Light Higgs associated with forward jets at the LHC: CompHEP calculation

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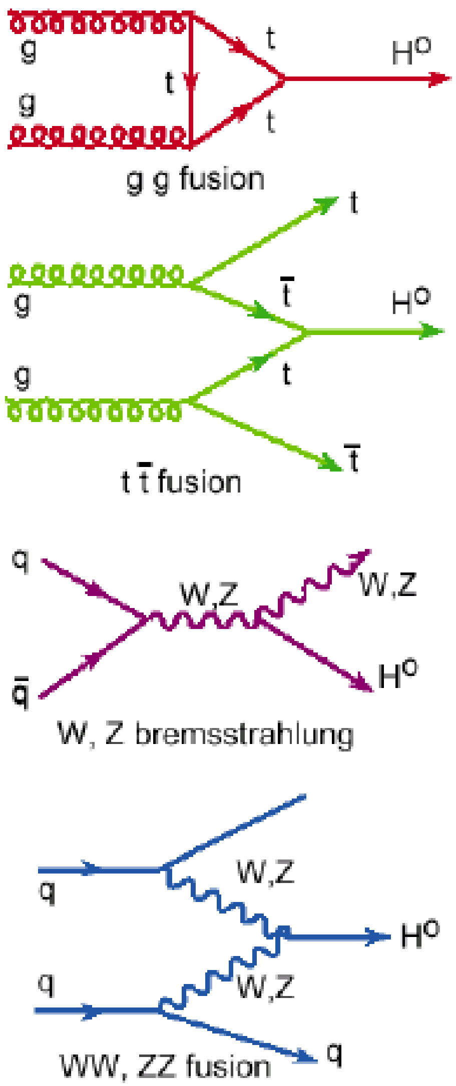
g
g
t
t
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g g fusion
g
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$\bar{t}$
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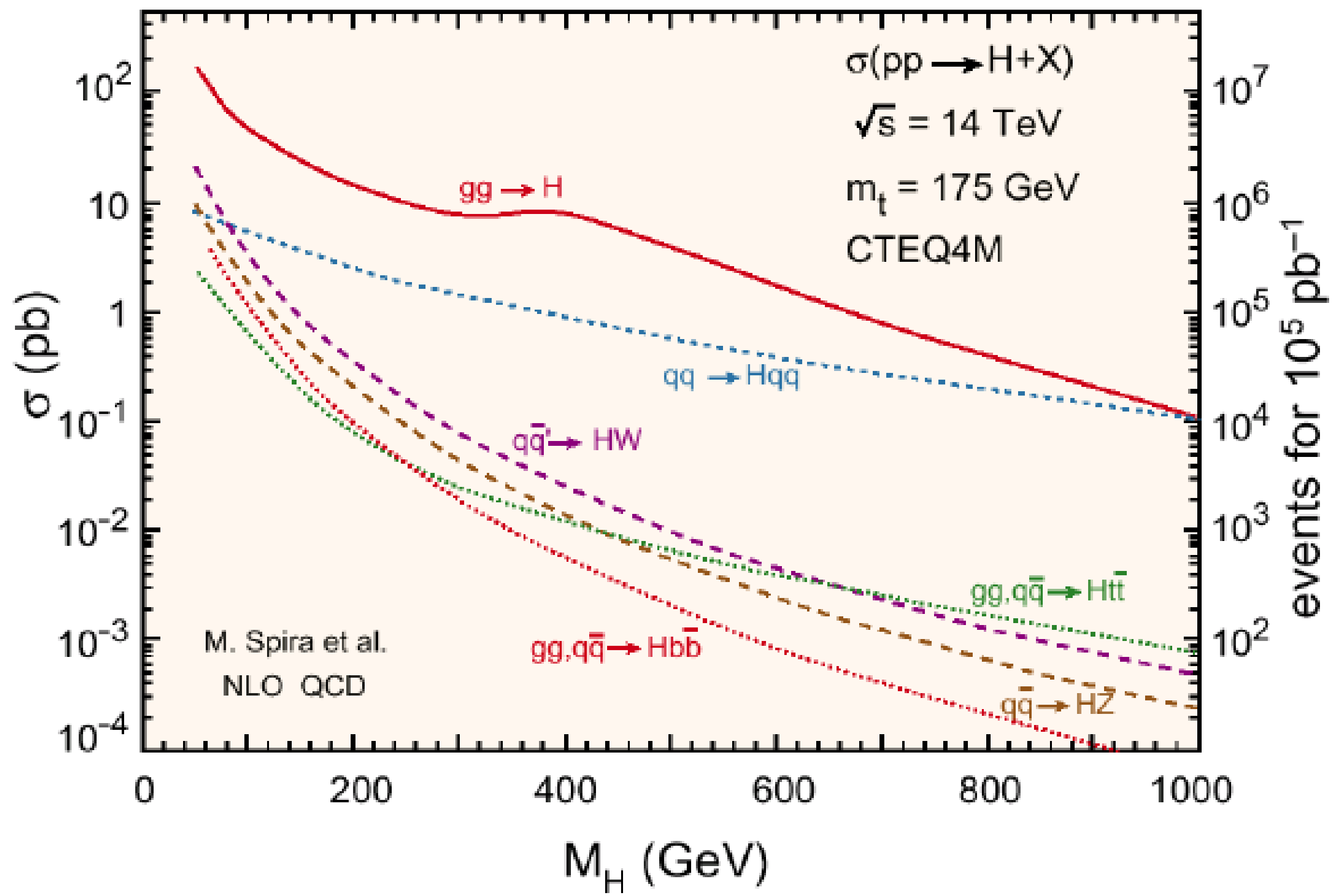
q
q
W,Z
W,Z
H^o
q
WW, ZZ fusion


σ(pp → H+X)
√s = 14 TeV
m$_t$ = 175 GeV
CTEQ4M
gg → H
qq → Hqq
q$\bar{q}$' → HW
gg,q$\bar{q}$ → Ht$\bar{t}$
gg,q$\bar{q}$ → Hb$\bar{b}$
q$\bar{q}$ → HZ
M. Spira et al.
NLO QCD
σ (pb)
M$_H$ (GeV)
events for 10^5 pb^{-1}
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^7
10^6
10^5
10^4
10^3
10^2
0
200
400
600
800
1000

