Search for the Flavor-Changing Neutral Current in Top Decays at ATLAS

Elizabeth Brost

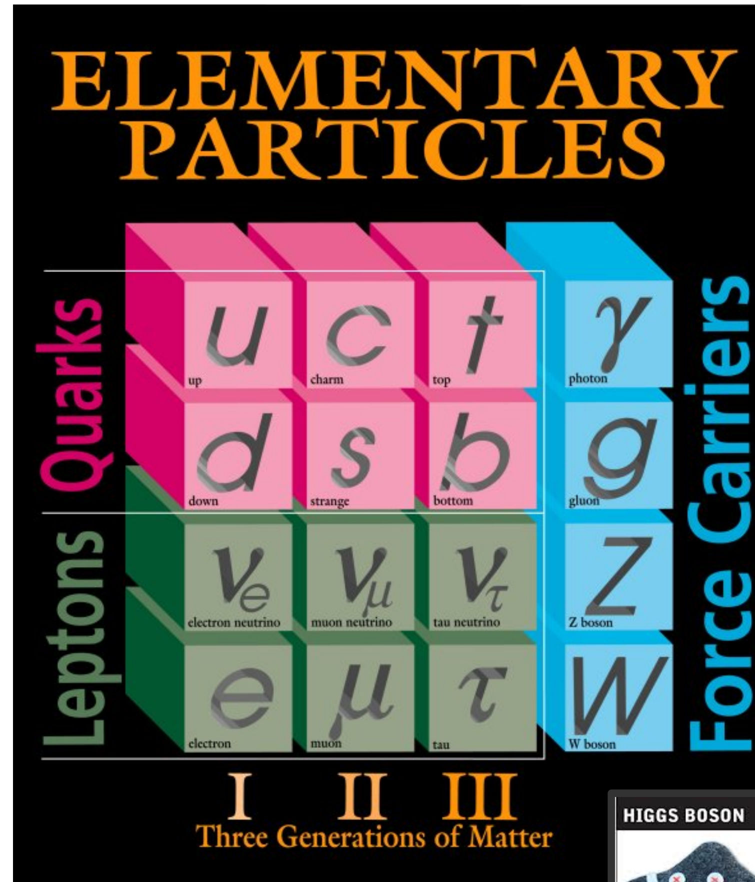
Comprehensive Exam
25 June 2013

Outline

- The Top Quark
- The ATLAS Experiment + the Large Hadron Collider
- Data & the ATLAS Trigger System in 2012
- Searching for Flavor-Changing Neutral Currents in Top Decays

The Standard Model

- Current front-runner in our ongoing effort to 'explain everything'
- Stands up well to nearly all experimental tests to date
- Brand-new addition this past summer!

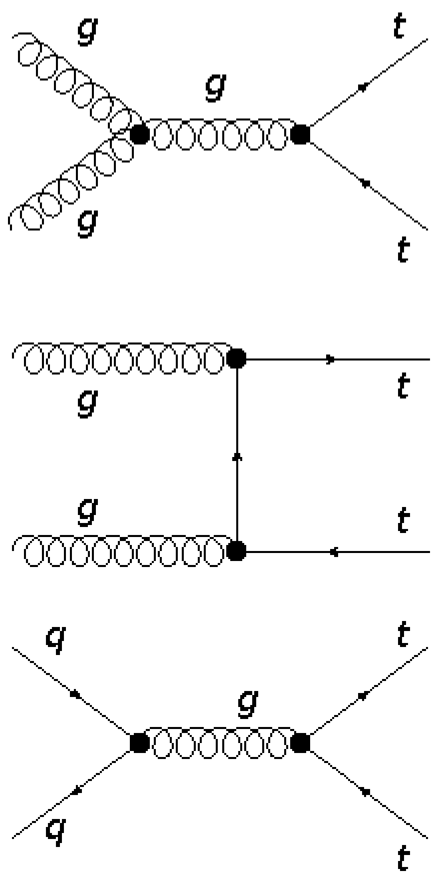


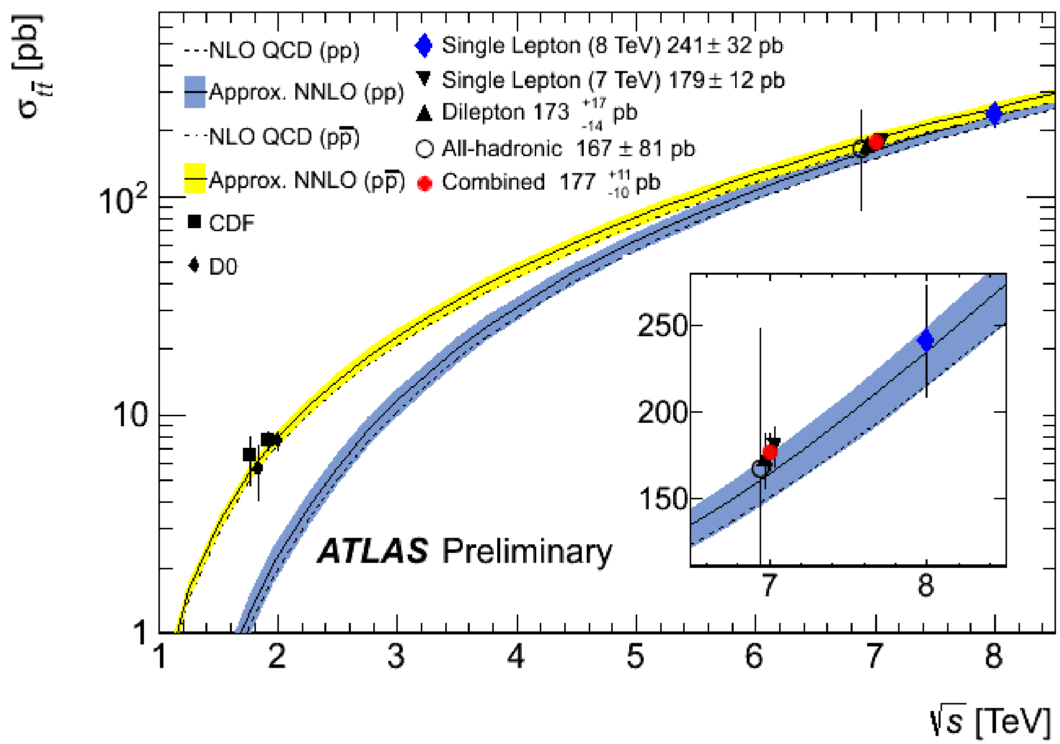
The Top Quark

- Heaviest fundamental particle (173.5 GeV/c^2 or 3.1*10^{-25} kg)
- Very short-lived (5*10^{-25} s)
- Cost per top quark: \$10.49 (at the Particle Zoo) or \$100* (at the LHC)

*many assumptions

Top Pair Production



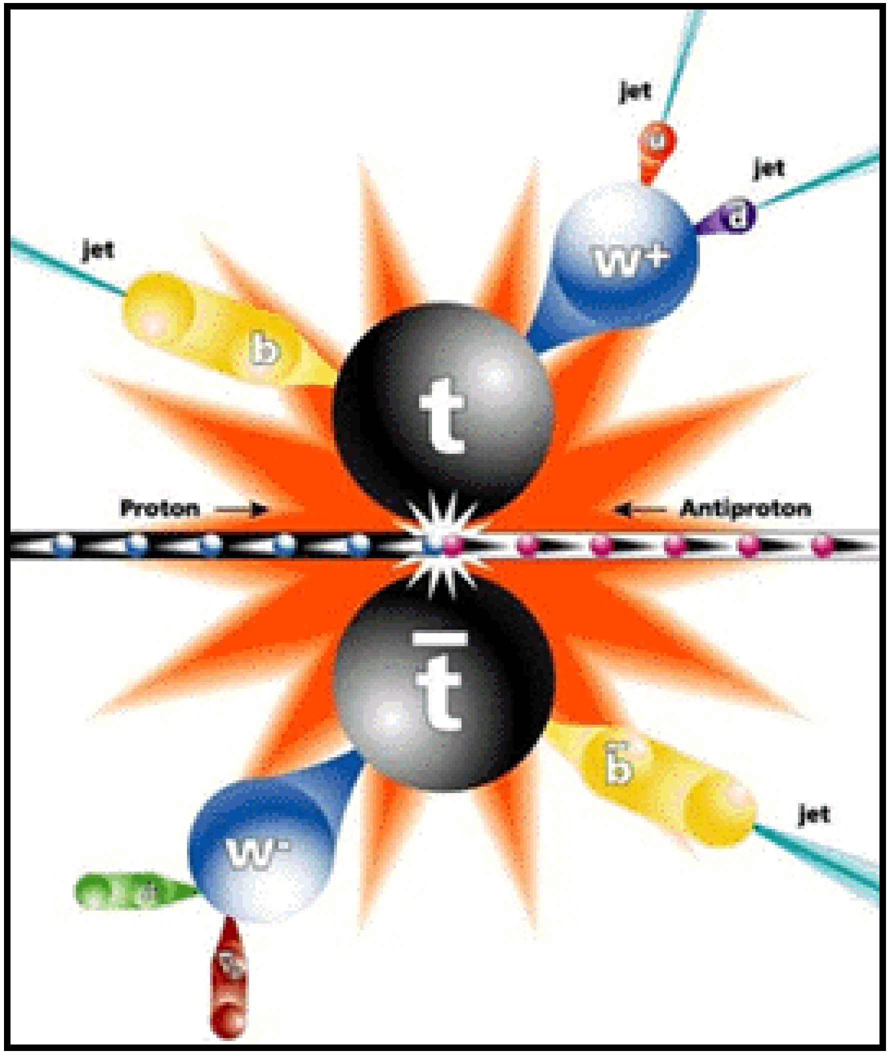


$\sigma_{t\bar{t}}$ = 241 pb @ 8TeV (ATLAS-CONF-2012-149)

Total top pairs in 2012 @ ATLAS: 241pb*22fb^{-1} ~ 5*10^{6}

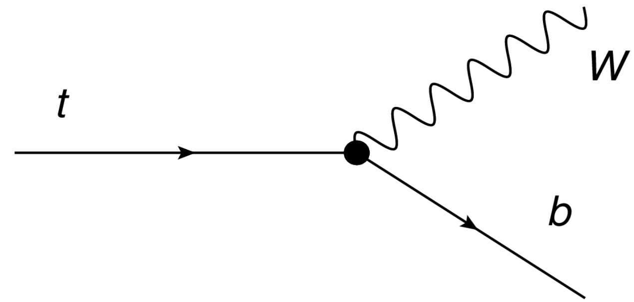
Top Quark Decays

- Top decays to Wb ~100% of the time
- … in the Standard Model.
- Observation of other decay modes would be indicative of new physics

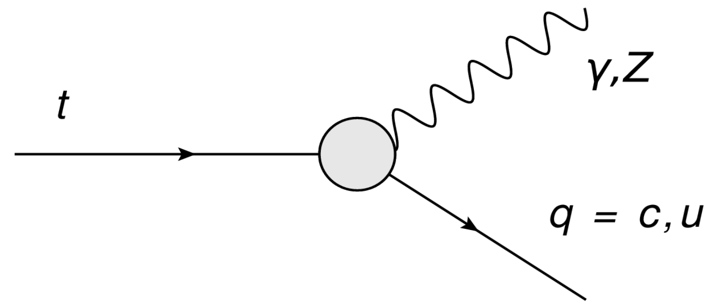


The Flavor-Changing Neutral Current

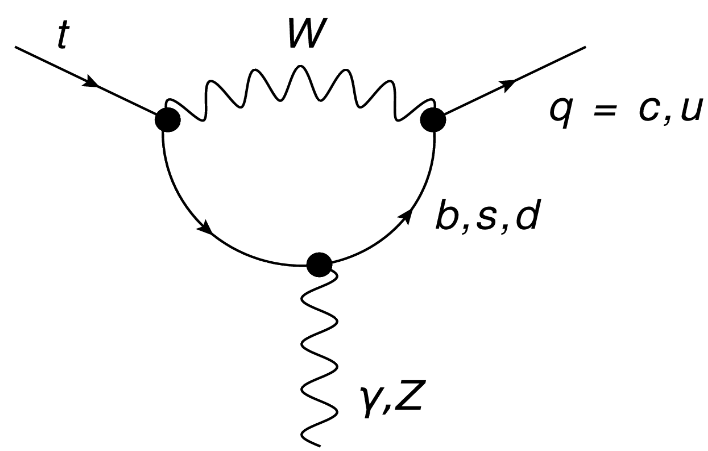
- Standard Model top decays: t → Wb



- No tree-level SM diagrams...



