SM Higgs search with H→γγ at CMS

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2010年高能物理年会, 南昌

April 16-21, 2010

Outline

- Introduction & motivation
- Sensitivity of Higgs searching with $H \rightarrow \gamma\gamma$ @ CMS
  - Overview of the $H \rightarrow \gamma\gamma$ analysis in CMS PTDR
  - Improved analysis @14TeV with MC samples @NLO (σ)
    - Improved Cut-based analysis with new selections
    - Improved event-optimized analysis related to TMVA.
- Ongoing work and near futrue plan with LHC collisions data @ 7TeV
- Conclusion

Introduction

➢ **LHC @ CERN**: **CMS** (Compact Muon Solenoid), **ATLAS** (A Toroidal LHC Apparatus), **ALICE** (A Large Ion Collider Experiment) & **LHCb** (LHC-beauty).

➢Main **Physics goal**: "God particle"-**Higgs Boson**

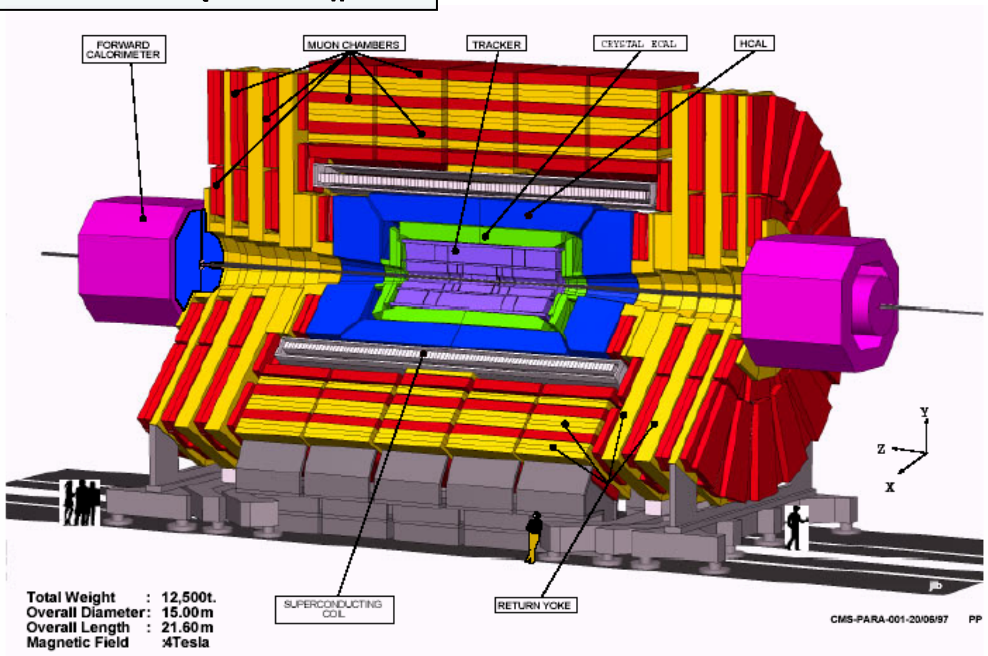
LHC for Higgs:

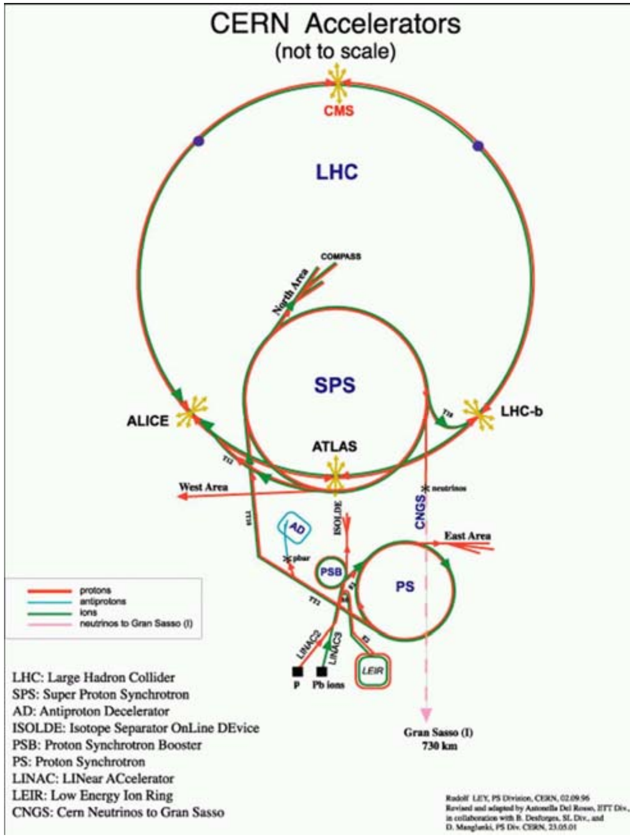
—**Direct searching**: **SM Higgs & non-SM Higgs**

—**Indirect searching**: **Precision measurements of m_t and m_W**

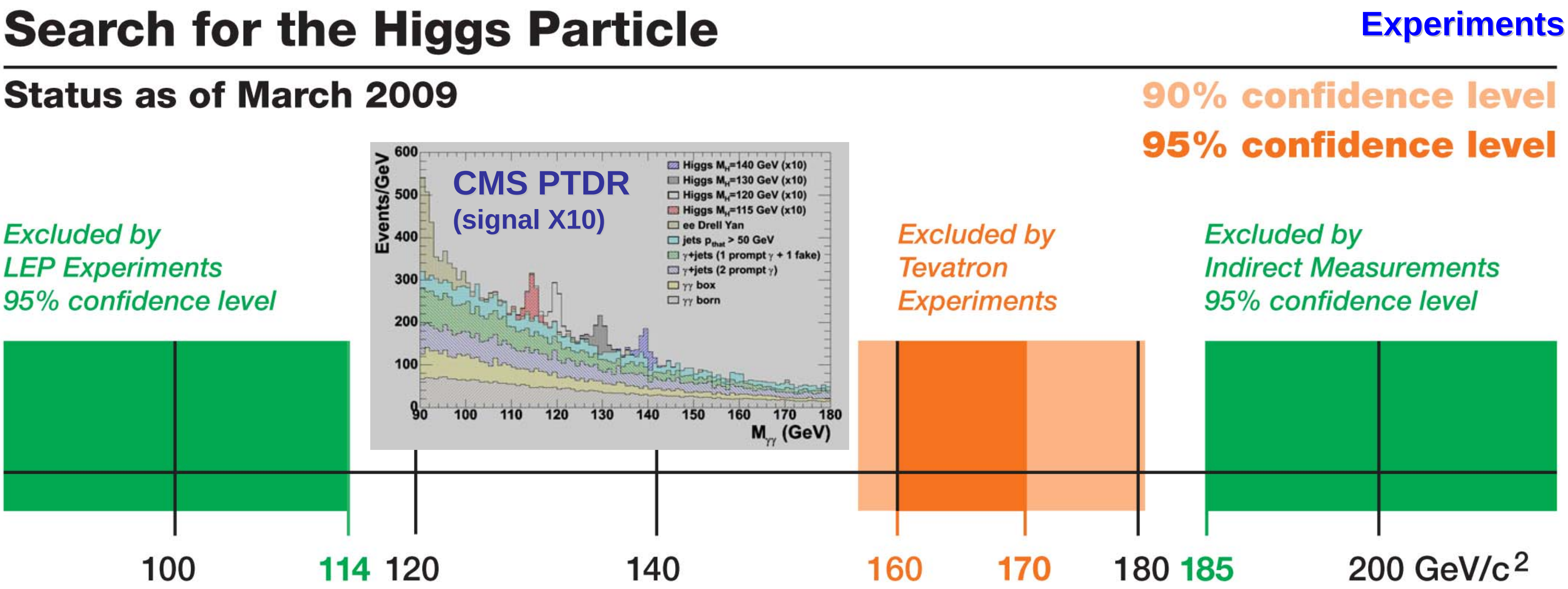
What is the source of mass?

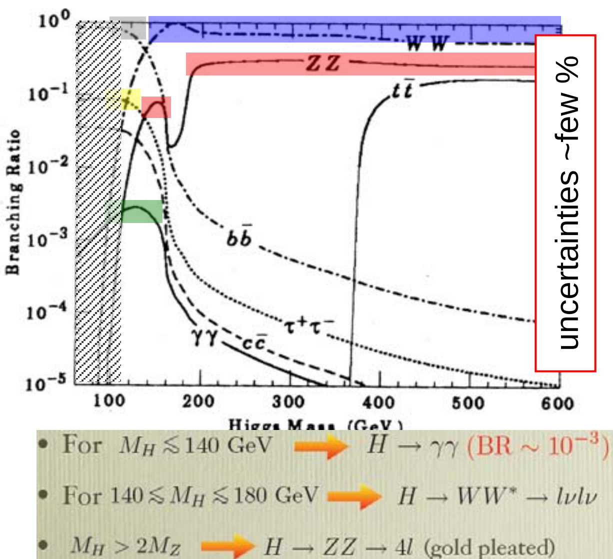
What breaks $SU(2)_L \times U(1)_Y$?

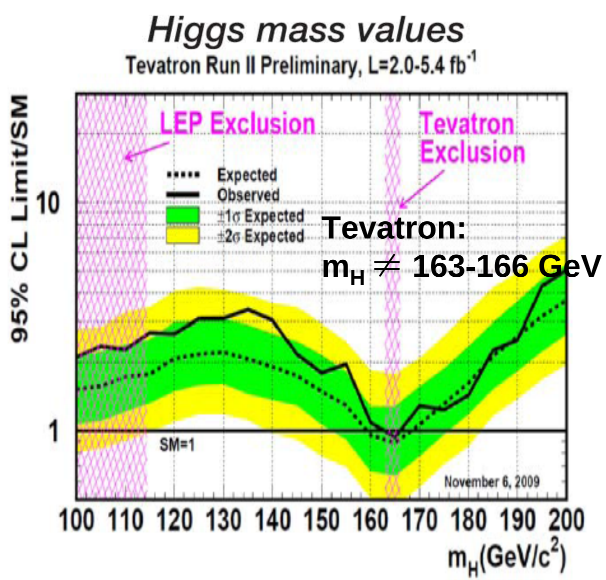


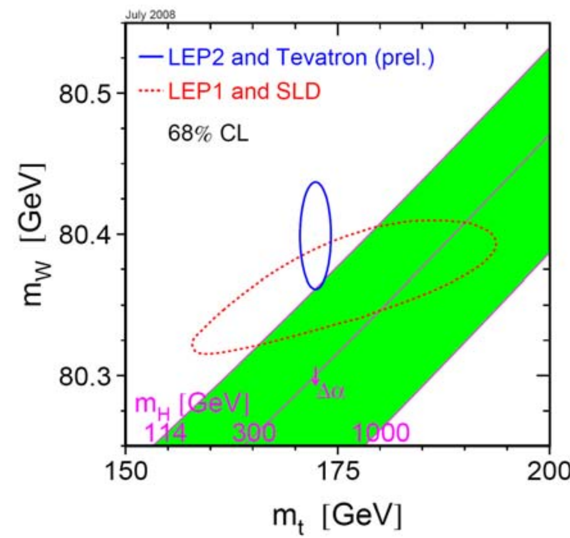


Motivation: The SM H→γγ search





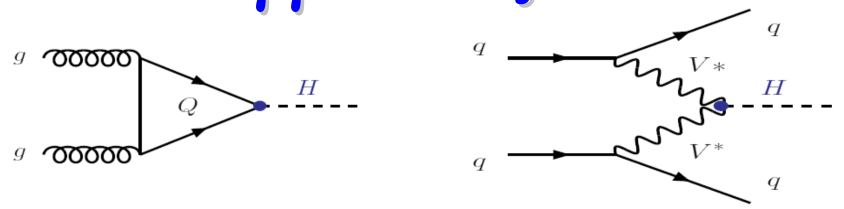




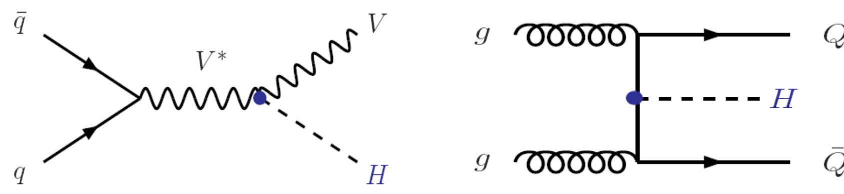
Signal & Backgrounds of H→γγ analysis

Inclusive signal productions

- **gg fusion** $(gg \to H)$
- Vector boson fusion (VBF) $(qq \to qqH)$
- Associated production with vector boson ($qq \to WH$、$qq \to ZH$) and quark pair (mainly *ttbar*) ($pp \to QQbarH$)



