tevatron concentrate on this process. Depending on the type and decay of the associated vector boson, final states that can be used for searches are $e(\mu)\nu b\bar{b}$, $jjb\bar{b}$, $\nu\nu b\bar{b}$ and $e^+e^-(\mu^+\mu^-)b\bar{b}$. The $e(\mu)\nu b\bar{b}$ and $e^+e^-(\mu^+\mu^-)b\bar{b}$ channels have low background, but the branching ratios are small, compared with the $jjb\bar{b}$ channel. However the latter channel has higher background contamination.

### *2.1 Search in the $e(\mu)\nu b\bar{b}$ channel*

This search looks for $WH$ production where $W$ decays leptonically to $e\nu$ or $\mu\nu$. The CDF result have been published[3], while that of DØ has been contributed to conferences[4]. The selection criteria of the two experiments are very similar: a high $p_T$ isolated electron or muon, large missing $E_T$, two high energy jets with at least one tagged as b-jet. DØ uses a soft lepton tagging (SLT) with muon only, while CDF uses a SLT with both electron and muon, as well as a secondary tagging method (SVX). Table 1 summarises the selection criteria from the two experiments.

With these cuts, CDF observed 36 events with single SVX b-tag, and 6 events with double tags of SVX-SLT and SVX-SVX, in a data sample of 109±9 pb$^{-1}$. The expected background, mainly from $Wb\bar{b}$, $Wc\bar{c}$, mistags and $t\bar{t}$ events, is 30±5 for single and 3.0±0.6 for double tags, respectively. The observation and background expectation agree at 1.5$\sigma$ level. DØ observed 27 events with at least one b-tag in their 100 pb$^{-1}$ data, in good agreement with the expected background of 25.5±3.3 events. In addition, the observed $b\bar{b}$ dijet mass distributions of the selected events from the two experiments are in good agreements with the predicted background

Table 1. Selection criteria of $WH$ search in the $e(\mu)\nu b\bar{b}$ channel.

| selection cut | CDF | DØ |
|---|---|---|
| isolated lepton | $E_T^e > 20$ GeV, $p_T^\mu > 20$ GeV/$c$ | $E_T^e > 25$ GeV, $p_T^\mu > 20$ GeV/$c$ |
| missing $E_T$ | $\not{E}_T > 25$ GeV | $\not{E}_T > 20$ GeV |
| dilepton removal | remove dilepton from $Z$, $t\bar{t}$, DY | remove dilepton from $Z$ |
| two jets | 2 jets, $E_T > 20$ GeV, $\|\eta\| < 2$ | $\geq 2$ jets, $E_T > 15$ GeV, $\|\eta\| < 2$ |
| b tagging | SVX and SLT ($p_T^{e,\mu} > 2$ GeV/$c$) | SLT ($p_T^\mu > 4$ GeV/$c$) |

shape, as shown in Figure 1. Likelihood fits are made to these distributions to extract 95% CL upper limits on the production cross section times branching ratio of this channel. The CDF limit is shown as the dashed curve in the right plot of Figure. 2 as a function of the Higgs mass, since the acceptance varies with this value. The DØ result is shown in the left plot of Figure. 3, where the limit derived from a simple counting method is also shown.