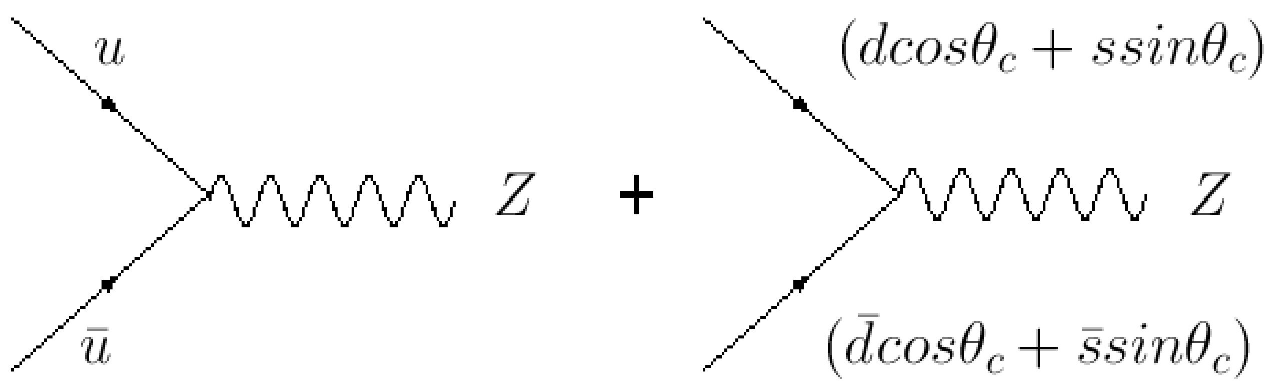
- FCNC Penguin diagram



The GIM mechanism

- Mechanism through which FCNC are naturally suppressed (proposed in 1970 by Sheldon Lee Glashow, John Iliopoulos, and Luciano Maiani)
- Weak neutral currents in the uds quark model SHOULD look like:

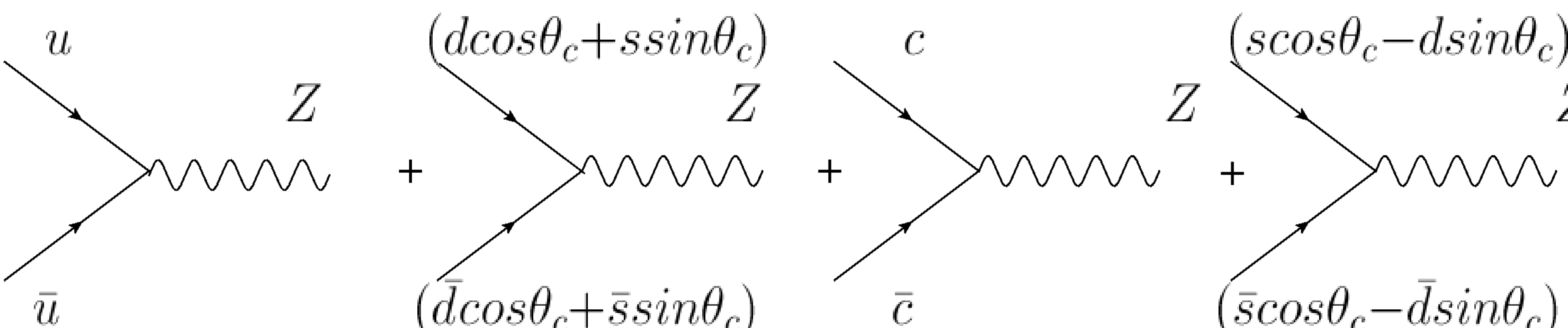
$$\underbrace{u\bar{u} + (d\bar{d}cos^2\theta_c + s\bar{s}sin^2\theta_c)}_{\Delta S = 0} + \underbrace{(s\bar{d} + d\bar{s})sin\theta_c cos\theta_c}_{\Delta S = 1}$$



The GIM mechanism, 2

- With the addition of the charm quark (proposed by GIM), there are no longer any strangeness-changing weak neutral currents
- Weak neutral currents now look like:

$$\underbrace{u\bar{u} + c\bar{c} + (d\bar{d} + s\bar{s})cos^2\theta_c + (s\bar{s} + d\bar{d})sin^2\theta_c)}_{\Delta S = 0} + \cancel{\underbrace{(s\bar{d} + d\bar{s} - s\bar{d} - d\bar{s})sin\theta_c cos\theta_c}_{\Delta S = 1}}$$



Top FCNC

Theoretical Predictions:

Process	SM	QS	2HDM	MSSM	$\not{R}$ SUSY
$t \to uZ$	8×10^{-17}	1.1×10^{-4}	—	2×10^{-6}	3×10^{-5}
$t \to u\gamma$	3.7×10^{-16}	7.5×10^{-9}	—	2×10^{-6}	1×10^{-6}
$t \to ug$	3.7×10^{-14}	1.5×10^{-7}	—	8×10^{-5}	2×10^{-4}
$t \to cZ$	1×10^{-14}	1.1×10^{-4}	$\sim 10^{-7}$	2×10^{-6}	3×10^{-5}
$t \to c\gamma$	4.6×10^{-14}	7.5×10^{-9}	$\sim 10^{-6}$	2×10^{-6}	1×10^{-6}
$t \to cg$	4.6×10^{-12}	1.5×10^{-7}	$\sim 10^{-4}$	8×10^{-5}	2×10^{-4}

Current best experimental limits:

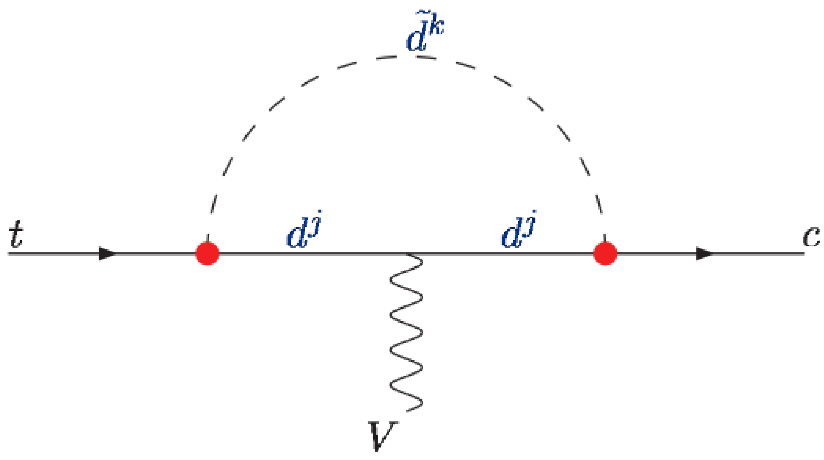
- BR($t \to Zq$) < 0.07% (CMS 2013)
- BR($t \to \gamma q$) < 0.46% (ZEUS 2011)

room for improvement!

Theoretical Examples

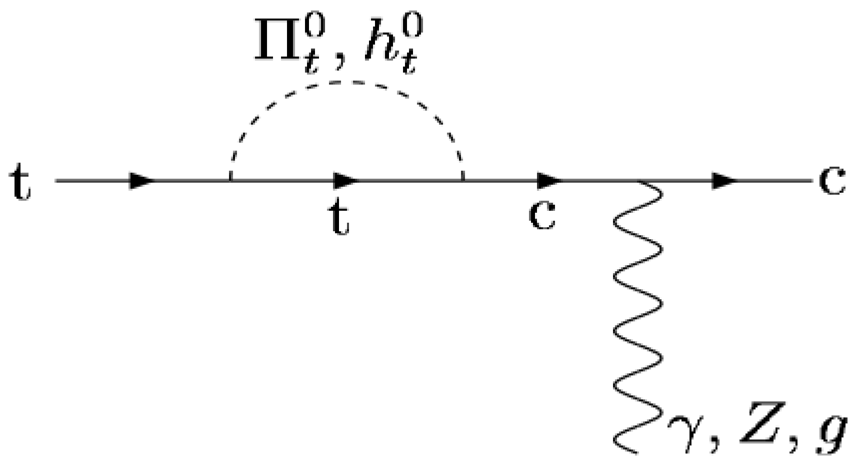
- R-parity-violating supersymmetric models

  [arXiv:hep-ph/9705341]



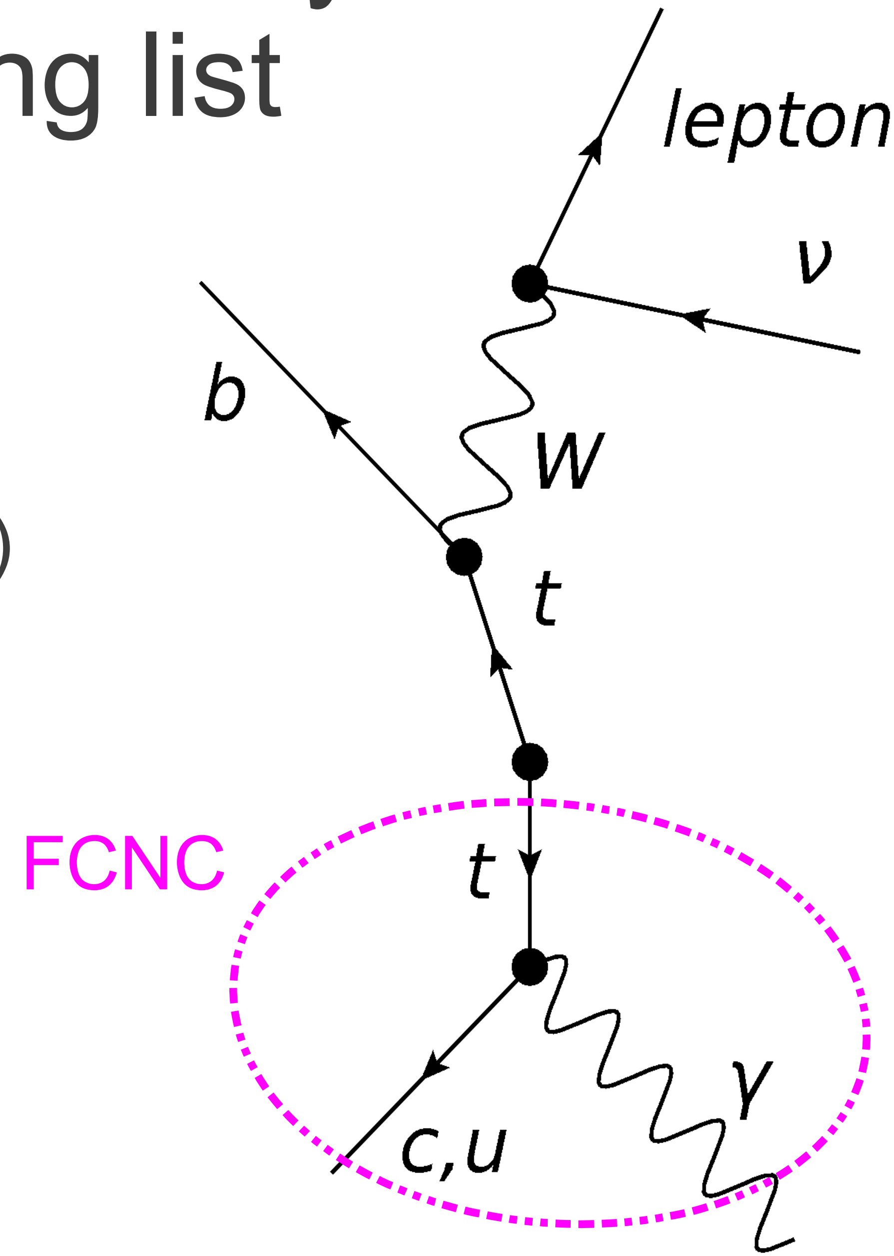
- Top-color-assisted technicolor models

  [arXiv:hep-ph/0303122]



FCNC in Top Decays: a shopping list

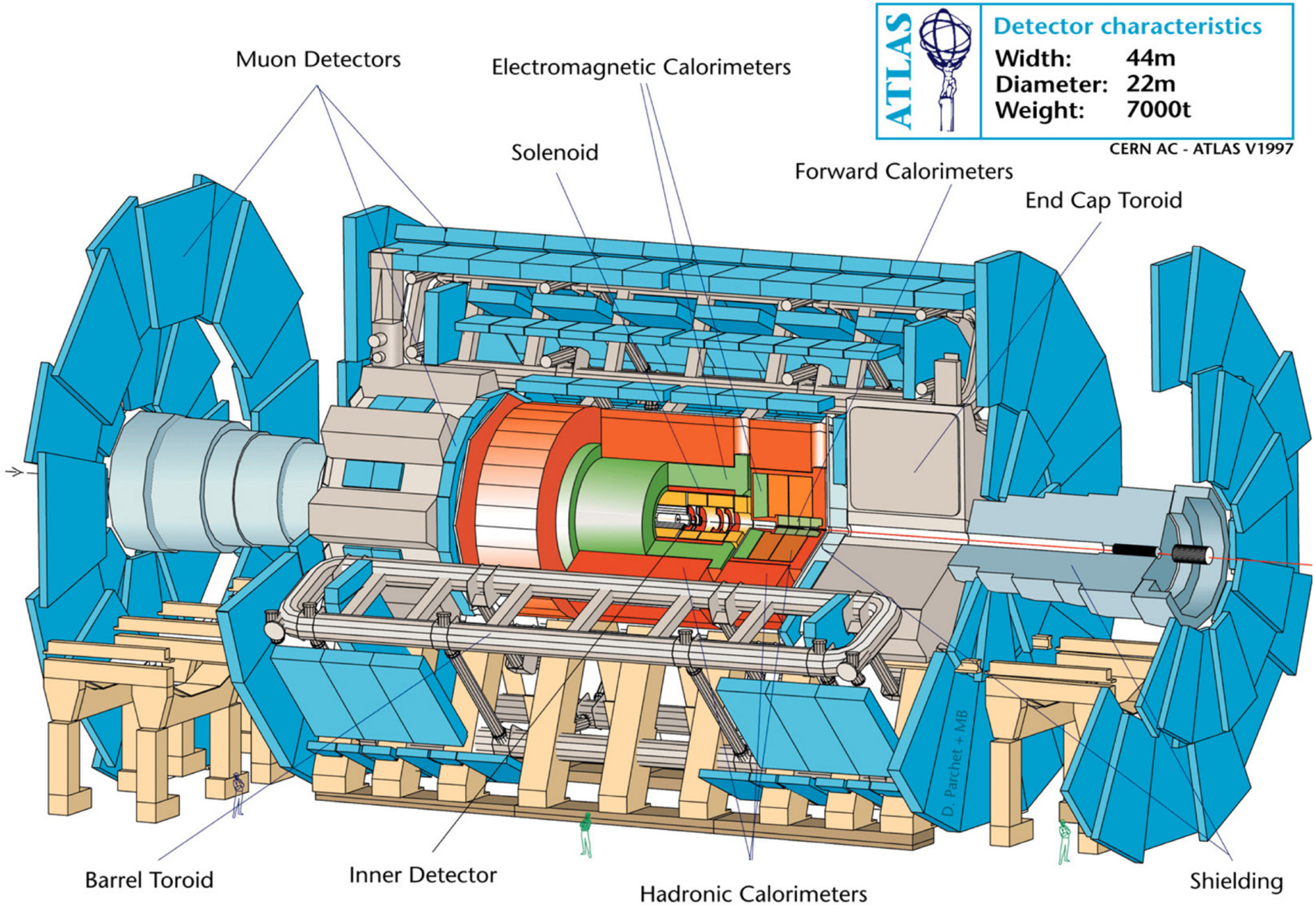
- $t\bar{t} \rightarrow Wb + q\gamma$
  - One photon
  - One jet (from c or u quark)
  - Another jet (from b quark)
  - One lepton (e or μ)
  - One neutrino



