Measuring the top quark Forward-Backward Asymmetry in Boosted $\ell +$ jets Events at the Large Hadron Collider

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Graduate Board Oral Examination

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Outline

- Introduction
- The Experiment
- Analysis Strategy
- My Work
- Next Steps and Thesis Proposal

The Standard Model of Particle Physics

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- Standard Model governs matter + EM and nuclear forces
- Atoms: protons, neutrons, electrons
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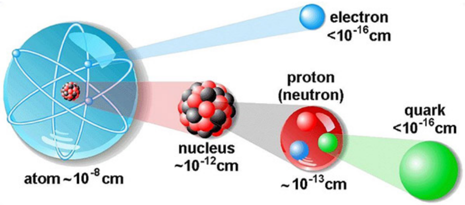

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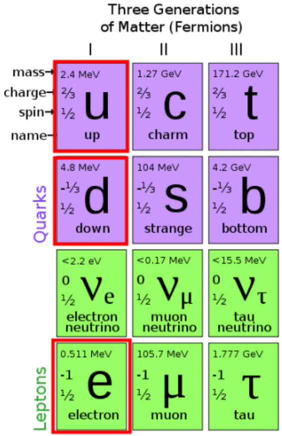

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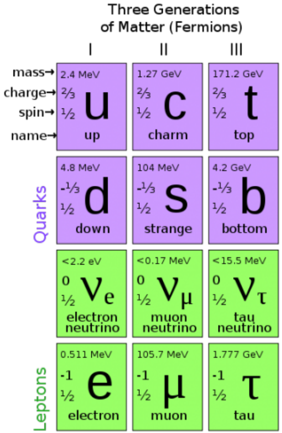

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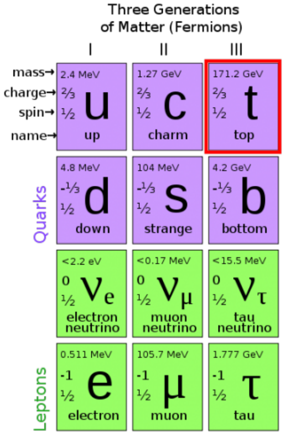

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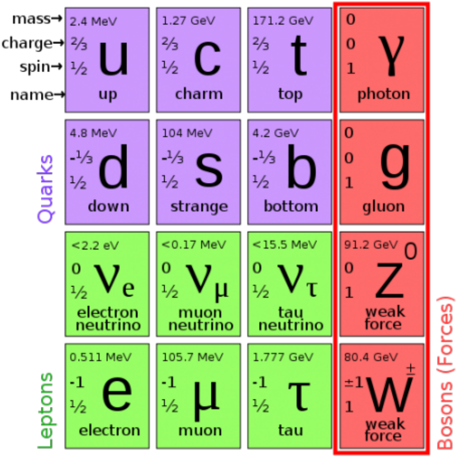
- "Gauge Bosons" mediate interactions



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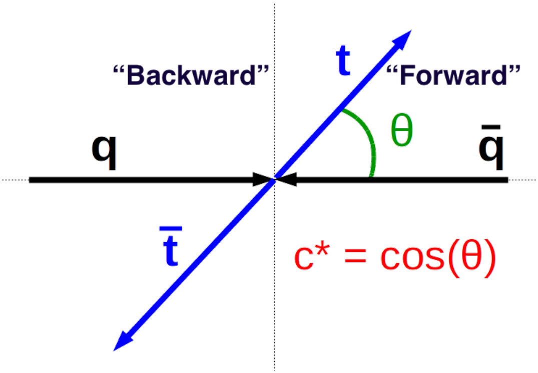
- Many theoretical extensions
- Experiments test these theories or look for new physics
- Our analysis seeks to investigate an anomalous measurement from 2011 that may be an indicator of new physics

The $t\bar{t}$ Forward-Backward Asymmetry A_{FB}

What is A_{FB}?

- Consider $q\bar{q} \to t\bar{t}$
- top and antitop leave back to back

Center of Mass frame



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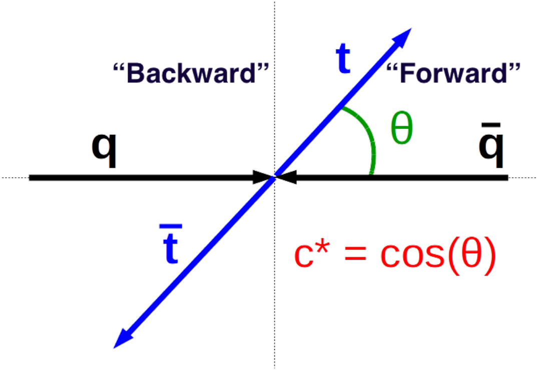

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- **Predicted from SM: $\mathbf{A}_{\mathrm{FB}}$ ≈10%**

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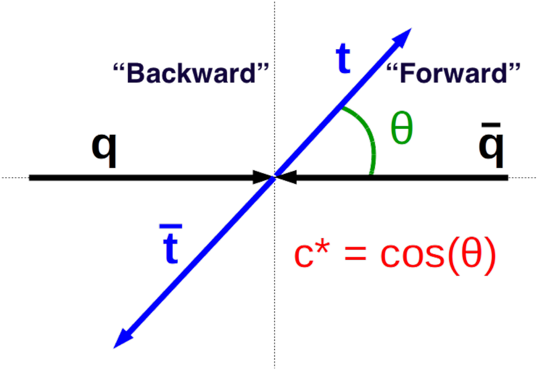

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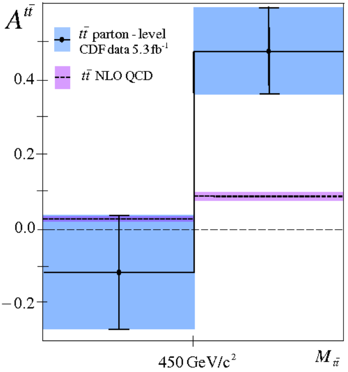
A_{FB} Predictions and Measurements

- Collider Detector at Fermilab (CDF) Experiment measured A_{FB} in 2011
- Found anomalously large value, $A_{FB} \approx 45\%$
- Using 3.2 fb^{-1} of data, found 2.3σ deviation from expectation
- Measurement of A_{FB} never performed by any LHC Experiment

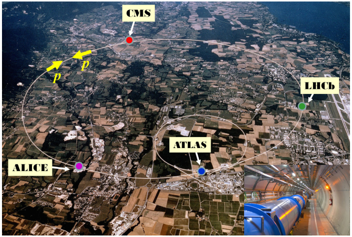


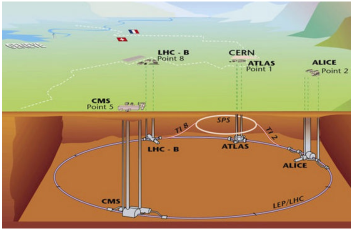
Plot: CDF Collaboration, *Evidence for a Mass Dependent Forward-Backward Asymmetry in Top Quark Pair Production*, **arXiv:1101.0034 [hep-ex]**

The Large Hadron Collider (LHC)
and the
Compact Muon Solenoid (CMS) Detector

The Large Hadron Collider

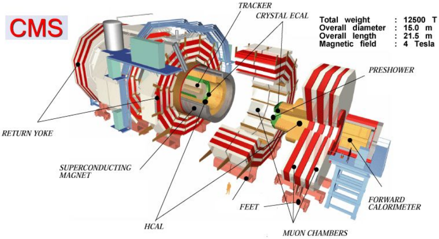
- Largest and highest energy particle collider in the world
- Collides beams of protons
- 27km circumference, 175m underground
- Built at CERN just outside of Geneva
- Massive international collaboration
- 4 main detectors

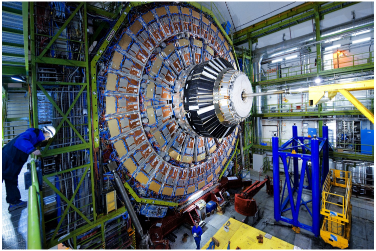


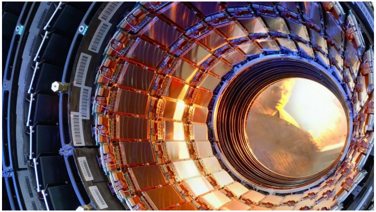


The CMS Experiment

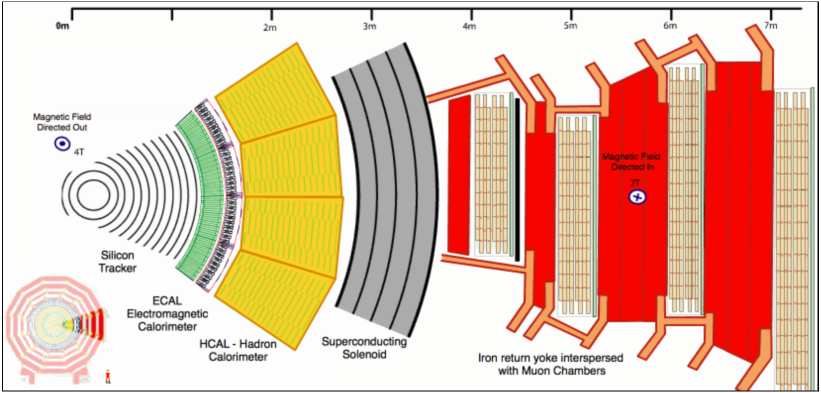
- General purpose detector
- Measures energies and paths of particles
- About 3,000 people, 40 countries







Particle Behavior in the CMS Detector



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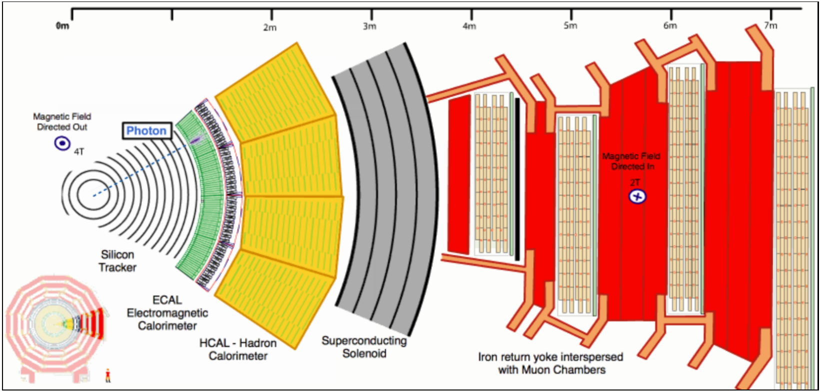

Photons leave energy deposits

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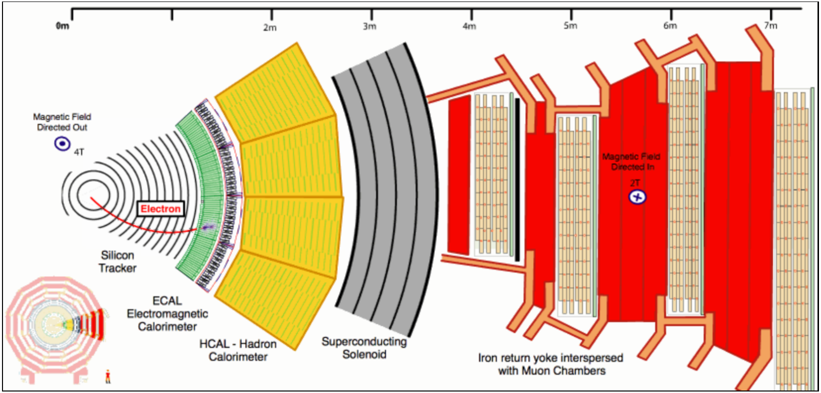

Leptons (Muons, Electrons) leave tracks and energy deposits

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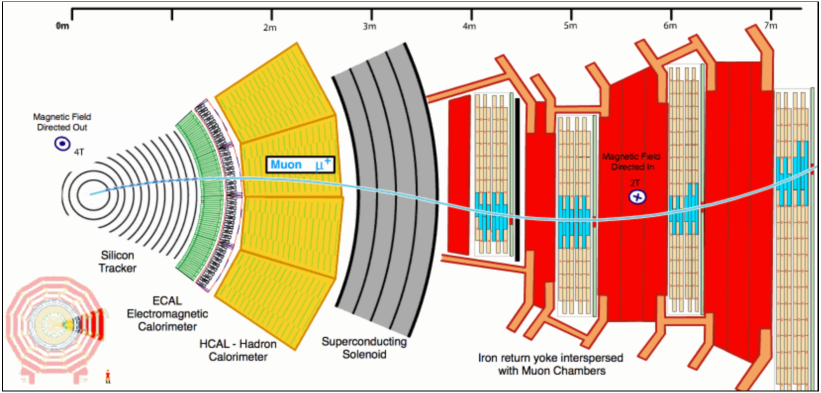

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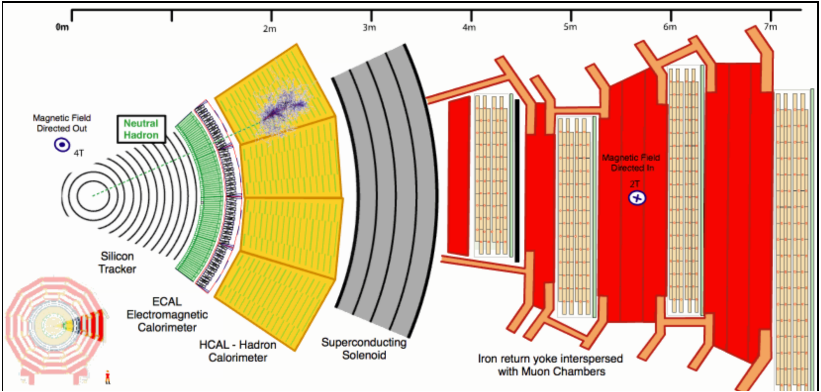

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Decaying heavy quarks leave many tracks that we collect into “Jets”

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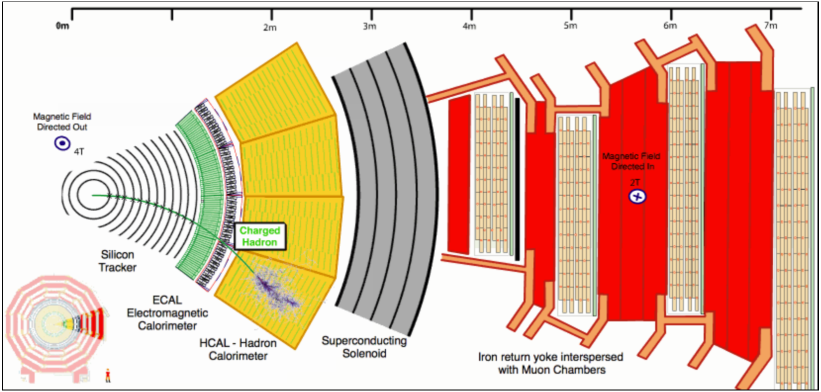

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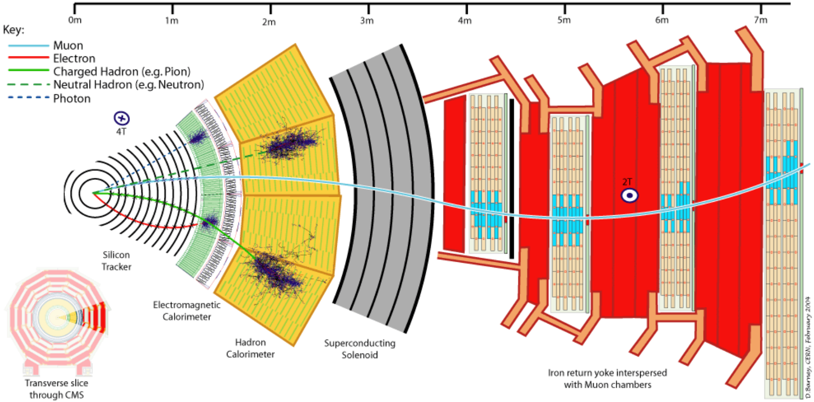

CMS measures all of the energy and momenta and anything left over ("Missing transverse energy" MET) is from an invisible neutrino

How we measure A_{FB}

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- quarks and gluons inside colliding protons combine energies to produce a wide variety of events.
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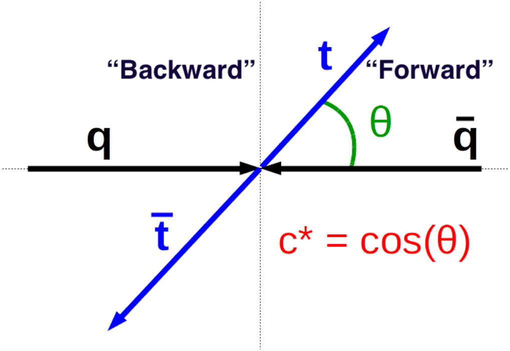
  - "Single top" events
  - "Non-top multi-jet" (NTMJ) events
- Distinguish top pairs using kinematics
- Choose observables to distinguish $q\bar{q}/gg/qg \to t\bar{t}$

Physical Observables

- Production direction c^*
  - Main observable: shows asymmetry
  - Provides good discrimination
- Boost amount $|x_F|$
- Pairwise invariant mass M



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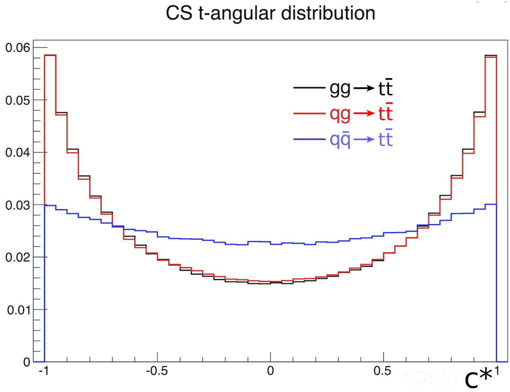

