Electroweak symmetry breaking

Search for the missing piece of the Standard Model II

Pedro Ferreira da Silva – psilva@cern.ch

(CERN/LIP)

LIP - Lisbon

7 May 2012

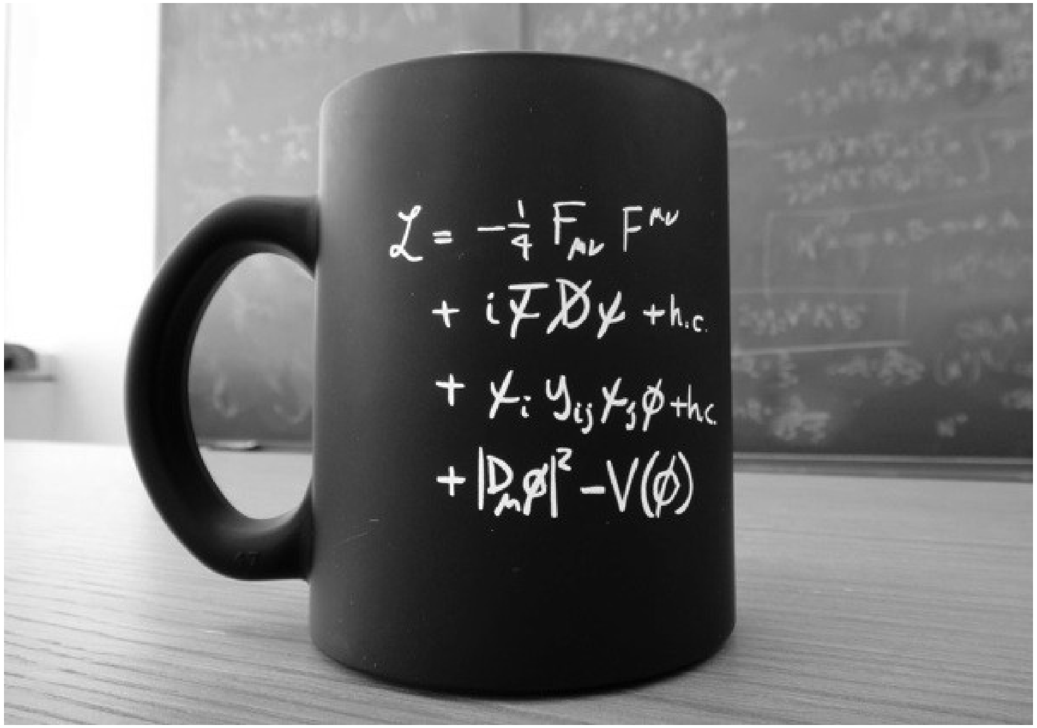
Plan for today

Summary from 1st lecture

ZZ production at the LHC

The golden channel: $H \rightarrow ZZ \rightarrow 4l$

High mass search: $H \rightarrow ZZ \rightarrow 2l2\nu$



Summary from 1st lecture

Gauge bosons have self interactions

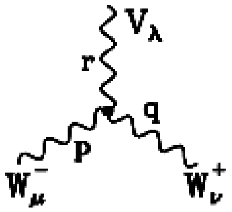
- The Standard Model allows for **pure gauge-bosons interactions**

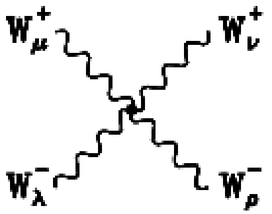
$$\boxed{\mathcal{L}_{\text{gauge-fixing}} = -\frac{1}{4}W_{\mu\nu}^{\ \ i}W^{\mu\nu^i} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}}$$

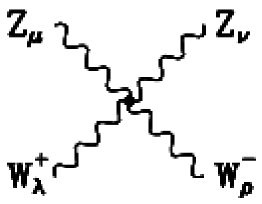
$F_{\mu\nu}$ is the field strength tensor which for the electroweak sector is given by:

$$W^i_{\mu\nu} = \partial_\mu W^i_\nu - \partial_\nu W^i_\mu - g_W \epsilon^{ijk} W^j_\mu W^k_\nu \qquad B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

- This **allows for triple and quartic gauge boson interactions**







etc.

$+ig_V\ [(p-q)_\lambda g_{\mu\nu} + (q-r)_\mu g_{\nu\lambda} + (r-p)_\nu g_{\lambda\mu}]$

(all momenta incoming,
$g_A = e,\ g_Z = g_W\ \cos\theta_W$)

$+ig_W^2[2g_{\mu\nu}g_{\lambda\rho} - g_{\mu\lambda}g_{\nu\rho} - g_{\mu\rho}g_{\nu\lambda}]$

$-ig_W^2\cos^2\theta_W[2g_{\mu\nu}g_{\lambda\rho} - g_{\mu\lambda}g_{\nu\rho} - g_{\mu\rho}g_{\nu\lambda}]$

Longitudinal vector boson scattering

- Longitudinal polarization is possible for the massive vector bosons

- **Scattering of longitudinal polarized W bosons breaks unitarity at high $s^{1/2}$**

$$\sigma(W_L^+W_L^- \to W_L^+W_L^-) \sim s$$

- At $s^{1/2}$ ~ 1 TeV interactions become strong unless unitarity is restored

- Scalar boson (H) interaction is a possible mechanism provided that:

$$g_{HWW} \sim M_W \qquad g_f \sim M_f \qquad M_H < 1 \text{ TeV}$$

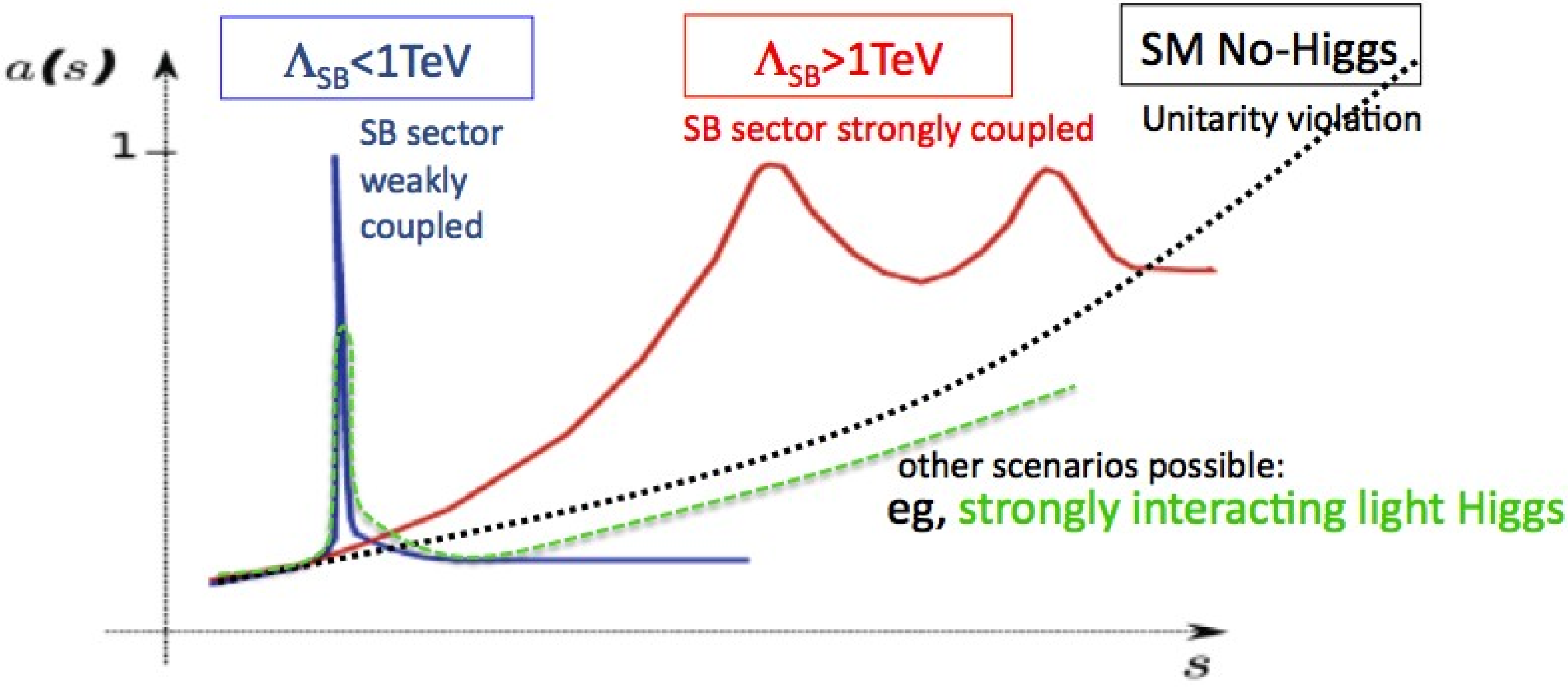
- Then the cross section satures (i.e.becomes constant) at high $s^{1/2}$

$$A(W^+W^- \to W^+W^-) \xrightarrow{s \gg M_W^2} \frac{1}{v^2}\left[s + t - \frac{s^2}{s - M_H^2} - \frac{t^2}{t - M_H^2}\right]$$

$$a_0 \overset{s \gg M_H^2}{\to} -\frac{M_H^2}{8\pi v^2} \quad \Rightarrow \quad \boxed{M_H < 870 \text{ GeV}}$$

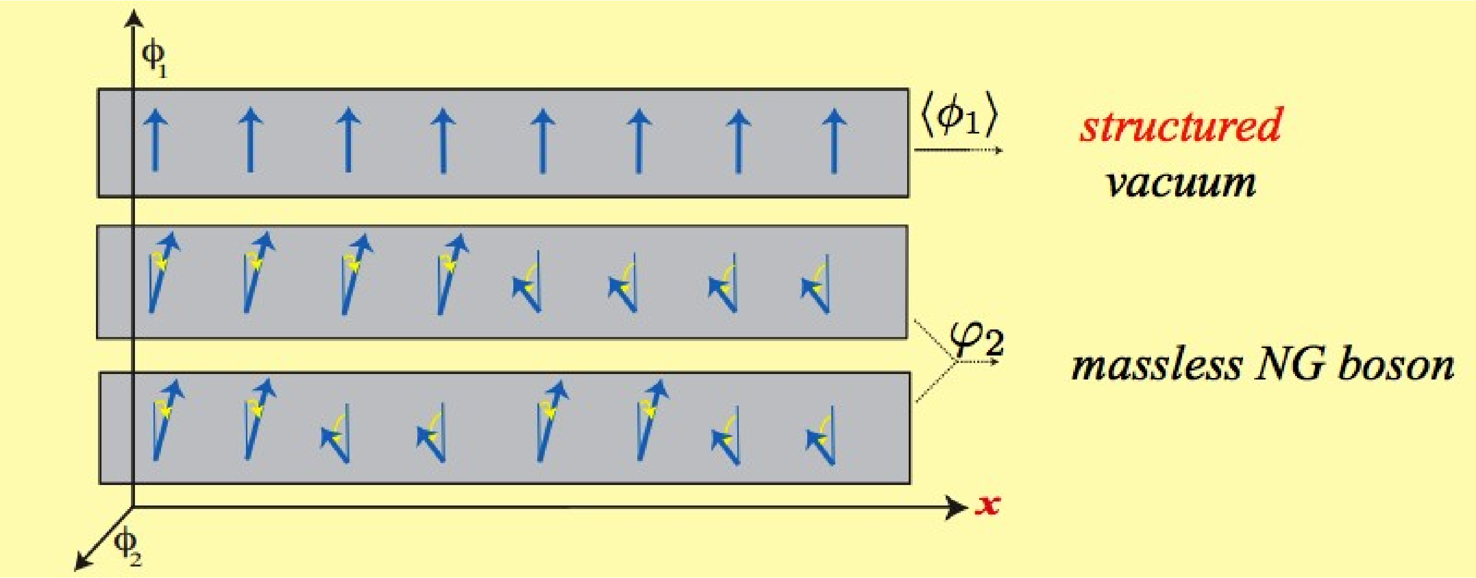
Possible scenarios for VV scattering

- If the scalar boson is strongly interacting / absent should observe distinct effects

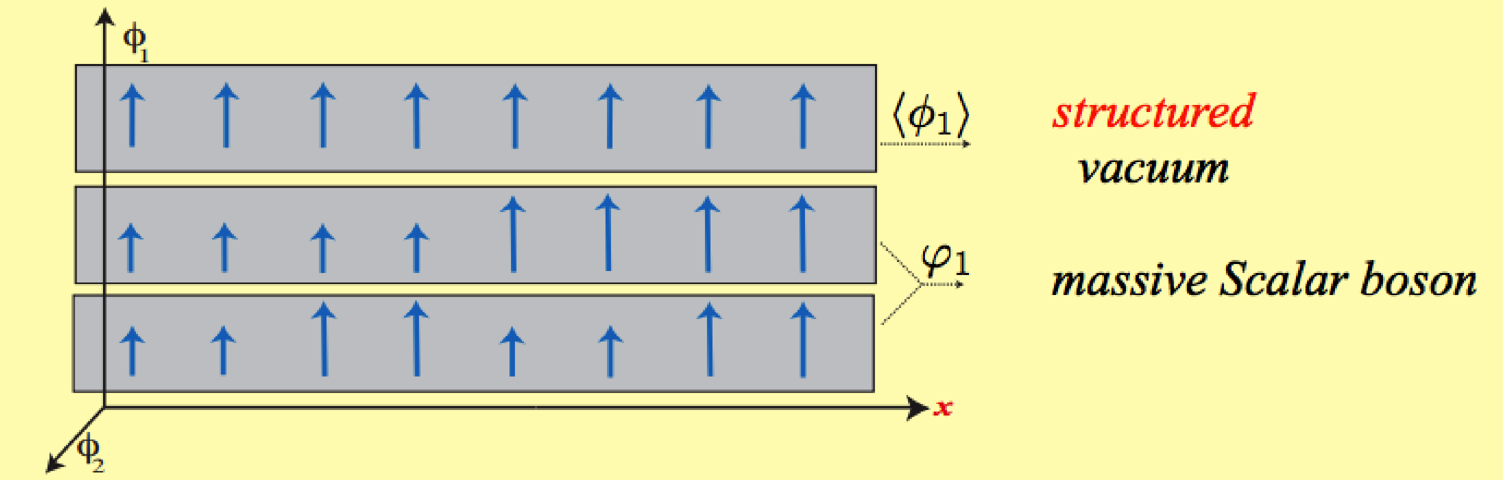


- VV scattering = fundamental probe of how the original EWK symmetry is broken

Original idea behind the Higgs mechanism



► characterizes a continuous SSB

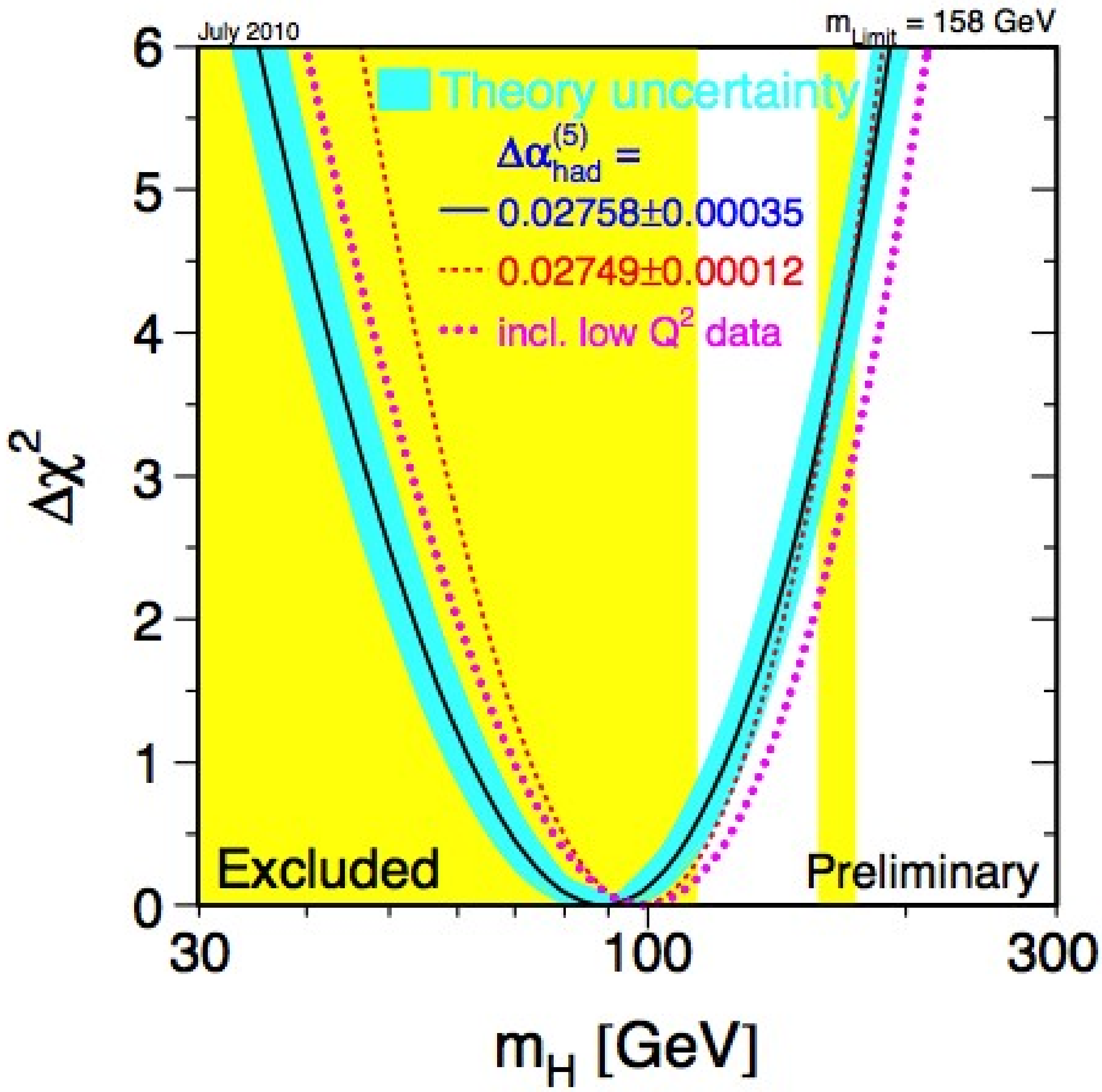


► measures the rigidity of the vacuum

The proponents

F. Englert and R. Brout PRL 13-[9] (1964) 321
P.W. Higgs PL 12 (1964) 132 and PRL 13-[16] (1964) 508
G.S. Guralnik, C.R. Hagen and T.W.B. Kibble PRL 13-[20] (1964) 585

What else do we know about the Higgs



EW-Fits:

$M_H = 89^{+35}_{-26}$ GeV

$M_H < 158$ GeV @ 95% CL

From direct search at LEP:

$M_H > 114$ GeV

@ 95% CL

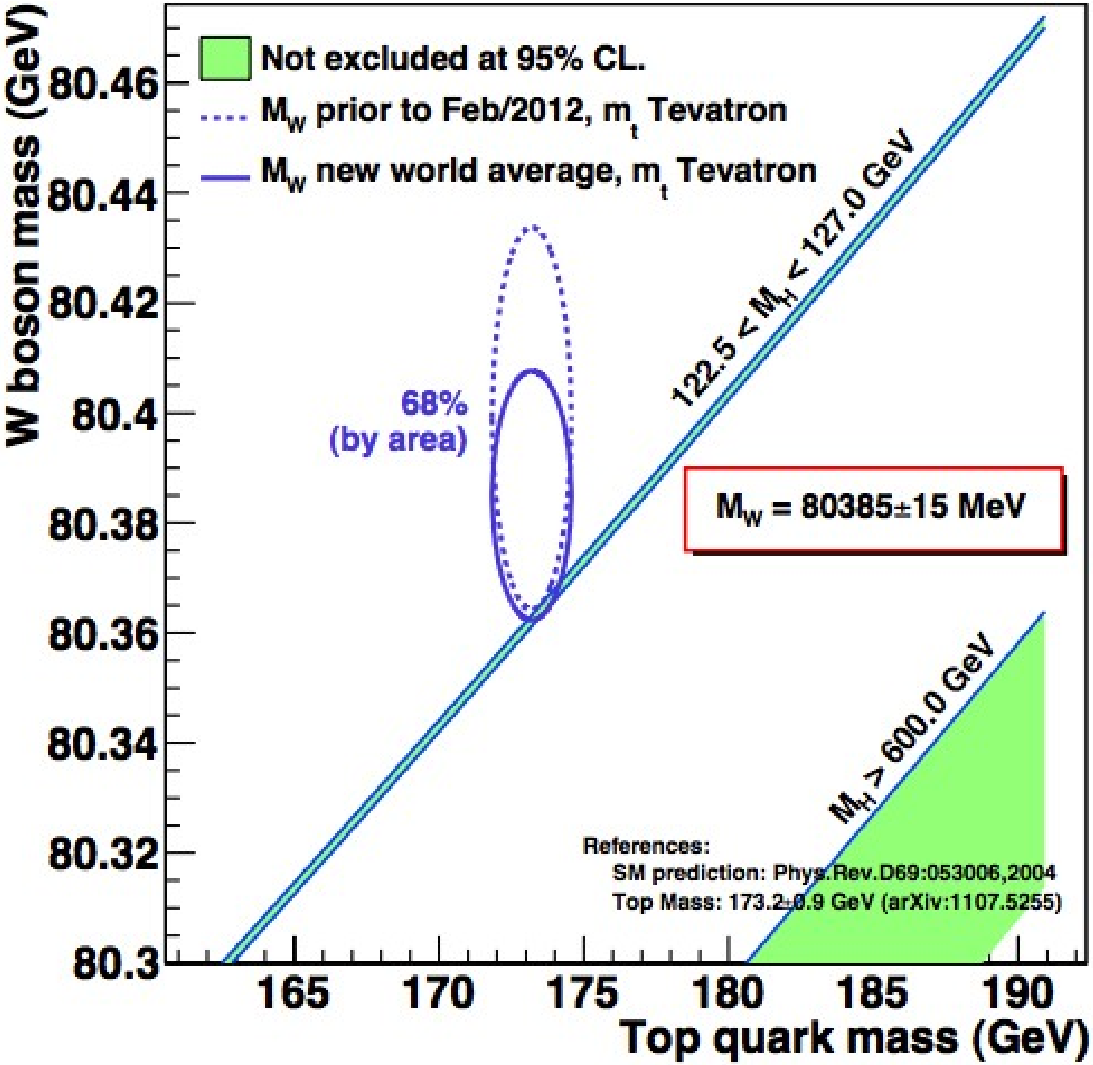
From direct search at Tevatron:

$158 < M_H < 175$ GeV

@ 95% CL

[Updated: Summer 2010]

What else do we know about the Higgs



- The mass of the heaviest particles is correlated from loop corrections including the Higgs boson
- The preferred region is still compatible at 68% CL with the not yet excluded SM Higgs mass at 95% CL

Higgs partial widths (tree level)

- **Fermions:** proportional to the mass and velocity dependent (1 factor from the matrix elem.+ 2 from phase space)

$$\boxed{\Gamma_{f\bar{f}} = \frac{N_c G_F m_f^2 M_H}{4\sqrt{2}\pi}\beta^3}$$

where $\beta = \sqrt{1 - \frac{4m_f^2}{M_H^2}}$

- **Vector bosons:** dominate due to the fact the longitudinal polarized bosons couple ~E → coupling to Higgs as to rise as fast

$$\boxed{\Gamma_{VV} = \frac{G_F M_H^3}{16\sqrt{2}\pi}\delta_V \beta \left(1 - x_V + \frac{3}{4}x_V^2\right)}$$

$$\text{where} \begin{cases} \delta_{W,Z} = 2, 1 \\ \beta = \sqrt{1 - x_V} \\ x_V = \frac{4M_V^2}{M_H^2} \end{cases}$$

- **Gluons:** through top quark loops

$$\boxed{\Gamma_{gg} = \frac{\alpha_s^2 G_F M_H^3}{16\sqrt{2}\pi^3}\left|\sum_i \tau_i[1 + (1 - \tau_i) f(\tau_i)]\right|^2}$$

$$\text{with} \quad \tau_i = \frac{4m_f^2}{M_H^2} \quad \text{and} \quad f(\tau) = \begin{cases} \left[\sin^{-1}\sqrt{1/\tau}\right]^2 & \tau \geq 1 \\ -\frac{1}{4}\left[\ln\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi\right]^2 & \tau < 1 \end{cases}$$

- **Photons through top and W boson loops** (Zγ partial width is similar in structure)

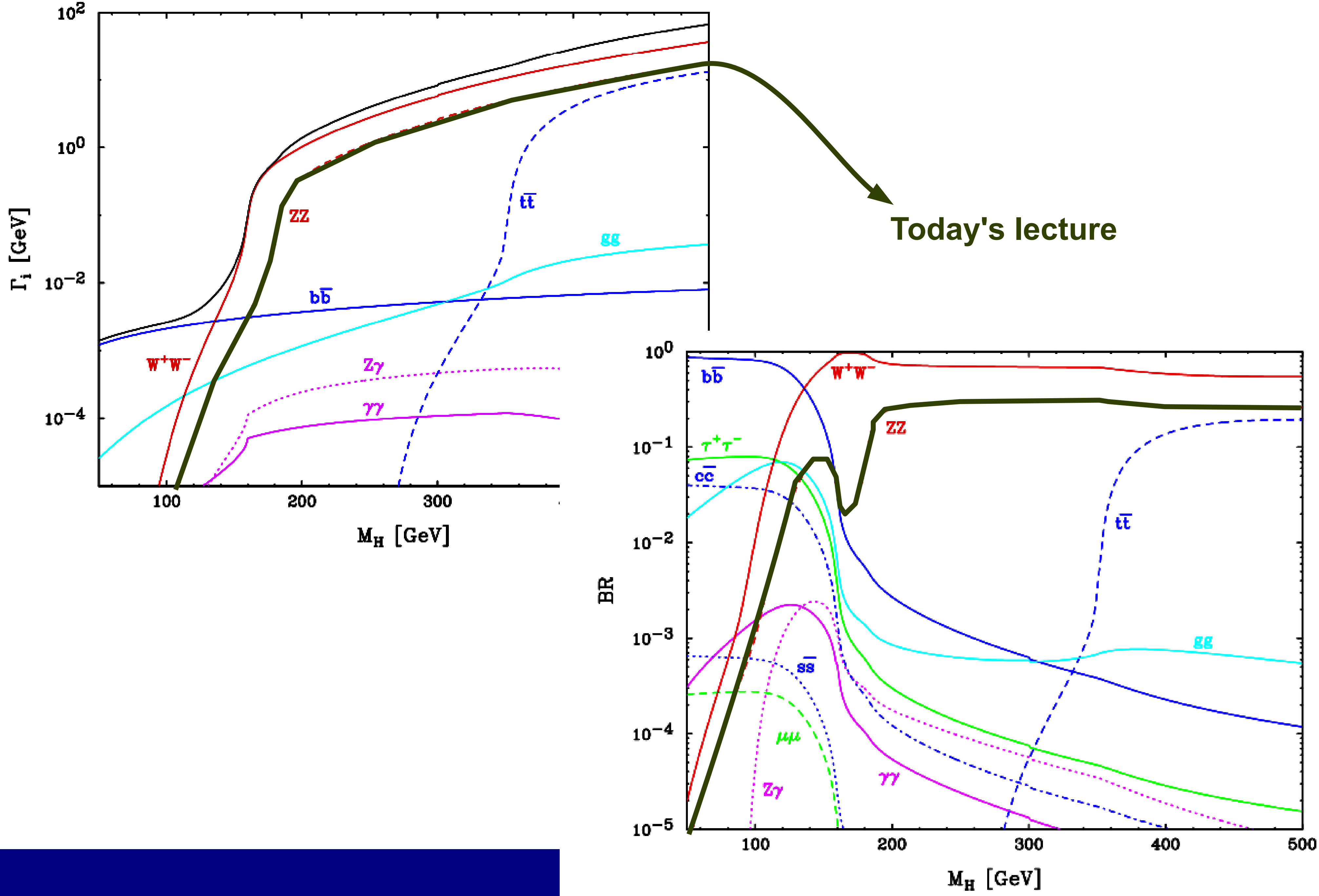
$$\boxed{\Gamma_{\gamma\gamma} = \frac{\alpha^2 G_F M_H^3}{128\sqrt{2}\pi^3}\left|\sum_i N_{c,i} Q_i^2 F_i\right|^2}$$

$$F_1 = 2 + 3\tau[1 + (2 - \tau) f(\tau)]$$

$$F_{1/2} = -2\tau[1 + (1 - \tau) f(\tau)]$$

$$F_0 = \tau[1 - \tau f(\tau)]$$

Higgs partial widths and branching ratios

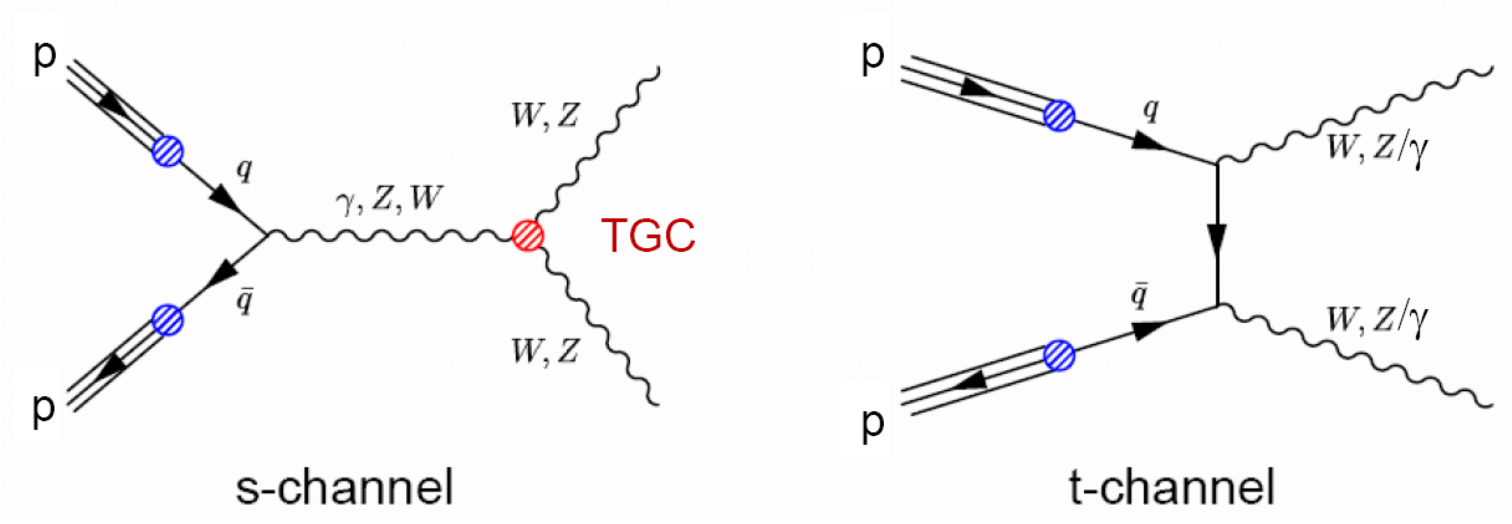


Today's lecture

ZZ production at the LHC

Diboson production

- Processes which produce **WW, WZ or ZZ final states can help answering**
  - why are EWK bosons massive?
  - **how does the EWK symmetry breaking occur**?
- New Physics expected to lead to EWKSB may be sought in di-boson production:
  - direct evidence of new particles
  - indirect evidence of observing anomalous TGCs



Anomalous Triple Gauge Couplings

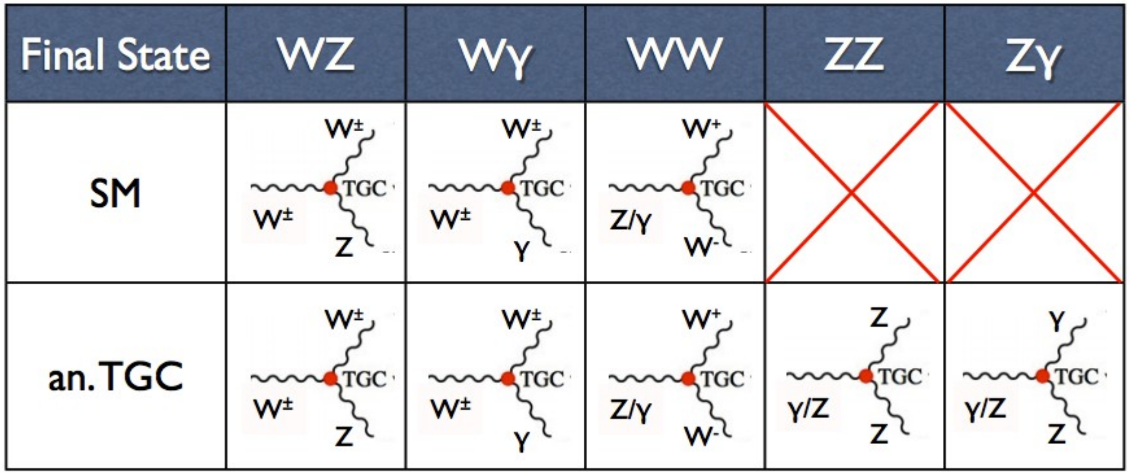
$$L/g_{WWV} = i g_1^V (W^*_{\mu\nu} W^\mu V^\nu - W_{\mu\nu} W^{*\mu} V^\nu) + i\kappa^V W^*_\mu W_\nu V^{\mu\nu} + \frac{\lambda^V}{M_W^2} W^*_{\rho\mu} W^\mu_\nu V^{\nu\rho}$$

charged

$$L = -\frac{e}{M_Z^2}[f_4^V (\partial_\mu V^{\mu\beta}) Z_\alpha (\partial^\alpha Z_\beta) + f_5^V (\partial^\sigma V_{\sigma\mu}) \tilde{Z}^{\mu\beta} Z_\beta]$$

neutral

- **All these anomalous terms are allowed in the SM lagrangian**
  - Couplings are usually proportional to s or $s^{1/2}$ and lead to tree level unitarity
  - Apply effective cut-off scale



Final State	WZ	Wγ	WW	ZZ	Zγ
SM	W± TGC W± Z	W± TGC W± γ	W+ TGC Z/γ W-	✗	✗
an.TGC	W± TGC W± Z	W± TGC W± γ	W+ TGC Z/γ W-	Z TGC γ/Z Z	γ TGC γ/Z Z

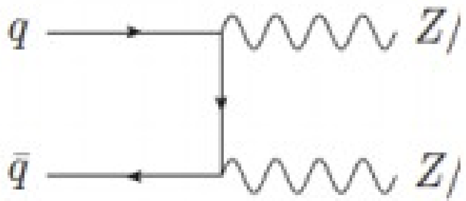
Coupling	Source	L (fb^{-1})	λ_Z	$\Delta\kappa_Z$	$\Delta\kappa_\gamma$	λ_γ
$WW\gamma$ from $W^\pm\gamma$	D0 [27]	0.16			[-0.88, 0.96]	[-0.2, 0.2]
WWZ from $W^\pm Z$	D0 [24]	1.0	[-0.17, 0.21]	[-0.12, 0.29]		
WWZ from $W^\pm Z$	CDF	1.9	[-0.13, 0.14]	[-0.82, 1.27]		
$WWZ = WW\gamma$ from W^+W^-	D0 [30]	0.25	[-0.31, 0.33]	[-0.36, 0.33]		
from W^+W^-, $W^\pm Z$	CDF [31]	0.35	[-0.18, 0.17]	[-0.46, 0.39]		

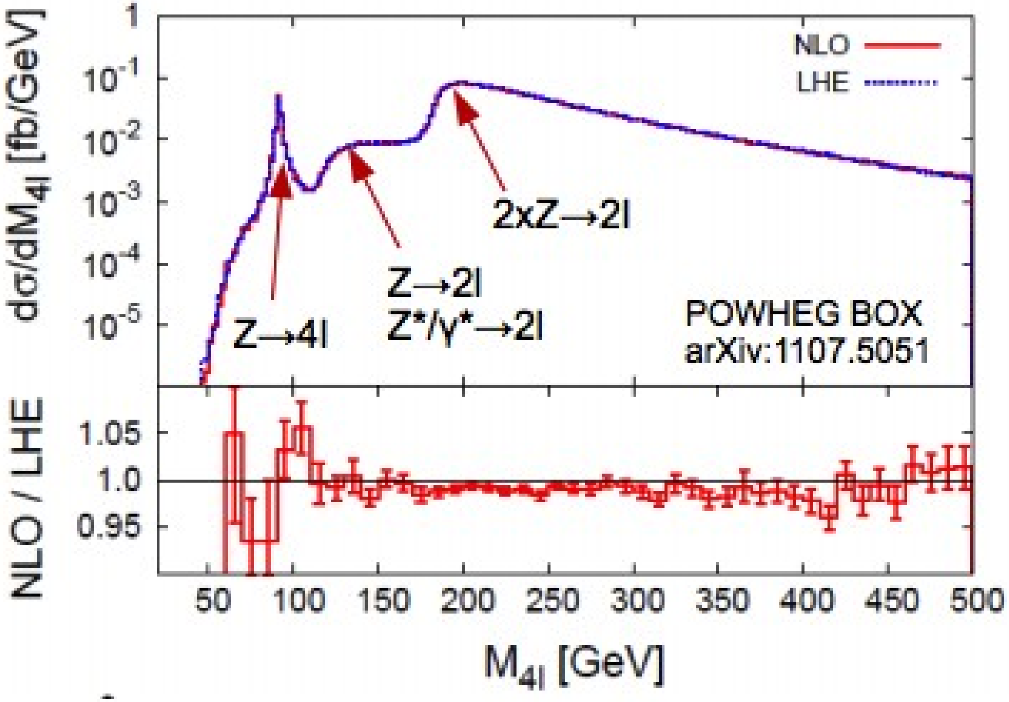
Note: more recent results are available, also from LHC experiments

ZZ production

- **t-channel production** dominates
  - unlike WZ and WW which have contribution from triple gauge coupling
- **s-channel** production is suppressed
  - $O(10^{-4})$
  - if in excess: **anomalous gauge couplings**
  - **resonant** production: Higgs, gravitons
- **Cross section measurement**
  - At the LHC only measured in 4l ▶
  - important to compare decay channels

    (in particular when looking for deviations)





