The road to the ElectroWeak Symmetry Breaking

14^{th} - 15^{th} February 2012
Seminar at DESY

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Outline

- The Higgs boson and the ElectroWeak Symmetry Breaking (EWSB)
- **Status:** CMS results in a nutshell, focusing on high mass H->VV
- **What's next ?**
  - move to **larger mass (>600 GeV beyond SM)**
    - control of V+jets background
    - jet merging
    - signal characterization (angular analysis)
  - improve sensitivity to **smaller xsec -> Vector Boson Fusion**
    - control of VV background
- The final arbiter: VV scattering

Why we need the Higgs

The Higgs boson provides

1) an EXPLICATION of the W,Z mass (ie EWSB)

2) a DESCRIPTION of the fermions masses

- 1 is really fundamental to make the SM "working" (next slides)

… even if not less arbitrary!

- 2 is just another way of formulating the same question:

why the fermions have those particular masses?

why the fermions have those particular Higgs couplings?

(SM works well without 2: just the fermio-phobic Higgs)

EWSB and the W, Z mass

$$L_{gauge} = -\frac{1}{4}W^i_{\mu\nu}W^{\mu\nu i} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \cancel{\frac{1}{2}m^2 W^i_{\mu\nu}W^{\mu\nu i} + \frac{1}{2}m^2 B_{\mu\nu}B^{\mu\nu}}$$

$$W^i_{\mu\nu} = \partial_\nu W^i_\mu - \partial_\mu W^i_\nu + g\varepsilon^{ijk}W^j_\mu W^k_\nu \quad \text{SU(2)}$$

×

$$B_{\mu\nu} = \partial_\nu B_\mu - \partial_\mu B_\nu \quad \text{U(1)}$$

Gauge invariance

scalar potential (λ>0, μ<0) $V(\Phi) = \mu^2|\Phi^+\Phi| + \lambda(|\Phi^+\Phi|)^2$

complex scalar doublet of SU(2) $\Phi = \begin{pmatrix}\phi^+ \\ \phi^0\end{pmatrix}$

with minimum **(= empty state)** at $\langle\Phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0 \\ v\end{pmatrix}$ **or** $\cancel{\langle\Phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}v \\ 0\end{pmatrix}}$ → ~~SU(2)~~

*(**v** = empty expectation value)*

generic Gauge

$$\Phi = \frac{1}{\sqrt{2}}e^{i\frac{\omega^i\tau^i}{2v}}\begin{pmatrix}0 \\ v+h\end{pmatrix}$$

1 physical scalar field $\langle h\rangle = 0$

3 Goldstone bosons ω_i

4 Gauge fields $W^i_{\mu\nu}, B_\mu$

Gauge unitario

$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix}0 \\ v+h\end{pmatrix}$$

1 physical scalar field -> Higgs

4 Gauge fields combined into known vector bosons:
W,Z with mass, photon massless

$$W^\pm_\mu = \frac{1}{\sqrt{2}}\left(W^1_\mu \mp iW^2_\mu\right) \qquad M^2_W = \frac{1}{4}g^2v^2$$

$$Z^\mu = \frac{-g'B_\mu + gW^3_\mu}{\sqrt{g^2+g'^2}} \qquad M^2_Z = \frac{1}{4}\left(g^2+g'^2\right)v^2$$

$$A^\mu = \frac{-gB_\mu + g'W^3_\mu}{\sqrt{g^2+g'^2}} \qquad M^2_A = 0$$

$U(1)_{EM}$

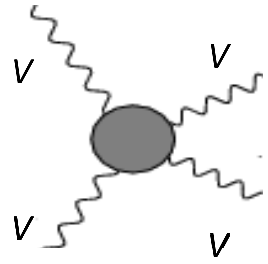
Higgs and unitarity in VBF

W,Z mass (-> longitudinal degrees of freedom) arise from the Higgs mechanism:

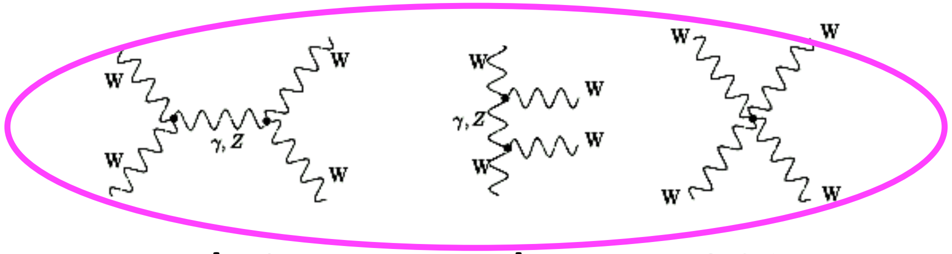
without Higgs, $W^+_L W^-_L \to W^+_L W^-_L$ would break unitarity

$$A(W_L^+W_L^- \to W_L^+W_L^-) \approx \frac{1}{v^2}\left(-s-t+\frac{s^2}{s-m_H^2}+\frac{t^2}{t-m_H^2}\right)$$

Vector Boson Fusion (VBF)



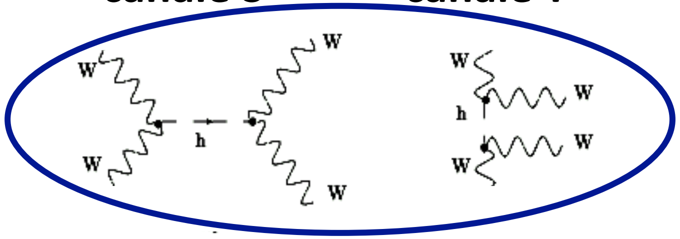
VV -> VV



canale S

canale T

QGC



Same behavior for all VV amplitudes

$$A(Z_L Z_L \to W_L^+W_L^-) \approx \frac{1}{v^2}\left(-s+\frac{s^2}{s-m_H^2}\right)$$ (s channel only)

$$A(Z_L W_L^- \to Z_L W_L^-) \approx \frac{1}{v^2}\left(-t+\frac{t^2}{t-m_H^2}\right)$$ (t channel only)

$$A(W_L^-W_L^- \to W_L^-W_L^-) \approx \frac{1}{v^2}\left(-u-t+\frac{u^2}{u-m_H^2}+\frac{t^2}{t-m_H^2}\right)$$

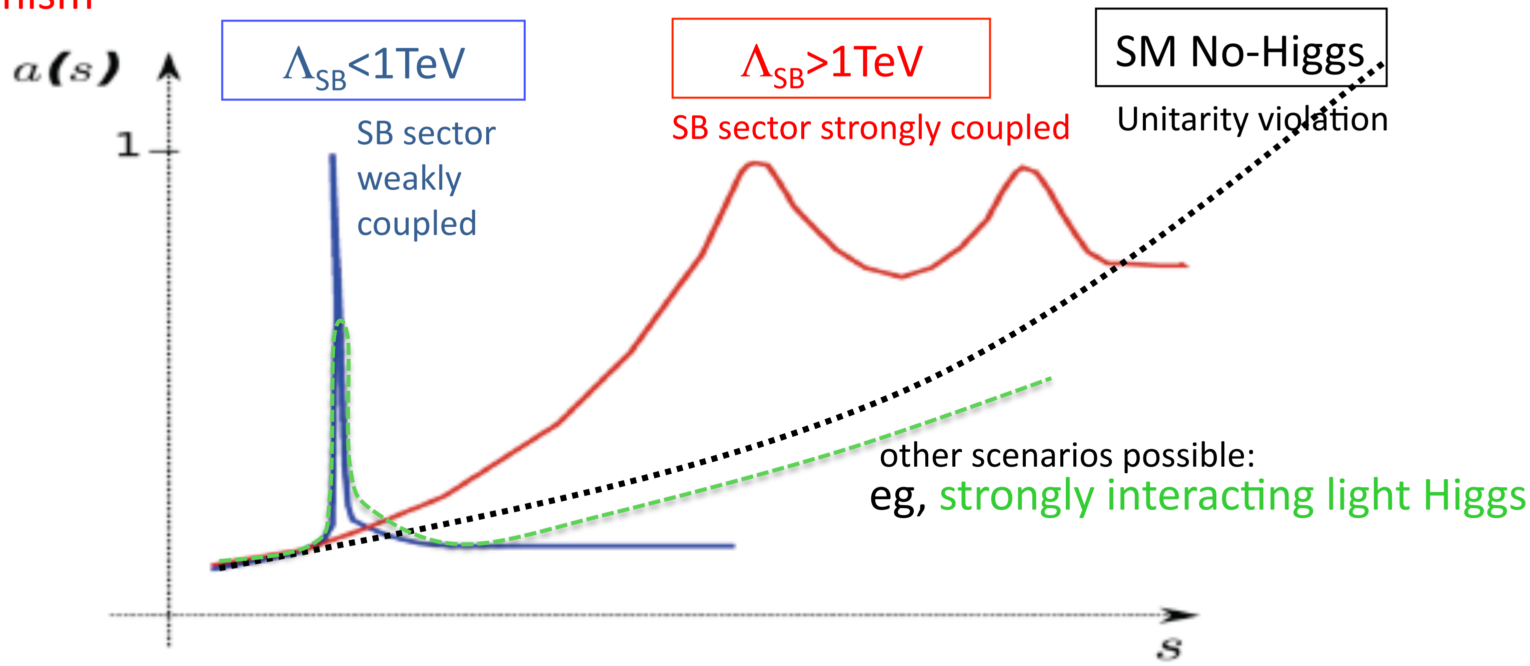
(t and u channels)

VBF is the smoking gun of the EWSB !

VBF and VV scattering

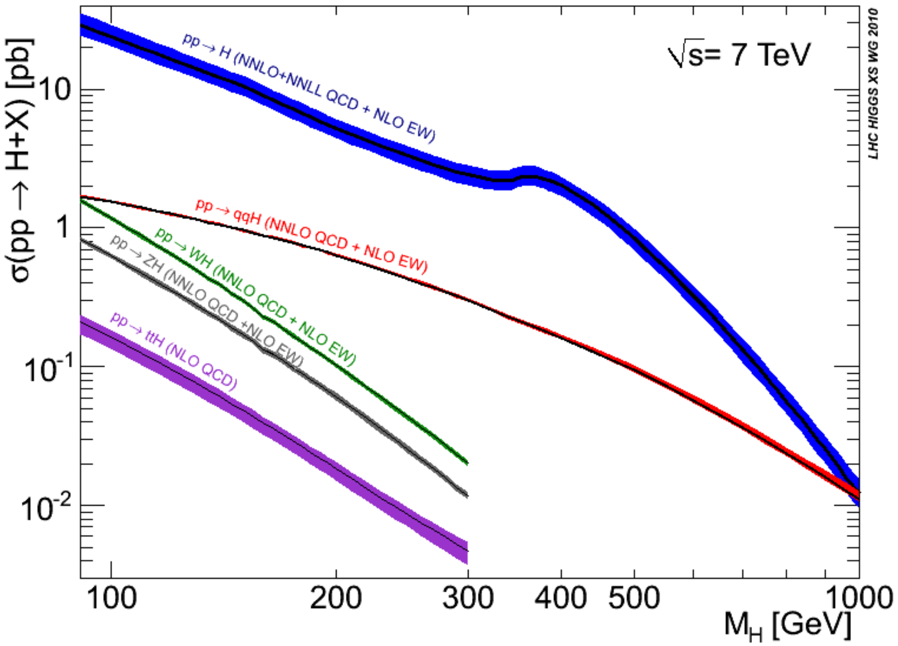
- **VV scattering spectrum σ(VV->VV) vs M(VV)**

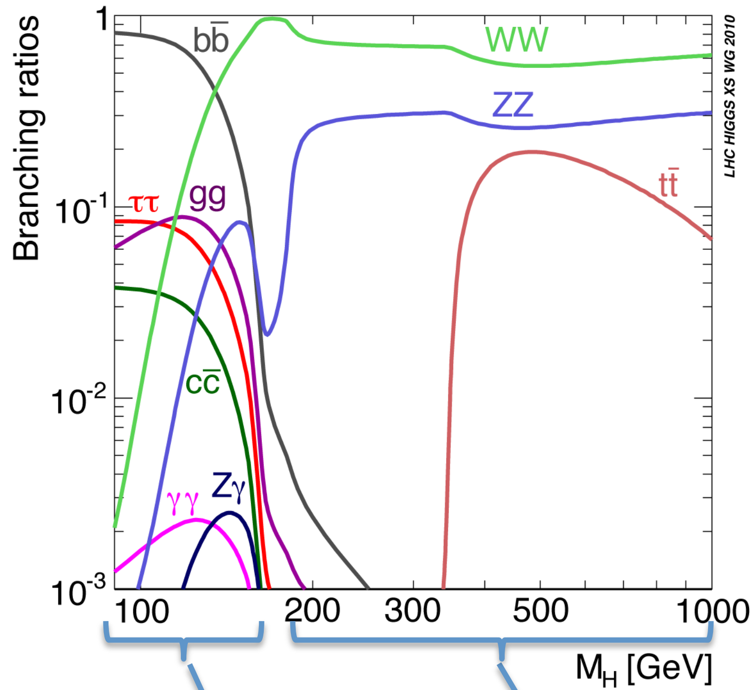
  is the fundamental probe to test nature of Higgs boson or to find alternative EWSB mechanism

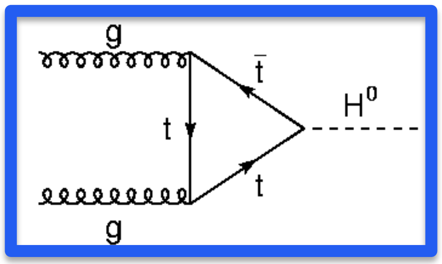


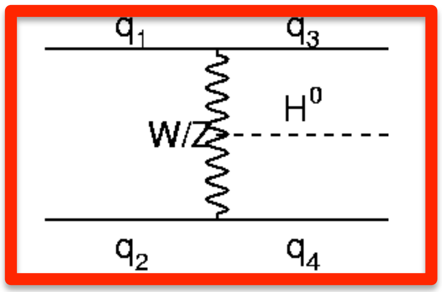
- Whatever we will see or not see at low mass (<2×m_W), the EWSB mechanism must be probed in the VV final state
  - search for possible resonances in VBF
  - measurement of VV scattering spectrum

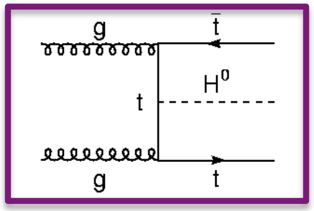
Higgs production and decay

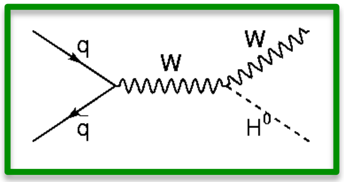


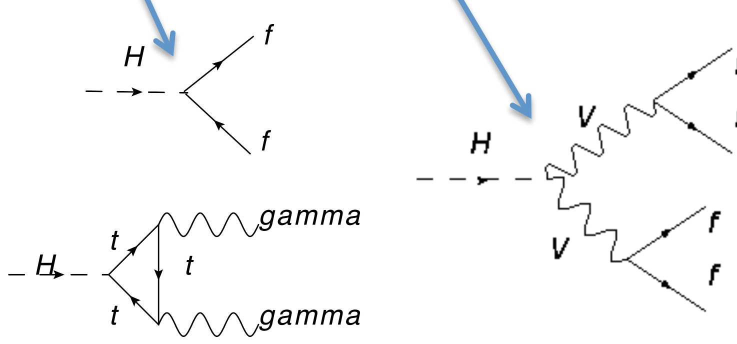




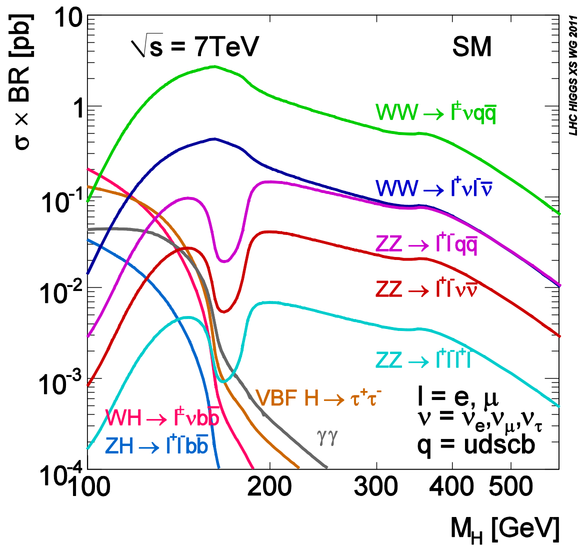


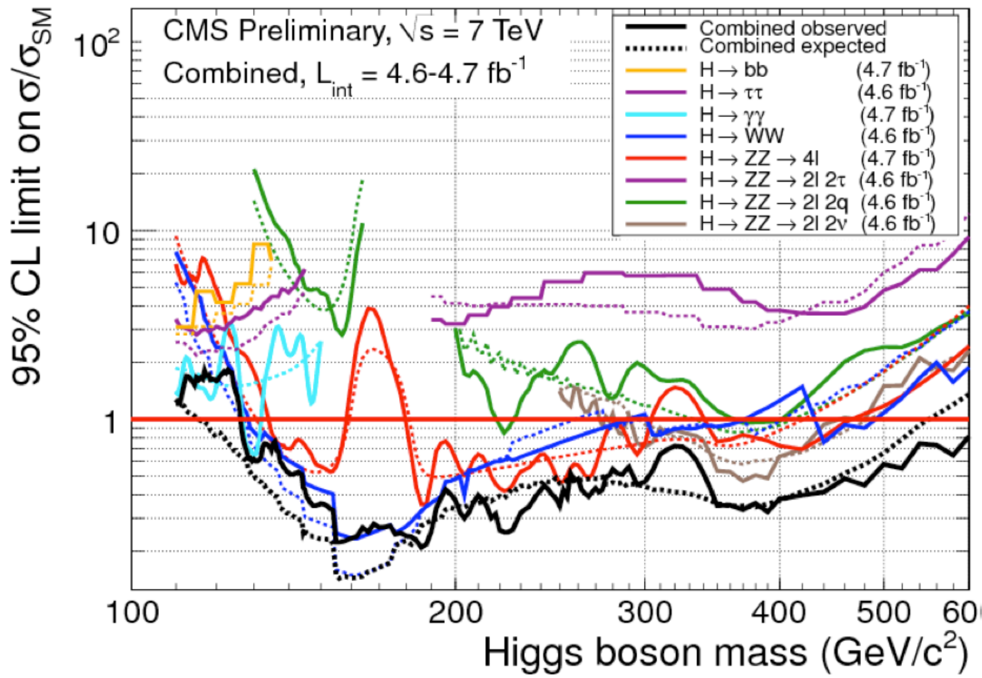






CMS results





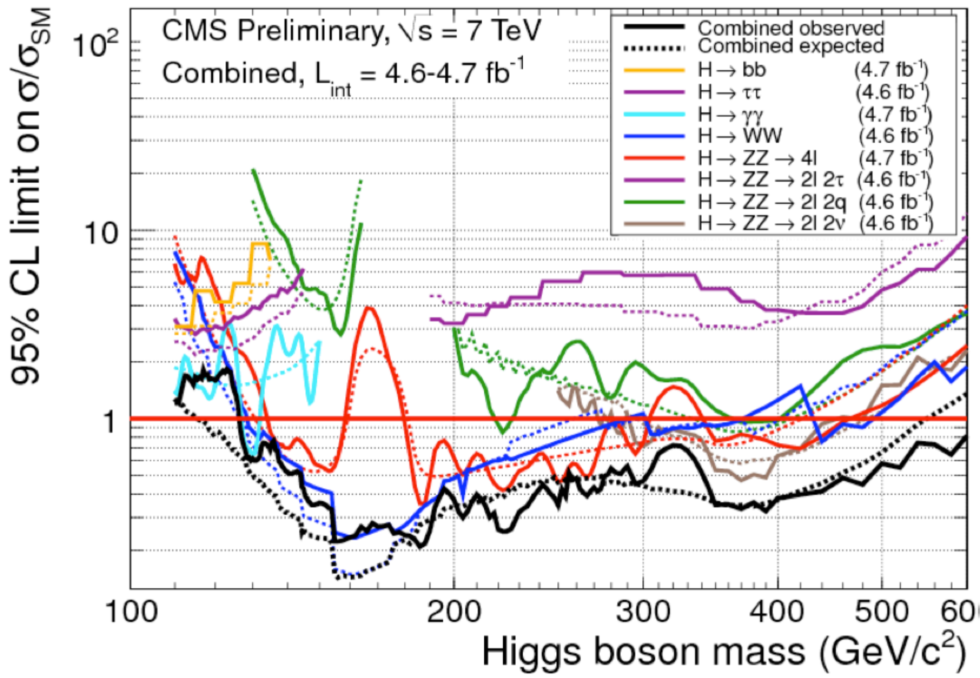
- **WW→lnqq, ZZ→llqq** limited by huge V+jets background, taken from simu/data with large theoretical/statistical error
- **WW→lnln** at high mass limited by signal << WW background ($\Delta\phi$ not effective)
- **ZZ→llnn**:
  - 200-400 GeV limited by non-Z background (top, W+jets, WW)
  - >400 GeV limited by Z+jets tail at high MET: not large but not well known (controlled with γ+jets → statistical error+met uncertainty)

  ⇨ **drives the UL for mH>300-400**

- **ZZ→4l** limited by statistics (only ZZ background: small and well known)

  ⇨ **drives the UL for mH 200-300**

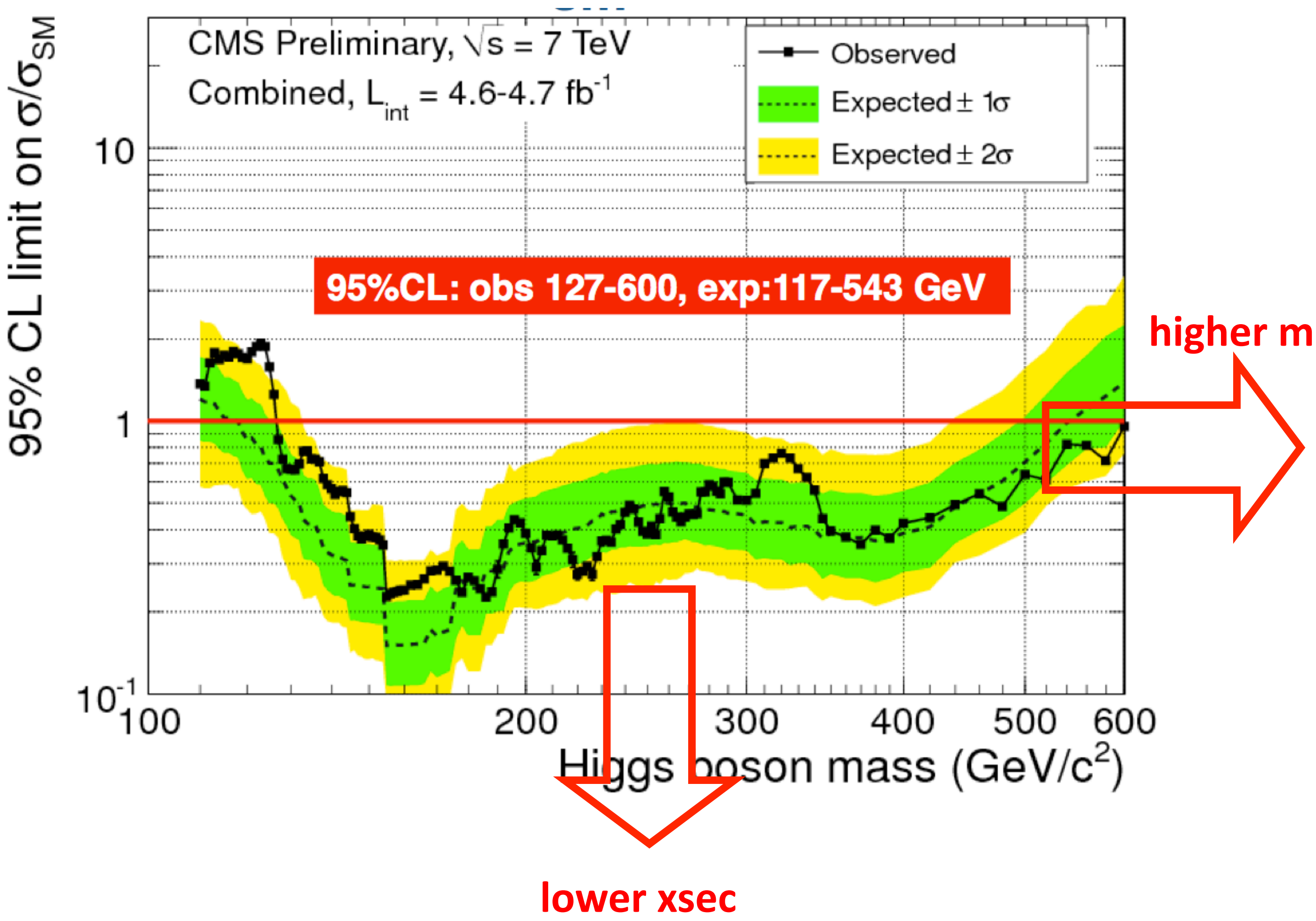
Future improvements ?



- Combination of >5 different channels (ele, mu, btag, …) Robust!

- Very optimized analyses, some space for further improvement. With higher lumi:
  - use shape analyses (where not yet done)
  - extract signal with multidimensional fit (now only mZZ fit)
  - extract background (norm and shape) from data with lower uncertainty

What's next ?



