ZH->llbb higgs search with MEM

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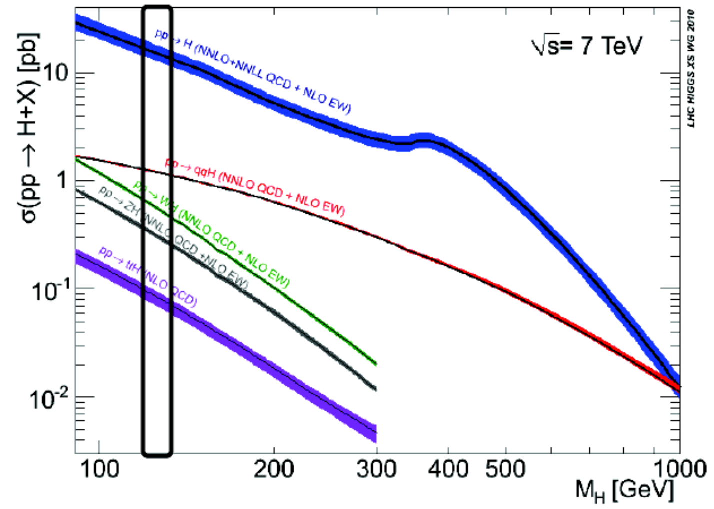
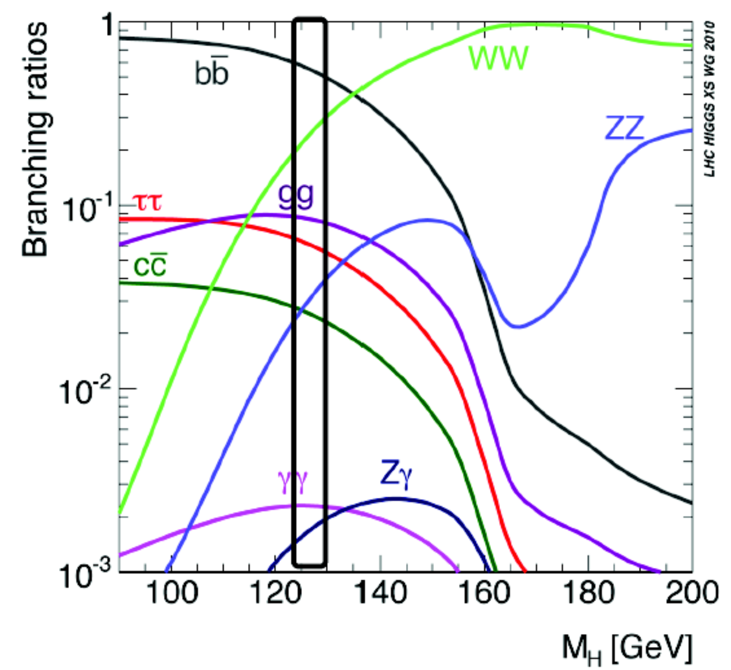
Motivation

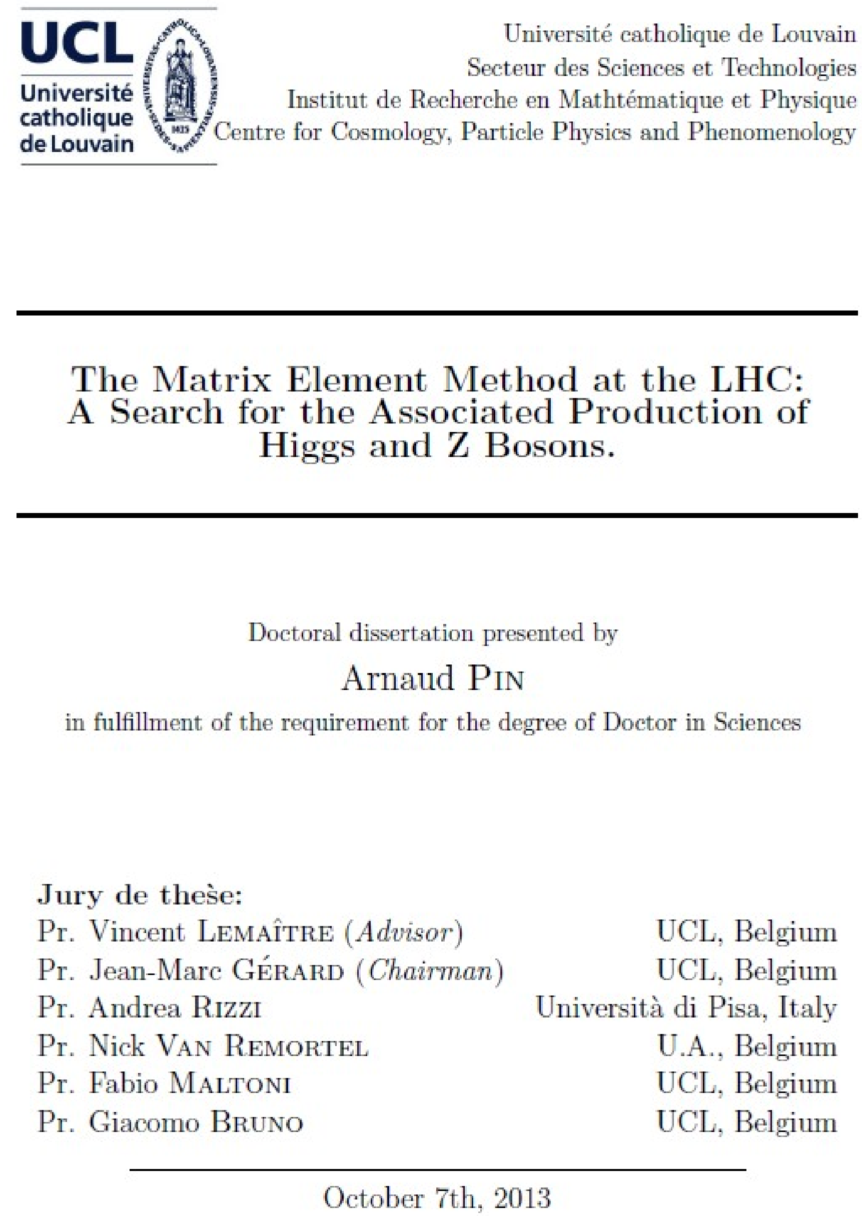
- Higgs-boson-like particle discovered first in bosonic final states
  - ◊ Interest to test couplings to fermions. In particular to quarks
- CMS best expected sensititivity worldwide to H → bb. Using all 7 (5fb^{-1}) and 8 (20 fb^{-1}) TeV data available. Mainly from associate production:
  - ◊ VH: Using **WH → lnubb, ZH →ννbb, ZH → llbb**
    - m_H=125 GeV → 1.89 (0.95) observed (expected) exclusion limit, μ = 1 ± 0.5
  - ◊ Implements Tevatron and new advanced analysis techniques:
    - Relatively boosted selection: tipically pT(V) > 100 GeV
    - training multivariate BDT: inputs such as Mbb, pT(V), ...
    - regression techniques to improve mass resolution





Motivation

- This presentation
  - **Alternative approach relying on a Matrix Element Technique for ZH → llbb channel**
    - Attempt to maximize usage of kinematic information
    - Cross check with the more classic BDT analysis can “validate” the MEM
  - Search uses full 7 and 8 TeV datasets (*CMS-AN-12-476*)
    - **Result is final**: full treatment of systematics, cross checks, unblinding of the results ongoing
    - CMS internal document for the moment
    - Todays results **only 7 TeV part** → *Arnaud Pin Thesis*[1]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Université catholique de Louvain
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Centre for Cosmology, Particle Physics and Phenomenology

The Matrix Element Method at the LHC:
A Search for the Associated Production of
Higgs and Z Bosons.

Doctoral dissertation presented by
Arnaud Pin
in fulfillment of the requirement for the degree of Doctor in Sciences

Jury de thèse:

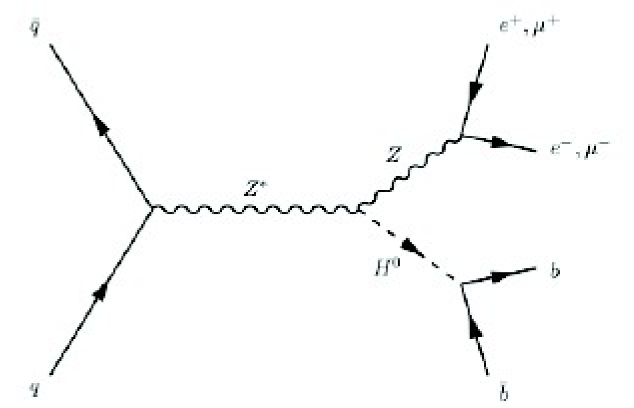
Pr. Vincent Lemaître (*Advisor*)	UCL, Belgium
Pr. Jean-Marc Gérard (*Chairman*)	UCL, Belgium
Pr. Andrea Rizzi	Università di Pisa, Italy
Pr. Nick Van Remortel	U.A., Belgium
Pr. Fabio Maltoni	UCL, Belgium
Pr. Giacomo Bruno	UCL, Belgium

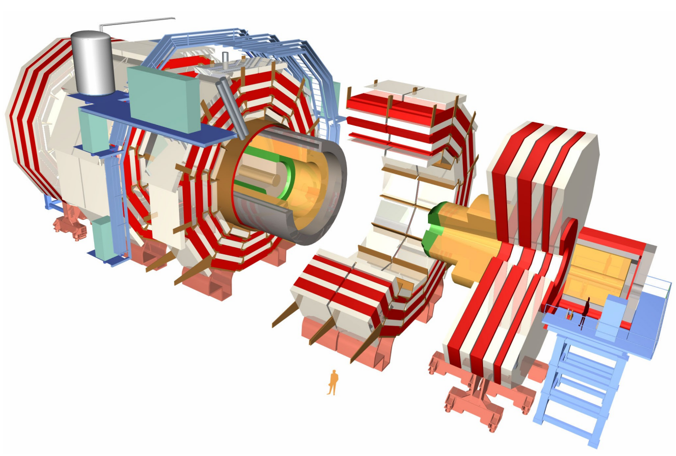
October 7th, 2013

1: http://cp3.irmp.ucl.ac.be/upload/theses/phd/Pin_Arnaud.pdf

Outline/Analysis Overview

- Event Selection
- Estimation of **MadWeight** Matrix-Element Weights (main subject of this talk)
  - Basic aspects of MEM weight calculation
  - Special **Treatment of ISR**
  - **Treatment of FSR** using the MEM
    - Related to **categorization** of events: **2-jet** and **>= 3 jet** categories
  - Treatment of ME for **overconstrained systems (ZZ, ZH)**
    - **E/P conservation**
    - **η/φ smearing TF**
  - Data/MC Validation
- Data-driven fit to normalize main background
  - Usage of MEM to improve accuracy
- Final multivariate discriminator using as inputs ME Weights
  - Basic Idea: Combine ME weights with MLP to produce discriminators
- Treatment and effects of experimental uncertainties

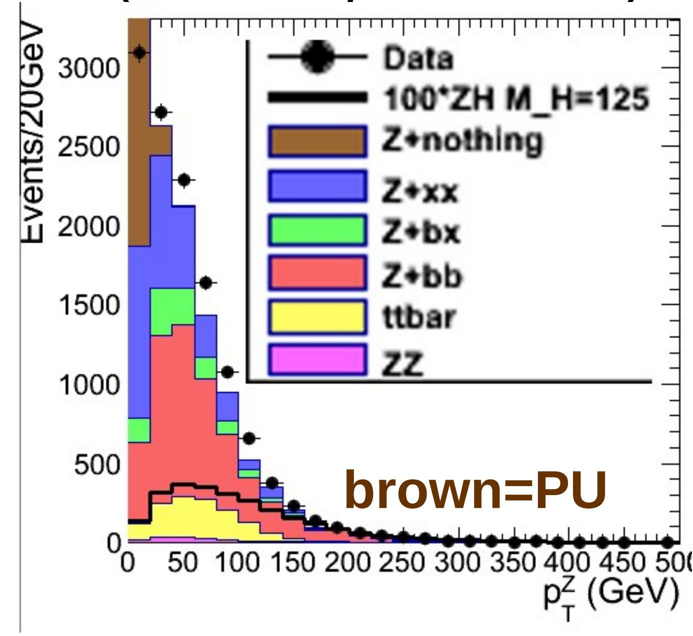




Event Selection

- Basic event selection (**as inclusive as possible**)
  - **2 leptons** pT>20 GeV
  - At least **2 jets**
    - Categorization: **njet=2** and **njet >= 3**
  - Anti PU cuts: $P_T$jet1>40, $P_T$jet2>25, P_TZ > 20 GeV
  - **2 b-tagged jets** (1 “Medium” + 1 “Loose” tags)
  - **small MET**: MET significance < 10

