Trigger and Data Acquisition Systems

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RAL

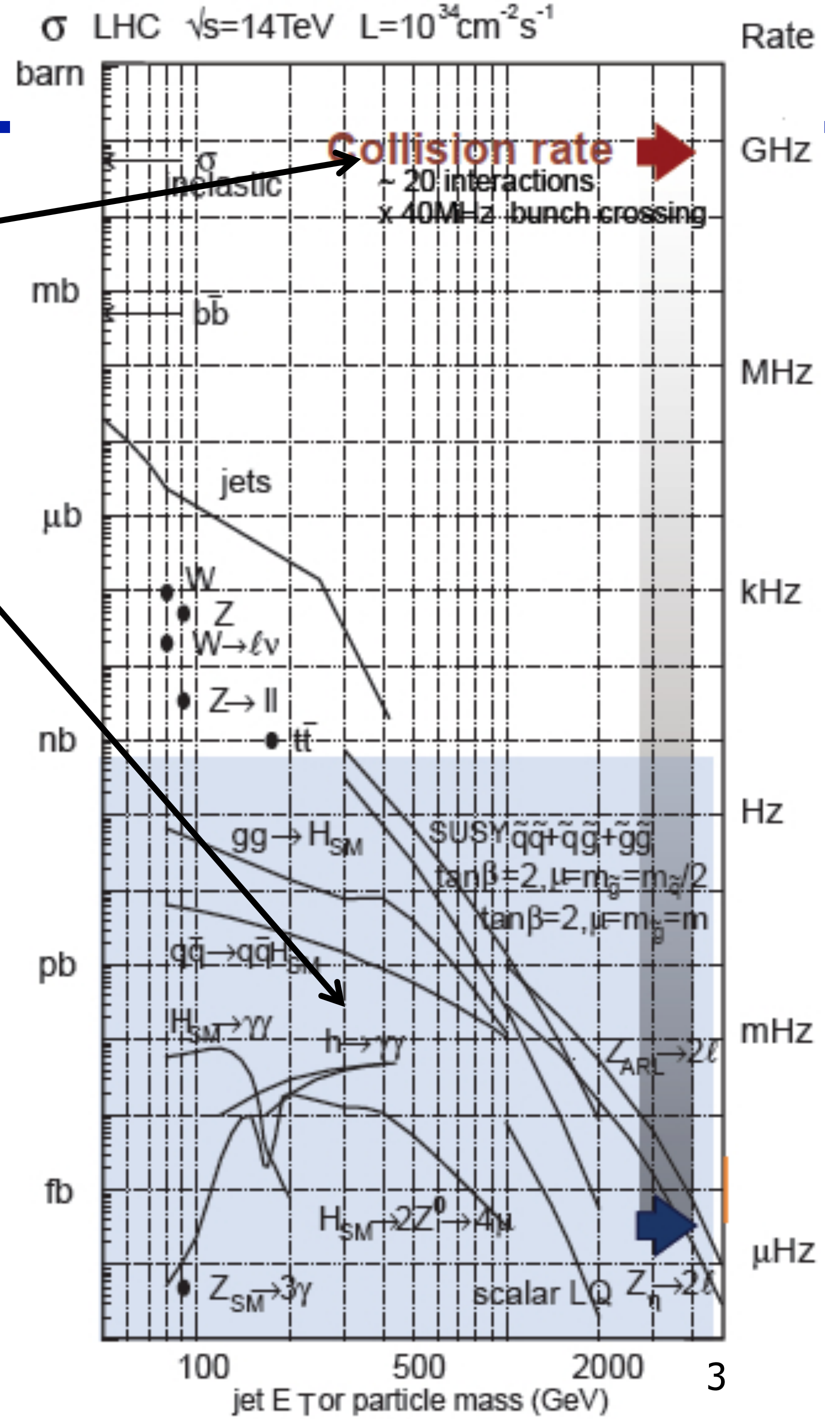
- Lecture 3
  - Trigger

Reminder from last time

- Last time we learned how to build a data acquisition system
- Studied several examples of data acquisition systems at the LHC
- We learned what a trigger is and how it works
  - Tells you when is the “right” moment to take your data
  - Decides very rapidly what output to keep if you can’t keep all of it. The decision is based on some ‘simple’ criteria
  - Can be done in several levels
- Now we’ll learn more how the trigger looks and how to devise the set of triggers needed for a physics analysis

Why do I need a trigger at the LHC?

- Huge incoming rate of mainly “uninteresting” collisions
  - Huge rejection needed from ~10^9 Hz to ~10^2 - 10^3 Hz for offline storage (physics analyses)
- Impossible to save all collisions
  - Would result in O(100000) PetaByte or O(1000) Exabyte per year of data per experiment
    - For comparison: 5 Exabytes: All words ever spoken by human beings.



