Search for Highly Ionizing Particles in 13 TeV proton-proton collisions with the ATLAS Detector

Priyanka Kumari

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What are magnetic monopoles?

- **Question:**
  - Could a magnetic particle with one pole exist?
- **Dirac Magnetic Monopoles:**
  - Magnetic monopoles are particles with a single magnetic charge - either South or North.
  - They are analogous to electrons - fundamental particle with electric charge “e”.
- In contrast to Dirac magnetic monopoles, the monopoles in Grand Unified Theory are composite particles that can be produced in early universe.
- ATLAS experiment is able to look for point-like and structureless Dirac monopoles - No assumptions about the spin and mass.

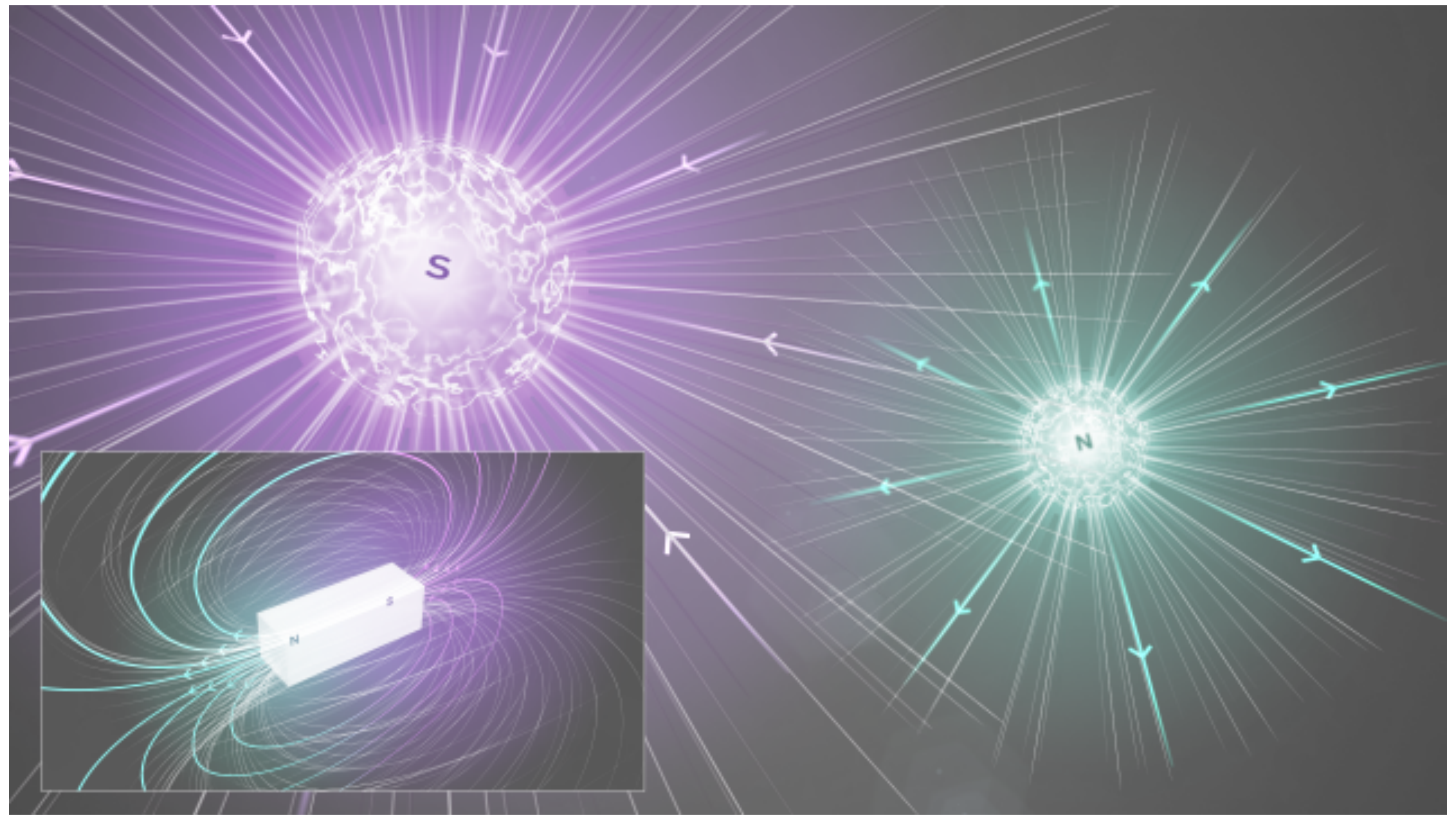


Figure : CERN

Why do we look for them?

- Their existence will restore the electric-magnetic dual symmetry in Maxwell's equations.

$$\nabla . E = \rho_e \ , \qquad \nabla \times E = -J_m - \frac{\partial B}{\partial t} \ , \qquad \nabla . B = \rho_m \ , \qquad \nabla \times B = J_e + \frac{\partial E}{\partial t}$$

(ρ_m - magnetic charge density, ρ_e - electric charge density), (J_m - magnetic current, J_e - electric current).