Plot for 8 TeV data (more important PU)



- Main backgrounds after event selection
  - **tt** (sizeable), **ZZ** (irreducible but small)
  - Main Z+jets: **Zbb, Zbx, Zxx.** Notation: b (x) → if gen level b-parton is (not) found within ΔR < 0.3 of reco jet

Number of expected signal and bkg events after selection (7 TeV analysis 5 fb^{-1})

Process	Zbb	Zbx	Zxx	tt	ZZ	ZH 125
# exp. events	**1060**	**767**	**886**	**231**	**49**	**8**

Event Selection: Additional consideration

- In this search sensitivity to ZH is based on training MLP using as inputs ME-weights
  - Available statistics for training are quite limited
  - Only few thousands of Zbb (main background)

Number of MC events available for training after event Selection

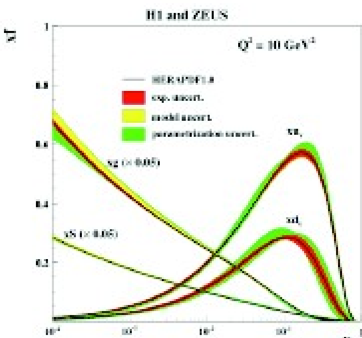
Sample	2jets events	> 2 jets events
Drell-Yan inclusive	1663	5530
DY $P_{tZ} > 100$ GeV	511	2386
$Zb\bar{b}$ (4F)	5561	16800
$t\bar{t}$	3834	9969
Z(ll)Z($b\bar{b}$)	3098	4927
Z(ll)H($b\bar{b}$) ($m_H = 125$ GeV)	12914	11481

- Important to reduce the number of input observables in this context

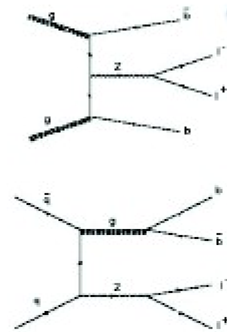
Evaluation of ME Weights: Intro

- Matrix Element evaluation based on **MadWeight**[1]

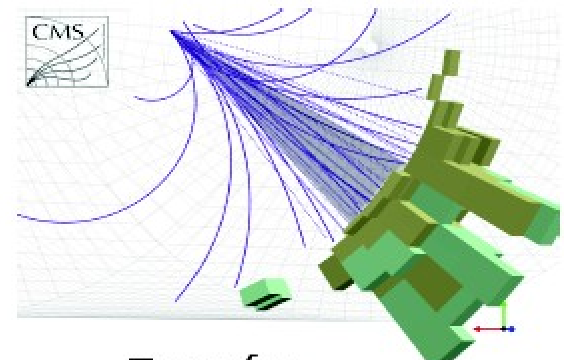
$$P(x^{vis}|\alpha) = \frac{1}{\sigma_\alpha}\int dx_1 dx_2 f(x_1) f(x_2) \int d\phi |M(p)_\alpha|^2 W(p^{vis}, p)$$



Parton Distribution Functions



Leading Order process



Transfer functions

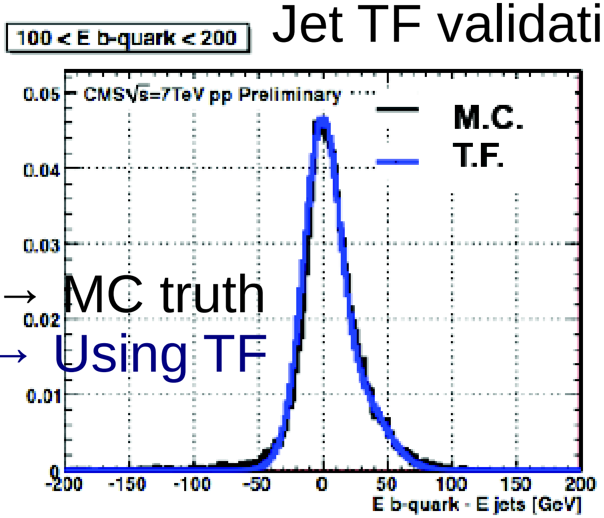
- This search uses non-normalize event probabilities (weights)
  - Normalization factor $1/\sigma_\alpha$ not taken into account
  - Zbb (gg, or qq production), tt, ZZ, ZH hypothesis considered
  - Usage of LR approach using probabilities will be explored in the future
- |M(p)|, pdf's provided by MadGraph/MadWeight
- User defined Transfer Functions are inputs of MadWeight

1: http://arxiv.org/abs/1106.0522

Evaluation of ME Weights: Transfer Function

- **Conditional Probability**: $W(p_{vis}; p) = P(p_{vis}|p)$
- **Factorization** assumed on the different particles (jets, leptons) and kinematical variables (Energy, η, φ)
- **Angular variables** assumed to be **well measured**
  - Use TF only on Jets and Lepton energies (or pT)
    - TF parametrized by double gaussian
    - Parameters extracted from likelihood fit using MC events

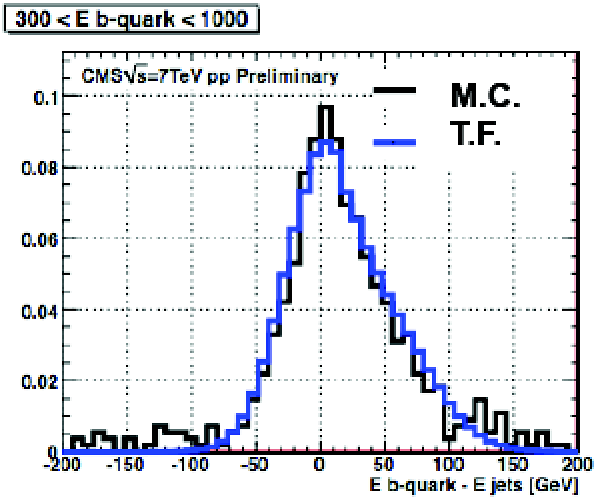
Jet TF validation



black → MC truth
blue → Using TF

$$W(E^{vis};E) = \frac{1}{\sqrt{2}(P_2 + P_3.P_5)} \cdot \left(e^{-\frac{(E-E^{vis}-P_1)^2}{2P_2^2}} + P_3 e^{-\frac{(E-E^{vis}-P_4)^2}{2P_5^2}} \right)$$

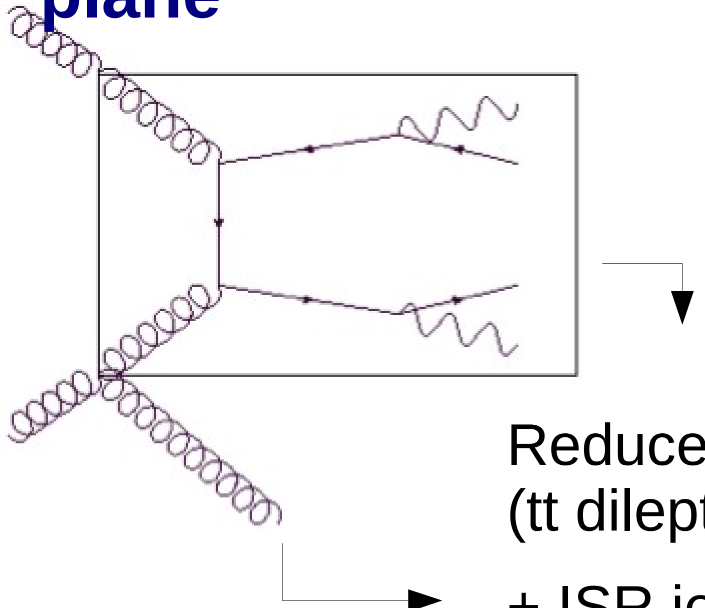
$$P_i = a_{i1} + a_{i2}E_{gen}(+a_{i3}\sqrt{E_{gen}})$$



  - For the future: Consider usage of “tabulated” TF

Evaluation of ME Weights: ISR treatment

- Matrix-Element Weights evaluated in MadWeight **at leading order**
- Effect of ISR introduced by applying **boost in the transverse plane**



Reduced event (tt dilepton)

+ ISR jet

- ◊ pT boost driven to evaluate ME in a framework where “reduced event” is at rest
  - choice driven by event hypothesis (process)

- If fully observable final state

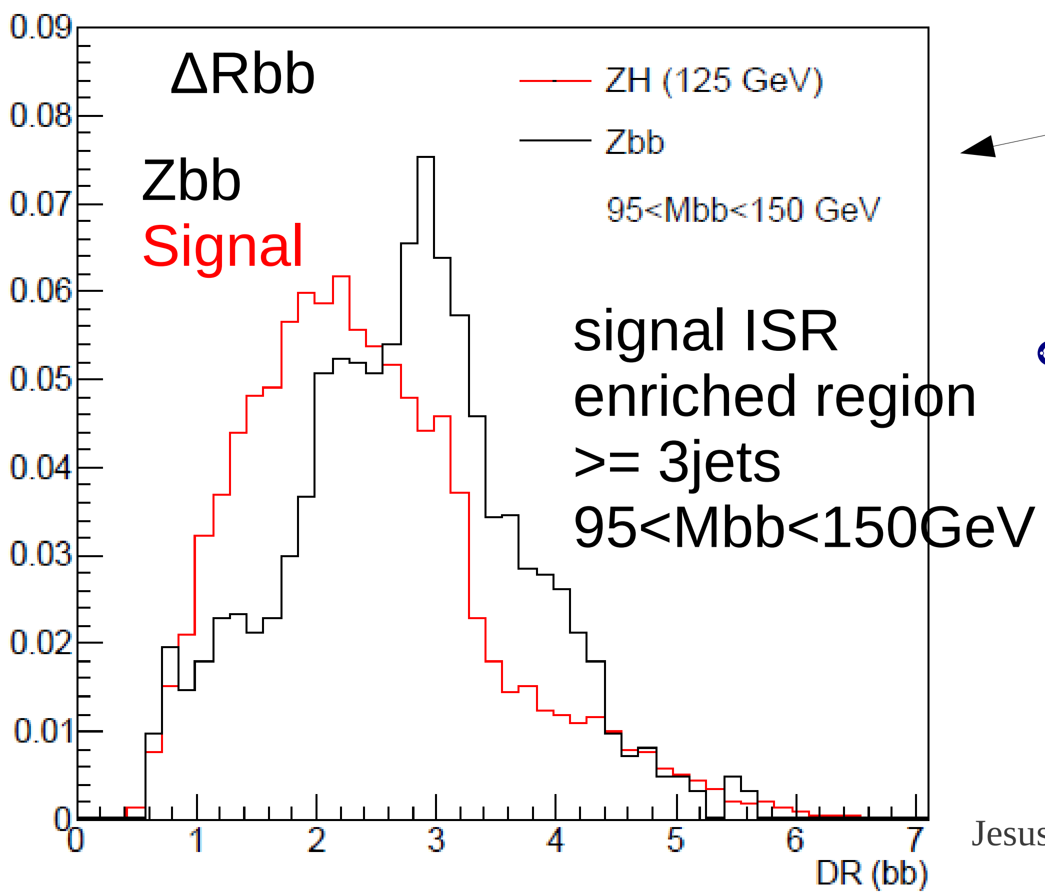
$$\vec{P}t_{boost} = \sum_{L.O.finalstate} \vec{P}t = -\sum_{radiation} \vec{P}t$$

- If not (tt dileptons)

$$\vec{P}t_{boost} = \sum_{L.O.finalstate} \vec{P}t + \vec{MeT} = -\sum_{radiation} \vec{P}t$$

Evaluation of ME Weights: ISR treatment Improvements?

