How to find the Higgs boson

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Trieste 2011, Lecture 3

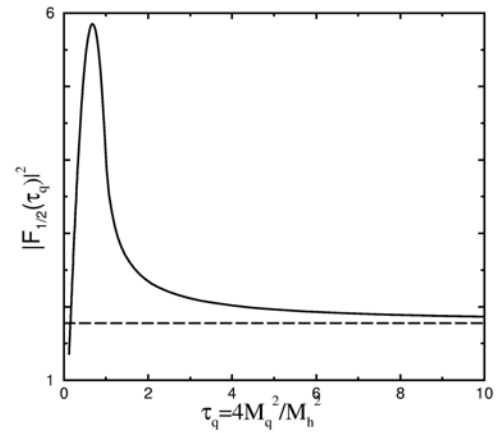
Some References

- The narrow width approximation
  - See Appendix B, arXiv:0508097 (Han)
- The Higgs mechanism (my viewpoint)
  - arXiv:0812.2190 (Dawson)

Gluon Fusion

- Lowest order cross section:
  - $\tau_q = 4m_q^2/M_h^2$
  - Light Quarks: $F_{1/2} \rightarrow (m_b/M_h)^2 \log^2(m_b/M_h)$
  - Heavy Quarks: $F_{1/2} \rightarrow -4/3$

$$\hat{\sigma}_{gg\rightarrow h}(\hat{s}) = \frac{\alpha_s(\mu_R)^2}{1024\pi v^2}\left|\sum_q F_{1/2}(\tau_q)\right|^2 \delta(1-\frac{M_h^2}{\hat{s}})$$



- Rapid approach to heavy quark limit: Counts number of heavy fermions
- NNLO corrections calculated in heavy top limit

Gluon Fusion

- Integrate parton level cross section with gluon parton distribution functions: $\hat{\sigma}_{gg\to h} = C_0 \delta(1 - \frac{M_h^2}{\hat{s}})$ $\hat{s} = x_1 x_2 S$

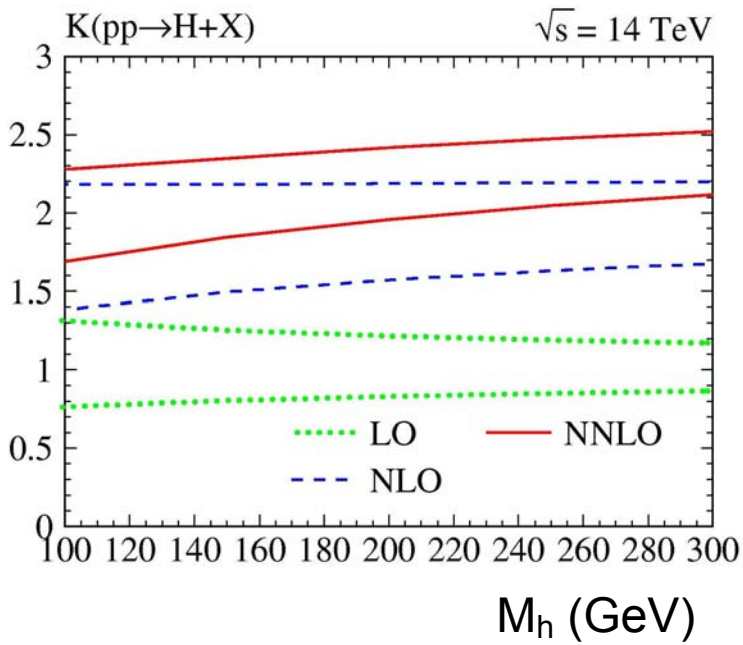
$$\sigma(pp \to h) = \int dx_1 dx_2 g(x_1, \mu_F) g(x_2, \mu_F) \hat{\sigma}_{gg\to h}(x_1 x_2 S)$$

$$\boxed{\sigma(pp \to h) = C_0 \int_{M_h^2/S}^{1} \frac{dx_1}{x_1} g(x_1, \mu_F) g\left(\frac{M_h^2}{S x_1}, \mu_F\right)}$$

$$\boxed{C_0 \to \frac{\alpha_s(\mu_R)^2}{576\pi v^2}}$$

  - S is hadronic center of mass energy
- Rate depends on μ_R, μ_F at $O(\alpha_s^3)$
  - μ_R, μ_F arbitrary renormalization/factorization scales
  - Numerically significant
- Uncertainty from gluon parton distribution functions

Higher order corrections to gg→h



Rates depend on renormalization scale, $\alpha_s(\mu_R)$, and factorization scale, $g(\mu_F)$

Bands show $.5M_h < \mu < 2\ M_h$

LO and NLO μ dependence bands don't overlap

μ dependence used as estimate of theoretical uncertainty

$$K \equiv \frac{\sigma_{NLO}}{\sigma_{LO}}$$

Vector Boson Fusion

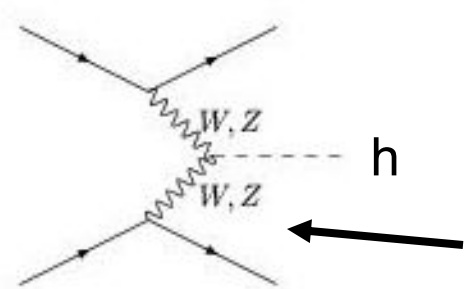
- $W^+W^- \rightarrow X$ is a real process: $\sigma_{pp\rightarrow WW\rightarrow X}(s) = \int dz \left.\frac{dL}{dz}\right|_{pp/WW} \sigma_{WW\rightarrow X}(zs)$