- Their existence will explains the quantisation of electric charge. According to Dirac quantization condition $\frac{q_e q_m}{\hbar c} = \frac{n}{2}$, the smallest magnetic charge a monopole can possess:

$$g_D = \frac{1}{2\alpha} \approx 68.5e$$

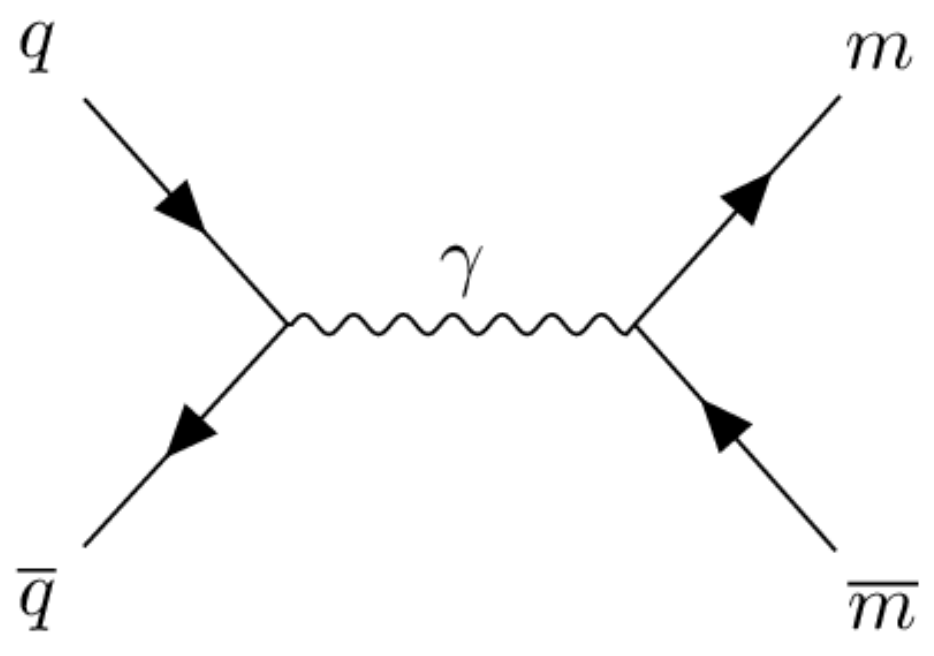
→ Due to magnetic charge conservation, a monopole would be stable (long lived particles).

→ Similar energy loss as of an ion carrying electric charge |z| = 68.5e hence, magnetic monopoles along with Highly-Electric-Charge-Objects (HECOs) are knowns as **Highly Ionizing Particles** (HIPs).

How do we produce them in LHC ?

- Two pair production mechanism are used to look for HIPs at LHC in proton-proton collisions:

- Drell-Yan



- Photon-fusion

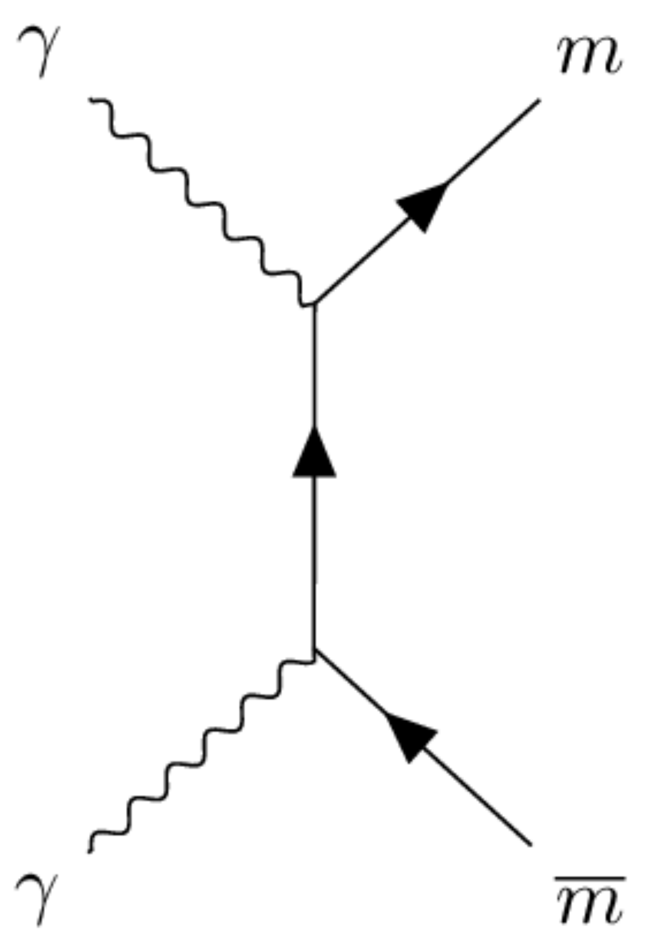


Fig: Feynman diagram for photon-mediated Drell-Yan (left) and Photon-Fusion (right) monopole pair production

- Charges - $1g_D$ and $2g_D$ monopoles, HECOs, |z| = 20 - 100.
- Masses - 200, 500, 1000, 1500, 2000, 2500, 3000 and 4000 GeV.
- We consider these charges/masses for our Run 2 analysis with p-p collisions at 13 TeV - 138 fb^{-1}.
- The dedicated HIP trigger (HLT_g0_hiptrt_L1EM22VHI) uses a region of interest from the EM calorimeter at level 1 and counts the low and high threshold TRT hits.

