# Development of a new B-Physics Trigger for the ATLAS Detector at CERN

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# Outline

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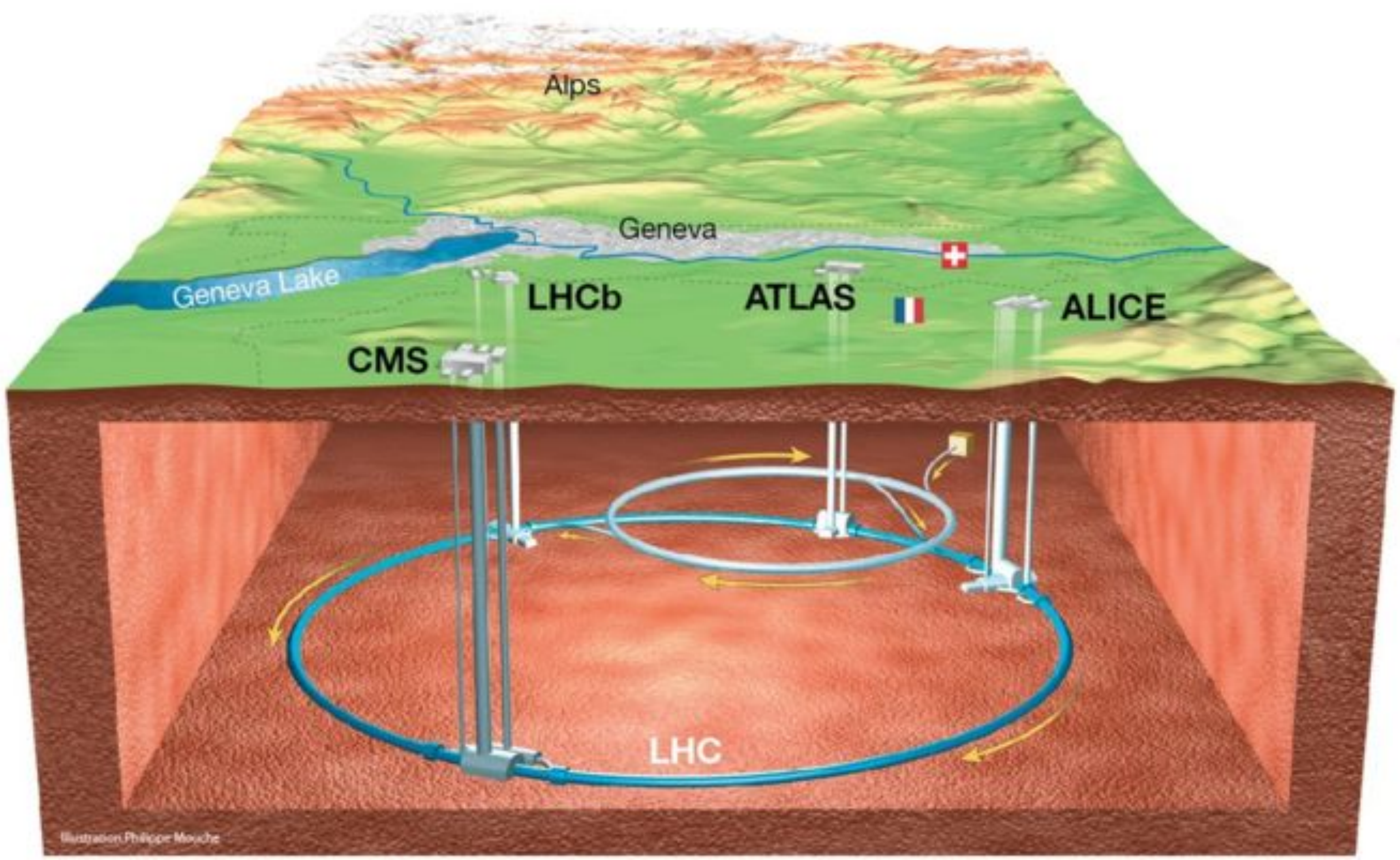
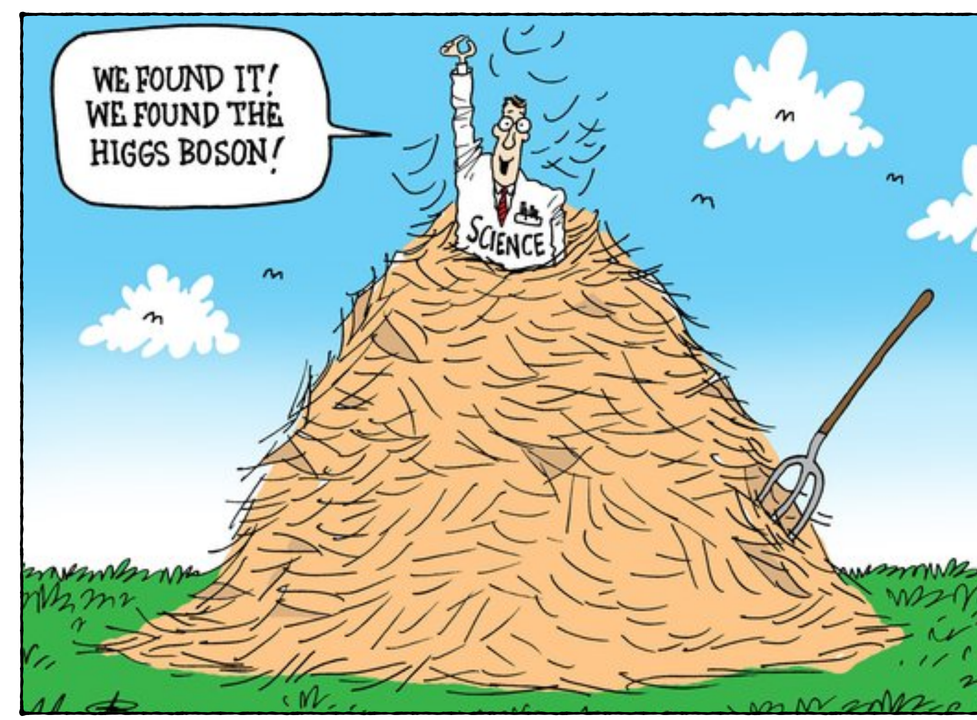
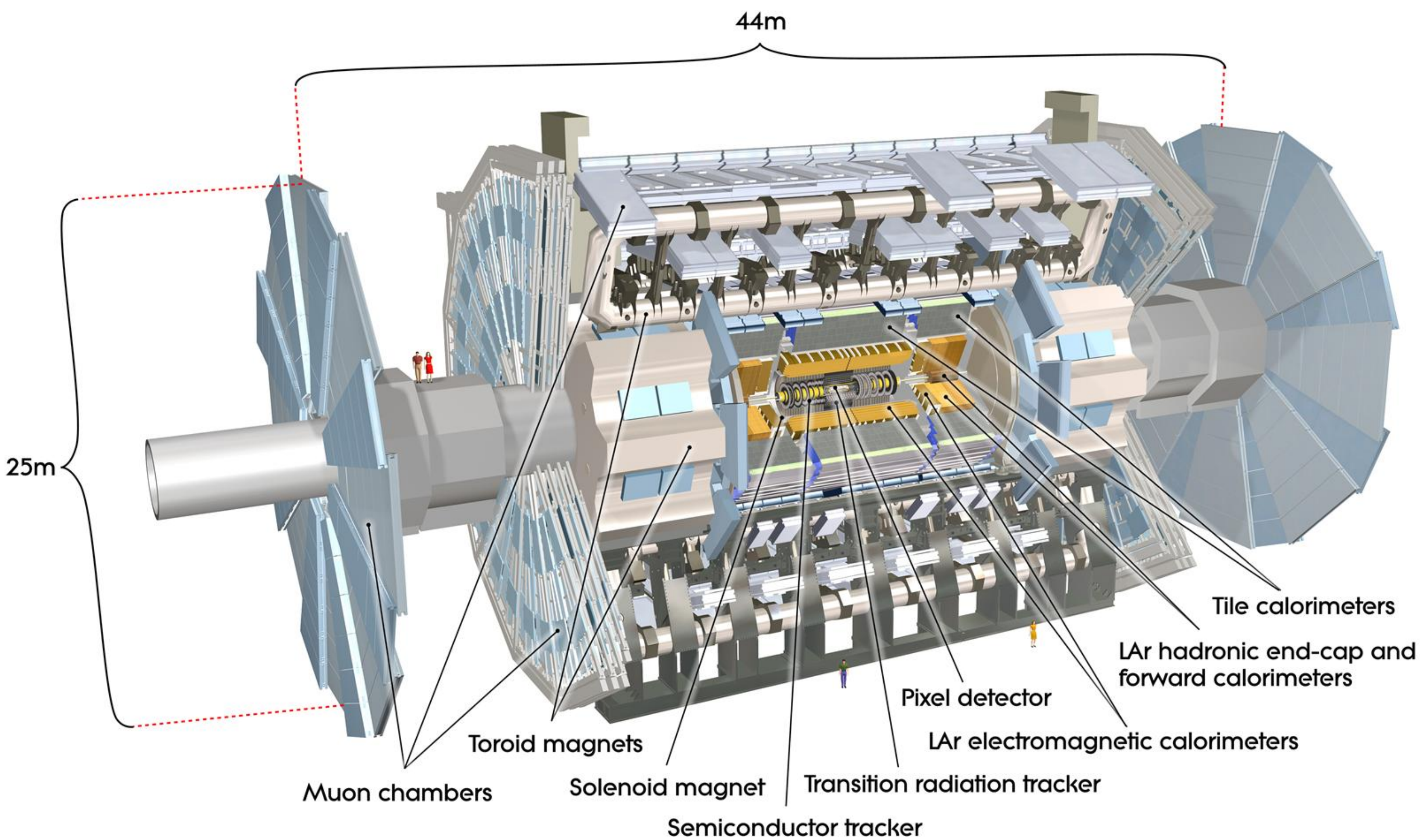
# Physics at the Large Hadron Collider