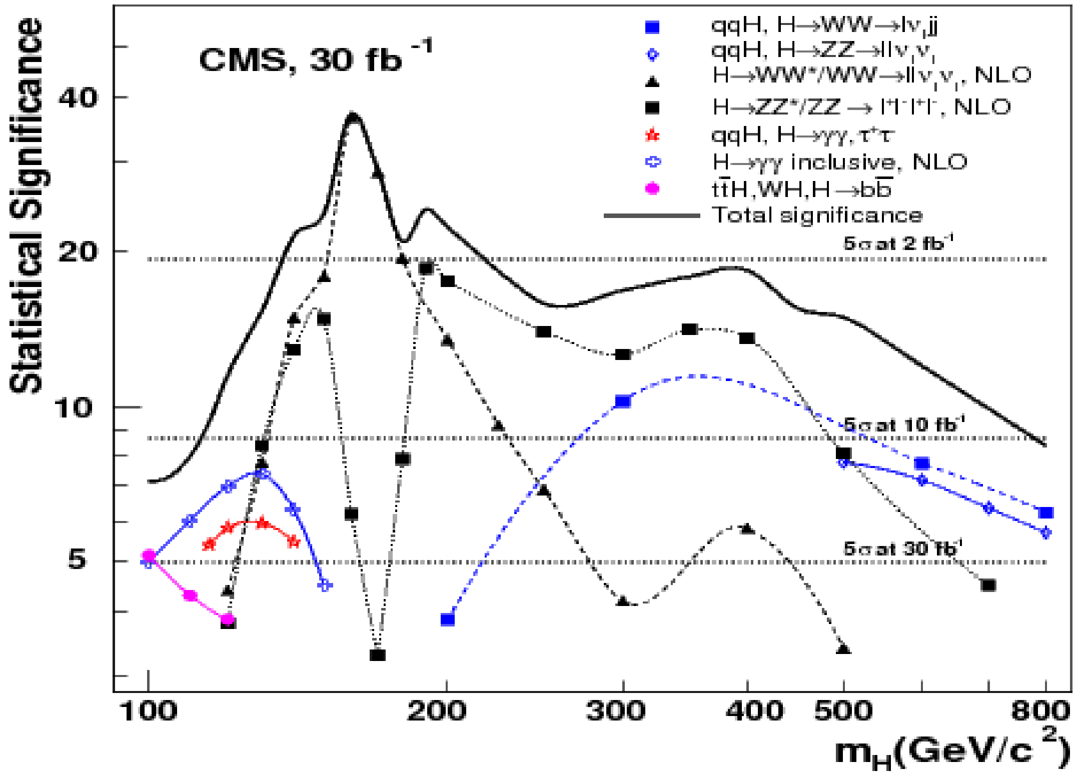


Figure 12: Expected statistical significance with 30 fb^{-1} for the SM Higgs boson as a function of m_H. The NLO cross sections for both signal and background were used for the inclusive $H \to \gamma\gamma$, $H \to ZZ^*/ZZ \to \ell^+\ell^-\ell'^+\ell'^-$ and $H \to WW^*/WW \to \ell\ell\nu_\ell\nu_\ell$ channels. Poisson statistics were used to calculate the statistical significance for the $H \to ZZ^*/ZZ \to \ell^+\ell^-\ell'^+\ell'^-$ channel.

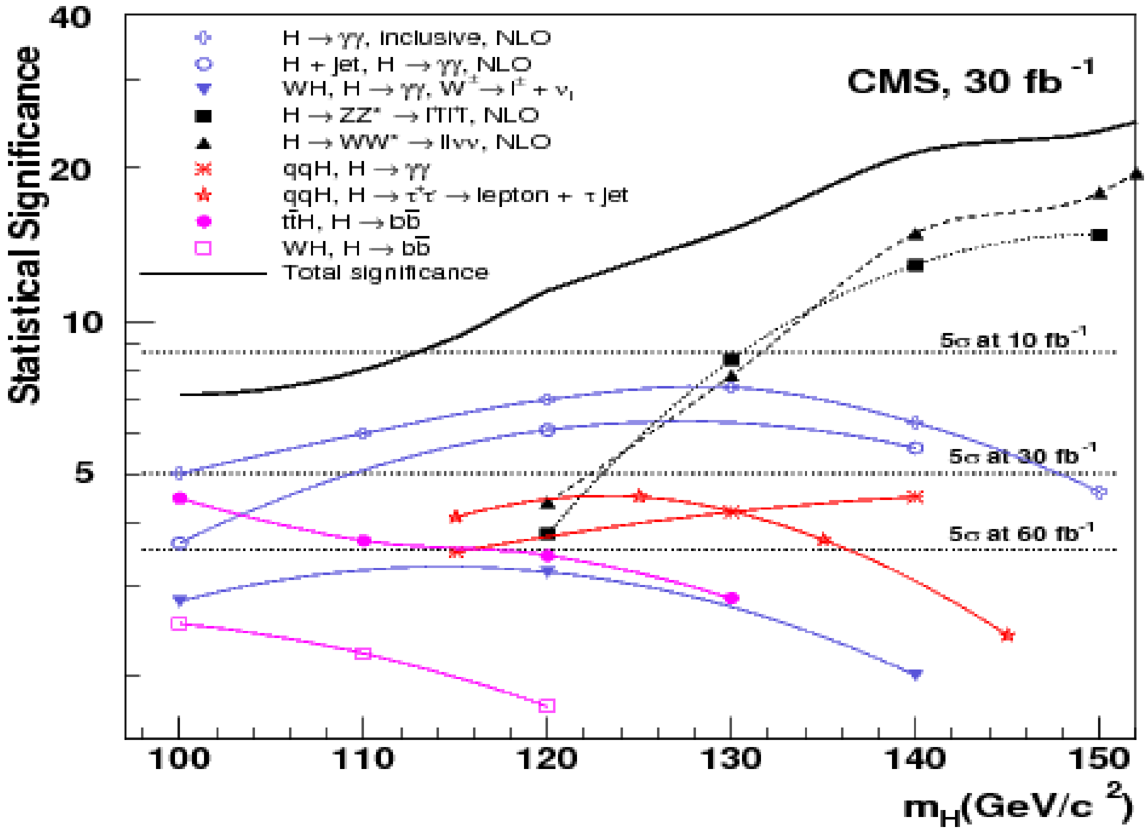
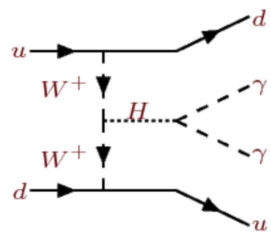
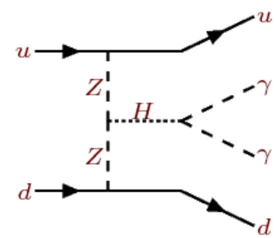


