Search for Flavor Changing Neutral Currents in Top Quark Decays

$t \to q\gamma$

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The Standard Model

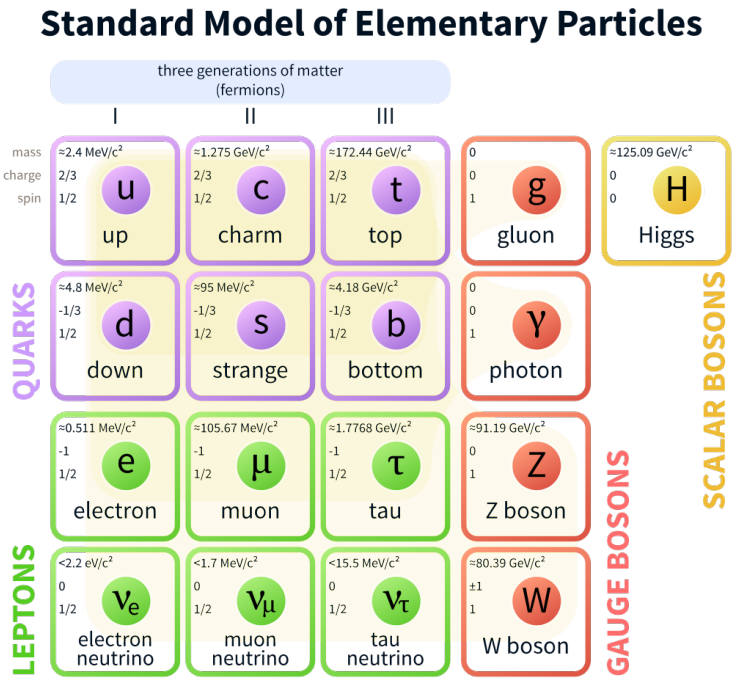


Figure: List of standard model particles

- Our current theory that attempts to explain everything
  - Experimentally precise and well behaved
  - Very few exceptions (i.e. Neutrino Mass, Matter-Antimatter Asymmetry, Dark Matter Abundance)

The Top Quark

- Heaviest fundamental particle, $172.5 GeV$
- Lifetime $5x10^{-25}s$, decays before hadronization
  - Allows us to study the decay of a single quark

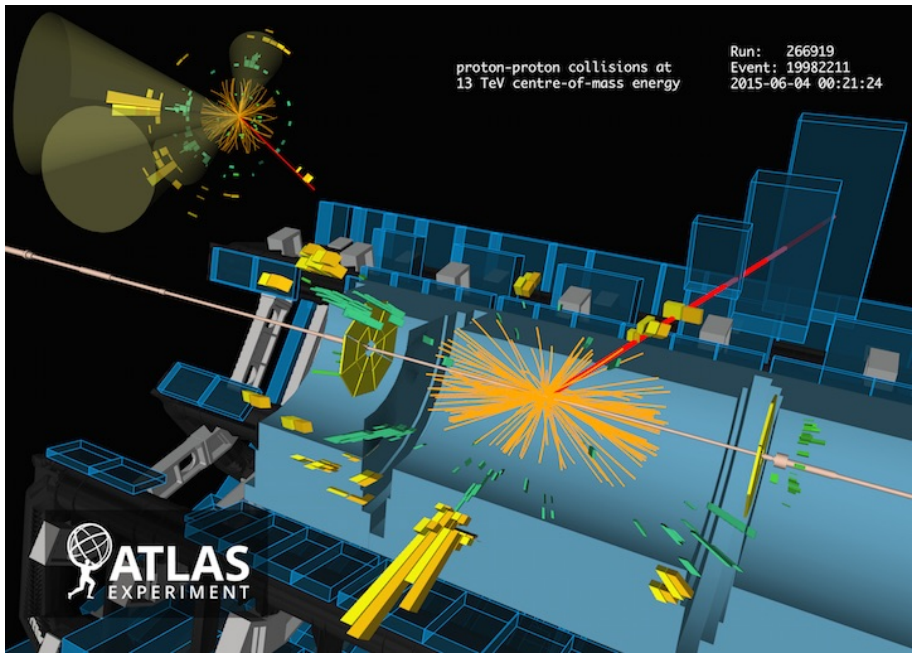


Figure: $t\bar{t}$ event in the ATLAS detector

Top Quark Pair Production

- Leading order processes for top quark production
  - Quark-antiquark annihilation $\approx 10\%$
  - Gluon-gluon fusion $\approx 90\%$

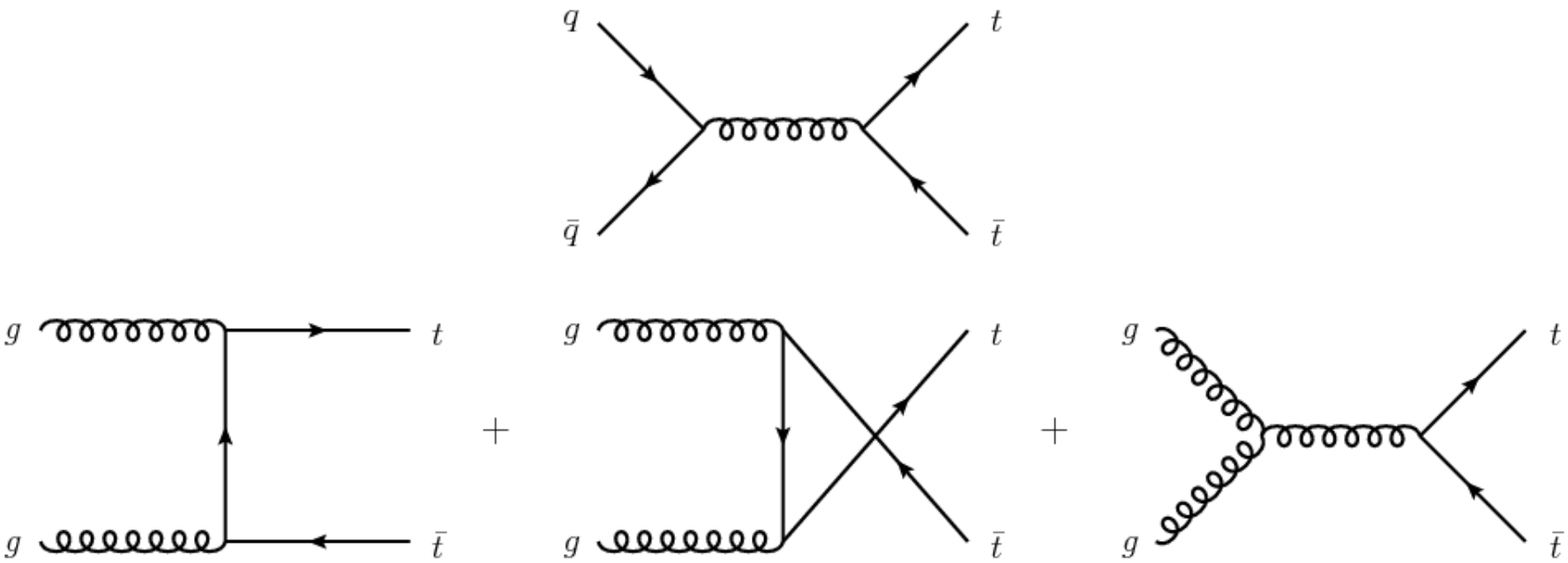


Figure: Leading order $t\bar{t}$ diagrams

Top Quark Pair Production

- At $\sqrt{s} = 13\,TeV$ for $m_t = 172.5\,GeV$, $\sigma_{t\bar{t}} = 831.76pb$

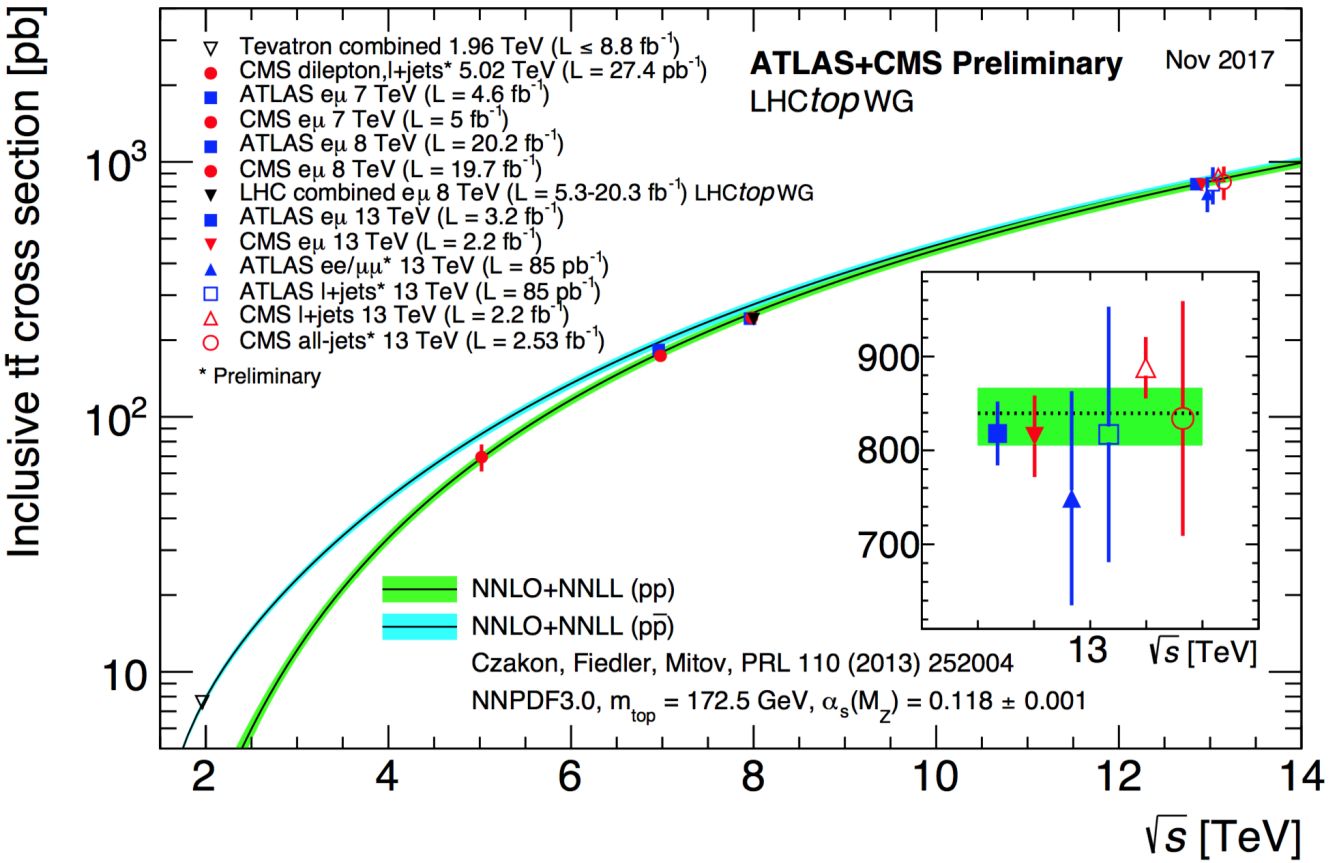


Figure: $t\bar{t}$ production cross section [TopWGSummaryPlots]

