Higgs searches with CMS

Roberto Salerno

Outline

✓ CMS's path to the Higgs

✓ Hunting the Higgs with the 2010 data
- ✓ status of CMS searches

✓ Higgs projections
- ✓ how we can discover the ("SM") Higgs (or prove it doesn't exist)

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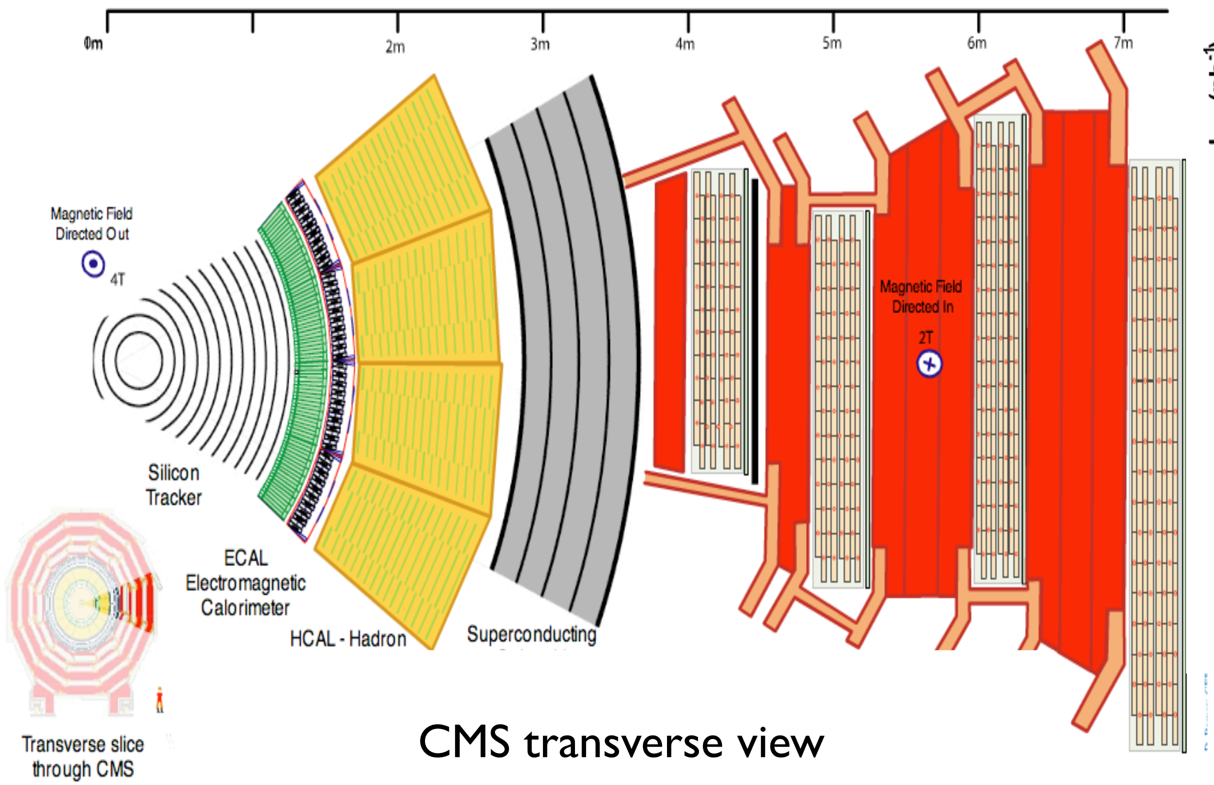
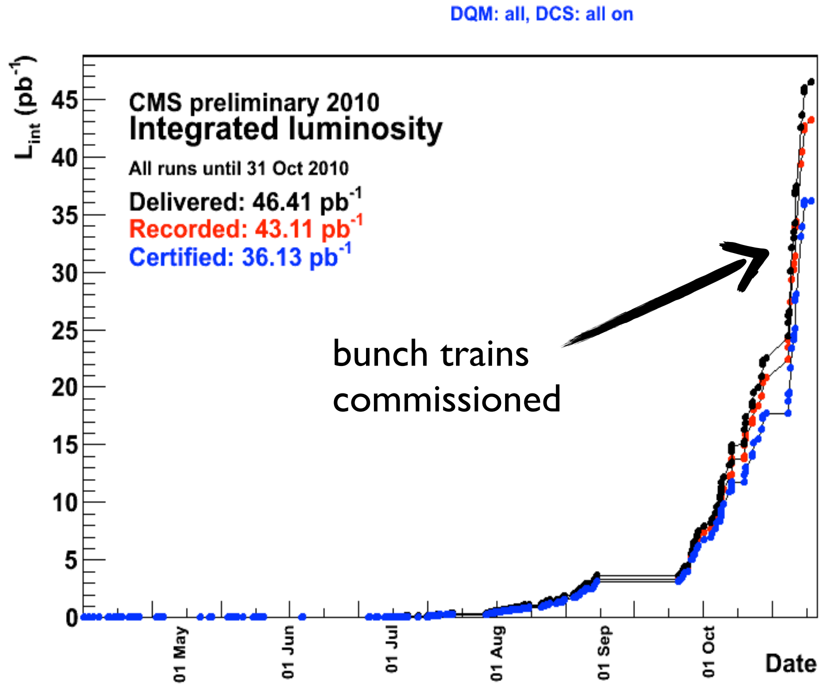
CMS detector



CMS transverse view



Luminosity uncertainty < 4% already!

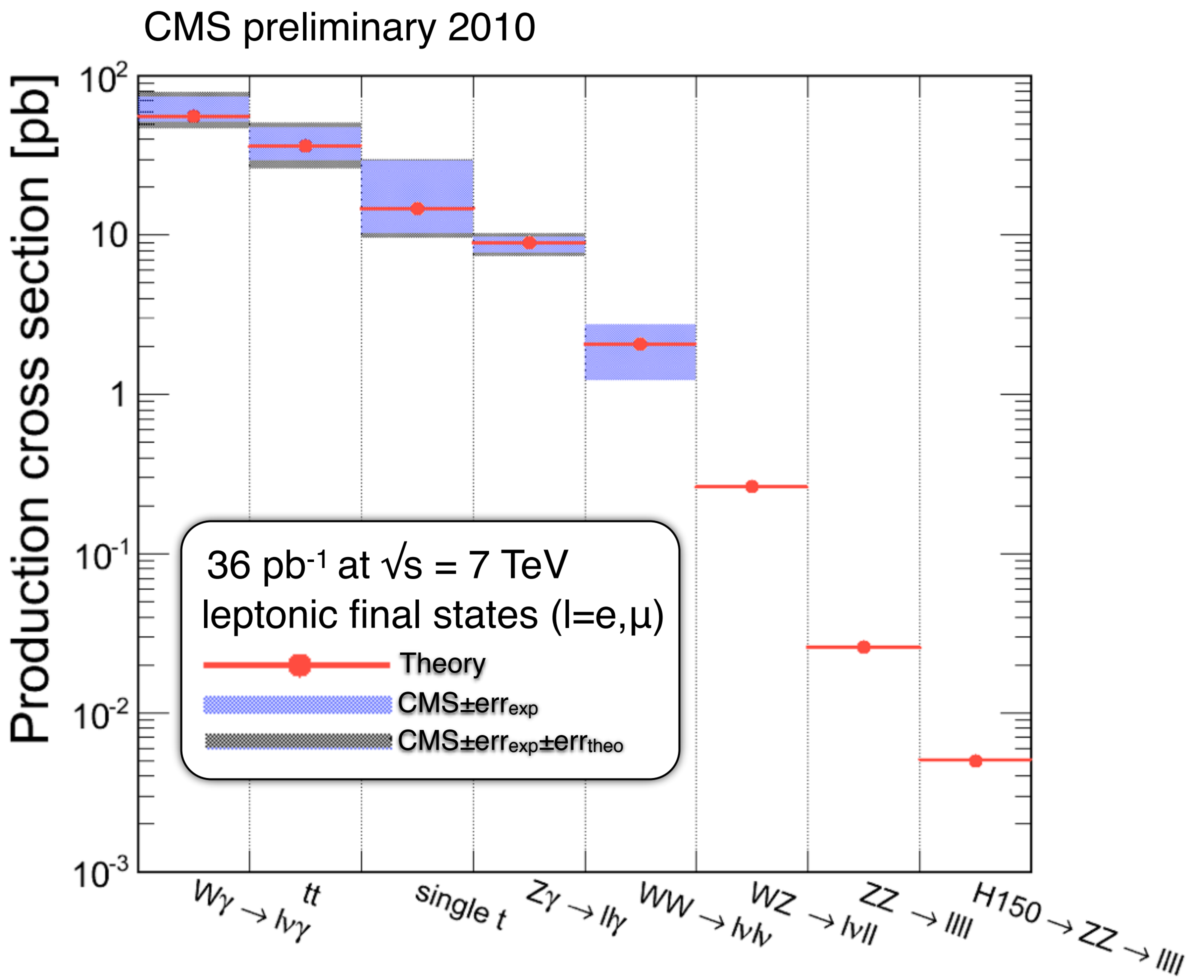
Good understanding of machine

≈100M channels each

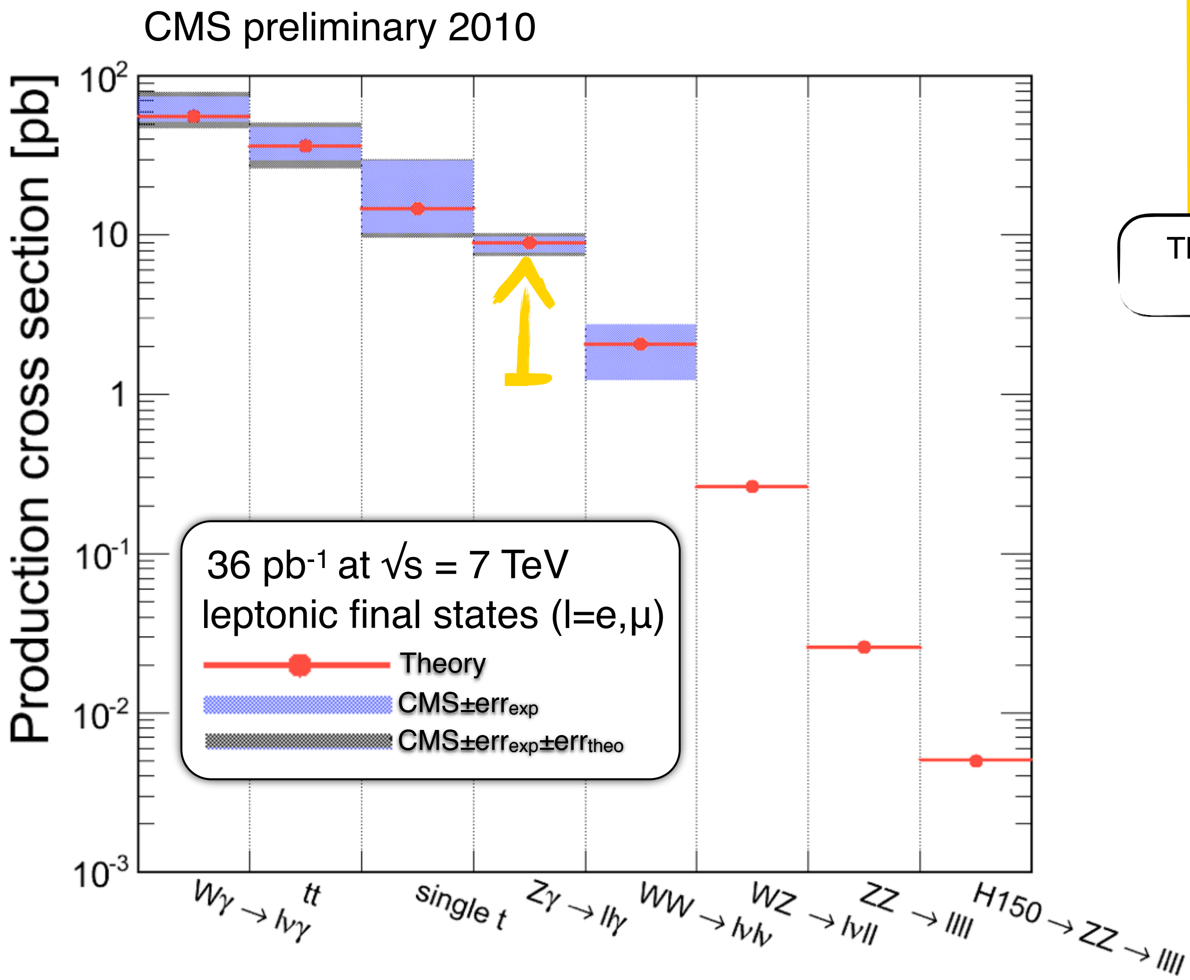
≈98% channels operational

Makes event reconstruction and comparison with simulations much easier

CMS's path to Higgs

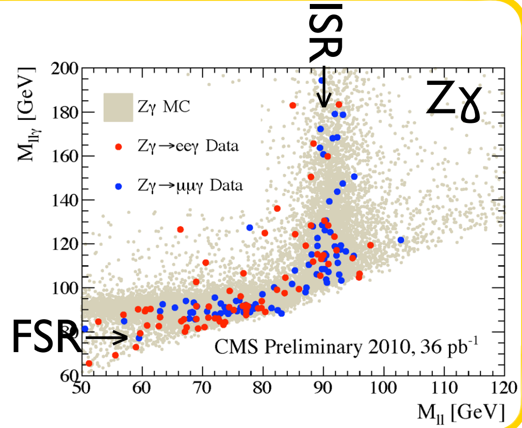


CMS's path to Higgs



W/Z + gamma production

The first di-boson observation



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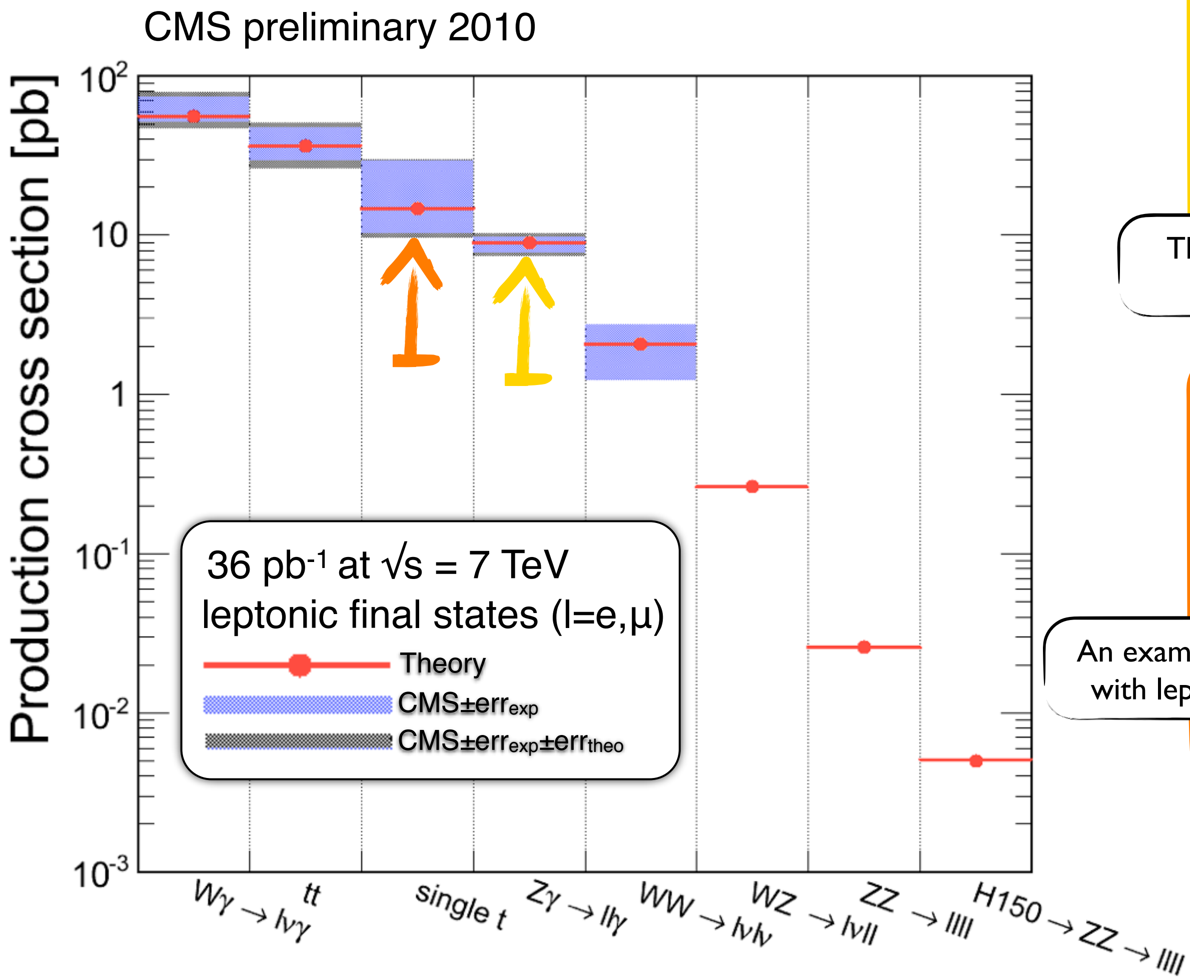

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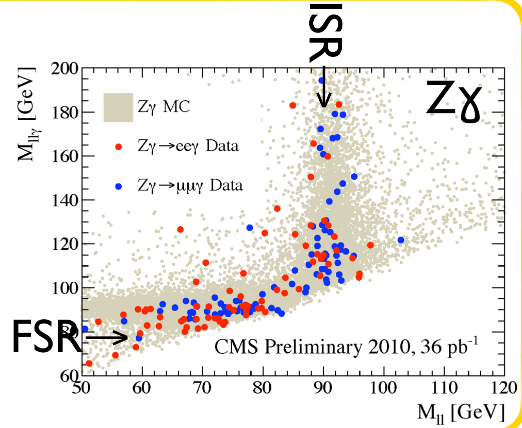
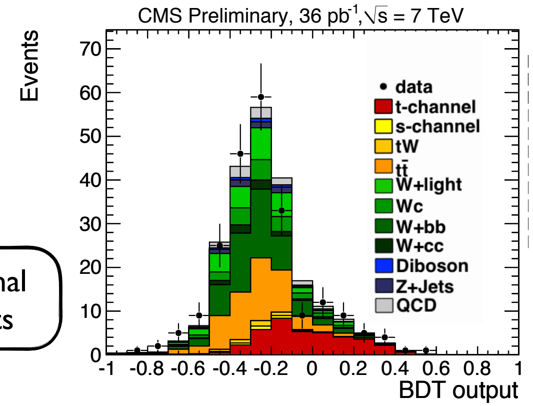
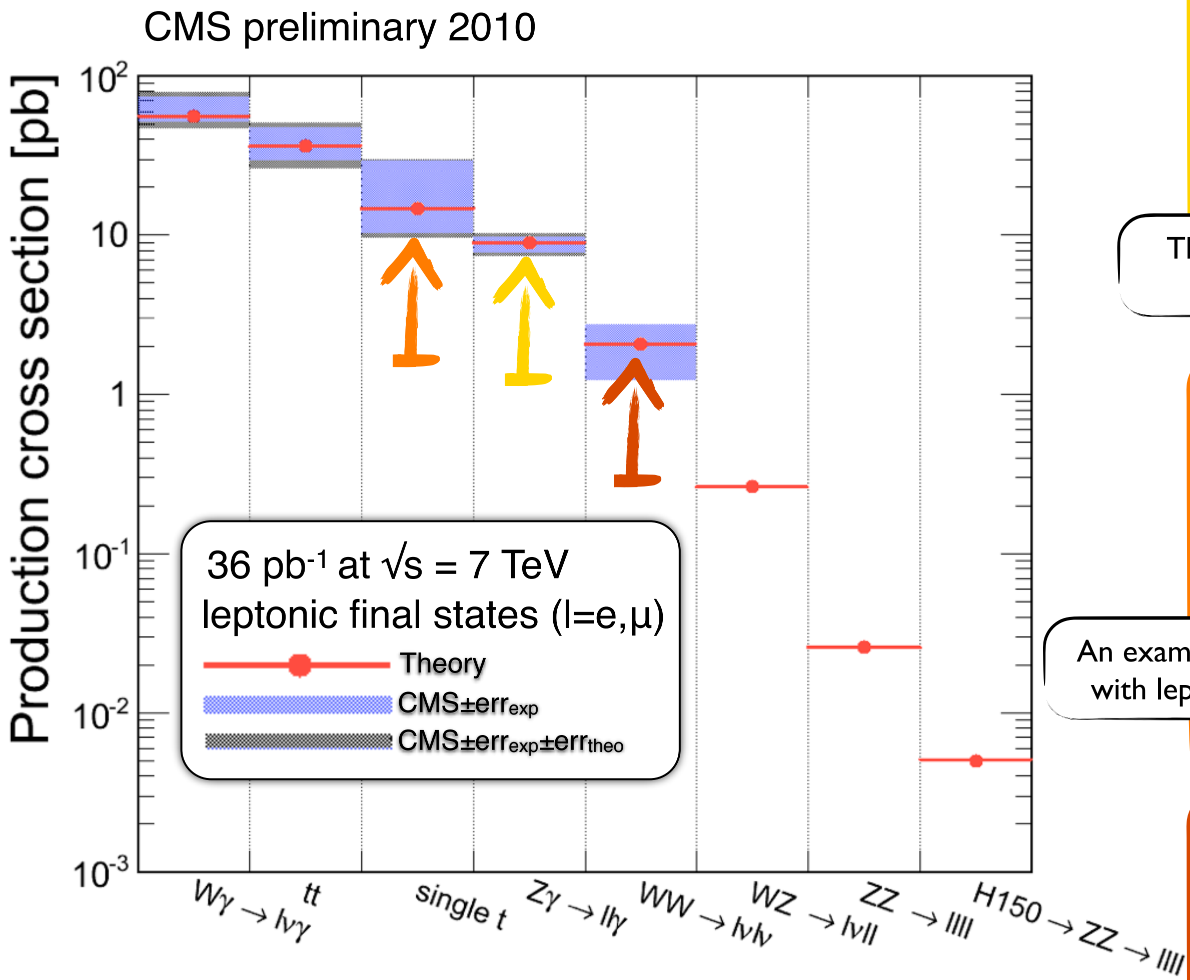