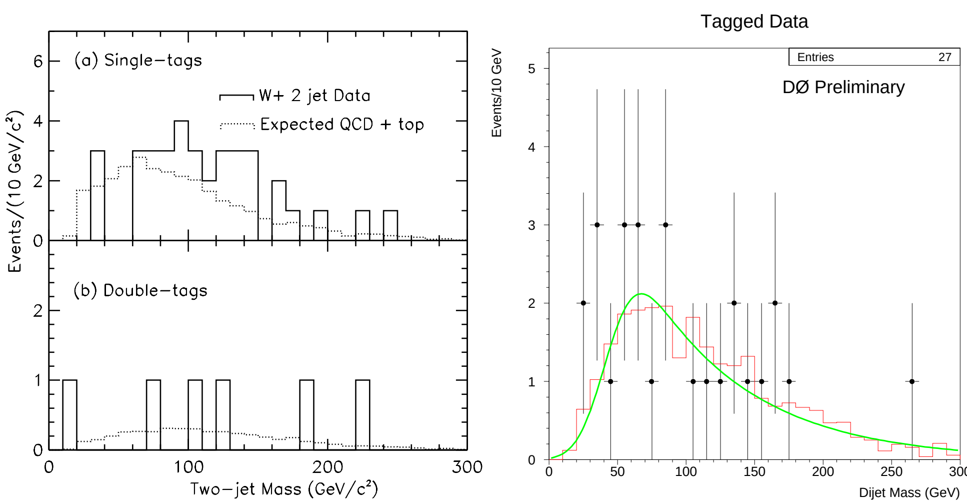


Figure 1. $b\bar{b}$ dijet mass distributions for the CDF (left) and DØ (right) SM Higgs selection in the $WH \to e(\mu)\nu b\bar{b}$ channel.

### *2.2 Search in the $jjb\bar{b}$ channel*

CDF has published[5] a search in the all-hadronic channel of the $WH$, $ZH$ process, where both $W$ and $Z$ decay to two quarks. As mentioned before, this channel has the highest branching ratio, but it also suffers from high QCD background.

The CDF analysis selects events from a multi-jet trigger sample of 91±7pb$^{-1}$. After removing high $p_T$ lepton events, the following cuts are applied: $\geq$ 4 jets with $E_T$ >15 GeV in $|\eta| < 2.1$, among which at least two are tagged as b-jets by the secondary vertex (SVX) tagging method, and the $p_T$ of the two b-jets system greater than 50 GeV$/c$. The last cut is applied to reduce QCD direct $b\bar{b}$ production and flavor excitation which tend to have low $p_T(b\bar{b})$. In all 589 events are selected. The $M(b\bar{b})$ distribution of these events is shown in the left plot of Figure 2 in comparison with contributions from main backgrounds from QCD, fake tags, $t\bar{t}$ and $Zjj$. A fit to this distribution with a combination of signal and backgrounds, leaving the normalizations for signal and QCD free, returns no signal contribution for $m_H \geq 80$ GeV$/c^2$. A 95% CL limit on $VH$ production is then derived and is shown as the solid curve in the right plot of Figure 2. This result is then combined with the one from the $e(\mu)\nu b\bar{b}$ channel from CDF, shown as the dotted curve in the same figure.

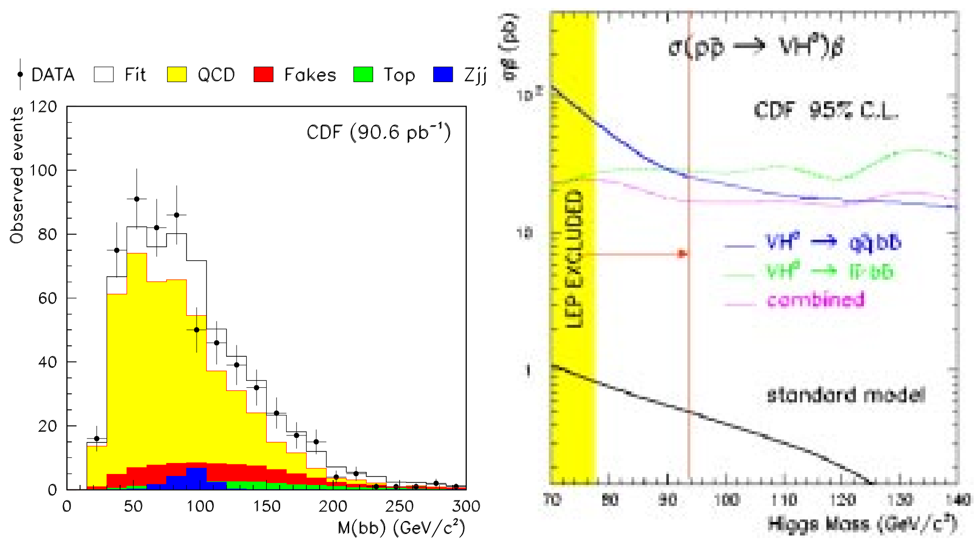


Figure 2. $b\bar{b}$ dijet mass distributions for the CDF SM Higgs selection in the $jjb\bar{b}$ channel (left) and the CDF 95% CL upper limit on $\sigma(VH)BR(H \to b\bar{b})$ (right).