ATLAS detector at LHC

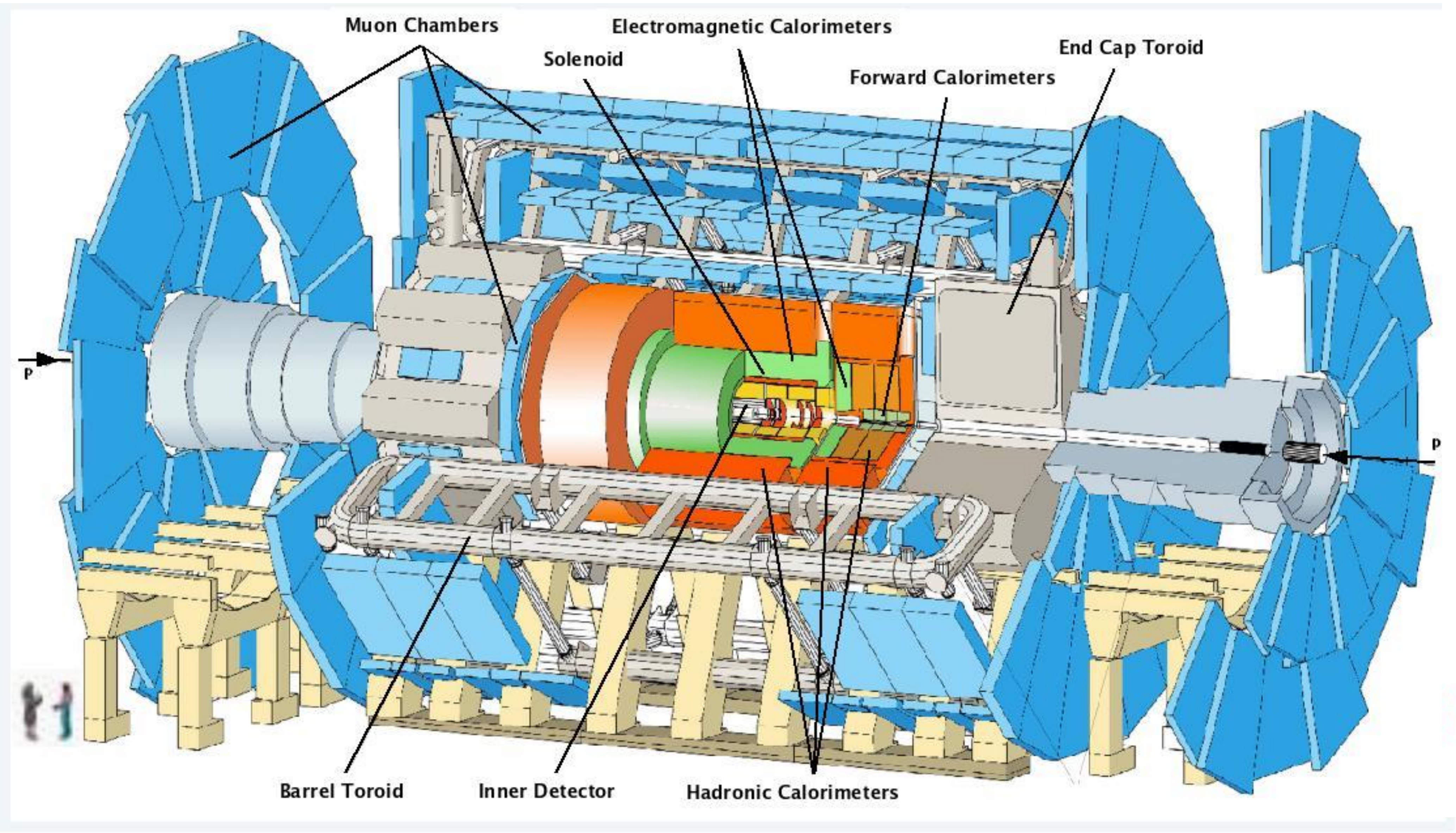


Fig:overall view of ATLAS detector

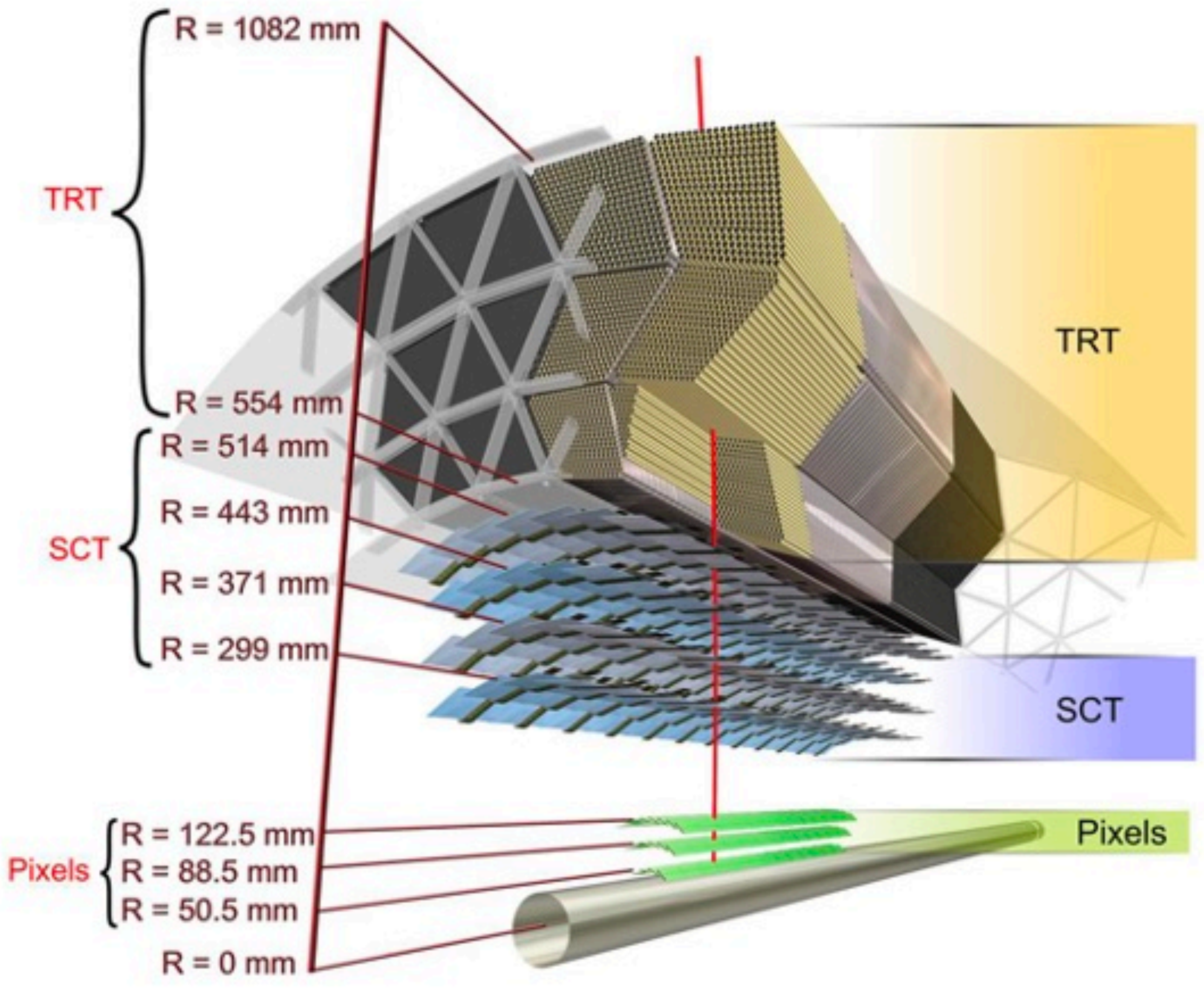


Fig: Inner detector geometry

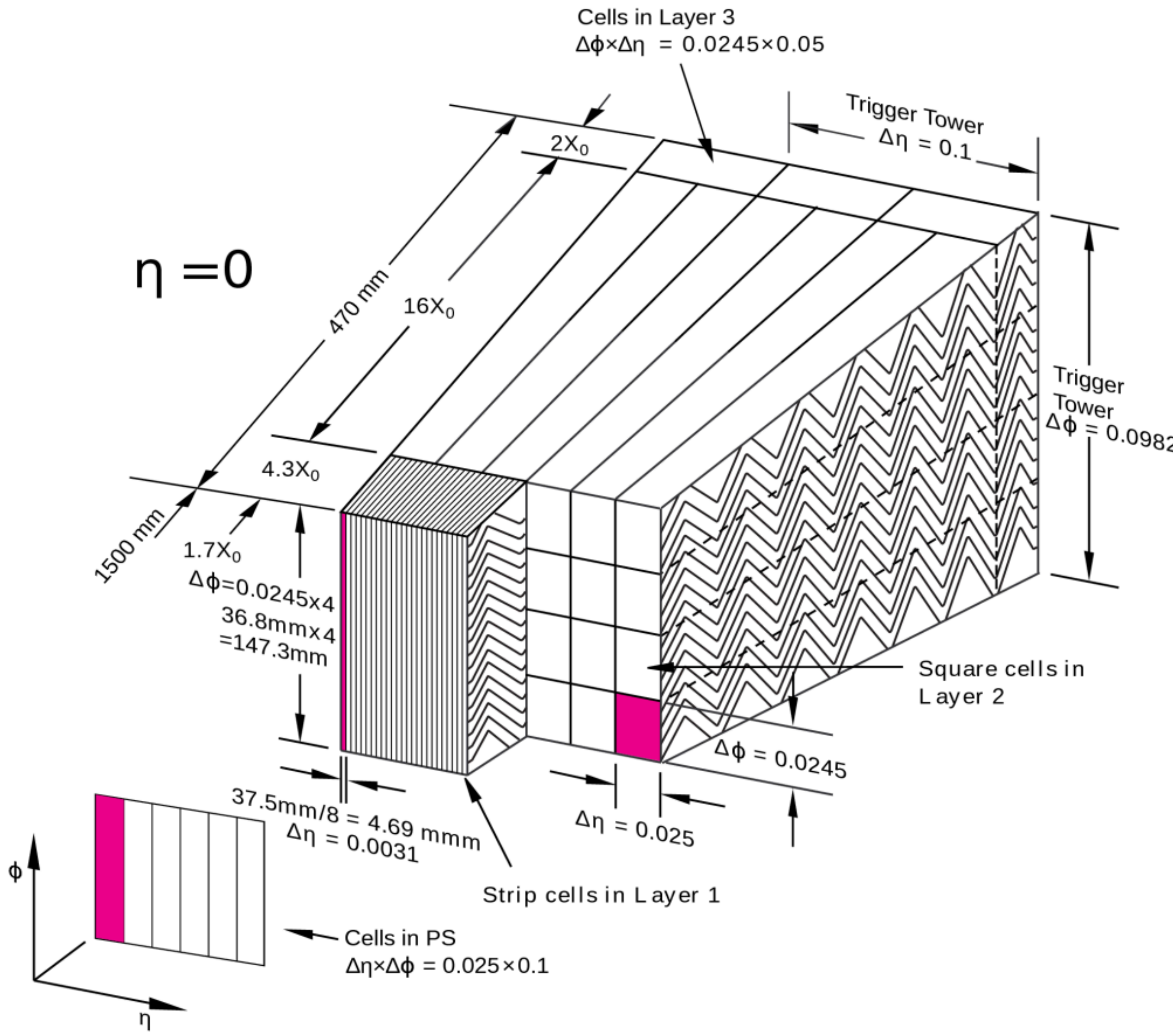


Fig: Layer structure of channels for the EM Calorimeter.

- Multipurpose detector to search for physics within and beyond the Standard Model (SM).
- Comprises Inner tracking detector (ID) surrounded by solenoid of 2T magnetic field, electromagnetic (EM) and hadronic calorimeters and a muon spectrometer.

- HIPs exploit their signature in Transition Radiation Tracker (TRT) in ID and EM calorimeter.

HIP Signal Signature

- Energy loss of HIPs is described by Bethe-Bloch equation:

$$-\frac{dE}{dx} = z^2 K \frac{Z}{A}\frac{1}{\beta^2}[ln\frac{2m_e c^2\beta^2\gamma^2}{I} - \beta^2]$$

- Energy loss $\propto$ (z)^2 - (4700 x more ionising than proton).
- High ionisation produces many large energy deposits in TRT region (low & high threshold hits).
- Large and narrow energy deposition in LAr EM calorimeter (too heavy to induce a shower like electron & photon.)
- HIPs also kick off lots of electrons from inner atomic orbitals, (δ-rays) which further ionise the detector material to produce more HT hits.
- Two signal/background discrimination variables:
  - **w** (calorimeter energy dispersion.)
  - **f_{HT}** (fraction of high-threshold (HT) hits.)