- **Simple Approach:** Adding extra variables sensitive to ISR helps?
  - **Benchmark:** ZH and Zbb separation power
  - **Comparison:** Using MLP discriminator using as inputs
    - ME weights (for Zbb and ZH processes) including ISR corr.
    - Adding or not extra variable senstive to ISR: **ΔR(bb)**

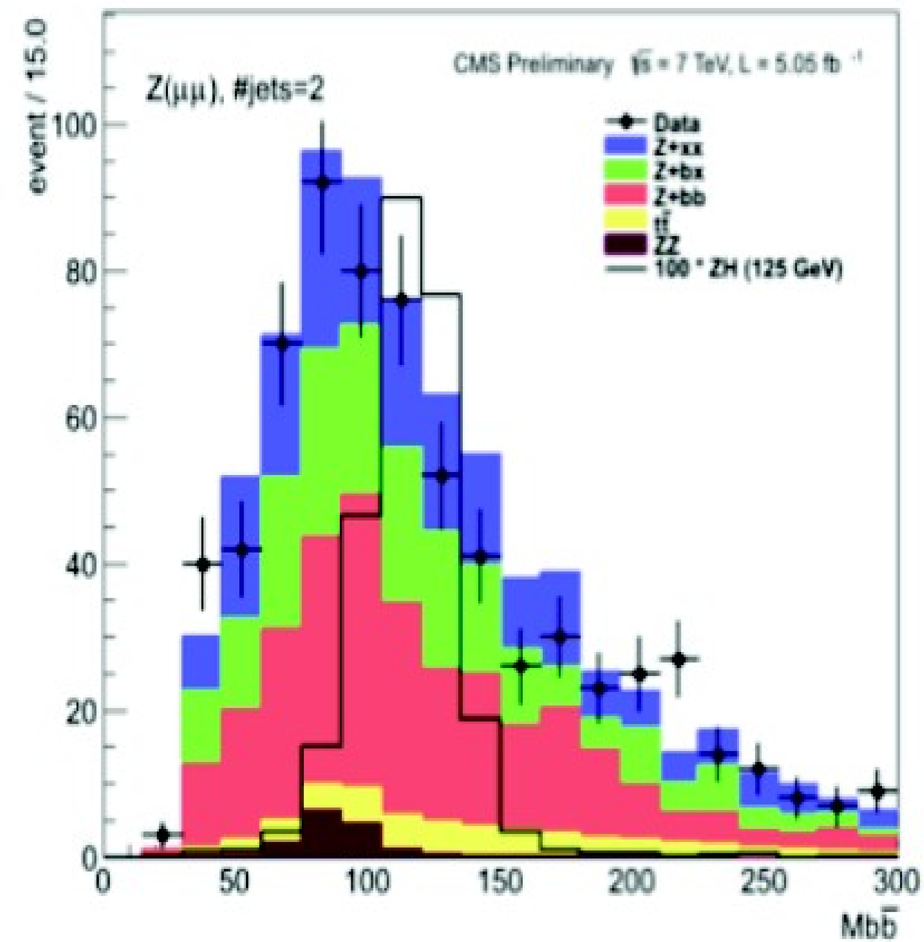


- **Result:** Despite good separation power of ΔR(bb) no visible improvement in ZH vs Zbb discrimination is seen
  - **Treatment of ISR based on pT boost seems sufficient**

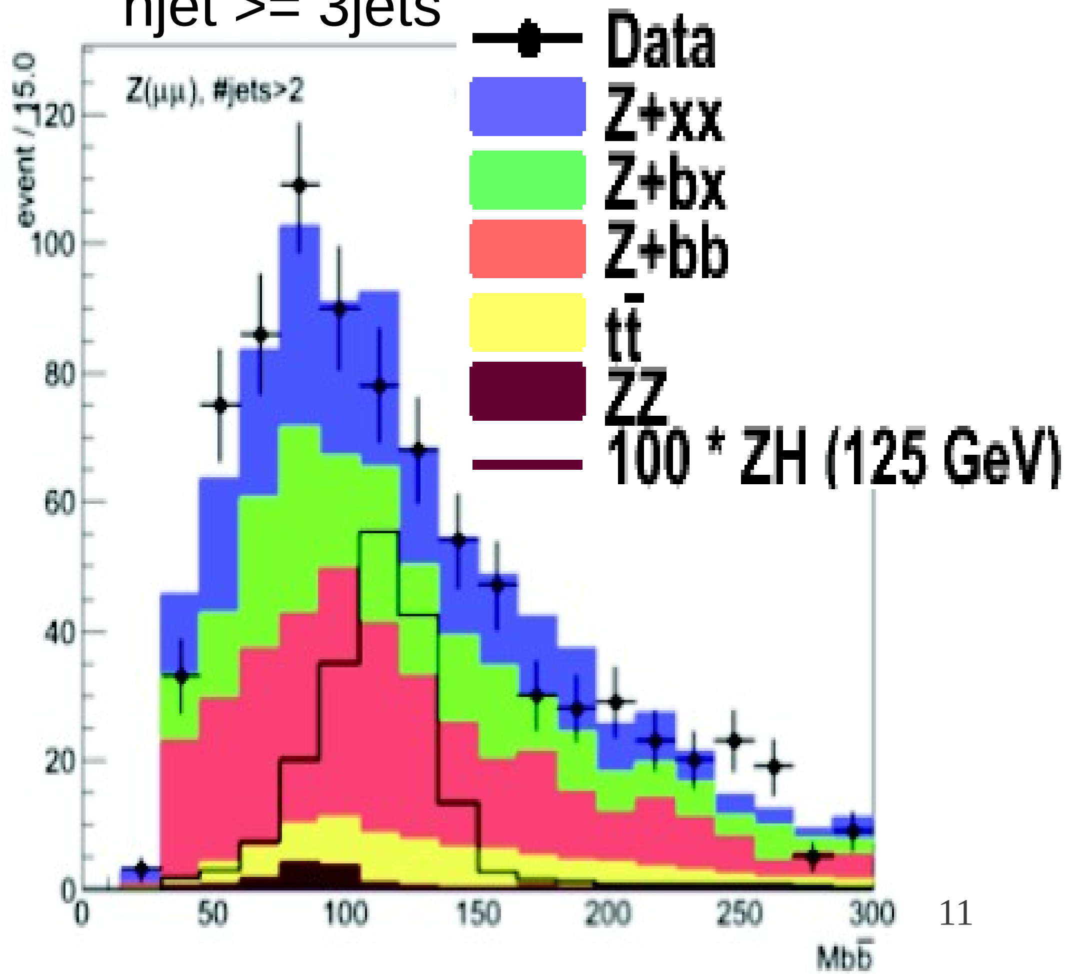
Evaluation of ME Weights: FSR treatment

- Drives categorization of events: **njet=2**, or **>= 3**
  - ISR taken into account by transverse boost corrections
  - FSR not considered in set of estimated ME weights
  - In addition, better mass resolution and S/B in njet=2

njet = 2

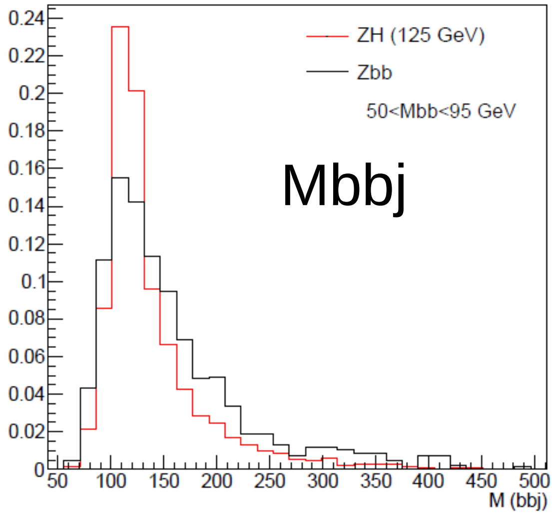


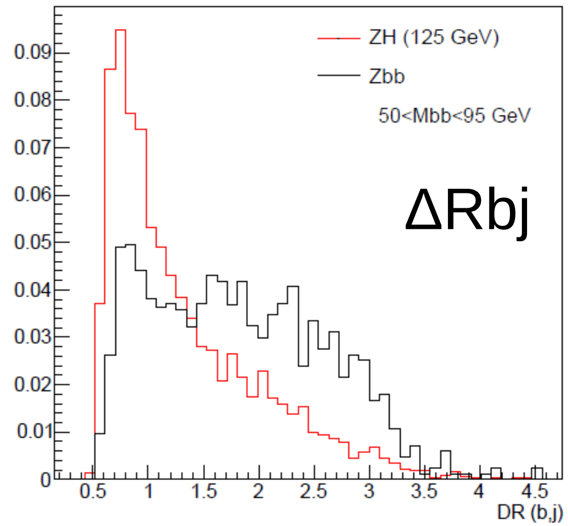
njet >= 3jets



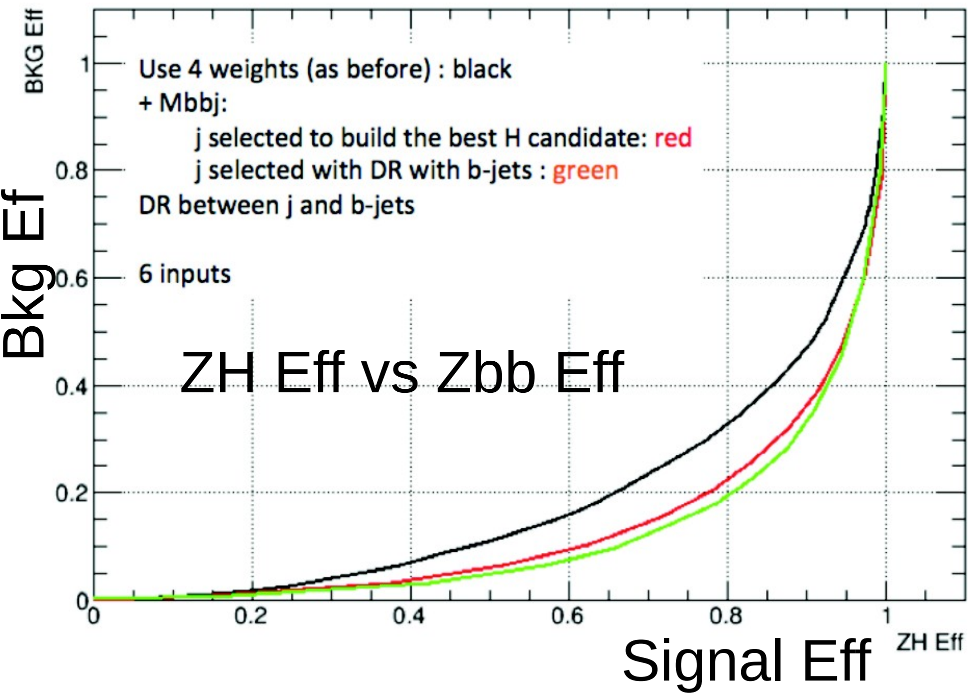
Evaluation of ME Weights: FSR treatment

- Simple Approach: Adding extra variables sensitive to FSR
  - In this case Mbbj, ΔR(b,j)





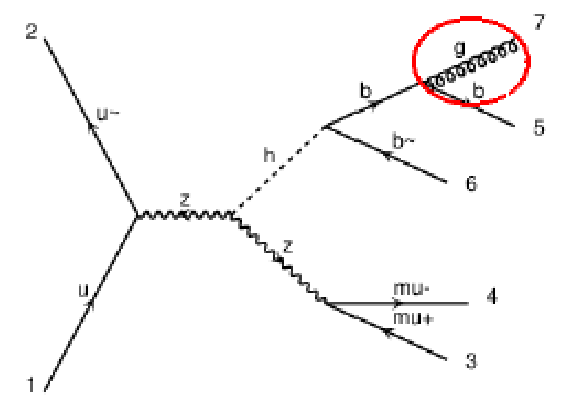
Signal FSR enriched region
njet >= 3
50<Mbb<95GeV



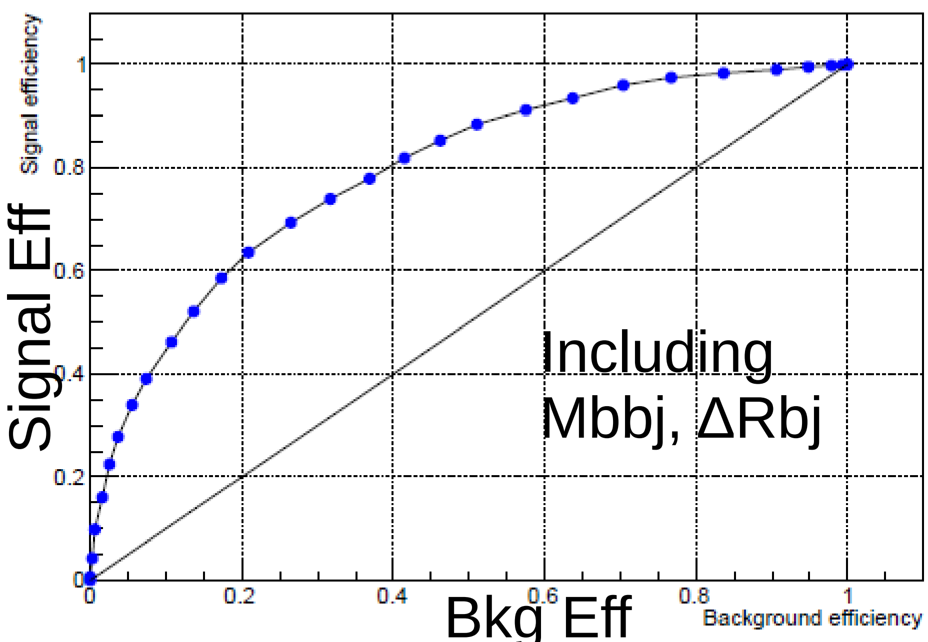
- **Result:** Important improvement
  - **Green: With Extra Variables**
  - **Black: W/O Extra Variables**
- Extra variables included in final MLP discriminator (in addition to ME weights)

