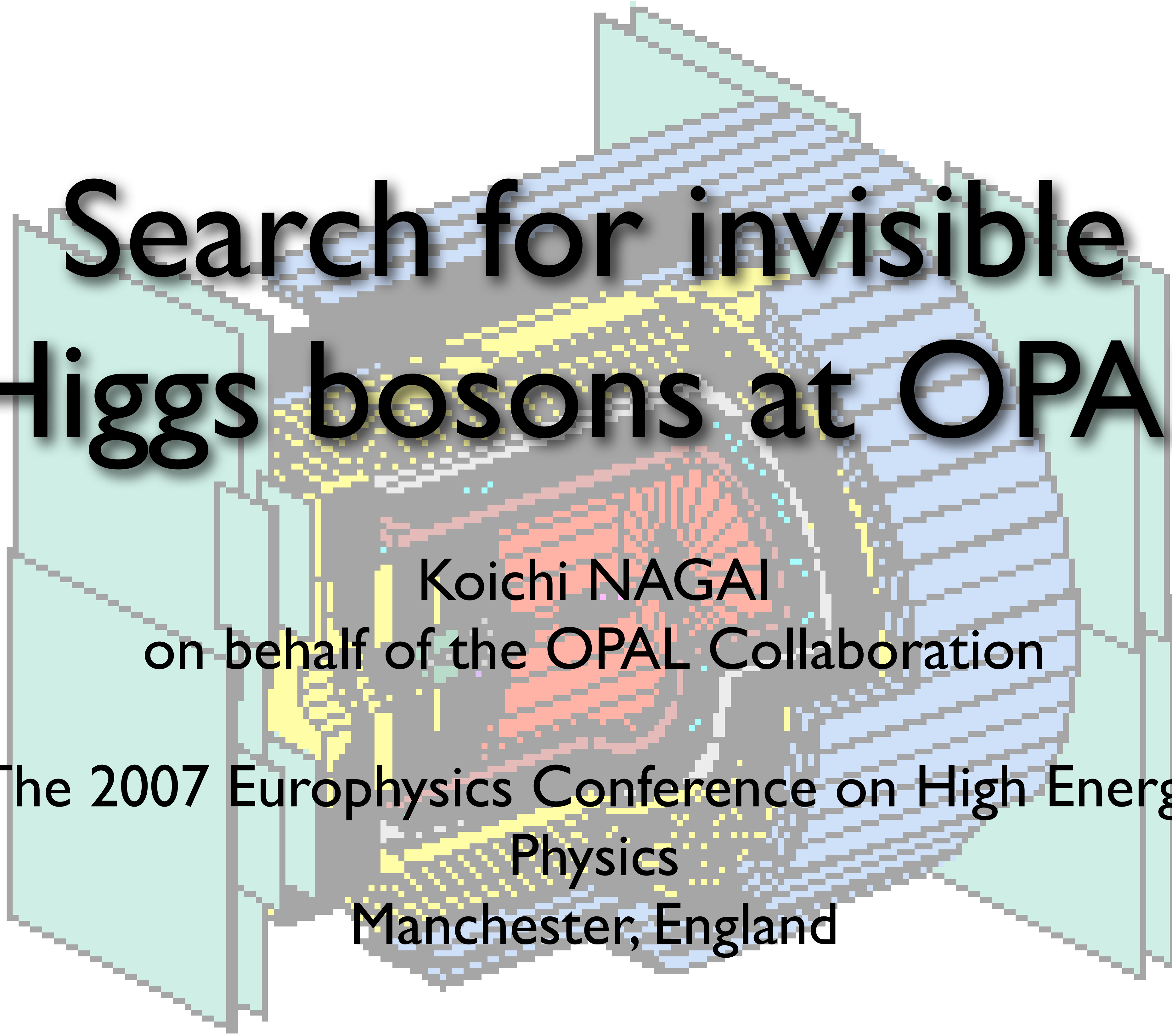
Search for invisible Higgs bosons at OPAL



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on behalf of the OPAL Collaboration

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Manchester, England

Introduction

- A tremendous effort to find the Higgs boson was carried out by all of the four LEP experiment in various search channels for the Standard Model and models beyond the Standard Model.
- In spite of the effort, no visible signal from the Higgs boson was found.
  - the Higgs boson is out of reach?
  - the Higgs boson is INVISIBLE by our detector?

Introduction

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- In spite of the effort, no visible signal from the Higgs boson was found.
  - the Higgs boson is out of reach?
  - the Higgs boson is INVISIBLE by our detector?
- There are many theoretical ideas which expect the invisibly decaying Higgs boson, where the Higgs boson decays to or can be invisible by
  - neutralinos in the Minimal Supersymmetric Standard models
  - heavy neutrinos
  - neutrinos + Goldstino in a non-linear supersymmetric model
  - Majorons
  - neutrinos or mixing with a scalar graviton "graviscalar", in models with extra dimensions
  - a hidden scalar sectors coupled to the Higgs boson, "stealthy Higgs"

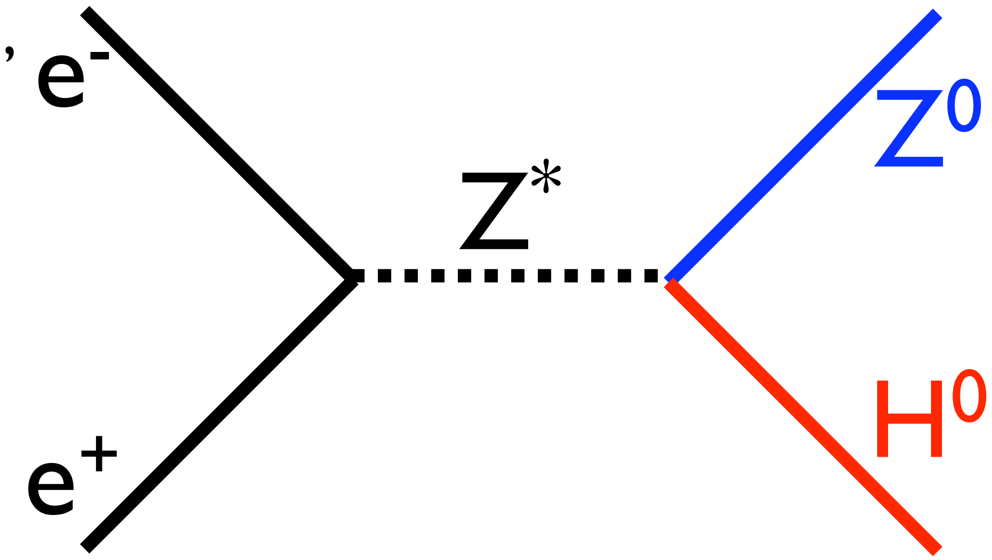
✓ Please see references in hep-ex/0707.0373 and Eur. Phys. J.C.49 (2007) 457

Introduction

- In those ideas of the invisibly decaying Higgs boson, there are two types studied,
  - assuming the Higgs boson has a negligible decay width ($\Gamma_H \approx 0$)
    - ★ MSSM; $H \rightarrow \tilde{\chi}^0_1 \tilde{\chi}^0_1$
  - Or a large decay width ($\Gamma_H > 0$)
    - ★ Stealthy Higgs model
      - ✓ Large decay width results in a broad resonance peak
      - ✓ The singlet fields called phions strongly couple only to the Higgs boson
- Also the Higgs boson can decay nearly invisibly
    - ★ $H \rightarrow \tilde{\chi}^0_1 \tilde{\chi}^0_2 \rightarrow \tilde{\chi}^0_1 \tilde{\chi}^0_1 Z^0/\gamma$
- Model independent searches were carried out for the invisibly decaying Higgs bosons with
      - ✓ negligible decay width ($\Gamma_H \approx 0$)
      - ✓ large decay width ($\Gamma_H > 0$)
  - on data of an integrated luminosity of 660 pb^{-1} at $\sqrt{s}$ =183-209 GeV

Topology of the invisibly decaying Higgs boson

- The Higgs boson would be produced in association with a Z0 boson, "Higgs-Strahlung" process
- The visible part of the events comes from Z^0 decay:
  - Hadronic 70%, Leptonic 10%, Invisible 20%
  - The invariant mass of event $=m_Z$
  - OPAL analysis were carried out for hadronic final states only.



- The main background are SM processes with ν from Z^0Z^0 & W^+W^- process
- Three types of signal sample were prepared using HZHA,
  - the Higgs boson with **Negligible** decay width ($\Gamma_H \approx 0$): produced as the SM Higgs boson
    - ✓ decaying completely invisibly
    - ✓ decaying nearly invisibly: a cascade decay chain with ΔM= 2 or 4 GeV
  - Invisible decay with a **Large** decay width ($\Gamma_H > 0$): simulated by combining the $\Gamma_H \approx 0$ samples with a weight according to expected mass distributions.

Event Selection

Negligible decay width ($\Gamma_H \approx 0$)

Large decay width ($\Gamma_H > 0$)

Preselection → Cut based-selection → Likelihood selection

Assure the data quality; requiring detector status, reducing events from two-photon processes, etc.
Forward energy veto to reject events with particles escaped around beam direction.

Reduce BKG keeping high signal efficiency
M_{vis}, p_T, $\cos\theta_{mis}$, $\cos\theta_{jet}$, ϕ_{acop}, $N_{Iso.Lepton}$.....

Likelihoods were built for the samples categorised by the event shape and kinematics

Preselection

Cut based-selection

Likelihood selection

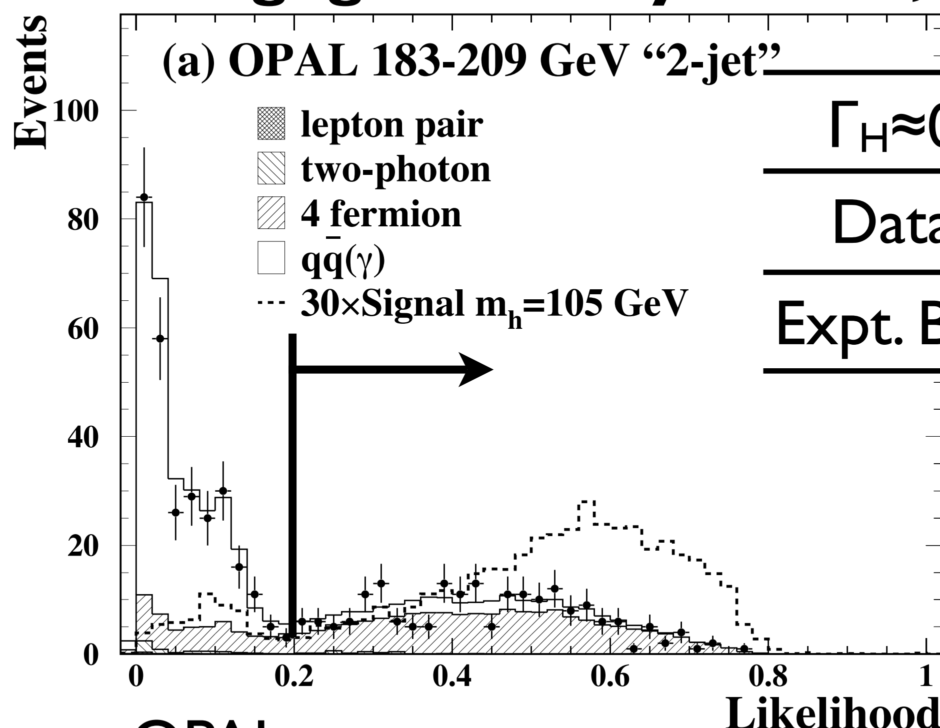
Sample was divided into two categories:
2-jet & >2-jet
The likelihood was built with
$H \rightarrow$ invisible signal
(kinematic limit to 10GeV below)
for 2-jet and >2-jet, separately at each $\sqrt{s}$

The same likelihood applied to signal samples of nearly invisible decay.

