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Standard Model @ Hadron Colliders
III. Top Quark (cont.)

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Is the top quark a normal fermion?

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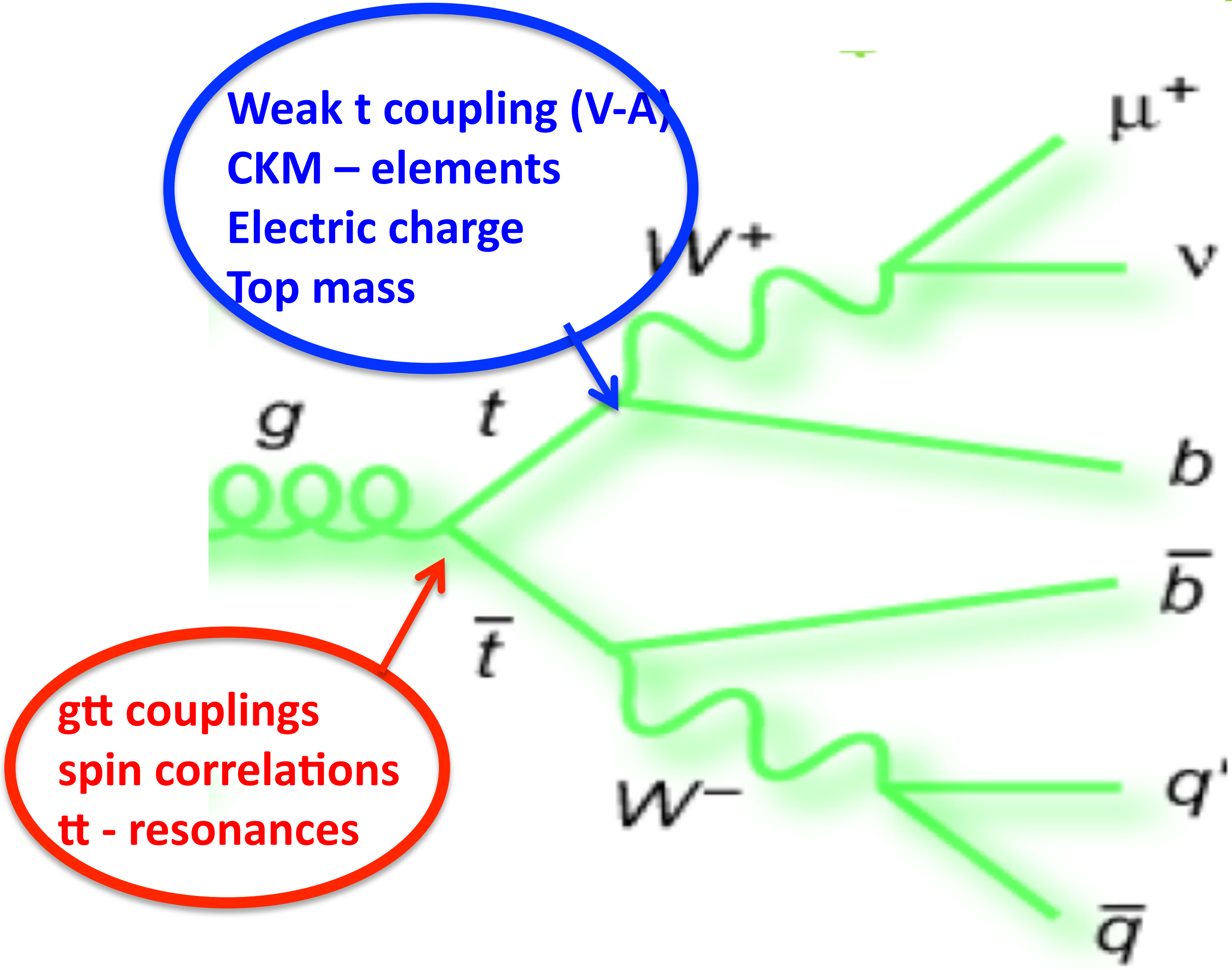

How to measure tt cross section

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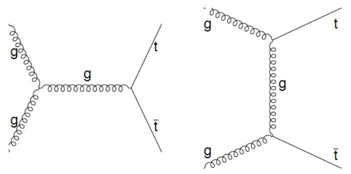
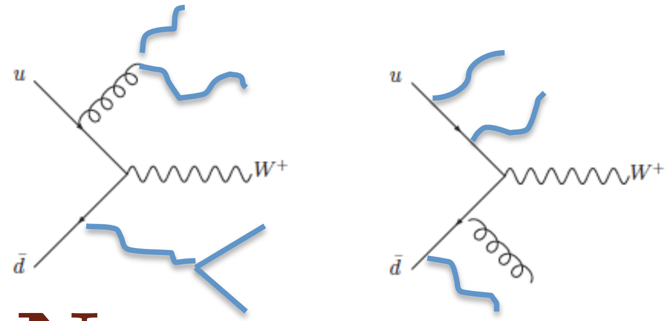


(Why should we?):
Sensitive to gluon –tt couplings
Test of QCD with massive quarks



Select events:
- 4 jets with p_T> 25 GeV
- isolated electron,muon p_T>20 GeV
- missing transverse energy > 20 GeV

$$\sigma_{t\bar{t}} = \frac{N_{\mathrm{measured}} - N_{\mathrm{background}}}{\epsilon \mathcal{L}}$$

What fraction of tt events are retained after selection

Luminosity:
How many proton-collisions?

Cross section determination

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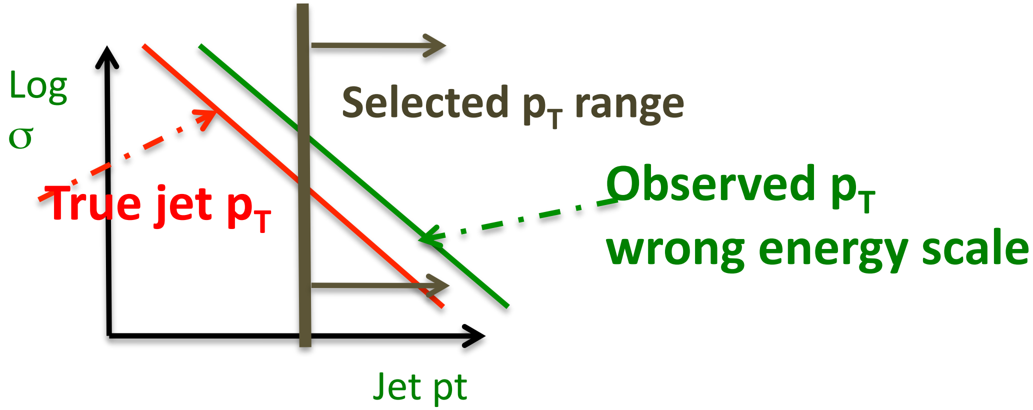
Experimental precision depends on how well
- background, efficiency, luminosity can be controlled

Key issue determine efficiency



Largest uncertainties:
- Jet energy scale
- bottom identification
- Background yield
- Jets from QCD
- selection efficiency e, μ, ...

Experimental uncertainty ~ 9%
Luminosity uncertainty ~ 4.4 %

Cross section measuremnt

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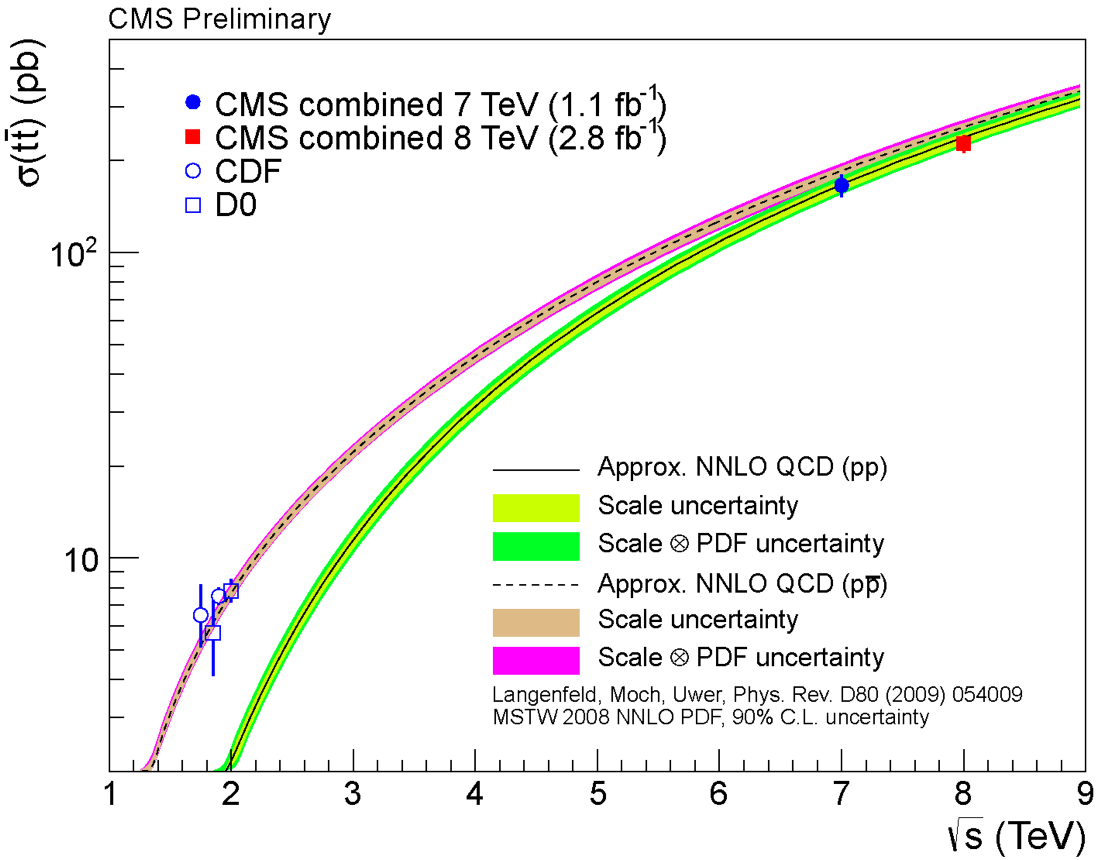

Theoretical uncertainty 7-10% partly NNLO

Theory & experiment uncertainty about equal

Very good agreement between data and expectation

Mass of the top quark

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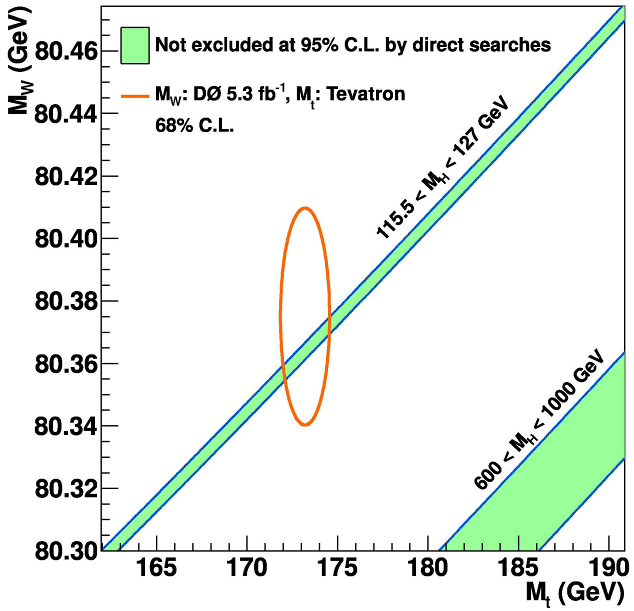
A fundamental parameter of the Standard Model



A broad spectrum of decays and methods

Note: first time a quark mass can be measured directly

(Lighter quarks to be inferred indirectly from hadron masses)

Top mass from l+jet decays

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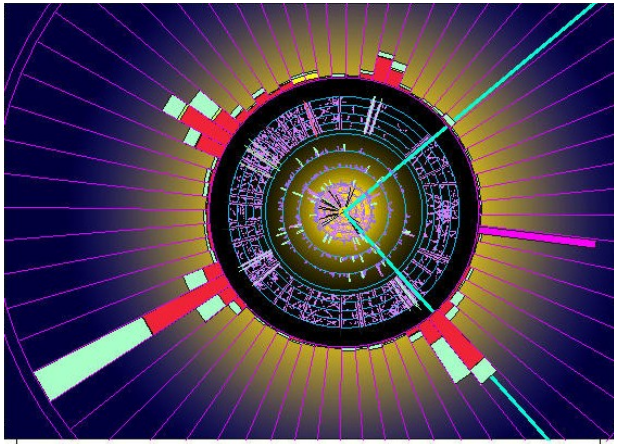
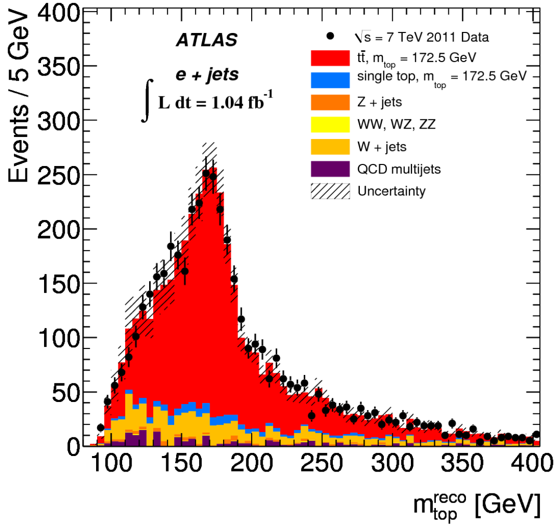
Favoured topology: $t\bar{t}$ → 4 Jets (2 b –jets) + e/μ + ν





$$M^2 = \Big(\sum_{jet\ i} E_{jet\ i} + E_l + E_\nu\Big)^2 - \Big(\sum_{jeti} \tilde{p}_{jeti} + \tilde{p}_l + \tilde{p}_\nu\Big)^2$$

The problems:

- How to get the z – component of ν
- Out of 4 (or more) jets: which jet belongs to which top?
- What is the energy scale of jets (and electrons)

Problem 1: $p_z(\nu)$

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Constraint from W - mass

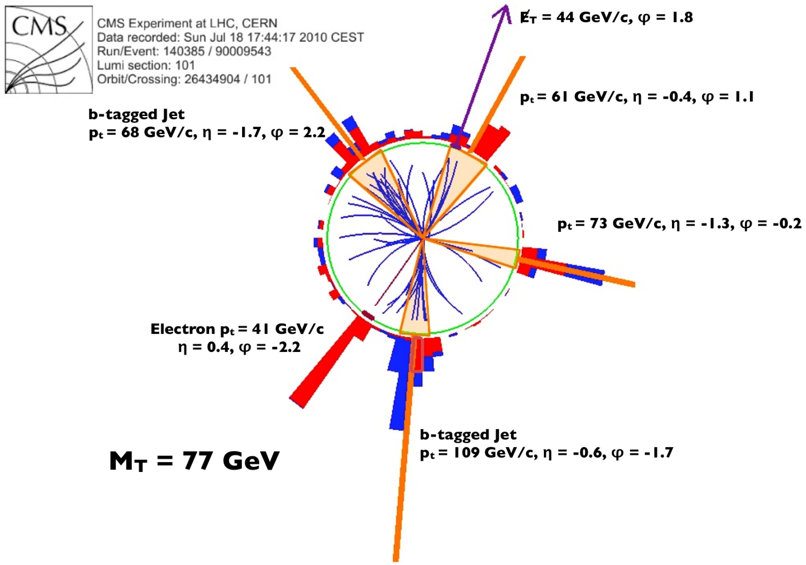
$$\mathbf{M_W^2 = (E_l + E_\nu)^2 - (p_x(l) + p_x(\nu))^2 - (p_y(l) + p_y(\nu))^2 - (p_z(l) + p_z(\nu))^2}$$

$$\mathbf{E_\nu = \sqrt{p_x^2(\nu) + p_y^2(\nu) + p_z^2(\nu)}}$$

Note: ν – mass completely negligible

Quadratic equation → 2 solutions
physics: in 70% the solution with smaller p_z correct

Problem 2: which jets?



Two facettes:

if more than 4 jets (initial state rad.)

mostly jets with highest p_T

if exactly 4 jets: which belongs to which top quark?