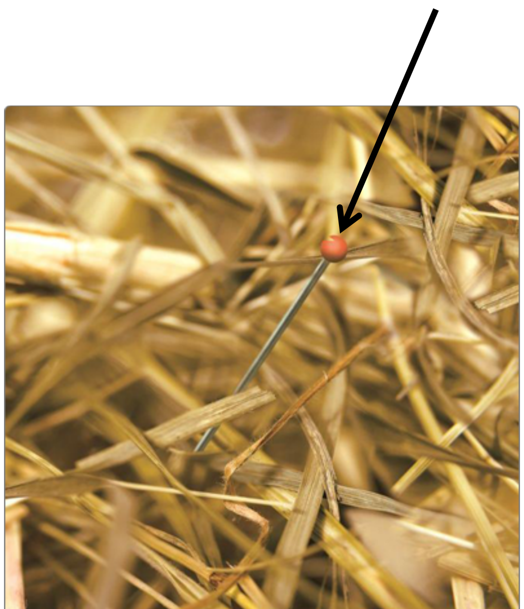
Trigger = Rejection

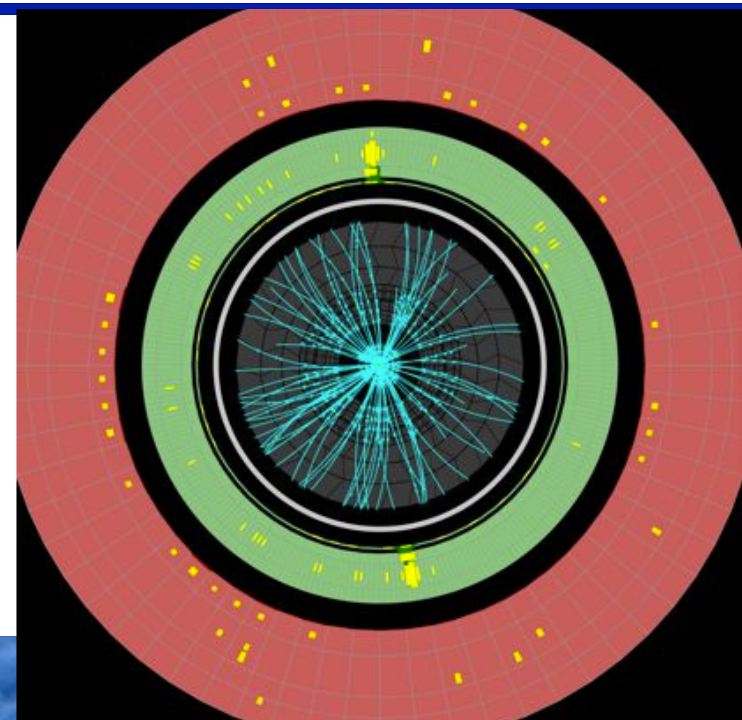
- Problem: We must analyse and reject most collisions prior to storage
- Solution: Trigger
  - Fast processing
  - High efficiency for interesting physics
  - Huge rejection factor $10^4 – 10^5$

- Note if the incoming rate is very high, the trigger itself is a ‘severe’ physics decision
- Make sure your favourite physics channel is selected with high efficiency
  - Many other trigger needed by other physics analyses will compete with you

Example: H→γγ

- Roughly one 125 GeV Higgs for every 10 billion pp interactions
- H→γγ is rare decay with BR ~10^{-3}
- Approx. 1 H→γγ per 10 trillion interactions
- Make sure you select them all….





Other Challenges

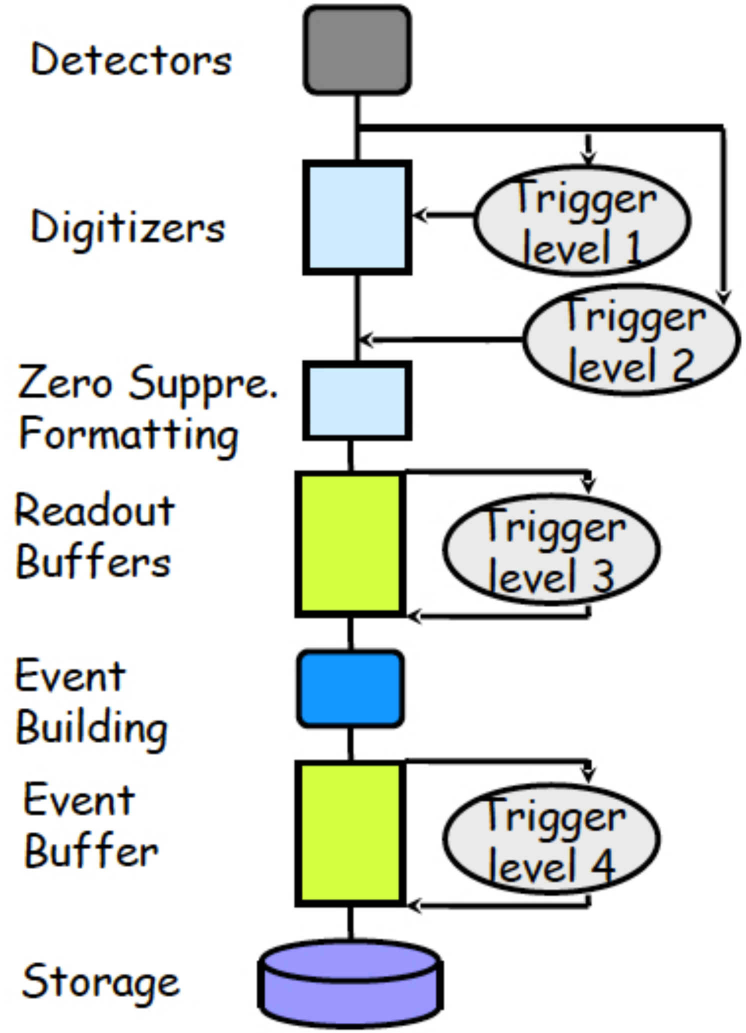
- Pile-up (overlapping collisions)
  - Bunch crossing frequency of 40 MHz
  - LHC produced up to 75 pileup events in Run 2. Every bunch crossing ~few 1000 particles are produced
- It's on-line (cannot go back and recover events)
  - Need to monitor selection - need very good control over all conditions
- Any event thrown away is lost for ever!

“Simple” Trigger

- Example: dark matter experiment
  - Detect a very small energy deposition seen as scintillation light from i.e LXe or LAr.
  - As there is only a low background can afford to select all events
  - Trigger rate: ~100Hz

Multi-level trigger system

- Sometime impossible to take a proper decision in a single place
  - Too many readout units
  - Too far away (transport signal)
  - Too long decision time
- Distribute the decision burden in several steps
  - E.g. reject 90% of your collisions per step
  - Usually $\tau_{N+1} >> \tau_N$, $f_{N+1} << f_N$
- Done in LHC experiments (see last lecture)