A total of 5 types of likelihoods were built
2 sets of input variables
X
3 signal mass range
Optimal way to build a likelihood was chosen by the search space (m_h,Γ_H)
Γ_H=1GeV - 3 TeV
X
m_h=1 - 120 GeV

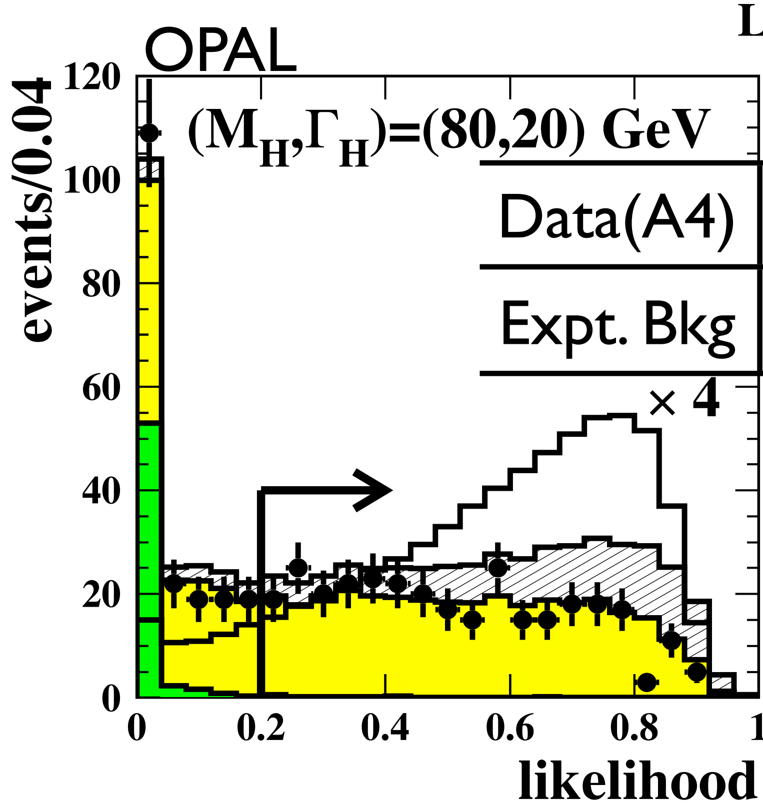
Likelihood Distributions

Negligible decay Width, $\Gamma_H \approx 0$



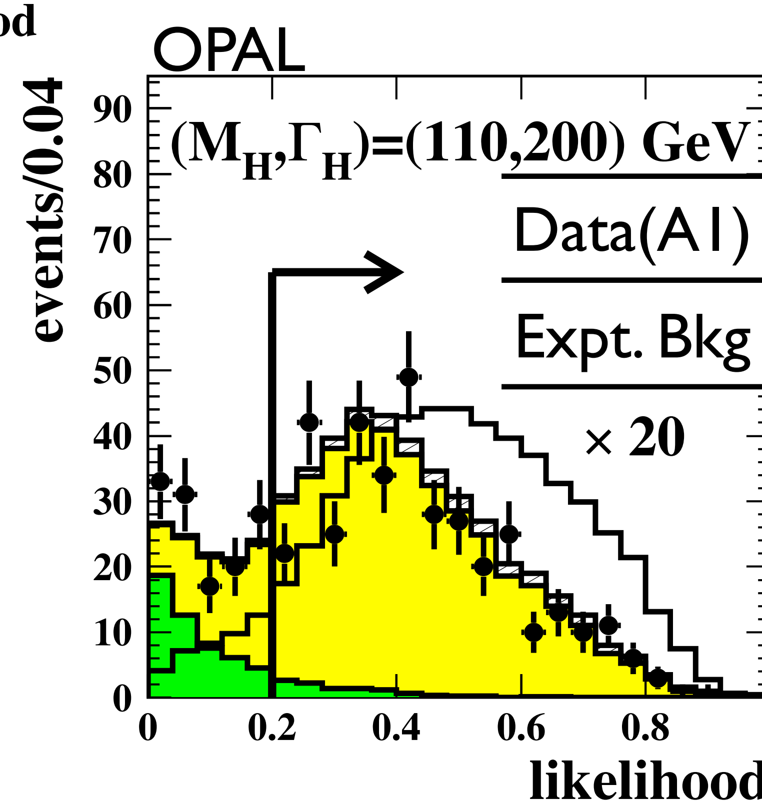
$\Gamma_H \approx 0$	2-jet	>2-Jet
Data	194	278
Expt. Bkg	206	279

- The cut value was optimised to get good S/N
  - ✓ LH > 0.2
- For large decay width(Γ_H>0): These distributions are used in the limit calculation with a likelihood ratio method.



Data(A4)	310
Expt. Bkg	317

Large decay width, Γ_H>0

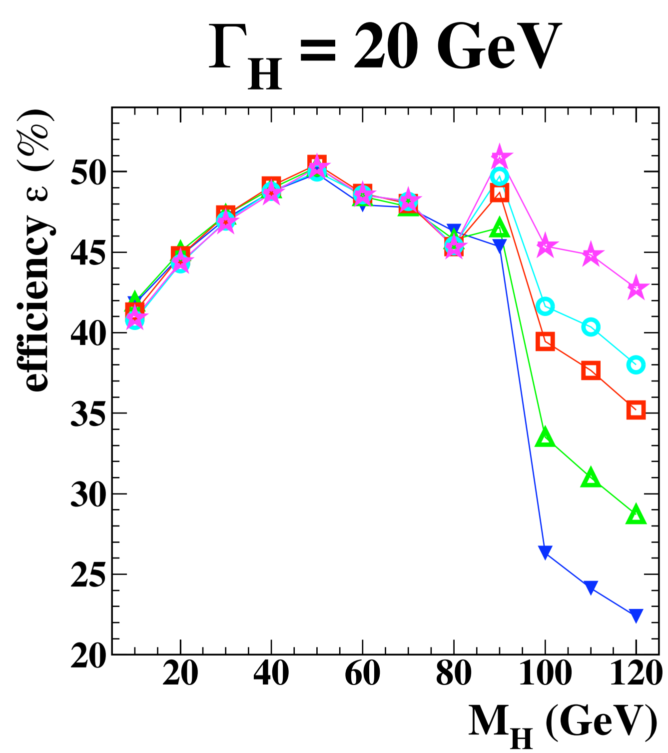


Data(A1)	369
Expt. Bkg	385

Efficiency

- Negligible decay width ($\Gamma_H \approx 0$):
  - Efficiencies in "2-jet" and ">2-jet" categories ~ 20 - 27% at m_h= 60 - 110 GeV

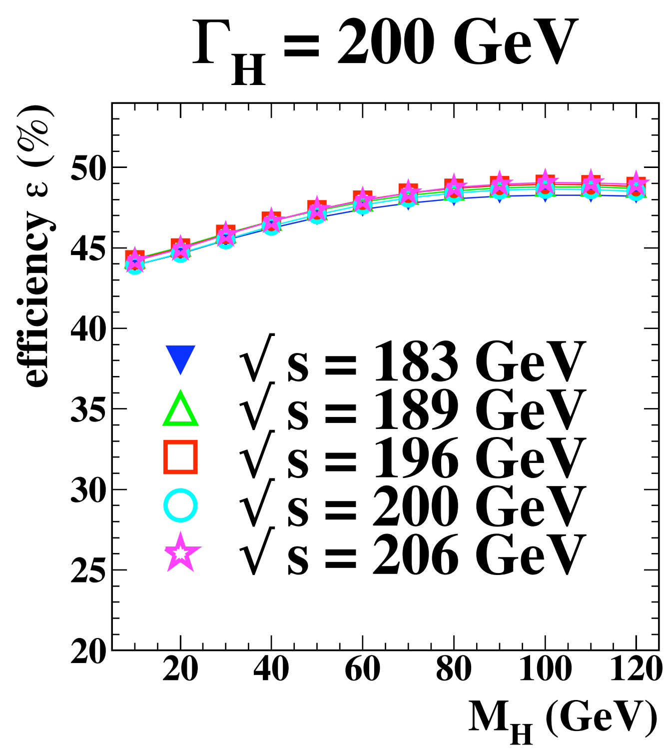
$\sqrt{s}$ =183-209GeV	2-jet	>2-Jet
Data	194	278
Expt. Bkg	206	279
Eff.@m_H=105GeV	24%	23%



- Large decay width (Γ_H>0):

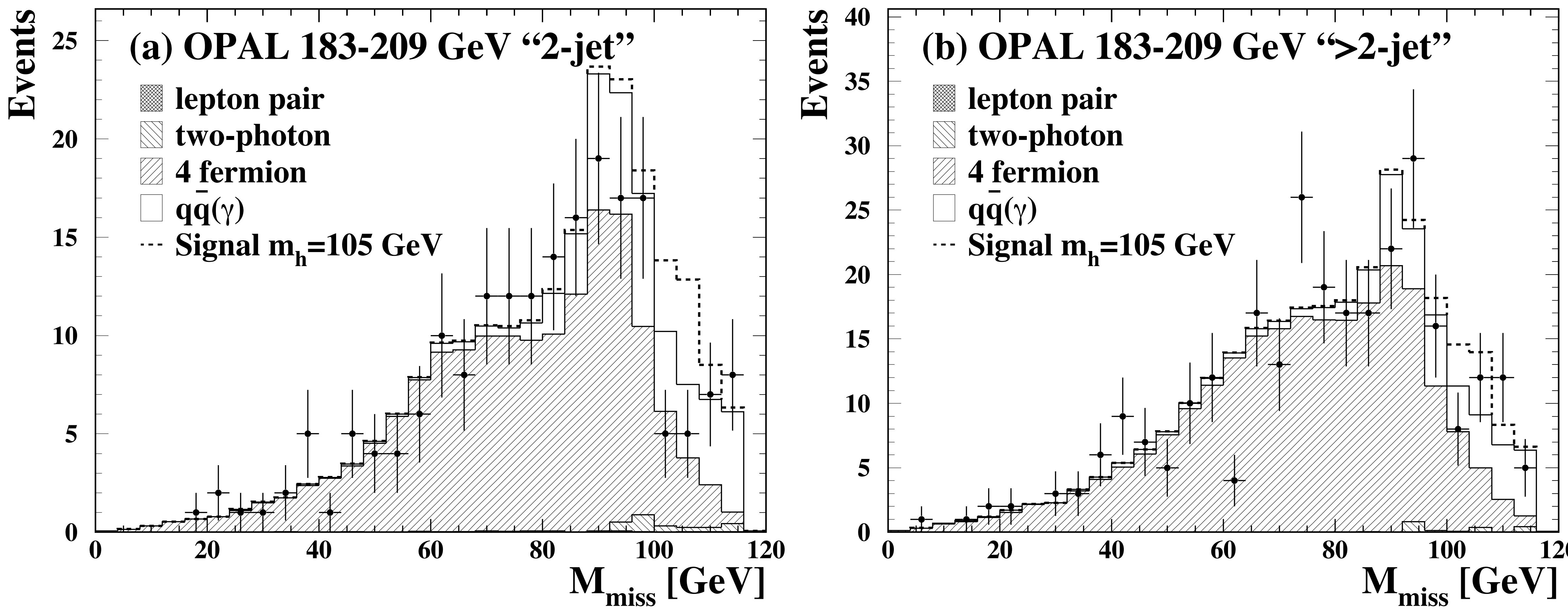
	A1	A2	A3	A4	A5
Data(A2)	369	370	305	310	253
Expt. Bkg	385	381	320	317	255
Efficiency	30 - 50%				

  - smaller decay width, the kinematic limit affects on the efficiencies
  - at larger decay width the effect was smeared due to the decay width.



