



**ACAT 2014**  
– bridging disciplines

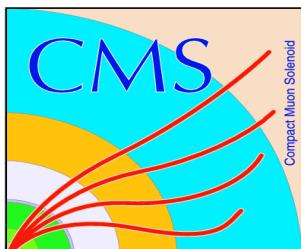
1-5 September 2014  
Prague, Czech Republic



# The Matrix Element Method within CMS

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On behalf of the CMS collaboration



# Outline

## Introduction

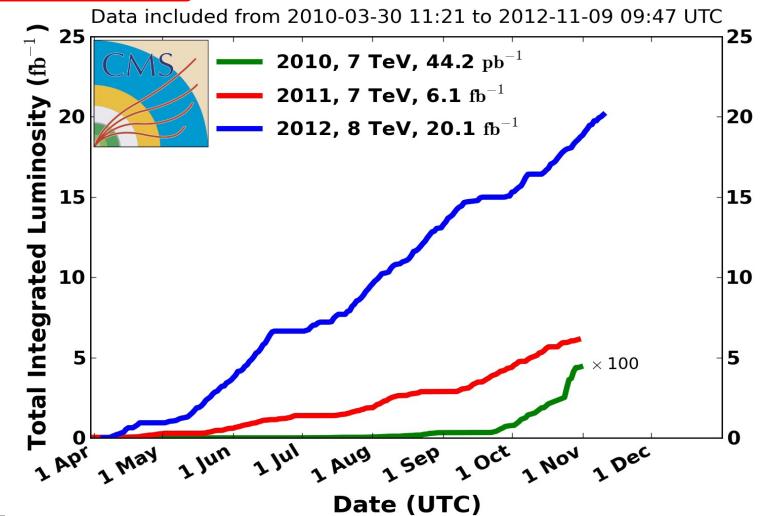
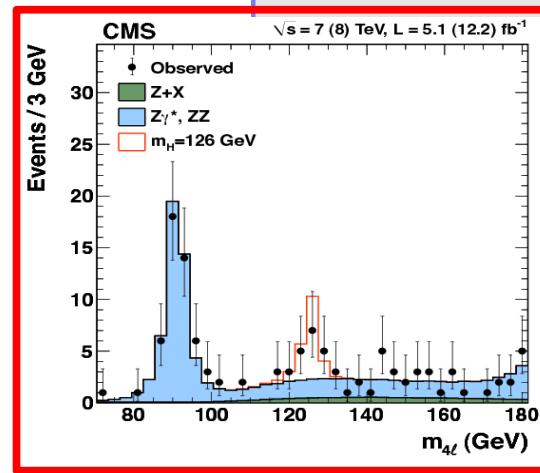
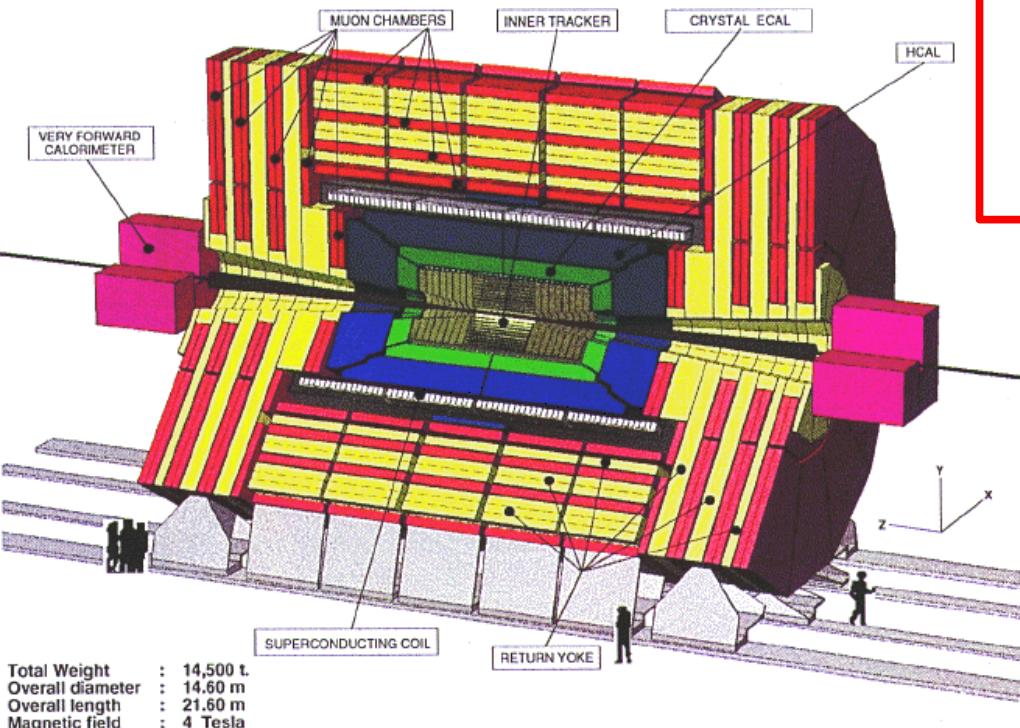
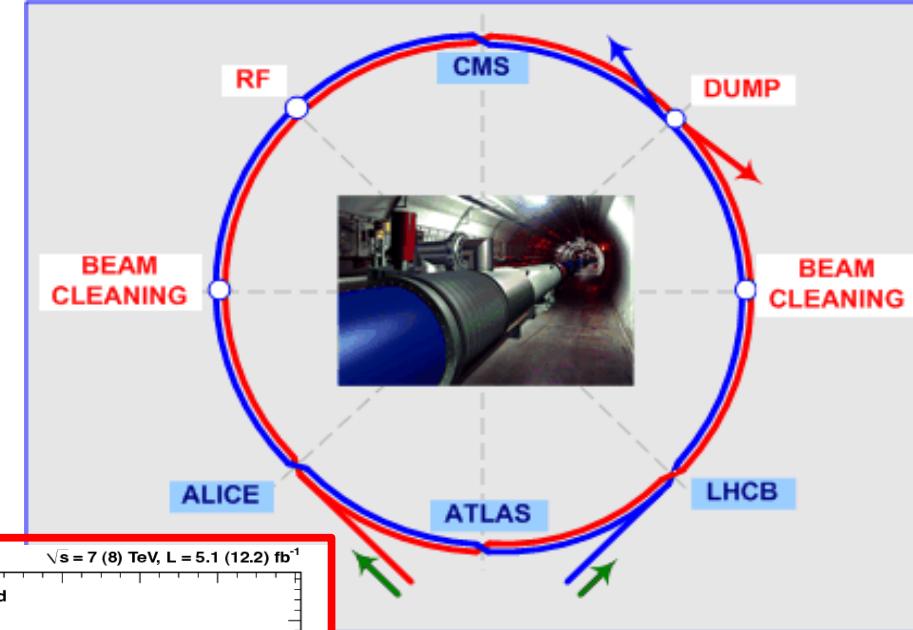
- CMS
- The Matrix Element Method

## Applications within CMS

- MELA
- Zbb analysis
- ttH analysis

# The LHC and CMS

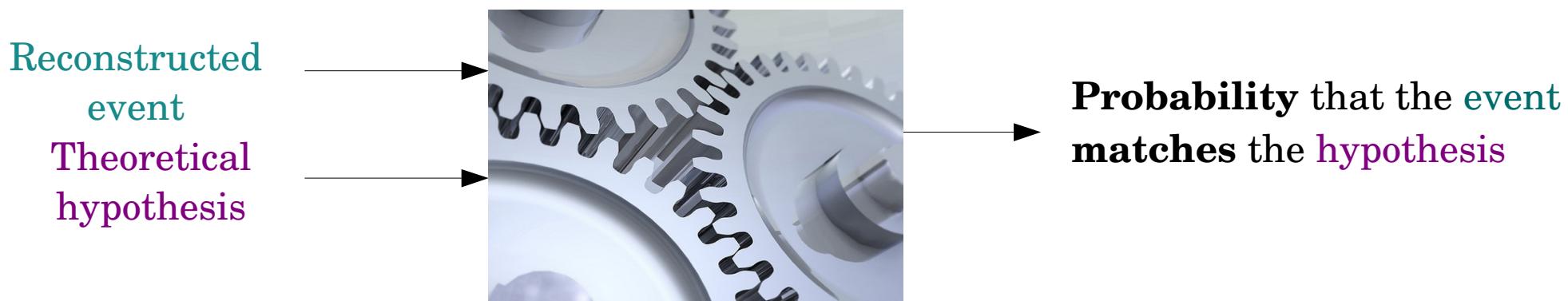
- LHC pp collider at  $\sqrt{s} = 7$  and 8 TeV, **13** in 2015
- **CMS** one of the 4 detectors around the ring
- Outstanding performances since 2010
- **Discovery of Higgs boson** 4th July 2012
- Properties has to be measured precisely
- Need ultimate analysis tools