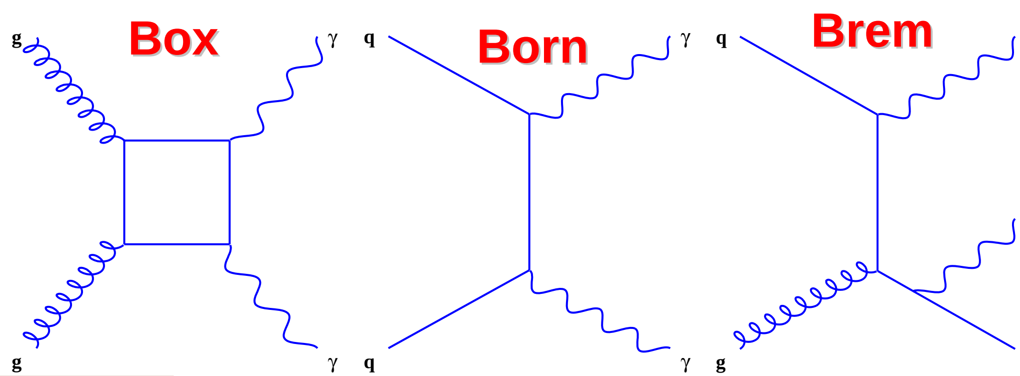
(a) 胶子熔合过程　(b) 矢量玻色子熔合过程



(c) 矢量玻色子关联产生过程　(d) 重夸克对关联产生过程

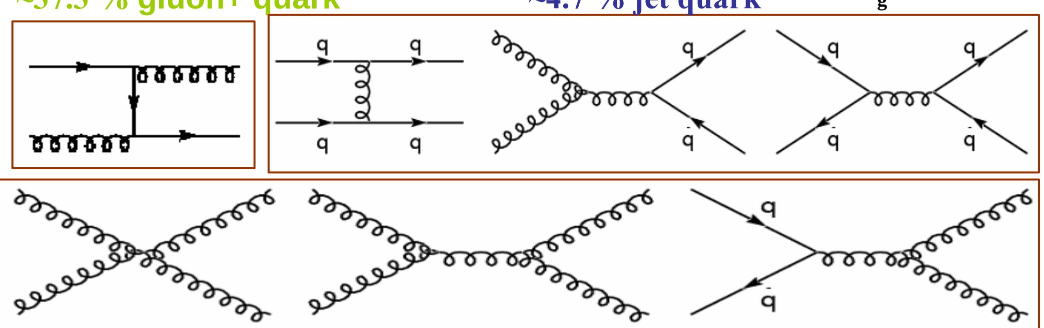
4 main backgroud processes

- **"irreduciable" backgrouds**
  - ✓ "Box" process: gg → γ γ
  - ✓ "Born" process: qqbar→ γ γ
  - ✓ γ+jet(Brem.): 2 prompt γ
- **"reducible" backgrouds**
  - ✓ γ+jet: 1 prompt γ+1 fake γ
  - ✓ pp→jets

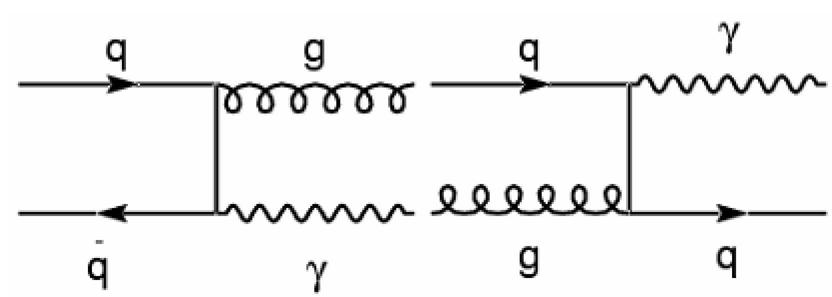


~37.3 % gluon+ quark

~4.7 % jet quark



~58 % jet gluon



MC samples for signal & backgronds

- Higgs Mass used in analysis: **mH=120GeV,130GeV,140GeV and 150GeV**
- **The cross section and BR** for **signal** were used: (**NLO**)

mH	**120 GeV**	**130 GeV**	**140 GeV**	**150 GeV**
σ (gg fusion)(**pb**)	**36.4**	**31.6**	**27.7**	**24.5**
σ (IVB fusion) (**pb**)	**4.5**	**4.1**	**3.8**	**3.6**
σ (HW, HZ, ttH) (**pb**)	**3.3**	**2.6**	**2.1**	**1.7**
Total (**pb**)	**44.2**	**38.3**	**33.6**	**29.7**
BR ($H \rightarrow \gamma\gamma$)	**2.21×10^{-3}**	**2.24×10^{-3}**	**1.95×10^{-3}**	**1.40×10^{-3}**
Inclusive σ x BR (fb)	**97.5**	**86.0**	**65.5**	**41.5**

- **Backgouds Cross section with PYTHIA (LO) and "K factor" (LO→NLO)**

Process	$P_{t\ hat}$ (GeV)	**σ after preselection (pb)**	**K-factor**
$pp \rightarrow \gamma\gamma$ (born)	>25	**45**	**1.5**
$pp \rightarrow \gamma\gamma$ (box)	>25	**36**	**1.2**
$pp \rightarrow \gamma$ +jets	>25	**600**	**1.72 (2 prompt)** **1.0 (1 prompt+1 fake)**
pp→jets	>50	**4800**	**1.0**

Overview of H→γγ analysis process in CMS PTDR

- (In CMS **Physics Technical Design Report** 2) Before 2006，older CMS softerware：OSCAR+ORCA …; now CMSSW.

- **“cut-based” analysis**：
  1). Passing the High Level Trigger of photons
  2). Kinematic cuts on 2 Rec. photons：ET(γ1)>40GeV、ET(γ2)>35GeV、|η|<2.5
  3). Photon isolation selection： Track ISO；ECAL ISO; HCAL ISO

- **“event-optimized” analysis**: Photon ISO ANN analysis & event optimization ANN analysis (preselections ET(γ)>40GeV、|η|<2.5 and loose ISO)

Pho ISO ANN 5 inputs

- 光子候选者与最近的横动量$P_T > 2.0GeV$的重建径迹的夹角。
- 除了光子候选者对应的超团外，在光子候选者周围$\Delta R < 0.3$的区域内ECAL中所有基团的横动量之和。
- 簇射形状变量R_9。
- 在光子候选者周围$\Delta R < 0.3$的区域内HCAL中所有重建towers的横动量之和。
- 在光子候选者周围$\Delta R < 0.2$的区域内Tracker中所有重建径迹的横动量之和。

Event optim. ANN 6 inputs

- ✓ Photons ISO: NNiso1, NNiso2
- ✓ $Et_{\gamma 1}/M_{\gamma\gamma}$
- ✓ $Et_{\gamma 2}/M_{\gamma\gamma}$
- ✓ $|\eta 1 - \eta 2|$ of γγ
- ✓ P_L of γγ (Higgs candidates)

Drawbacks of the analysis in CMS PTDR

- **No γ/π^0 discrimination** (to suppress the reducible backgrounds with fake photon).

- When **event optimization analysis**， the other information of one event was not considered, such as ***jets*** and ***MET*** etc., to separate the signal and backgrouds.

- **Backgroud decision/estmation with sideband was not included**.

- Didn't give out the **selection efficiency** in event optimization analysis. The number of events is unknown for signal and backgrounds respectively.

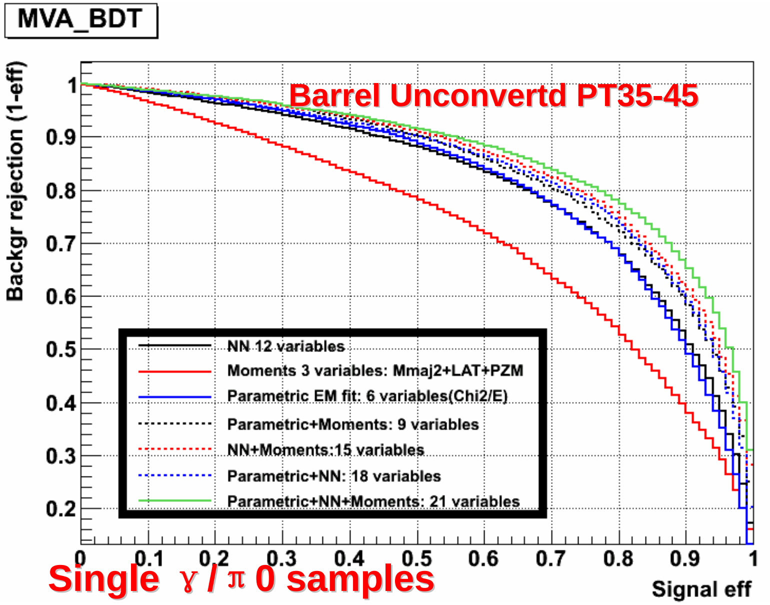
- Etc.