The Large Hadron Collider

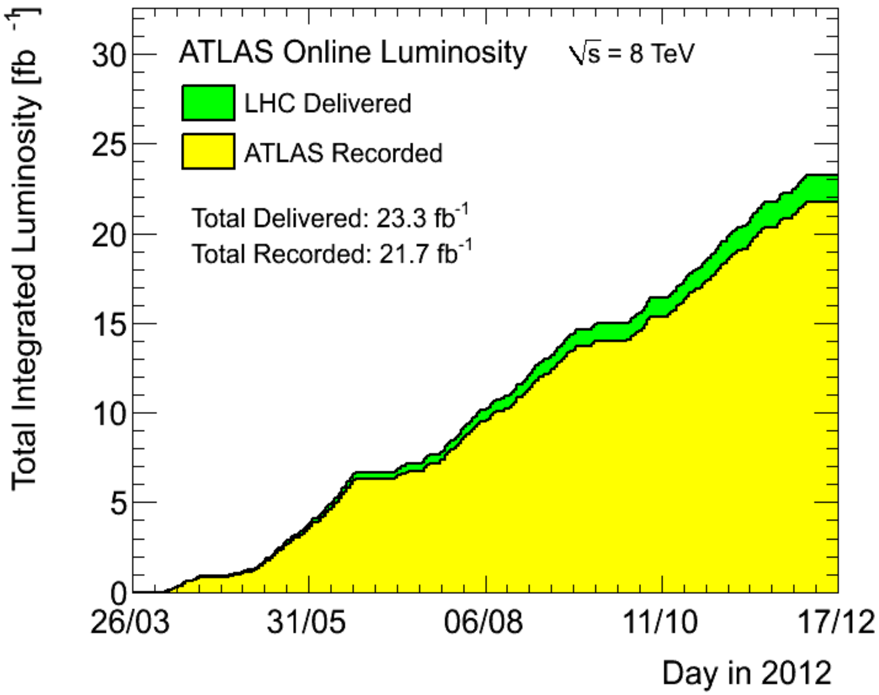
- ~27 km + 4 experiments
- Proton-proton collisions
- CM energy: 8TeV (w/ upgrade to 14TeV shortly)

The ATLAS detector

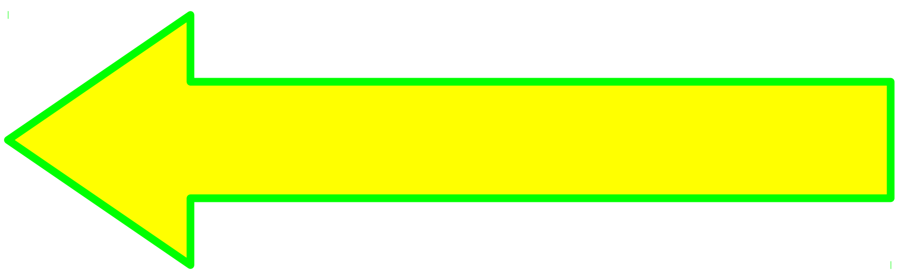


ATLAS Data in 2012

- A unique problem in high-energy particle physics: too much data ?
- ATLAS collected L ~ 22fb^{-1} in 2012



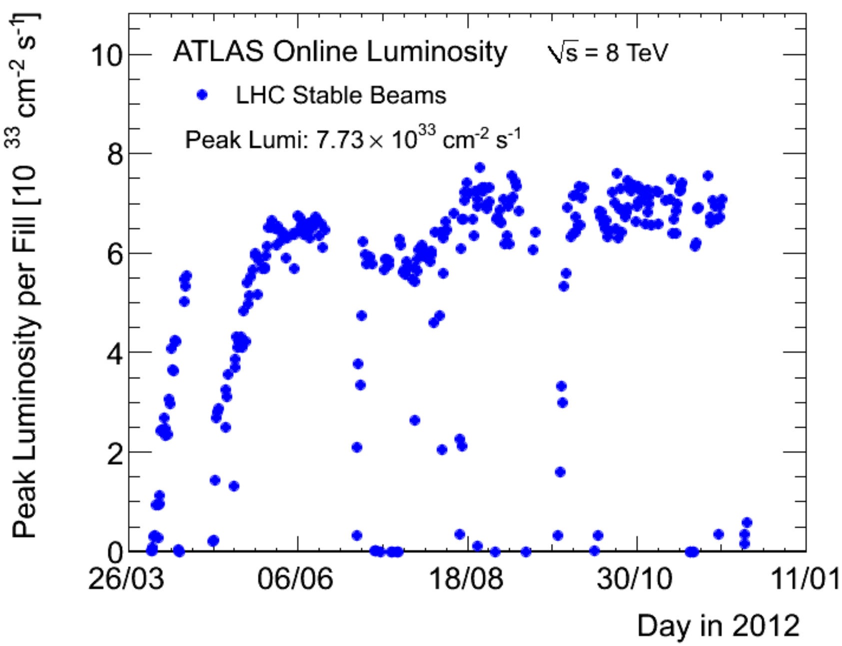
… but what does that mean ?



What is “Integrated Luminosity”?

Instantaneous Luminosity: ~ $7*10^{33}$ $cm^{-2}s^{-1}$

(# of particles / area and time)



So INTEGRATED luminosity (L) is measured in units of 1/area

(we usually express that area in barns –
1 barn = 10^{-24} cm^2)

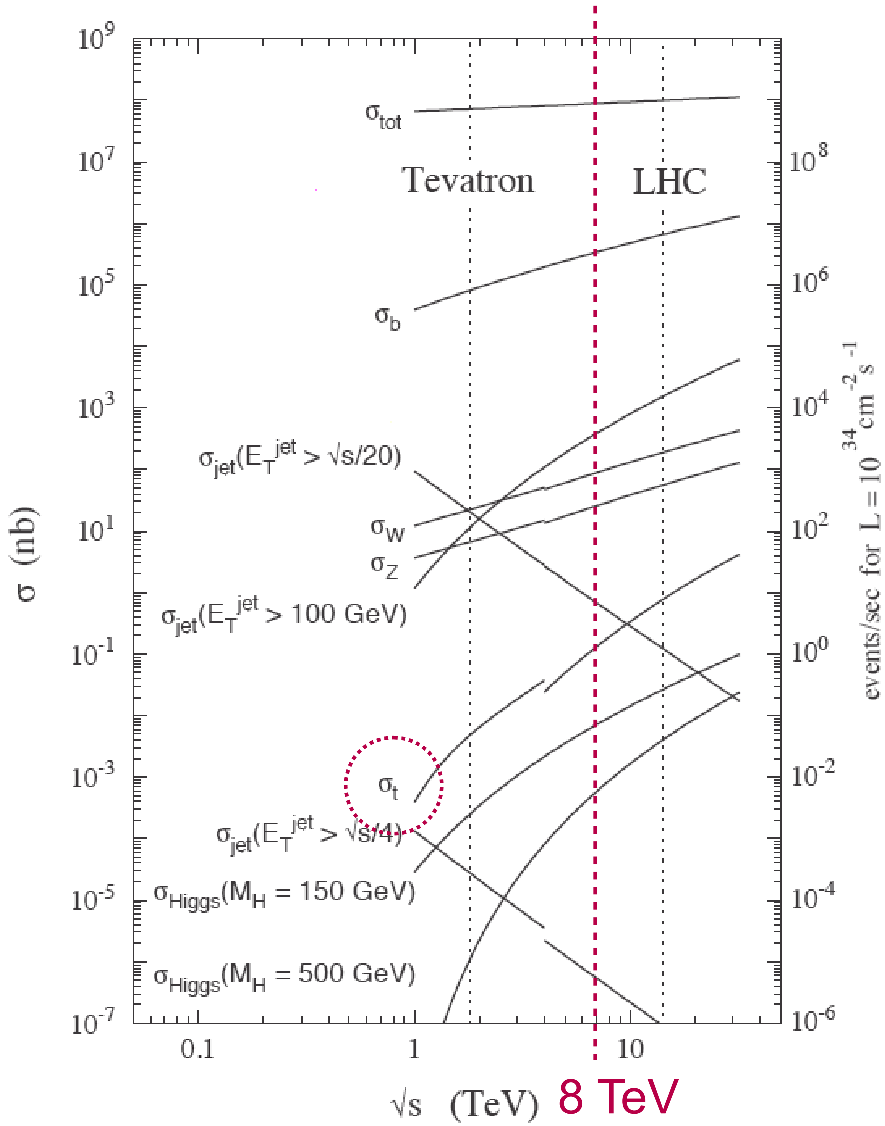
What is in all that data ?

- For each process, the number of particles produced $N = \sigma L$
- A process with cross section 240pb would happen

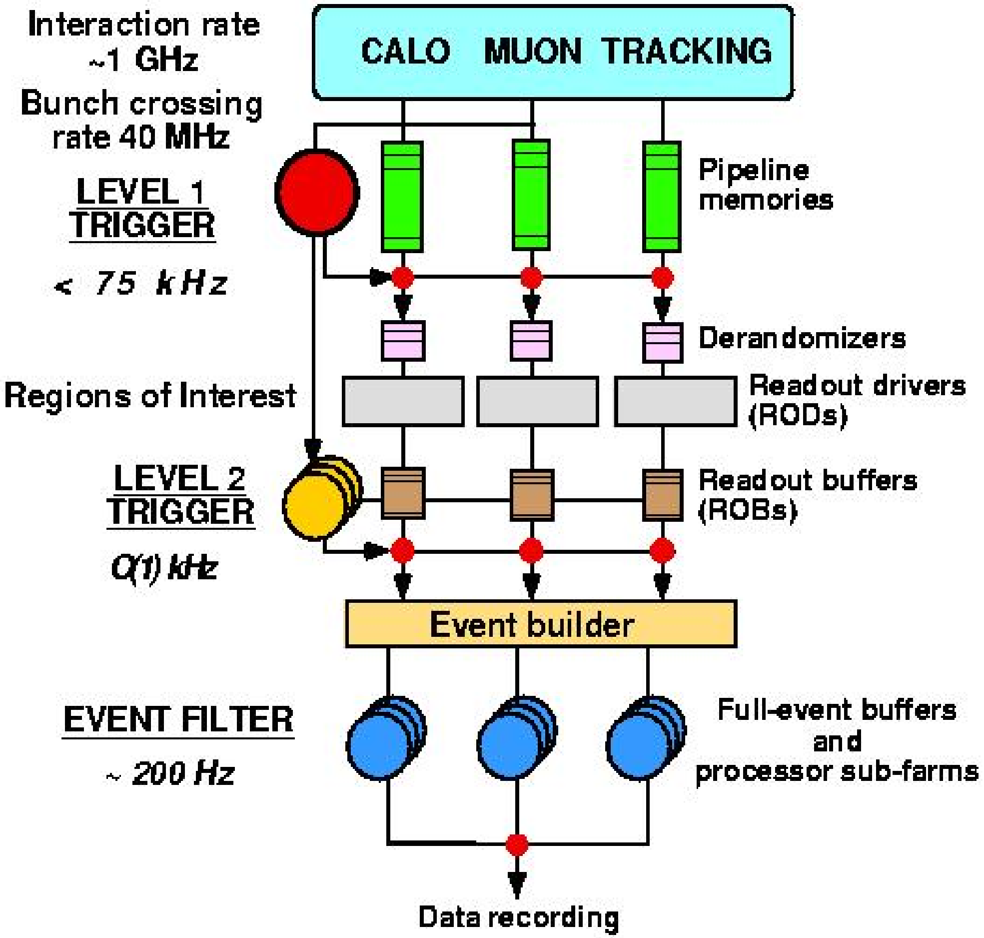
  $N = 240\text{pb} * 22\text{fb}^{-1}$
  $= \sim 5.3$ million times in 2012 at the LHC

- The total cross section (σ_{tot}) corresponds to $10^{8}\text{nb} * 22\text{fb}^{-1}$