Top Quark Decays

- Standard model top branching ratio to bW $\simeq 100\%$

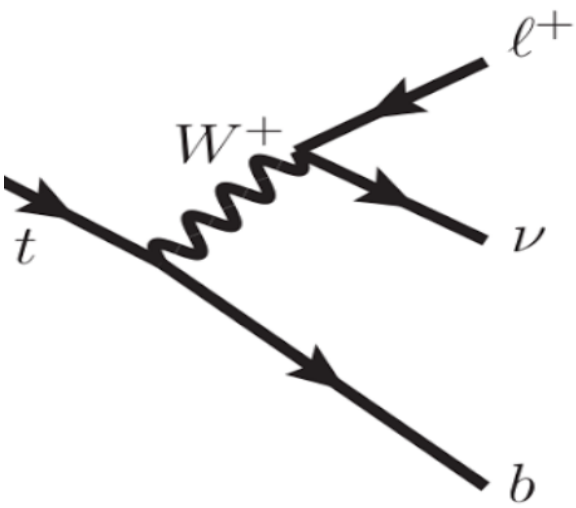


Figure: Leptonic final state diagram for a top decay

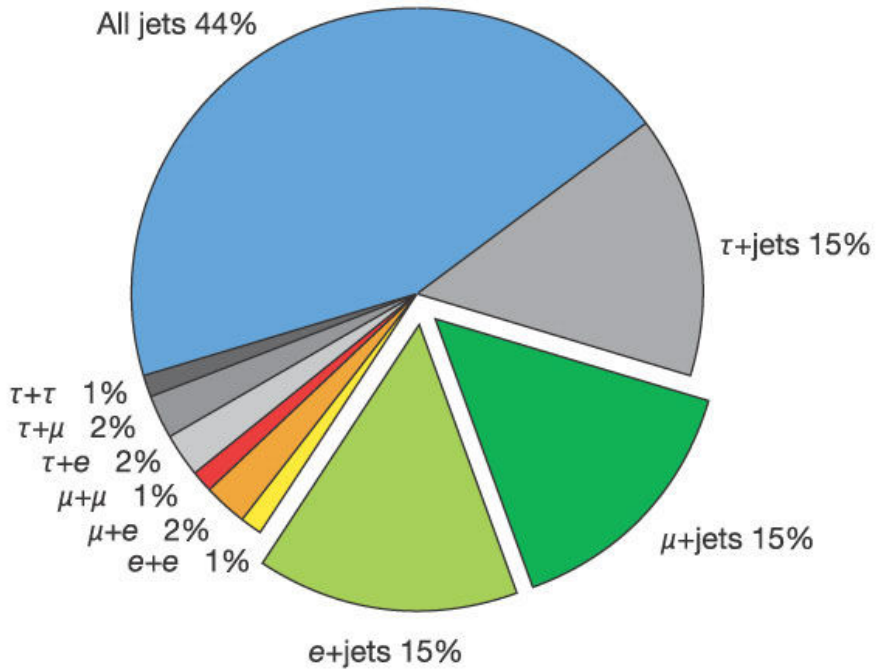
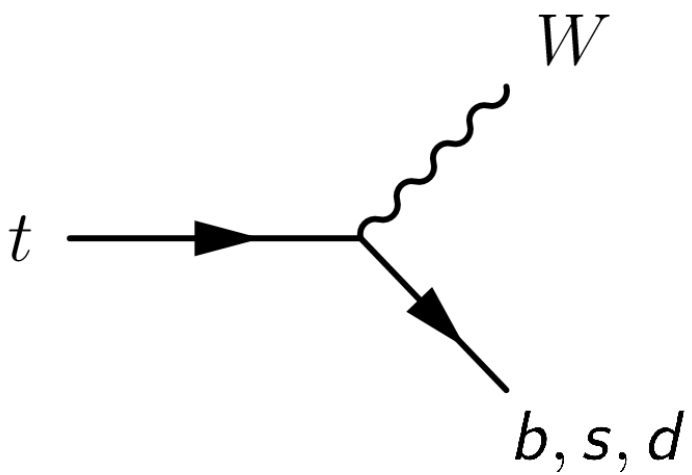
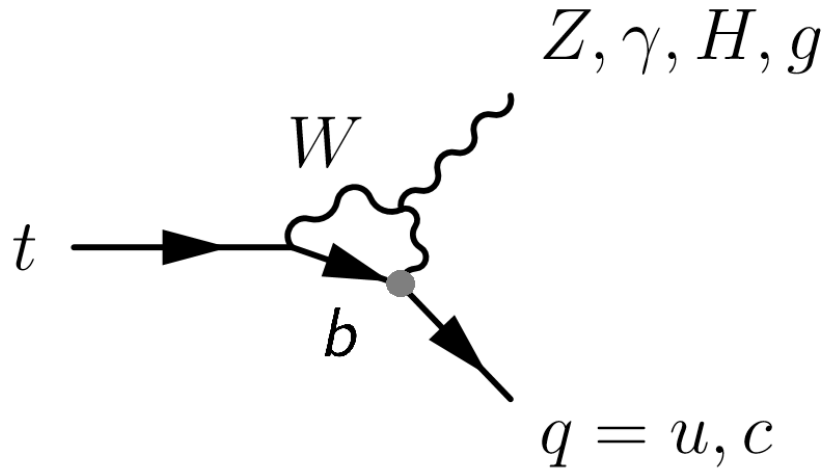


Figure: Top quark pair decay final states [Nature]

Top Quark Decays in the SM





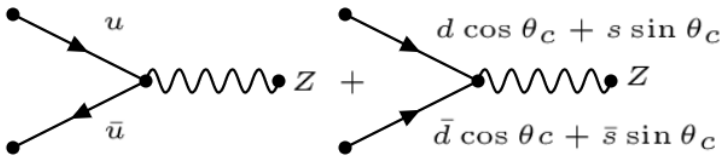
- $t \to bW \approx 99.83\%$
- $t \to sW \approx 0.16\%$
- $t \to dW \approx 0.01\%$

- $t \to q_{u,c}X \approx 10^{-17} - 10^{-12}$

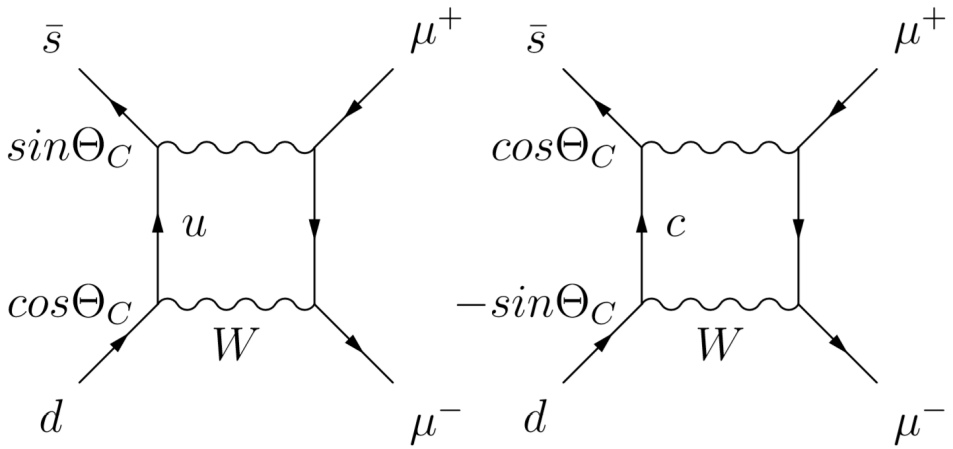
GIM Mechanism

- Cabibbo model - 3 quarks (u, d, s)
- Studies of kaon decays showed the existence of $K^+ \rightarrow \mu^+\nu_\mu$ but an absence of predicted $K_L^0 \rightarrow \mu^+\mu^-$
- Even in the absence of a tree level decay K_L^0 decay the box diagram would be possible through an exchange of W bosons
- Weak neutral current interactions in the uds model have the form

$$u\bar{u} + (d\bar{d}\cos^2\theta_C + s\bar{s}\sin^2\theta_C)) + (s\bar{d} + d\bar{s})sin\theta_C cos\theta_C$$



GIM Mechanism



- Glashow, Iliopoulos, and Maiani [Phys. Rev. D (1970)] propose a machanism through which FCNCs are suppressed in loop diagrams
  - Introduction of charm quark
- Kaon decays imply no neutral current/natural suppression of neutral current

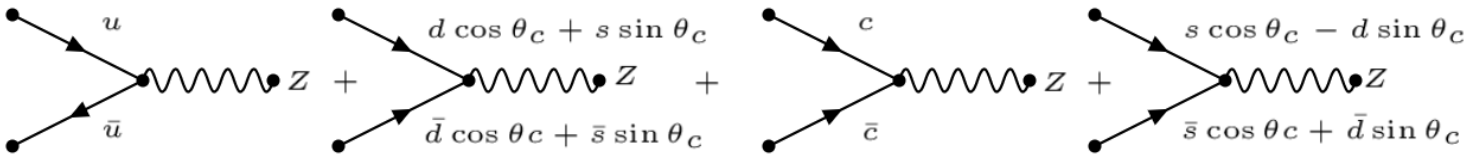
GIM Mechanism

$$\begin{bmatrix} d' \\ s' \end{bmatrix} = \begin{bmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{bmatrix} \begin{bmatrix} d \\ s \end{bmatrix}$$

- The addition of the charm changes our weak neutral current interactions
- With four quarks the weak neutral interactions now have the form:

$$u\bar{u}+c\bar{c}+(d\bar{d}+s\bar{s})\cos^2\theta_C+(s\bar{s}+d\bar{d})\sin^2\theta_C+(s\bar{d}+d\bar{s}-d\bar{s}-s\bar{d})sin\theta_C cos\theta_C$$

- Flavor changing neutral current diagrams cancel out at tree level (as $m_c \to m_u$)



CKM Matrix

$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} = \begin{bmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.00065 & 0.00351^{+0.00015}_{-0.00014} \\ 0.22520 \pm 0.00065 & 0.97344 \pm 0.00016 & 0.0412^{+0.0011}_{-0.0005} \\ 0.00867^{+0.00029}_{-0.00031} & 0.0404^{+0.0011}_{-0.0005} & 0.999146^{+0.000021}_{-0.000046} \end{bmatrix}$$

Figure: CKM Matrix

- Decay rates proportional to $|V_{tX}|^2$
- Top decay through a $W^{\pm}$ boson is a charged current interaction.
- Flavor changing processes are proportional to off-diagonal elements of the CKM matrix
- GIM/CKM suppression of these FCNC processes in the Standard Model make them unlikely to be seen without some new physics

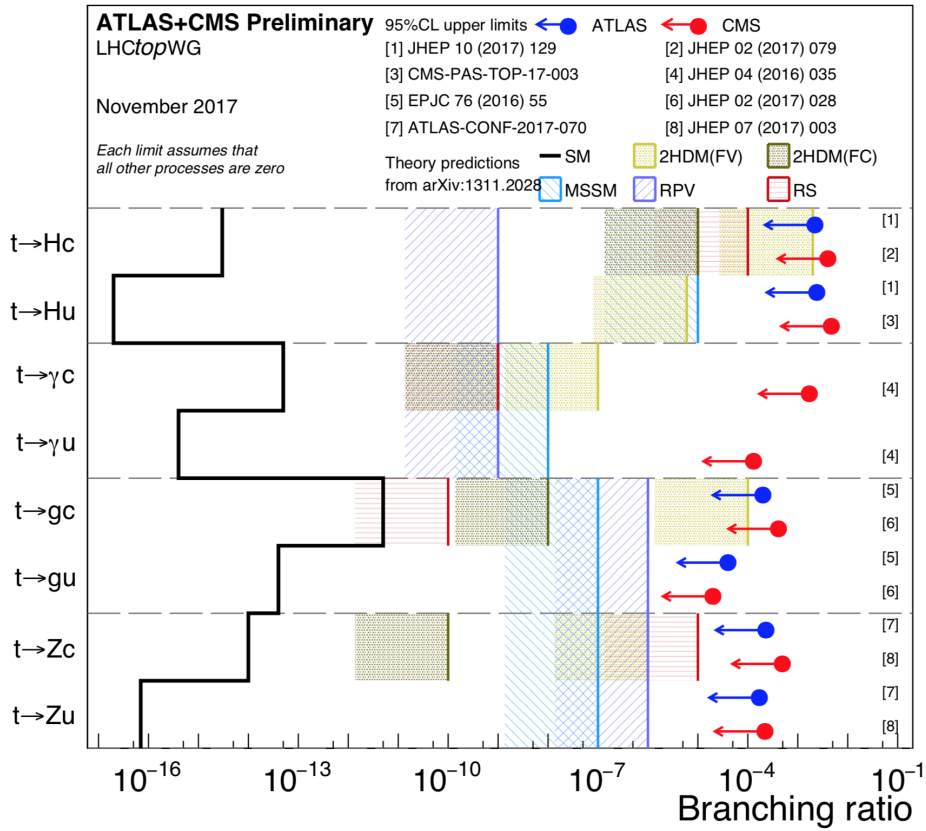
Top Flavor Changing Neutral Currents (FCNCs)

Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \to Zu$	7×10^{-17}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to Zc$	1×10^{-14}	$\leq 10^{-6}$	$\leq 10^{-10}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-5}$
$t \to gu$	4×10^{-14}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\leq 10^{-4}$	$\leq 10^{-8}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-10}$
$t \to \gamma u$	4×10^{-16}	–	–	$\leq 10^{-8}$	$\leq 10^{-9}$	–
$t \to \gamma c$	5×10^{-14}	$\leq 10^{-7}$	$\leq 10^{-9}$	$\leq 10^{-8}$	$\leq 10^{-9}$	$\leq 10^{-9}$
$t \to hu$	2×10^{-17}	6×10^{-6}	–	$\leq 10^{-5}$	$\leq 10^{-9}$	–
$t \to hc$	3×10^{-15}	2×10^{-3}	$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$

Table: Branching ratio enhancements in various beyond the standard model theories [Snowmass Top Report]

Top Flavor Changing Neutral Currents

- Current Limits on FCNC Decays



- Limits on $t \to \gamma q$ processes: [JHEP 04 (2016) 035]
  - $t \to \gamma u < 1.3x10^{-4}$
  - $t \to \gamma c < 1.7x10^{-3}$

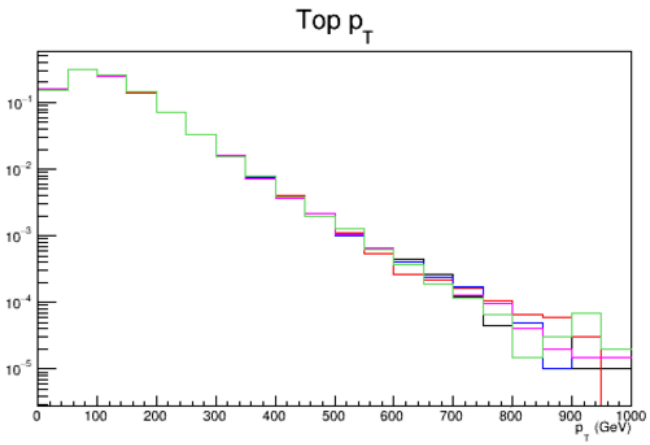
Monte Carlo Production of FCNC Signal Samples

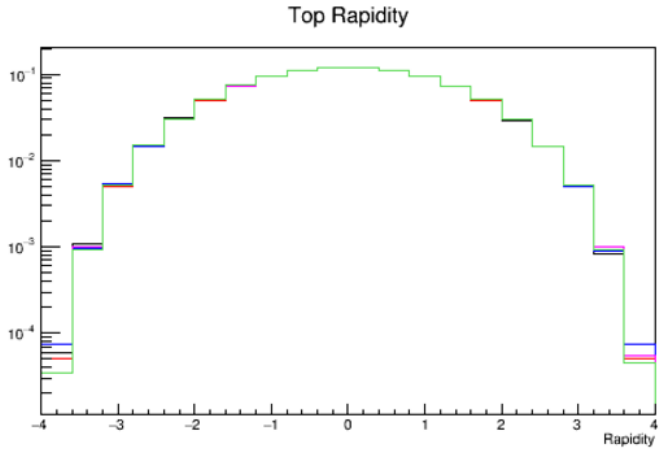
- Due to the low cross sections we must create our own Monte Carlo Samples for our Signal
- An effective field theory approach was taken in the creation of the model [Degrande et al. Phys. Rev. D 91, 034024 (2015)]
- This model takes advantage of dimension-6 operators

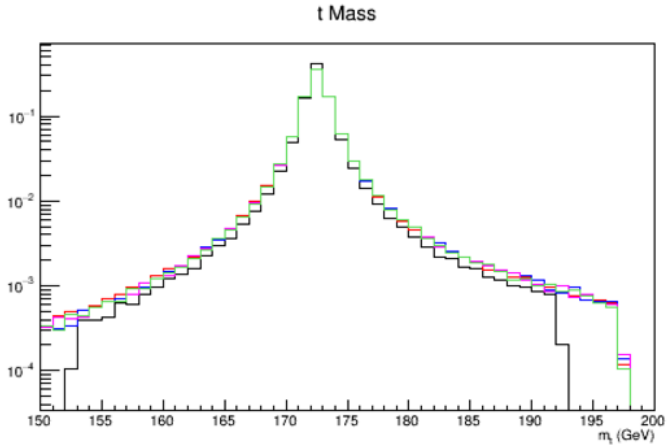
$$\mathcal{L}_{SM} = \mathcal{L}_{SM}^{(4)} + \mathcal{L}^{eff} \text{ where } \mathcal{L}^{eff} = \frac{1}{\Lambda^2} \sum_k C_k^{(6)} Q_k^{(6)}$$

$$\mathcal{L}_{tq\gamma}^{eff} = C\sigma^{\mu\nu} q_\nu (\lambda_{ct}^L P_L + \lambda_{ct}^R P_R) t A_\mu + H.c.$$

Top FCNC Signal Creation - Kinematic Checks







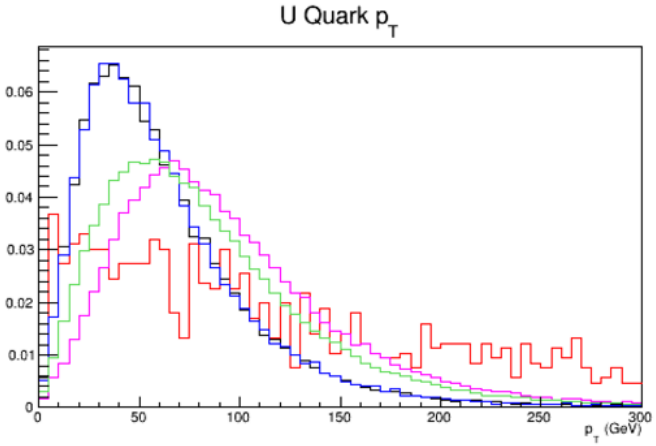
<p_T> = 121.1GeV

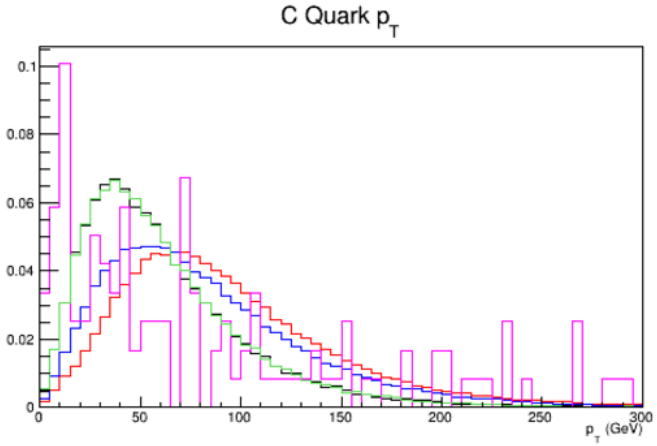
<m_t> =172.7
official **σ**= 2.79
FCNC **σ**= 3.46

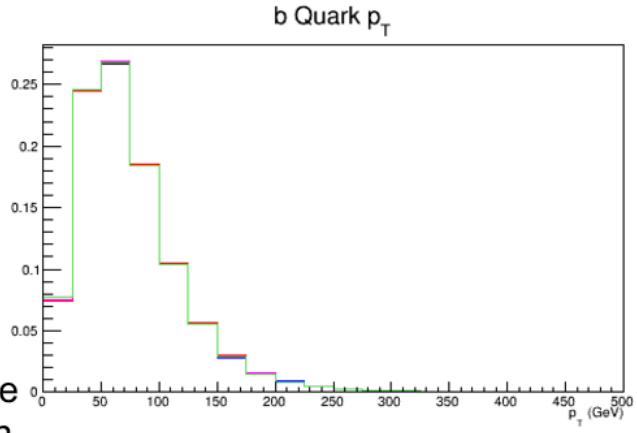
Consistent to official production
Difference in top mass
width obvious, not large

-----: Official MC Production
-----: $t\bar{t} \to bW(\to l\nu)c\gamma$
-----: $t\bar{t} \to bW(\to jj)c\gamma$
-----: $t\bar{t} \to bW(\to l\nu)u\gamma$
-----: $t\bar{t} \to bW(\to jj)u\gamma$

Top FCNC Signal Creation - Kinematic Checks





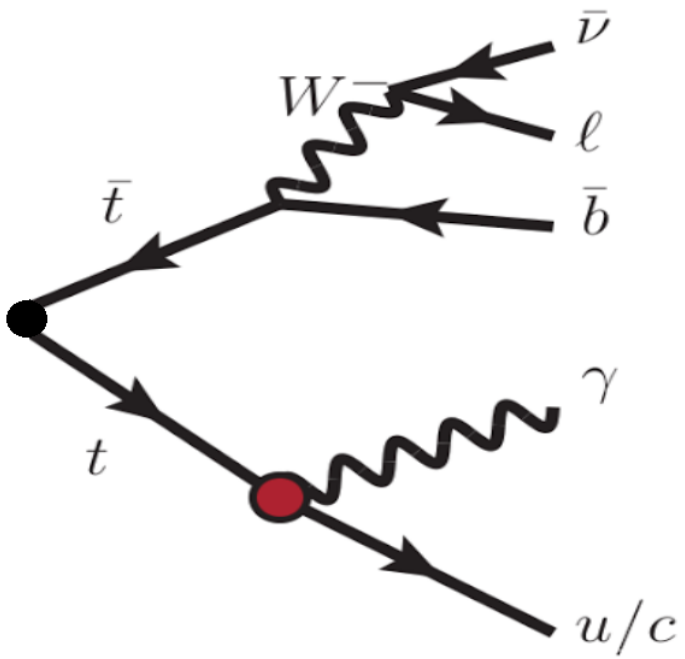


Misplaced quarks from
NLO processes, W decays
Expect jj processes with opposite
quark to mirror official production

-----: Official MC Production
-----: $t\bar{t} \to bW(\to l\nu)c\gamma$
-----: $t\bar{t} \to bW(\to jj)c\gamma$
-----: $t\bar{t} \to bW(\to l\nu)u\gamma$
-----: $t\bar{t} \to bW(\to jj)u\gamma$

FCNC: What are we looking for? $t\bar{t} \rightarrow W(\rightarrow l\nu)b + q\gamma$