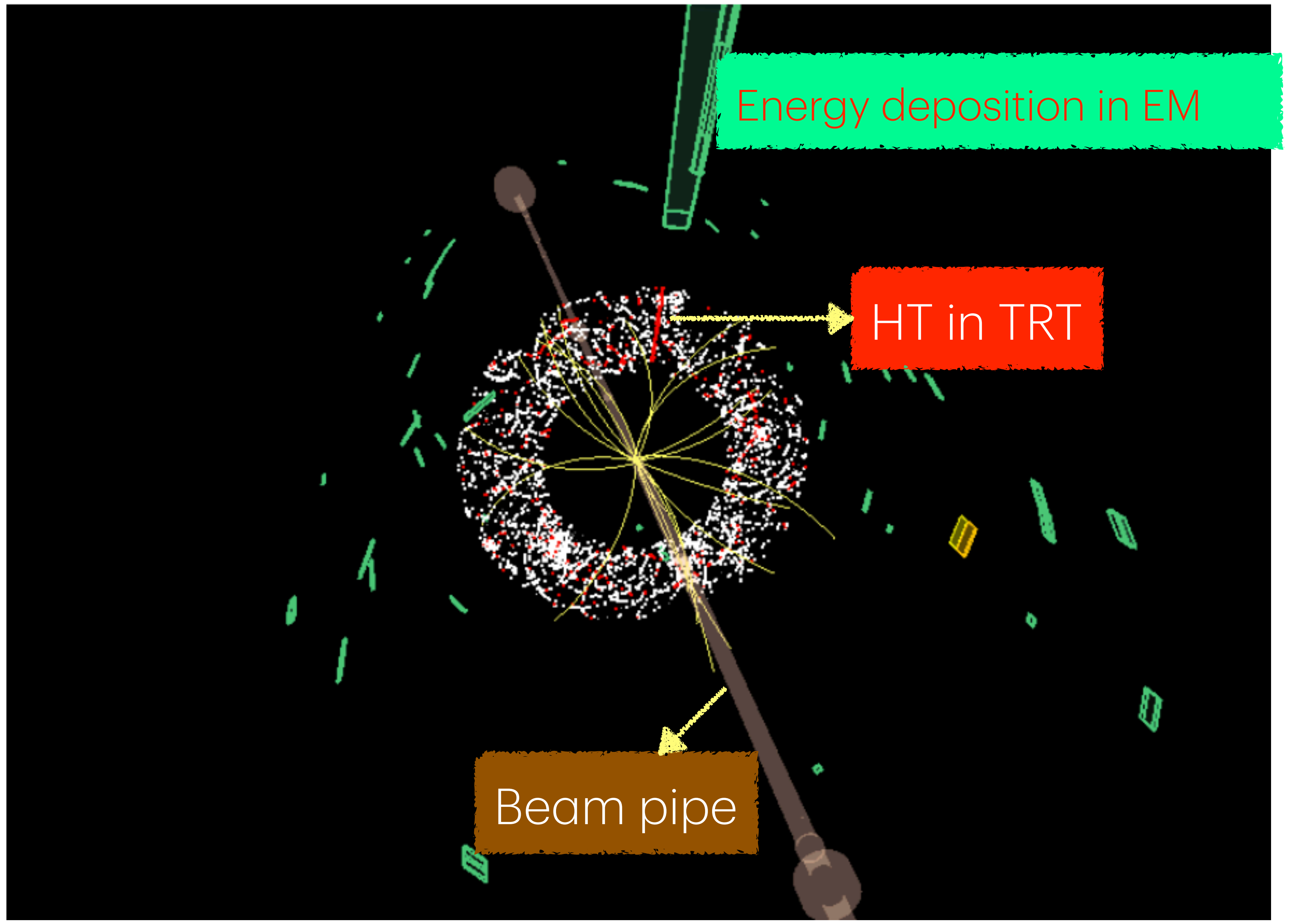
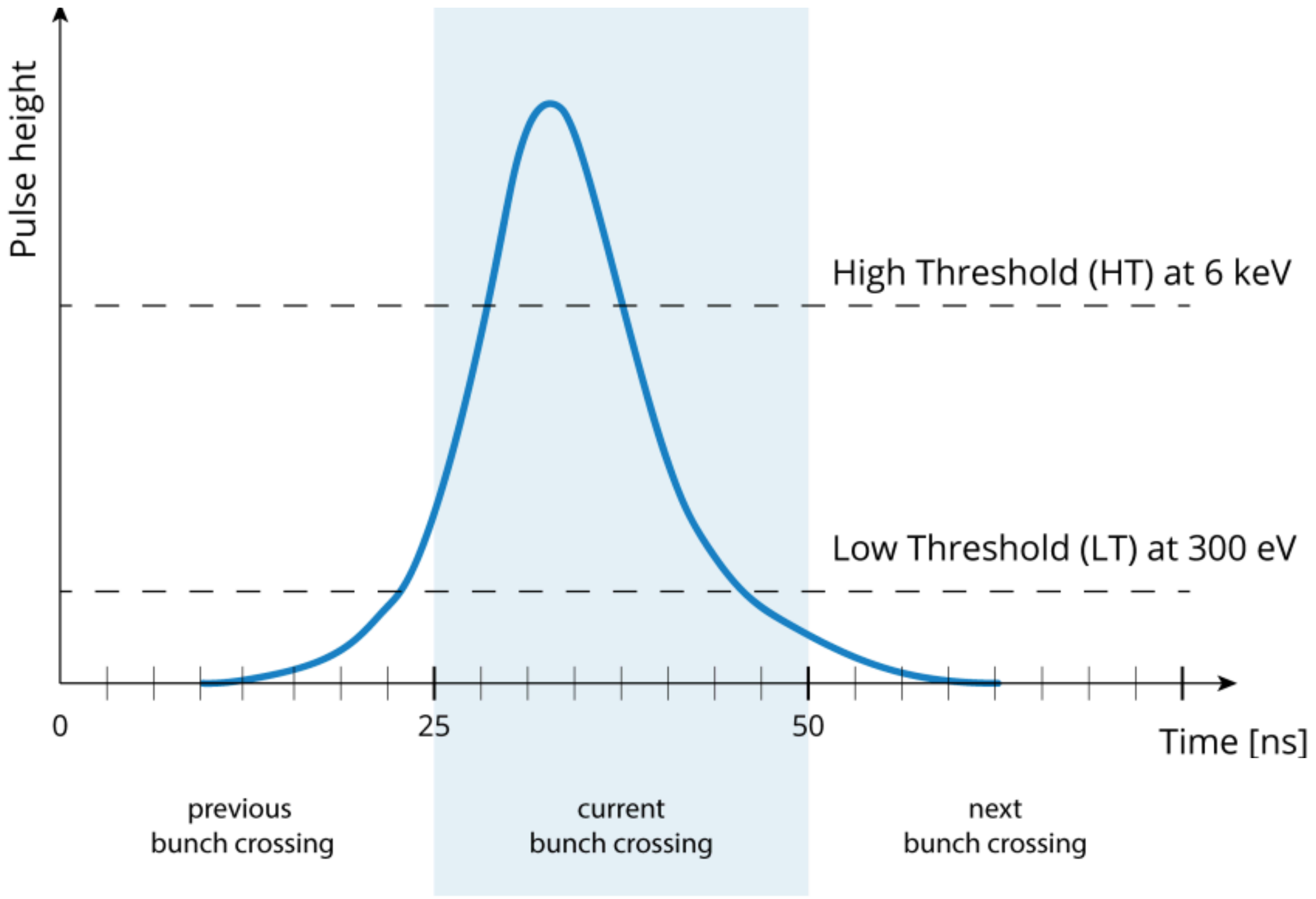