# The Matrix Element Method

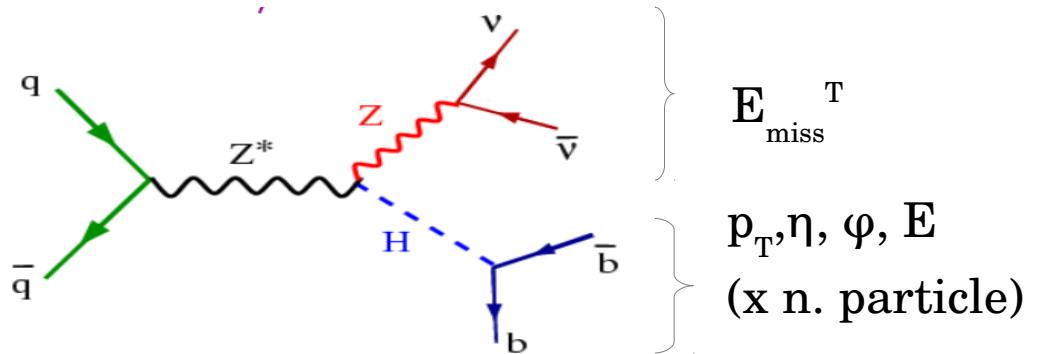
# The Matrix Element Method

- Event-by-event **discriminator** built upon matrix elements
- Contain the maximal amount of **theoretical information** available for the hard process
- Combined with **reconstruction** level information



# A powerfull tool

What you have: 4-vector of particles  
in final state



Standard approach:

1) **Choose/compute** your variables  
(which one are the most relevant ?  $p_T$  distribution, invariant mass, etc)

2) **Combine** them with MVA method  
(which one ? Training ? Statistics ?)

3) Final discriminant variable

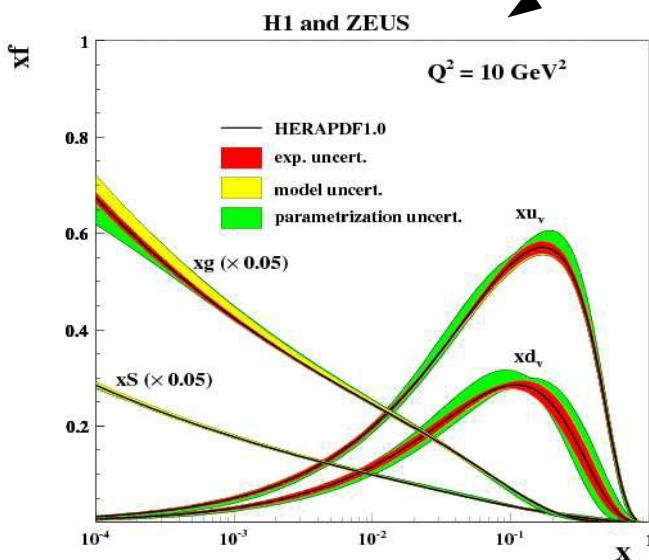
MEM method approach:

1) Final discriminant variable

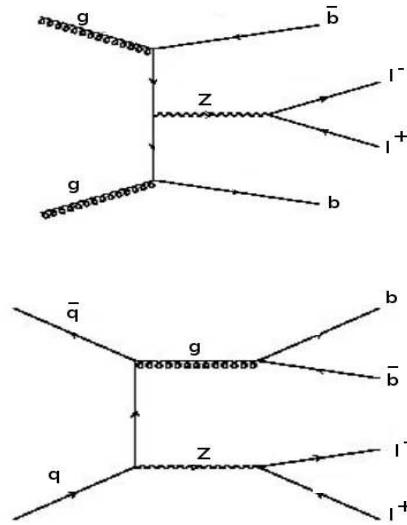
# Building the discriminant

Probability that the event with reconstructed kinematics  $x$  matches the hypothesis  $\alpha$ :

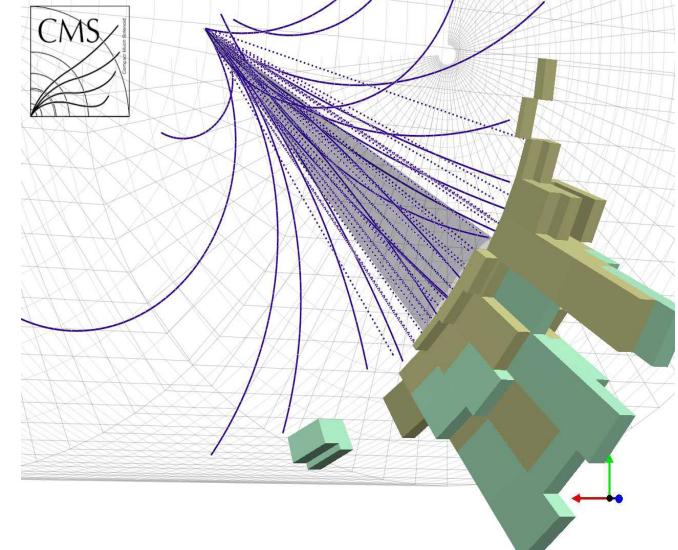
$$P(x^{vis}|\alpha) = \frac{1}{\sigma_\alpha} \int dx_1 dx_2 f(x_1) f(x_2) \int d\phi |M(p)_\alpha|^2 W(p^{vis}, p)$$



Proton density functions



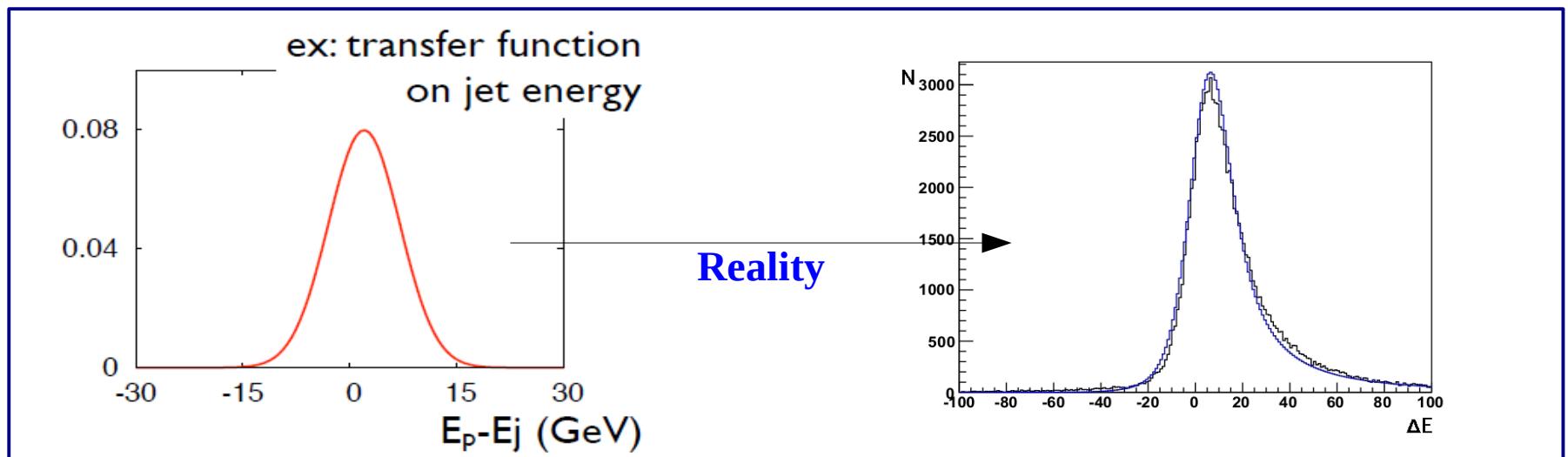
Matrix Element at LO  
of the hypothesis



Transfer functions  
extracted from simulation

# The Transfer Functions

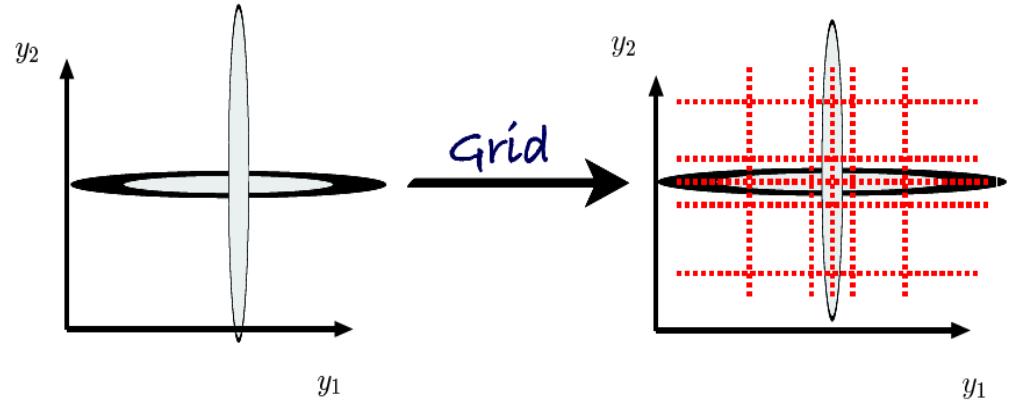
- Transfer function: take account of **showering/hadronization** effects + experimental **resolution/reconstruction**  $\rightarrow P(x,\alpha)$  convoluted with a TF  $W(p^{\text{vis}}, p)$ 
  - Likelihood **fit** on  $\Delta(E_{\text{parton}} - E_{\text{jet}})$
  - Can use another variable (ex: muon  $\rightarrow$  dependence in  $1/pT$ )
  - Imply particles not correlated
  - No TF for **neutrinos**