CMS Preliminary, √s = 7 TeV
Combined, L_{int} = 4.6-4.7 fb^{-1}
Observed
Expected ± 1σ
Expected ± 2σ
95%CL: obs 127-600, exp:117-543 GeV
95% CL limit on σ/σ_{SM}
10
1
10^{-1}
100
200
300
400
500
600
Higgs boson mass (GeV/c^2)
higher mass
lower xsec

1 TeV masses: not anymore “the” Higgs

→ **General search for X→VV→4f:** **exotic models** (eg, Technicolor, ExtraDimension, …)

RS Graviton vs SM Higgs:

Signal Channels				
	140 GeV	250 GeV	500 GeV	1 TeV
$\sigma(H_{SM} \to ZZ^{(*)})$	9.26×10^2	1.14×10^3	2.40×10^2	-
$\sigma(G_{RS} \to ZZ)$ at $c = 0.01$	–	1.94×10^3	6.83×10^1	1.41
$\sigma(G_{RS} \to ZZ)$ at $c = 0.05$	–	4.83×10^4	1.69×10^3	3.53×10^1
$\sigma(G_{RS} \to ZZ)$ at $c = 0.1$	–	1.94×10^5	6.76×10^3	1.41×10^2
$\mathcal{B}(H_{SM} \to ZZ^{(*)})$	0.068	0.295	0.260	-
$\mathcal{B}(G_{RS} \to ZZ)$	–	0.052	0.049	0.046
$\mathcal{B}(ZZ \to 4l)$	$\sim 0.067 \times 0.067 \simeq 4.48 \times 10^{-3}$			
$\mathcal{B}(ZZ \to 2l2j)$	$\sim 2 \times 0.067 \times 0.699 \simeq 8.96 \times 10^{-2}$			
$N(H_{SM} \to ZZ^{(*)} \to 4\mu)$	0.52	0.64	0.13	-
$N(H_{SM} \to ZZ^{(*)} \to 4e)$	0.52	0.64	0.13	-
$N(H_{SM} \to ZZ^{(*)} \to 2\mu 2e)$	1.04	1.28	0.27	-
$N(H_{SM} \to ZZ \to 2\mu 2j)$	–	22.4	38.9	-
$N(H_{SM} \to ZZ \to 2e2j)$	–	21.5	45.5	-
$N(G_{RS} \to ZZ \to 4\mu)$ at $c = 0.01$		1.7	0.06	0.0013
$N(G_{RS} \to ZZ \to 4e)$		1.7	0.06	0.0013
$N(G_{RS} \to ZZ \to 2\mu 2e)$		3.4	0.12	0.0025
$N(G_{RS} \to ZZ \to 4\mu)$ at $c = 0.05$		42.9	1.4	0.028
$N(G_{RS} \to ZZ \to 4e)$		42.9	1.4	0.028
$N(G_{RS} \to ZZ \to 2\mu 2e)$		85.8	2.8	0.055
$N(G_{RS} \to ZZ \to 4\mu)$ at $c = 0.1$		162	5.3	0.11
$N(G_{RS} \to ZZ \to 4e)$		162	5.3	0.11
$N(G_{RS} \to ZZ \to 2\mu 2e)$		324	10.6	0.22

CMS AN-2010-35:
Angular Analysis of Resonances pp → X → ZZ
A. Bonato, A.V. Gritsan, Z.J. Guo, N.V. Tran, A. Whitbeck
Johns Hopkins University, Baltimore, MD, USA

xsec larger than Higgs:

first, repeat “Higgs” search for different spin, width resonance

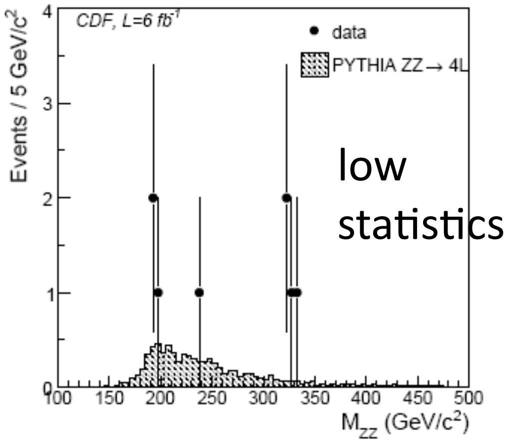
at high mass still very low number of events per fb^{-1}

→ importance of semileptonic final states

Available results: ZZ

- **CDF search for G→ZZ**: same features discussed for high mass Higgs @ LHC

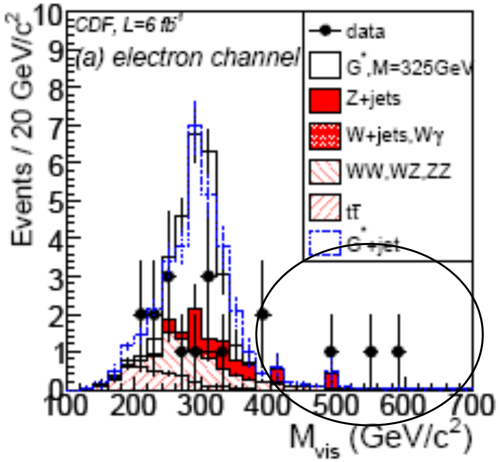
ZZ→4l

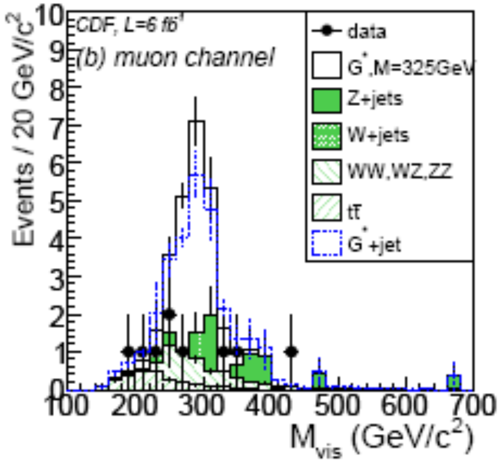


low statistics

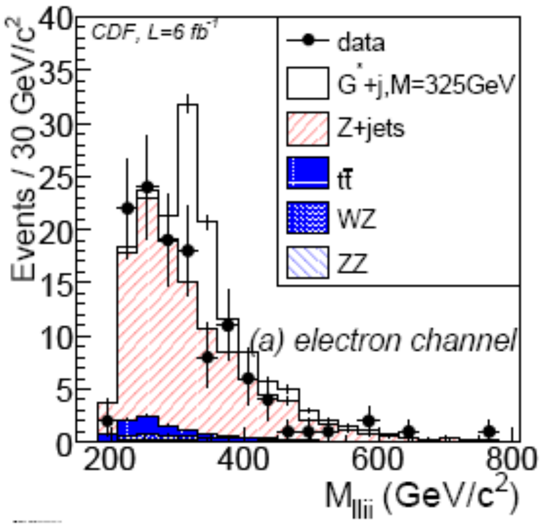
ZZ→llnn

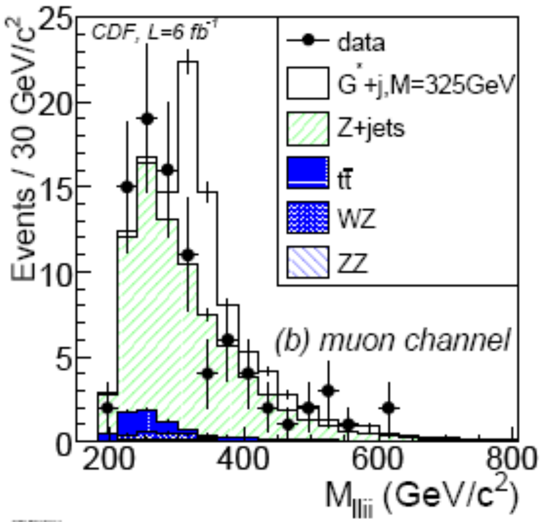
MET control V+jets

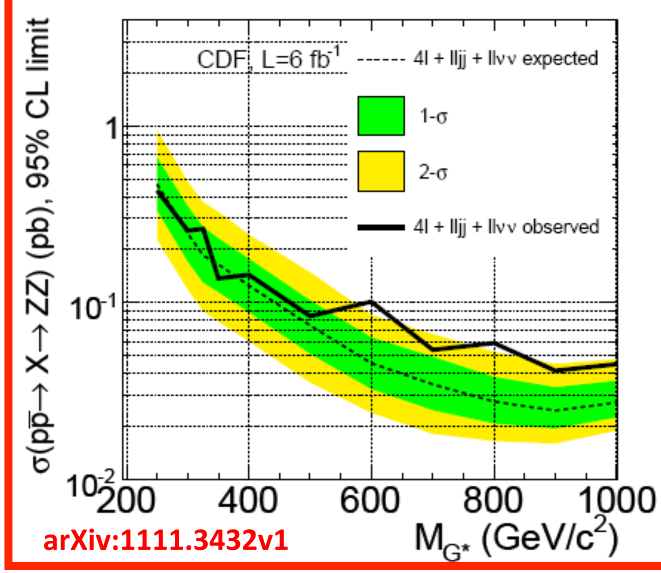




ZZ→lljj: large V+jets



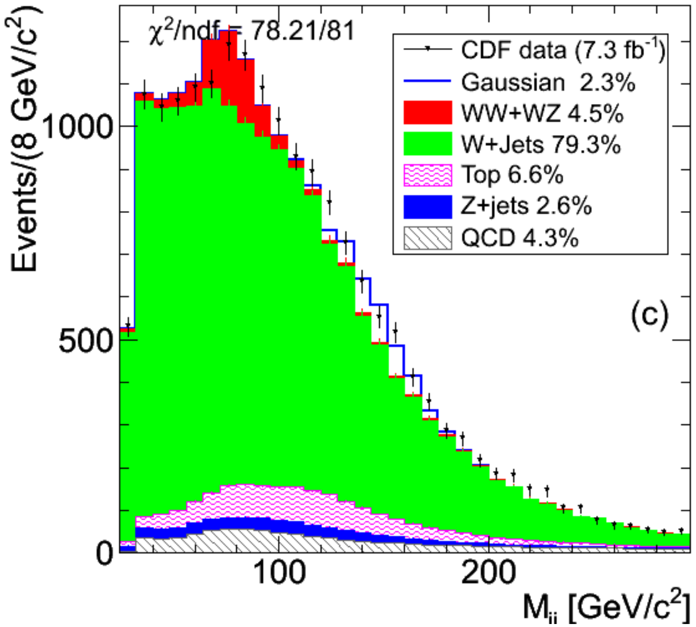


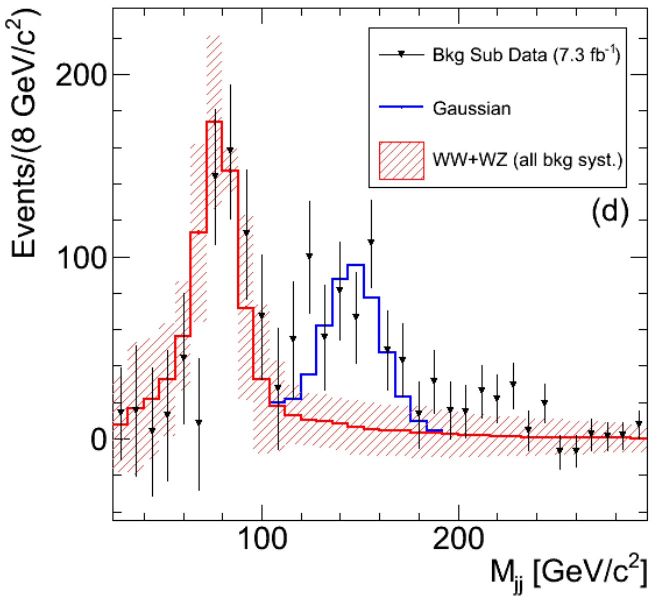


arXiv:1111.3432v1

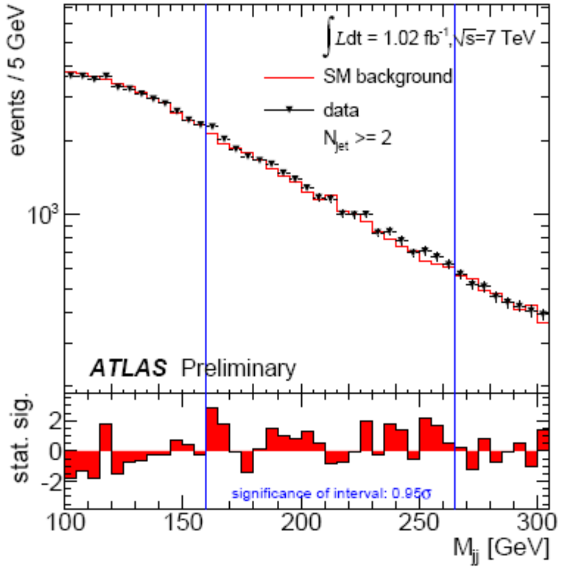
Available results: W+2jets

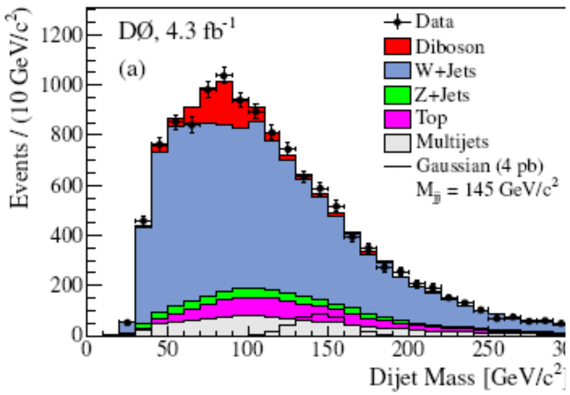
CDF “bump”

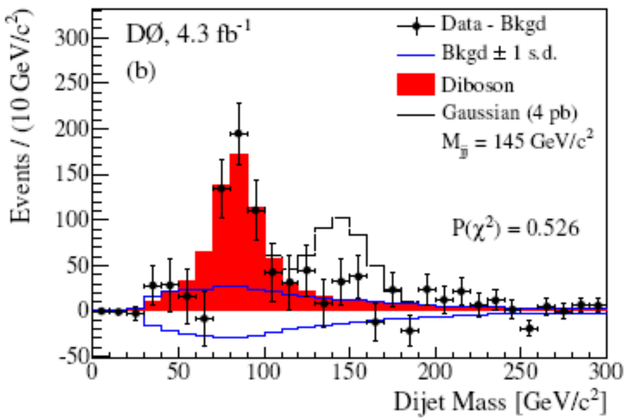




ATLAS & D0 xchecks







Control of V+jets

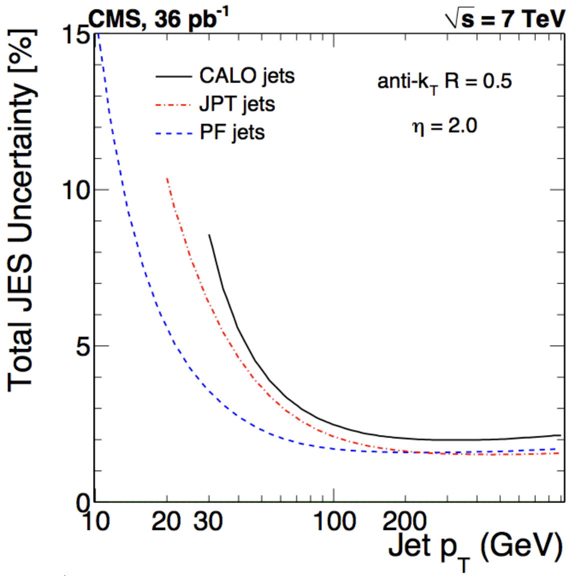
- ❑ Control region (eg, Z→jj sidebands) has very low stat for M(lljj)~1 TeV

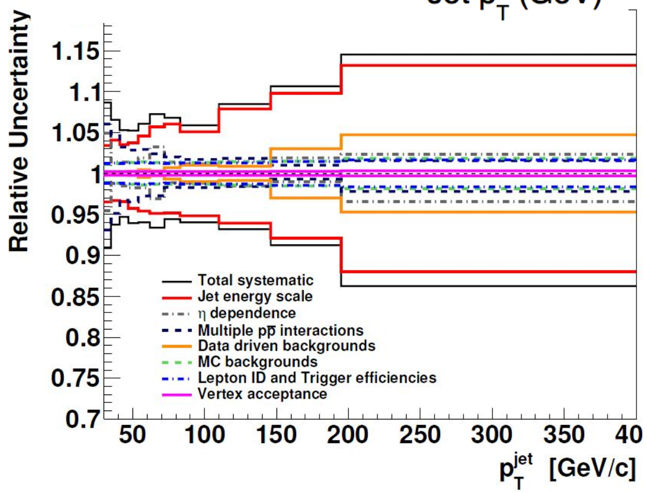
- ❑ Improving theoretical tools (Blackhat, Madgraph, …)
  - test them where we have statistics
  - rely on them to extrapolate at higher energy/multiplicity

V+jets

- **QCD measurement** (jet p_T>20-30 GeV):

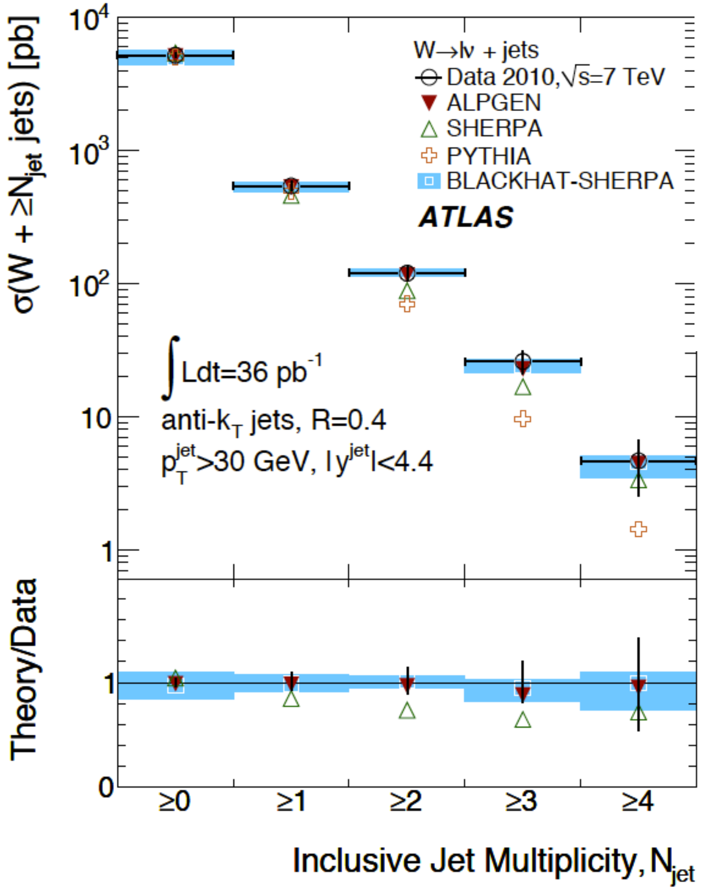
  → syst. dominated by jet scale, PileUp removal

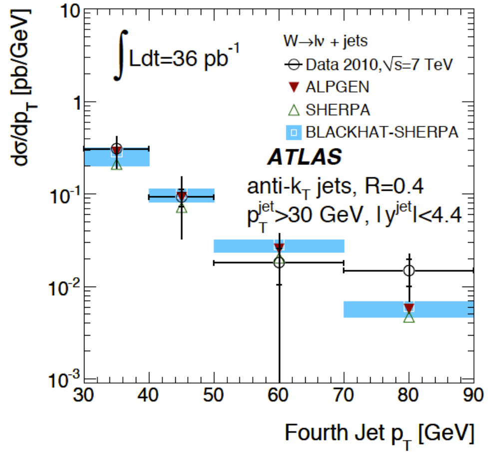


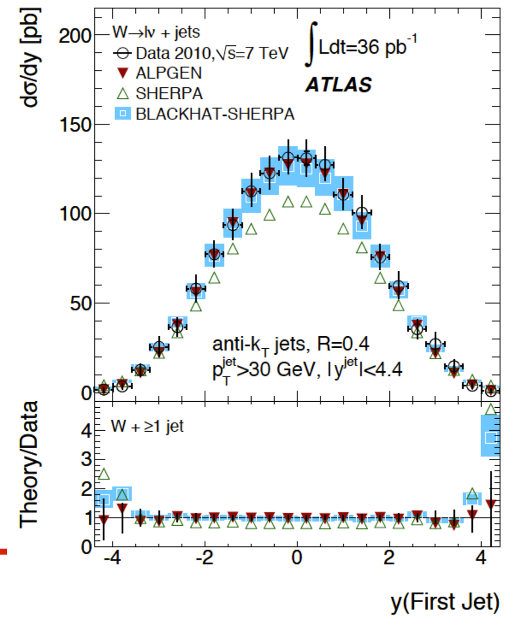


- Data unfolded for detector effects → compared to NLO ("hadron level")

ATLAS:







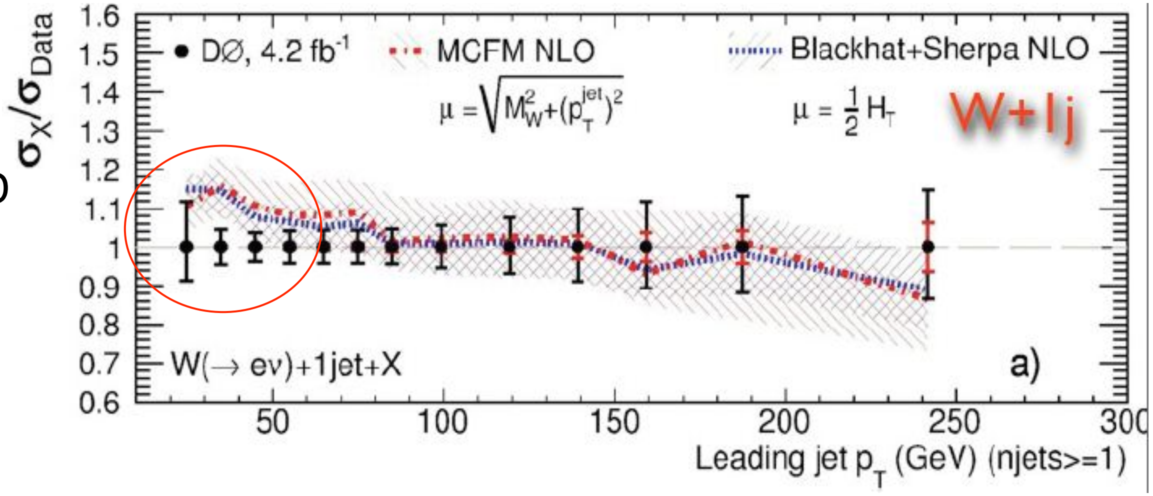
V+jets at Tevatron

At low p_T, low multiplicity:

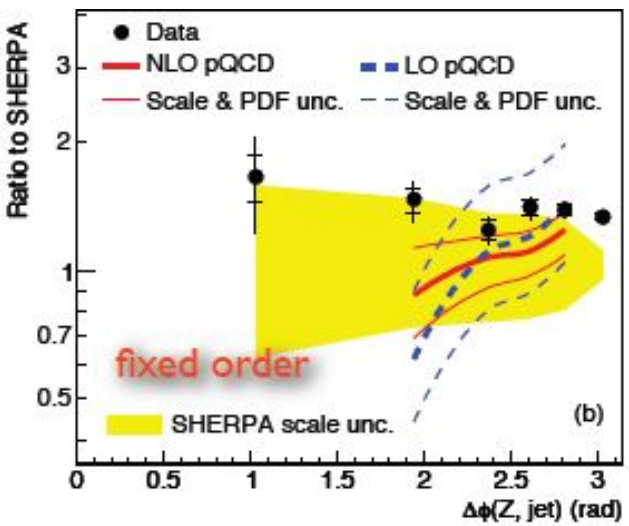
interesting discrepancy data-NLO observed

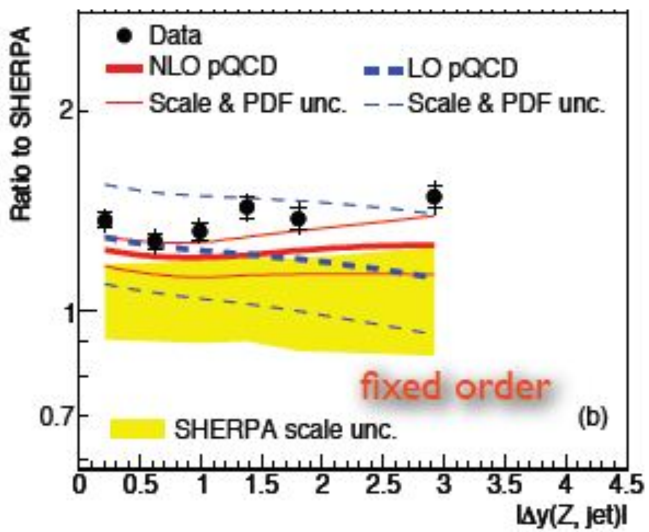
but **results limited by systematics**

→ new variables



D0 novel measurement: angular correlations have much lower systematics





High mass: what's new ?

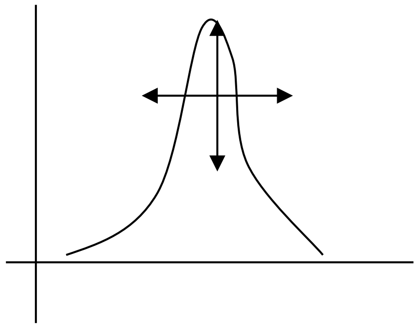
- Can we simply keep the same Higgs analysis strategy? Not at very high masses!