4 jets ➔ 4 possible assigments

($j_A j_B J_C / j_D$, $j_A j_B j_D / j_C$, ...)

Note: if b – jets identified, reduced to 2 possibilities

Important constraints

- mass (jjj) = mass(jlν) (= M_t)
- mass (jj) = M_W

Problem 3: jet energy scale

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Measure signals in calorimeter ➔ derive jet energy

Implies uncertainty!

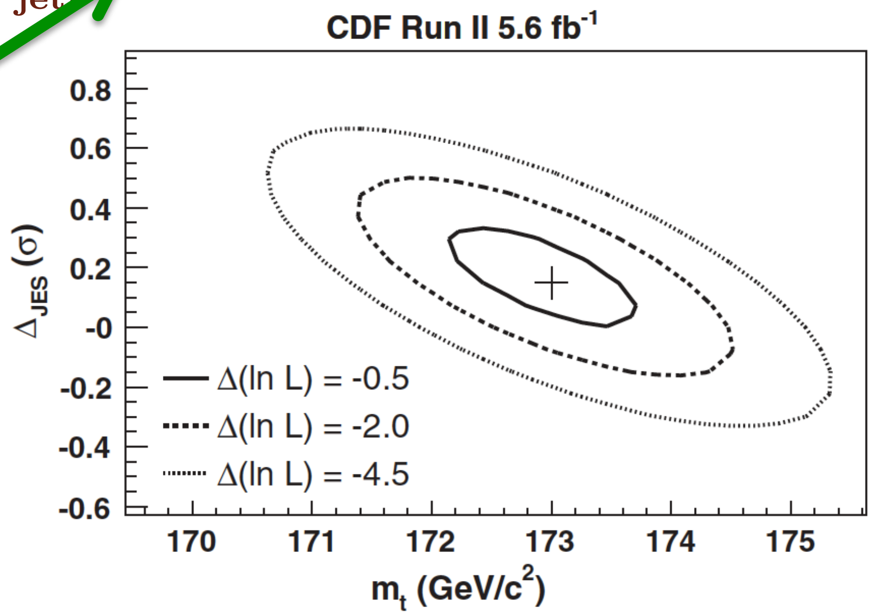
➔ relates directly to top mass

$$M^2 = \left(\sum_{\text{jet } i} E_{\text{jet } i} + E_l + E_\nu\right)^2 - \left(\sum_{\text{jet} i} \tilde{p}_{\text{jet}i} + \tilde{p}_l + \tilde{p}_\nu\right)^2$$

Top – quarks offer ‚self calibration'

M(jj) has to be equal M_W

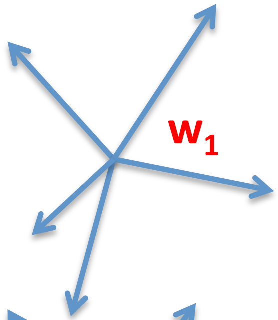
➔ change JES such that fulfilled



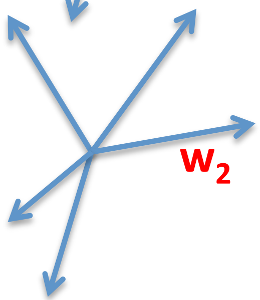
Still the (slightly) dominant uncertainty of M_t

Use all information

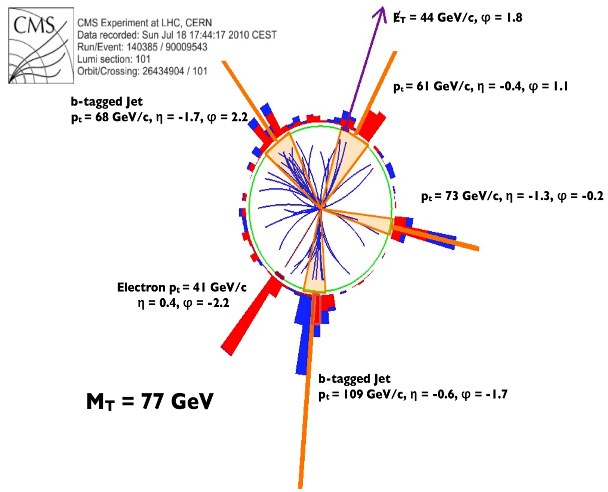
Theoretical pred with M_1(top)



Theoretical pred with M_2(top)



Convolute with experimental effects



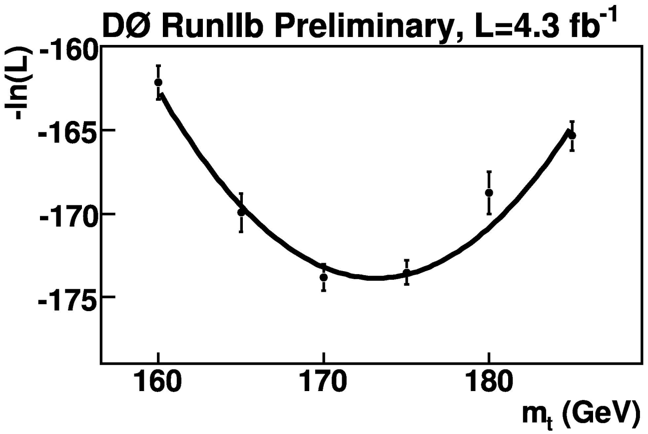
Sum over all events and find combine weights

$$W(M_1(top)) = w_A \cdot w_B \cdot w_C \cdot ...... = \Pi w_i \Longrightarrow \mathcal{L}(M_1(top))$$

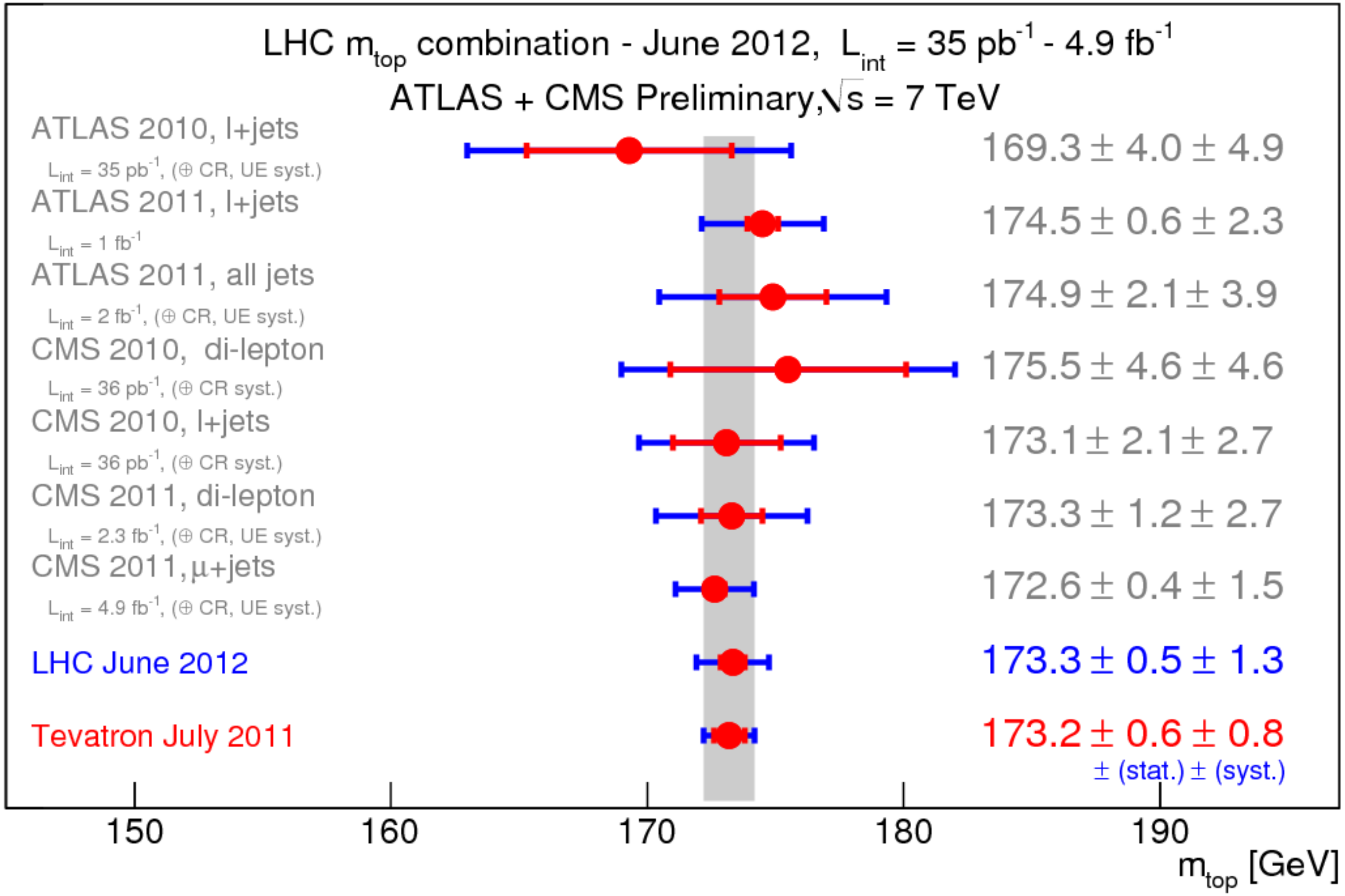
$$W(M_2(top)) = w_A \cdot w_B \cdot w_C \cdot ...... = \Pi w_i \Longrightarrow \mathcal{L}(M_2(top))$$

......

Find M(top) with maximum weight



Measurements of M_{top}



Measuring high tt - Masses

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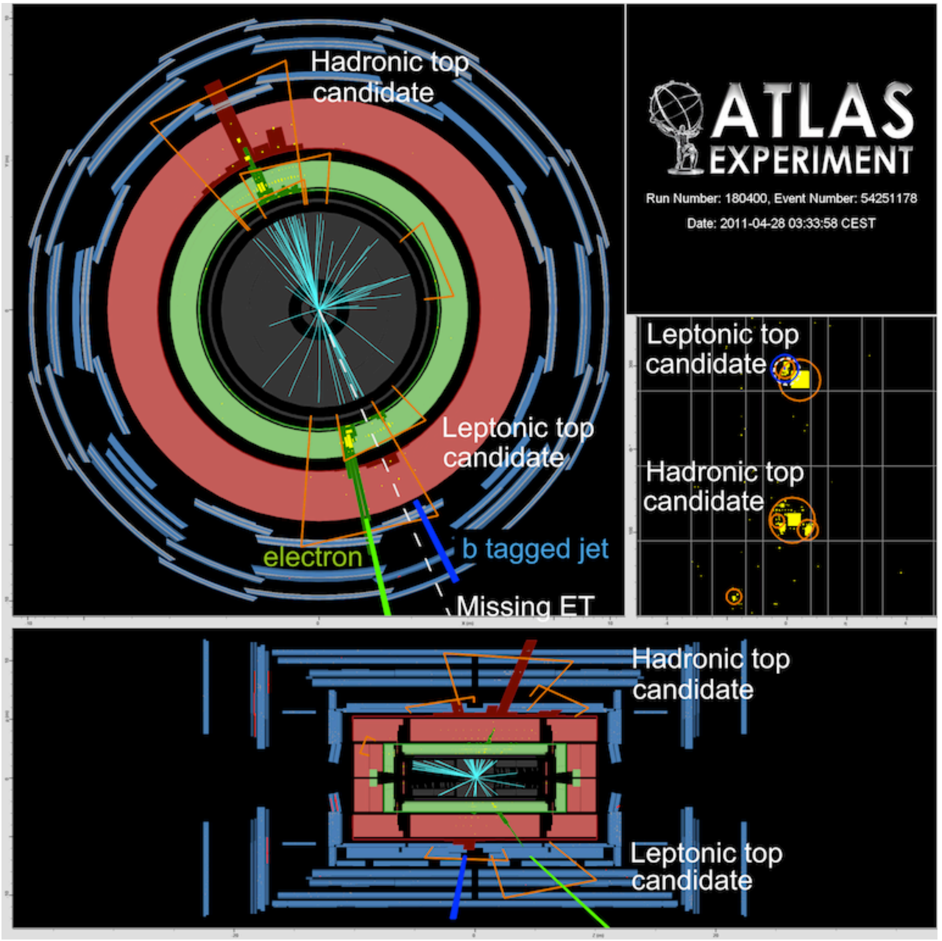
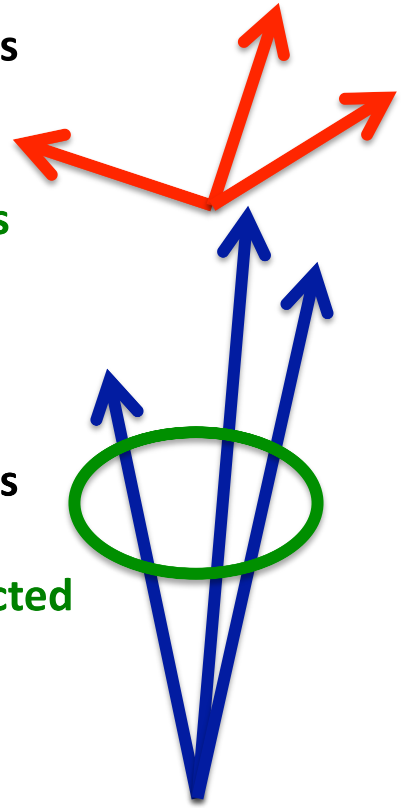


tt ➔ 3 partons at low p_T
➔ three distinct jets

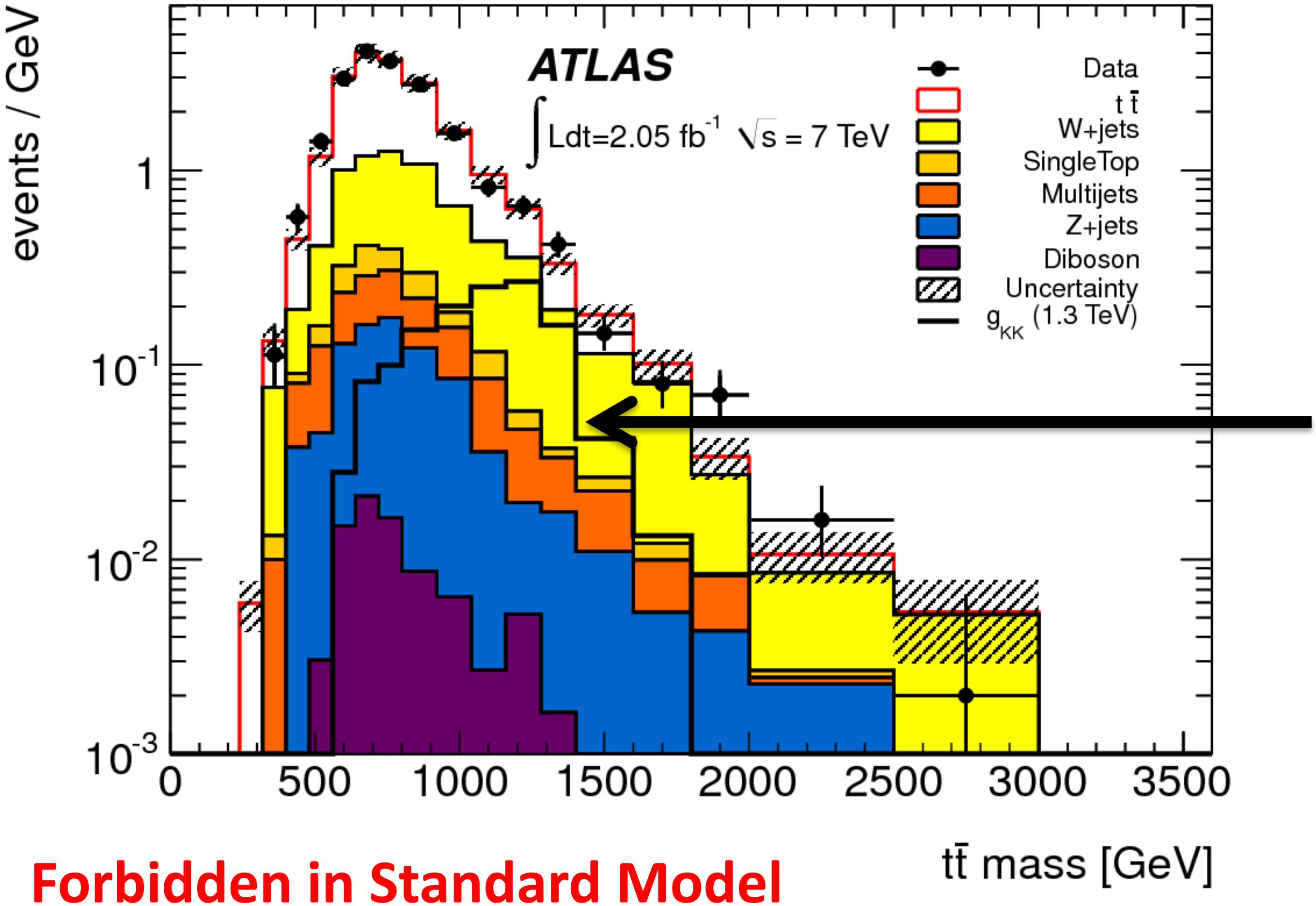


tt ➔ 3 partons at high p_T
➔ Reconstructed as one jet

High p_T top quarks: jets merge! ‚Boosted Top Quarks'