Figure 13: Expected statistical significance with 30 fb^{-1} for the SM Higgs boson as a function of $m_{\rm H}$ for $m_{\rm H} < 150$ GeV/c^2. The NLO cross sections for both signal and background were used for the inclusive $\rm H \rightarrow \gamma\gamma$, for H + jet with $\rm H \rightarrow \gamma\gamma$ and for $\rm H \rightarrow ZZ^* \rightarrow \ell^+\ell^-\ell'^+\ell'^-$ and $\rm H \rightarrow WW^* \rightarrow \ell\ell\nu_\ell\nu_\ell$. Poisson statistics were used to calculate the statistical significance for the $\rm H \rightarrow ZZ^* \rightarrow \ell^+\ell^-\ell'^+\ell'^-$, $\rm H \rightarrow \gamma\gamma$ in the WH production and $\rm H \rightarrow \gamma\gamma$ and $\rm H \rightarrow \tau^+\tau^-$ channels in the $\rm qq \rightarrow qqH$ production.

Signal diagrams

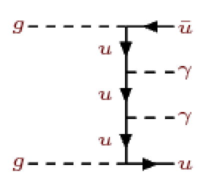
183 partonic subprocesses, 28 non-negligibly contribute



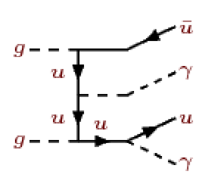


Irreducible background diagrams (QCD gluon exchange and EW W boson exchange gauge invariant subsets in the complete tree level set $q_i q_j \to \gamma\gamma q_k q_l$ - some examples)

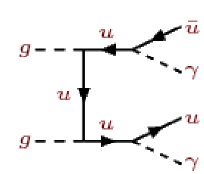
QCD



diagr.1

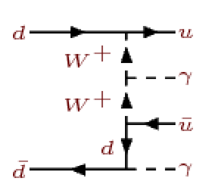


diagr.2

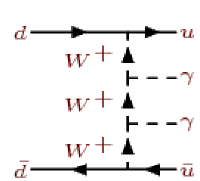


diagr.3

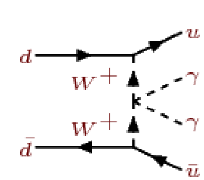
EW



diagr.1



diagr.2



diagr.3

Acceptance and isolation cuts:

- $p_t^{\gamma_{1,2}} > 20$ GeV
- $p_t^{j_{1,2}} > 30$ GeV
- $|\eta_{\gamma_{1,2}}| < 2.4$
- $|\eta_{j_{1,2}}| < 4.5$
- $\Delta R(j_1, j_2) > 0.7, \quad \Delta R(\gamma, j) > 0.7,$

Double forward jet tagging cuts:

- $|\eta_{j_1} - \eta_{j_2}| \geq$4.4, $\quad \eta_{j_1} \cdot \eta_{j_2} \leq$0,
  min$[\eta_{j_1}, \eta_{j_2}]$+0.7$\leq \eta_{\gamma_{1,2}} \leq$ max$[\eta_{j_1}, \eta_{j_2}]$ -0.7

More flexible than 'η-symmetric' cuts when each of the jets has the rapidity outside the central region $|\eta|$ $\geq$2.4 and photons are between the jets in the rapidity space. One of the jets can appear in the central rapidity region not violating the requirement that the photons are between the jets.

Simplification of Flavour Combinatorics in the Evaluation of Hadronic Processes

A serious computational problem is the large number of partonic subprocesses (Some of them are very much similar)

- many quark partons with different flavors
- many additional diagrams for each subprocess because of CKM quark mixing

Two approximations:

- $V_{CKM} \Longrightarrow \begin{pmatrix} V & 0 \\ 0 & 1 \end{pmatrix}, \qquad V = \begin{pmatrix} \cos\vartheta_c & \sin\vartheta_c \\ -\sin\vartheta_c & \cos\vartheta_c \end{pmatrix}$
  where ϑ_c is the Cabbibo angle.
- $M_u = M_d = M_s = M_c = 0$

Basic ideas:

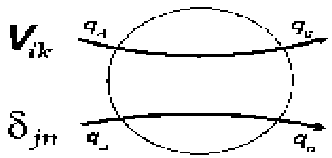
- rotation of down quarks, thus, transporting the mixing matrix elements from vertices of subprocess Feynman diagrams to the parton distribution functions
- diagrams are divided into gauge invariant classes with different topology of the quark line

New rules for convolution with structure functions depend on the topology of the gauge invariant class [a]

E.B., V.Ilyin et al. JHEP 0005 (2000) 052

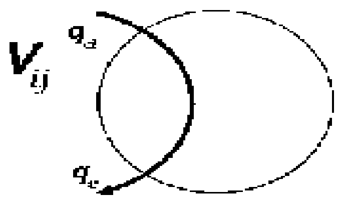
Examples

Scattering topology. 1st Rule



$$|\mathcal{D}_{sc}|^2 \Longrightarrow \int dx_1 dx_2\, [f_d(x_1)+f_s(x_1)]\, [f_{\bar{u}}(x_2)+f_{\bar{c}}(x_2)]\, |\mathcal{M}|^2$$