Example: Higgs

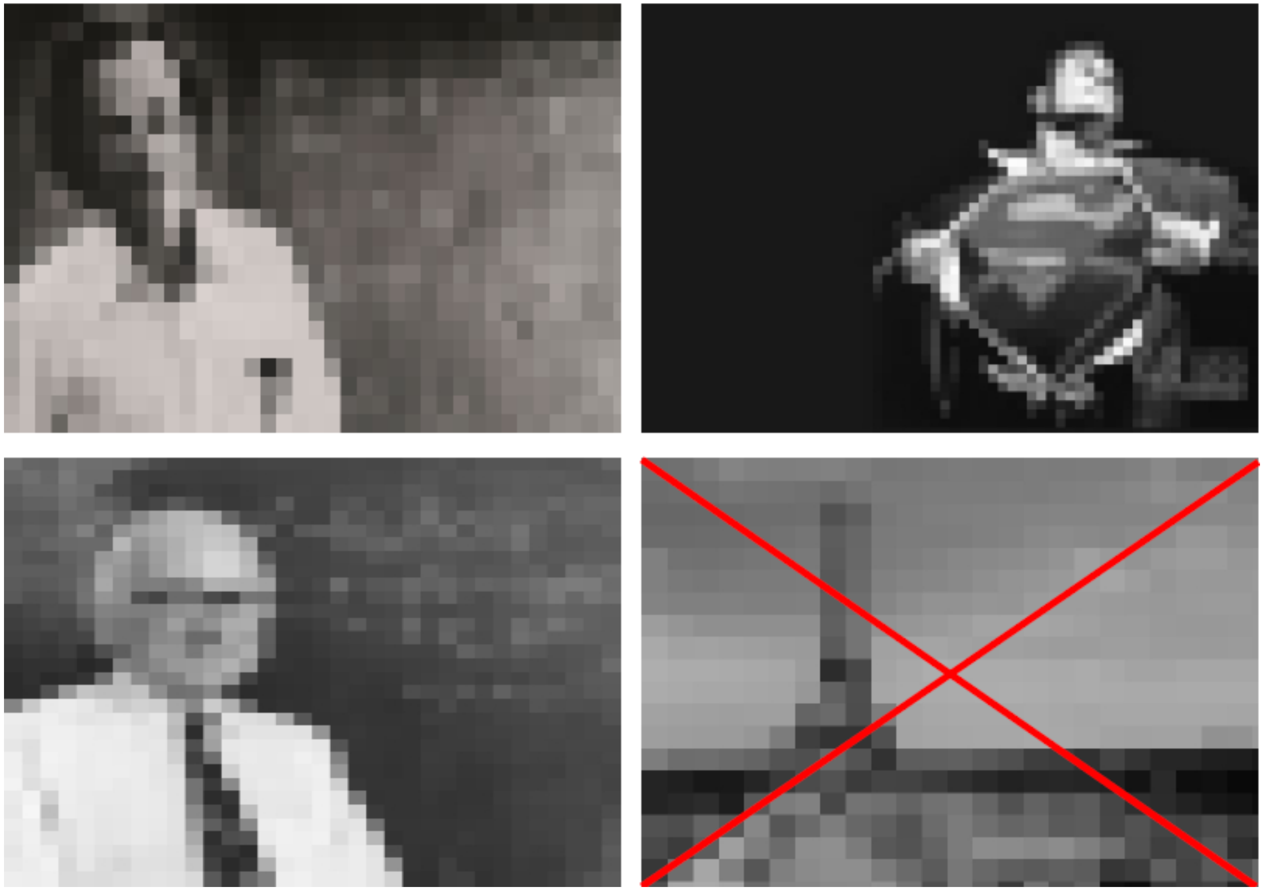
- L1

  Coarse granularity

Example: Higgs

- L2

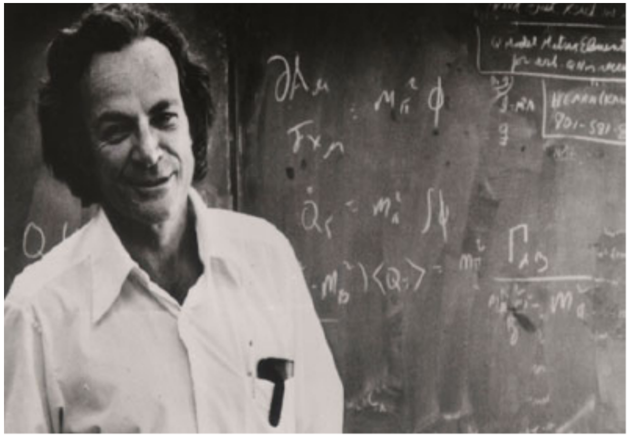
  Improved reconstruction, improved ability to reject events