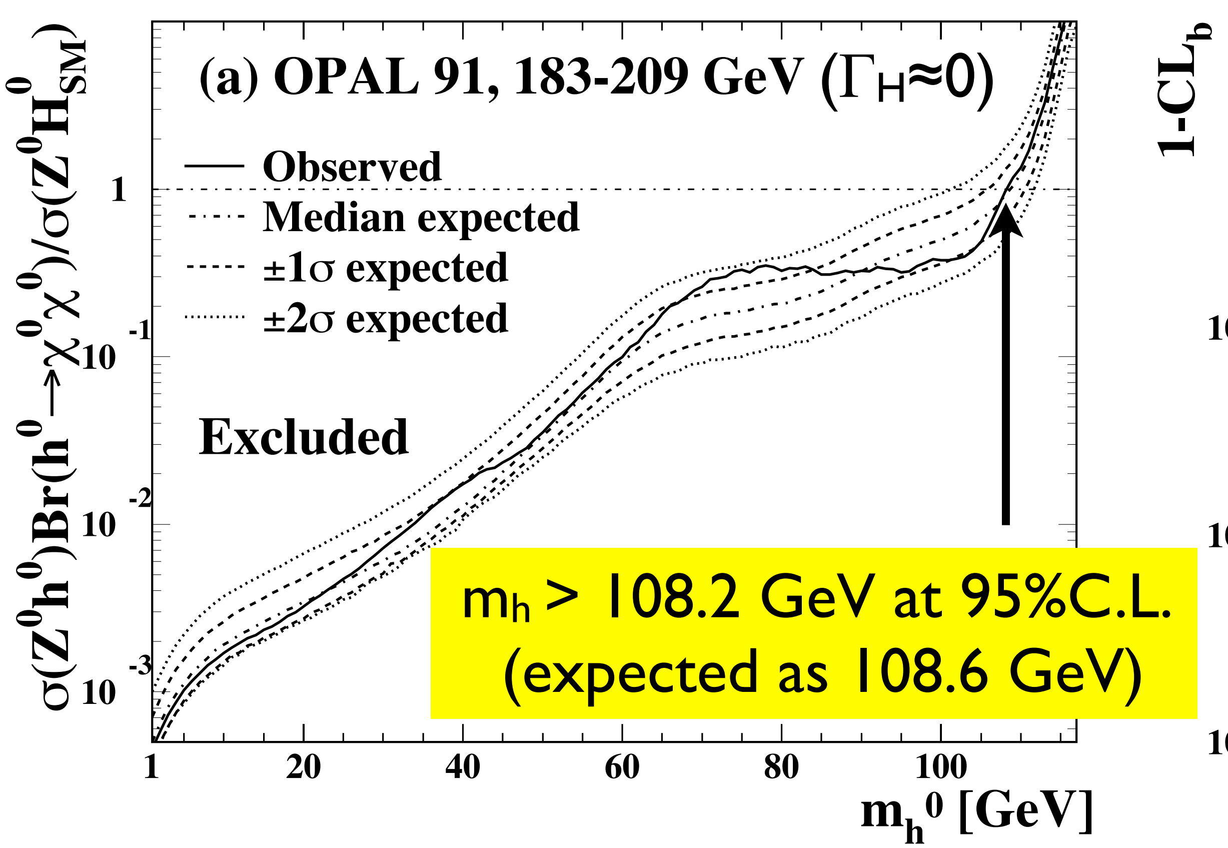
Missing Mass Distributions ($\Gamma_H \approx 0$)

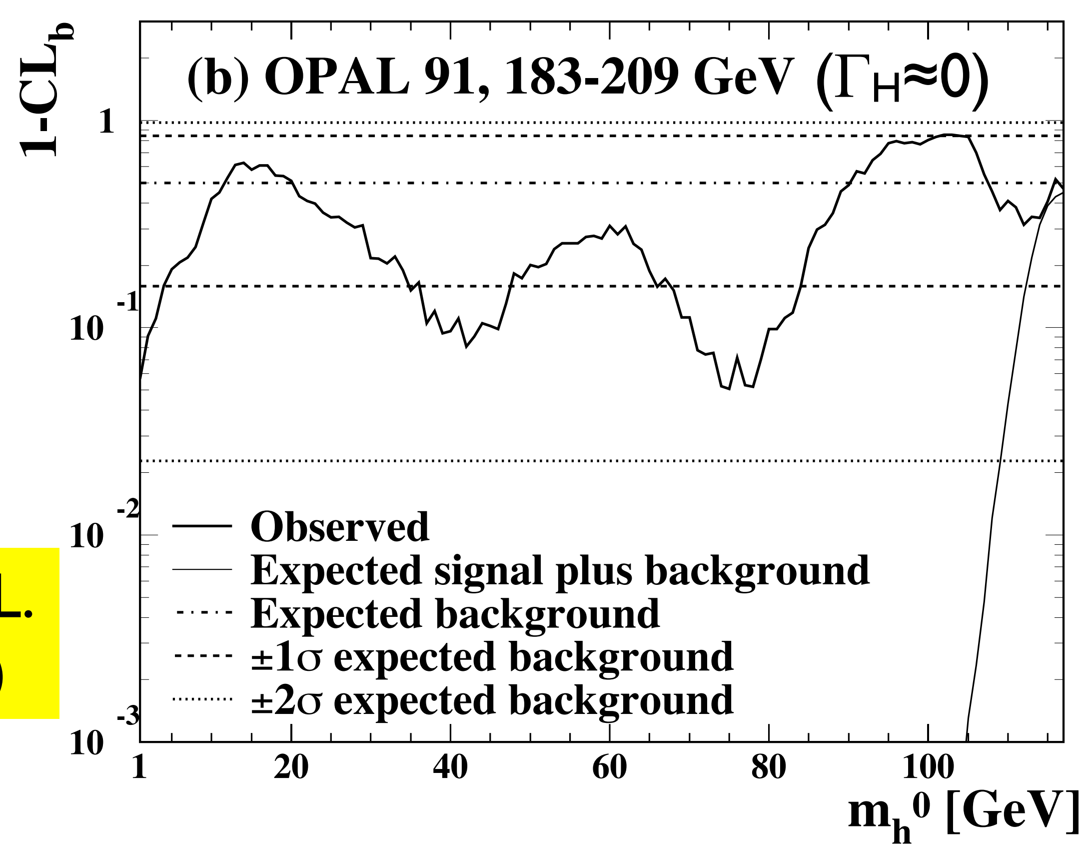
- The selected data distributions are consistent to the SM expectations.
  - There are no evidence of invisibly decaying Higgs bosons.
  - Z^0Z^0 and W^+W^- events are dominated in the background
- limit calculations were performed using likelihood-ratio method with missing mass for negligible ($\Gamma_H \approx 0$) and likelihood for large decay width ($\Gamma_H > 0$)



Limit on the production cross-section ($\Gamma_H \approx 0$)

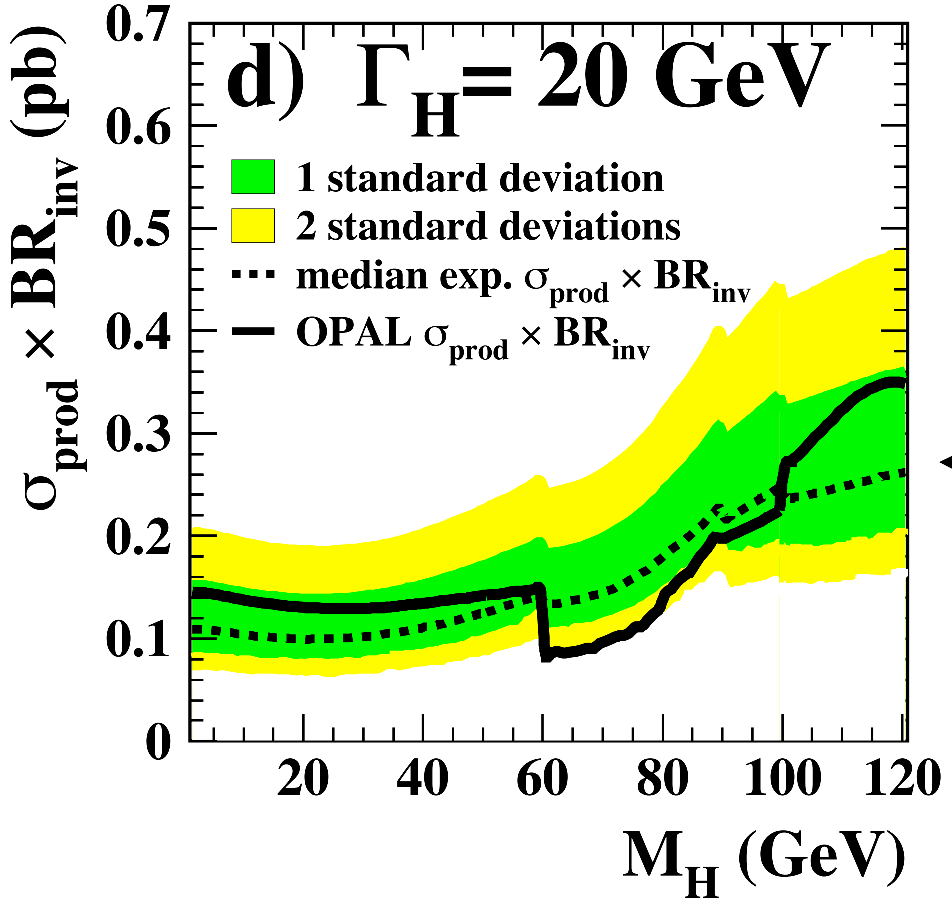
- The limits for the invisibly decaying Higgs boson with negligible decay width ($\Gamma_H \approx 0$) are calculated for m_h = 1 - 120 GeV, assuming 100% BR(H→invisible).
- The observed limit is placed in the band of ±2σ expected limit.
  - ✓ also for nearly invisibly decaying Higgs bosons:
    - ➡ ΔM=2 GeV: m_H>108.4 GeV (108.2 GeV expected)
    - ➡ ΔM=4 GeV: m_H>107.0 GeV (107.3 GeV expected)
- The compatibility of data with the expected BKG was quantified by 1-CL_b

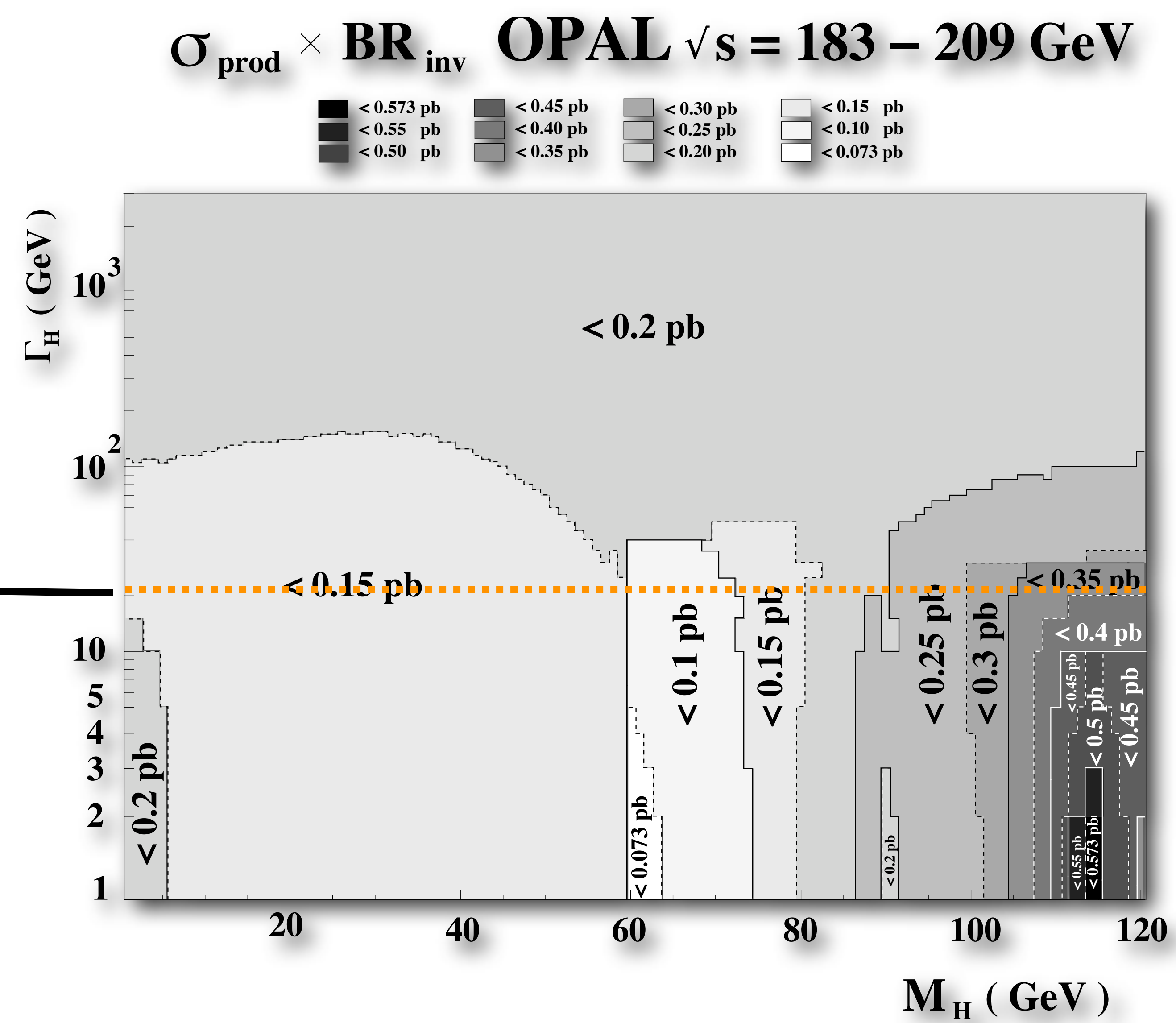




Limits on Production Cross-section (Large decay width, $\Gamma_H > 0$)

- Model independent limits on the production cross-section x Br(H→invisible) were evaluated to be between 0.07 and 0.57 pb.
- Discontinuity in the slice plot is coming from boundary of likelihood selections.