Separate from ‚normal' QCD: new algorithms required

Search for a high mass tt - resonance



Adapting analysis procedure for boosted tops

This is how a tt – resonance would look like

Forbidden in Standard Model

Postulated in many BSM scenarios

➔ As yet no new particle observed: M > 1.4 TeV

Single top production

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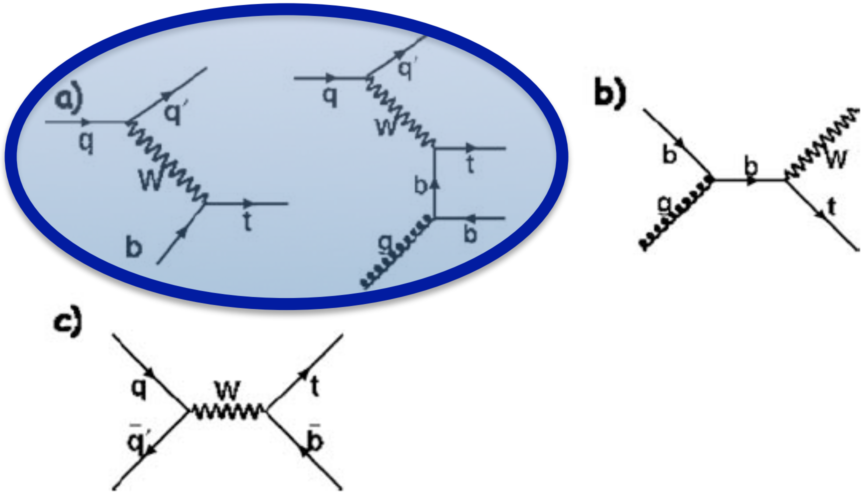
top pairs due to strong coupling,
weak coupling ➔ single top quarks

Dominant
σ(7 TeV) = 65 pb

(half of tt – Xsection)



Remember:
$W^{\pm}$ couples to fermion doublets

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}, \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}, \ldots\ldots \begin{pmatrix} t \\ b \end{pmatrix}$$

Single top production

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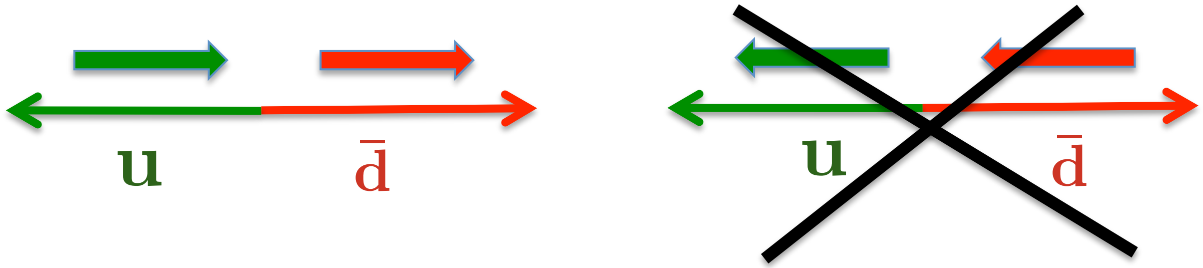
Allows detailed studies of the weak coupling of top quarks

- How often does W➔tb (and not ts, td, or something else?) i.e. measuring CKM element $|V_{tb}|$
- Does the top couple completely left handed to the W? (as all other fermions do)

Example: $W^+ \rightarrow u\bar{d}$

Spin direction

Momentum



Forbidden in weak interactions

- new particles, additional couplings ....

Fighting substantial background

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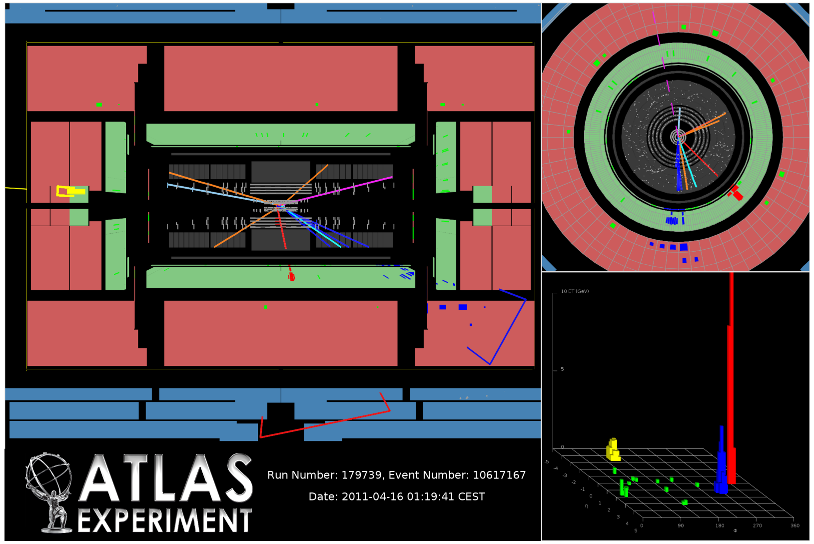
After selection (in 1 fb^{-1} LHC data)

Expect ~ 175 signal events

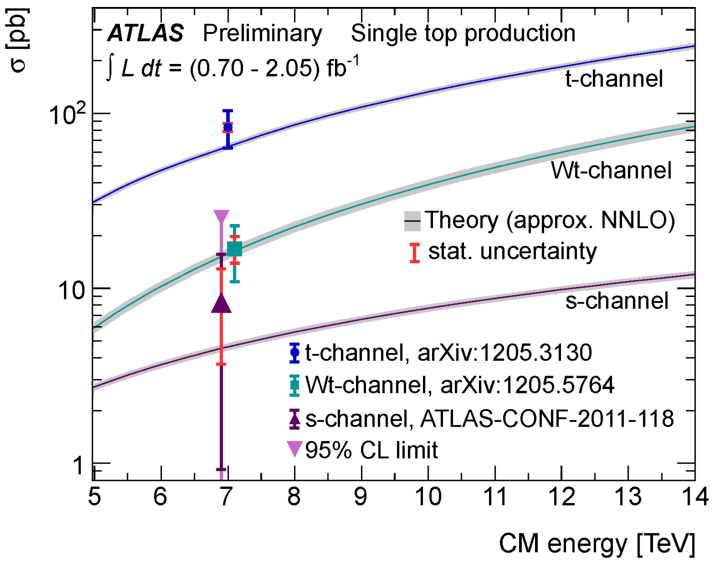
~ 250 background events



Require:

2 jets, 1 isolated lepton

missing energy



Individual components measured

precise measurements to follow

Top Quarks @ hadron colliders

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- Top quark heaviest known particle
- LHC will be a ‚top – factory'
- Top mass known to~ 1% ➔ input to SM fits
- (Differential) cross section: search for new resonance
- Decay properties tested
- Single top a window to weak top couplings

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Standard Model @ Hadron Colliders
IV. Higgs Boson: the exclusion range

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Electroweak symmetry breaking

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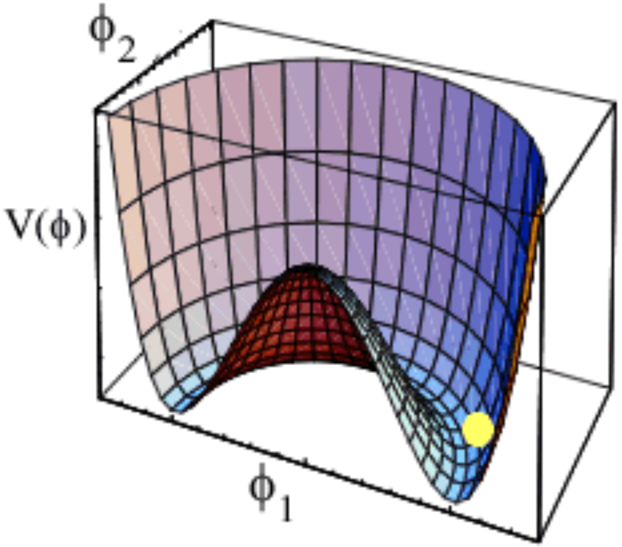
Masses of bosons and fermions break basics ingredients:
- fermion masses break local gauge invariance
- boson masses violate unitarity
  partial wave analysis of weak $W_L W_L$ scattering suggests

$$M_H \leq \left(\frac{8\pi\sqrt{2}}{3G_F}\right)^{1/2} \sim 1 \ \mathrm{TeV}$$

Alternatively: strongly coupled theory ➔ many W's, ...

At least around the TeV scale
- either generation of masses (W_L scattering) is solved
- or new phenomena

The solution ‚Higgs mechanism‘



The Standard Model answer:

Higgs fields

- gives mass to bosons
- provides means for fermion mass
- implies elementary physical particle
- gives mass to Higgs Boson

$$\mathbf{V} = -\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

$$\frac{\partial \mathbf{V}}{\partial \phi} = 0 \Longrightarrow \phi_0 = \mathbf{v}^2 = \frac{\mu^2}{\lambda}$$

v: ‚vacuum expectation value‘

M_W ➔ v = 246 GeV

Introduce potential (by hand)

Two unknowns: λ, μ

Mass of W	$M_W = \frac{1}{2} v \cdot g$
Mass of Higgs	$M_h = \sqrt{2 \cdot \lambda} \cdot v$
Mass of fermions	$M_f = \frac{1}{\sqrt{2}} G_f \cdot v$

A few notes on mass

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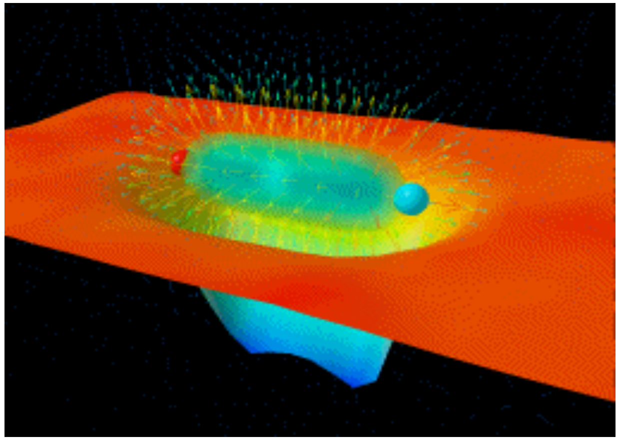
Persistenly basic problem of physics Newton, Einstein

What makes the mass of a proton to be 939 MeV

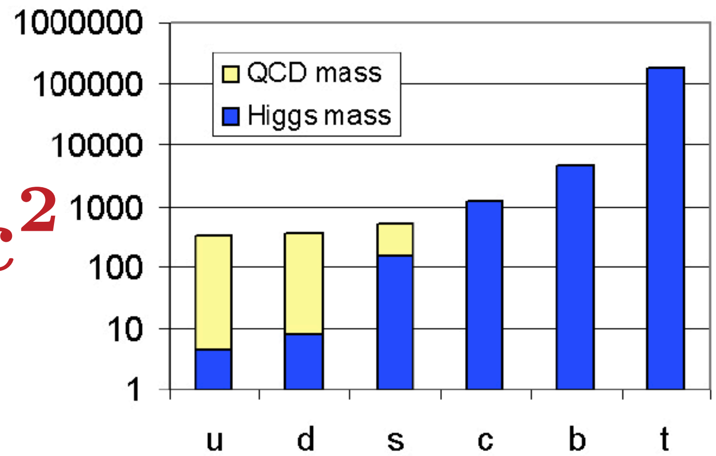
If (2 $m_u + m_d$ ~ 10 MeV)

Derek Leinweber



$$E = m \cdot c^2$$

B.Müller



A dynamical generation of hadron masses →

99% of visible matter due to strong interaction

This principle does not work if particles are elementary!

The Higgs Boson: well known!

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..... except its mass!

What is to be known to search for the Higgs boson:

- how is it produced?
- how strongly is it produced?
- how does it decay?

Devise search strategy along this line

How does the Higgs decay?

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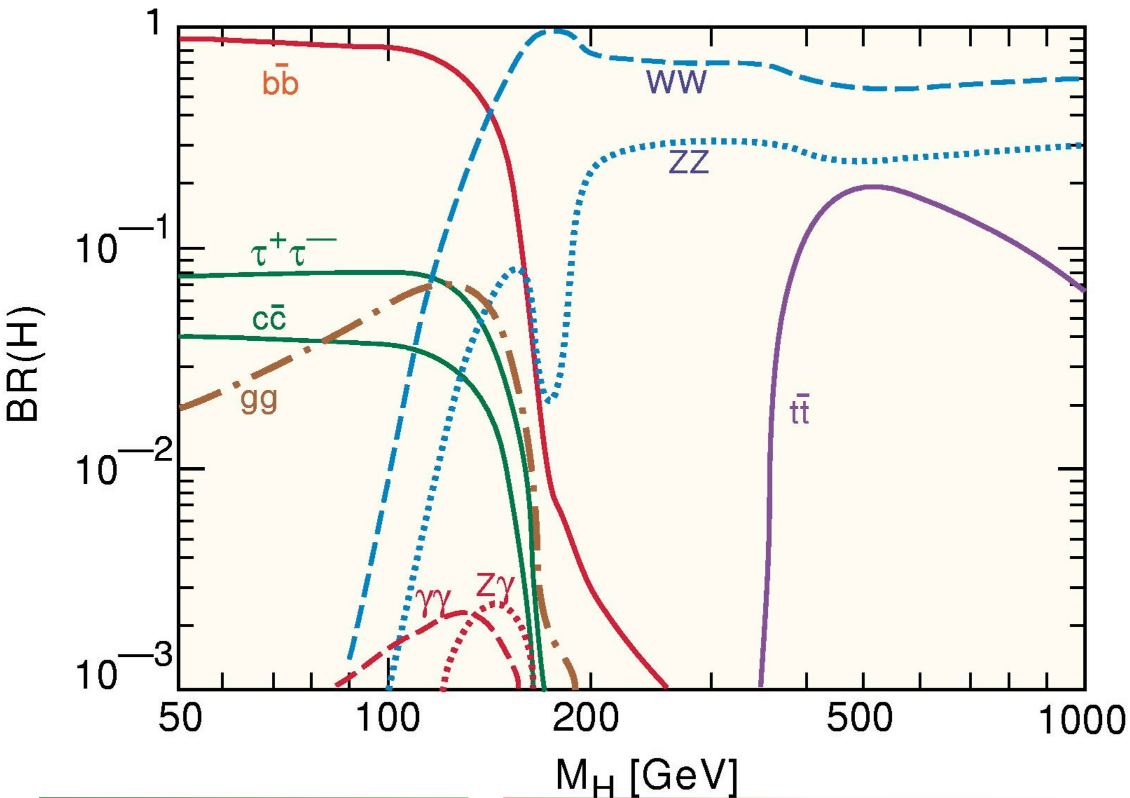
i.e. to which particle does it preferentially couple?



Preference: fermions (especially bottom quark)

Preference: weak bosons (especially W^+W^-)

How strong is the coupling?