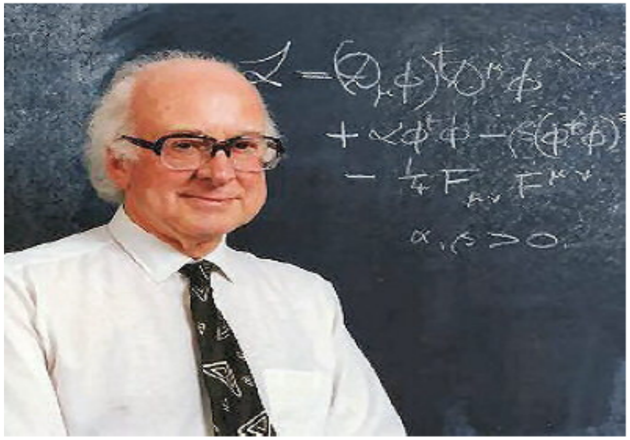


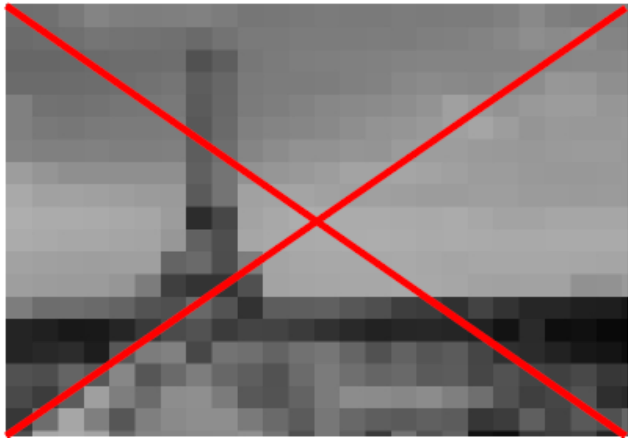
Example: Higgs

- L3

  high quality reconstruction, improved ability to reject events

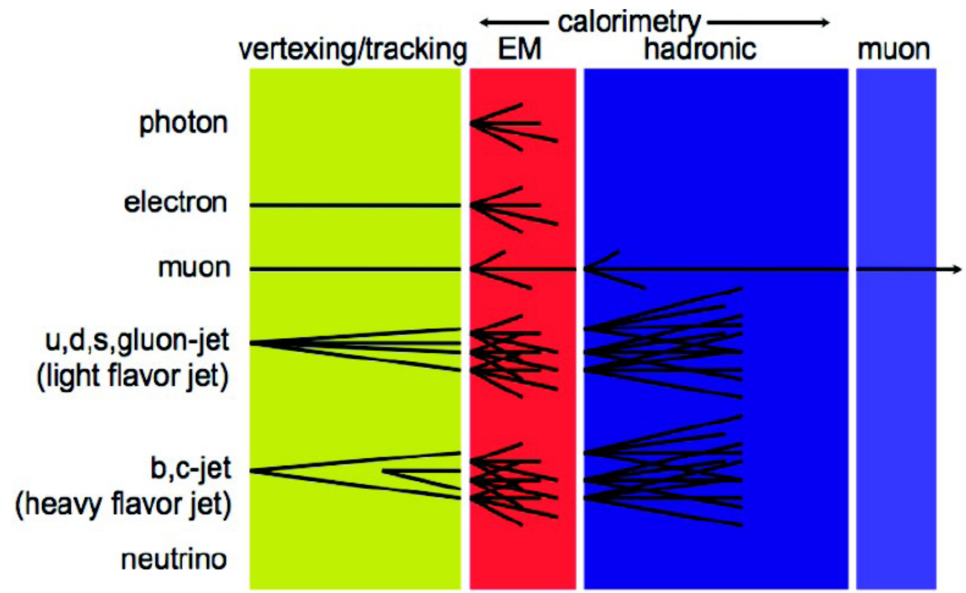




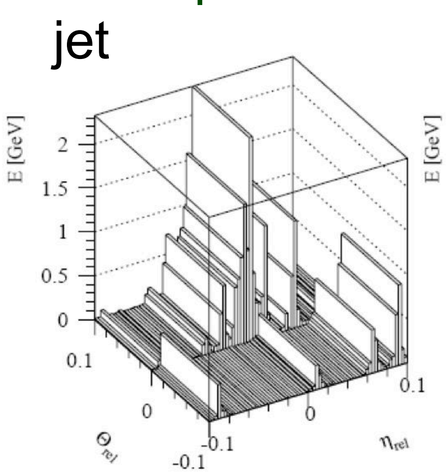


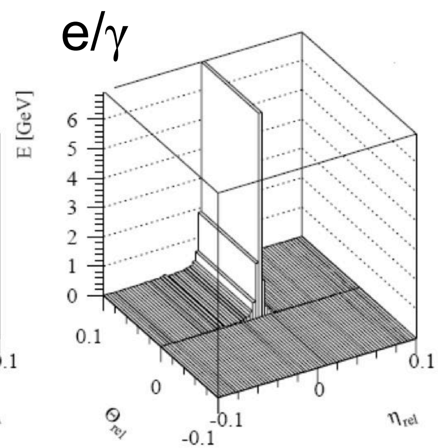
How do I select interesting collisions

- Need to identify the different particles produced
  - Muons, electrons, photons, taus, jets missing E_T

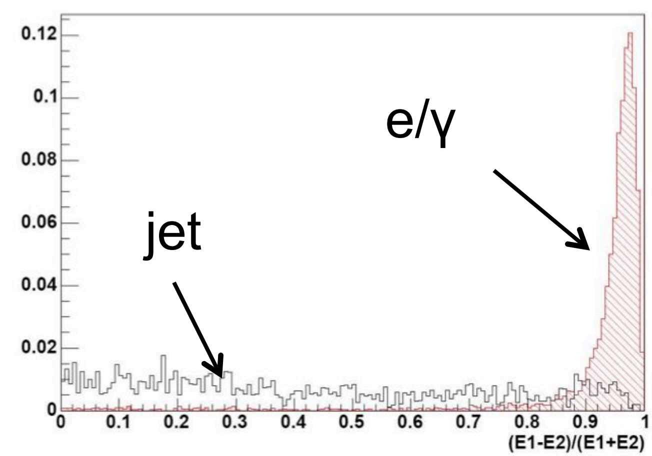


Detector feature
(deposit in EM calorimeter)



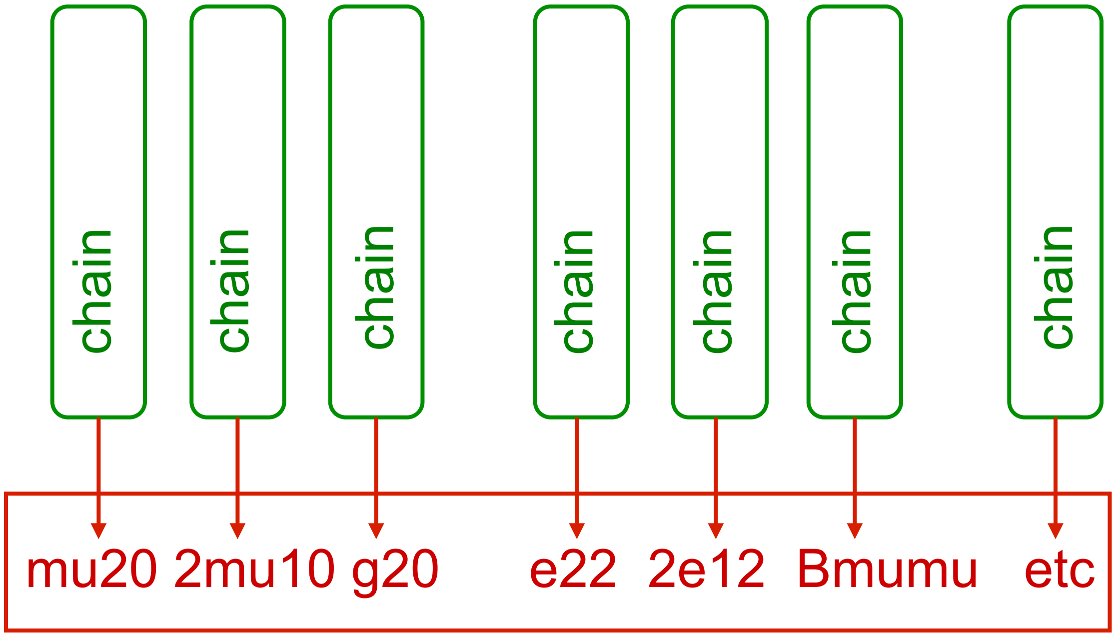


Trigger quantity



How do I select interesting collisions

- For each trigger / signature there is a chain of processing steps for each trigger level (L1, L2, L3,…)
  - Called: Trigger Chain, Trigger Path
  - E.g: reconstruct cluster - identify electron - reconstruct track - identify $e^{\pm}$

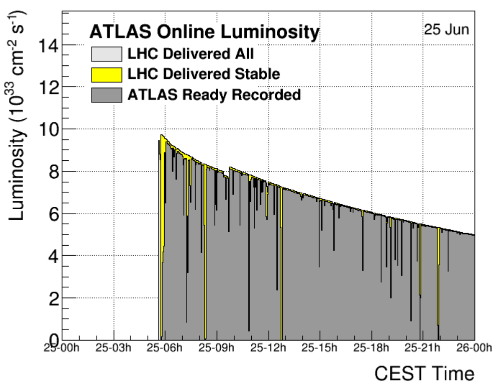


Trigger Path

- Use the identified particles above given (transverse) momentum thresholds
  - Isolated electron, muon and photons
  - τ-, central- and forward-jets, jets from b-decays
  - Events with missing E_T, missing E_T significance
- You can select events according to multiplicity
  - E.g. one electron and one muon, 4 jets etc
- Or even more complicated (topological trigger)
  - Select events with a jet and a photon which are back-to-back
  - Select events with 2 γ's with invariant mass ~ Higgs mass
- The set of triggers or trigger items to be run online is called Trigger Menu
- Each trigger item can be prescaled, thus only a fraction of the selected events is recorded.