  $= 2*10^{15}$ events



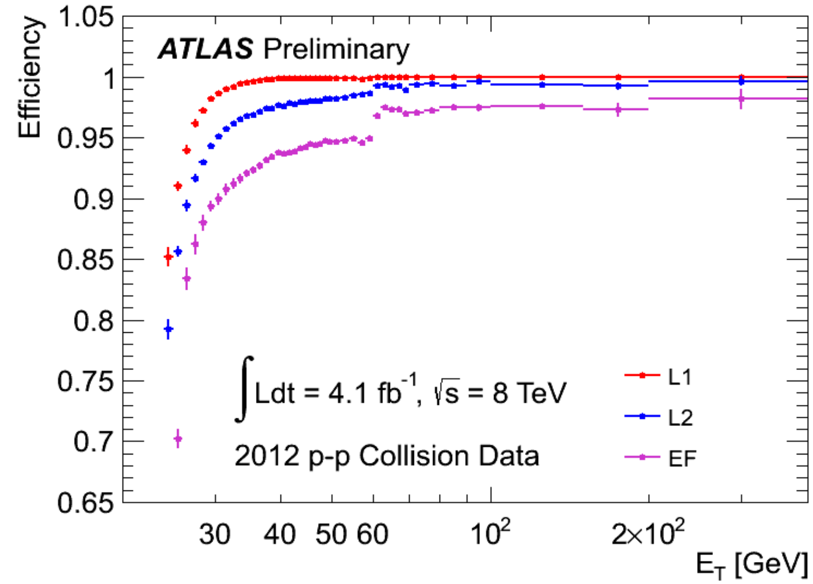
ATLAS Trigger System

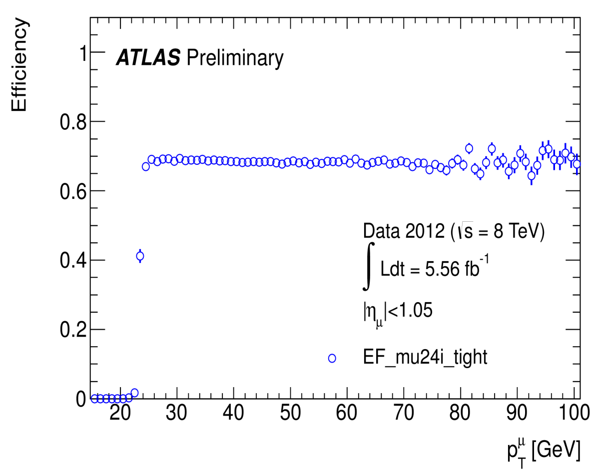


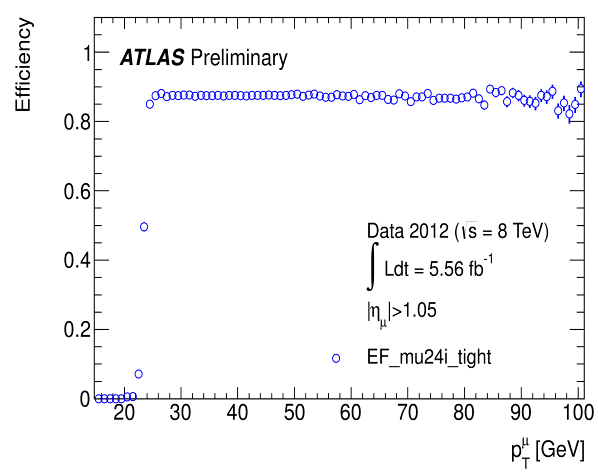
- Use event topology to save “interesting” events
- Reduce from interaction rate (~GHz) to the number of events we are able to write (~400Hz)

Lepton Triggers

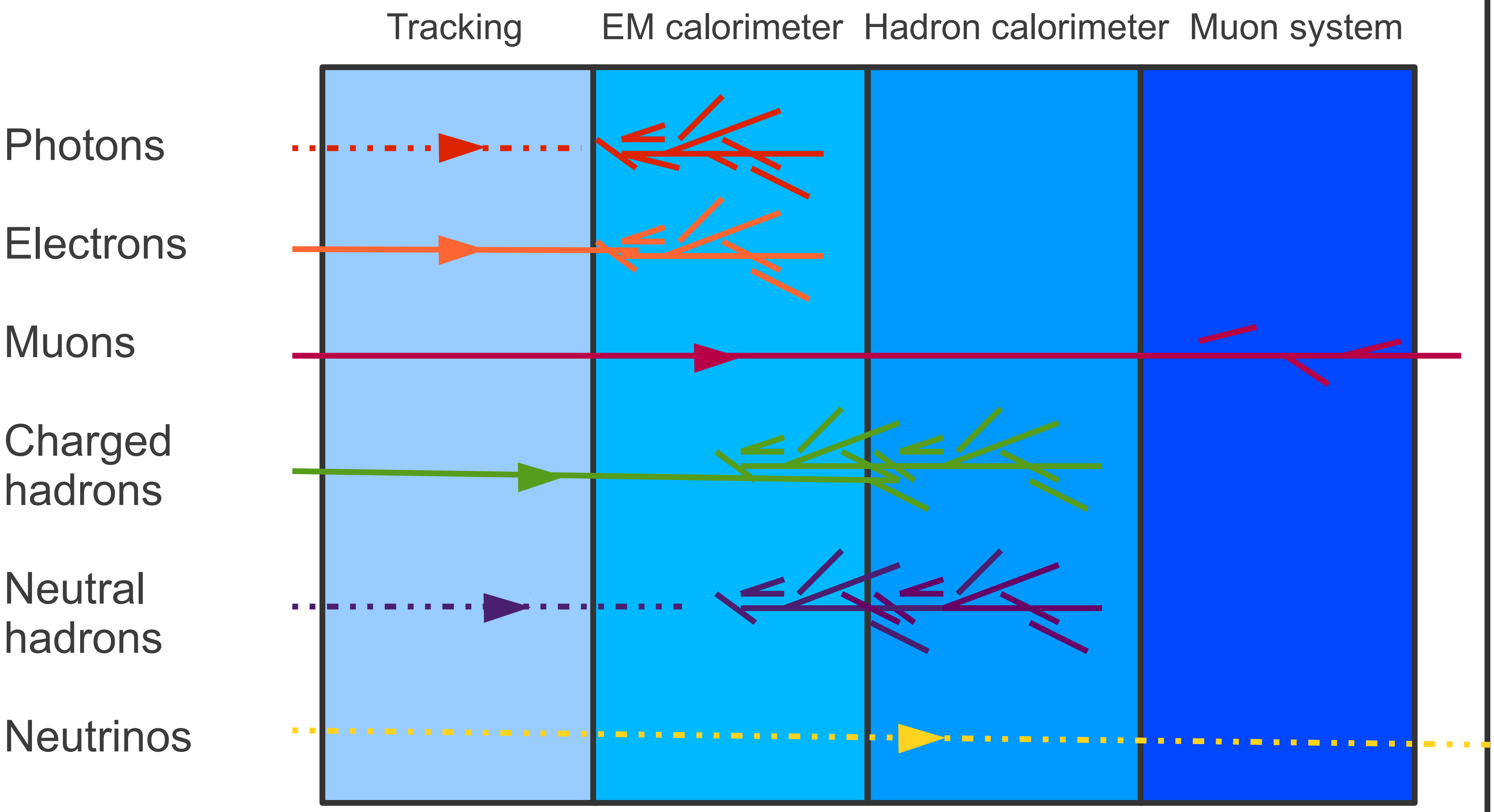
- Electron triggers: EF_e24vhi_medium1, EF_e60_medium1
- Muon triggers: EF_mu24i_tight, EF_mu36_tight



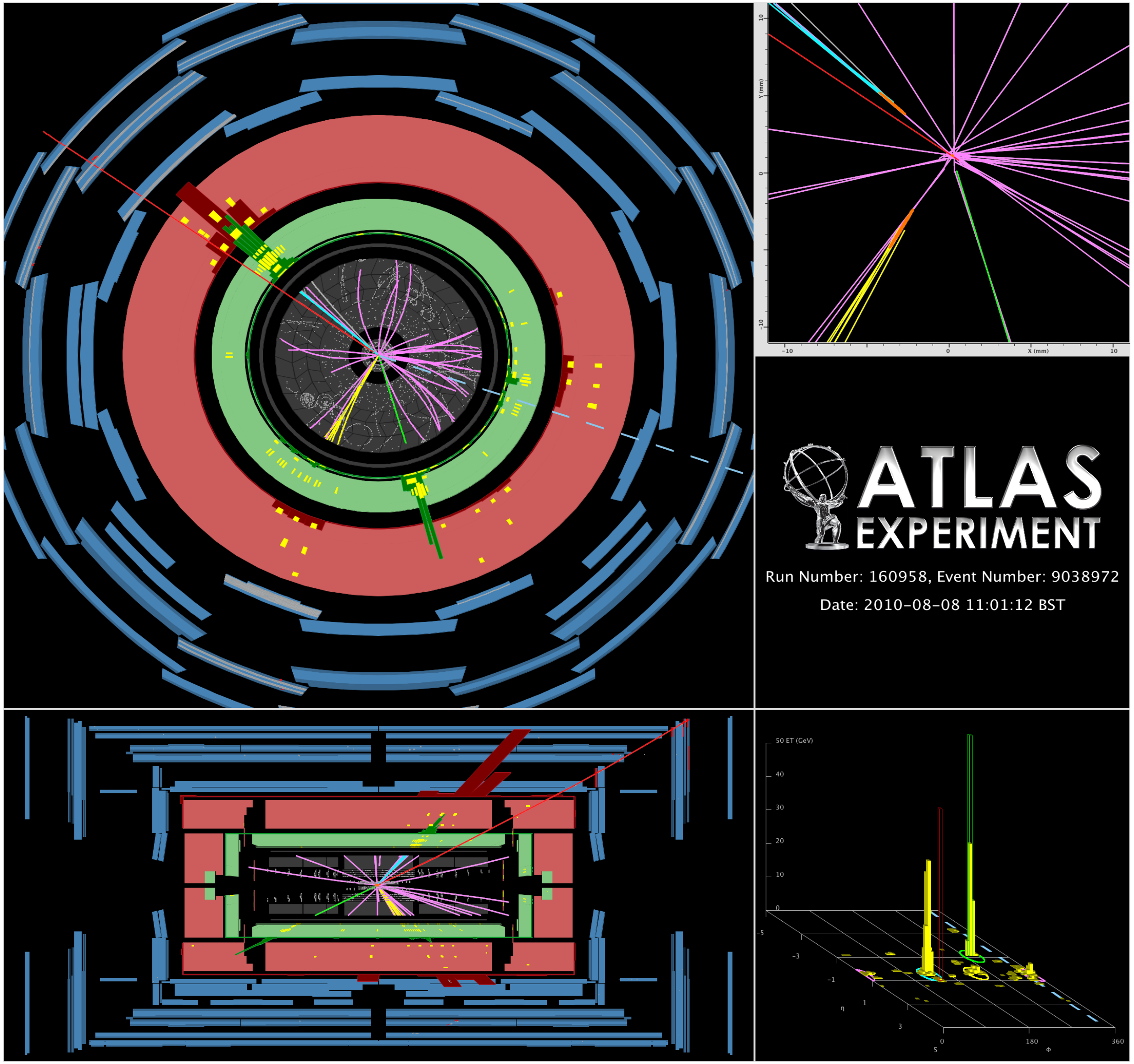




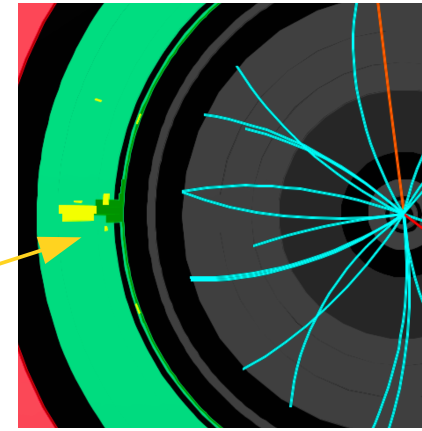
Particles in the ATLAS Detector



Event Display ($t\bar{t}$ candidate event)

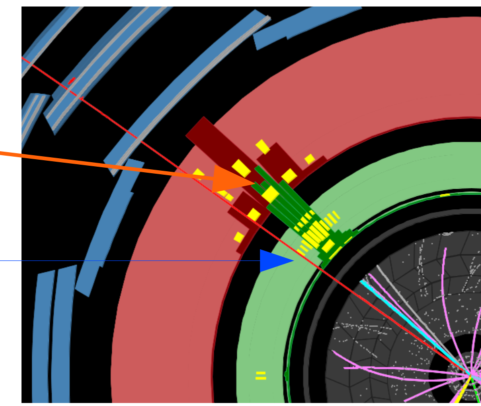


FCNC in Top Decays - Initial Selection

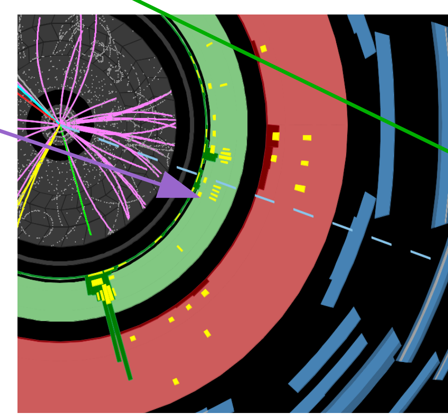


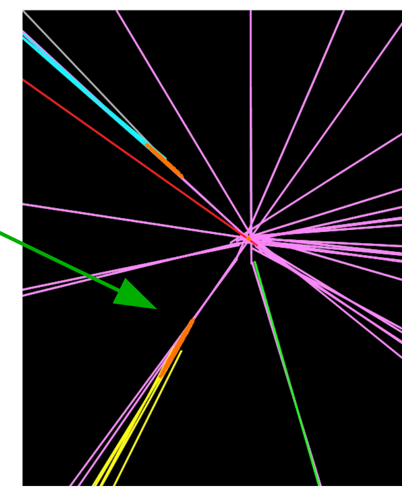
$$t\bar{t} \rightarrow Wb + q\gamma \rightarrow l\nu j + j\gamma$$

- At least one photon
- At least two jets (p_T > 25GeV)