- Rate increases at large s: $\sigma \approx (1/M_W^2)\log(s/M_W^2)$
- Integral of cross section over final state phase space has contribution from W boson propagator:

$$\int \frac{d\theta}{(k^2 - M_W{}^2)^2} \approx \int \frac{d\theta}{(2EE'(1-\cos\theta) + M_W{}^2)^2}$$

Peaks at small θ

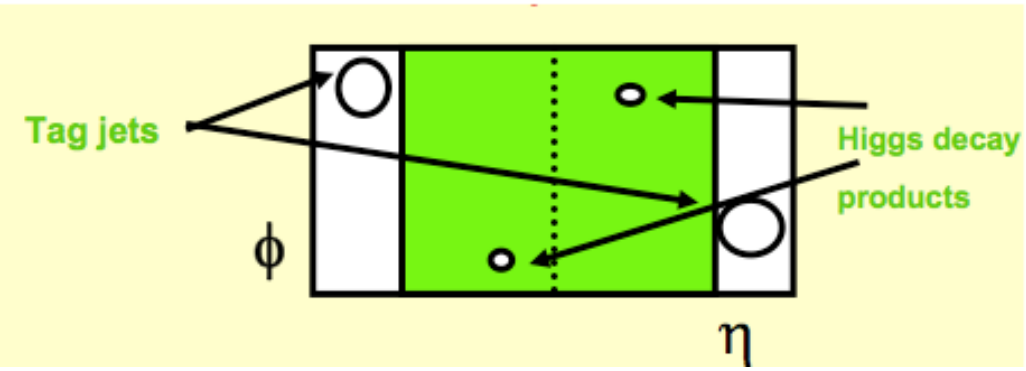
- Outgoing jets are mostly forward and can be tagged



k=W,Z momentum

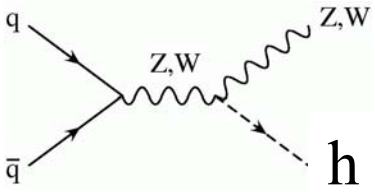
Vector Boson Fusion

- Idea: Tag 2 high-p_T jets with large rapidity gap in between
- No color flow between tagged jets – suppressed hadronic activity in central region

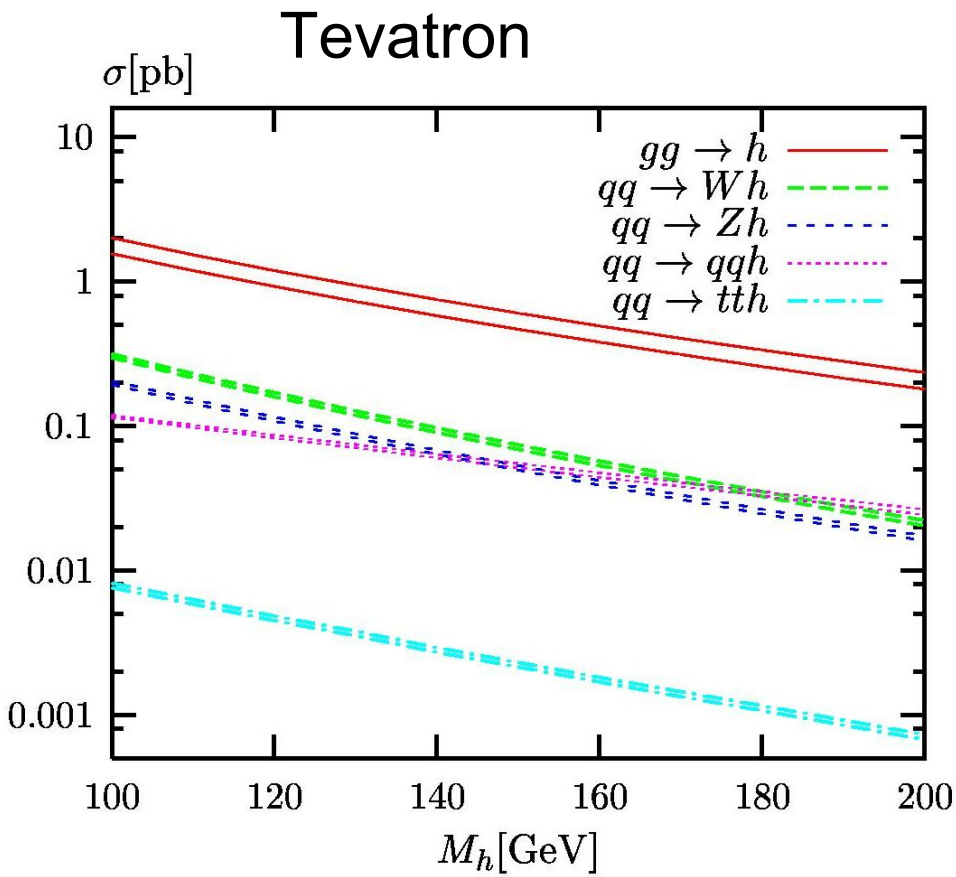


W(Z)-strahlung

- W(Z)-strahlung ($q\bar{q} \rightarrow Wh$, Zh) important at Tevatron
  - Same couplings as vector boson fusion
  - Rate proportional to ***weak*** coupling
- Theoretically very clean channel