Trigger Menu

- Prepare a Trigger Menu
  - Defines the physics we want to do
  - Each trigger item defined by trigger chain
  - Event is stored if one or more trigger items are passed
- Need flexibility
  - Cope with changing luminosities



  - Be able to add triggers if needed (e.g. new triggers upon discovery)
- LHC exp. ~1000 triggers run online!

Today's Specials

Electrons

e24 (24 electron raviolis)	£7.95
2e12 (2 12 oz electron steaks)	£9.95

Muons

Mu24 (24 dl muon soup)	£5.95
2mu10 (2 muons 10cm ⃠)	£7.95

Jets

4j50 (4 jet pancakes)	£8:95
J500 (500g grilled jet fish)	£16:95

Mixed triggers

J50_ETmiss50 (yummy jet with missing french fries)	£10:95
Tau40_e20 (tau salad with electrons)	£8.95

What makes up a Menu

- Physics triggers (typically take all of them)
  - e.g. mu25 (one muon with p_T>25GeV, useful for many analysis from SM/Higgs to searches for new particles (Susy, Dark Matter…)
  - Obviously most of the trigger bandwidth is used for these
- Supporting trigger or cross trigger (typically prescaled)
  - Needed to understand (support) your physics analysis for e.g.
    - Measure trigger/offline efficiency
    - Understand your backgrounds
  - Calibration Triggers
    - E.g. select events selected by L1 only
  - Monitoring triggers
    - E.g. select $Z\rightarrow ll$ events
- Trigger menu determines the physics we can do in the offline analysis!

Trigger Menu

- Example from CMS: how menu changed as a function of luminosity (in 2010)

$L = 8 \times 10^{29}$ Hz/cm^2
Rate ~ 200-300 Hz (*)

Jets, MET, Tau: 15%
Electrons: 25%
Muons: 25%
"Support" Triggers: 50%

Early-Mid 2010

$L = 2 \times 10^{32}$ Hz/cm^2
Rate ~ 300-500 Hz

Jets, MET: 30%
b, Tau: 15%
Electrons: 25%
Muons: 30%
"Support" Triggers: 10%

End 2010

$L = 2 \times 10^{33}$ Hz/cm^2
Rate ~ 200-300 Hz

Jets, etc.: 20%
Tau: 5%
Electrons: 20%
Muons: 20%
Cross Triggers: 20%
"Support" Triggers: 5%

2011

(*) Numbers and fractions approximate, and do not account for trigger overlap

How to design a trigger

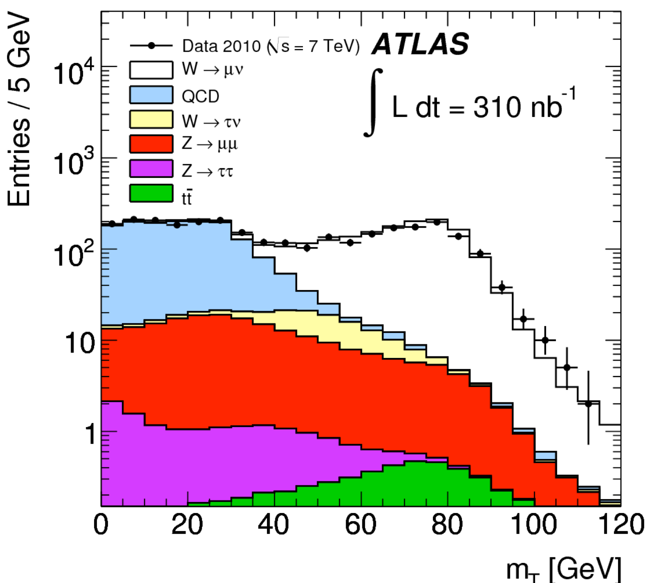
- First understand the physics you want to do
  - Which are the particles in your final state and how high is their p_T?
- Understand the existing trigger menu
  - Figure out if there is already a trigger in place which does the job
    - No need to design a new one if it's already covered
- If not, think up a new trigger
  - Can you combine several particles into one trigger, e.g. muon + 2 b-jets?
  - Can you take advantage of the topology of your event, e.g. invariant mass, back-to-back topology?
  - Also keep in mind that the trigger reconstruction is not as good as the offline one and your selections need to be looser
- Figure out if also other analyses might profit from your trigger
  - The more analyses there are the more likely your trigger will be accepted to run online

How to design a trigger

- General rule:
  - Make it as simple as possible
    - Less trigger losses
    - Avoids unnecessary trigger biases in your analysis
    - Less demand for supporting/cross triggers
    - More robust
  - If possible, create a new trigger based on a already existing (older more inclusive) trigger
    - Already validated and easier to implement

Example: W cross section measurement (ATLAS/CMS)

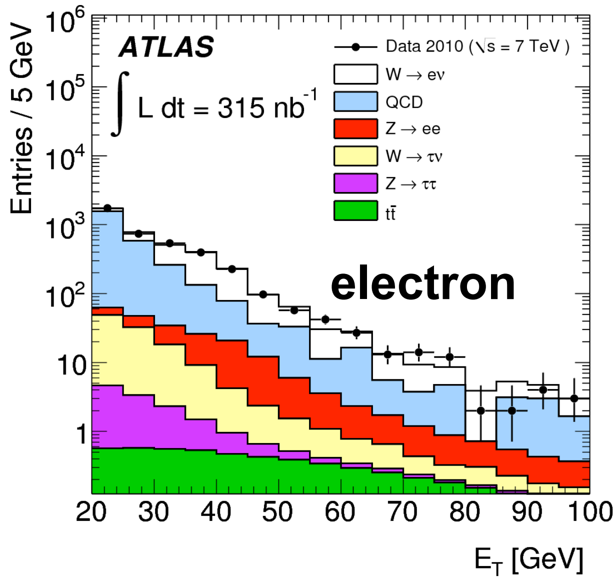
- How do I reconstruct $W \rightarrow l\nu$, l=e,μ in the offline?
  - Select events containing 1 electron or muon with high transverse momentum ($p_T > 25$ GeV)
  - Select events with high missing transverse energy ($E_T^{miss} > 20$ GeV)
  - Calculate transverse mass
    - $M_T^2 = (E_{T,1} + E_{T,2})^2 - (\vec{p}_{T,1} + \vec{p}_{T,2})^2$
  - Extract background and subtract
  - Count events and convert in cross section
    - $\sigma(\text{signal}) = \dfrac{(N_{cand} - N_{bkg})}{\alpha \cdot \varepsilon_{trig} \cdot \varepsilon_{offline} \cdot \int L\,dt}$

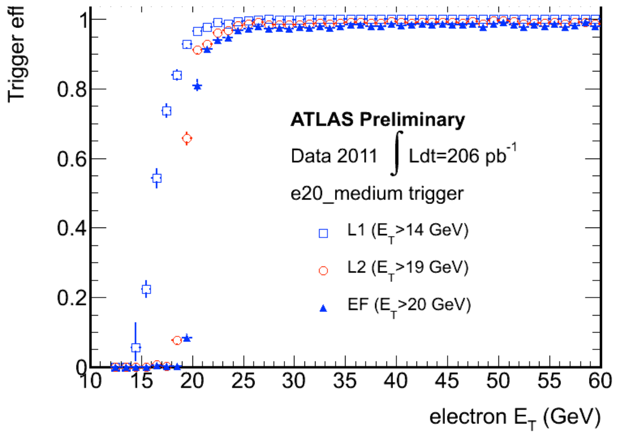


- Trigger can select these events selecting high energetic electrons or muons and/or via E_T^{miss}
  - So what should I choose?