### *2.3 Search in the $\nu\nu b\bar{b}$ channel*

DØ has searched for $ZH$ production in the $Z \to \nu\bar{\nu}$ decay channel. Since their b-tagging method uses soft muons, this analysis is done with a data sample of single and dimuon events. B-jet tagging is done with muon with $p_T^{\mu}$ >3.5 GeV$/c$. In the dimuon case, two b-tagged jets ($E_T$ >10 GeV, $\Delta R(\mu - jet) < 0.5$) are required. In the case of single muon, one b-tagged jet and another jet with $E_T$ >25 GeV, $|\eta| < 1.5$ are required. The $W \to \mu\nu$ and $t\bar{t}$ background in the single muon events are reduced by removing events with isolated muons or with large total transverse energy ($H_T$). Finally a cut of $\not{E}_T$ >35 GeV is applied to select $Z \to \nu\bar{\nu}$ events. This leaves 2 events in the data, in good agreement with the expected background of 2.6±0.7 events. The derived 95% CL limit on $\sigma(ZH)BR(H \to b\bar{b})$ is shown in the right plot in Figure 3.

Search in this channel at CDF is in progress.

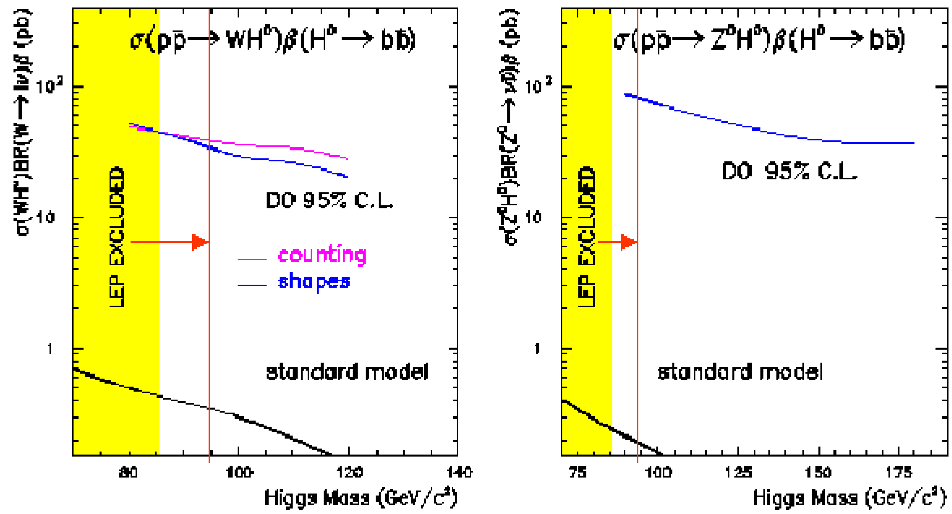


Figure 3. DØ 95% CL upper limits on $\sigma(WH)BR(H \to b\bar{b})$ from the $e(\mu)\nu b\bar{b}$ channel (left) and on $\sigma(ZH)BR(H \to b\bar{b})$ from the $\nu\nu b\bar{b}$ channel (right).

## 3 Search for MSSM Higgs

In the Minimum Supersymmetric Standard Model (MSSM), spontaneous electroweak symmetry braking is the natural consequence of the evolution of a gauge invariant theory from a high energy scale down to electroweak scale. Supersymmetry requires two Higgs doublets, one couples to u-type quarks, another couples to d-type quarks and charged leptons. As a result of the symmetry braking, 5 Higgs particles are predicted: 2 scalars ($h^0$, $H^0$), 1 pseudoscalar ($A^0$) and 2 charged scalars ($H^{\pm}$). At tree level, a mass hierarchy of $m_{h^0} < m_{H^0} < m_{A^0}$ and $m_{h^0} < m_Z < m_{H^0}$, $m_{H^{\pm}} > m_W$ is predicted. However large radiative corrections to tree level masses are possible. When these effects are taken into account, it is expected that $m_{h^0}$ <130-150 GeV$/c^2$.

The enlarged Higgs sector is determined by two free parameters. Besides one of the Higgs masses (normally taken as $m_A$), a new parameter, $\tan\beta$, which is the ratio of the vacuum expectation values of the two Higgs doublets, is introduced.