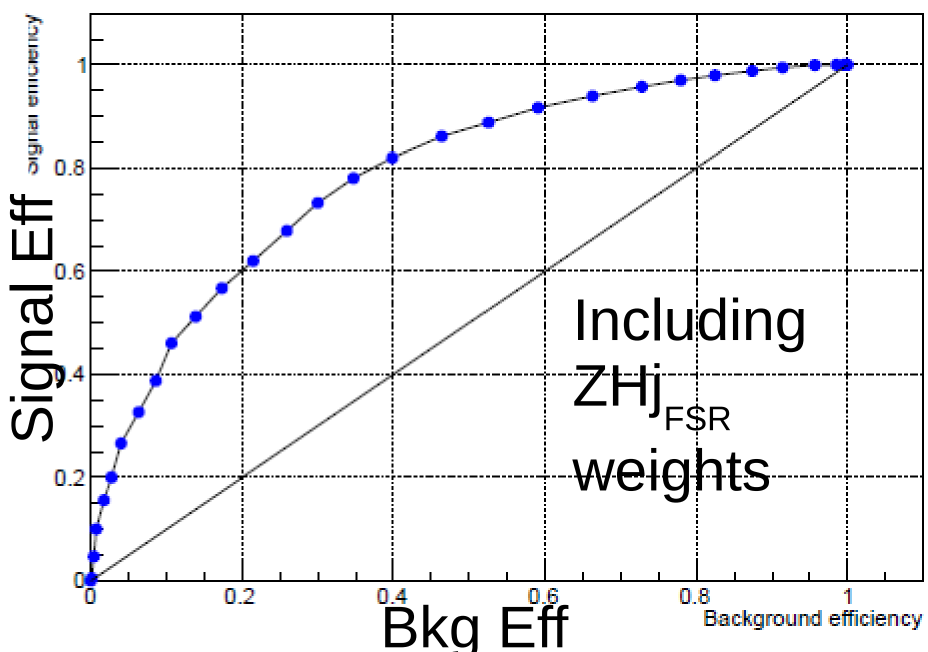
Evaluation of ME Weights: FSR treatment improvement

Final State Radiation : Zhj_{FSR}



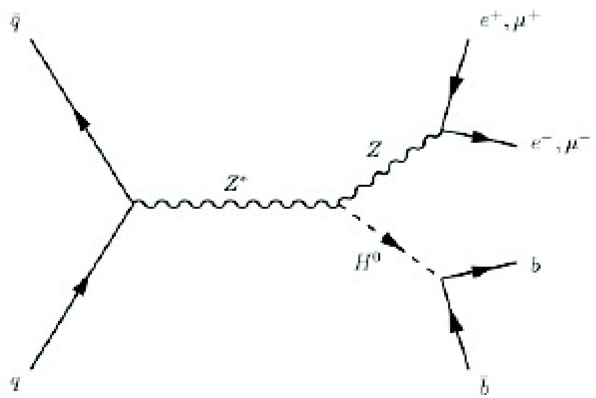
- For the future: Evaluation of ME Weights with 1 extra FSR jet
  - ◊ As expected: **Similar performance that introducing extra variables** → Brieuc Francois Master Thesis
  - ◊ Advantages
    - More consistent approach
    - It can result in a reduction of number of input variables
  - ◊ Disadvantage: longer CPU time to compute ME weights → Around factor 6



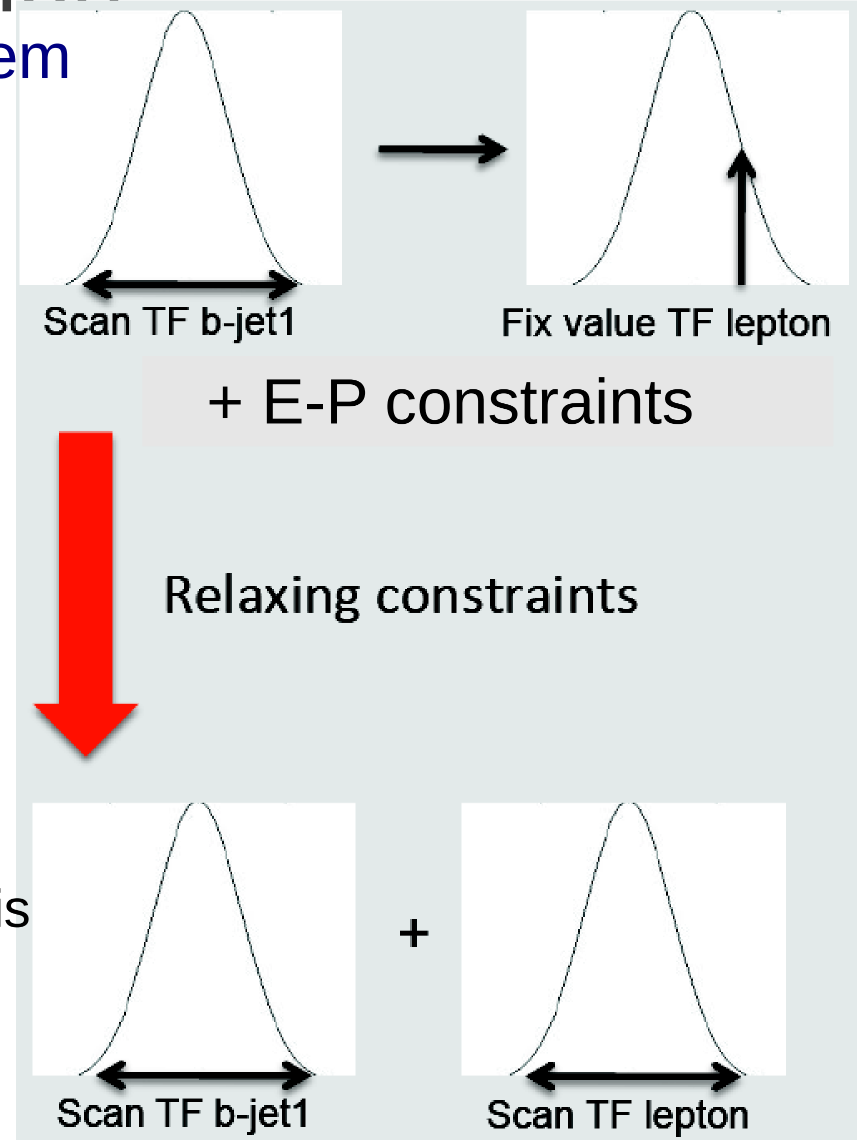


Evaluation of ME Weights: Overconstrained Processes → E-P conservation

- ZH, ZZ Production: Overconstrained system due to 2 intermediate resonances



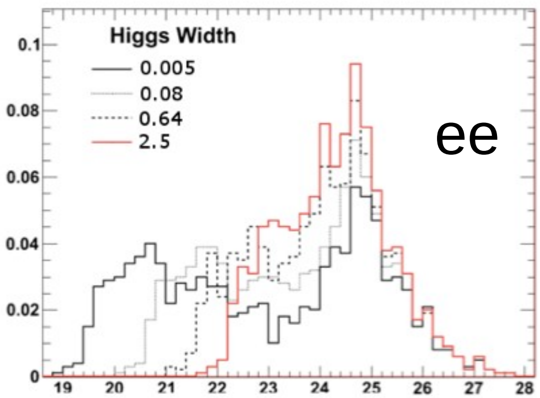
- Phase space covered by the 2 lepton + 2 jet TF is not probed
  - Kinematic of one particle is probed (integration over 1 TF)
  - E-P conservation fixes the kinematics of the other particles (TF evaluated but no integration is performed)
- Solution: **Relax E-P conservation** in the transverse plane
  - **Both weights** (relaxing or not E-P) conservation for ZH and ZZ **considered in the analysis**



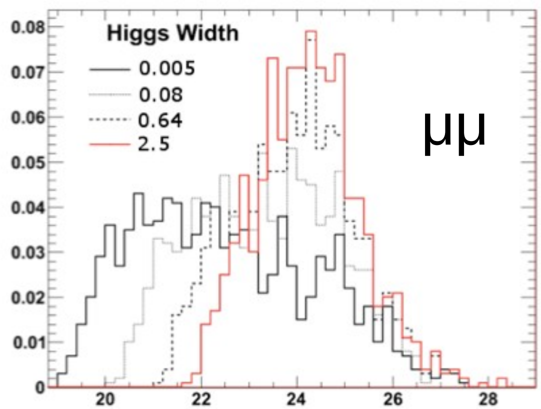
larger phase space probed allowing to maximize the weights fro double resonance processes

Evaluation of ME Weights: Overconstrained System ZH →Narrow width approximation

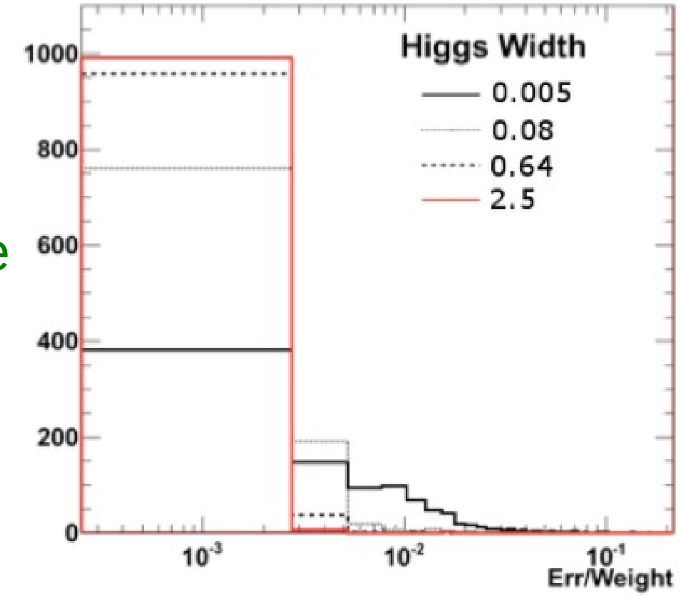
- Feature in ZH weight enforcing E-P conservation
  - Double peak structure in ee (but not in μμ channel)
  - Reason → Tail of electron TF drops faster than muon one
- Solution: Enlarge $\Gamma_H = 5.10^{-3}$ → 2.5 GeV
  - Double peak structure disappears
  - e and mu weights become similar
  - Numerical relative uncertainty on the weights decrease
  - Discriminative power not dramatically affected

