Introduction to Hadron Collider Physics (II)

April 4, 2021

Outline: Introduction to Hadron Collider Physics

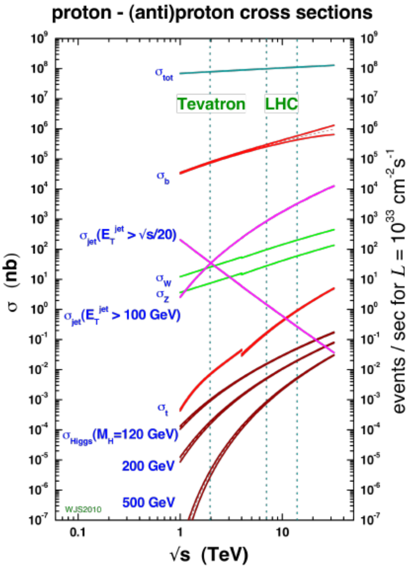
Yesterday

- Introduction and overview
- Cross section calculations: The basics
- Soft Physics: Min bias and underlying event
- Jet Physics
- What we have learned so far

Today

- W and Z production
- Top physics
- The Higgs
- Conclusions

Reminder: Cross Sections at Hadron Colliders

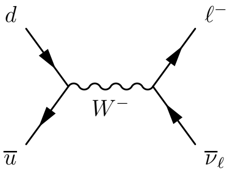


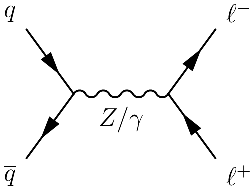
- Rates determined by
  - Hard Scattering Cross Section
  - Parton luminosity
- QCD processes dominate
  - EW rates lower by α/α_S
- Main background for W and Z production: QCD jets
- Cannot see single $W \to q\overline{q}'$ or $Z \to q\overline{q}$ above jet background
  - Almost all studies of W and Z in hadron colliders in leptonic decay modes

$$\begin{array}{ccc} W^{\pm} & \to & \begin{array}{c}\ell^-\nu_\ell \\ \ell^+\overline{\nu}_\ell\end{array} \\ Z & \to & \ell^+\ell^- \end{array}$$

Production of W and Z Bosons

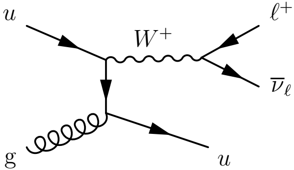
- Lowest order diagram: quark annihilation

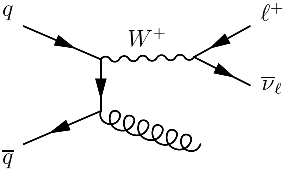




At lowest order (pure electroweak), W and Z are produced with no p_T

- Adding diagrams of order α_S: Annihilation and Compton Scattering:

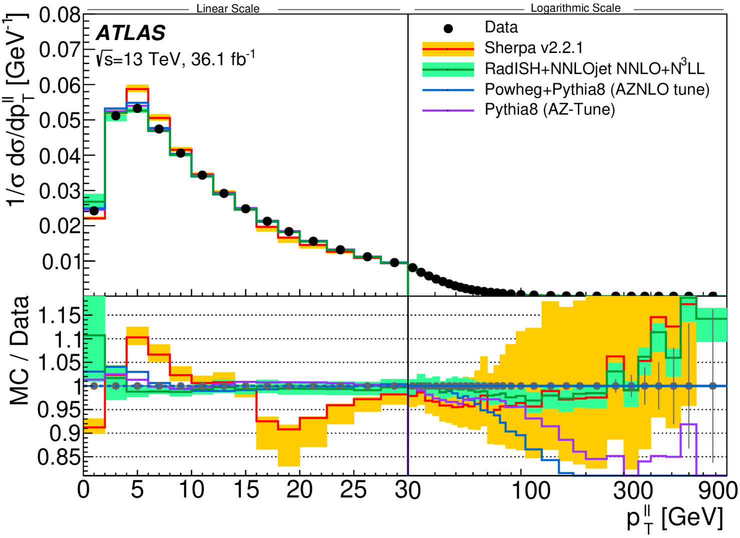




These give the W and Z p_T

- In addition to these one gluon diagrams, must include emission of multiple soft gluons: Can be handled using resummation techniques