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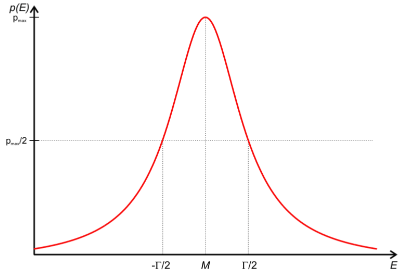
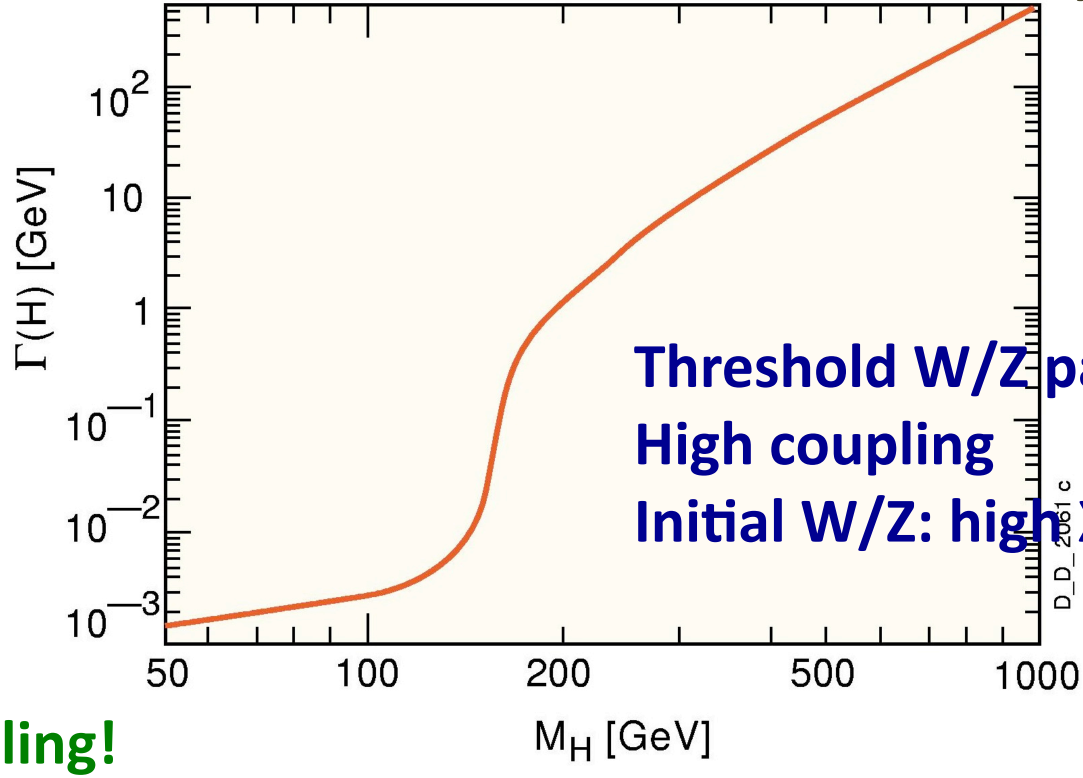
Visualised by width of higgs boson

$\Gamma(H) \sim M(H)$





Threshold W/Z passed:
High coupling
Initial W/Z: high X-section

Very small coupling!

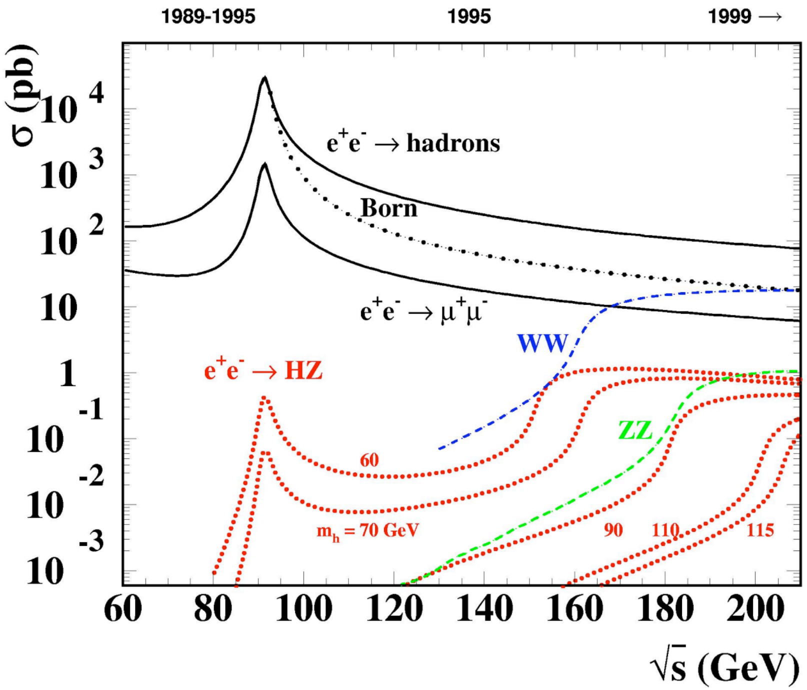
LEP: first serious go at the Higgs

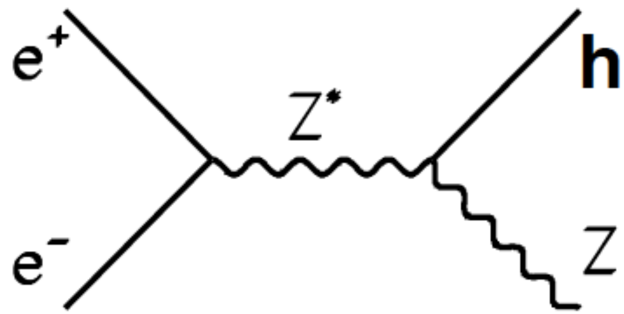
Colliders have electrons or u, d quarks in initial state

➔ too small X – section, i.e. e^+e^- and pp – collisions need catalyst

‚lots' of Z^0 (or $W^{\pm}$) required to produce Higgs bosons

CERN's e^+e^- collider LEP the first machine to produce these





Predominantly decaying into bb - pairs

The excitement of 2000

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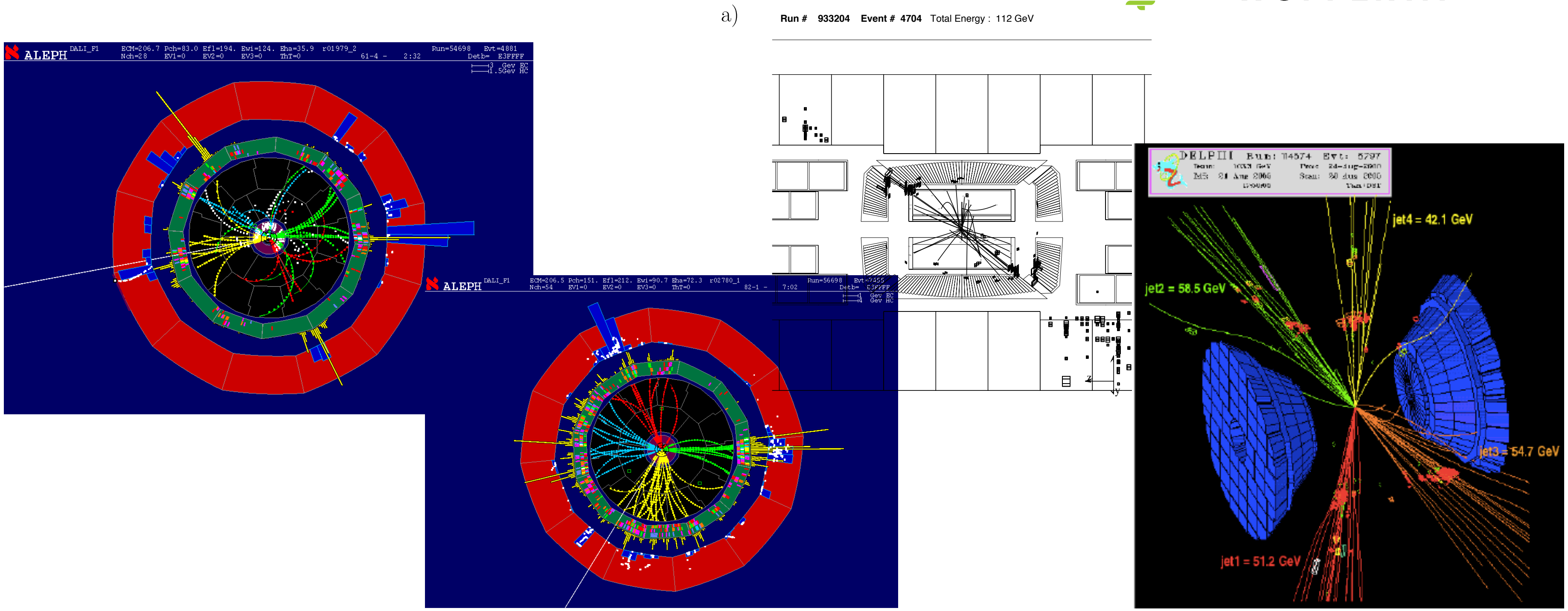

Close before LEP shutdown: experiments observed excess of ‚Higgs – like' events
2.3 standard deviations
‚should I stay or should I go?'

Described in recent book on Higgs

The LEP legacy

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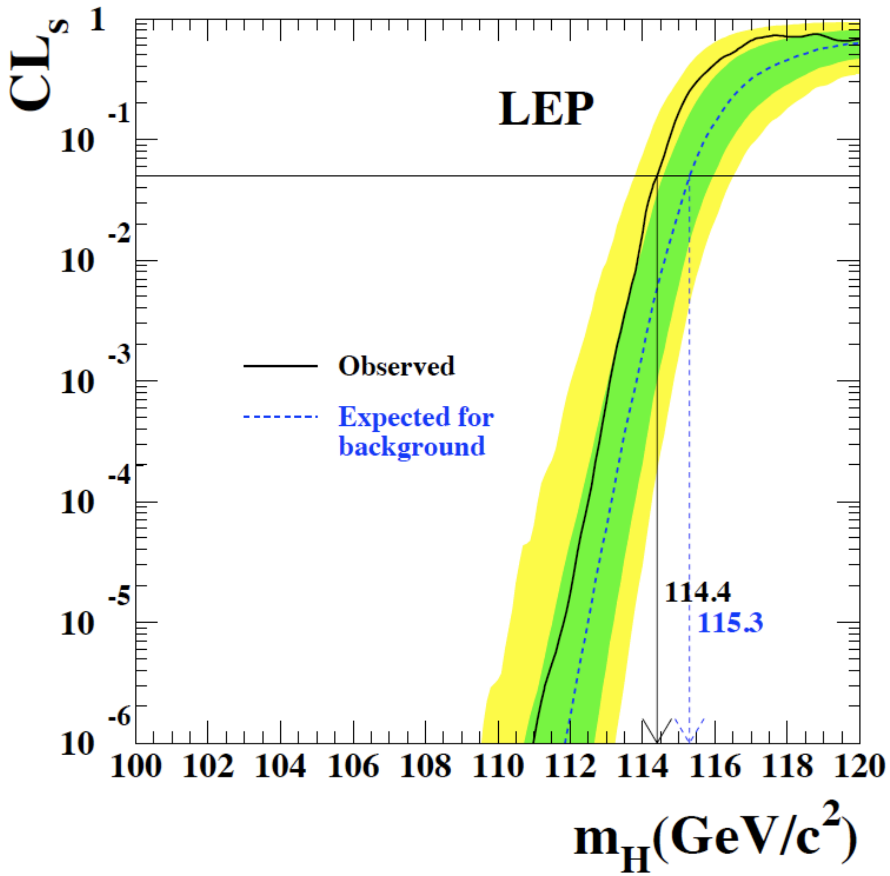
More detailed study: some excess of 1.7 standard deviations
Nothing to claim evidence

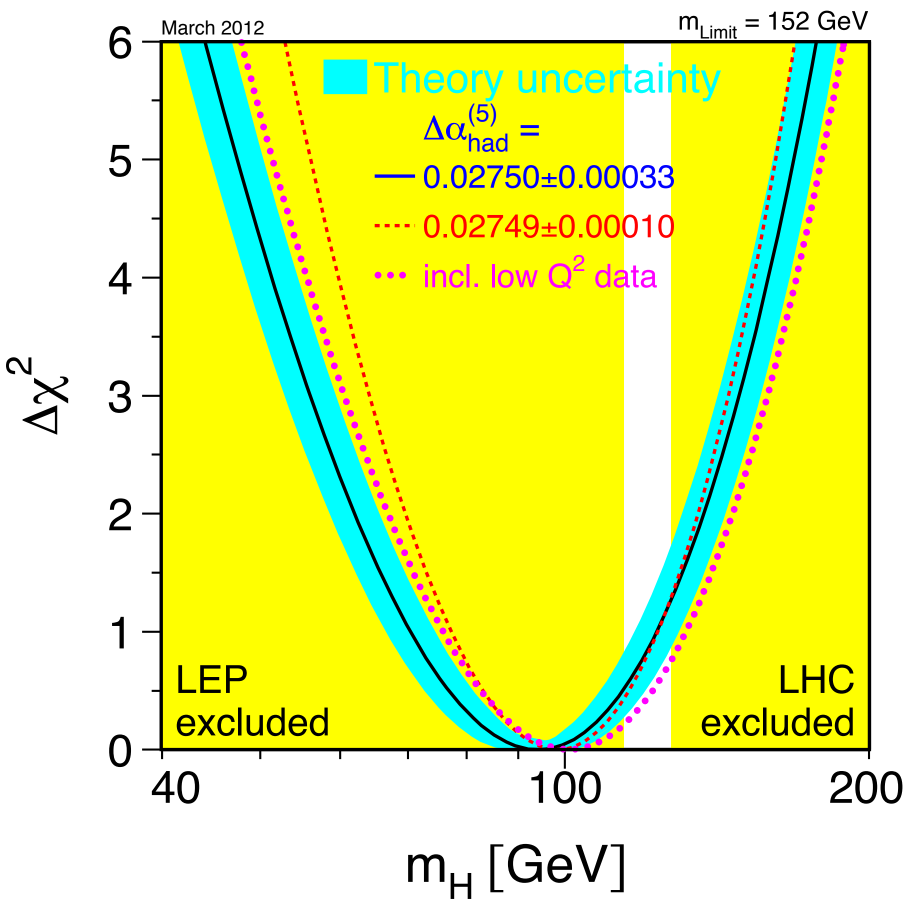


Combination of four LEP experiments:

m_H > 114.4 GeV

BTW: note ‚expected' > ‚observed' limit

+ limits from quantum fluctuations



Electroweak fits

$$M_H = 92^{+34}_{-26}\,\mathrm{GeV}$$

$$M_H < 185\,\mathrm{GeV} \quad @95\%\mathrm{CL}$$

Preferred value below excluded range

➔ Light Higgs preferred

Theory constraints

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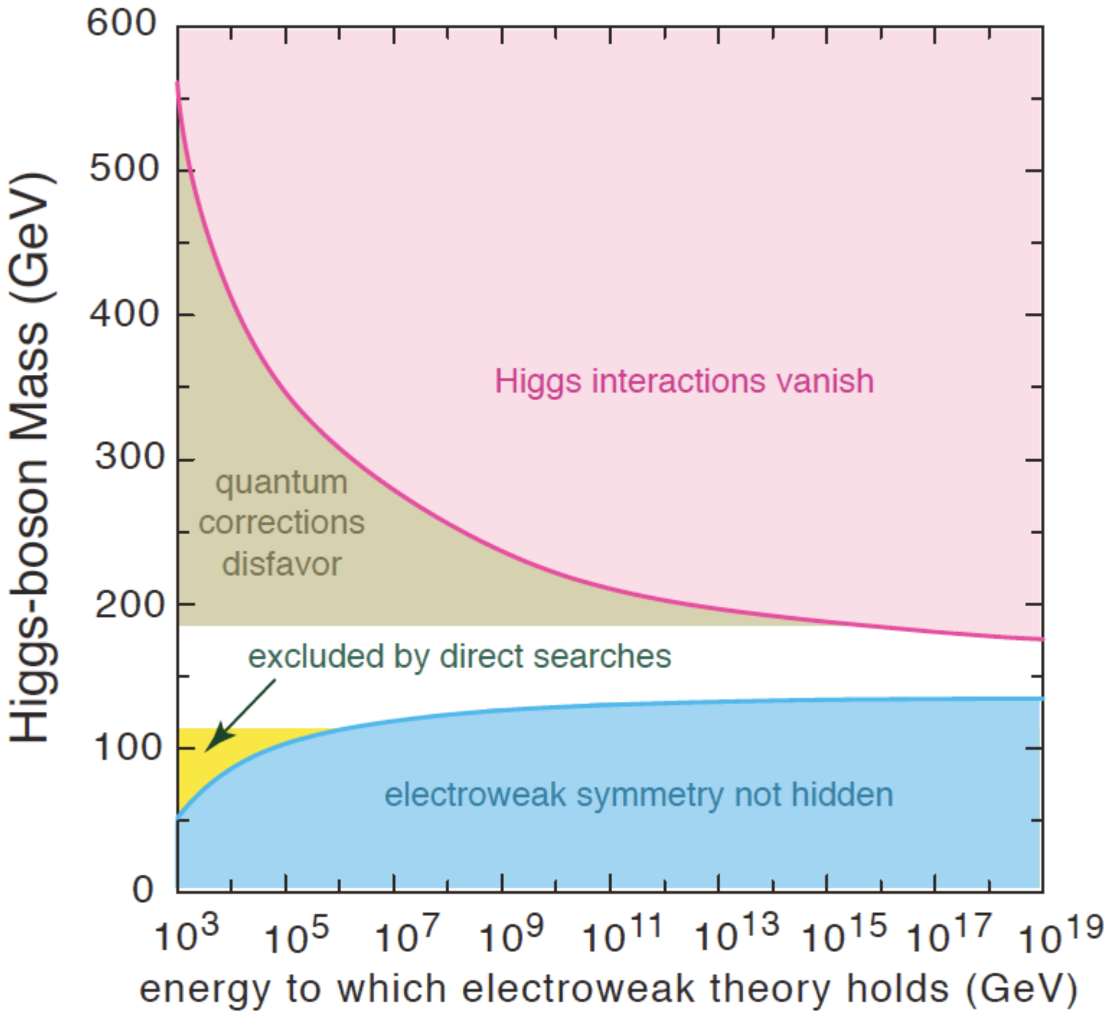
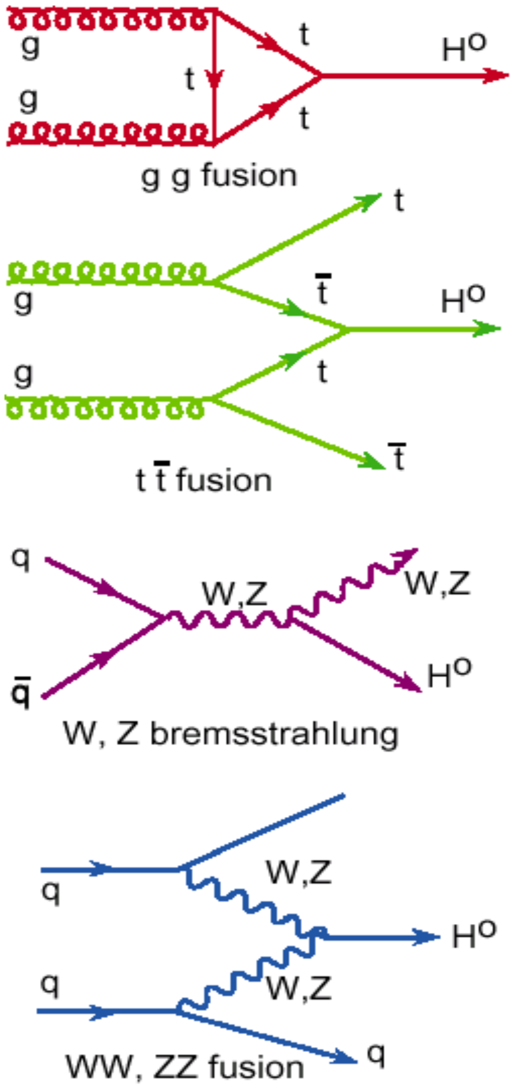
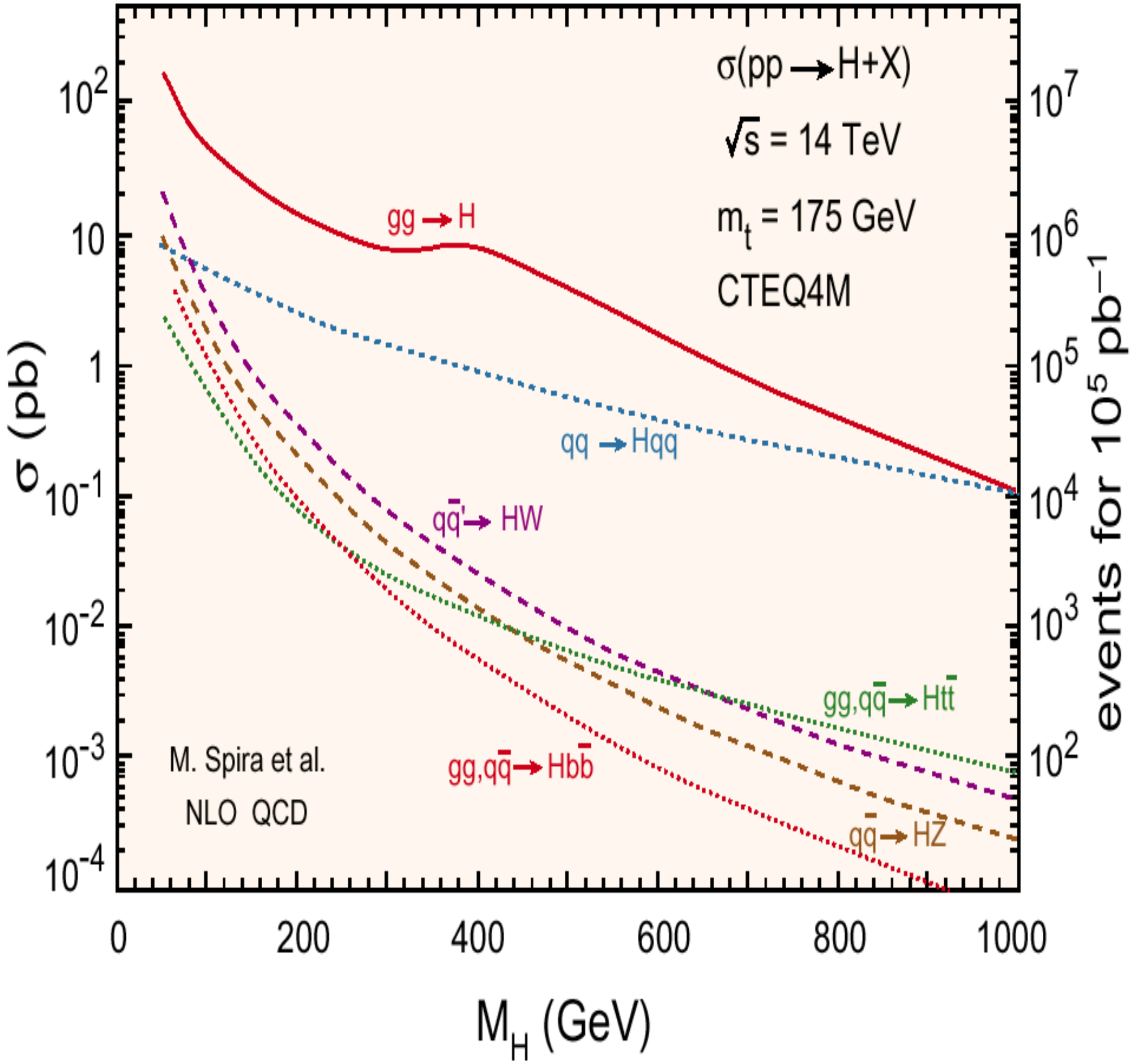


Theoretical calculations:
m_H < 800 GeV

If <134 or >177 GeV extension of Standard Model required

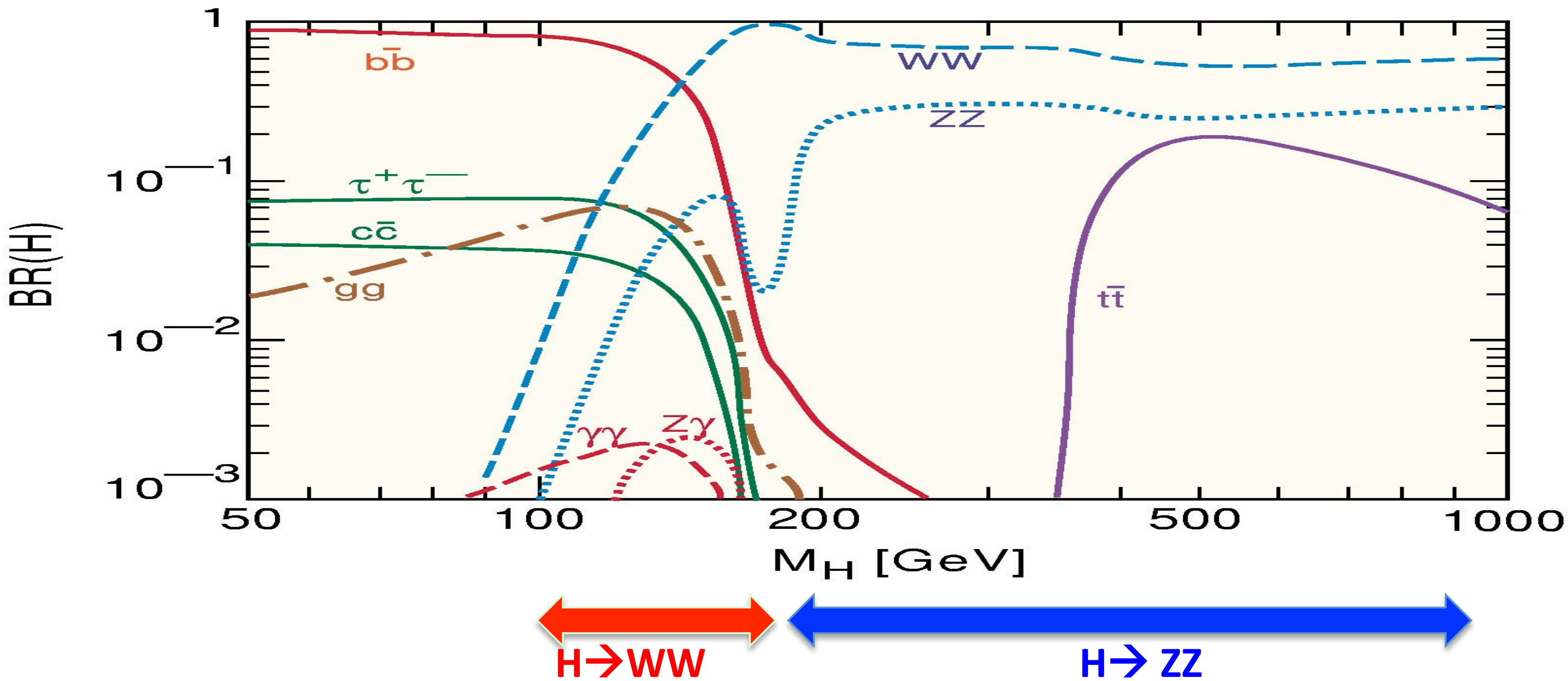
Higgs searches at Hadron Colliders





Favoured signatures @ LHC

- No decays in jets! Background formidable → leptons
- Special properties: mass peaks
- High branching ratios



Approaching the 125 GeV signal

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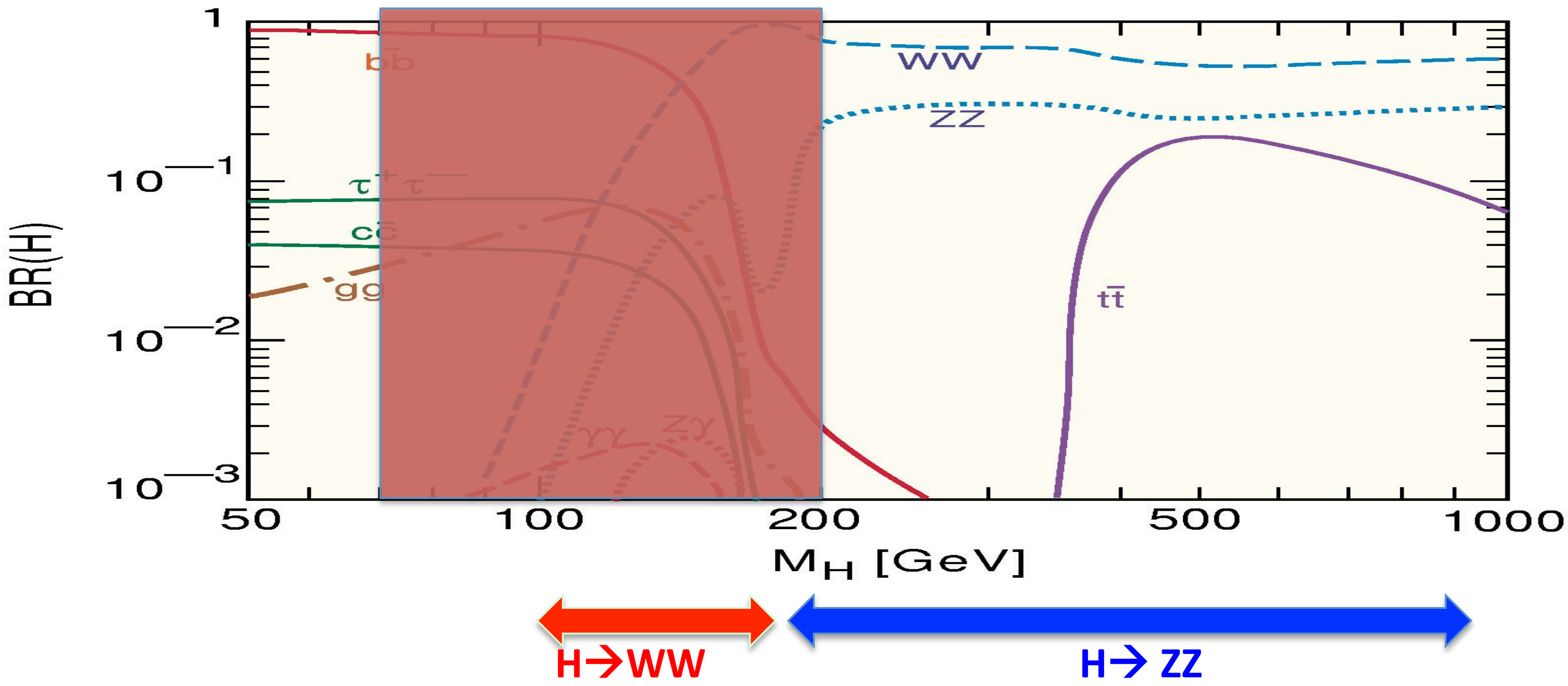
Today: discuss results in high mass region



The easiest channel: H➔ZZ

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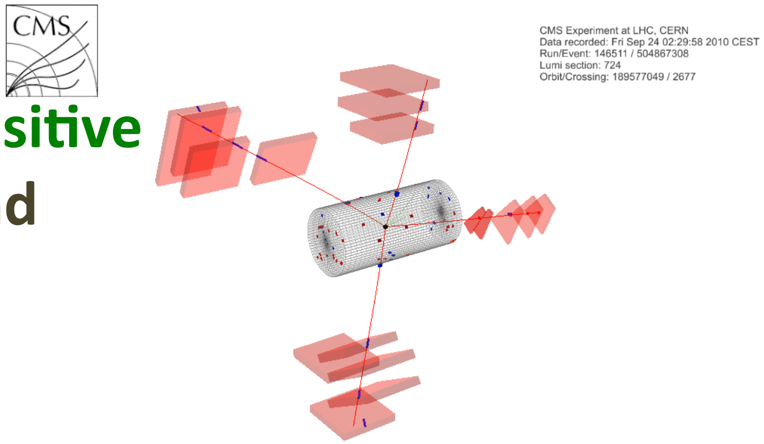
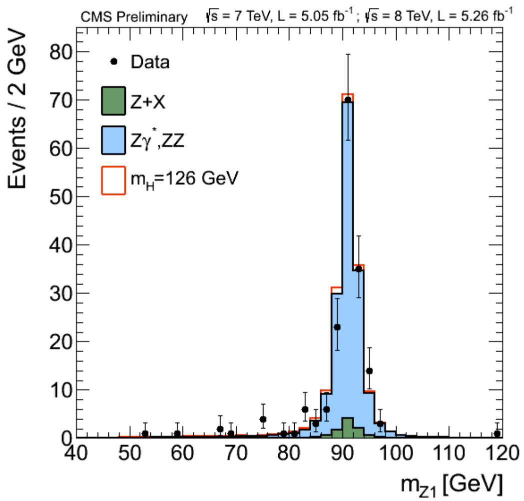
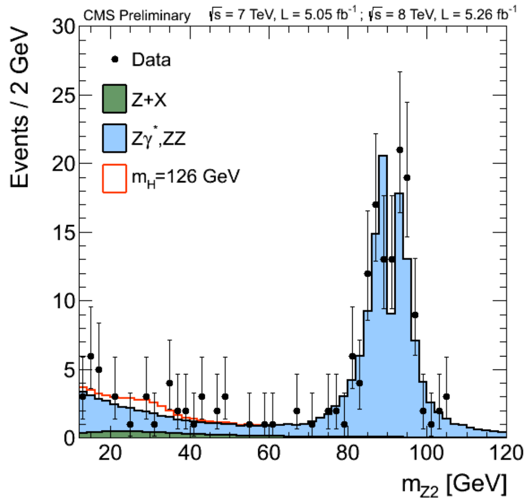
Higgs masses > 200 GeV:

H➔ ZZ ➔ four charged leptons most sensitive



a. 4 high energy leptons little background
b. Frequent H➔ ZZ decays, but only 0.4% decay into lepton pairs!
c. Pairs of (e^+e^-), (μ^+,μ^-) to have Z^0 mass
d. $M(Z^0Z^0) = M(H)$ very good mass resolution!





