Standard Model Processes

Course on Physics at the LHC

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The Standard Model is...

One of the most predictive, precisely tested theories of nature in human history
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Kind of a bricolage, with good reasons to believe it’s incomplete

=> Where will we see the SM predictions fail?
“Standard Model” encompasses many areas

Electroweak sector (this lecture)

- Properties and interactions of $W$, $Z$, $\gamma$
  - Is the SM self-consistent? (Precision measurements)
  - Do EWK particles interact at the expected rates? (Cross sections & anomalous couplings)

QCD

Interactions of gluons and quarks - see lecture on March 3

If time today - W/Z as tools to study QCD

Flavor and top physics

Properties and interactions of top and other heavy quarks or leptons
See lectures March 24- April 5 and May 3

Higgs physics

Properties and interactions of the Higgs boson
See lectures April 7-19
The tools: Large Hadron Collider at CERN

- proton-proton collisions at 7/8 TeV (Run 1), 13 TeV (Run2)
- SM-Electroweak mainly studied at the large general-purpose detectors CMS and ATLAS
  - Also at LHCb in the forward direction
The players: $W, Z, \gamma$
W and Z decays

- Most of the time, W and Z bosons decay into quarks/hadrons
  - Followed by decays to neutrinos for the Z
  - High rate, but also low experimental resolution, high background
- **Decays with muons and electrons**
  - **Low rate, but lowest background/cleanest signals**
  - Taus: Can be reconstructed via either decays to e/μ, or to hadrons
Leptonic Z reconstruction

- \( Z \rightarrow ll \): One of the cleanest signatures at a hadron collider
  - Opposite charge high-\( p_T \) muons or electrons, with invariant mass near the Z mass (~91 GeV)
  - Lepton isolation (require leptons separated from other tracks/calorimeter deposits):
    - Suppress “fake” backgrounds from QCD/misidentified hadrons, light meson decays-in-flight
    - Suppress “non-prompt” leptons from decays of heavy flavor bottom/charm quarks
Leptonic $W$ reconstruction

- $W \rightarrow l\nu$: high-$p_T$ isolated muon or electron, with “missing transverse energy” inferred from sum of all particles from the collision vertex

- Presence of undetected neutrino => no clear invariant mass peak, so rely on other variables
  - Lepton $p_T$
  - Missing $E_T$ or $p_T$
  - “Transverse mass”, using angle between lepton and missing energy/momentum

\[
m_T = \sqrt{2p_T^\ell p_T^{miss} \cos \Delta \phi}
\]
Leptonic W and Z signals

- Huge samples of W’s and Z’s produced via q/qbar interactions
  - Even in the low branching-fraction leptonic decays
- In 150fb-1 at 13 TeV, expect:
  - ~3B $W \rightarrow l\nu$ events produced
  - ~300M $Z \rightarrow ll$ events produced
- Very high signal/background, especially in $Z \rightarrow ll$
Electroweak physics:
Precision measurements of SM parameters
Precision SM measurements

- Is the Standard Model self-consistent?
  - Measure many observables closely related to SM parameters, then check if SM can fit all the data

- Electroweak sector traditionally the domain of e⁺e⁻ colliders: LEP@CERN, SLC@SLAC

- Hadron colliders unique for top, Higgs inputs (see upcoming lectures)

- But LHC also produces enormous numbers of W,Z bosons => in some cases, can also do precision EWK measurements
Precision SM measurements: $W$ mass

- Basic approach: Generate many Monte Carlo “templates” simulated with different $W$-mass values

- Fit to the data, to determine the best-fit mass

- **Requires extremely precise control of systematics**
  - Experimental aspects
    - Precision of lepton momentum/energy measurement
    - Control of missing $E_T$ reconstruction
  - Theory/model aspects
    - Uncertainties due to PDFs
    - Uncertainties due to “underlying event” activity produced together with the $W$
  - Use comparisons to well-reconstructed $Z$ samples to control (some of) these
Precision SM measurements: W mass