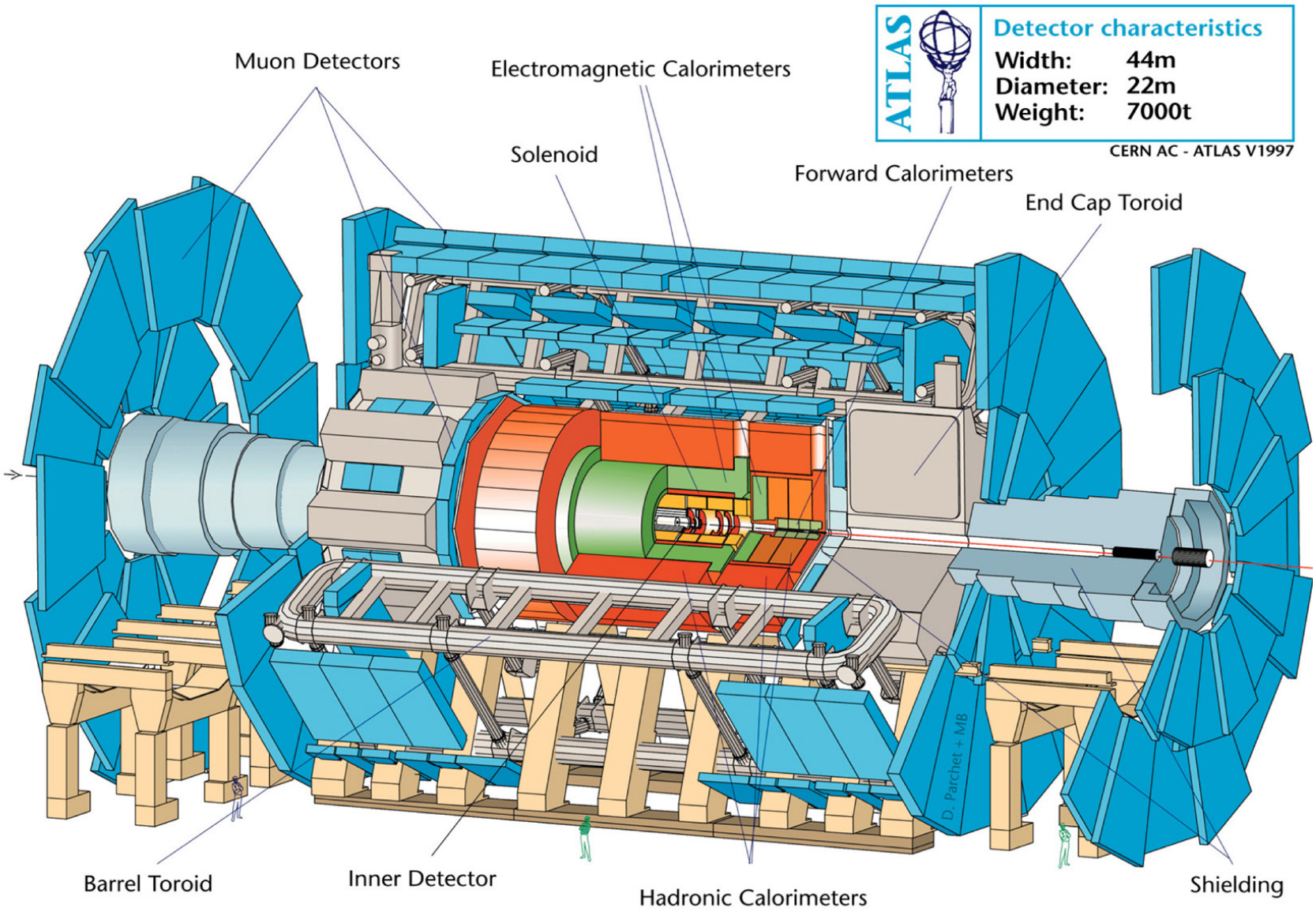
- Final state topology
  - One Neutrino, from W
  - One Lepton, from W
  - One B-jet, SM top
  - One Photon, FCNC Top
  - One Jet, FCNC Top



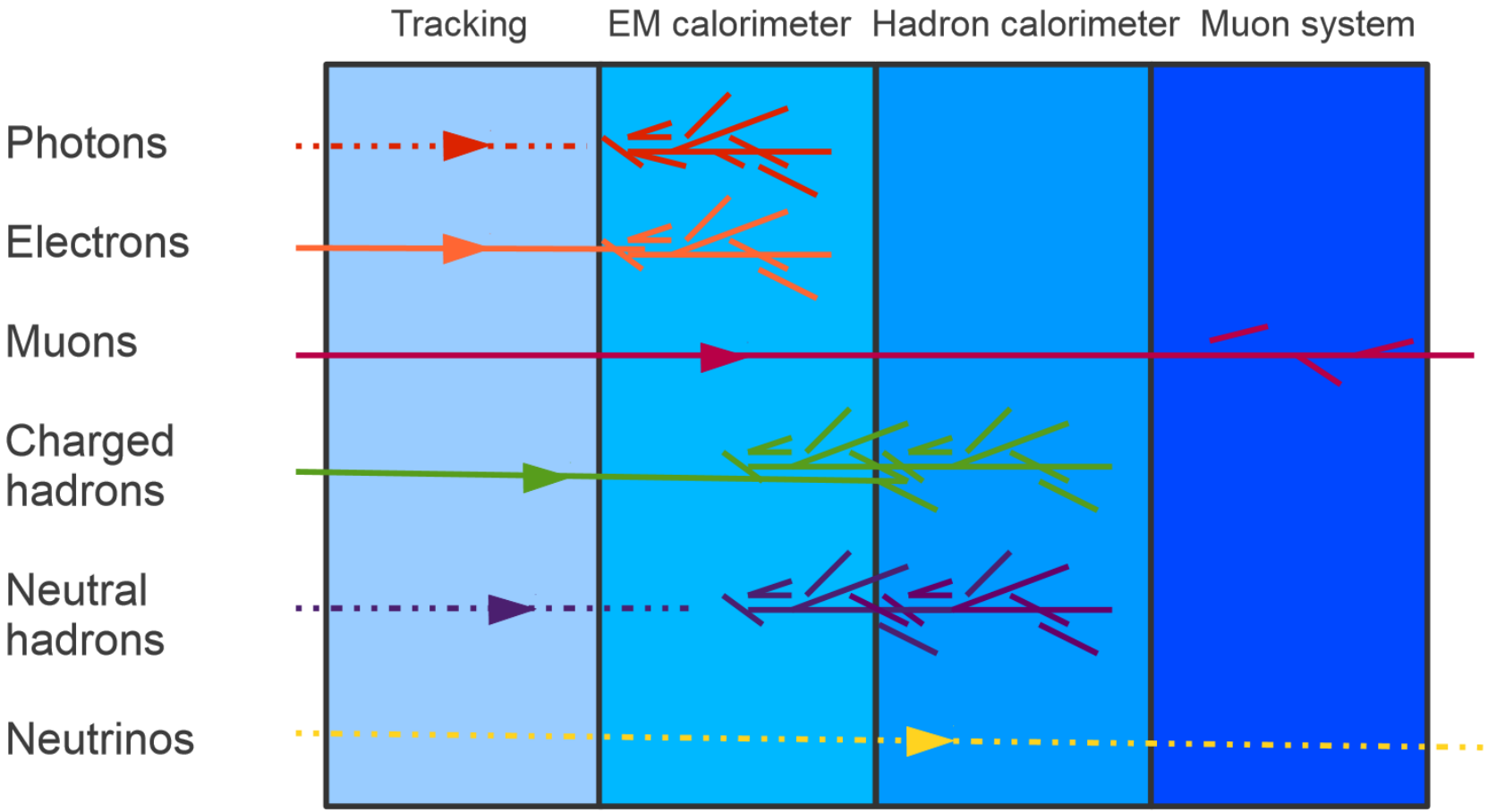
The Large Hadron Collider (LHC)

- $27km$ ring beneath France-Switzerland border
- 4 Major Experiments
- Collides protons at $\sqrt{s} = 13TeV$