Producing the Higgs at the Tevatron

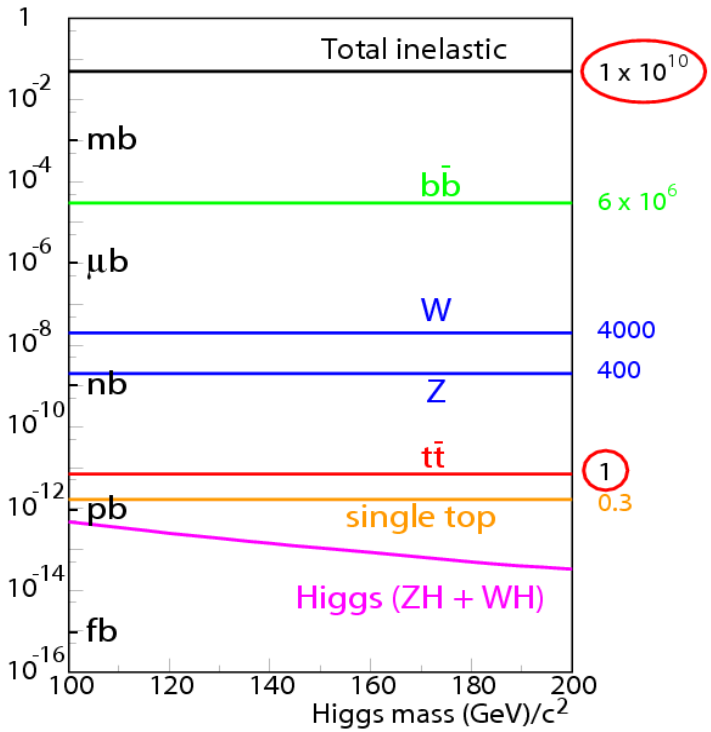


NNLO or NLO rates

$M_h/2 < \mu < M_h/4$

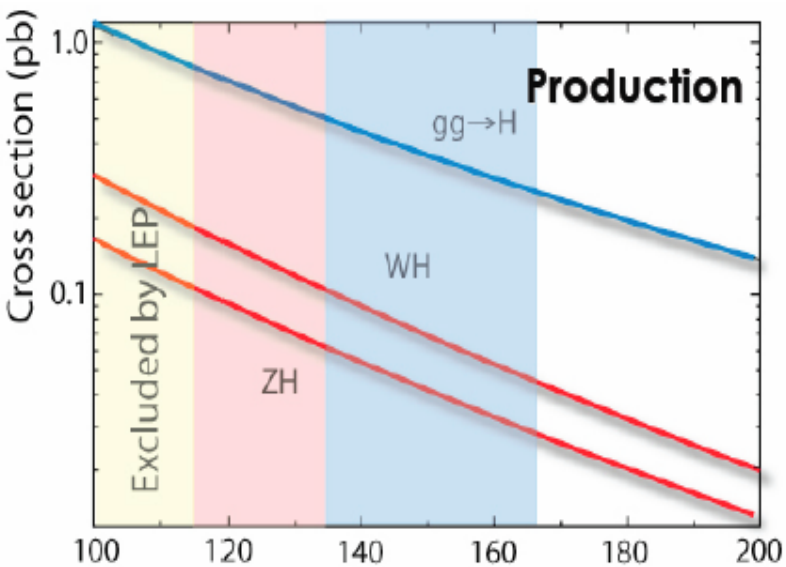
Higgs at the Tevatron

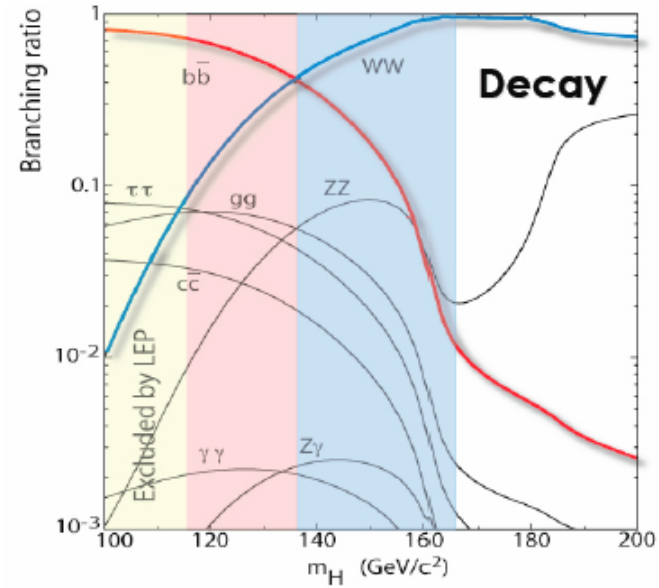
- Largest rate, $gg \rightarrow h$, $h \rightarrow b\bar{b}$, is overwhelmed by background