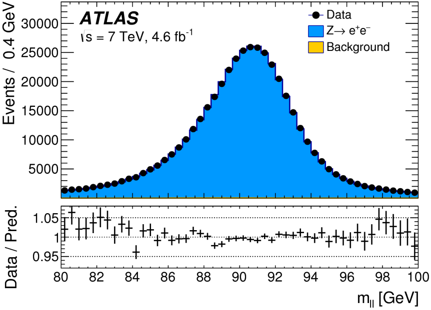
Full QCD Calculation: Boson p_T Remains Small

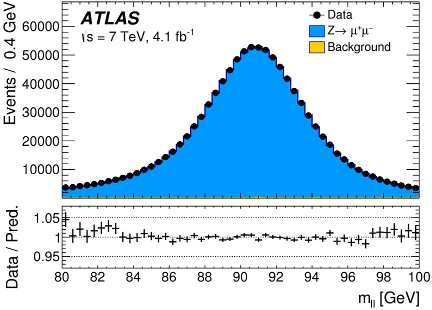


Distribution dominated by multiple soft gluon emission

Reconstruction of Z Bosons

- In general, limited to leptonic modes
- Large QCD jet background swamps signal in jet channel
- In principle, can find regions of phase space where hadronic mode can be reconstructed, but in very specialized analyses with other objects
- Two high p_T leptons, nearly back-to-back
- Reconstruction straightforward, background small





Reconstruction of W Bosons

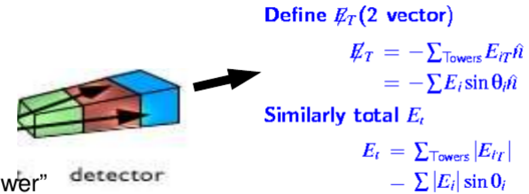
- Again, restricted to lepton channels
- But here, one of the nearly back-to-back leptons is a neutrino

  How do we "detect" a particle that doesn't interact in our detetor?
- Look for momentum imbalance and assign the missing momentum to the ν

  But in hadron colliders, limited to using only the 2 transverse components of the momentum

Neutrino Reconstruction

- Must add the momentum of all objects in the event
- The traditional way: calorimeter only



Calorimeter “Tower”

Define $\not{E}_T$ (2 vector)

$$\not{E}_T = -\sum\nolimits_{\text{Towers}} E_{iT}\hat{n} = -\sum E_i \sin\theta_i \hat{n}$$

Similarly total E_t

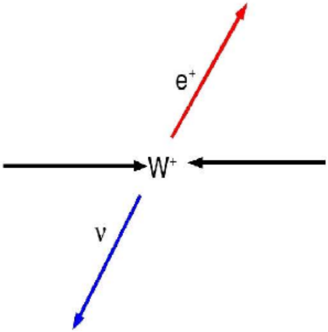
$$E_t = \sum\nolimits_{\text{Towers}} |E_{iT}| = \sum |E_i| \sin\theta_i$$

  - Create a grid of calorimeter towers
  - Treat each tower as a massless particle with momentum direction normal to the tower
- For better resolution: Use reconstructed objects
  - “Particle-flow”: Use tracking information to improve calorimeter resolution (pioneered by CMS)

OR:

  - Combine the momentum of all the jets and electrons, muons
  - Then add the remaining unused energy using towers as above
  - When combining, can have different calibrations to each object

W Decay: Lepton p_T Distribution



- In CM frame, e and ν are back-to-back and balance p_T:

$$ {p_T}^2 = \frac{1}{4}\hat{s}\sin^2\theta $$

- Changing variables from $\cos\theta$ to p_T introduces a Jacobean:

$$ \frac{d\cos\theta}{dp_T^2} = -\frac{2}{\hat{s}\cos\theta} $$

- But we know

$$ \frac{d\sigma}{d\cos\theta} \propto (1 + q\lambda\cos\theta)^2 $$

where q is the charge and λ is helicity wrt beamline

so

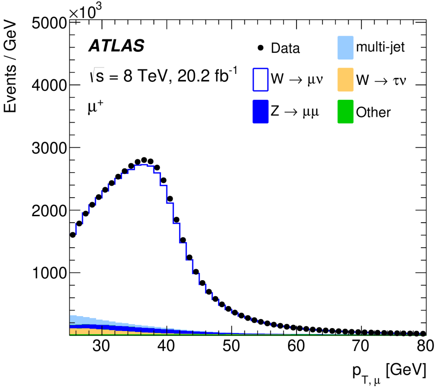
$$ \frac{d\sigma}{dp_T^2} \propto \frac{(1+\cos^2\theta)}{\hat{s}\cos\theta} \propto \frac{2\left(1 - 2p_T^2/\hat{s}\right)}{\hat{s}\,(1 - 4p_T^2/\hat{s})^{\frac{1}{2}}} $$