Single top production

An example of finding tiny signal with leptons, MET, b-tag & jets



CMS's path to Higgs



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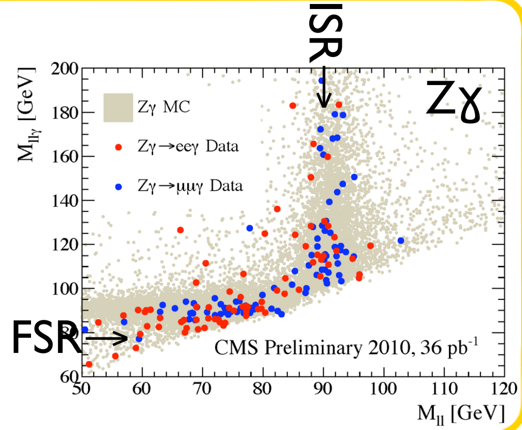

Single top production

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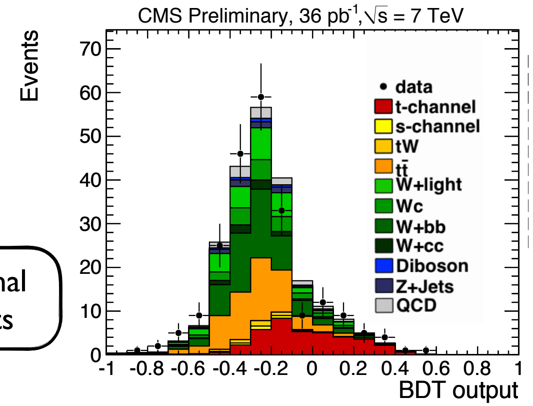
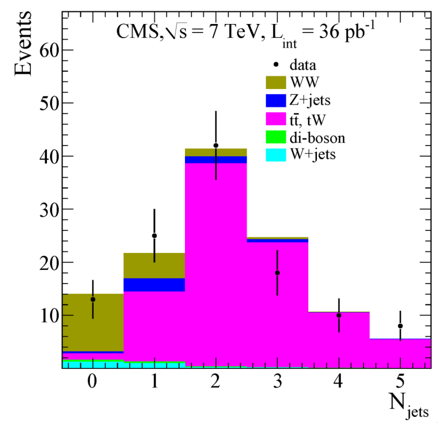
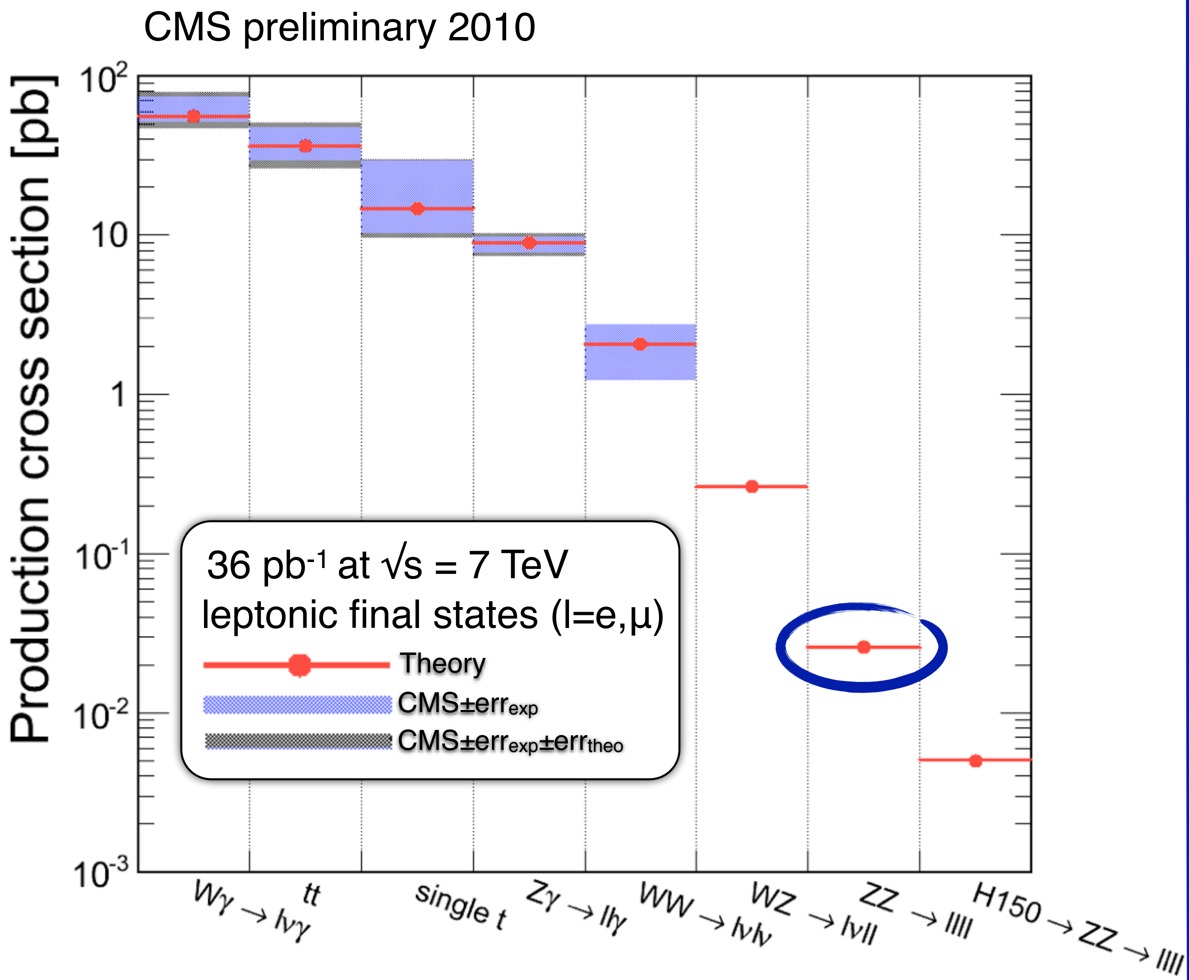


WW production

The hunt is starting ...

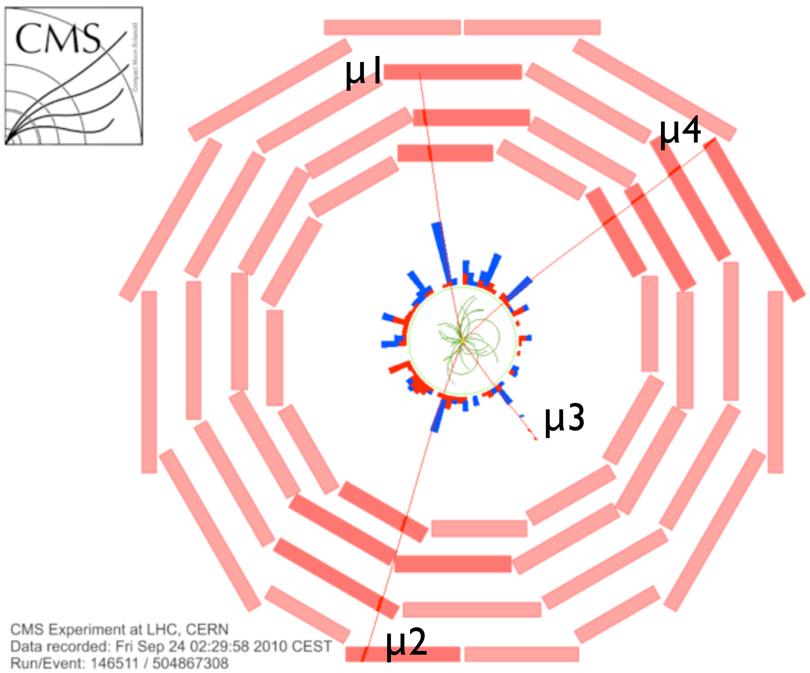


CMS's path to Higgs



ZZ observation

A beautiful event observed in data (walked in early !)



$P_T^{\mu 1}$ = 48.1GeV/c
$P_T^{\mu 2}$ = 43.4GeV/c
$P_T^{\mu 3}$ = 25.9GeV/c
$P_T^{\mu 4}$ = 19.6GeV/c

$M_{\mu 1 \mu 2}$ = 92.15 GeV/c^2
$M_{\mu 3 \mu 4}$ = 92.15 GeV/c^2
$M_{4\mu}$ = 201 GeV/c^2

Probability of observing a pp→ ZZ →4μ event in 36 pb^{-1} is ~ 20%

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Hunting the Higgs with the 2010 data

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gg→H→WW*→lνlν

- ✓ The signature
  - ✓ 2 opposite charged isolated leptons
  - ✓ high missing energy
  - ✓ no jet activity
- ✓ The backgrounds

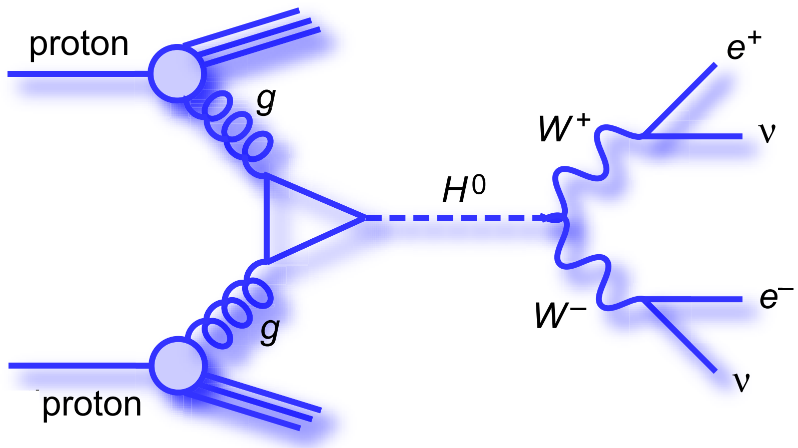
  real or fake sources of leptons and MET:

  ttbar, tW, DY, W+jets

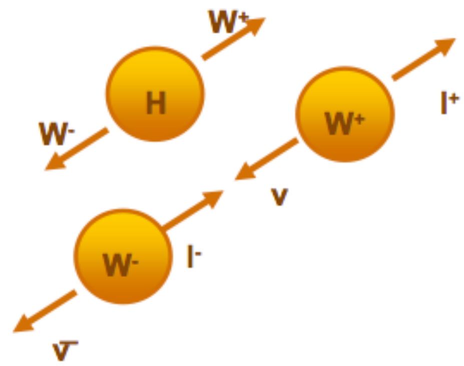
  irreducible:

  WW

  - ✓ Use spin correlation

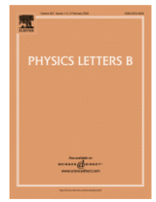


- ✓ No narrow mass peak can be reconstructed
- ✓ Count excess
  - ✓ cut based analysis
  - ✓ multivariate approach

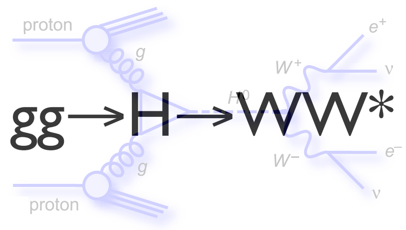


Among various channels for the Standard Model Higgs searches, CMS only published Higgs to WW in di-lepton final state.
Other channels don't have enough sensitivity with 36 pb^{-1} of data at 7 TeV

arXiv:1102.5429, accepted by PLB for publication

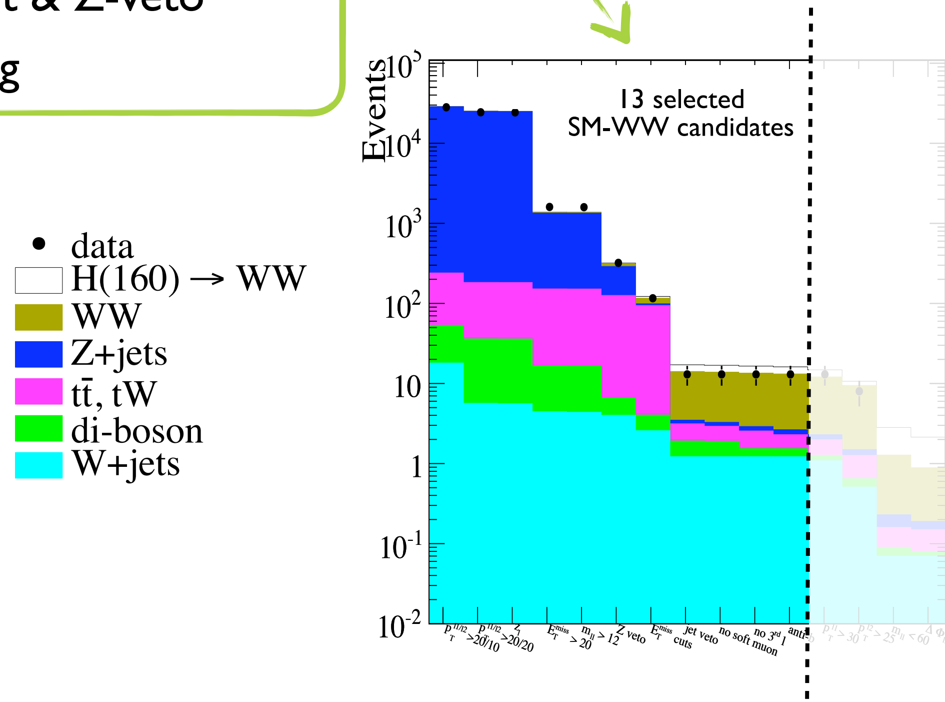


Selections



Di-boson WW selection

- ✓ 2 OS leptons, p_T > 20 GeV/c
- ✓ m_{l+l-} > 12 GeV/c²
- ✓ projected MET cut & Z-veto
- ✓ jet-veto & b-jet tag



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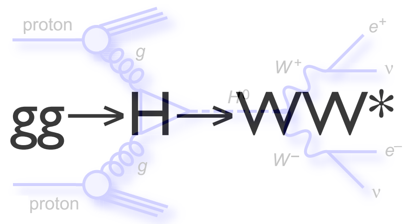

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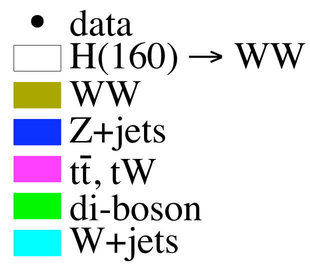
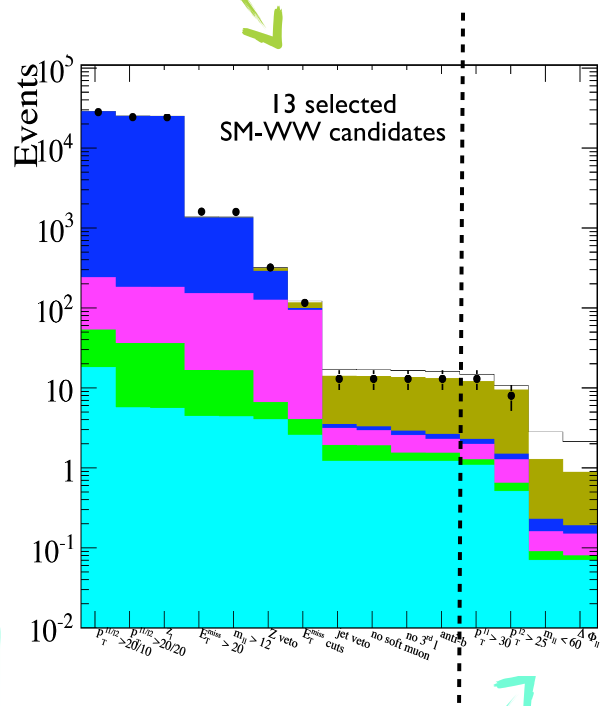
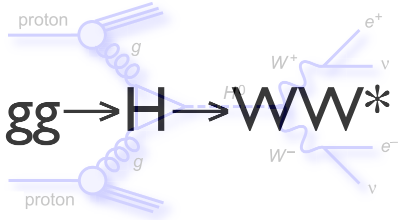




Higgs WW selection

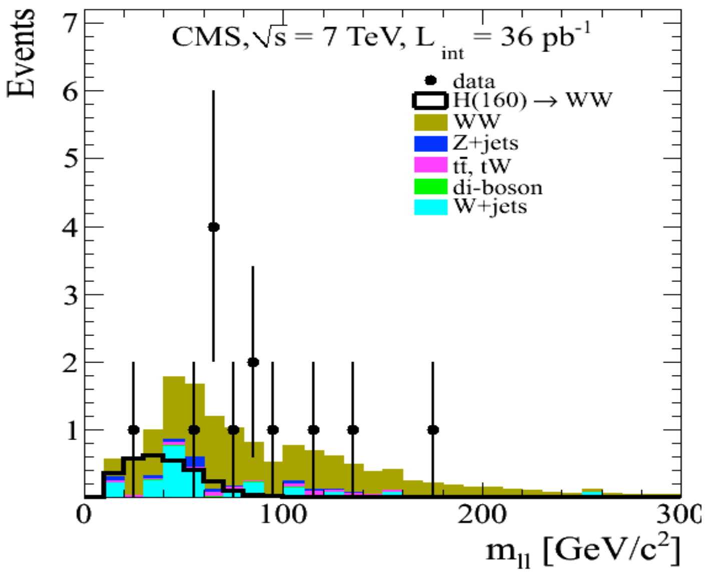
- ✓ optimize cuts as a function of m_H
- ✓ cut based approach
  variables: m_{ll}, $p_{T,l}^{max}$, $p_{T,l}^{min}$, $\Delta\varphi_{ll}$
- ✓ multivariate approach
  BDT

Background estimation



Irreducible WW

- ✓ pp→WW: data-driven
  - ✓ depending on m_H hypothesis, m_{ll} can be inverted to obtain a signal-free region, dominated by WW
  - ✓ WW extrapolated in the signal region (cancelation of systematics in the ratio)
  - ✓ ~50% uncertainty with $L=36pb^{-1}$



- ✓ gg→WW: from MC
  - ✓ ~50% uncertainty from PDFs, QCD renormalization and scale

Background estimation

gg→H→WW*

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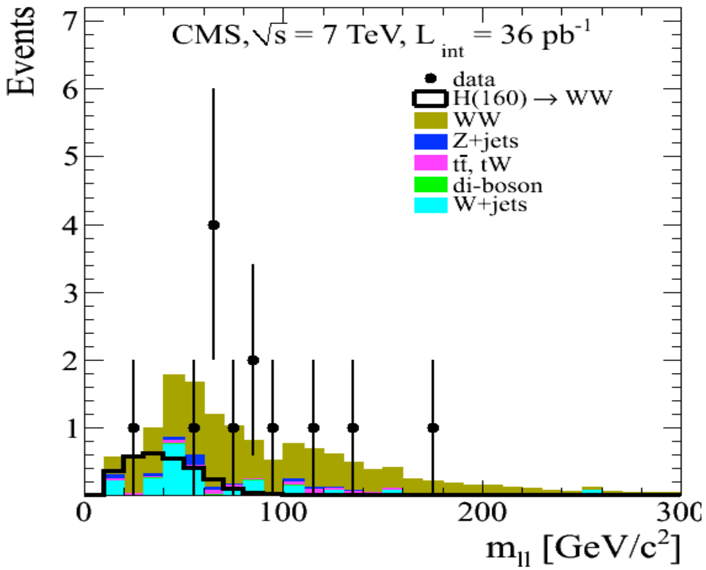

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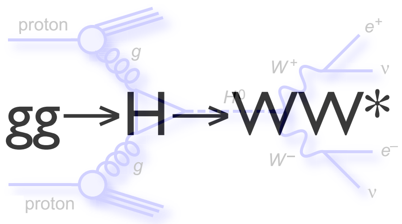
Reducible backgrounds

- W+jets background (W+fake lepton)
  - estimated from fake rate on a jet dominated sample, systematics from jet composition in control and signal sample
- Top background in the 0th jet bin
  - estimated from MC due to lack of statistics (100% systematic)
  - strategy on top-enriched sample for the future
- DY/γ* background
  - extrapolation from Z peak region in the signal region

Background	Estimate	Source
W+jets	1.7±0.4(stat)±0.7(syst)	data-driven
top	0.77±0.05(stat)±0.77(syst)	from MC
DY/γ*	0.2±0.2(stat)±0.3(syst)	data-driven
others	0.62±0.07(stat)	from MC

Systematics



Dominating uncertainties: luminosity, jet veto

Source	Relative uncertainty (%)
Luminosity	11
Trigger ε	1.5
Muon ε	1.9
Electron ε	2.4
Momentum scale	1.4
MET	1.0
Jet veto ε	6.9
PDF	3.0

