Reminder: Cross Sections at Hadron Colliders

- Rates determined by
  - Hard Scattering Cross Section
  - Parton luminosity
- QCD processes dominate
  - EW rates lower by $\alpha/\alpha_S$
- Main background for $W$ and $Z$ production: QCD jets
- Almost impossible to see single $W \rightarrow q\bar{q}'$ or $Z \rightarrow q\bar{q}$ above jet background
  - UA2 managed to do this with special trigger and very large background
  - But almost all studies of $W$ and $Z$ in hadron colliders in leptonic decay modes:
    - $W^\pm \rightarrow \ell^-\nu_\ell$
    - $\ell^+\bar{\nu}_\ell$
    - $Z \rightarrow \ell^+\ell^-$
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 $\alpha_S$: 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 detector?
• Look for momentum imbalance and assign the missing momentum to the $\nu$
  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

$E_T (2 \text{ vector})$

\[
E_T = -\sum_{\text{Towers}} E_{iT}\hat{n} \\
= -\sum E_i \sin \theta_i \hat{n}
\]

Similarly total $E_i$

\[
E_i = \sum_{\text{Towers}} |E_{iT}| \\
- \sum |E_i| \sin \theta_i
\]

Calorimeter “Tower”

- 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
A Comment on Resolution

• Calorimeter resolution depends on energy deposited

\[ \frac{\sigma}{E_T} \propto \sqrt{\sum E_T} \]

• Measurement is also sensitive to detector cracks and noise
• Degrades with pileup
W Decay: Lepton $p_T$ Distribution

- In CM frame, $e$ and $\nu$ 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 Jacobian:

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

- But we know

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

where $q$ is the charge and $\lambda$ is helicity wrt beamline

so

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

- Notice

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

Diverges for \( \theta = \pi/2 \) (which is \( p_T = \sqrt{s}/2 \))

- Divergence results from the Jacobean factor in transformation 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 $\ell$ and $\nu$ by same boost
- Define $\ell$-$\nu$ transverse mass:

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

- Note that for $p_W^T = 0$, $m_T = 2|p_\ell^T| = 2|p_\nu^T|$
- 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 $m_T$ distribution not very sensitive to modeling of boson $p_T$
- But $m_T$ more sensitive to detector resolution since depends on measurement of the $\nu$
- Background small in both $e$ and $\mu$ 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 $\mu$ and for $+$ and $-$ leptons
- Compare fits of different kinematic variables

We’ll come back to importance of this measurement later today
Top-Pair Production

• Strong production: $t\bar{t}$ pairs

• Tevatron: ($p\bar{p}$ collider)
  ▶ Production rate suppressed: $2m_{top} \sim 0.2\sqrt{s}$
  ▶ 15% $gg$, 85% $q\bar{q}$

• LHC: ($pp$ collider)
  ▶ Production rate larger $2m_{top} \sim 0.05\sqrt{s}$
  ▶ 90% $gg$, 10% $q\bar{q}$
Top Decay Signatures ($t\bar{t}$ Production)

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

- Top Pair production gives:
  
  **Top Pair Branching Fractions**

  - "alljets" 46%
  - $\tau + \text{jets}$ 15%
  - $\mu + \text{jets}$ 15%
  - $e + \text{jets}$ 15%
  - "dileptons"
  - "lepton+jets"
• Top pairs yield 6 high $p_T$ objects
• Separate search strategies for dilepton, single lepton and all hadronic channels
  ▶ Dilepton clean, but 2$\nu$’s so full mass reconstruction not possible
  ▶ Single lepton: Good S:B. The golden channel
  ▶ All-hadronic: Must separate from very large QCD multijet background: possible with $b$-tagging, but difficult to get a pure signal
Goal: Maximize top signal while reducing QCD background

Top decay products central and at high $p_T$

- Typical Tevatron cuts: $p_T > 15$ GeV
- Typical LHC cuts: $p_T > 25$ GeV

Di- and single lepton channels have missing $E_T$

- Define $H_T = \sum_i E_T$ where sum is over reconstructed objects

Two $b$-jets in final state: identification of $b$’s greatly reduced background rate
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, multivariate techniques combine all information into a single metric
Reconstructing Top in Single Lepton Channel