$\sigma(gg \rightarrow h) \sim 1$ pb << $\sigma(b\bar{b})$

Looking for the Higgs at the Tevatron

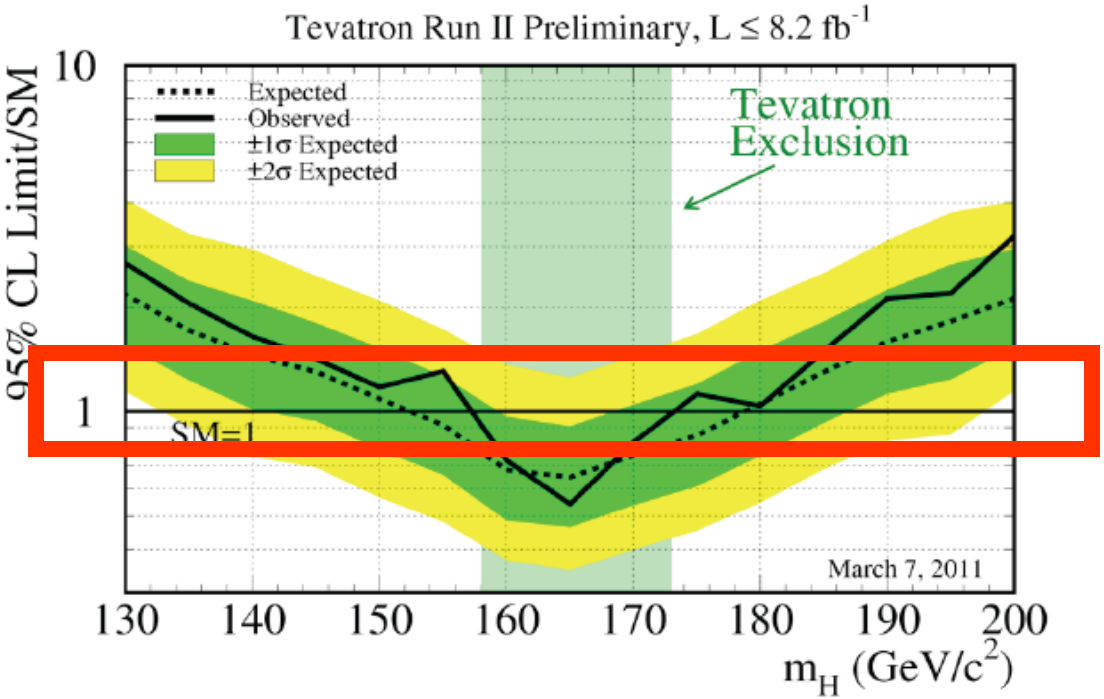




- High mass: Look for $h \to WW \to l\nu l\nu$
  Large $gg \to h$ production rate

- Low Mass: $h \to b\bar{b}$, Huge QCD $b\bar{b}$ background
  Use associated production with W or Z

Tevatron Higgs Exclusion

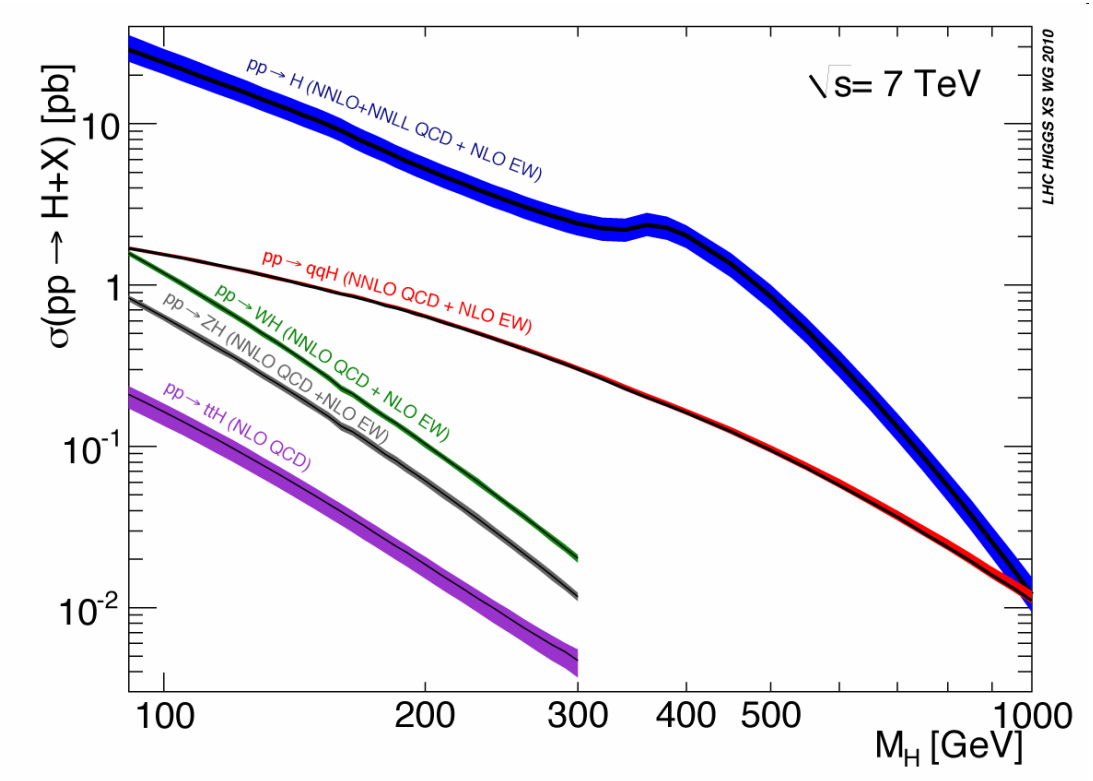


Theory uncertainties on both background and signal

Limits normalized to Standard Model predictions

Tevatron Exclusion: [158 GeV < M_h < 173 GeV]