Jet Veto

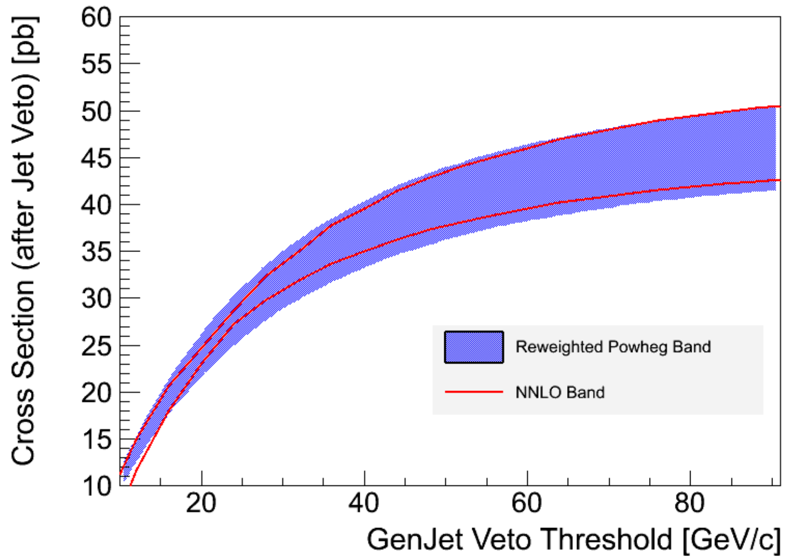
✓ the most delicate ingredient of the analysis

✓ estimate from data as a ratio:

$$\varepsilon^{data}_{H\to WW} = \varepsilon^{MC}_{H\to WW}\ (\varepsilon^{data}_{Z}/\varepsilon^{MC}_{Z})$$

- ratio $\varepsilon^{MC}_{H\to WW}/\varepsilon^{MC}_{Z}$ is known theoretically
- experimental uncertainties cancel out

✓ Estimate of uncertainties using different generators

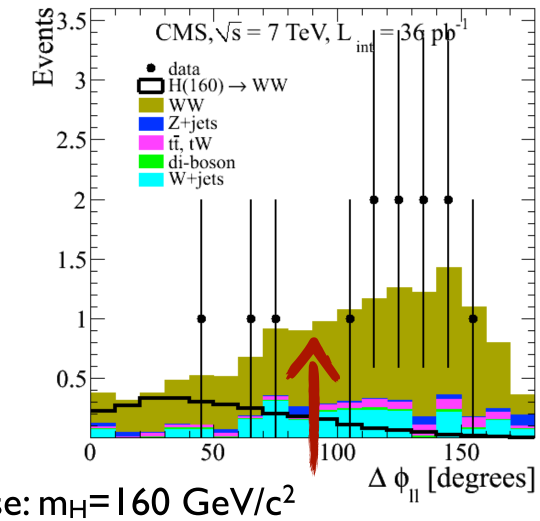


Event yields

gg→H→WW*

Cut based analysis

Mass (GeV/c²)	SM Higgs	4th Gen	Background	DATA
130	0.3 ± 0.01	1.73 ± 0.04	1.67 ± 0.10	1
160	1.23 ± 0.02	10.35 ± 0.16	0.91 ± 0.05	0
200	0.47 ± 0.01	3.94 ± 0.07	1.47 ± 0.09	0
250	0.26 ± 0.01	1.98 ± 0.04	1.64 ± 0.08	1



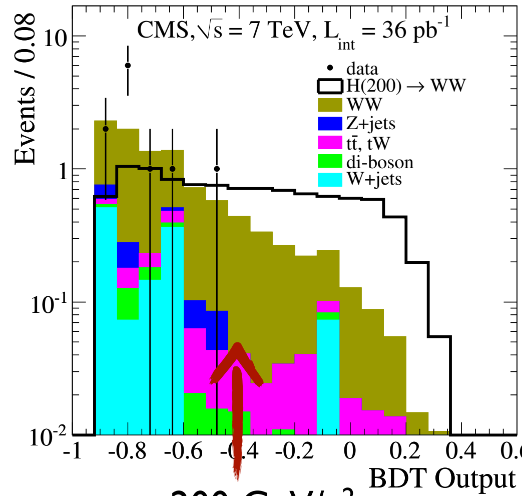
SM case: m_H=160 GeV/c^2

$\Delta\varphi_{ll}$ one of the 4 selection variables

Boosted decision tree

Mass (GeV/c²)	SM Higgs	4th Gen	Background	DATA
130	0.34 ± 0.01	1.98 ± 0.04	1.32 ± 0.18	1
160	1.47 ± 0.02	12.31 ± 0.17	0.92 ± 0.10	0
200	0.57 ± 0.01	4.76 ± 0.07	1.47 ± 0.07	0
250	0.30 ± 0.01	2.30 ± 0.04	1.67 ± 0.10	0

MVA gives roughly ~20% better sensitivity

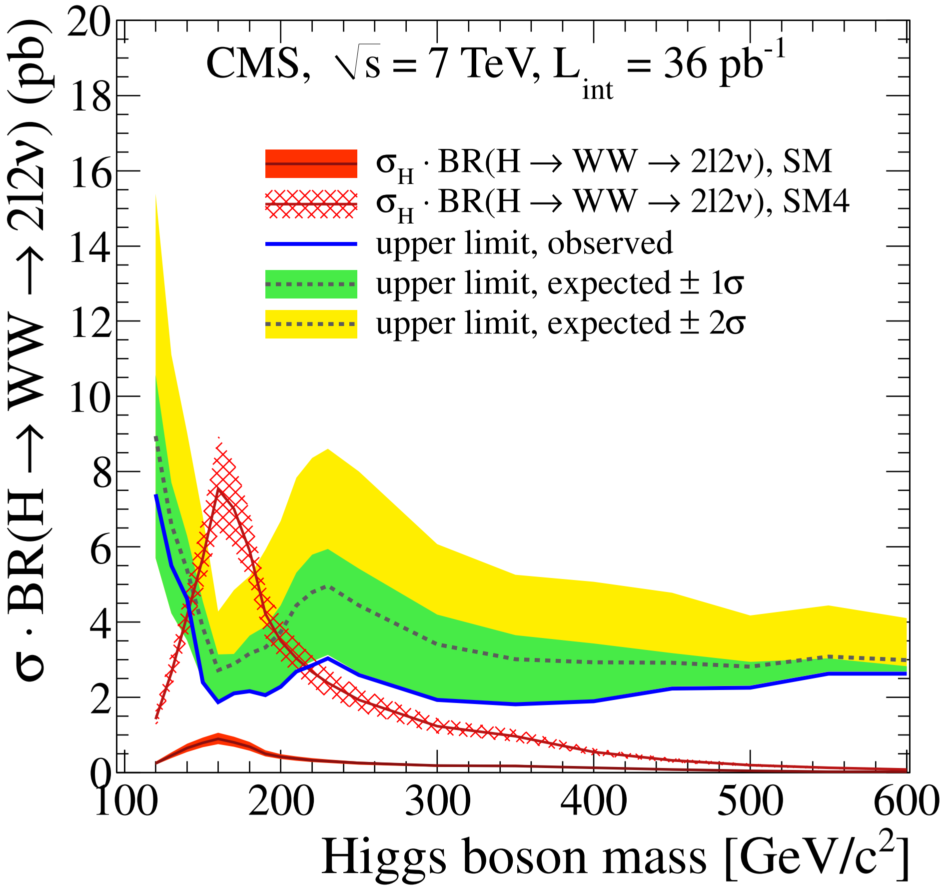


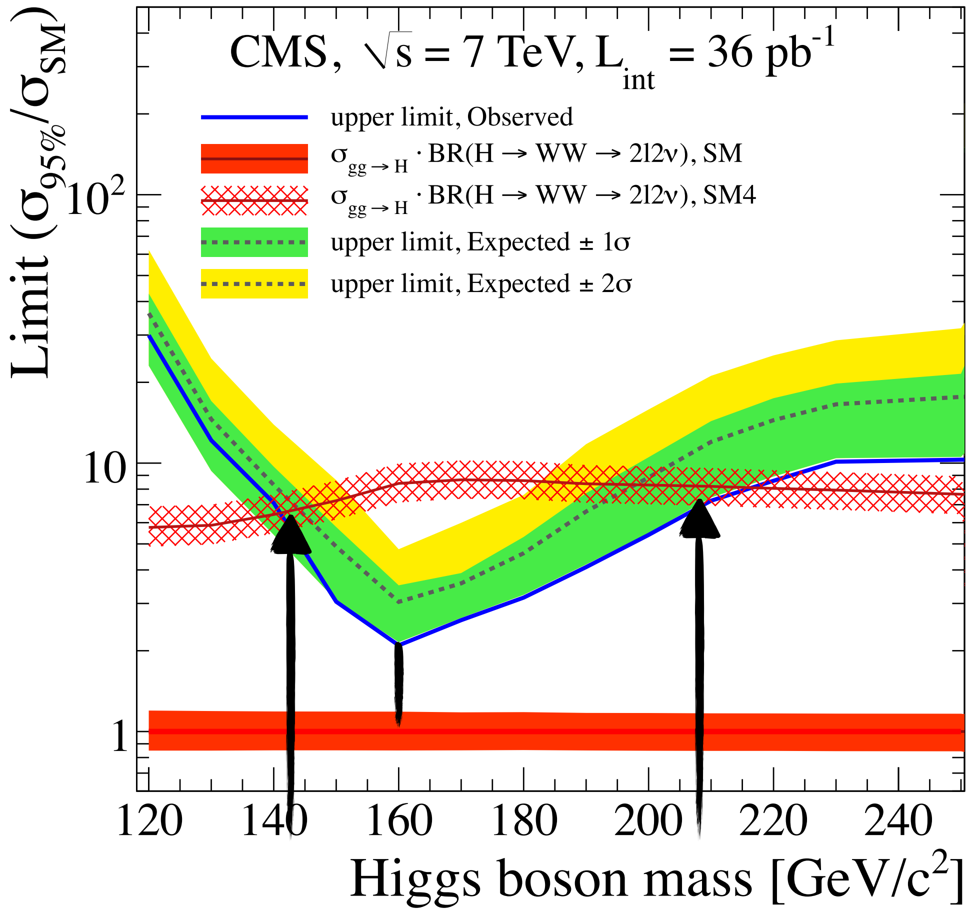
4th Gen. case: m_H=200 GeV/c^2

BDT output

Results

gg→H→WW*





✓ Not yet sensitivity to SM Higgs (factor **2.1** @ m_H =160 GeV/c^2)

✓ In a 4th generation model with infinite quark masses (conservative), Higgs mass excluded in the range **[144-207]** GeV/c^2 at 95% C.L.

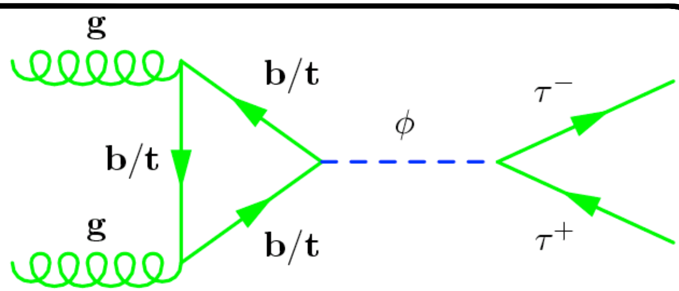
✓ Competitive with TeVatron limits (m_H = [131-204] GeV/c^2 with 4.8+5.4 fb^{-1})

$gg \rightarrow (bb)\varphi \rightarrow \tau\tau$

Looking beyond the Standard Model the Higgs sector becomes much richer

- ✓ in the **MSSM** 2 doublet of Higgs fields → 5 physical Higgs bosons
  h,H,A,H^+,H^-
- ✓ couplings of Higgs to down-type quarks enhanced at high tanβ
  cross-section increases and BR($\varphi \rightarrow \tau\tau$) are enhanced by $(\tan\beta)^2$

✓ Search for **$gg \rightarrow \varphi(bb) \rightarrow \tau\tau$**
φ = h,H,A masses are degenerate depending on regime



+ associated bbφ production

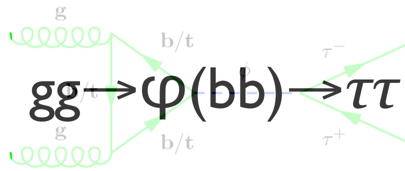
✓ Three decay channels considered:

- ✓ $\varphi(bb) \rightarrow \tau\tau \rightarrow \mu + \tau h$ (τh=hadronic decay)
- ✓ $\varphi(bb) \rightarrow \tau\tau \rightarrow e + \tau h$ (τh=hadronic decay)
- ✓ $\varphi(bb) \rightarrow \tau\tau \rightarrow e + \mu$

Selection

$Z \rightarrow \tau\tau$ selection

- ✓ close to WW electron and muon selections
- ✓ particle flow based electron and muon isolations
- ✓ identified taus
- ✓ $M_T(e/\mu, MET)$



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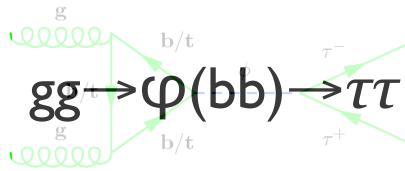
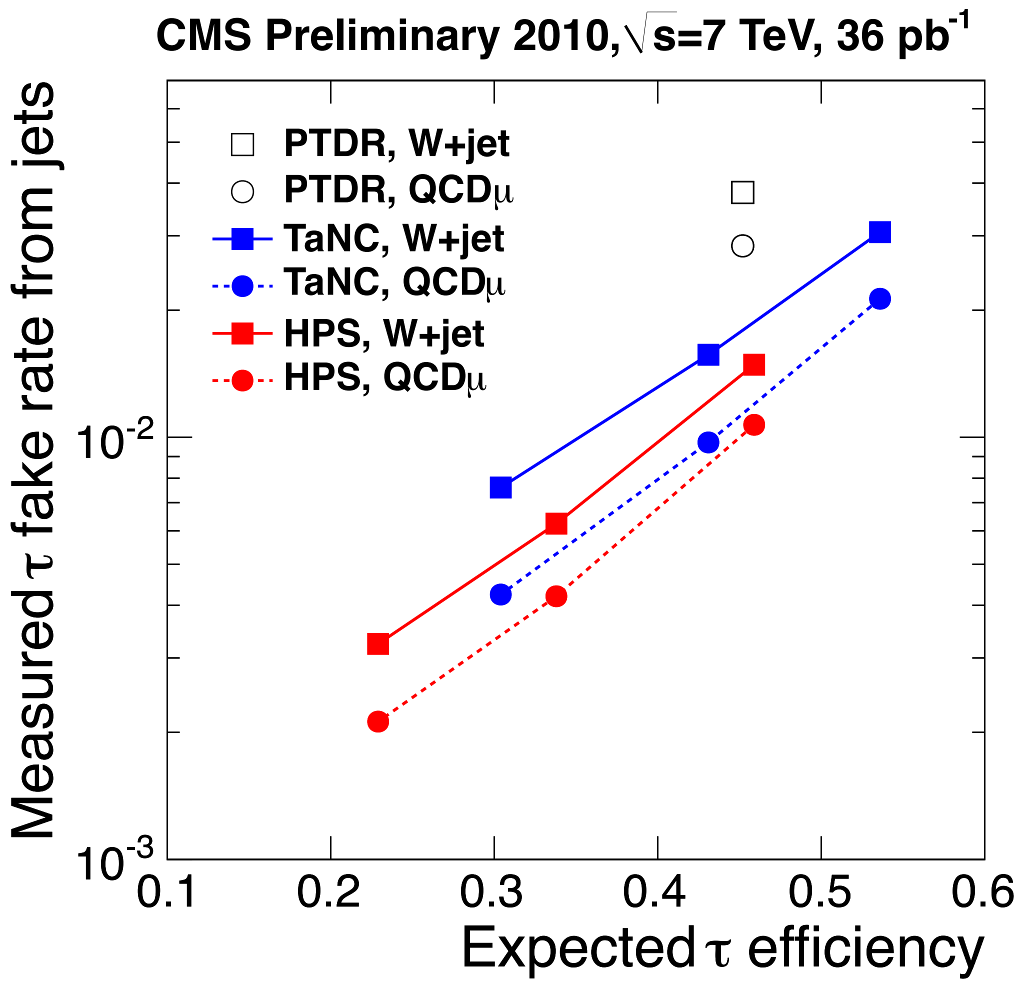
↓

Higgs $\tau\tau$ selection

- ✓ **SVFIT** mass: likelihood fit of tau momenta

τ identification (HPS)



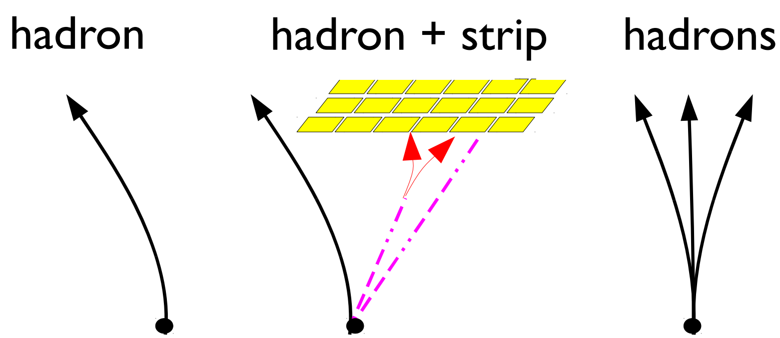


A decay mode algorithm

✓ High performance of τ identification (ID) using the hadron plus strips algorithm (HPS)

✓ HPS reconstructs the individual resonances of the τ decays, based on Particle Flow

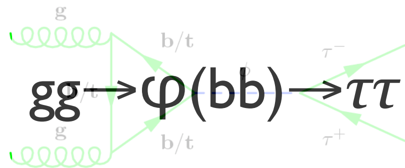
✓ The jet fake rate is 1% while achieving an efficiency of 50%



Fake rate: dijets p_T>15 GeV/c, tau p_T>15 GeV/c (data)

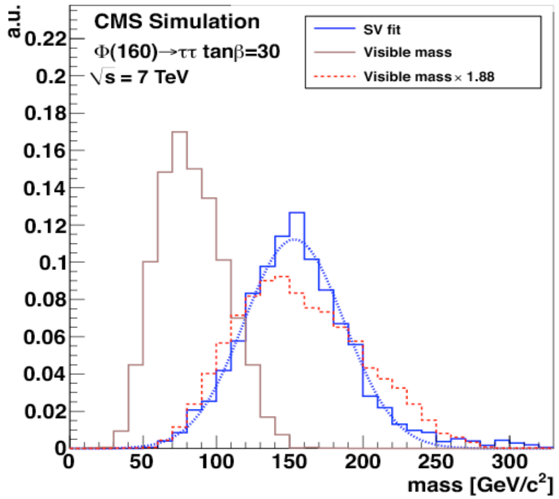
Signal Efficiency: visible taus p_T >15 GeV/c ($Z\to\tau\tau$ MC)

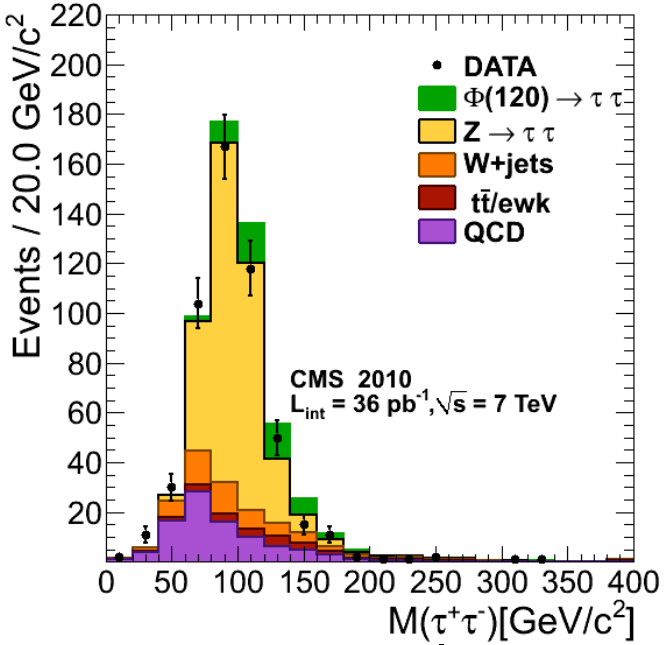
ττ mass reconstruction



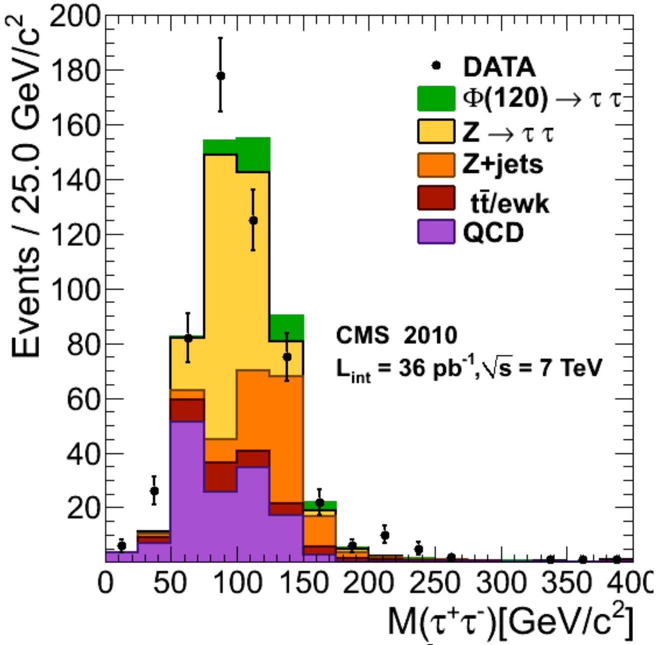
✓ Likelihood fit of momenta of visible decay products and of neutrinos produced in τ decays (SVFIT)

✓ Improvement in resolution w.r.t. previous techniques and not events loss due to unphysical solution