- Proton-proton and heavy-ion collisions.
- Beam interaction points at four major experiments in the LHC ring - ATLAS, CMS, LHCb and ALICE (heavy-ion).
- Proton-proton bunch collisions happen at at total energy of 13 TeV, every 25 ns - 600 million collisions per second.
- However, the *cross sections of interesting physics* processes are extremely *low…*
- Need a robust trigger and data acquisition system.



# The ATLAS Detector




**Studies of the performance of the ATLAS detector using cosmic-ray muons**
ATLAS Collaboration (G. Aad (Freiburg U.) *et al.*)

*Inner Detector : Measures the momentum of charged particles*

*Calorimeter : Measures energies carried by neutral and charged particles*

*Muon Spectrometer : Identifies muons and measures their momenta*

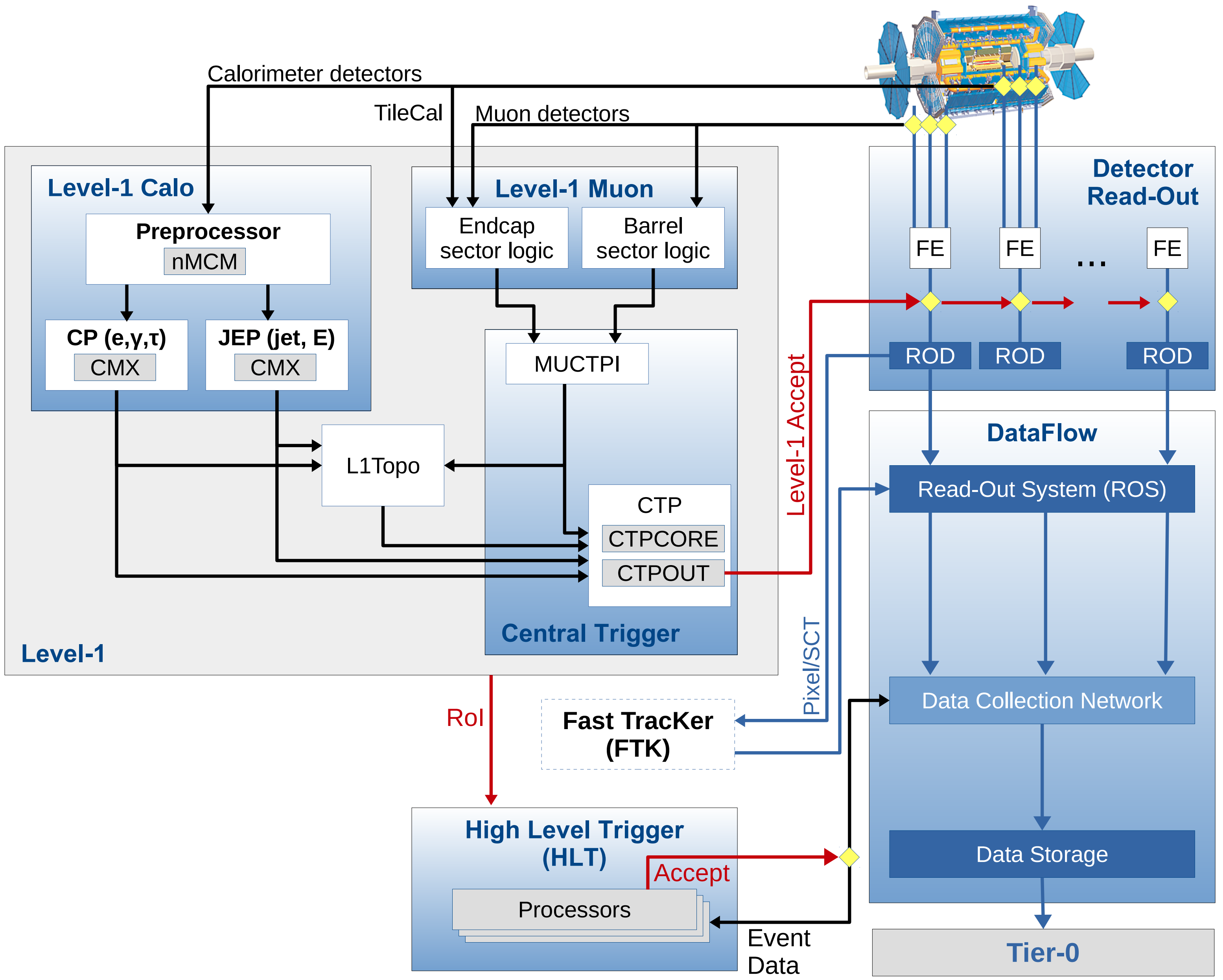
*Magnet System : Bends the trajectories of charged particles to measure its momentum*

*Trigger and Data Acquisition System and the Computing system support the functioning of the detector*

ATLAS EXPERIMENT

# ATLAS Trigger and Data Acquisition System (TDAQ)

- TDAQ system *selects interesting physics events* during collisions and stores them for further analysis.
- The ATLAS Trigger is divided into two levels - Level 1 (L1) and the High Level Trigger (HLT)
- **Hardware-based Level L1 trigger :**
  - Finds *regions of interest (RoI)* using coarse detector information
  - Reduces event rates from 40 MHz to 100 kHz
- **Software-based HLT :**
  - Receives input from Level-1 trigger
  - Output rate - 1000Hz
  - Performs object reconstruction in the RoI using algorithms