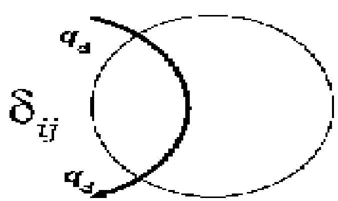
Annihilation CC topology. 2nd Rule



$$|\mathcal{D}_a^{CC}|^2 \Longrightarrow \int dx_1 dx_2 [f_d(x_1)\, f_{\bar{u}}(x_2)\, \cos^2\vartheta_c + f_s(x_1)\, f_{\bar{c}}(x_2)\, \cos^2\vartheta_c +$$

$$+ f_d(x_1)\, f_{\bar{c}}(x_2)\, \sin^2\vartheta_c + f_s(x_1)\, f_{\bar{u}}(x_2)\, \sin^2\vartheta_c] |\mathcal{M}|^2$$

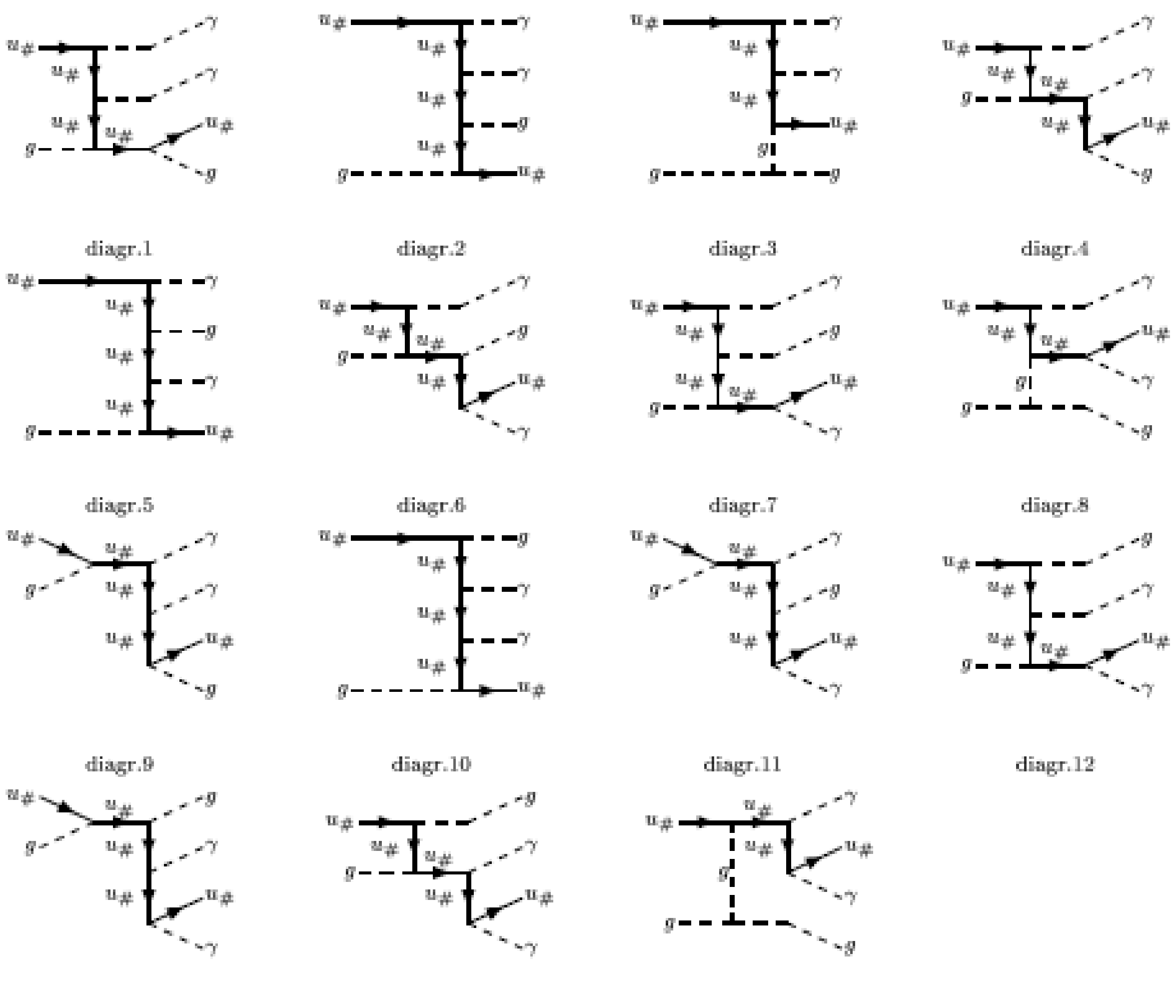
Annihilation NC topology. 3d Rule



$$|\mathcal{D}_a^{NC}|^2 \Longrightarrow \int dx_1 dx_2\, [f_d(x_1)\, f_{\bar{d}}(x_2) + f_s(x_1)\, f_{\bar{s}}(x_2)]\, |\mathcal{M}|^2$$

The Exchange topology and all possible interferences between the above topologies lead to the same rules

Example: regularization of the amplitude pp → $\gamma\,\gamma$ + 2 jet (irreducible QCD background to the light Higgs boson signal at the LHC in the channel $\gamma\gamma$ + jets). 36 partonic subprocesses in the «hash-model» format, each of them includes 15-20 diagrams with 10-20 singularities.



diagr.1 diagr.2 diagr.3 diagr.4 diagr.5 diagr.6 diagr.7 diagr.8 diagr.9 diagr.10 diagr.11 diagr.12 diagr.13 diagr.14 diagr.15

Regularization

Momentum	|> Mass	<|> Width	<| Power|
13	|0	|0	|1
14	|0	|0	|1
15	|0	|0	|1
25	|0	|0	|1
26	|0	|0	|1
134	|0	|0	|2
135	|0	|0	|2
145	|0	|0	|2
256	|0	|0	|2
236	|0	|0	|2
246	|0	|0	|2
36	|0	|0	|1
46	|0	|0	|1
56	|0	|0	|1
356	|0	|0	|1
456	|0	|0	|1
346	|0	|0	|1
12	|0	|0	|2