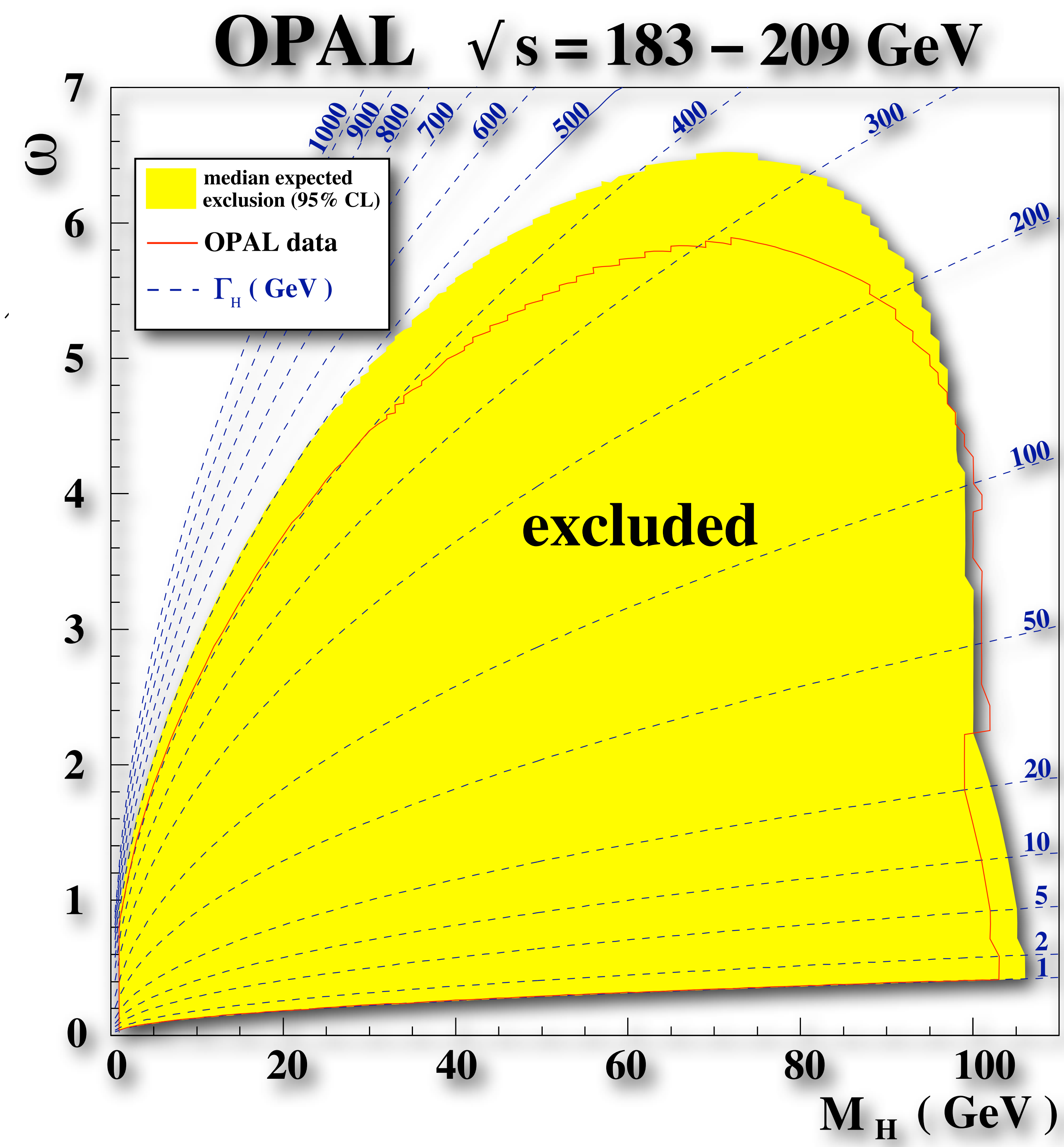


Interpretation in the stealthy Higgs

- Assuming m_{phion}=0, Γ_H is a function of the coupling ω between the Higgs boson and Phion, and M_H

$$\Gamma_{\mathrm{H}}(M_{\mathrm{H}}) = \Gamma_{\mathrm{SM}}(M_{\mathrm{H}}) + \frac{\omega^2 v^2}{32\pi M_{\mathrm{H}}}$$

- the cross section limit has been translated into the ω - M_H parameter space.
- At small ω ≈ smaller Γ_H region (close to Γ_H≈0), M_H<103 GeV is excluded.