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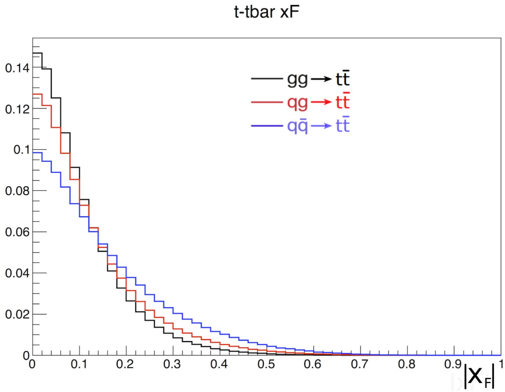

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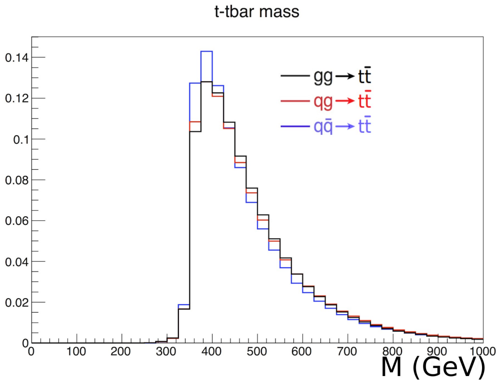
- Pairwise invariant mass M
  - CDF result: A_{FB} is $M_{t\bar{t}}$-dependent
  - Gives good separation for "boosted" events

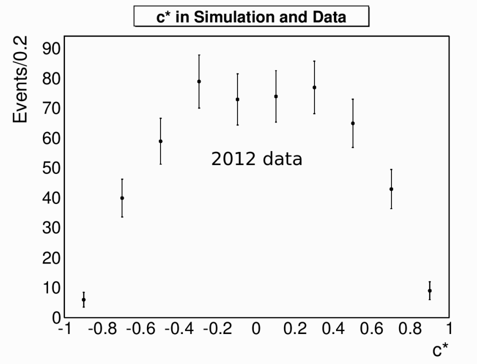


Differential Cross Section

If $\vec{x} \equiv (c^*, x_F, M)$:

$$\frac{d\sigma}{d\vec{x}}(total) \propto \frac{d\sigma}{d\vec{x}}(background) + \frac{d\sigma}{d\vec{x}}(gg; M^2) + \frac{d\sigma}{d\vec{x}}(q\bar{q}; M^2)$$

Describe how many events we expect with given c^*,x_F,and M



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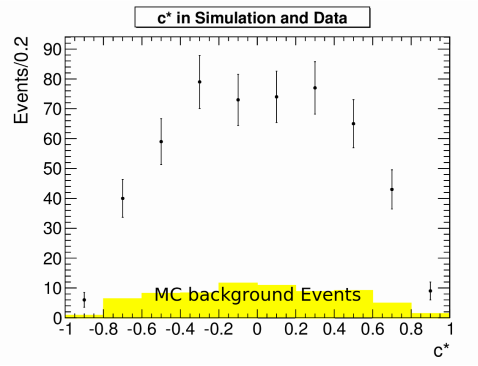
All Background Processes



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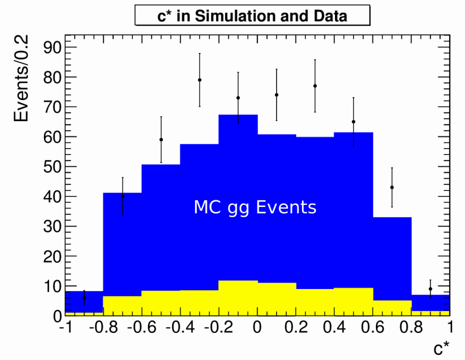
For each subprocess:

$$\frac{d\sigma}{d\vec{x}}(gg; M^2) \propto F_{gg}(M^2, \beta, c^{*2})$$



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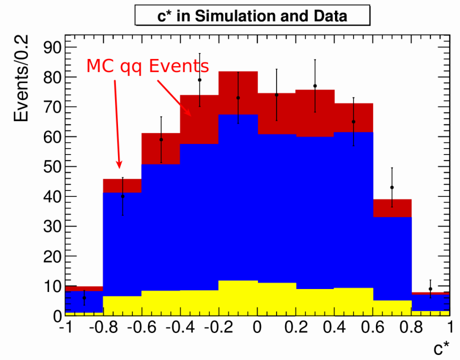

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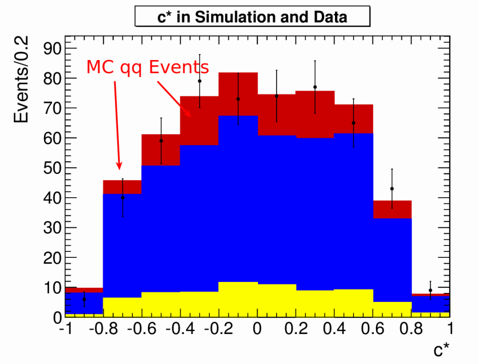
A_{FB}: Linear Asymmetry



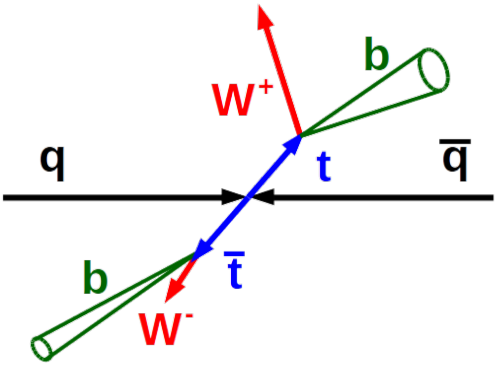
Fitting Plan

1. Simulate $q\bar{q} \to t\bar{t}$, $gg/qg \to t\bar{t}$, and background processes
2. Select and Reconstruct Monte Carlo and data events in the same way
3. Build 3D template (histogram in observables) from Monte Carlo for each term in cross section
   - Symmettrize/Antisymmetrize $q\bar{q} \to t\bar{t}$ to make $F_{q\bar{q}s}/F_{q\bar{q}a}$
4. Sum all the templates and allow their relative amounts to float in a fit to data
5. Extract A_{FB}

My Work

What do Our Signal Events Look Like?

"Boosted Semileptonic $t\bar{t}$"



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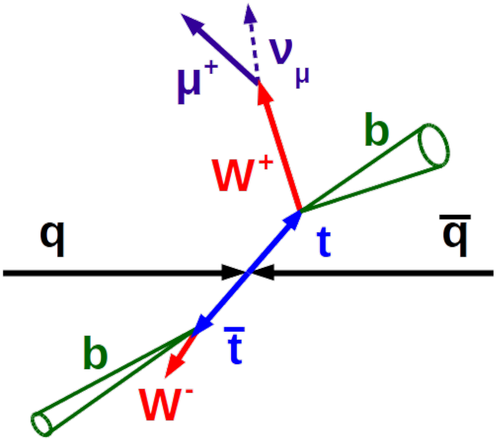

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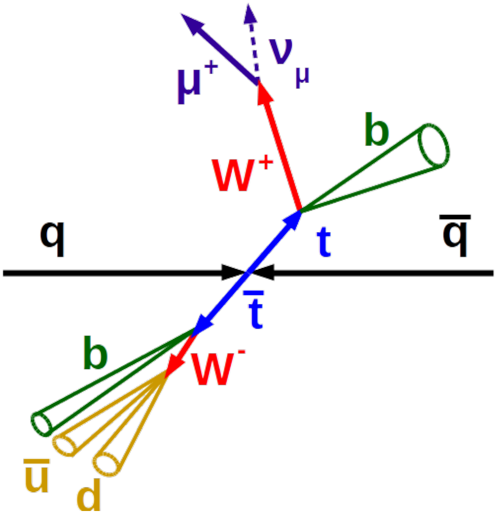

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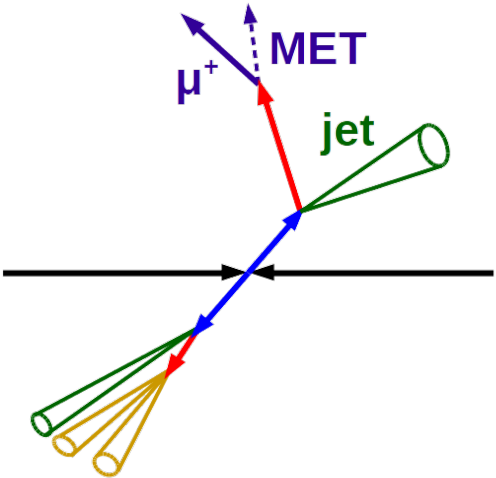

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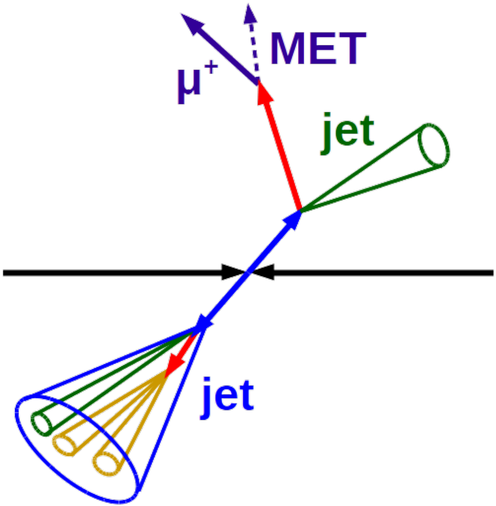

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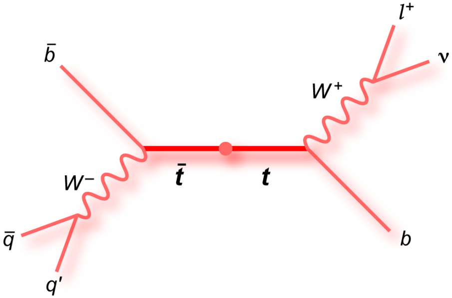
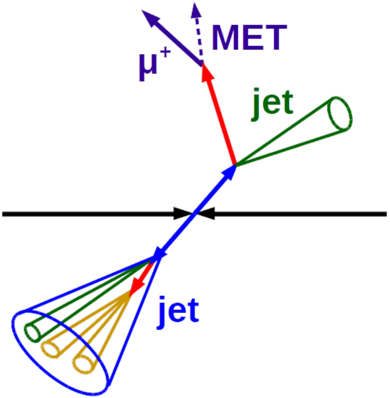


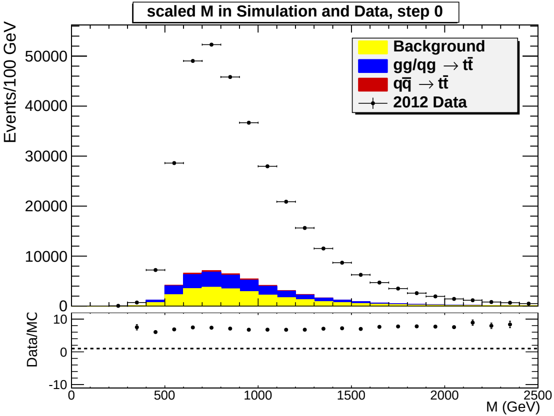


Semileptonic $t\bar{t}$ is best laboratory

- Gives charge assignment
- High cross section
- Efficient selection

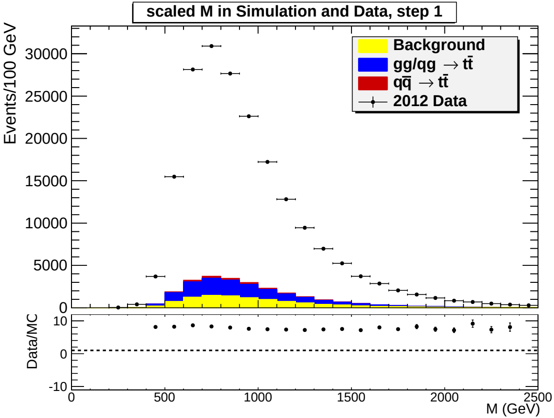
Event Selection

- Preselection
  - One heavy jet and one other jet
- Leptonic Side
- Hadronic Side



Event Selection

- Preselection
- Leptonic Side
  - Lepton Trigger



- Hadronic Side

Event Selection

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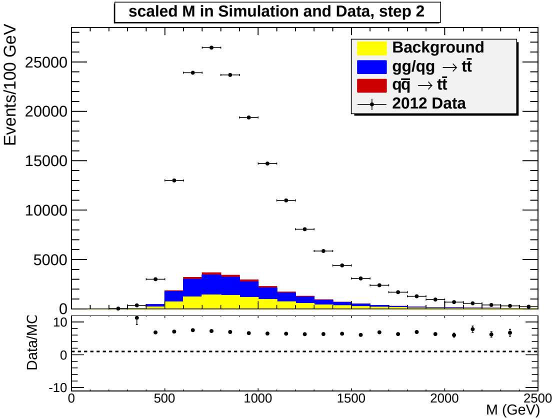
  - High momentum lepton in clean detector range



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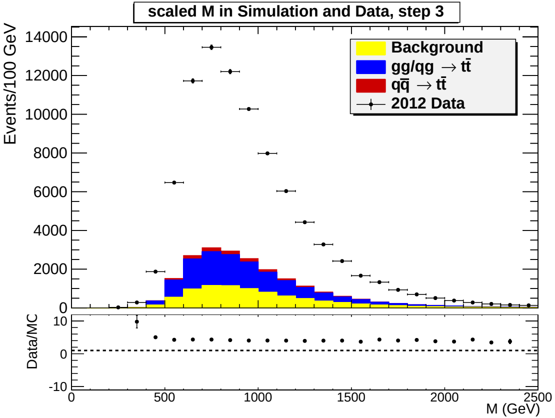

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Event Selection

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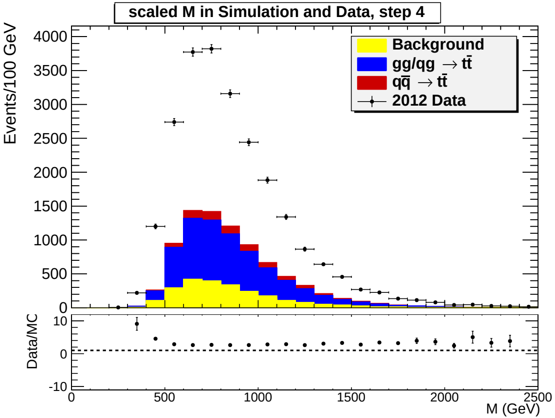
    - High momentum lepton in clean detector range
    - ID and isolation requirement
    - Lepton + MET + lighter jet have mass near t mass
- Hadronic Side



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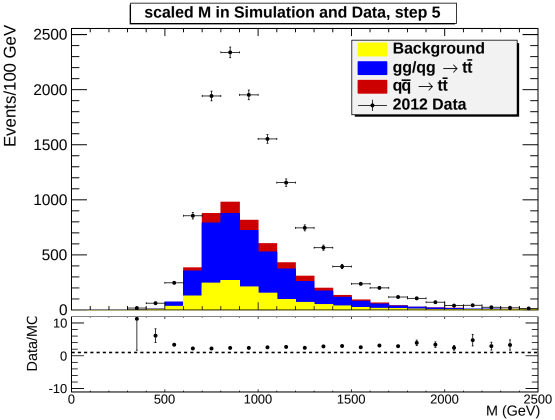
  - Very high momentum jet
  - Guarantees fully merged t jet



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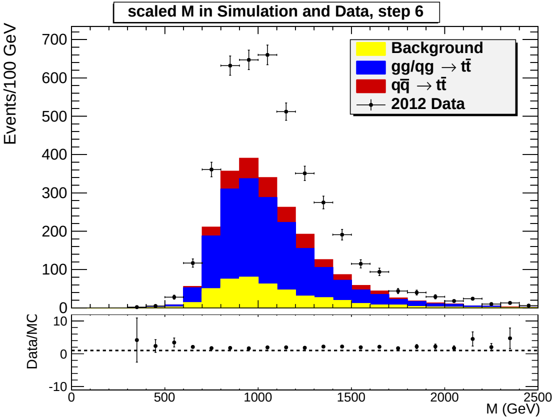
    - Very high momentum jet
    - Guarantees fully merged t jet
    - Mass comparable to t mass



Event Selection

- Preselection
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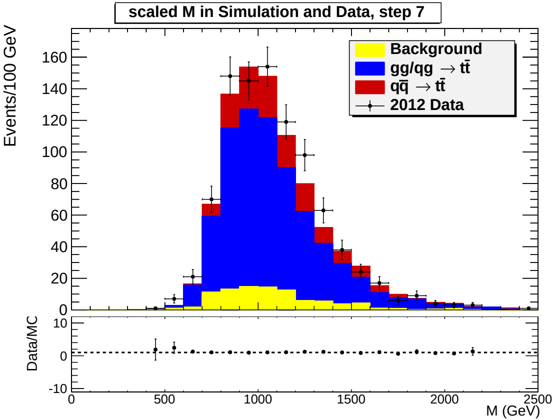
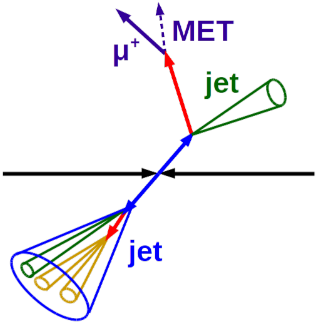
- Hadronic Side
  - Very high momentum jet
  - Guarantees fully merged t jet
  - Mass comparable to t mass
  - Looks like three subjets



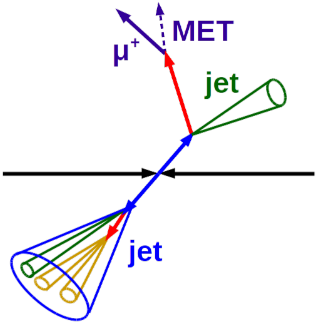
Event and Observable Reconstruction

- Now need to calculate observables



Event and Observable Reconstruction

- Now need to calculate observables
- Need to reconstruct top and anti-top, x_t^μ and $x_{\bar{t}}^\mu$
- Wiggle object momenta, check mass constraints ("kinematic fit")