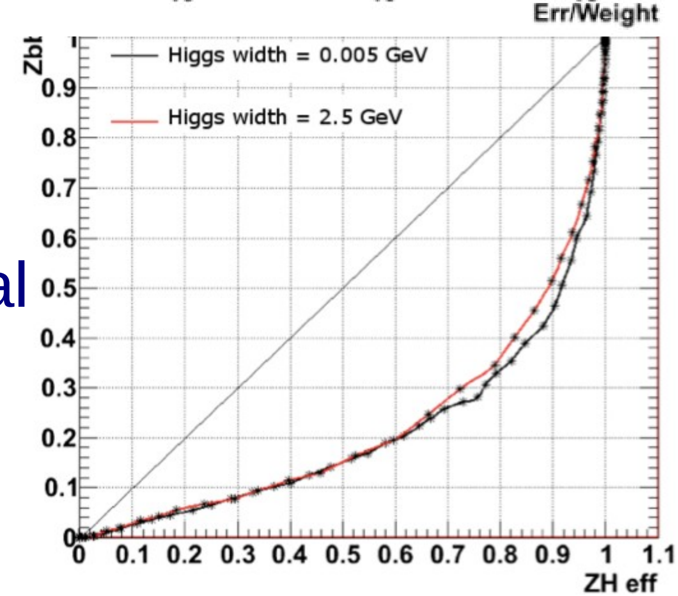


ZH weight



ZH weight

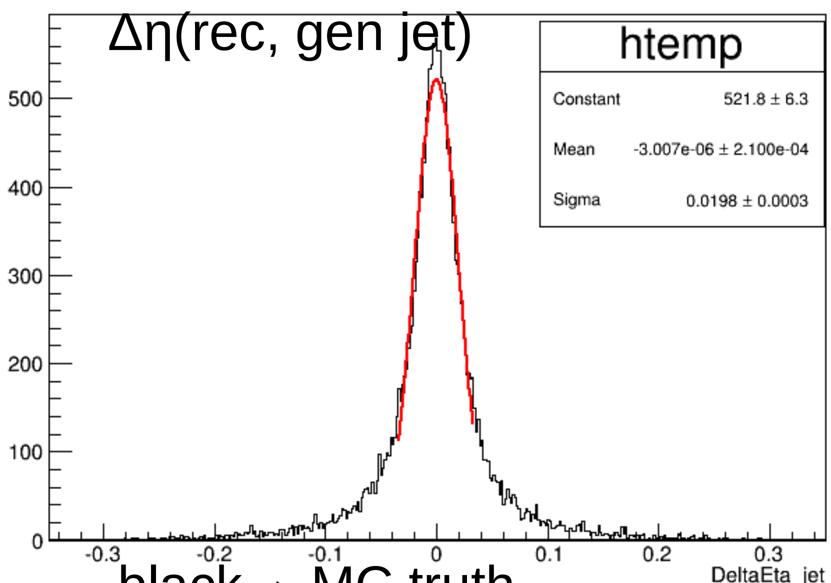




- Shows interplay between TF and ME theoretical constrains

Evaluation of ME Weights: Overconstrained Systems → Further improvments

- For the future: Further explore interplay between theoretical constrains and TF
  - Goal: Usage of a **single ME weight** containing all theoretical constraints (E-P conservation, nominal Γ_H) improving TF description
  - For the moment: add angular TF on jet directions while imposing E-P conservation (and nominal Γ_H): Simple gausian parametrization



black → MC truth

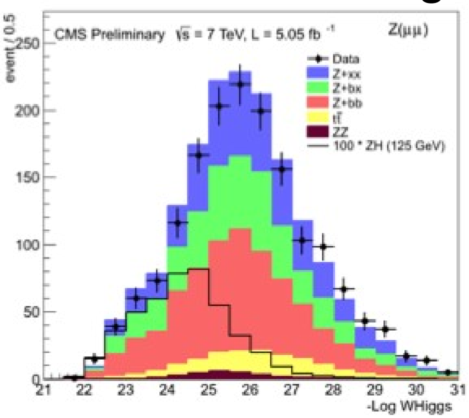
red → gaussian TF

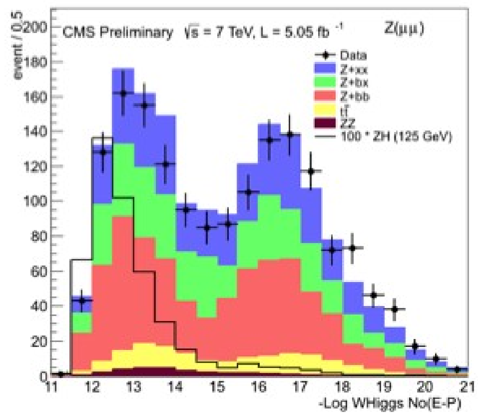
- Preliminary results:
  - Double peak structure in ee channel disappear but worse discrimination power of ZH weights
  - Further investigation ongoing
    - Use proper parametrization of angular TF
    - ...

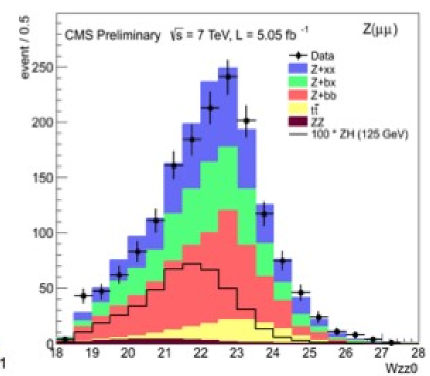
Evaluation of ME Weights: Data/MC Validation

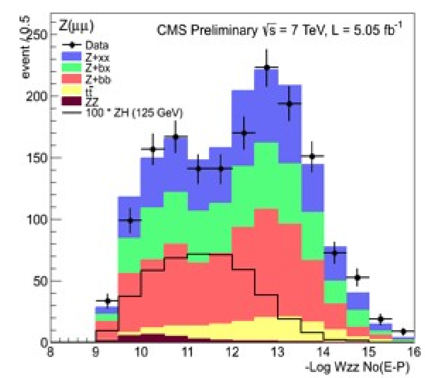
- Set of 7 ME weights evaluated as described in previous slides well modeled
  - Using Data-Driven bkg normalization (next slide)
  - Important signal discrimination power
    - Mainly from ZH weights
    - Additional separation from other weights

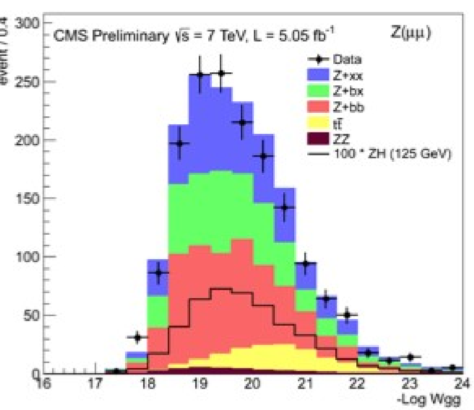
Process	Hypothesis	ISR correction	E-P conservation
Higgs	$qq \to ZH \to l^- l+ b\bar{b}$	without MeT	conserved
Higgs	$qq \to ZH \to l^- l+ b\bar{b}$	without MeT	Not conserved
$t\bar{t}$	$pp \to t\bar{t} \to l^- l + \nu\bar{\nu}\ b\bar{b}$	with MeT	conserved
$Zb\bar{b}$	$gg \to l^- l+ b\bar{b}$	without MeT	conserved
$Zb\bar{b}$	$qq \to l^- l+ b\bar{b}$	without MeT	conserved
ZZ	$qq \to ZZ \to l^- l+ b\bar{b}$	without MeT	conserved
ZZ	$qq \to ZZ \to l^- l+ b\bar{b}$	without MeT	Not conserved

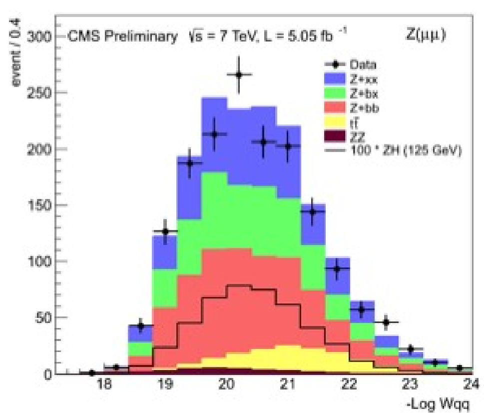


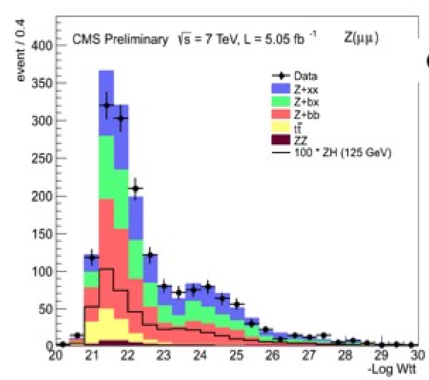


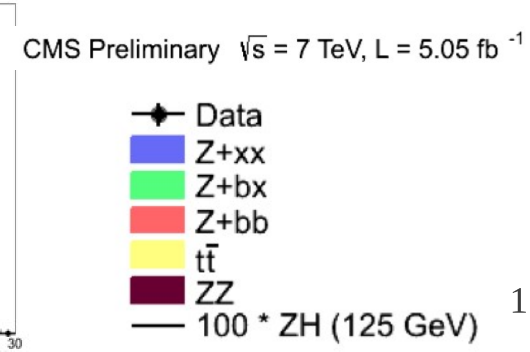








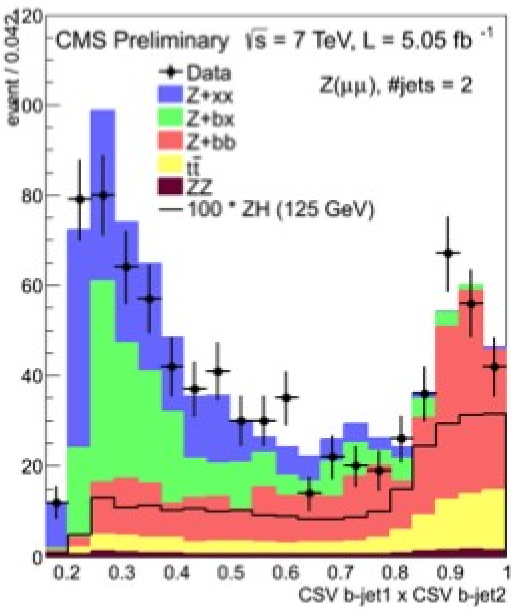




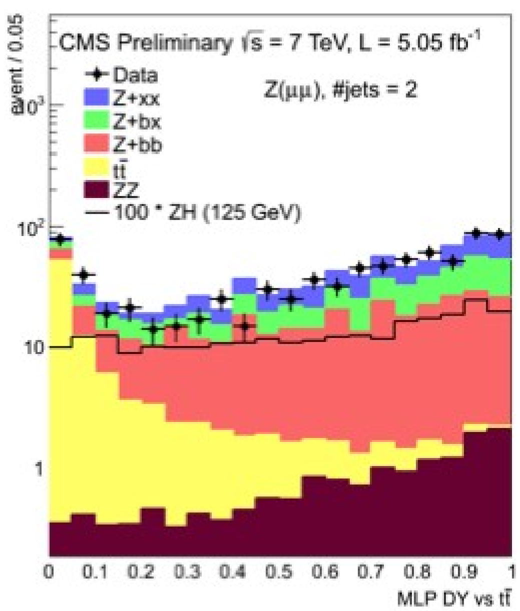
Data-Driven Background Normalization

- Normalization of main backgrounds tt, Zbb (njet=2), Zb+extra jet, Zxx based on 2-D fit to data in Control Region (inversion of Mbb cut)
  - Variable to separate mistags from backgrounds with real bjets: **b-tag discriminator**
  - Variable to separate Zbb from tt: MLP using Zbb (gg, qq) and tt weights
    - Simultaneous fit 2 lepton x 2 jet categories

pos-fit variables for μμ 2-jet channel



b-tag discr.

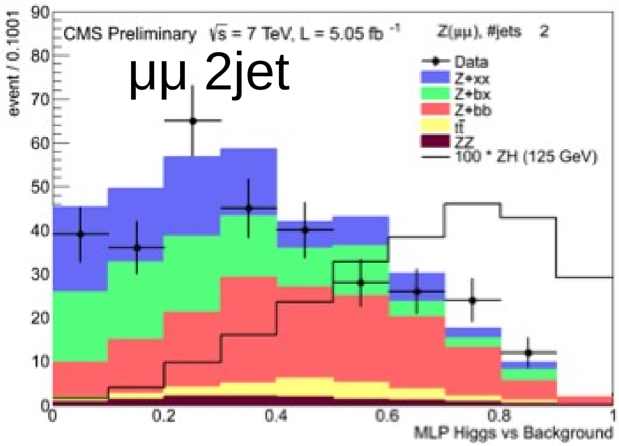


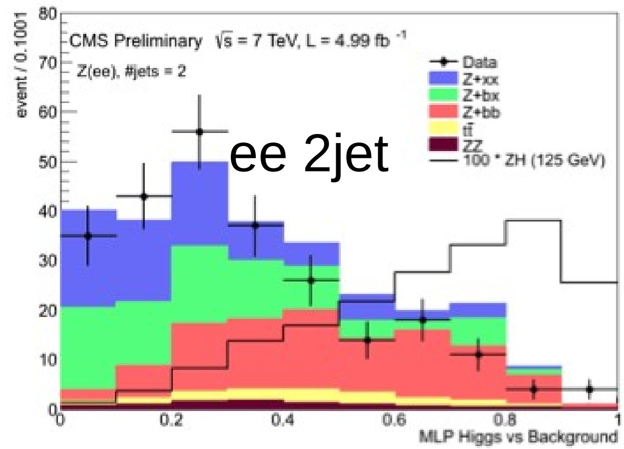
Zbb vs tt discr

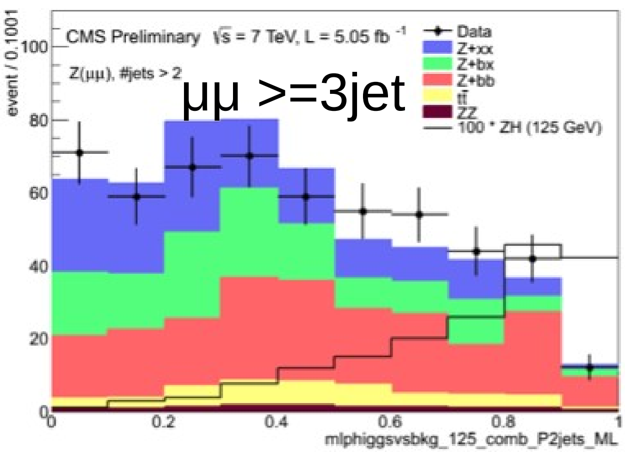
- Usage of Zbb VS tt discriminator instead of simpler discriminator such as Mll results in 25% improvement in accuracy in normalization factor
  - Tested on similar context