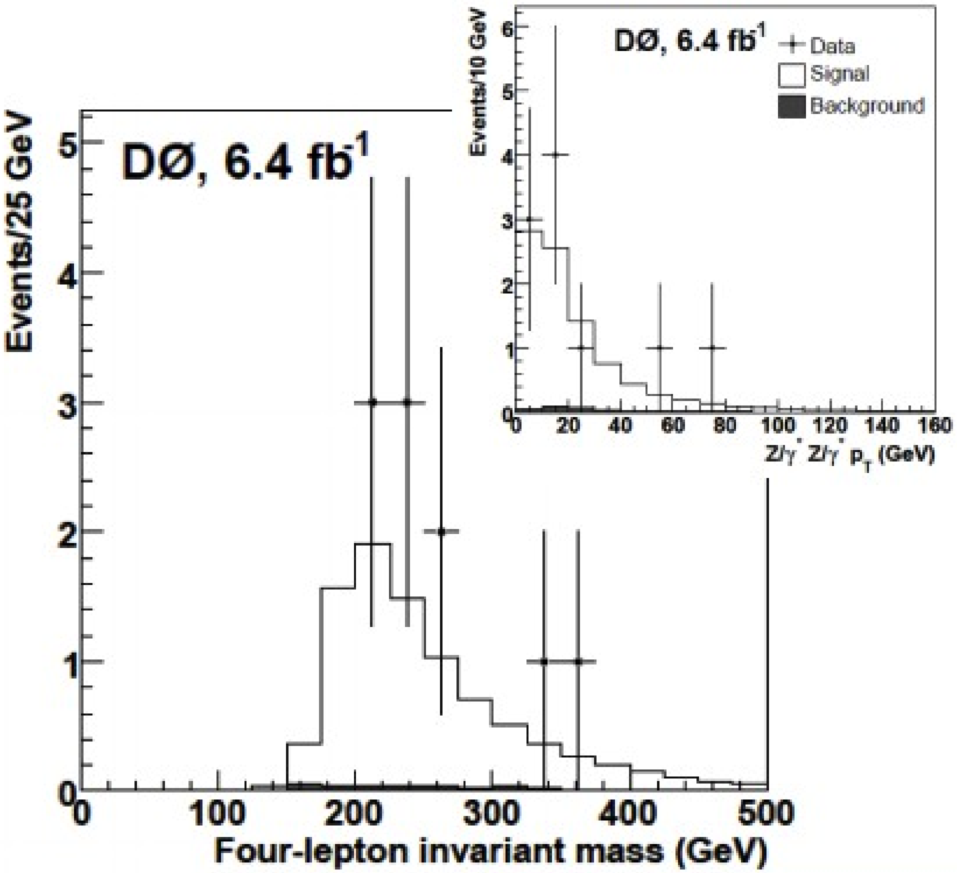
$\sigma(pp \to ZZ) \times BR(Z \to ll)^2 = 6.4 \pm 0.3$ (NLO)

ATLAS: $ZZ \to llll$	$8.4^{+2.7}_{-2.3}(stat)^{+0.4}_{-0.7}(syst) \pm 0.3(lumi)$
CMS: $ZZ \to llll$	$3.8^{+1.5}_{-1.2}(stat) \pm 0.2(syst) \pm 0.2(lumi)$

Search for resonant ZZ production at the Tevatron

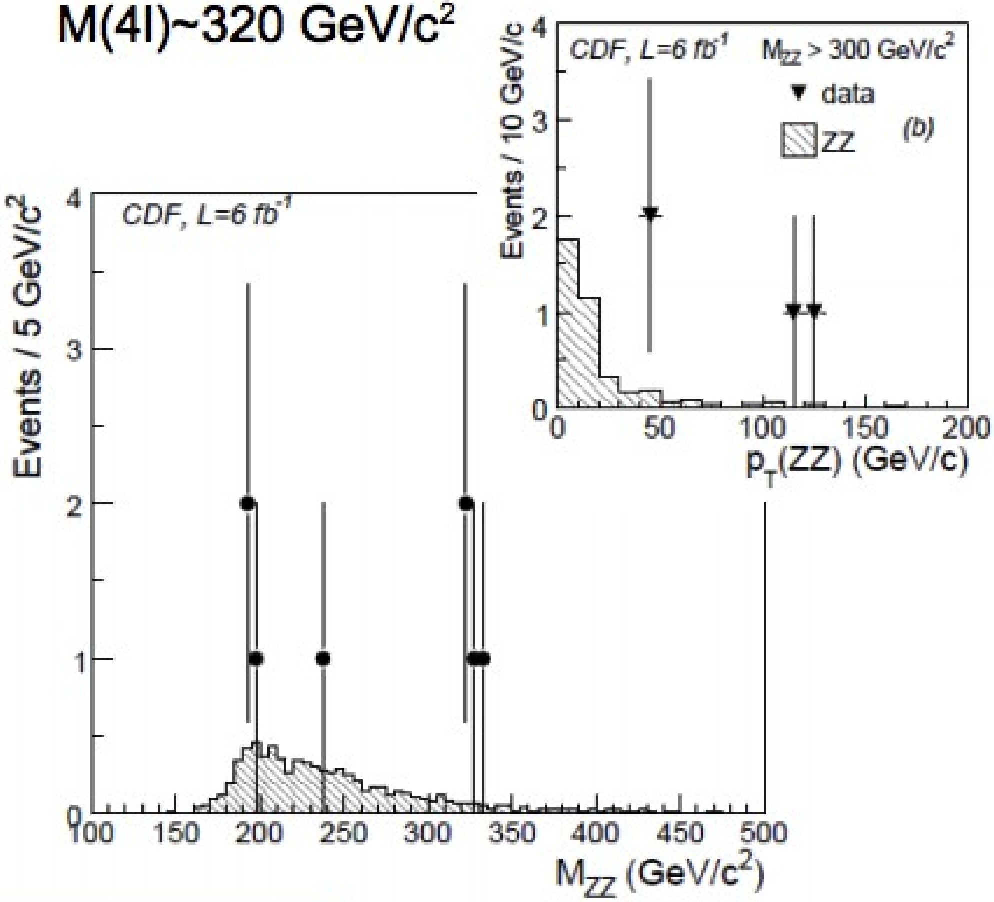
D0 – arXiv:1104.3078

- cross section in agreement with SM
- No particular excess in M(4l)



CDF – arXiv:1111.3432

- Cross section in agreement with SM
- Clustering of high p_T events at M(4l)~320 GeV/c^2



Crucial to compare decay channels

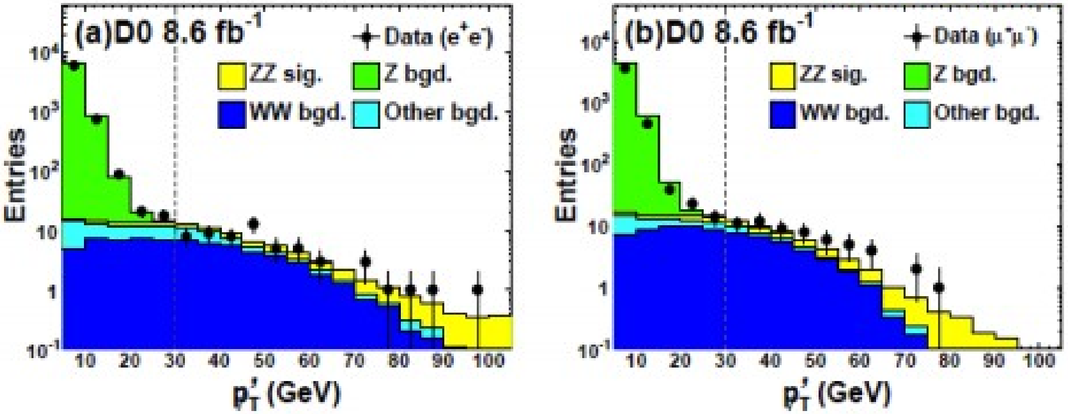
Search for resonant ZZ production at the Tevatron

- **Privileged role in resonant production searches** for M_X>200 GeV/c^2
  - BR(ZZ→2l2ν) ≈ 6 x BR(ZZ→4l)
  - Expected to lead exclusion limits
- **Challenges**:
  - partial reconstruction of the kinematics $E_T^{miss} = p_T(\nu_1)+p_T(\nu_2)$
  - resonant signature through transverse or visible mass spectrum

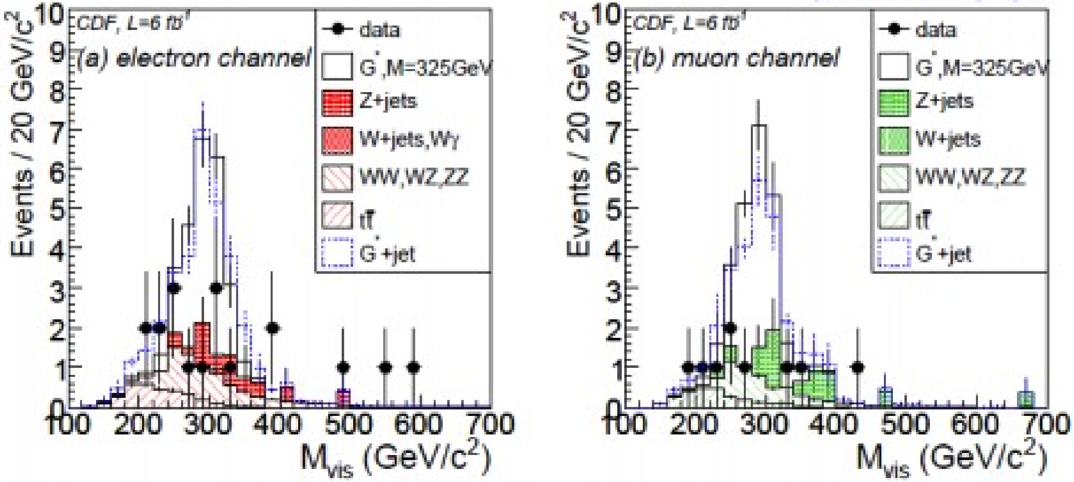
$$M_T^2(ZZ) = [\sqrt{M_Z^2 + p_T^2(\ell\ell)} + \sqrt{M_Z^2 + p_{Tmiss}^2}]^2 - |\vec{p_T}(\ell\ell) + \vec{p}_{Tmiss}|^2$$

  - backgrounds: Z+jets (instrumental) and di-bosons (mainly SM ZZ)

arXiv:1201.5652



arXiv:1111.3432

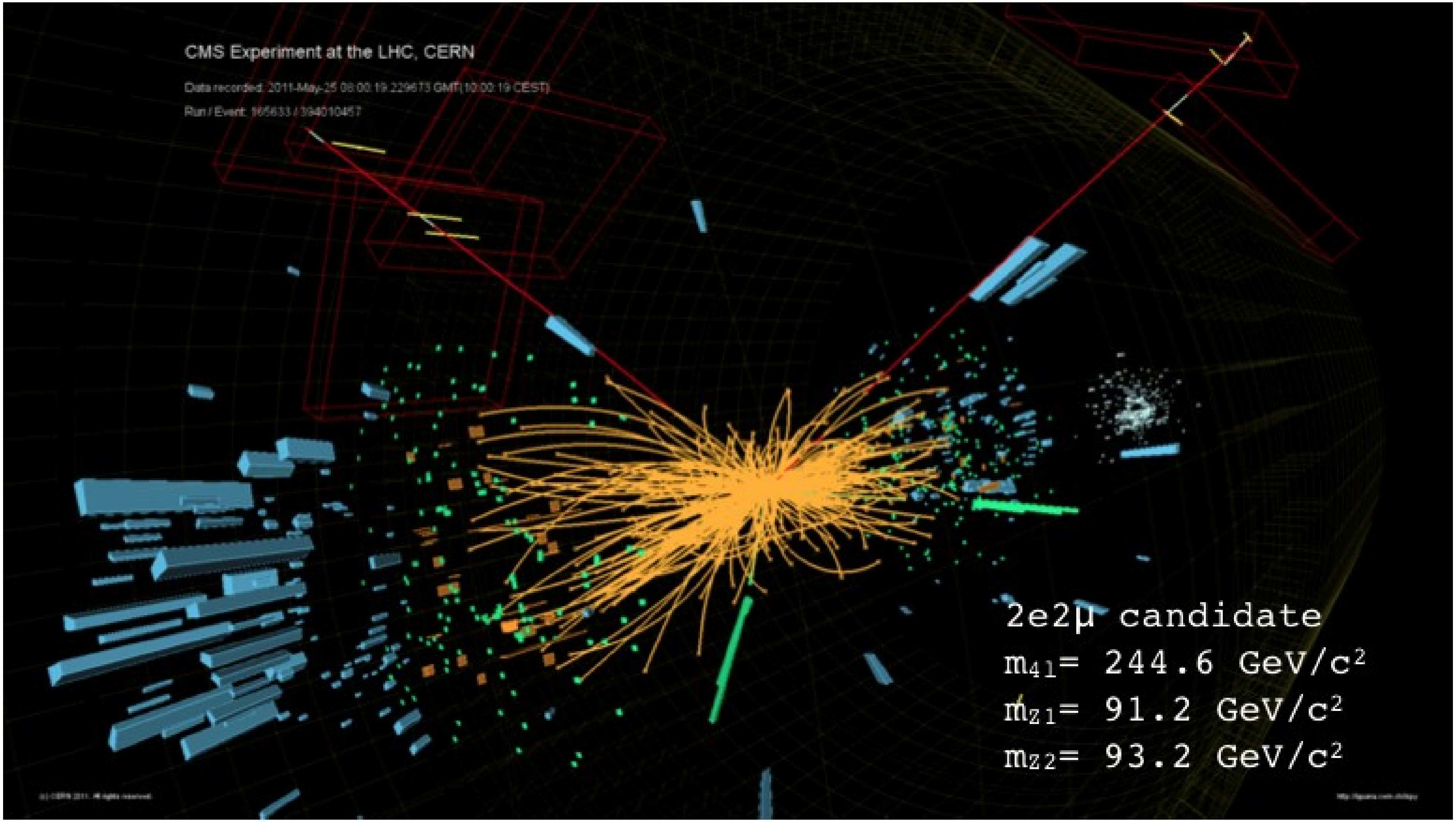


Neither CDF or D0 observe significant excesses in the 2l2ν final states

(similar results in the 2l2q channel)

The golden channel

$H \rightarrow ZZ \rightarrow 4l$



2e2μ candidate

m_{4l}= 244.6 GeV/c^2

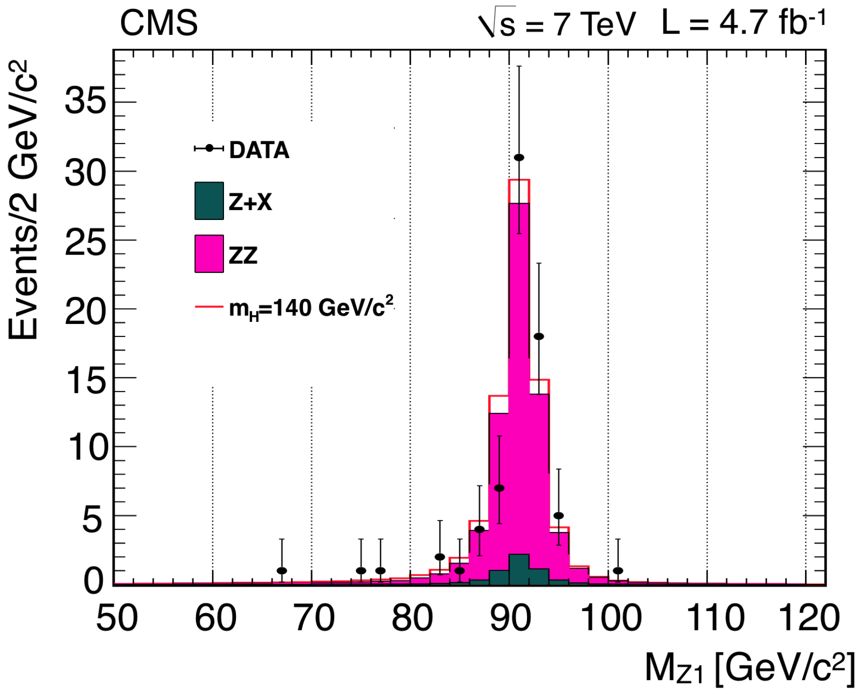
m_{Z1}= 91.2 GeV/c^2

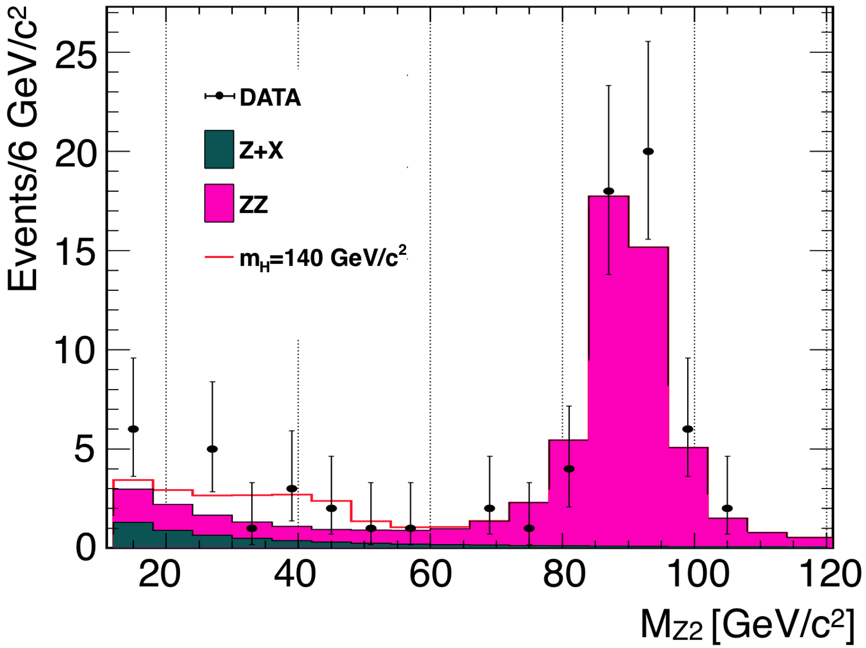
m_{Z2}= 93.2 GeV/c^2

Channel signature - 1

- It's the **cleanest channel among all**
  - **2 high mass lepton pairs :** $50 < m_{Z1} < 120\ \mathrm{GeV/c^2}$ and $12 < m_{Z2} < 120\ \mathrm{GeV/c^2}$

    (the second pair is allowed to be an off-shell Z)