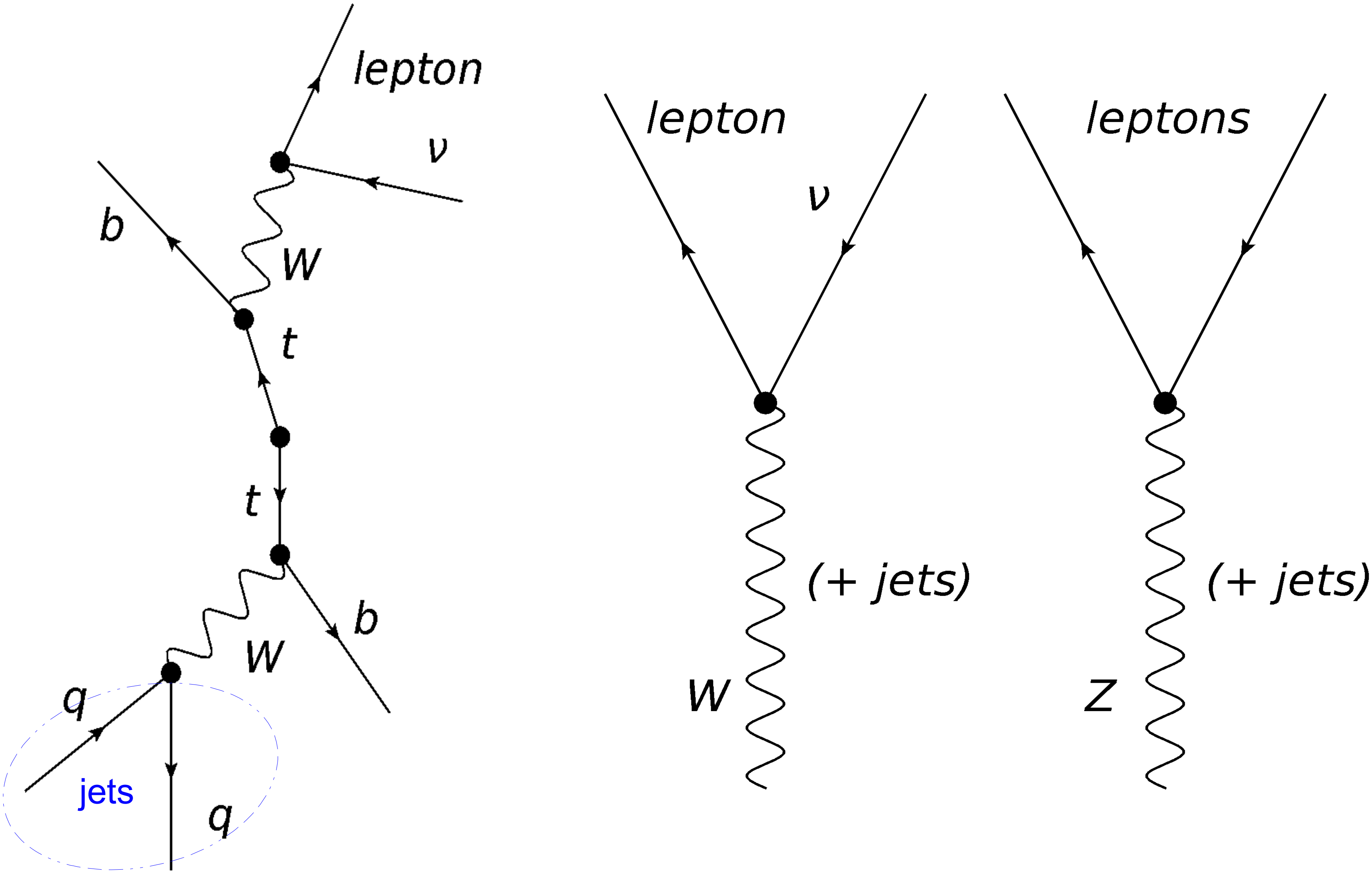


- One lepton (e or μ) (p_T > 25GeV)
- At least one b-tagged jet
- Missing transverse energy (> 25GeV)



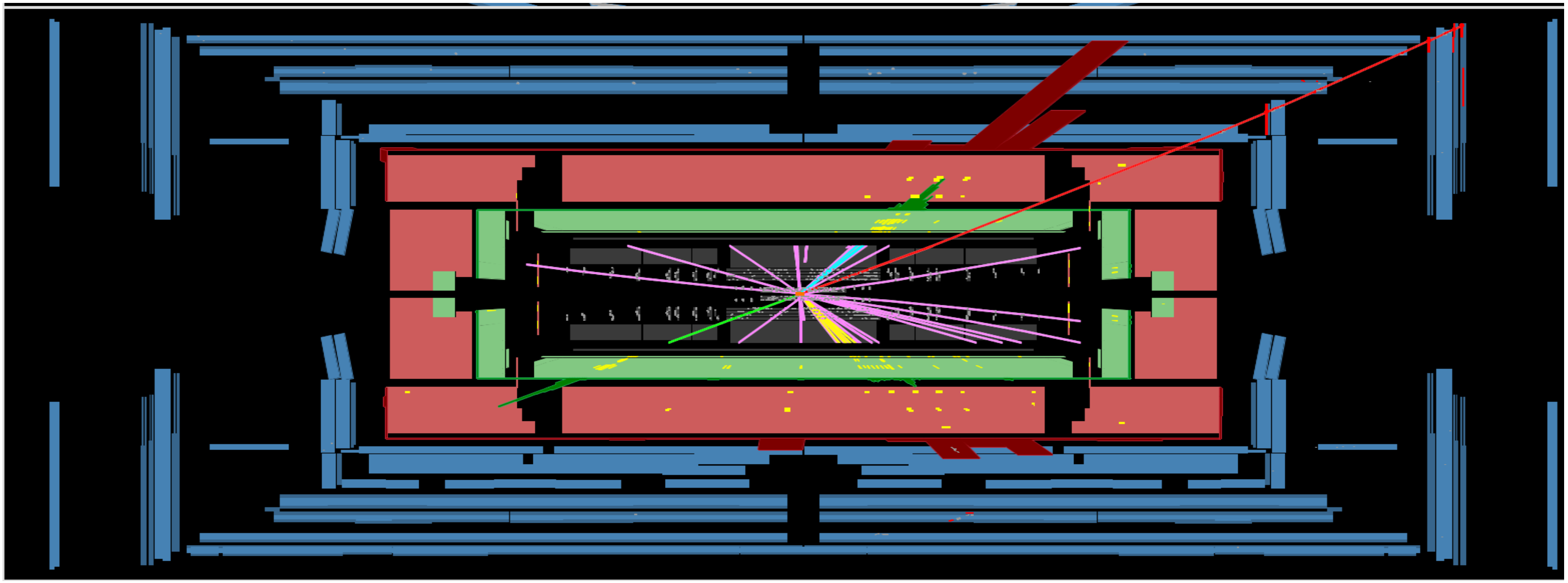


Background Processes



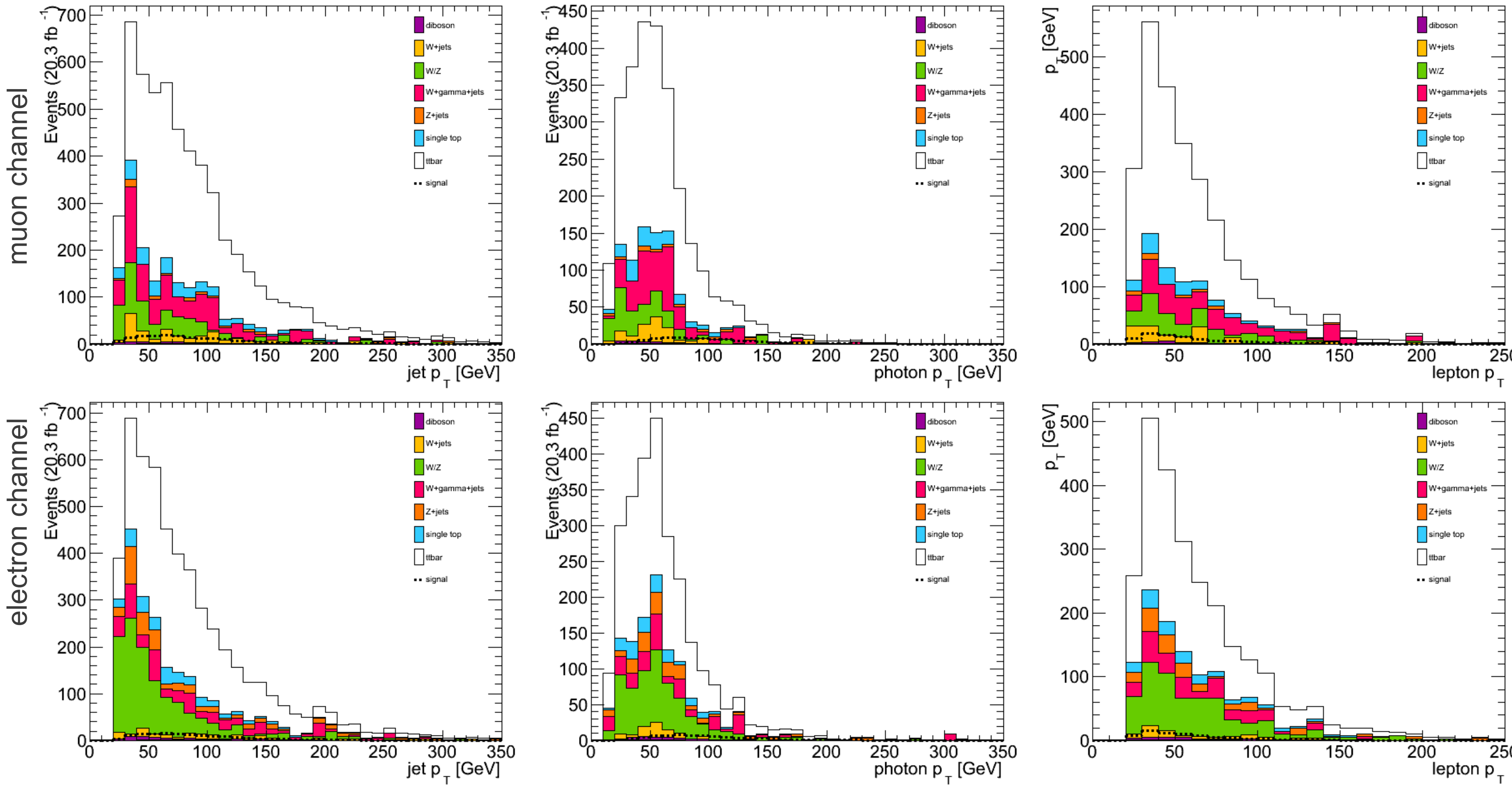
FCNC in $t\bar{t}$ Events - Final Selection

- Photon energy > 50GeV
- Exactly one b-jet (suppress SM $t\bar{t}$ background)
- 'Z' mass cut (suppress Z background)

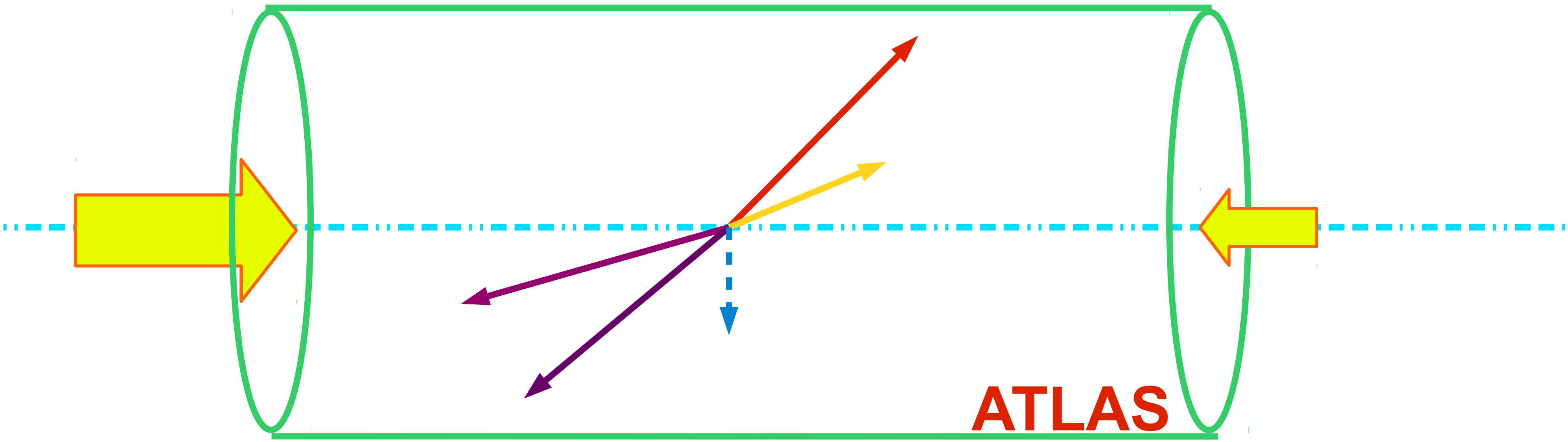


Initial Object Selection

Jets | Photon | Lepton



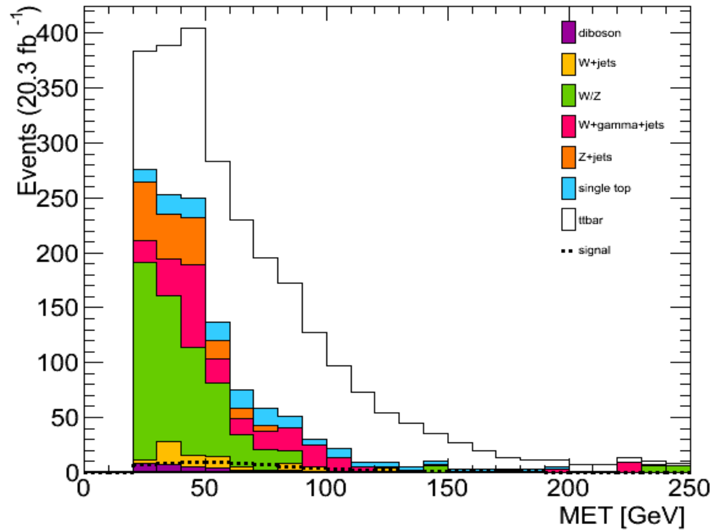
So where are the top quarks ?



- MET – balance the event energy in transverse plane
- We can “reconstruct” the original particles using vector addition!
  - (photon + jet = FCNC top)
  - (b-jet + lepton + neutrino = SM top)

How to 'reconstruct' the neutrino?