- New experimental issues at very high mass (1 TeV and above)

  X → boosted VV → **jet merging (and nearby leptons)**

- Unknown signal and very small background → no point in pushed optimization! Keep **model independent approach** as much as possible

- How to disentangle the various models?
  - peak → mass and width, xsec and BR
  - spin! → **angular analysis**



>1 TeV M(ZZ)→4f : jet merging (1)

❑ **Jet merging:**

$$\Delta R_{qq} \approx \frac{1}{\sqrt{z(1-z)}} \frac{M_Z}{p_Z^T} \xrightarrow{\text{approx}}$$

$(z = |\vec{p}_q| / |\vec{p}_Z|)$

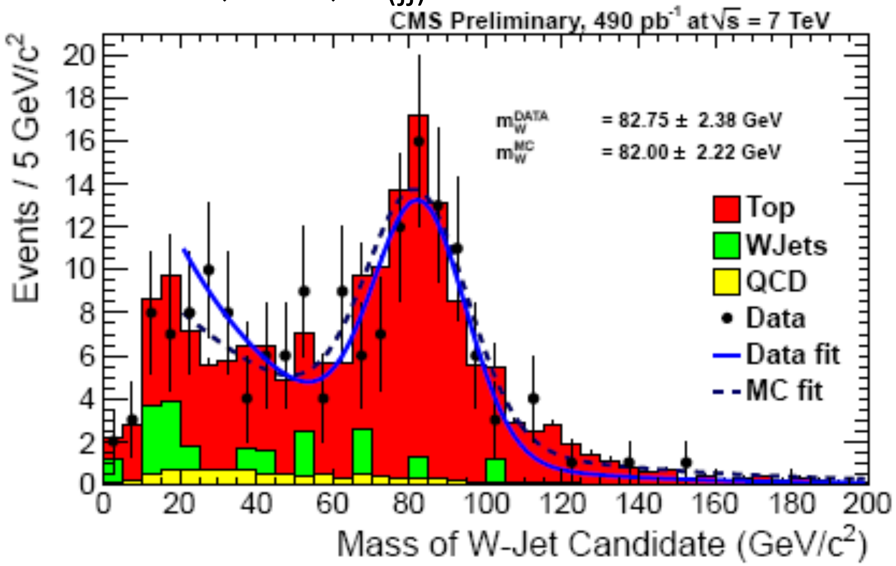
ΔR 0.8 (CA) → M_X>600 GeV

ΔR 0.5 (Akt) → M_X>900 GeV

Handles to distinguish wrt to jets from QCD (eg, X→ZZ→2l2j VS Z+jets):

- **jet mass**

ttbar → WW→ln (jj) *CMS EXO-11-006*

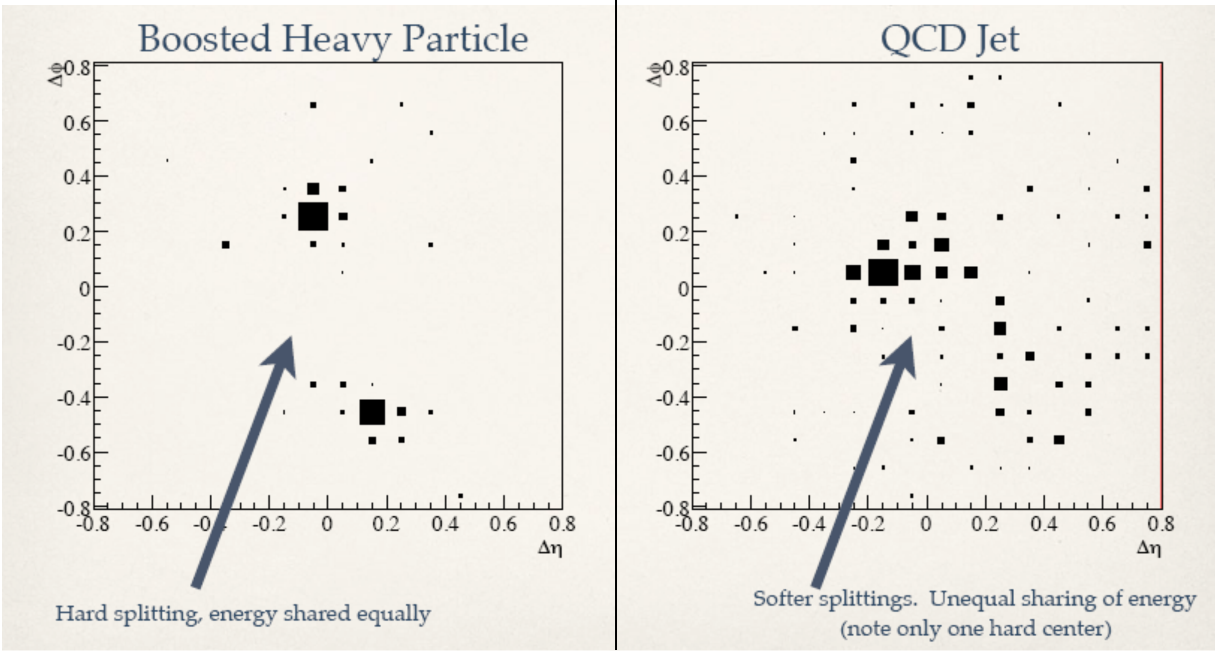


Jet merging (2)

Handles to distinguish wrt to jets from QCD (eg, X→ZZ→2l2j VS Z+jets):

- **jet radiation**:

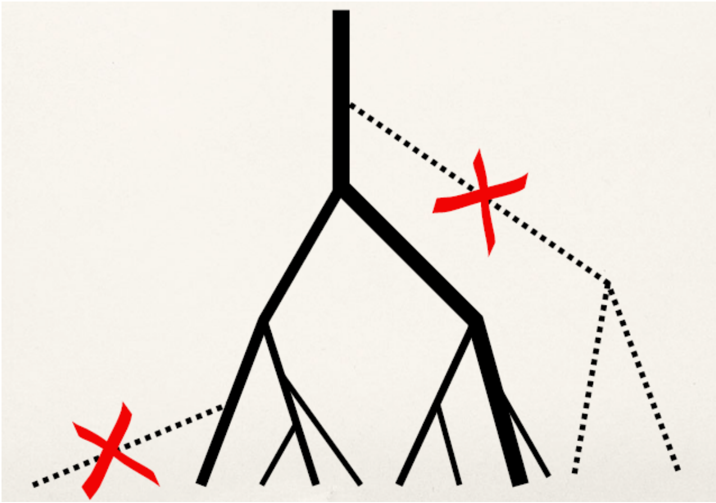
no singularity, just decay! | soft/collinear singularity in QCD



JHU seminar: **Path-Integral Jets** by David Krohn (Harvard)
www.pha.jhu.edu/groups/particle-theory/seminars/talks/F11/talk.khron.pdf

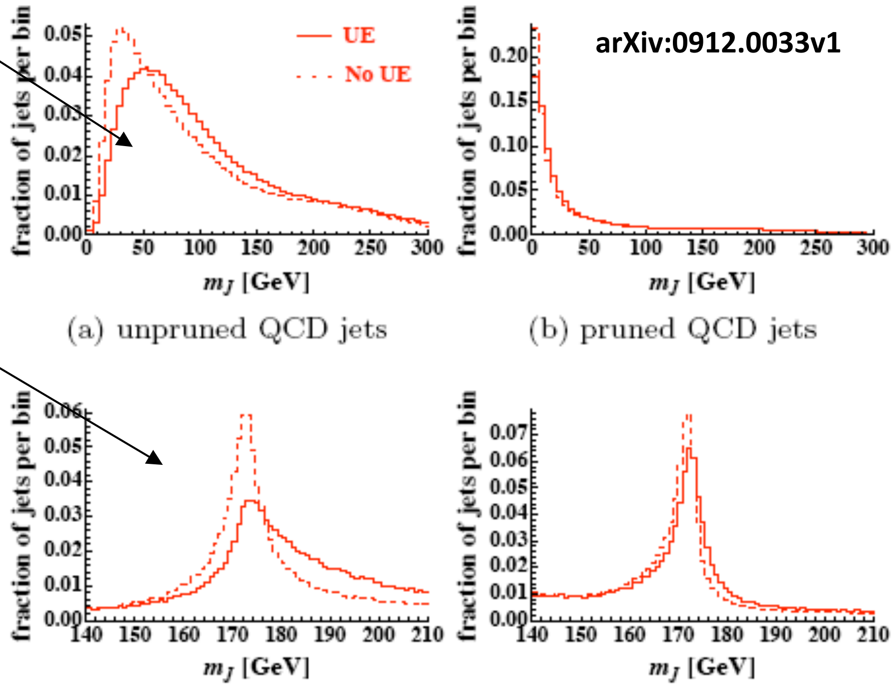
Jet pruning

- ❑ Remove all parts of the jet which are soft and wide angle



- ❑ QCD jets mass substantially decreased -> lower backgrounds

Boosted objects mass reconstruction improved



(a) unpruned QCD jets
(b) pruned QCD jets
(c) unpruned top jets
(d) pruned top jets

Typically used for boosted top or boosted H→bb …

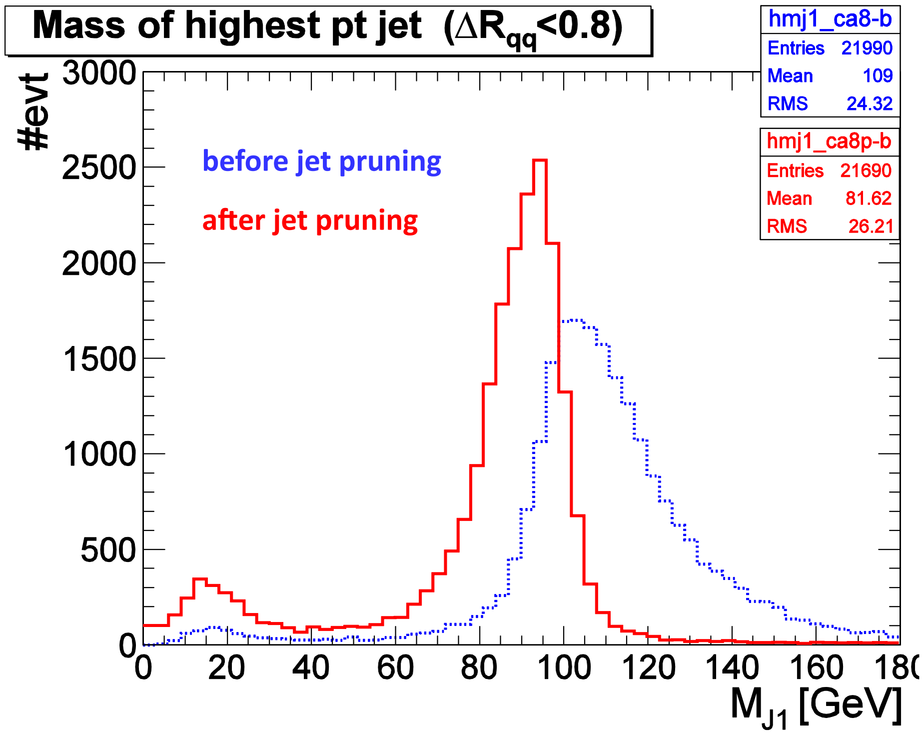
Example in X→ZZ→2l2j

First look at Z boosted (no numbers yet) …

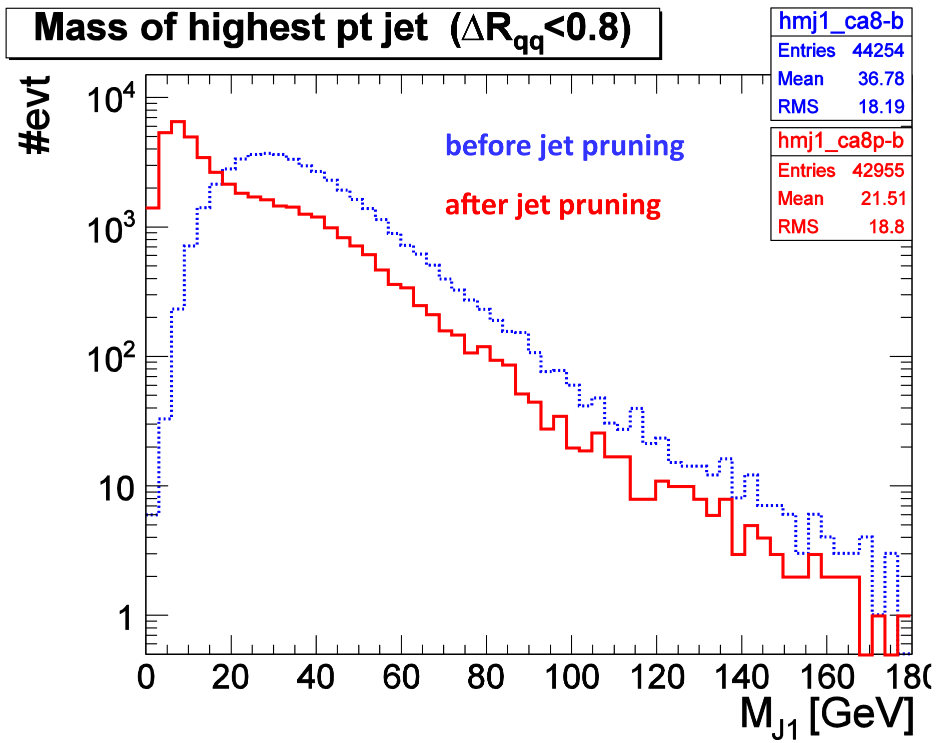
preliminary, A.Bonato, R.Covarelli

- RS Graviton
- M_G 1500 GeV
- CA 0.8

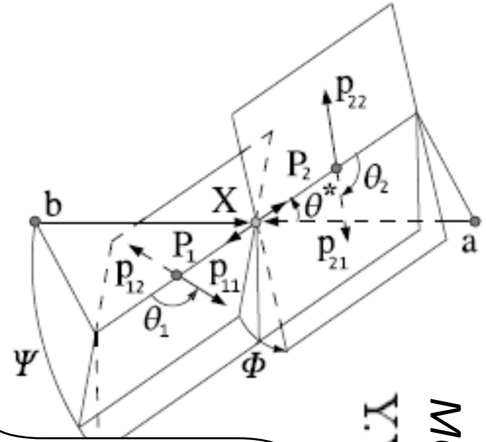
X->ZZ->2l2q signal



Z+jets



Angular analysis (1)



- ❑ X→ZZ→4f decay kinematic fully defined by 5 angles

signal (M_X 250):

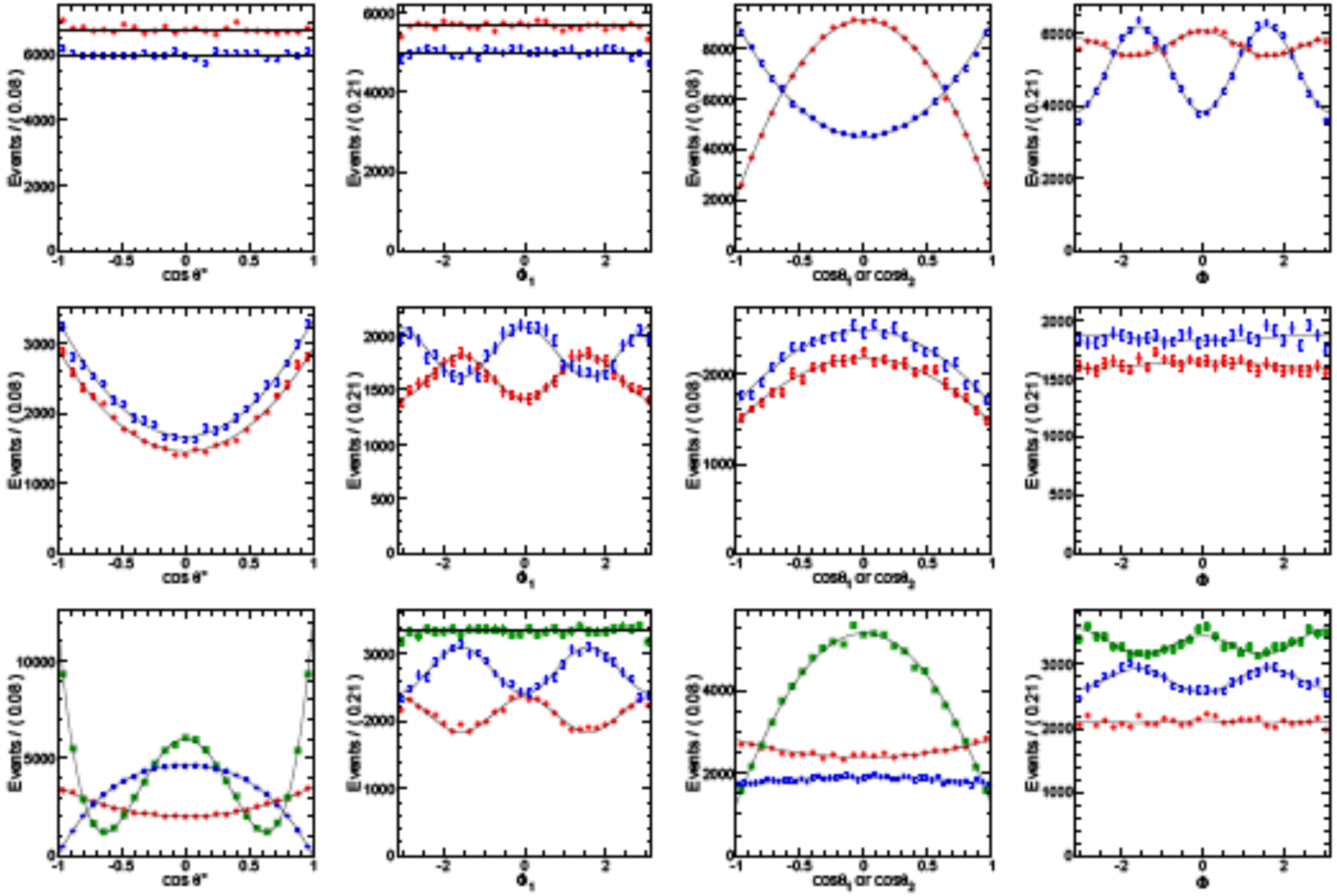
X→ZZ

Z decays

0+ , 0-

1+ , 1-

2+m , 2+L , 2-

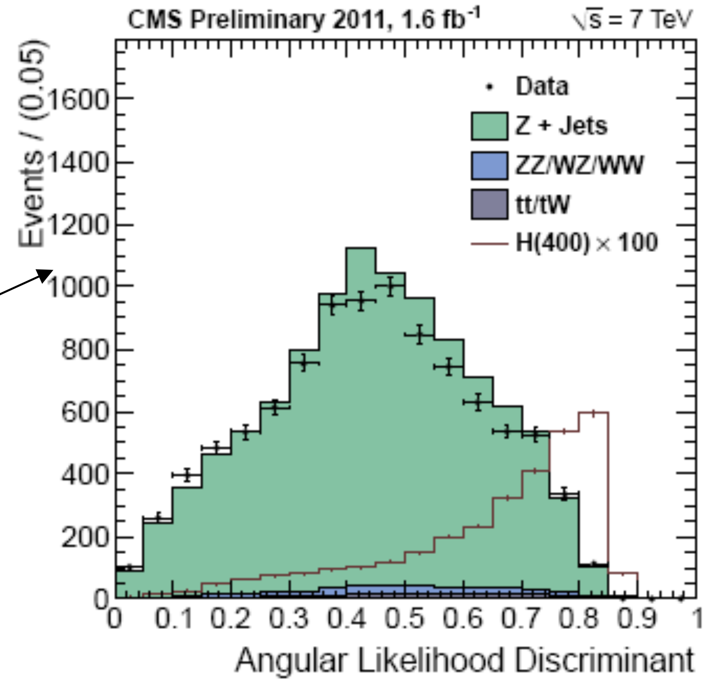


MC from Johns Hopkins

Y.Y. Gao *et al.*, Phys. Rev. D **81**, 075022 (2010).

Angular analysis (2)

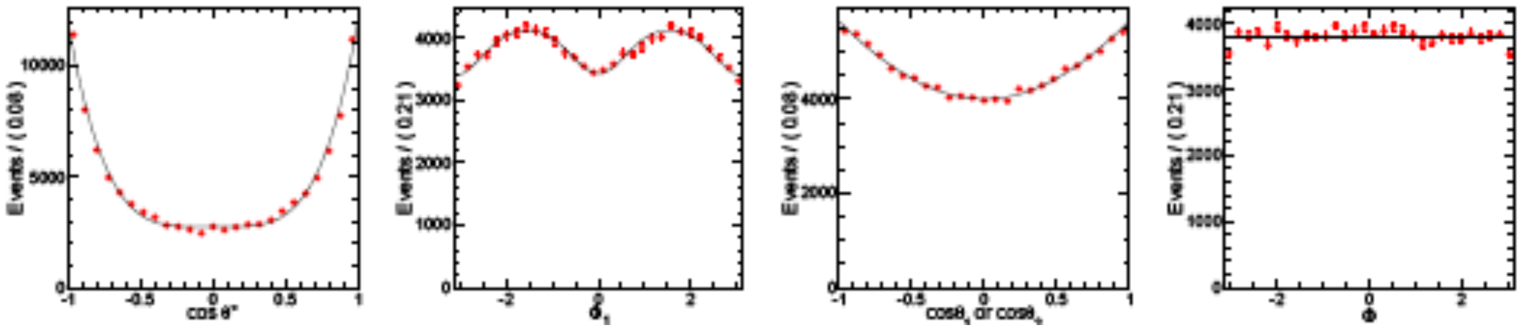
CMS PAS -11- 017



- ❑ Can be clearly used to disentangle different signals… but what about background?

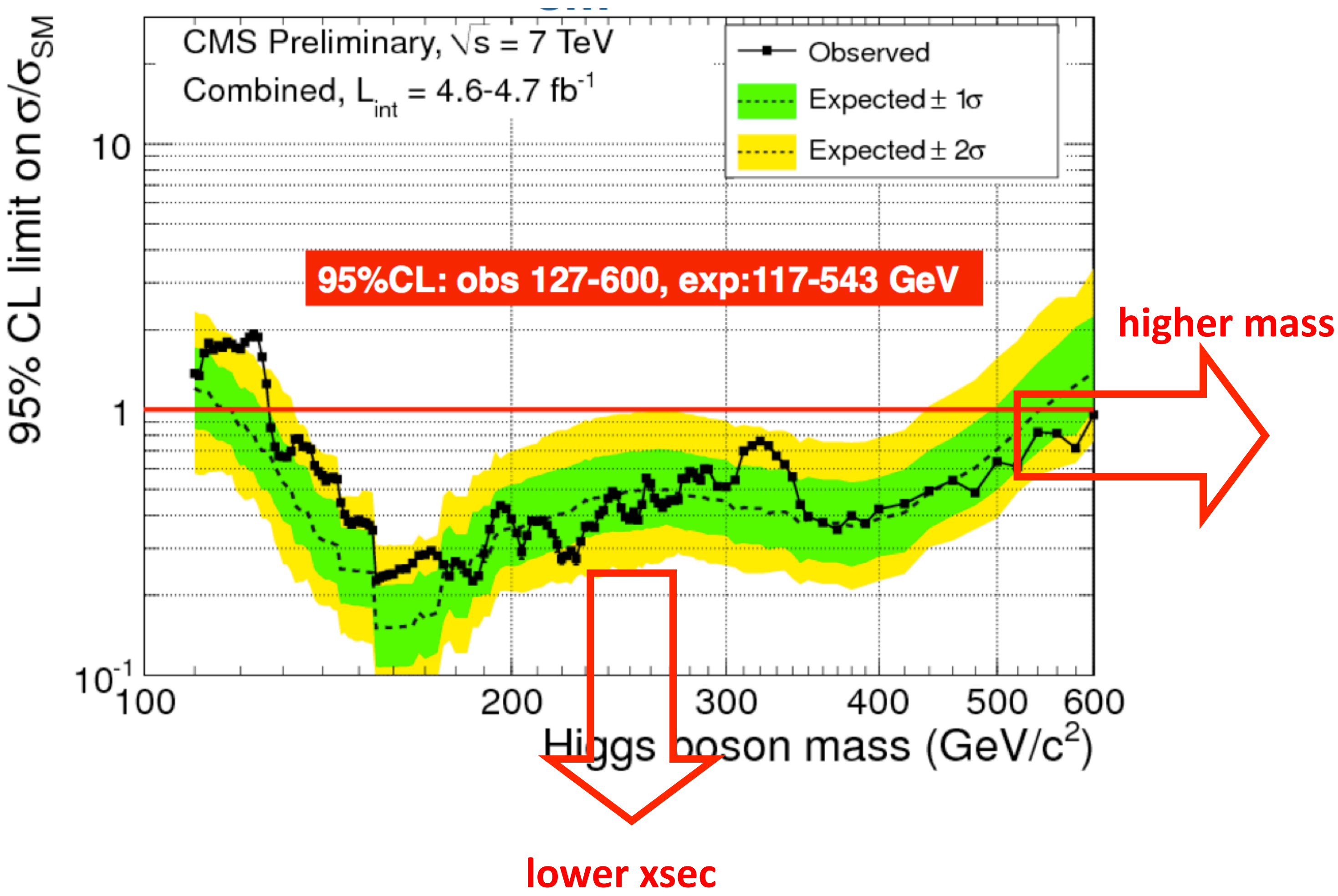
- ❑ Already used in H→ZZ→2l2q: cut on likelihood
  - signal: ideal × uncorr. accept
  - Z+jets from MC: no correlations, (background from jj sidebands)

- ❑ To optimize further (multidimensional fit), need full theoretical description of background:
  - qq → ZZ:



  - gg also available → can be used to disentangle qq-gg!!