Chance for us to participate in the $H \rightarrow \gamma\gamma$ analysis at CMS

γ/π^0 discrimination: unconverted photons in Barrel

- **Unconverted case in Barrel**

PT bins (GeV)	π 0 rejection efficiency for keeping 90% photon efficincy (%) (BDT in Barrel)			
	N12	M3	F6	**C22**
20-25	69.6±0.6	51.2±0.6	63.8±0.6	**72.5±0.6**
25-35	61.6±0.4	39.4±0.4	57.0±0.4	**66.9±0.4**
35-45	50.7±0.5	30.9±0.4	48.5±0.5	**60.0±0.5**
45-55	40.0±0.5	26.0±0.4	41.7±0.5	**50.9±0.5**
55-65	34.5±0.5	23.9±0.4	34.1±0.5	**42.8±0.5**
65-75	29.6±0.5	21.7±0.4	29.8±0.5	**37.0±0.5**



Single γ / π 0 samples

Diffrent method and combinetions

NN+Moments+Parametric formula fitting

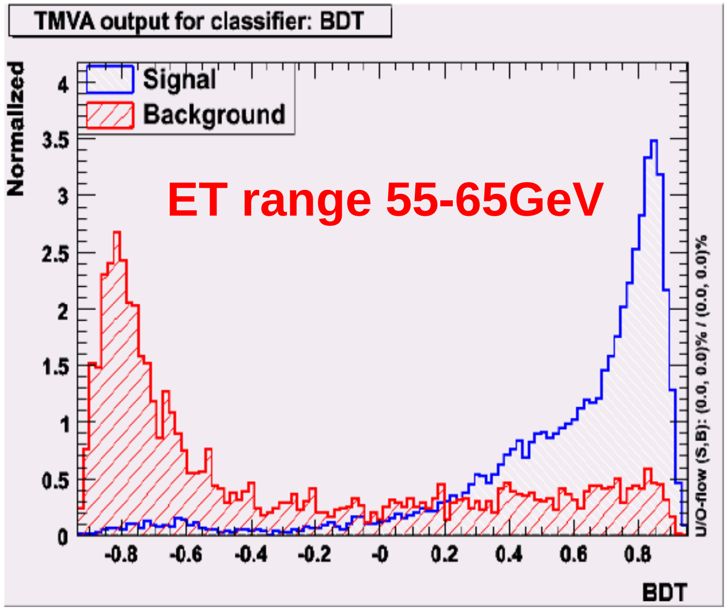
- **Unconverted case in Endcap:**

P_T (GeV)	保持90%光子效率的π^0排斥率(%)
20-25	64.1±2.0
25-35	62.1±1.3
35-45	57.1±1.3
45-55	54.4±1.2
55-65	51.8±1.0

γ/π^0 discrimination: Converted photons

➢ **Shower shape viriables and converted tracks etc.:**

ET range	π0 rejection for keeping 90% γ efficiency (%)
20-25	31.5
25-35	48.0
35-45	67.3
45-55	74.0
55-65	75.1
65-75	71.5



Improved Cut-based analysis with M_H=120GeV

- **Preselection**:2 photons with ET>20GeV & |η|<2.5
- **Same slections as CMS PTDR**

分析过程	$\mathcal{L}(5\sigma)$	$\mathcal{L}(3\sigma)$	$\mathcal{L}(95\%exclusion)$
1整个样本	35.2	12.7	5.4

- **Improved analysis**: **Event counting; Unit: fb^{-1}**

1). **Same ISO selections** as CMS PTDR

$$\mathcal{L}(5\sigma) = 37.5 fb^{-1}$$

2). **F_{PT} cuts**: **F_{PT} =ET γ /PT of jet including this γ for both γ: >0.90**
F_{SumPT} =(ETγ1+ ETγ2)/(PTjet1+ PTjet2) including these 2 γ: >0.95

$$\mathcal{L}(5\sigma) = 34.8 fb^{-1}$$

3). **Application of γ/π0 dis.**: $NN_{\gamma/\pi^0} > NN^{Min}_{\gamma/\pi^0}$

$$\mathcal{L}(5\sigma) = 29.7 fb^{-1}$$

4). **Kinematic**: ET(γ1)>50GeV、ET(γ2)>25GeV

$$\mathcal{L}(5\sigma) = 25.9 fb^{-1}$$

- **Improved result**

$$S_{cL} = \sqrt{2\sum_{i=1}^{n}((s_i + b_i)\log(1 + s_i/b_i) - s_i)}$$

分析过程	$\mathcal{L}(5\sigma)$	$\mathcal{L}(3\sigma)$	$\mathcal{L}(95\%exclusion)$
计数计算法	25.9	9.3	4.0
lnQ "pdf" 分布	23.9	8.6	3.7

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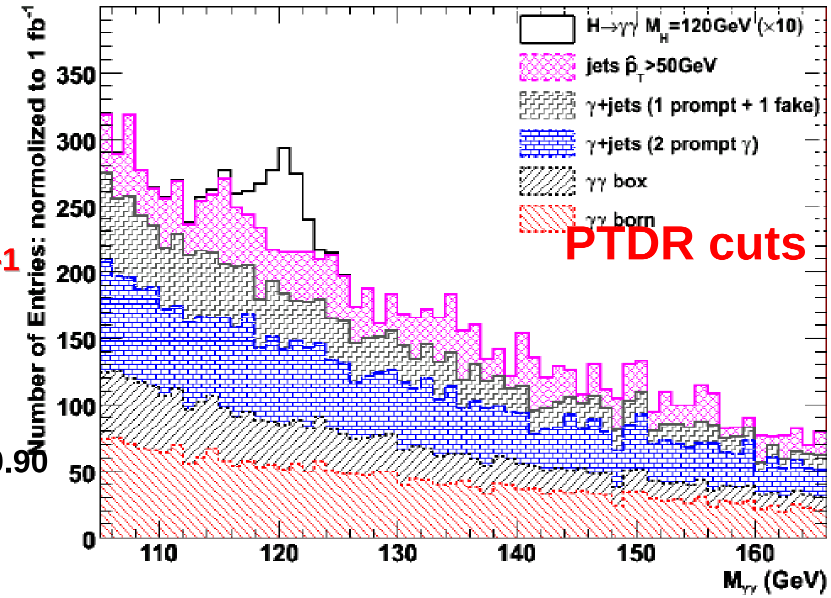
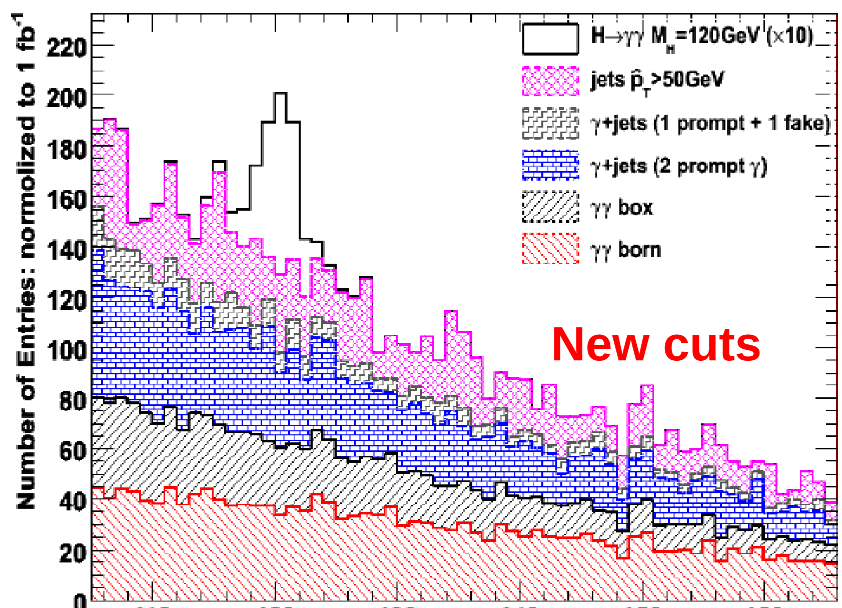


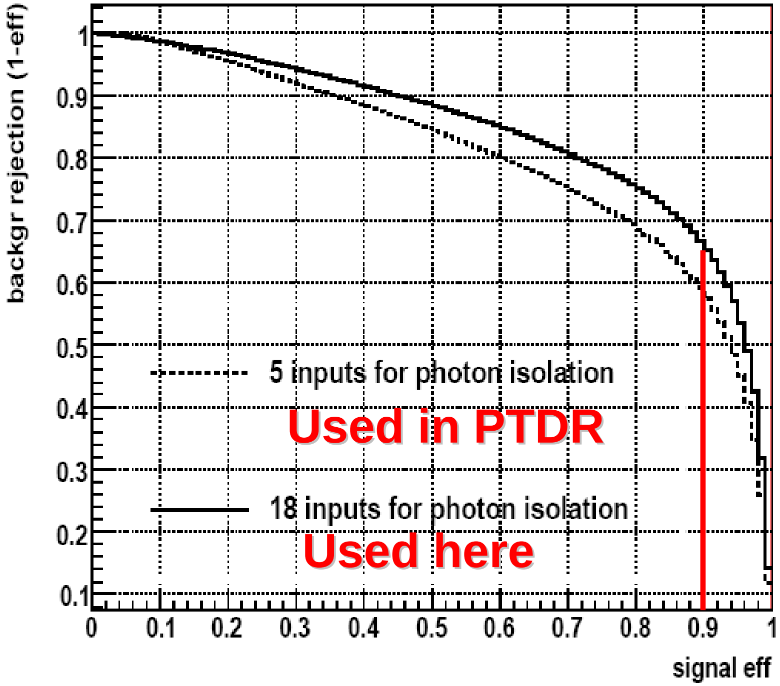


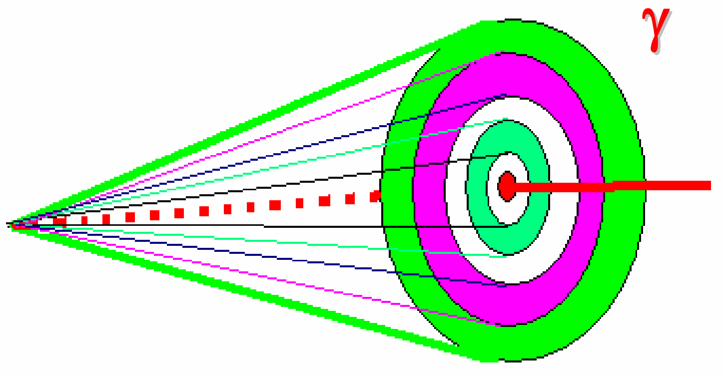
Normolized to 1/fb, signal×10

Event-optimized analysis: Photon ISO

- **Information with different cone size** around the photon used for inputs.
  - ✓Training signal: Reco. γ from gg fusion H (Isolated).
  - ✓Training background: Reco. γ from jets sample (Nonisolated)

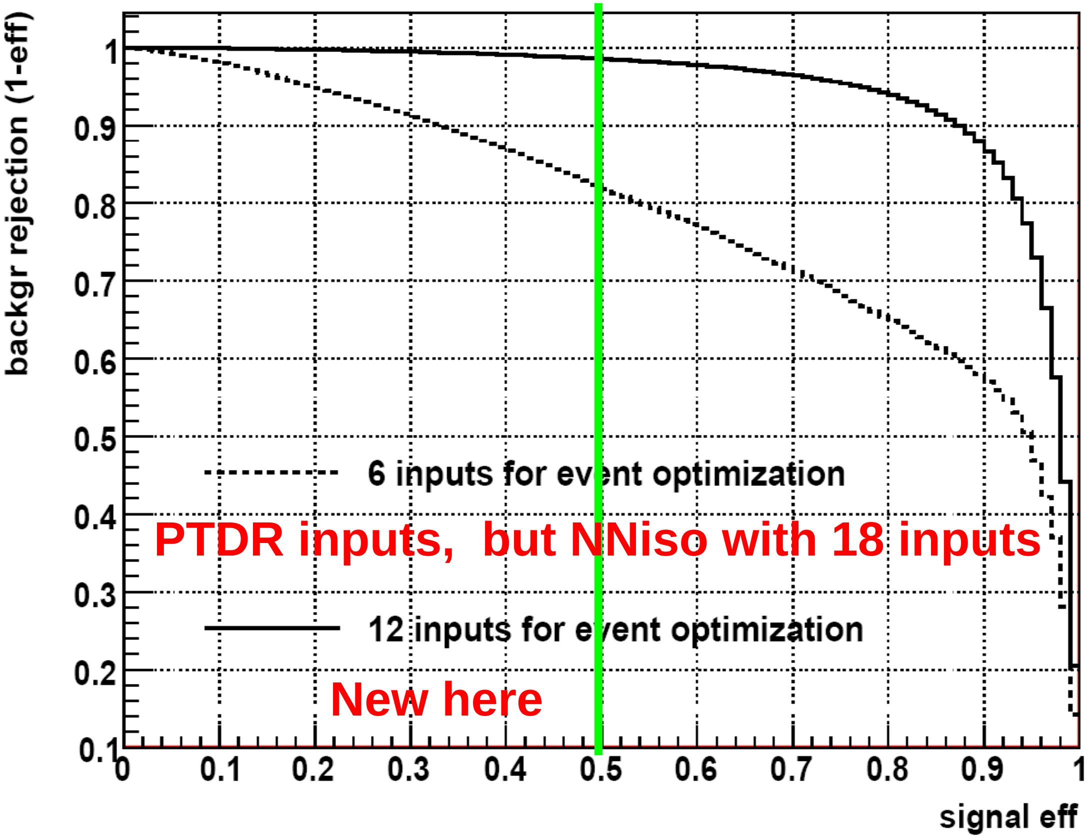
- Results: signal efficiency vs bkg rejection





- For **keeping 90% signal** (**ISO photons**), **~8% higher bkg (Non-ISO) rejection**

Event-optimized analysis: Event Opt.