Production Mechanisms at the LHC



Bands show scale dependence

All important channels calculated to NLO or NNLO

Do some numbers…

- ATLAS and CMS have ~ 500 pb^{-1} = .5 fb^{-1} of data
- For M_h=120 GeV:
  - σ(gluon fusion)=17 pb
  - 8500 Higgs events
  - But we have to see them:
    - Branching ratio $h \rightarrow \gamma\gamma$ = 2 x 10^{-3} $\Rightarrow$ 17 events
    - Branching ratio $h \rightarrow$4 leptons = 8 x 10^{-5} (l=e,μ) $\Rightarrow$ .7 events
- For M_h=180 GeV:
  - σ(gluon fusion)=7 pb
  - 3500 Higgs events
    - Branching ratio $h \rightarrow \gamma\gamma$ = 1 x 10^{-4} $\Rightarrow$ .35 events
    - Branching ratio $h \rightarrow$4 leptons = 3 x 10^{-4} (l=e,μ) $\Rightarrow$ 1 event

Event numbers further reduced by detector efficiency….

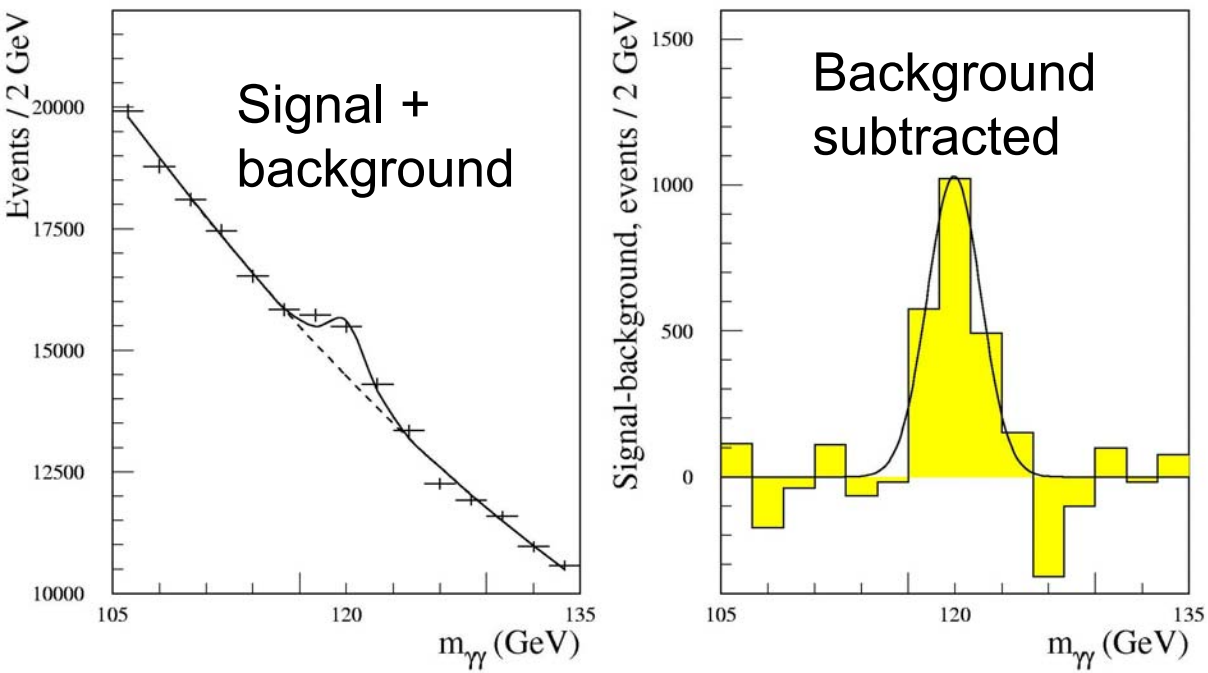
Search Channels at the LHC

$gg \rightarrow h \rightarrow b\bar{b}$ has huge QCD background: Must use rare decay modes of h

- $gg \rightarrow h \rightarrow \gamma\gamma$
  - Small BR (10^{-3} – 10^{-4})
  - Only measurable for $M_h < 140$ GeV
- Largest Background: QCD continuum production of $\gamma\gamma$
- Also from γ-jet production, with jet faking γ, or fragmenting to π^0
- Fit background from data