Fig: Event display for charge 1gD and mass 1000 GeV monopole in ATLAS

Signal Selection Variables

f_{HT}

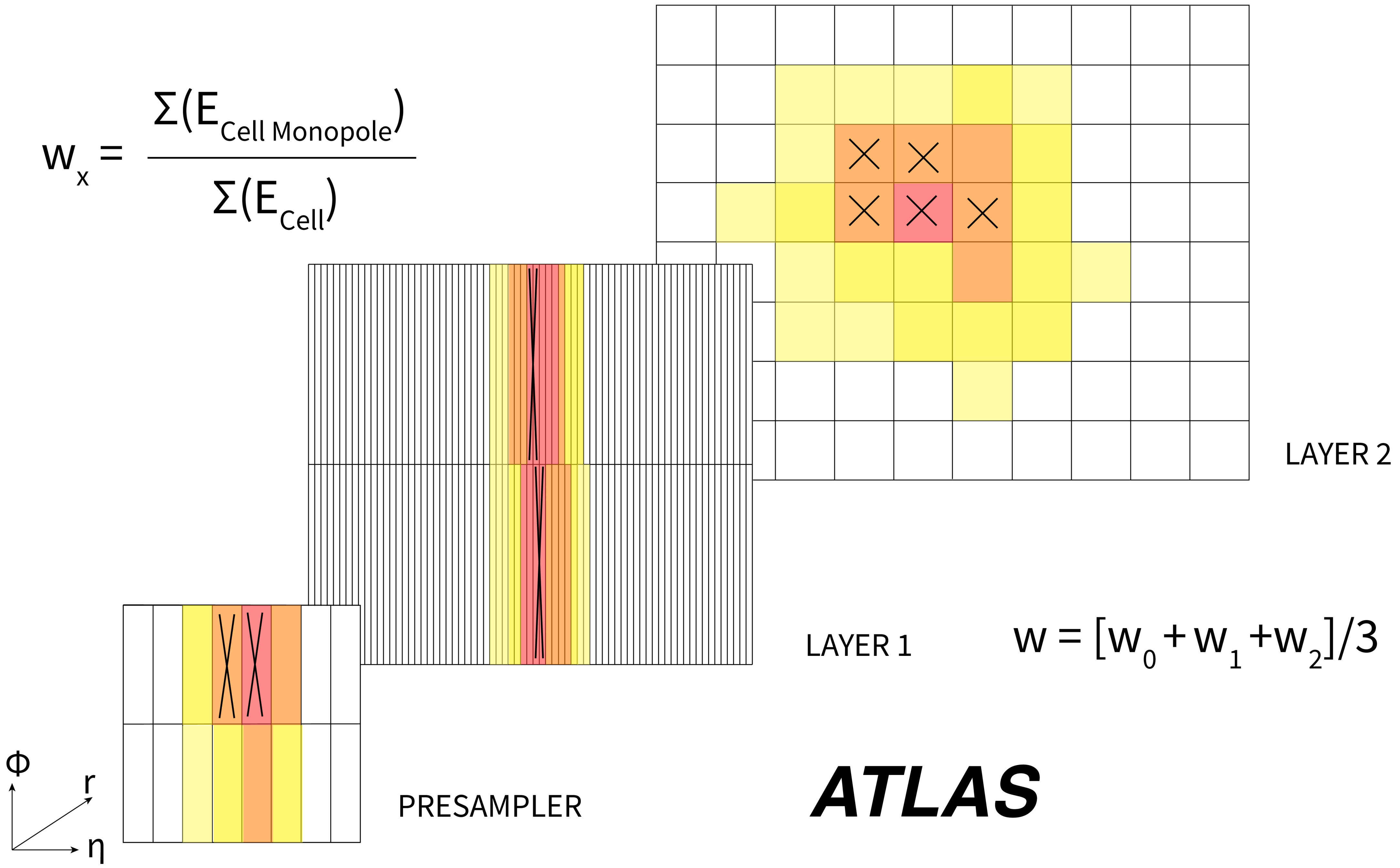
$$f_{HT} = \frac{HT_{hits}}{HT_{hits} + LT_{hits}}$$