- **NNiso for both photons as inputs.**
- **Add 6 new inputs: Jets & MET etc.**

- Considering preselection efficiency for signal: ~65%, **if keeping 50% signal efficiency here**, the combined **signal eff.** will be **~33%** .
- **Much higher bkg rejection eff.: ~16.4%**

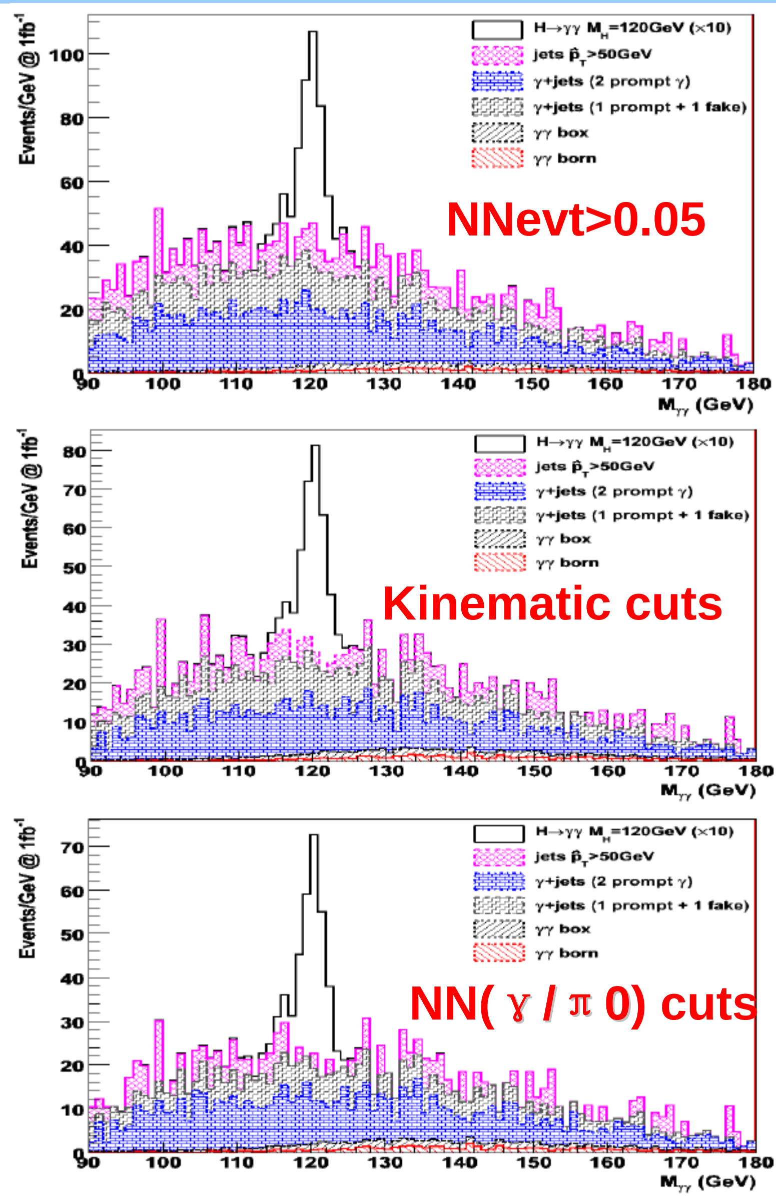
Event-optimized analysis

➢**Direct cut on the TMVA-BDT output here.** Required **NNevt>0.05**

➢ **Kinematic cuts on photons:** PT(Leading γ)>40.0, PT(Trailing γ)>35.0, |η|<2.5

➢**NN(γ / π 0) cuts**: **(NN>NNmin)**, NNmin is the same as cut-based analysis

mH (GeV)	S_L @ 1fb-1	5 σ Discovery	3 σ evidence	95% CL exclusion
120	1.76	8.0 /fb	2.9 /fb	1.3 /fb
130	1.55	10.4 /fb	3.7 /fb	1.6 /fb
140	1.23	16.4 /fb	5.9 /fb	2.6 /fb
150	0.69	52.0 /fb	18.7 /fb	8.2 /fb

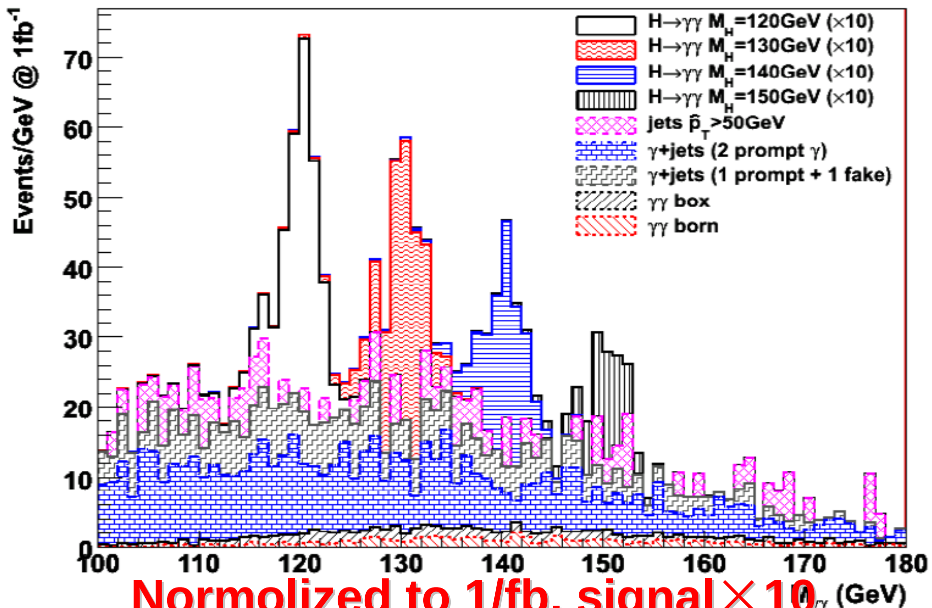


Normolized to 1/fb, signal×10

Analysis with 6 categories

➢ **Different s/b** in **different categories** based on **R9** and **pseudo-rapidity** of photons.

➢**Discovery sensitivity** for diferent Higgs mass



Normolized to 1/fb, signal×10

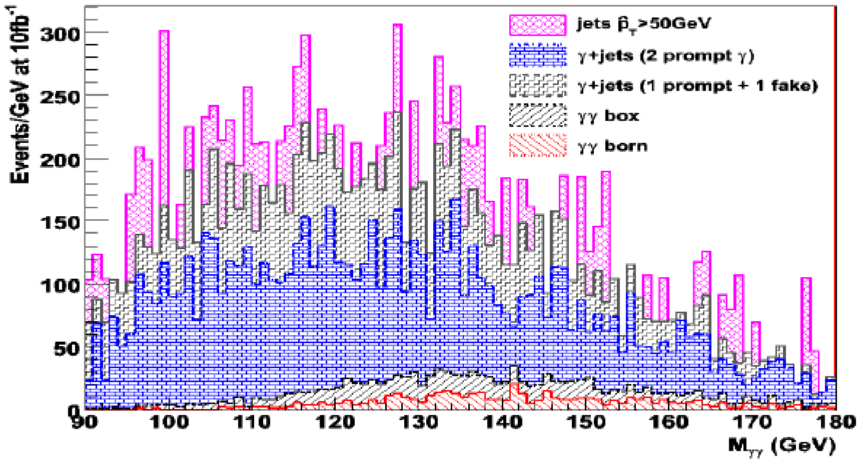
mH (GeV)	5 σ Discovery	3 σ evidence	95% CL exclusion
120	7.8 /fb	2.8 /fb	1.3 /fb
130	10.0 /fb	3.6 /fb	1.6 /fb
140	15.9 /fb	5.7 /fb	2.5 /fb
150	36.8 /fb	13.2 /fb	6.0 /fb

Estimation of background

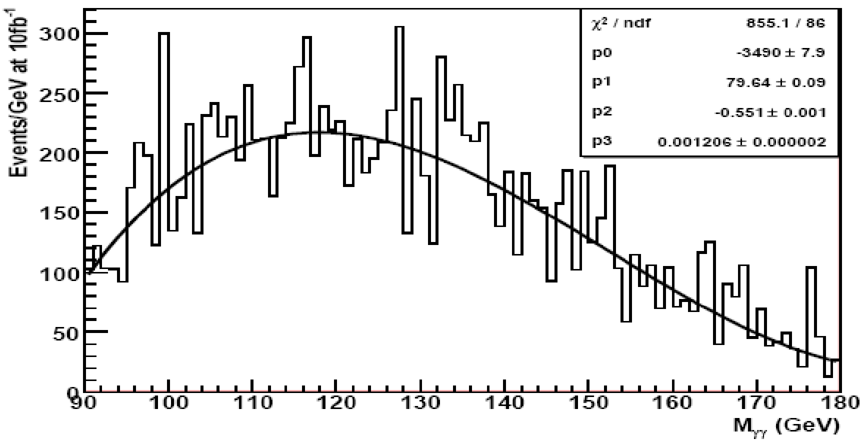
- **Error on bkg estimation** with "sideband".

✓ **Uncertainty of the fit function**
✓ **Statistics error with the events for fitting**

- Fitted with ***a 3rd order polynomial function.***



- At **10 fb-1**, for **1 whole category**, the error from **the fit function is ~0.6%;** the **statistical error is ~0.9%.** The **total error is estimated to be 1.1%.**



- For **6 categories**, total error: **~2.3%.**

Systematic error on the signal

- **20% uncertainties on the signal in total**

Sources	Uncertainties
Theory	~15%
Int. Luminosity	~3%
Trigger	~1%
Others	~1%

Event-optimized results with sys. error

- With **1.1% systematic error of bkg and 20% uncertainty on signal**, the significance:

whole samples as 1 category

mH (GeV)	5 σ Discovery	3 σ evidence	95% CL exclusion
120	12.6 /fb	4.5 /fb	2.0 /fb
130	16.1 /fb	5.8 /fb	2.6 /fb
140	25.9 /fb	9.3 /fb	4.1 /fb
150	80.6 /fb	29.0 /fb	12.8 /fb

- With **2.3% systematic error of bkg and 20% uncertainty on signal**, the significance:

Analysis with 6 categories

mH (GeV)	5 σ Discovery	3 σ evidence	95% CL exclusion
120	12.3 /fb	4.4 /fb	2.1 /fb
130	15.8 /fb	5.7 /fb	2.6 /fb
140	25.3 /fb	9.1 /fb	4.0 /fb
150	55.6 /fb	20.0 /fb	9.4 /fb

Results when assuming 30% uncertainty on Bkg

- Backgrouds generated with **PYTHIA (LO)**

- For the **"K-factor" uncertainty of ~20-30% (LO→NLO),** we assumed another **30% uncertainty on Bkg** here

- The **discovery sensitivities**:

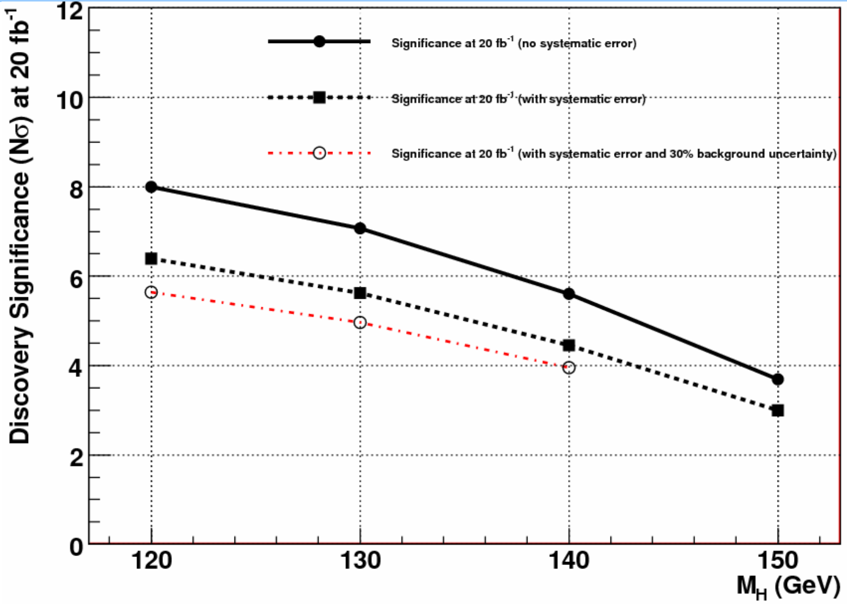
mH (GeV)	5 σ Discovery	3 σ evidence	95% CL exclusion
120	15.7 /fb	5.7 /fb	2.5 /fb
130	20.3 /fb	7.3 /fb	3.3 /fb
140	32.1 /fb	11.5 /fb	5.1 /fb

- For **the insensitivity of the Higgs research with mH=150GeV by the channel H→γγ** , the result with 30% uncertainty on Bkg is not shown here.

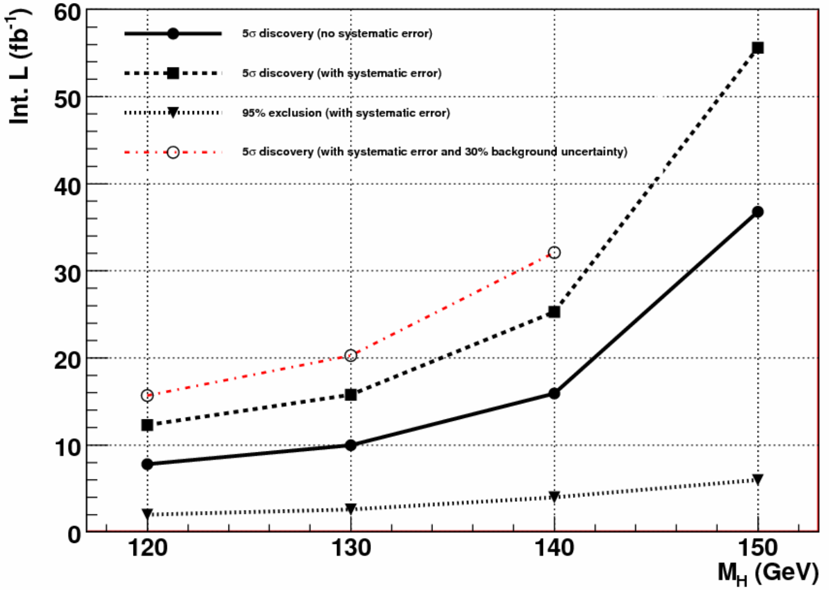
Significance and sensitivity of Higgs research with the channel $H \rightarrow \gamma\gamma$ @ CMS

➢ **Significance** with **20 fb^{-1}** (6 categories)

mH (GeV)	No sys.	With sys.	Sys. + 30% uncertainty on Bkg
120	8.0	6.4	5.6
130	7.1	5.6	5.0
140	5.6	4.5	4.0
150	3.7	3.0	-



➢ **Int. L for 5 σ discovery** (6 categories)



Junquan Tao

Ongoing work with collisions @ 7TeV: Photon Calibration

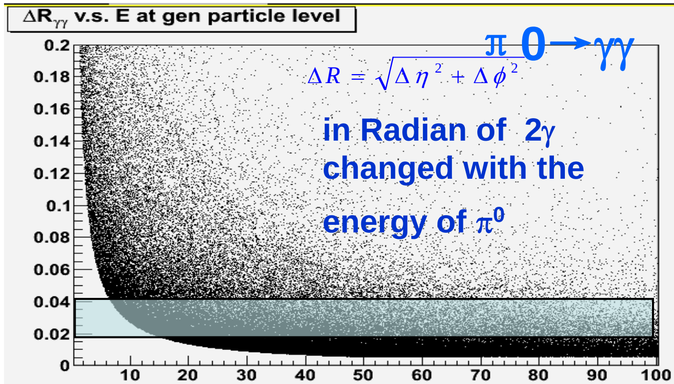
➢ With LHC 7TeV collisions, 2010 is THE YEAR for calibration activities.

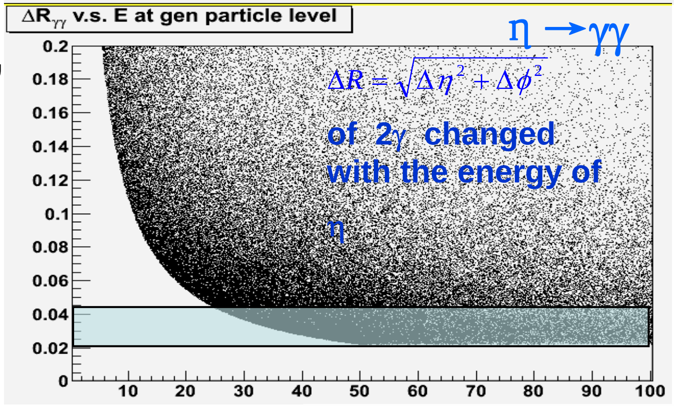
➢ECAL **calibration with $\pi 0 \rightarrow \gamma\gamma$ and $\eta \rightarrow \gamma\gamma$** at the startup.

➢ Cluster of γ candidates based on 3x3 crystals array, if the energy is higher, there will be **overlapping between 2 γ candidates**

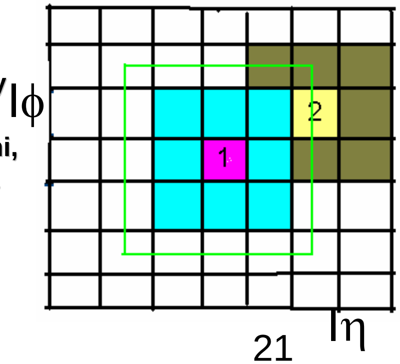
➢Try to **solve the shower overlapping problem** in the higher energy region. **The parametric shower shape profile method is being used for such purpose.**

➢ **In a higher energy region,** to keep the precision of photon energy measurement.





Overlapping: 2 cry distance from seed1 in Eta or Phi, △Imax=Max(△Iη, △Iϕ)>=2



Near futrue plan with collisions @ 7TeV:

Di-photons in CMS

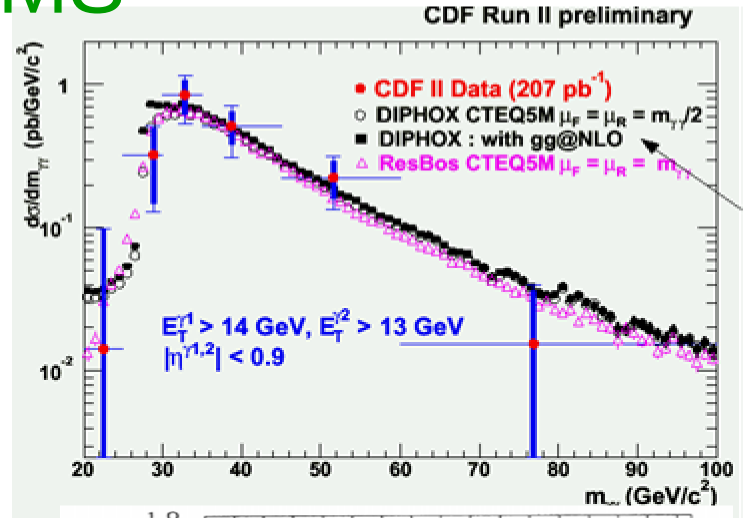
- σ (γ γ + X) CDF published with 200pb^{-1} (hep-ex/0412050)

- Due to higher cross section, CMS will have equivalent statistics with ~10pb^{-1}.

- How to solve the photon purity problem?

- The parametric shower shape profile method as in CDF analysis (unconverted photon case).

- "Template method" trying with the outputs of Neural Network with $\gamma/\pi 0$ discrmination analysis.



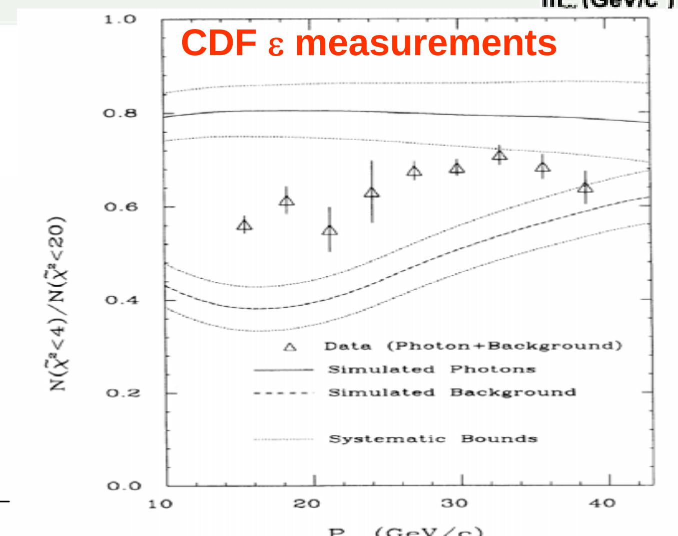
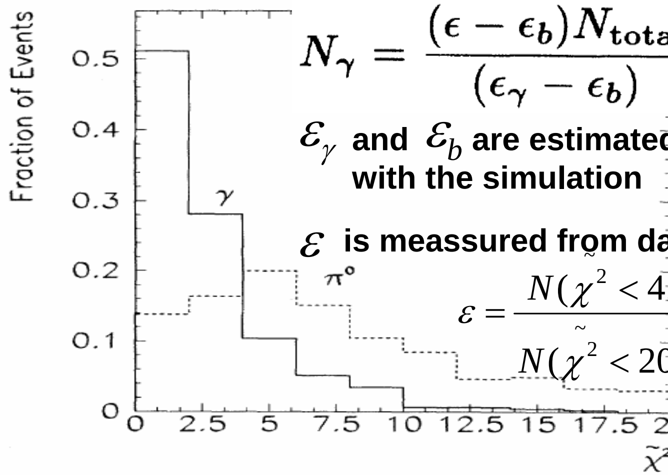


FIG. 23. Signal and background $\tilde{\chi}^2$ efficiencies for the profile method. Also shown are the total systematic uncertainties on these efficiencies, and the measured efficiency of the data as a function of photon P_t.



$$N_\gamma = \frac{(\epsilon - \epsilon_b) N_{total}}{(\epsilon_\gamma - \epsilon_b)}$$

ε_γ and ε_b are estimated with the simulation

ε is meassured from data

$$\varepsilon = \frac{N(\tilde{\chi}^2 < 4.0)}{N(\tilde{\chi}^2 < 20.0)}$$

FIG. 3. Simulated $\tilde{\chi}^2$ distributions for 15 GeV/c photons (solid) and π^0's (dashed).