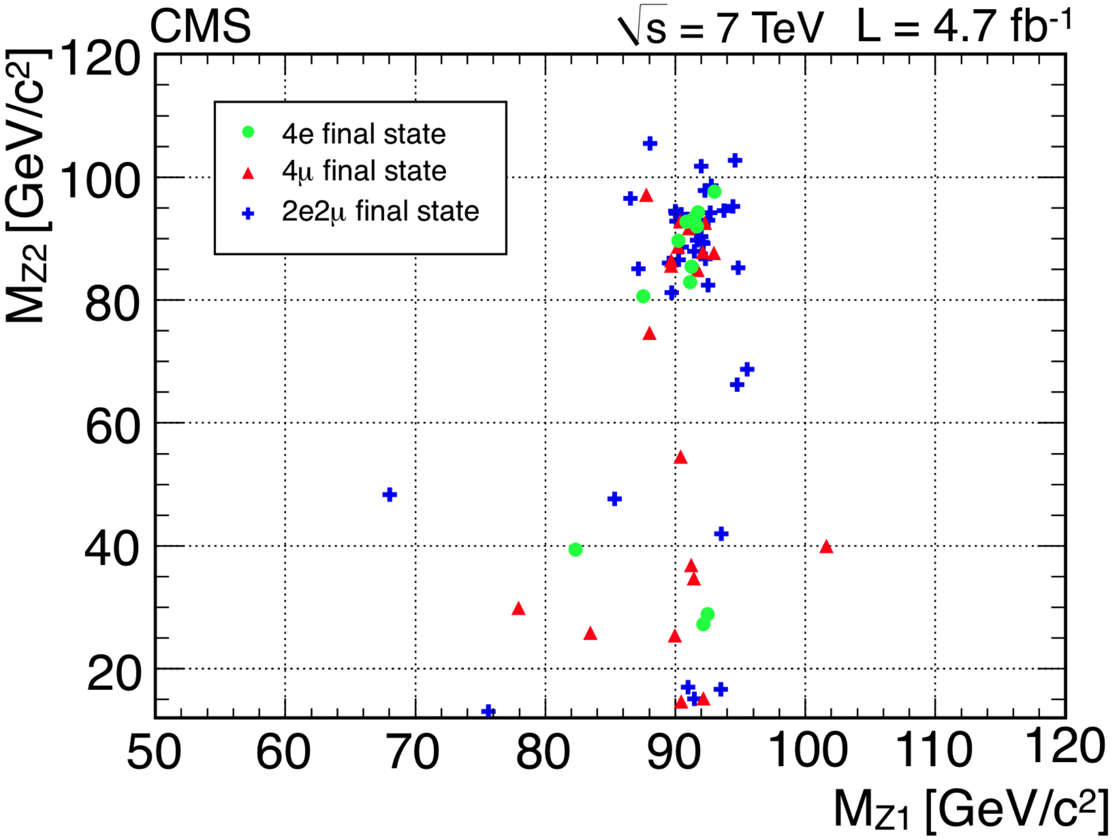




Channel signature - 2

- It's the **cleanest channel among all**
  - **2 high mass lepton pairs :** 50 < m_{Z1}< 120 GeV/c^2 and 12 < m_{Z2} < 120 GeV/c^2

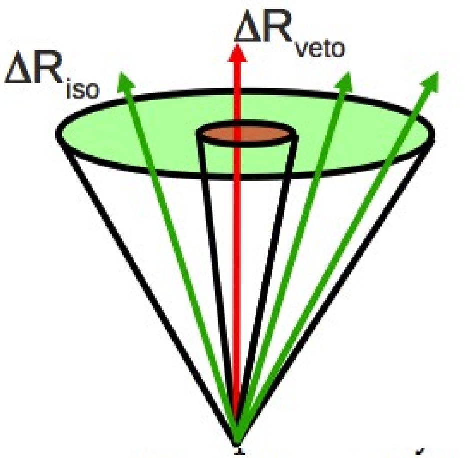
    (the second pair is allowed to be an off-shell Z)



Channel signature - 3

- **4 isolated leptons in the final** state: 4e / 2e2μ /4μ
  - **Leptons are soft in p_T** : $p_T^e > 7$ GeV/c $p_T^\mu > 5$ GeV/c
  - Relative isolation is defined from the sum of tracks / calorimeter deposits in a R=0.3 cone built around the lepton thrust

$$R_{\text{iso}} = (1/p_T^\ell) \times \left(\sum_i p^i_{T,\text{track}} + \sum_j E^j_{T,\text{ECAL}} + \sum_k E^k_{T,\text{HCAL}}\right)$$

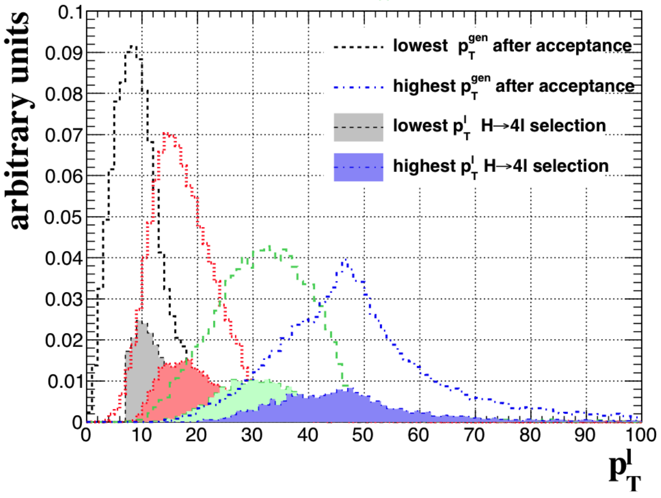


$$R_{\text{iso},i} + R_{\text{iso},j} < 0.35$$

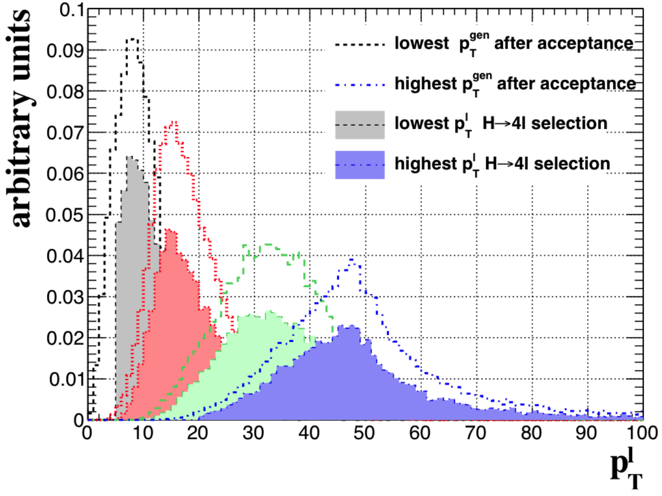
→ for any pair or charge of the leptons

  - Selection efficiency is affected accentance, p_T and mass requirements ▼

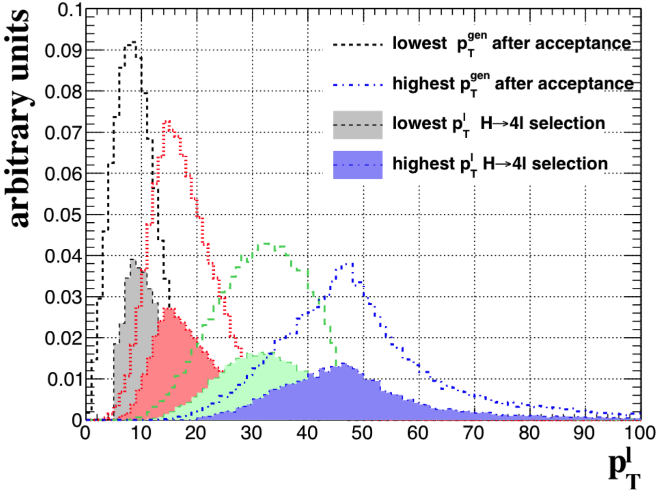
H→ZZ*→4e, m_H = 120 GeV



H→ZZ*→4μ, m_H = 120 GeV



H→ZZ*→2e2μ, m_H = 120 GeV



Lepton efficiencies

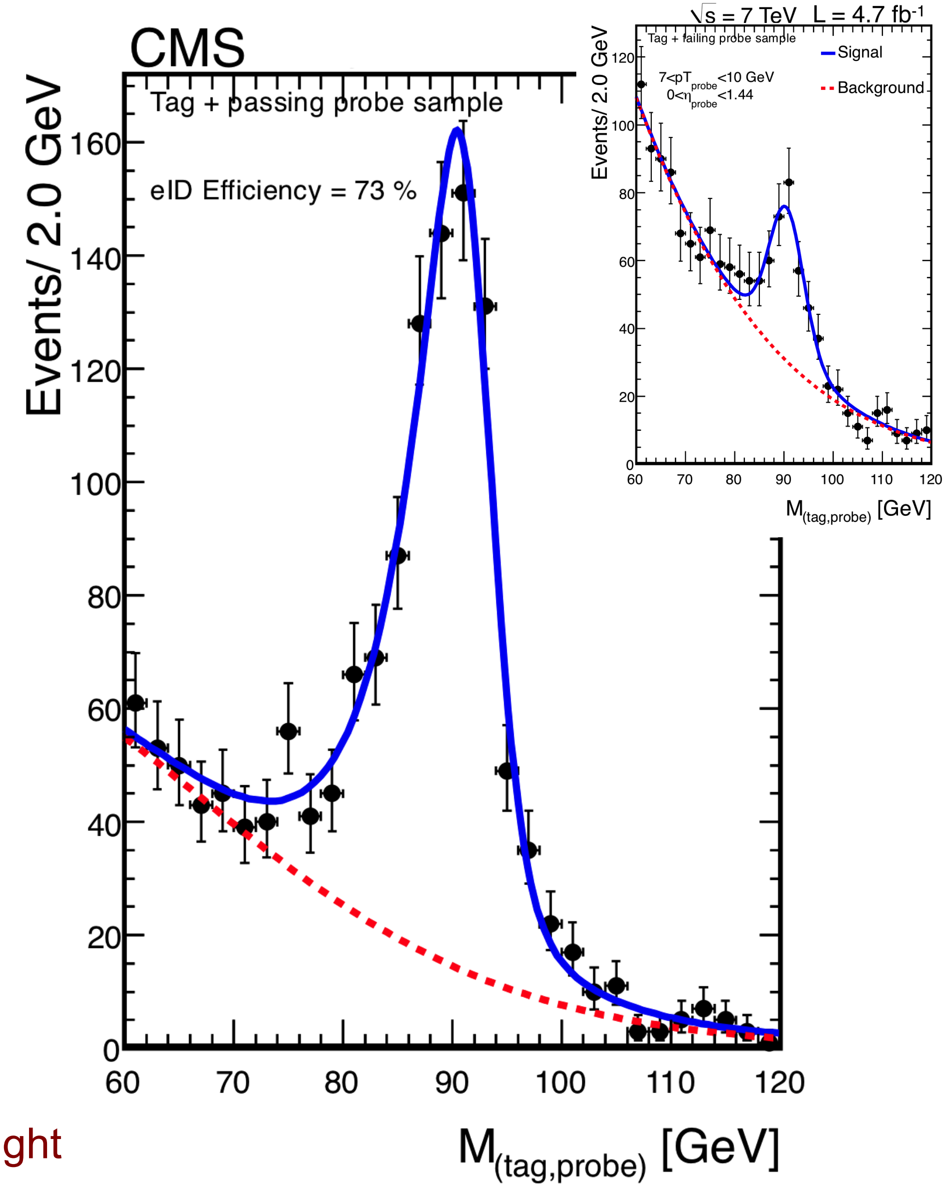
- Usually determined with a tag and probe method
- Choose a dilepton candle: Z, J/ψ → ll
- Select tightly the first lepton (=tag) and loosely the second lepton (=probe) constrained by the resonance mass
- Efficiency is measured from:

$$\varepsilon_{\text{“tag and probe”}} = \frac{N_{1p}+2N_{2p}}{N_{1f}+N_{1p}+2N_{2p}} = \frac{N_\mathrm{p}}{N_\mathrm{T}}$$

1 fails tight requirement

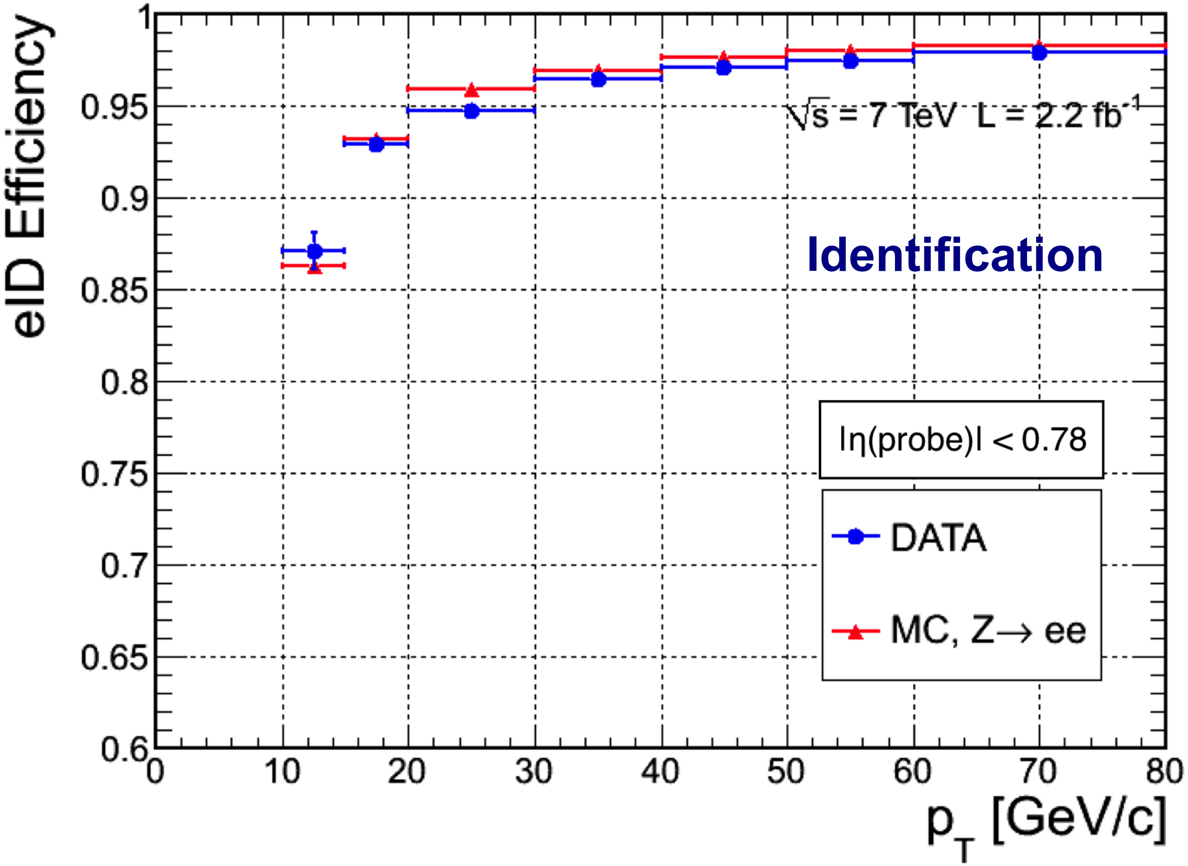
1 passes tight requirement

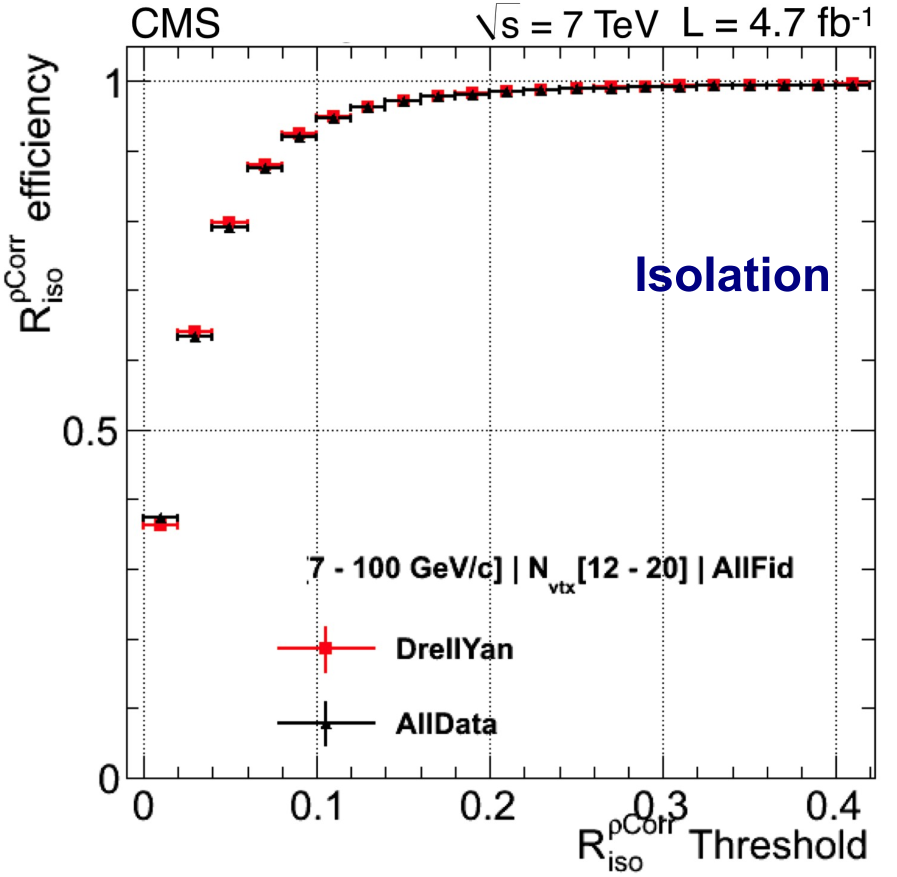
Both passes tight requirements



Lepton efficiencies

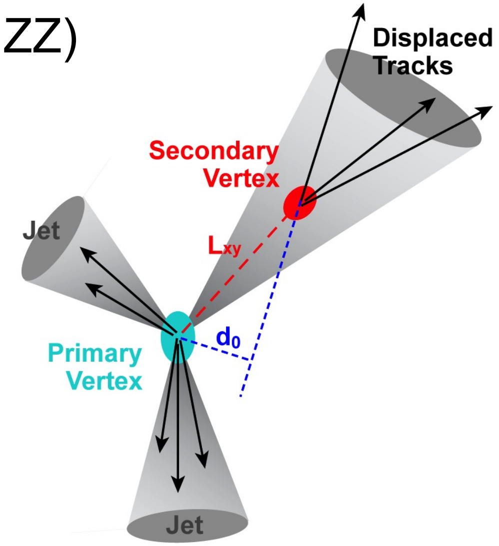
- Tag and probe used to derive separately trigger, reconstruction, identification and isolation efficiencies (efficiency of other cuts can be evaluated the same way)
- The Data/MC ratio is used to correct the simulation (re-weighting)
- Efficiencies drop fast at low p_T (<80%)