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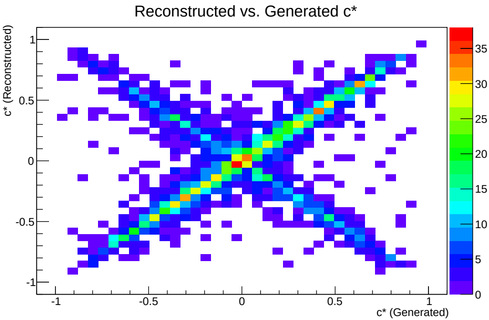
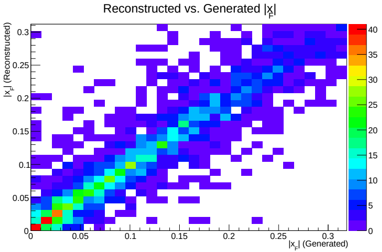
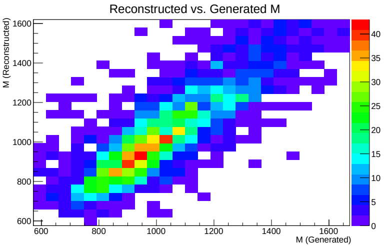
if $Q^\mu = x_t^\mu + x_{\bar{t}}^\mu$:

$$c^* = \hat{x}_t \cdot \hat{x}_q$$
$$x_F = {}^{2Q_z}\!/\!\sqrt{s}$$
$$M = \sqrt{Q \cdot Q}$$

Observable Reconstruction Comparison



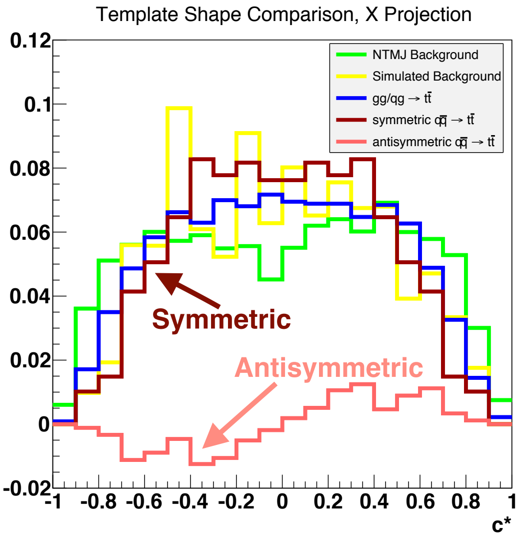




Possible sign-flip from Collins-Soper

Template Shape Comparison

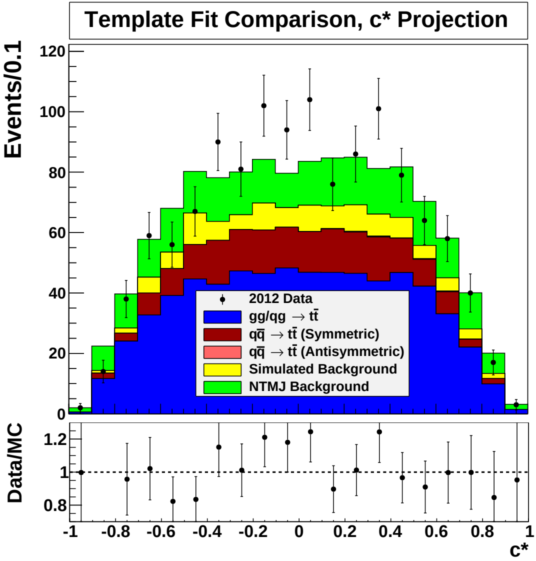
Events added to 3D histograms
$F_{q\bar{q}s}/F_{q\bar{q}a}$ distributions
symmetrized/antisymmetrized



Template Fit Results

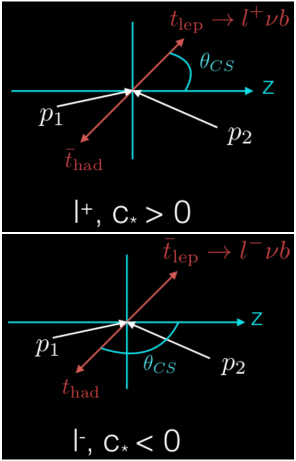
Result:

$$\mathbf{A_{FB} = 7.9\% \pm 7.7\%}$$



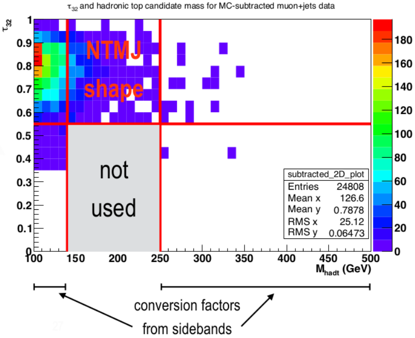
Missing Pieces

- Charge Separation & CP Symmetry



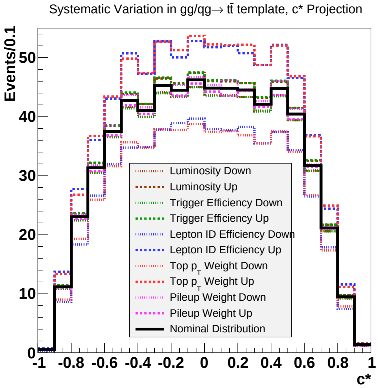
Missing Pieces

- Charge Separation & CP Symmetry
- Data-driven NTMJ background estimation ("template morphing")



Missing Pieces

- Charge Separation & CP Symmetry
- Data-driven NTMJ background estimation ("template morphing")
- Sytematics
  - Jet Energy Corrections
  - Pileup & Luminosity
  - Lepton Trigger & ID efficiency
  - Two different types of top p_T reweighting
  - Monte Carlo Statistics Uncertainty
  - PDF choice uncertainty



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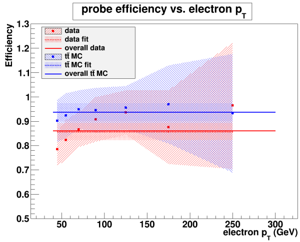

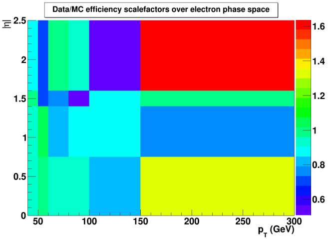

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- Measuring Electron Trigger and ID efficiency (“tag-and-probe”)
- Low-mass “resolved” analysis with Lei (Raymond) Feng (AN2015-020)

Available on CMS information server **CMS AN -2015/020**

The Compact Muon Solenoid Experiment

Analysis Note

The content of this note is intended for CMS internal use and distribution only

22 January 2015

Measuring the $t\bar{t}$ Forward-Backward Asymmetry at the LHC

N. Eminizer, L. Feng, M. Swartz

Abstract

This note discusses a scheme to extract the top quark forward-backward asymmetry from LHC data. The technique is based upon a linear extension of the tree-level cross section for quark-antiquark initial states and it sensitively isolates those initial states from gluon-gluon and quark-gluon initial states. The statistical power of the technique exceeds that of the charge asymmetry technique that has been in use to study LHC data. The quantity produced by this technique is already corrected to parton level and is directly comparable to similar quantities derived from the Tevatron measurements.

In the longer term, this technique could be used to search for interference effects from $t\bar{t}$ resonances at larger pair masses using partly merged semileptonic events. Because large interference effects can occur at pair masses well below or above the actual resonance mass and are insensitive to the resonance width, this technique would be quite complementary to techniques that search for “bumps” in the $t\bar{t}$ mass spectrum.

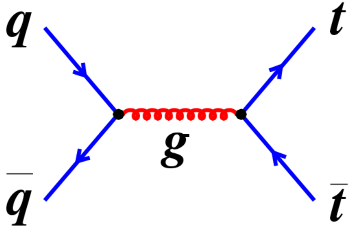
What's Next

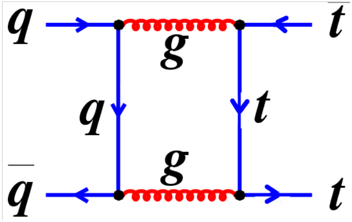
Next Steps

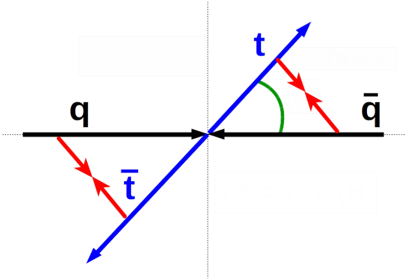
- A few refinements
- "Start over" with 13TeV data
  - Higher cross section ($\sigma^{t\bar{t}}_{incl} = 248pb \rightarrow 816pb$)
  - Greater Luminosity
  - Increased boosted event abundance
- Extension to anomalous chromoelectric/chromomagnetic moments
- Adapt as high-mass $t\bar{t}$ resonance search

Backup

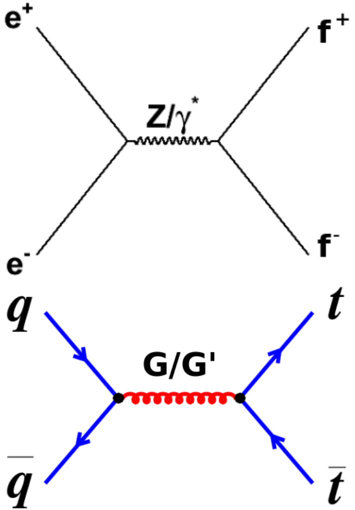
Why is $A_{FB} \neq 0$ in the Standard Model?

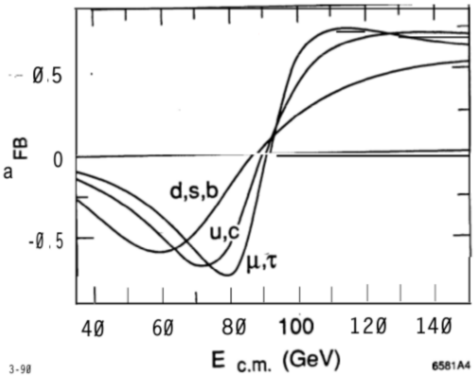






New physics with A_{FB}

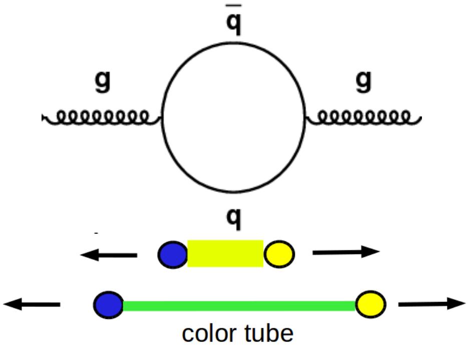




Chiral couplings can create large A_{FB} effects even far from resonances

What is a jet?

- Strong force is weaker at larger separation and energy ("asymptotic freedom")
- Begin pulling a meson apart
- "Antiscreening" leads to a "color tube"



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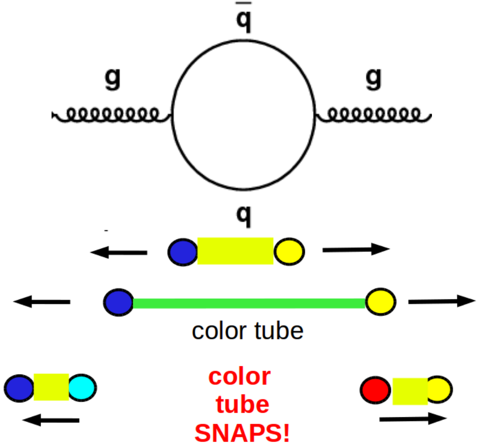

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- Begin pulling a meson apart
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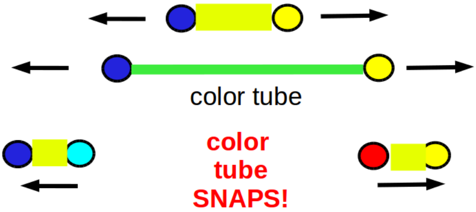
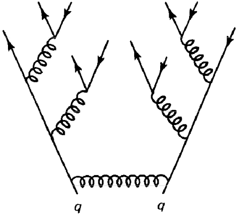
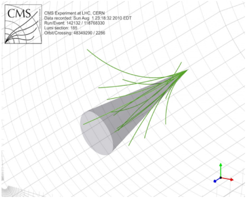
- The virtual pair becomes real and there are now two mesons
- A decaying quark becomes a shower of hadrons, or "jet"

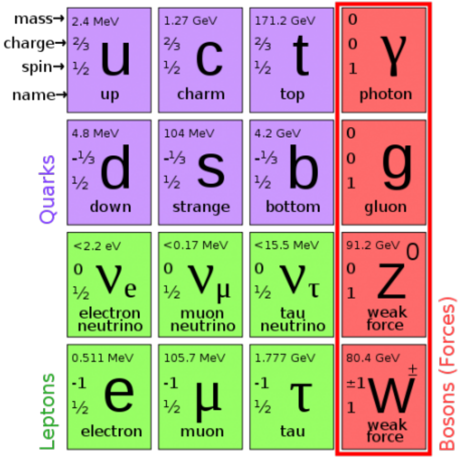






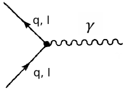
The Standard Model: Interactions

- "Bosons" mediate interactions

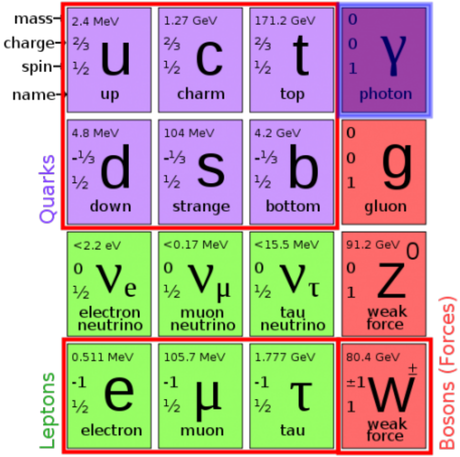


The Standard Model: Interactions

- Electromagnetism
    - Mediated by photon (γ)
    - Couples particles with electric charge
    - Quarks, charged leptons, $W^{\pm}$ bosons

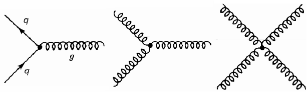


- Strong Force
- Weak Force (Neutral)
- Weak Force (Charged)

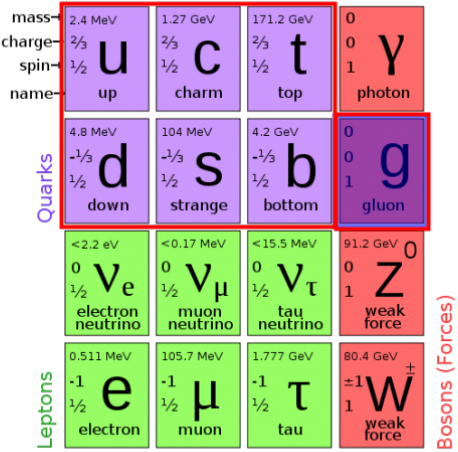


The Standard Model: Interactions

- Electromagnetism
- Strong Force
  - Mediated by gluons (g)
  - Couples particles with "color charge"
  - Quarks, other gluons

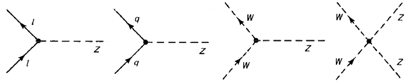


- Weak Force (Neutral)
- Weak Force (Charged)

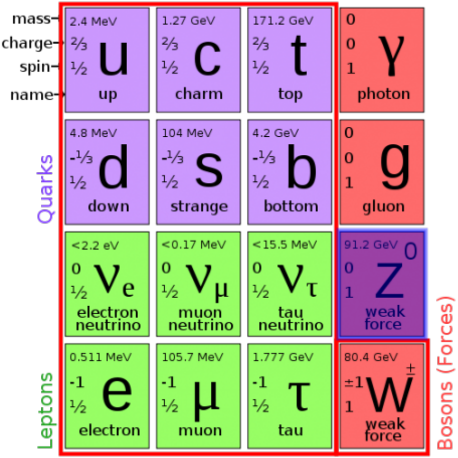


The Standard Model: Interactions

- Electromagnetism
- Strong Force
- Weak Force (Neutral)
  - Mediated by Z^0 boson
  - Quarks, Leptons, $W^{\pm}$ boson

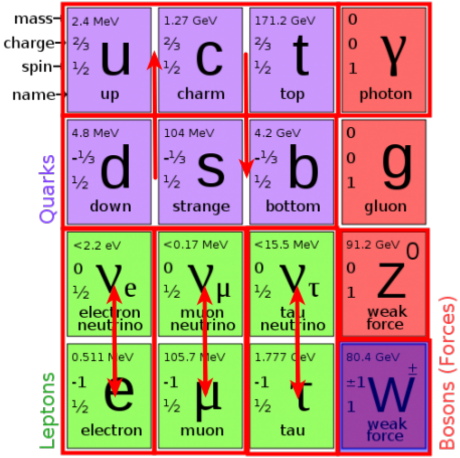


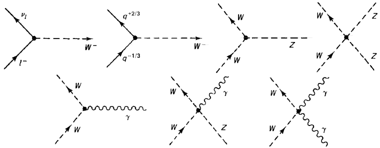
- Weak Force (Charged)



The Standard Model: Interactions

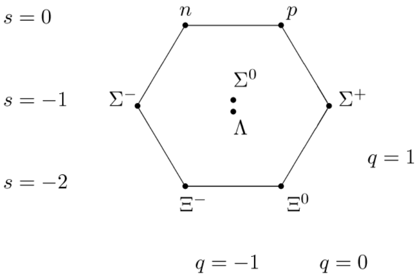
- Electromagnetism
- Strong Force
- Weak Force (Neutral)
- Weak Force (Charged)
  - Mediated by $W^{\pm}$ bosons
  - Quarks, Leptons, photon, Z boson, other $W^{\pm}$ bosons
  - Only "flavor-changing" interactions