- First LHC measurement at 7 TeV, using lepton $p_T$ and $M_T$ distributions
  - Split in many bins of charge, $\eta$

- Consistent with, and approaching precision of, best previous measurements

$$m_W = 80370 \pm 7 \text{ (stat.)} \pm 11 \text{ (exp. syst.)} \pm 14 \text{ (mod. syst.) MeV}$$

- Ultimate LHC goal: uncertainties <10 MeV
**Precision SM measurements: weak mixing angle**

- Weak mixing angle $sin^2\theta_{eff}$
- Enters in $f \rightarrow Z \rightarrow l^+l^-$ production via vector-axial interference
- The two most precise measurements at $e^+e^-$ colliders are marginally consistent

- **Can be measured from “forward-backward” asymmetry of leptons**
  - Count number of positively charged leptons along the inferred quark vs. the anti-quark direction
Precision SM measurements: weak mixing angle

- Afb measured in many bins of invariant mass and rapidity
  - Fit for best value of $\sin^2 \theta_{\text{eff}}$
  - LHC measurements not yet the most precise, but becoming competitive

$\sin^2 \theta_{\text{eff}}^\ell = 0.23101 \pm 0.00036 \text{ (stat)} \pm 0.00018 \text{ (syst)} \pm 0.00016 \text{ (theo)} \pm 0.00031 \text{ (PDF)}$
Global SM fits: impact of precision measurements

- In green: the direct measurements of $\sin^2 \theta_{\text{eff}}$ and $M_W$
- In blue: SM fit prediction, without $\sin^2 \theta_{\text{eff}}$ or $M_W$ (or $\Gamma_Z$) measurements
- Will green/blue eventually overlap, or diverge (=breakdown of SM)?
  - TBD with more data/higher precision measurements

[Ref]
Electroweak physics: cross sections and gauge boson couplings
Rates of Standard Model processes and electroweak couplings

• Another way to test the Standard Model:
  
  • Do W/Z/γ's interact with each other as predicted by the Standard Model?
  
  • In other words - does LHC measure cross sections involving gauge boson interactions at the rates expected from the SM?
  
  • Especially interesting to look in the high-energy tails of distributions

• Legacy of the LEP e+e− collider: existence of charged triple gauge (WWZ/WWγ) couplings established

• LHC: increase in energy from ~0.2 TeV to ~13/14 TeV!
Gauge boson self-interactions

- Reminder: The SM precisely predicts the strength of EWK gauge boson interactions

- True triple and quartic couplings involving $W$-pairs are predicted to occur

- True neutral triple and quartic couplings (with all $Z$’s or all $\gamma$’s) are forbidden

- Processes can occur through higher-order (loop/box) diagrams at very low rates

[Ref]
**Triple gauge couplings: different views**

- Usually more than 1 way to probe each coupling
  - Different experimental systematics, backgrounds, etc.
  - **Study all of them to get a complete picture**

**Processes sensitive to WWγ couplings**

- \(Z \rightarrow WW\)
  - (diboson production)
- \(W \rightarrow WZ\)
  - (diboson production)
- \(WW \rightarrow Z\)
  - (vector-boson fusion)
“Anomalous” gauge couplings

- Differences (or not) from the SM can be quantified with “anomalous gauge couplings”
  - Mostly model-independent/agnostic about details of new physics
- Modern interpretation
  - Assume new physics occurs at energies too high to directly produce new particles at the LHC
  - Anomalous couplings are “fingerprints” at lower energies from off-shell or loop-level effects
Anomalous couplings and indirect searches

- Classic analogy: beta decay of neutrons
  - Discovered in 1899
  - Apparent “Anomalous quartic coupling” of $npe\nu$ in original Fermi theory

- Higher energies (better microscope) were needed to allow direct observation of the mediator particle
  - $W$-boson finally detected in 1983

- Indirect searches/anomalous couplings sometimes point to new physics long before direct detection
Triple gauge couplings: anatomy of a LHC analysis