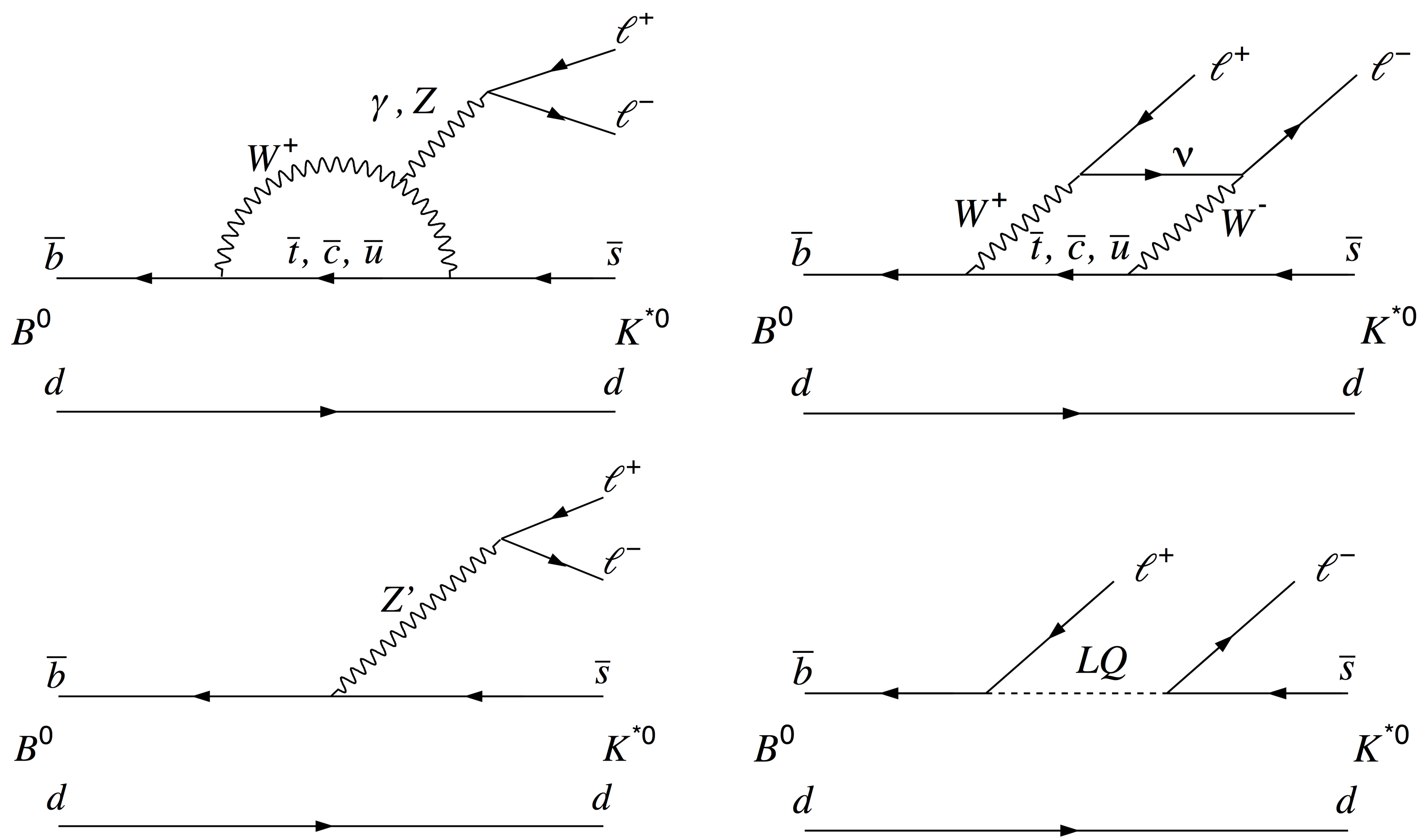


# Lepton Flavour Universality

- The electroweak couplings of leptons to gauge bosons are **independent of their flavour**
- Flavour-changing neutral-current (FCNC) processes (quark changes its flavour without altering its electric charge) - good tests for LFU

*Standard Model*

*New Physics*

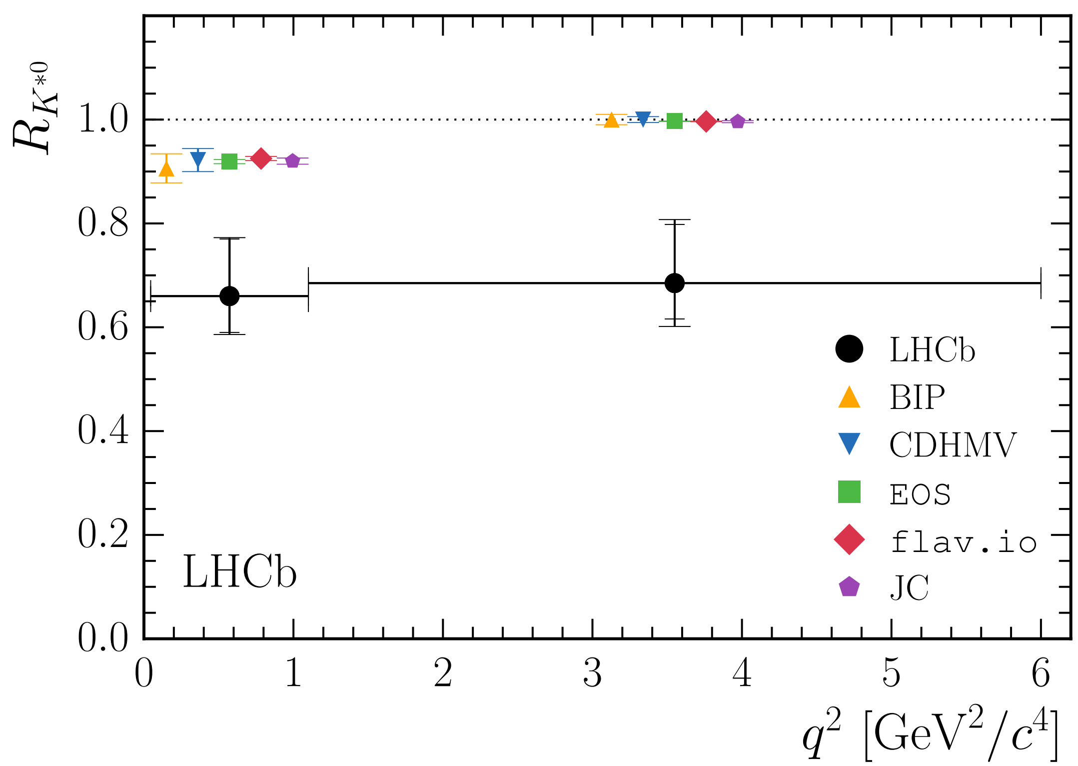


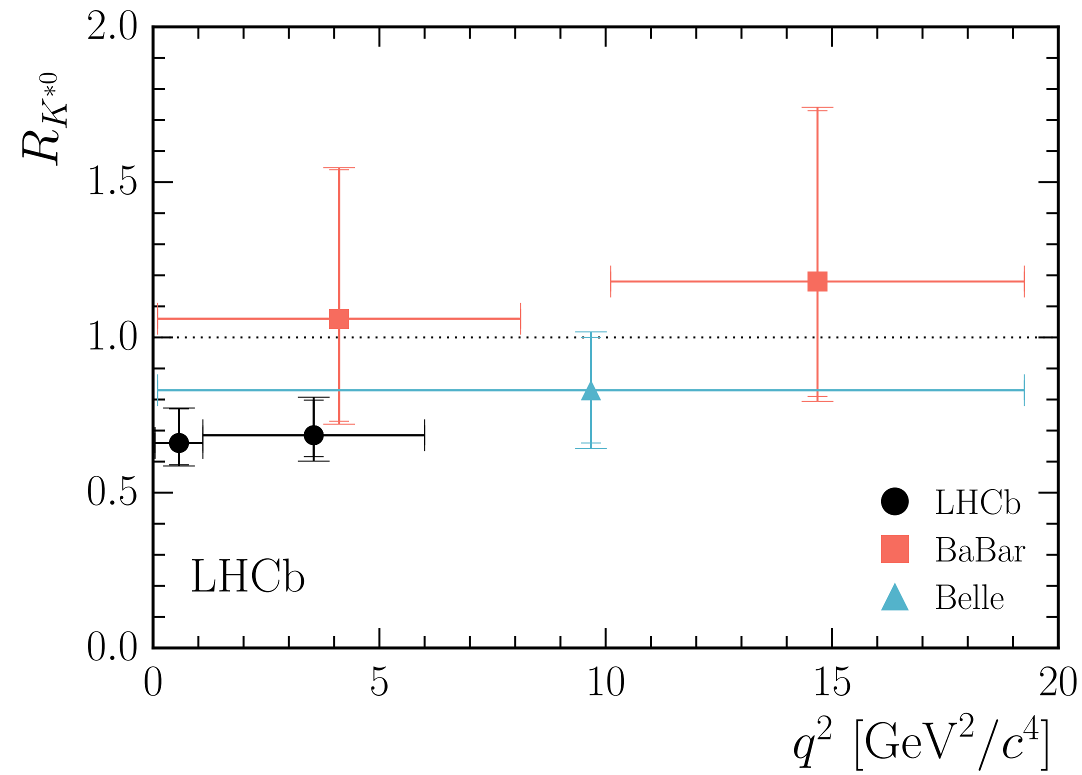

Feynman diagrams of the ***Standard Model*** : $B^0 \to K^{*0} l^+ l^-$ decay for the (top left) electroweak penguin and (top right) box diagram. Possible contributions violating LFU: ***New Physics*** - tree-level diagram mediated by a new gauge boson $Z'$ (bottom left) and (bottom right) tree-level diagram involving a leptoquark LQ.