# The challenges

## The challenges

- Integral computation → **not trivial** ! Presence of sharp functions:
  - Breit-Wigner
  - Transfer functions
- Degrees of freedom of your system
  - if same number peaks aligned
  - if not, average of several weights
- The adaptive Monte-Carlo Technique picks point in interesting areas, make the integral **converge**
- This is model dependent → need to be **automatic**, model independent, **fast** and smart
- Real experiment: a reconstructed event cannot be weighted by a **unique** ME → average between several weights (parton-jet matching combination)
- Missing energy →  $P(x,\alpha)$  must be summed over the unobserved degrees of freedom



# Pros and cons of the method

- ✓ **Maximize** the amount of theoretical information for your discrimination
- ✓ **No “training”** as for most MVA methods
- ✓ Many potential **applications** (Tevatron: top mass measurement, single top discovery, CMS: Higgs search, spin correlation measurement, ...)
- ✗ Depending on your model, probability computation can be **CPU-demanding**

Time to compute the weight of one event, using MadWeight 5 [1]

ZH	< 5 s
tt fully leptonic	10 s
Zbb	18 s
tt semi-leptonic	41 s
ttH fully leptonic	1 min

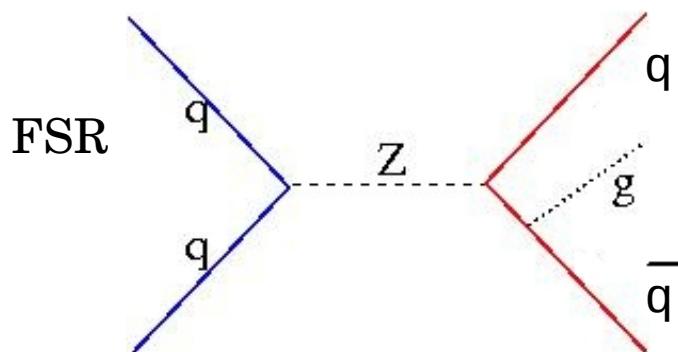
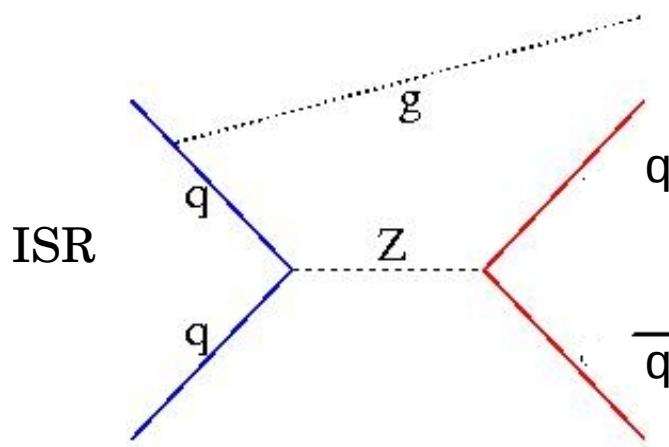
x thousand  
of events !

- ✗ ME at **LO only** (assignment between reconstructed jets and partons can be ambiguous beyond LO)

[1] P. Artoisenet, V. Lemaître, F. Maltoni, OM: JHEP 1012:068

# NLO effects

## Focus on NLO effects: Initial/Final State Radiation (ISR/FSR)



The  $Z$  produced is not at rest → induce a transverse **boost** of the system  
→ Matrix Element doesn't match anymore

- Correct for the boost

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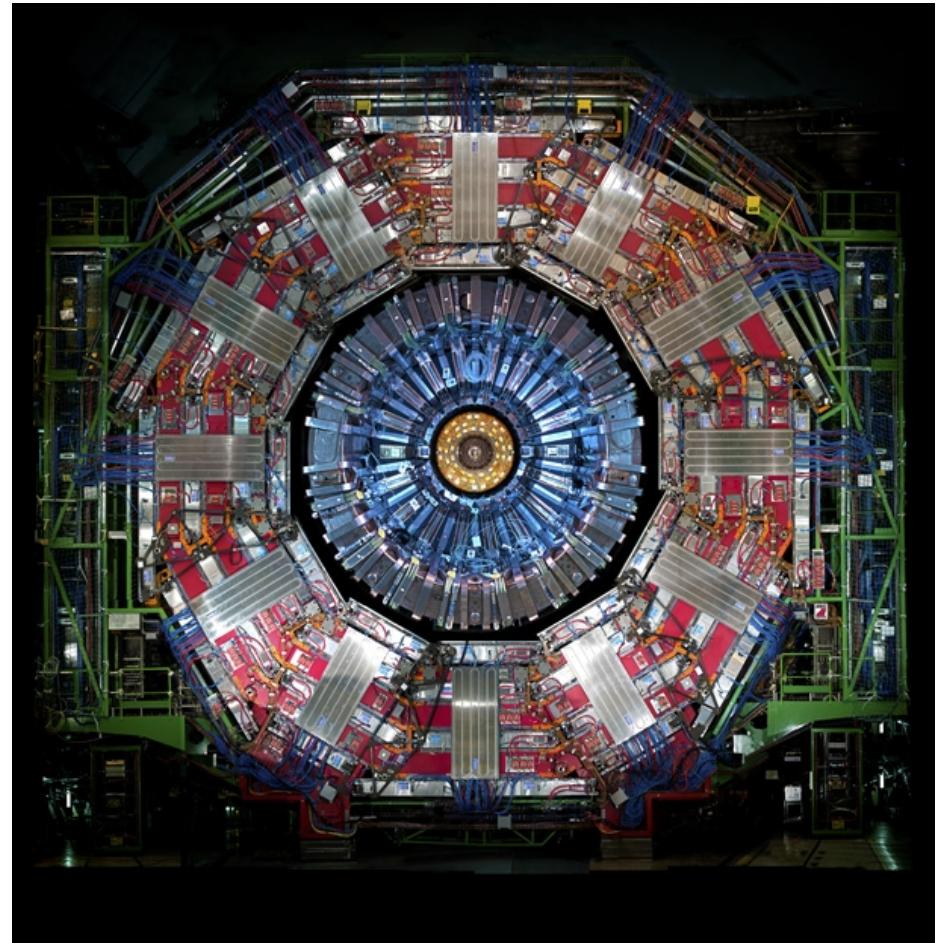
Instead of having 2 particles in the final state → 3  
→ Matrix Element doesn't match anymore

- Apply another Matrix Element: signal+extra object
- Recombine the extra jet+particle it comes from before applying MEM

# The Matrix Element Method

## In CMS:

- Simplified approach with MELA (no integration)
- “Automatized” tool using MadWeight in the Zbb analysis
- MEM applied in the ttH analysis

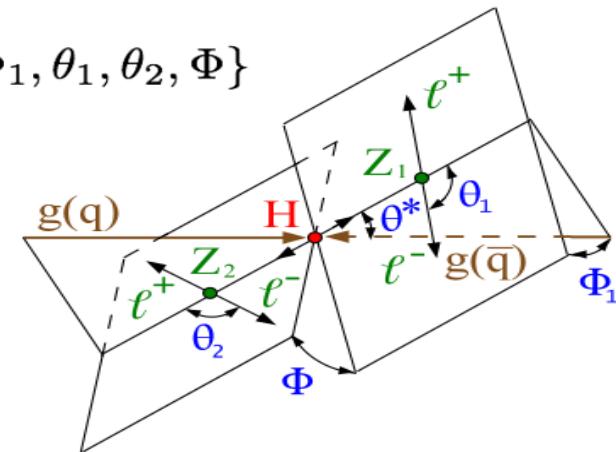


# Simplified application: MELA

# MELA

$$\vec{\Omega} = \{\theta^*, \Phi_1, \theta_1, \theta_2, \Phi\}$$

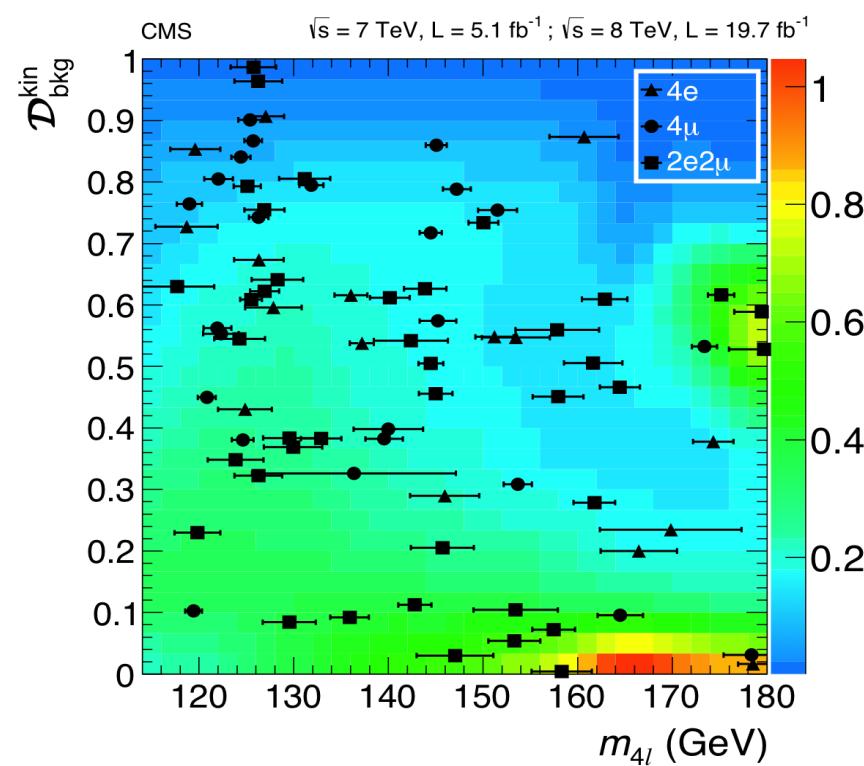
MELA (Matrix Element Likelihood Analysis) **simplest MEM**  
**no integration**, no transfer function because only leptons