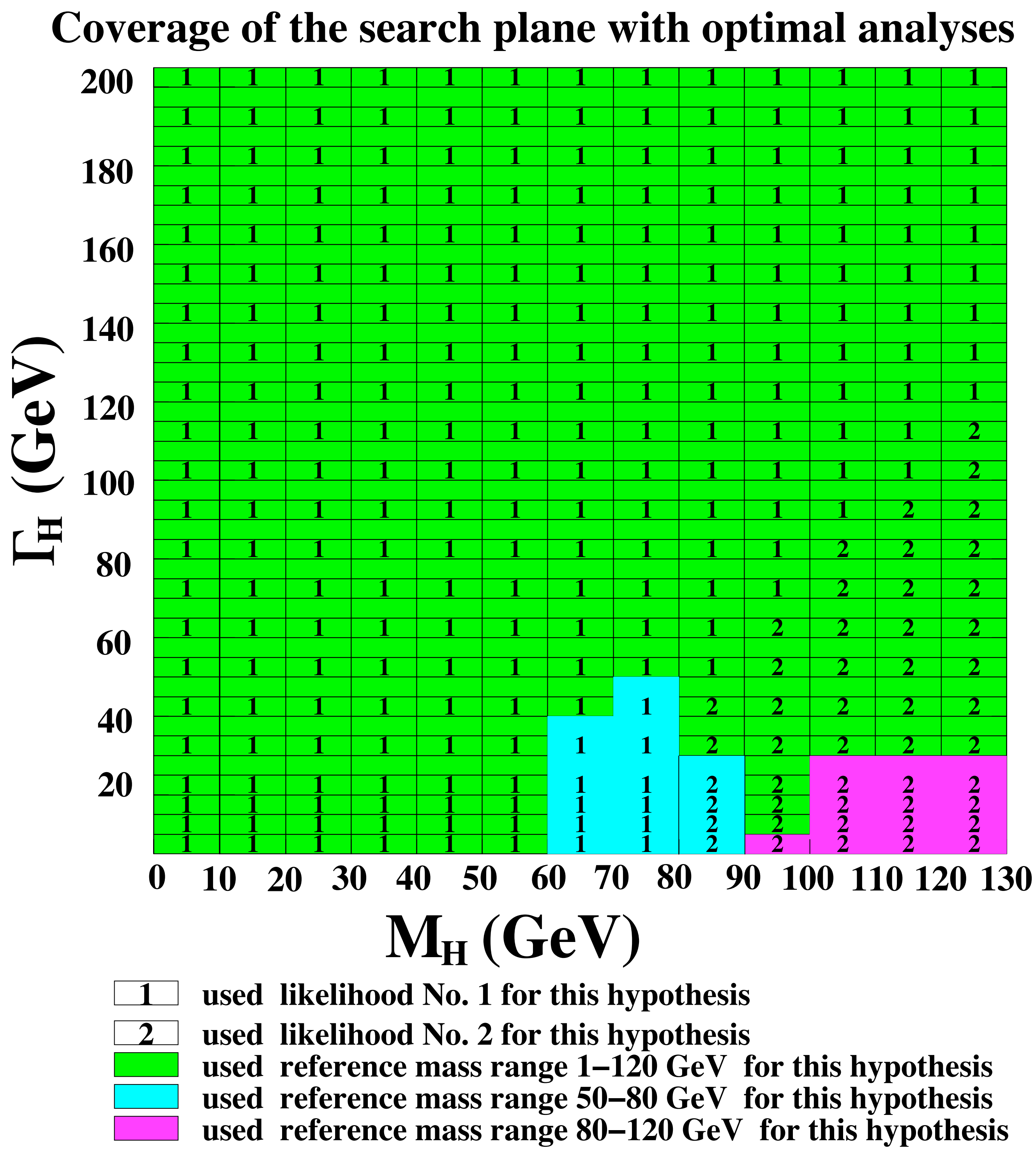


Conclusion

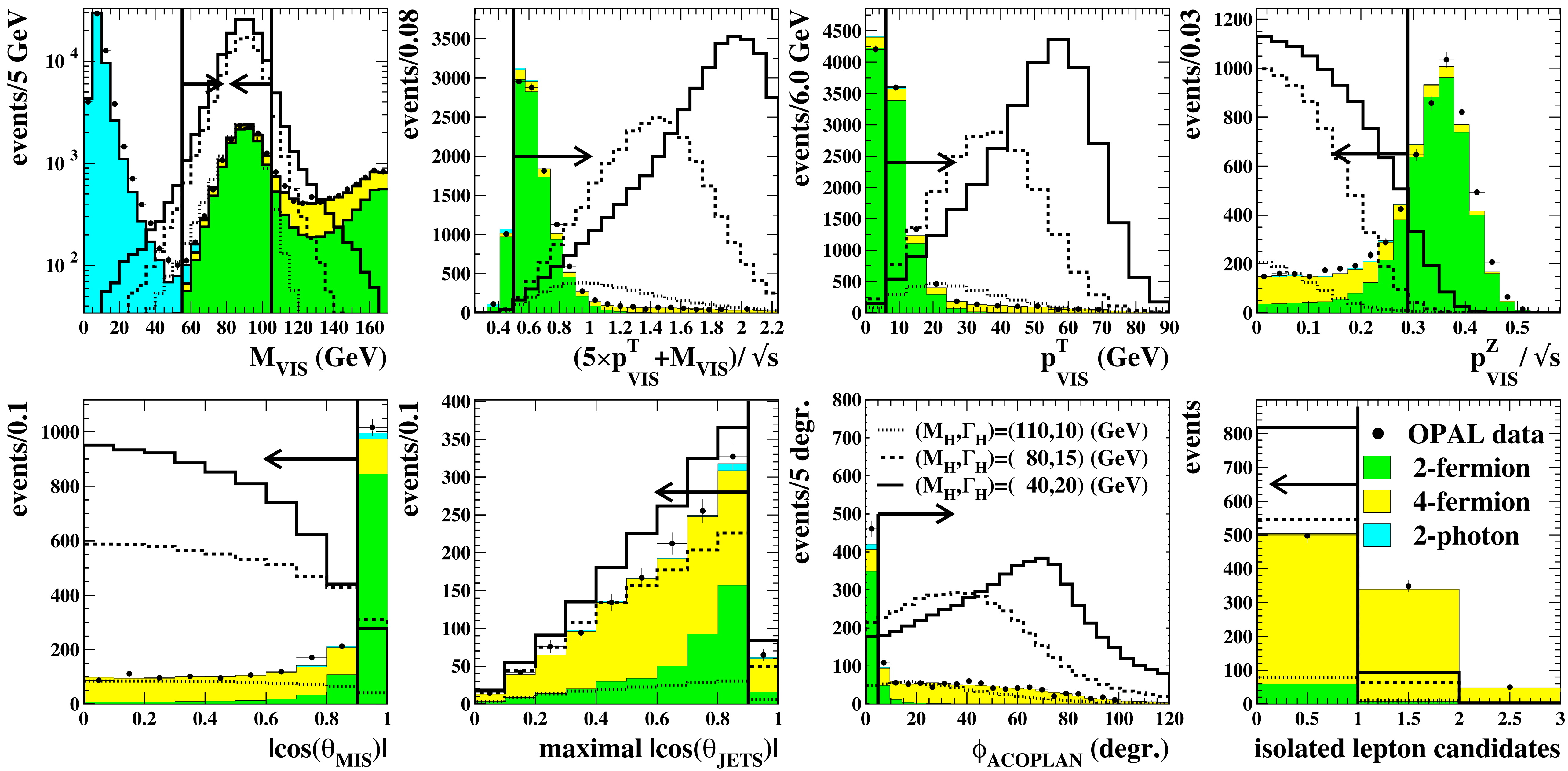
- We didn't see the evidence of invisibly decaying Higgs bosons at the OPAL experiment. We searched for signals from several kinds of Higgs bosons
  - With negligible decay width ($\Gamma_H \approx 0$);
    - ★ Invisibly decaying Higgs bosons
    - ★ Nearly invisibly decaying Higgs bosons
  - Invisibly decaying Higgs bosons with large decay width ($\Gamma_H > 0$)
- Limits are evaluated at 95%C.L.
  - With negligible decay width ($\Gamma_H \approx 0$):
    - ★ Invisibly decaying Higgs: $m_H > 108.2$ GeV (expected as 108.6 GeV)
    - ★ Nearly invisibly decaying Higgs
      - ✓ $\Delta M = 2$ GeV: $m_H > 108.4$ GeV (108.2 GeV)
      - ✓ $\Delta M = 4$ GeV: $m_H > 107.0$ GeV (107.3 GeV)
  - With Large decay width ($\Gamma_H > 0$):
    - ★ Define the production cross-section limit invisibly decaying higgs over the Γ_H-m_H parameter space: $\sigma < 0.07 - 0.57$ pb
    - ★ Exclusion for ω-m_H parameter space.

Invisibly Decaying Higgs Bosons With Large Decay Width

Coverage of analysis



Selection for the large decay width (Γ_H>0)

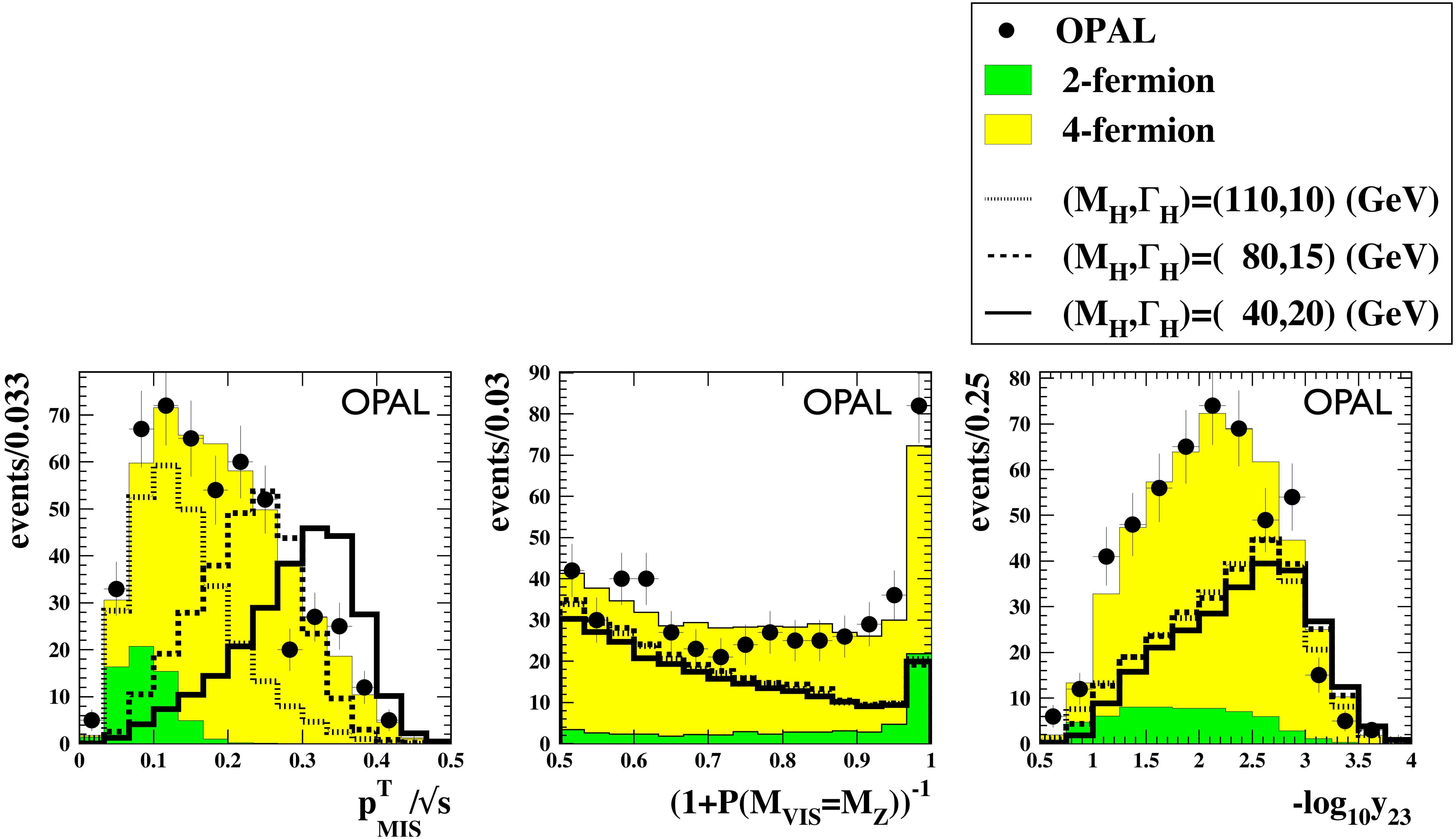


Signal efficiency: 39 - 55% for small decay widths

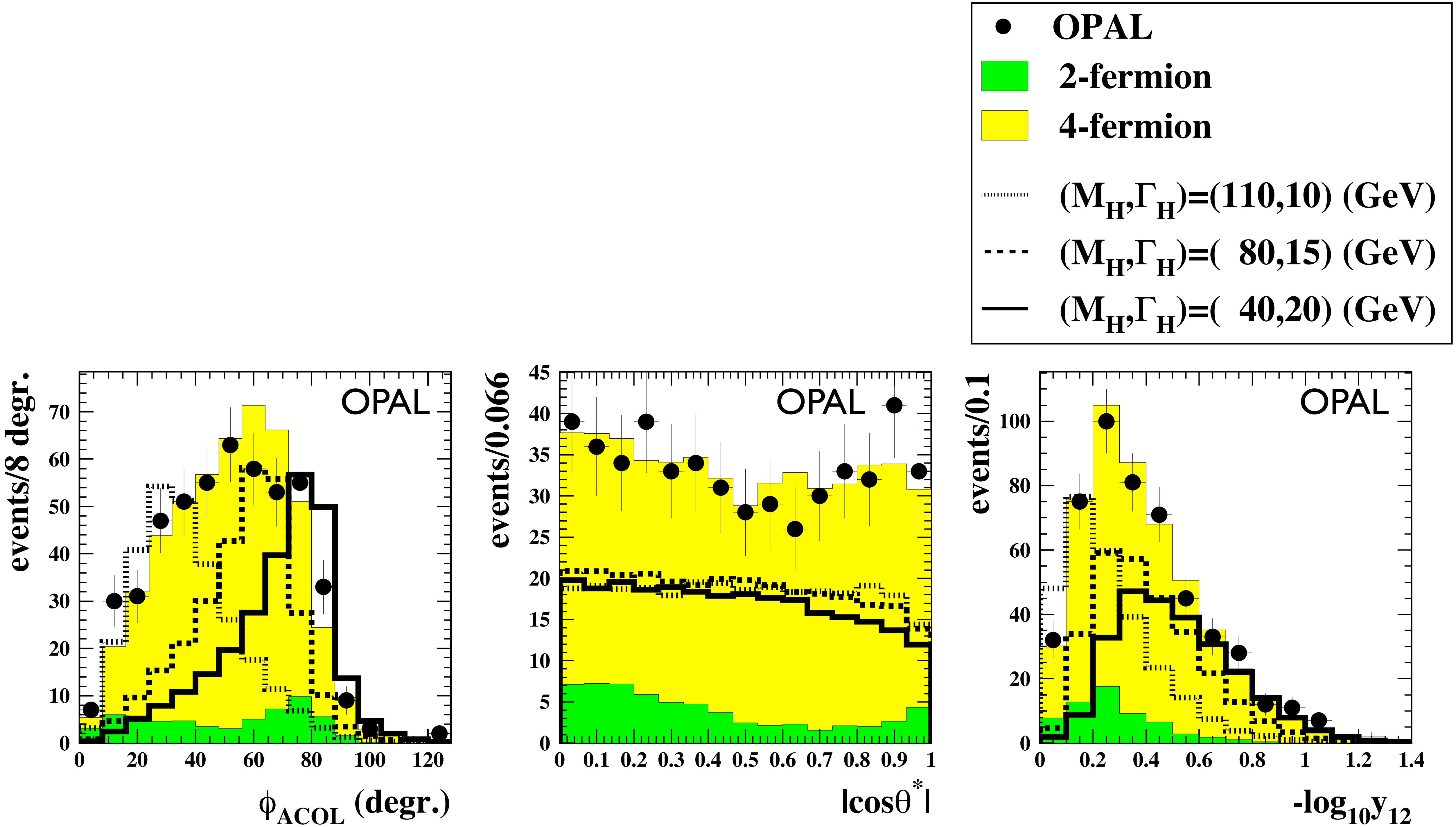
45 - 53% for larger decay widths above Γ_{H}=100 GeV

Signal distributions are scaled arbitrarily. BKG distributions are summed over all $\sqrt{s}$