Test of lepton universality with $B^0 \to K^{*0} l^+ l^-$ .The LHCb collaboration, arXiv:1705.05802

# Recent Results : LHCb Collaboration

- $R_{K^{*0}} = \frac{Br(B^0 \to K^{*0}\mu^+\mu^-)}{Br(B^0 \to K^{*0}e^+e^-)}$, inclusion of charge-conjugate processes is implied.
- $R_{K^{*0}}$ is expected to be close to unity in the Standard Model.




$$R_{K^{*0}} = \begin{cases} 0.66 \,{}^{+\,0.11}_{-\,0.07}\,(\text{stat}) \pm 0.03\,(\text{syst}) & \text{for } 0.045 < q^2 < 1.1 \;\; \text{GeV}^2/c^4\,, \\ 0.69 \,{}^{+\,0.11}_{-\,0.07}\,(\text{stat}) \pm 0.05\,(\text{syst}) & \text{for } 1.1 \;\; < q^2 < 6.0 \;\; \text{GeV}^2/c^4\,. \end{cases}$$

LHCb Public results : http://lhcbproject.web.cern.ch/lhcbproject/Publications/LHCbProjectPublic/LHCb-PAPER-2017-013.html

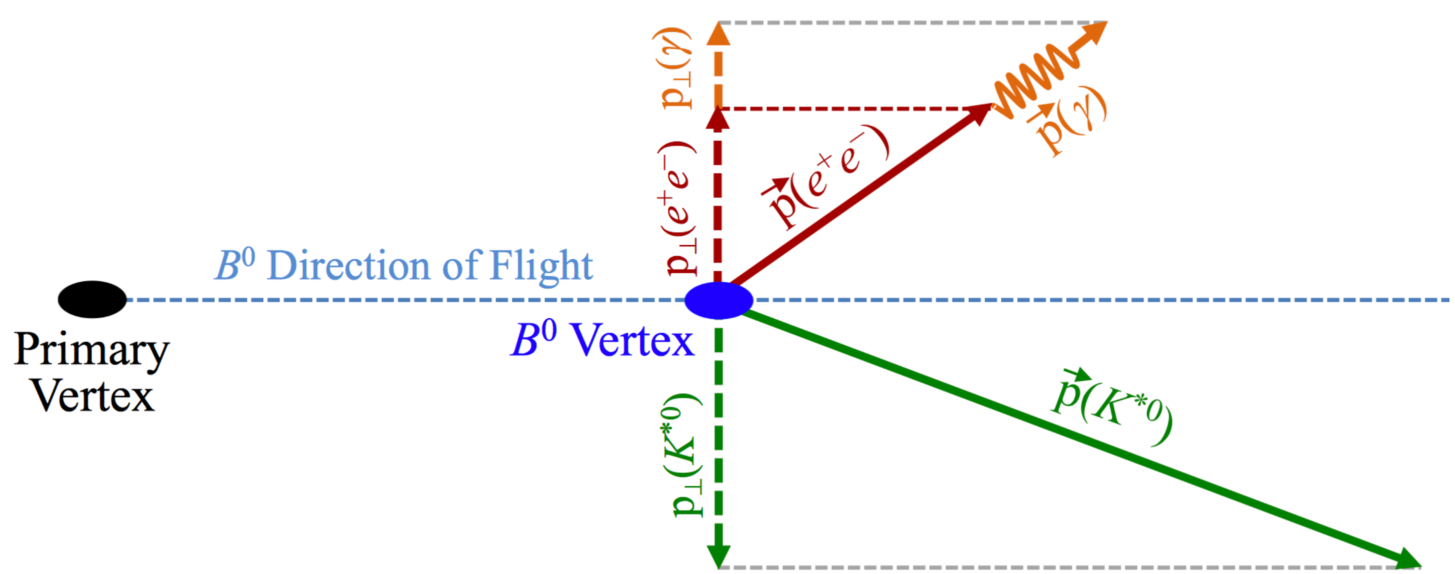
LHCb Paper : https://arxiv.org/pdf/1705.05802.pdf

Test of lepton universality with $B^0 \to K^{*0}l^+l^-$. The LHCb collaboration, arXiv:1705.05802

# Development of a new B-Physics trigger

$B^0 \to K^{*0}e^+e^-$

- Exciting results from LHCb hinting at Lepton Flavour Universality (LFU) violation in B-meson decays.
- Proposal for developing a new B-physics trigger for the ATLAS detector to cross check the results by studying similar decay processes.
- The B-Physics trigger will be designed for specifically selecting $B^0 \to K^{*0}e^+e^-$ events.




$B^0 \to K^{*0}e^+e^-$ decay topology $p_T$ lost via bremsstrahlung = ($K^{*0}$ $p_T$ - $e^+e^-$ $p_T$)
Calculated with respect to the $B^0$ meson direction of flight.

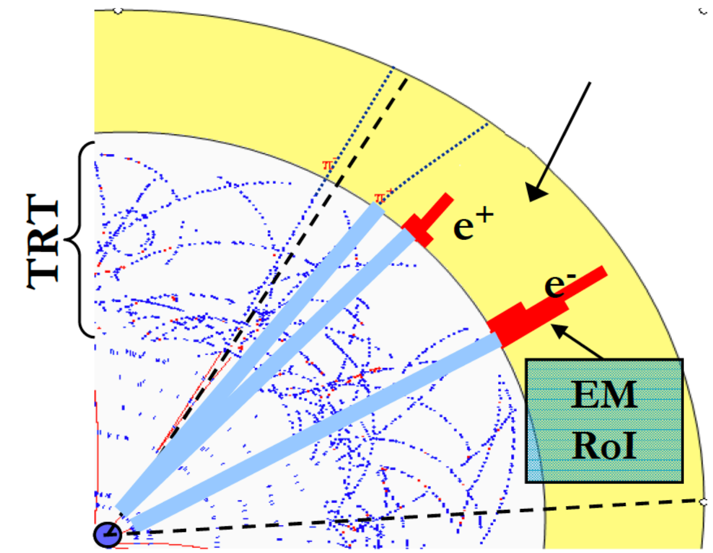
Test of lepton universality with $B^0 \to K^{*0}l^+l^-$ .The LHCb collaboration, arXiv:1705.05802

# Ongoing work in ATLAS

- Goal- To calculate the ratio $R_{K^{*0}} = \frac{Br(B^0 \to K^{*0}\mu^+\mu^-)}{Br(B^0 \to K^{*0}e^+e^-)}$
- Trigger for $B^0 \to K^{*0}\mu^+\mu^-$ already exists and data has been recorded using this trigger.
- A new trigger has to be developed for $B^0 \to K^{*0}e^+e^-$ decay process.
- Monte Carlo simulation (*Pythia8* + *BEvtGen*) is used to generate the decay process and is used for Level 1 and HLT trigger efficiency studies.
- The trigger should select *two opposite sign, low pT electrons* and reconstruct the invariant mass of $K^{*0}e^+e^-$ = invariant mass of the B-meson.
- $K^{*0}$ is reconstructed by requiring $K^+$ and $\pi^-$ tracks.
- Useful triggers for selecting soft electrons are already implemented for other analyses: $J/\psi \to e^+e^-$, $Z \to e^+e^- \gamma$, $H \to \gamma\gamma^* \to \gamma\, e^+e^-$.

# Level 1 Trigger Efficiency

- The currently implemented J/$\psi$ L1Topo triggers are emulated and modified to study the trigger efficiencies.
- Trigger efficiencies are plotted against three variables from the $B^0 \rightarrow K^{*0}e^+e^-$ MC simulation:
  - Invariant Mass of the two daughter electrons - Mass (ee)
  - Angular distance ($\Delta$R) between the two electrons - $\Delta$R (ee)
  - Transverse momentum of the B-Meson - B-meson pT