- We have: MET



- We need:

  z-component of neutrino momentum

$$p_{z\nu} = \frac{p_{z\ell}(p_{x\ell}p_{x\nu} + p_{y\ell}p_{y\nu} + \frac{m_W^2}{2}) \pm E_\ell\sqrt{(p_{x\ell}p_{x\nu} + p_{y\ell}p_{y\nu} + \frac{m_W^2}{2})^2 - E_{T\nu}^2(E_\ell^2 - p_{z\ell}^2)}}{E_\ell^2 - p_{z\ell}^2}$$

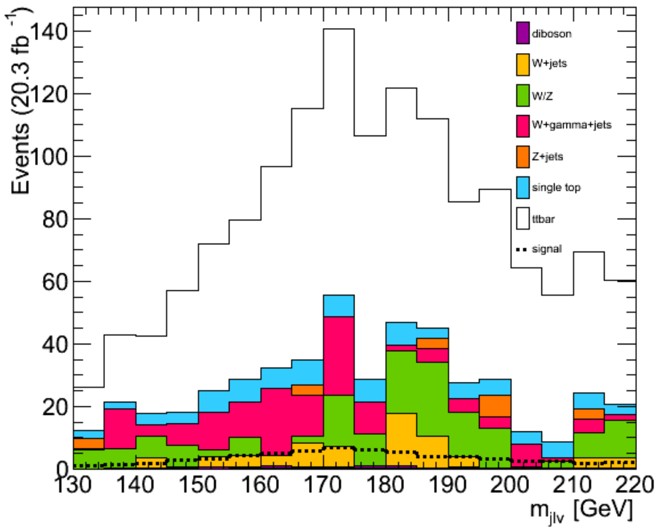
Choose $p_{z\nu}$ that minimizes this χ^2:

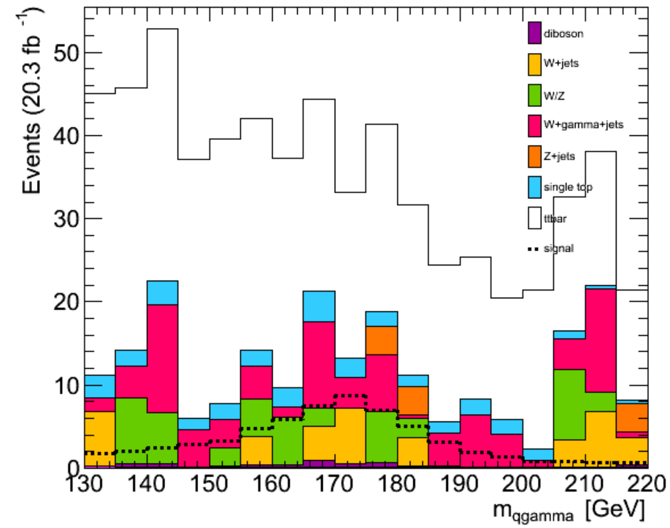
$$\chi^2 = \frac{(m_{jet_{light}\gamma} - m_t)^2}{\sigma_t^2} + \frac{(m_{jet_b\ell\nu} - m_t)^2}{\sigma_t^2} + \frac{(m_{\ell\nu} - m_W)^2}{\sigma_W^2}$$

Reconstructed Top Mass (before b-jet requirement)

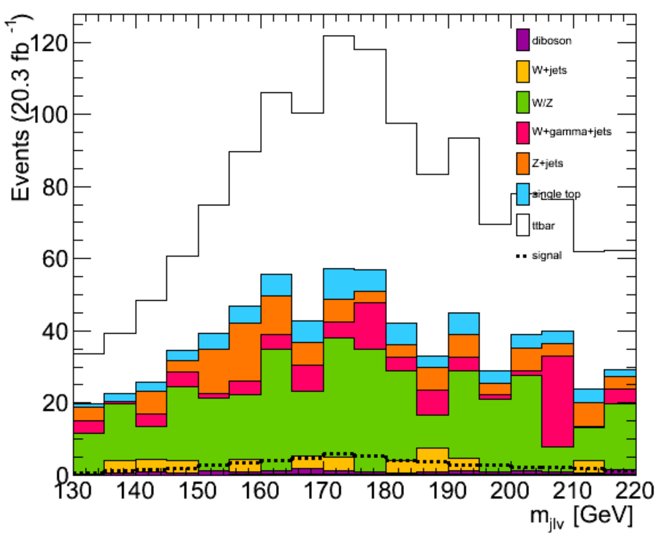
SM top mass | FCNC top mass

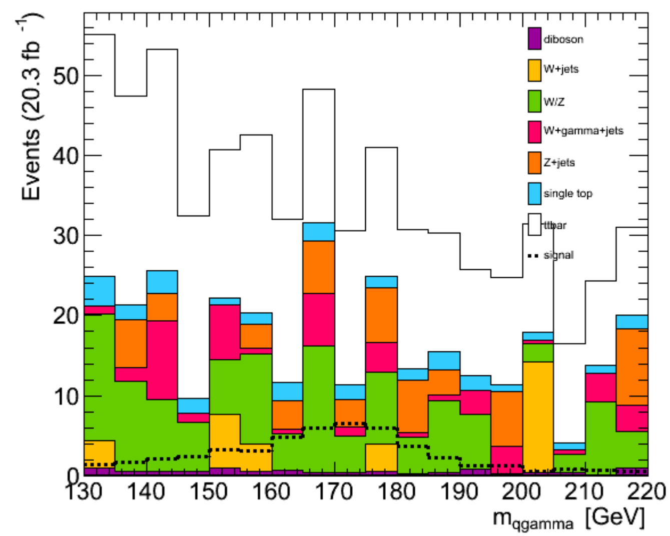
muon channel





electron channel





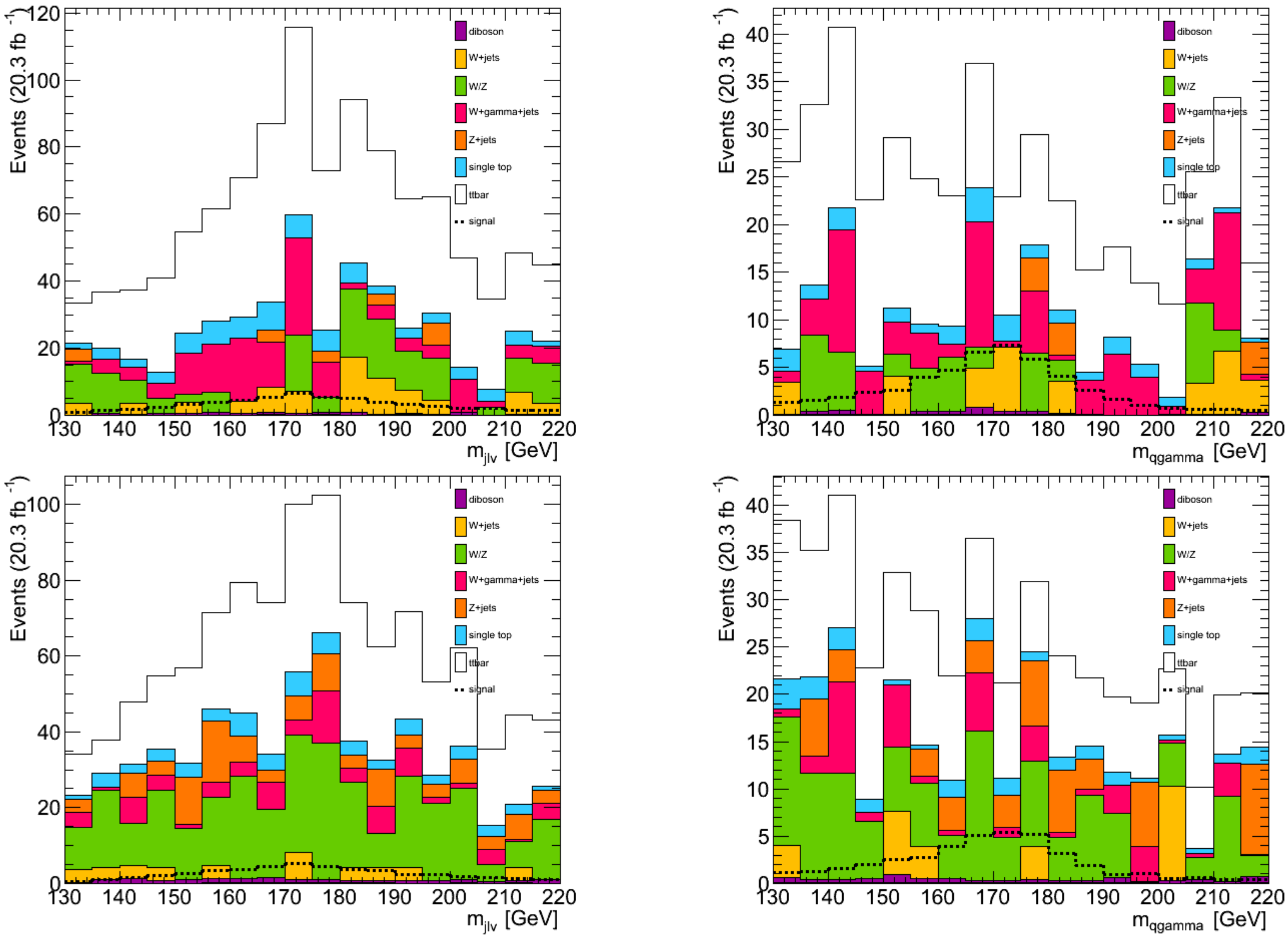
Reconstructed Top Mass (after b-jet requirement)