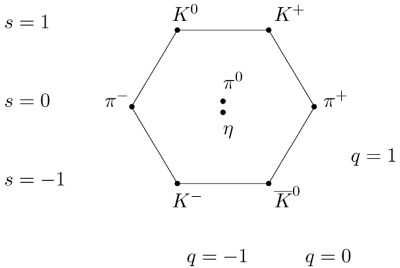


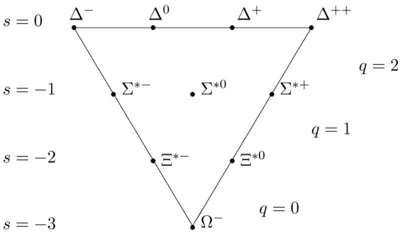


The Eightfold Way

- Proposed by Gell-Mann in 1960s before quark theory
- Organizes lightest mesons/baryons into representations of SU(3)
- Approximate strong interaction flavor symmetry for u, d, s
- Can be extended to flavor SU(6)







Isospin Analysis of Scattering

In the three-quark model, lightest mesons and baryons can be assigned a vector quantity called "Isospin" (I) with a projection value I_3 in analogy to spin, i.e. :

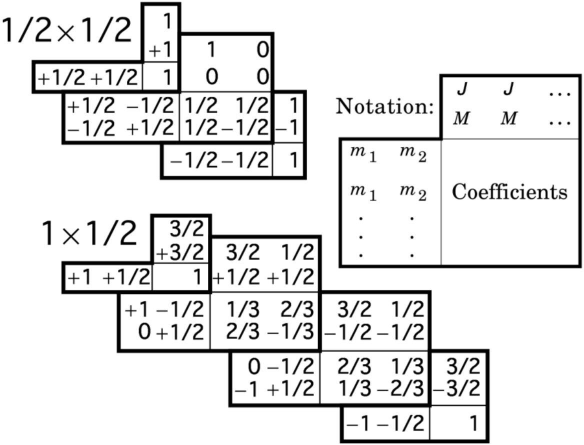
$$\pi^+ = |I = 1 \;\; I_3 = 1\rangle, \qquad \pi^0 = |1 \;\; 0\rangle, \qquad \pi^- = |1 \;\; -1\rangle$$
$$p = |{}^1\!/\!_2 \;\; {}^1\!/\!_2\rangle, \qquad n = |{}^1\!/\!_2 \;\; -{}^1\!/\!_2\rangle$$

Strong interactions conserve isospin, so scattering amplitude relations can be calculated by decomposing scattering processes into isospin components :

$$\begin{aligned}\pi^+ + n \to \pi^+ + n &= \left(\langle {}^1\!/\!_2 \;\; -{}^1\!/\!_2|\langle 1 \;\; 1|\right)\left(|{}^1\!/\!_2 \;\; -{}^1\!/\!_2\rangle|1 \;\; 1\rangle\right)\\ &= \frac{1}{3}\langle {}^3\!/\!_2 \;\; {}^1\!/\!_2|{}^3\!/\!_2 \;\; {}^1\!/\!_2\rangle + \frac{2}{3}\langle {}^1\!/\!_2 \;\; {}^1\!/\!_2|{}^1\!/\!_2 \;\; {}^1\!/\!_2\rangle = \frac{1}{3}\mathscr{M}_3 + \frac{2}{3}\mathscr{M}_1\\ \pi^+ + n \to \pi^0 + p &= \left(\langle {}^1\!/\!_2 \;\; {}^1\!/\!_2|\langle 1 \;\; 0|\right)\left(|{}^1\!/\!_2 \;\; -{}^1\!/\!_2\rangle|1 \;\; 1\rangle\right)\\ &= \frac{\sqrt{2}}{3}\langle {}^3\!/\!_2 \;\; {}^1\!/\!_2|{}^3\!/\!_2 \;\; {}^1\!/\!_2\rangle - \frac{\sqrt{2}}{3}\langle {}^1\!/\!_2 \;\; {}^1\!/\!_2|{}^1\!/\!_2 \;\; {}^1\!/\!_2\rangle = \frac{\sqrt{2}}{3}\mathscr{M}_3 + \frac{\sqrt{2}}{3}\mathscr{M}_1\end{aligned}$$

$$\frac{\sigma\left(\pi^+ + n \to \pi^+ + n\right)}{\sigma\left(\pi^+ + n \to \pi^0 + p\right)} = \frac{|\mathscr{M}_3 + 2\mathscr{M}_1|^2}{2|\mathscr{M}_3 + \mathscr{M}_1|^2} \approx \frac{1}{2}$$

Clebsch-Gordan Coefficients



The Feynman Rules (External Lines, Propagators, and QED vertex factors)

External Lines

Spin 0: (nothing)

Spin $\frac{1}{2}$: $\begin{cases} \text{Incoming particle: } u \\ \text{Incoming antiparticle: } \bar{v} \\ \text{Outgoing particle: } \bar{u} \\ \text{Outgoing antiparticle: } v \end{cases}$

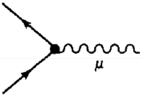
Spin 1: $\begin{cases} \text{incoming: } \epsilon^{\mu} \\ \text{outgoing: } \epsilon^{\mu *} \end{cases}$

Propagators

Spin 0: $\dfrac{i}{q^2 - (mc)^2}$

Spin $\frac{1}{2}$: $\dfrac{i(\not{q} + mc)}{q^2 - (mc)^2}$

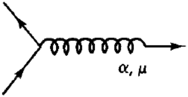
Spin 1: $\begin{cases} \text{Massless: } \dfrac{-ig_{\mu\nu}}{q^2} \\ \text{Massive: } \dfrac{-i[g_{\mu\nu} - q_{\mu}q_{\nu}/(mc)^2]}{q^2 - (mc)^2} \end{cases}$

QED: 

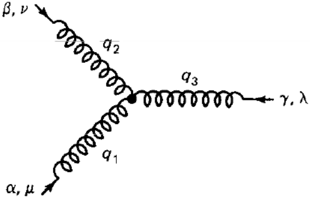
$ig_e\gamma^{\mu}$ $\quad (g_e = \sqrt{4\pi\alpha})$

The Feynman Rules (QCD vertex factors)

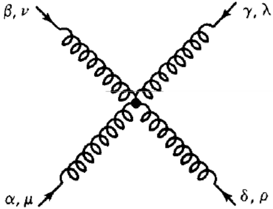
QCD:



$$\frac{-ig_s}{2}\lambda^\alpha\gamma^\mu$$

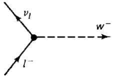


$$-g_s f^{\alpha\beta\gamma}[g_{\mu\nu}(q_1-q_2)_\lambda + g_{\nu\lambda}(q_2-q_3)_\mu + g_{\lambda\mu}(q_3-q_1)_\nu]$$



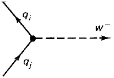
$$-ig_s^2[f^{\alpha\beta\eta}f^{\gamma\delta\eta}(g_{\mu\lambda}g_{\nu\rho}-g_{\mu\rho}g_{\nu\lambda}) + f^{\alpha\delta\eta}f^{\beta\gamma\eta}(g_{\mu\nu}g_{\lambda\rho}-g_{\mu\lambda}g_{\nu\rho}) + f^{\alpha\gamma\eta}f^{\delta\beta\eta}(g_{\mu\rho}g_{\nu\lambda}-g_{\mu\nu}g_{\lambda\rho})]$$

The Feynman Rules (Electroweak vertex factors)



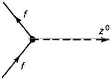
$$\frac{-ig_w}{2\sqrt{2}}\gamma^\mu(1-\gamma^5)$$

(Here l is any lepton, and ν_l the corresponding neutrino.)



$$\frac{-ig_w}{2\sqrt{2}}\gamma^\mu(1-\gamma^5)U_{ij}$$

(Here $i = u, c$, or t, and $j = d, s$, or b; U is the Kobayashi–Maskawa matrix.)

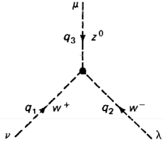


$$\frac{-ig_z}{2}\gamma^\mu(c_V^f - c_A^f\gamma^5)$$

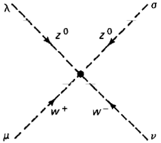
(Here f is any quark or lepton.)

f	c_V	c_A
ν_e, ν_μ, ν_τ	$\frac{1}{2}$	$\frac{1}{2}$
e^-, μ^-, τ^-	$-\frac{1}{2} + 2\sin^2\theta_w$	$-\frac{1}{2}$
u, c, t	$\frac{1}{2} - \frac{4}{3}\sin^2\theta_w$	$\frac{1}{2}$
d, s, b	$-\frac{1}{2} + \frac{2}{3}\sin^2\theta_w$	$-\frac{1}{2}$

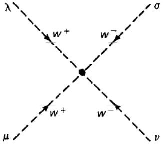
The Feynman Rules (Electroweak vertex factors)



$$ig_w \cos\theta_w[g_{\nu\lambda}(q_1-q_2)_\mu + g_{\lambda\mu}(q_2-q_3)_\nu + g_{\mu\nu}(q_3-q_1)_\lambda]$$

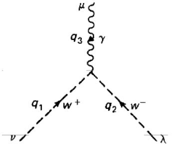


$$-ig_w^2\cos^2\theta_w(2g_{\mu\nu}g_{\lambda\sigma} - g_{\mu\lambda}g_{\nu\sigma} - g_{\mu\sigma}g_{\nu\lambda})$$

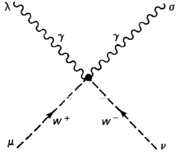


$$ig_w^2(2g_{\mu\lambda}g_{\nu\sigma} - g_{\mu\nu}g_{\lambda\sigma} - g_{\mu\sigma}g_{\nu\lambda})$$

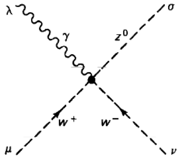
The Feynman Rules (Electroweak vertex factors)



$$ig_e[g_{\nu\lambda}(q_1 - q_2)_\mu + g_{\lambda\mu}(q_2 - q_3)_\nu + g_{\mu\nu}(q_3 - q_1)_\lambda]$$



$$-ig_e^2(2g_{\mu\nu}g_{\lambda\sigma} - g_{\mu\lambda}g_{\nu\sigma} - g_{\mu\sigma}g_{\nu\lambda})$$



$$-ig_e g_w \cos\theta_w(2g_{\mu\nu}g_{\lambda\sigma} - g_{\mu\lambda}g_{\nu\sigma} - g_{\mu\sigma}g_{\nu\lambda})$$

Conserved Quantities

When writing down particle interactions and Feynman Diagrams, check conservation of:

1. Electric charge (some may be carried away by a $W^{\pm}$)
2. Color charge (only applicable to strong interactions, gluons are dual-colored)
3. Baryon number
4. Lepton number (only applicable to EM/weak)
5. Lepton flavor (except for neutrino oscillations)
6. Quark flavor (only applicable to EM/strong)

Weak Interaction Selection Rules

1. Conservation of Lepton Flavor Number L_e, L_μ, L_τ
   - In absence of neutrino oscillations
2. Strangeness changing interactions ($\Delta S \neq 0$) are suppressed by a factor of ≈ 10
   - $\Delta S = 2$ interactions are extremely suppressed
3. For hadrons in $\Delta S \neq 0$ interactions, $\Delta S = \Delta Q$
   - i.e. $K^+ \to \pi^0 \mu^+ \nu_\mu$ but not $K^+ \to \pi^+ \pi^+ e^- \bar{\nu}_e$
4. No $\Delta S = 1$ neutral currents at tree level
   - "GIM Mechanism"
5. Same rules apply for changes in any heavy flavor number (ΔS, ΔC, ΔB)

Fermi's Golden Rule

Transition rate from one state to another is the magnitude (amplitude squared) multiplied by the available phase space

Decays $(1 \rightarrow 2 + 3 + \ldots + n)$

$$\Gamma = \frac{S}{2m_1} \int |\mathscr{M}|^2 (2\pi)^4 \delta^4(p_1 - \ldots - p_n) \times \prod_{j=2}^{n} 2\pi\delta(p_j^2 - m_j^2)\theta(p_j^0) \frac{d^4 p_j}{(2\pi)^4}$$

Two-body $(1 \rightarrow 2 + 3)$

$$\Gamma = \frac{S|\mathbf{p}|}{8\pi m_1^2} |\mathscr{M}|^2$$

Scattering $(1 + 2 \rightarrow 3 + 4 + \ldots + n)$

$$\sigma = \frac{S}{4\sqrt{(p_1 \cdot p_2)^2 - (m_1 m_2)^2}} \int |\mathscr{M}|^2 (2\pi)^4 \delta^4(p_1 \pm \ldots - p_n) \times \prod_{j=3}^{n} 2\pi\delta(p_j^2 - m_j^2)\theta(p_j^0) \frac{d^4 p_j}{(2\pi)^4}$$

Two-body, CM frame $(1 + 2 \rightarrow 3 + 4)$

$$\frac{d\sigma}{d\Omega} = \left(\frac{1}{8\pi}\right)^2 \frac{S}{(E_1 + E_2)^2} \frac{|\mathbf{p}_f|}{|\mathbf{p}_i|} |\mathscr{M}|^2$$

Generalized Free Particle Lagrangians and Equations of Motion

Spin 0 (scalar) field ϕ ("Klein-Gordon")

$$\mathscr{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m^2\phi^2 \qquad (-\partial_\mu\partial^\mu + m^2)\phi = 0$$

Spin 1/2 (spinor) field ψ ("Dirac")

$$\mathscr{L} = i\bar{\psi}\partial\!\!\!/\psi - m^2\bar{\psi}\psi \qquad (i\partial\!\!\!/ - m)\psi = 0$$

Spin 1 (vector) field A^μ ("Proca")

$$\mathscr{L} = \frac{-1}{16\pi}F^{\mu\nu}F_{\mu\nu} + \frac{1}{8\pi}m^2A^\nu A_\nu \qquad \partial_\mu F^{\mu\nu} + m^2A^\nu = 0$$

where $F^{\mu\nu} \equiv \partial^\mu A^\nu - \partial^\nu A^\mu$

Gamma Matrices

$$\gamma^0 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}, \quad \gamma^1 = \begin{pmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 \\ -1 & 0 & 0 & 0 \end{pmatrix}$$

$$\gamma^2 = \begin{pmatrix} 0 & 0 & 0 & -i \\ 0 & 0 & i & 0 \\ 0 & i & 0 & 0 \\ -i & 0 & 0 & 0 \end{pmatrix}, \quad \gamma^3 = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \\ -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}.$$

Gamma Matrices

Num	Identity
1	$\gamma^\mu\gamma_\mu = 4I_4$
2	$\gamma^\mu\gamma^\nu\gamma_\mu = -2\gamma^\nu$
3	$\gamma^\mu\gamma^\nu\gamma^\rho\gamma_\mu = 4\eta^{\nu\rho}I_4$
4	$\gamma^\mu\gamma^\nu\gamma^\rho\gamma^\sigma\gamma_\mu = -2\gamma^\sigma\gamma^\rho\gamma^\nu$
5	$\gamma^\mu\gamma^\nu\gamma^\rho = \eta^{\mu\nu}\gamma^\rho + \eta^{\nu\rho}\gamma^\mu - \eta^{\mu\rho}\gamma^\nu - i\epsilon^{\sigma\mu\nu\rho}\gamma_\sigma\gamma^5$

Gamma Matrices

Num	Identity
0	$\mathrm{tr}(\gamma^\mu) = 0$
1	trace of any product of an odd number of γ^μ is zero
2	trace of γ^5 times a product of an odd number of γ^μ is still zero
3	$\mathrm{tr}(\gamma^\mu\gamma^\nu) = 4\eta^{\mu\nu}$
4	$\mathrm{tr}(\gamma^\mu\gamma^\nu\gamma^\rho\gamma^\sigma) = 4(\eta^{\mu\nu}\eta^{\rho\sigma} - \eta^{\mu\rho}\eta^{\nu\sigma} + \eta^{\mu\sigma}\eta^{\nu\rho})$
5	$\mathrm{tr}(\gamma^5) = \mathrm{tr}(\gamma^\mu\gamma^\nu\gamma^5) = 0$
6	$\mathrm{tr}(\gamma^\mu\gamma^\nu\gamma^\rho\gamma^\sigma\gamma^5) = 4i\epsilon^{\mu\nu\rho\sigma}$
7	$\mathrm{tr}(\gamma^{\mu1}\ldots\gamma^{\mu n}) = \mathrm{tr}(\gamma^{\mu n}\ldots\gamma^{\mu1})$

Gamma Matrices

Weyl (chiral) basis [edit]

Another common choice is the *Weyl* or *chiral basis*, in which γ^k remains the same but γ^0 is different, and so γ^5 is also different, and diagonal,

$$\gamma^0 = \begin{pmatrix} 0 & I_2 \\ I_2 & 0 \end{pmatrix}, \quad \gamma^k = \begin{pmatrix} 0 & \sigma^k \\ -\sigma^k & 0 \end{pmatrix}, \quad \gamma^5 = \begin{pmatrix} -I_2 & 0 \\ 0 & I_2 \end{pmatrix},$$

or in more compact notation:

$$\gamma^\mu = \begin{pmatrix} 0 & \sigma^\mu \\ \bar{\sigma}^\mu & 0 \end{pmatrix}, \quad \sigma^\mu \equiv (1, \sigma^i), \quad \bar{\sigma}^\mu \equiv (1, -\sigma^i).$$

The Weyl basis has the advantage that its chiral projections take a simple form,

$$\psi_L = \frac{1}{2}(1-\gamma^5)\psi = \begin{pmatrix} I_2 & 0 \\ 0 & 0 \end{pmatrix}\psi, \quad \psi_R = \frac{1}{2}(1+\gamma^5)\psi = \begin{pmatrix} 0 & 0 \\ 0 & I_2 \end{pmatrix}\psi.$$

The idempotence of the chiral projections is manifest. By slightly abusing the notation and reusing the symbols $\psi_{L/R}$ we can then identify

$$\psi = \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix},$$

Gell-Mann Matrices

An important representation involves 3×3 matrices, because the group elements then act on complex vectors with 3 entries, i.e., on the fundamental representation of the group. A particular choice of this representation is

$$\lambda_1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda_2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\lambda_4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} \quad \lambda_5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix}$$

$$\lambda_6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} \quad \lambda_7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix} \quad \lambda_8 = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}$$

and $g_i = \lambda_i/2$.