Example: Trigger for measuring W cross section

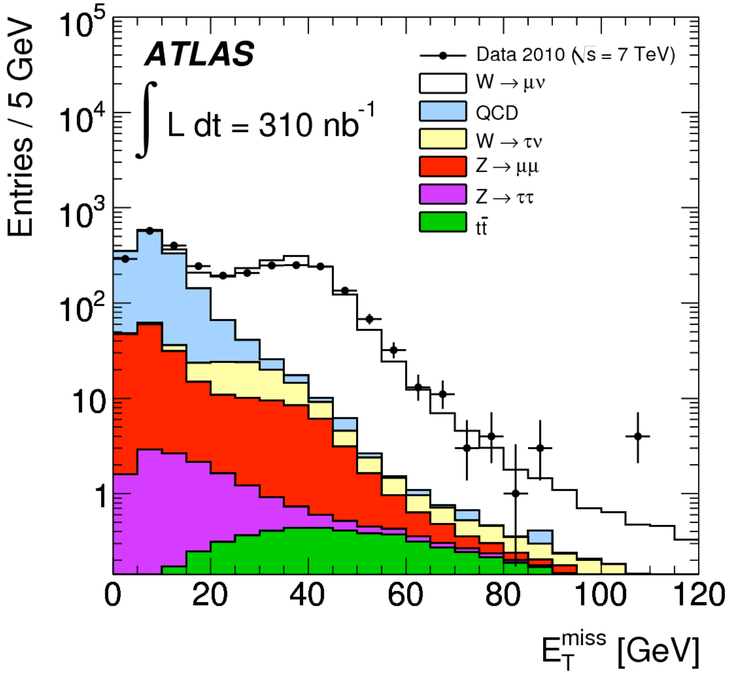
- E_T of the electrons and muons
  - Selection of E_T>20 GeV e/μ's will keep most of the W's
- ➡ Select events containing one high p_T e/μ
- Next: check the turn-on – trigger efficiency w.r.t. offline E_T near the trigger threshold
  - E.g. $e^{\pm}$-trigger with E_T = 20 GeV threshold (e20) efficient for offline E_T > 22 GeV, plateau for E_T > 25 GeV
  - ➡ Trigger threshold few GeV lower than what you want in offline analysis (resolution effect)
- Check the rate:
  - Assume: Rate ≈ 500 Hz
  - ➡ need higher threshold and tighter selection
  - ➡ Rate: 60 Hz

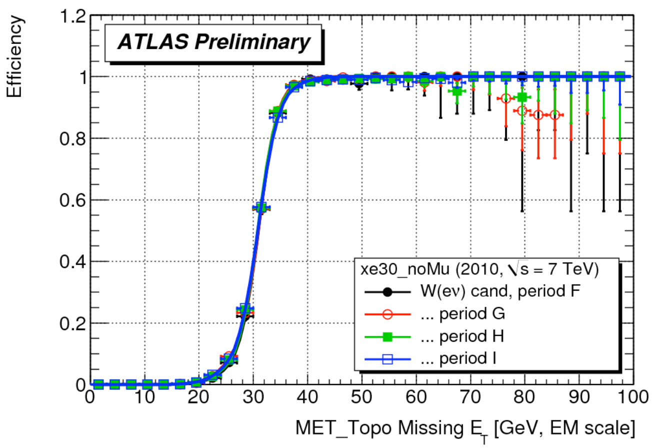




Example: Trigger for measuring W cross section

- And if the rate is still too high?
  - Even tighter selection (typical lower eff)
  - Even higher E_T
- Could we rather use missing E_T for the trigger?
  - Promising for E_T^{miss}>30 GeV
- Let's look at turn-on for E_T^{miss} > 30GeV
  - Efficient at offline E_T^{miss} > 40 GeV
  - Rate: ~5 kHz
- Combine E_T^{miss} with e/μ
  - e/μ with E_T > 25 GeV + E_T^{miss} > 30 GeV: 20 Hz
  - But now less analyses can use this trigger… perhaps rather higher E_T?
    - Best compromise needed…





Example: Trigger for measuring W cross section

- Another possible solution if you do not need the full data statistics
  - Prescaling
  - Find out how many events you need to do a useful analysis!
- If you also want to measure W+1, 2, 3, etc jets cross section
  - Add another trigger selecting based on e/μ (+ E_T^{miss}) + jets

What other triggers do I need: background trigger

- Now we e.g. select events with:
  - e/μ + E_T^{miss}
- I need to estimate the background under my signal
  - Often done via cut-reversal (ABCD) method
- Need sample of events selected with loose or “failed” electron selections
  - e.g. need e25_loose
  - Do not need all of them, so you can prescale by e.g. a factor of 100
    - Enough events for the analysis

	Pass $e^{\pm}$ identif.	Fail $e^{\pm}$ identif.
Low E_T^{miss}	A **(bkg enriched)**	B **(mainly bkg)**
High E_T^{miss}	C **(Signal + bkg)**	D **(bkg enriched)**

What other triggers do I need: efficiency extraction

- Trigger efficiency needs to be precisely measured since it enters in the calculation of the cross-sections

$$\varepsilon_{\text{trig}} = \frac{\text{Number of events passing trigger selection}}{\text{Number of events without trigger selection}}$$

- Trigger efficiency is usually measured w.r.t. offline, such that

$$\sigma(\text{signal}) = \frac{(\text{N}_{\text{cand}} - \text{N}_{\text{bkg}})}{\alpha \cdot \varepsilon_{\text{trig}} \cdot \varepsilon_{\text{offline}} \cdot \int L\,dt} \text{ with } \varepsilon_{\text{trig}} = \varepsilon(\text{L1}) \cdot \varepsilon(\text{L2}) \cdot \varepsilon(L3)$$

- Your trigger is used to collect your data
  - You cannot blindly use your data to study efficiency as your trigger might have introduced a bias
- Need an unbiased measurement of trigger and offline efficiency