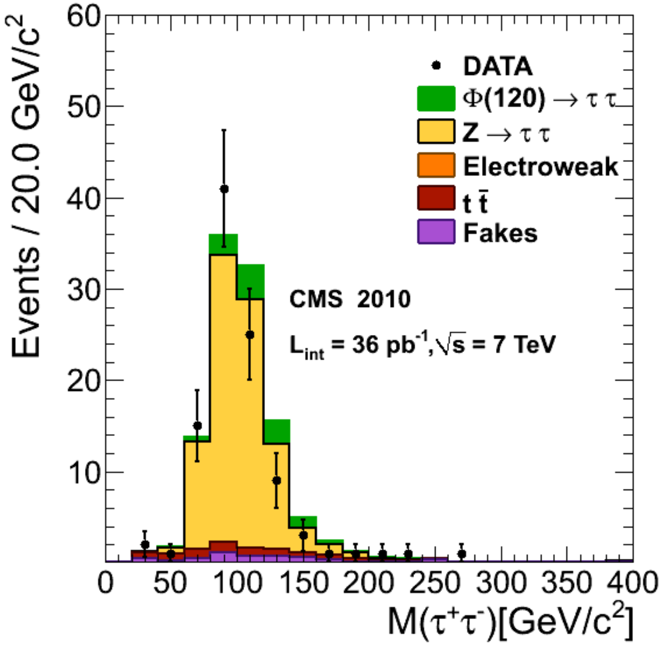




ττ→μ+τh

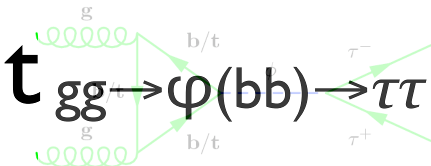


ττ→e+τh

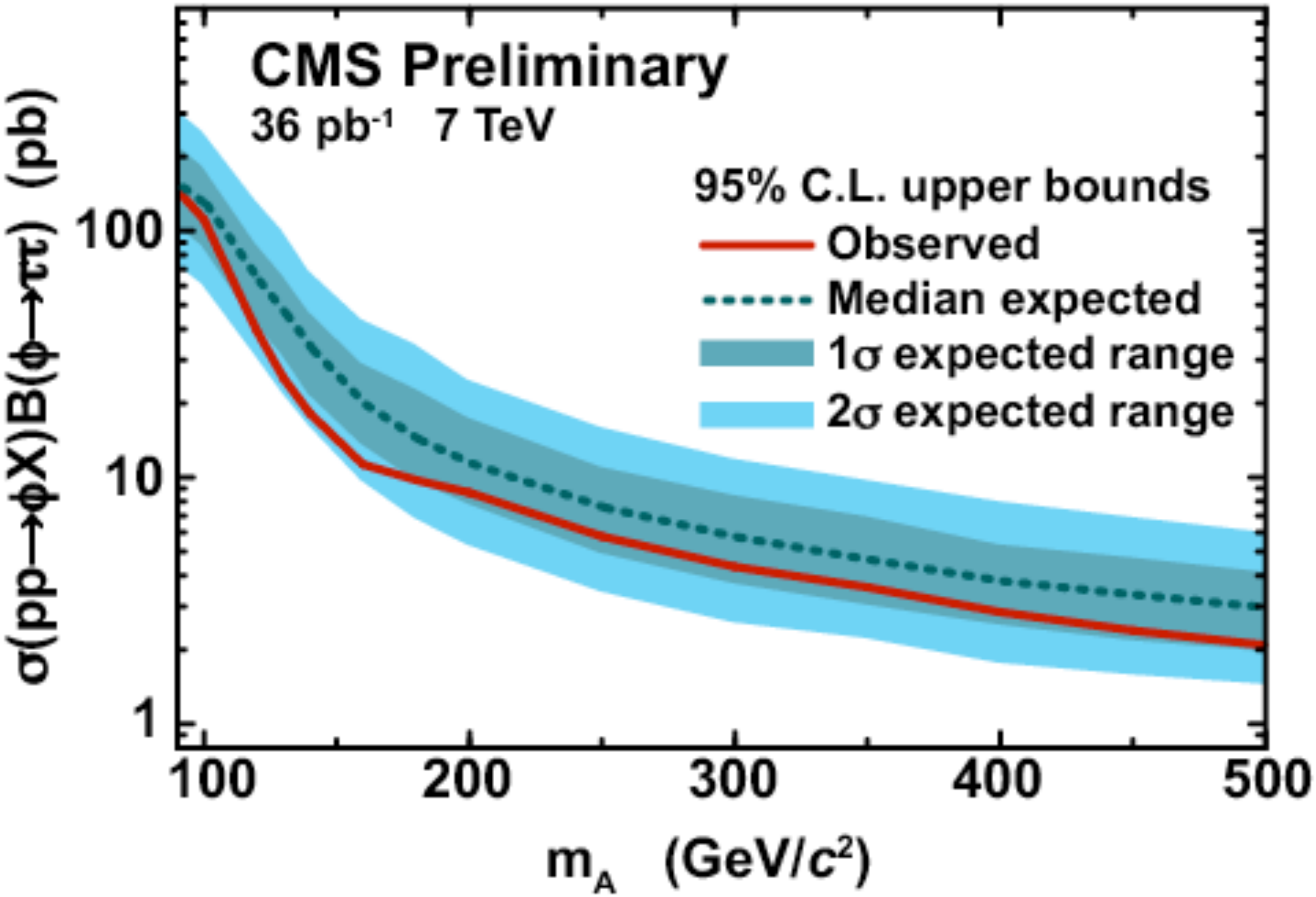


ττ→e+μ

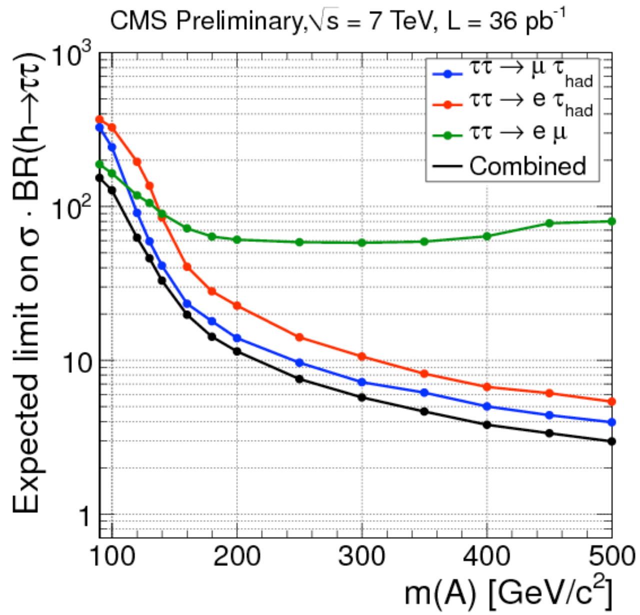
(bb)φ→ττ cross section limit gg→φ(bb)→ττ



φ: Sum of (pseudo-scalar + scalar) Higgs of about same mass



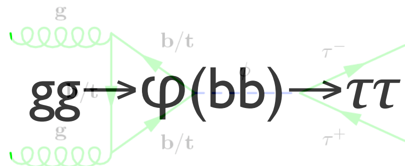
The observed and the expected 95% C.L. upper limit on σ x BR computed for different mass hypotheses m_A

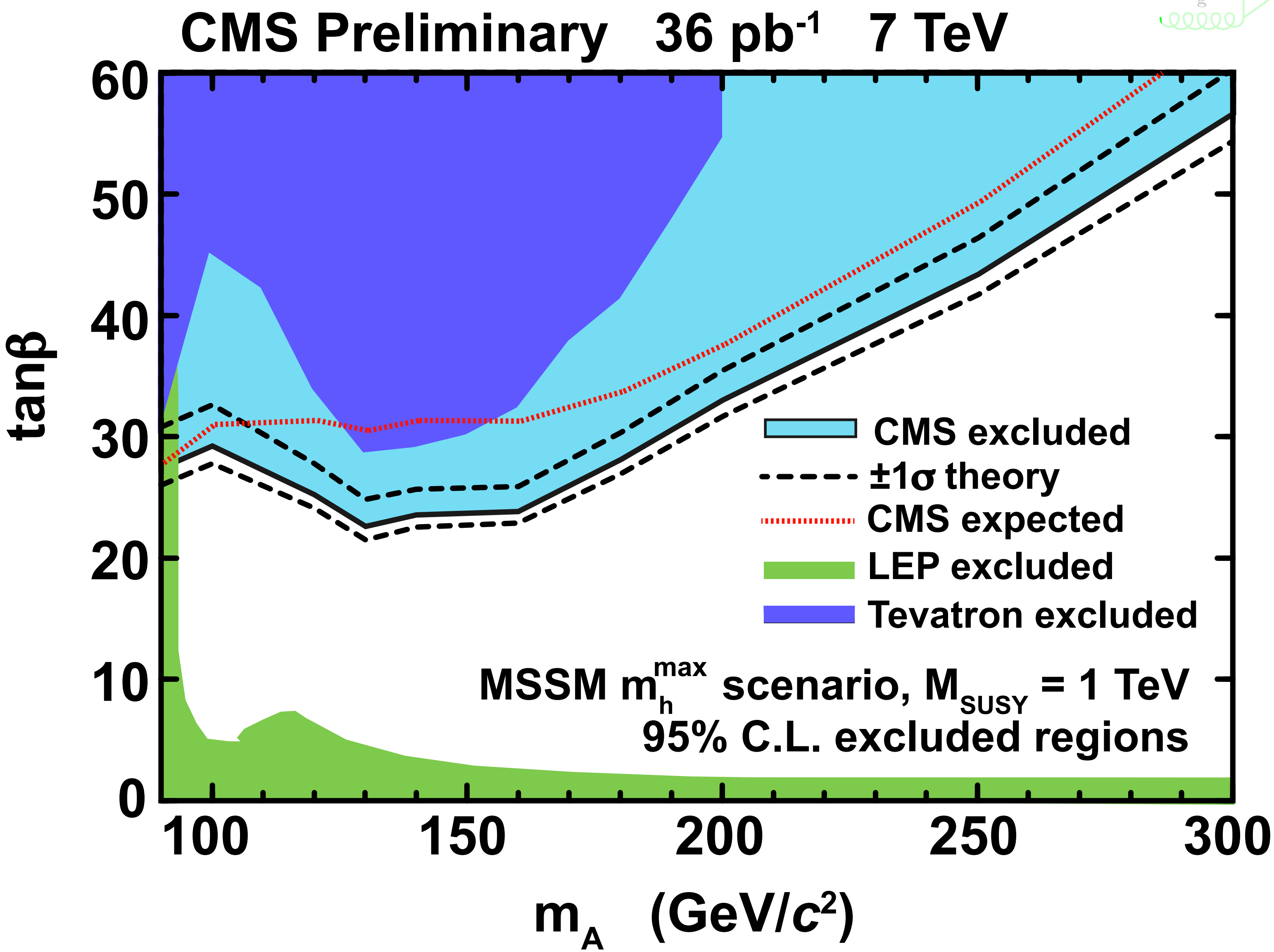


The expected 95% C.L. upper limits on σ x Br for each final state μ+τh, e+τh, e+μ and in combination

No evidence for signal, observed limit agrees with expected sensitivity

Limit on tanβ vs. m_A

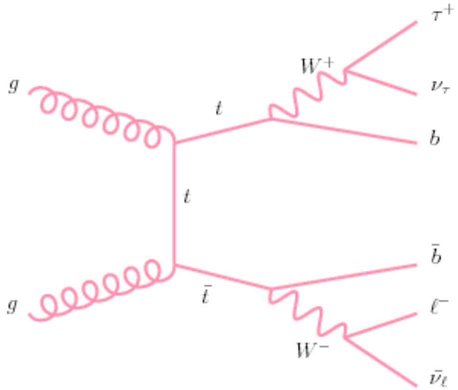


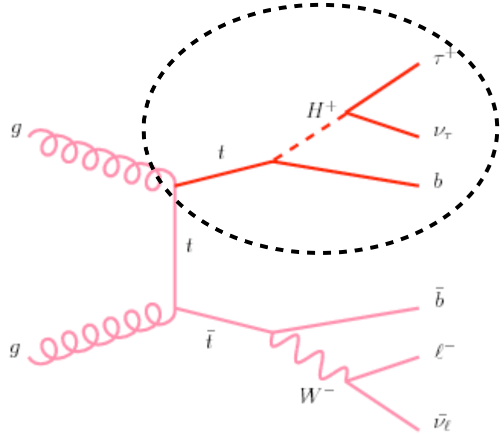


- ✓ 95% C.L. upper limit on σ x BR converted into limit on MSSM Parameter tanβ vs. m_A
- ✓ CMS limit more stringent than TeVatron limit over whole mass range

$t \to H^+ \to \tau^+ b \nu$

Charged **MSSM** Higgs bosons may contribute to ttbar decays

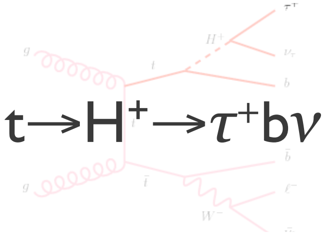




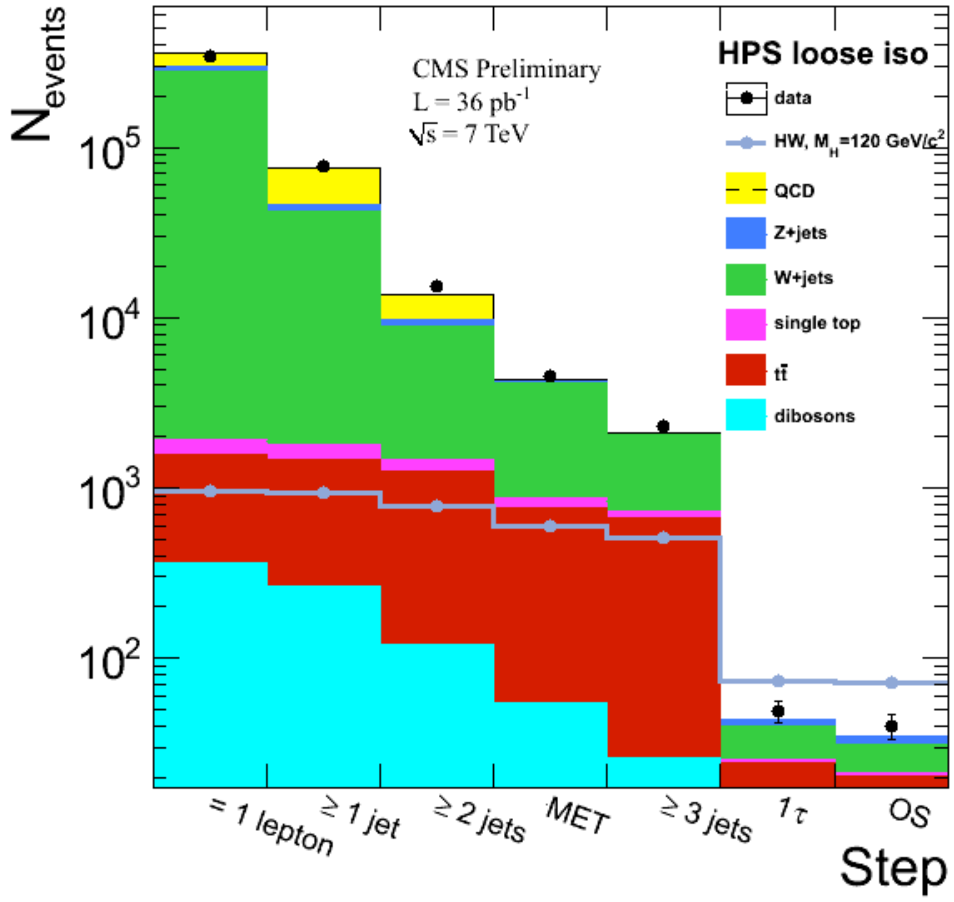
Substitute $H^\pm$ for $W^\pm$ in ttbar decays to τ

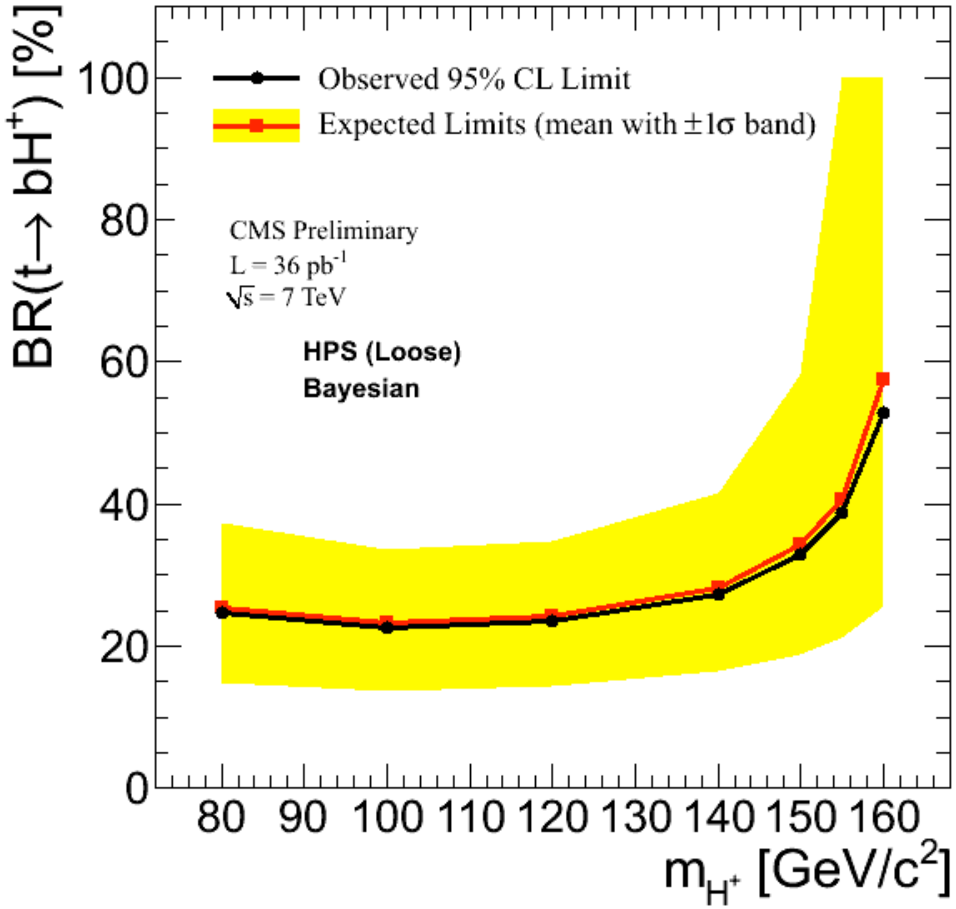
- ✓ Two di-lepton channels considered: **eτ** and **μτ**
- ✓ Backgrounds in two categories:
  - ✓ Fake hadronic τ: use fake rate method to estimate from data
  - ✓ Real hadronic τ: use simulation to estimate background
- ✓ Selection as for ttbar cross section measurement
  - ✓ One electron (muon) with p_T > 30 (20) GeV/c
  - ✓ Hadronic τ with p_T > 20 GeV/c, HPS identification
  - ✓ At least two jets p_T > 30 GeV/c
  - ✓ MET > 40 GeV

Limit



$t \to H^+ \to \tau^+ b\nu$





No signal observed

- ✓ Set 95% C.L on BR ($t \to H^+ b$) assuming BR($H^+ \to \tau^+ \nu$)=1
- ✓ Limit ~0.25-0.30 for 80 GeV/c^2 < m_{H+} < 140 GeV/c^2
- ✓ Limits comparable with TeVatron

Outline

- ✓ CMS's path to the Higgs
- ✓ Hunting the Higgs with the 2010 data
  - ✓ status of CMS searches
- ✓ Higgs projections
  - ✓ how we can discover the ("SM") Higgs (or prove it doesn't exist)

Higgs projections

Higgs projections

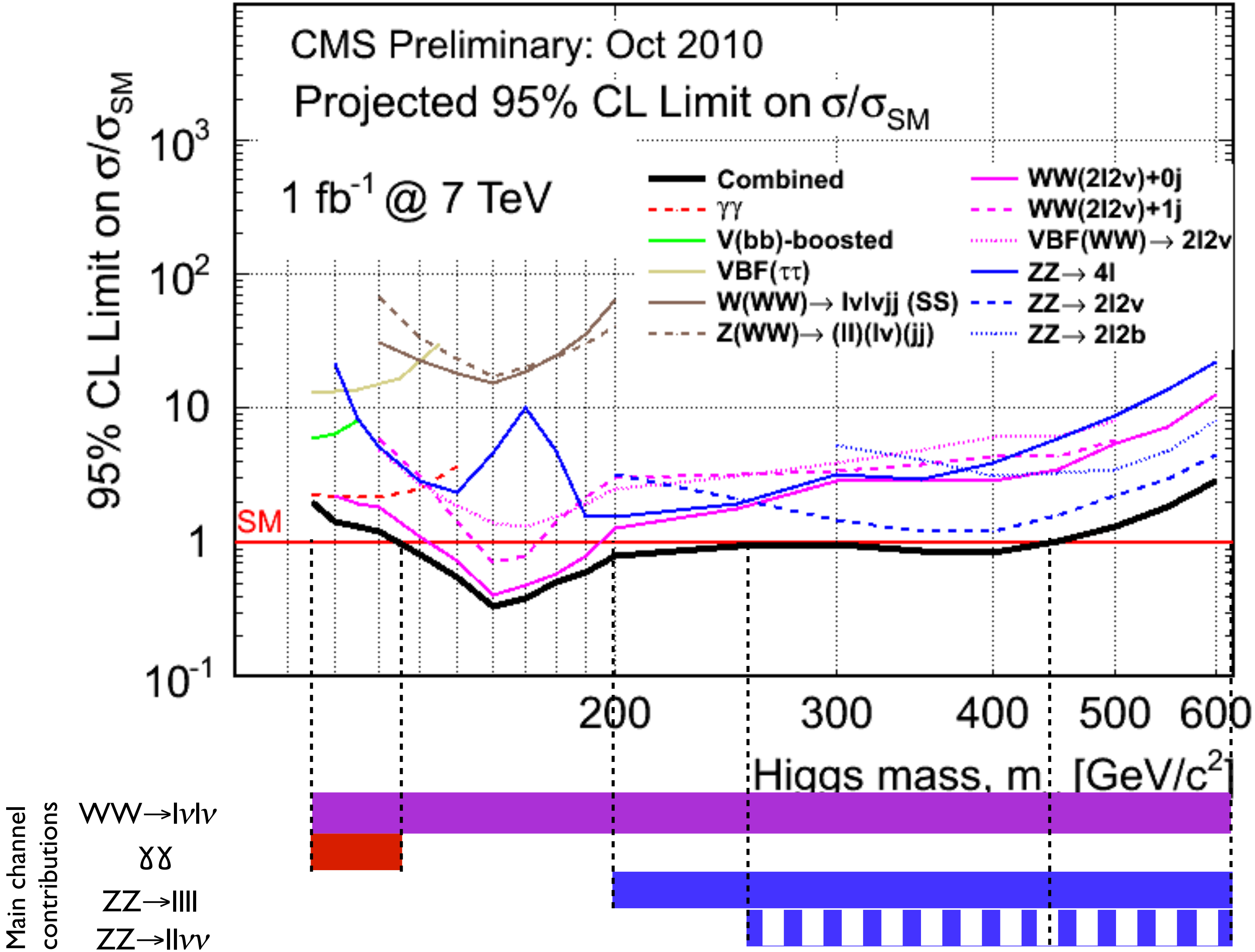
for 2011-2012

- ✓ Used state of the art cross-sections
  - ✓ signal NNLO for gg, NLO for VBF,VH
  - ✓ background processes at NLO
- ✓ Full GEANT based detector simulation
- ✓ Simple cut-based analysis, mostly counting events:
  - ✓ no SHAPE analysis used (can improve sensitivity by ~(20-100)%)
- ✓ Validation from 2010 data:
  - ✓ **excellent agreement between data and detector simulation**
  - ✓ detector performance close to design in most cases
  - ✓ measured production rates of background processes in good agreement with expectations (5-30 % uncertainties)
- ✓ In general, analyses with data more sensitive than the simulation based studies used in the projections...and will continue to improve!
  - ✓ as CDF & D0 have already shown

Projections are indicative not predictive !