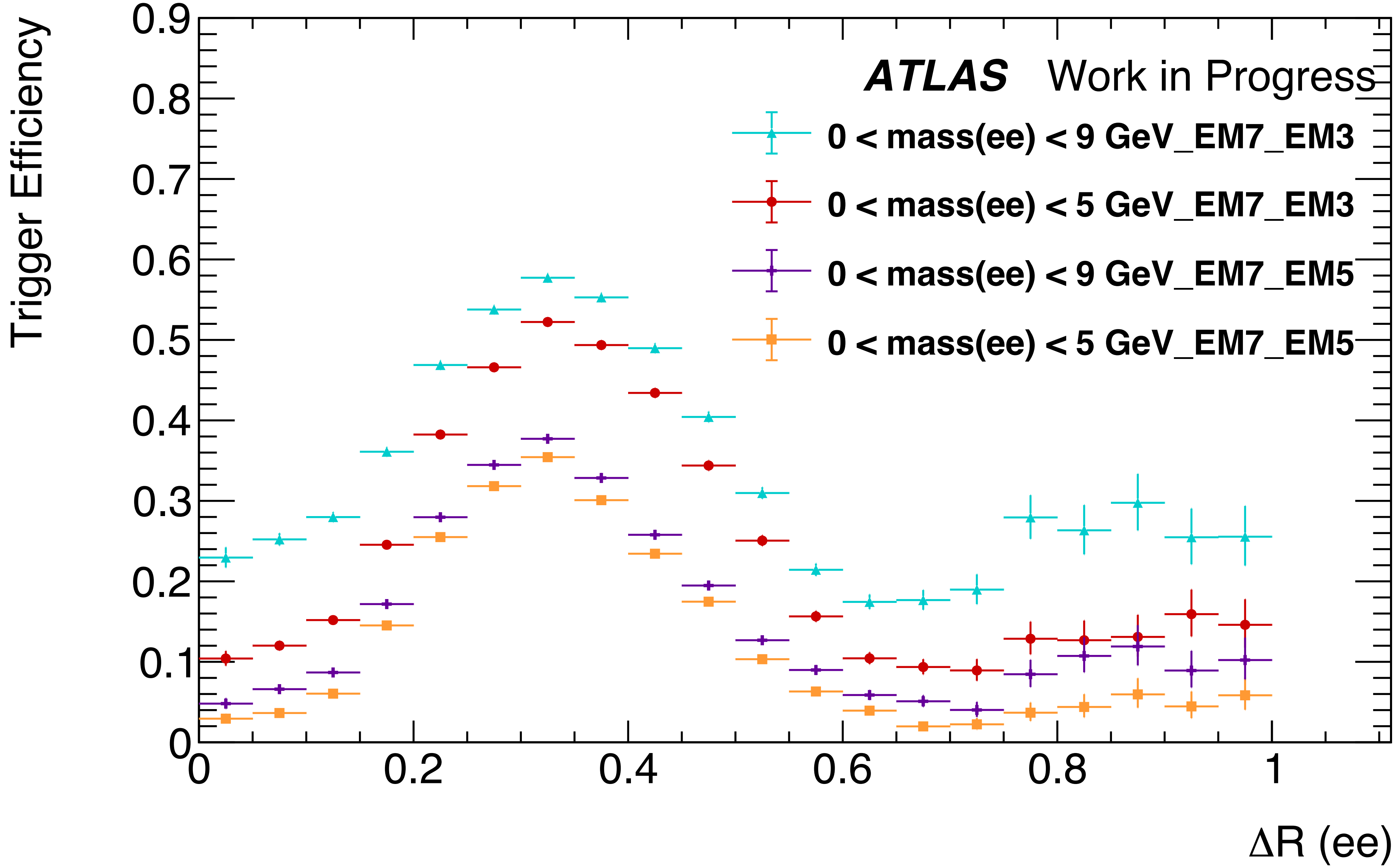


Courtesy: Julie Kirk

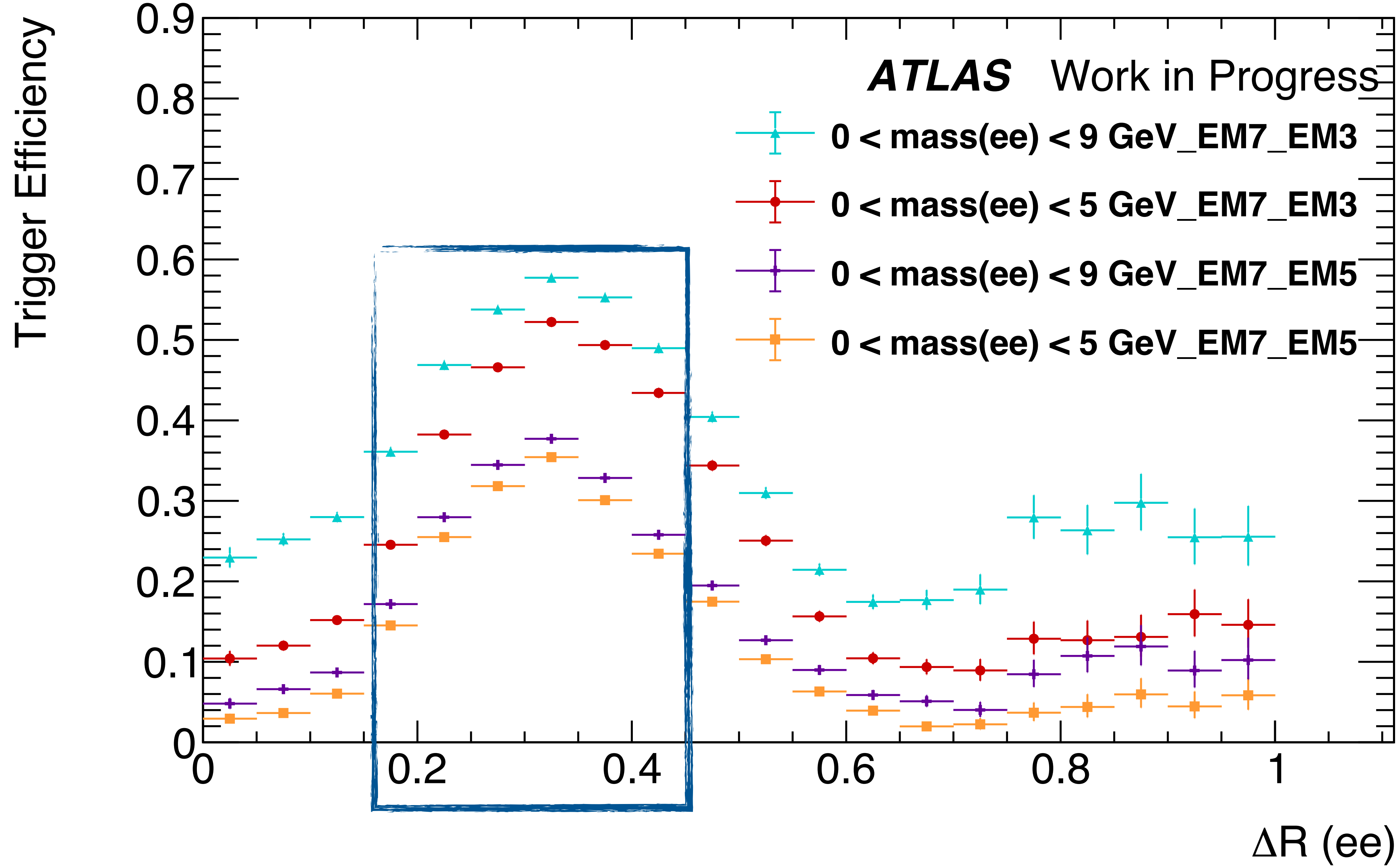
- $$Trigger\ Efficiency = \frac{L1_{selected}\ \&\ Truth_{ee,matched}}{Truth_{ee,matched}}$$

- ***Truth electrons*** - electrons generated by the MC simulation, ***Reconstructed electrons*** - electrons after they pass the detector simulation.
- $L1_{selected}$ - events passing specific L1 Trigger cuts.
- $Truth_{\ ee,matched}$ - electron pairs with both matched to truth electrons, if they lie within $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.1$
- EM7, EM5, EM3 - RoI objects in the Electromagnetic Calorimeter; 7, 5, 3 are the transverse momentum (pT) cuts (EM7 : EM RoI with pT > 7 GeV).