At the Tevatron, $h^0$, $H^0$ and $A^0$ can be produced similarly to SM Higgs. But at large $\tan\beta$, their couplings to $b\bar{b}$ are greatly enhanced. This results in a large production cross section for the process of Higgs radiation off a heavy quark: $p\bar{p} \to b\bar{b}h^0, b\bar{b}H^0, b\bar{b}A^0$, as well as an enhanced branching ratio of $b\bar{b}$ decay of the Higgs. For a $m_{h^0}$ at 100 GeV$/c^2$, the cross section is about 10 pb at $\tan\beta = 30$. A clean signature of MSSM neutral Higgs production at the Tevatron is then four high energy b-jets.

CDF has conducted a search in this channel using 91±7 $\mathrm{pb}^{-1}$ multi-jet triggers. Events that have at least 4-jets with $E_T > 15, 30, 50, 70$ GeV are then selected. At least two of the jets must be tagged as b-jets by the SVX method. The number of events selected is in good agreement with expected backgrounds, consisting mainly of QCD heavy flavor, mistags, $t\bar{t}$, and $Zjj$ events. Limits at 95% CL are then set on the mass of the MSSM neutral Higgs as a function of $\tan\beta$. These limits are preliminary and not presented at this conference.

Charged Higgs can be produced at the Tevatron through top decays, and have been searched by CDF and DØ both directly and indirectly. The latest results are presented by a separate contribution to this conference[6].

## 4 Search for Bosonic Hiigs

In the Standard Model, the same Higgs doublet is used to give masses to bosons and to leptons and quarks. However it is possible that different Higgs doublets are separately responsible for boson and fermion mass generations. This is in fact postulated in several models with a extended Higgs sector. The result is that there is a 'bosonic' Higgs that only couples to W and Z at the tree level. Its couplings to fermions occur only through higher order loop diagrams and is highly suppressed. At low mass (below 90 GeV/$c^2$), a bosonic Higgs decays to $\gamma\gamma$ predominantly, instead of $b\bar{b}$, thus provides a clean signature of $W\gamma\gamma$ and $Z\gamma\gamma$ for the $HW$, $HZ$ production.

Both CDF and DØ have searched for such a signal[7,8]. DØ uses only the hadronic decay channels of the vector bosons while CDF looks for leptonic decay channels as well. The DØ selection is the following: 2 isolated photons with $E_T > 30$ and 15 GeV, 2 jets with $E_T > 30$, $|\eta| < 2.0$ and $E_T > 15$, $|\eta| < 2.25$, and the mass of the two jets between 40 and 150 GeV/$c^2$. In the 101.2±5.5 $\mathrm{pb}^{-1}$ data, 4 events and observed, compared with 6.0±2.1 background expectation. The mass distributions of the $\gamma\gamma$ and $jj$ system of these events is shown in Figure 4. It can be seen that there is no candidate events above $M(\gamma\gamma)$= 60 GeV/$c^2$. The resulting 95% CL limit on the cross section times branching ratio of this process is shown in the right plot of Figure 4. Using a production cross section and branching ratio to $\gamma\gamma$ of bosonic Higgs calculated with a SM coupling to bosons[9], a 95% CL lower mass limit of 78.5 GeV/$c^2$ of the bosonic Higgs is obtained.

CDF selects events with 2 isolated photons with $E_T > 22$ GeV. Then to search for a vector boson in this sample, either a high $p_T$ electron or muon with $E_T > 20$ GeV, or $\not{E}_T > 20$ GeV, or two jets with $E_T > 15$ GeV and $M(jj)$ between 40 and 130 GeV/$c^2$ is required. At the end 6 events are left, in agreement of a expected background of 6.2±2.1. The left plot of Figure 5 shows the $M(\gamma\gamma)$ distributions for events before and after the vector boson requirement. Using a NLO cross section calculation[10] and branching ratio for bosonic Higgs[9], a 95% CL lower mass limit of 82 GeV/$c^2$ is obtained. The CDF result is also presented in the right plot of Figure 5 as an upper limit on the $BR(H \to \gamma\gamma)$ by dividing the cross section limit by the predicted cross section.