w

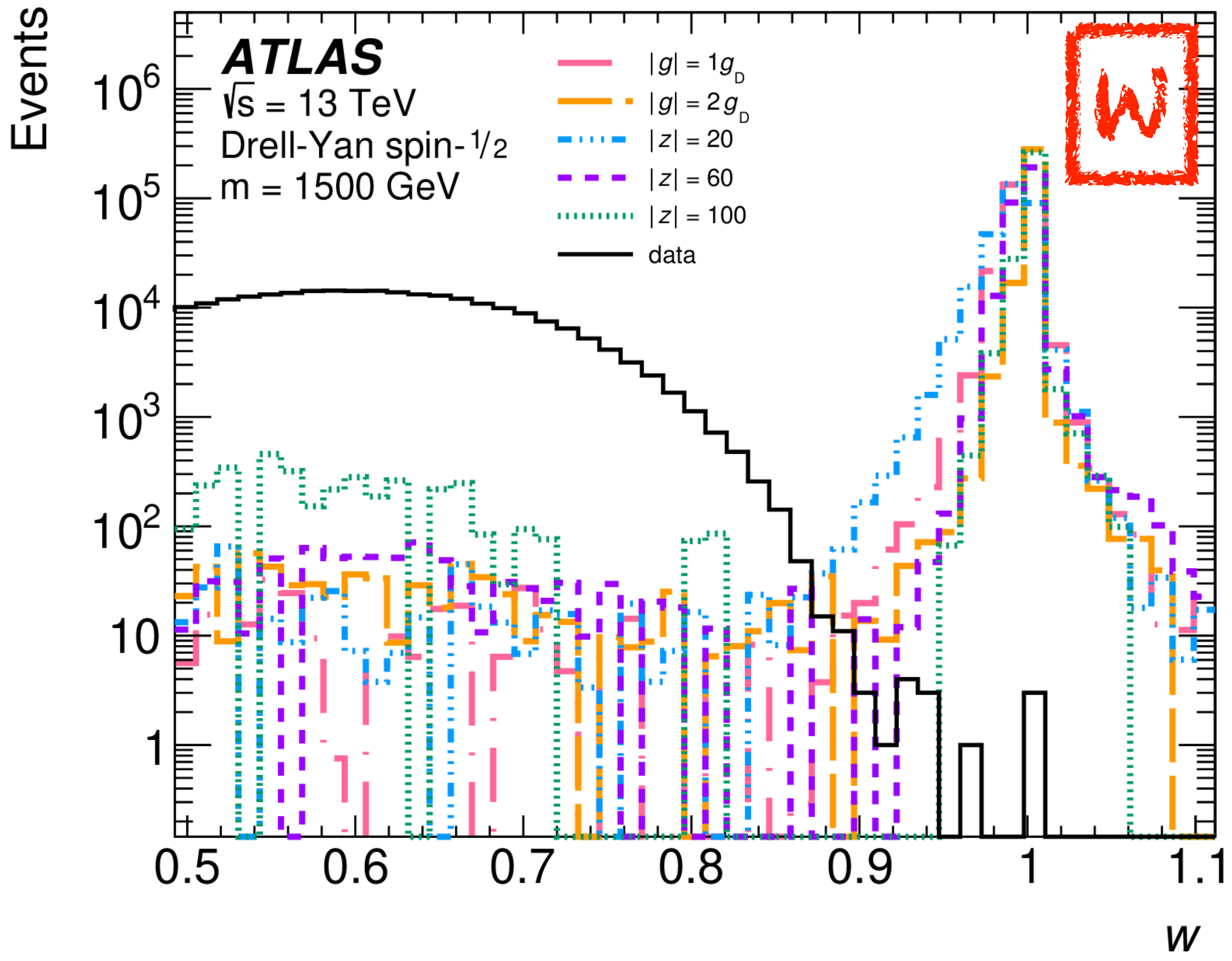
"w" - measures the lateral energy dispersion of EM cluster candidate.

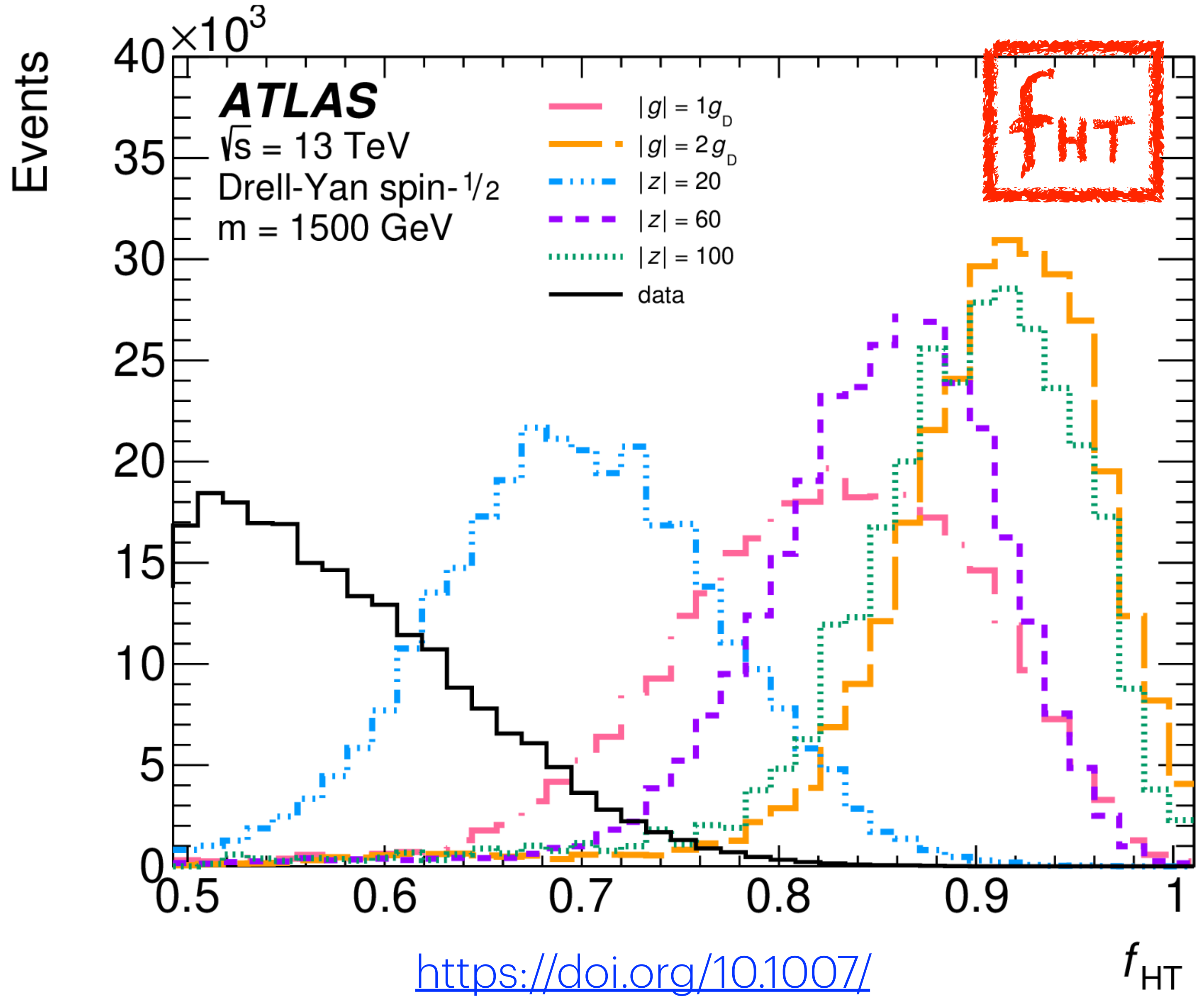
$$w_x = \frac{\Sigma(E_{Cell\ Monopole})}{\Sigma(E_{Cell})}$$