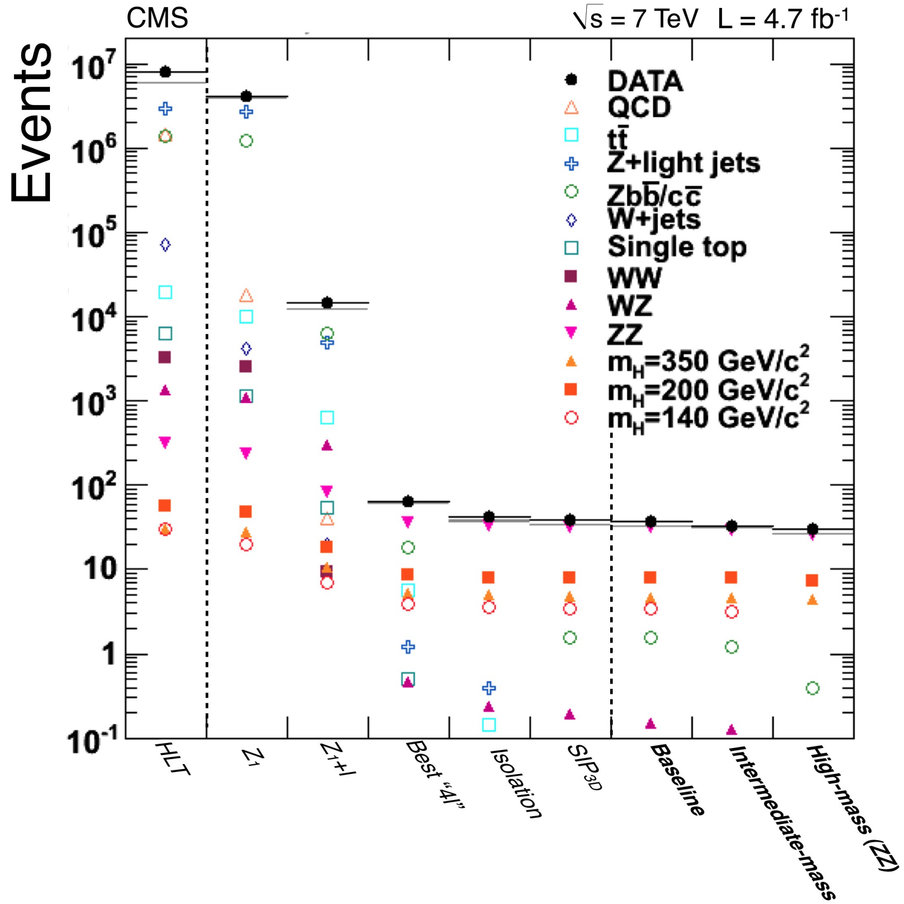




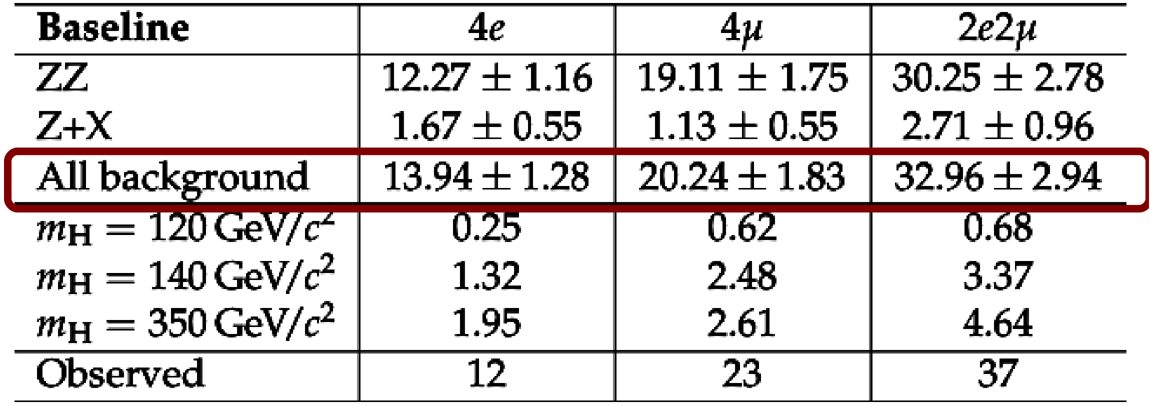
Event selection

- After selection **almost no background expected** (besides SM ZZ)
  - Residual backgrounds from Z + heavy flavor production removed with impact parameter significance cut $|SIP_{3D}|<4$ (reject displaced leptons from B hadron decays)





- **Number of selected events is consistent with expectations → look for resonance**



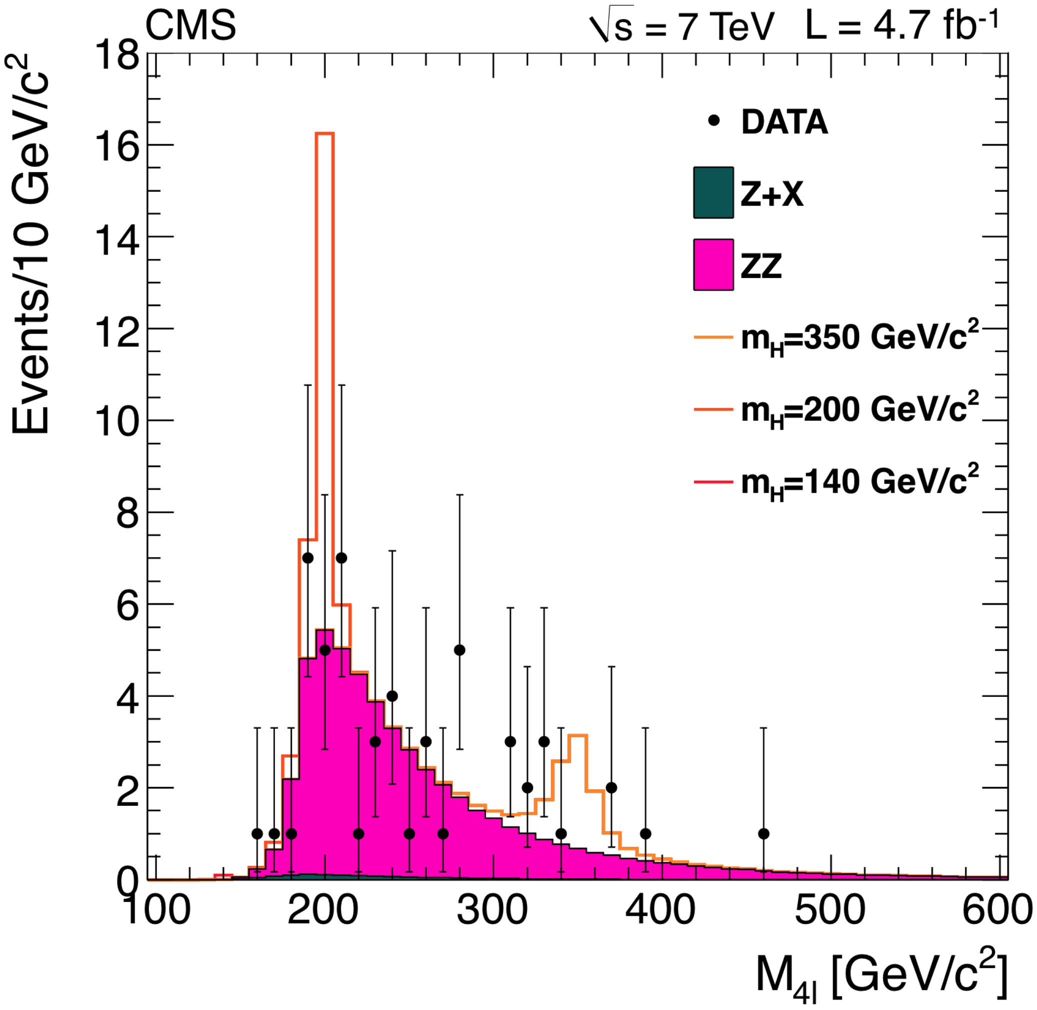
Baseline	$4e$	4μ	$2e2\mu$
ZZ	12.27 ± 1.16	19.11 ± 1.75	30.25 ± 2.78
Z+X	1.67 ± 0.55	1.13 ± 0.55	2.71 ± 0.96
All background	13.94 ± 1.28	20.24 ± 1.83	32.96 ± 2.94
$m_H = 120$ GeV/c^2	0.25	0.62	0.68
$m_H = 140$ GeV/c^2	1.32	2.48	3.37
$m_H = 350$ GeV/c^2	1.95	2.61	4.64
Observed	12	23	37

4 lepton invariant mass

High mass selection

- We select 72 events
- Expect 67± 6 events from background
- Slight excess around 350 GeV

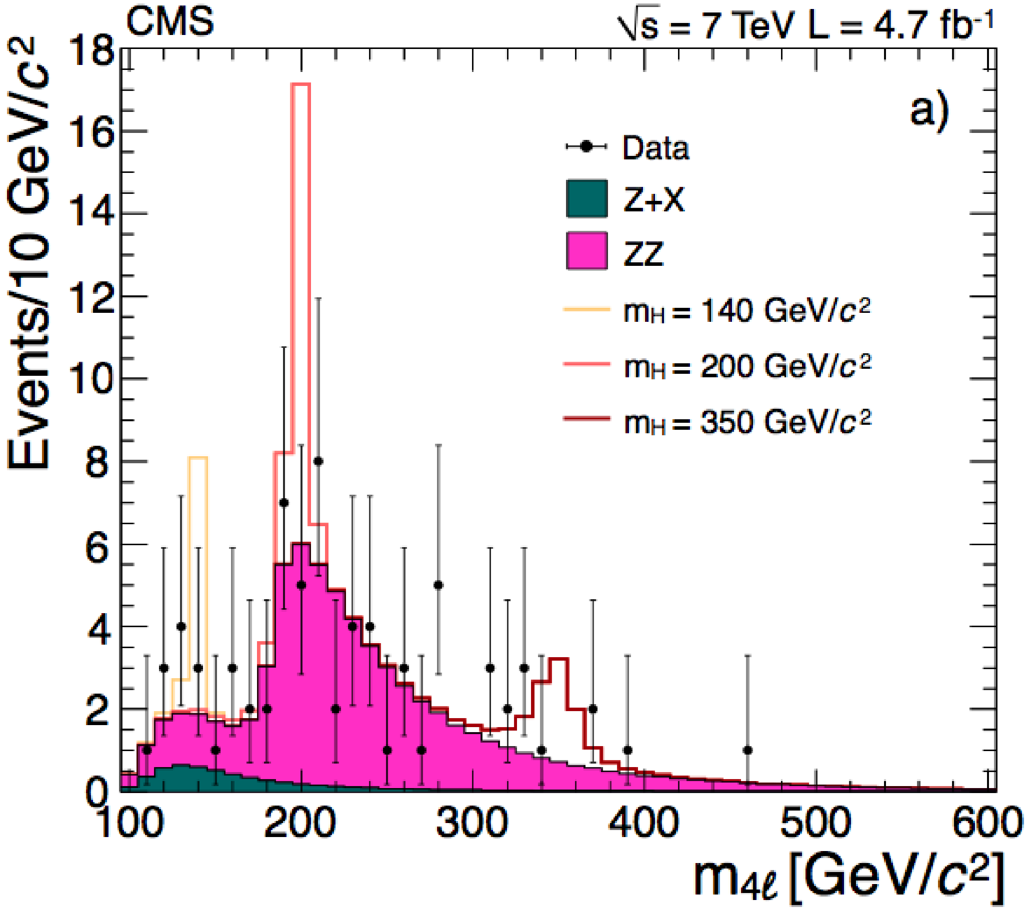
(similar to CDF observation)

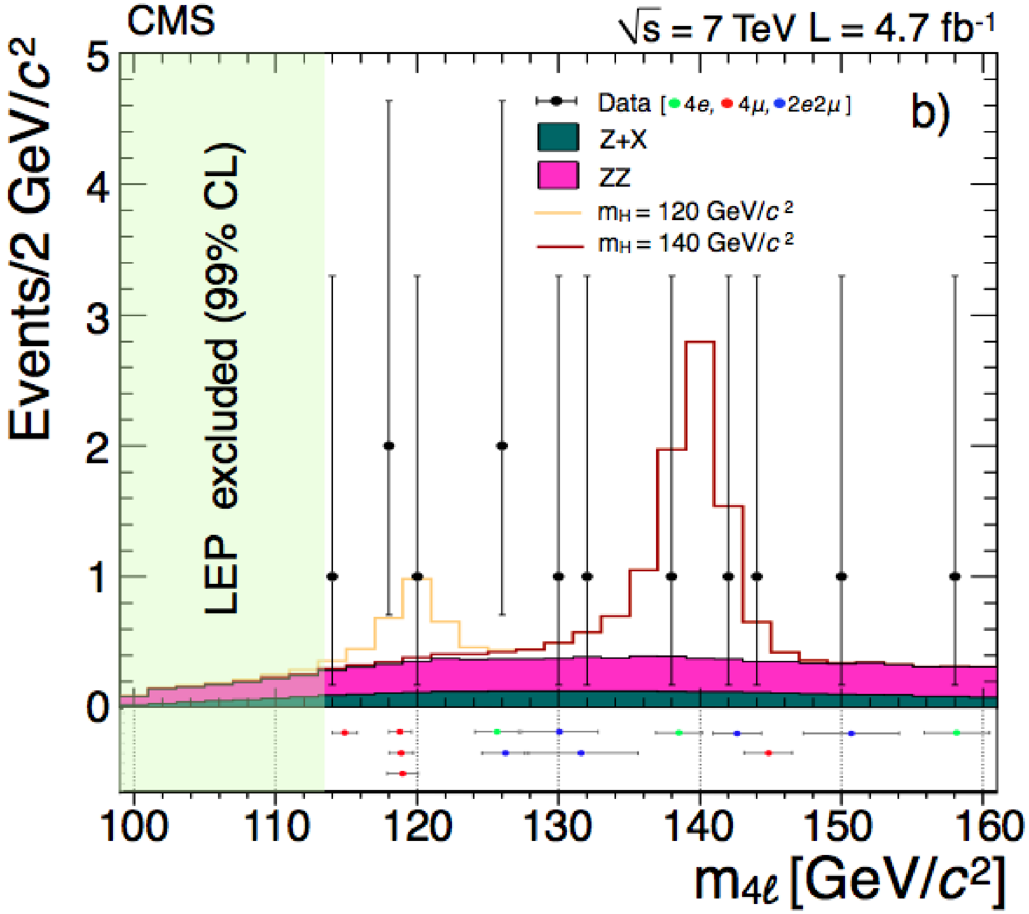


4 lepton invariant mass

Baseline selection and zoom on low mass

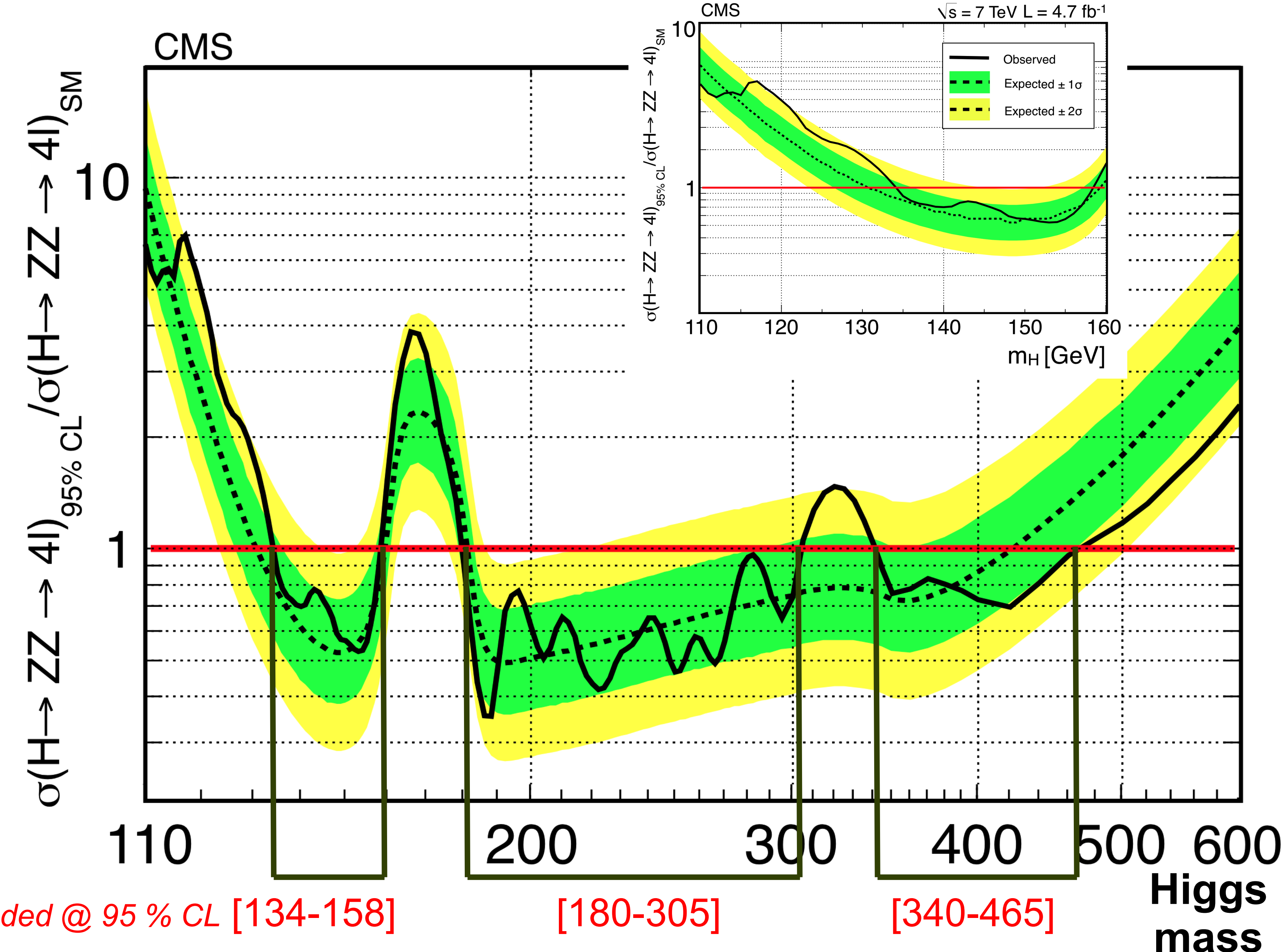
- Observe 13 events between 100 and 160 GeV (expect 9.5 ± 1.3 events)
- Most significant clustering at 119.5 GeV/c^2





Statistical interpretation

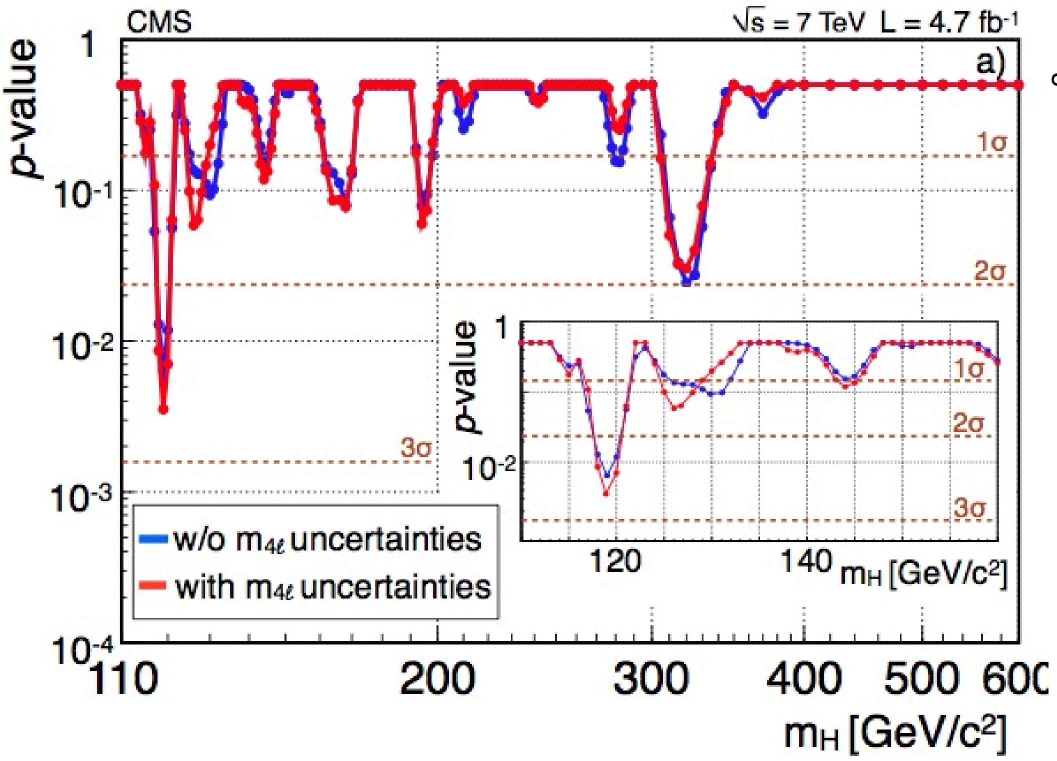
- With the full 2011 data the statistics is still low → set limits on Higgs production