# Trigger Efficiency vs ΔR (ee)



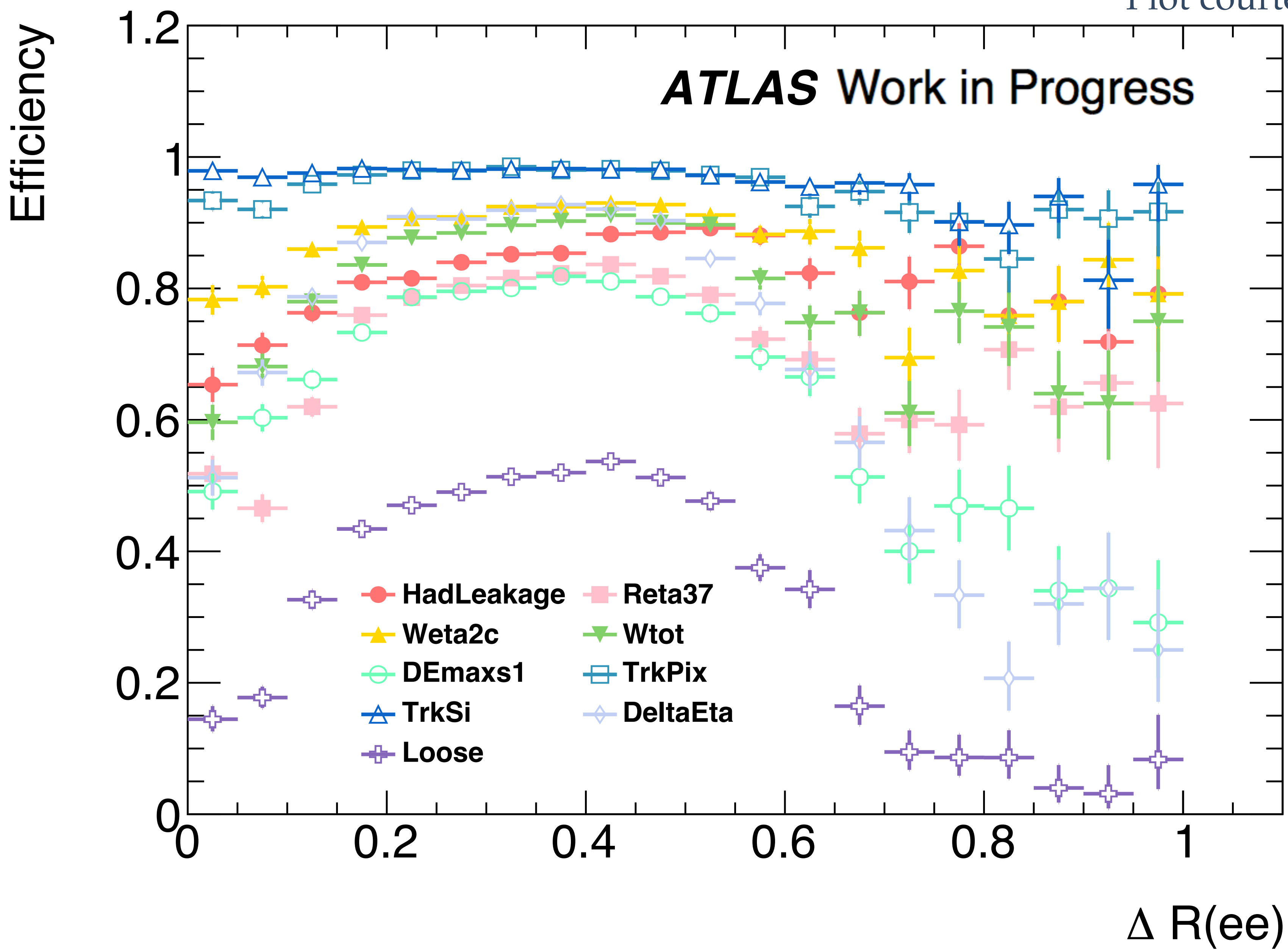
# Trigger Efficiency vs ΔR (ee)




- Highest trigger efficiency : 0 < mass (ee) < 9GeV_EM7_EM3. But, highest efficiency ≠ best trigger
- 0 < mass (ee) < 9 GeV_EM7_EM5 is selected as the best L1 Trigger; background rate is high for the other triggers.

# Cut-Based Trigger Efficiency vs ΔR (ee)

Plot courtesy : Heather Russell



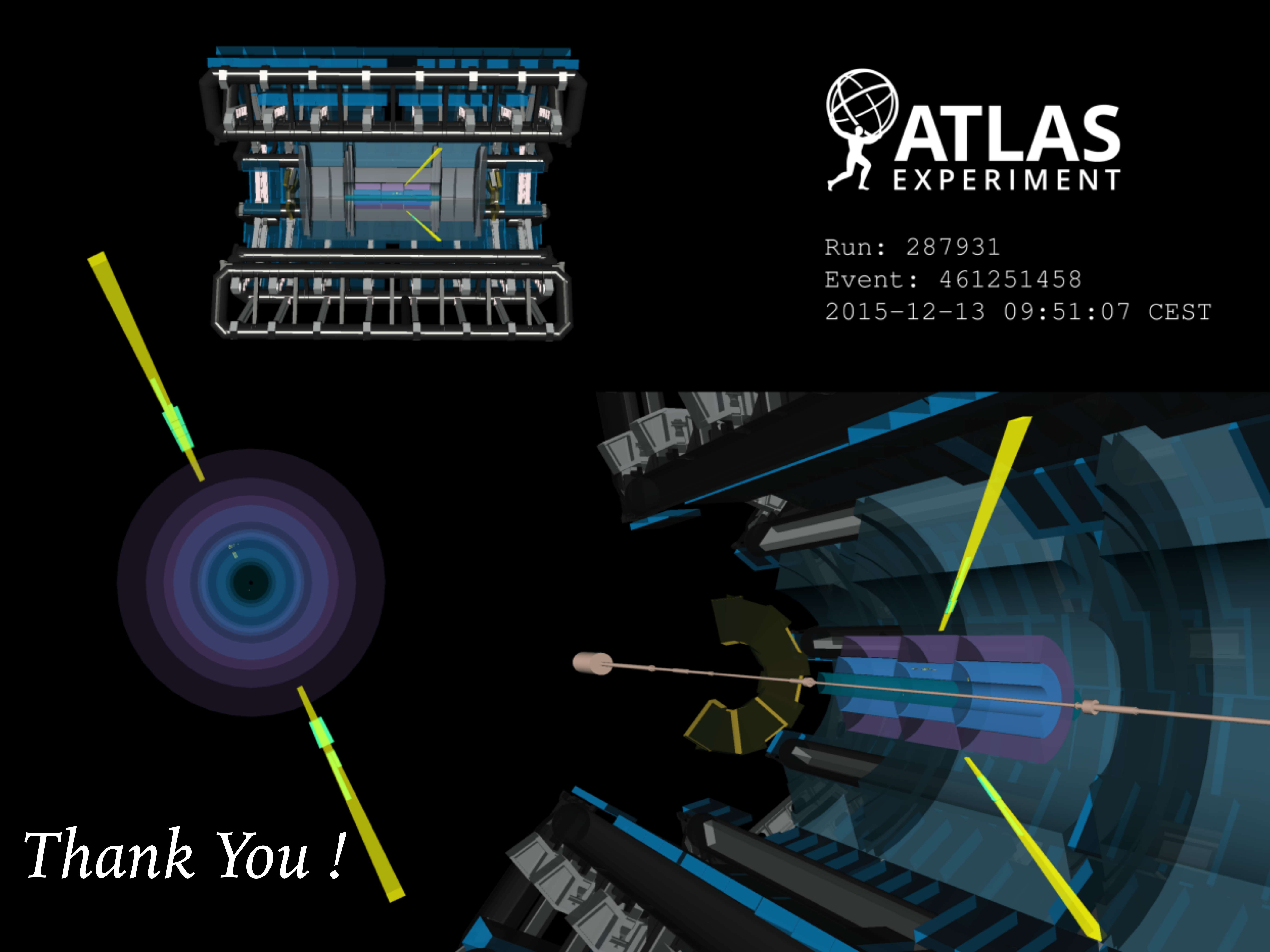

- Efficiency of triggers (*Efficiency to pass HLT_e9_X_e5_X, for events that pass L1 cuts, X is the cut, e.g. e9_loose_e5_loose*) is the highest at low ΔR values. Boosted B-meson = low ΔR (ee).
- Need to define a new Electron ID for selecting close-by electrons.

# Summary and Next Steps

- ATLAS is developing a new B-Physics Trigger for the $B^0 \rightarrow K^{*0}e^+e^-$ decay process to study Lepton Flavour Universality and validate the results ($R_{K^{*0}}$) observed in B-meson decays.

$B^0 \rightarrow K^{*0}\mu^+\mu^-$ and $B^0 \rightarrow K^{*0}e^+e^-$

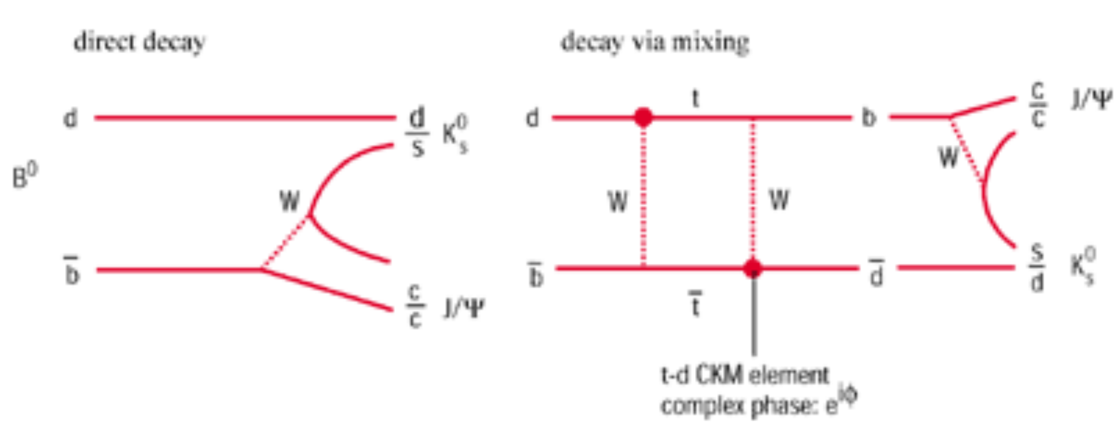
- Prospects for the trigger look promising, existing L1Topo J/$\psi$ trigger has been modified and applied.
- Currently testing a Likelihood Electron ID definition and defining a new electron ID in terms of low $\Delta R$ which is correlated with the boost of the B-meson.