• Sample contains lepton, missing energy and \( \geq 4 \) jets
  (additional jets from initial or final state radiation)
  ▶ 2 jets reconstruct to \( W \) mass
  ▶ \( \ell + \nu \) reconstruct to \( W \) mass
    (must use transverse mass since \( p_T^\nu \) not measured)
  ▶ 2 jets are \( b \)-jets
  ▶ Each \( W + b \) reconstructs to a top

• Many possible combinations of objects possible
  ▶ Can apply constraints to pick the best combinatorial choice
  ▶ Or can use all choices, weighting with probability

• Signal can be observed without \( b \)-tagging if high \( H_T \) cut applied
• But \( b \)-tagging reduces combinatorial background
With b-tagging, Top dominated sample was selected at the Tevatron

Single b-tag and HT>200 GeV

Double Tag
At LHC, large, clean samples available

- Above require single b-tagged jet
- Right hand plot after kinematic likelihood fit and requirement of at least 4 jets
Top Pair Cross Section

- Good agreement with pQCD predictions
- Important since top a major background to BSM searches
The measurements of top mass goes through some common steps:

1. assign a likelihood for each event, function of the top mass: \( L_i (m_t; ...) \)

2. maximize a global likelihood \( L (m_t; ...) = \prod_{i \in \text{events}} L_i (m_t; ...) \), including all the events, to extract the \( m_t \) estimator

3. calibrate to remove any bias of the method

- our analyses are calibrated on Monte Carlo simulation
  - we measure \( m_t \) with the definition implemented in MC!
- the precision of the experimental measurements helps the interpretation of this parameter \( \text{(cfr. PRD 80, 071102 (2009))} \)
Measuring the Top Mass (II)

Methods: Matrix Element

Matrix Element method exploits the full topology of the event:

$$P(x, m_t) = \frac{1}{\sigma(m_t)} \int \sum_{\text{flavours}} f(q_1) f(q_2) \sigma(y, m_t) \mathcal{W}(x, y) \, dq_1 \, dq_2 \, dy$$

*scattering matrix element* (in $\sigma$) for a final-state parton configuration “$y$” (including 4-momenta of all the 6 final state particles)

Probability $f(q_{1/2})$ of having a specific initial state (*Parton Distribution Functions*)

Probability $\mathcal{W}$ of reconstructing the scattering final state “$y$” as our measured jets/lepton objects “$x$” (*Transfer Functions*)
Templates method interprets the distribution of one or more observables sensitive to $m_t$ as probability densities:

- distributions are extracted from full detector simulation
- correlations between observables can be included
- up to three observables used
Measuring the Top Mass (IV)

**in situ** Jet Energy Scale Calibration

- in some final states, $W$ boson can be **fully reconstructed**
- $\Rightarrow$ constrain a $m_W$ estimator with the known $W$ mass
- “nuisance parameter” $\Delta_{JES}$ is measured, describing an additional global scale of jet energy
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 $m_{\text{top}}$ and $m_W$ matter?

- $m_W$ depends quadratically on $m_{\text{top}}$ and logarithmically 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
Are things consistent with Electroweak fits?

- No signs of disagreement to date
Single Top Production Through EW Processes

- Characterize as “s-channel”, “t-channel”, ”$W + t$”
- t-channel is the largest contribution, s-channel the smallest
- More difficult to isolate than the strong pair production
Single Top Production

Inclusive cross-section [pb]

Single top-quark production
September 2018

ATLAS+CMS Preliminary
LHCtopWG

$V_e [T_s]$

$\alpha_s \oplus \text{PDF} \oplus \text{scale}$

$\Delta m_{top} = 172.5$ GeV

$\sqrt{s} \text{ [TeV]}$
Many possible searches

Just one example here: Search for flavor changing neutral current top decays

Will talk more about BMS searches the last week of semester