What's next ?



CMS Preliminary, √s = 7 TeV
Combined, L_int = 4.6-4.7 fb^-1
Observed
Expected ± 1σ
Expected ± 2σ
95%CL: obs 127-600, exp:117-543 GeV
95% CL limit on σ/σ_SM
Higgs boson mass (GeV/c²)
higher mass
lower xsec

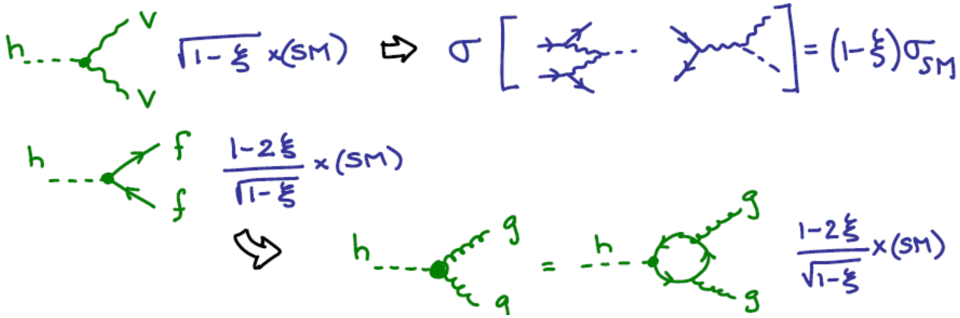
Improve sensitivity

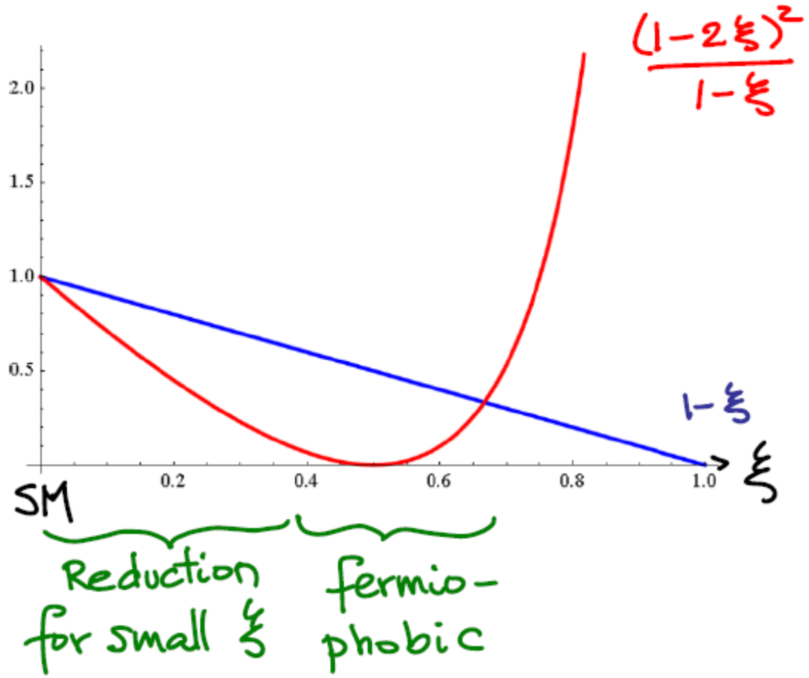
First LHC to Terascale Workshop (Sept 2011):
LCH at LHC by J.R. Espinoza

- **WHY? Models with lower xsec**

  Ex of (light) composite higgs:

$$\frac{1}{p^2-m_H^2} \rightarrow \frac{1}{1+\xi c_H}\frac{1}{p^2-m_H^2}$$

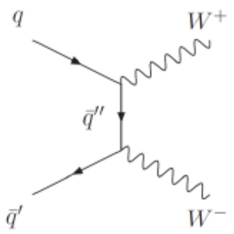




- **HOW?**
  - Factor 5 in luminosity wrt to present results
  - Improve theoretical control of
    - signal: → NNLO&NNLL effects, precise mass shape prediction, signal-background interference (back-up)
      (studied in the Higgs Xsec WG and documented in 2 Yellow Report)
    - background: → control of ZZ, WW ewk continuum

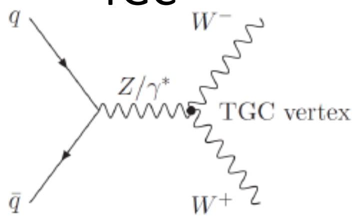
Diboson production (WW,WZ,ZZ)

qqbar → VV



WW,WZ,ZZ

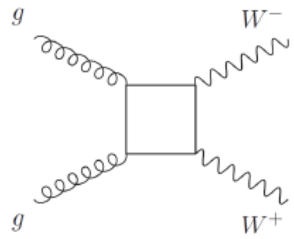
TGC



forbidden for ZZ

+ NLO qqbar +

gg→ VV



forbidden for ZW

(LHC: few % of xsec with ~50% uncertainty)

- SM test: TGC fixed by ewk gauge structure

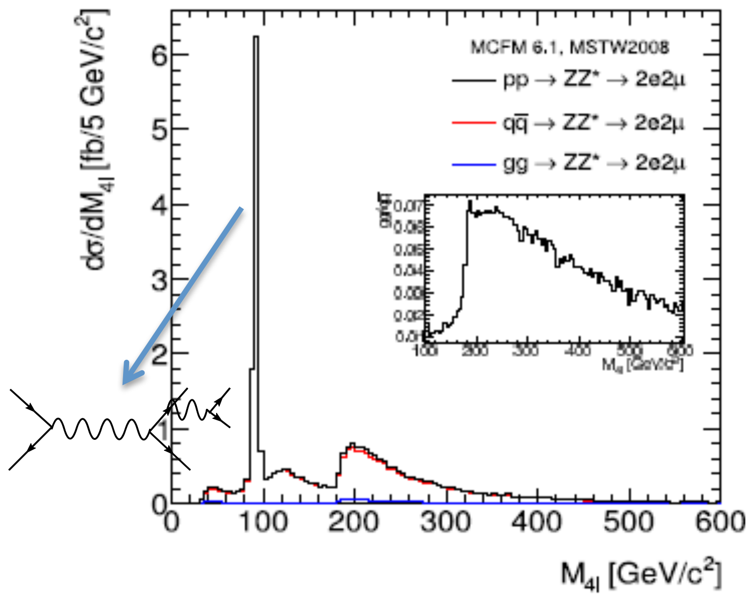
  → any deviation from SM in VV xsec is direct hint of NP in bosonic sector

- Backgrounds for high mass Higgs→VV

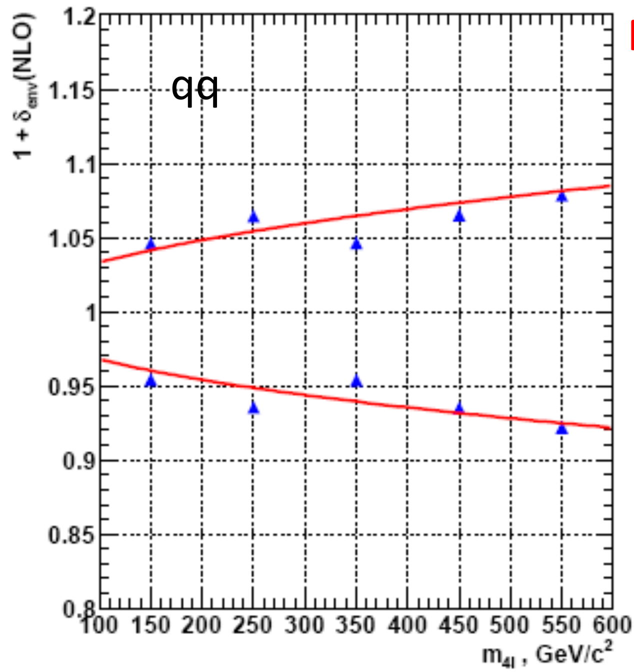
LHC focused on leptonic final state, Tevatron looked at semileptonic but limited by systematics (V+jets)

VV: theoretical prediction

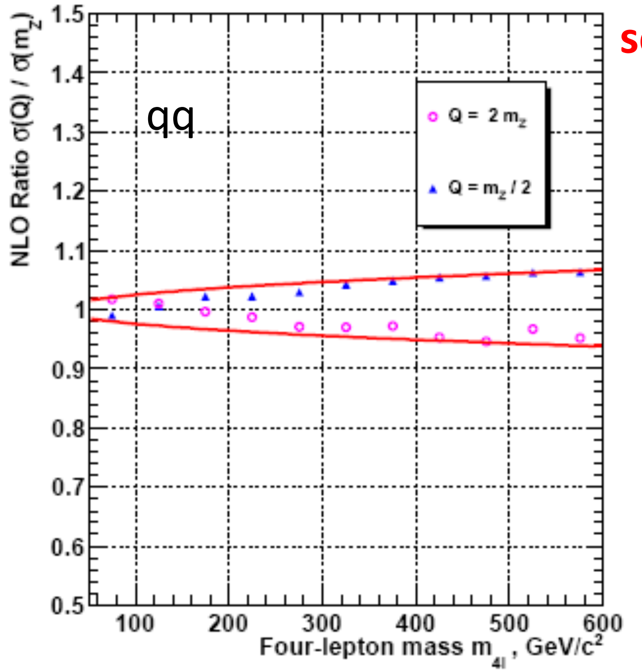
qq→ZZ NLO + gg→ZZ



PDF+α_s



scale



- ❑ Uncertainty dominated by QCD part

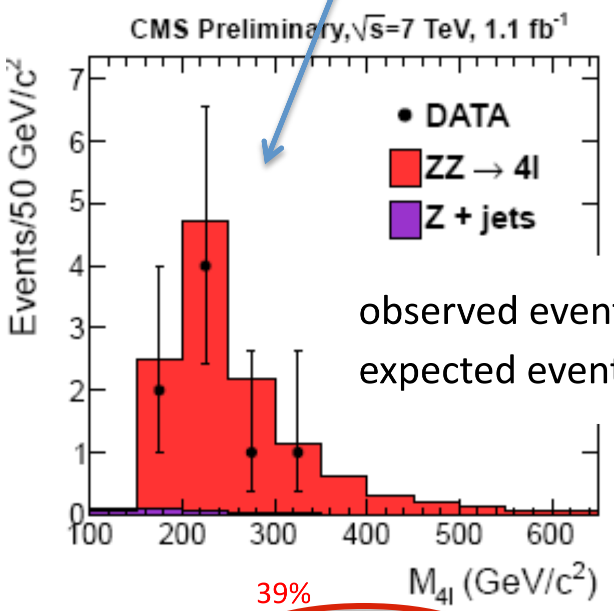
- ❑ WW in jet bins: uncertainty on σ(>=N) + modeling: MC@NLO vs ALPGEN

$\Delta\sigma_{\geq 0}$ (%)	$\Delta\sigma_{\geq 1}$ (%)	$\Delta\sigma_{\geq 2}$ (%)	$\Delta\sigma_{\geq 3}$ (%)
3	6	42	100

ZZ→4l: measurement

- 4l is 0.5% of ZZ xsec but very clean

Dedicated EWK analysis with very low luminosity, Higgs results much beyond that

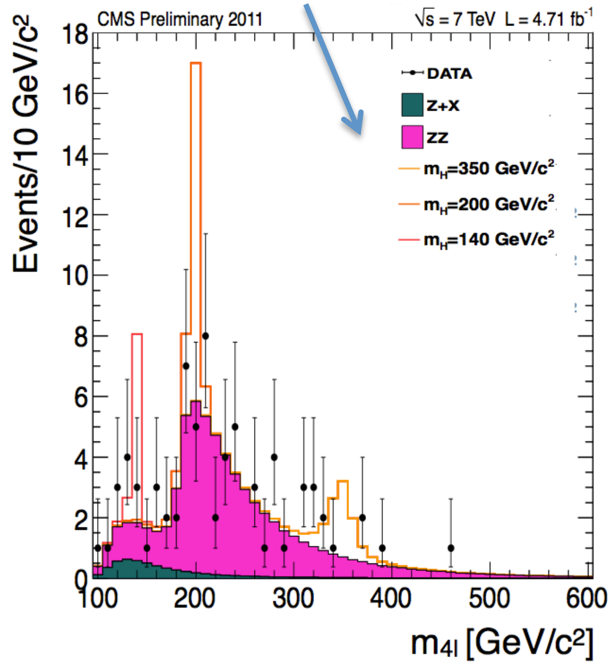


observed events: 8

expected events: 12.5±1.1

39%

$$\sigma(ZZ) = 3.8^{+1.5}_{-1.2}(stat) \pm 0.2(syst) \pm 0.2(lumi)\, pb$$



16%

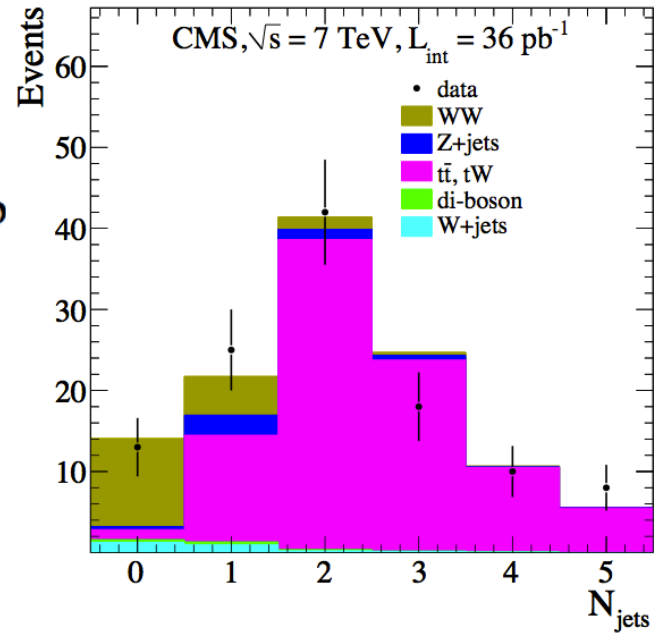
$$\sigma(pp \rightarrow ZZ + X) \times \mathcal{B}(ZZ \rightarrow 4\ell) = 28.1^{+4.6}_{-4.0}(\text{stat.}) \pm 1.2(\text{syst.}) \pm 1.3(\text{lumi.})\ \text{fb}$$

WW->lnln: measurement

- Dedicated EWK results only with very low luminosity,

37%

$$\sigma_{W^+W^-} = 41.1 \pm 15.3\,(\text{stat}) \pm 5.8\,(\text{syst}) \pm 4.5\,(\text{lumi})\ \text{pb}$$



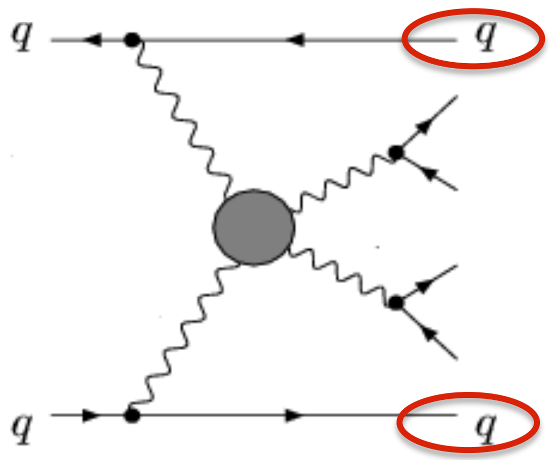
- Higgs analysis much beyond that:

	data	all bkg.	$q\bar{q} \to W^+W^-$	$gg \to W^+W^-$	$t\bar{t}$+tW	W + jets
0-jet	1359	1364.8 ± 9.3	980.6 ± 5.2	58.8 ± 0.7	147.3 ± 2.5	99.3 ± 5.0
1-jet	909	951.4 ± 9.8	416.8 ± 3.6	23.8 ± 0.5	334.8 ± 3.0	74.3 ± 4.6
2-jet	703	714.8 ± 13.5	154.7 ± 2.2	5.1 ± 0.2	413.5 ± 2.7	37.9 ± 3.6

	WZ/ZZ	$Z/\gamma^* \to \ell^+\ell^-$	$W\gamma$	$Z/\gamma^* \to \tau^+\tau^-$
0-jet	33.0 ± 0.5	16.6 ± 4.0	26.8 ± 3.5	2.4 ± 0.5
1-jet	28.7 ± 0.5	39.4 ± 6.4	13.0 ± 2.6	20.6 ± 0.4
2-jet	15.1 ± 0.3	56.1 ± 11.7	10.8 ± 3.6	21.6 ± 2.1

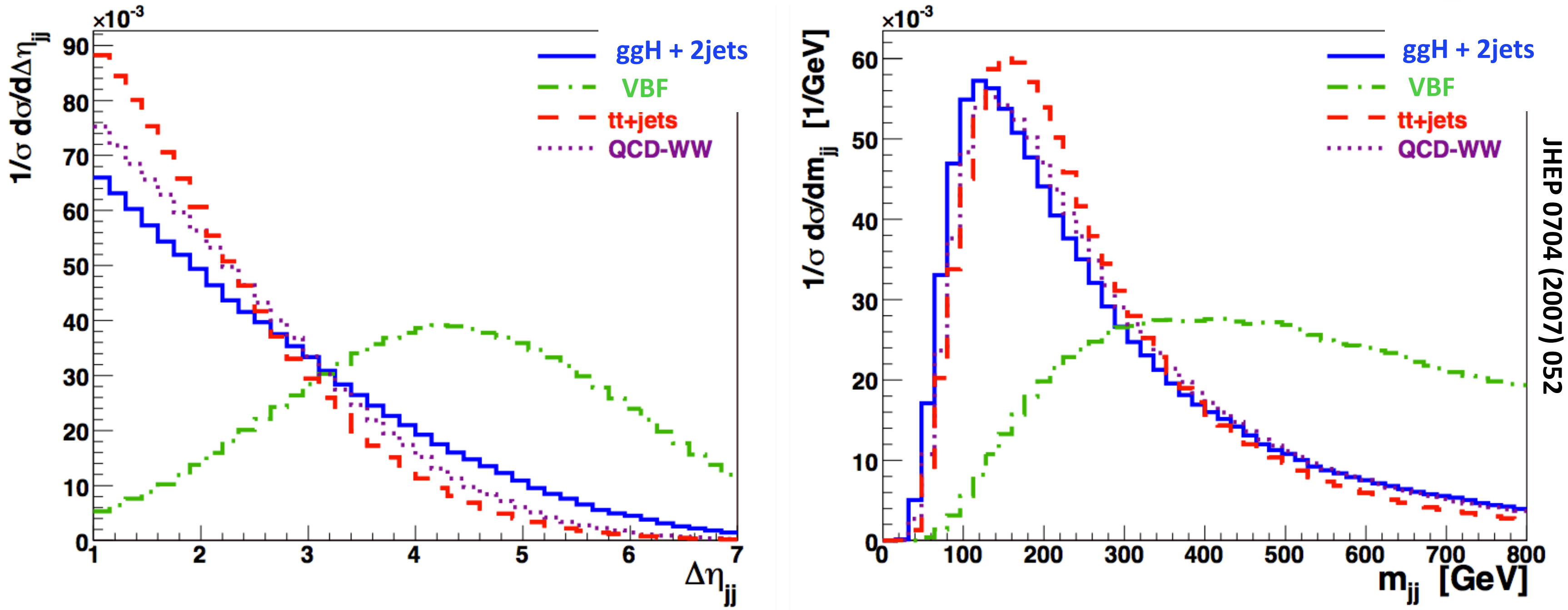
stat. and syst. errors included

From VBF to VV scattering



- **First** **search for a VBF resonance, feasible in 2012**
- **Measurement of** **VV scattering spectrum with higher lumi** **(>50 fb^{-1})**

Typical signature: forward-backward "spectator" jets with very high energy



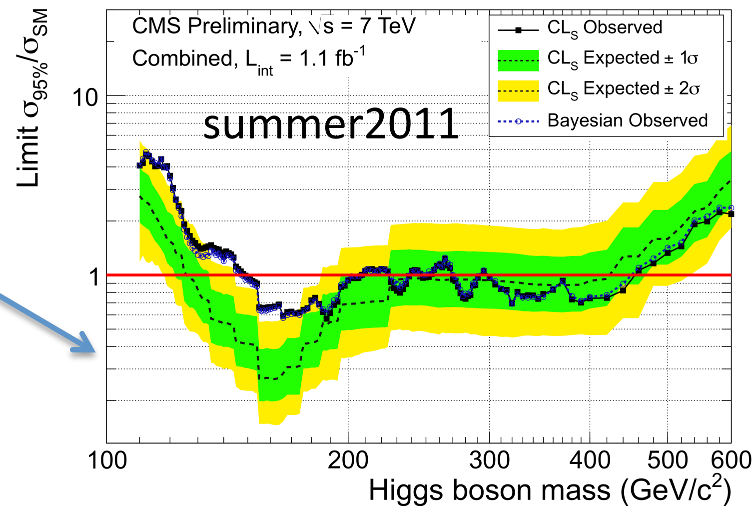
Higgs-like resonance in VBF

❑ **RE-DO all the analyses in VBF mode**

❑ Today only WW→lnln. **Expectations for next year**:

- lumi > 10 fb-1
- σ(vbf) ~ 0.1×σ(gg)
- 0.5 effic. VBF cuts

} VBF yields in 2012 ~ 0.5 gg yields of 2011 summer results,



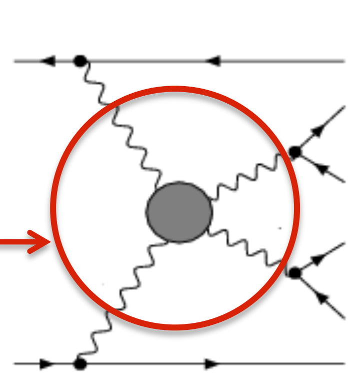
with much less background:

- ZZ→4l will be still limited by statistics
- WW→lnln will improve S/B (signal/10, WW*α_s^2)
- semileptonic final states will have **reasonable signal yields + much lower background** than inclusive analysis

eg, ZZ→lljj :
- signal yields for m_H 300-500 ~ 15 – 5 events
- V+(N+1)jets/V+N jets ~ 0.15 → asking 2 jets reduces background to 2%!
- S/B may increase of a factor 2 (eff 0.5 × σ 0.1 / 0.02)

VV scattering spectrum

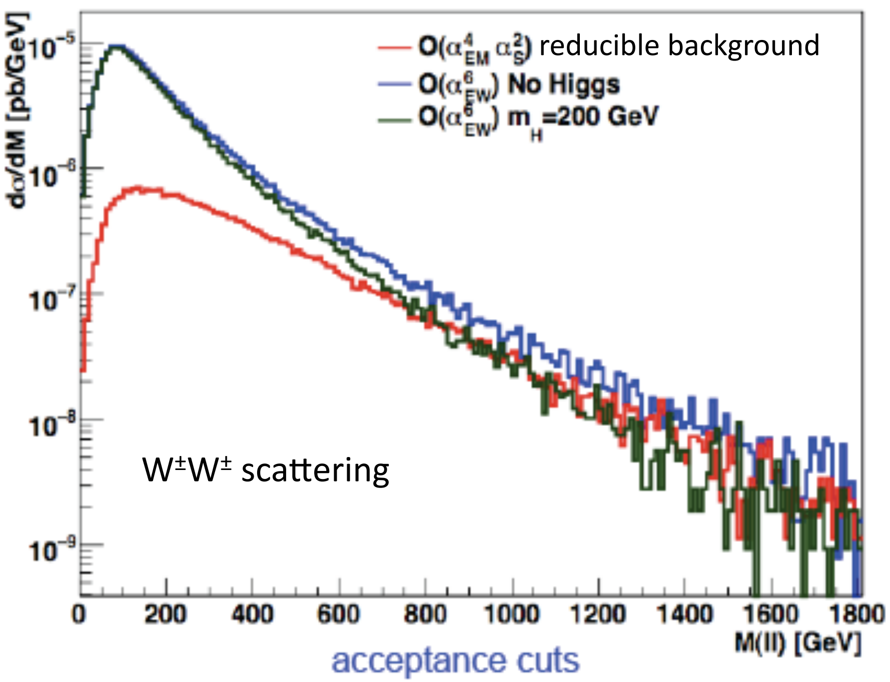
- In no Higgs case: $A\left(W_L^+W_L^- \rightarrow W_L^+W_L^-\right) \approx \frac{1}{v^2}\left(-s-t+\cancel{\frac{s^2}{s-m_H^2}+\frac{t^2}{t-m_H^2}}\right)$

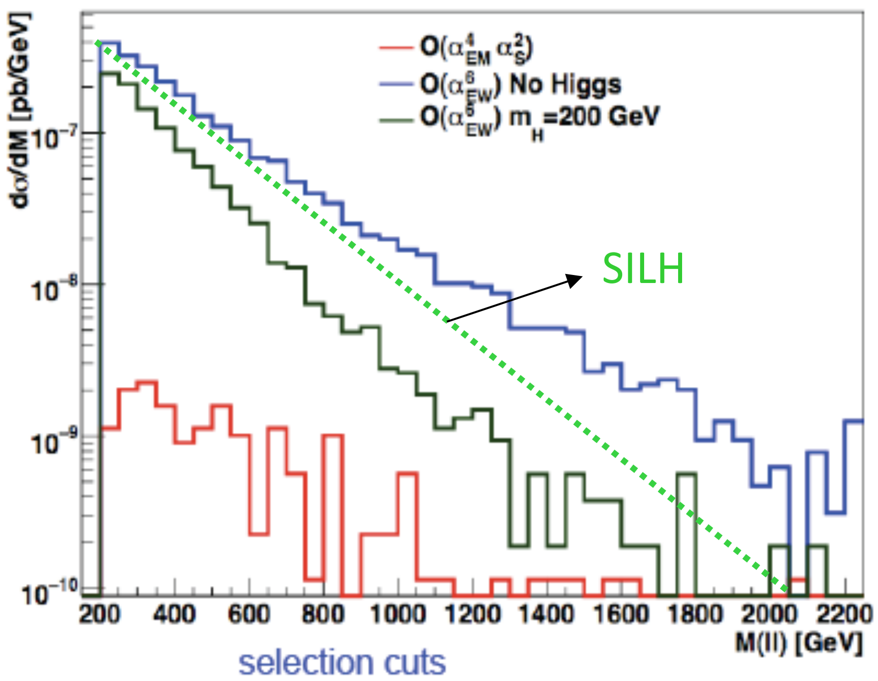


BUT increasing of xsec at high VV is suppressed by

- PDF
- offshell bosons
- unpolarized bosons

→ small difference btw SM and violation of unitarity (no Higgs)