- Measure cross section or # of events,
  - Ideally in several bins (of pT, mass, energy… depending on the final state)

- Compare bulk of distribution to SM prediction+backgrounds
  - Quantify any deviations in the high energy tails

[Ref]
Triple gauge couplings with $WW$ production

- Measure cross sections for events with 2 leptons + missing $E_T$
  - High statistics
  - Fairly low backgrounds from top quark production, QCD fakes - estimated from data control samples and simulation
    - (Even the Higgs could be considered a background here!)
  - Overall, cross sections as a function of $p_T$ agree with the Standard Model
    (Run 1 data shown)
  - **Reminder:** $WW\gamma$ and $WWZ$ couplings are allowed in the SM, and are included the cross section prediction
• Anomalous couplings?

• Plot $m_{ll}$ and zoom on the high-mass tails

• No sign of excess, data agrees with the SM

• Convert into upper limits on anomalous coupling parameters

• One-by-one, or for several couplings in a 2-d space
Golden signature: 4 leptons, with 2 pairs compatible with a $Z^{(*)}$ (either $e^+e^-$, $\mu^+\mu^-$)

- Very little background, especially at high mass
- Cross sections compatible with SM at lower $m_{ZZ}$
- No sign of BSM couplings at large $m_{ZZ}$
- Reminder: no direct $ZZZ$ or $\gamma ZZ$ couplings in the SM, prediction comes from $q$-$\bar{q}$ interactions
Summary of TGCs

- LHC has studied many more processes sensitive to TGCs
  - Charged TGCs are consistent with SM predictions
  - Neutral TGCs are consistent with 0 (=SM prediction) - not shown

Charged aTGCs (measured - SM)

- LHC limits on new physics in TGCs now the world’s best
From TGCs to QGCs

- **Triple Gauge Couplings** seem to agree with the SM, within the current experimental precision
  - WWZ and WWγ measured at expected rates
  - No sign of unexpected all-neutral couplings

- **What about the Quartic Gauge Couplings?**
  - Much smaller cross sections
  - Much less explored before the LHC
Quartic gauge interactions: triple-boson production

- One way to probe quartic couplings: look for events with 3 final-state gauge bosons

- With leptonic W or Z decays: 4, 5, or 6 leptons

- Very low cross sections - a few events expected with all the currently available LHC data
Quartic gauge interactions: triple-boson production

- Backgrounds from top quark production, diboson production + fake/non-prompt leptons
- Hunt for signal in tails of transverse mass (leptons+missing $E_T$), or using multi-variate analyses

Small excesses over background in several channels - compatible with SM signal!
Quartic gauge interactions: vector-boson scattering

- Scattering of 2 vector bosons to produce 2 vector bosons
  - $W \rightarrow W$

- Spectacular signatures:
  - Typically 2 high energy forward-backward quark jets, in addition to 2 vector bosons
Quartic gauge interactions: \( \text{WW} \rightarrow \text{WW} \) scattering

- Intimately connected to Higgs sector and new physics

  - SM cross section would grow and become unitarity violating/unphysical at \(~\text{TeV}\) scales, unless:

    - There is a Higgs boson OR other new physics

- Signal appears as excess of events with large \( m(jj) \) and \( m_T \)

  - Fit for sum of signal and backgrounds

- Now observed with \( >5\sigma \) significance at the LHC

  - Next frontier with more data - probe W polarization for greater sensitivity
**Quartic gauge interactions: other VBS processes**

- **What about other vector-boson scattering processes?**
  - No anomalous excesses
  - Several processes observed for the first time

**WW → ZZ**

**WZ → WZ**

**WW → Zγ**

**Wγ → Wγ**
• What about processes with *initial-state* photons radiated off of protons?

• Special case: usually no forward jets, infer γγ production by *lack* of other activity besides 2 W-bosons