SM top mass

FCNC top mass

muon channel

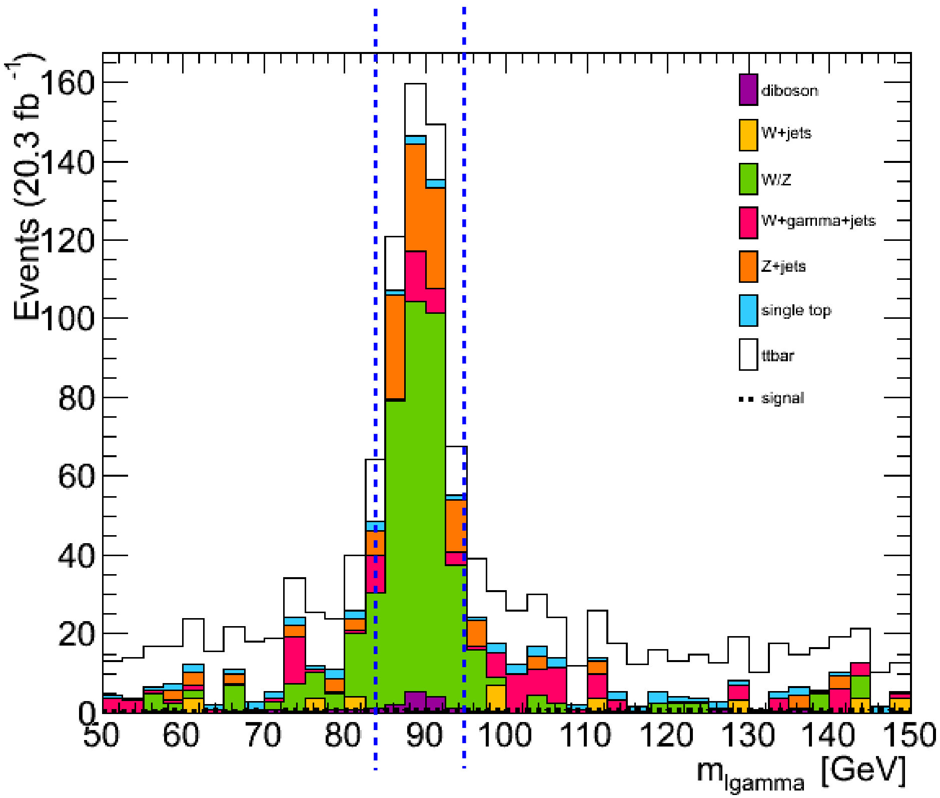
electron channel



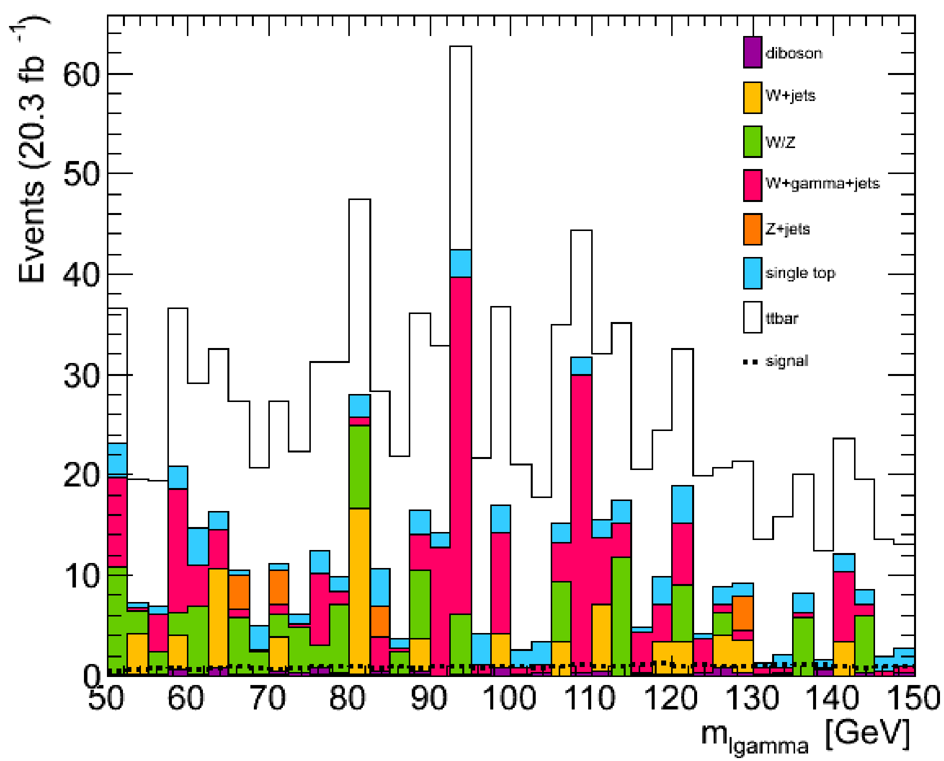
Cut on Z mass

→ reconstruct "Z" from lepton and photon

electron channel

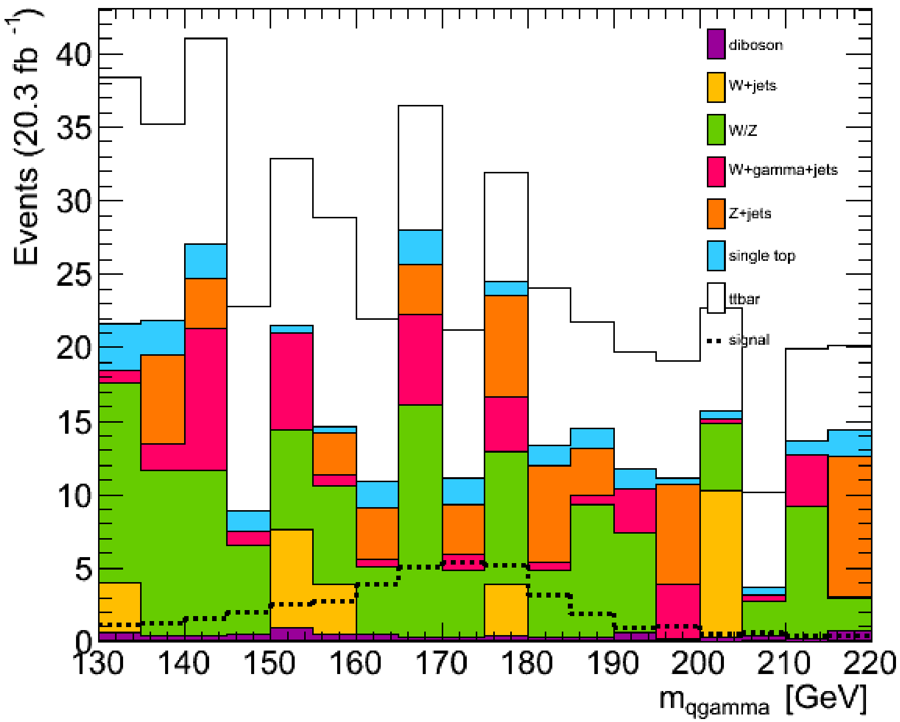


muon channel

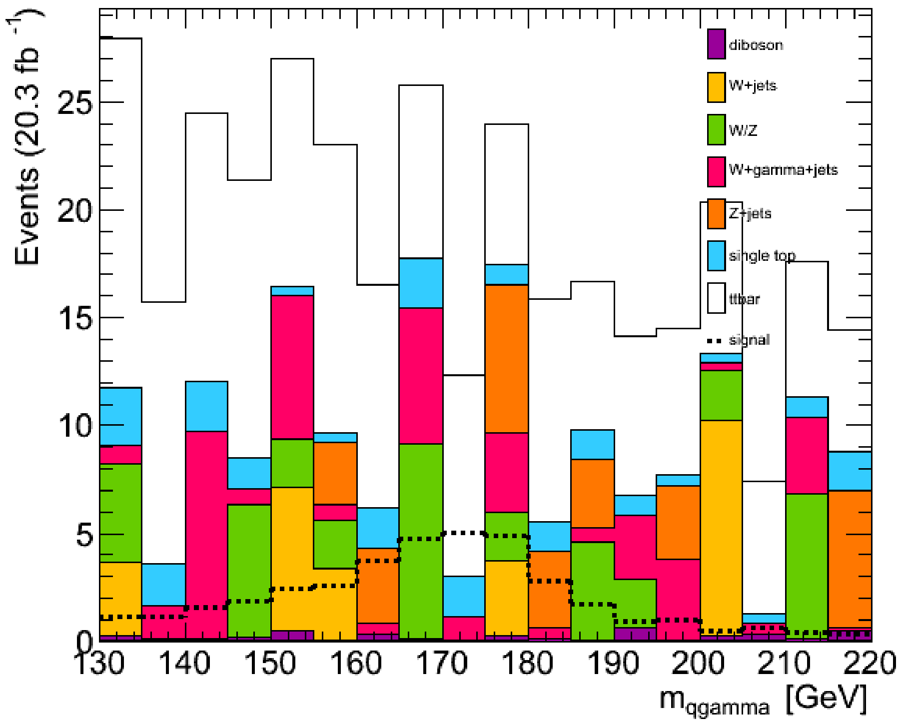


Electron channel - cut on “Z” mass

before



after



… Yay!

What's next?

- Use Monte Carlo distributions to set an expected limit on BR($t \rightarrow q\gamma$)
- Use data to set an upper limit on BR($t \rightarrow q\gamma$)

  SM: BR($t \rightarrow q\gamma$) $\sim 10^{-14}$

  highest theoretical prediction: BR($t \rightarrow q\gamma$) $\sim 10^{-6}$

  current best limit: BR($t \rightarrow q\gamma$) $< \sim 10^{-3}$

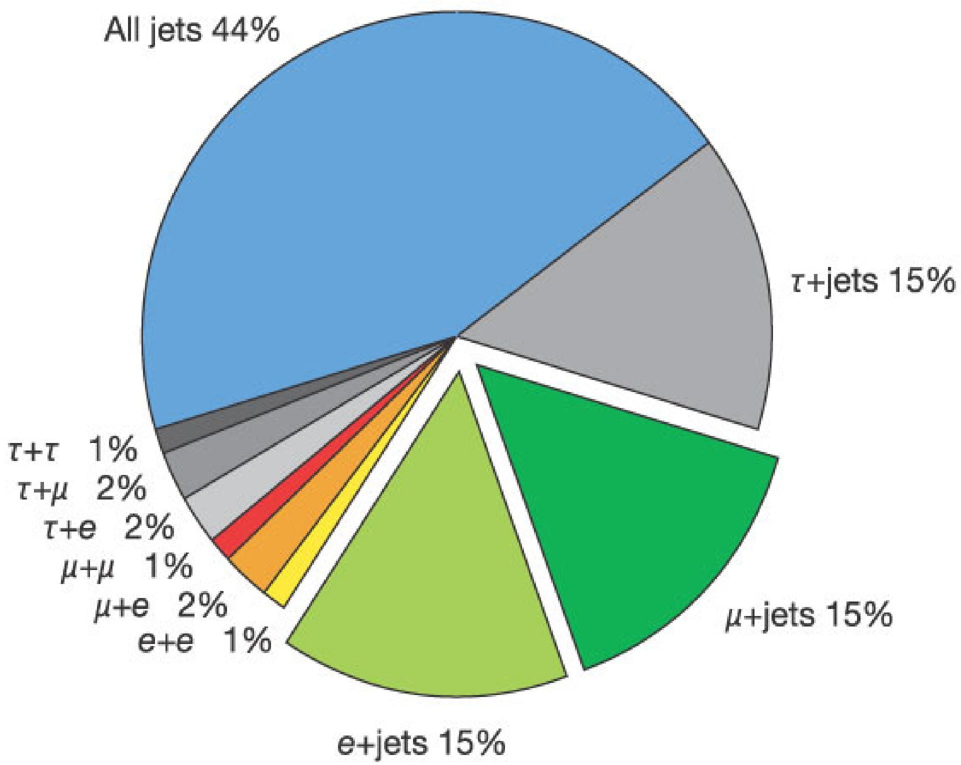
- How much data would it take to measure the SM branching ratio? $300 fb^{-1}$? $3000 fb^{-1}$?

Conclusions

- FCNC top decays could give us a handle on new physics at the LHC
- Excellent performance of the LHC in 2012 provides an unprecedented dataset for such searches

Backup Slides

Looking for Top Quark Pairs

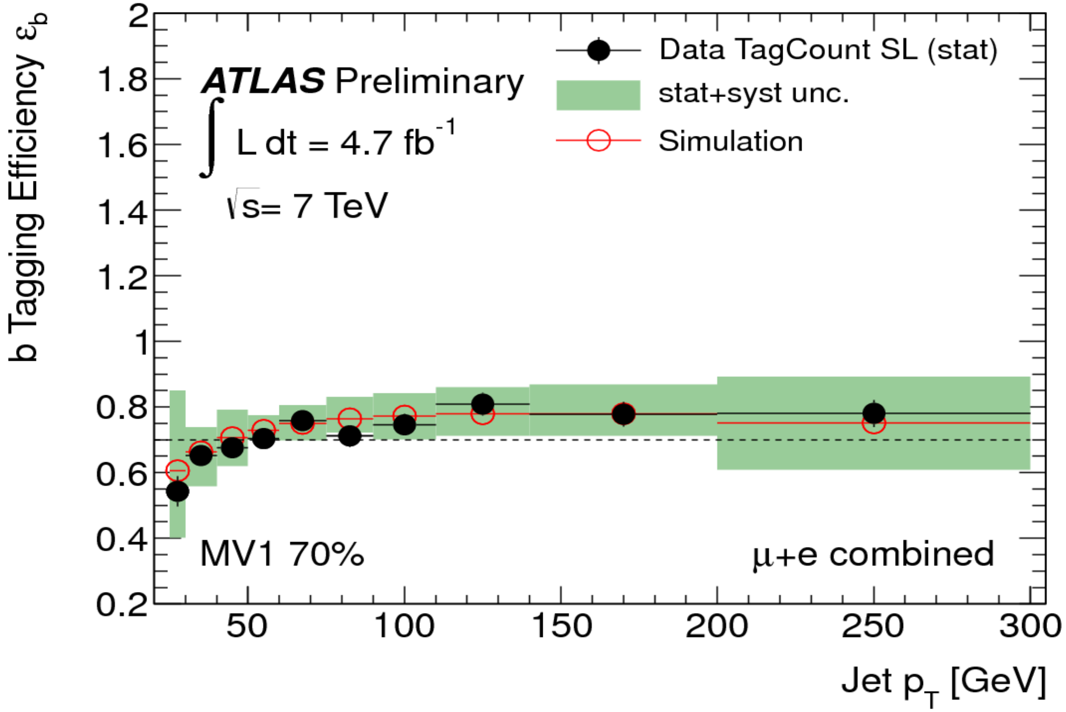


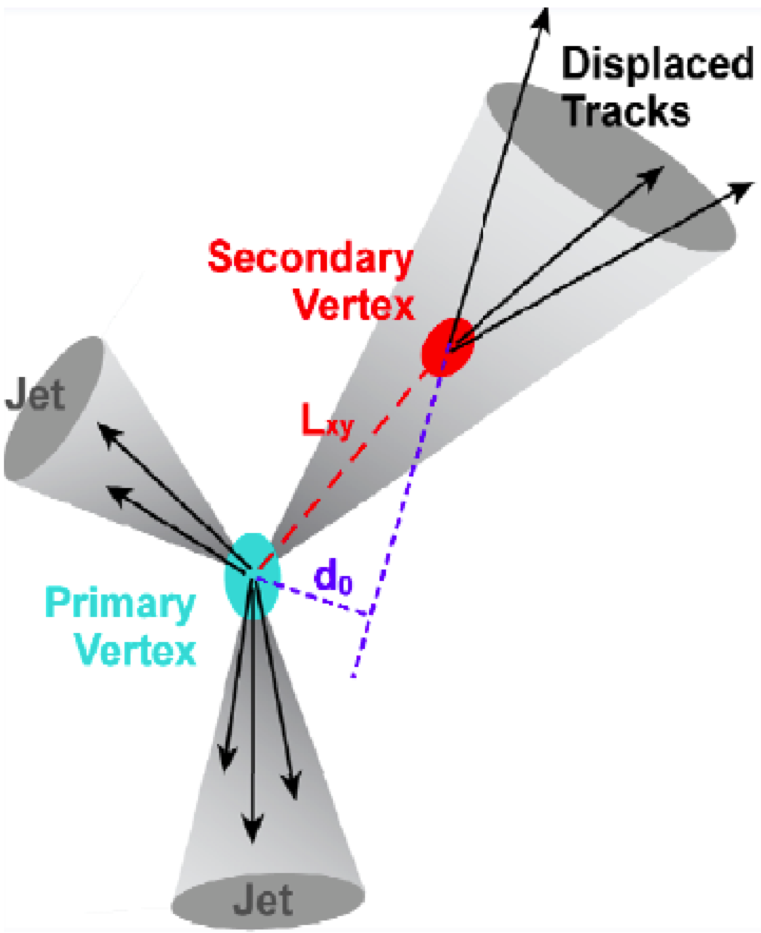
Three main scenarios (from most to least difficult to find):

- “fully hadronic” (44%)
- “semi-leptonic” (30%)
- “fully leptonic” (4%)