The ATLAS Detector



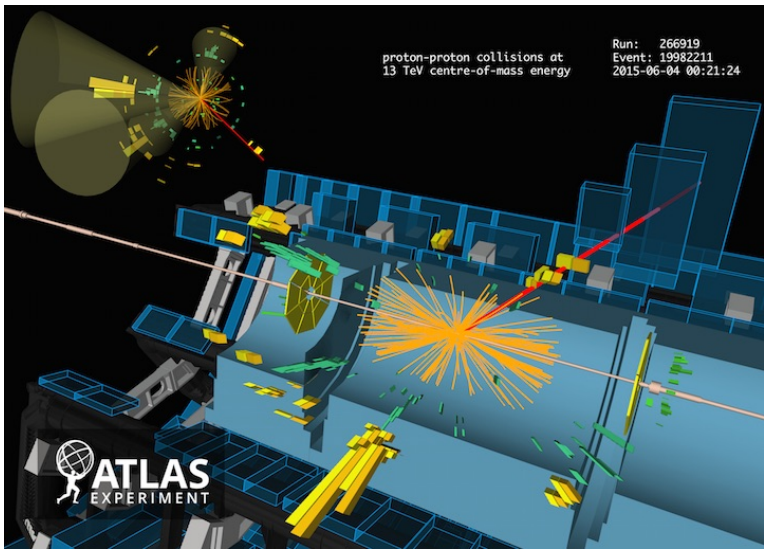
Particles in ATLAS

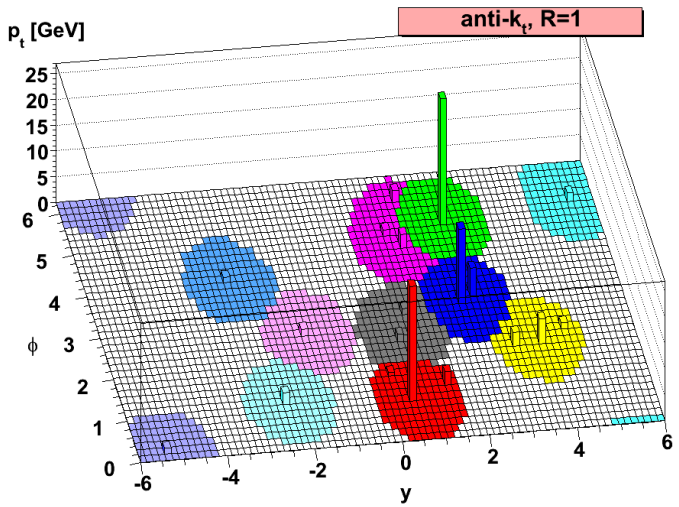


*Courtesy of Liza Brost

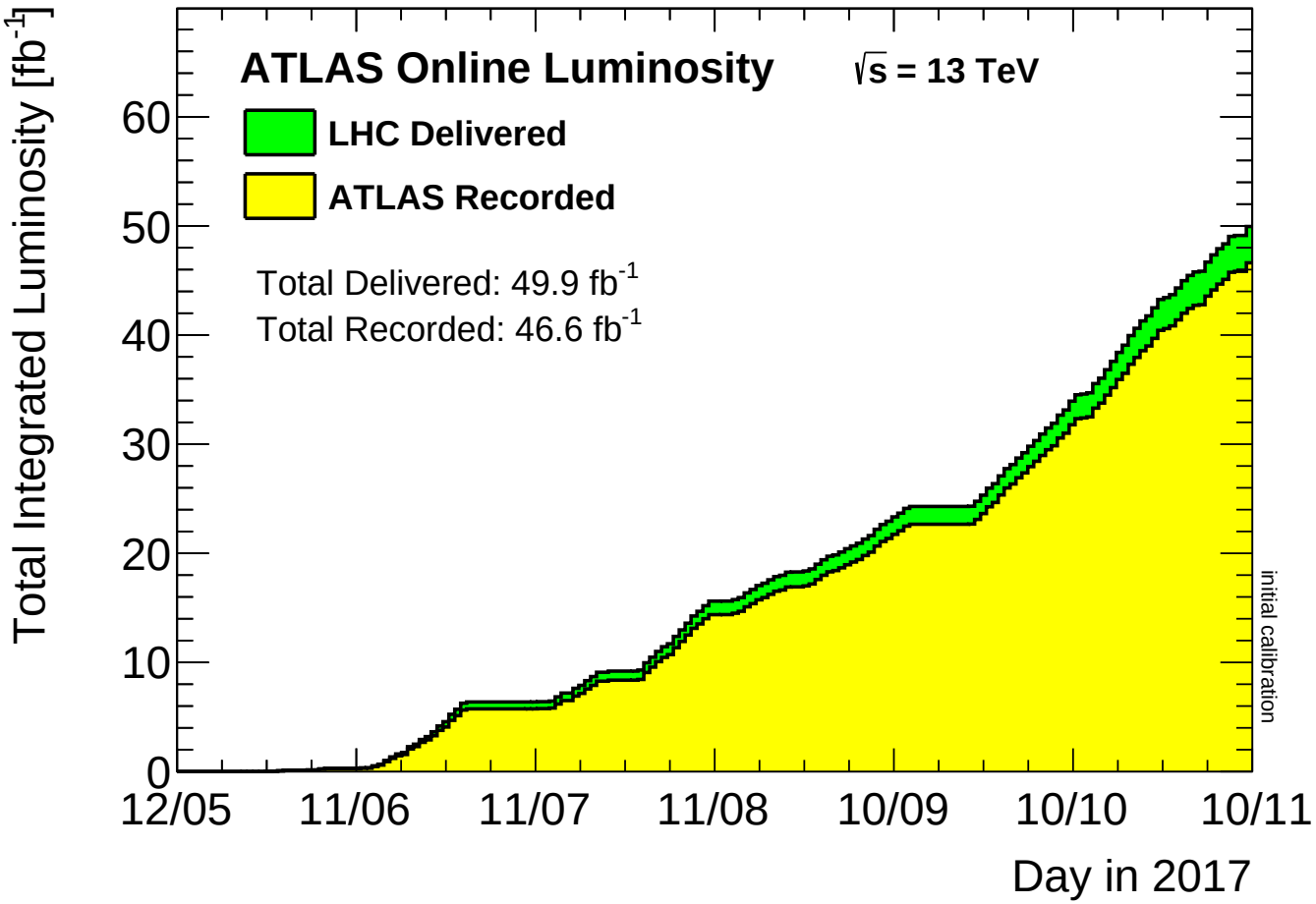
Jets

- Quarks leaving from the interaction form into narrow cones of particles
- Jets are identified with the anti-k$_T$ algorithm



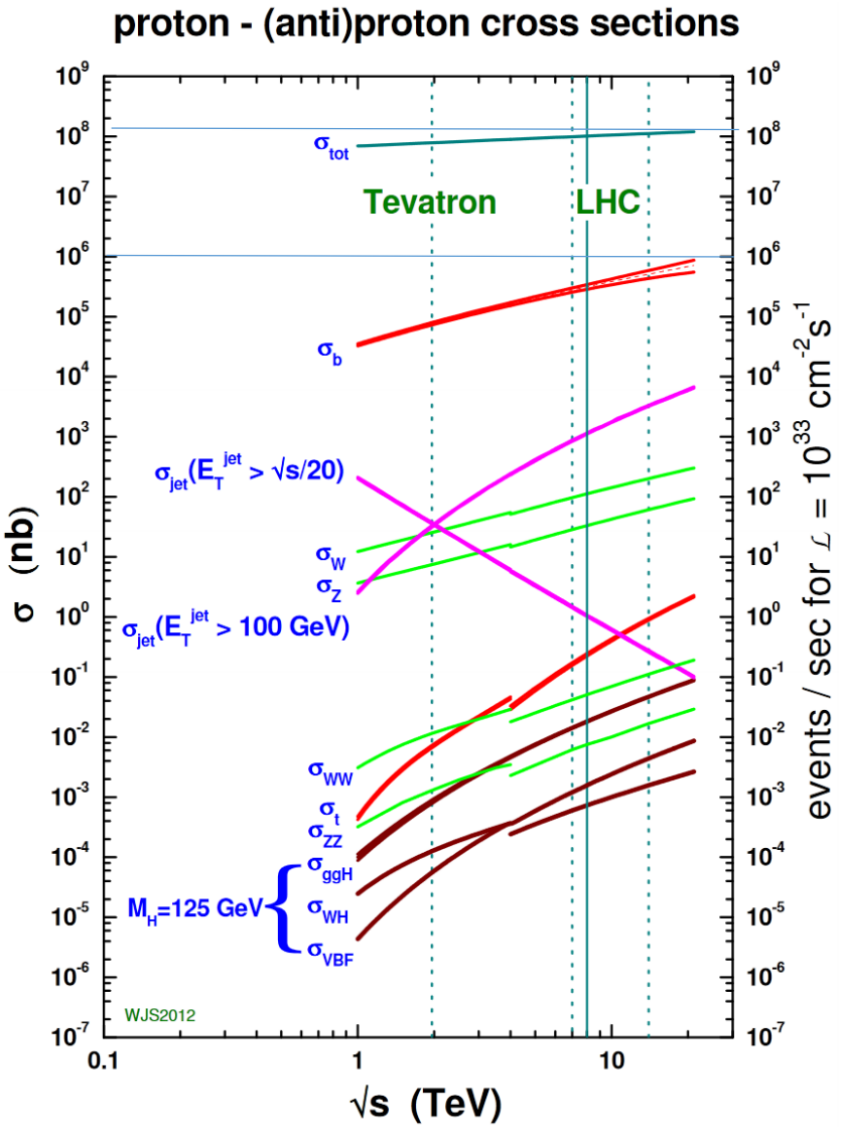


ATLAS Data



- Total recorded integrated luminosity at $\sqrt{s} = 13\,TeV$: 86.4fb^{-1}

What's in the data?

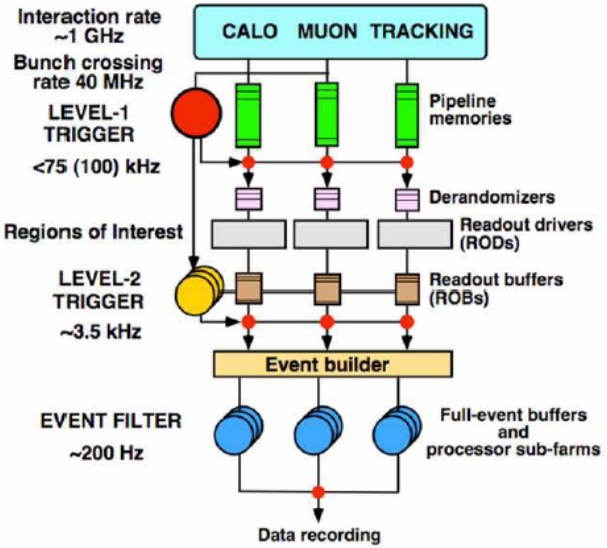


- The number of events we see is $N = \sigma L$
- $\sigma_{t\bar{t}} = 831.76\text{pb}$
- $N_{t\bar{t}} \approx 72x10^6$
- $N_{tot} \approx 8.6x10^{15}$ events produced during the 13TeV data runs

Data Acquisition

- The LHC provides around 600 million interactions every second
- Raw event data is about $1MB \Rightarrow 600TB$ event data per second
- Absolutely impossible to save this amount of data
- We need a way to pick out interesting events to save

Trigger System



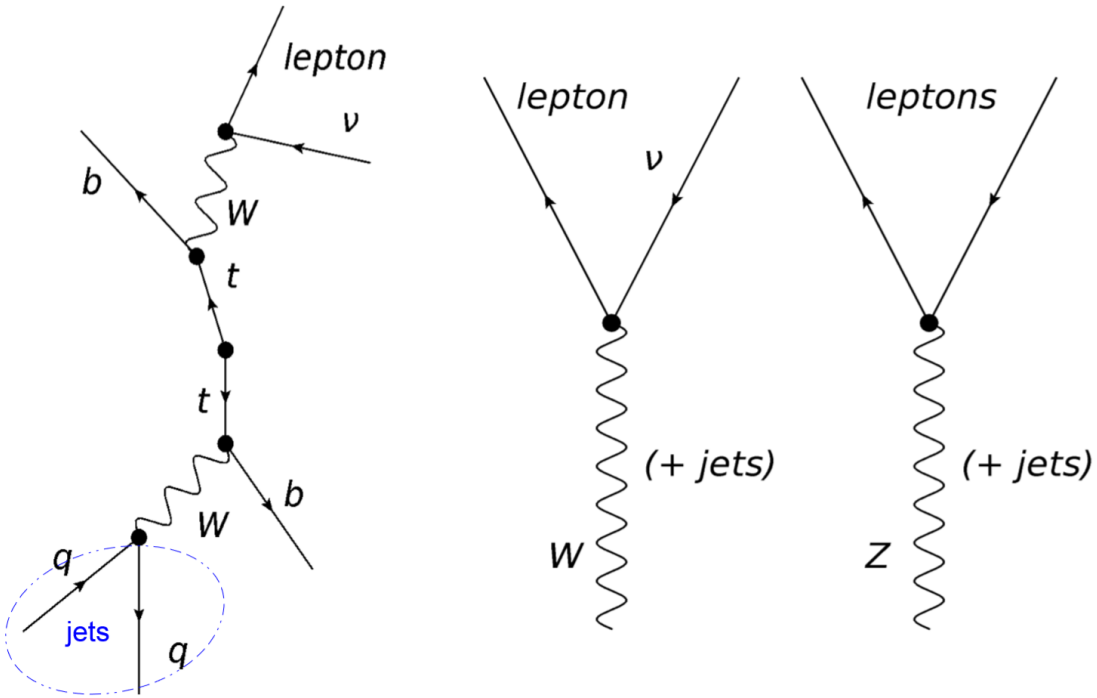
- We look for events with compelling topologies
  - Leptons, High Energy Events, Missing Energy, etc.
- We only write these interesting events reducing *GHz* interaction rate to around 200*Hz* to disk

Object Preselection

- We preselect events with objects that look like our expected topology
- Require:
  - Exactly one lepton (e or μ) $\geq$ 25 GeV
  - Exactly one Good photon $\geq$ 25GeV
  - Missing Transverse Energy $\geq$ 30GeV
  - $\geq$ 2 Jets (at least one being b-tagged)
- All following plots will have signal scaled to 1% of $\sigma_{t\bar{t}}$, MC scaled to $36.07 fb^{-1}$

Background Processes

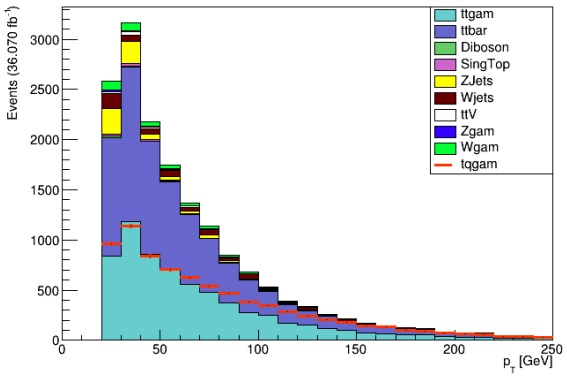
- Due to all of the processes at hadron colliders it is important to model similar event topologies well.
- Major backgrounds include $t\bar{t}$, W+Jets, Z+Jets, + processes with an associated photon