- Key to  $H \rightarrow ZZ \rightarrow 4l$  **observation**
- Uses the golden channel  $H \rightarrow 4l$  ( $l=e,\mu$ ),  $2l2\tau$ , very clean signature; main background  $ZZ$
- Kinematic of the event fully describe by 5 angles  
+ 2 inv. Mass
- Discriminant  $D_{\text{bkg}}^{\text{kin}}$  constructed from the ratio of probabilities for signal and backgrounds

$$D_{\text{bkg}} = \left[ 1 + \frac{\mathcal{P}_{\text{bkg}}(m_{4\ell}; m_1, m_2, \vec{\Omega})}{\mathcal{P}_{\text{sig}}(m_{4\ell}; m_1, m_2, \vec{\Omega})} \right]^{-1}$$

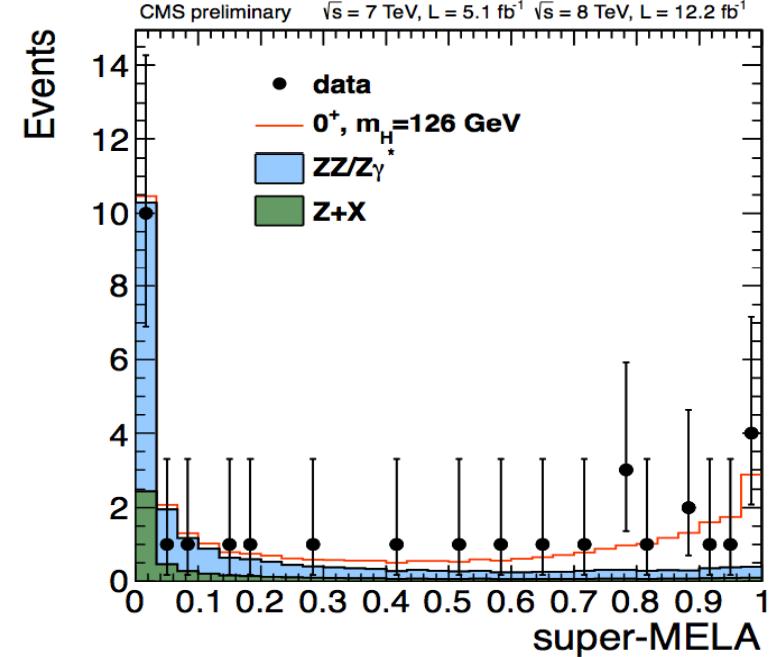
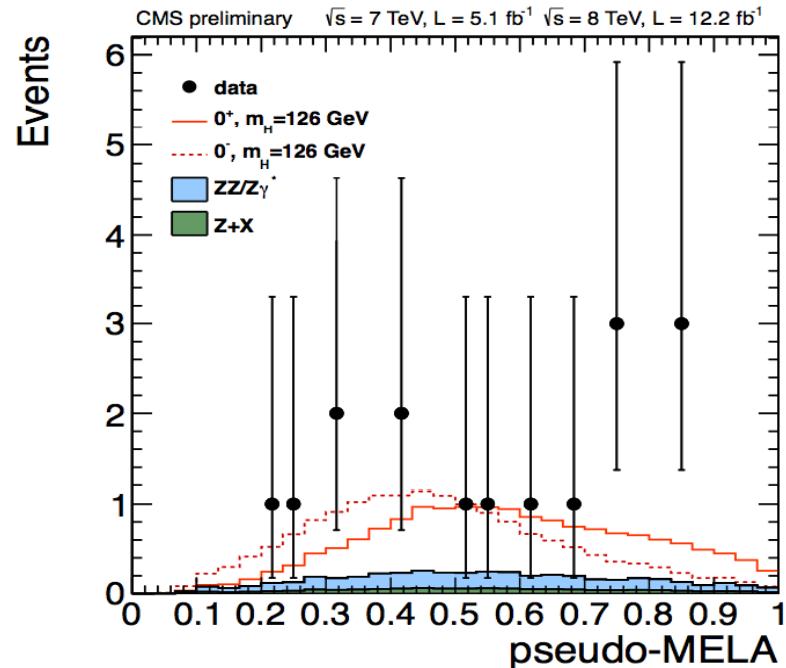
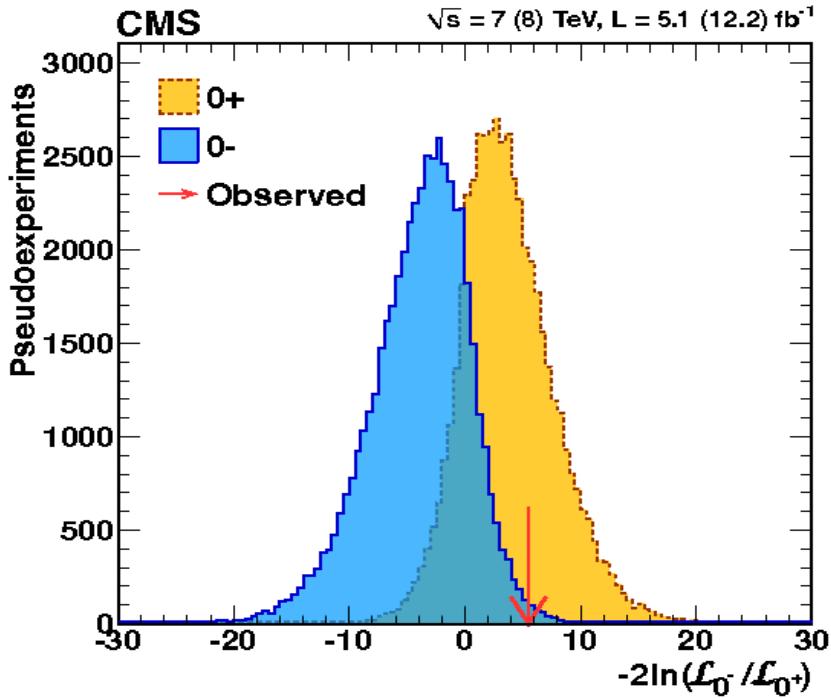
- Use then as kinematic discriminant to discriminate two different JCP hypothesis ( $D_{\text{jx}}^{\text{P}}$ )



# MELA

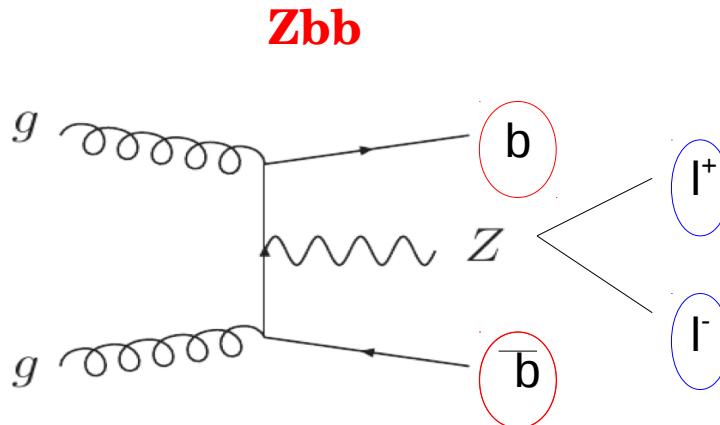
Phys. Rev. Lett. 110, 081803 (2013)

- **Pseudo-MELA:** discrimination  $0^+/0^-$
- **Super-MELA:** add mass to the fit  
hyp. Signal( $0^+$ ) VS background
- **Likelihoods** with signal rate as free parameter,  
mean of one distribution is 2 standard  
deviations in the tail of the other distribution
- $q = -2\ln(L_{0^-}/L_{0^+})$  consistent with  $0^-$  within 2.4  
standard deviations and consistent with  $0^+$   
within 0.5 standard deviations  $\rightarrow 0^+$  favored