The Jacobean Peak

- Notice

  $$\frac{d\sigma}{dp_T} \propto \frac{1+\cos^2\theta}{\cos\theta}$$

  Diverges for $\theta = \pi/2$ (which is $p_T = \sqrt{\hat{s}}/2$)
- Diverence results from the Jacobean factor in tranformation to p_T
- Integration over Breit-Wigner removes singularity but leaves the peak
- HO corrections give W transverse momentum and further smear the peak



Transverse Mass

- W p_T gives ℓ and ν by same boost
- Define ℓ-ν transverse mass:

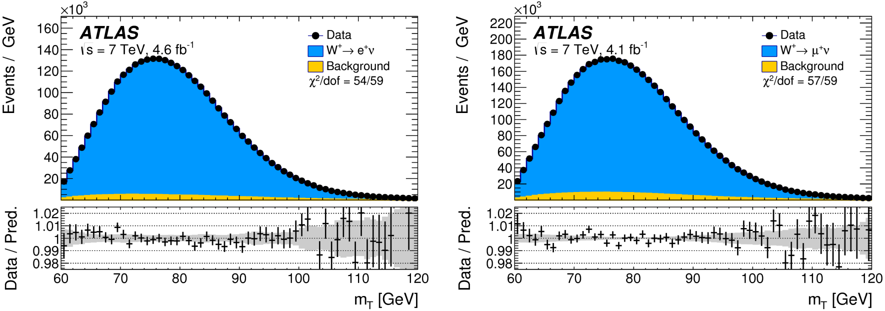
$$m_T^2 = (E_T^\ell + E_T^\nu)^2 - (\vec{p}_T^\ell + \vec{p}_T^\nu)^2$$

- Note that for $p_T^W = 0$, $m_T = 2|p_T^\ell| = 2|p_T^\nu|$
- Thus

$$\frac{d\sigma}{dm_T^2} = 4\frac{d\sigma}{dp_T^2}$$

- m_T sensitive to transverse boosts only at second order
  - Predicted m_T distributuion not very sensitive to modeling of boson p_T
- But m_T more sensitive to detector resolution since depends on measurement of the ν

Transverse Mass for W Bosons

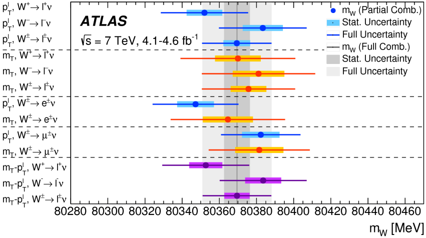


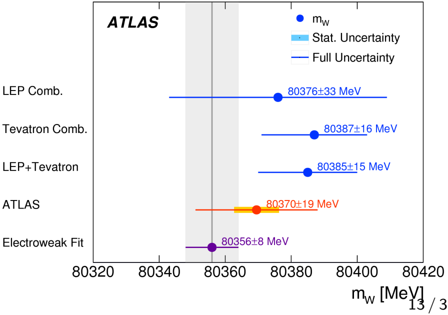
- Background small in both e and μ channels
- Small theoretical uncertainties: a better choice of variable than lepton p_T in most cases

W-mass Measurement

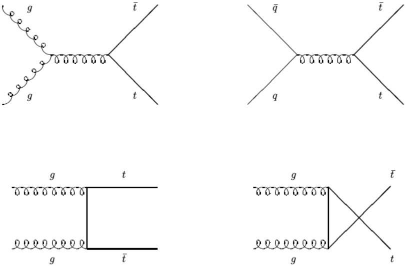
- Precision measurement that depends on detailed control of systematic uncertainties
- Select well-measured subset of events: No jet activity
- Separate fits in e and μ and for $+$ and $-$ leptons
- Compare fits of different kinematic varibles