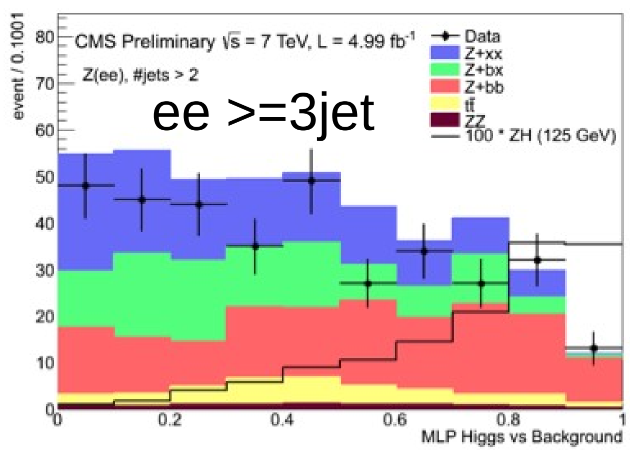
Final discriminator for ZH search

- In order to deal with limited statistics better, 3 intermediate MLP's are trained
  - ZH vs Zbb, ZH vs tt, ZH vs ZZ
  - Using involved ME weights (+ extra FSR variables)
- Final MLP trained
  - Using as inputs previous 3 MLP's and a combined sample of all backgrounds







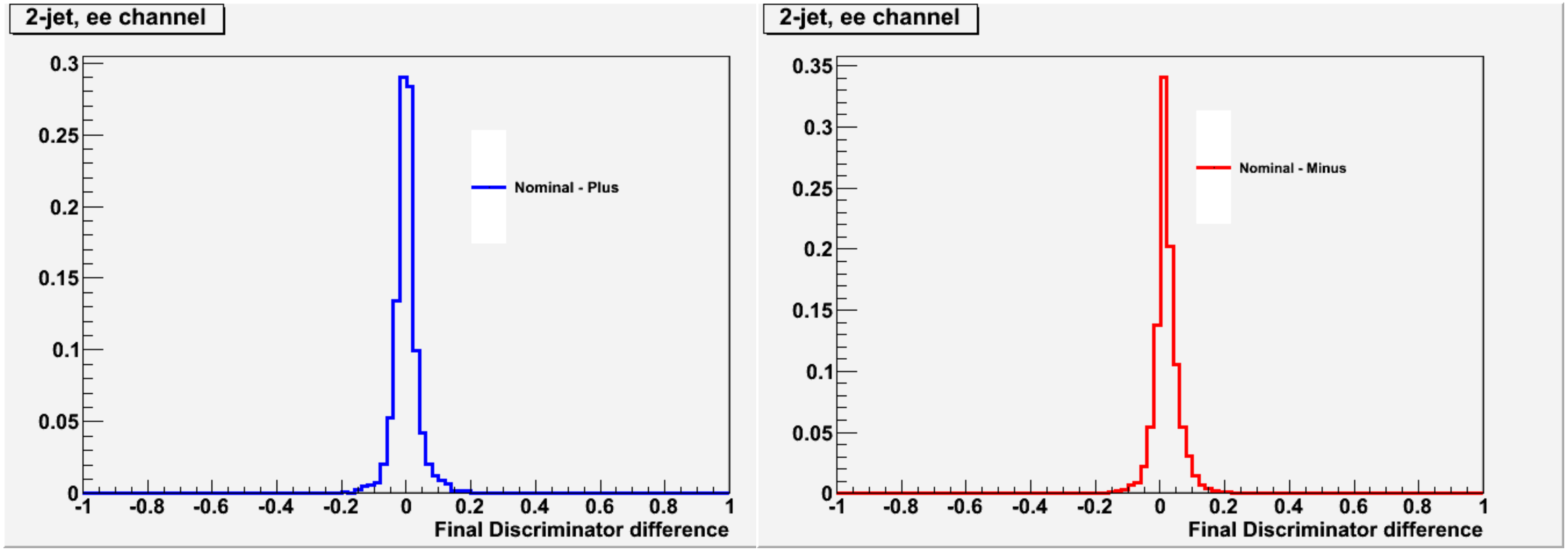


- Final discriminator very sensitive to ZH and well modeled in low score bins

Systematics

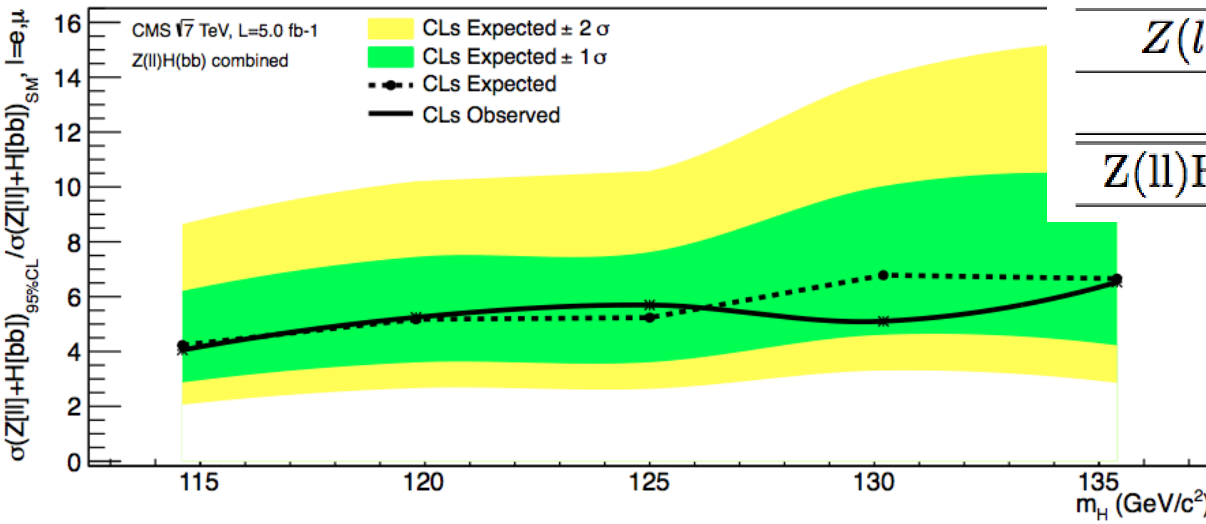
- Extensive list of sources of systematic errors considered
  - Main systematics due to statistical uncertainty in background normalization fit → limiting factor available data
  - Statistical fluctuation on background shapes due to limited MC samples
- Systematics affecting shape of ME-based final discriminator such as JES or b-tagging uncertainties
  - JES → estimated evaluating ME-weights for ±1σ variation
  - **small impact in result ~1%**

Difference between nominal discriminator and discriminator for lus and Minus JES shifts (ZH sample)



Results

- Limits set on ZH production x BR (H → bb)



$Z(ll)Hb\bar{b}$ $\sqrt{s}=7$ TeV - $m_H=125$ GeV			
	Blind	Expected	Observed
Z(ll)H($b\bar{b}$)	$4.8^{+2.3}_{-1.5}$	$5.2^{+2.4}_{-1.6}$	5.7

Exclusion at 95% C.L. of 5.7 times the Z(ll)H(bb) process using only 7 TeV data

- Sensitivity comparable to the one of BDT analysis
  - More improvements will be pursued in order to assess wether the MEM is the most optimal analysis technique for this kind of searches

Summary

- Presented ZH → llbb search based on MadWeight ME method
- Treatment of ISR by using transerve boost correction
- Treatment of FSR can be improved by events with extra jet evaluating weights at higher QCD
- Interplay between angular TF, E-P requirement (and Γ_H) for overconstrained hypothesis
- Validated different Matrix-Element weights using data
- Full treatment of systematics
  - ME-based discriminator not too affected by **JES**, b-tag
- Results competitive wrt advance BDT based analysis

Plans

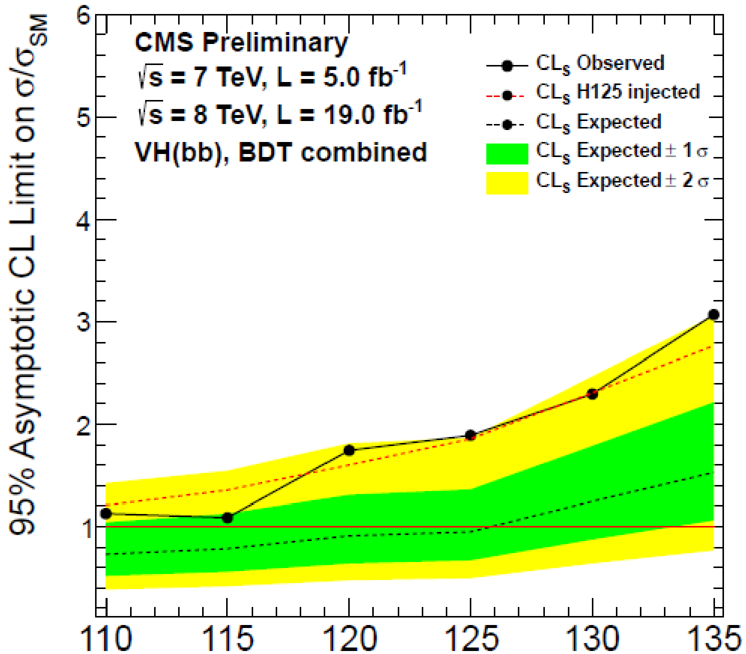
- Analysis improvements
  - Exploit better S/B for higher pT(Z)
  - Usage of regression techniques to improve Mbb
    - Inclusion of regressed Mbb in MLP doesn't improve result
    - TF will be derived on regressed jet energies
  - ...

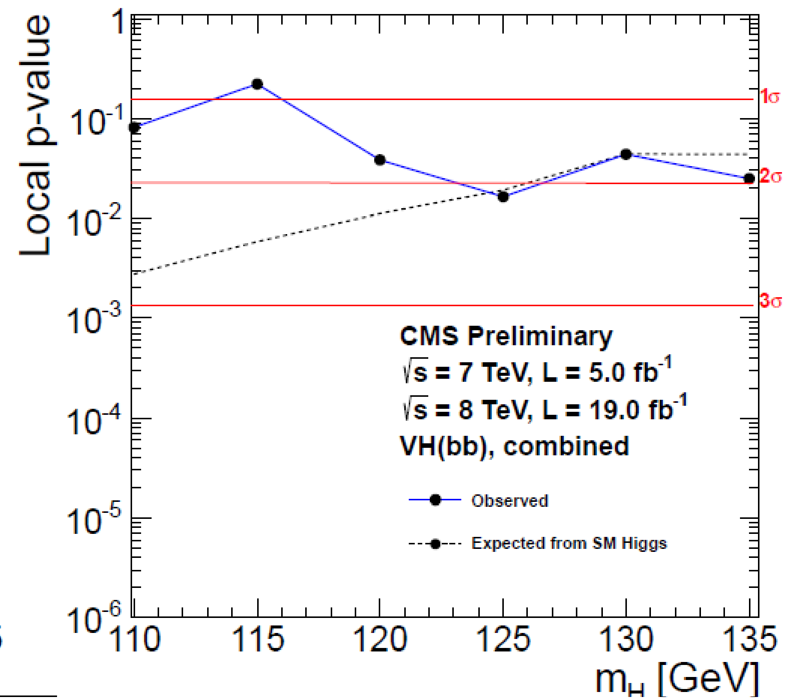
- Improvements in ME method
  - Use Tabulated TF's
  - Estimation of ME weights for higher order QCD (treatment of FSR)
  - Optimize evaluation of ME weights for overconstrained hypotheses by optimizing angular TF. Also related to E-P conservation (and Γ_H)
  - Usage of LR using event probabilities instead of ME weights
  - Calculate ME weights for Z+xx hypothesis
  - ...