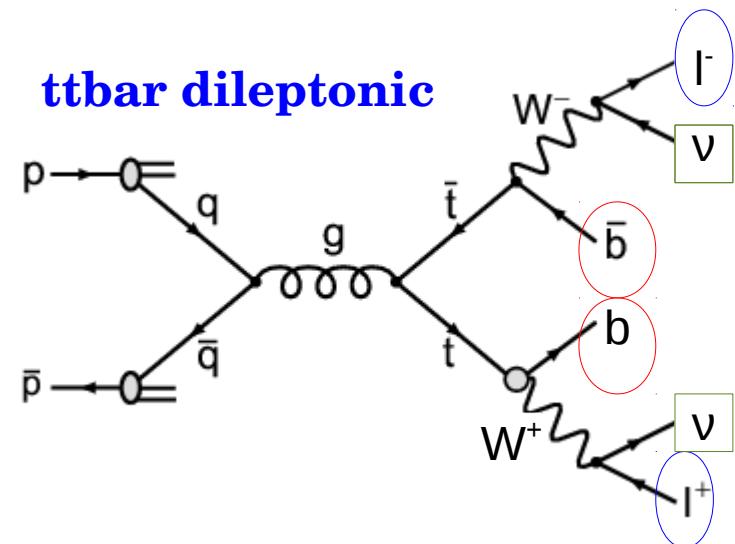


# Automatized tool: Zbb analysis

# Zbb analysis



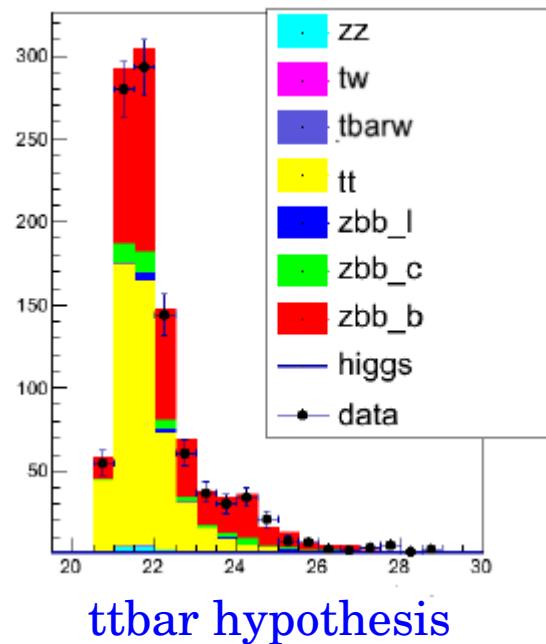
**VS**



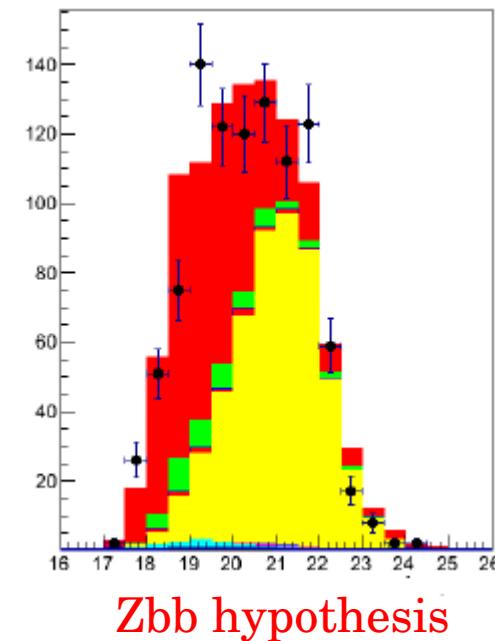
- **MEM** used as cross check for standard analysis to **discriminate Zbb and ttbar dileptonic processes**  
 → very similar processes, same objects in final state,  $E_{\text{miss}}^T$  cut, then ?
- Use MadWeight to compute probability that even  $x$  matches Zbb/ttbar
  - fully **automatized** procedure
  - transfer function for electrons, muons,  $b$ -jets
  - correction for ISR jets
- Use MVA (Neural Network) to improve discrimination

# Results

MEM output

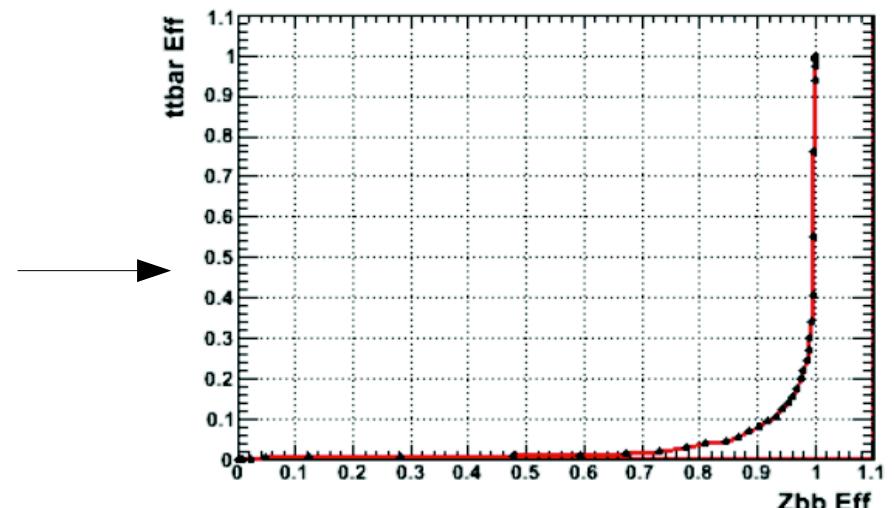
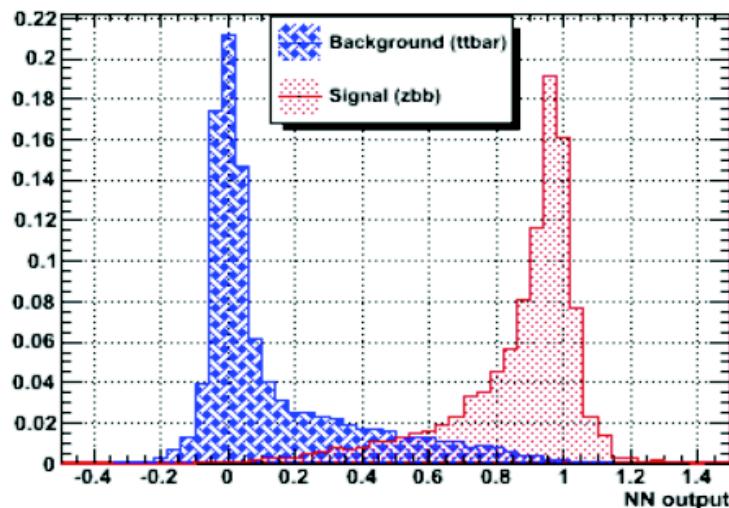


$t\bar{t}$  hypothesis



$Zbb$  hypothesis

MVA output

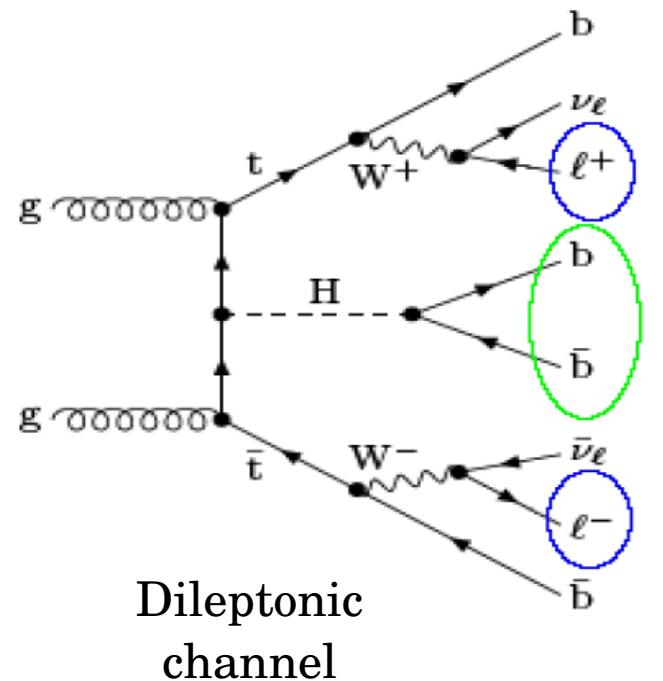
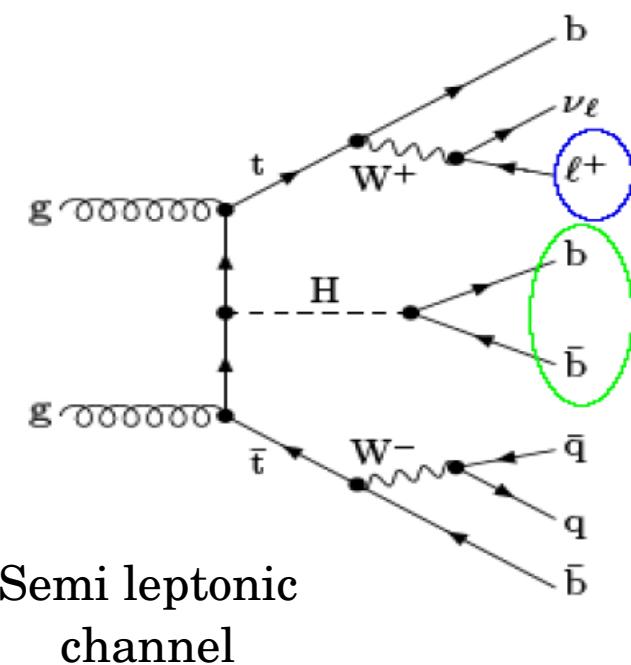
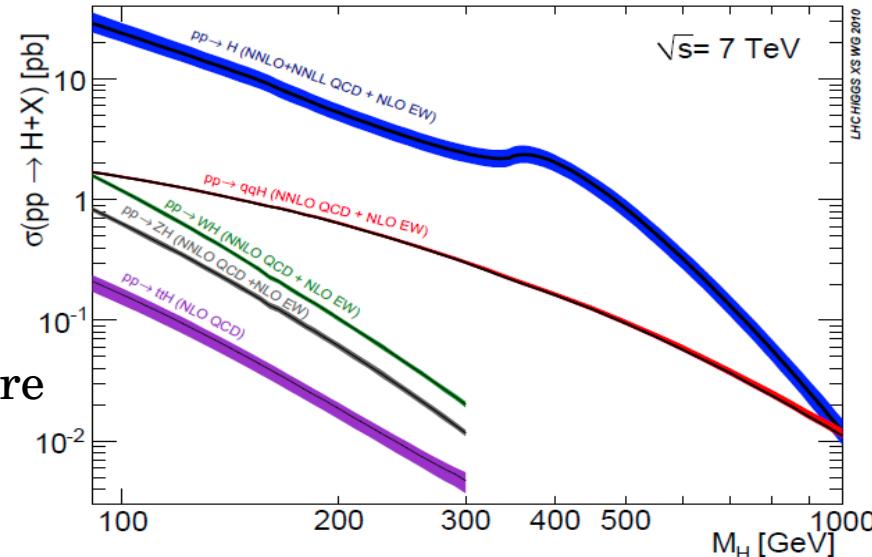