We'll come back to importance of this measurement later today





Top-Pair Production

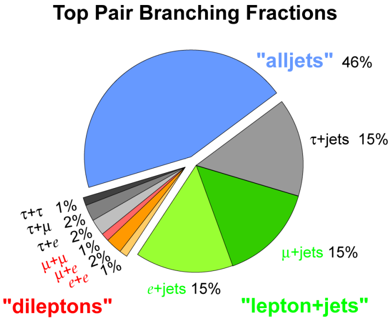


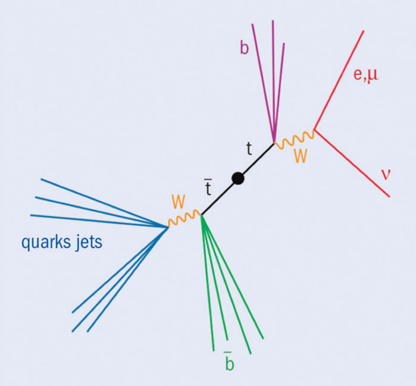
- Strong production: $t\bar{t}$ pairs
- Tevatron: ($p\overline{p}$ collder)
  - Production rate suppressed: $2m_{top} \sim 0.2\sqrt{s}$
  - 15% gg, 85% $q\overline{q}$
- LHC: (pp collider)
  - Production rate larger $2m_{top} \sim 0.05\sqrt{s}$
  - 90% gg, 10% $q\overline{q}$

Top Decay Signatures ($t\bar{t}$ Production)

- $t \to Wb$ BR$\sim 100\%$ in SM (V_{tb})
- Top lifetime $\sim 5 \times 10^{-25}$ sec

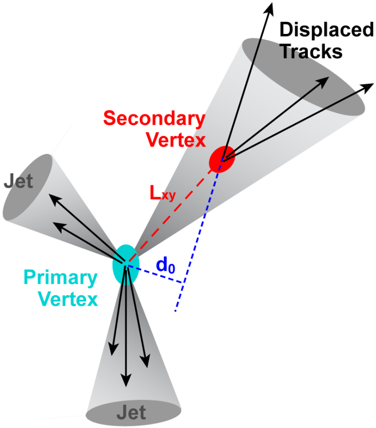
  Decays before hadronization
- Top Pair production gives:



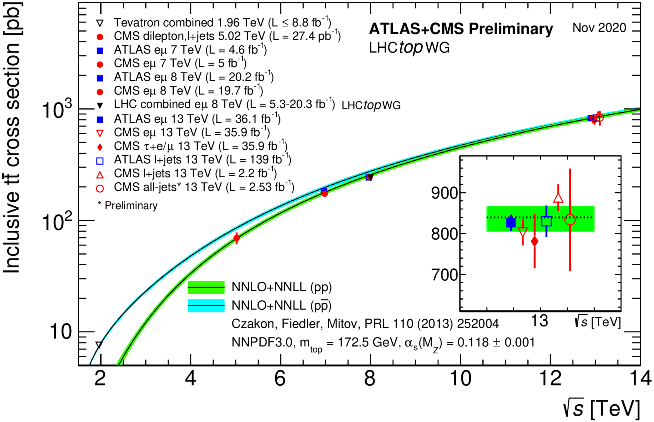


Jets Produced from b-quarks

- Characteristics of B decays':
  - B lifetime long
  - Semileptonic BR 10% per species
- Two methods of b-tagging
  - Displaced vertex tag
  - "Soft" leptons inside jets
- Today, multivariant techniques combine all information into a single metric

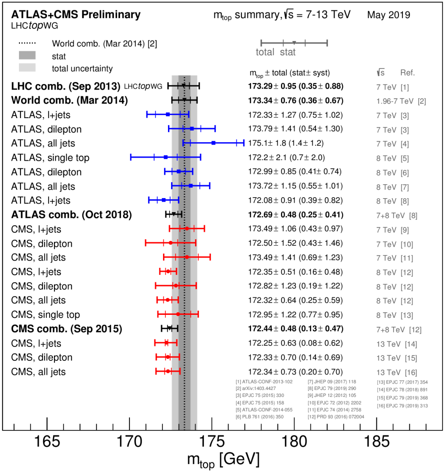


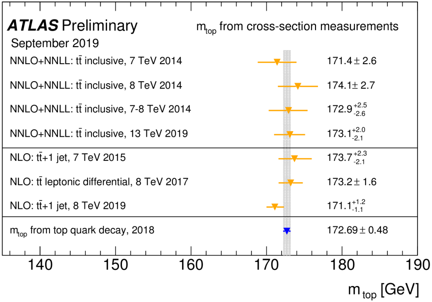
Top Pair Cross Section



- Good agreement with pQCD predictions
- Important since top a major background to BSM searches