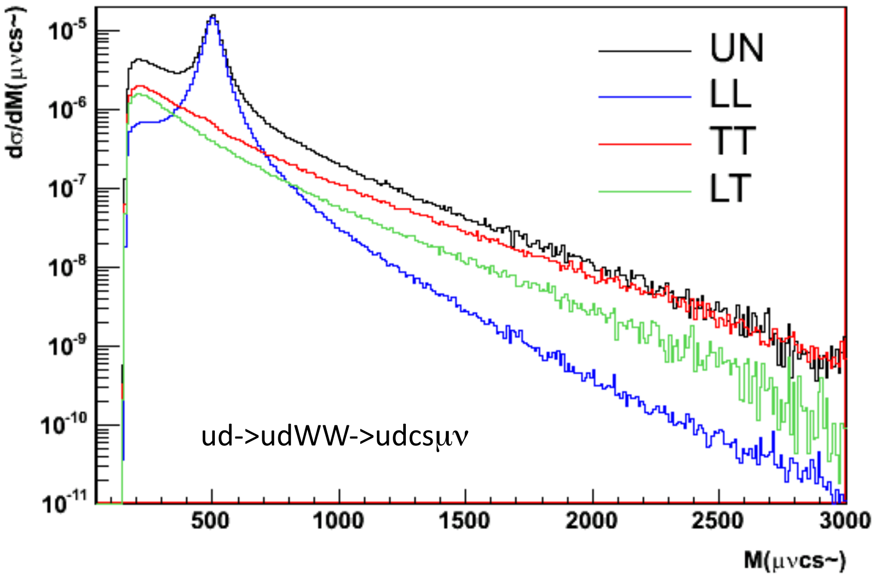




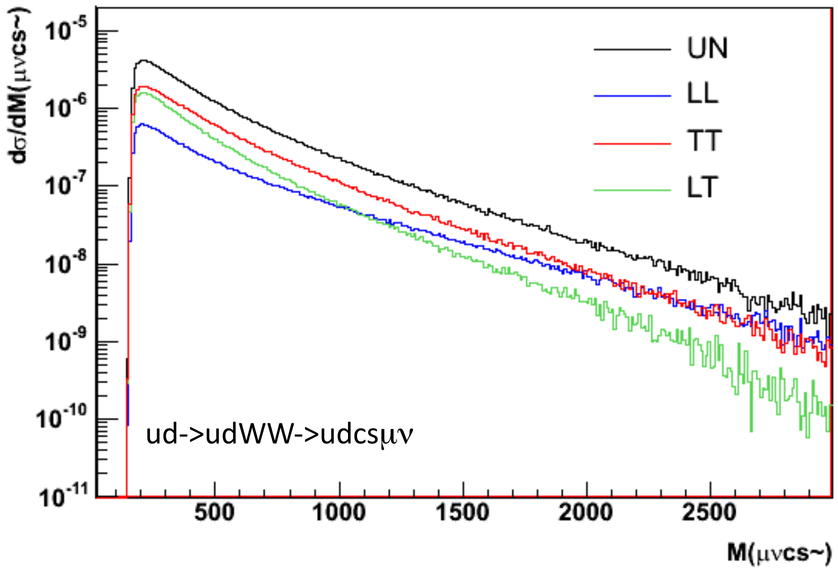
→ with proper cut (eg Δη jets) can be enhanced -> selection of the longitudinal W

Longitudinal polarization

mH 500 GeV

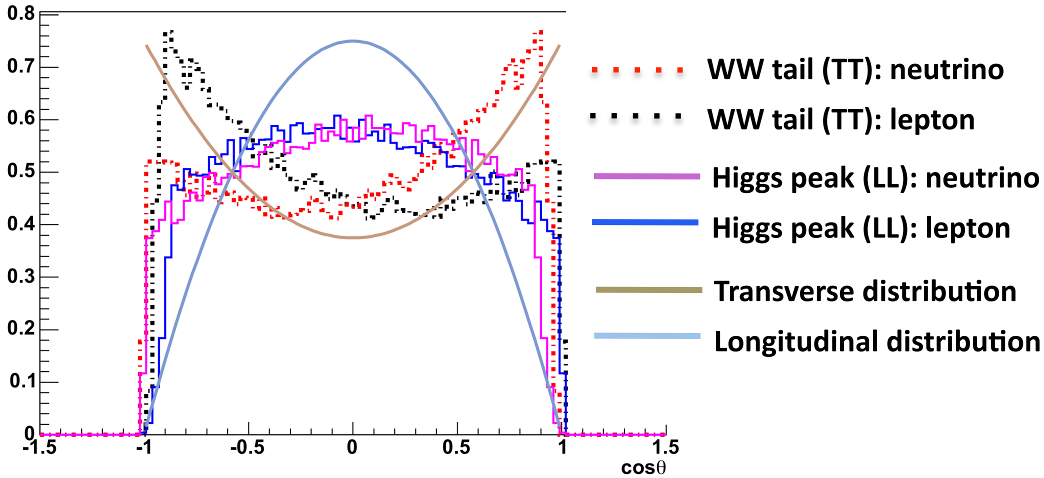


noHiggs (unitarity violation)



- ❑ Angular analysis can boost LL-TT separation (new!):

partonic study in the center of mass of W

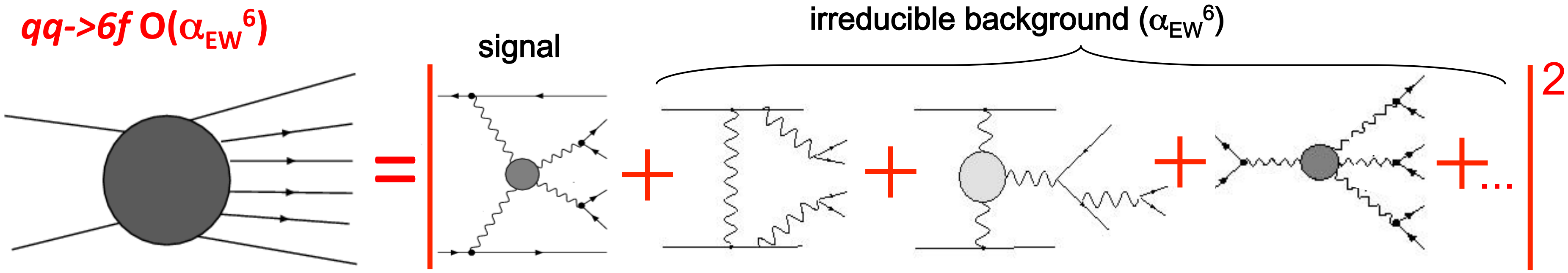


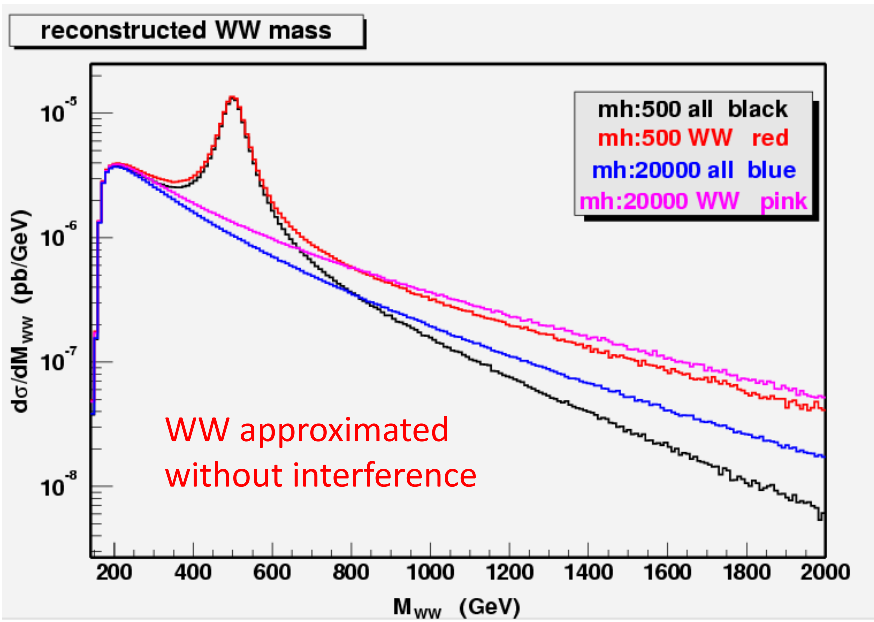
VV scattering: interference effects

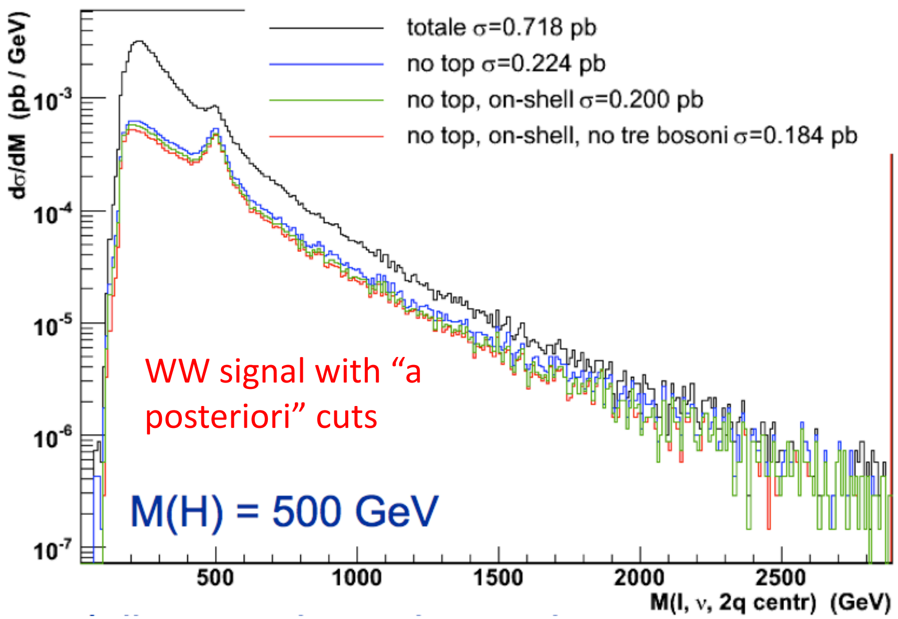
JHEP 0603 (2006) 093
Accomando, Ballestrero, Bolognesi, Maina, Mariotti

- Big interference effects considered only in **Phantom**

qq->6f O(α_{EW}^6)







Summary

- ❑ The first aim of the Higgs search is **the understanding of the EWSB**

  -> focus on H->VV final state

- ❑ Main steps:
  - search for generic resonance **X->ZZ->4f**
  - search for **VBF** resonance and measuring of **VV scattering** spectrum

  } angular analysis

- ❑ Ingredients along the EWSB road:
  - control of **V+jets** (jet pruning)
  - control uncertainties on **VV EWK continuum**

The road to the ElectroWeak Symmetry Breaking

BACK-UP

18th January 2012

Seminar at Johns Hopkins University

S.Bolognesi (Johns Hopkins University)

Sources

CMS AN-2010-35: **Angular Analysis of Resonances pp → X → ZZ**

A. Bonato, A.V. Gritsan, Z.J. Guo, N.V. Tran, A. Whitbeck
Johns Hopkins University, Baltimore, MD, USA

→ Y.Y. Gao *et al.*, Phys. Rev. D **81**, 075022 (2010).

JHU seminar: **Path-Integral Jets** by David Krohn (Harvard)

www.pha.jhu.edu/groups/particle-theory/seminars/talks/F11/talk.khron.pdf

First LHC to Terascale Workshop (Sept 2011):

LCH at LHC by J.R. Espinoza

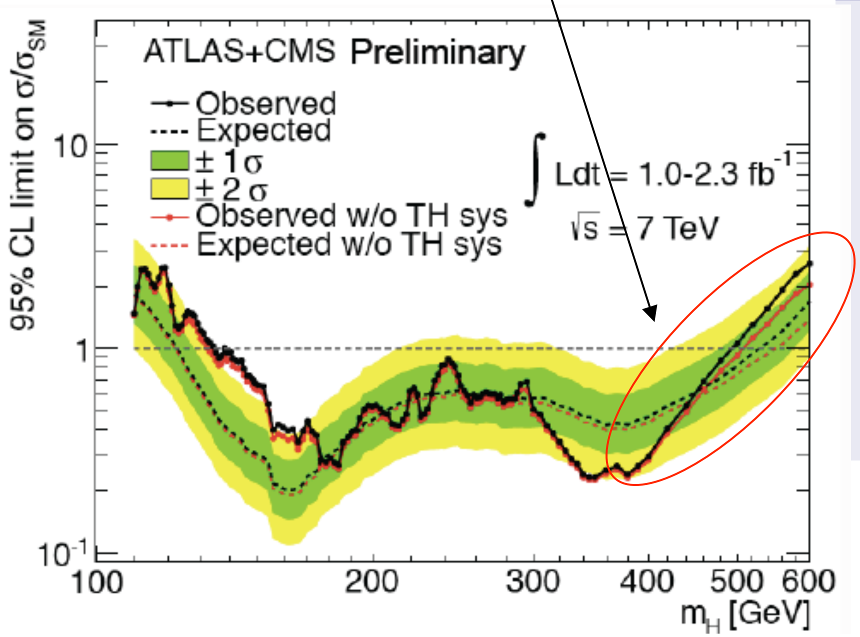
Boson Boson scattering analysis by A.Ballestrero (INFN Torino)

Mass shape

From Passarino talk at last LHC to Terascale WS

- Present approx:
  - xsec for on-shell Higgs production and decay in zero width approx
  - acceptance from MC with ad-hoc BW distribution

10-30% uncertainty on xsec for mH 400–600 GeV



The off-shell Higgs production

is currently computed according to

$$\sigma_{OS}(\mu_H^2)\,\delta(z\,\hat{s} - \mu_H^2) \quad \Longrightarrow \quad \sigma_{OFS}(z\,\hat{s})\,\mathrm{BW}(z\,\hat{s}),$$

at least at lowest QCD order, where the *so-called* modified Breit–Wigner distributions is defined by

$$\mathrm{BW}(s) \;=\; \frac{1}{\pi}\,\frac{s\,\Gamma_H^{OS}/\mu_H^2}{\left[s-\mu_H^2\right]^2 + (s\,\Gamma_H^{OS}/\mu_H)^2},$$

where now $\mu_H = M_H^{OS}$.

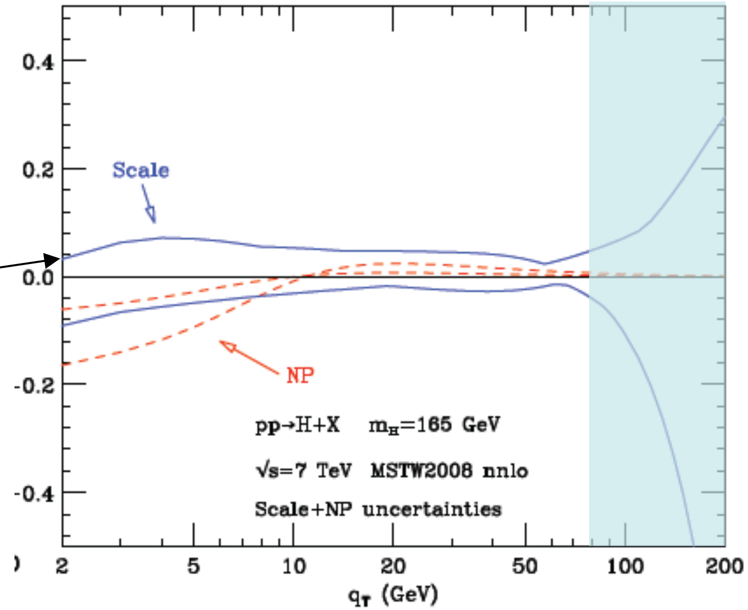
This ad-hoc Breit–Wigner

- cannot be derived from QFT and also is not normalizable in $[0\,,\,+\infty]$.
- Its practical purpose is to enforce a *physical* behavior for low virtualities of the Higgs boson but the usage cannot be justified.
- This modified Breit–Wigner cannot be derived from QFT.
- Note that this Breit–Wigner for a running width comes from the substitution of $\Gamma \rightarrow \Gamma_(s) = \Gamma\,s/M^2$ in the Breit–Wigner for a fixed width Γ. This substitution is not justifiable.

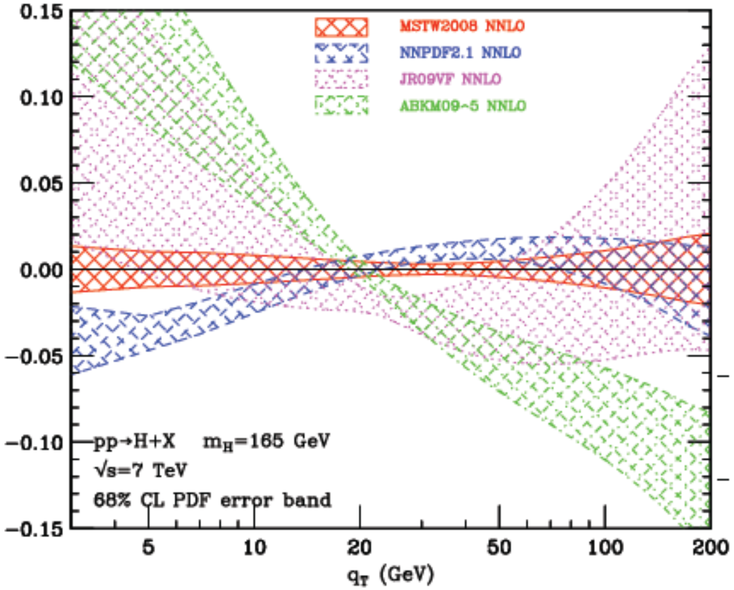
Study with QFT-consistent Higgs propagator in the YR2

Higgs qT

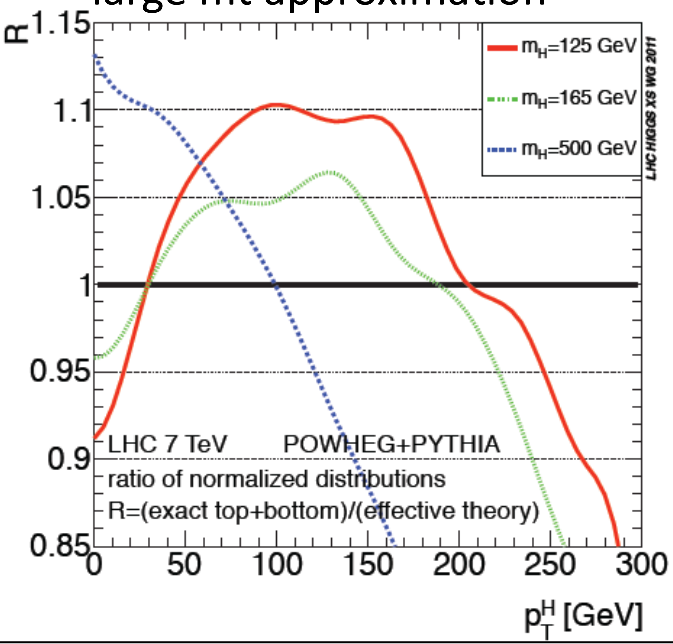
- **HqT:** q_T > mH NNLO
  q_T << mH NNLL (resumming $\ln(mH^2/q_T^2)$)



Uncertainties:
- factor/renorm scale
- non perturb. effects
  (smearing with NP form factor)
- PDF



- large mt approximation

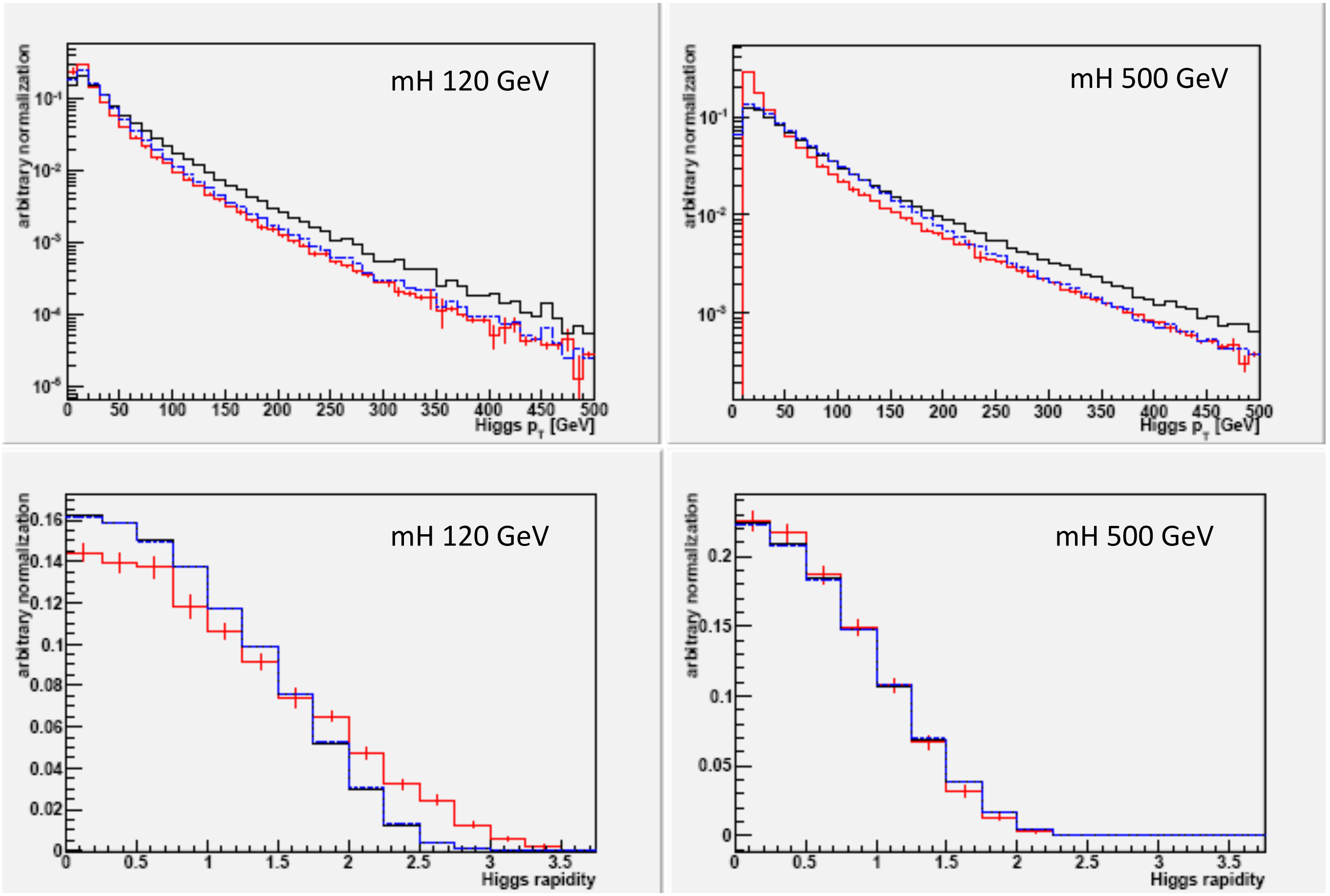


Reweight to HqT

- HqT used to reweight full event generators (POWHEG at NLO)

H p_T

H y



Powheg

Powheg re-weighted to Hqt

(to be redone before PS)

HNNLO

- Very small effect on acceptance in 4l: 1-2% (larger if jet veto!)