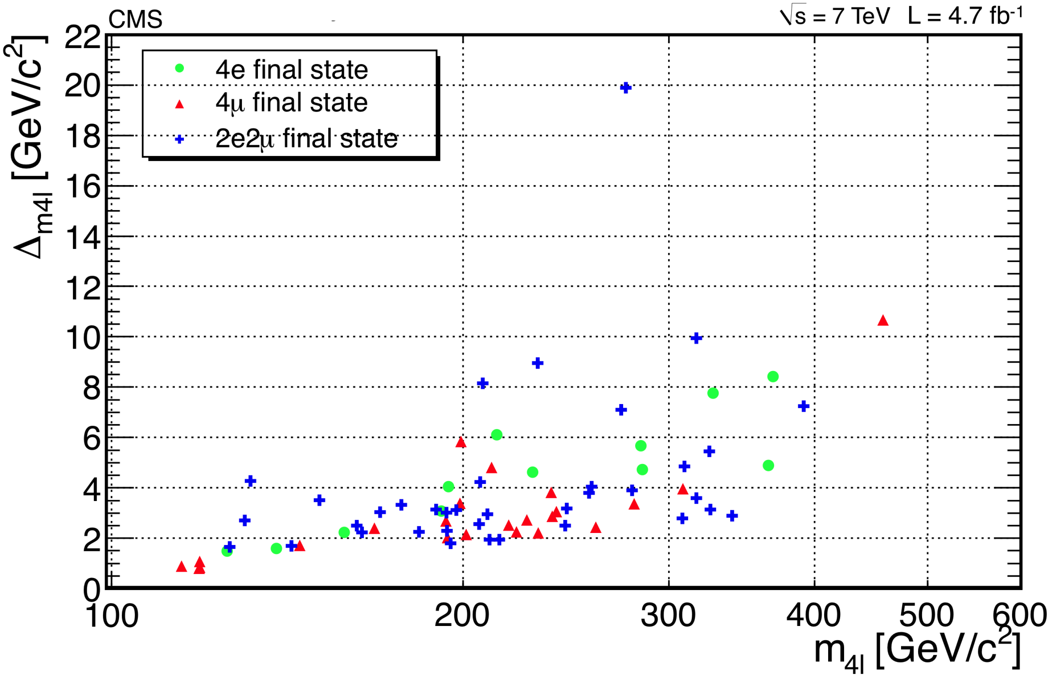


Excluded @ 95 % CL [134-158] [180-305] [340-465]

Statistical interpretation

- **Interpret excesses as p-values** (probability that the background fluctuates upward)
  - Compare the result taking into account or not the uncertainty on M(4l)





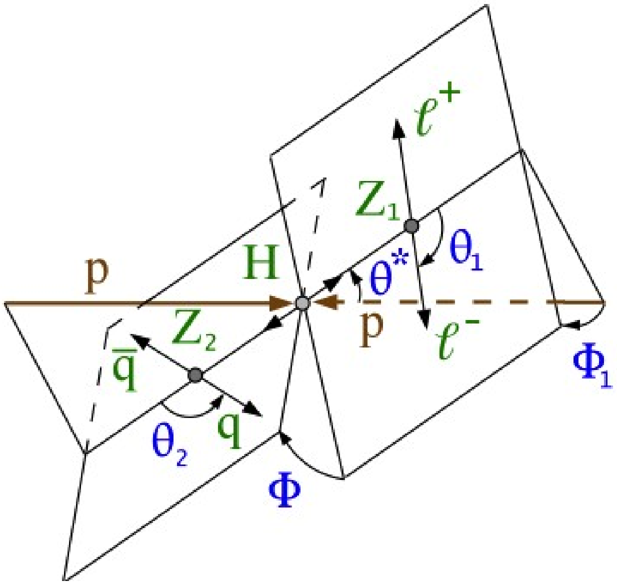
- **Largest excess observed at 119.5 GeV with local significance 2.5σ**
  - global significance 1.0σ in the full mass range, 1.6σ in the mass range 100-160 GeV

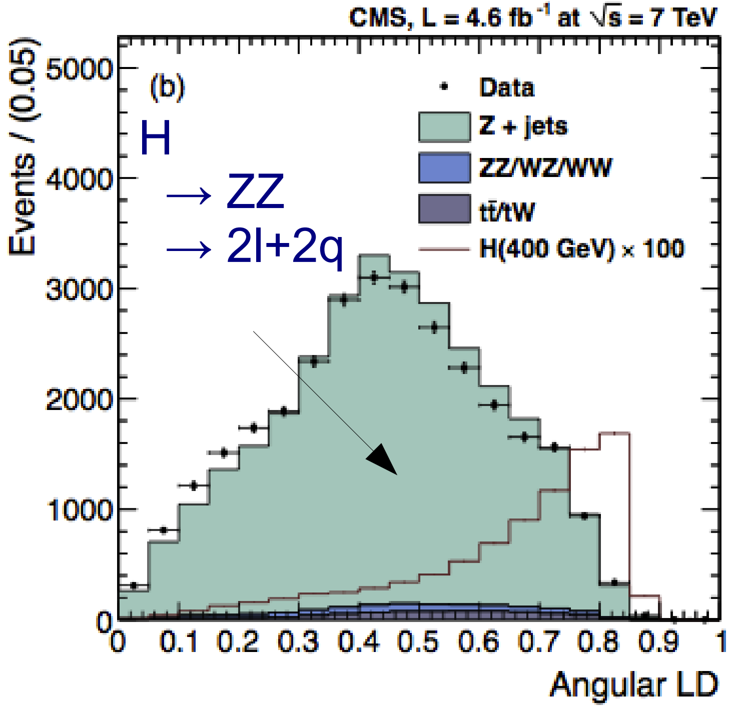
Next steps: angular discriminant analysis

- **We have more handles on the signal than just the invariant mass**
- Expand the resonant decay in all possible angles
  - Build the expected distribution of the signal and the main backgrounds
  - Use the PDFs to **construct a LLR**

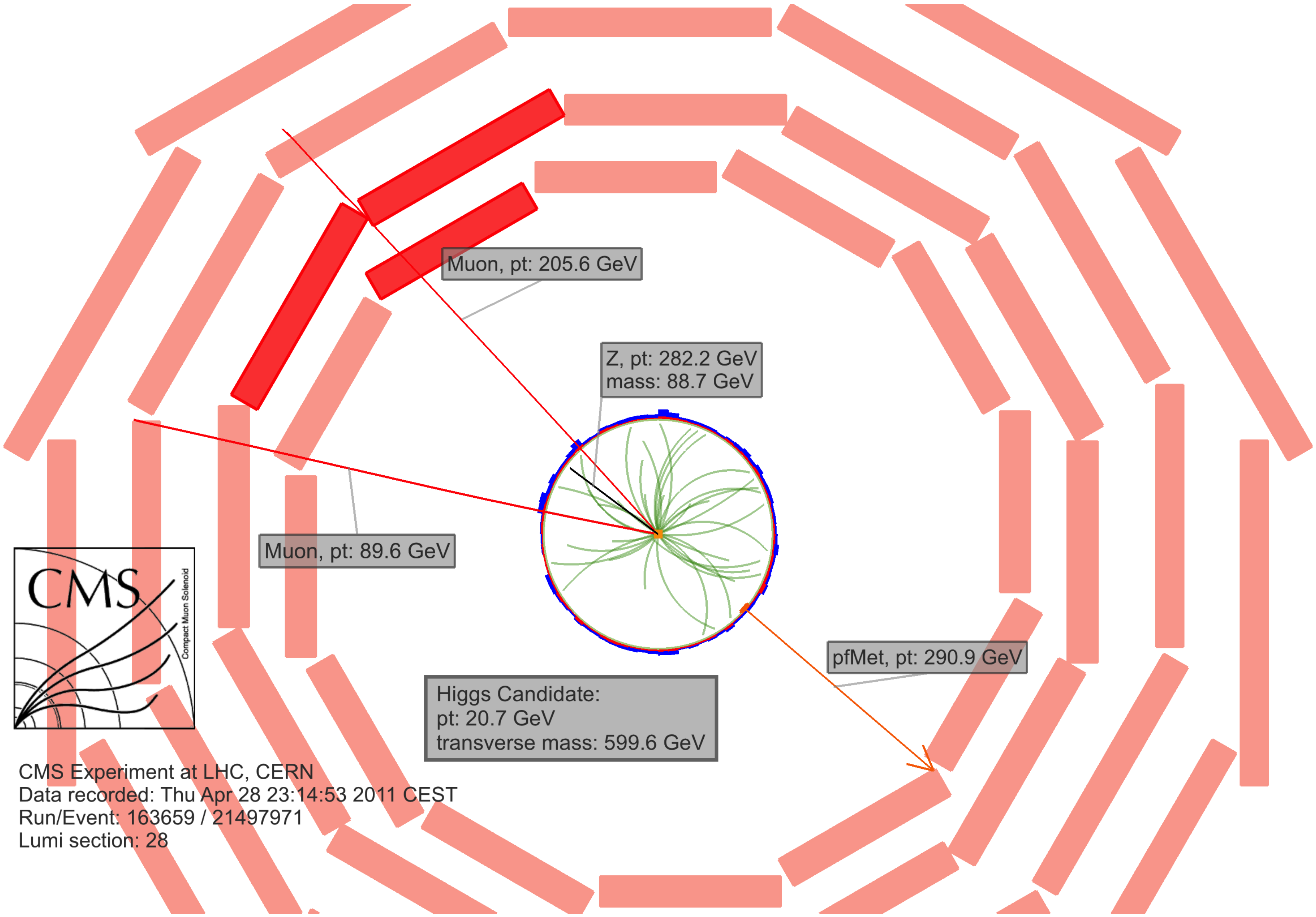
$$LR_S(x_{obs}) \equiv \frac{P_S(x_{obs})}{P_S(x_{obs}) + \Sigma_i k_i P_i(x_{obs})}$$

- Result can be used in two ways: **select events or find evidence for properties of the signal** (e.g. spin or parity)





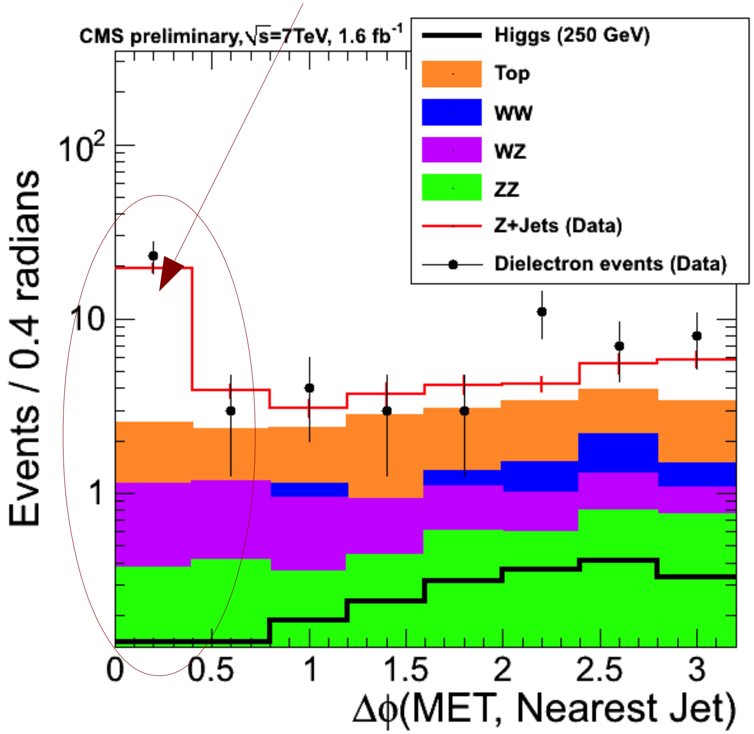
High mass search:
$H \rightarrow ZZ \rightarrow 2l2\nu$


Muon, pt: 205.6 GeV
Z, pt: 282.2 GeV
mass: 88.7 GeV
Muon, pt: 89.6 GeV
pfMet, pt: 290.9 GeV
Higgs Candidate:
pt: 20.7 GeV
transverse mass: 599.6 GeV
CMS
Compact Muon Solenoid
CMS Experiment at LHC, CERN
Data recorded: Thu Apr 28 23:14:53 2011 CEST
Run/Event: 163659 / 21497971
Lumi section: 28

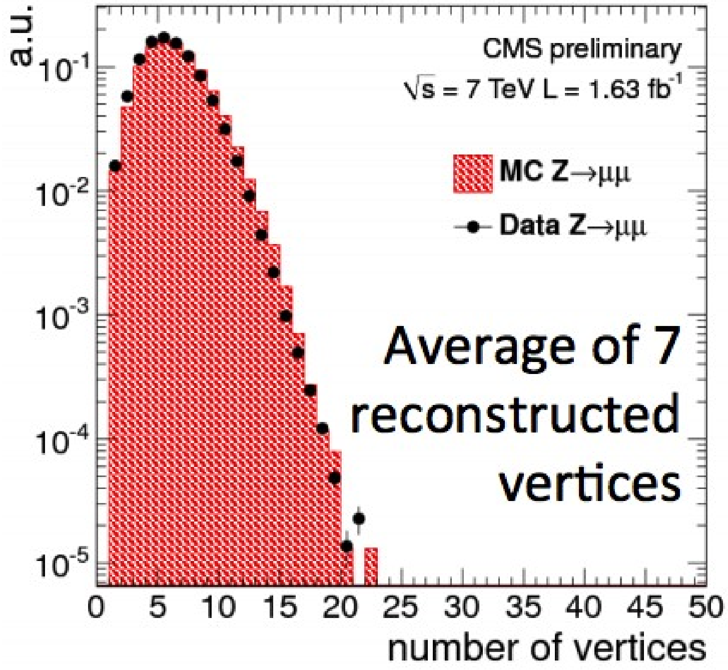
Channel signature

- A dilepton compatible with **Z → ll decay, recoiling against nothing**
  - BR(ZZ → 2l2v) / BR(ZZ → 4l) ≈ 6
  - Large branching ratio, but also large background contamination
- Need a **robust handle against two main contaminations**

Mis-reconstruction of the Z recoil



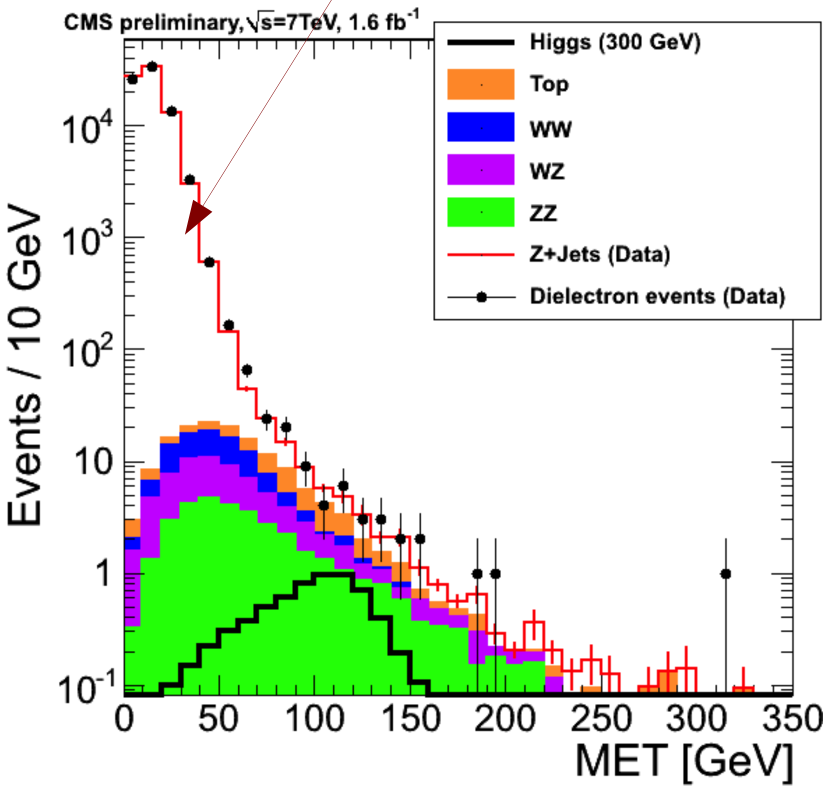
Pileup contamination

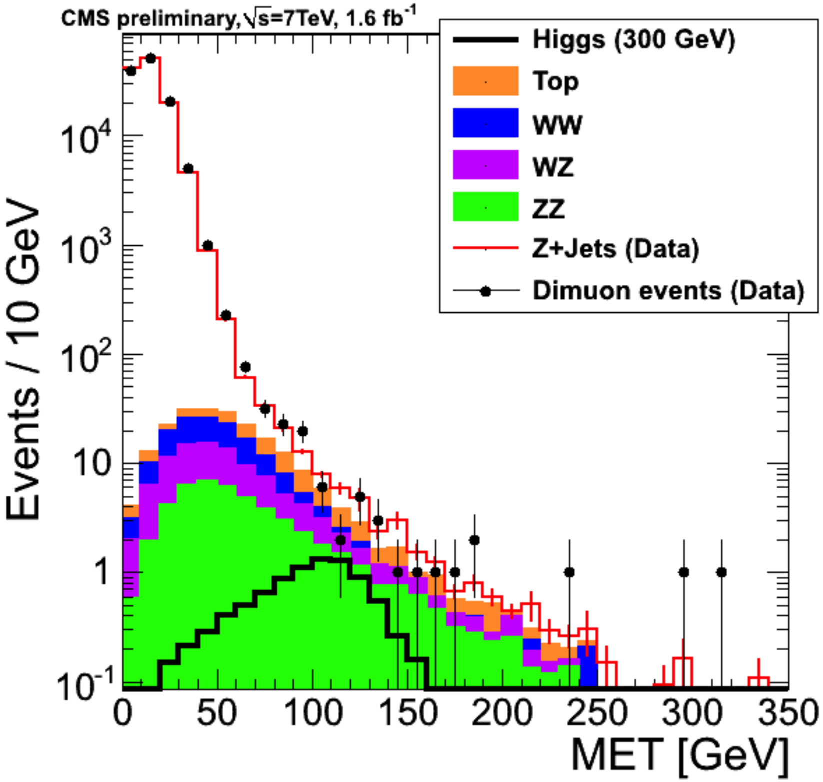


Average of 7 reconstructed vertices

Missing transverse energy

- **Built from the flux of the reconstructed particle momenta :** $\vec{E}_{\mathrm{T}}^{\mathrm{miss}} = -\sum_{\mathrm{particles}} \vec{p}_{T,i}$
- The main background is Z → ll production, similar to γ+jets production:
  - Use photon sample and re-weight to match the Z p_T spectrum to derive E_T^{miss} shape