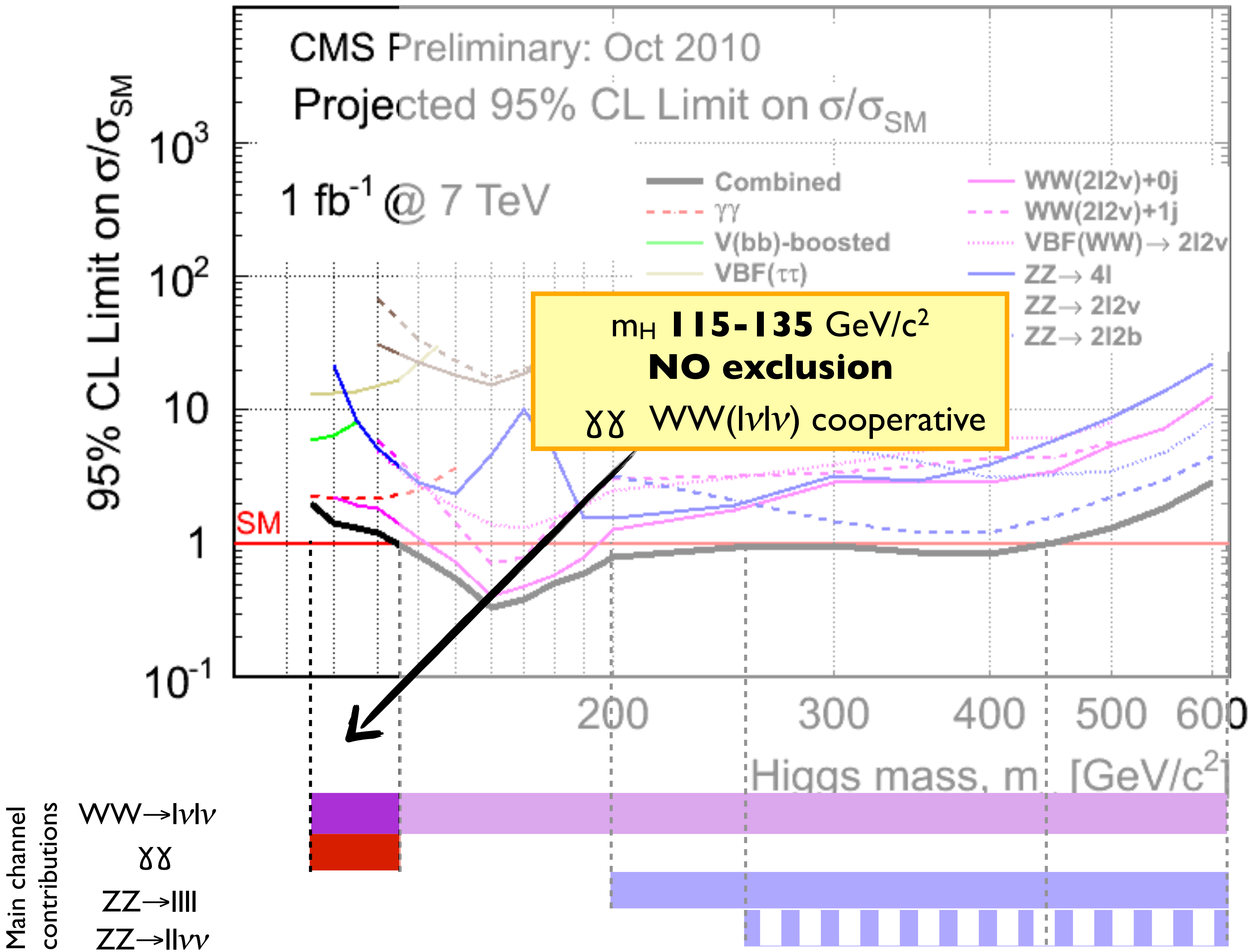
SM-Higgs Exclusions: 1 fb^{-1} @ 7 TeV

a possible 2011 scenario



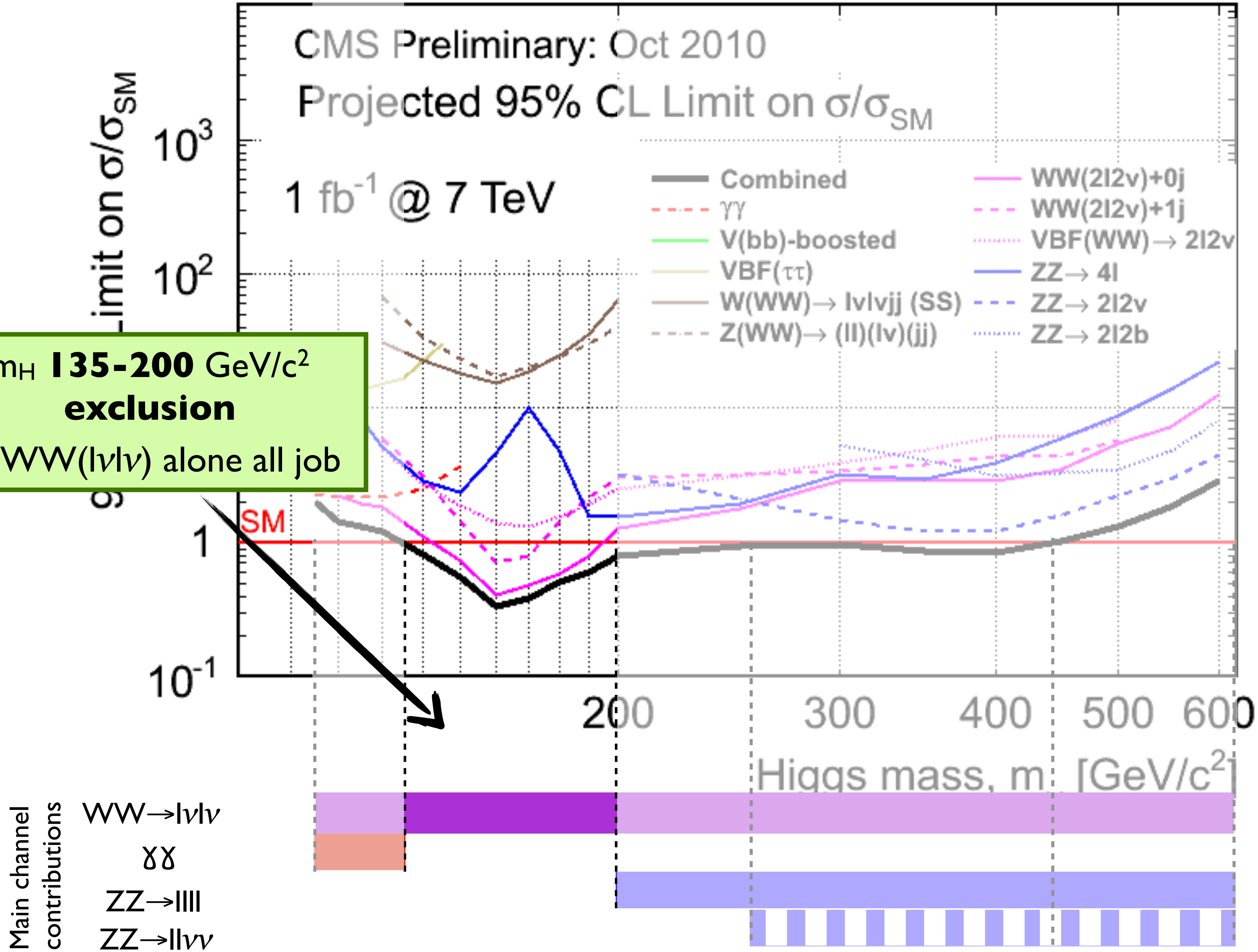
SM-Higgs Exclusions: 1 fb^{-1} @ 7 TeV

a possible 2011 scenario



SM-Higgs Exclusions: 1 fb^{-1} @ 7 TeV

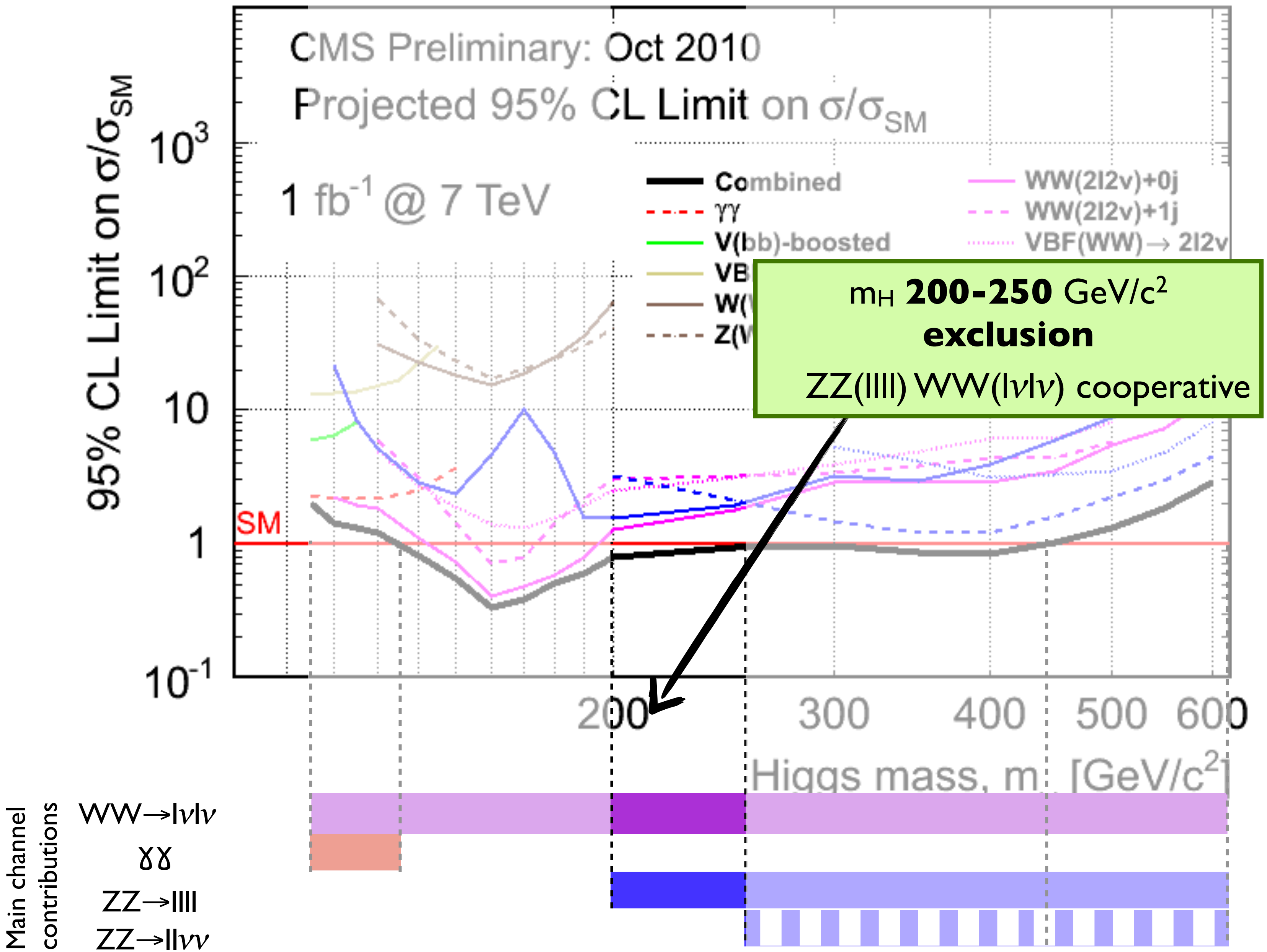
a possible 2011 scenario



m_H **135-200** GeV/c^2
exclusion
WW(lνlν) alone all job

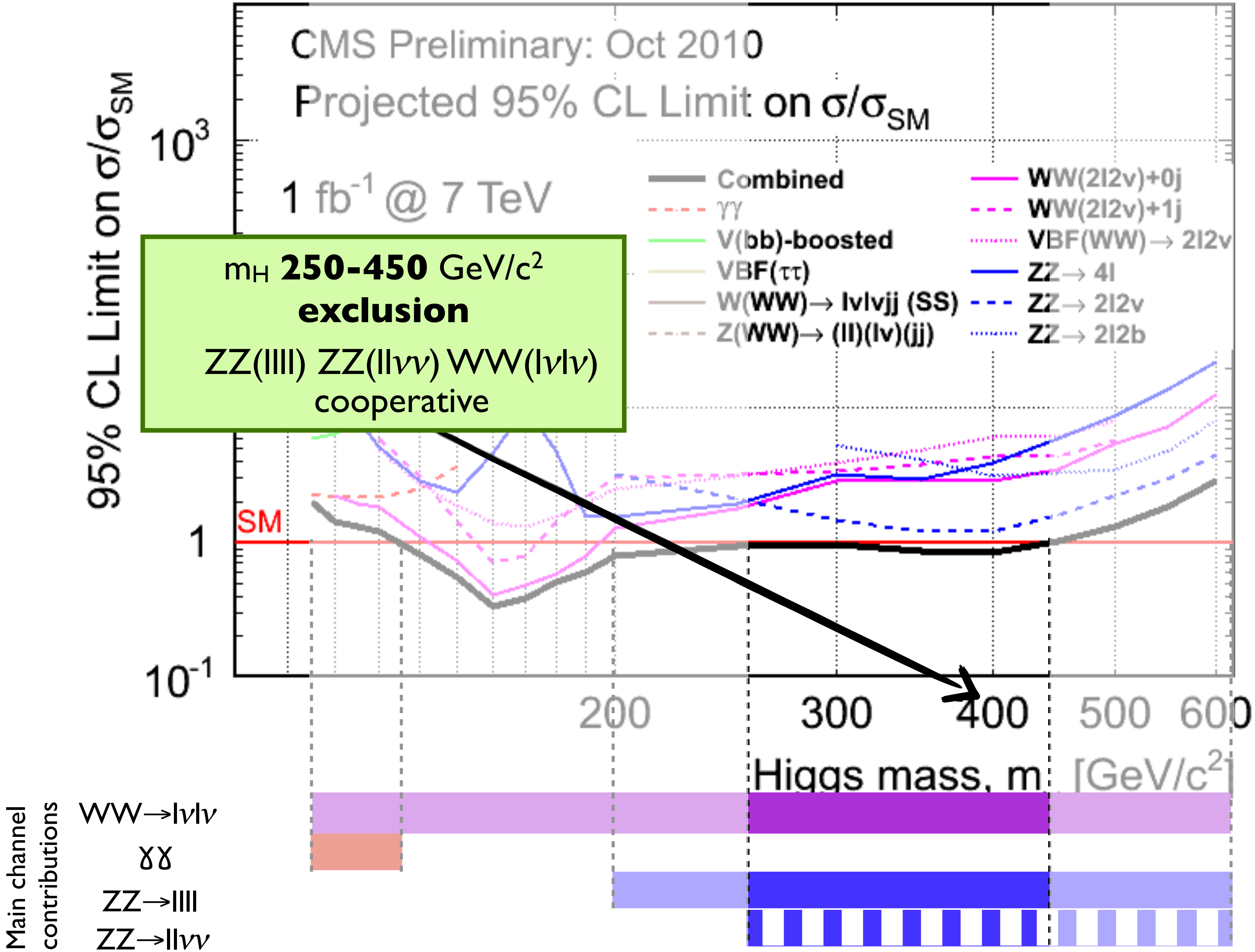
SM-Higgs Exclusions: 1 fb^{-1} @ 7 TeV

a possible 2011 scenario



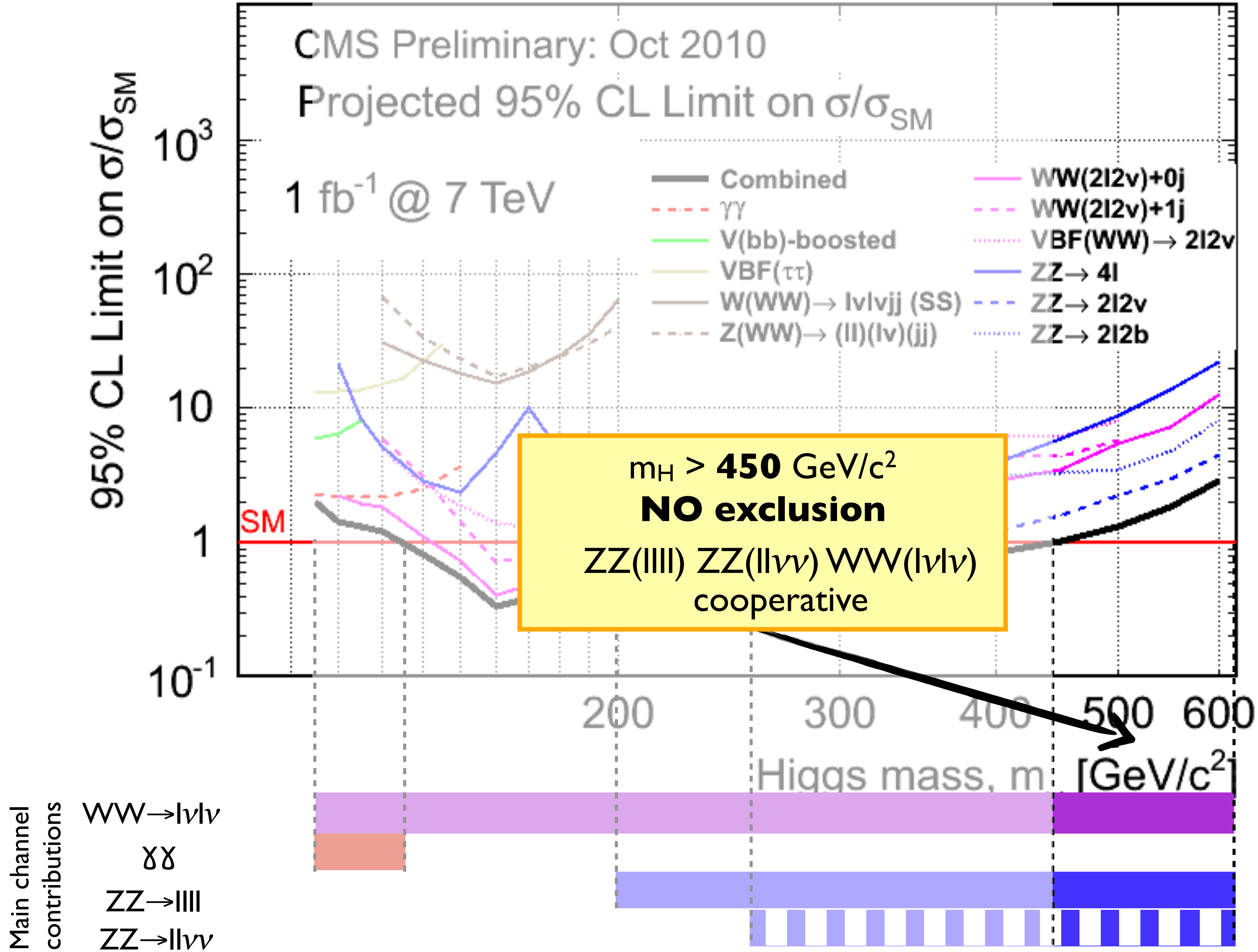
SM-Higgs Exclusions: 1 fb^{-1} @ 7 TeV

a possible 2011 scenario

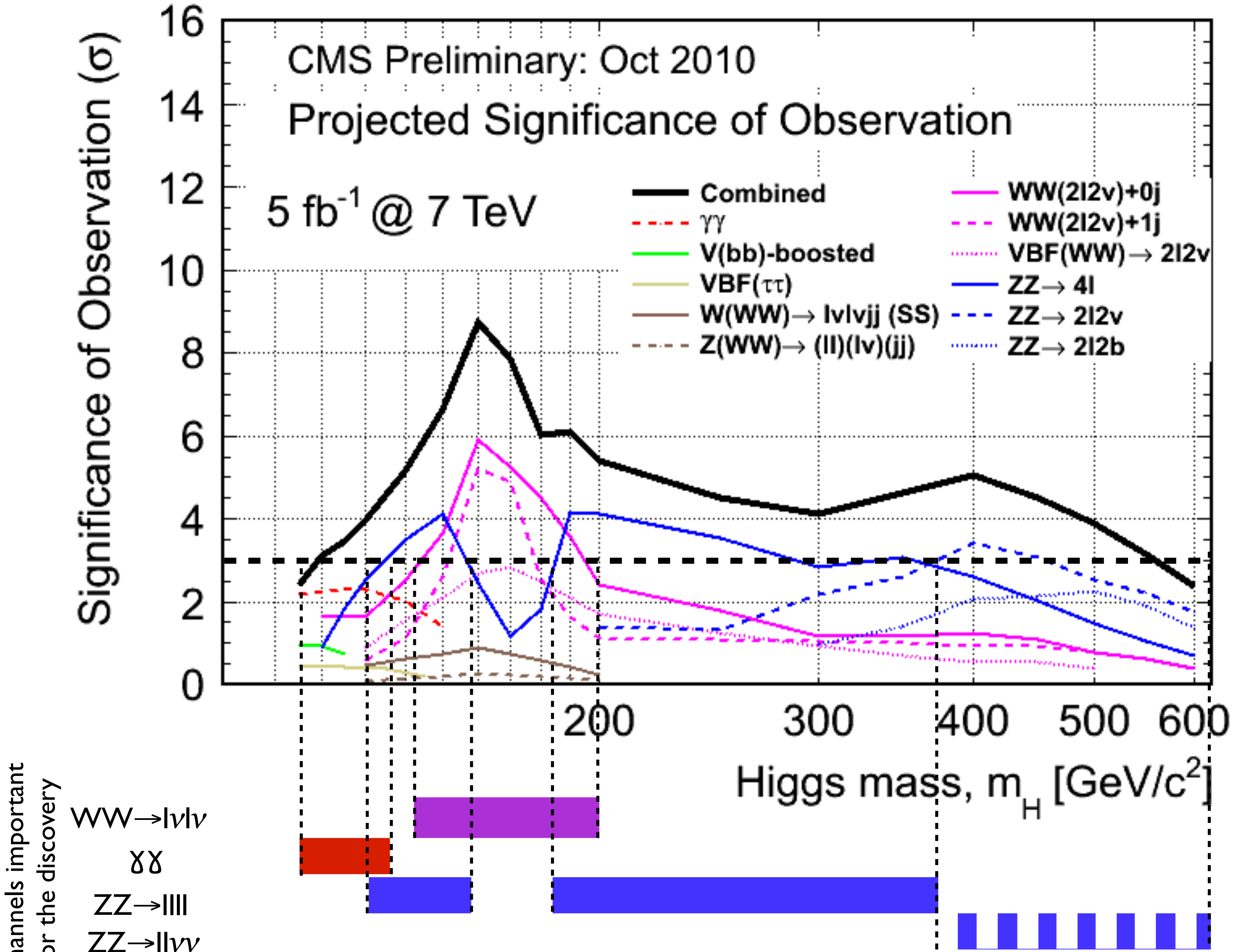


SM-Higgs Exclusions: 1 fb^{-1} @ 7 TeV

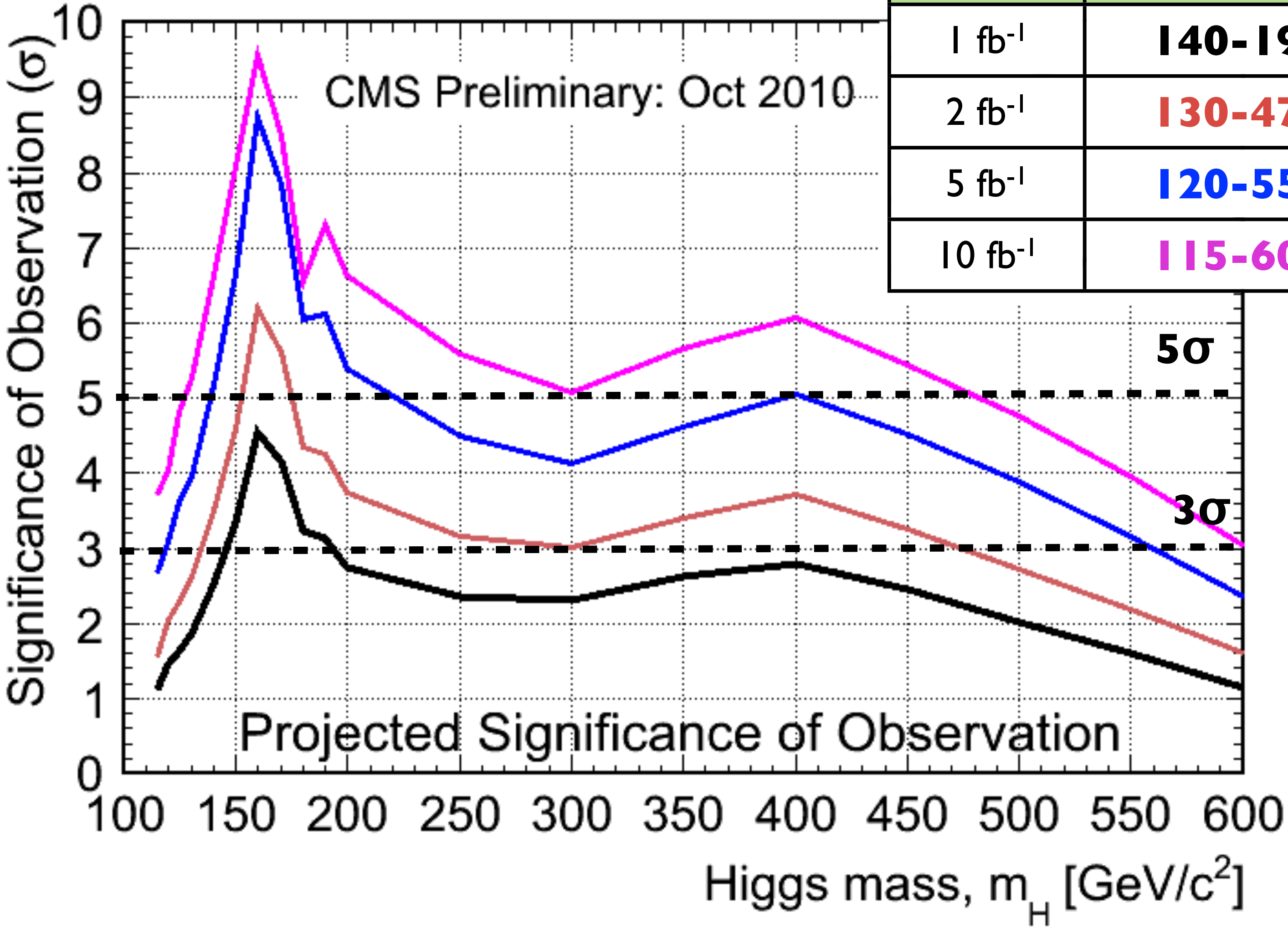
a possible 2011 scenario



Significance of Observation 5 fb^{-1} @ 7 TeV



SM-Higgs Sensitivity 1/2/5/10 fb^{-1} @ 7 TeV



Integrate luminosity	3σ sensitivity	5σ sensitivity
1 fb^{-1}	**140-190**	**none**
2 fb^{-1}	**130-475**	**150-170**
5 fb^{-1}	**120-550**	**140-220**
10 fb^{-1}	**115-600**	**130-475**

Conclusion

✓ The CMS experiment has revisited the Standard Model in a new regime at record centre-of-mass energy of 7 TeV for p-p collisions

✓ A **solid ground** has been established, with EWK boson candles, first di-bosons, di-top and single top measurements, on the route towards the Higgs boson(s)

✓ A SM-Higgs boson with mass in **144-207 GeV/c²** range in an extension of the Standard Model with 4-fermion generations is excluded

✓ New territories are being explored for **extending Higgs sector** (e.g. from mSUSY theories)

✓An **exclusion** of the SM-Higgs is possible at the **95% CL** for and integrated luminosity of **1fb^{-1}** for masses between **135-450 GeV/c²**

✓ A **5σ discovery** for the SM-Higgs bosons is possible for integrated luminosity of **10 fb^{-1}** and masses above **130 GeV/c²**

✓ Very low masses **115 < M_H < 130 GeV/c²** will require the highest integrated luminosity and relay for a discovery mostly on H in 2 gamma and H in ZZ* (+possibly boosted Higgs in bb)

Very exciting physics in the years to come at the LHC

References

✓ "Measurement of WW Production and Search for the Higgs Boson in pp Collisions at sqrt(s)=7 TeV"
arXiv:1102.5429 CMS-EWK-10-009 CMS-HIG-10-003 CERN-PH-EP-2011-015