These matrices are traceless, Hermitian, and obey the extra relation $\mathrm{tr}(\lambda_i\lambda_j) = 2\delta_{ij}$. These properties were chosen by Gell-Mann because they then generalize the Pauli matrices for SU(2). They also naturally extend to general SU(n), cf. Generalizations of Pauli matrices.

Electromagnetism and $U(1)$

- Begin with Dirac Lagrangian for a spin-1/2 field
- Assert global phase symmetry also holds locally
- Must change derivative to "covariant derivative"
- Introduces a massless vector field

$$\mathscr{L} = i\bar{\psi}\partial\!\!\!/\psi - m\bar{\psi}\psi$$

$$\psi \to e^{i\theta}\psi \text{ becomes } \psi \to e^{i\theta(x)}\psi$$

$$\partial_\mu \to \mathscr{D}_\mu \equiv \partial_\mu + iqA_\mu$$

$$\mathscr{L}_{\mathrm{QED}} = \bar{\psi}(i\mathscr{D}\!\!\!/ - m)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

The electromagnetic interaction and the photon are the result of demanding Abelian $U(1)$ Gauge inavariance of the Dirac Lagrangian

The Strong Interaction and flavor $SU(3)$

- Begin with Dirac Lagrangian for three spin-1/2 fields with three possible colors

$$\mathscr{L} = i\bar{\psi}\partial\!\!\!/\psi - m\bar{\psi}\psi \text{ where } \psi = \begin{pmatrix} \psi_r \\ \psi_g \\ \psi_b \end{pmatrix}$$

- Invariant under unitary transformations $U(3)$

$$\psi \to U\psi \text{ with } U = e^{i\theta}e^{i\boldsymbol{\lambda}\cdot\mathbf{a}}$$

- Write generators in terms of a $U(1)$ phase and $SU(3)$ Gell-Mann matrices λ_α
- Demand locality of $SU(3)$ symmetry

$$\psi \to e^{i\theta(x)}e^{-iq\boldsymbol{\lambda}\cdot\boldsymbol{\phi}(x)}\psi$$

- New covariant derivative

$$\partial_\mu \to \mathscr{D}_\mu \equiv \partial_\mu + iq\boldsymbol{\lambda}\cdot\mathbf{A}_\mu$$

- Introduces a photon and eight gluons (one for each $SU(3)$ generator)

$$\mathscr{L}_{\rm QCD} = \bar{\psi}(i\mathscr{D}\!\!\!/ - m)\psi - \frac{1}{16\pi}F_{\mu\nu}F^{\mu\nu}$$

Flavor Changing Interactions

W bosons couple between three "Weak Interaction Generations"

$$\begin{pmatrix} u \\ d\prime \end{pmatrix}, \begin{pmatrix} c \\ s\prime \end{pmatrix}, \begin{pmatrix} t \\ b\prime \end{pmatrix}$$

Where the weak eigenstates are related to the mass eigenstates by three Euler angles θ_{12},θ_{23},θ_{13} and a CP-violating phase δ (here $c/s_{12} \equiv \cos\theta_{12}/\sin\theta_{12}$, etc.):

$$\begin{pmatrix} d\prime \\ s\prime \\ b\prime \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = V \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

The magnitudes of the "CKM" matrix elements are (experimentally) :

$$|V_{ij}| = \begin{pmatrix} 0.97427 & 0.22534 & 0.00351 \\ 0.22520 & 0.97344 & 0.04120 \\ 0.00867 & 0.04040 & 0.99915 \end{pmatrix}$$

The Wolfenstein Parametrization

The CKM Matrix can be approximated as

$$V \approx \begin{pmatrix} 1 - {}^{\lambda^2}\!/_2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - {}^{\lambda^2}\!/_2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

Where the new parameters are :

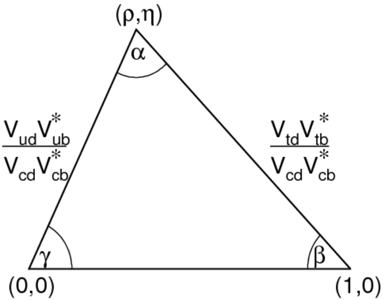
$$\lambda \equiv \sin\theta_{12},\ A\lambda^2 \equiv \sin\theta_{23},\ \text{and}\ A\lambda^3(\rho - i\eta) \equiv \sin\theta_{13} e^{-i\delta}$$

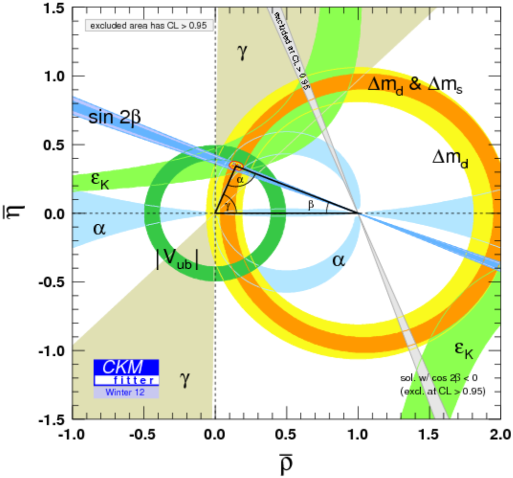
Or, experimentally:

$$\lambda = 0.2257,\ A = 0.814,\ \rho = 0.135,\ \text{and}\ \eta = 0.349$$

The Unitarity Triangle

The CKM matrix must be unitary in the Standard Model





Electroweak Unification

- Project out "left-handed" components of fermion spinors

$$u_{\mathrm{L}} \equiv \frac{(1-\gamma^5)}{2} u, \; v_{\mathrm{L}} \equiv \frac{(1+\gamma^5)}{2} v$$

- i.e. for $\ell \to \nu_\ell + W^\pm$, vertex factor is entirely "left-handed"

$$\bar{v}_{\nu_\ell,\mathrm{L}} \gamma_\mu u_{\ell,\mathrm{L}}$$

- Construct $SU(2)_{\mathrm{L}} \otimes U(1)$ symmetry group with weak isospin/hypercharge by considering oppositely charged weak current

$$\mathbf{j}_\mu = \frac{1}{2} \bar{\chi}_{\mathrm{L}} \gamma_\mu \boldsymbol{\tau} \chi_{\mathrm{L}}, \; j_\mu^{\mathrm{Y}} = 2 j_\mu^{em} - 2 j_\mu^3$$

- Weak isospin couples to a triplet of vector bosons, **W**, and weak hypercharge (including EM) couples to an isosinglet vector boson B

$$-i \left[g_W \mathbf{j}_\mu \cdot \mathbf{W}^\mu + \frac{g'}{2} j_\mu^{\mathrm{Y}} B^\mu \right]$$

Electroweak Unification

Physical $W^{\pm}$ bosons are charged combinations of **W** components

$$W_\mu^{\pm} \equiv \tfrac{1}{\sqrt{2}} \left(W_\mu^1 \mp i W_\mu^2 \right)$$

Physical Z and γ (A_μ)are combinations of neutral **W** component and B_μ related by the "weak mixing angle" θ_w (where $\cos\theta_w = {}^{M_W}/_{M_Z}$)

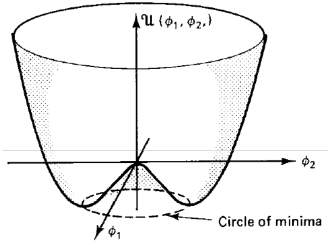
$$A_\mu = B_\mu \cos\theta_w + W_\mu^3 \sin\theta_w,\ Z_\mu = -B_\mu \sin\theta_w + W_\mu^3 \cos\theta_w$$

The electromagnetic and weak interactions are both the result of an $SU(2)_\mathrm{L} \otimes U(1)$ symmetry; the experimental force carriers are rotations of the vector bosons that couple to separate components of the weak isospin/hypercharge space, and the CP-violating nature of the weak interaction is a direct consequence of this construction as well.

The Higgs Mechanism

- Add a potential to a Lagrangian with a spontaneously broken continuous symmetry

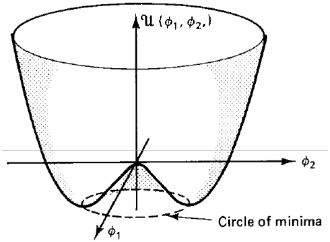
$$U = -\frac{1}{2}\mu^2(\phi_1^2 + \phi_2^2) + \frac{1}{4}\lambda^2(\phi_1^2 + \phi_2^2)^2$$



The Higgs Mechanism

$$U = -\frac{1}{2}\mu^2(\phi_1^2 + \phi_2^2) + \frac{1}{4}\lambda^2(\phi_1^2 + \phi_2^2)^2$$

- Add a potential to a Lagrangian with a spontaneously broken continuous symmetry
- Find minima of the potential to apply Feynman calculus



choose $\phi_{1,min} = {}^{\mu}/_{\lambda}$, $\phi_{2,min} = 0$

The Higgs Mechanism

- Add a potential to a Lagrangian with a spontaneously broken continuous symmetry
- Find minima of the potential to apply Feynman calculus
- Rewrite Lagrangian in terms of minimized coordinates

define $\eta \equiv \phi_1 - \mu/\lambda,\ \xi \equiv \phi_2$

$$\mathfrak{L} = \left[\frac{1}{2}(\partial_\mu \eta)(\partial^\mu \eta) - \mu^2\eta^2\right] + \left[\frac{1}{2}(\partial_\mu \xi)(\partial^\mu \xi)\right] - \left[\mu\lambda(\eta^3 + \eta\xi^2) + \frac{\lambda^2}{4}(\eta^4 + \xi^4 + 2\eta^2\xi^2)\right] + \frac{\mu^4}{4\lambda^2}$$

The Higgs Mechanism

- Add a potential to a Lagrangian with a spontaneously broken continuous symmetry
- Find minima of the potential to apply Feynman calculus
- Rewrite Lagrangian in terms of minimized coordinates
- Massive and massless ("Goldstone") scalar bosons emerge

define $\eta \equiv \phi_1 - {}^{\mu}/_{\lambda}$, $\xi \equiv \phi_2$

$$\mathfrak{L} = \boxed{\left[\frac{1}{2}(\partial_\mu \eta)(\partial^\mu \eta) - \mu^2\eta^2\right]} + \boxed{\left[\frac{1}{2}(\partial_\mu \xi)(\partial^\mu \xi)\right]} - \left[\mu\lambda(\eta^3 + \eta\xi^2) + \frac{\lambda^2}{4}(\eta^4 + \xi^4 + 2\eta^2\xi^2)\right] + \frac{\mu^4}{4\lambda^2}$$

The Higgs Mechanism

$$\mathcal{L} = \left[\frac{1}{2}(\partial_\mu\eta)(\partial^\mu\eta) - \mu^2\eta^2\right] + \left[\frac{1}{2}(\partial_\mu\xi)(\partial^\mu\xi)\right]$$
$$+ \left[-\frac{1}{16\pi}F^{\mu\nu}F_{\mu\nu} + \boxed{\frac{1}{2}\left(\frac{q}{\hbar c}\frac{\mu}{\lambda}\right)^2 A_\mu A^\mu}\right] - 2i\left(\frac{\mu}{\lambda}\frac{q}{\hbar c}\right)(\partial_\mu\xi)A^\mu$$
$$+ \left\{\frac{q}{\hbar c}[\eta(\partial_\mu\xi) - \xi(\partial_\mu\eta)]A^\mu + \frac{\mu}{\lambda}\left(\frac{q}{\hbar c}\right)^2\eta(A_\mu A^\mu) + \frac{1}{2}\left(\frac{q}{\hbar c}\right)^2(\xi^2 + \eta^2)(A_\mu A^\mu)\right.$$
$$\left. - \lambda\mu(\eta^3 + \eta\xi^2) - \frac{1}{4}\lambda^2(\eta^4 + 2\eta^2\xi^2 + \xi^4)\right\} + \left(\frac{\mu^2}{2\lambda}\right)^2$$

Applying this language to a complex field and demanding local gauge invariance yields a massive scalar (The “Higgs Boson”), and a *massive* vector boson

The Higgs Mechanism is the method by which the Z and $W^\pm$ bosons acquire masses

The Higgs Mechanism (conceptually)

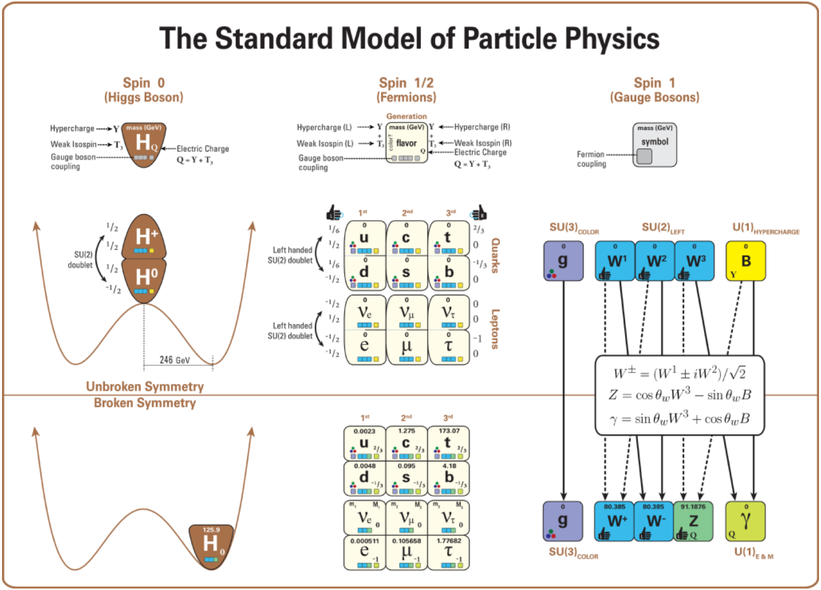
- Particles interact with the photon field in a way proportional to their charge
- The photon is an excitation of the EM field
- Particles interact with the Higgs field in a way proportional to their mass
- The Higgs Boson is an excitation of the Higgs field
- The Higgs field spontaneously breaks electroweak symmetry, giving mass to the $W^{\pm}$ and Z bosons that interact with it
- Fermions gain their bare mass from the Higgs field, but not by EWSB

The Standard Model, Mathematically

- Begin with spinor fermions (ψ), vector gauge bosons ($\mathbf{W}/B$) and gluons (G_a), and scalar Higgs field (ϕ)
- Total symmetry group is $SU(3)_{color} \otimes SU(2)_{\mathrm{L}} \otimes U(1)_{\mathrm{Y}}$

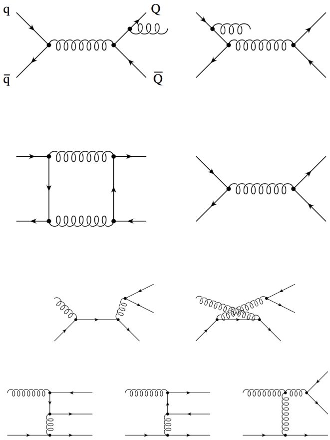
- 19 known input parameters :
  - 9 quark/charged lepton masses
  - 3 CKM mixing angles and 1 CP-violating phase
  - $SU(3)$, $SU(2)$, and $U(1)$ gauge coupling strengths
  - QCD "vacuum angle"
  - Higgs VEV and mass
- With neutrinos, 7 others :
  - 3 masses
  - 4 PMNS matrx parameters

- Before spontaneous EWSB :
  - massless Higgs doublet
  - massless chiral fermions
  - massless gauge bosons (3 V-A)
- After spontaneuos EWSB :
  - massive Higgs boson
  - massive fermions of mixed chiralities
  - massive Weak carriers (2 V-A)
  - massless photon

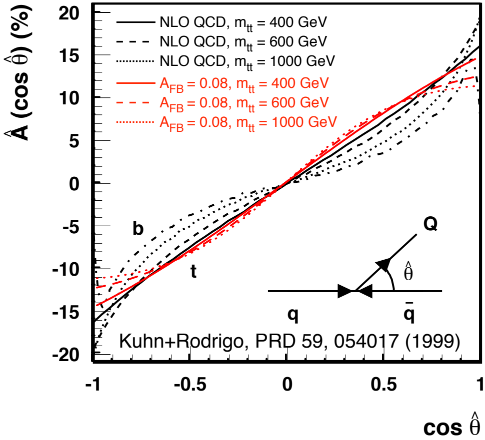

The Standard Model of Particle Physics
Spin 0 (Higgs Boson)
Spin 1/2 (Fermions)
Spin 1 (Gauge Bosons)
Hypercharge
Weak Isospin
Gauge boson coupling
Electric Charge
Q = Y + T3
Generation
flavor
mass (GeV)
symbol
Fermion coupling
SU(2) doublet
Left handed SU(2) doublet
Quarks
Leptons
246 GeV
Unbroken Symmetry
Broken Symmetry
SU(3)COLOR
SU(2)LEFT
U(1)HYPERCHARGE
U(1)E & M
$W^{\pm} = (W^1 \pm iW^2)/\sqrt{2}$
$Z = \cos\theta_w W^3 - \sin\theta_w B$
$\gamma = \sin\theta_w W^3 + \cos\theta_w B$
125.9
0.0023 1.275 173.07
0.0048 0.095 4.18
0.000511 0.105658 1.77682
80.385 80.385 91.1876

The $t\bar{t}$ Charge Asymmetry

- Perturbative QCD calculations
- Pair-produced $t\bar{t}$ should have an intrinsic differential charge asymmetry $\hat{A}(\cos\theta)$
  - See different amount of top- and antitop-quarks at a given angle
  - Due to interference of different production processes
- Can be reframed as a forward-backward asymmetry A_{FB}