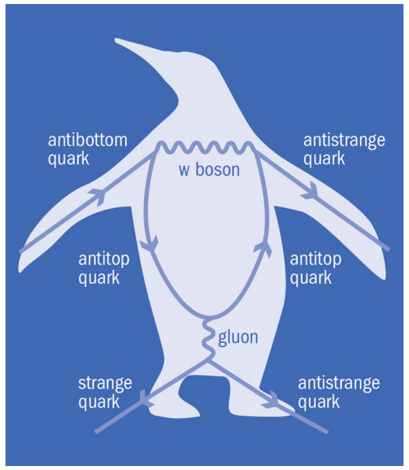

ATLAS
EXPERIMENT
Run: 287931
Event: 461251458
2015-12-13 09:51:07 CEST
Thank You !

# Backup - LHC, FCNC Processes

- The beams travel in opposite directions in separate beam pipes kept at ultrahigh vacuum. guided by a strong magnetic field maintained by superconducting electromagnets - superconducting state (-271.3°C)
- The beams in the LHC are made up of bunches of protons, spaced seven metres (25 nanoseconds) apart, with each one containing more than 100 billion protons. 2556 is the maximum possible number of bunches.
- 40 million bunch crossings per second, less than 100,000 are kept by the Level-1 trigger.
- The **trigger** system selects 100 interesting events per second out of 1000 million total.

- Flavor-changing neutral currents (FCNC) - hypothetical expressions that change the flavor of a fermion current without altering its electric charge.
- Occurs in the Standard Model beyond the tree level, but they are highly suppressed by the GIM mechanism.
- The Tevatron CDF experiment first observed the FCNC decay of the strange B-meson to phi mesons in 2005.
- B decays are characterized by three angles:
  - $\theta_K$, which describes the $K^*$ decay
  - $\theta_l$, which describes the dilepton decay; and Φ,
  - the angle between the $K^*$ and
  - the dilepton decay planes.
- Leptoquark - Color-triplet bosons that carry both lepton and baryon numbers. Not observed yet, LHC has excluded range to about 1 TeV.



# Backup - Results LHCb Collaboration

- Results presented are for $3fb^{-1}$ data and 7 and 8 TeV center of mass energy, BR (B-> K*ee
- B meson : 5.29 GeV, $K^{*0}$ reconstructed in the final state $K^{+}\pi^{-}$, invariant mass within $100 MeV/c^2$ of the known $K^{*}$(89
- *H* -> hadron containing an s quark (a K or a K* meson)
- Γ -> decay rate, integrated over $q^2$.

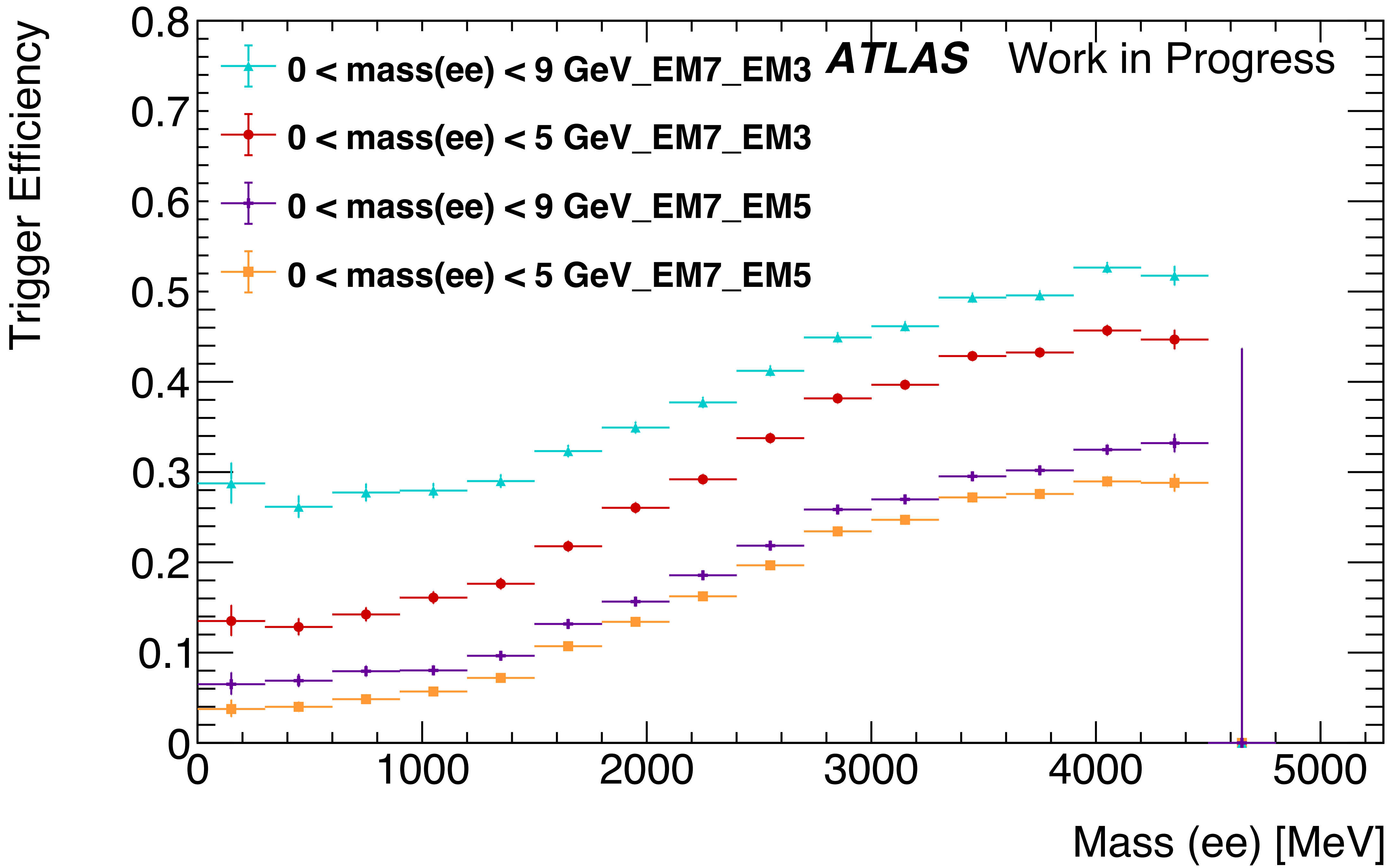
- Plots on Slide 7 (Left) Comparison of the LHCb $R_{K^{*0}}$ measurements with the SM theoretical predictions: BIP, CDHMV, EOS, flav.io, JC.
- (Right) Comparison of the LHCb $R_{K^{*0}}$ measurements with previous experimental results from the B factories .

$$R_H = \frac{\int \frac{d\Gamma(B\to H\mu^+\mu^-)}{dq^2}\, dq^2}{\int \frac{d\Gamma(B\to He^+e^-)}{dq^2}\, dq^2}$$