Signal: jet counting

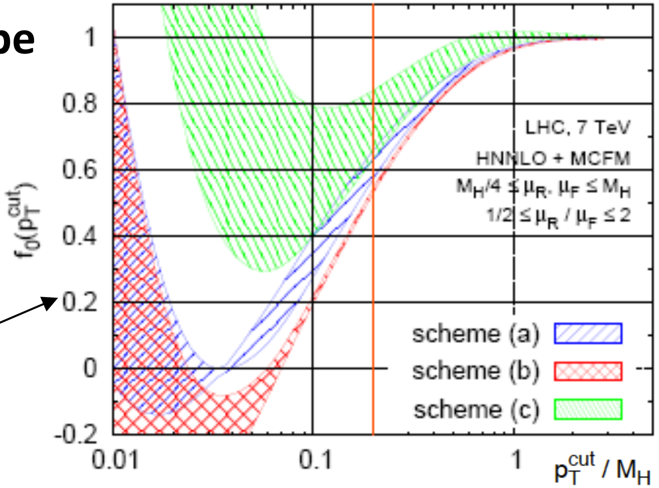
- **Analysis in exclusive jet bins** (ex, WW+0,1,2 jets)

  → **theoretical uncert in jet bins to be combined with correlations**

- if background depends on Njets
- for VBF

  ▪ varying renormalization and factorization scales in the fixed-order predictions for each exclusive jet cross section σN

  (results as 100% correlated)



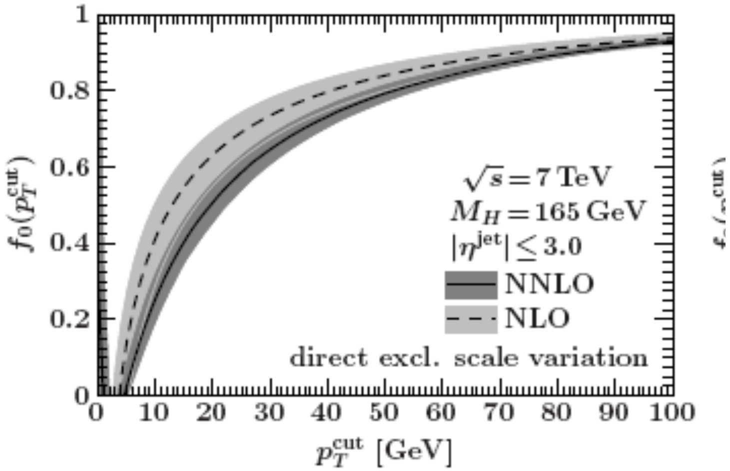
different treatments of the uncontrolled higher-order $O(\alpha^3 s)$ terms

i.e., different NNLO expansions

  ▪ inclusive xsec (σ≥Njets), as source of perturbative uncertainties

  σN = σ≥N − σ≥N+1

  with error propagation



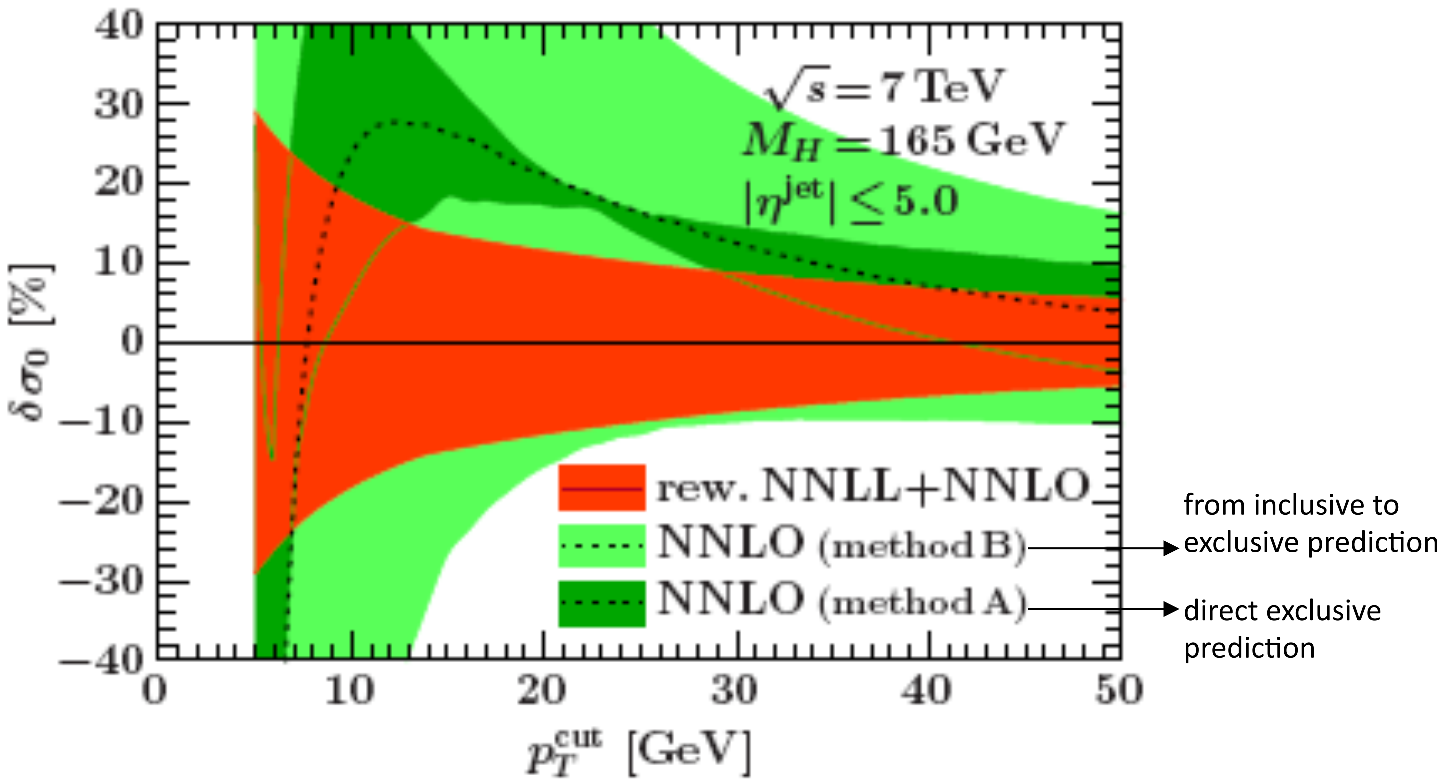
Signal: jet veto

- Resummation of jet-veto logarithms ($\ln(p_{cut}/mH)$), induced by jet cut parameter p_{cut}

  Presently doable only on beam thrust variable

  $\mathcal{T}_{\mathrm{cm}} = \sum_k |\vec{p}_{Tk}| e^{-|\eta_k|} = \sum_k (E_k - |p_k^z|)$ (~raw approx of p_{cut})

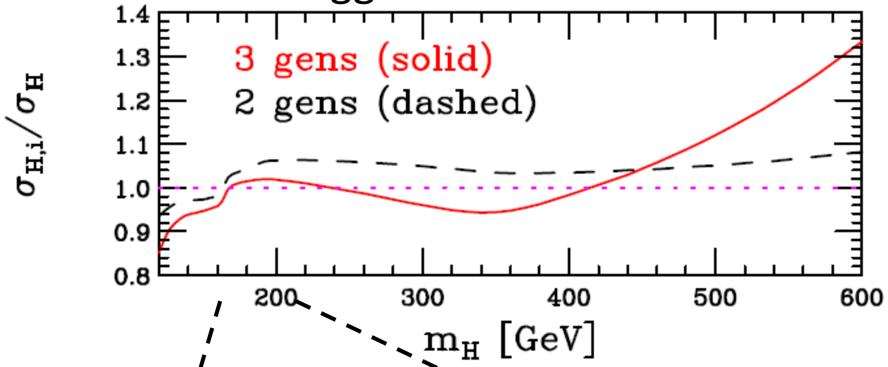
  and used to reweight MC@NLO

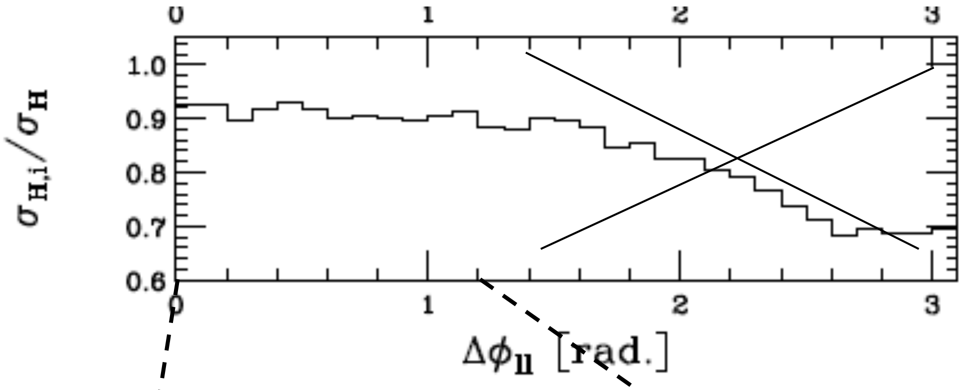


Signal-background interference

- Recent results for WW, but focused on low mass (arXiv:1107.5569v1)

Effect on gg→H→WW at LO

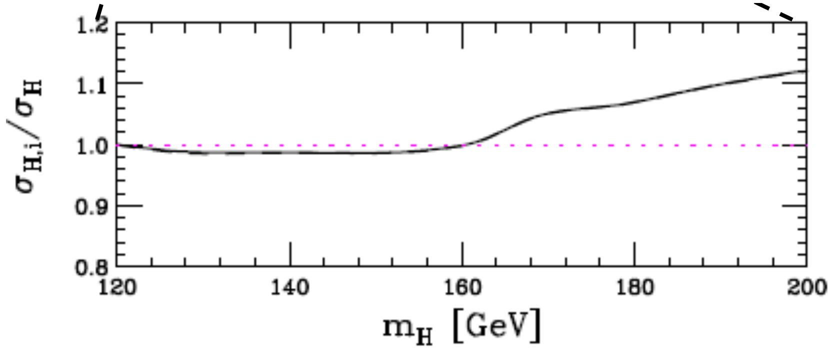


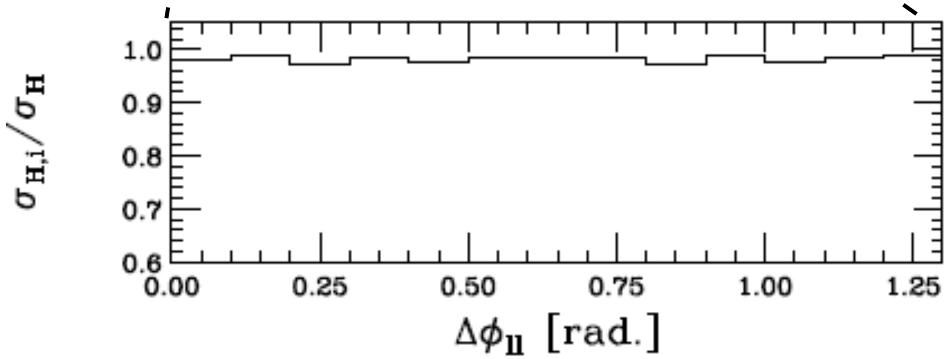


m_T < mH

non-resonant diagrams can be large for m_T > mH

also shape effects!



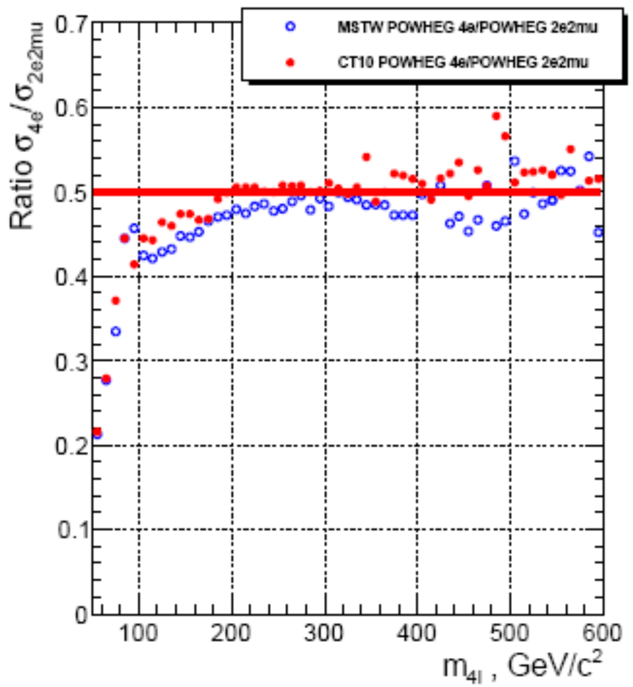


- Worth to investigate further at high mass?

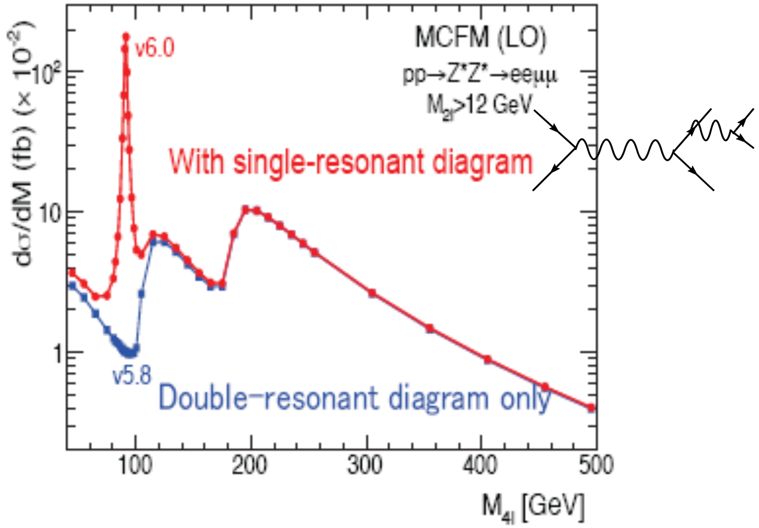
ZZ: theoretical prediction

- ZZ fully from MC, well under control

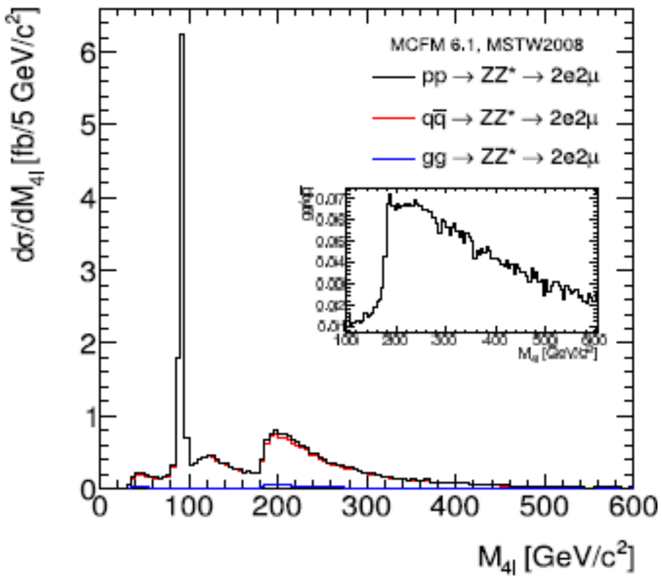
Interference in the final state with identical leptons



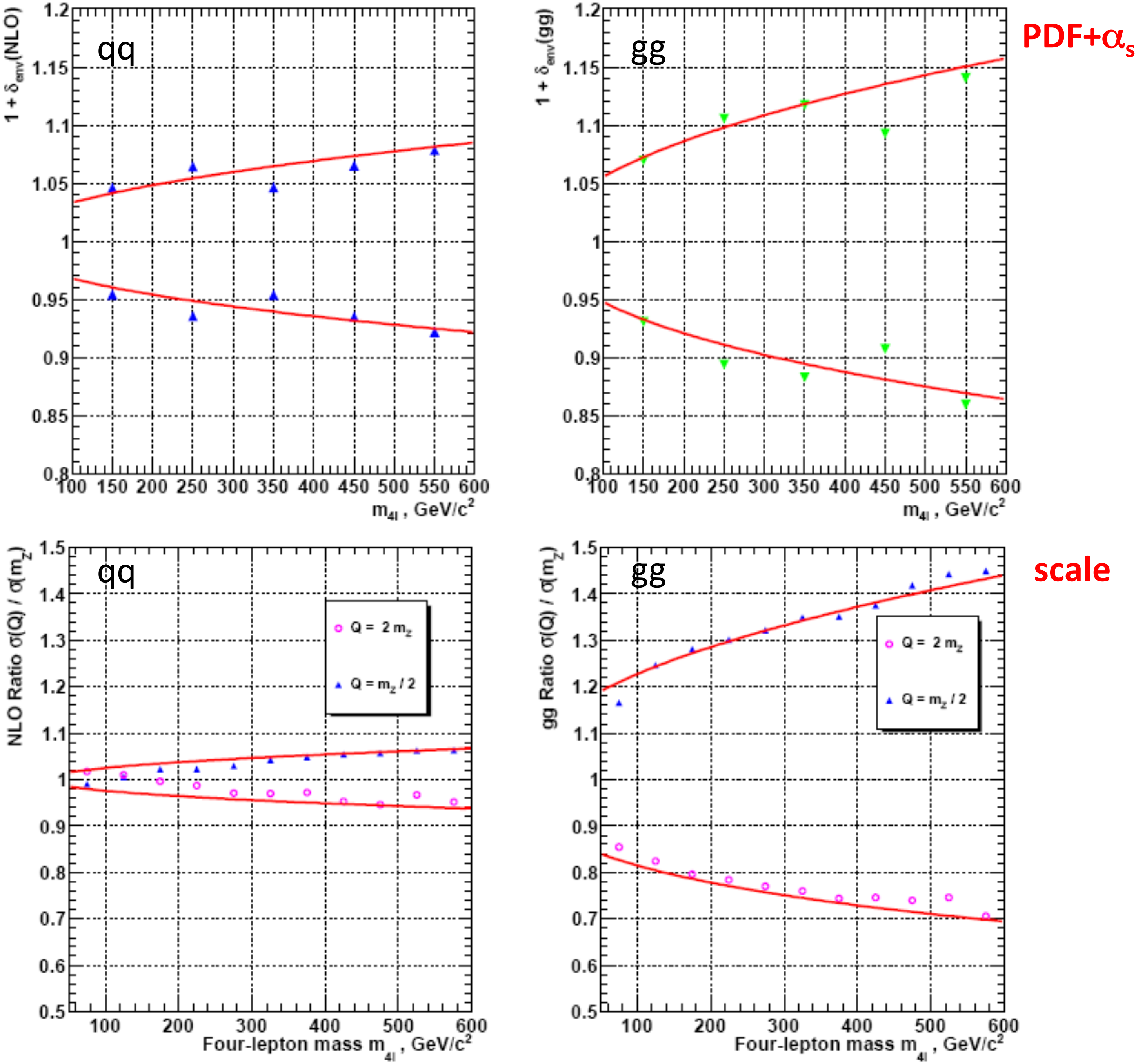
Single resonant contribution



qq→ZZ NLO + gg→ZZ



ZZ: theoretical uncertainties



WW: theoretical uncertainties

- WW taken from MC for large m_H
  - → gg+qq NLO available (MCFM)
  - PDF+α_s and scale uncertainty dominates
  - in jet bins using uncert on σ(>=N) + modeling: MC@NLO vs ALPGEN

$\Delta\sigma_{\geq 0}$ (%)	$\Delta\sigma_{\geq 1}$ (%)	$\Delta\sigma_{\geq 2}$ (%)	$\Delta\sigma_{\geq 3}$ (%)
3	6	42	100

- WW from control region for m_H<200 GeV (mll, $\Delta\phi$ll)

	scale	pdf CTEQ 6.6 error set	pdf central (CTEQ6.6, MSTW2008, NNPDF2.1)	Modelisation
α_{WW}^{0j}	2.5%	2.6%	2.7 %	3.5%
α_{WW}^{1j}	4%	2.5%	1.4 %	3.5 %

WW→lνlν measurement

- Complex analysis (no mass peak→counting experiment, many backgrounds)

- Main systematics:
  - background estimate:

Background	Cuts
W+jets	tight lepton quality
top	(b-)jet veto
Drell-Yan	Z mass veto missing E_T
WZ, ZZ, Wγ	2 leptons → estimated from MC

(W+jets, top, Drell-Yan: estimated from data)

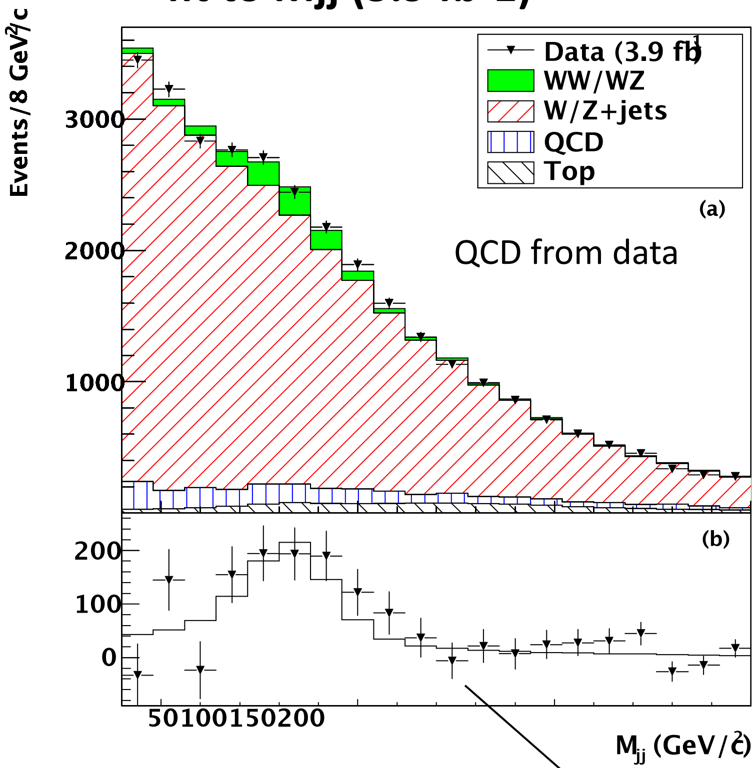
Sample	Yield
$qq \to W^+W^-$	349.7 ± 30.3
$gg \to W^+W^-$	17.2 ± 1.6
$W + \text{jets}$	106.9 ± 38.9
$t\bar{t} + tW$	63.8 ± 15.9
$Z/\gamma^* \to \ell\ell + WZ + ZZ$	12.2 ± 5.3
$Z/\gamma^* \to \tau\tau$	1.6 ± 0.4
WZ/ZZ not in $Z/\gamma^* \to \ell\ell$	8.5 ± 0.9
$W + \gamma$	8.7 ± 1.7
signal + background	568.6 ± 52.2
Data	626

  - signal acceptance: jet-veto efficiency
    leptonic efficiency
    missing E_T uncertainty
    theoretical (gg box, PDF)

WW/WZ→lν2j at CDF

- ❑ First observation: 5.4σ (first evidence at D0 with 4.4σ in 2008)
- ❑ Much larger backgrounds, no resolution to distinguish W/Z→jj

fit to Mjj (3.9 fb-1)



+ matrix element method: (2.7 fb-1)

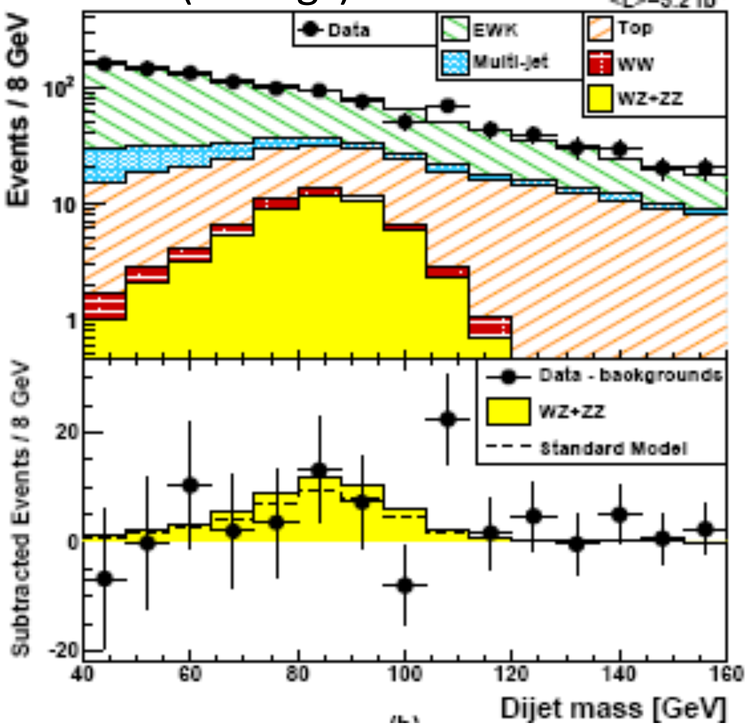
- discriminant exploiting full kinematic information, based on calculations of differential xsec of signal and background
- data-MC validation of input kinematic variables
- fit to shape of discriminant

$$\sigma(WW + WZ) = 16.0 \pm 3.3(stat + syst)\, pb$$ (NLO expected $16.1 \pm 0.9)\, pb$

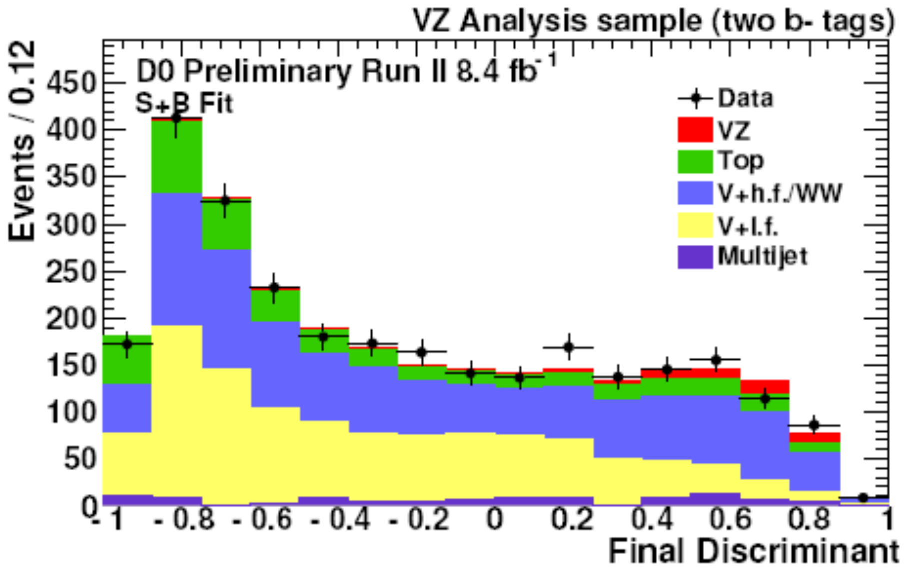
WZ/ZZ→lν/νν+2b at Tevatron

- Crucial for Higgs search (ZH→ννbb). Very complex analysis!
  - WZ → lνbb + ZZ → ννbb ⇒ b-tag jets + missing E_T (+ topological cuts)
  - No leptons! → huge background: multijets QCD, V+jets (from data)
  - very sophisticated techniques: b-tag probability with Boosted Decision Tree or Neural Network which exploits much info and different variables