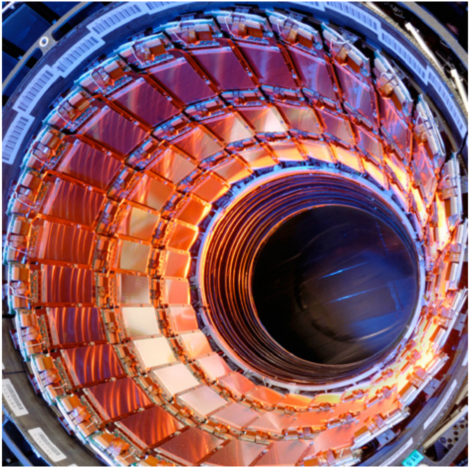


Linear Approximation of A_{FB}



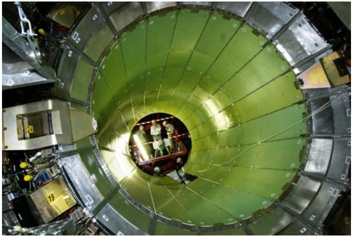
Parts of the Detector

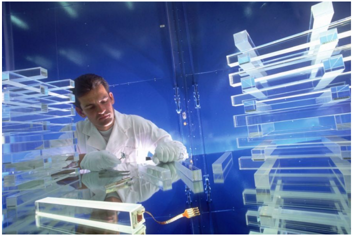
- Tracker
  - Silicon
  - Pixels & Microstrips
  - Shows paths of charged particles
  - Measures momenta
- Electromagnetic Calorimeter (ECAL)
- Hadronic Calorimeter (HCAL)
- Magnet
- Muon Systems and Return Yoke



Parts of the Detector

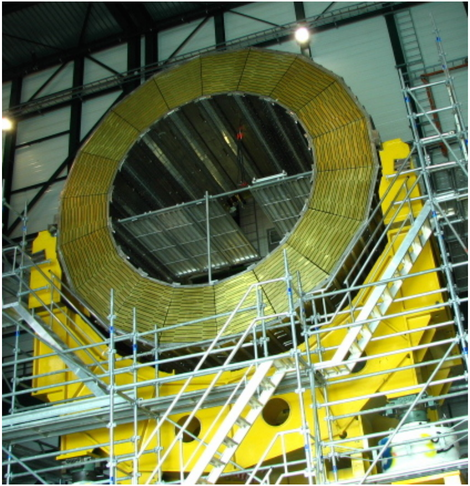
- Tracker
- Electromagnetic Calorimeter (ECAL)
  - Lead Tungstate
  - Crystal Scintillators
  - Electrons/photons dump energies
- Hadronic Calorimeter (HCAL)
- Magnet
- Muon Systems and Return Yoke





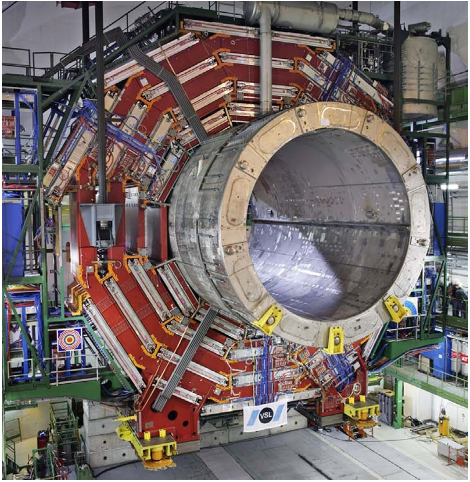
Parts of the Detector

- Tracker
- Electromagnetic Calorimeter (ECAL)
- Hadronic Calorimeter (HCAL)
  - Brass, plastic scintillators
  - “Hermitic”
  - Hadrons dump energies
- Magnet
- Muon Systems and Return Yoke



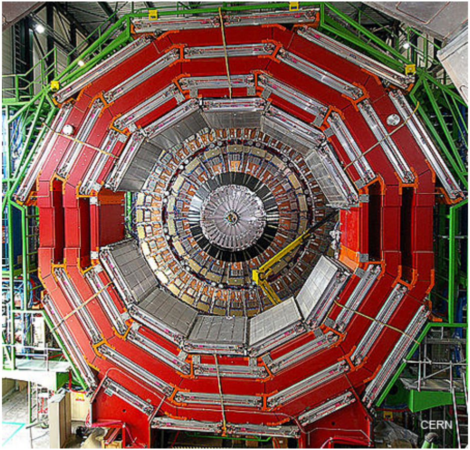
Parts of the Detector

- Tracker
- Electromagnetic Calorimeter (ECAL)
- Hadronic Calorimeter (HCAL)
- Magnet
  - Niobium-Titanium
  - Superconducting Solenoid
  - 4T magnetic field
- Muon Systems and Return Yoke

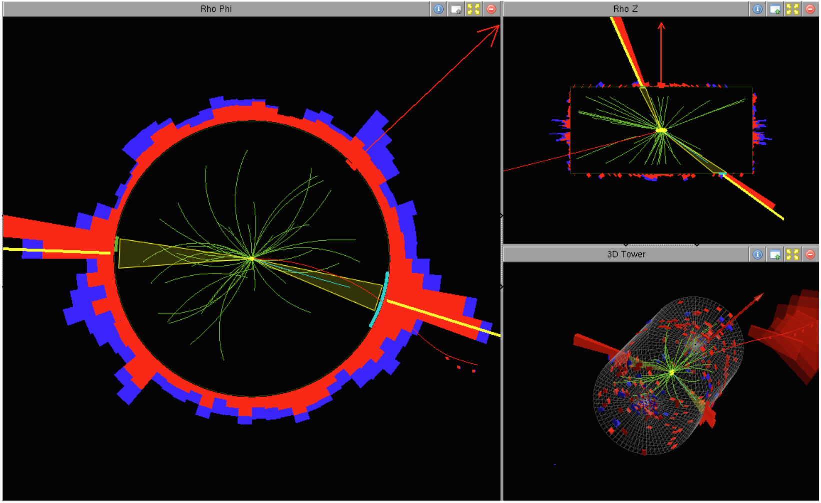


Parts of the Detector

- Tracker
- Electromagnetic Calorimeter (ECAL)
- Hadronic Calorimeter (HCAL)
- Magnet
- Muon Systems and Return Yoke
  - Drift Tubes
  - Cathode Strip Chambers
  - Resistive Plate Chambers
  - Iron Return Yoke



Physics Objects in the CMS Detector



Antisymmetric Event Reweighting

New tree-level $q\bar{q}$ cross section with antisymmetric extension:

$$\frac{d\sigma}{dc^*}(q\bar{q}; M^2) = R\frac{\pi\alpha_s^2}{9M^2}\beta\left\{1+\beta^2 c^{*2} + (1-\beta^2) \right.$$
$$\left. + A_{\mathrm{FB}}^{(1)} 2\left[1+\frac{1}{3}\beta^2 + (1-\beta^2)\right] c^* \right\}$$

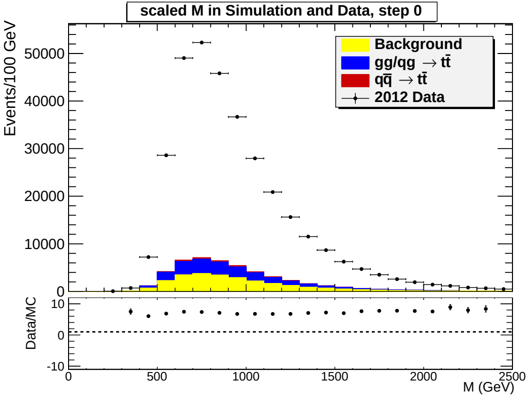
Means the antisymmetric distribution with $A_{\mathrm{FB}}^{(1)}$ factored out can be built from the symmetric one by multiplying by an event weight w_{a}:

$$w_{\mathrm{a}}(M^2, c^*) = 2\frac{1+\frac{1}{3}\beta^2+(1-\beta^2)}{1+\beta^2 c^{*2}+(1-\beta^2)}c^*$$

Therefore no special Monte Carlo simulation required to describe effect!

Event Selection

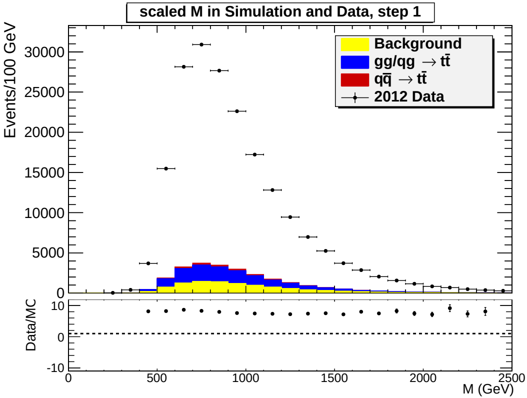
- Preselection
  - One heavy jet and one other jet
- Leptonic Side
- Hadronic Side
- Top Jet Structure



hadt_M>100 GeV, lepb_M>0 GeV

Event Selection

- Preselection
- Leptonic Side
  - Lepton Trigger

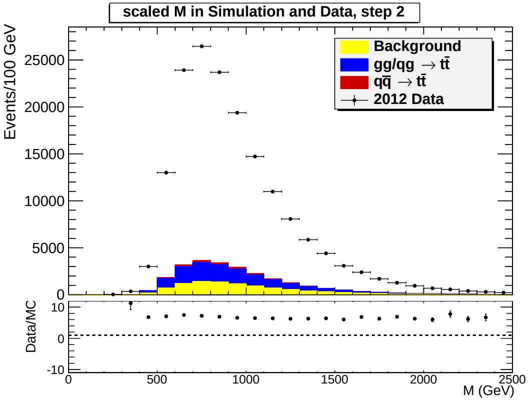


Trigger: `HLT_Mu40_eta2p1_v*` for muons, `HLT_Ele30_CaloIdVT_TrkIdT_PFNoPUJet100_PFNoPUJet25_v*` for electrons

- Hadronic Side
- Top Jet Structure

Event Selection

- Preselection
- Leptonic Side
  - Lepton Trigger
  - High momentum lepton in clean detector range

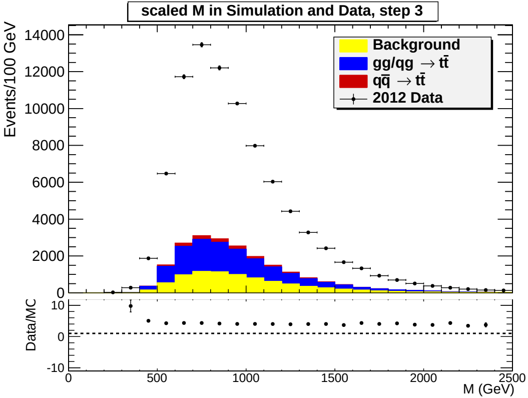


p_T >45 GeV, $|\eta|$ <2.1

- Hadronic Side
- Top Jet Structure

Event Selection

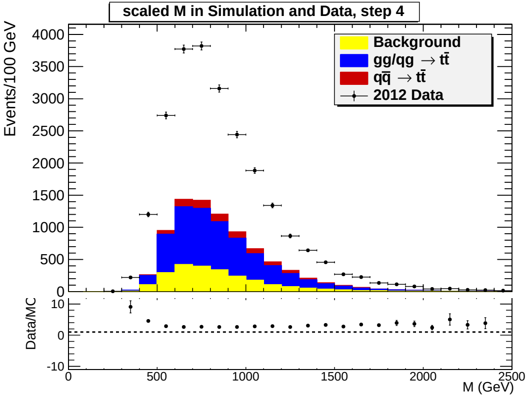
- Preselection
- Leptonic Side
    - Lepton Trigger
    - High momentum lepton in clean detector range
    - ID and isolation requirement
- Hadronic Side
- Top Jet Structure



loose ID (isolation-free)
and
$p_{T,rel}$ >50 GeV or $\Delta R_{nearestjet}$ >0.5

Event Selection

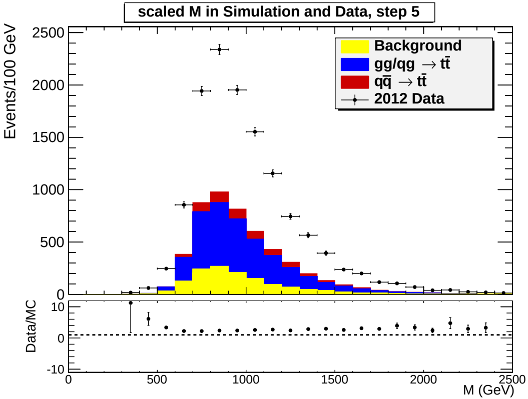
- Preselection
- Leptonic Side
    - Lepton Trigger
    - High momentum lepton in clean detector range
    - ID and isolation requirement
    - Lepton + MET + lighter jet have mass near t mass
- Hadronic Side
- Top Jet Structure



140 GeV $<$ `lept_M` $<$ 250 GeV

Event Selection

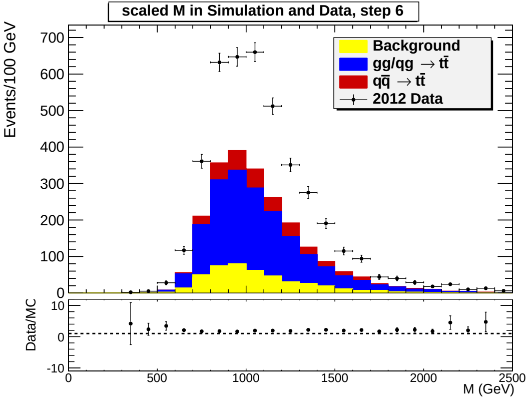
- Preselection
- Leptonic Side
- Hadronic Side
  - Very high momentum jet
  - Guarantees fully merged t jet
- Top Jet Structure



hadt_pT>300 GeV

Event Selection

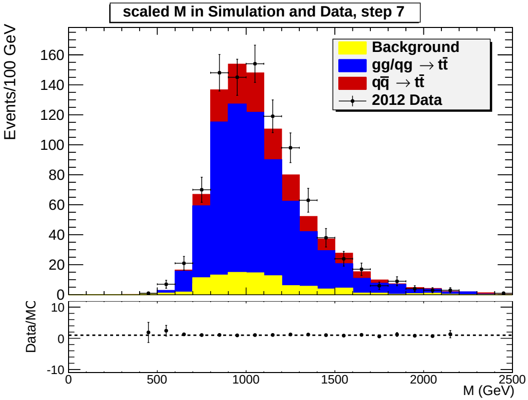
- Preselection
- Leptonic Side
- Hadronic Side
- Top Jet Structure
  - Mass comparable to t mass



$140\ \text{GeV} < \texttt{hadt\_M} < 250\ \text{GeV}$

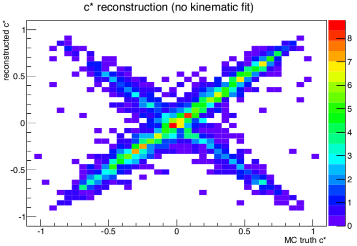
Event Selection

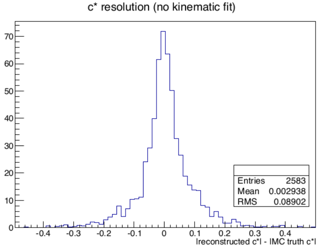
- Preselection
- Leptonic Side
- Hadronic Side
- Top Jet Structure
  - Mass comparable to t mass
  - Looks like three subjets