→ Can achieve excellent separation

Direct application:  
 $ttH \rightarrow bb$

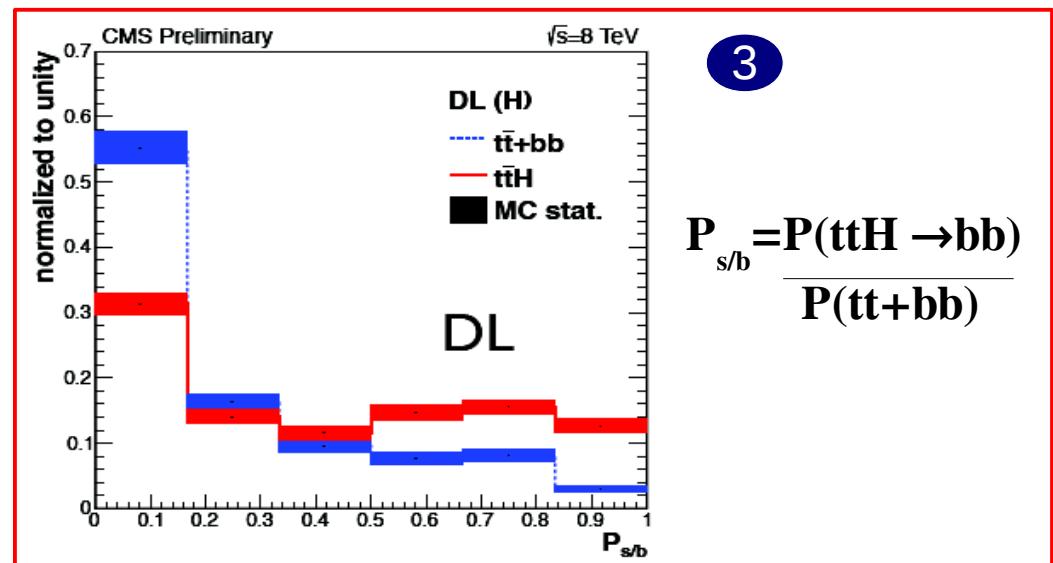
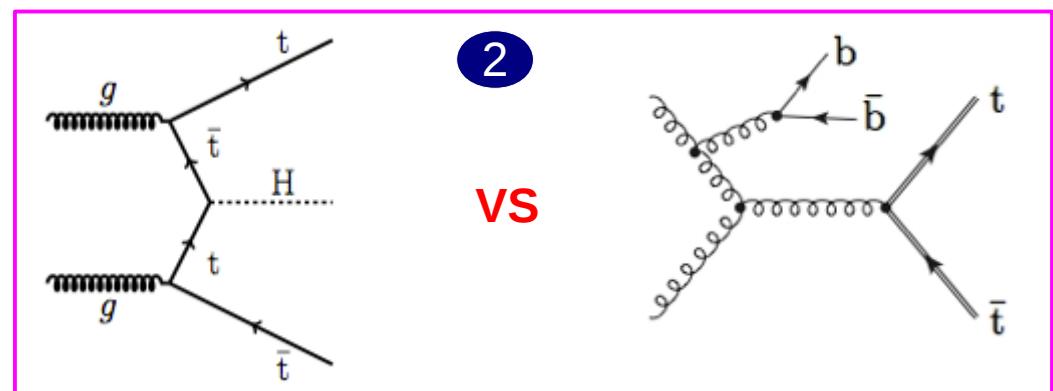
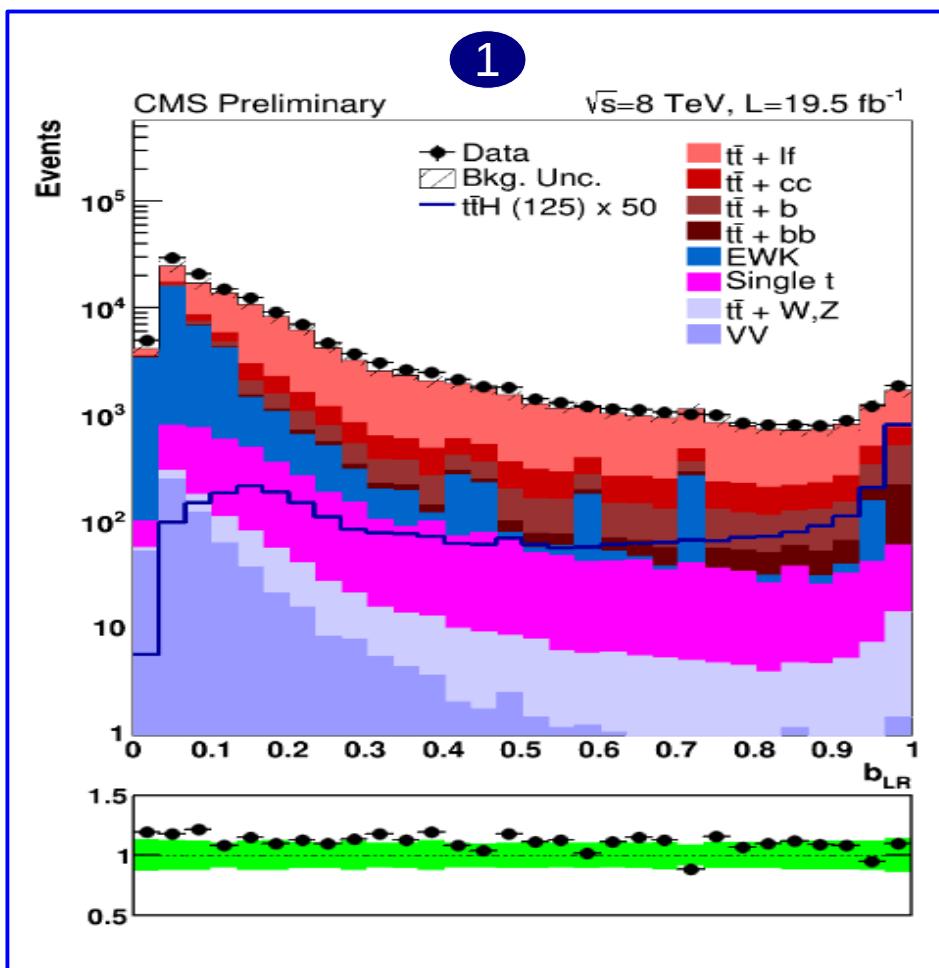
# The MEM for ttH with H → bb

- One of the most challenging channel because of low production rate
- H → bb highest BR but M(bb) low resolution  
→ no clear peak
- Final states with lot of objects → very clear signature but weight computation CPU-demanding



# The MEM for ttH with H → bb

- 1 Build likelihood ratio discriminant to distinguish signal and tt+bb/cc (irreducible bkg) from tt+l. Flavor
- 2 Discrimination Signal and tt+bb/cc improved by the **MEM**
- 3 Build the final discriminant with the probabilities computed by the MEM