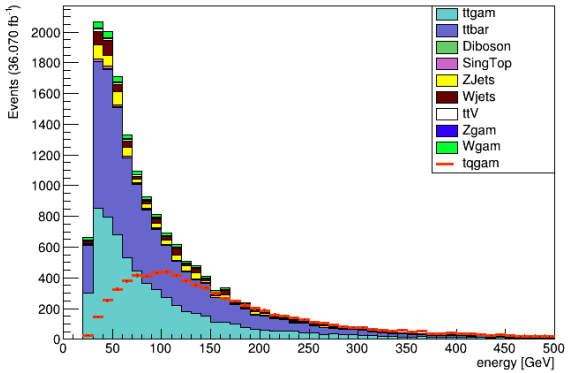
Preselection Objects

Electron Channel

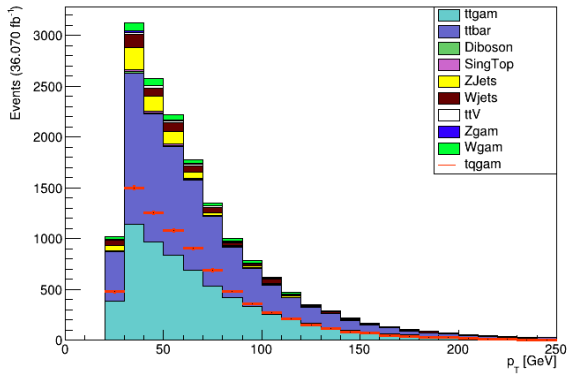
- Leading Jet p_T



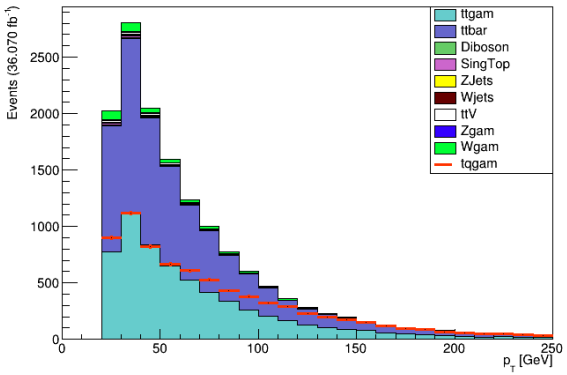
- Photons

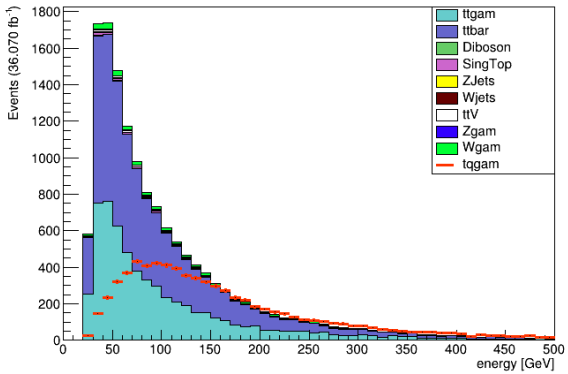


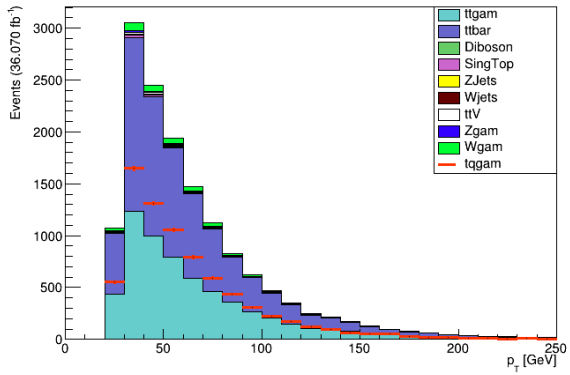
- Leptons



Muon Channel







Where are the Tops?

- Must be 'reconstructed' from these objects as well as b-jets and E_T^{miss}
- E_T^{miss} is calculated to balance the event energy in the transverse plane of the detector
- The other particles are combined in the only way the signal topology would allow two top quark candidates
  - Standard model top candidate: b-jet + lepton + neutrino
  - FCNC Top: Photon + Light Jet

Neutrinos

- All missing energy in signal topology is from neutrino
- We have E_T^{miss} and its' direction
  - Can calulate E_{Tx}^{miss} and E_{Ty}^{miss} easily
  - Ambiguous direction along the z-axis
- A minimization of this χ^2 will allow us to determine the z momentum of the neutrino: $\chi^2 = \frac{(m_{b,l,\nu} - m_t)^2}{\sigma^2_{SMtop}} + \frac{(m_{l,\nu} - m_W)^2}{\sigma^2_W}$

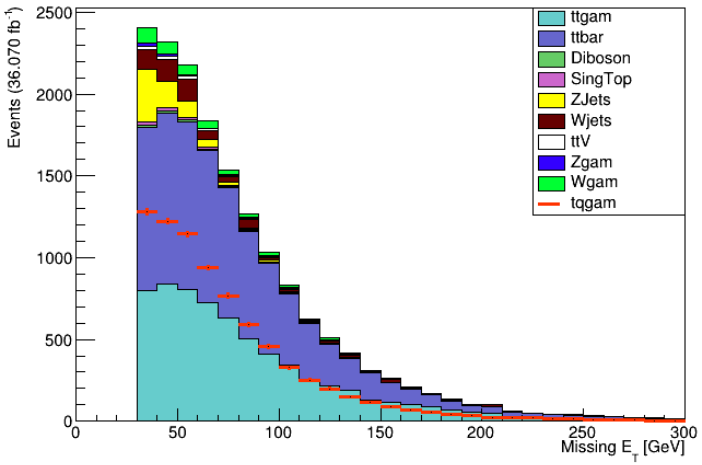


Figure: e-channel E_T^{miss} distribution

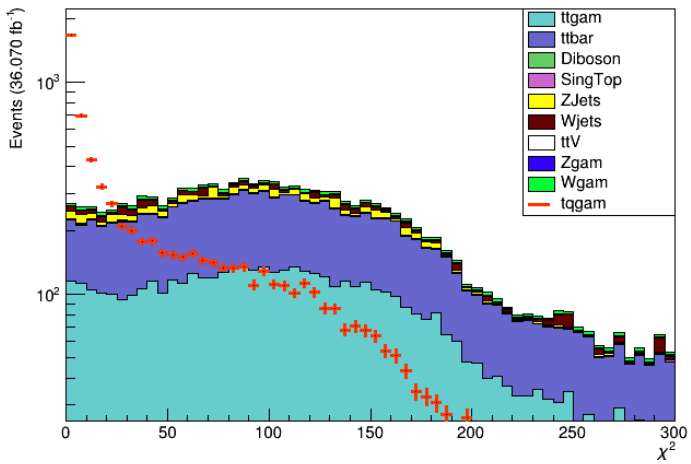
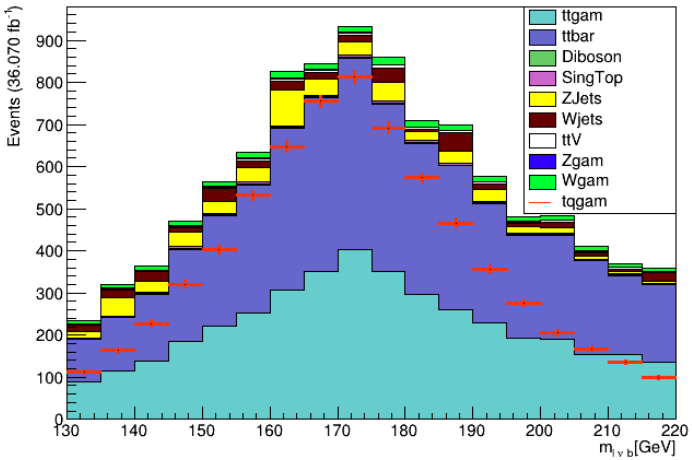


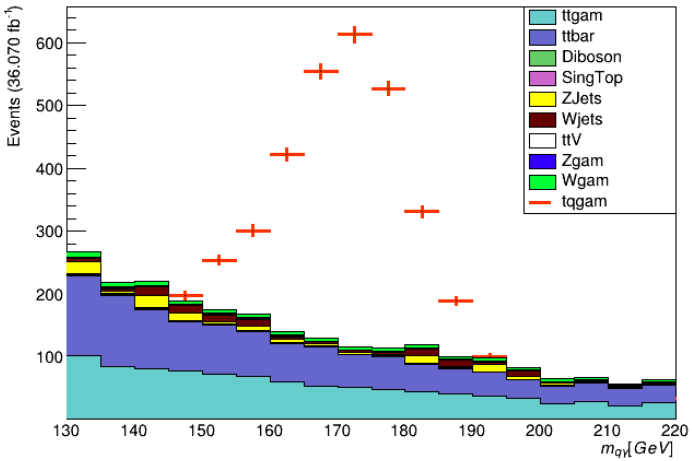
Figure: e-channel χ^2 distribution

Reconstructed Tops

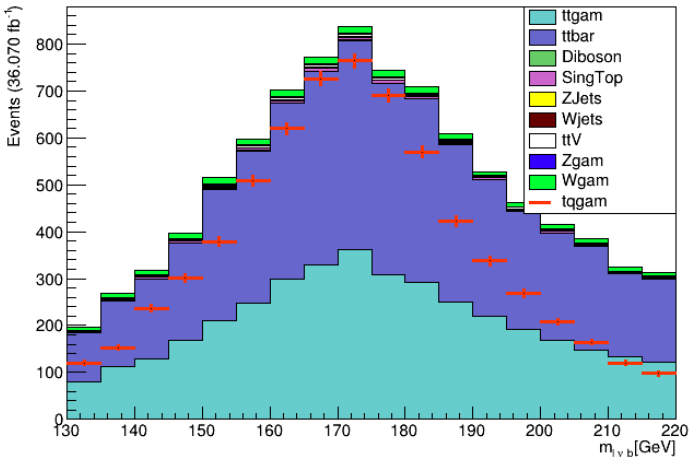
- SM Top
- FCNC Top

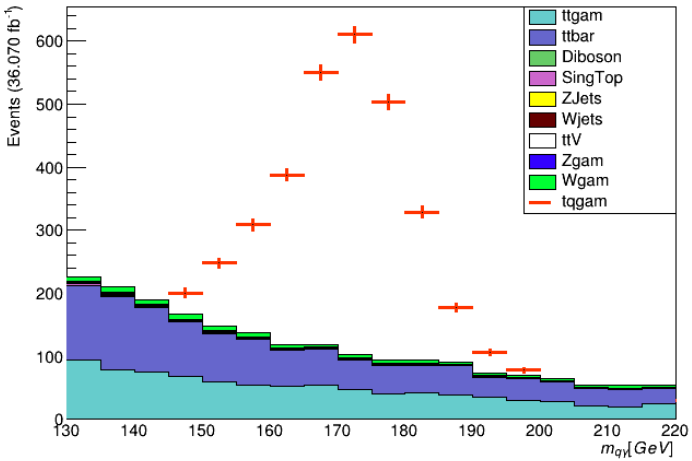
Electron Channel





Muon Channel

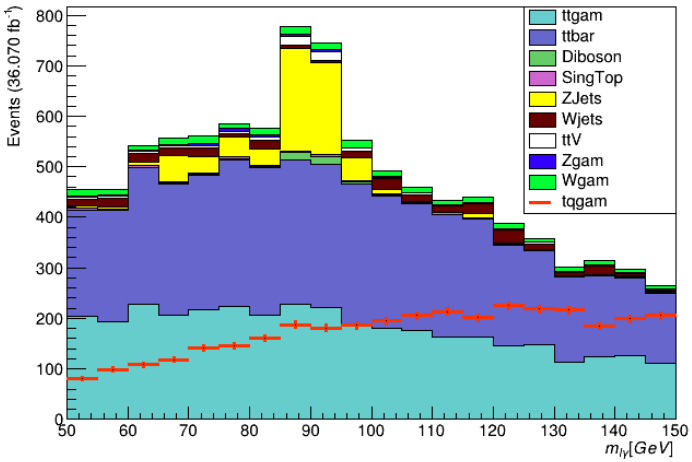


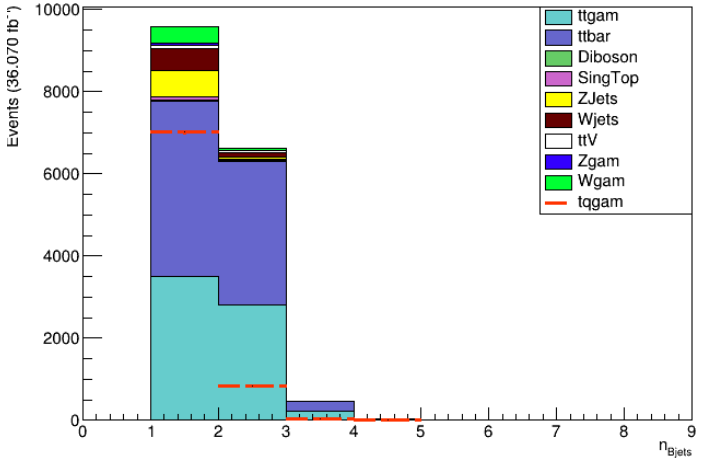


Thinning Out Backgrounds

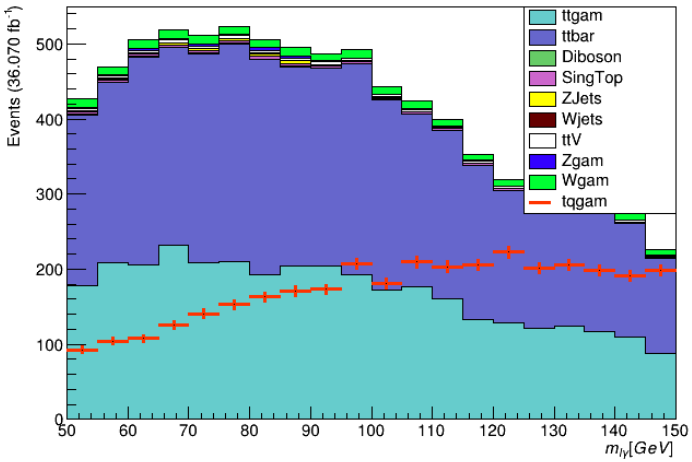
- Reconstructing Z mass
- Number of BJets