Methods for trigger efficiency measurements

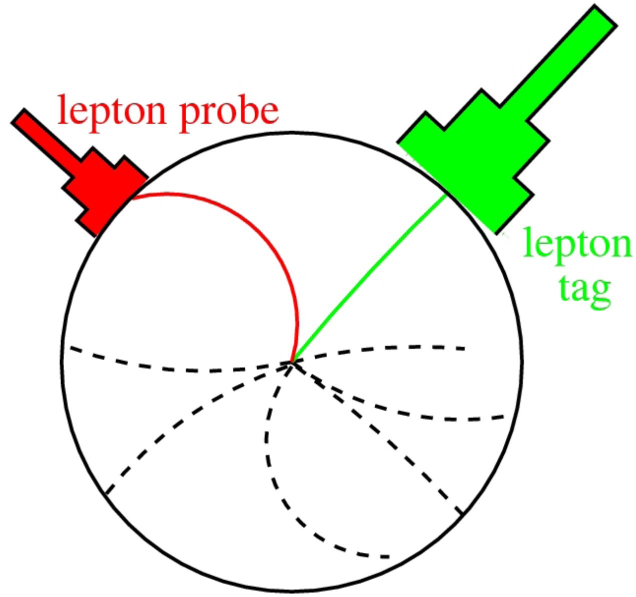
- Random sample of collisions
- Bootstrapping via pass-through triggers
  - Use looser trigger, e.g. apply only L1 selection, but nothing at L2, L3,…

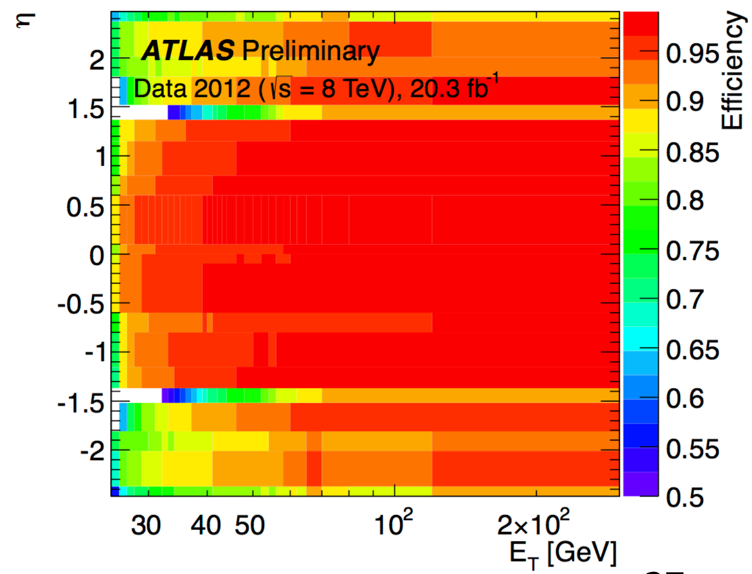
$$\varepsilon(\mathrm{L2\ mu20}) = \frac{\text{events passing L2 mu20}}{\text{events passing L2 mu20 in pass – through}}$$

  - Drawback: you might measure the efficiency of your signal plus some background
- Use "orthogonal" trigger
  - Trigger on certain particle type in the event, measure another one
    - For example use muon triggered events to measure electron trigger efficiency
  - Method might suffers from your topology (you might select more (less) crowded events), you measure signal + background
- Use simulations
  - Monte-Carlo must very well describe the data

Efficiency Measurement

- Use well-known physics processes and do "tag & probe"
  - $Z \rightarrow ll$, $J/\Psi \rightarrow ll$: trigger only on one leptons
    - Most precise way to calculate efficiencies
  - $W \rightarrow l\nu$: trigger on missing E_T
- Example: $Z \rightarrow ee$ tag and probe
  - Trigger on one of the electrons
  - Select offline events with 2 good electrons which have an invariant mass around the Z mass
  - "tag" electron: well identified, coincides with electron which triggered event
  - "probe" electron: check if this one passed or failed the trigger selection



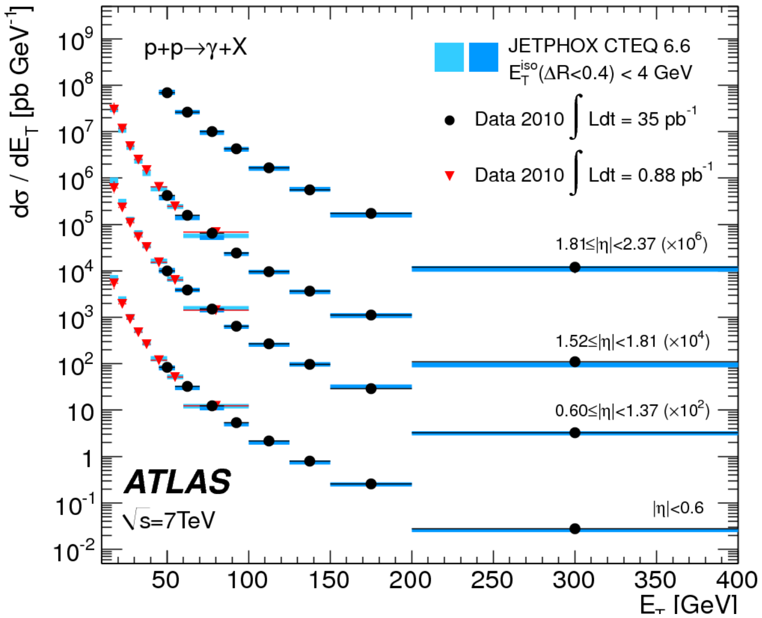


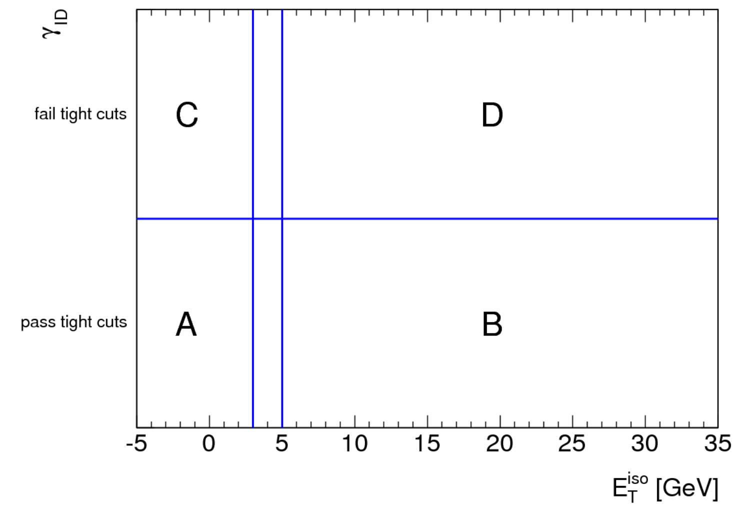
Summary: triggers for W cross section measurement