to be published in Phys. Lett. B

✓ "Search For Neutral MSSM Higgs Boson Production via Decays to Tau Pairs in pp Collisions at sqrt(s)=7 TeV"
CMS-HIG-10-002-002 CERN-PH-EP-2011-027
to be submitted to arXiv and published

✓ "Search for the charged Higgs boson in the etau and mutau dilepton channels of top quark pair decays"
CMS-PAS-HIG-11-002

✓ "Inclusive search for doubly charged higgs in leptonic final states at sqrt(s)=7 TeV"
CMS-PAS-HIG-11-001

✓ "Projected sensitivity for Standard Model Higgs boson searches at 7 and 8 TeV, and 1-10 fb^{-1}"
CMS-NOTE-2010-008

Higgs boson(s) spectrum

✓ Standard Model:

1 doublet of Higgs fields → 1 physical Higgs boson
CP-even H

What is good about it?

- ✓ exact unitary cancellation ($W_L W_L$ scattering)
- ✓ coherent solution for origin of EWK masses
- ✓ nature tends to be economic: only one additional particle
- ✓ model makes very precise predictions: decay kinematics, couplings, cross section...
- ✓ direct search or indirect constraints (via radiative corrections)

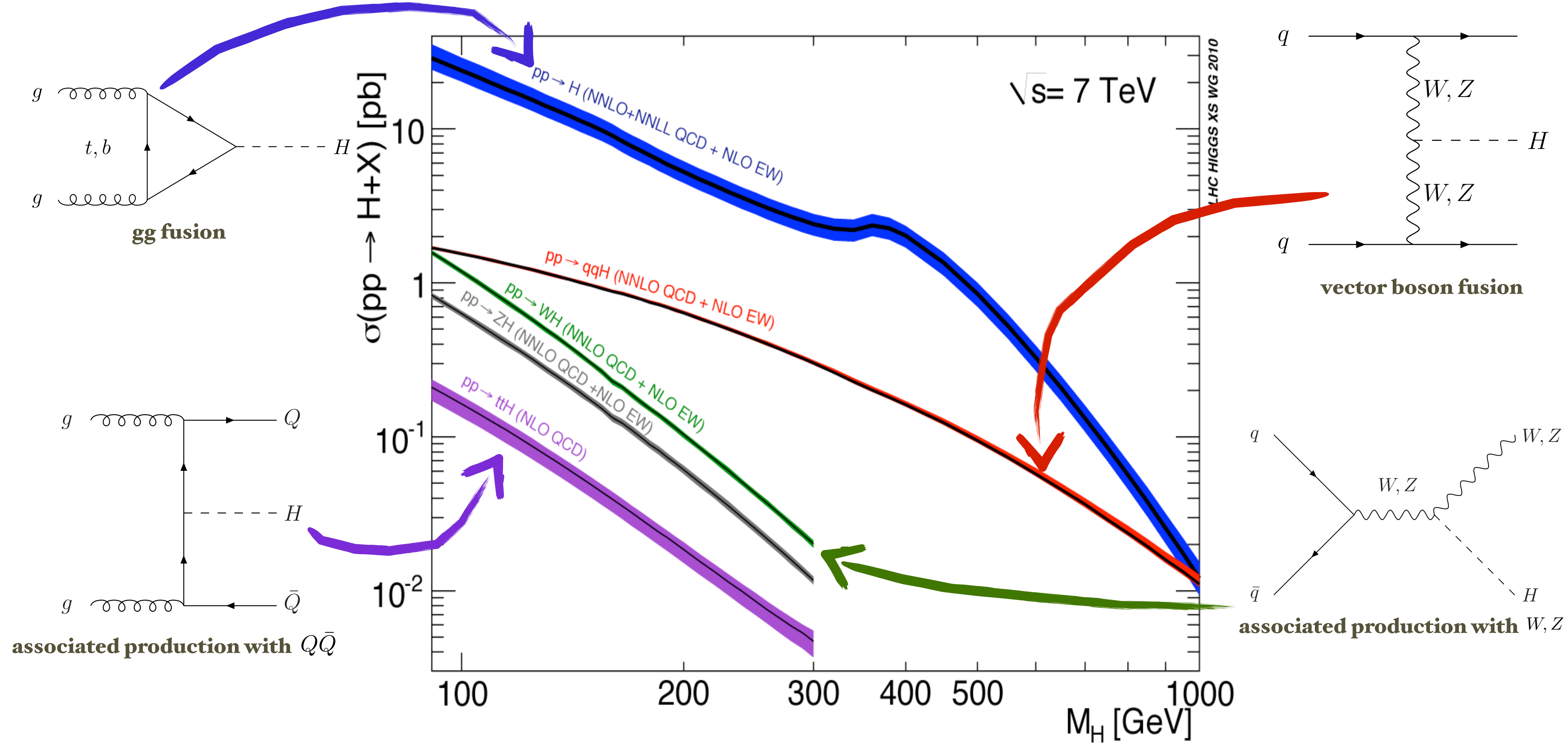
What is not good about it?

- ✓ Higgs boson mass and fermion masses are not predicted by the theory
- ✓ Higgs boson mass is sensitive of radiative corrections (unstable)
- ✓ Standard Model still unsatisfactory

✓ Minimal Supersymmetric Standard Model:

2 doublet of Higgs fields (effective 2HDM model) → 5 physical Higgs bosons
2CP-even: h, H 1Pseudoscalar: A 2Charged: H^+,H^-
At tree level the Higgs sector in mSUSY is determined by two parameters
e.g. M_A and $\tan\beta$
Including radiative corrections in mSUSY: $M_h \leq 140$ GeV/c^2

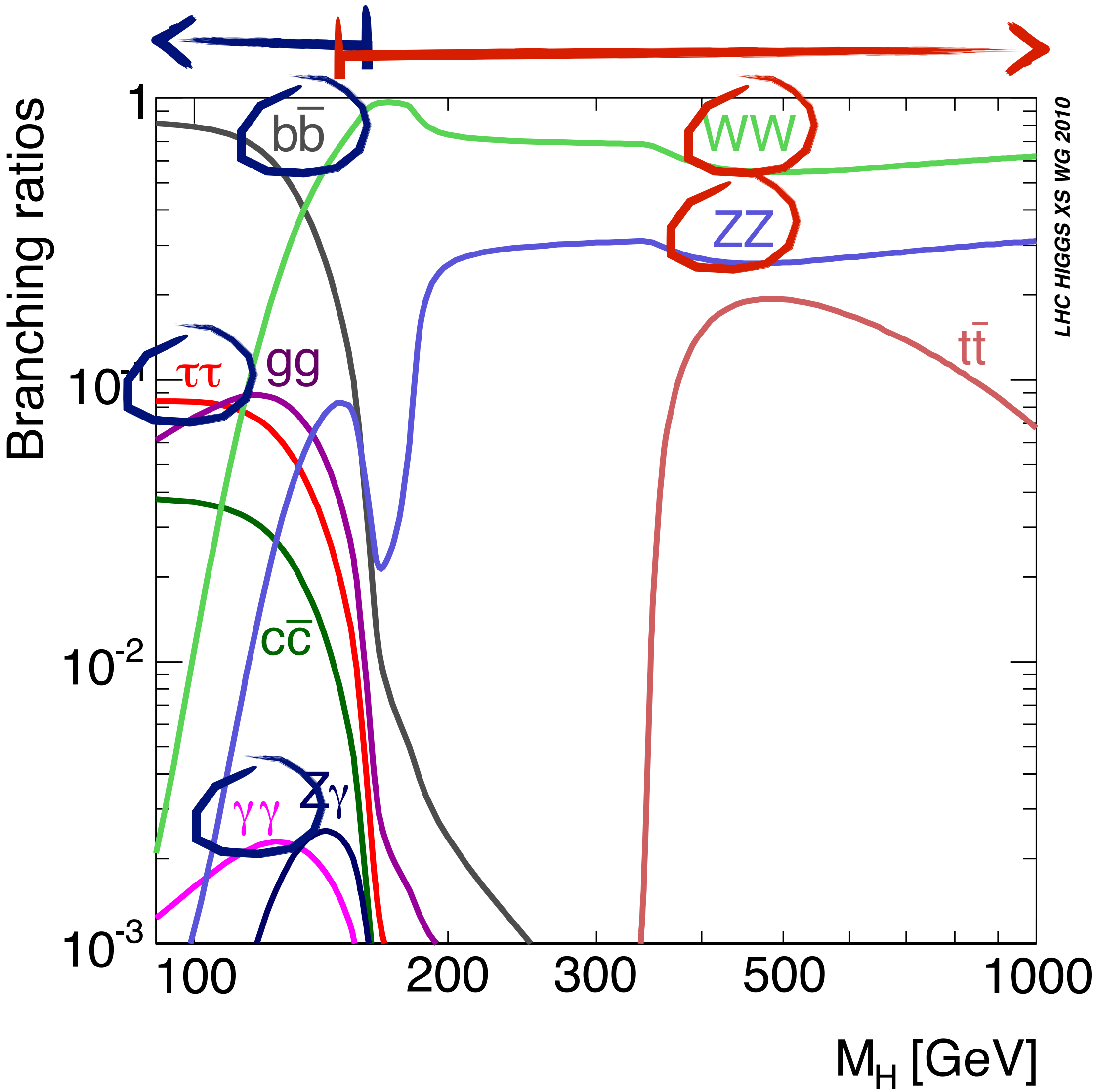
SM-Higgs production @ LHC



$$\sigma(p_1, p_2; M_H) = \sum_{a,b} \int_0^1 dx_1 dx_2 \, f_{h_1,a}(x_1, \mu_F^2) \, f_{h_2,b}(x_2, \mu_F^2) \times \hat{\sigma}_{ab}(x_1 p_1, x_2 p_2, \alpha_S(\mu_R^2); \mu_F^2)$$

Precise predictions for **σ** depend on good knowledge of
BOTH **parton distributions** and **partonic cross section**

SM-Higgs decay modes



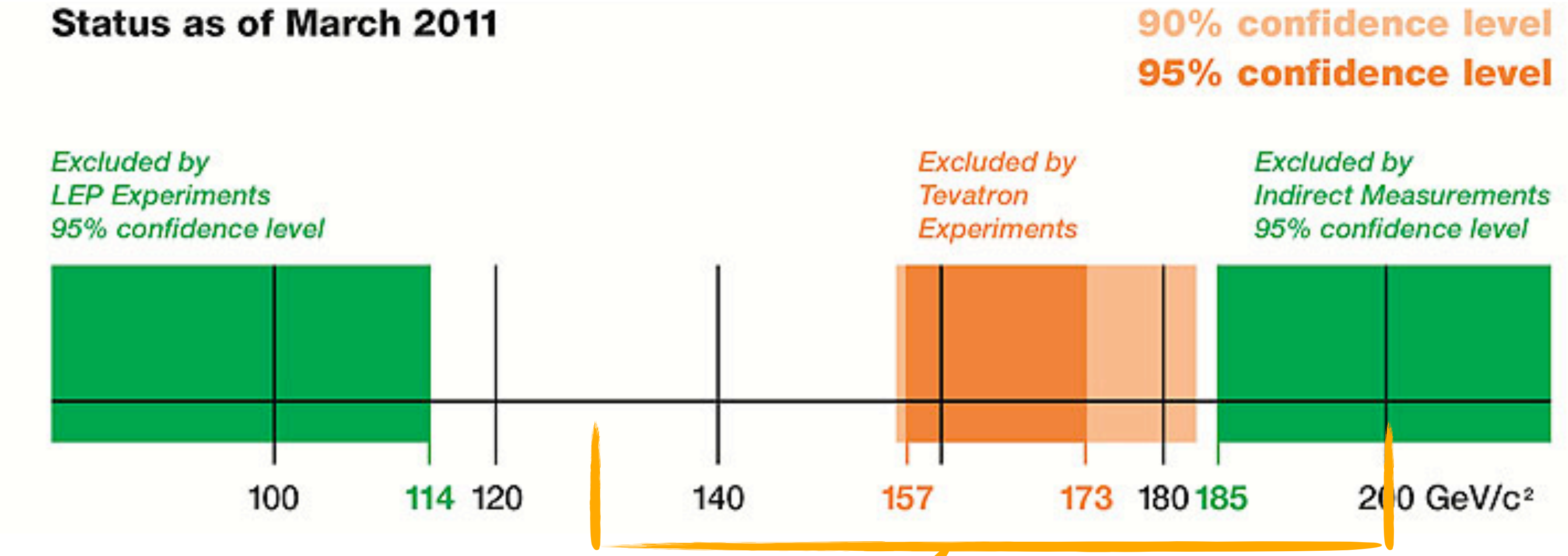
Low mass regime:
m_H < 140 GeV/c²

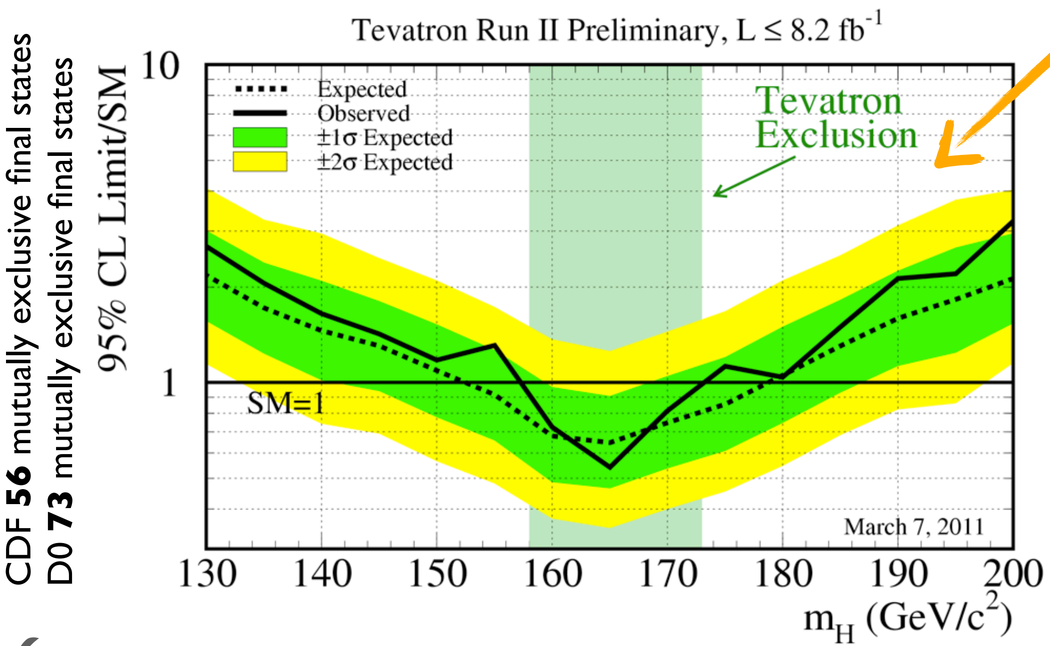
- ✓ $H \rightarrow b\bar{b}$
  - ✓ associated production, VBF
- ✓ $H \rightarrow \tau\tau$
  - ✓ VBF
- ✓ $H \rightarrow \gamma\gamma$
  - ✓ extremely low B.R.