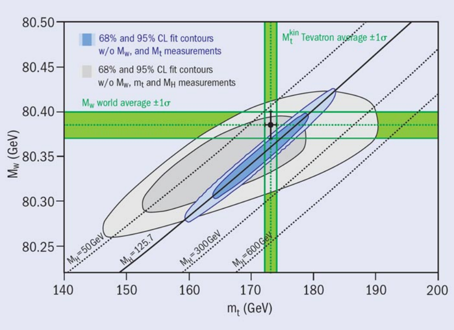
Top Mass Measurement Summary

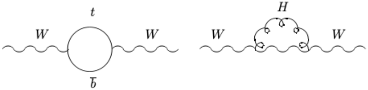




- Good agreement between experiments for direct measurement of m_{top}
- m_{top} derived from cross section consistent with direct measurements

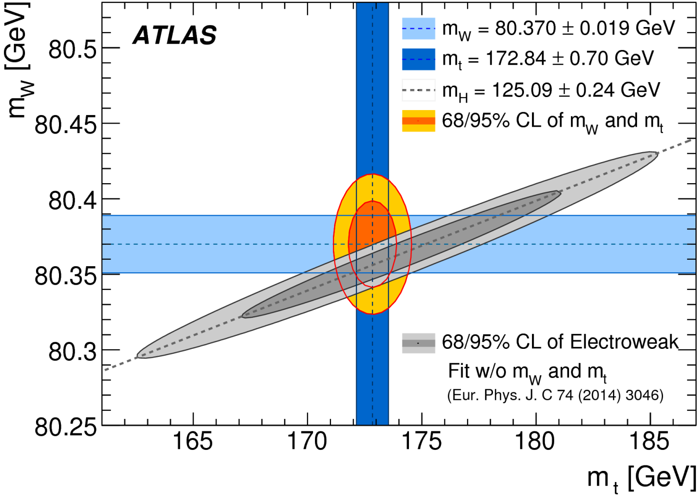
Why do m_{top} and m_W matter?





- m_W depends quadratically on m_{top} and logrithmically on m_{Higgs}
- Would also be sensitive to other BSM particles with moderate mass
- Before Higgs discovered, gave prediction for its mass
- Now, can constrain possible BSM physics

m_W vs m_{top} Are things consistent with Electroweak fits?



- No signs of disagreement to date

EWSB and the Higgs Boson

- Without Higgs, Lagrangian does not contain mass terms for the gauge bosons or the fermions
- If we introduce a mass term “by hand” for the gauge fields, it violates gauge invariance

  → That’s why the photon is massless in QED
- For the fermions, a mass term would have the form

  $$-m_\ell \left(\bar{e}_R e_L + \bar{e}_L e_R \right)$$

  But e_L is an isodoublet and e_R is an isosinglet: this term violates weak isospin symmetry
- The trick around this: Dynamic symmetry breaking
  - Maintain gauge invariance of $\mathcal{L}$
  - Introduce a new field that has self interactions
  - These interactions induce a non-zero vacuum expectation value of one component of the field
  - Change of coordinate system to reinterpret this field in terms of physical states

Choose a Scalar Field

- Introduce a complex $SU(2)_L$ doublet

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} \quad Y_\phi = +1$$

- With the following Lagrangian

$$\begin{aligned} \mathcal{L}_{scalar} &= \mathcal{D}^\mu \phi \mathcal{D}_\mu \phi - V(\phi^\dagger \phi) \\ \mathcal{D}_\mu &\equiv \partial_\mu + \frac{ig'}{2} A_\mu Y + \frac{ig}{2} \vec{\tau} \cdot \vec{B}_\mu \\ V(\phi^\dagger \phi) &= \mu^2 (\phi^\dagger \phi) + |\lambda| (\phi^\dagger \phi)^2 \end{aligned}$$

- Introduce interactions between scalar field and the fermions

$$\mathcal{L}_{yukawa} = -\frac{g_f}{\sqrt{2}} \left(\overline{L} \phi R + \overline{R} \phi L \right)$$

  couples fermion states of opposite helicity (as mass term in QED did)

  Each fermion has own g_f: m_f remain free parameters!