$h \rightarrow \gamma\gamma$

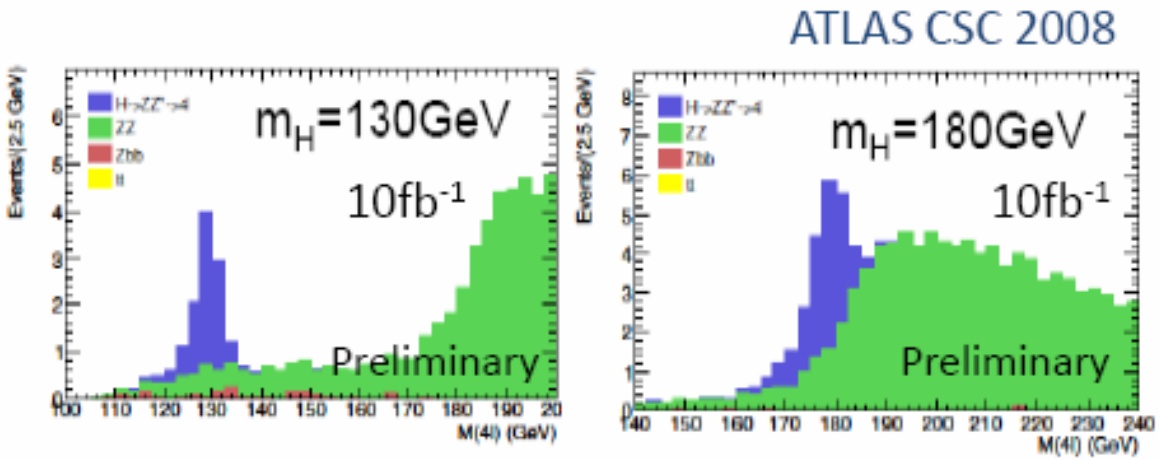
M_h=120 GeV; L=100 fb^{-1}



[Monte Carlo predictions]

Golden Channel: h→ZZ→4 leptons

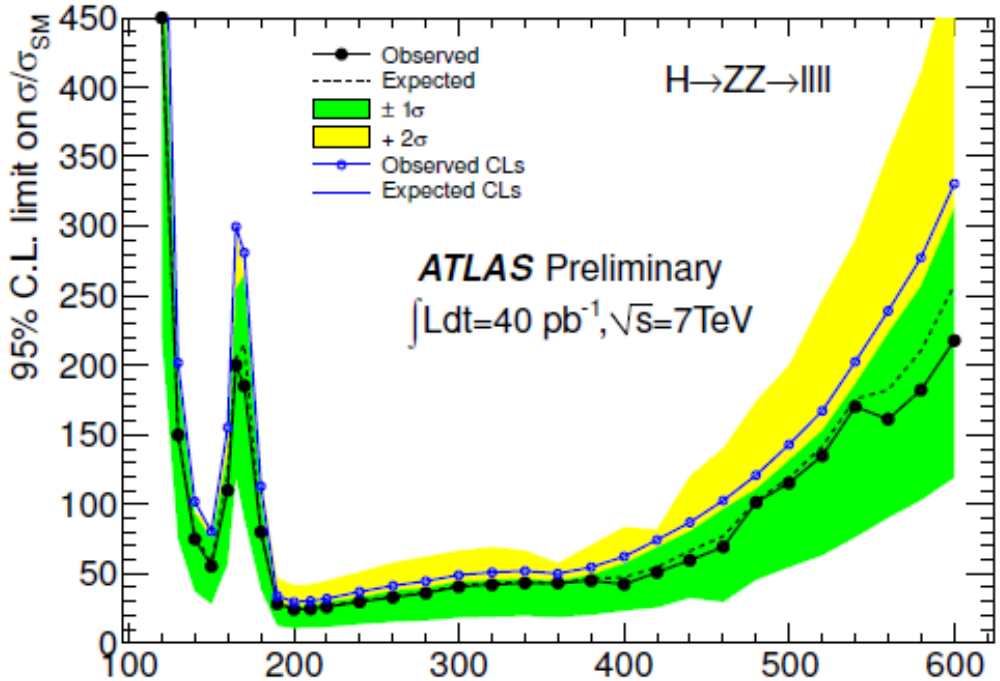
- Reconstruct Higgs mass



- Below M_h ~130 GeV, rate is too small for discovery

[Monte Carlo predictions]

Limits on h→ZZ →(4 leptons)

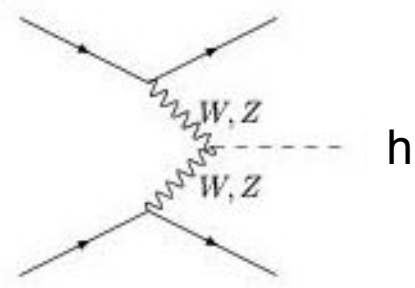


M_h (GeV)

[Data!]