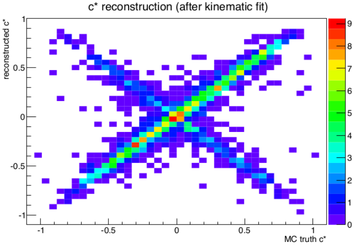
hadt_tau32<0.55

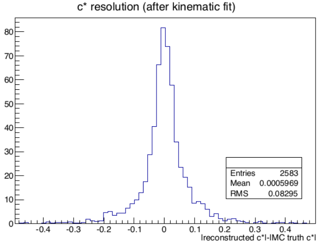
Reconstruction with a Kinematic Fit





before kinematic fit

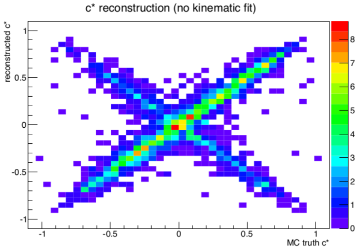


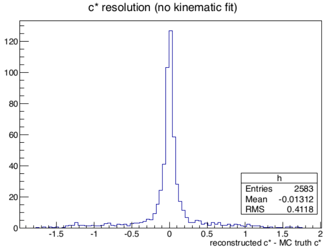


after kinematic fit

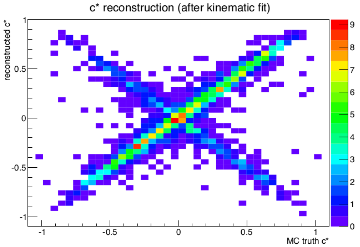
17

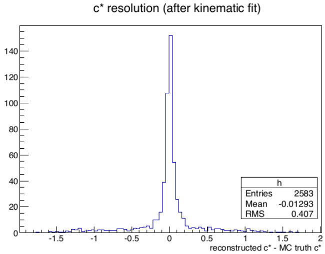
Reconstruction with a Kinematic Fit





before kinematic fit

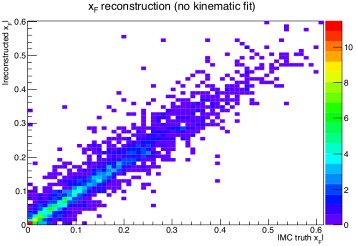




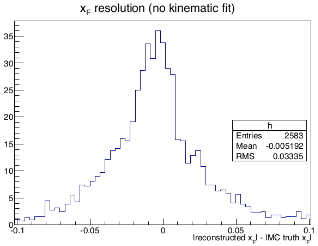
after kinematic fit

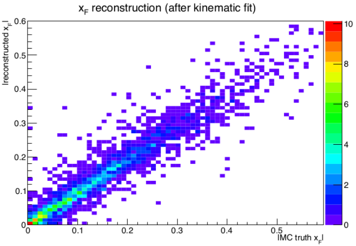
18

Reconstruction with a Kinematic Fit

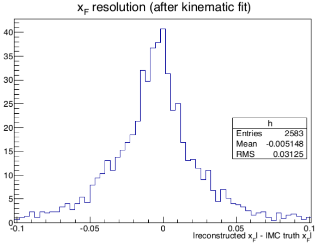


before kinematic fit



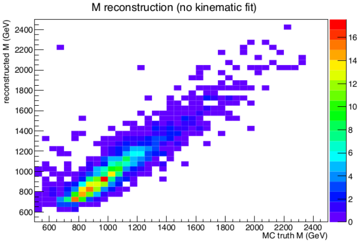


after kinematic fit

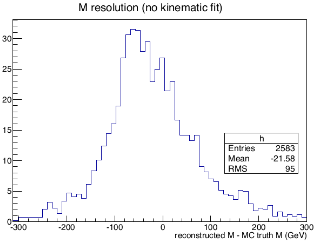


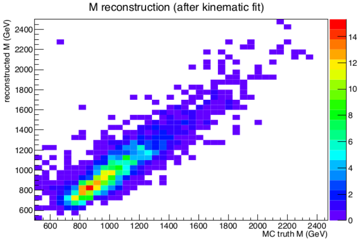
19

Reconstruction with a Kinematic Fit



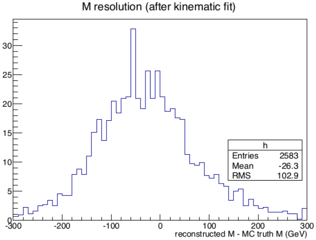
before kinematic fit





after kinematic fit

20



Monte Carlo Samples

Process	PAT sample and location	CS (pb)	Events
TT	TT_CT10_TuneZ2star_8TeV-powheg-tauola/ StoreResults-Summer12_DR53X-PU_S10_START53_V7A-v2_TLBSM_53x_v3_bugfix_v1	245.8	21560109
W+Jets	W1JetsToLNu_TuneZ2Star_8TeV-madgraph/ StoreResults-Summer12_DR53X-PU_S10_START53_V7A-v1_TLBSM_53x_v3	6662.8	23038253
	W2JetsToLNu_TuneZ2Star_8TeV-madgraph/ StoreResults-Summer12_DR53X_PU_S10_START53_V7A_v1_TLBSM_53x_v3_rev1	2159.2	33993463
	W3JetsToLNu_TuneZ2Star_8TeV-madgraph/ StoreResults-Summer12_DR53X_PU_S10_START53_V7A_v1_TLBSM_53x_v3_rev1	640.4	15507852
	W4JetsToLNu_TuneZ2Star_8TeV-madgraph/ StoreResults-Summer12_DR53X-PU_S10_START53_V7A-v1_TLBSM_53x_v3	264.0	13326400
DY+Jets	DY1JetsToLL_M-50_TuneZ2Star_8TeV-madgraph/ StoreResults-Summer12_DR53X-PU_S10_START53_V7A-v1_TLBSM_53x_v3	660.6	23994669
	DY2JetsToLL_M-50_TuneZ2Star_8TeV-madgraph/ StoreResults-Summer12_DR53X-PU_S10_START53_V7A-v1_TLBSM_53x_v3	215.1	2345857
	DY3JetsToLL_M-50_TuneZ2Star_8TeV-madgraph/ StoreResults-Summer12_DR53X-PU_S10_START53_V7A-v1_TLBSM_53x_v3	65.79	10655325
	DY4JetsToLL_M-50_TuneZ2Star_8TeV-madgraph/ StoreResults-Summer12_DR53X-PU_S10_START53_V7A-v1_TLBSM_53x_v3	28.59	5843425
Single Top	T_s-channel_TuneZ2star_8TeV-powheg-tauola/ StoreResults-Summer12_DR53X-PU_S10_START53_V7A-v1_TLBSM_53x_v3	3.79	259176
	T_t-channel_TuneZ2star_8TeV-powheg-tauola/ StoreResults-Summer12_DR53X-PU_S10_START53_V7A-v1_TLBSM_53x_v3	56.4	3748155
	T_tW-channel-DR_TuneZ2star_8TeV-powheg-tauola/ StoreResults-Summer12_DR53X-PU_S10_START53_V7A-v1_TLBSM_53x_v3	11.1	495559
	Tbar_s-channel_TuneZ2star_8TeV-powheg-tauola/ StoreResults-Summer12_DR53X-PU_S10_START53_V7A-v1_TLBSM_53x_v3	1.76	139604
	Tbar_t-channel_TuneZ2star_8TeV-powheg-tauola/ StoreResults-Summer12_DR53X-PU_S10_START53_V7A-v1_TLBSM_53x_v3	30.7	1930185
	Tbar_tW-channel-DR_TuneZ2star_8TeV-powheg-tauola/ StoreResults-Summer12_DR53X-PU_S10_START53_V7A-v1_TLBSM_53x_v3	11.1	491463

Data Samples

Data Section	PAT sample and location	Luminosity (/pb)
2012 A	SingleMu/StoreResults-Run2012A-22Jan2013-v1_TLBSM_53x_v3 SingleElectron/StoreResults-V2-Run2012A-22Jan2013-v1_TLBSM_53x_v3	888
2012 B	SingleMu/StoreResults-V2-Run2012B-22Jan2013-v1_TLBSM_53x_v3 SingleElectron/StoreResults-Run2012B-22Jan2013-v1_TLBSM_53x_v3	4442
2012 C	SingleMu/StoreResults-V2-Run2012C-22Jan2013-v1_TLBSM_53x_v3 SingleElectron/StoreResults-V2-Run2012C-22Jan2013-v1_TLBSM_53x_v3 SingleElectron/knash-Run2012C-22Jan2013-MissingLumi_take2-v1_TLBSM_53x_v3	7110
2012 D	SingleMu/StoreResults-Run2012D-22Jan2013-v1_TLBSM_53x_v3 SingleElectron/StoreResults-Run2012D-22Jan2013-v1_TLBSM_53x_v3	7308
Total Luminosity		19748

Cutflow (muons)

Cut	# of data events passing	Semileptonic TT efficiency	Dileptonic TT efficiency	Hadronic TT efficiency	W+Jets efficiency	DY+Jets efficiency	Single Top efficiency
pruning (muons)	150412						
preselection	59208	0.568(3)	0.57(1)	0.358(4)	0.544(5)	0.56(1)	0.46(1)
muon kinematics	39892	0.702(4)	0.80(2)	0.401(6)	0.732(8)	0.89(2)	0.62(2)
muon ID	59187	1.000(6)	1.00(3)	1.00(1)	1.00(1)	1.00(2)	1.00(3)
muon 2D cut	37274	0.838(5)	0.87(3)	0.76(1)	0.890(9)	0.93(2)	0.74(2)
leptonic top mass	20617	0.422(3)	0.29(1)	0.195(4)	0.261(4)	0.24(1)	0.28(1)
hadronic pretag	6106	0.285(2)	0.20(1)	0.079(3)	0.185(3)	0.203(9)	0.121(7)
signal: mass	2023	0.485(7)	0.28(3)	0.45(2)	0.246(9)	0.24(2)	0.37(4)
signal: tau32	686	0.268(4)	0.09(1)	0.20(1)	0.049(4)	0.034(7)	0.17(2)
full selection	488	0.064(1)	0.012(2)	0.013(1)	0.0036(4)	0.003(1)	0.014(2)

- Preselection removes events across the board without a boosted hadronic top
- muon ID is very efficient
- 2D cut is effective at removing events that lack a distinctive muon
- leptonic top mass cut is very effective
- pretagging leaves mostly top events and multijet background
- NTMJ statistics in the final signal region are expected to be very very small

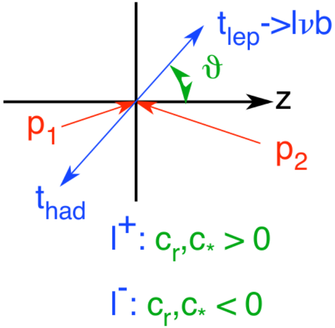
Cutflow (electrons)

Cut	# of data events passing	Semileptonic TT efficiency	Dileptonic TT efficiency	Hadronic TT efficiency	W+Jets efficiency	DY+Jets efficiency	Single Top efficiency
pruning (electrons)	37345						
preselection	14558	0.558(3)	0.57(1)	0.302(3)	0.543(4)	0.54(1)	0.406(9)
electron kinematics	12370	0.697(5)	0.79(3)	0.480(7)	0.702(7)	0.87(2)	0.66(2)
electron ID	4813	0.557(4)	0.62(2)	0.0022(4)	0.634(7)	0.72(2)	0.37(1)
electron 2D cut	9718	0.850(5)	0.88(3)	0.688(9)	0.872(8)	0.90(2)	0.78(2)
leptonic top mass	3418	0.408(3)	0.30(1)	0.212(4)	0.257(4)	0.26(1)	0.25(1)
hadronic pretag	1299	0.219(2)	0.170(9)	0.0004(2)	0.130(3)	0.173(8)	0.104(7)
signal: mass	494	0.472(8)	0.28(3)	0.7(4)	0.23(1)	0.25(2)	0.39(4)
signal: tau32	226	0.264(5)	0.08(1)	0.7(4)	0.043(4)	0.051(9)	0.17(3)
full selection	179	0.049(1)	0.007(1)	0.0003(1)	0.0015(3)	0.004(1)	0.014(2)

- Electron ID is much less efficient than muon ID
- Pretagging is also slightly less efficient
- Everything else is comparable between the two channels

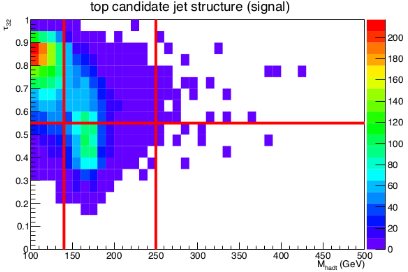
Exploiting CP symmetry

When separating events and templates by lepton charge, CP symmetry can be exploited to add each event with a symmetric initial state to two templates at once by conjugating lepton charge and flipping the sign of c^*



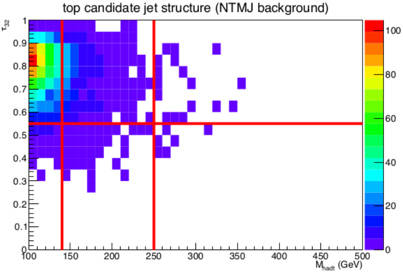
This increases statistics in F_{gg} templates and forces the absolute symmetry/antisymmetry of the F_{qs} and F_{qa} templates

Data-Driven NTMJ background estimation

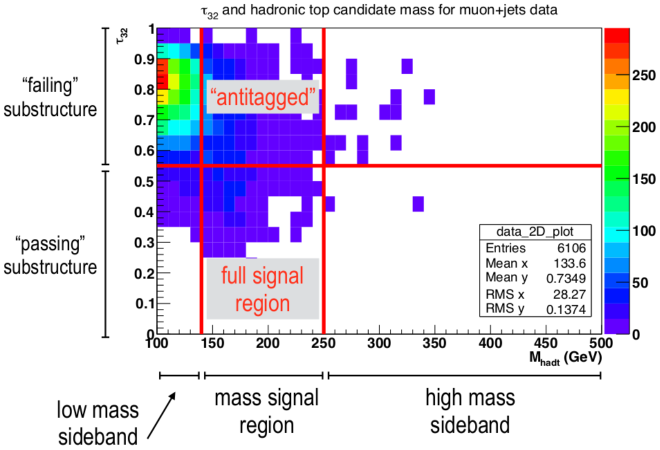


Semileptonic ttbar (simulated)

W/Z/gamma+jets (simulated)



Data-Driven NTMJ background estimation



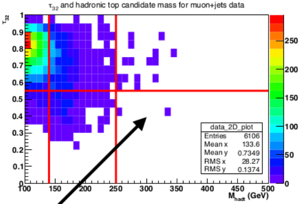
Consider all data and MC after hadronic pretagging

MC corrected with:
-lumi*(cs/#events)
-top p_T reweighting
-pileup reweighting

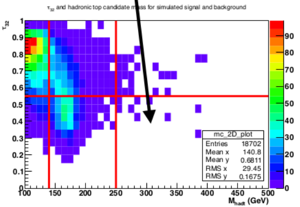
Data-Driven NTMJ background estimation

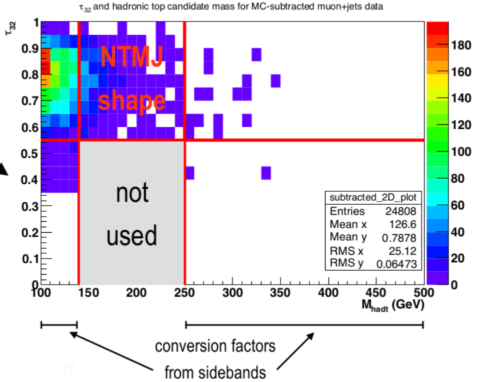
subtract MC from data in the antitagged region to get the NTMJ background shape

nominal normalization comes from interpolating conversion factors in mass sidebands

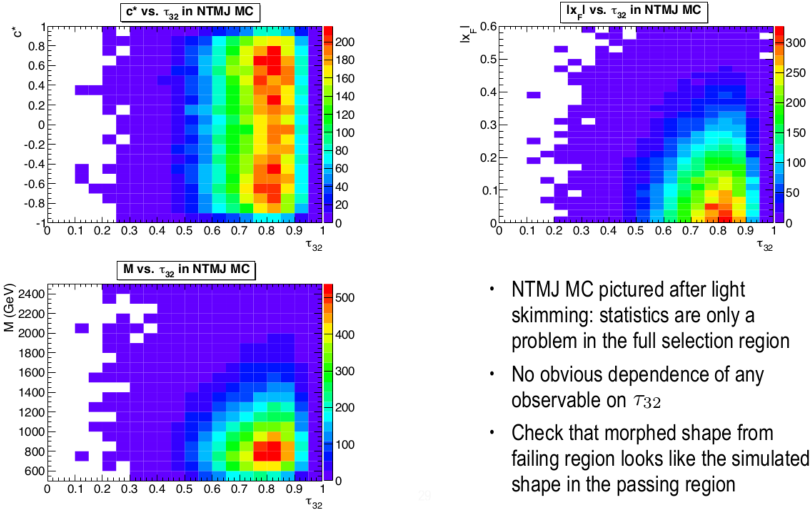


data - MC = NTMJ



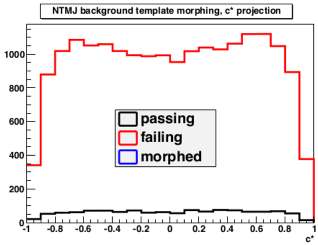


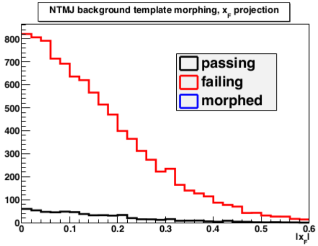
Data-Driven NTMJ background estimation

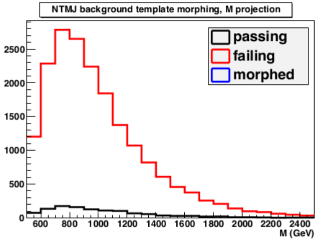


- NTMJ MC pictured after light skimming: statistics are only a problem in the full selection region
- No obvious dependence of any observable on τ_{32}
- Check that morphed shape from failing region looks like the simulated shape in the passing region

Data-Driven NTMJ background estimation

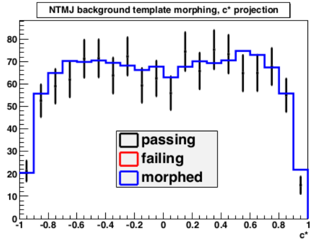


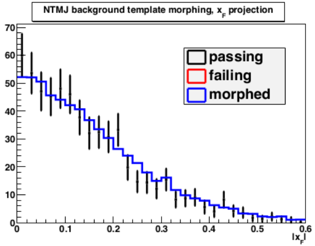


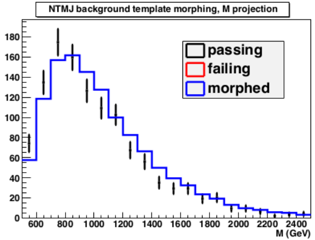


- Many more events fail the cut than pass as expected for background
- Shapes are close but need a scale factor

Data-Driven NTMJ background estimation







- Applying hadronic top candidate mass-dependent scale factor brings shapes and event yields more in line
- Morphing the templates in the failing region describes simulated events in the passing region well
- Systematics of morphing function are likely a small effect

Systematics

1. Jet Energy Corrections
   - Jet Energy Scale (corrects measured jet energies to values seen in data)
   - Jet Energy Resolution (smears jet angular and p_T distributions to values seen in data)
2. Pileup reweighting
   - Morphs generated pileup values to look like that measured in data
3. Top pT reweighting
   - low p_T (corrects generated top cross section to NNLO prediction)
   - high p_T (corrects generated top cross section to measurement in data)
4. Lepton ID and trigger efficiencies
   - Correct for differences in efficiencies in data/MC
   - Used accepted values for muons, measured for electrons
5. Luminosity (uncertainty on total luminosity is $\approx$2.6%)
6. PDF systematics (PDF choice parameterized by many values with uncertainties)
7. Finite Monte Carlo Statistics

Measuring Electron ID efficiency

- Using a simple muon pT trigger in the muon+jets channel
  - HLT_Mu40_eta2p1_v*
- electron+jets channel isn't as clean: choose a trigger with jet requirements
  - HLT_Ele30_CaloIdVT_TrkIdT_PFNoPUJet100_PFNoPUJet25_v*
- These two triggers are independent
- Measure electron trigger efficiency in e/mu dileptonic ttbar events

4

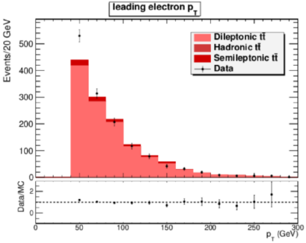
Measuring Electron ID efficiency

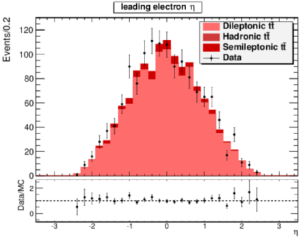
- Events must fire muon trigger
- Select leading muon and electron:
  - Loosely ID'd (isLoose for muons, “isPseudoLoose” for electrons)
  - $P_T > 40$ GeV, $|\eta| < 2.4$
  - 2D cut for “isolation”: $p_{T,rel} > 25$ GeV or $\Delta R_{\text{nearest jet}} > 0.5$
- Veto events with any additional leptons passing the above