• γγ→WW studied by CMS and ATLAS, results consistent with the SM
Even more quartic gauge interactions: “Light-by-light” scattering

- What about processes with *only* photons: $\gamma\gamma \rightarrow \gamma\gamma$?
  - Very difficult in normal p-p collisions, so new techniques/detectors developed
- Heavy-ion collisions
  - Look for back-to-back photons with no other activity
  - SM-like cross section measured, no new physics seen up to ~100 GeV
- p-p collisions with new forward proton detectors
  - No excesses observed from ~300 GeV to ~2 TeV -> limits on anomalous $\gamma\gamma\gamma\gamma$ couplings
Putting it all together:
cross sections and anomalous couplings
Production rates via gauge boson interactions

- Back to the original question:

- **Does LHC measure cross sections involving gauge boson interactions at the rates expected from the SM?**

- **So far, yes…**

  - Over almost 6 orders of magnitude in cross section!
Rates of VBS/tri-boson processes

- What about the very rare processes?
- Zoom in on tri-boson production and vector boson scattering
  - Plot ratio of measurement/SM prediction
- Large uncertainties, but so far so good
Anomalous gauge couplings scorecard (I)

- LHC exploring all the possible EWK 3-boson couplings
- Many upper limits placed on anomalous triple-gauge couplings
- So far no deviations from the SM!
Anomalous gauge couplings scorecard (II)

- LHC exploring all the possible EWK 4-boson couplings

- Many upper limits placed on anomalous quartic-gauge couplings
  - Several for the first time
  - So far no deviations from the SM!
Electroweak physics - where to go from here?

- LHC precision measurements of some SM parameters start to be competitive with the best from $e^+e^-$ colliders
  - Important impact on global fits and combinations with Higgs, top data
- Pattern of gauge boson interactions/couplings so far agrees with the Standard Model
  - Including several very rare processes observed for the first time at the LHC
  - In most cases, sensitivity is to ~TeV scale new physics with large couplings

- ~20x more data expected by the end of the HL-LHC program - probe smaller deviations from the SM
- Program of detector upgrades will enable new measurements/analysis techniques
W/Z as tools for QCD
W/Z as tools for QCD: PDFs

• Apart from “purely” electroweak physics, W/Z can also be used to probe structure of the proton

• Major uncertainty in many LHC measurements and searches: Parton Distribution Functions
  
  • Describe fraction of proton momentum carried by the partons (quarks or gluons)

• Jet production more sensitive to gluon PDFs, Z and W depend on quark PDFs
W/Z as tools for QCD: PDFs

- Measure differential cross sections
  - In invariant mass+rapidity for Z (or non-resonant Drell-Yan)
  - Separately for $W^+$ and $W^-$
  - Different sensitivity to up and down quark PDFs

- Differences between different PDF predictions

- $\Rightarrow$ Use data as input to improve PDF fits
W/Z as tools for QCD: Double-parton scattering

- Usually only 1 “hard” quark or gluon interaction in a single proton-proton collision
  - In rare cases can have 2 or more => “Double parton scattering”
- Can produce spectacular/“weird” signatures
- Potential background to new physics searches, and electroweak measurements
**W/Z as tools for QCD: Double-parton scattering**

- Similar W/Z reconstruction as electroweak measurements
  - Look for pairs of particles from the same vertex, with non-correlated kinematics
    - Unbalanced $p_T$, phi, etc.
  - Several DPS processes seen for the first time at LHC ($W^+W^+$, $W+$jets, $Z+$jets...), for others still looking ($ZZ$...)

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![Graphs and charts showing event distributions for different processes](image-url)
Summary

• The electroweak sector of the Standard Model has been so far remarkably (ridiculously) successful, even at LHC energies

• Attempts to break it are ongoing from all directions
  
  • Combination of precision measurements of SM parameters
  
  • Searches for excesses in high-energy tails of distributions/anomalous couplings
  
  • Close connections to Higgs, top, flavor-physics studies (see upcoming lectures)
Extra