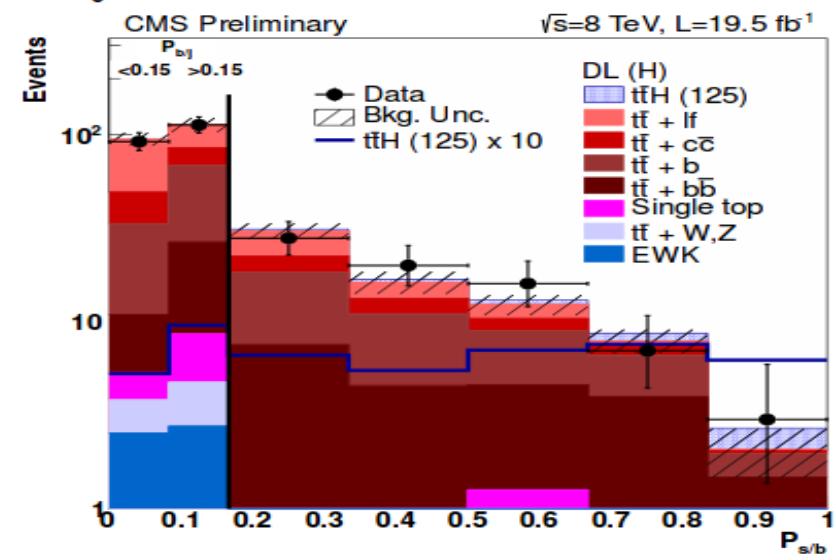
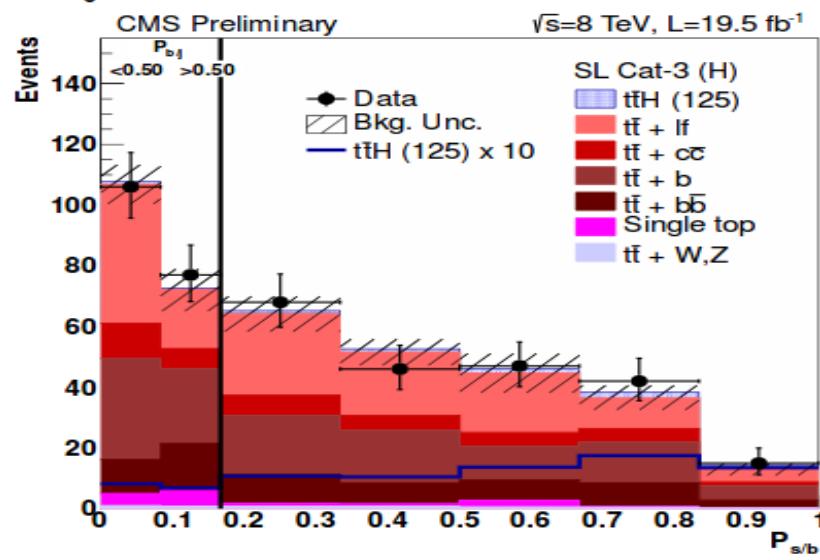
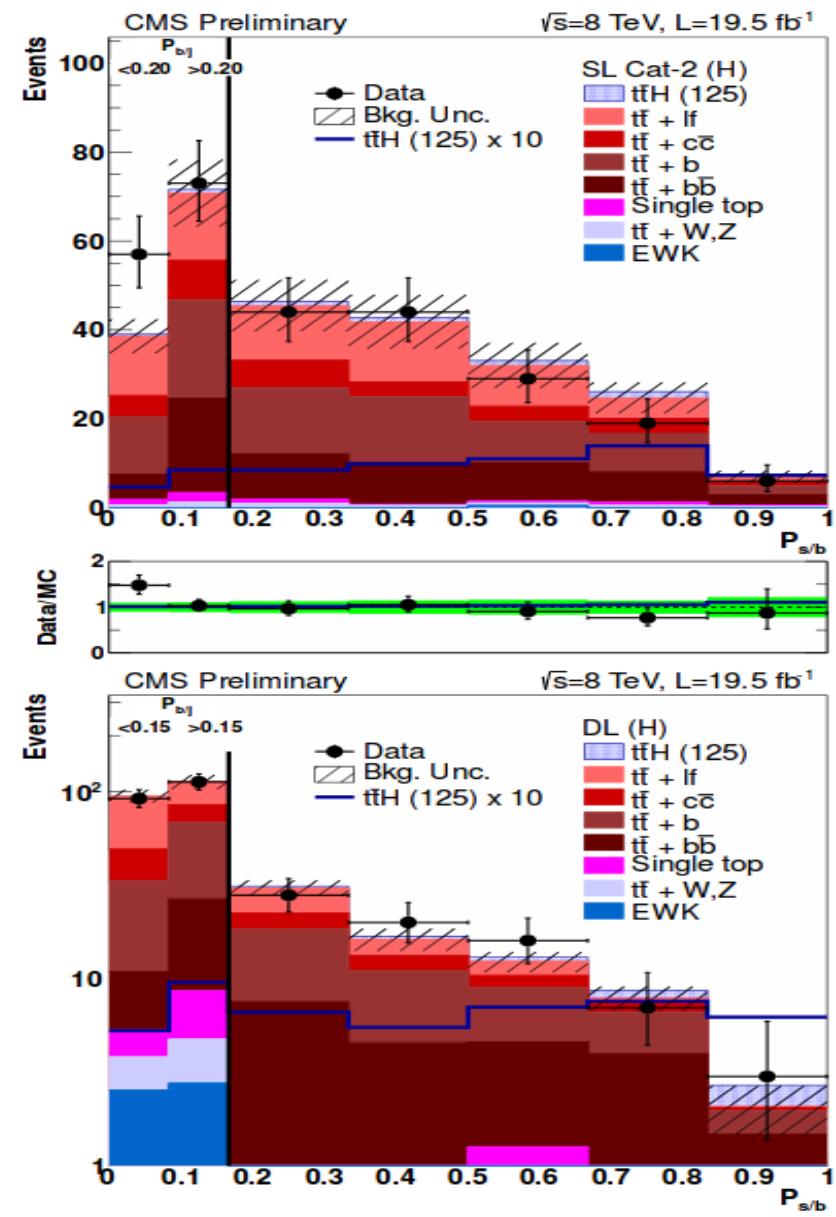
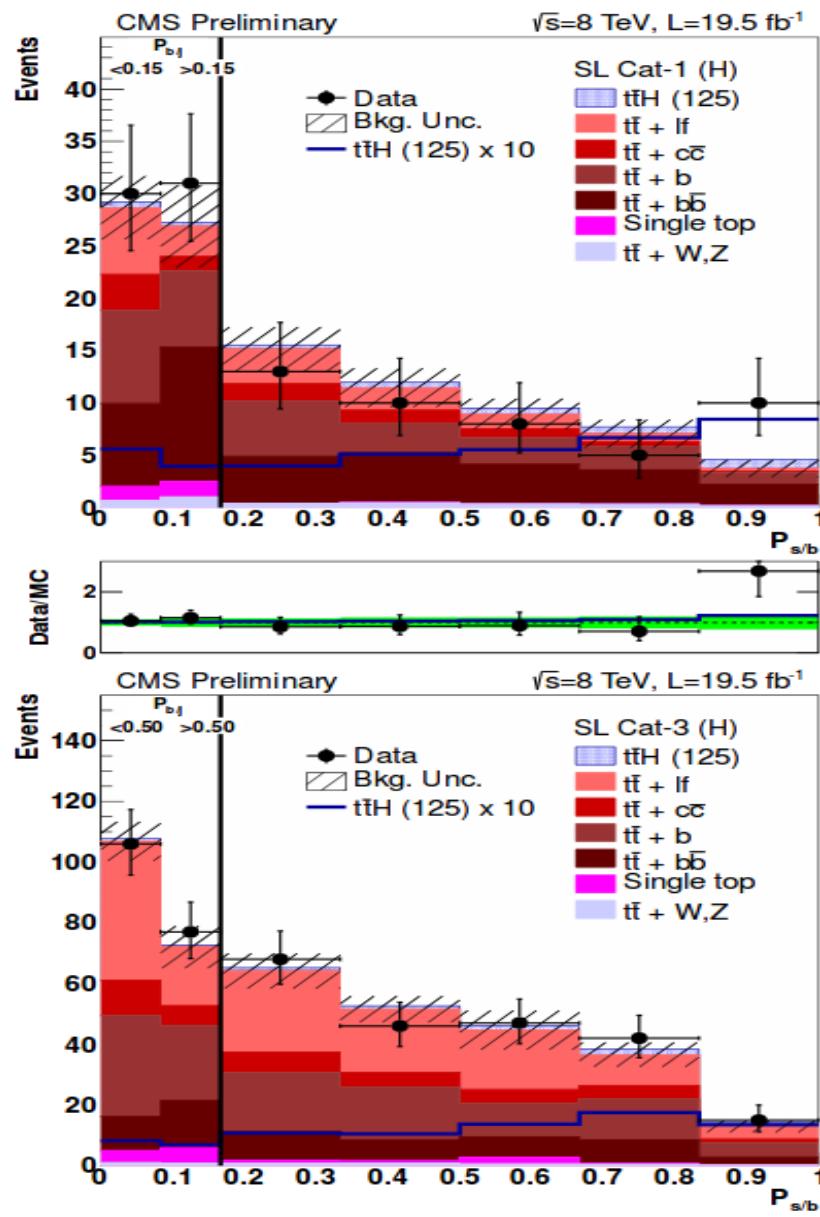