Measuring Electron ID efficiency

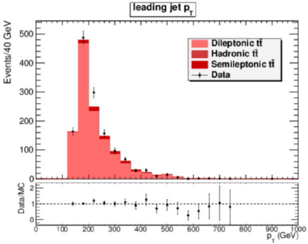
- Additional leptonic side criteria
  - Leading e/mu have opposite charges
  - leptonic W $p_T > 50$ GeV
  - leptonic top mass in $140 < M_{tlep} < 250$ GeV
- Require at least two jets with $p_T > 150$ and 50 GeV respectively
- Resulting events are clean e/mu dileptonic ttbar
- Will measure efficiency for these events to also fire the electron trigger in data and ttbar MC

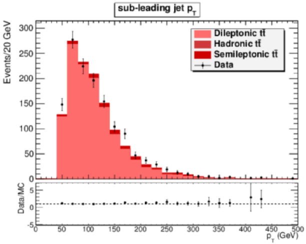
Measuring Electron ID efficiency





- MC scaled by Lumi and CS
- Pileup reweighting applied
- Generally good agreement
- Very little data unaccounted for by ttbar





Measuring Electron ID efficiency

- Data events selected = 1364
- Data events passing trigger = 1174
- Efficiency in data = 0.86 ± 0.03

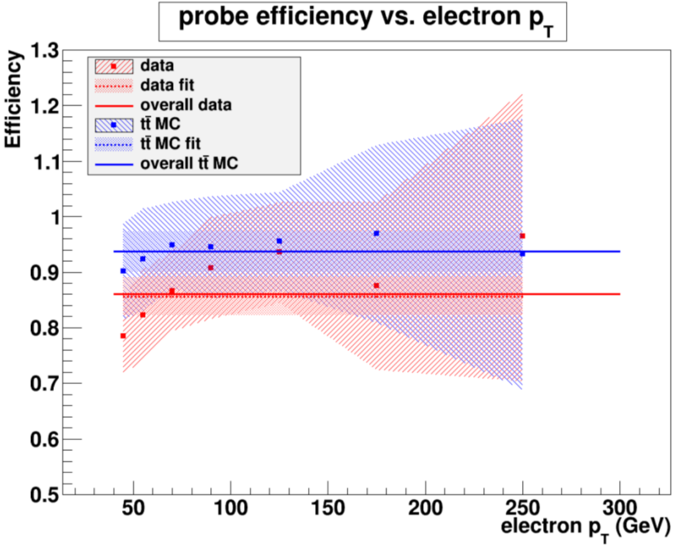
- MC events selected = 5750 (1290 scaled)
- MC events passing trigger = 5389 (1218 scaled)
- Efficiency in MC = 0.94 ± 0.04

- Data/MC Scalefactor = 0.92 ± 0.05

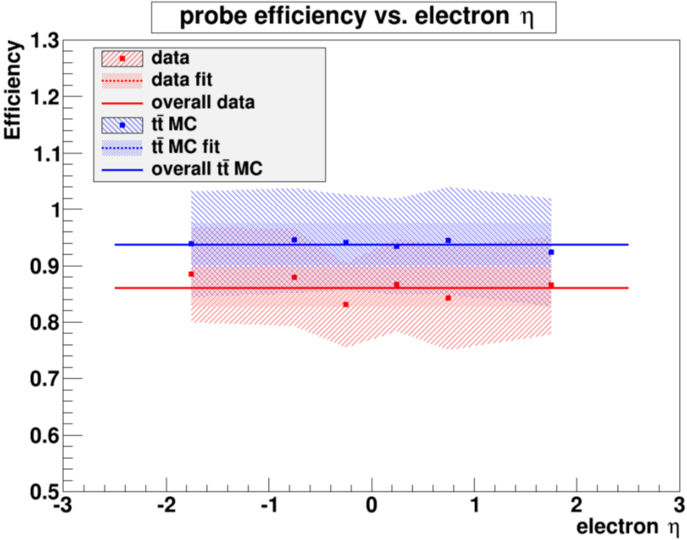
Measuring Electron ID efficiency

- Data/MC Scalefactor = 0.92 ± 0.05
- All errors statistical only
- Correction applied to all MC as simple nominal/up/down scalefactors
- No significant dependence on phase space (checked electron kinematics and jet p_T because of jet involvement in trigger)

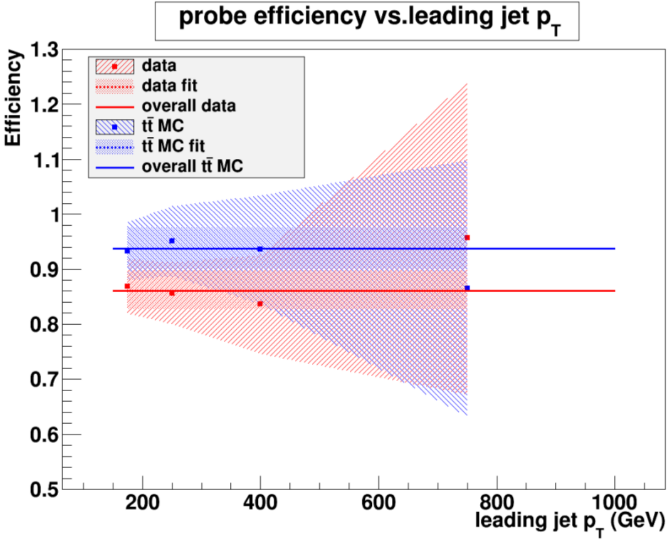
Measuring Electron ID efficiency



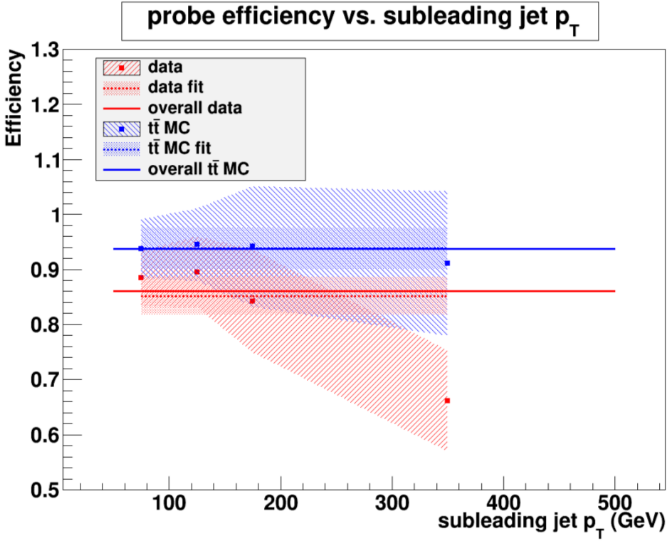
Measuring Electron ID efficiency



Measuring Electron ID efficiency



Measuring Electron ID efficiency



Measuring Electron Trigger efficiency

- In the boosted lepton+jets channel we're not expecting an isolated lepton
- Most versions of ID used are informed by isolation for electrons
  - Cut-based (“isLoose”, “isTight”) has a cut on PFIso
  - MVA ID is calculated partially using isolation
  - MVA ID working points are also paired with companion cuts on PFIso in practice
- We're using cut-based “isLoose” but with the isolation requirement explicitly bypassed (“isPseudoLoose”)

Measuring Electron Trigger efficiency

- This isolation has no published scalefactors so we measure the efficiency in data and MC using a tag-and-probe method
- Tags are clear electrons from a leptonic top
- Probes are other kinematically valid electrons
- We make additional cuts to examine mostly ttbar$\rightarrow e^+/e^-$+jets events, and test the efficiency for probe electrons to pass our selection

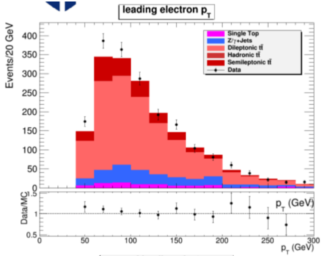
Measuring Electron Trigger efficiency

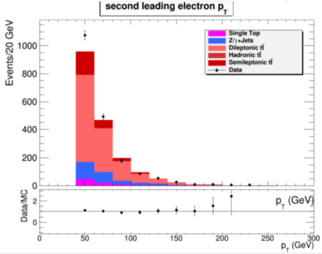
- Tag Selection:
  - Electron passing "isPseudoLoose"
  - With p_T>40 GeV, $|\eta|<2.4$, passing 2D cut
  - Reconstructed W p_T>50 GeV
- Probe Selection:
  - Second electron with p_T>40 GeV, $|\eta|<2.4$, passing 2D cut
- Veto events with any valid muons passing "isLoose" with the same kinematic requirements as above

Measuring Electron Trigger efficiency

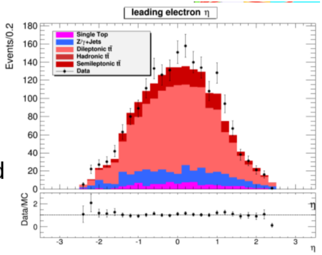
- Also require the two electrons to have opposite charges
- Cut on combined e^+/e^- mass M_{ee}
  - M_{ee}>12 GeV to legitimize dilepton topology
  - M_{ee} outside Z-mass window (76-106 GeV) to reject Z+jets → e^+/e^-+jets events
- Hadronic cuts
  - At least two jets with p_T>150, 50 GeV respectively
  - At least one loose btag (using CSV tagger with loose working point)

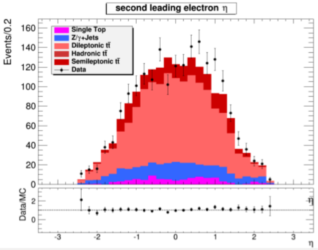
Measuring Electron Trigger efficiency





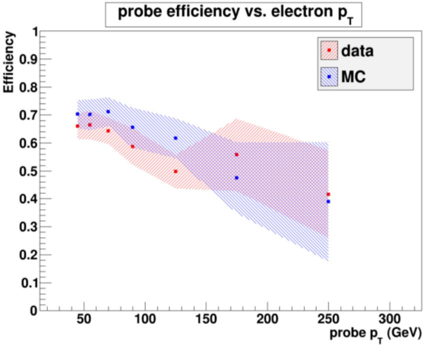
- Not as clean as e/mu selection for trigger
- More MC used to account for data (Z+jets and single top added)
- Still missing something (probably QCD) but description isn't terrible





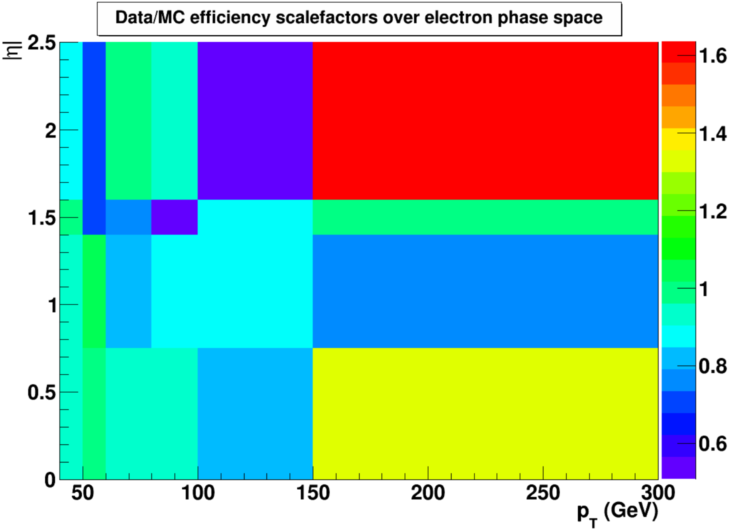
Measuring Electron Trigger efficiency

- 1943 tag/probe pairs in data
- 8842 (1812 scaled) pairs in MC
- Generally lower efficiency than seen for standard $Z \rightarrow e^{+}/e^{-}$+tag-and-probe measurements
  - Maybe due to boosting?
  - Maybe due to choice of ttbar?
  - Regardless these events look more like those in our analysis
- Strong dependence of efficiency on probe electron parameters
- Dependence consistent between MC and data
- Apply scalefactors that vary over electron phase space

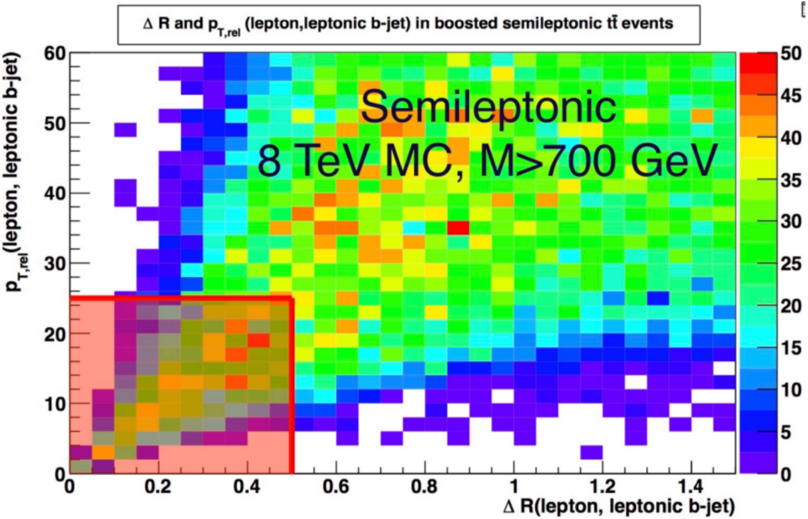


20

Measuring Electron Trigger efficiency

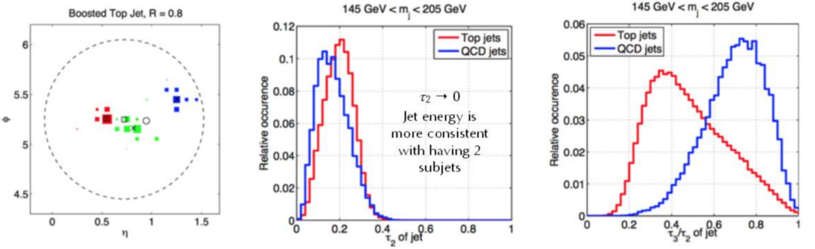


Boosted lepton "Isolation": 2D cut



Jet Substructure: N-subjettiness

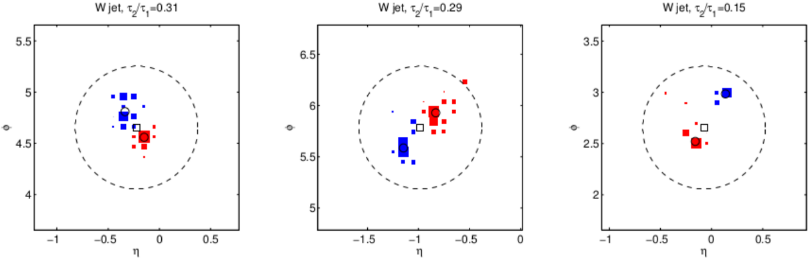
- A low τ_n means a jet is more consistent with n subjets
- Merged top jet should have three subjets
  - Cut on τ_3/τ_2



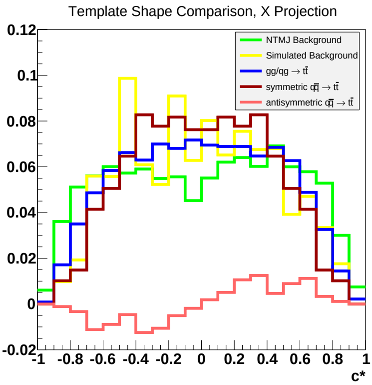
Plots From James Dolen: JetMET Algorithms and Reconstruction Meeting - June 6, 2013

Jet Substructure: N-subjettiness

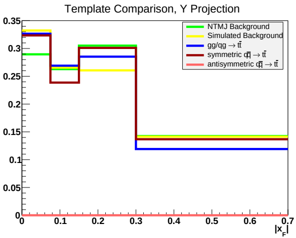
$$\tau_{N_2 N_1} = \frac{\sum_k p_{T,k} min\left[\Delta R_{1,k}, ..., \Delta R_{N_2,k}\right]}{\sum_k p_{T,k} min\left[\Delta R_{1,k}, ..., \Delta R_{N_1,k}\right]}$$

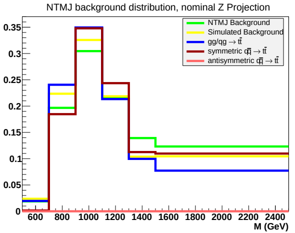


Template Shape Comparison

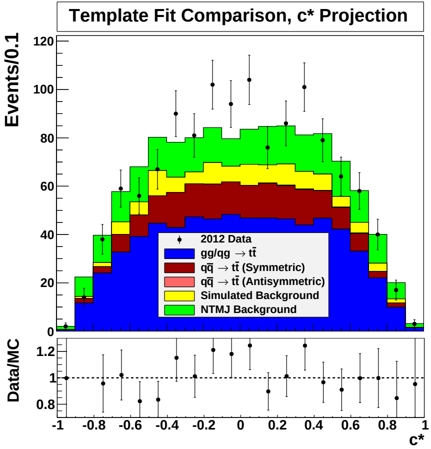


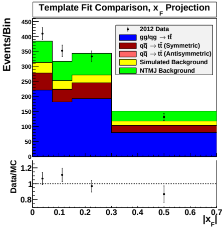
Events added to 3D histograms
$F_{q\bar{q}s}/F_{q\bar{q}a}$ distributions
symmetrized/antisymmetrized

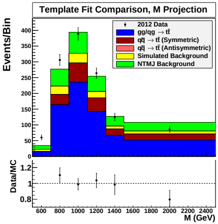




Template Fit Results







Result: $A_{FB} = 7.9\% \pm 7.7\%$