- Coupling of gauge bosons to the Higgs specified by $\mathcal{D}_\mu$

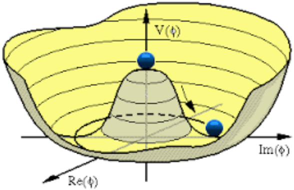
  Gauge boson masses predicted

the VeV

$$V(\phi^\dagger\phi) = \mu^2(\phi^\dagger\phi) + |\lambda|(\phi^\dagger\phi)^2$$

- Now, suppose μ^2 is negative

  Form of potential in complex space:



- Minimum not at $<\phi>=0$
- Define minimum as "vacuum expectation value" (VeV) v:

$$v = \frac{|\mu|}{\sqrt{\lambda}}$$

Chosing a direction for the VeV

- $V(\phi^\dagger\phi)$ has a degenerate ground state
- Pick vaccum to make $<\phi>_0$ real

$$<\phi>_0 = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}; \quad v = \sqrt{-\mu^2/|\lambda|}$$

- Spontaneous symmetry breaking in choice of ground state similar to how ferromagnet spontaneously chooses direction of B field
- Our choice conserves charge but breaks $SU(2)_L \times U(1)$ symmetry
- Examine small excitations about the ground state

$$\phi(x) = \phi_0 + h(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + \eta(x) \end{pmatrix}$$

- Substituting into $\mathcal{L}_{scalar}$:

$$\begin{aligned} \mathcal{L}_{scalar} &= \mathcal{D}^\mu \phi \mathcal{D}_\mu \phi - V(\phi^\dagger\phi) \\ &= \frac{1}{2}(\partial_\mu \eta)^2 - \lambda v^2 \eta^2 - \lambda v \eta^3 - \frac{1}{4}\lambda \eta^4 + const \end{aligned}$$

- 1^{st} term is kineteic energy term, 2^{nd} looks like mass term, others look like self interactions

  Interpret field η as particle (the Higgs) with mass $m_\eta = \sqrt{2\lambda}v$

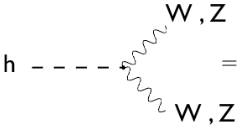
Some Observations

- Single fundamental Higgs is only simplest possible theory
- Important aspect is *dynamic* symmetry breaking where vacuum state breaks the symmetry rather than the Lagrangian
- SM predicted W and Z mass using values of G_F and $\sin\theta_W$ measured in β-decay and ν-scattering respectively
  - Predicted before W and Z decays observed experimentally
  - Gave motivation to build accelerators able to reach these energies
- Higgs mass not predicted by SM
  - $m_\eta = \sqrt{2\lambda v^2}$
  - We know v but not λ
- Fermion masses "explained" but masses themselves are just parameters of the theory

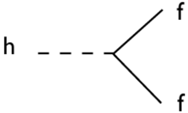
$$\mathcal{L}_{Yukawa} = -\frac{g_f}{\sqrt{2}}\left(\overline{L}\phi R + \overline{R}\phi L\right)$$

with unknown g_f

Couplings of the Higgs Completely Specified in SM



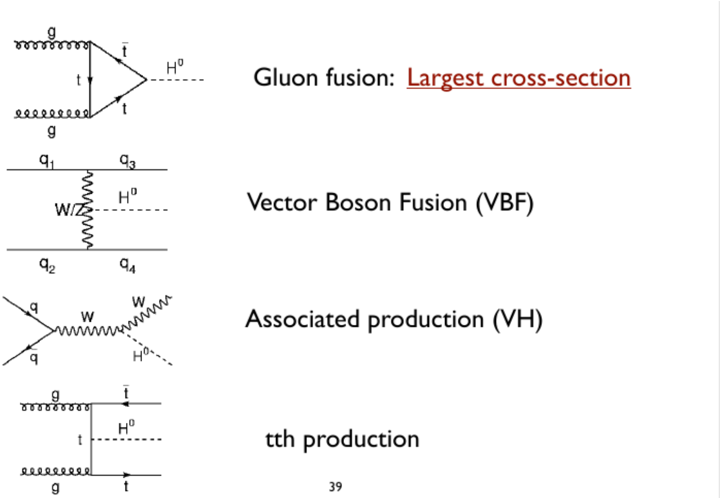
$$= \quad gM_W \quad , \quad \frac{gM_Z}{\cos\theta_W}$$



$$= \quad \frac{gM_f}{2M_W}$$

- But Higgs mass is an unknown parameter (since λ not determined)