Vector Boson Fusion

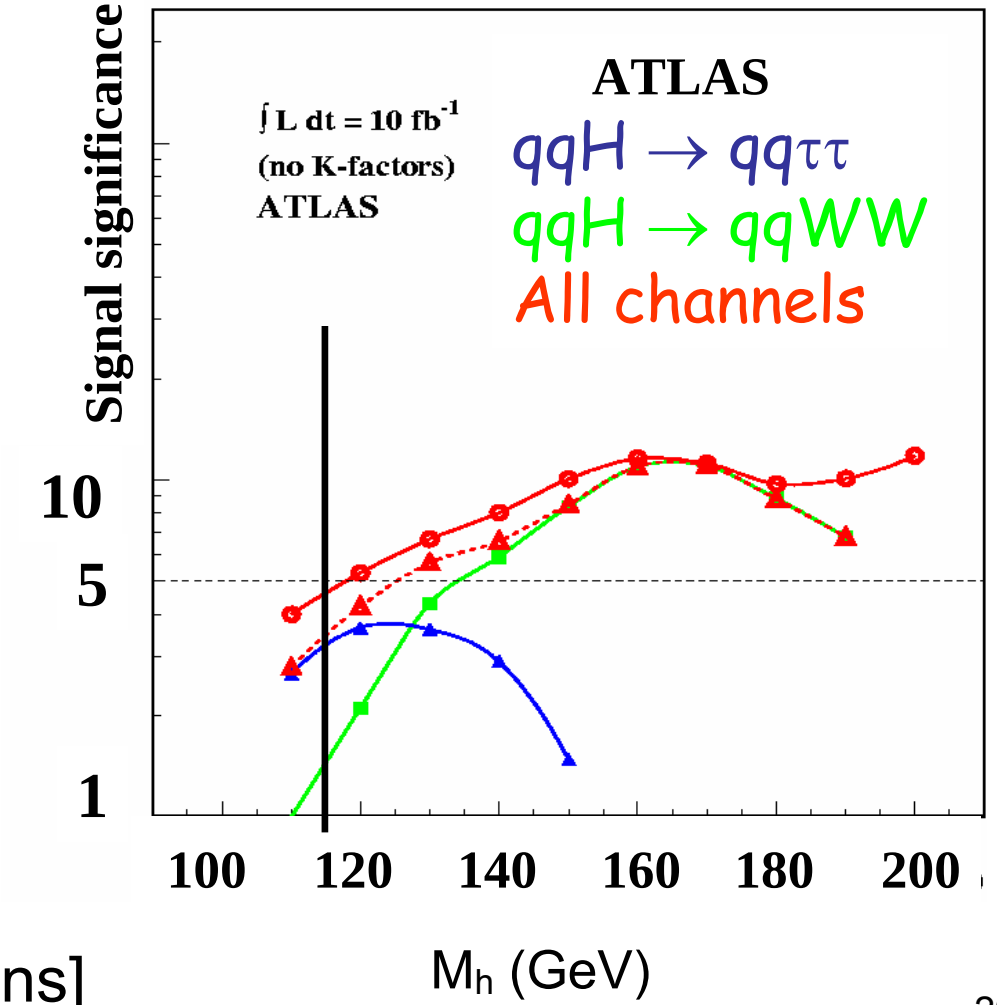
- Outgoing jets are mostly forward and can be tagged
  - Little jet activity in central rapidity region
- Idea: Look for different h decay channels in vector boson fusion
  - Ratio will have smaller errors than total rate



Vector Boson Fusion for light Higgs

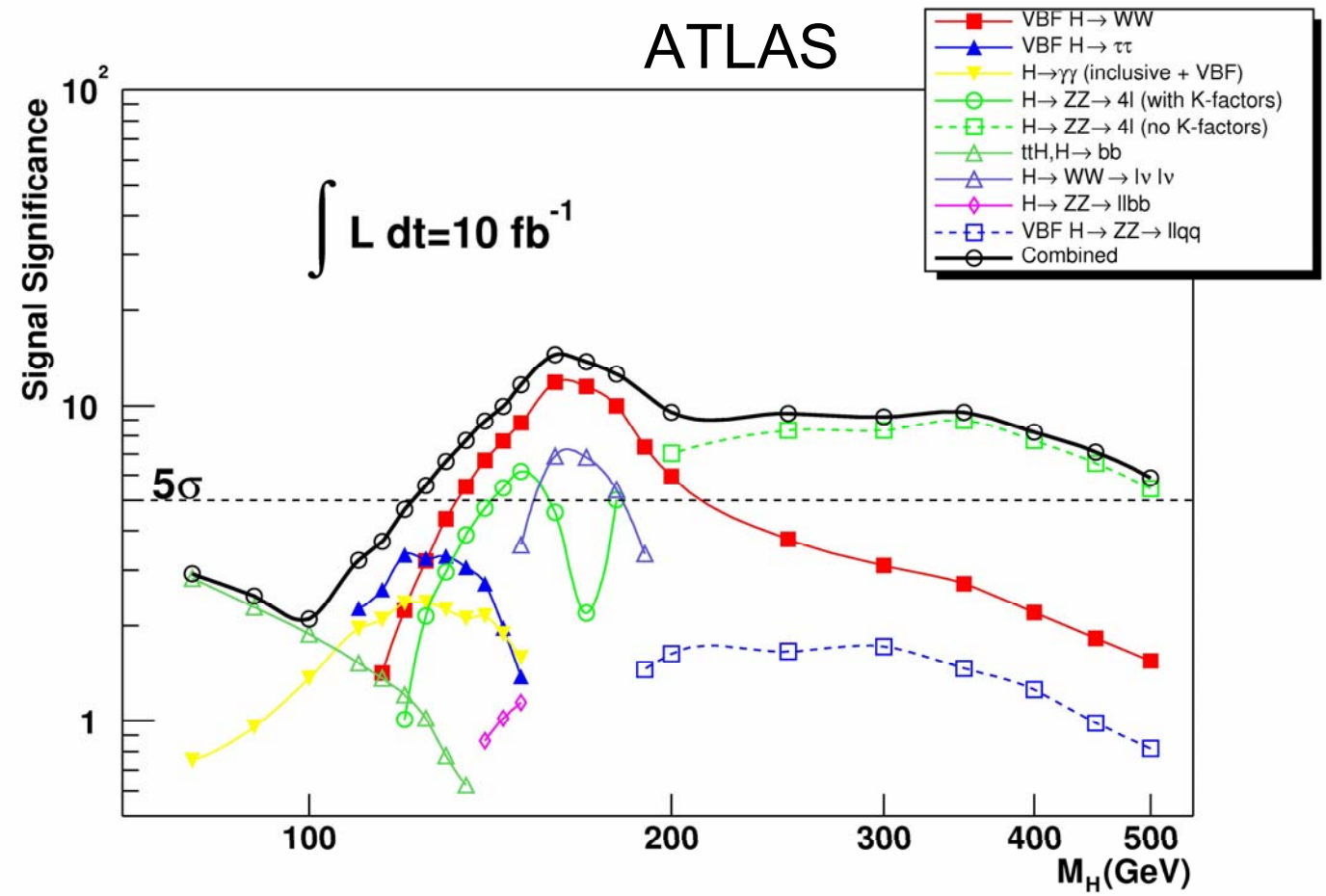
Vector boson fusion effective for measuring Higgs couplings