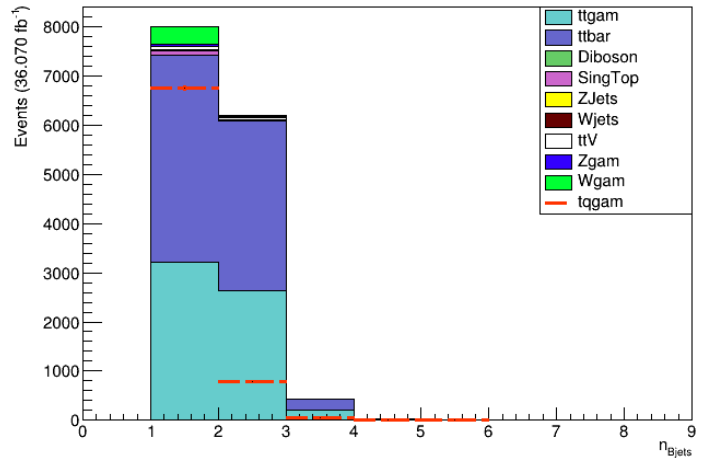
Electron Channel





Muon Channel

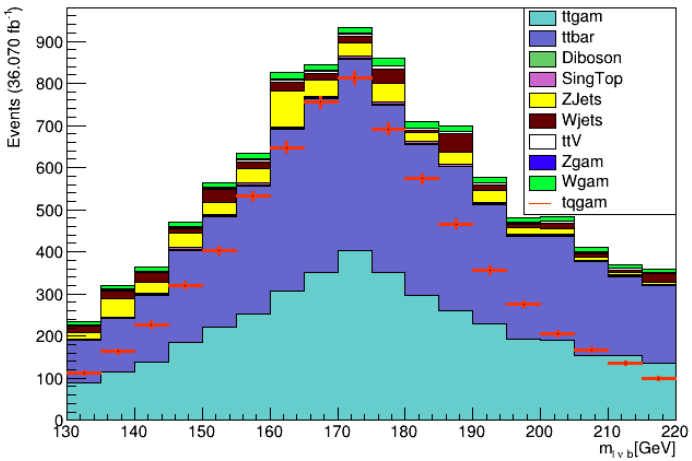


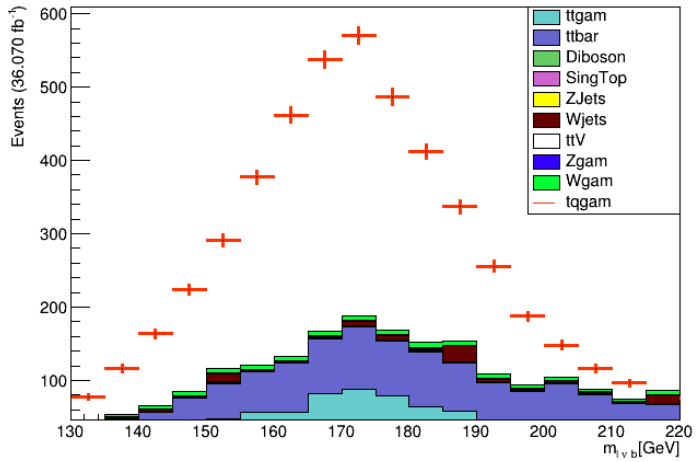


Thinning Out Backgrounds: SM Top ($m_{l\nu b}$)

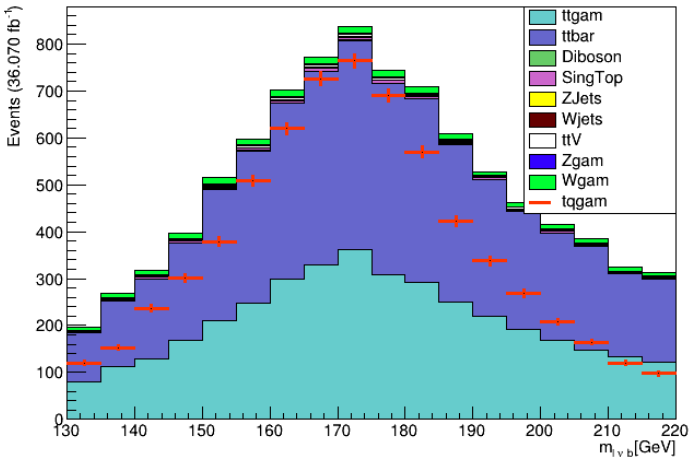
- Before Z-mass, Bjet cuts
- After Cuts

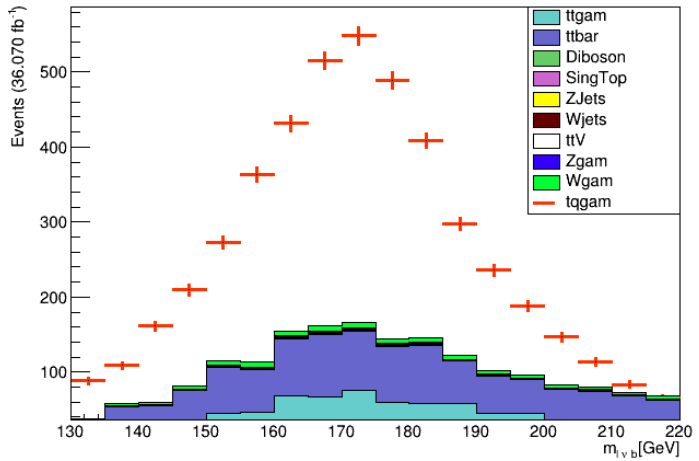
Electron Channel





Muon Channel

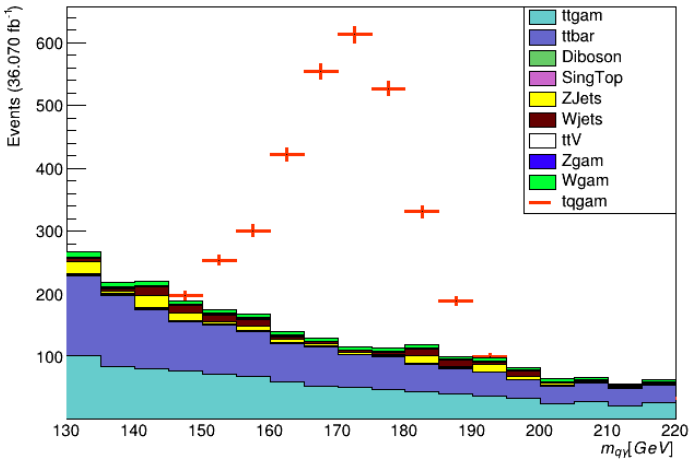


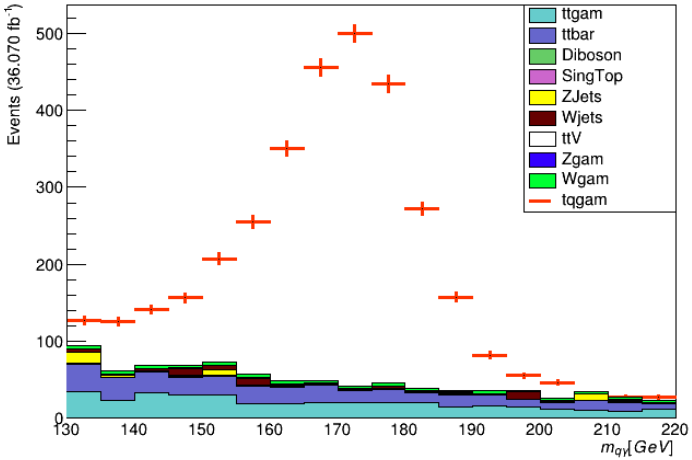


Thinning Out Backgrounds: FCNC Top

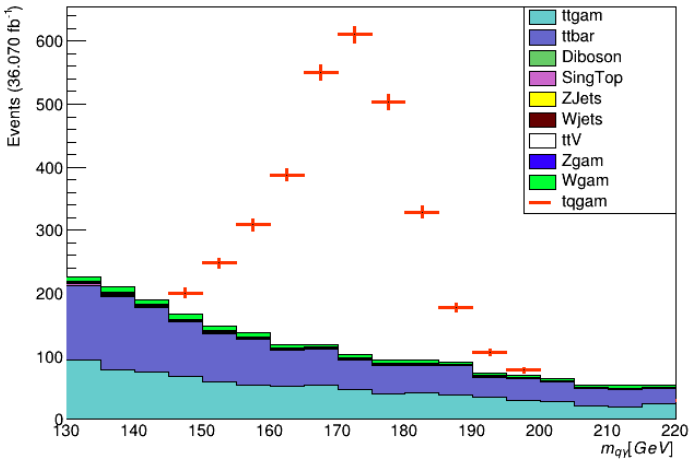
- Before Z-mass, Bjet cuts
- After Cuts

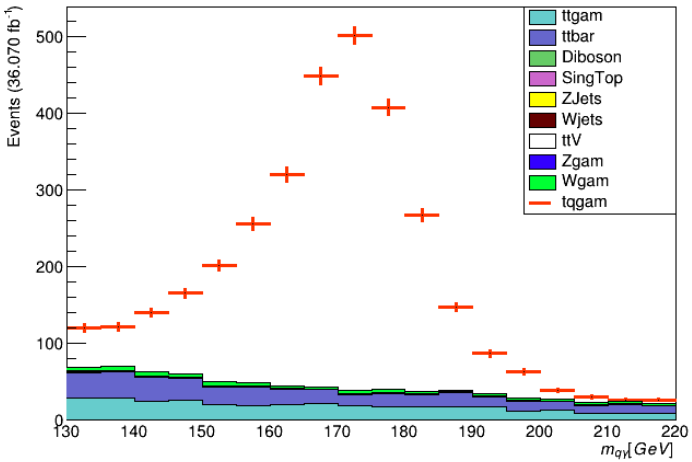
Electron Channel





Muon Channel





Outlook

- Many improvements can be made to the analysis
  - Investigation of χ^2 as a discriminating variable
  - Inclusion of isolation and spatial proximity cuts
- Monte Carlo distributions can be used to set an expected limit on the Branching Ratio