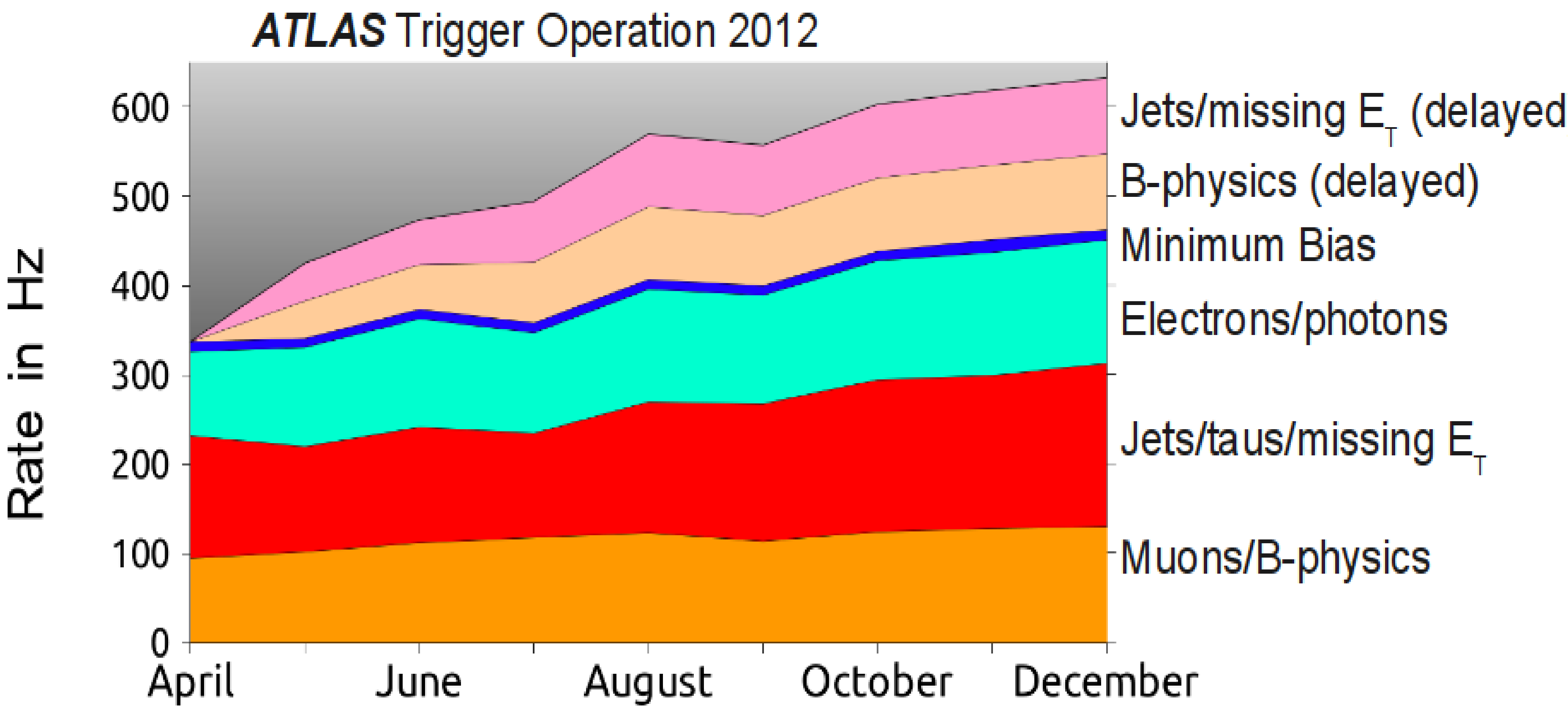
B-tagging @ ATLAS

- MV1, 70% efficiency





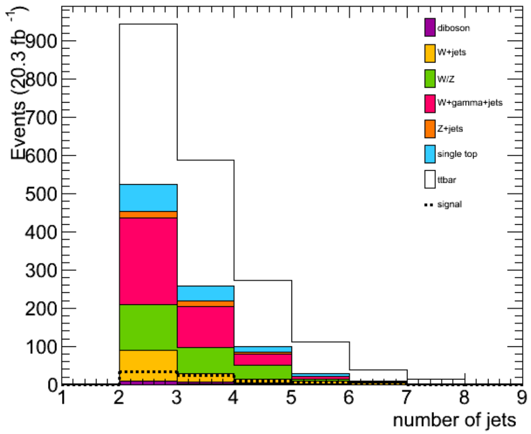
2012 Trigger Rates (by stream)

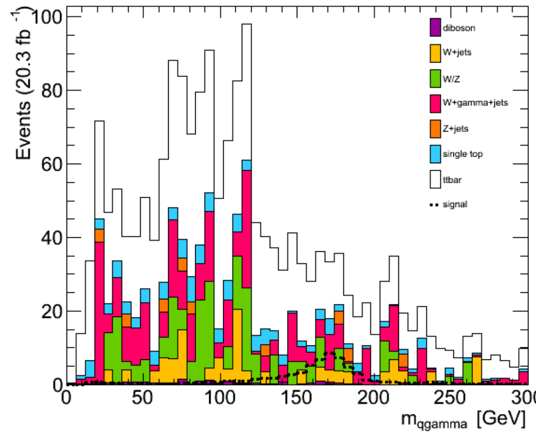


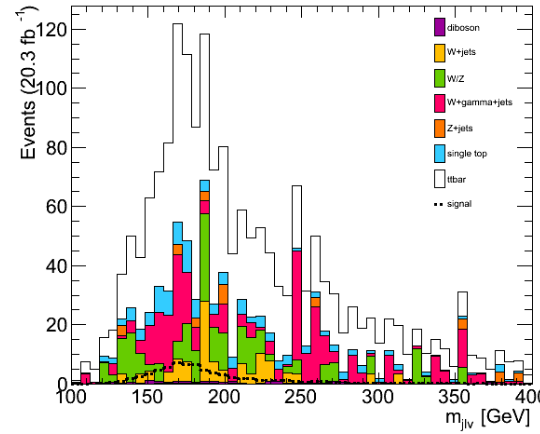
Extra plots

of Jets | FCNC top mass | SM top mass

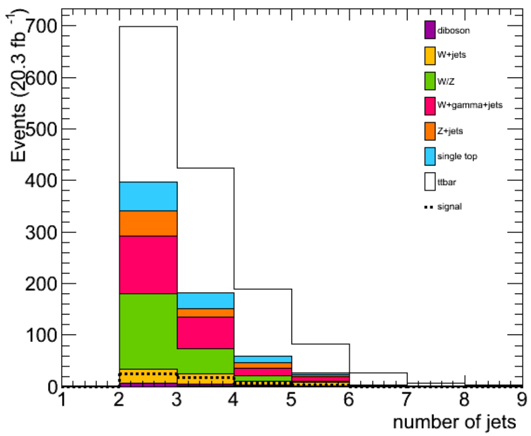
muon channel

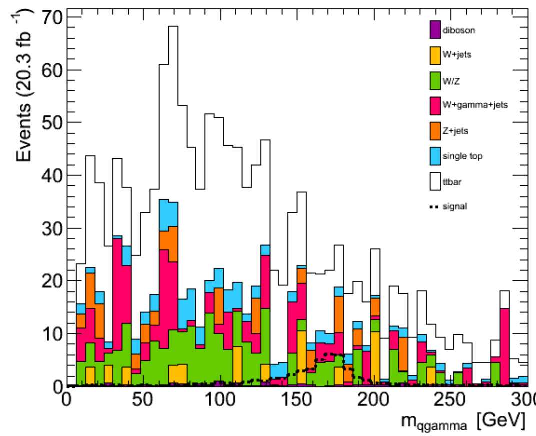


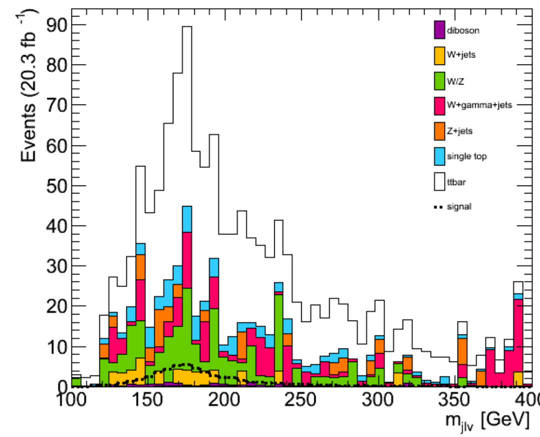




electron channel







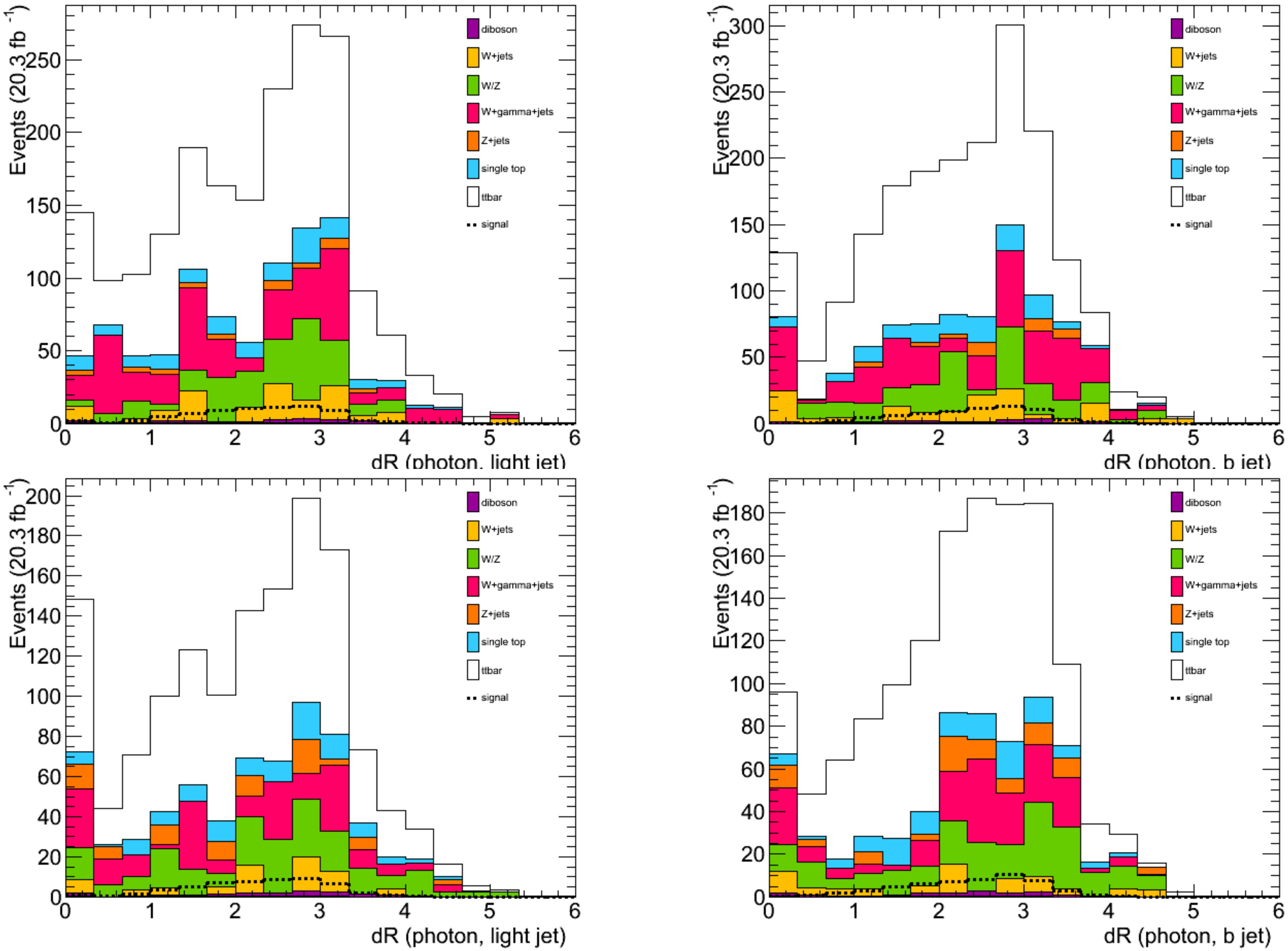
Photon + jets

photon + light jet

photon + b-jet

muon channel

electron channel



Event Selection - Skim (muon channel)

Using MiniSLG from TRCR 14-00-07:

- OR the lowest unprescaled muon triggers: EF mu24i tight, EF mu36 tight
- Require a primary vertex with Ntracks > 4
- At least one muon (> 25 GeV)
- Exactly one muon (> 25 GeV)
- No good electrons
- Require trigger matching
- Remove events with e-mu overlap
- Reject event if there is a LooseBad jet
- At least two good jets
- MET > 20GeV
- MET+MTW > 60GeV
- b-tag (At least one good jet has MV1 > 0.772)
- Photon selection (At least one good photon)

Event Selection - Skim (electron channel)

Using MiniSLG from TRCR-14-00-07:

- OR lowest unprescaled isolated and non-isolated triggers: EF e24vhi medium1, EF e60 medium1
- Require a primary vertex with Ntracks > 4
- More than zero good electrons (> 25 GeV, eta < |2.47| → excluding crack region 1.37-1.52)
- Exactly one good electron (> 25 GeV)
- No good muons
- Require trigger matching
- Remove events with e-mu overlap
- Reject event if there is a LooseBad jet
- At least two good jets
- MET > 20GeV
- MTW > 30GeV
- b-tag (At least one good jet has MV1 > 0.772)
- Photon selection (At least one good photon)

Cut Flow - Electron channel

	skim	Photon cut	b-jet	“Z” mass
ttbar+V+jets	9.42	6.82	3.72	3.14
diboson	41.2	29.5	26.8	14.5
W+jets	102	64.8	61.1	61.1
W/Z	853	556	517	207
W+gamma+jets	439	259	224	201
Z+jets	238	170	170	78.1
Single top	248	144	111	105
SM ttbar	2262	1403	812	759
signal	75.5	71.8	57.9	54.6

Cut Flow - Muon channel

	skim	Photon cut	b-jet
ttbar+V+jets	10.9	7.42	3.98
diboson	26.9	18.1	17.3
W+jets	192	125	125
W/Z	399	248	230
W+gamma+jets	566	400	375
Z+jets	60.4	36.6	36.6
Single top	287	166	132
SM ttbar	2788	1791	1047
signal	95.6	91.0	73.4