14 TeV



[Monte Carlo predictions]

Early Higgs Physics



Discovery requires many channels

Higgs Discovery

$\sqrt{s}$=7 TeV

ATLAS + CMS ≈ 2 x CMS	95% CL exclusion	3σ sensitivity	5σ sensitivity
1 fb^{-1}	120 - 530	135 - 475	152 - 175
2 fb^{-1}	114 - 585	120 - 545	140 - 200
5 fb^{-1}	114 - 600	114 - 600	128 - 482
10 fb^{-1}	114 - 600	114 - 600	117 - 535

2011

2012

If the SM Higgs exists, we'll know its mass soon

If we find a “Higgs-like” object, what then?

- We need to:
  - Measure Higgs couplings to fermions & gauge bosons
  - Measure Higgs spin/parity
  - Reconstruct Higgs potential
  - Is it the SM Higgs?
- Reminder: Many models have other signatures:
  - New gauge bosons (little Higgs)
  - Other new resonances (Extra D)
  - Scalar triplets (little Higgs, NMSSM)
  - Colored scalars (MSSM)

Is it a Higgs?

- How do we know what we've found?
- Measure couplings to fermions & gauge bosons

$$\frac{\Gamma(h \to b\bar{b})}{\Gamma(h \to \tau^+\tau^-)} \approx 3\frac{m_b{}^2}{m_\tau{}^2}$$

- Measure spin/parity

$$J^{PC} = 0^{++}$$

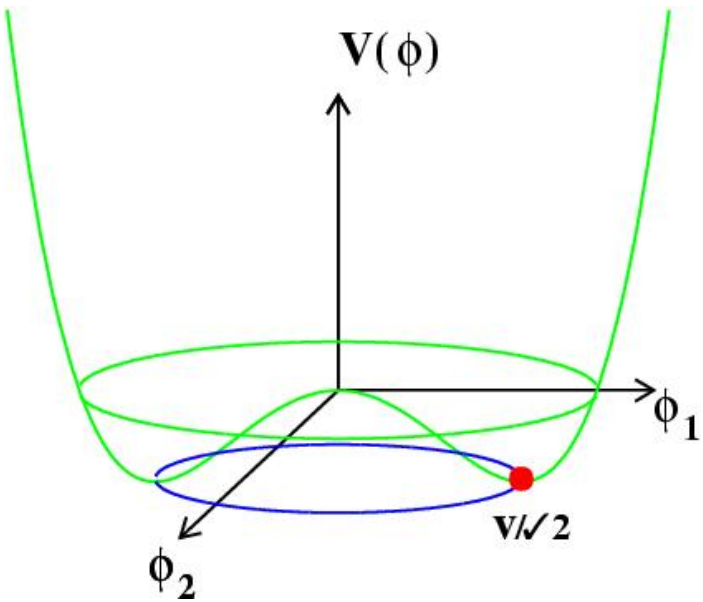
- Measure self interactions

$$V = \frac{M_h{}^2}{2}h^2 + \frac{M_h{}^2}{2v}h^3 + \frac{M_h{}^2}{8v^2}h^4$$

Can we reconstruct the Higgs potential?

$$V = \frac{M_h^{\ 2}}{2} h^2 + \lambda_3 v h^3 + \frac{\lambda_4}{4} h^4$$

$$\boxed{SM: \ \lambda_3 = \lambda_4 = \frac{M_h^{\ 2}}{2v^2}}$$



- Fundamental test of model!

- We have no idea how to measure λ_4