Higgs Production at the LHC



Gluon fusion: Largest cross-section

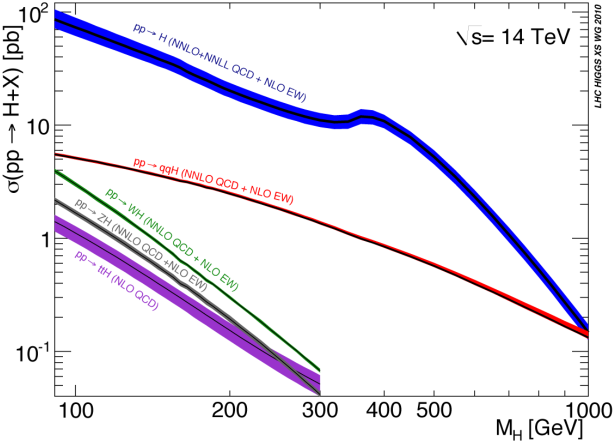
Vector Boson Fusion (VBF)

Associated production (VH)

tth production

39

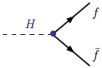
Cross Sections Calculated to NNLO



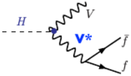
- Gluon fusion dominates
- Importance of VBF increases with m_H
- Associated production falls rapidly with m_H
- $t\bar{t}H$ always small

Higgs Branching Fractions

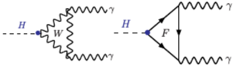
$h \to bb, \tau\tau$

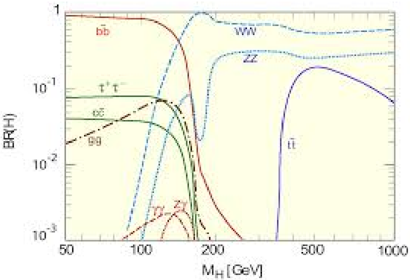


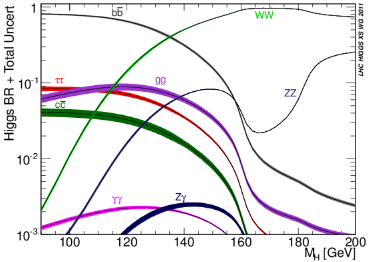
$h \to VV^* \to Vff$



$h \to \gamma\gamma$

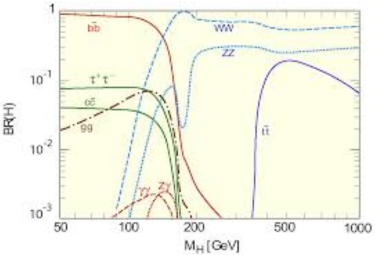






- Higgs likes to decay to the heaviest available states
- Once diboson channels open, they dominate
- Low mass: $h \to b\bar{b}$ largest mode
- $h \to VV^*$ significant for $m_h > 120$ GeV

Search Strategy (I)



- Before Higgs discovered, mass could be anywhere below ~ 1 TeV
- Indirect measurements favored light Higgs ($m_h <\sim 240$ GeV)
- Broad search strategy for all masses, production and decay modes
- If $m_h > 2M_Z$, $h \to ZZ$ is the golden mode
- For $m_h < 2M_Z$ look in multiple modes
  - Largest BR ($h \to b\bar{b}$) has huge background from QCD HF production
  - $h \to ZZ^*$ with leptonic decays clean but low rate ($BR(Z \to \ell\ell) \sim 3\%$ per species)
  - $h \to \gamma\gamma$ has good mass resolution but large continuum background
  - $h \to \tau\tau$ requires good τ identification

Search Strategy (II)

- Independent search in each decay mode
- For given mode, categorize events into categories with different S:B
    - These categories will also tell us about production mechanism
    - Important for measuring coupling
- Measure rate relative to SM prediction

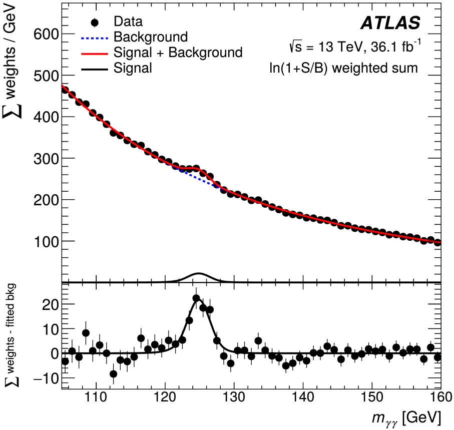
$$\mu \equiv \frac{\sigma \times BR}{(\sigma \times BR)_{SM}}$$