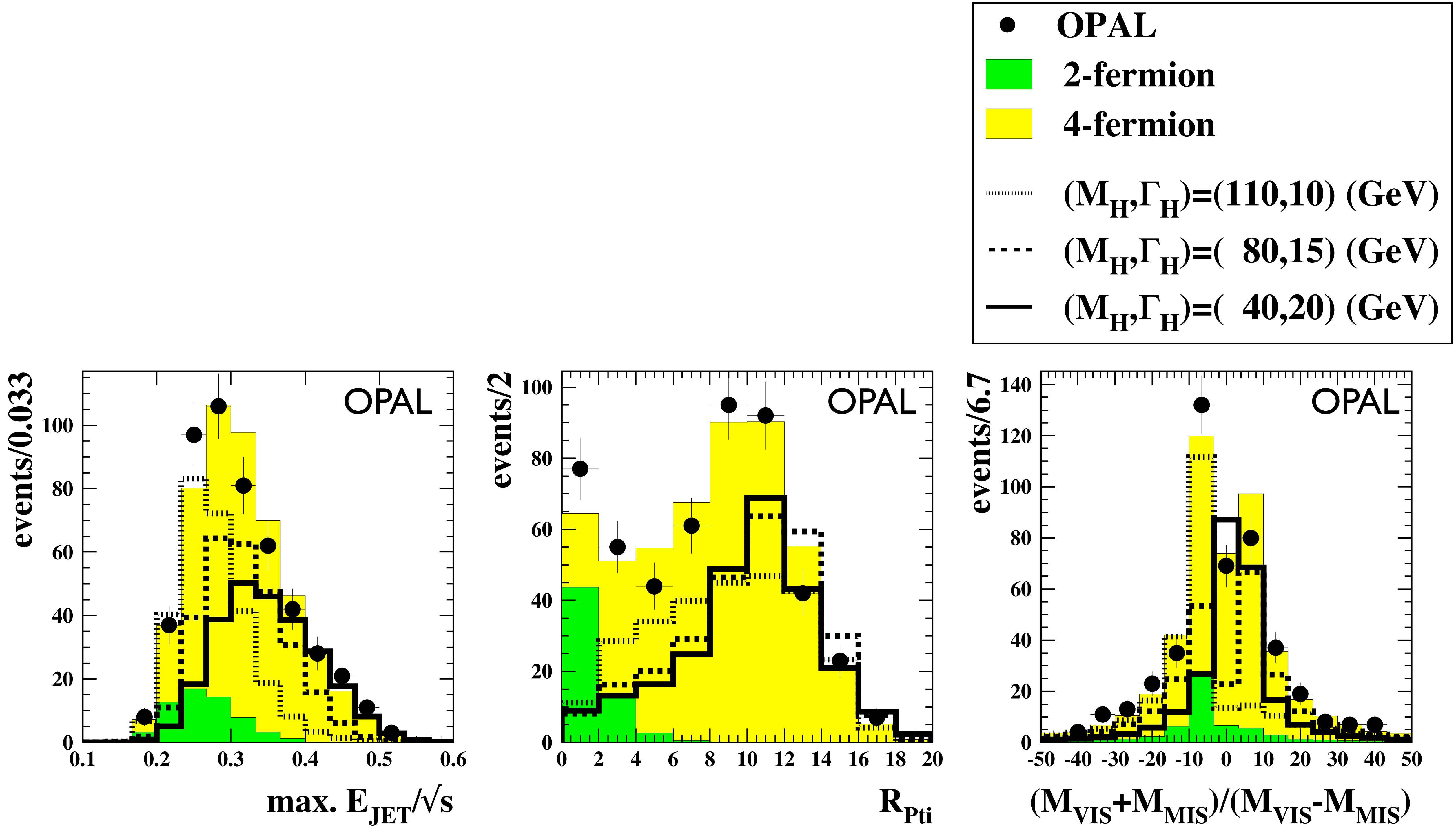
Variables in Likelihoods 1 & 2



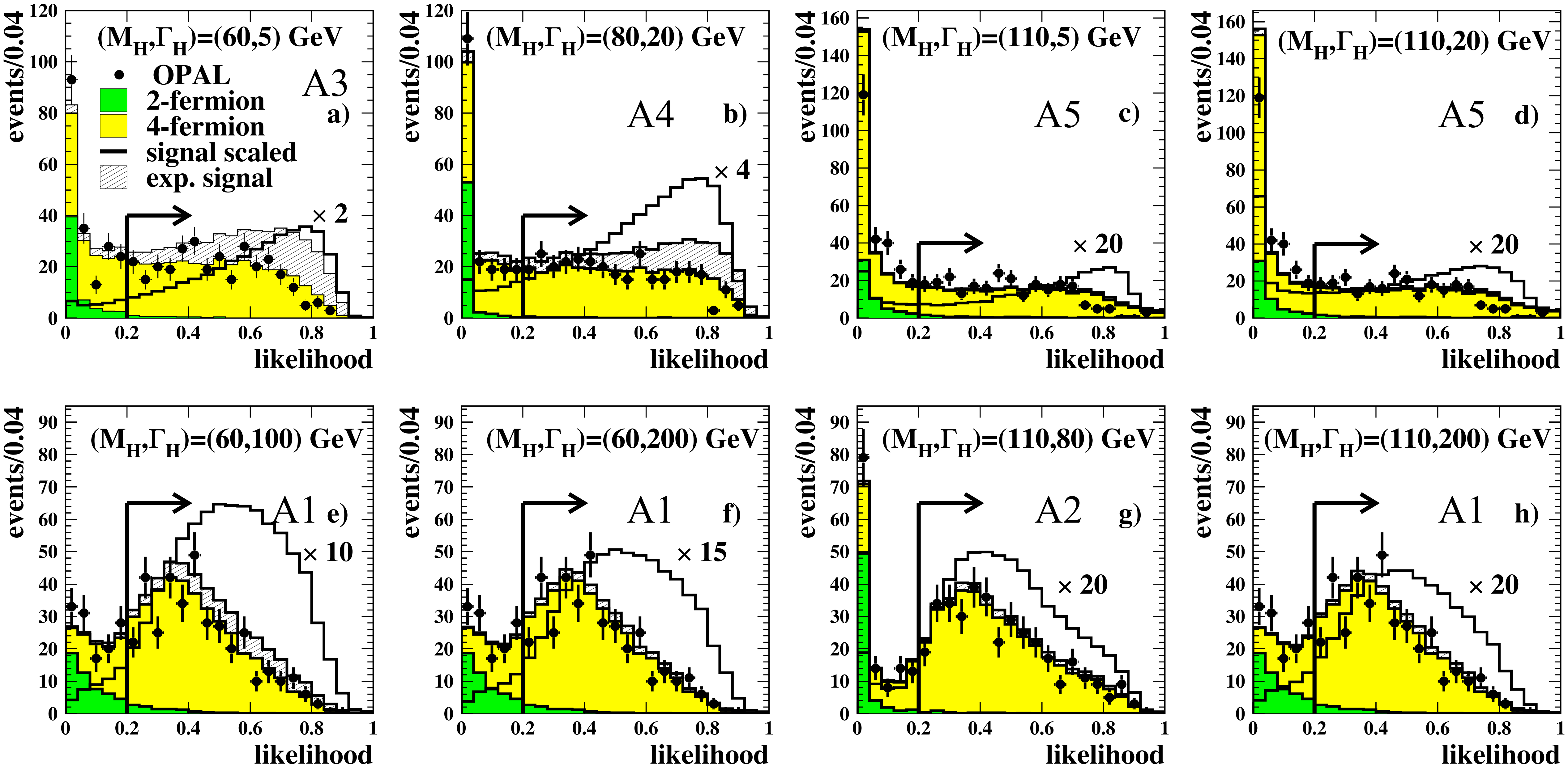
Variables in Likelihood 1



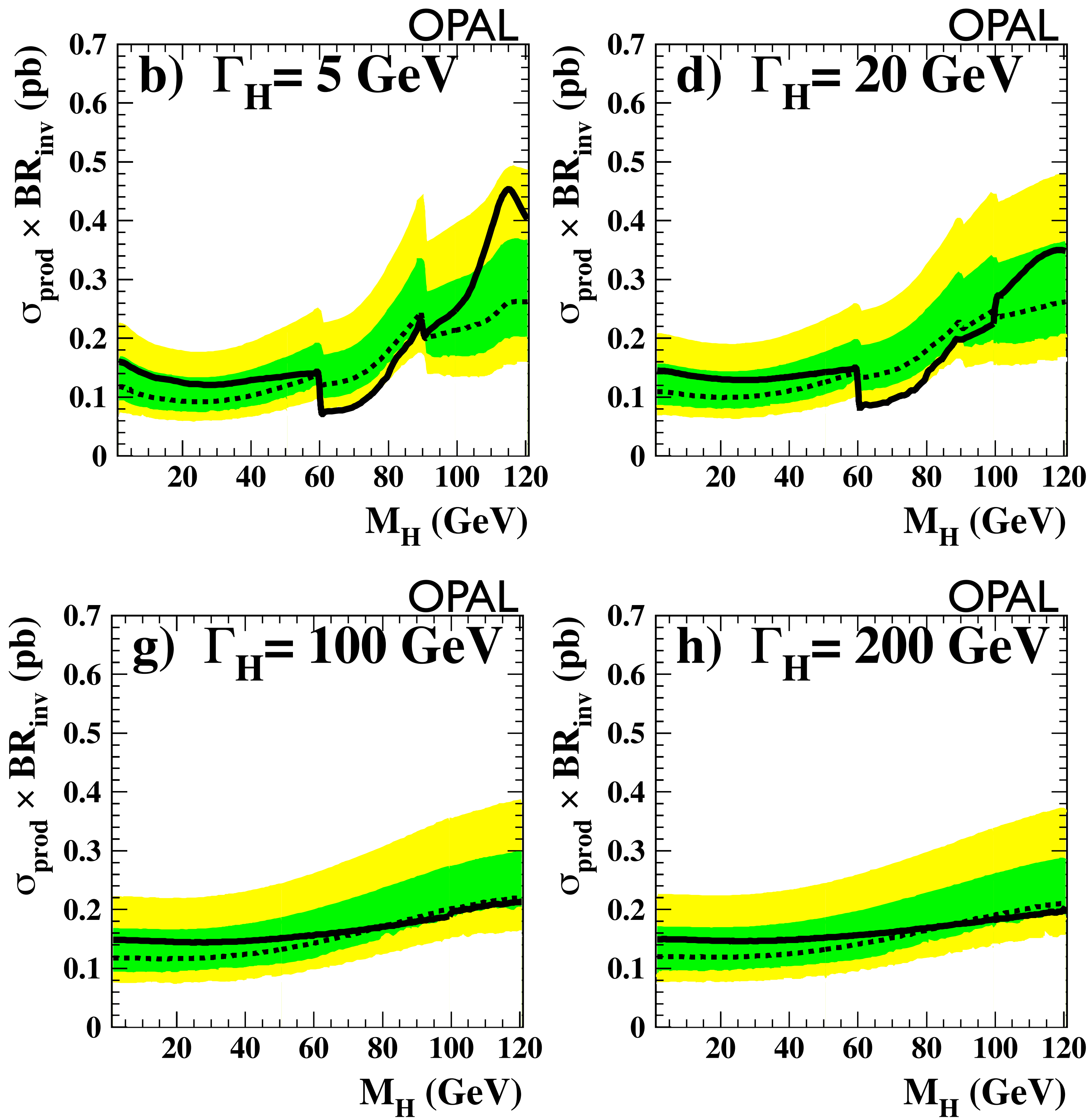
Variables in Likelihood 2



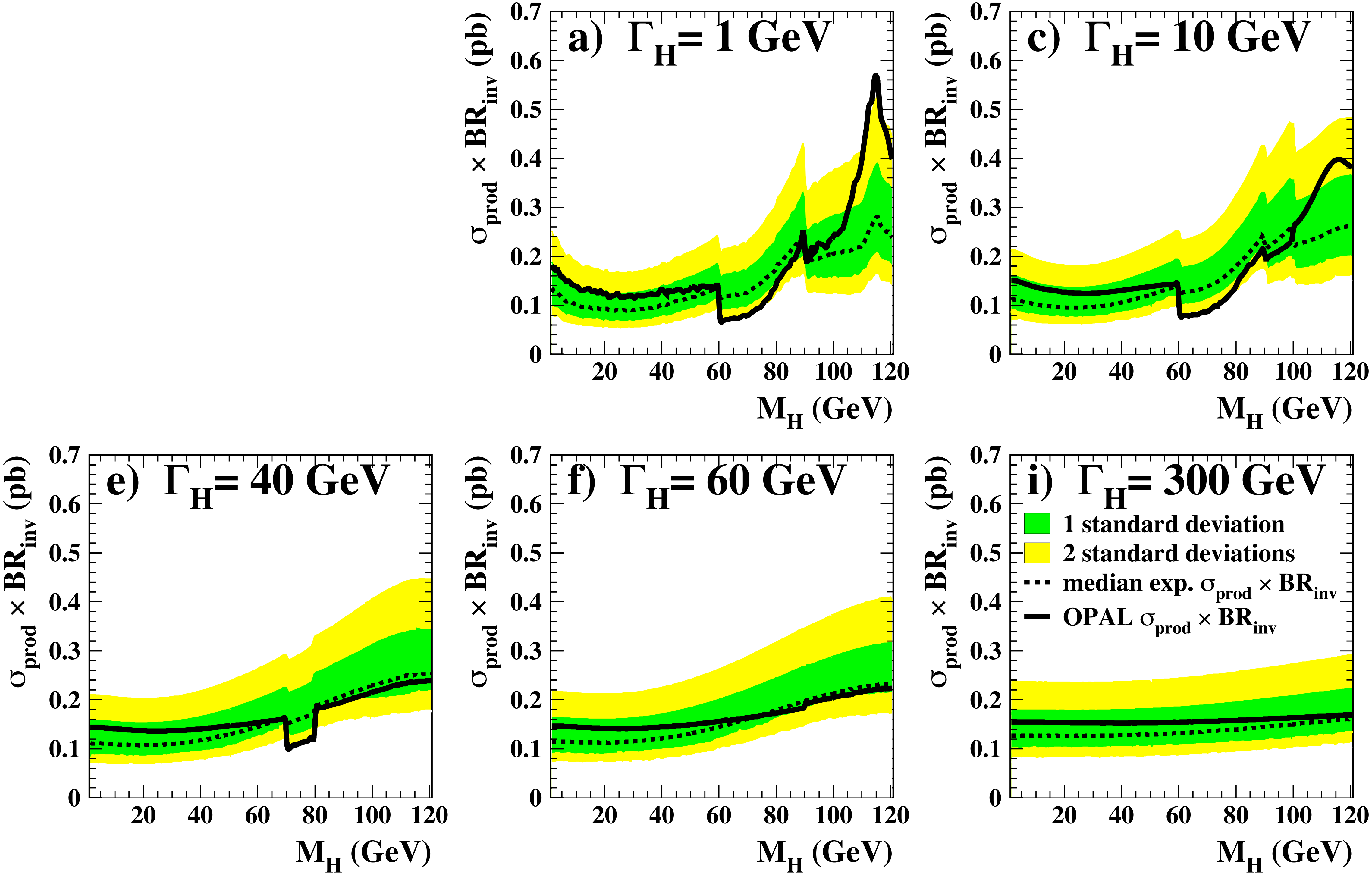
Likelihood Distributions



Limits


OPAL
b) Γ_H= 5 GeV
d) Γ_H= 20 GeV
g) Γ_H= 100 GeV
h) Γ_H= 200 GeV
$\sigma_{prod} \times BR_{inv}$ (pb)
M_H (GeV)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
20
40
60
80
100
120

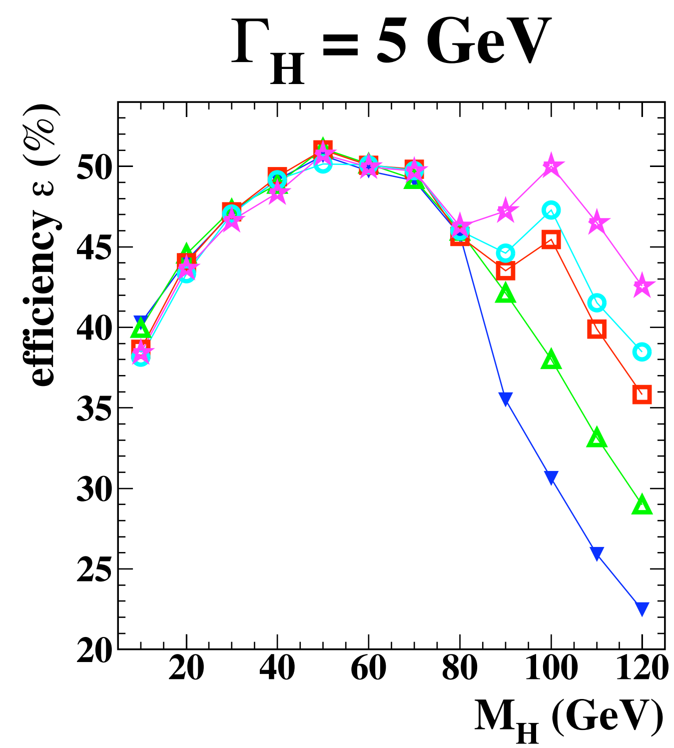
Limit

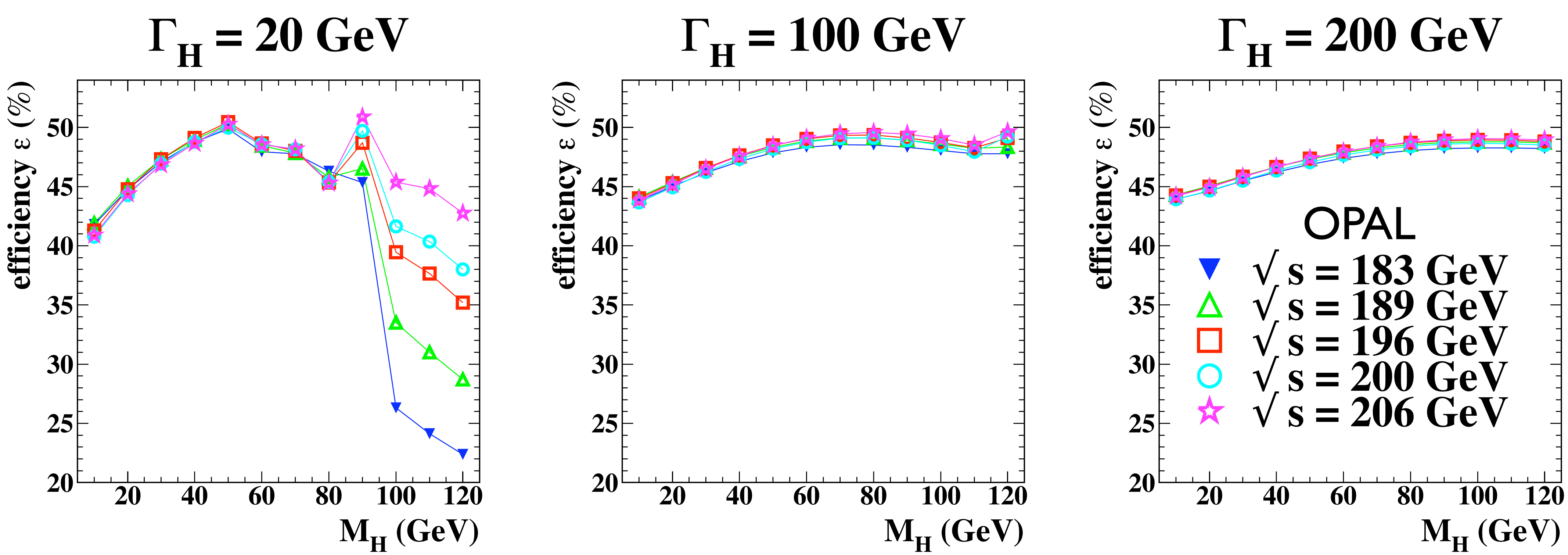


a) Γ_H = 1 GeV
c) Γ_H = 10 GeV
e) Γ_H = 40 GeV
f) Γ_H = 60 GeV
i) Γ_H = 300 GeV
σ_prod × BR_inv (pb)
M_H (GeV)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
20
40
60
80
100
120
1 standard deviation
2 standard deviations
median exp. σ_prod × BR_inv
OPAL σ_prod × BR_inv