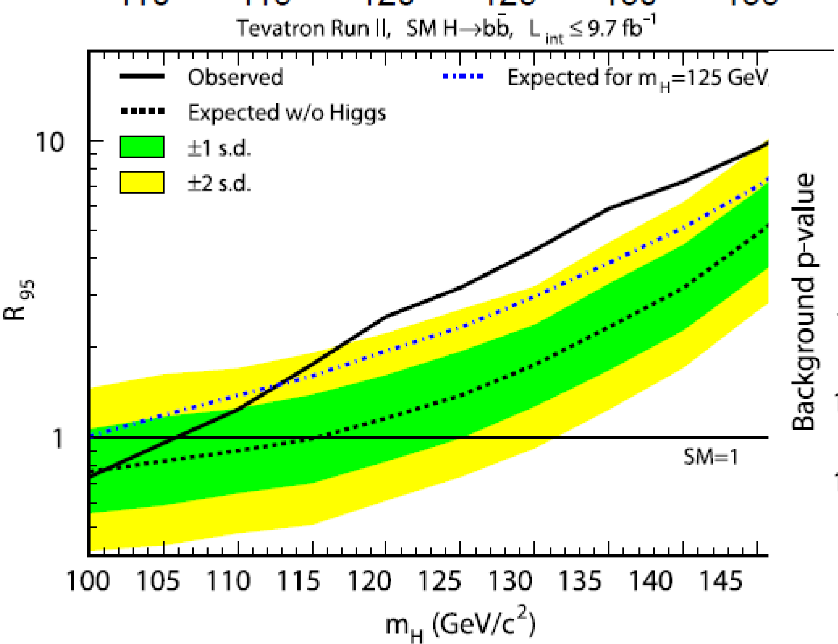
Backup

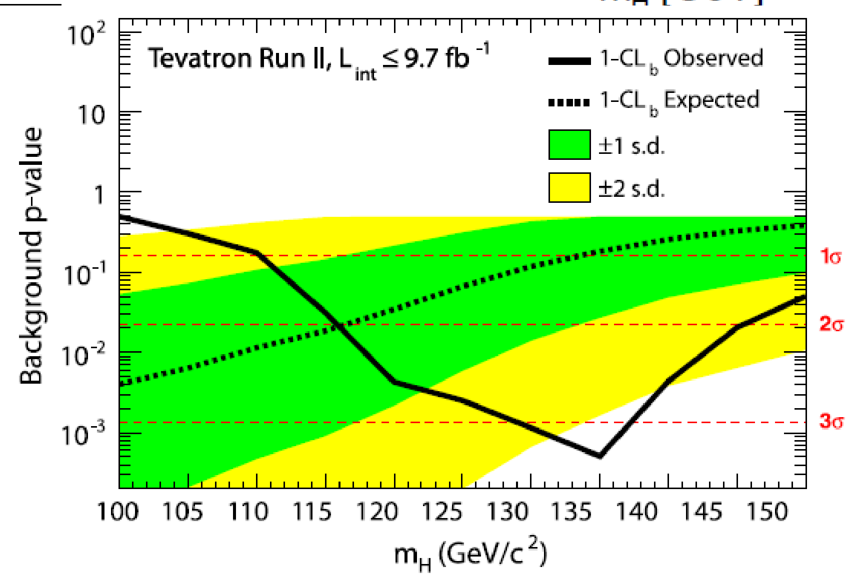
CMS and Tevatron VH->bb

CMS: local significance of 2.1 standard deviations (for 125 GeV)





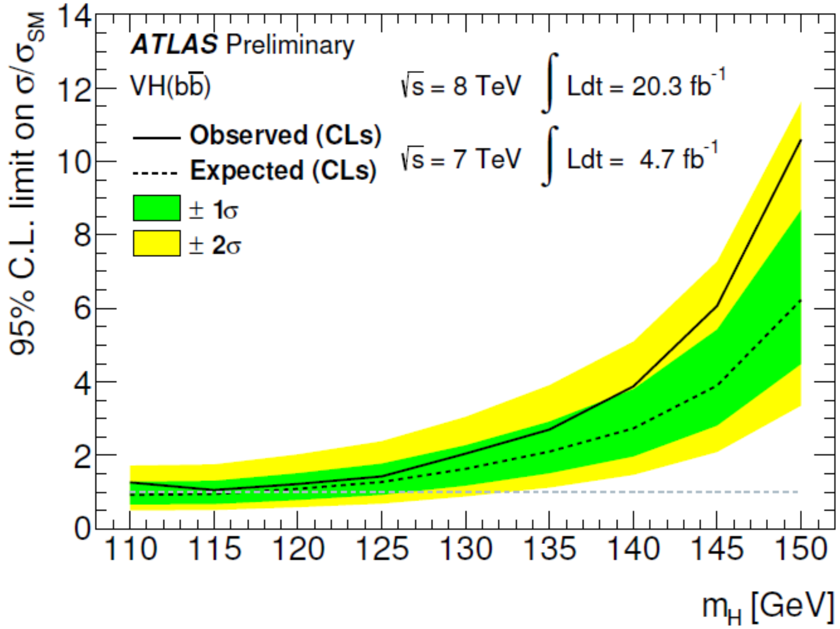




Tevatron: maximum local significance of 3.3 standard deviations

ATLAS VH → bb

CMS: local significance of 2.1 standard deviations (for 125 GeV)



ATLAS: expected upper limit for mH = 125 GeV: 1.3

$$\mu = 0.2 \pm 0.5(\text{stat.}) \pm 0.4(\text{syst.}).$$

CMS standard BDT analysis

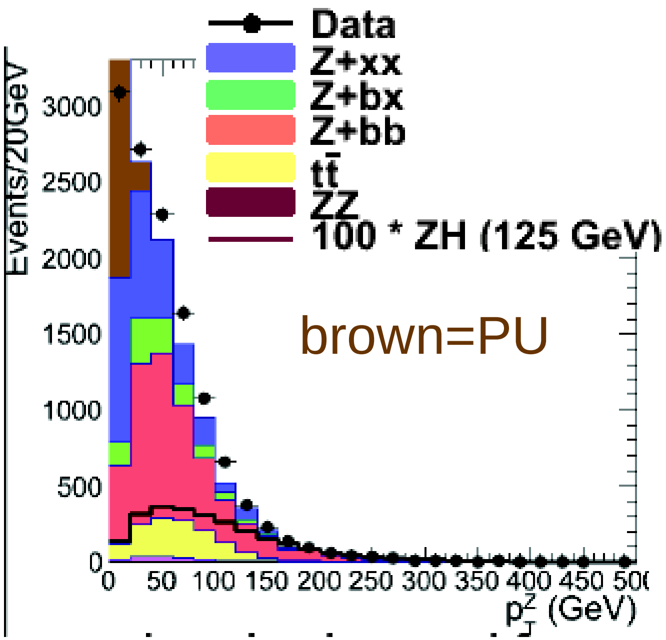
8 TeV	WH		ZH		H → bb	
M_H	σ(pb)	± (%)	σ(pb)	± (%)	$\mathcal{B}(H \to b\bar{b})$	± (%)
110	1.0600	+3.9, −4.4	0.5869	+5.4, −5.4	0.745	+2.1, −2.2
115	0.9165	+4.0, −4.5	0.5117	+5.6, −5.5	0.704	+2.4, −2.5
120	0.7966	+3.5, −4.0	0.4483	+5.0, −4.9	0.648	+2.8, −2.8
125	0.6966	+3.7, −4.1	0.3943	+5.1, −5.0	0.577	+3.2, −3.2
130	0.6095	+3.7, −4.1	0.3473	+5.4, −5.3	0.493	+3.7, −3.8
135	0.5351	+3.5, −4.1	0.3074	+5.4, −5.2	0.403	+4.2, −4.3
140	0.4713	+3.6, −4.2	0.2728	+5.6, −5.4	0.315	+3.4, −3.4
145	0.4164	+3.9, −4.5	0.2424	+6.0, −5.8	0.232	+3.7, −3.7
150	0.3681	+3.4, −4.0	0.2159	+5.7, −5.4	0.157	+4.0, −4.0

Variable
$p_T(j)$: transverse momentum of each Higgs daughter
$m(jj)$: dijet invariant mass
$p_T(jj)$: dijet transverse momentum
$p_T(V)$: vector boson transverse momentum (or E_T^{miss})
CSV_{max}: value of CSV for the Higgs daughter with largest CSV value
CSV_{min}: value of CSV for the Higgs daughter with second largest CSV value
$\Delta\phi(V, H)$: azimuthal angle between V (or E_T^{miss}) and dijet
$\lvert\Delta\eta(jj)\rvert$: difference in η between Higgs daughters
$\Delta R(jj)$: distance in η–ϕ between Higgs daughters
N_{aj}: number of additional jets
$\Delta\theta_{pull}$: color pull angle [34]
$\Delta\phi(E_T^{miss}, jet)$: azimuthal angle between E_T^{miss} and the closest jet (only for $Z(\nu\nu)H$)
$maxCSV_{aj}$: maximum CSV of the additional jets in an event (only for $Z(\nu\nu)H$ and $W(\ell\nu)H$)
$min\Delta R(H, aj)$: mimimum distance between an additional jet and the Higgs candidate (only for $Z(\nu\nu)H$ and $W(\ell\nu)H$)
Angular variables: HV system mass, Angle Z-Z*, Angle Z-l, Angle H-jet (only for $Z(\ell\ell)H$)

Detailed Event Selection

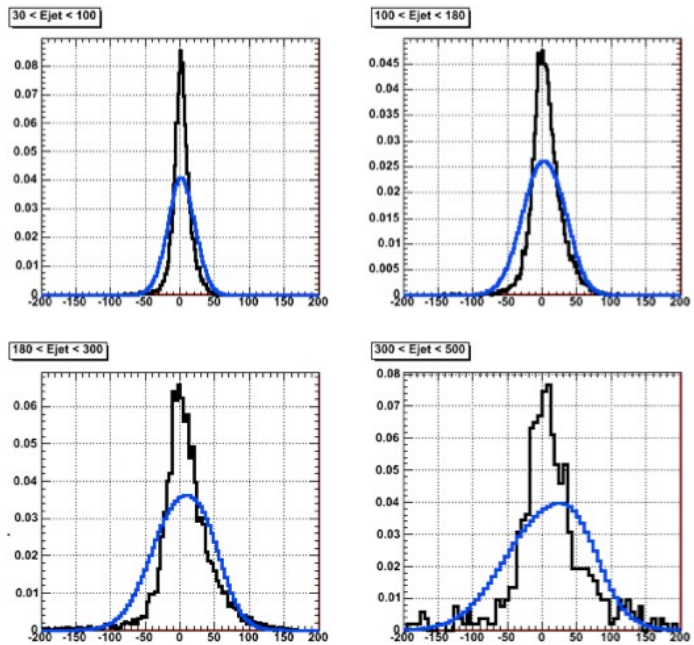
- Basic event selection (**as inclusive as possible**)
  - 2 leptons pT>20 GeV, |η| <2.4, 76 < Mll < 106 GeV
  - At least 2 jets with PT>20 GeV, |η| <2.4
    - Categorization: njet=2 and njet >= 3
  - 2 b-tagged jets (1 “Medium” + 1 “Loose” tags)
  - small MET: MET significance < 10
- Extra kinematical cuts
  - **$P_T$jet1>40, $P_T$jet2>25, P_TZ > 20 GeV**
    - PU suppression
  - mbb
    - **80<Mbb<150** GeV (if njet=2)
    - **50<Mbb<150** GeV (if njet>2)
    - Inversion of this cut to define “Control Region”
- Main backgrounds after event selection
  - **tt** (sizeable), **ZZ** (irreducible but small)
  - Main Z+jets: **Zbb, Zbx, Zxx.** Notation: b (x) → if gen level b-parton is (not) found within ΔR < 0.3 of reco jet

- Plot for 8 TeV data (more important PU)



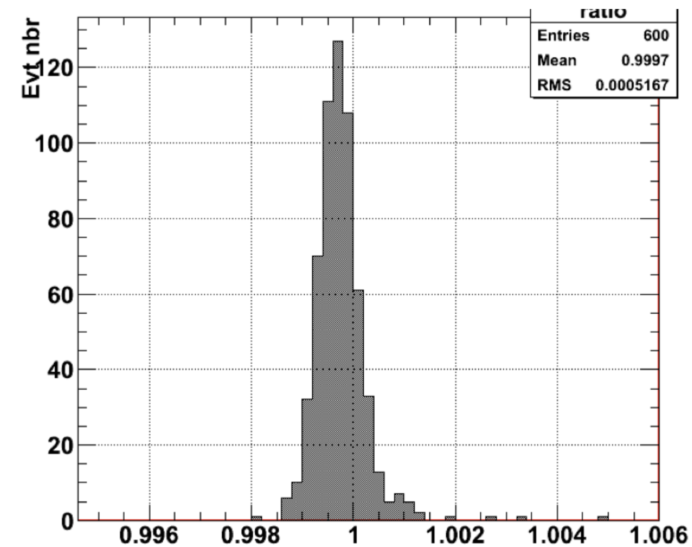
Effect of transfer function on the M.E. Weight