Decay channel ZZ → (l^+l^-) (l^+l^-)

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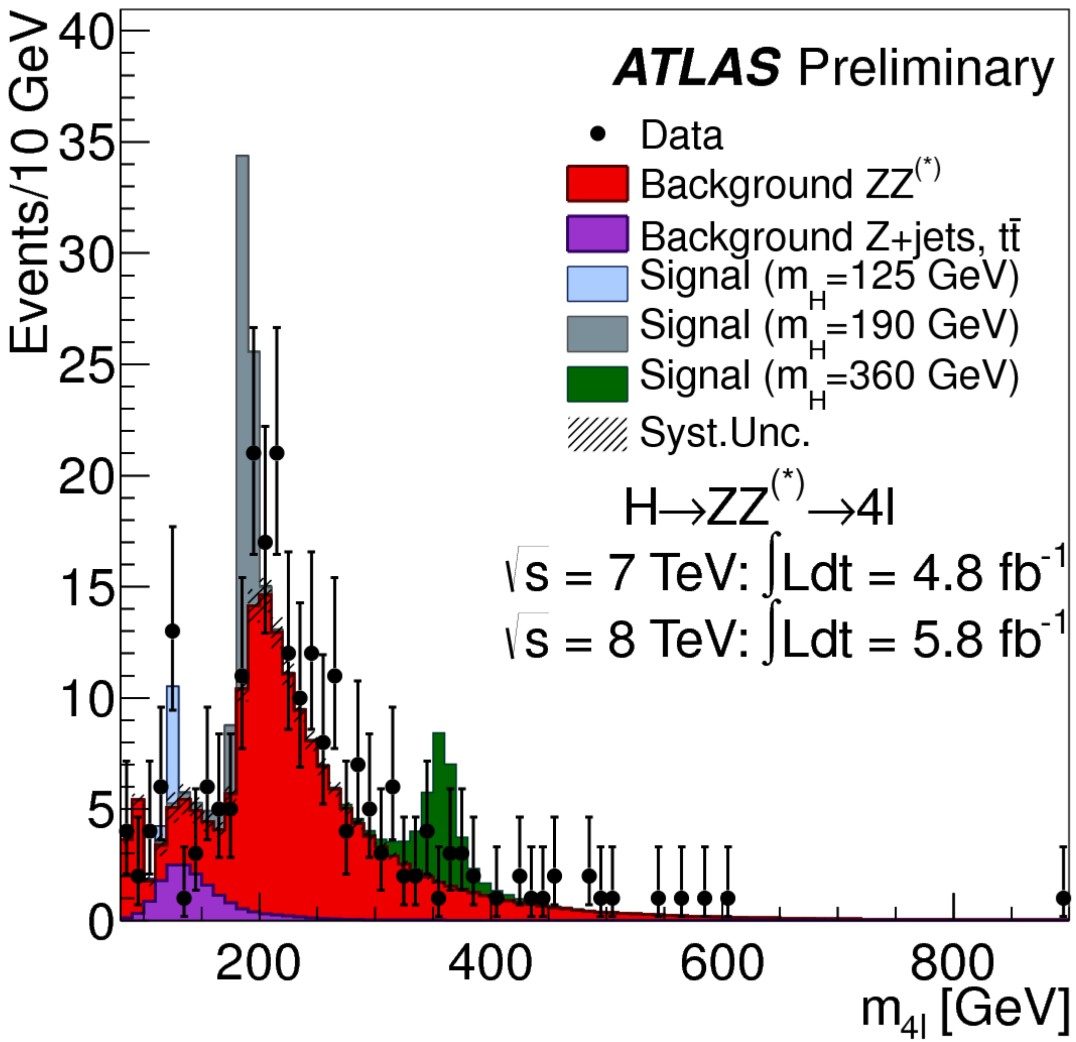

For masses > 200 GeV:

- **yield and shape agree**
- **well with continuum ZZ production**
- **no resonance observed**

→ proceed to set limits

95% CL Limits ZZ → $(l^+l^-)(l^+l^-)$

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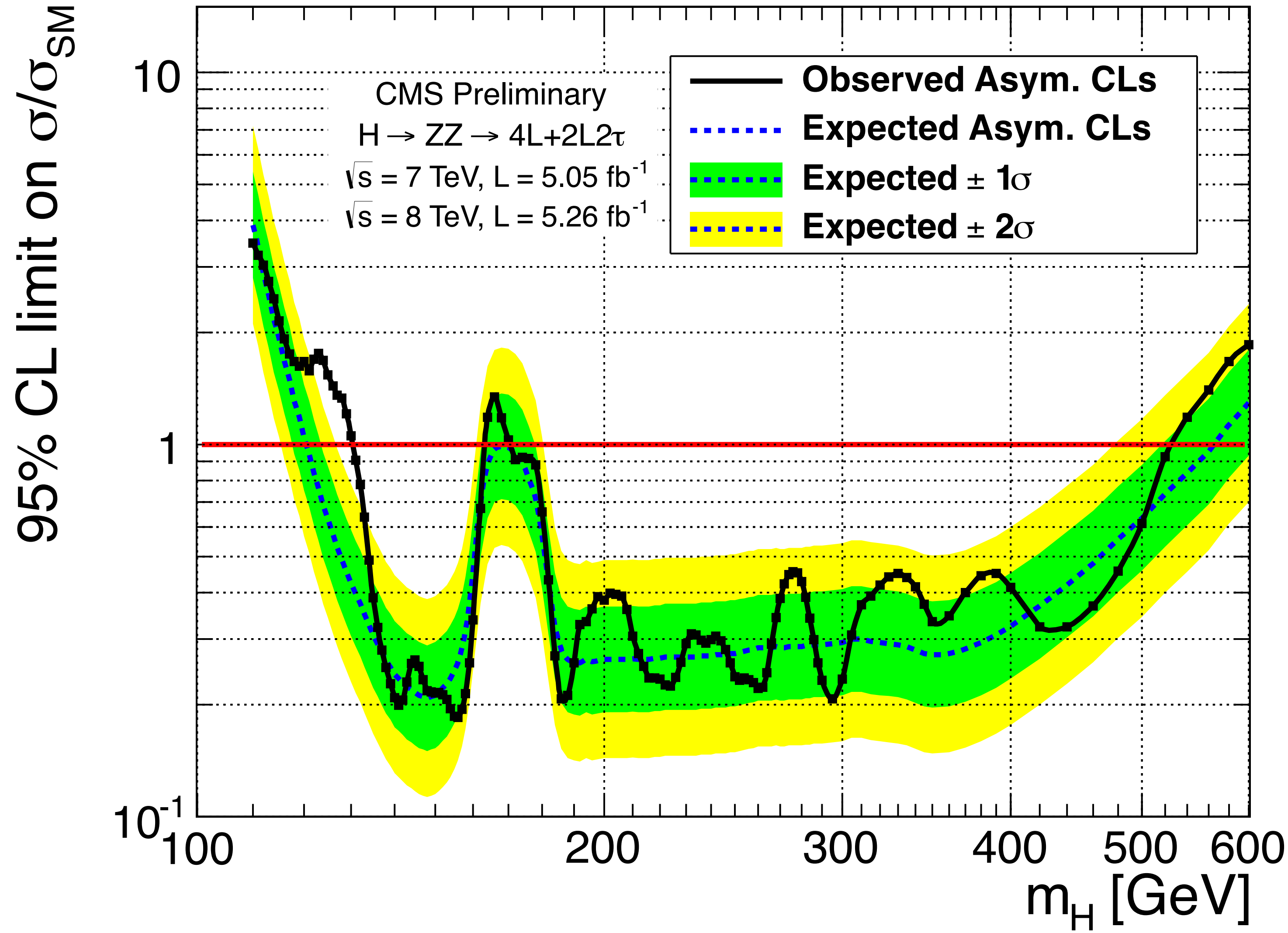


Test if data EXCLUDE hypothesis

Step 1: X-section at mass m_H that can be excluded @ 95% CL

Step 2: Plot ratio *σ(exclusion)/ σ (Xsec of SM expectation)*

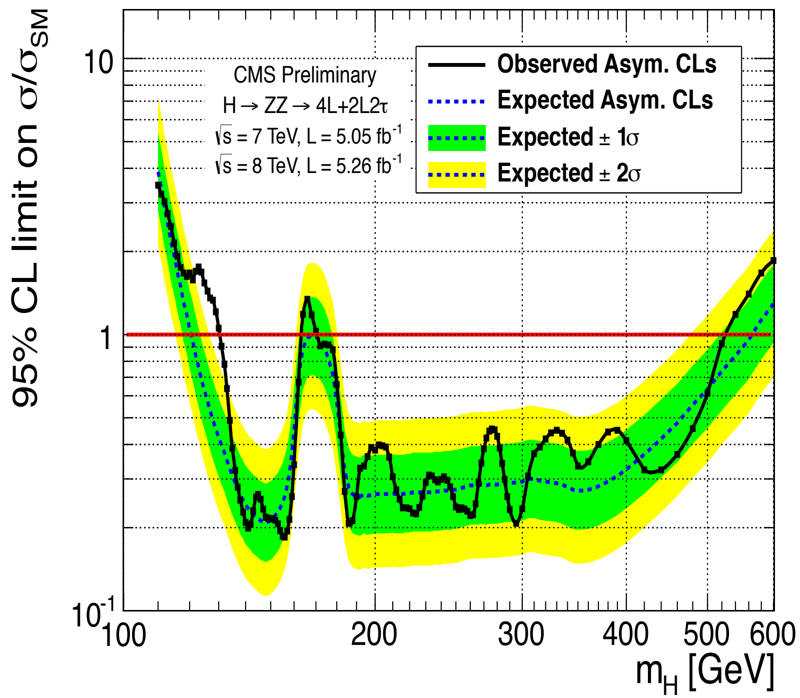
➔If *below* 1:

Higgs excluded in mass range

➔If *above* 1:

Higgs cannot excluded since either: ‚hint', ... ‚signal'

***or*: no sensitivity for exclusion**



Sensitivity of *exclusion* (not discovery): expected, dotted line

IF data line *above* dotted line: more observed than expected

IF data line *below* : less observed than expected

95% CL Limits ZZ → $(l^+l^-)(l^+l^-)$

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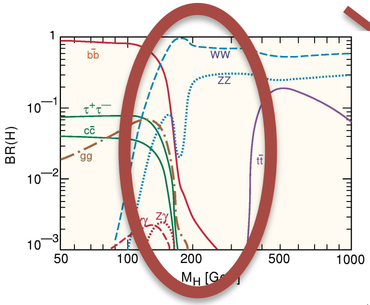
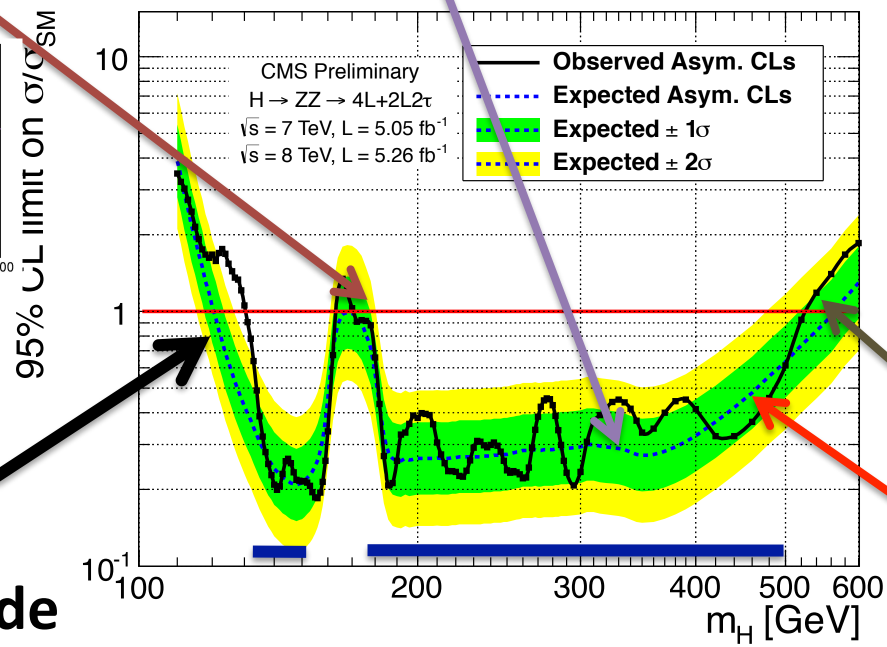
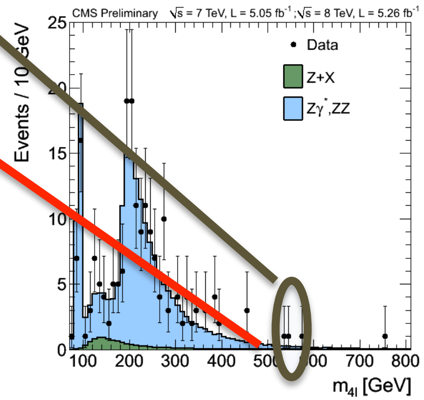
Simulation with NO signal, but luminosity, detector effects, ...
➔ EXPECTED limit

No sensitivity
Small σ*BR





Oscillations around expectation: more or less events than background expectation



INTERESTING!
Data can exclude less than expected by large margin

Regions of ratio < 1
EXCLUSION!