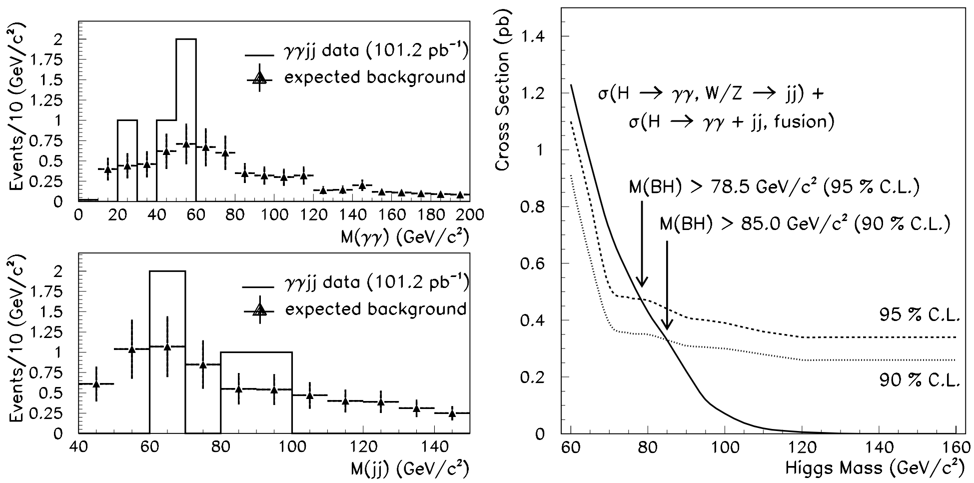


Figure 4. Diphoton and dijet mass distributions (left) and upper limits on the production times branching ratio (right) from the DØ bosonic Higgs search.

## 5 Conclusion

A summary of the Higgs searches with the CDF and DØ experiments at the Tevatron is presented. A wide range of possible signatures of Standard Model Higgs production have been investigated, in particular $WH$ and $ZH$ productions. Search for MSSH neutral Higgs is ongoing, and is particular interesting for the case of large $\tan\beta$. Bosonic Higgs predicted in some extended Higgs models has also been

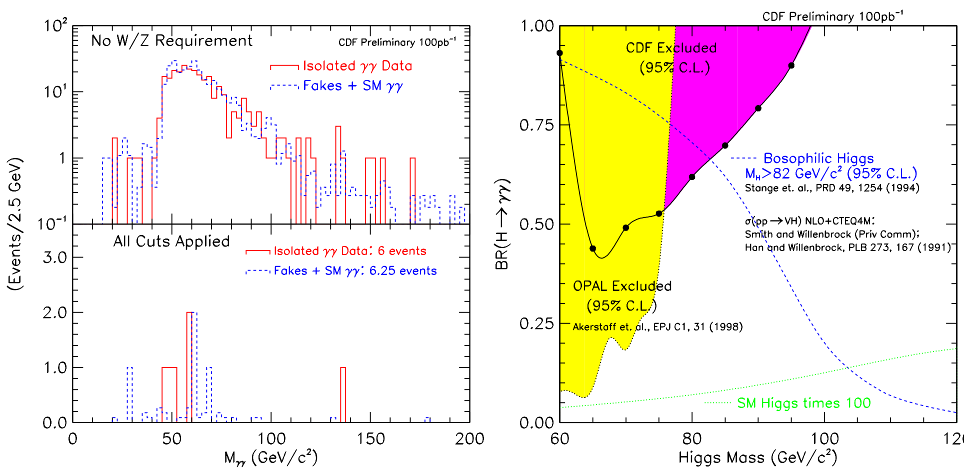


Figure 5. Diphoton mass distribution before and after the vector boson requirement (left) and and upper limits on the $BR(H \to \gamma\gamma)$ from the CDF bosonic Higgs search.

searched. No evidence of signal has been found with the full Run I data sample in the reported search channels and 95% CL limit on model parameters have been obtained. Various other search channels are still under investigation and results are expected to be reported in the near future.

It is realized in these searches that good b-tagging method is fundamental to the Higgs searches at the Tevatron energy. Two methods, the secondary vertex tagging and soft lepton tagging, developed for the discovery of the top quark have been adapted for Higgs searches and demonstrated to be powerful in background rejection. Both experiments are now under major detector upgrades, especially for enhanced b-tagging and b-triggering capabilities. The upcoming Tevatron Run II, with a total of 2 $fb^{-1}$ integrated luminosity expected, will provide a unique hunting ground for Higgs bosons up to the intermediate mass range, as reported in a separate contribution to this conference[11].

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