- Initial discovery presented as p-value plot vs m_h
- Construct likelihood function from Poisson probabilities

$$L(data|\mu,\theta) = \prod_i L(data_i|\mu,\theta_i)$$

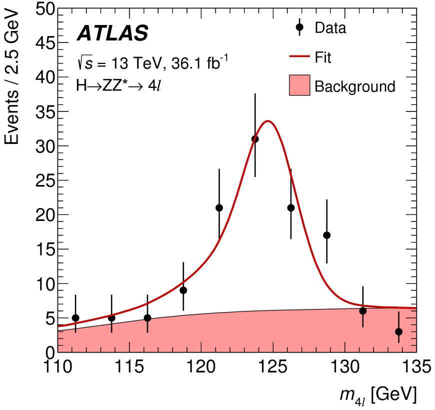
where i are the categories and θ are “nuisance parameters” representing systematic uncertainties

$h \to \gamma\gamma$



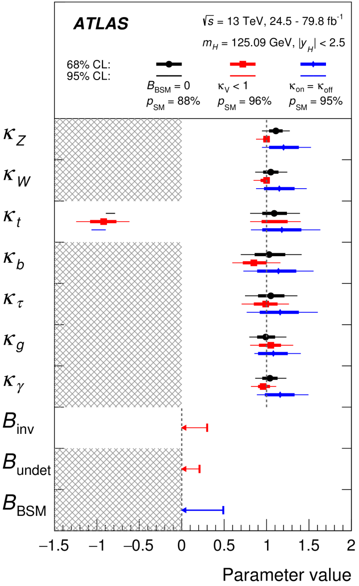
- Narrow peak over large continuum background
- Determine background from fit to data itself
- Depends critically on mass resolution
- Likelihood performed summing over different event categories

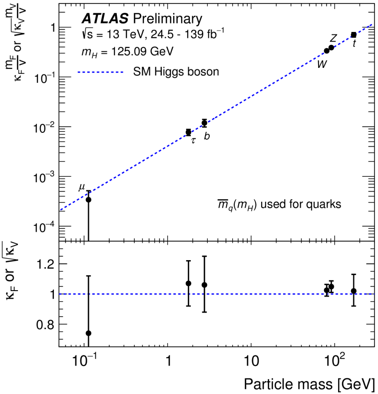
$h \to ZZ^* \to 4\ell$



- Clean signature with narrow peak
- SM background largely from ZZ
- Low statistics due to small BR but very clean
- Important mode for constraining Higgs spin and parity

Constraining Higgs couplings



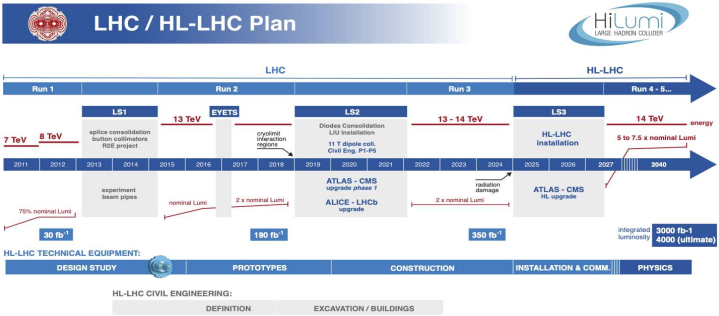


- Coupling to W, Z and 3rd gen. fermions consistent with SM
- $h \to \mu^+\mu^-$ not yet unambiguously seen (only 2σ significance)
- Dependence of couplings on mass established and consistent with SM

What's next for Higgs Measurements?

- Tighten constraints on Higgs-boson and Higgs-fermion couplings
- Look for possible admixture of CP-odd state with the Higgs
- Higgs width measurements to constrain decays to unseen states
- Rare decays to look for new particles in loops
- Can we see the Higgs self coupling (di-Higgs production)?

The future of the LHC



- Current Run 2 data set: 140 fb^{-1}
- Run 3: 2022-2024 ~ 200 fb^{-1}
- High luminosity LHC: 2027-2040, 14 TeV $\sim 3000 - 4000$ fb^{-1}
- Large future data sets and improved detector will allow
  - Increased reach in direct searches for new BSM particles and interactions
  - Strong constraints or evidence of new physics via loop diagrams through precision measurements
  - Insightful probes of new physics using the Higgs boson as a tool, including probes of the Higgs self coupling

Exciting times ahead!