p - value probability of stat. fluctuation

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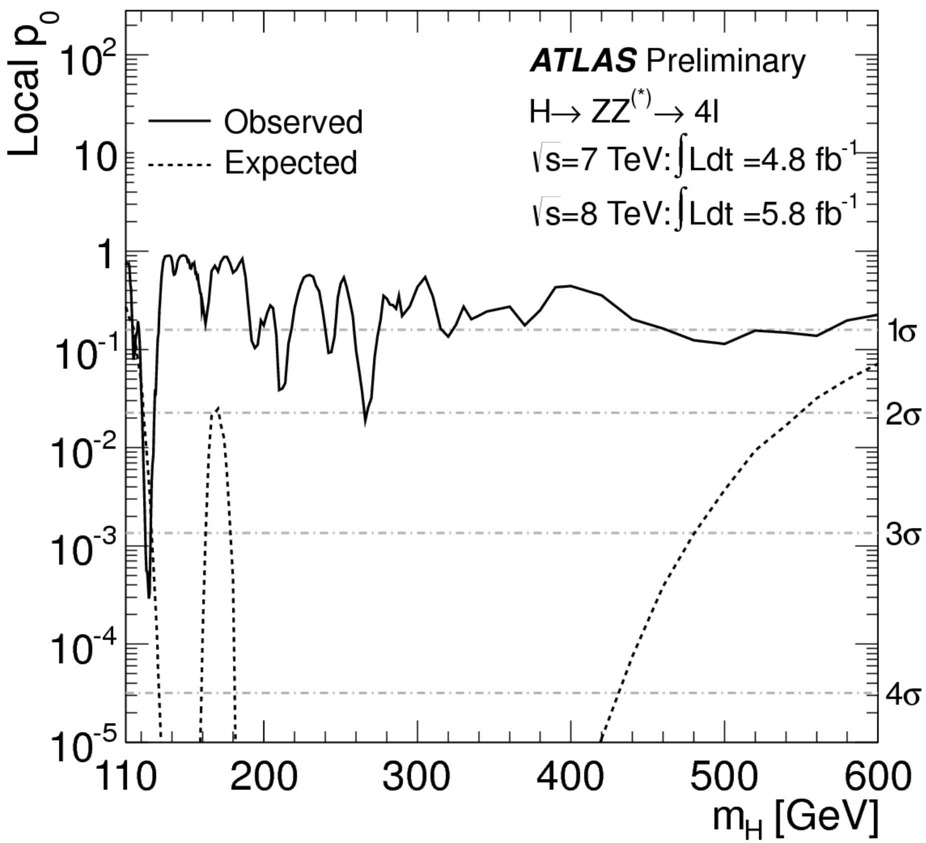
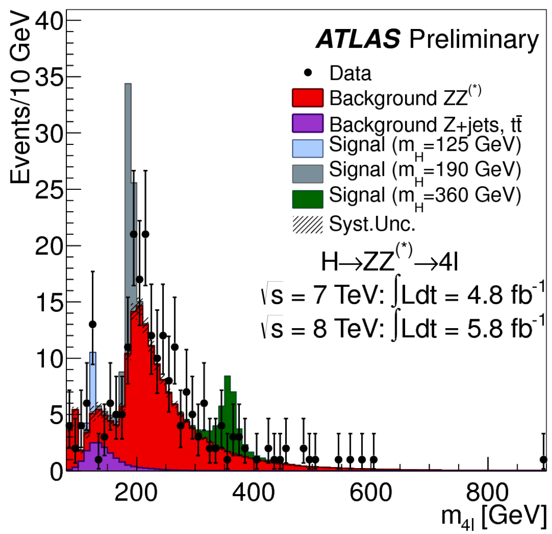
‚p – value' : how likely is it that at a certain mass M_H
- the expected background fluctuates upward
- to produce at least the number of observed events





Observed dearth or excess reflected in wiggles

Convention:

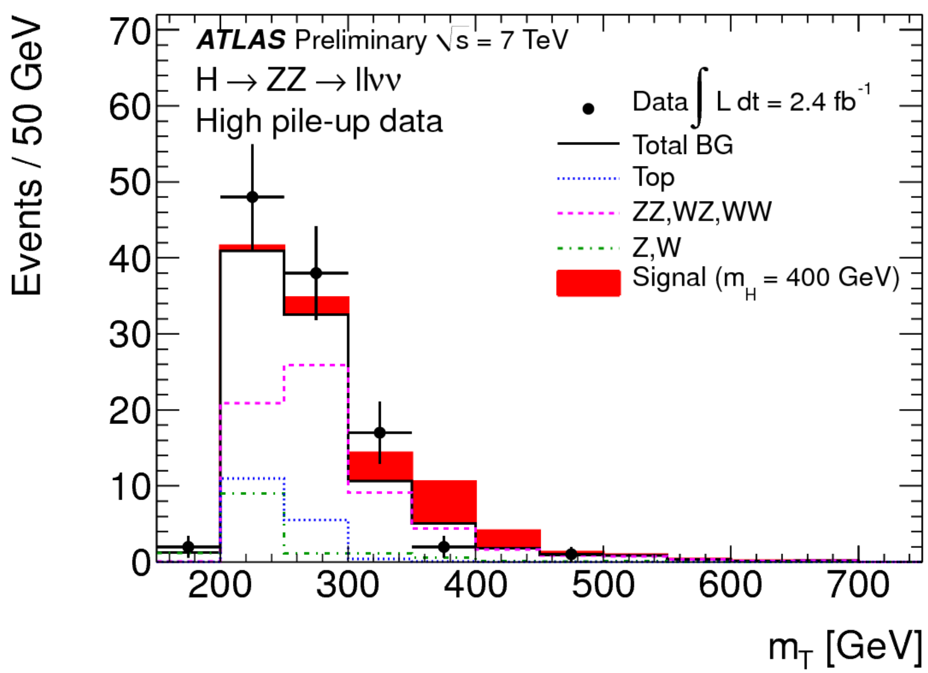
Signal observed if p > 5σ

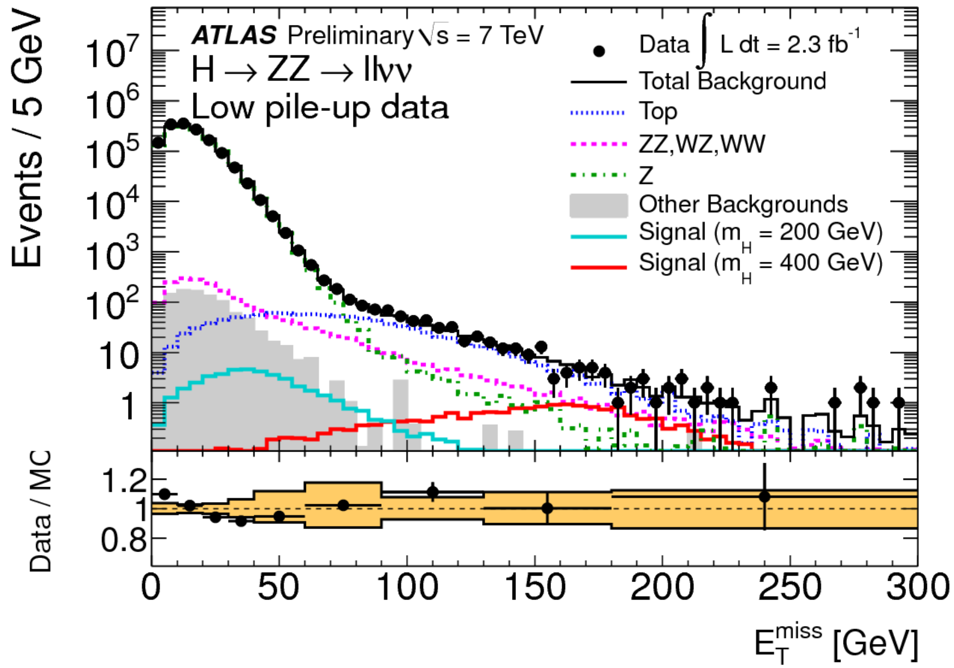
Decay channel ZZ → llνν

Decays into e^+e^-, $\mu^+\mu^-$ die out because of statistics for high masses

Increase statistics by using one Z → νν: 6x as large

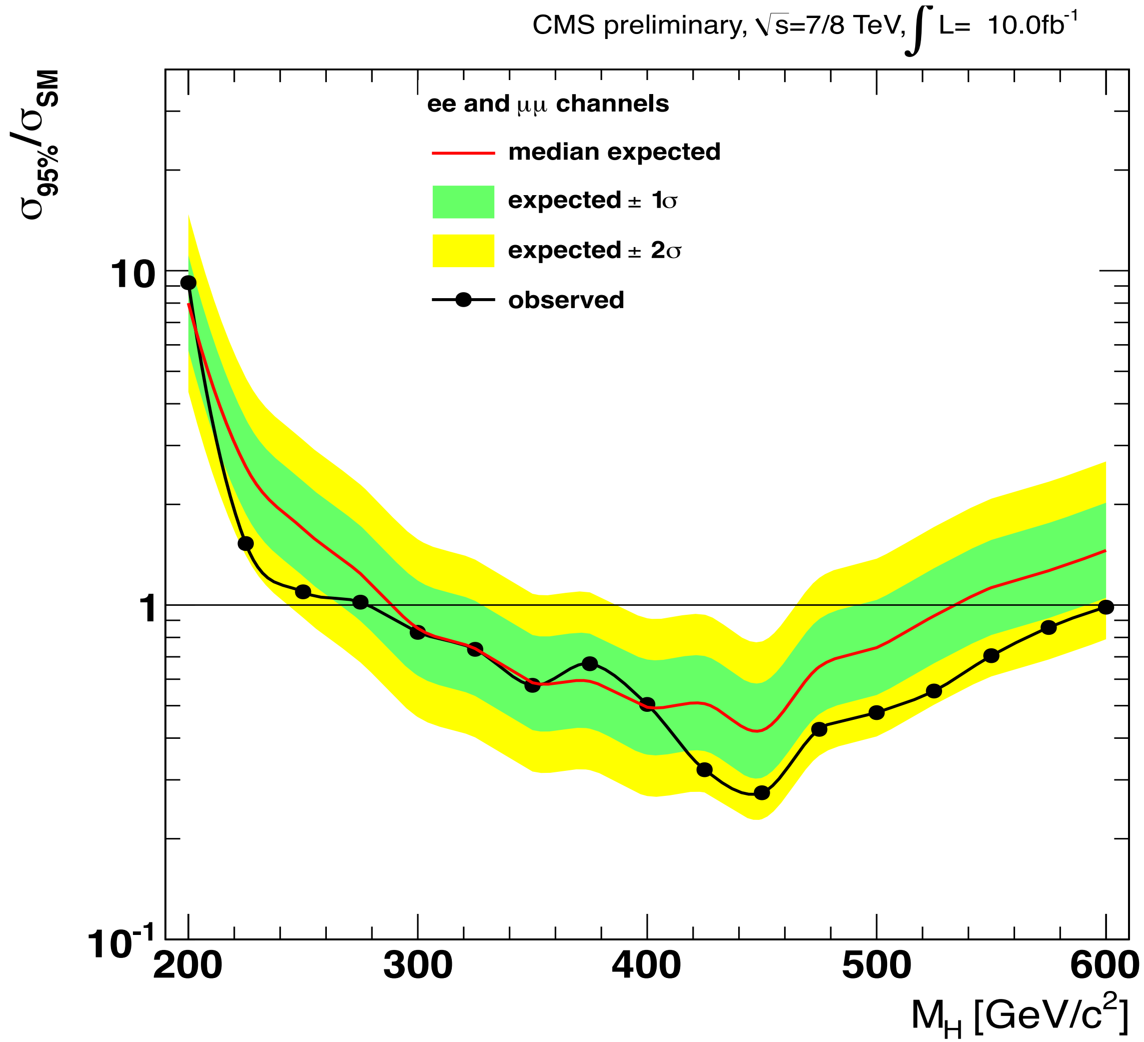
Note: advantage of mass resolution dissolves at high M_{Higgs}





Key ingredient: excessive missing transverse energy

95% CL Limits ZZ → (l^+l^-) (nunu)



Standard Model Higgs excluded for masses 280 – 600 GeV

i.e. higher limits than four lepton channel

(Note EXPECTED sensitivity about equal)

Combining all searches

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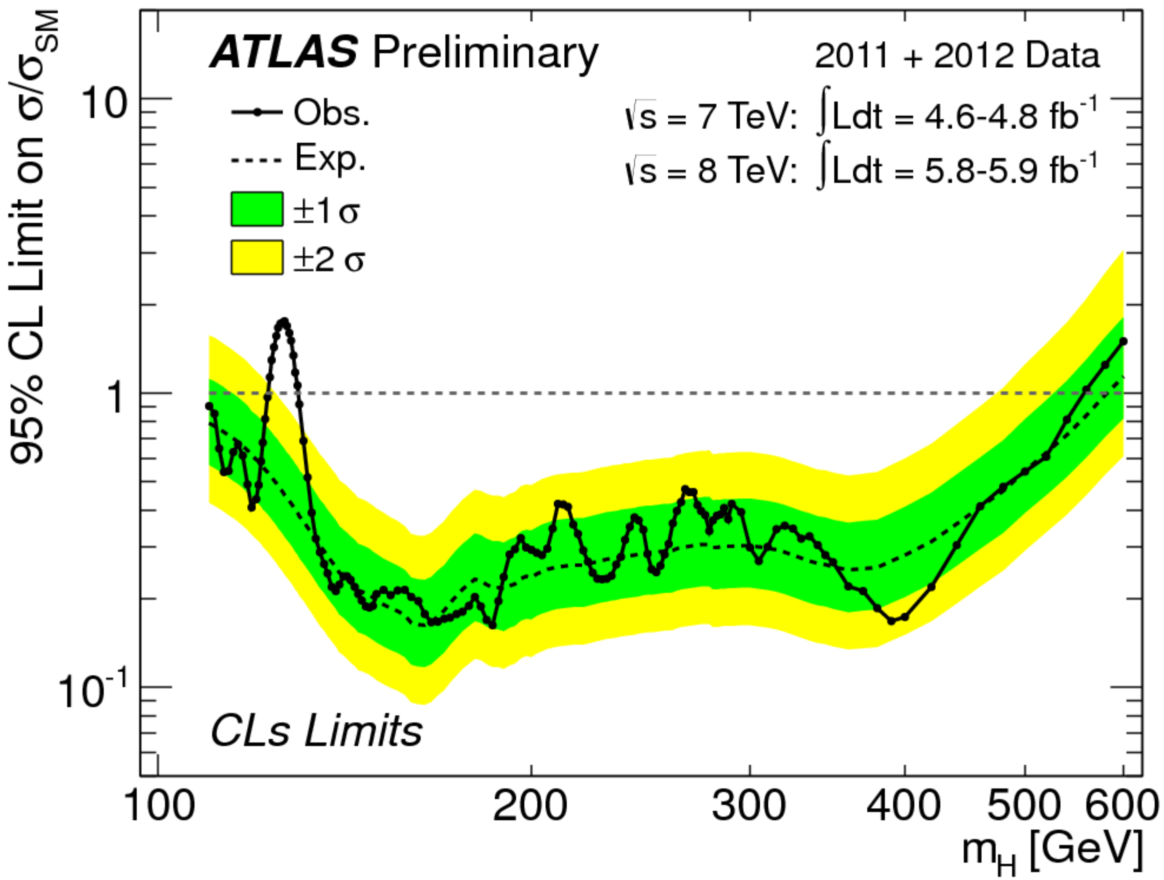
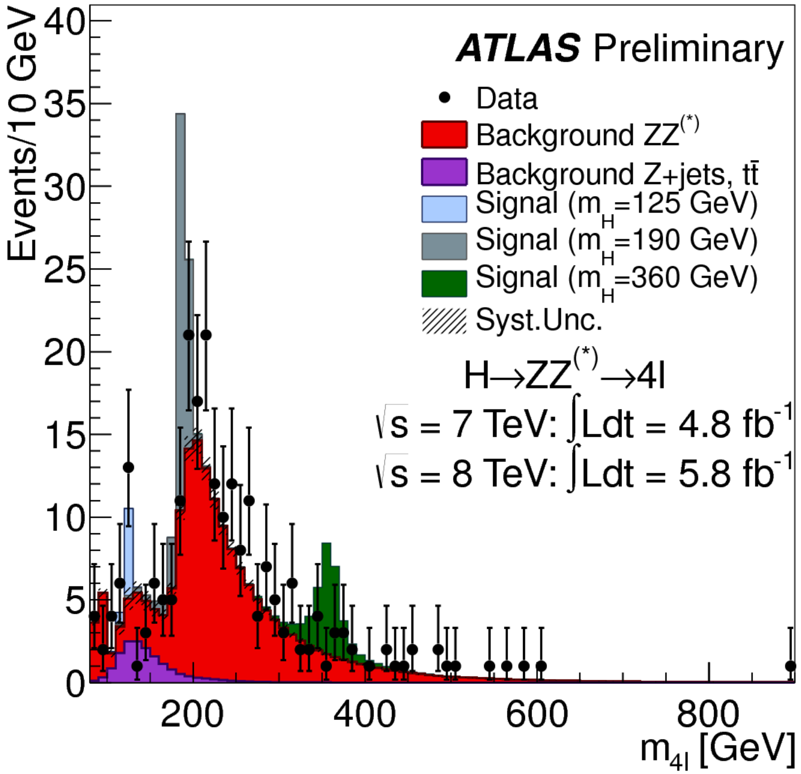