==

Example: regularization of the amplitude pp → γ + 3 jet (QCD misidentification (or fake) background [jet ⇨ γ] to the light Higgs boson signal at the LHC in the channel $\gamma\gamma$+ jets). 50 partonic subprocesses in the «hash-model» format, each of them includes 30-40 diagrams with 10-20 singularities. Total number of QCD diagrams about 2000

	subprocess	σ, [pb]	$\frac{\sigma}{\sigma_{max}}$
1	u#,u# → A,G,u#,u#	514.1	0.36
2	u#,U# → A,G,u#,U#	123.2	0.09
3	u#,U# → A,G,d#,D#	0.3	0
4	u#,U# → A,G,G,G	2.4	0
5	u#,d# → A,G,u#,d#	208.1	0.15
6	u#,D# → A,G,u#,D#	101.4	0.07
7	u#,G → A,u#,u#,U#	52.5	0.04
8	U#,G → A,u#,d#,D#	30.3	0.02
9	u#,G → A,G,G,u#	1397.7	1
10	U#,u# → A,G,u#,U#	125.7	0.09
11	U#,u# → A,G,d#,D#	0.3	0
12	U#,u# → A,G,G,G	2.4	0
13	U#,U# → A,G,U#,U#	19.1	0.01
14	U#,d# → A,G,U#,d#	41.9	0.03
15	U#,D# → A,G,U#,D#	17.2	0.01
16	U#,G → A,u#,U#,U#	8.5	0.01
17	U#,G → A,U#,d#,D#	4.5	0
18	U#,G → A,G,G,U#	196.5	0.14
19	d#,u# → A,G,u#,d#	206.9	0.15
20	d#,U# → A,G,U#,d#	41.9	0.03
21	d#,d# → A,G,d d#	49.7	0.03
22	d#,D# → A,G,u#,U#	0.1	0
23	d#,D# → A,G,d#,D#	23.3	0.02
24	d#,D# → A,G,G,G	0.4	0
25	d#,G → A,u#,U#,d#	23.9	0.02
	d#,G → A,d#,d#,D#	8.0	0
	d#,G → A,G,G,d#	195.2	0.14
	D#,u# → A,G,u#,D#	98.7	0.07
	D#,U# → A,G,U#,D#	17.6	0.01
	D#,d# → A,G,u#,U#	0.1	0
	D#,d# → A,G,d#,D#	23.2	0.02
	D#,d# → A,G,G,G	0.4	0
	D#,D# → A,G,D#,D#	9.0	0
	D#,G → A,u#,U#,D#	9.6	0
	D#,G → A,d#,D#,D#	2.8	0
	D#,G → A,G,G,D#	69.1	0.05
	G,u# → A,u#,u#,U#	53.3	0.04
	G,u# → A,u#,d#,D#	29.7	0.02
	G,u# → A,G,G,u#	1400.0	1
	G,U# → A,u#,U#,U#	9.5	0
	G,U# → A,U#,d#,D#	4.5	0
	G,U# → A,G,G,U#	198.6	0.14
	G,d# → A,u#,U#,d#	23.8	0.02
	G,d# → A,d#,d#,D#	7.7	0
	G,d# → A,G,G,d#	190.9	0.13
	G,D# → A,u#,U#,D#	9.9	0
	G,D# → A,G,G,D#	2.9	0
	G,D# → A,G,G,D#	68.8	0.05
	G,G → A,G,u#,U#	277.9	0.20
	G,G → A,G,d#,D#	69.5	0.05
	pp → A,j,j,j	5970.4	