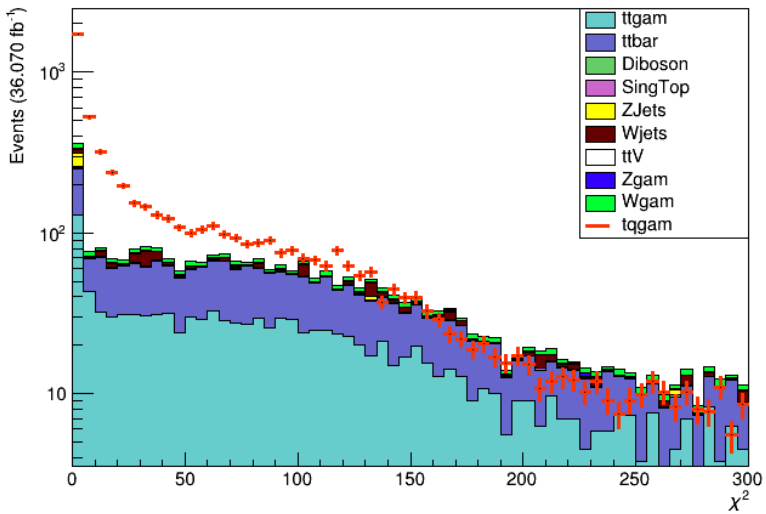


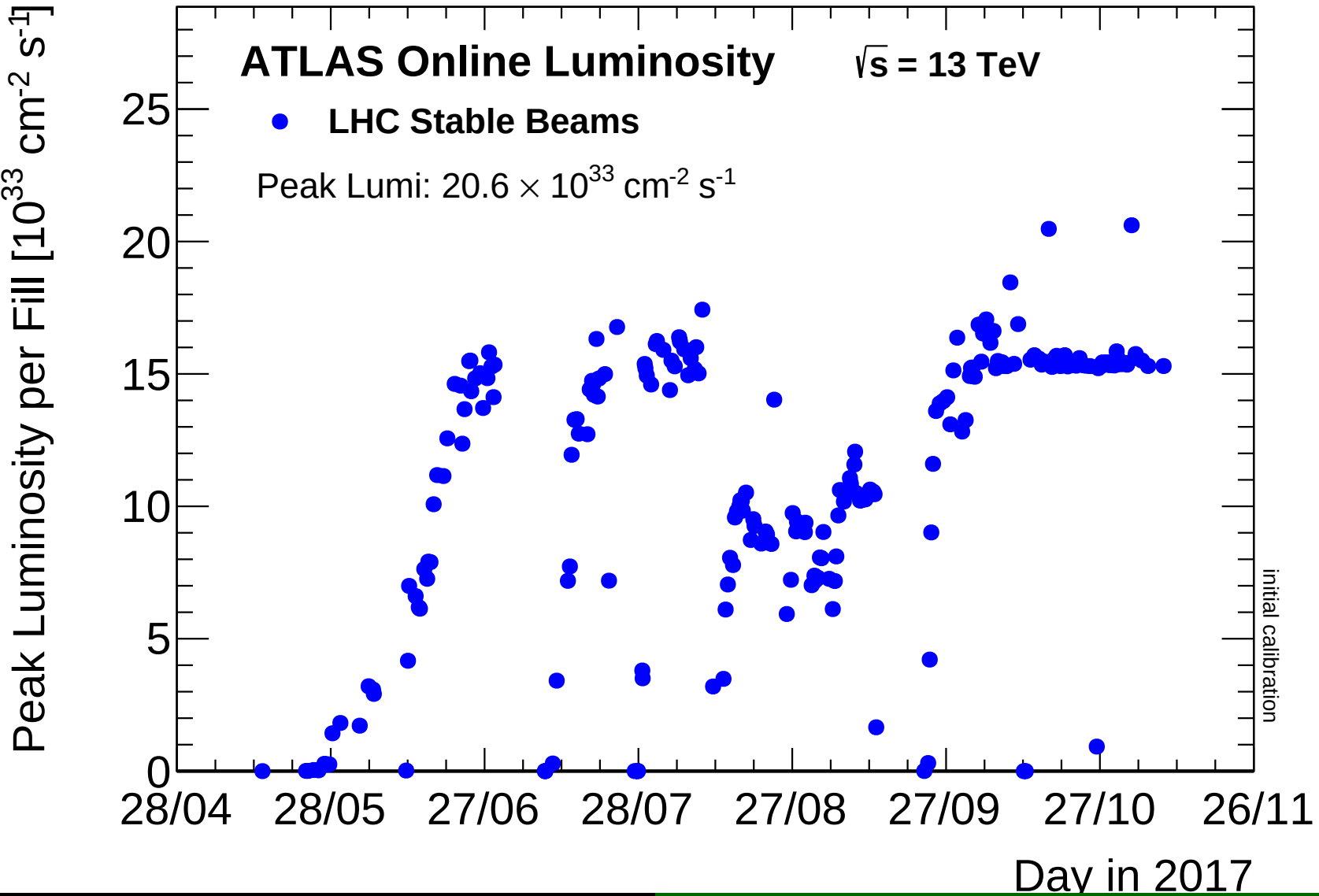
Figure: e-channel χ^2 after Z, Bjet cuts

Conclusion

- An excess signal would be indicative of some physics beyond the Standard Mode that couples strongly to the top sector
- The search for FCNCs with enhanced rates are important pieces of testing many new theories
- The LHC continues to produce copious data to look though for these events!
- Barring any excess: with $\approx 150\text{fb}^{-1}$ data at $\sqrt{s} = 13\text{TeV}$ setting an upper limit of $\text{BR}(t \to q\gamma) < 3x10^{-5}$ is a reasonable goal, extrapolating from past results.

Backup

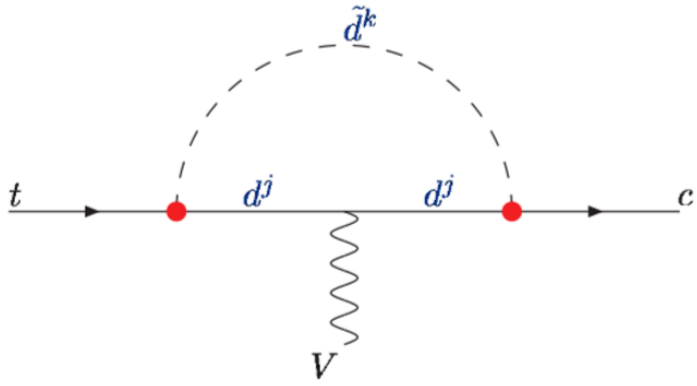
Integrated Luminosity



A Couple BSM Diagrams

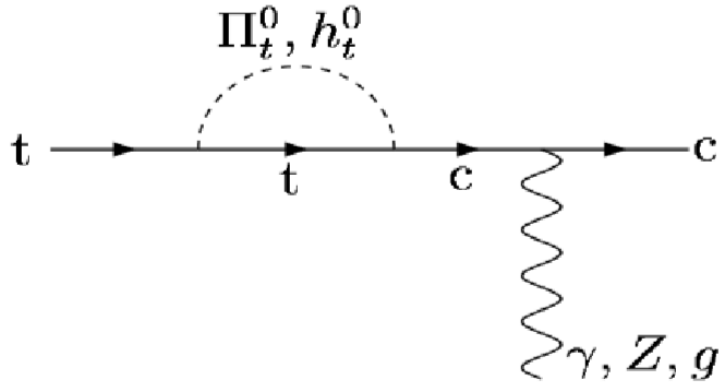
- R-parity-violating supersymmetric models

  [arXiv:hep-ph/9705341]



- Top-color-assisted technicolor models

  [arXiv:hep-ph/0303122]



Jets/AntiKT

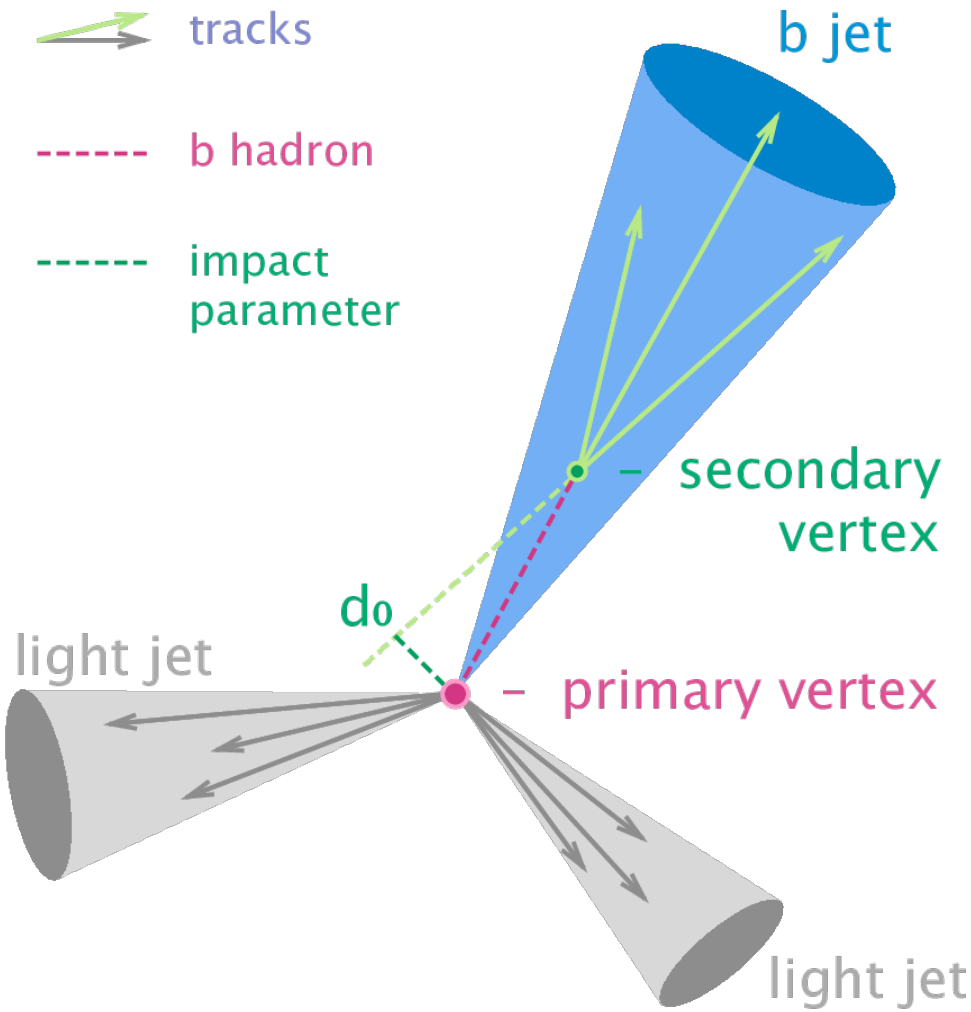
$$d_{ij} = min(\frac{1}{p_{ti}^2}, \frac{1}{p_{tj}^2})\frac{\Delta_{ij}^2}{R^2}$$

$$d_{iB} = \frac{1}{p_{ti}^2}$$

$$\Delta_{ij}^2 = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2$$

- Find minimum of entire set of $\{d_{ij}, d_{iB}\}$
- If d_{ij} is the minimum particles i,j are combined into one particle and removed from the list of particles
- If d_{iB} is the minimum i is labelled as a final jet and removed from the list of particles
- Repeat until all particles are part of a jet with distance between jet axes Δ_{ij} is greater than R

B-tagging


tracks
b hadron
impact parameter
b jet
secondary vertex
d0
light jet
primary vertex
light jet

$$\mathcal{L}^{eff}_{tq\gamma} = -e\bar{c}\frac{i\sigma^{\mu\nu}q_\nu}{m_t}(\lambda^L_{ct}P_L + \lambda^R_{ct}P_R)tA_\mu + H.c.$$