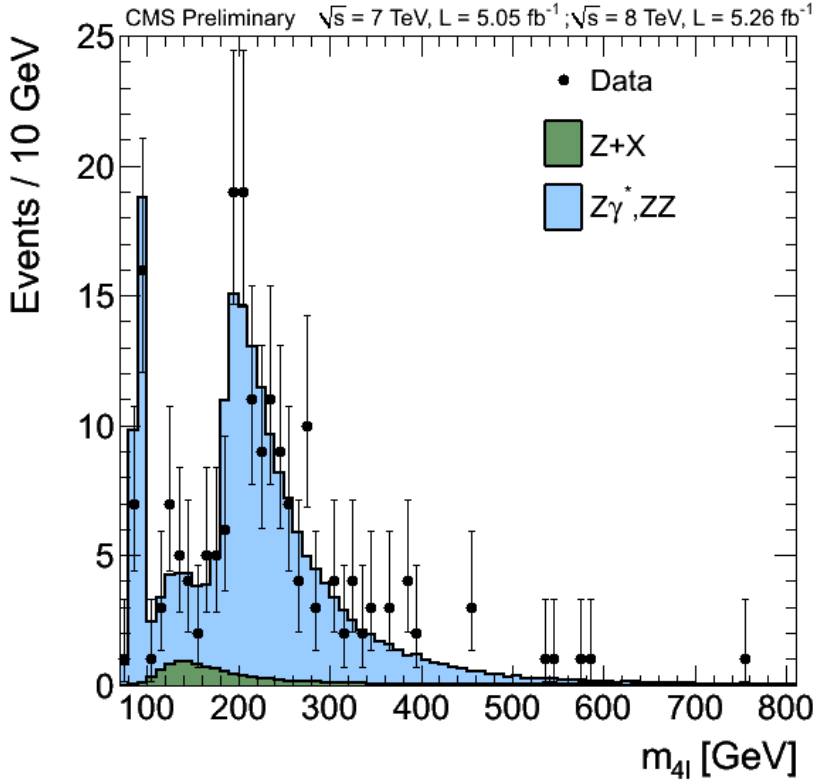
Higgs EXCLUDED $2 \cdot M_W < M_H < 558$ GeV (CMS: 600GeV)

High mass Standard Model Higgs boson (almost) excluded

BACK - UP

Decay channel ZZ → (l^+l^-) (l^+l^-)





95% CL Limits ZZ → (l^+l^-) (l^+l^-)

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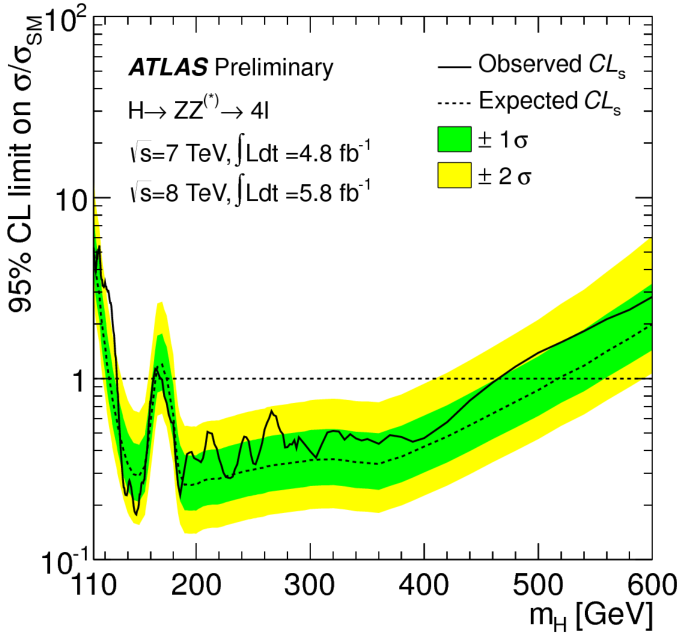
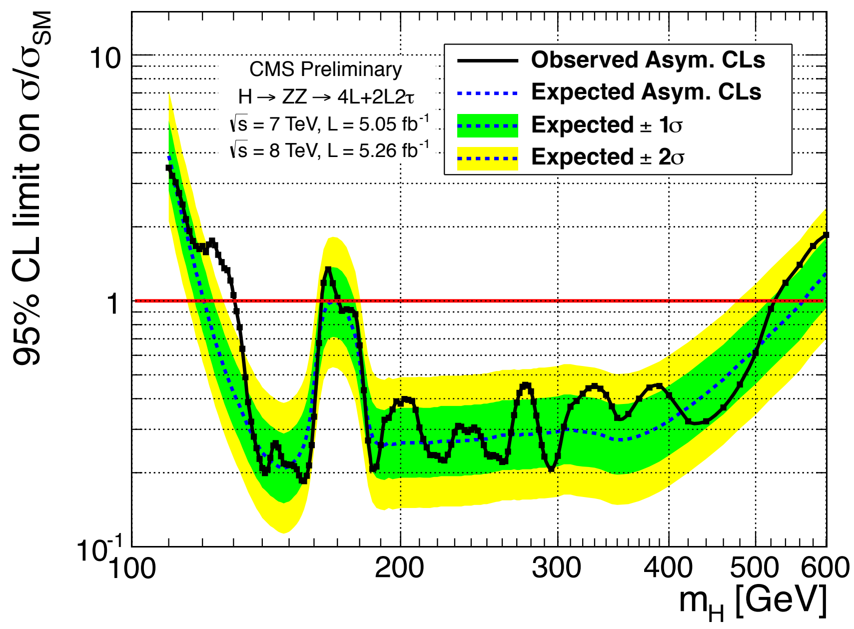
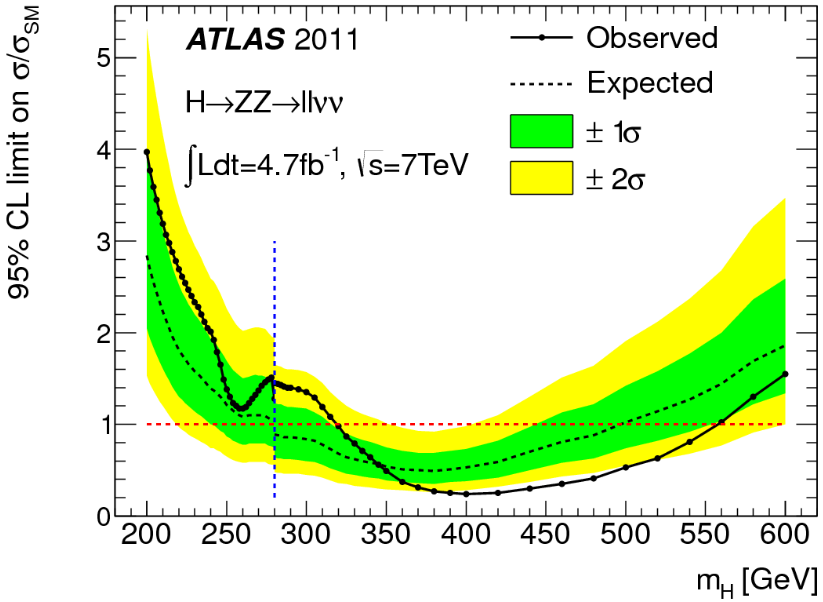
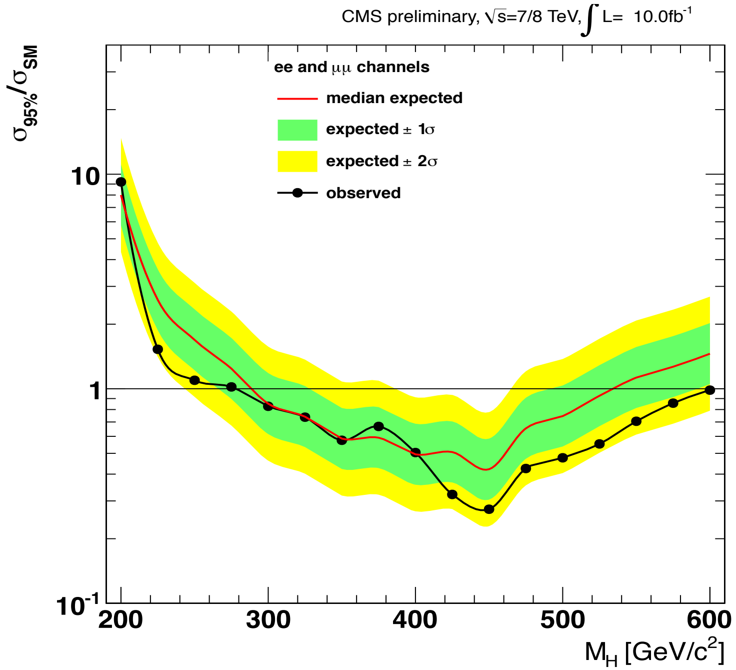


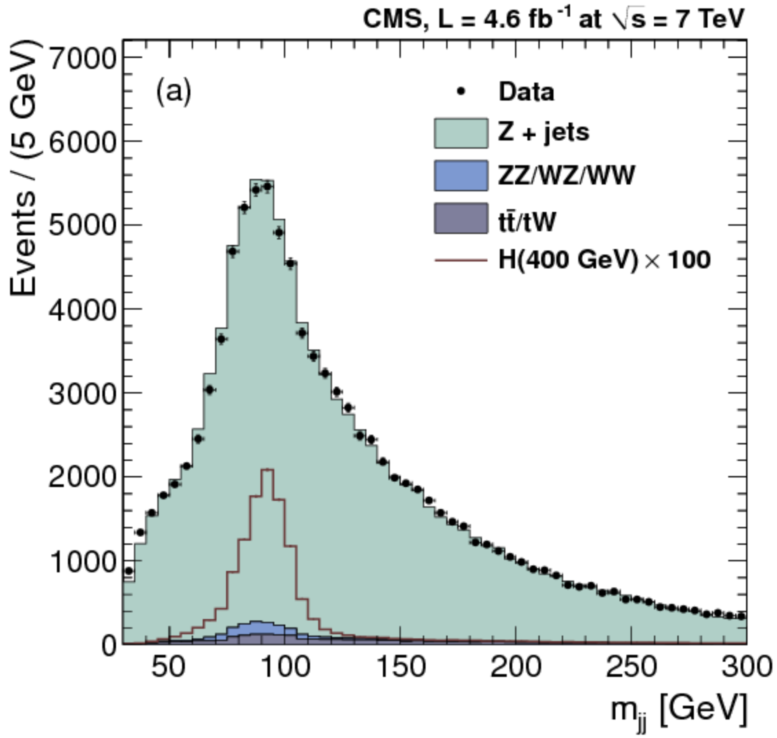


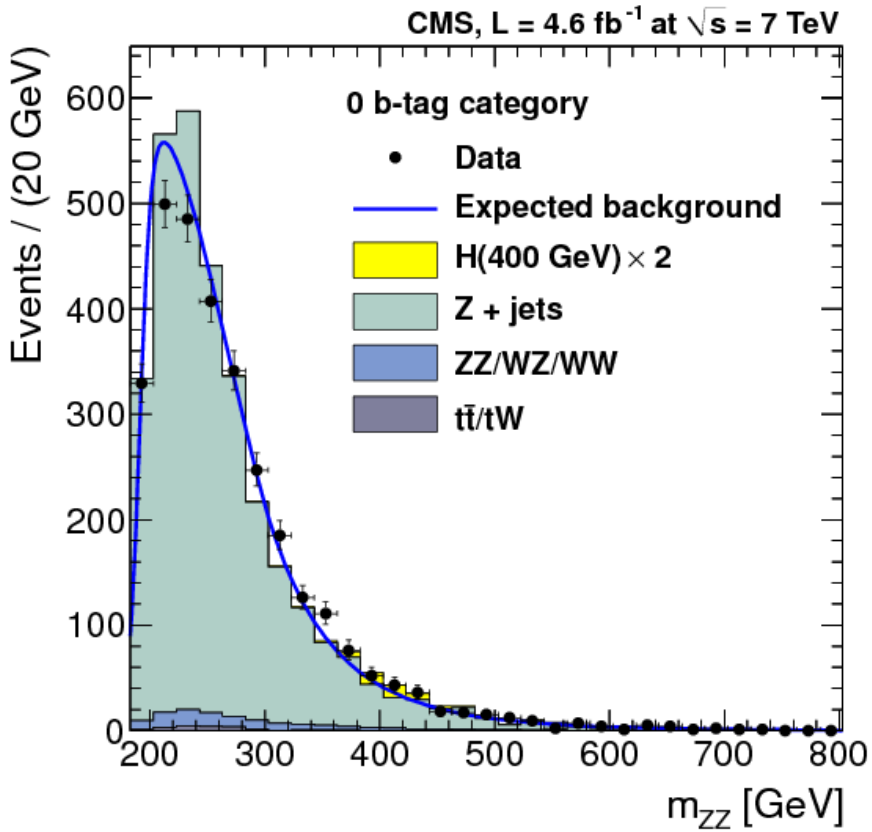
95% CL Limits ZZ → (l^+l^-) (nunu)





Decay channel ZZ → llqq





Combining all searches

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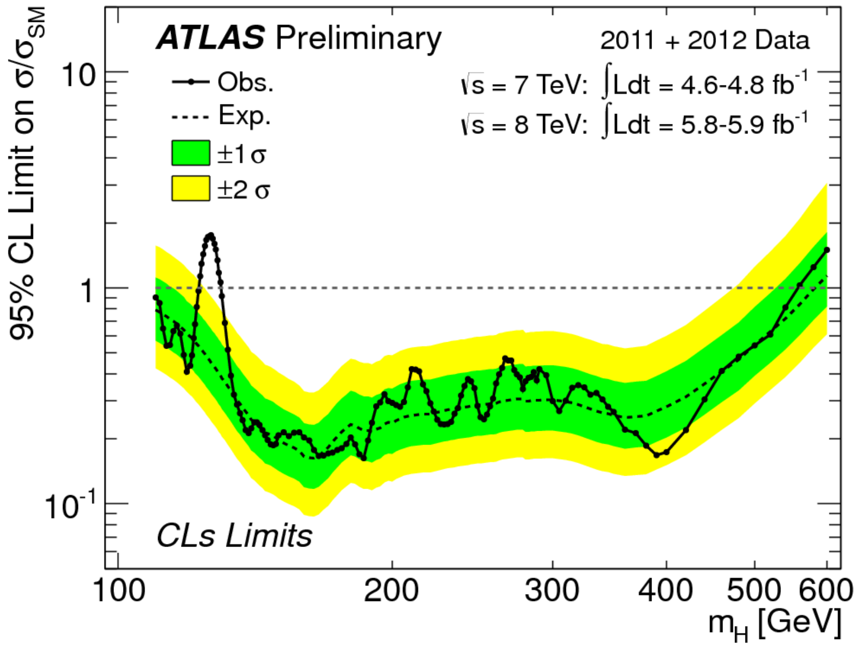

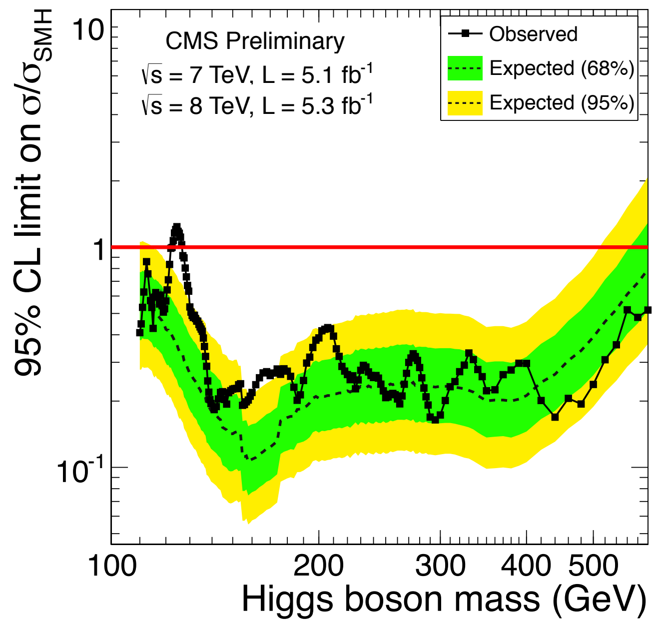

Higgs EXCLUDED

$2 \cdot M_W < M_H < 558$ GeV

Higgs EXCLUDED

$2 \cdot M_W < M_H < 600$ GeV

High mass Standard Model Higgs boson (almost) excluded