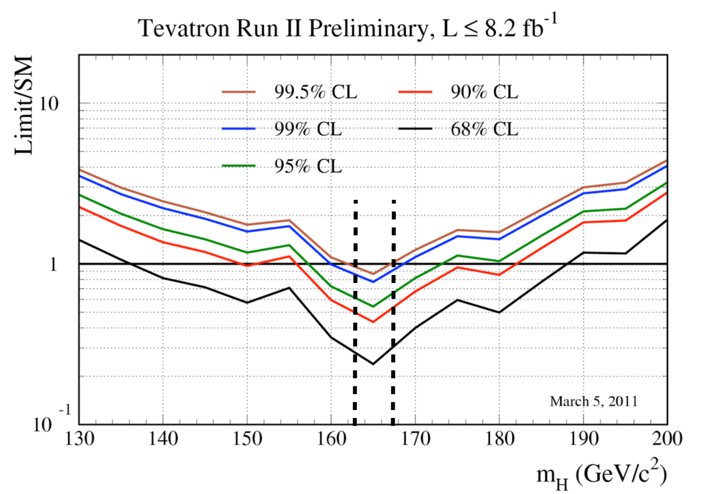
Intermediate-High mass regime:
m_H > 130 GeV/c²

- ✓ H→WW
  - ✓ no mass peak
- ✓ H→ZZ
  - ✓ discovery channel

Search for SM-Higgs



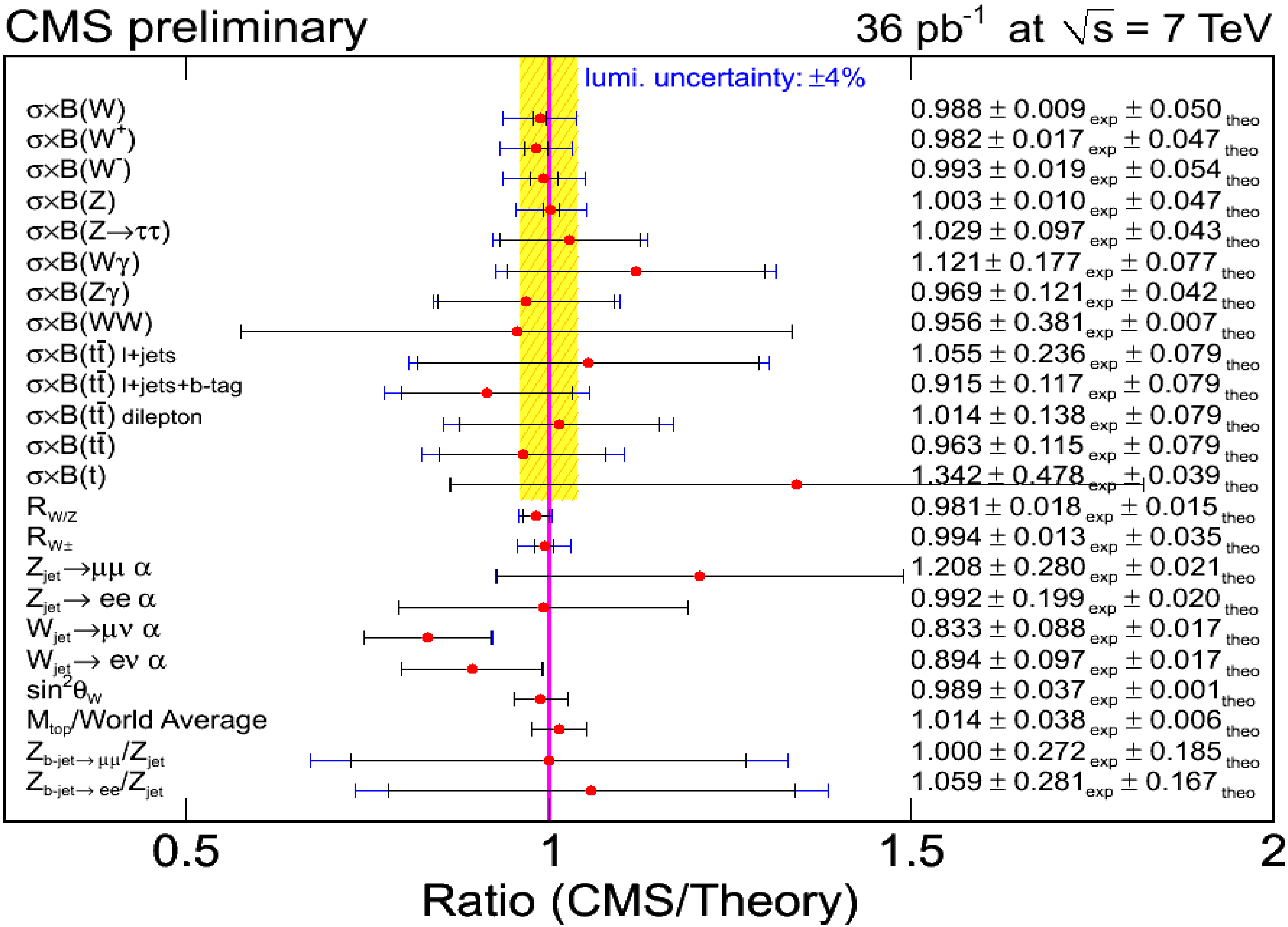




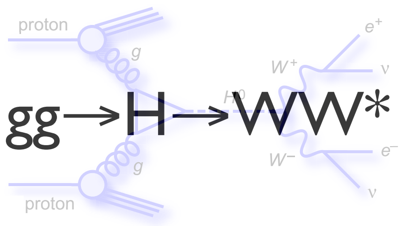
TeVatron excludes SM-Higgs at **99.5% CL** for $162 < m_H < 166$ GeV/c^2

- ✓ TeVatron excludes SM-Higgs at 95% CL for **158** < m_H < **173** GeV/c^2
- ✓ Sensitive to exclude SM-Higgs at 95% CL for $153 < m_H < 179$ GeV/c^2

Summary

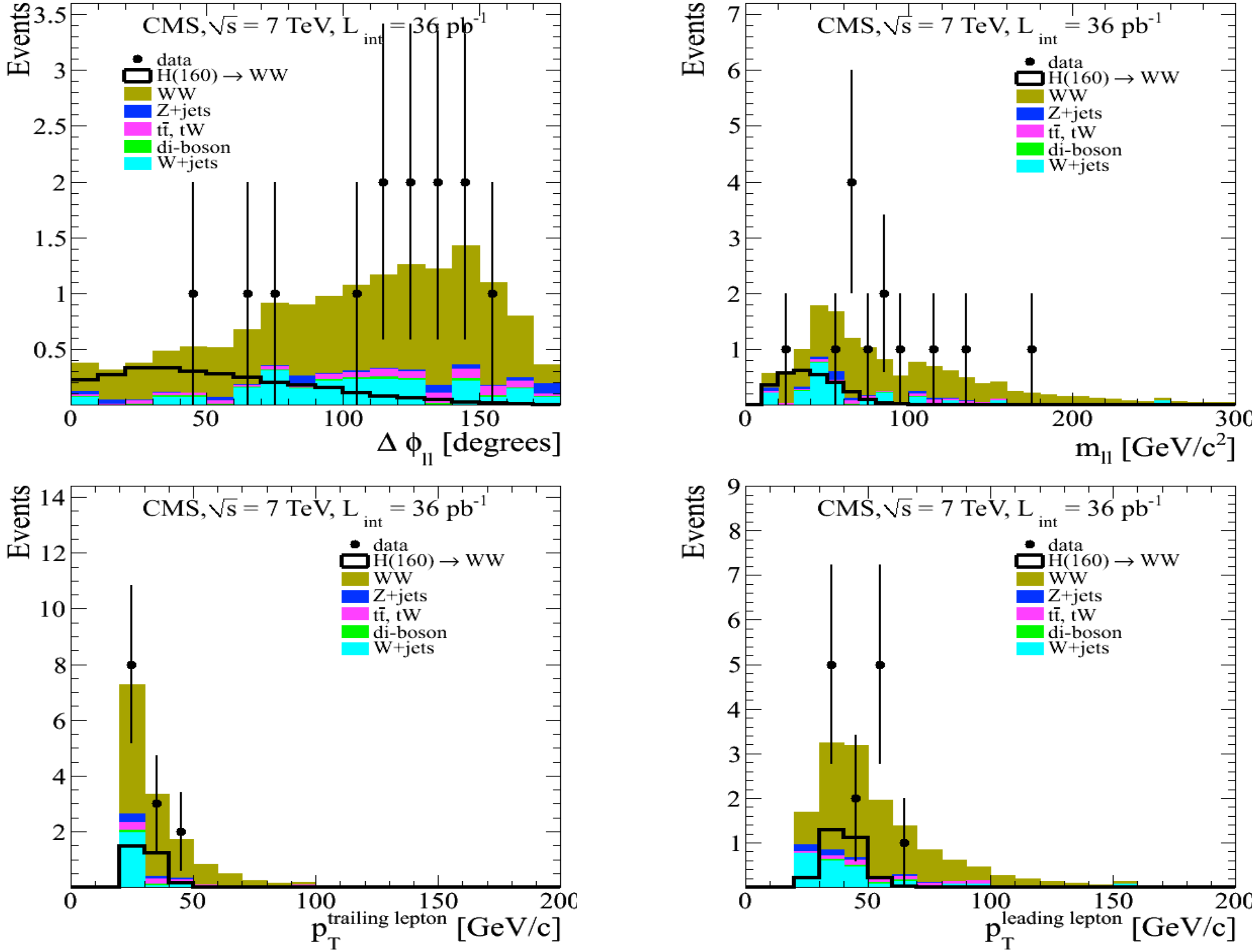

CMS preliminary
36 pb-1 at √s = 7 TeV
lumi. uncertainty: ±4%
σ×B(W)
σ×B(W+)
σ×B(W-)
σ×B(Z)
σ×B(Z→ττ)
σ×B(Wγ)
σ×B(Zγ)
σ×B(WW)
σ×B(tt̄) l+jets
σ×B(tt̄) l+jets+b-tag
σ×B(tt̄) dilepton
σ×B(tt̄)
σ×B(t)
R W/Z
R W±
Z jet→μμ α
Z jet→ ee α
W jet→μν α
W jet→ eν α
sin2θW
Mtop/World Average
Z b-jet→ μμ/Z jet
Z b-jet→ ee/Z jet
0.988 ± 0.009 exp ± 0.050 theo
0.982 ± 0.017 exp ± 0.047 theo
0.993 ± 0.019 exp ± 0.054 theo
1.003 ± 0.010 exp ± 0.047 theo
1.029 ± 0.097 exp ± 0.043 theo
1.121 ± 0.177 exp ± 0.077 theo
0.969 ± 0.121 exp ± 0.042 theo
0.956 ± 0.381 exp ± 0.007 theo
1.055 ± 0.236 exp ± 0.079 theo
0.915 ± 0.117 exp ± 0.079 theo
1.014 ± 0.138 exp ± 0.079 theo
0.963 ± 0.115 exp ± 0.079 theo
1.342 ± 0.478 exp ± 0.039 theo
0.981 ± 0.018 exp ± 0.015 theo
0.994 ± 0.013 exp ± 0.035 theo
1.208 ± 0.280 exp ± 0.021 theo
0.992 ± 0.199 exp ± 0.020 theo
0.833 ± 0.088 exp ± 0.017 theo
0.894 ± 0.097 exp ± 0.017 theo
0.989 ± 0.037 exp ± 0.001 theo
1.014 ± 0.038 exp ± 0.006 theo
1.000 ± 0.272 exp ± 0.185 theo
1.059 ± 0.281 exp ± 0.167 theo
0.5
1
1.5
2
Ratio (CMS/Theory)

After WW selection



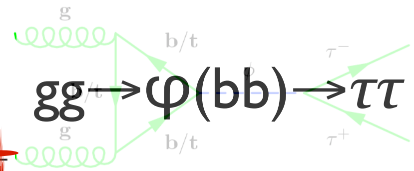
13 selected SM-WW candidates

2 ee / 1 μμ / 10 eμ

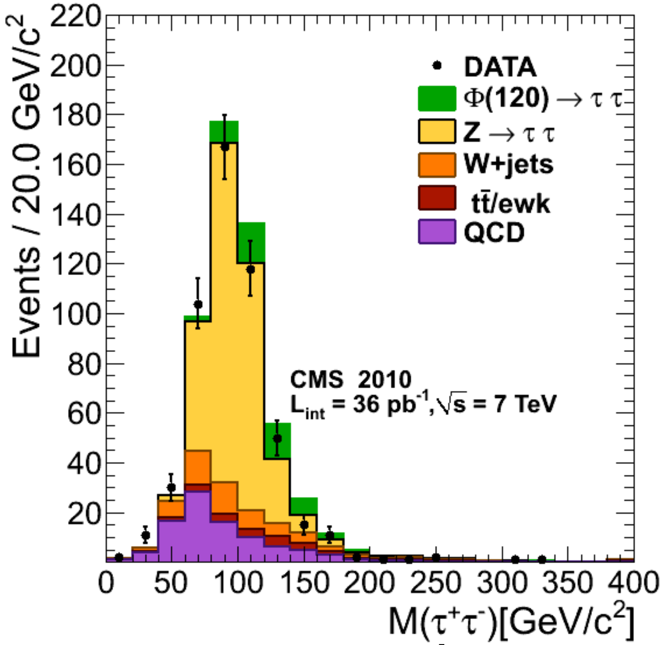


Variables used in the cut based selection

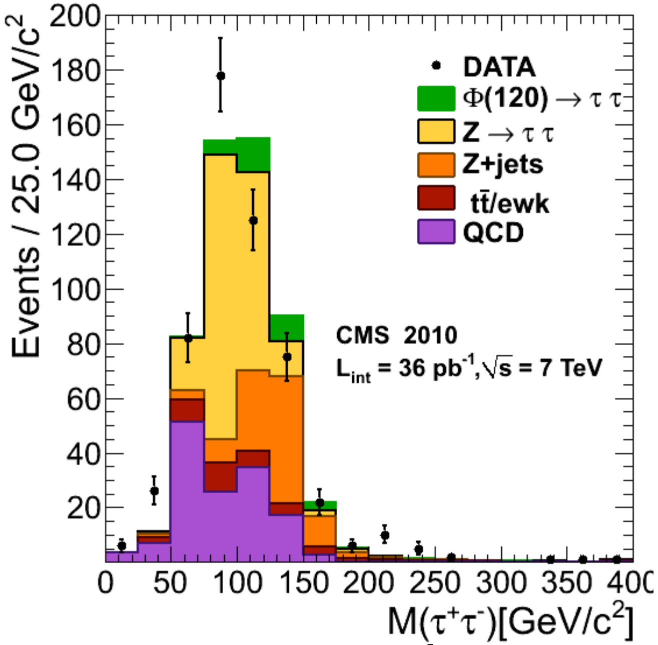
$\tau\tau$ event yields



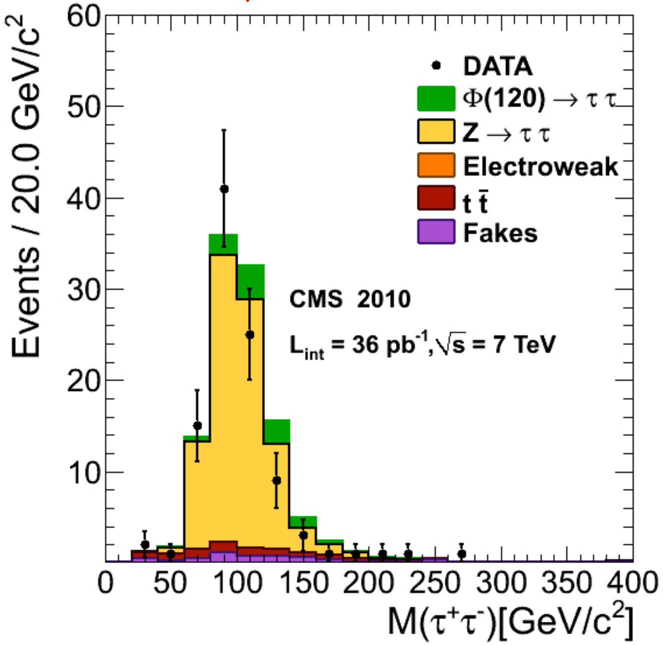
Process	$\mu\tau_h$	$e\tau_h$	$e\mu$
$Z \to \tau\tau$	329 ± 77	190 ± 44	88 ± 5
$t\bar{t}$	6 ± 3	2.6 ± 1.3	7.1 ± 1.3
$Z \to \ell\ell, jet \to \tau_h$	6.4 ± 2.4	15 ± 6.2	
$Z \to \ell\ell, \ell \to \tau_h$	13.3 ± 3.6	119 ± 28	
$W \to \ell\nu$	54.9 ± 4.8	30.6 ± 3.1	
$W \to \tau_\ell\nu$	14.7 ± 1.3	7.0 ± 0.7	3.9 ± 1.2
QCD	132 ± 14	181 ± 23	
$WW/WZ/ZZ$	1.6 ± 0.8	0.8 ± 0.4	3.0 ± 0.4
Total	558 ± 79	546 ± 57	102 ± 5
Observed	540	517	101
Signal Efficiency ($m_A = 120$ GeV$/c^2$)	0.0253	0.0156	0.00561



$\tau\tau \to \mu + \tau h$

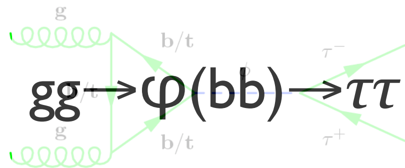


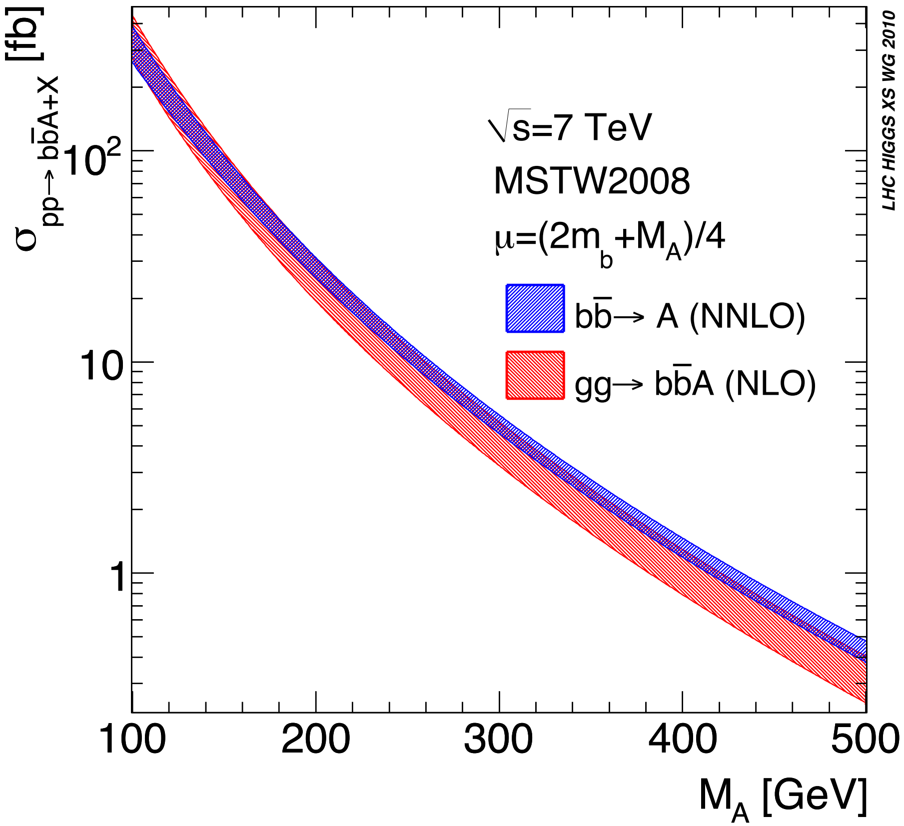
$\tau\tau \to e + \tau h$



$\tau\tau \to e + \mu$

4FS vs 5FS





$\sigma(bbA)$: Theoretical Uncertainties					
4FS calculation			5FS calculation		
M_A (GeV)	scale	PDF+α_s	M_A (GeV)	scale	PDF+α_s
100	24%	-	100	5%	3%
300	24%	-	300	2%	6%
500	26%	-	500	2%	8%
1000	30%	-	1000	1%	2%

Comparison of the 4-flavour NLO and 5-flavour NNLO bbHiggs cross section for a pseudo-scalar Higgs.