CDF (2b-tags)



different channels combined (0,1,2 b-tag)



D0: $\sigma(WZ, ZZ) = 6.9 \pm 1.3(stat) \pm 1.8(syst)\ pb$

(expected 4.6 pb)

CDF: $\sigma(WZ, ZZ) = 5.8^{+3.6}_{-3.0}\ pb$

(expected 5.1 pb)

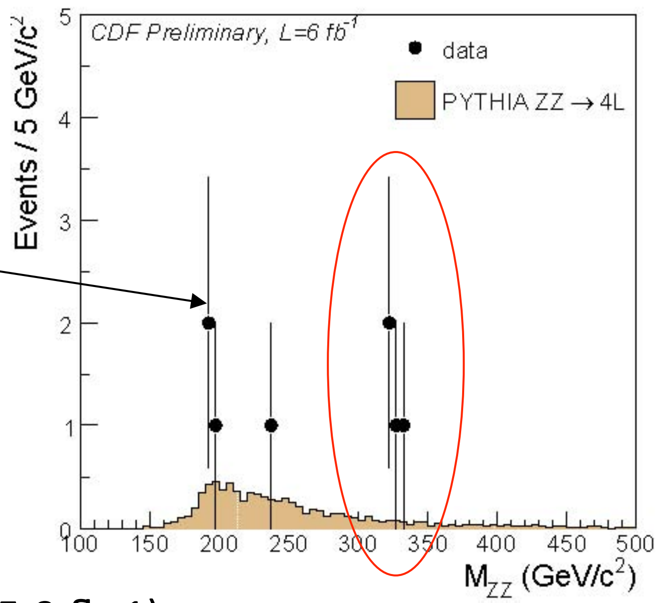
ZZ at CDF

- **ZZ→4l** (6 fb-1) excess of events at high M_{ZZ} (eg Randall Sundrum Graviton)
  - But xsec still compatible with SM

$$\sigma(p\bar{p} \to ZZ) \;=\; (2.8\ ^{+1.2}_{-0.9}\ (\mathrm{stat.})\ \pm\ 0.3\ (\mathrm{syst.}))\,\mathrm{pb}$$

$$(1.4 \pm 0.1)\,\mathrm{pb}$$

  - No excess in other final states



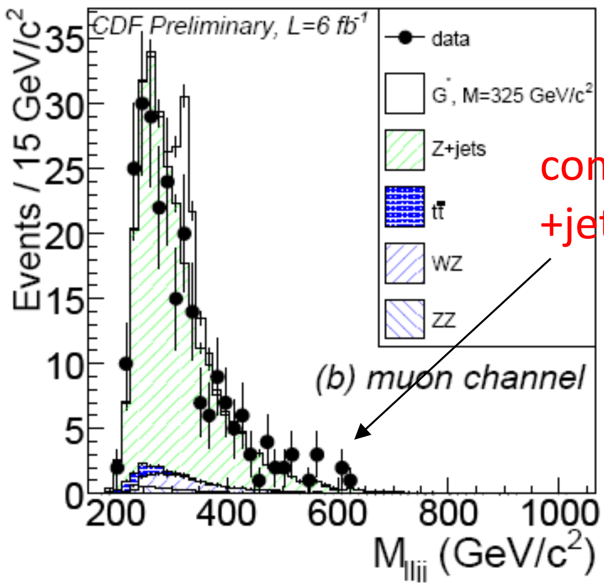
- **ZZ→2l2ν** (5.9 fb-1)

Shape analysis with fit to neural network

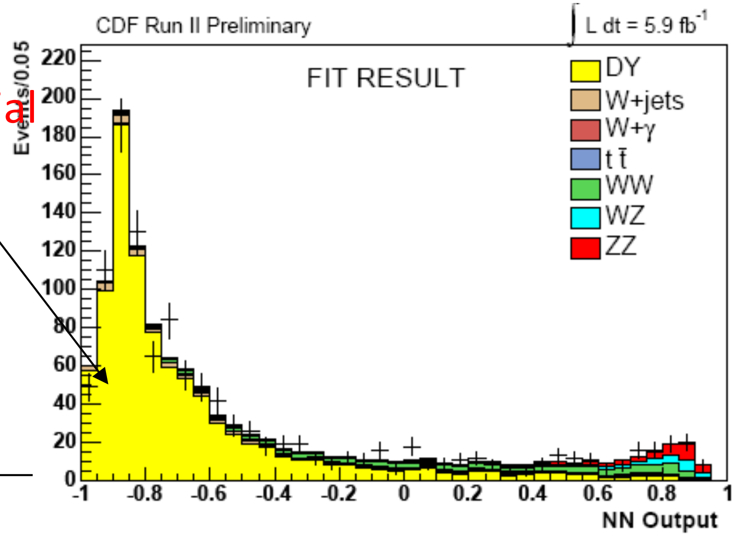
$$\sigma(p\bar{p} \to ZZ) \;=\; 1.45^{+0.45}_{-0.42}(stat.)^{+0.41}_{-0.30}(syst.)\ \mathrm{pb}$$

$$\sigma(ZZ) \;=\; 1.21^{+0.05}_{-0.04}(scale)^{+0.04}_{-0.03}(PDF)\ \mathrm{pb}.$$

- **ZZ→2l2j**



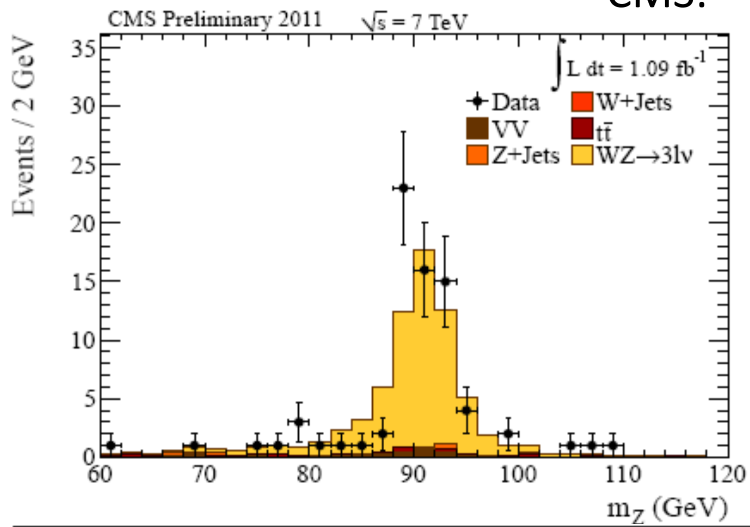
control of Z +jets is crucial



WZ→3l+ν at LHC

- Very clean, low background

CMS:

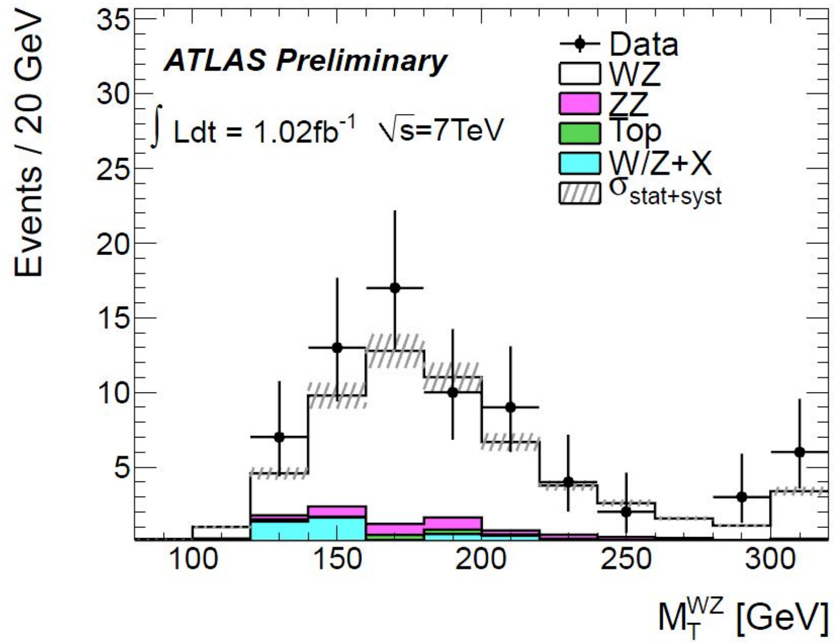


Sample	$3e0\mu$	$2e1\mu$	$1e2\mu$	$0e3\mu$
Background	2.95	2.14	1.31	1.72
$WZ \to 3\ell\nu$	14.47	17.49	13.95	18.56
All MC	17.42	19.62	15.26	20.28
Data	22	20	13	20

$$\sigma(WZ) = 17.0 \pm 2.4(stat) \pm 1.1(syst) \pm 1.0(lumi)\ pb$$

(NLO expected $18.75^{+1.1}_{-0.8}\ pb$)

ATLAS:



$$\sigma(WZ) = 21.1^{+3.1}_{-2.8}(stat) \pm 1.2(syst)^{+0.9}_{-0.8}(lumi)\ pb$$

(NLO expected $17.2^{+1.2}_{-0.8})pb$

Recent WZ→3l+ν at Tevatron

- ❑ Possible only at hadron colliders (charged final state)
  - **D0 with 4.1 fb-1**

    statistics 2 times smaller than LHC, while xsec is 6 times smaller

    $$\sigma(WZ) = 3.90^{+1.06}_{-0.90}\, pb$$

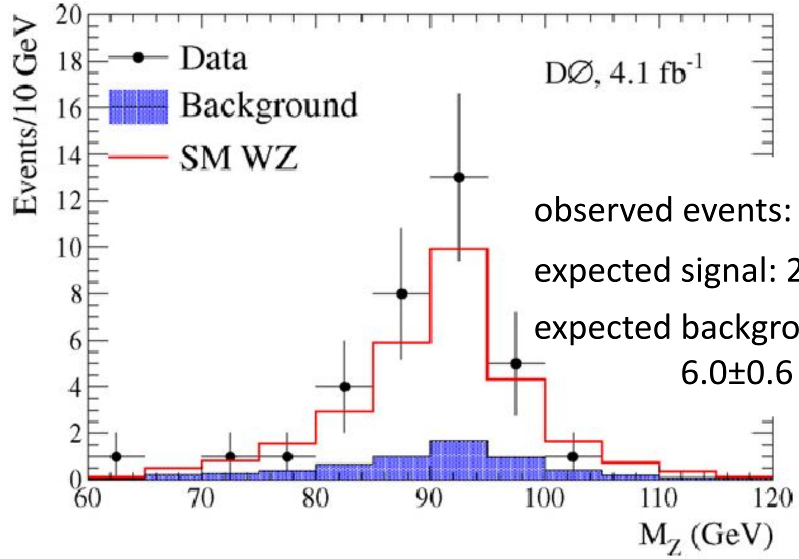
    (NLO expected $3.25 \pm 0.19\, pb$

  - **CDF with 7.1 fb-1**

    Shape analysis with fit to neural network

    $$\sigma(WZ) = 3.9^{+0.6}_{-0.5}(stat)^{+0.6}_{-0.4}(syst)\, pb$$

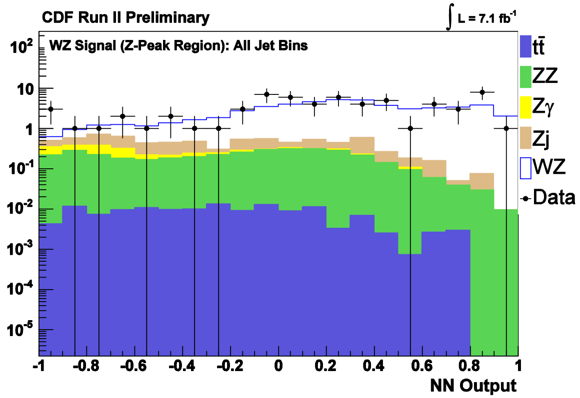
    (NLO expected $3.46 \pm 0.21\, pb$



observed events: 34

expected signal: 23.3±1.5

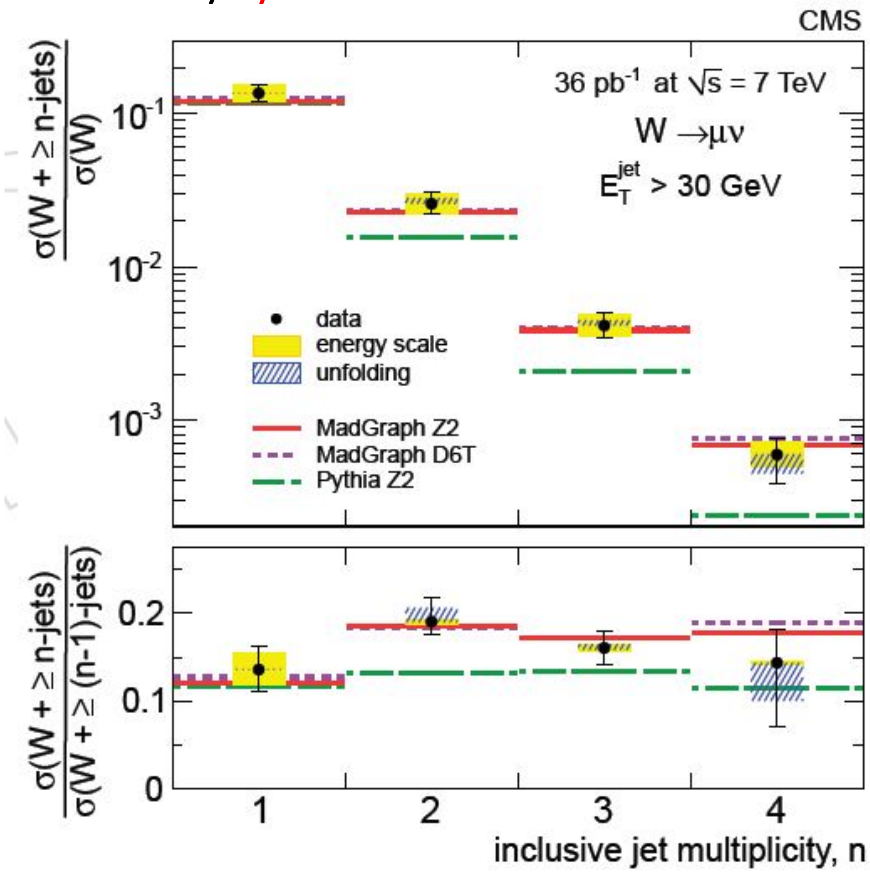
expected background: 6.0±0.6



V+jets: ratios

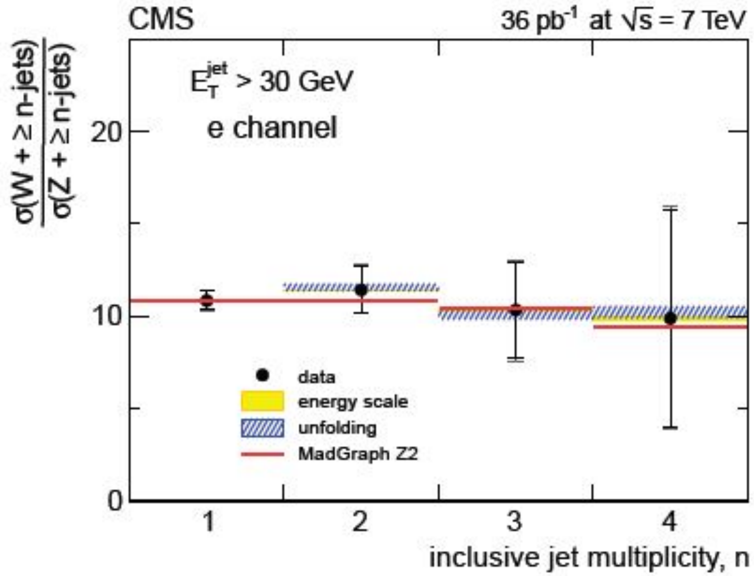
CMS PAS EWK-10-011

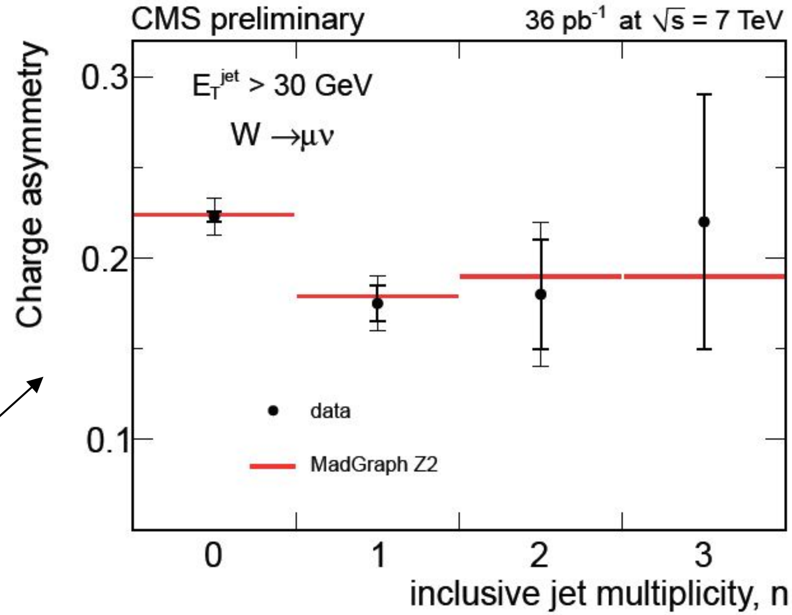
- ❑ Many systematics cancel out



- ❑ Very well known theoretically → any deviation is hint of NP

- Use high statistics W sample to predict Z+jets background for NP



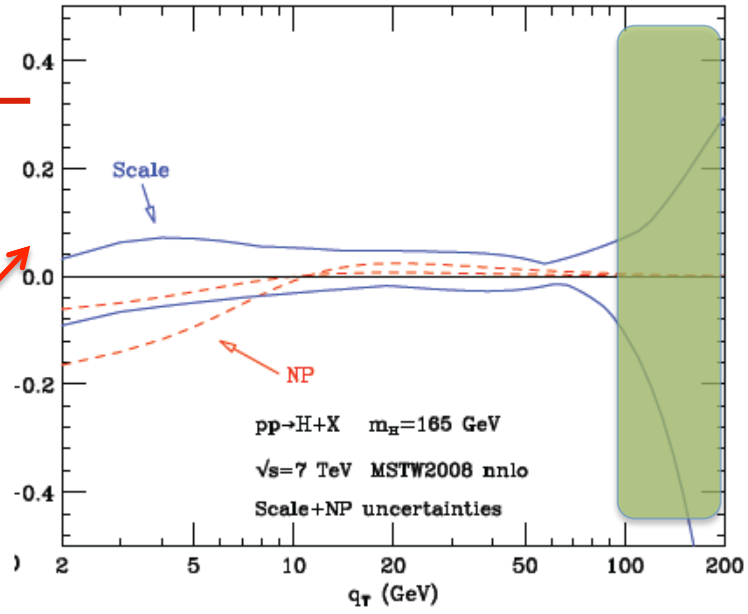


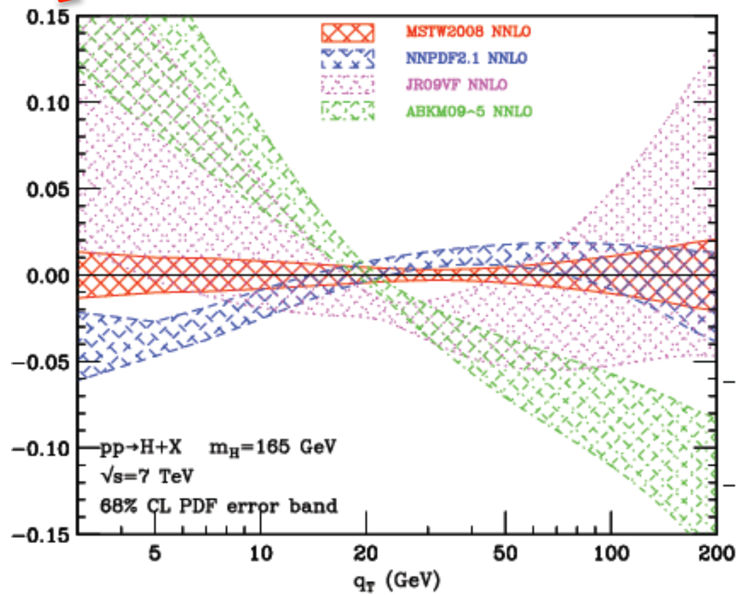
The input: signal description

Common effort CMS-ATLAS-theoreticians:
Higgs Xsec working group
(2 yellow reports published: **arXiv:1101.0593 [hep-ph]**
arXiv:1201.3084 [hep-ph])

- Higgs p_T reweighted at NNLO+NNLL (Powheg+HqT+HNNLO)

  uncertainties:
  - factor/renorm scale
  - non perturb. effects, PDF





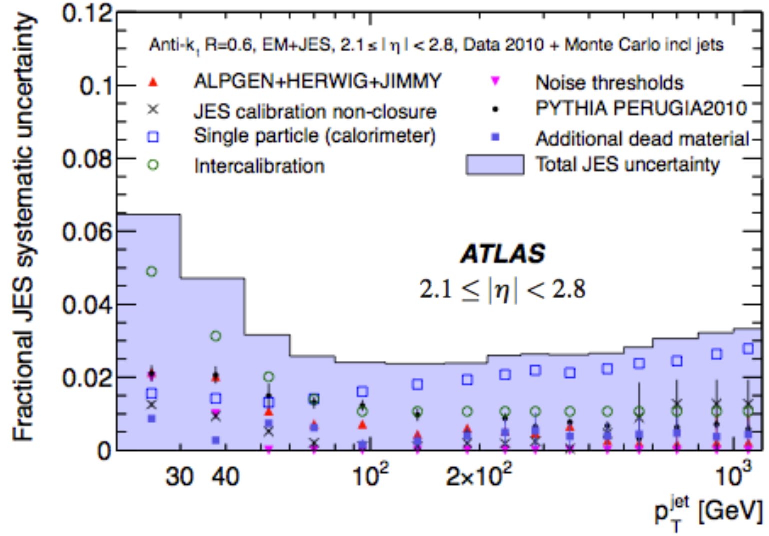
- Mass shape uncertainty at high mass:
  - xsec for on-shell Higgs production and decay in zero width approx
  - acceptance from MC with ad-hoc BW distribution

10-30% uncertainty on xsec for mH 400–600 GeV

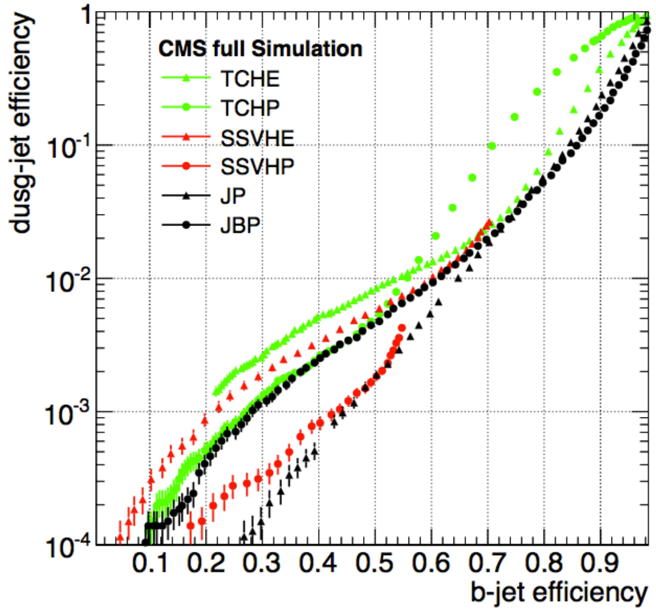
Now shape from proper (QFT-consistent) Higgs propagator available!