Efficiency

- Negligible decay width ($\Gamma_H \approx 0$):
  - Efficiencies in "2-jet" and ">2-jet" categories ~ 20 - 27% at m_h= 60 - 110 GeV
- Large decay width ($\Gamma_H > 0$):
  - at smaller decay width (5, 20), the kinematic limit affects on the efficiencies
  - at larger decay width the effect was smeared due to the decay width.





systematic errors

Large decay width (Γ_H>0)		
Source	Uncertainty	
	Background	Signal Efficiency
Kinematic variable	2.4%	1.9%
Isolated lepton veto	2.4%	0.7%
Limited MC statistics	1.0%	0.2%
prediction 2- or 4-f σ	2.0%	-
Total	4.1%	2.0%

Invisibly Decaying Higgs Boson

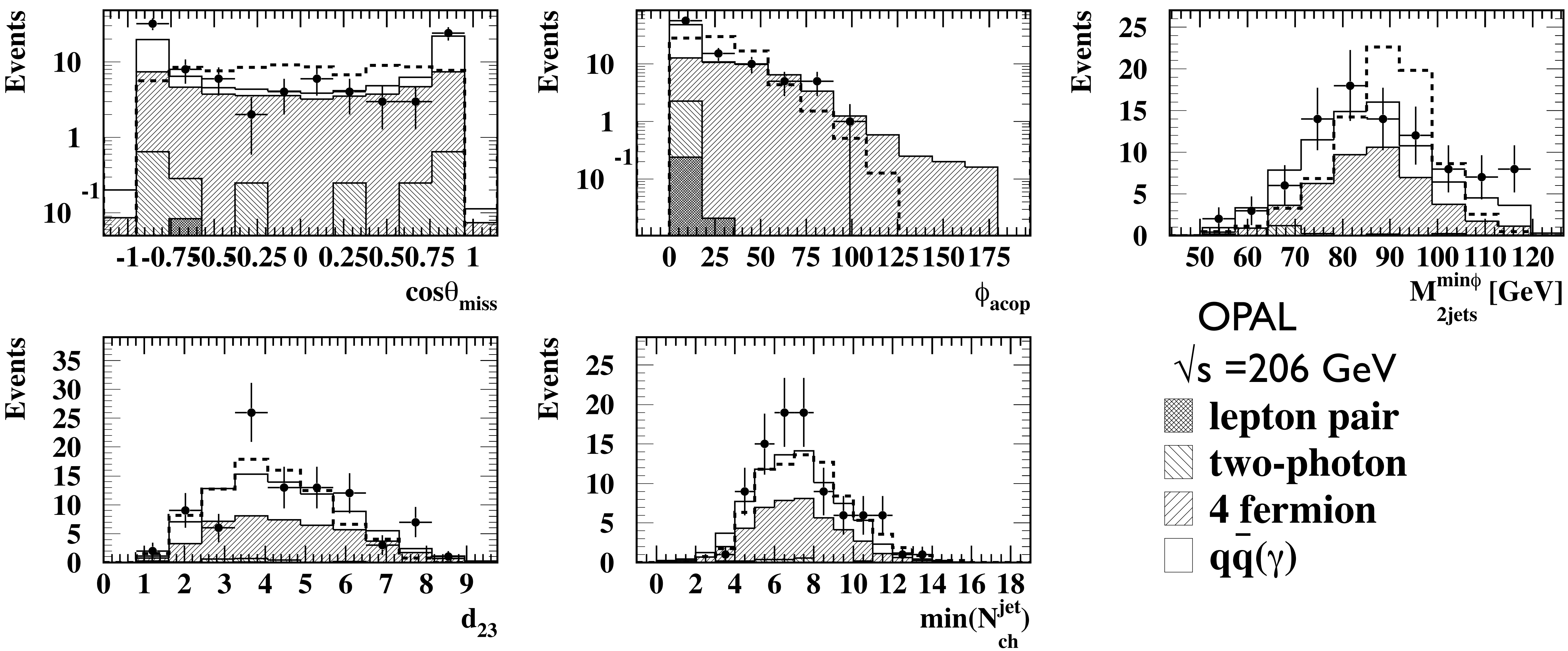
Other Results From LEP

- Individual LEP collaborations
  - ALEPH: m_H > 114.1 (112.6) §GeV
  - DELPHI: m_H > 112.1(110.5) GeV
  - L3
    - ★ hadron: 112.1 (111.4) GeV
    - ★ lepton: 91.3 (88.4) GeV