Conclusion

- **We finished the SM $H \to \gamma\gamma$ analysis with 14TeV @CMS based on the MC samples @NLO** .

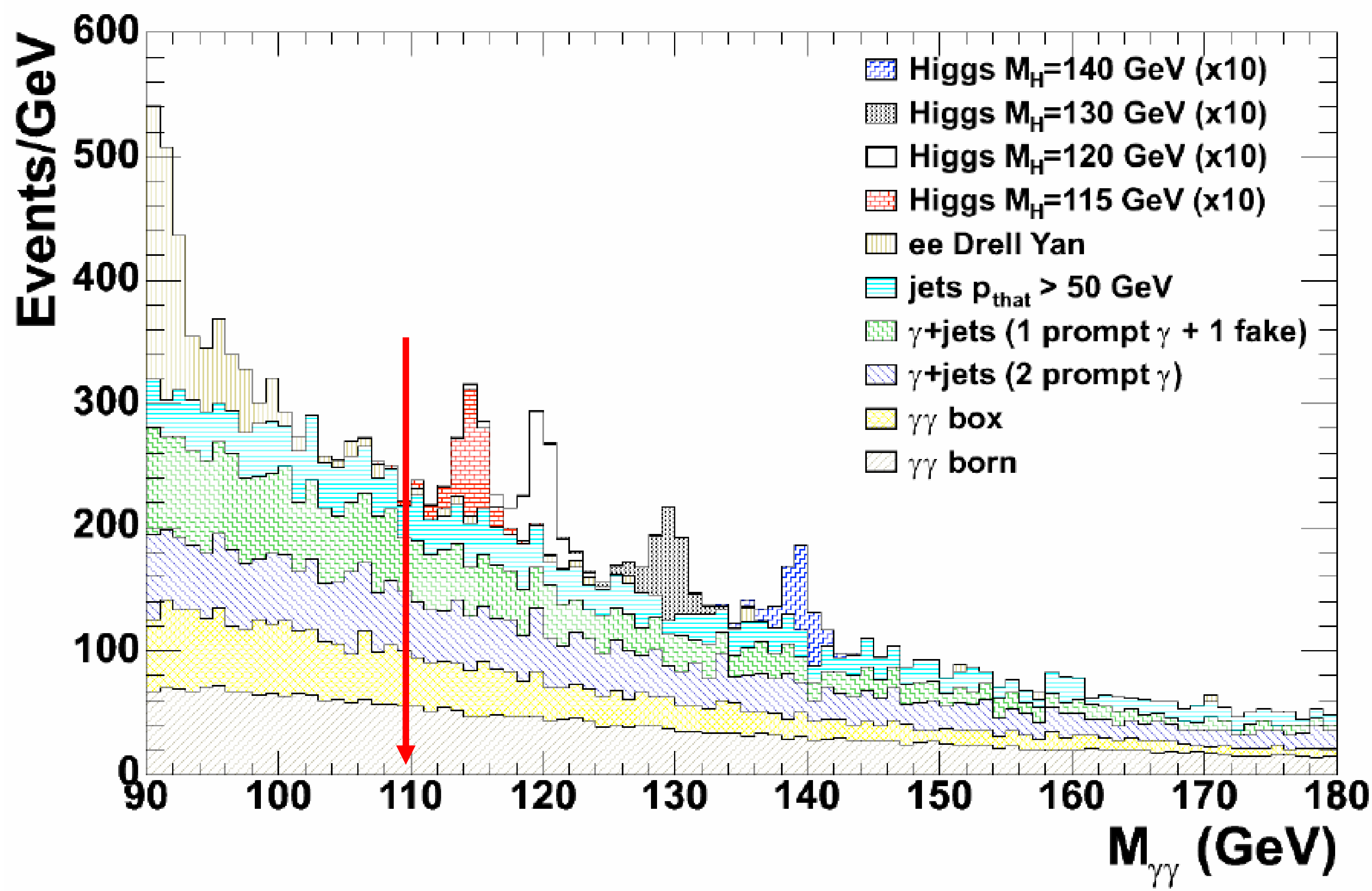
- For both **cut-based analysis** **and** **event optimized analysis**, with the backgound can be fixed by the sidebands fit, **better results** can be obtained.

- For **Higgs mass less than 140 GeV**, **5** σ **discovery** result or at least **a strong exist evidence** of Higgs can be obtained with the **data of 20 /fb**.

- Expect to **contribute** a lot to the task force of **SM $H \to \gamma\gamma$ analysis @ CMS with the LHC colision data.**


Thanks for your attention

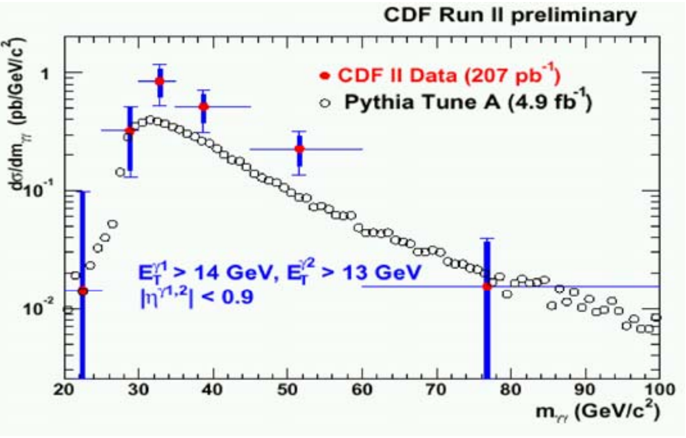
Backup

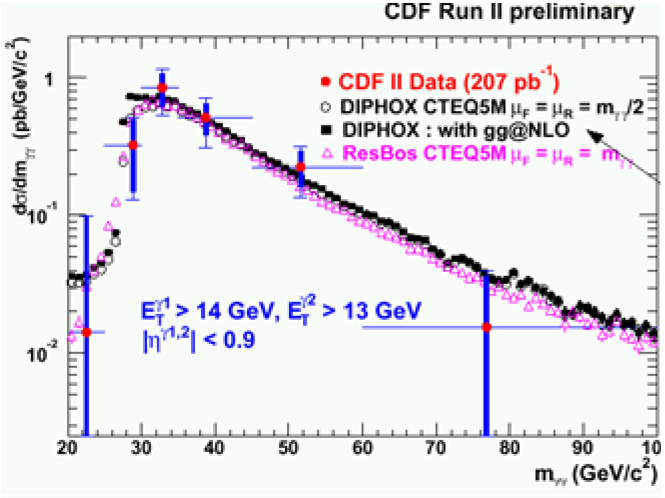


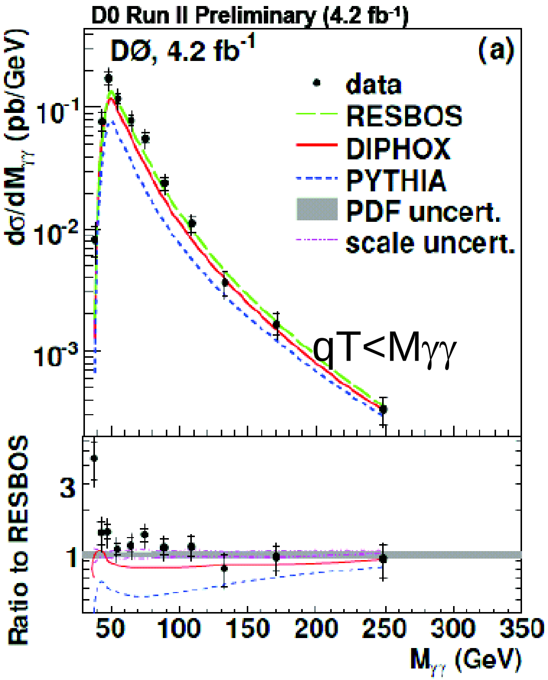
Di-photon invariant mass spectrum after the selection for the cut-based analysis. Events are normalized to an integrated luminosity of 1 fb−1 and the Higgs signal, shown for different masses, is scaled by a factor 10.

Higher order γγ Generator Studies

Motivation : γγ+X measurement







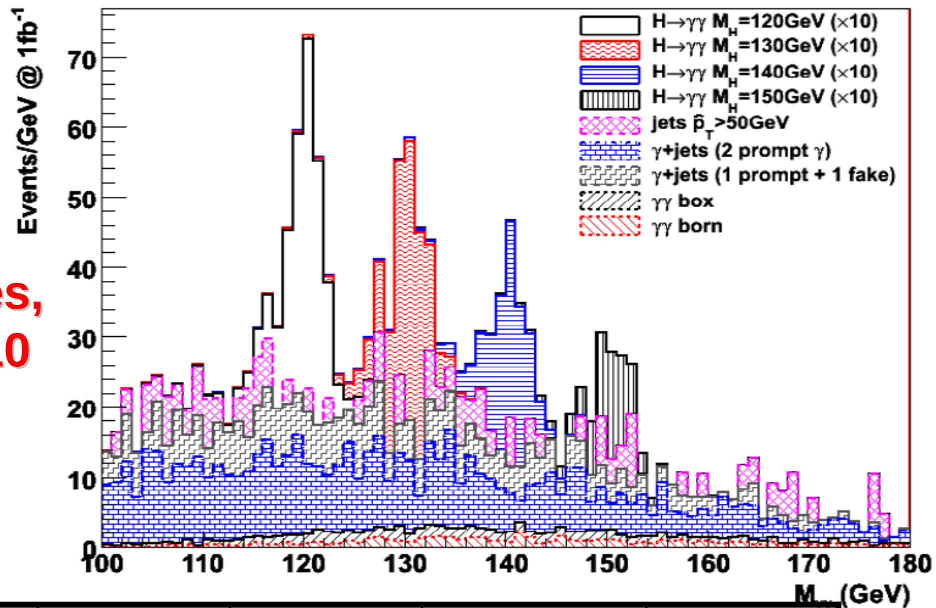
Why studying γγ+X processes ?