# The MEM for ttH with H → bb

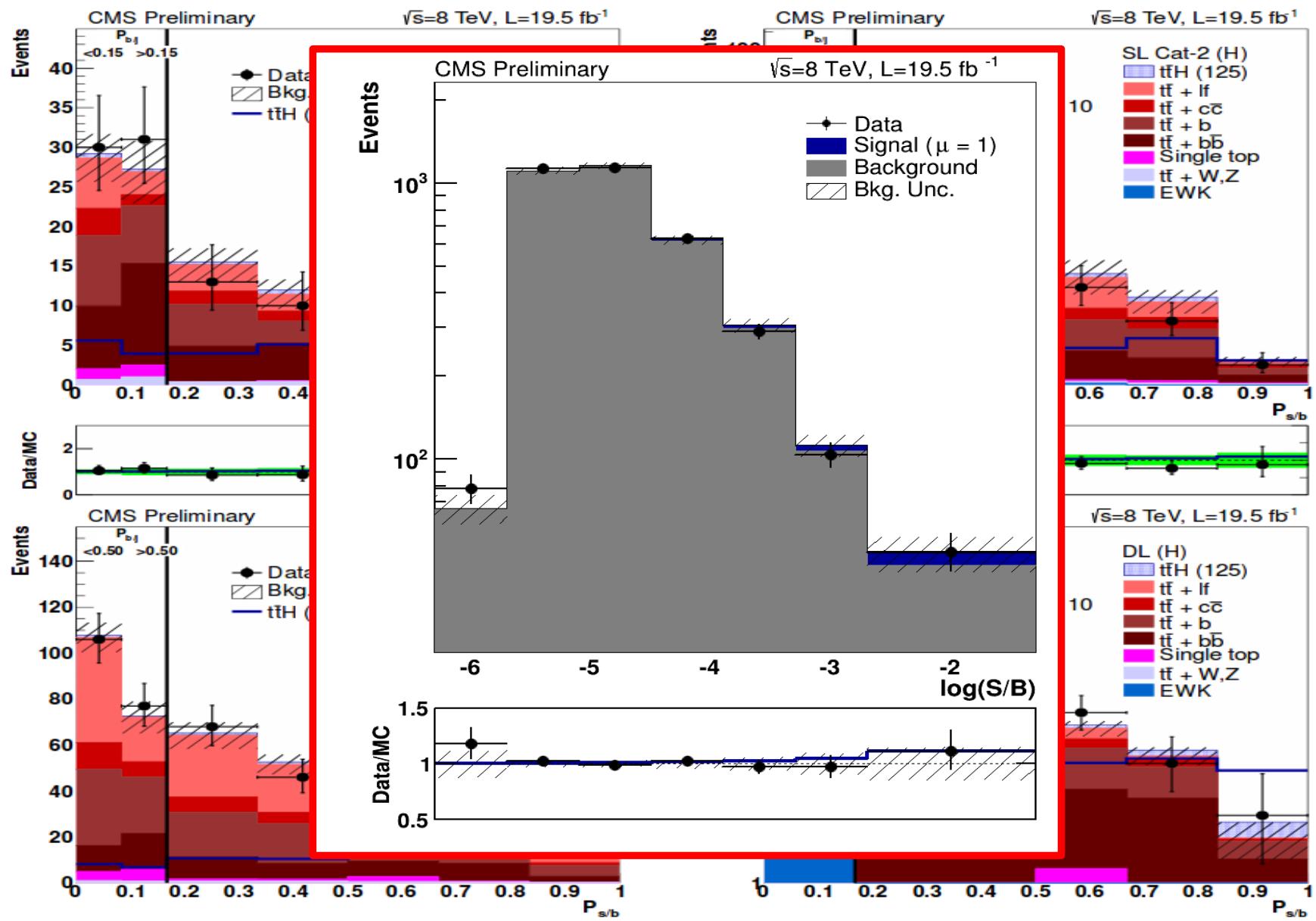
- Improved sensitivity by **categorization** at generator level: 3 semi-leptonic (SL) categories based on W reconstruction + 1 dileptonic category (DL)
- **MEM based categorization** to improve signal purity: SL Cat-1 and DL very pure categories because signal theoretical hypothesis matches exactly experimental signature
- In standard analysis: **2 more categories !**

single-lepton			di-lepton
“SL Cat-1”	“SL Cat-3”	“SL Cat-2”	“DL”
$tt \rightarrow b\ell\nu b\bar{q}q$  all quarks reconstructed  (+ gluon(s))	$tt \rightarrow b\ell\nu b\bar{q}q$  all quarks but one W-quark reconstructed	$tt \rightarrow b\ell\nu b\bar{q}q + g$  all quarks but one W-quark reconstructed  + ≥ 1 gluon(s)	$tt \rightarrow b\ell\nu b\ell\nu$  all quarks reconstructed

# The MEM for ttH with H $\rightarrow$ bb



# The MEM for ttH with H → bb

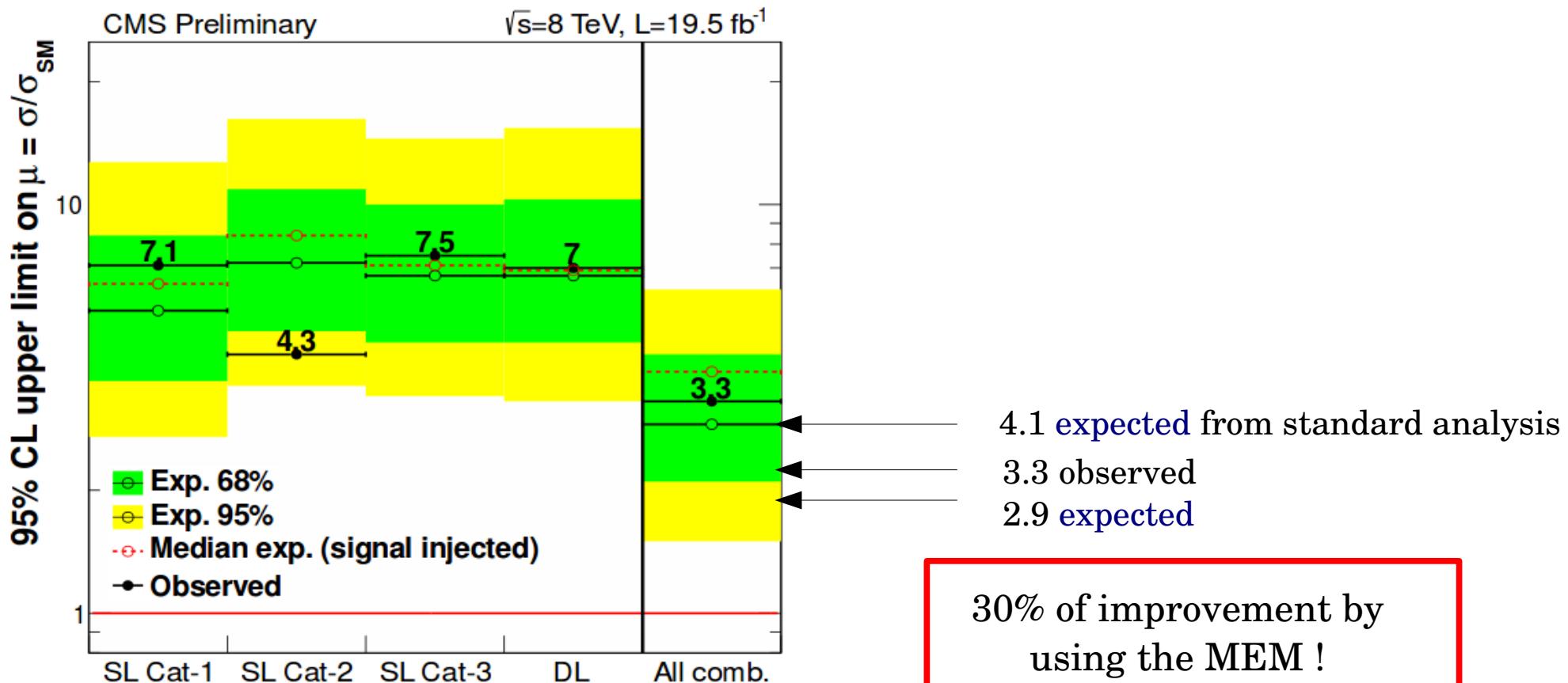


# The MEM for ttH with H → bb

[CMS-PAS-HIG-14-010](#)

## Results:

Expected limits of x: we are able to exclude our signal x times the  $\sigma_{\text{SM}}$   
→ the lower the limit is, the better it is !



# Conclusion

- Matrix Element Method **powerful** method
- Help to improved signal/background discrimination
- Unfortunately not easy tool
- Still lot of approximations, need **improvements** in the future
- Used to for the **discovery of the Higgs** and **Higgs spin** determination (MELA)
- Used in **ttH analysis** to improve signal/background discrimination  
→ improvement compare to the standard analysis
- **Other CMS analysis** use this method: Zbb analysis, MEM as cross check for background discrimination, also considered for Z(bb)H(bb) and H(WW)H(bb) analysis, work on going...