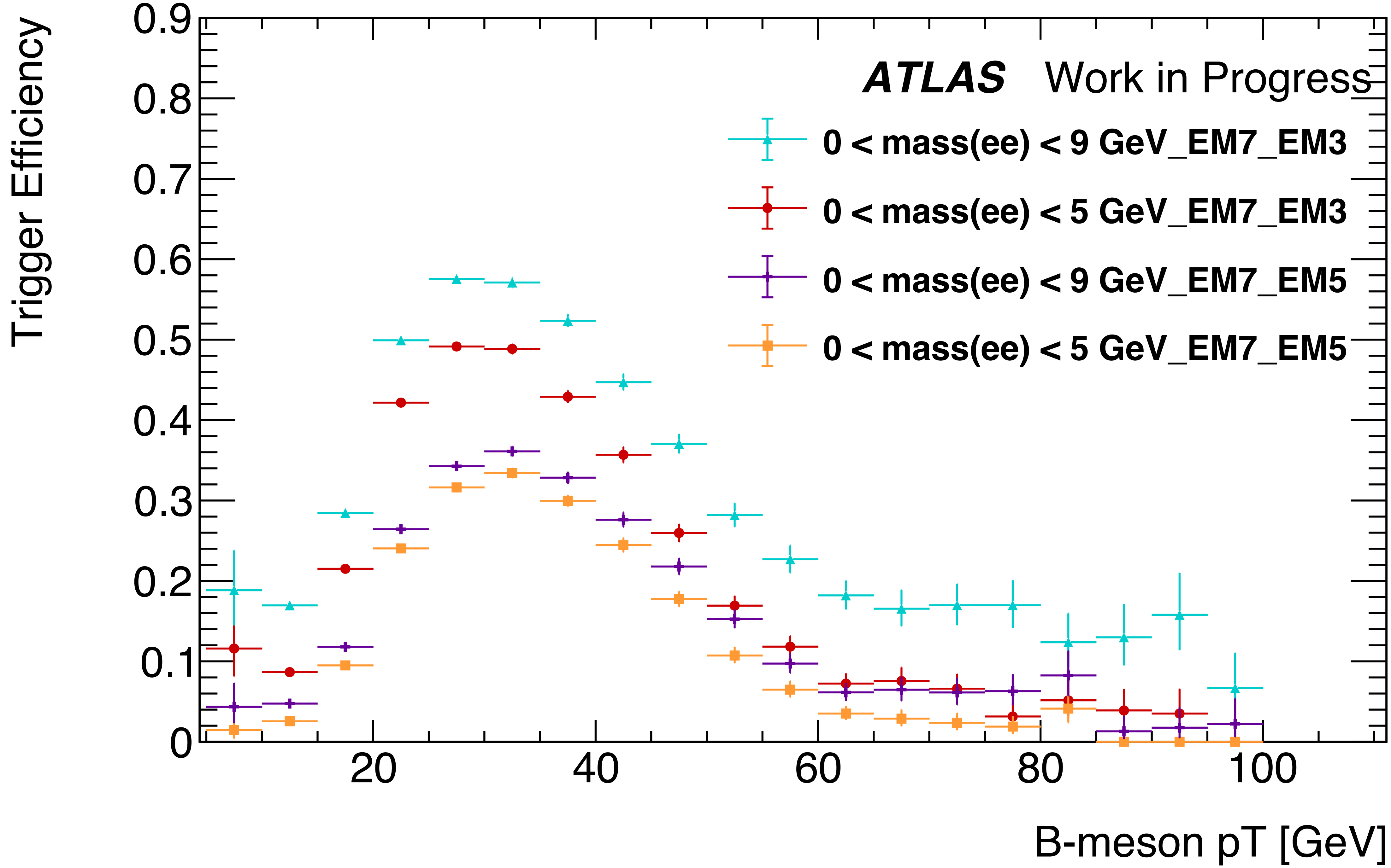
$$R_{K^{*0}} = \frac{\mathcal{B}(B^0\to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0\to K^{*0}J/\psi(\to\mu^+\mu^-))}\Bigg/\frac{\mathcal{B}(B^0\to K^{*0}e^+e^-)}{\mathcal{B}(B^0\to K^{*0}J/\psi(\to e^+e^-))}$$

- The lower boundary of the low-$q^2$ region roughly corresponds to the di-muon production threshold. The 6 $GeV^2/c^4$ upper boundary is chosen to reduce a possible contamination from the J/ψ particle.
- Double Ratio = reduce systematics
- The corresponding 95.4% confidence level intervals are [0:52; 0:89] and [0:53; 0:94]. The ratio, is compatible with the Standard Model expectations at the level of 2.1 - 2.3 and 2.4 - 2.5 standard deviations in the two $q^2$ regions, respectively

# Trigger Efficiency vs Mass (ee)



# Trigger Efficiency vs B-meson pT



# Backup - Electron Cut-Based Variables

Challenges - low pT, forward region, B meson pT = 30 GeV (comparatively very low pT)

Currently Implemented - This common electron selection is a simple cut-based selection using the particle identification variables

The *Electron Likelihood* takes one dimensional signal and background PDFs as input, and returns a likelihood discriminate

- Need to define a new Electron ID at the HLT level for low dR electrons
- Using Jpsi decays, because they are a good source of soft electrons

***Likelihood method for Electron ID definition***

- Create Signal Parton Distribution (PDF) function in which the selection is defined for to select the soft electrons. Currently using $J/\psi$ dataset set to a $\Delta$R range of 0 -0.4
- Create Background PDF - Used Fakes (EGAM7 derivation) - pass at least one HLT e/gamma trigger with one electron pT > 4.5GeV
- Running the LH code on the signal and background PDFs
- Note : All PDFs are currently Data Driven

Table 1: Definition of electron discriminating variables.

| Type | Description | Name |
|---|---|---|
| Hadronic leakage | Ratio of $E_T$ in the first layer of the hadronic calorimeter to $E_T$ of the EM cluster (used over the range $\|\eta\| < 0.8$ or $\|\eta\| > 1.37$) | $R_{Had1}$ |
| | Ratio of $E_T$ in the hadronic calorimeter to $E_T$ of the EM cluster (used over the range $0.8 < \|\eta\| < 1.37$) | $R_{Had}$ |
| Back layer of EM calorimeter | Ratio of the energy in the back layer to the total energy in the EM accordion calorimeter | $f_3$ |
| Middle layer of EM calorimeter | Lateral shower width, $\sqrt{(\Sigma E_i \eta_i^2)/(\Sigma E_i) - ((\Sigma E_i \eta_i)/(\Sigma E_i))^2}$, where $E_i$ is the energy and $\eta_i$ is the pseudorapidity of cell $i$ and the sum is calculated within a window of $3 \times 5$ cells | $W_{\eta 2}$ |
| | Ratio of the energy in $3 \times 3$ cells to the energy in $3 \times 7$ cells centred at the electron cluster position | $R_\phi$ |
| | Ratio of the energy in $3 \times 7$ cells to the energy in $7 \times 7$ cells centred at the electron cluster position | $R_\eta$ |
| Strip layer of EM calorimeter | Shower width, $\sqrt{(\Sigma E_i (i - i_{max})^2)/(\Sigma E_i)}$, where $i$ runs over all strips in a window of $\Delta\eta \times \Delta\phi \approx 0.0625 \times 0.2$, corresponding typically to 20 strips in $\eta$, and $i_{max}$ is the index of the highest-energy strip | $w_{stot}$ |
| | Ratio of the energy difference between the maximum energy deposit and the energy deposit in a secondary maximum in the cluster to the sum of these energies | $E_{ratio}$ |
| | Ratio of the energy in the strip layer to the total energy in the EM accordion calorimeter | $f_1$ |
| Track quality | Number of hits in the b-layer (discriminates against photon conversions) | $n_{Blayer}$ |
| | Number of hits in the pixel detector | $n_{Pixel}$ |
| | Total number of hits in the pixel and SCT detectors | $n_{Si}$ |
| | Transverse impact parameter | $d_0$ |
| | Significance of transverse impact parameter defined as the ratio of the magnitude of $d_0$ to its uncertainty | $\sigma_{d_0}$ |
| | Momentum lost by the track between the perigee and the last measurement point divided by the original momentum | $\Delta p/p$ |
| TRT | Total number of hits in the TRT | $n_{TRT}$ |
| | Ratio of the number of high-threshold hits to the total number of hits in the TRT | $F_{HT}$ |
| Track–cluster matching | $\Delta\eta$ between the cluster position in the strip layer and the extrapolated track | $\Delta\eta_1$ |
| | $\Delta\phi$ between the cluster position in the middle layer and the extrapolated track | $\Delta\phi_2$ |
| | Defined as $\Delta\phi_2$, but the track momentum is rescaled to the cluster energy before extrapolating the track to the middle layer of the calorimeter | $\Delta\phi_{res}$ |
| | Ratio of the cluster energy to the track momentum | $E/p$ |
| Conversions | Veto electron candidates matched to reconstructed photon conversions | isConv |

# Likelihood Approach

- Electron LH uses of signal and background probability density functions (PDFs) of the discriminating variables, PDFs are data-driven.
- The signal and background probabilities for a given electron candidate are combined into a discriminant $d_{\mathcal{L}}$

$$d_{\mathcal{L}} = \frac{\mathcal{L}_S}{\mathcal{L}_S + \mathcal{L}_B}, \qquad \mathcal{L}_{S(B)}(\vec{x}) = \prod_{i=1}^{n} P_{S(B),i}(x_i)$$

- $\eta$ range = 0, 0.6, 0.8, 1.15, 1.37, 1.52, 2.37, 1.81, 2.01, 2.37; $E_t$ range (GeV) = 4-7, 7-10, 10…45 (in intervals of 5 GeV).