- Interesting from a theoretical point of view because prompt diphoton production is between pure QCD and QED
- It's a background to light Higgs searches (and new physics in some BSM models)

- CDF/D0 show that Pythia (LO) can not describe accurately the shapes of γγ+X events => need for NLO calculations

Applying to other Higgs mass samples

➢Applying the TMVA result and the final selections to other signal samples with mH=130GeV,140GeV and 150GeV

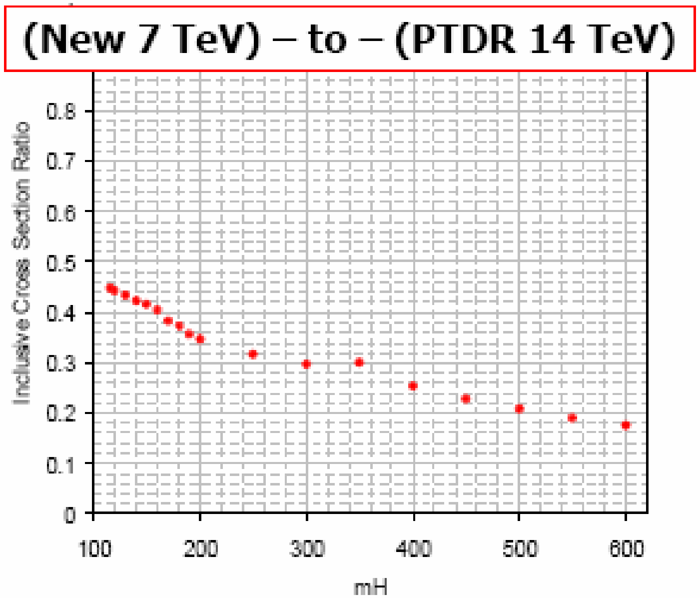


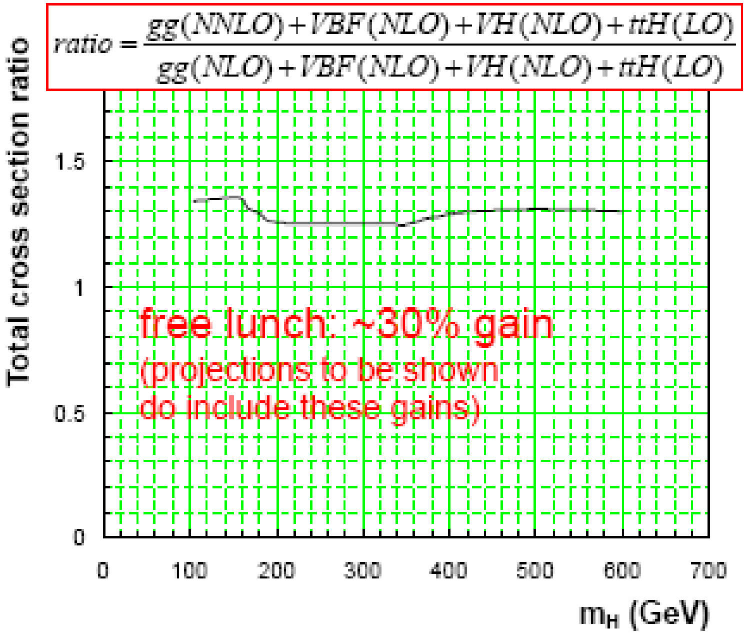
Analysis with CSA07 samples, normolized to 1/fb, signal×10

➢Selection efficiencies for signal samples

mH (GeV)		Selection Eff.	events @1fb-1	mH (GeV)	Selection Eff.	events @1fb-1
120	gg fusion	**22.26%**	**17.9**	**130**	**21.08%**	**14.9**
	IVB	**14.34%**	**1.4**		**16.07%**	**1.5**
	ZH,WH,ttH	**11.87%**	**0.9**		**12.63%**	**0.7**
140		**20.79%**	**11.2**	**150**	**18.59%**	**6.4**
		16.36%	**1.2**		**15.84%**	**0.8**
		12.60%	**0.5**		**12.42%**	**0.3**

SM Higgs cross sections at 7 TeV



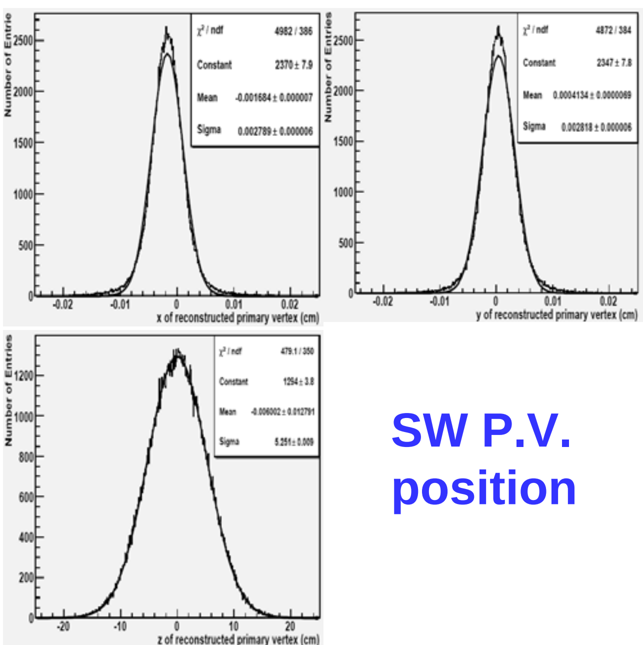


Sub-process	PTDR	now	tools used now
gg fusion	NLO	NNLO	HggTotal
VBF	NLO	NLO	VV2H
VH	NLO	NLO	V2HV
ttH	LO	LO	HQQ

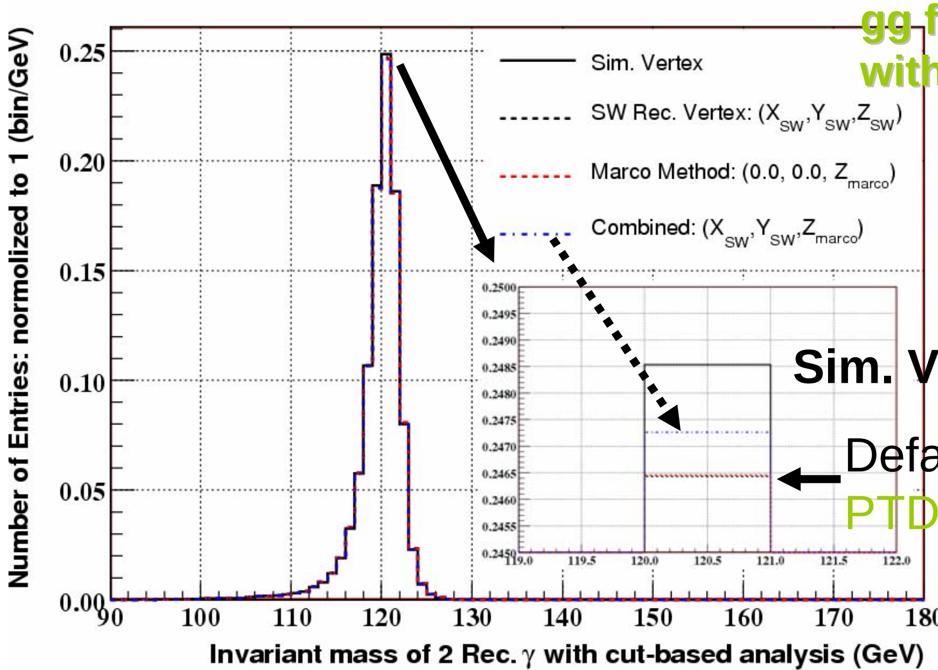
Pre-analysis

- **Filter:** at least **2 Rec. correctedPhotons with pT Min.=20GeV.**
- **L1 & HLT:** Previous studies show ~99% efficiency for L1 and HLT after analysis selection. **The inefficiency due to trigger is negligible**.
- Also **pseudo-rapidity cuts** on Photons: $|\eta|<2.5$
- **Primary vertex selection:**

✓ Using the default object "offlinePrimaryVerticesFromCTFTracks".
✓ For gg fusion with mH=120GeV, the PV rec. efficiency is ~98%.
✓ If no PV, using the nominal vertex (0.0, 0.0, 0.0) instead.
✓ **Only z position correction as PTDR** has the same result as the default P.V. in the invariant mass calculation of 2 photons



SW P.V. position



Variables as TMVA inputs

- **NN 12 variables (N-12)**

- $V_0 = |S_{2\times5Right} - S_{2\times5Left}|/S_{25}$
- $V_1 = \sigma_{\eta\eta}/0.0004$
- $V_2 = \sigma_{\phi\phi}/0.001$(假如$\sigma_{\phi\phi} < 0.001$，否则$V_2 = 0.0$)
- $V_3 = S_1/S_9$
- $V_4 = (S_9 - S_1)/(S_{25} - S_1)$
- $V_5 = S_4/S_{25}$
- $V_6 = |S_{2\times5Bottom} - S_{2\times5Top}|/S_{25}$
- $V_7 = E_{3\times2Ration}$
- $V_8 = S_6/S_9$
- $V_9 = \lambda_2/\lambda_1$
- $V_{10} = (E_2 + S_1)/S_9$
- $V_{11} = (E_2 + S_1)/S_4$

- **3 Moments variables** (M-3): M_{MAJ}^2, **LAT& PZM**

端盖未转化的情况

- <u>25个输入变量</u>

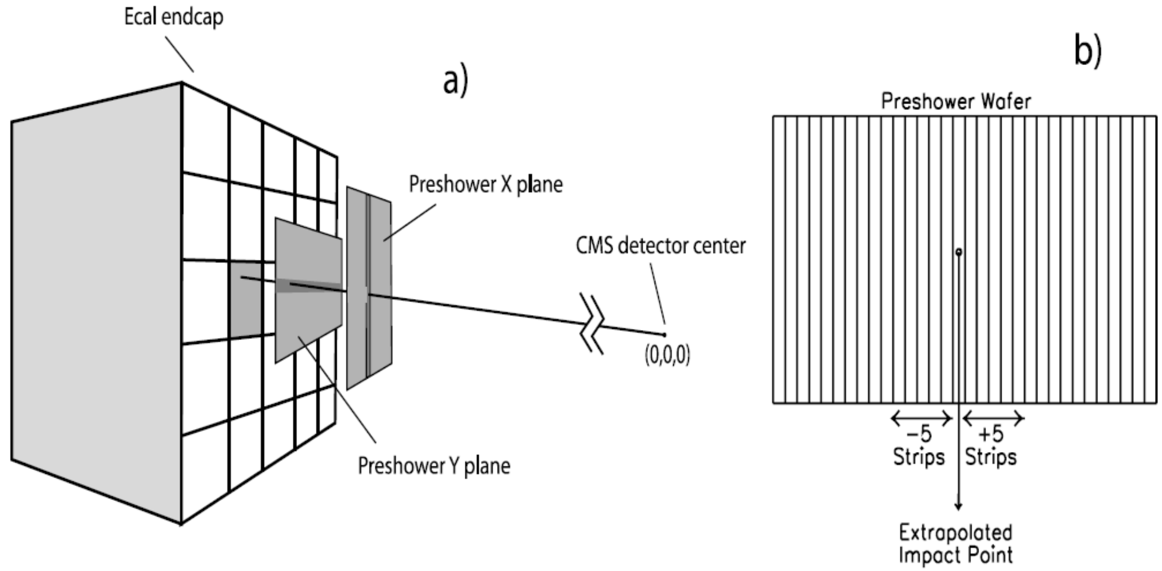


图 5.5: (a)端盖使用神经网络方法时的示意图。通过连接ECAL端盖簇射中心与对撞点（0.0，0.0，0.0）的连线，找出与preshower的交点。(b)神经网络中使用到的preshower每一层11条硅微条（相交点左右±5条硅微条），其大约为2cm宽

- Preshower X-层上11个变量：V_0、V_1、...、$V_{10} = \frac{E_i^X}{C_X}$。其中$i = 0, \pm1, \pm2, ..., \pm5$，即中间硅微条（$X_{imp}$所在硅微条），左右±1一直到±5的硅微条。$E_i^X$为该层上第$i$根硅微条的能量读出。对于中心及±1的硅微条，$C_X = 0.02$，对其余硅微条$C_X = 0.01$。