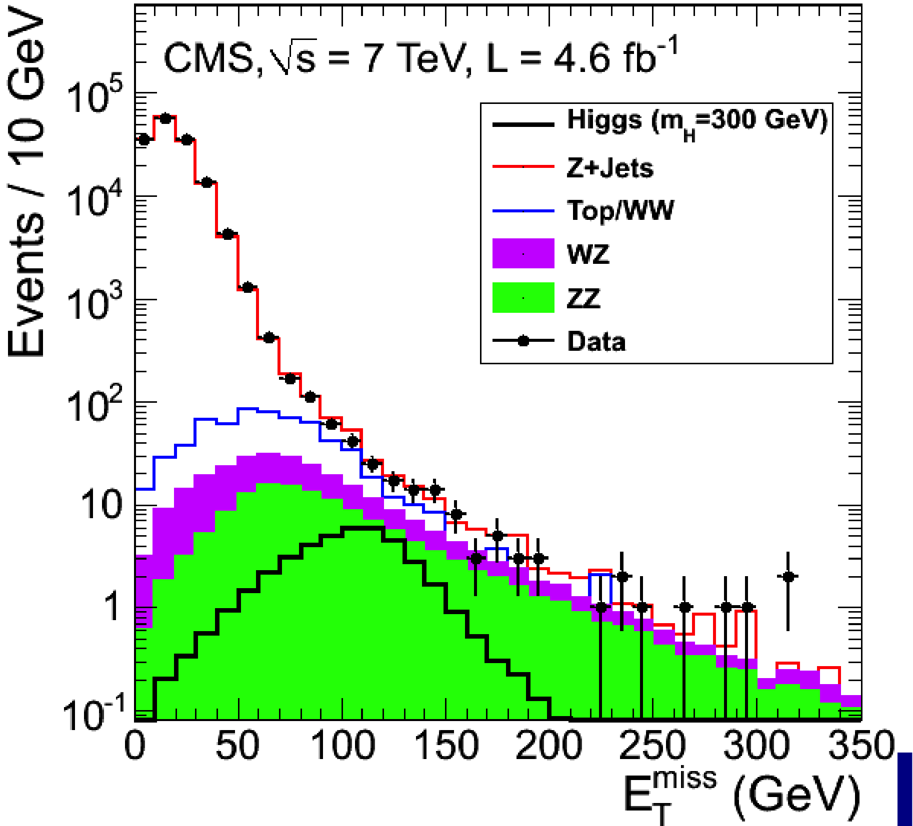
Missing transverse energy

- Built from the flux of the reconstructed particle candidates momenta

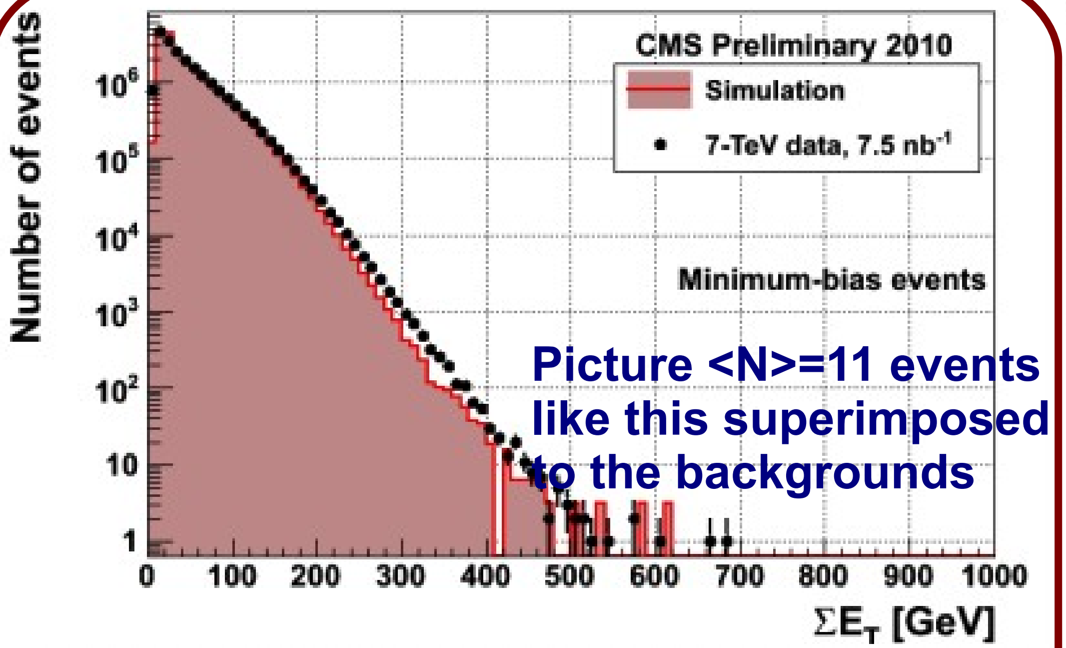
$$\vec{E}_{\mathrm{T}}^{\mathrm{miss}} = -\sum_{\mathrm{leptons}} \vec{p}_{T,i} - \sum_{\mathrm{jets}} \vec{p}_{T,i} - \sum_{\mathrm{unclustered}} \vec{p}_{T,i}$$

  - Charged particles and jets with associated **tracks can be constrained to the primary vertex**
  - **Neutrals can't be easily associated**
  - All must be taken into account, otherwise additional imbalance is found in the event

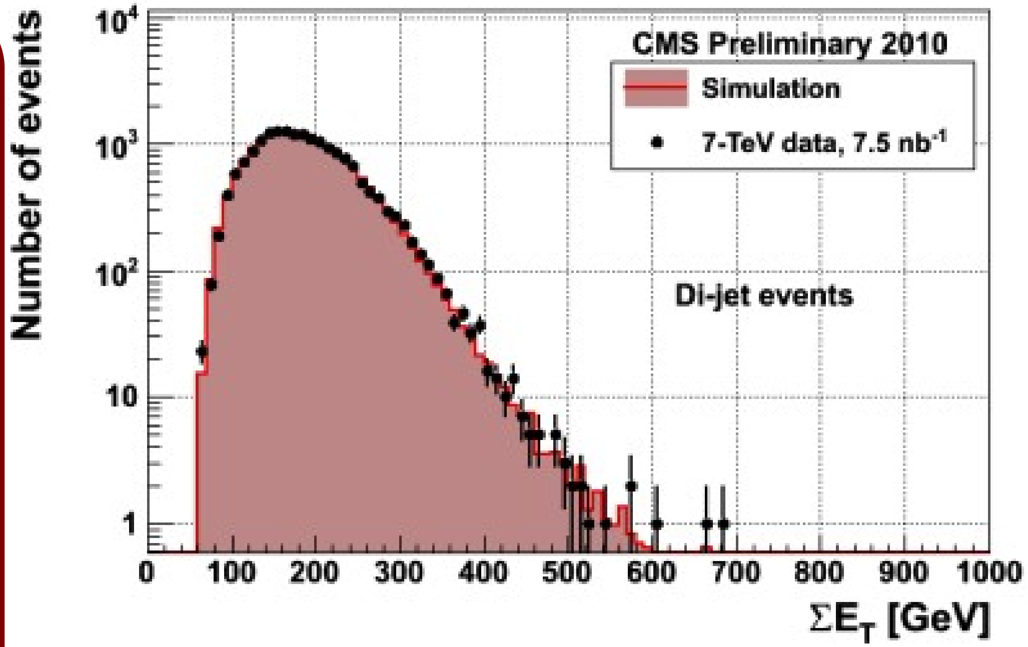
- E_T^{miss} measurement is furthermore affected by:
  - **jet energy scale**/resolution effects
  - noise in the calorimeters, dead cells, ...

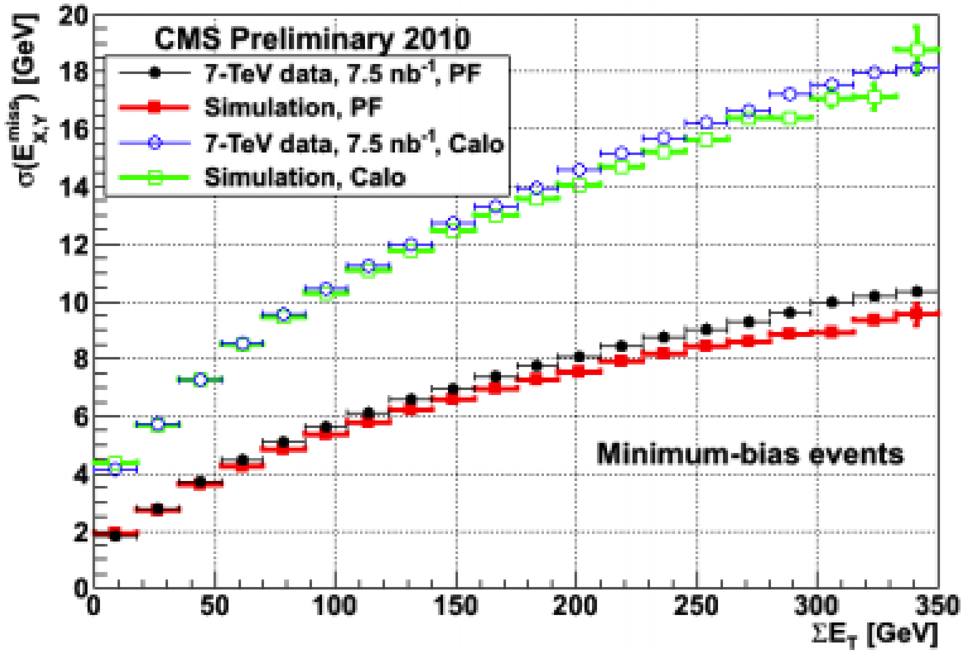


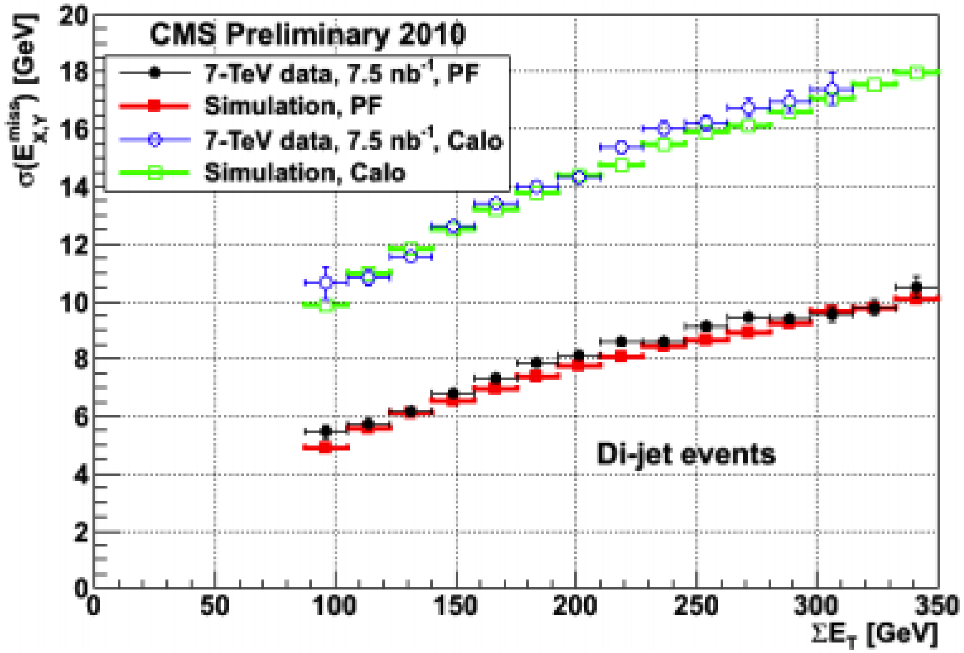
E_T^{miss} resolution in minimum bias events



Picture <N>=11 events like this superimposed to the backgrounds





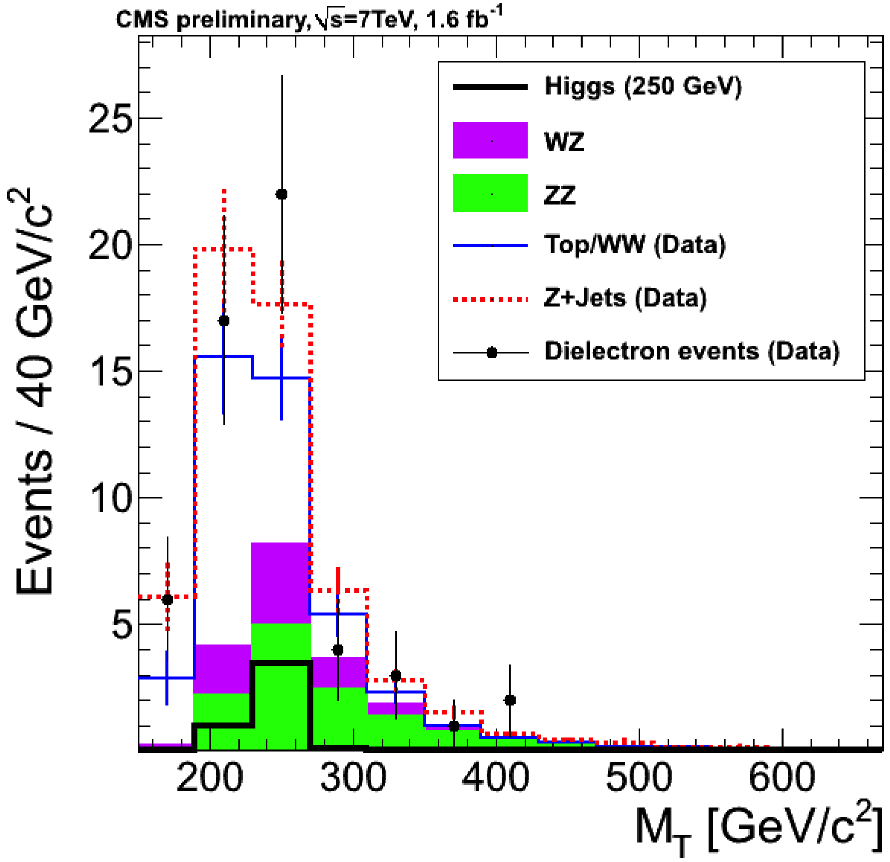


Key distribution: transverse mass

- Due to the presence of two neutrinos the mass the f**ull kinematics can't be reconstructed** (one degree of freedom left)
- Use the **transverse mass of the dilepton + E_T^{miss} system:**

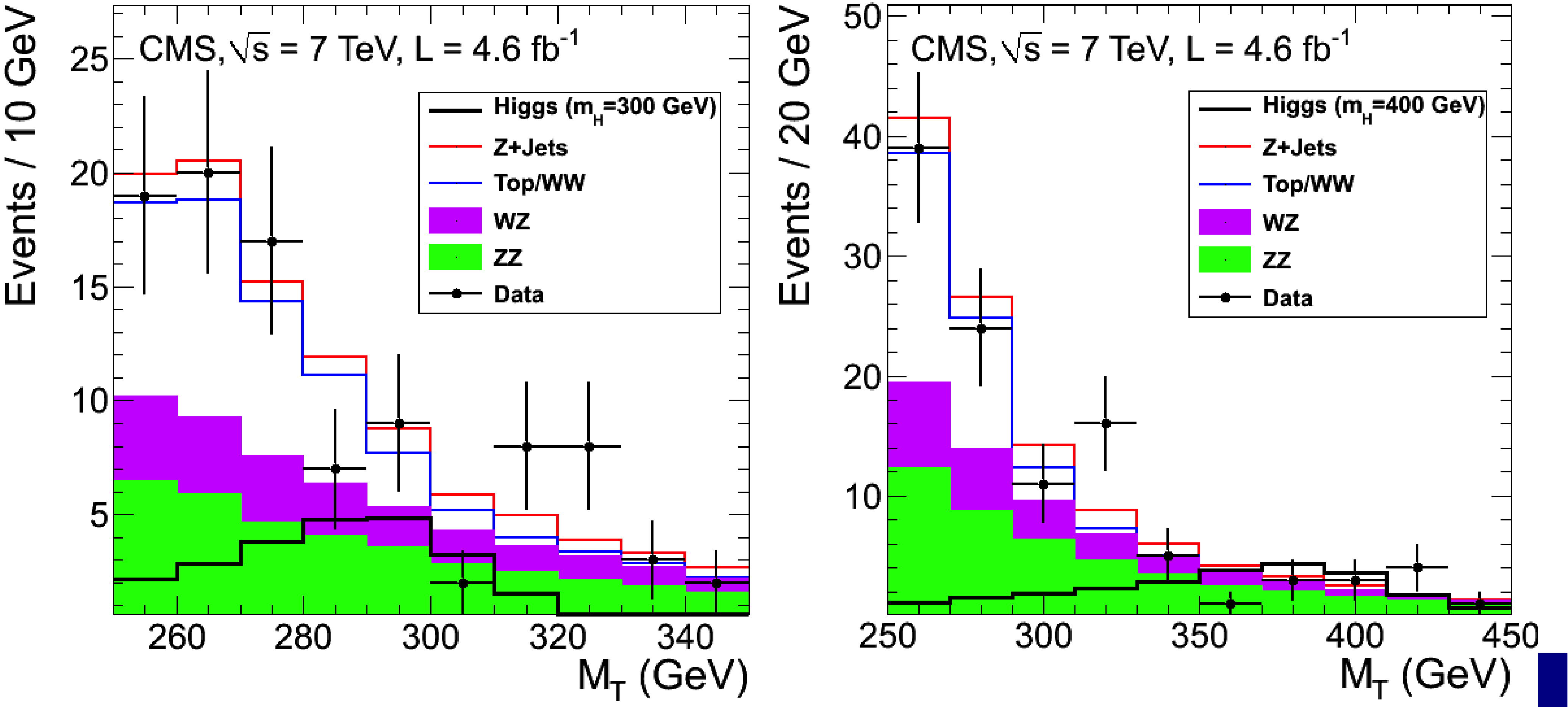
$$M_T^2 = \left(\sqrt{p_T(\ell\ell)^2 + M(\ell\ell)^2} + \sqrt{E_T^{miss\,2} + M(\ell\ell)^2}\right)^2 - (\vec{p}_T(\ell\ell) + \vec{E}_T^{miss})^2$$

  - assuming same mass for the two decay legs
  - Lower bound for will be $M_T \sim 2\ M_Z$



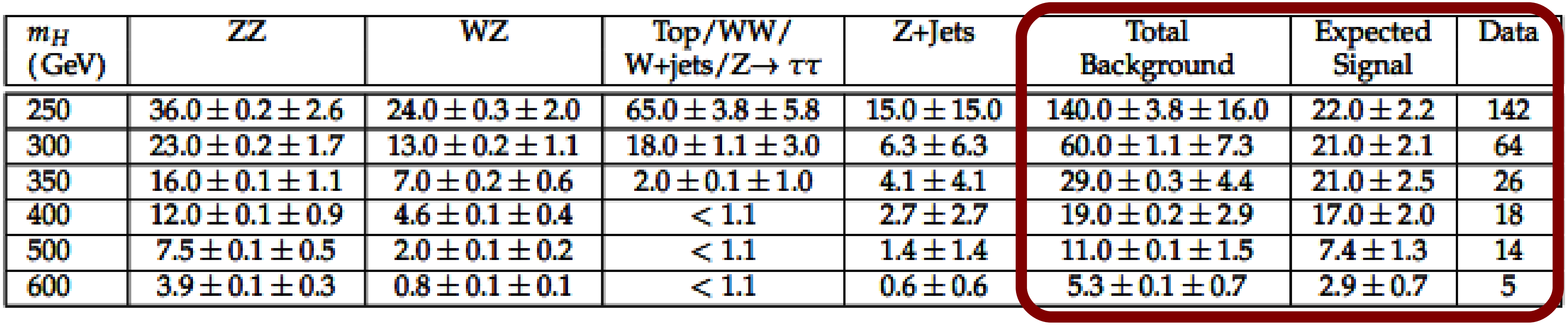
Transverse mass analysis

- The M_T distribution can be analyzed in two ways:
  - **Count** the number of events in a given region: simple, robust analysis
  - **Analyze the observed shape**: fit components, use sidebands to constrain backgrounds