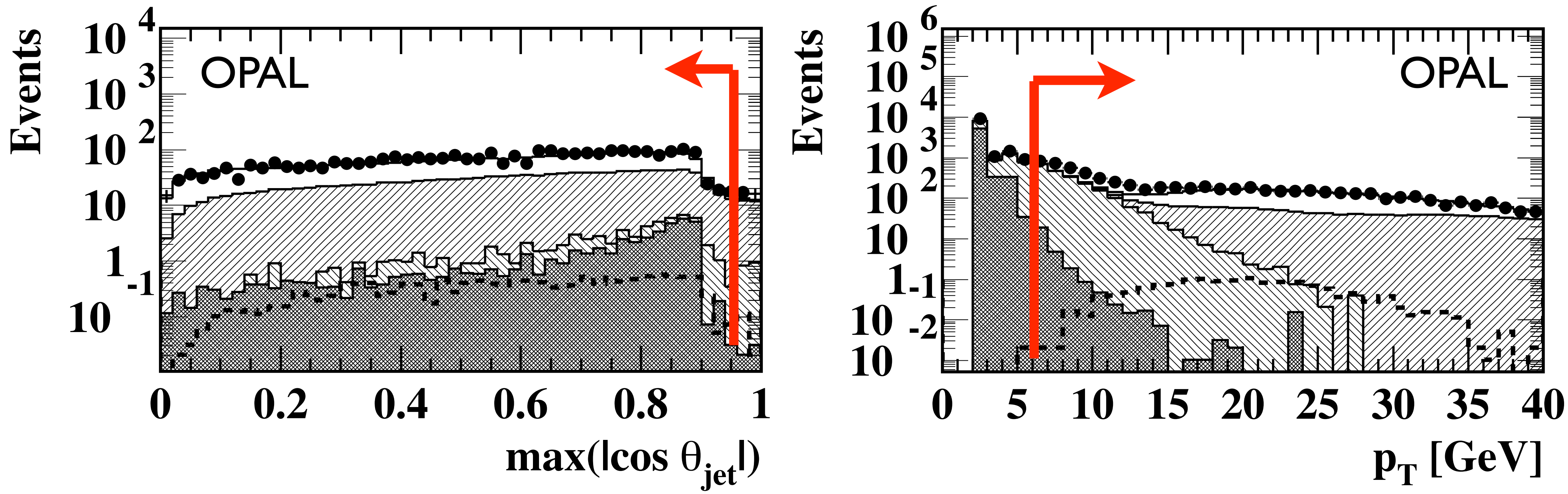
- LEP combined: m_H > 114.4 (113.5) GeV

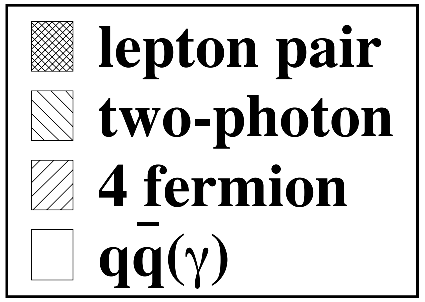
Variables in Likelihood “2-jet” ($\Gamma_H \approx 0$)

- The remaining backgrounds are mainly
  - $e^+e^- \to Z^0Z^0 \to \nu\nu qq$ (irreducible)
  - $e^+e^- \to W^+W^- \to \nu l q q'$
  - $e^+e^- \to qq(\gamma)$
- The dashed line: signal at m_h=105 GeV normalised to the expected N_{BKG}



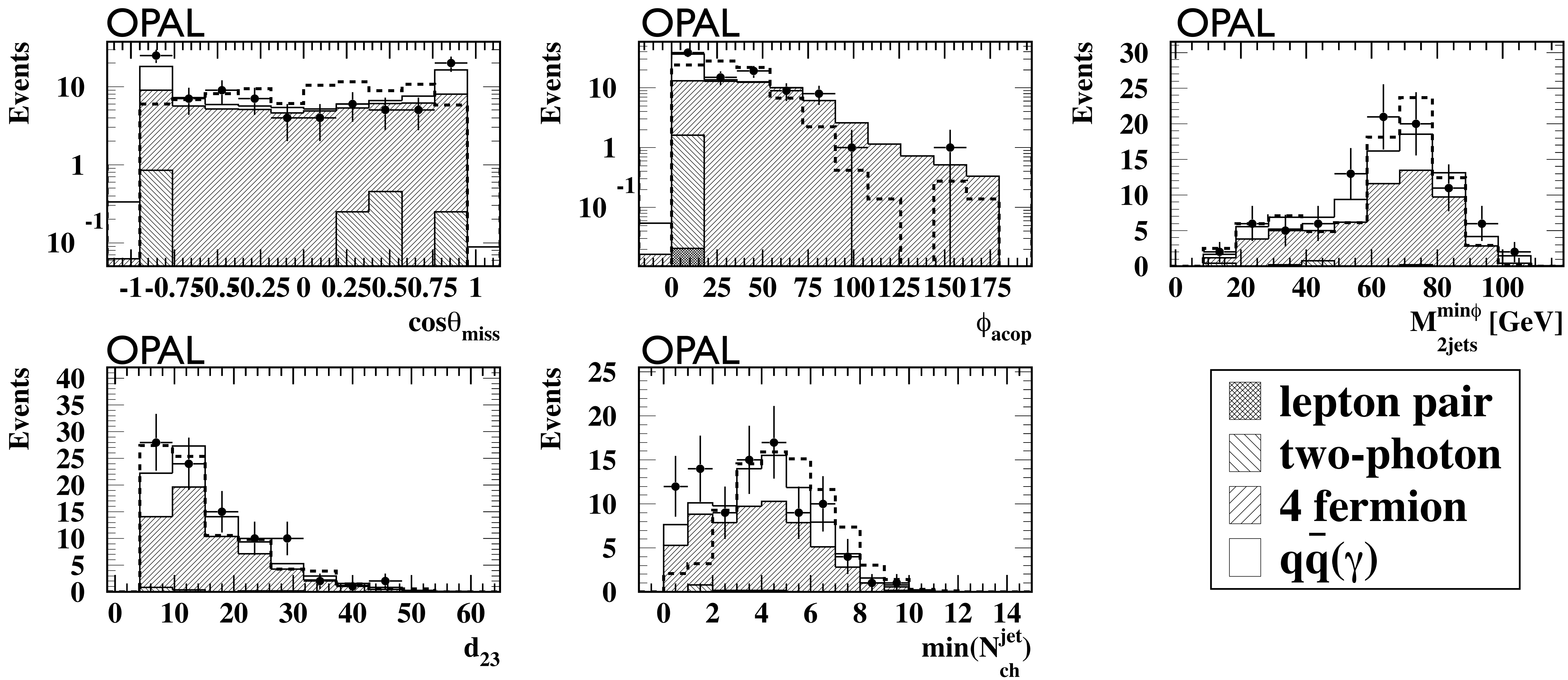
Cut-based analysis for $\Gamma_H \approx 0$



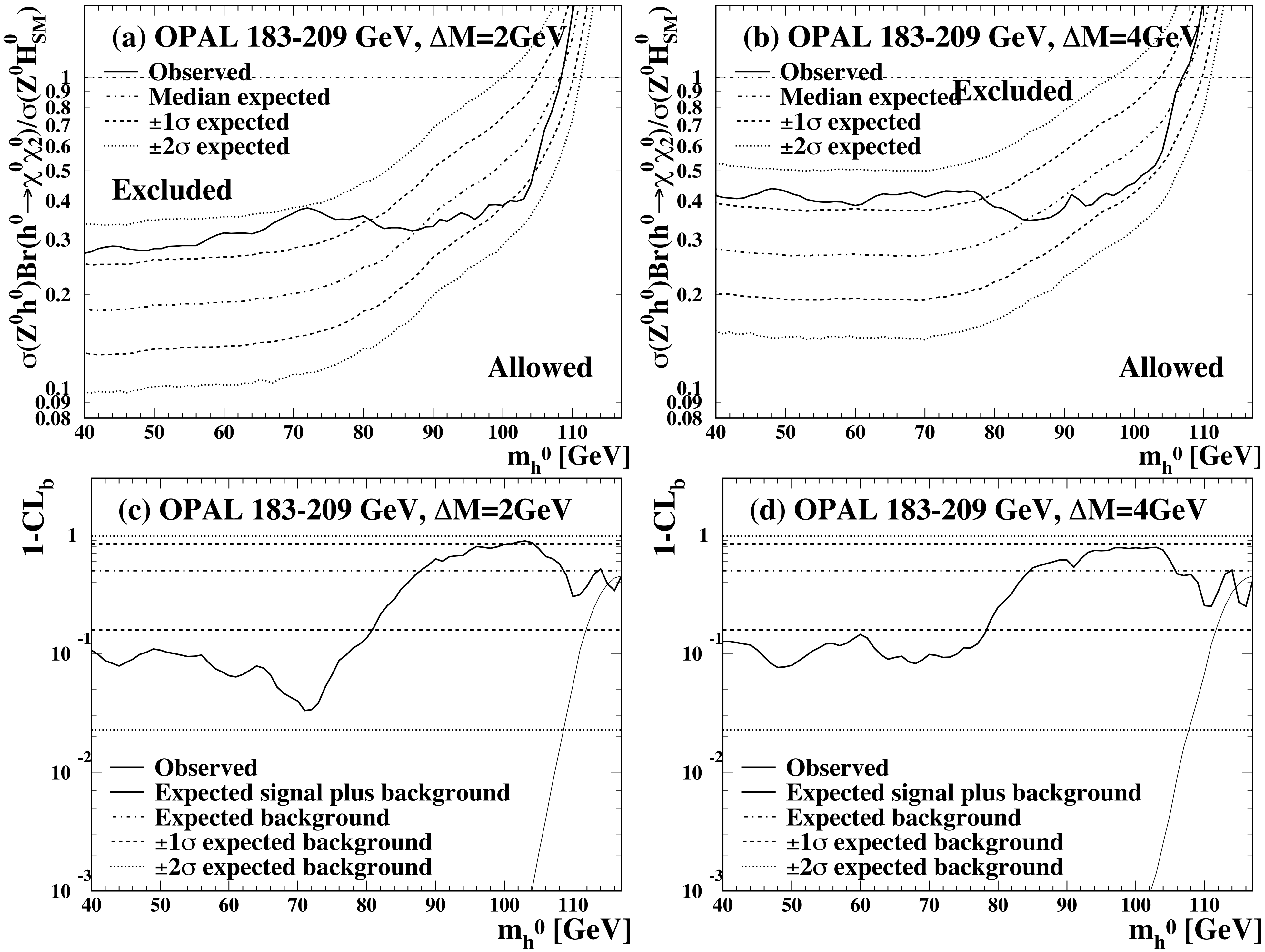


- Two cut variables from the negligible decay width($\Gamma_H \approx 0$) analysis
- The after the cut based-selection the efficiency is kept high
  - 56% at m_h = 105 GeV (luminosity weighted average)
- Events from two-photon processes strongly eliminated.

Input variables in Likelihood selection ($\Gamma_H \approx 0$, >2-jet)



Nearly Invisible Decay



systematic errors

Negligible decay width ($\Gamma_H \approx 0$)								
Source	Uncertainty(%)							
	"2-jet"				">2-jet"			
	BKG	Signal efficiency			BKG	Signal efficiency		
		Invisible	ΔM=2GeV	ΔM=4GeV		Invisible	ΔM=2GeV	ΔM=4GeV
Selection variables	0.7-2.2	0.2-3.9	0.0-5.0	0.0-11.1	10.-1.9	0.3-4.1	0.4-4.7	0.6-10.3
MC Statistics	1.9-3.8	3.3-7.3	5.2-10.9	6.5-15.4	1.4-2.7	3.6-8.8	5.0-9.5	4.8-11.0
Int. Lum.	0.5							
Total	2.2-4.4	3.5-7.8	5.3-10.7	5.8-17.4	1.9-3.4	3.7-9.5	5.1-7.8	4.8-11.4