Variation of the jet (electron) energy transfer function of



Same events.
Weights estimated with:
- nominal TF: W
- modified TF: W*

Ratio: $$\frac{-Log_{10}(W)}{-Log_{10}(W^*)}$$

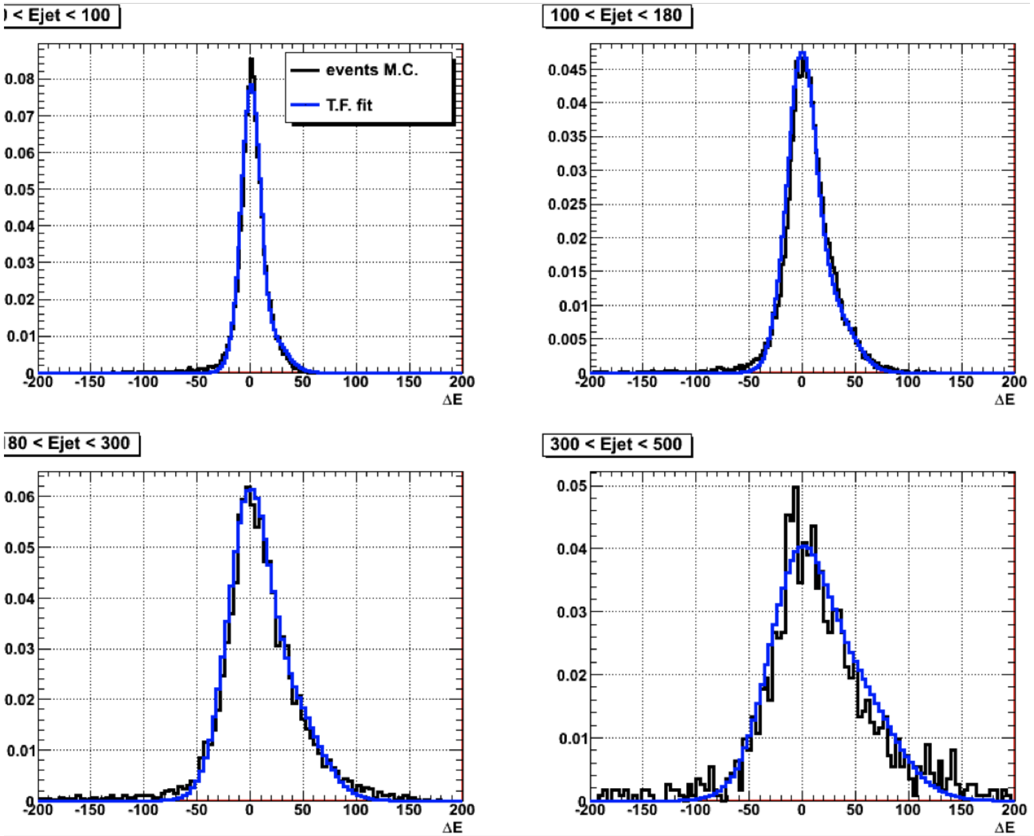


Sample		$t\bar{t}$	qqToZ(ee)bb	ggToZ(ee)bb
Jet energy TF variations				
$t\bar{t}$	RMS	$8.8\ 10^{-3} \pm 2\ 10^{-4}$	$5.2\ 10^{-4} \pm 1.2\ 10^{-5}$	$5.8\ 10^{-4} \pm 1.3\ 10^{-5}$
	peak	1.00	0.99	1.00
Z(ee)$b\bar{b}$	RMS	$1.153\ 10^{-4} \pm 3\ 10^{-4}$	$5.1\ 10^{-4} \pm 1.5\ 10^{-5}$	$6.4\ 10^{-4} \pm 1.8\ 10^{-5}$
	peak	1.004	0.99	0.99
Electron energy TF variations				
$t\bar{t}$	RMS	$7.6\ 10^{-4} \pm 2\ 10^{-5}$	$6.8\ 10^{-3} \pm 1\ 10^{-4}$	$7.3\ 10^{-3} \pm 2\ 10^{-4}$
	peak	1.001	1.003	1.004
Z(ee)$b\bar{b}$	RMS	$1.310{-}3 \pm 1\ 10{-}4$	$6.4\ 10^{-3} \pm 510^{-5}$	$6.7\ 10^{-3} \pm 2\ 10^{-4}$
	peak	1.00	0.99	0.99

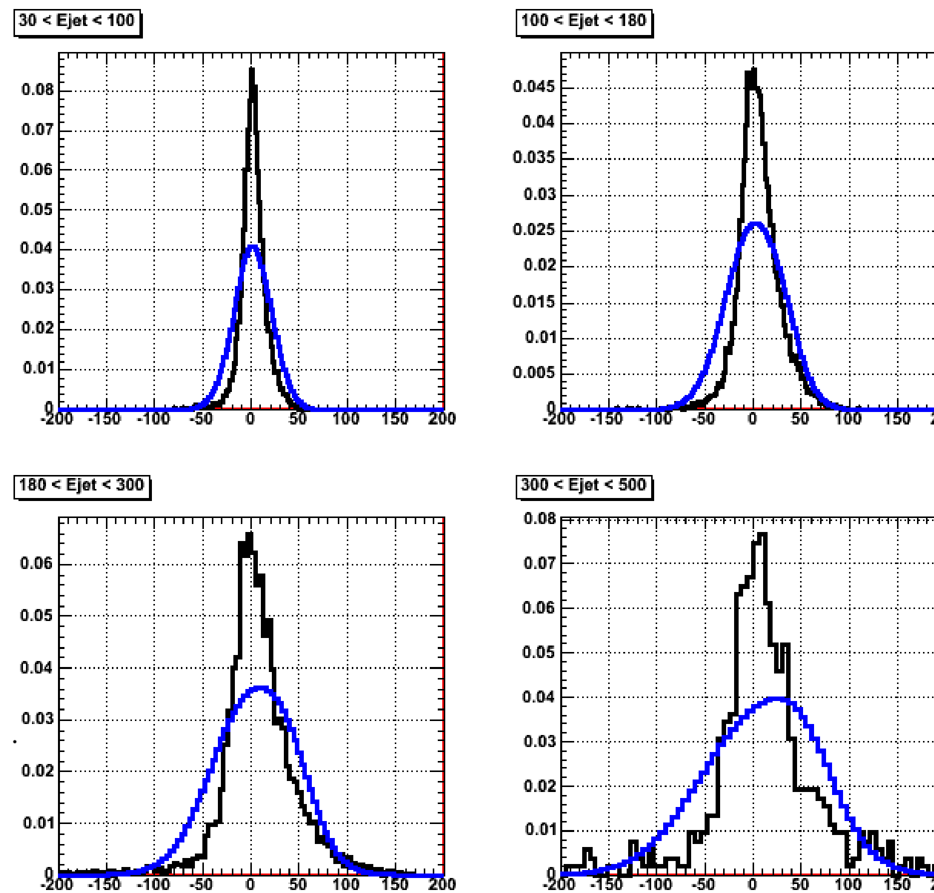
The –Log10 of the weight is stable with transfer function variations (that correspond to energy resolution fluctuation).

Effect of transfer function fluctuation on weights

Varying the jet transfer function.



But :
2 * width of the first gaussian
P2 -> 2 x P2

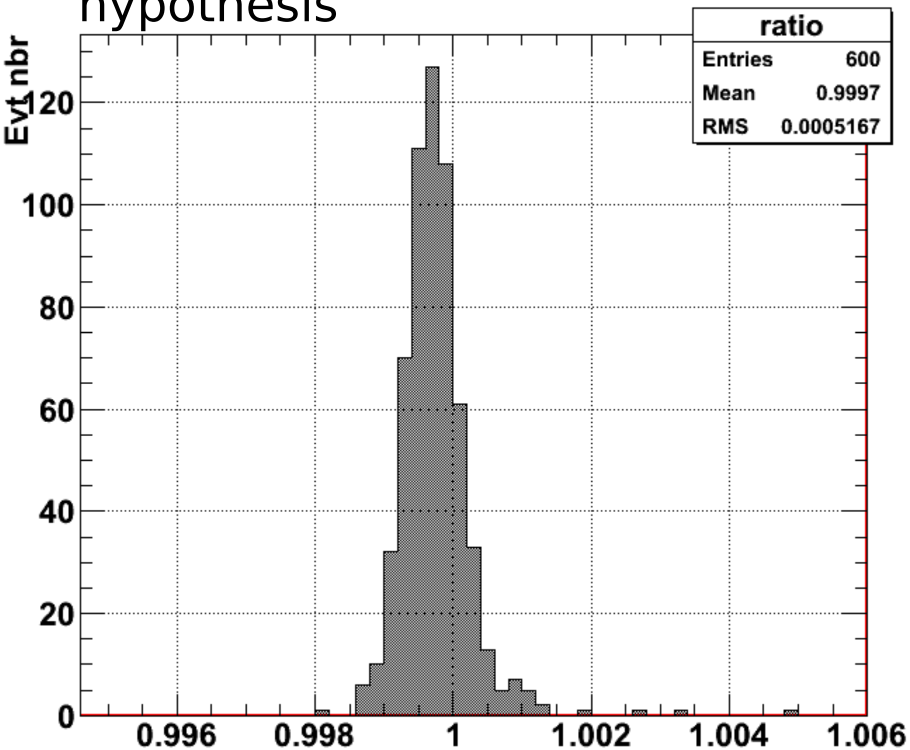


Still using :

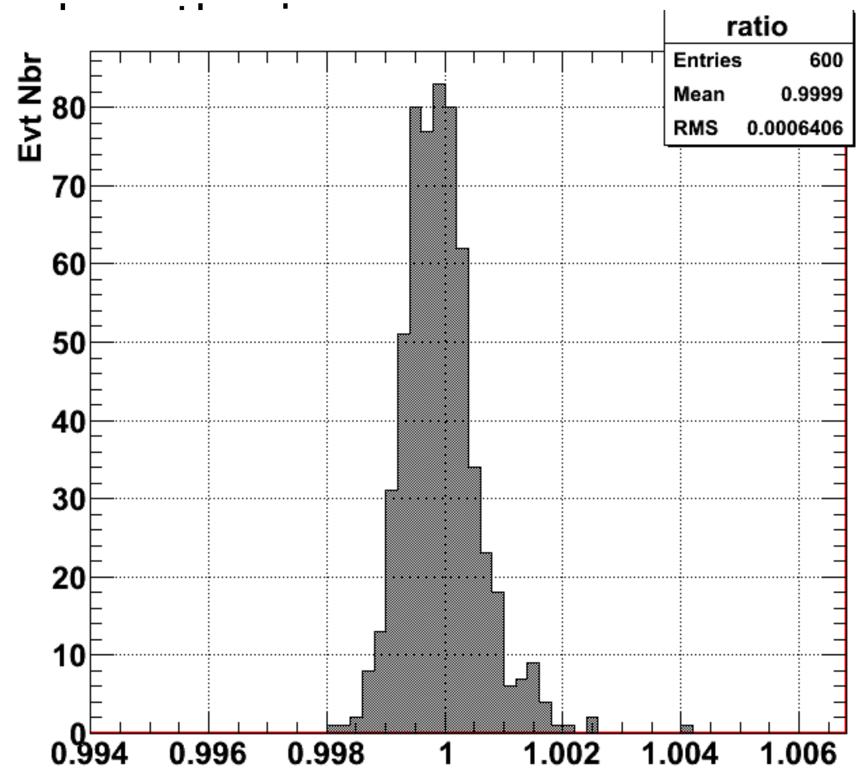
$$W(E_j, E_{part}) = \frac{1}{\sqrt{2}(P_2 + P_3.P_5)}.\left(e^{-\frac{[(E_{part}-E_j)-P_1]^2}{2.P_2^2}} + P_3.e^{-\frac{[(E_{part}-E_j)-P_4]^2}{2.P_5^2}}\right).$$

Effect of transfer function fluctuation on weights

DY events with qqToZbb hypothesis



DY events with ggToZbb hypothesis



TF jets robust against Pile-Up

- It appears that the jets energy transfer function are not depending of the Pile-Up
- The use of the FastJet correction provide an non dependency to the Pile-Up condition.