- Trigger to select signals
  - Well identified electrons/muons with E_T > 25 GeV and certain identification criteria
    - Might even consider prescaling
  - electron/muon with E_T > 25 GeV and E_T^{miss}>30GeV
- Trigger needed for background subtractions
  - Prescaled trigger with loosely identified electron/muon candidates with E_T > 25 GeV
- Triggers for efficiency extraction
  - Well identified electrons/muons with E_T > 25 GeV (use the electrons from Z decays)
  - E_t^{miss} trigger to measure offline efficiency from W decays

Example 2: Measurement of direct photon production

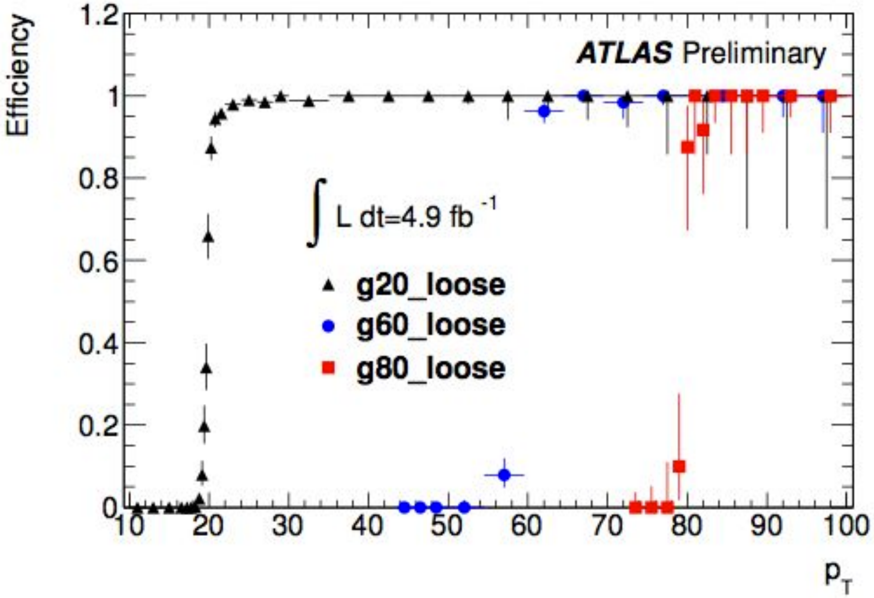
- Measure spectrum starting with E_T > 15 GeV
- Can't keep all the collisions with photons at low E_T
  - Use prescaled triggers
    - g10, g20, g40, g60, etc until rate low enough
  - Prescale each trigger to give ~1Hz rate
- Trigger for background extraction
  - If photons loosely selected, can use same sample to extract the background from jets faking γ's
    - Identification criteria vs isolation





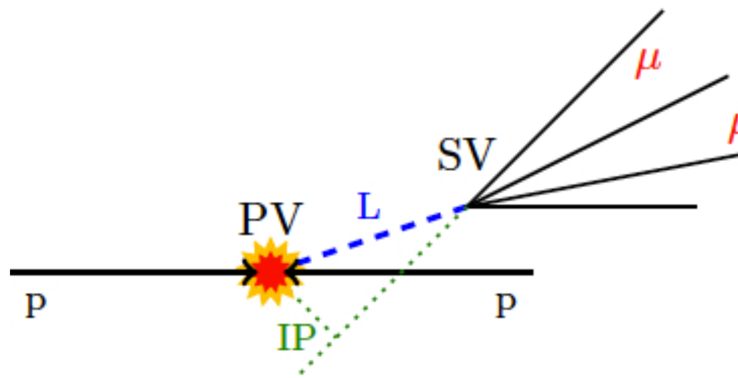
Example 2: Measurement of direct photon production

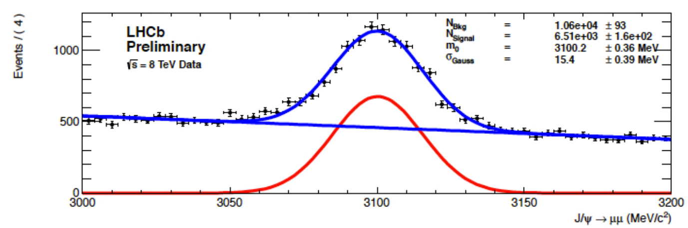
- Efficiency
  - Use bootstrapping
    - use photon candidates selected by L1 only, measure photon efficiency w.r.t. L1
    - Use unbiased sample e.g. minimum bias to measure L1 efficiency
    - $\varepsilon_{Trigger} = \varepsilon_{L1} \bullet \varepsilon_{L2,\ L3}$
    - Advantage: 2-step approach results in less overall statistics needed due to high rejection at each trigger level
  - Use Z->eeγ events (tag & probe)

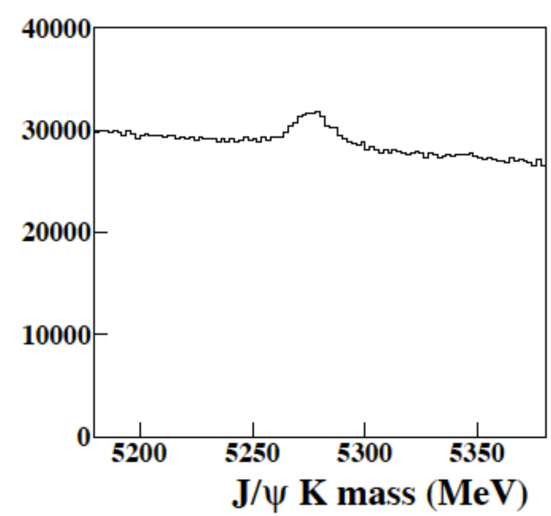


Example 3: B→ J/ψ K (LHCb)

- Select events with
  - Displaced vertex
  - 2 muons from J/ψ decay
    - Muons come from displaced vertex
- Such a trigger is also useful for other analyses
  - $B \to \mu\mu$, $B_s^0 \to J/\psi\ \phi$, $B^0 \to K^{*0}\mu\mu$
- If you can't afford the rate
  - Muons need to fall in inv. mass window around J/ψ mass
  - Combine with loosely identified K







Summary

- Introduction to trigger selection
  - Introduction to some slang: trigger path, trigger menu…
  - Trigger strategy is trade-off between physics requirements and affordability
  - How to devise a trigger for a physics analysis
    - Will be (hopefully) useful for your physics analysis