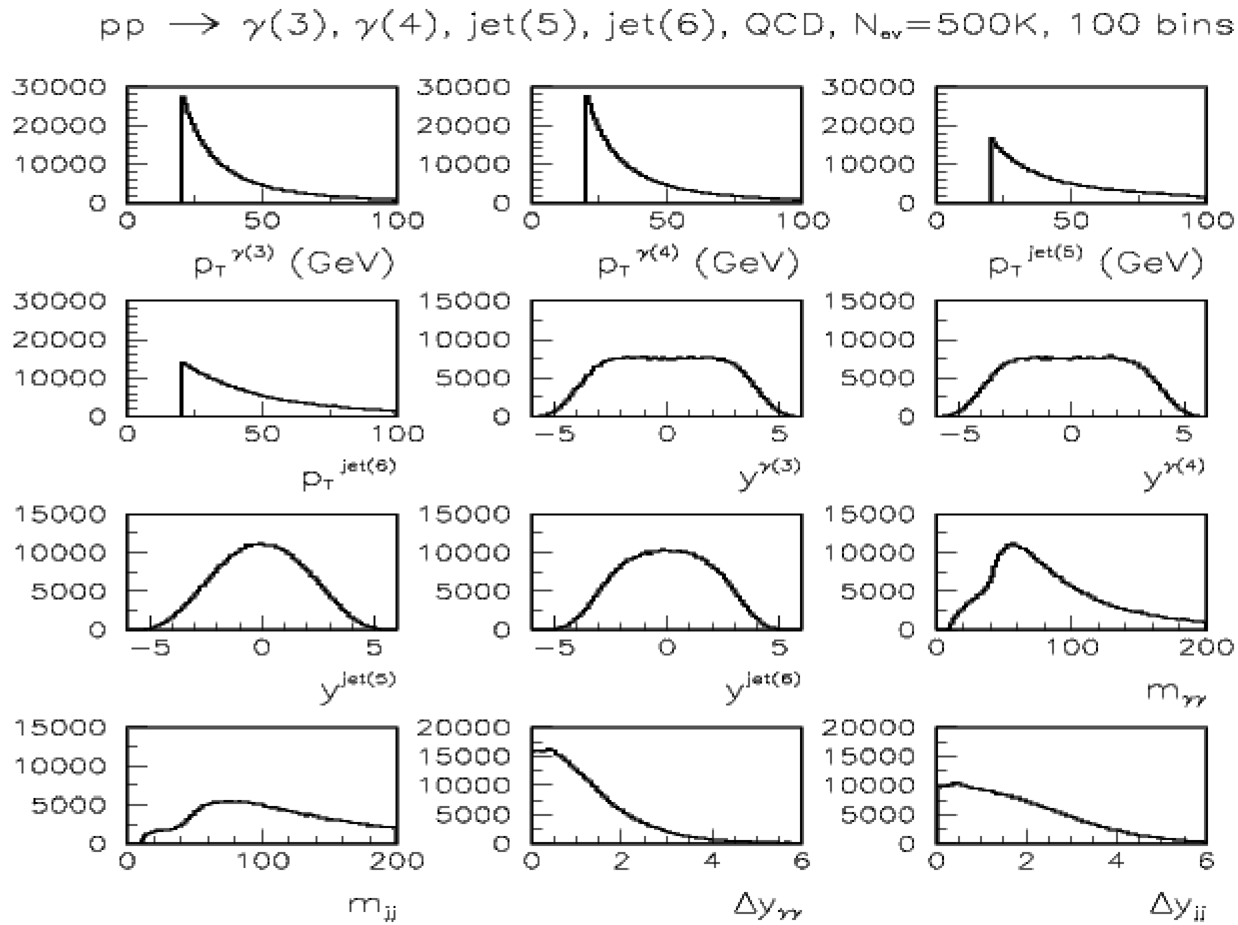


Figure 1: Partonic level distributions for the process $pp \to \gamma\gamma +$ 2 jets generated from the 500K QCD event sample.

CompHEP-PYTHIA interface

PYTHIA has the built-in data base of matrix elements for hard subprocesses which are basically of the $2 \to 2$ type. The CompHEP-PYTHIA interface allows to use processes $2 \to 3, 4, 5, 6$ computed by means of CompHEP as new processes for PYTHIA and include in this way ISR/FSR, hadronization (jet fragmentation), and decays as it is done in PYTHIA. Thus, integrated package is available.

- CompHEP v.41.10 generates unweighted events and writes them to the file events_N.txt , where N is the number of working session, for each of the subprocess
- The command mixPEV mixes randomly several subprocesses in one event flow according to their relative weights, $\sigma_i/\Sigma_j\sigma_j$, where σ_i is the cross section of the i-th subprocess, and writes events to the file Mixed.PEV . The file is ready to be red by main.f of PYTHIA 6...or 5.7
- The command makePGEN46 or makePGEN45 compiles all necessary fortran files from PYTHIA and the interface directory interf46 and creates the executable module PGEN.exe
- After PGEN.exe one gets events in PYTHIA format

Generation of color flows for events

For a fragmentation and hadronization PYTHIA needs in an information on color flows. PYTHIA format for color flows requires an indication of colorless pairs. In terms of QCD such sequence of colorless pairs, *color chain*, corresponds to one of the elements of the color basis taken in the limit $N_c = \infty$. CompHEP calculates exactly the cross section with number of colors $N_c = 3$ The following procedure is realised in CompHEP in order to match that:

$$M = \sum_d L_d T_d$$

where Feynman diagrams are summed, L_d is Lorentz part of the diagram, and T_d is its color structure.

$$|M|^2 = \sum_{d \otimes d'} L_{d \otimes d'} C_{d \otimes d'}$$

$L_{d \otimes d'} = L_d{}^* \cdot L'_d\,;\quad L_{d \otimes d'} = L_d{}^* \cdot L'_d$, where $d \otimes d'$ is squared diagram contributed in the squared matrix element.

In the limit $N_c = \infty$ the color structures of diagrams can be decomposed over the elements of color basis (color chains):

$$T_d \implies T_d^{N_c=\infty} = \sum_i C_d^i t_i$$

where basis elements are orthonormal, $t_i \otimes t_j = \delta_{ij}$. Thus squared matrix element is a sum of positive numbers:

$$|M_{N_c=\infty}|^2 = \sum_i k_i\,, \qquad k_i = |\sum_d L_d C_d^i|^2\,, \qquad w_i = \frac{k_i}{\sum_j k_j}$$

$$
\begin{aligned}
A_0 = \sum_{i=1}^{15} A_i \quad = \quad & I_g^u \otimes I_u^g \otimes A_{10}(u\bar{u} \to \gamma\gamma) + I_\gamma^u \otimes I_u^g \otimes [A_2(u\bar{u} \to \gamma g) + A_5(u\bar{u} \to \gamma g)] \\
+ \quad & [A_4(ug \to u\gamma) + A_6(ug \to u\gamma) + A_9(ug \to u\gamma) + A_{11}(ug \to u\gamma)] \otimes F_\gamma^u \otimes F_g^u \\
+ \quad & I_\gamma^u \otimes A_1(ug \to u\gamma) \otimes F_g^u + I_g^u \otimes A_{12}(ug \to u\gamma) \otimes F_\gamma^u \\
+ \quad & I_g^g \otimes [A_8(ug \to u\gamma) + A_{15}(ug \to u\gamma)] \otimes F_\gamma^u + I_\gamma^u \otimes I_g^g \otimes A_3(ug \to u\gamma) \\
+ \quad & I_\gamma^u \otimes A_7(ug \to ug) \otimes F_\gamma^u + [A_{13}(ug \to ug) + A_{14}(ug \to ug)] \otimes F_\gamma^u \otimes F_\gamma^u
\end{aligned}
$$