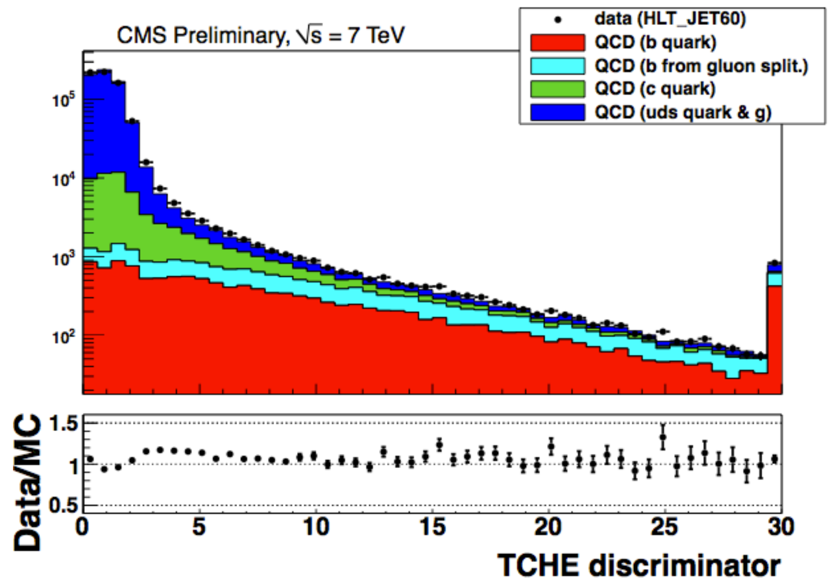
The input: object reconstruction

- Leptons (e,μ) from V: p_T>20 GeV, isolated, if from Z then M(ll)~91 GeV
  -> optimal performances, see previous lecturer
- Jets: ATLAS: clusters of calorimeter deposits, p_T>25 GeV
  CMS: particle-flow (full particle identification with tracker+calo), p_T>30 GeV



- B-tagging

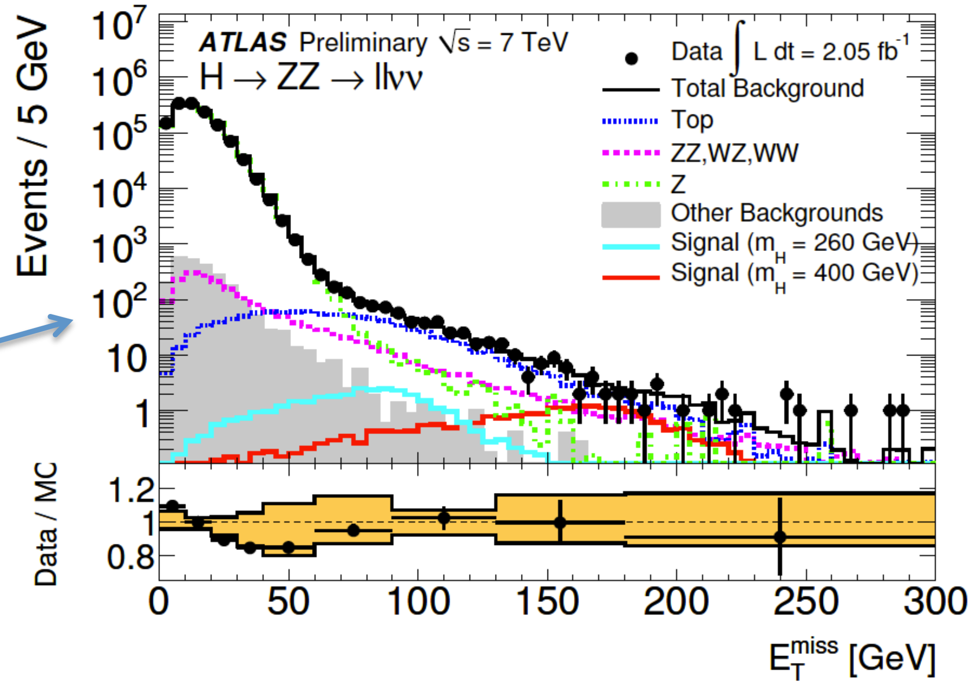




- MET : calorimeter deposits (in CMS also part. flow)

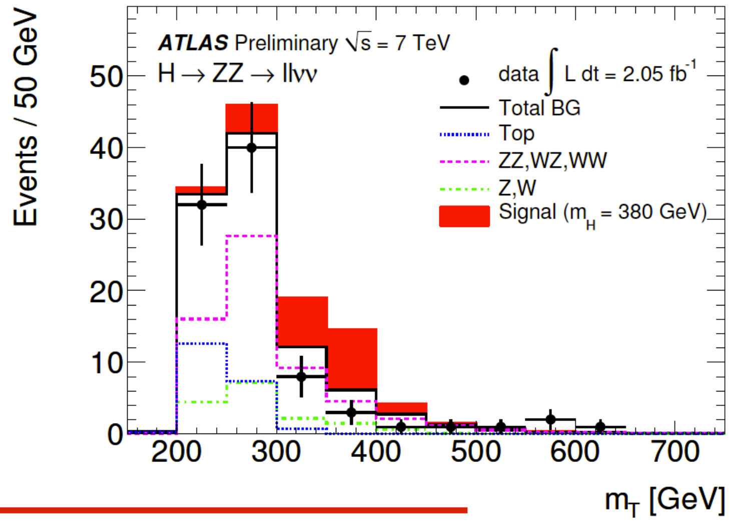
H->ZZ->llνν

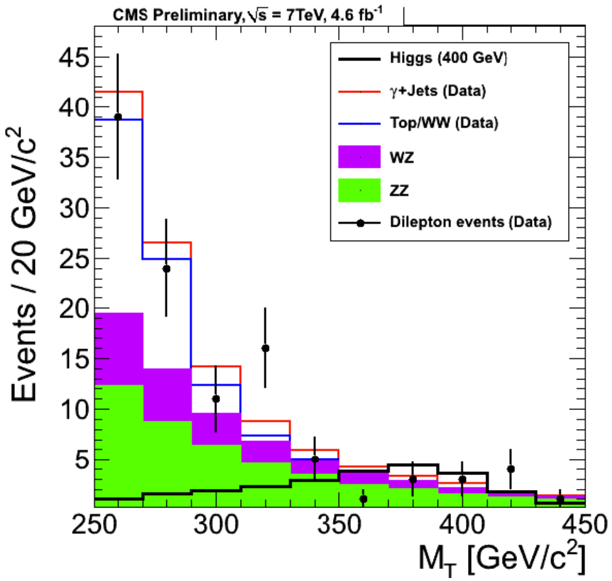
- 2 leptons from Z + MET.
  - **Backgrounds:**
    - Z+jets removed asking for high, "real" MET
      high Δϕ(jet-MET, Z-MET)
    - ttbar removed vetoing b-tag jets
    - VV mainly irreducible
    - W+jets with lepton fake or from HF



$$m_{\mathrm{T}}^2 \equiv \left[\sqrt{m_Z^2 + |\vec{p}_{\mathrm{T}}^{\,\ell\ell}|^2} + \sqrt{m_Z^2 + |\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}|^2}\right]^2 - \left[\vec{p}_{\mathrm{T}}^{\,\ell\ell} + \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}\right]^2$$

- **Final cuts:**
  - high MET
  - high Δϕ(ll) or p_TZ -> for high mH
  - UL from fit to m_T broad distribution but pretty good S/B





H->ZZ->llνν: Z+jets control

- **Z+jets is $10^5\times$ signal and steeply falling** with MET and $p_T Z$
  - high MET tail dominated by fake MET (difficult to simulate)
  - cut on Z boost depends on Z+jets modeling

ATLAS

MET shape comparison
pythia-alpgen (5-20%)

JES systematics on MET

normalization data-MC comparison m(ll) (2.5%)

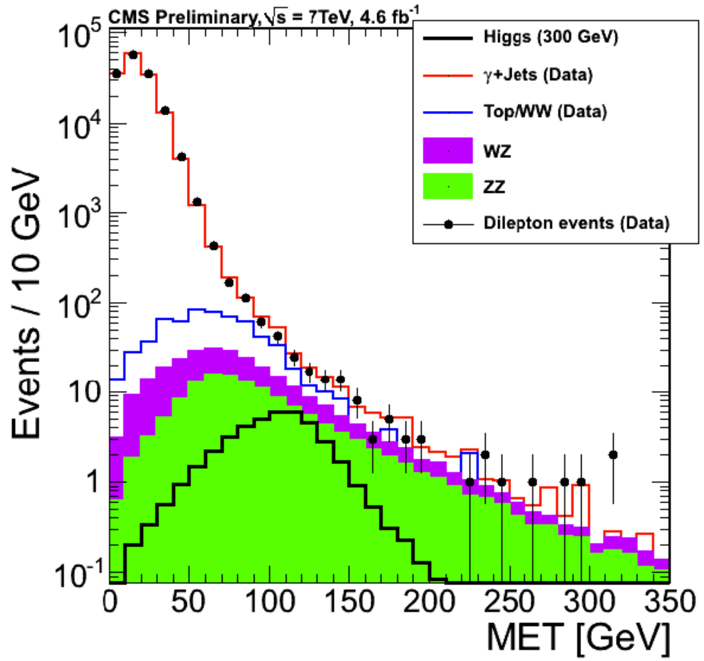
↓

7% uncertainty

CMS: fully data-driven

γ+jets reweighted vs N jets, boson p_T, N vertices

boson mass by sampling Z line-shape from fit to data



Main systematics: contamination from γ + real MET

↓

Z+jets left float btw 0 and γ+jet prediction
(-100%,+0% uncertainty)

H->ZZ->ll$\nu\nu$: non resonant backgrounds

- **ATLAS:**
  - ttbar from MC
    - xcheck in control regions (mll sidebands, e+mu)
    - systematics btag eff and mistag rate

  -> 9% uncertainty

  - W+jets normalization from control region (same-sign ll + MET)

  -> 100% uncertainty

- **CMS:**
  - non resonant from data: e+mu and m(ll) sidebands

$$N_{\mu\mu} = \frac{N^{SB}_{\mu\mu}}{N^{SB}_{e\mu}} \times N_{e\mu}$$

systematics from statistics in e+mu data

-> 15-100% uncertainty

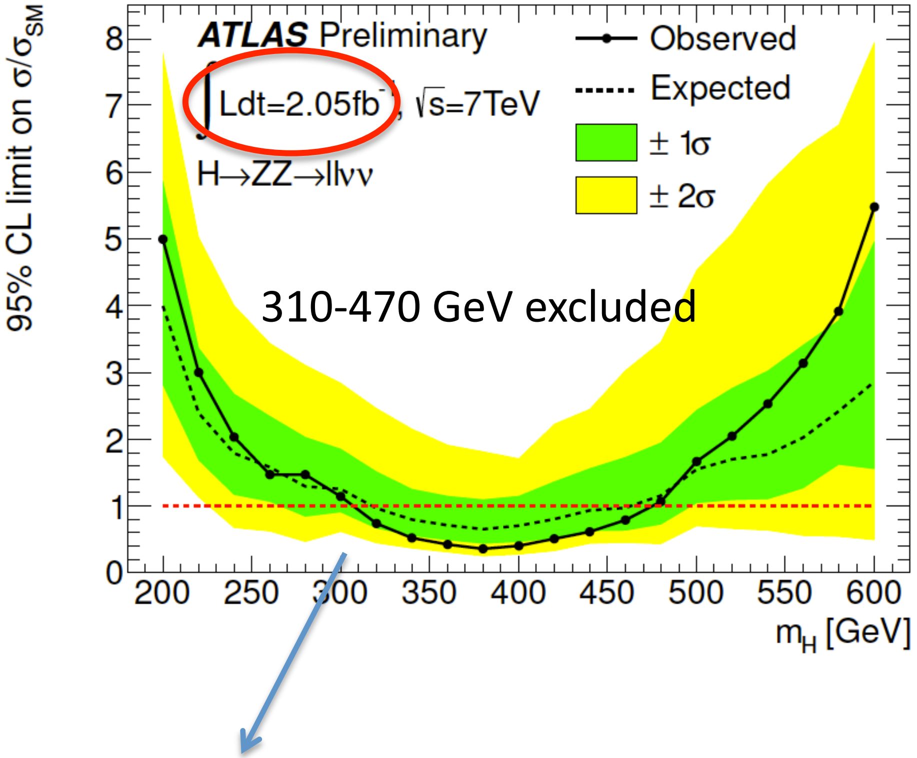
- VV from MC ->systematics on norm from PDF, scale, missing VZ*

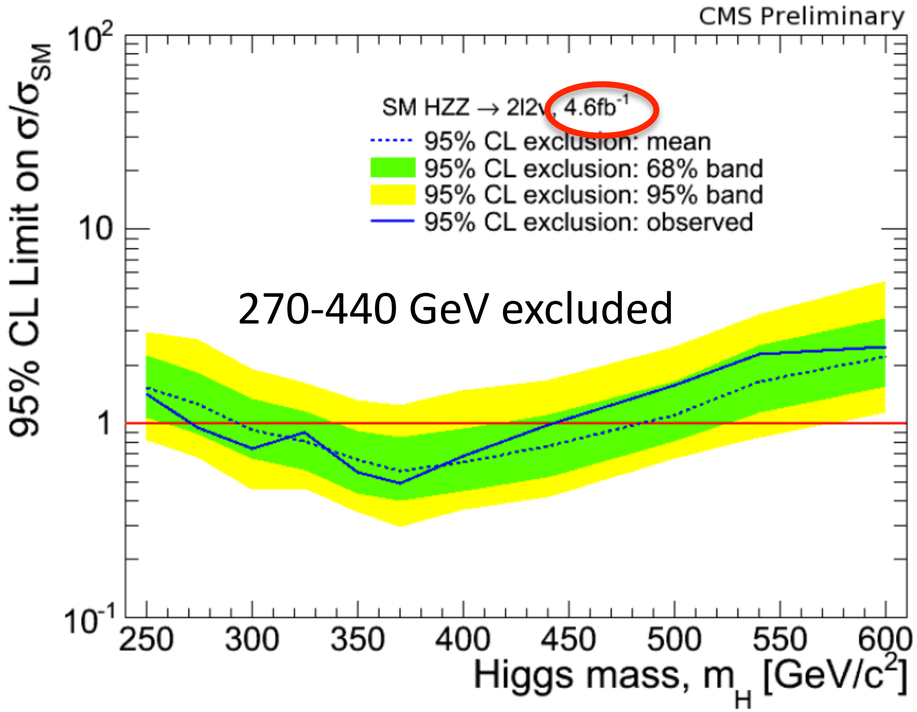
  -> 5-10% uncertainty

CMS 4.6 fb^{-1}

m_H (GeV/c^2)	ZZ	WZ	Top/WW/ W+jets/Z→ $\tau\tau$	Z+Jets	Total	Signal	Data
400	$12 \pm 0.13 \pm 0.87$	$4.6 \pm 0.14 \pm 0.39$	0	2.7 ± 2.7	$19 \pm 0.19 \pm 2.9$	17 ± 1.6	18

H->ZZ->llνν: results





ATLAS includes H->WW->lνlν (13%-77%) and H->ZZ->4l, H->ZZ->2l2q

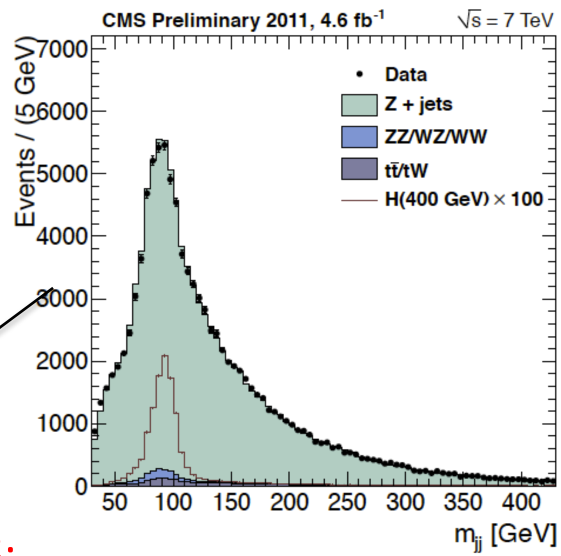
(exclusive cuts wrt to dedicated analysis to avoid double counting in combination)

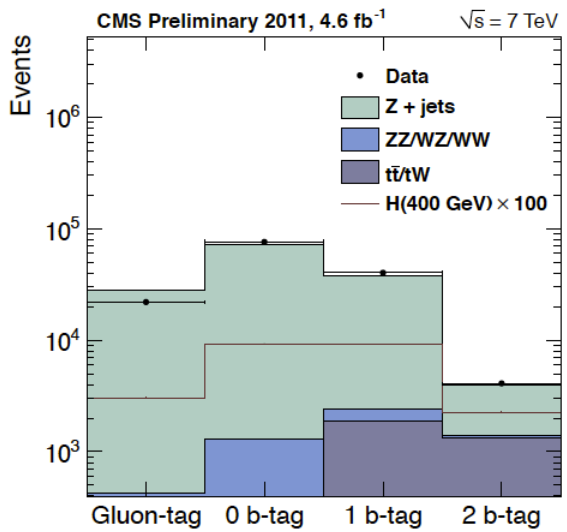
H->ZZ->lljj

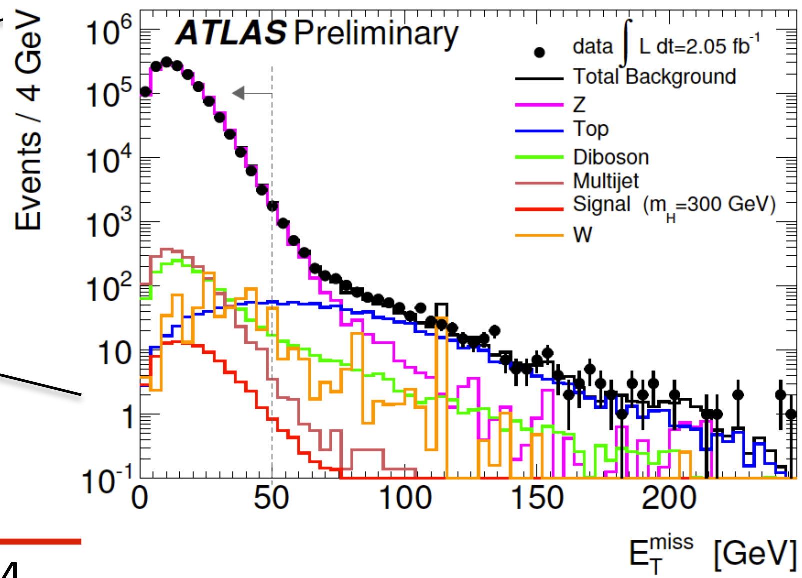
- ❑ 2l from Z + 2jets from Z
  (to improve mH resolution: kinematic fit M(Z->jj) in CMS, mZ/mjj rescaling in ATLAS)

- ❑ Main background Z+jets
  - still peaking ~M_Z because of kinematic pT cuts
  - no b-jets -> b categories (CMS: 0,1,2 bjet; ATLAS: 2 bjets or less)
  - (CMS remove jet from gluons with qg-likelihhod discriminant)

- ❑ In 2 btag ttbar relevant -> MET cut
(MET significance in CMS)





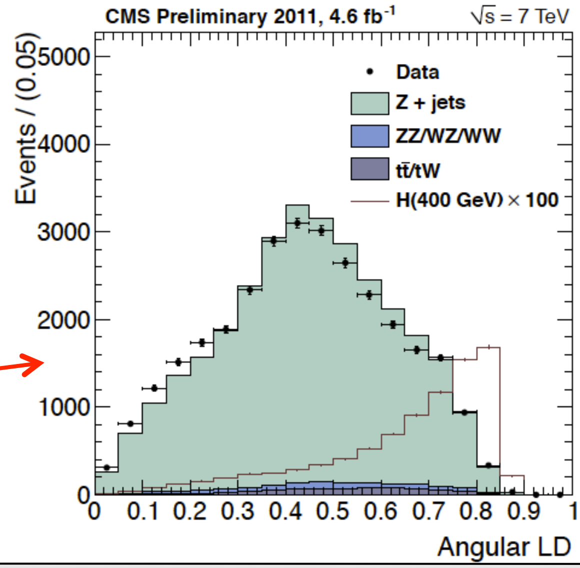


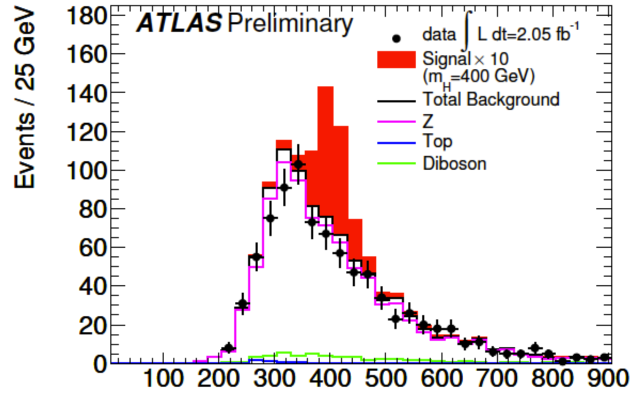
H->ZZ->lljj: final cuts

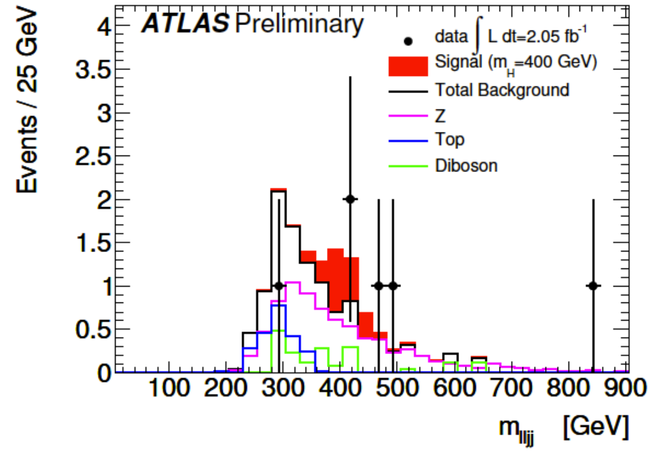
- **ATLAS**: higher p_T jets + small $\Delta\phi(jj)$, $\Delta\phi(ll)$ -> high Z p_T for high mass Higgs
- **CMS**: exploit full angular info H(spin0) -> ZZ ->4f :

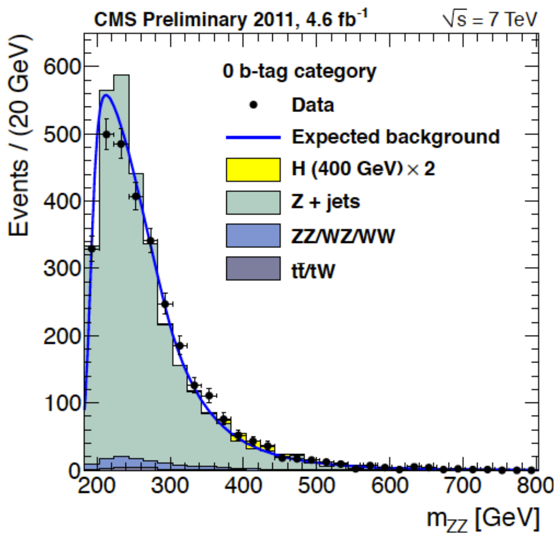
  likelihood discriminant built with angles distributions

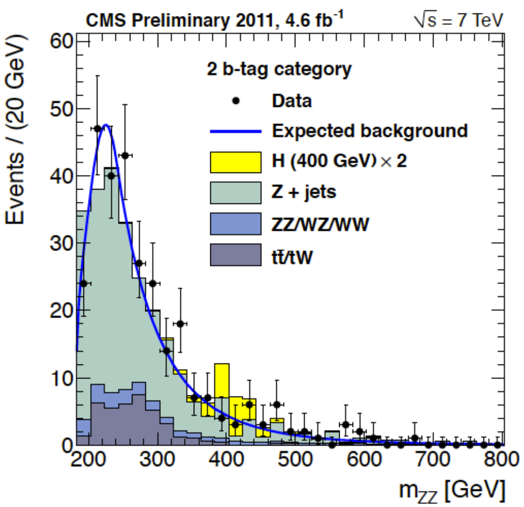
  ->no m(jj) bias -> background from sidebands
- UL from fit to m(lljj)











H->ZZ->lljj: background control

❑ **ATLAS:**

- **Z+jets**
  - shape from MC -> uncertainty from Pythia-Alpgen comparison
  - normalization from data M(jj) sidebands -> uncertainty from data statistics: 1-12% depend. on mH and untagged (16%)
- **ttbar from MC**
  - xcheck in MET>50 GeV, M(ll) sidebands

    -> uncertainty from data statistics + theoretical uncertainty (~15-20%)

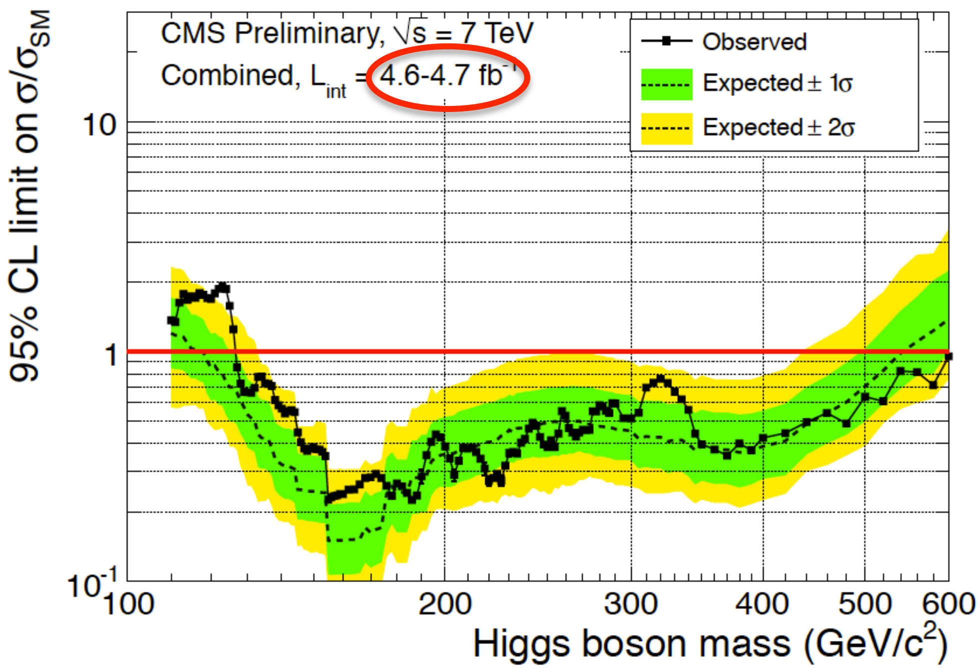
❑ **CMS:**

- **All background at once, data-driven** (highly dominated by Z+jets)
  - shape and normalization from data M(jj) sidebands
  - rescaled SB/SR from MC

  -> uncertainty from statistics

Combined results: high mass

127-600 GeV 95% CL exclusion



131-237 251-468 GeV 95% CL exclusion