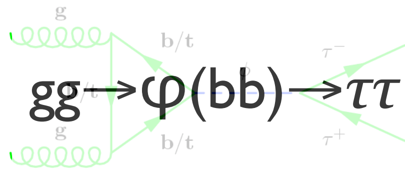
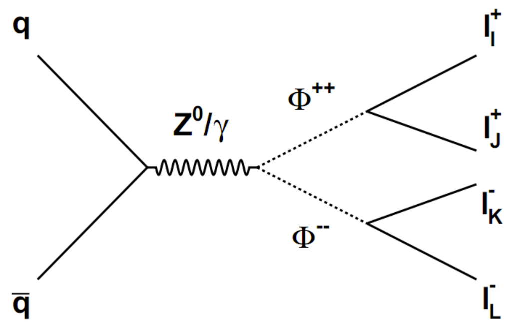


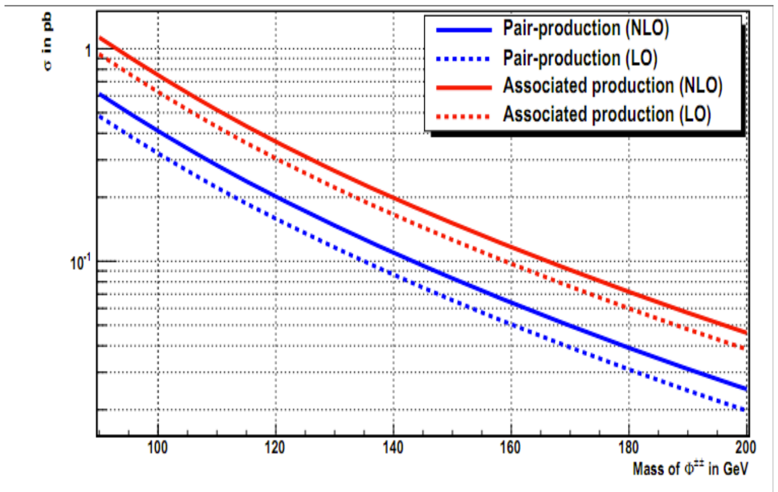
Table 16: Nuisance parameters entering the likelihood for the cross section fit, for the various channels and mass reconstruction algorithms. The following notations have been used for the probability distributions: $G(\mu, \sigma)$ for Gaussian, $\Gamma(\gamma, \theta)$ for Gamma and $\mathrm{Ln}(\mathrm{median}, \kappa)$ for Log-normal

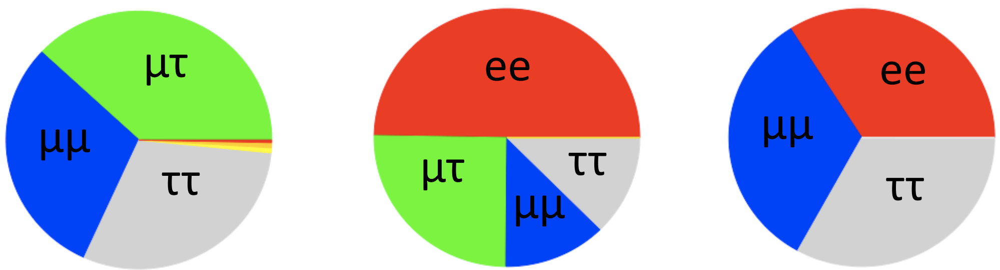
Parameter	Channels	Distribution	Output
Luminosity	all	$\mathrm{Ln}(1.0, 1.11)$	$0.99^{+0.11}_{-0.10}$
$Z \to \ell\ell$	all	$\mathrm{Ln}(0.96, 1.04)$	$0.957^{+0.035}_{-0.028}$
Tau id. efficiency	$e\tau$, $\mu\tau$	$\mathrm{Ln}(1.0, 1.23)$	$0.917^{+0.064}_{-0.062}$
Elecron id. efficiency	$e\tau$, $e\mu$	$\mathrm{Ln}(0.968, 1.036)$	$0.971^{+0.024}_{-0.023}$
Elecron trigg. efficiency	$e\tau$	$\mathrm{Ln}(0.959, 1.02)$	$0.961^{+0.019}_{-0.019}$
Muon efficiency	$\mu\tau$, $e\mu$	$\mathrm{Ln}(0.963, 1.005)$	$0.963^{+0.003}_{-0.003}$
Electron energy scale	$e\tau$, $e\mu$	$G(0, 1)$	$-0.1^{+0.8}_{-0.7}$
Hadronic tau energy scale	$e\tau$, $\mu\tau$	$G(0, 1)$	$+0.3^{+0.6}_{-0.9}$
Non-tau jet energy scale	all (SVfit)	$G(0, 1)$	$-0.2^{+0.9}_{-0.7}$
Unclusteded candidates energy scale	all (SVfit)	$G(0, 1)$	$-0.1^{+0.6}_{-0.6}$
QCD background	$\mu\tau$	$\Gamma(107, 1.45)$	148^{+13}_{-12}
W background	$\mu\tau$	$\Gamma(132, 0.52)$	66^{+6}_{-5}
$Z \to \mu\mu$, $\mu \to \tau$ background	$\mu\tau$	$\Gamma(13.4, 0.98)$	$11.1^{+3.4}_{-2.8}$
$Z \to \mu\mu$, jet$\to \tau$ background	$\mu\tau$	$\Gamma(7.1, 0.90)$	$5.2^{+2.4}_{-1.8}$
$t\bar{t}$	$\mu\tau$	$\mathrm{Ln}(6, 1.5)$	$4.6^{+2.1}_{-1.5}$
di-boson	$\mu\tau$	$\mathrm{Ln}(1.6, 1.5)$	$1.3^{+0.7}_{-0.4}$
QCD background	$e\tau$	$\Gamma(61.9, 2.92)$	214^{+18}_{-17}
W background	$e\tau$	$\Gamma(90.3, 0.42)$	38^{+4}_{-4}
$Z \to ee$, $e \to \tau$ background	$e\tau$	$\mathrm{Ln}(109.3, 1.26)$	80^{+12}_{-11}
$Z \to ee$, jet$\to \tau$ background	$e\tau$	$\Gamma(5.9, 2.6)$	14^{+7}_{-5}
$t\bar{t}$ and di-boson background	$e\tau$	$\mathrm{Ln}(3.4, 1.5)$	$3.1^{+1.6}_{-1.0}$
QCD, W and $Z \to \ell\ell$ background	$e\mu$	$\mathrm{Ln}(3.9, 1.31)$	$3.6^{+1.1}_{-0.9}$
$t\bar{t}$ background	$e\mu$	$\mathrm{Ln}(7.1, 1.18)$	$6.9^{+1.2}_{-1.1}$
Di-boson background	$e\mu$	$\mathrm{Ln}(3.0, 1.13)$	$3.0^{+0.4}_{-0.3}$

$pp \to \varphi^{++} \to ll$

- ✓ Extend Standard Model adding scalar triplet: $\Phi^{\pm\pm}, \Phi^{\pm}, \Phi^{0}$
- ✓ Triplet Yukawa couplings are responsible for neutrino masses
- ✓ Consider model where BR($\Phi^{\pm\pm} \to ll$)=100%
- ✓ Final states with three or four isolated leptons (earlier multi-lepton search)
- ✓ Look for resonance peaks in dilepton mass distributions
- ✓ BRs for a different $l_1 l_2$ pairs depend on the neutrino mass hierarchy and phase

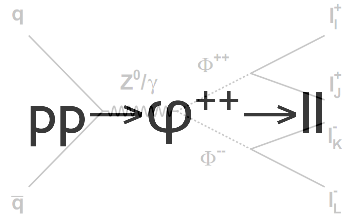


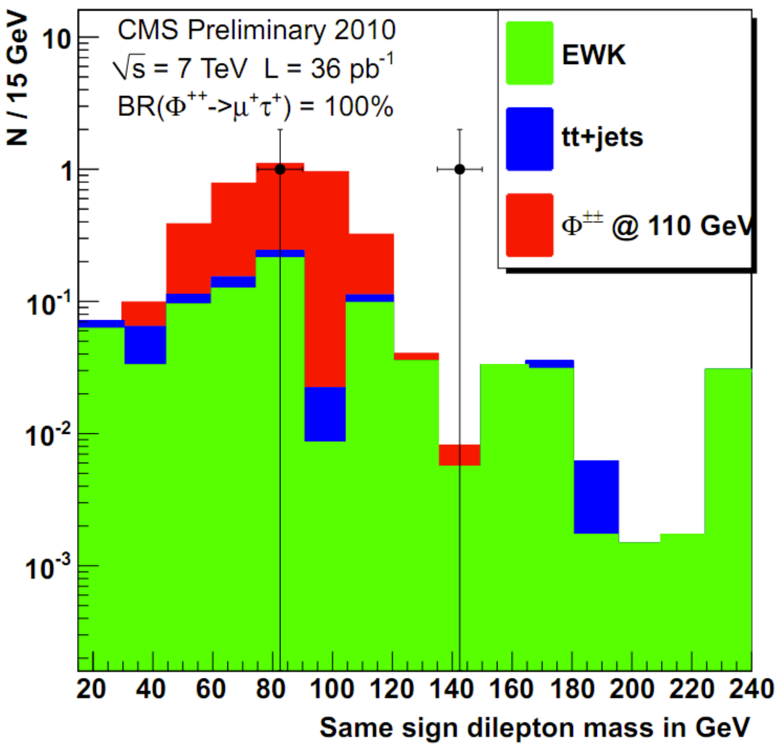


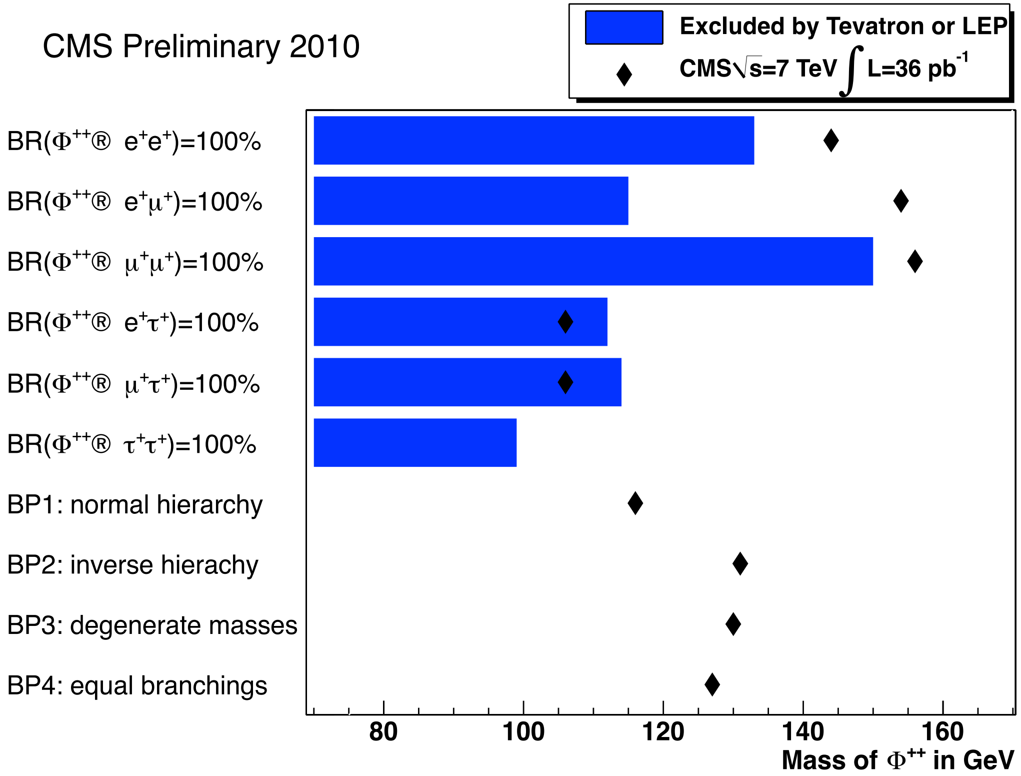


Normal Hierarchy / Inverse Hierarchy / Degenerate State

Limit





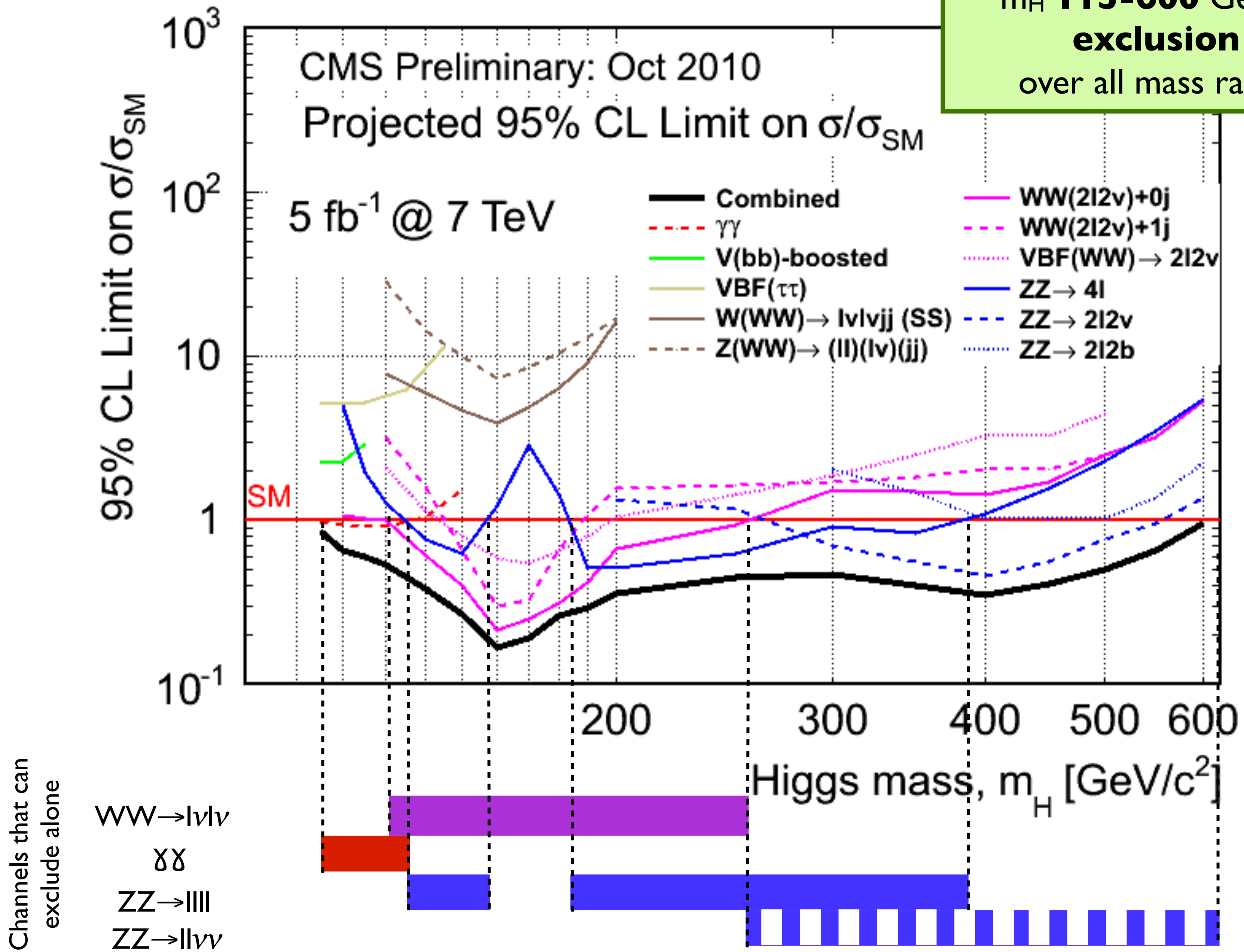


Example for $\mu^+\tau^+$ final state (one of many considered)

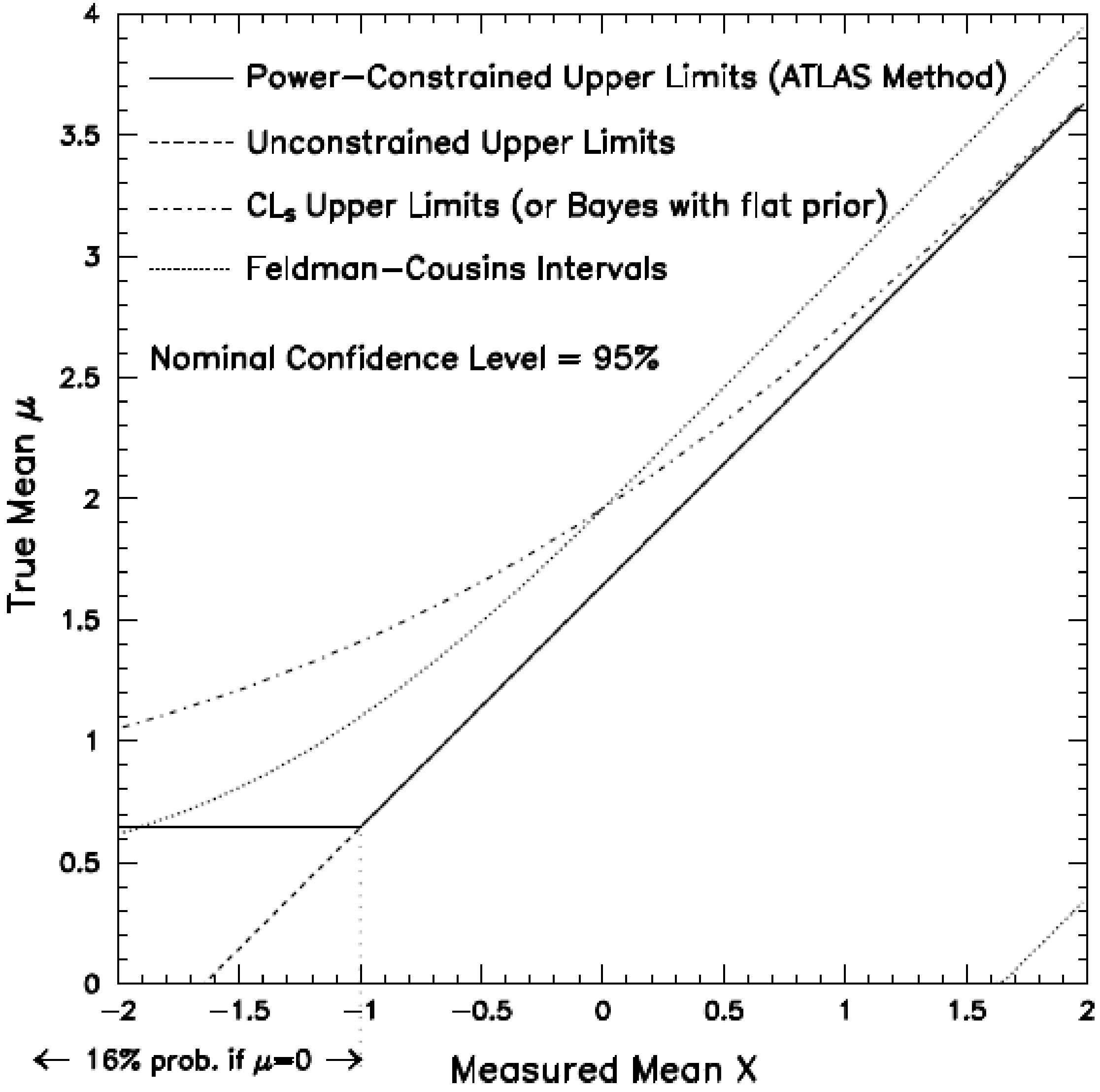
No peak observed → set limit extending reach of previous experiments

SM-Higgs Exclusions: 5 fb^{-1} @ 7 TeV

m_H **115-600** GeV/c^2
exclusion
over all mass range



Comparison of ATLAS PCL with the three methods in PDG



(Atlas unconstrained U.L. is zero, not null, for x < -1.64)

ATLAS PCL re-opens discussion on use of diagonal line along with ad hoc constraint, out of favor for many years, not recommended by CMS SC.

CMS and ATLAS SC's are reviewing arguments and what has been learned in 25+ years. Academic statisticians have commented as well.

Just tip of iceberg: Poisson example brings in other issues. Nuisance parameters yet more. Choice of test statistic varies.

2