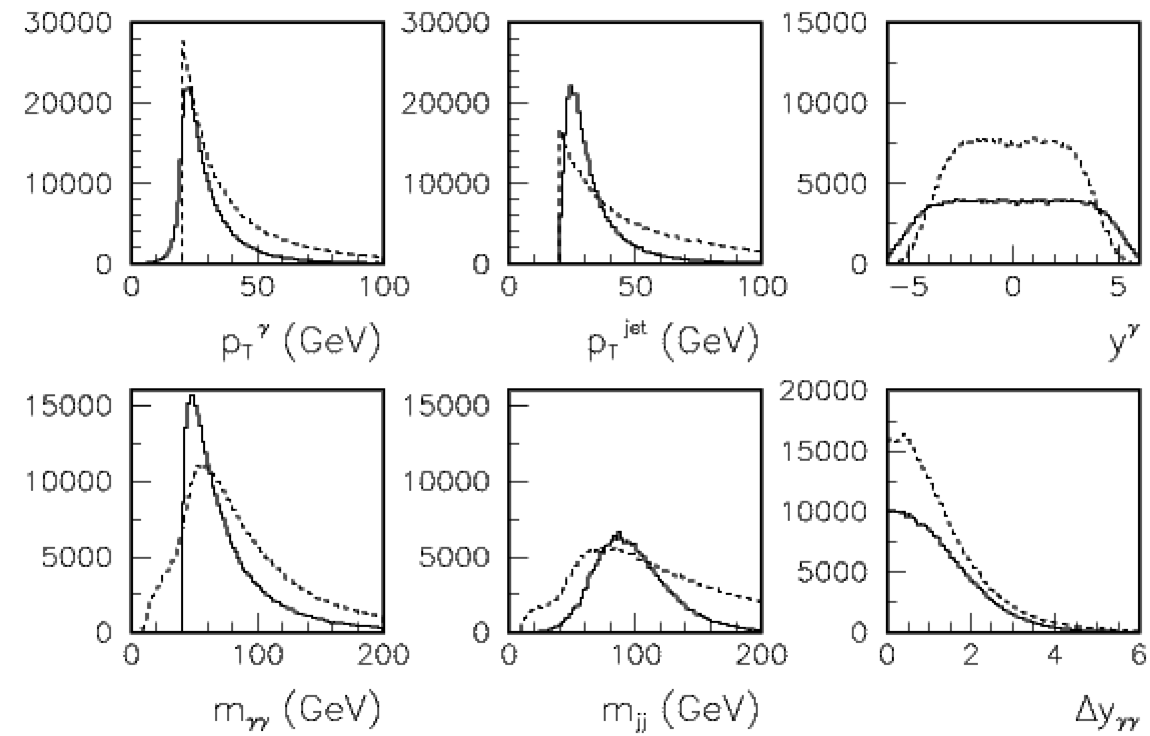


Figure 4: PYTHIA (solid line) and CompHEP (dashed line) partonic level distributions for the irreducible background $\gamma\gamma$ + 2jets

Batch Modes in CompHEP 4.5

Both parts (symbolic & numerical) have batch regimes:

Perl scripts: symb_batch.pl and num_batch.pl

Why the scripts are useful?

Computations of many subprocesses – laborious task, can be significantly simplified

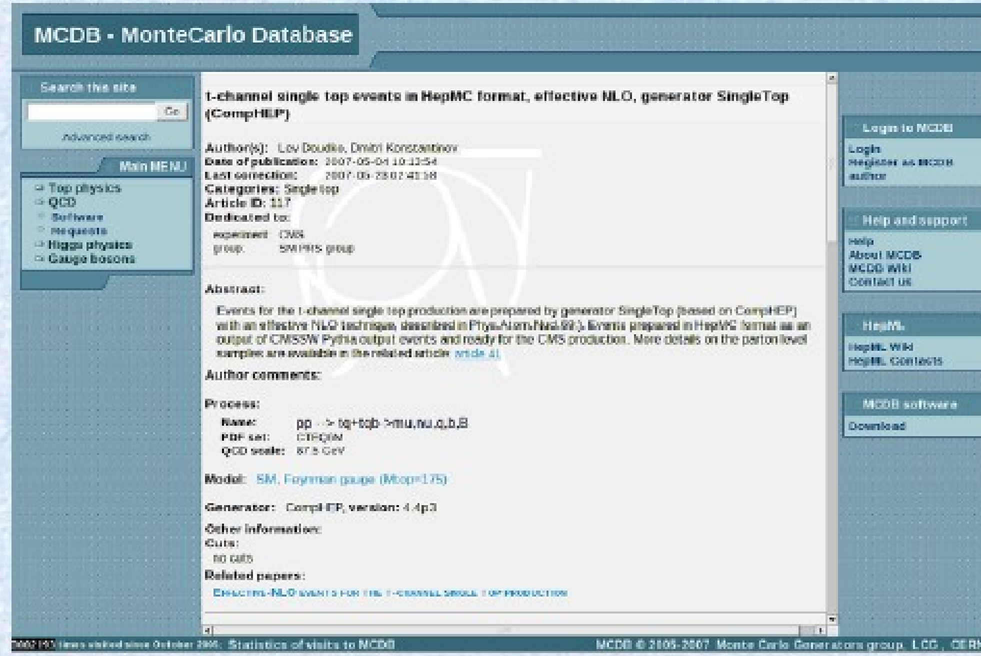
Long/large-scale calculations: GUI is not handy

Support of parallel calculations: very helpful for N*CPU machines/computer clusters (pbs/lsf is available; grid in progress)

"Knowledge transfer": theorists/phenomenoligists can prepare model/process.dat/batch.dat for further simulations by experimentalists