Final event selection from cut and count

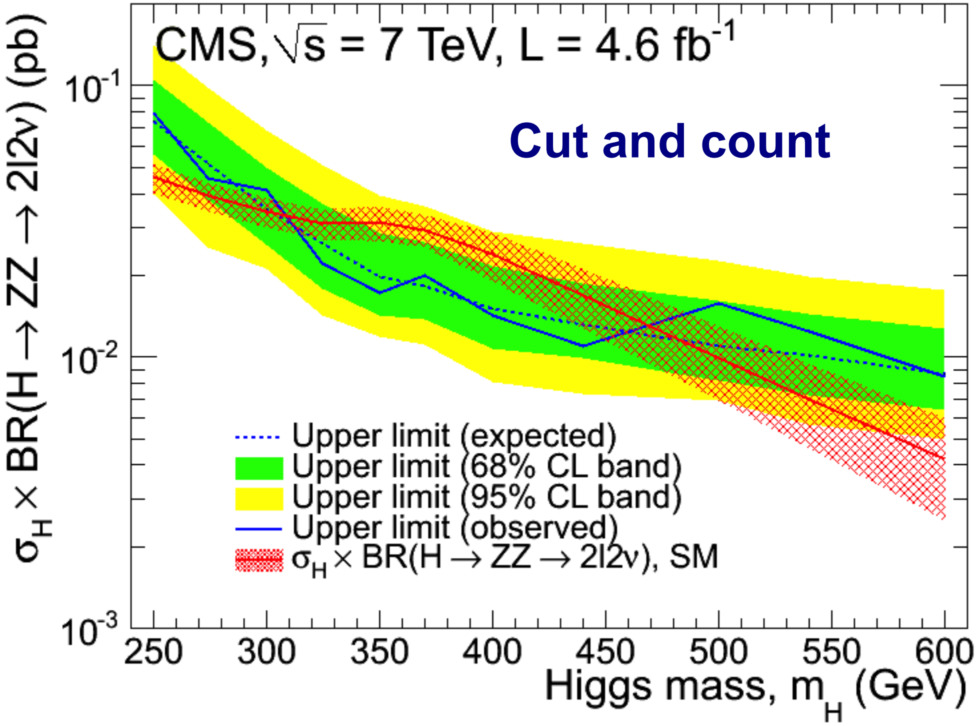
- **Optimize E_T^{miss} and M_T cuts for best limits** → run several pseudo-experiments before looking at real data, then apply cuts to data
- **Number of selected events is compatible with background expectations**
  - Z+jets modeled directly from the γ+jets sample
  - Non-resonant background extracted from dilepton mass side-band in the eμ channel

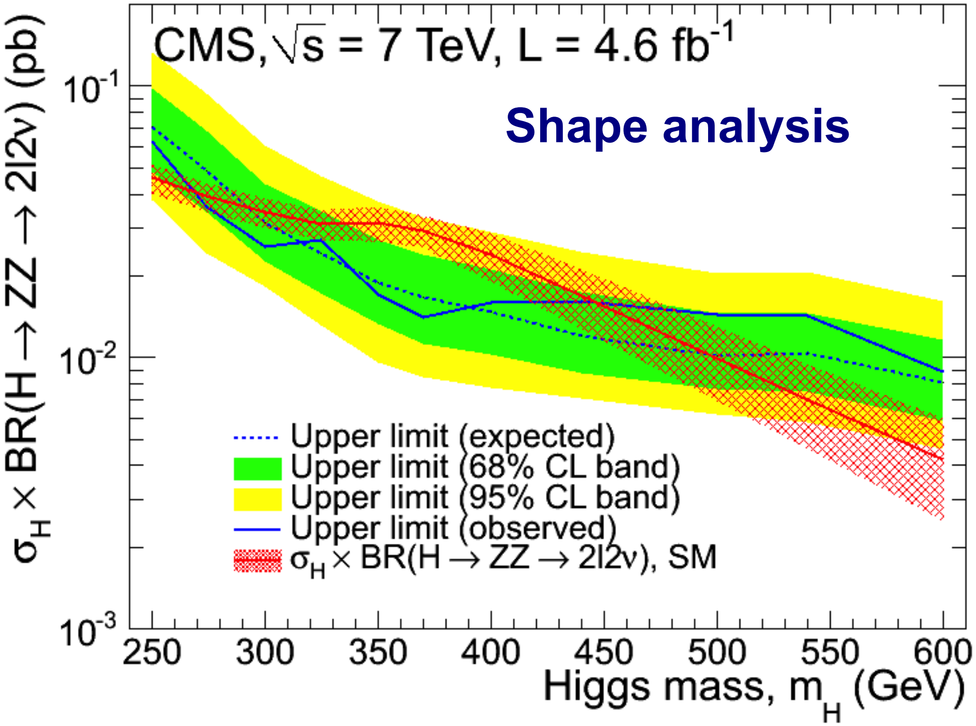


m_H (GeV)	ZZ	WZ	Top/WW/ W+jets/Z→ $\tau\tau$	Z+Jets	Total Background	Expected Signal	Data
250	$36.0 \pm 0.2 \pm 2.6$	$24.0 \pm 0.3 \pm 2.0$	$65.0 \pm 3.8 \pm 5.8$	15.0 ± 15.0	$140.0 \pm 3.8 \pm 16.0$	22.0 ± 2.2	142
300	$23.0 \pm 0.2 \pm 1.7$	$13.0 \pm 0.2 \pm 1.1$	$18.0 \pm 1.1 \pm 3.0$	6.3 ± 6.3	$60.0 \pm 1.1 \pm 7.3$	21.0 ± 2.1	64
350	$16.0 \pm 0.1 \pm 1.1$	$7.0 \pm 0.2 \pm 0.6$	$2.0 \pm 0.1 \pm 1.0$	4.1 ± 4.1	$29.0 \pm 0.3 \pm 4.4$	21.0 ± 2.5	26
400	$12.0 \pm 0.1 \pm 0.9$	$4.6 \pm 0.1 \pm 0.4$	< 1.1	2.7 ± 2.7	$19.0 \pm 0.2 \pm 2.9$	17.0 ± 2.0	18
500	$7.5 \pm 0.1 \pm 0.5$	$2.0 \pm 0.1 \pm 0.2$	< 1.1	1.4 ± 1.4	$11.0 \pm 0.1 \pm 1.5$	7.4 ± 1.3	14
600	$3.9 \pm 0.1 \pm 0.3$	$0.8 \pm 0.1 \pm 0.1$	< 1.1	0.6 ± 0.6	$5.3 \pm 0.1 \pm 0.7$	2.9 ± 0.7	5

Results

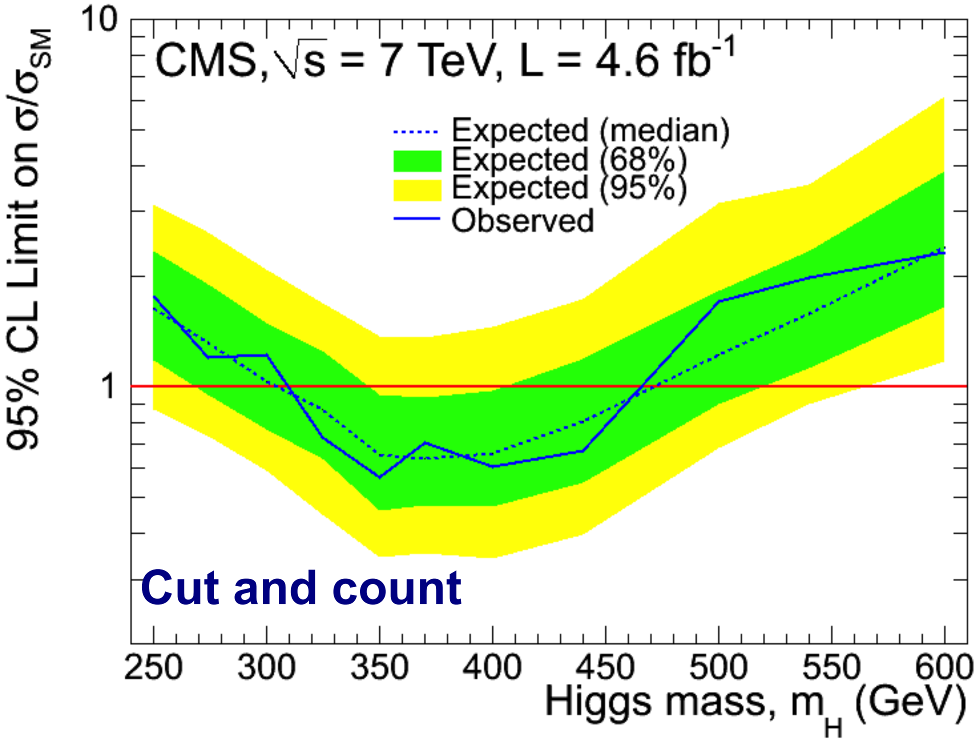
- Set **limits on cross section for resonant ZZ → 2l2v production from Higgs**
  - At low mass: Z+jets background overwhelms the signal, hard to probe
  - At high mass: dominated by theory uncertainties in particular in the Higgs mass shape

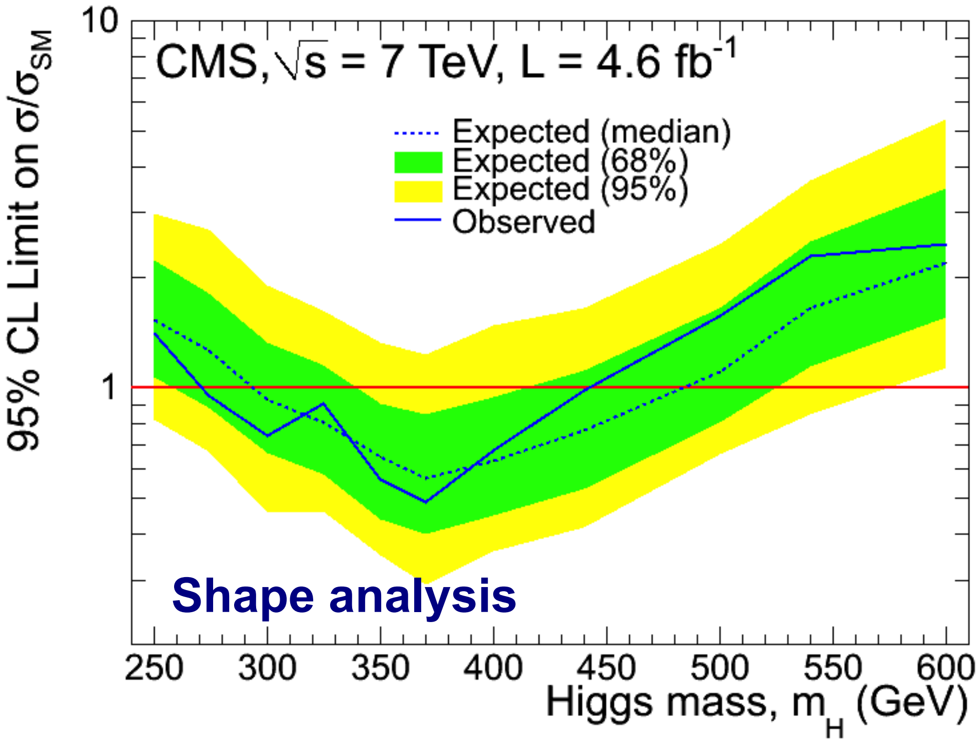




Results - 2

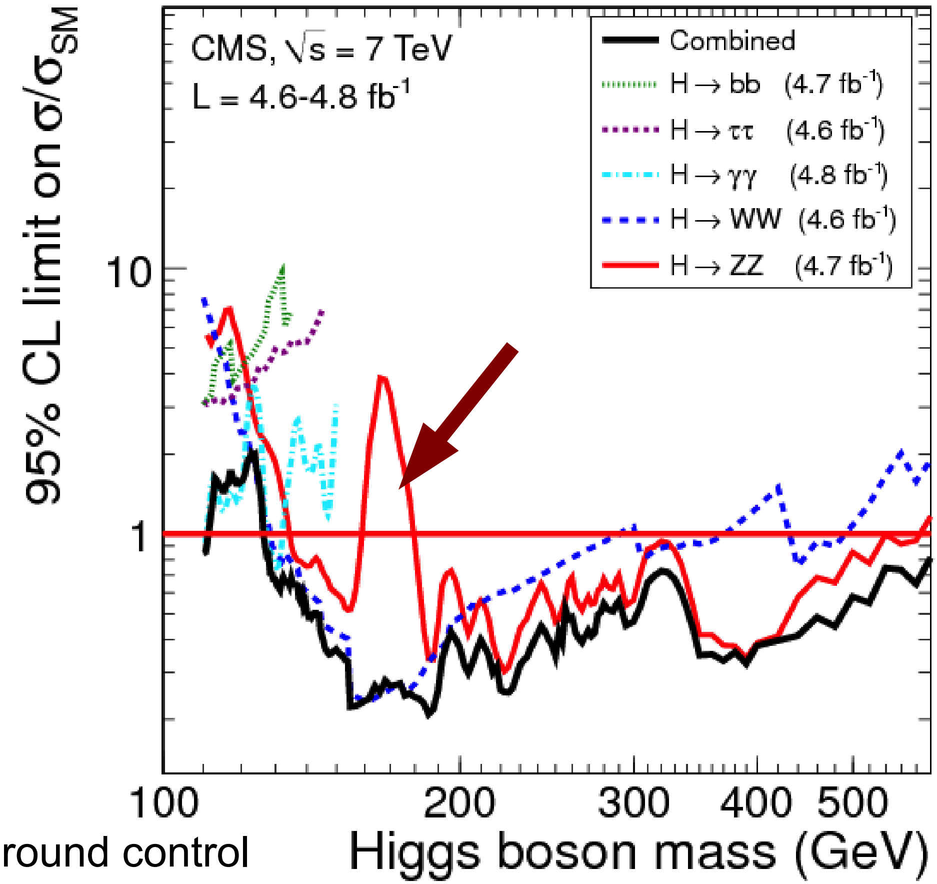
- **Limits on R = σ/σ_{SM} at 95% CL**
  - no particular excess in the mass range analyzed: all is compatible with background only
  - **exclude 270-440 GeV/c^2 mass range**





Conclusions

- *Today I have focused on the ZZ process and the search for Higgs in its production*
- **ZZ s-channel production is highly suppressed** – deviations can be interpreted as
  - anomalous triple gauge couplings
  - resonant production of the ZZ channel
- **ZZ → 4l is the golden channel**
  - Optimal resolution, but lowest branching ratio
  - Slight excess ~119.5 GeV/c^2
- **ZZ → 2l2v leads the search at high mass**
  - Larger branching ratio but needs robust background control
  - Observations are compatible with background only hypothesis



End of Lecture II on Higgs Physics

References

- ATLAS Collaboration, "*Expected Performance of the ATLAS Experiment: Detector, Trigger and Physics*", CERN-OPEN-2008-020
- **CMS Collaboration, "*Search for the standard model Higgs boson in the decay channel H→ZZ→4l in pp collisions at* $s^{1/2}$ *= 7 TeV", arXiv:1202.1997***
- **CMS Collaboration, *"Search for the standard model Higgs boson in the H → ZZ → 2l2v channel in pp collisions at* $s^{1/2}$ *= 7 TeV",arXiv:1202.3478***
- CMS Collaboration, "*Search for a Higgs boson in the decay channel* $H \rightarrow ZZ^{(*)} \rightarrow qq\, ll$", *arXiv:1202.1416*

Setting limits on Higgs production

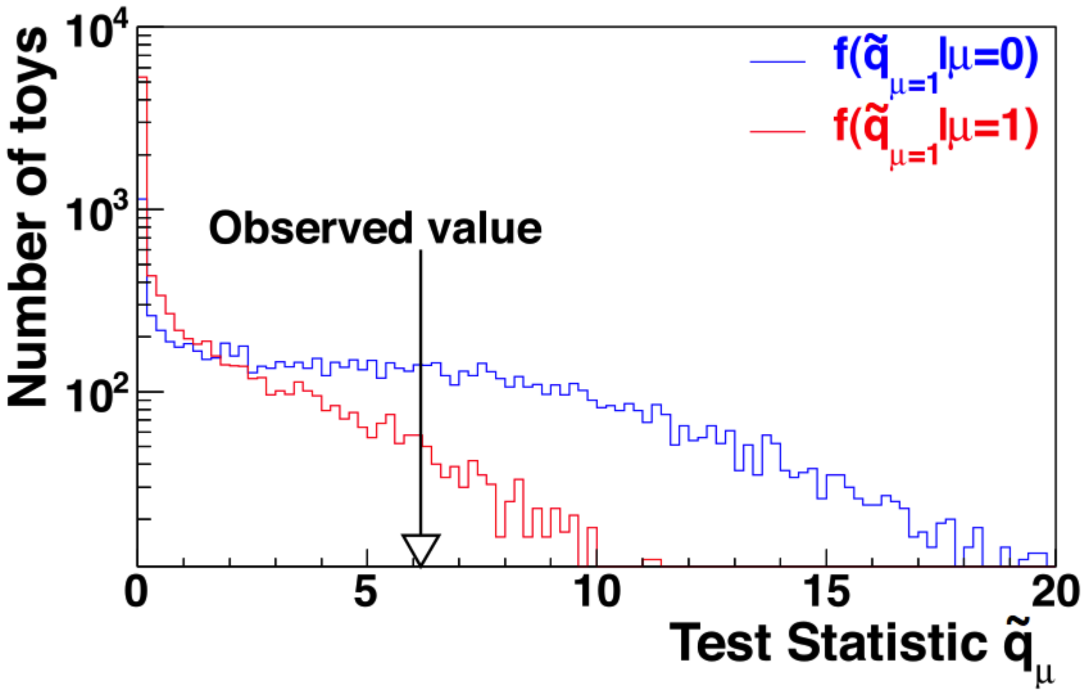
- **When no excess is observed the strategy is to set limits on σ(H)**
  - Assess from data what is the allowed signal strength i.e. $\mu=\sigma/\sigma_{SM}$
  - We measure the compatibility of the data with the signal hypothesis using a test statistics
- **Likelihood and test statistics definition**
  - The data vs S+B hypothesis is tested with a likelihood

$$\mathcal{L}(\text{data}\,|\,\mu,\theta) = \text{Poisson}\,(\,\text{data}\,|\,\mu\cdot \underbrace{s(\theta)}_{\text{Signal expected}} + \underbrace{b(\theta)}_{\text{background expected}}\,)\cdot \underbrace{p(\tilde{\theta}|\theta)}_{\text{nuisance paramters: uncertainty on rates, shapes, etc.}}$$

  - Signal+background and background only hypothesis tested with $\tilde{q}_\mu = -2\ln\dfrac{\mathcal{L}(\text{data}|\mu,\hat{\theta}_\mu)}{\mathcal{L}(\text{data}|\underbrace{\hat{\mu},\hat{\theta}}_{\text{maximize likelihood}})}$

Setting limits – CL_s method

- In data we **compute** the **observed value of the test statistics** and find the best values of all nuisance parameters to fit background and background only hypothesis $\hat{\theta}_0^{obs}$ and $\hat{\theta}_\mu^{obs}$
- From MC/data-driven expectations we generate pseudo-experiments for each hypothesis



$$CL_s(\mu) = \frac{p_\mu}{1 - p_b}$$

Probability that S+B test statistics exceeds the observed value in S+B hypothesis

Similar, for background only hypothesis

- If **CL_s < 5% signal is excluded at 95%**
- We call **upper endpoint** , i.e. μ_{up} , to the **signal strength for which CL_s=5%**