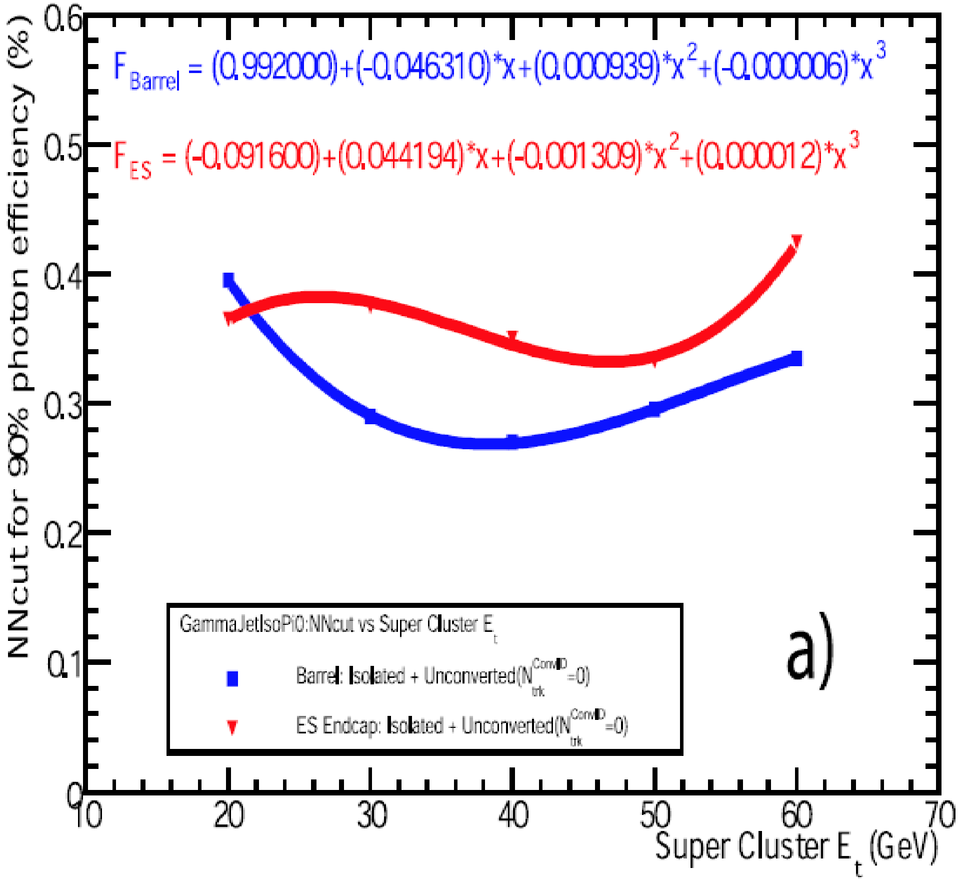
- Preshower Y-层上11个变量：V_{11}、V_{12}、...、$V_{21} = \frac{E_i^Y}{C_Y}$。其中$i$的定义与X-层一样。$E_i^Y$为该层上第$i$根硅微条的能量读出。对于中心及±1的硅微条，$C_Y = 0.04$，对其余硅微条$C_Y = 0.02$。

- ECAL端盖中有关能量沉积的3个变量：$V_{22} = S_1/C_{EE}$、$V_{23} = S_9/C_{EE}$、$V_{24} = S_{25}/C_{EE}$。其中S_1、S_9、S_{25}的定义与桶部的一样，分别为最大能量沉积的晶体的能量、中心晶体周围3×3晶体矩阵中的总能量、中心晶体周围5×5晶体矩阵中的总能量。假如$S_{25} < 500GeV$，系数$C_{EE} = 500GeV$；假如$500GeV < S_{25} < 1000GeV$，系数$C_{EE} = 1000GeV$；假如$1000GeV < S_{25} < 7000GeV$，系数$C_{EE} = 7000GeV$。

Application of γ/π0 discrimination: Unconverted case

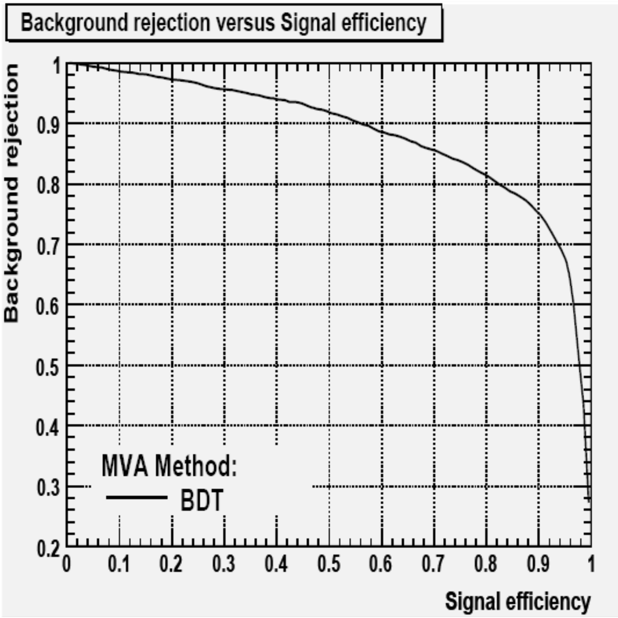
- Selection of unconverted case: "N_{trk}^{ConvID}=0" method, "track finding for identification of converted photons"

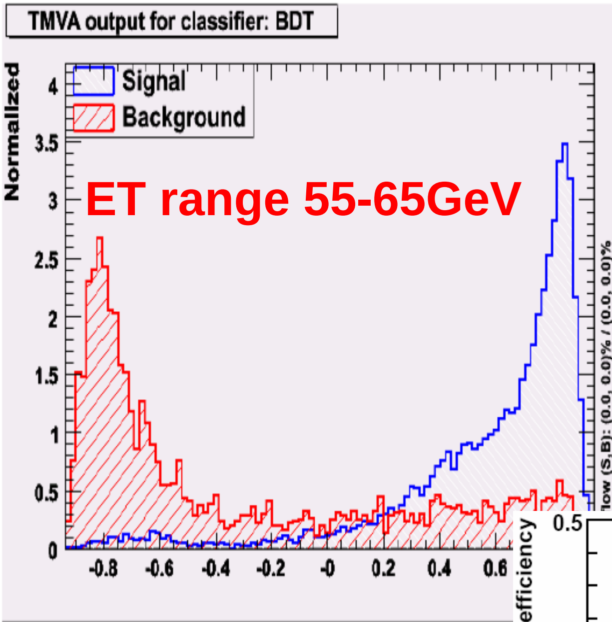
- NN cut value vs SC Et: (ANN results from CMS AN-2008/063)



Resuls of γ/π0 discrimination: Converted case

➢ TMVA BDT analysis results for different pTrange

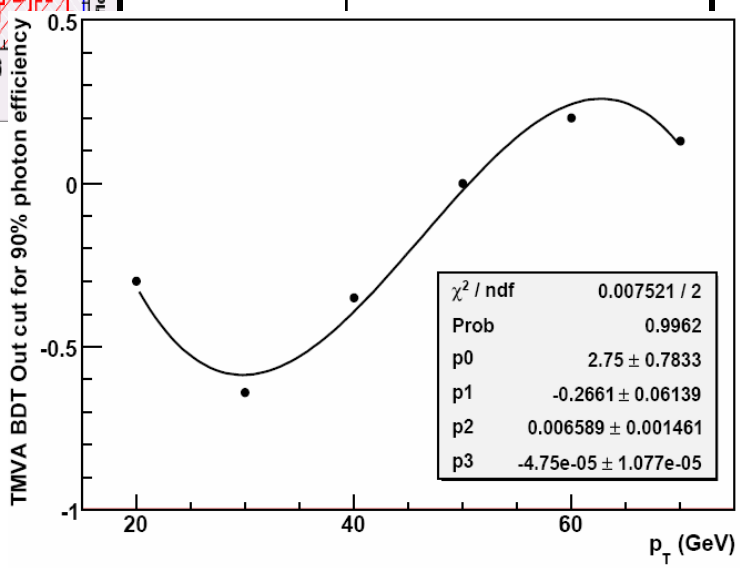




ET range	π0 rejection for keeping 90% γ efficiency
20-25	31.5
25-35	48.0
35-45	67.3
45-55	74.0
55-65	75.1
65-75	71.5

➢TMVA_BDT out cut value vs Photon Et

$$f(x = P_T) = 2.75 - 0.2661x + 0.006589x^2 - 0.0000475x^3$$



其他研究组的结果

➢**UCSD** (*University of California, San Diego*) Marco Pieri (convenor)

1. 可确定本底, CMS Note-2006/112 “cut-based”的结果 (老数据): mH=120GeV,不考虑系统误差

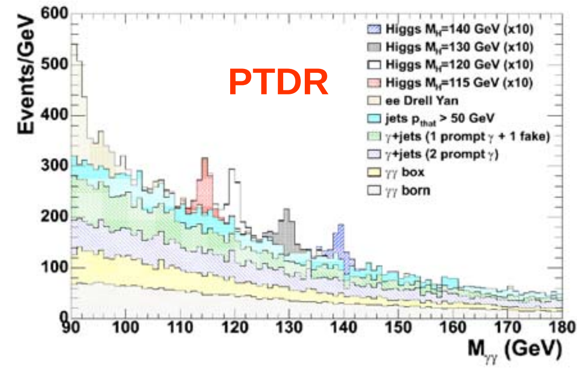
Analysis	5 σ discovery no systematic error
Counting experiment	27.4 /fb
1 category	24.5 /fb
4 categories	21.3 /fb
12 categories	19.3 /fb

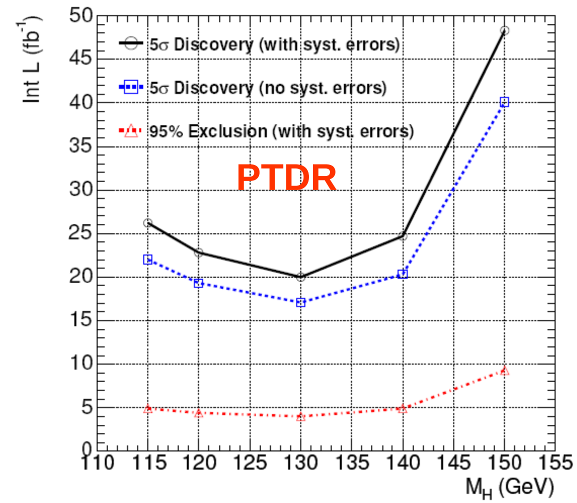
2. CSA07优化分析结果(2008.12.04的报告, 不能确定本底): mH=120GeV,不考虑系统误差, **L(5 σ)~11fb^{-1}**

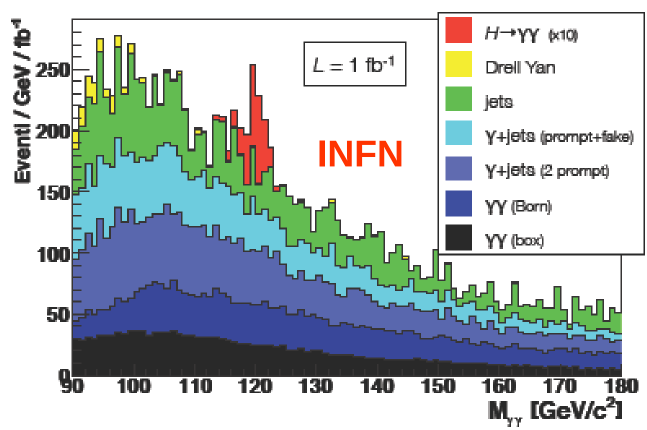
➢**Università di Roma “La Sapienza” and INFN Sez. Roma**, Francesco Pandolfi (2008.11.21的报告) CSA07分析结果,有本底谱,不考虑系统误差时5 σ 发现所需要的积分亮度

mH=120GeV	19.3 /fb
mH=130GeV	20.5 /fb
mH=140GeV	28.0 /fb
mH=150GeV	53.1 /fb

Junquan Tao







Event-optimized analysis: inputs

- **$Et_{\gamma 1}/M_{\gamma\gamma}$, $Et_{\gamma 2}/M_{\gamma\gamma}$, $|\eta 1 - \eta 2|$ and PL are almost independent of the Higgs mass**