MCDB — Knowledge Base

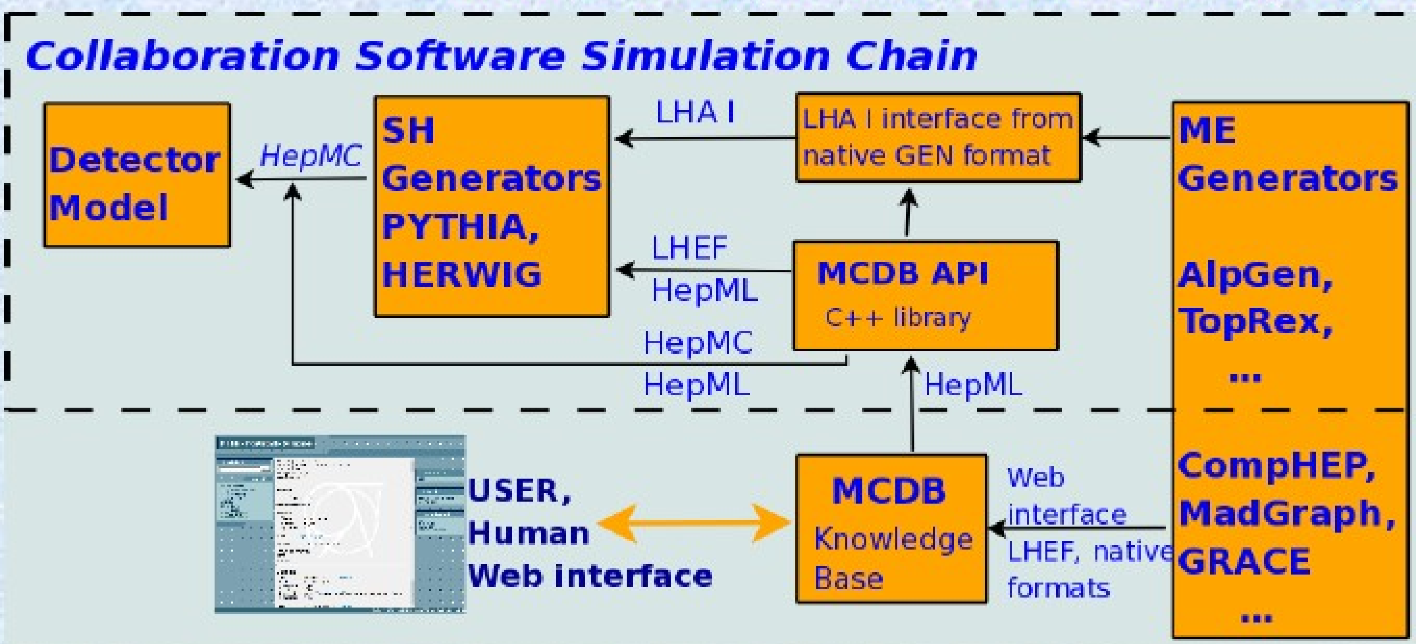
http://mcdb.cern.ch



Database of sophisticate MC simulated events and their description. It is Integrated with CMS software already

CompHEP group uses this project to distribute and document CompHEP events for LHC community

S.Belov, L.Dudko, A.Sherstnev et. al CPC178,222(2008)



New Features in CompHEP 4.4 (Interfaces)

- CompHEP->PYTHIA (CPYTH) (ready)
- CompHEP->PYTHIA-TAUOLA (ready)
- CompHEP->HERWIG (ready)
- CompHEP->HERWIG++ (in progress)
- Interfaced to Exp. Collaboration SW:
  SIMDET(ILC), CMKIN(CMS), ATHENA(ATLAS) and D0 (Tevatron) Run II software.
- Macros of interface to ROOT graphics (in progress)
- Output Events are ready for LCG MCDB Data Base

LHEF, LHAPDF, SUSY LHA

LHEF - the format adopted by almost all developer groups

hep-ph/060917

Now CompHEP supports 3 formats:

cpyth-1, cpyth-2 (for experiments, where the formats are used),

LHEF with HepML header .

There is a special option -- Generator (LHEF format) -- in the event menu in n_comphep.

All modern PDFs are available via LHAPDF: CTEQ, MRST, Alekhin PDF, etc.

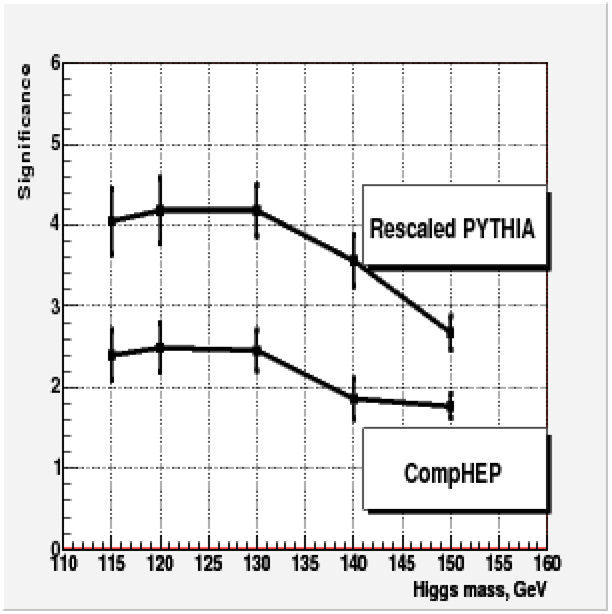
Both options, LHAPDF and internal PDF, are available in CompHEP 4.5
with the same functionality in both regimes

SUSY LHA

The SLHA interface is implemented in SUGRA and GMSB models of CompHEP

(instead of ISASUSY in the previous versions)

By default the slhaScript file invokes suSpect



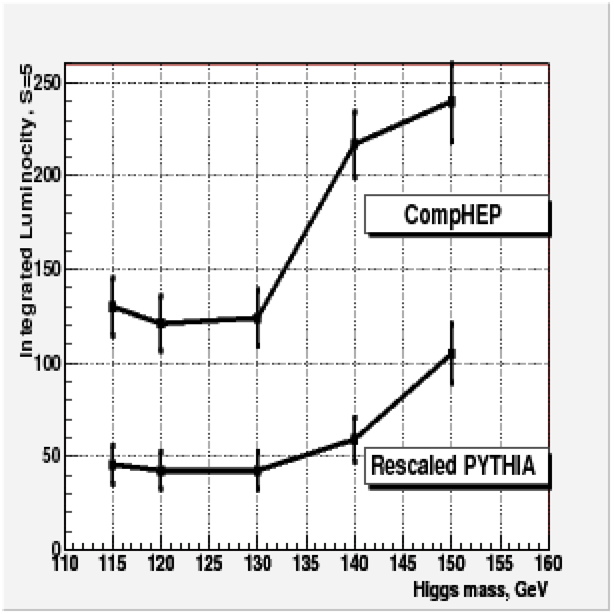


Figure 11: Significance vs Higgs boson invariant mass (left), normalized to 30 fb^{-1} and integrated luminosity, needed to reach 5σ significance for the two different scenarious described in Section 6

From M.D., Y.Ma, H.Newman, M.Pieri, CMS Note 2006

Conclusions

CompHEP simplification of flavor combinatorics and generation of color chains are important ingredients for successful generation of unweighted events then interfaced to PYTHIA for showering.

CompHEP batch modes for calculations with parallel processors (pbs, lsf) are important utilities for event generation in hadronic interactions at reasonable CPU time

Misidentification backgrounds seem to be as important (or more Important) as the irreducible ones. Partonic level significance gives only rough estimate of a realistic full detector simulation significance.