$$w = [w_0 + w_1 + w_2]/3$$

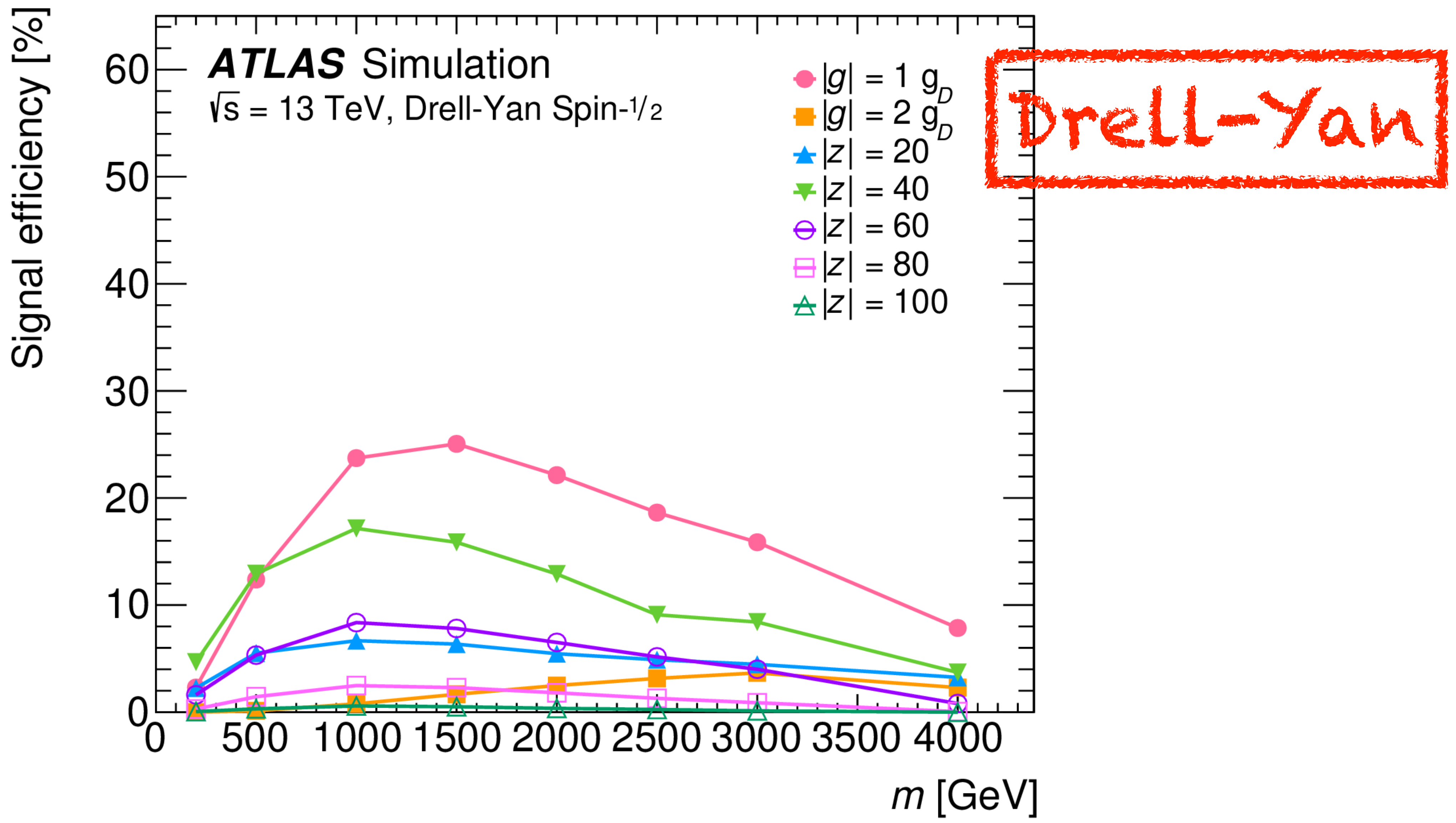
Discriminating Variables

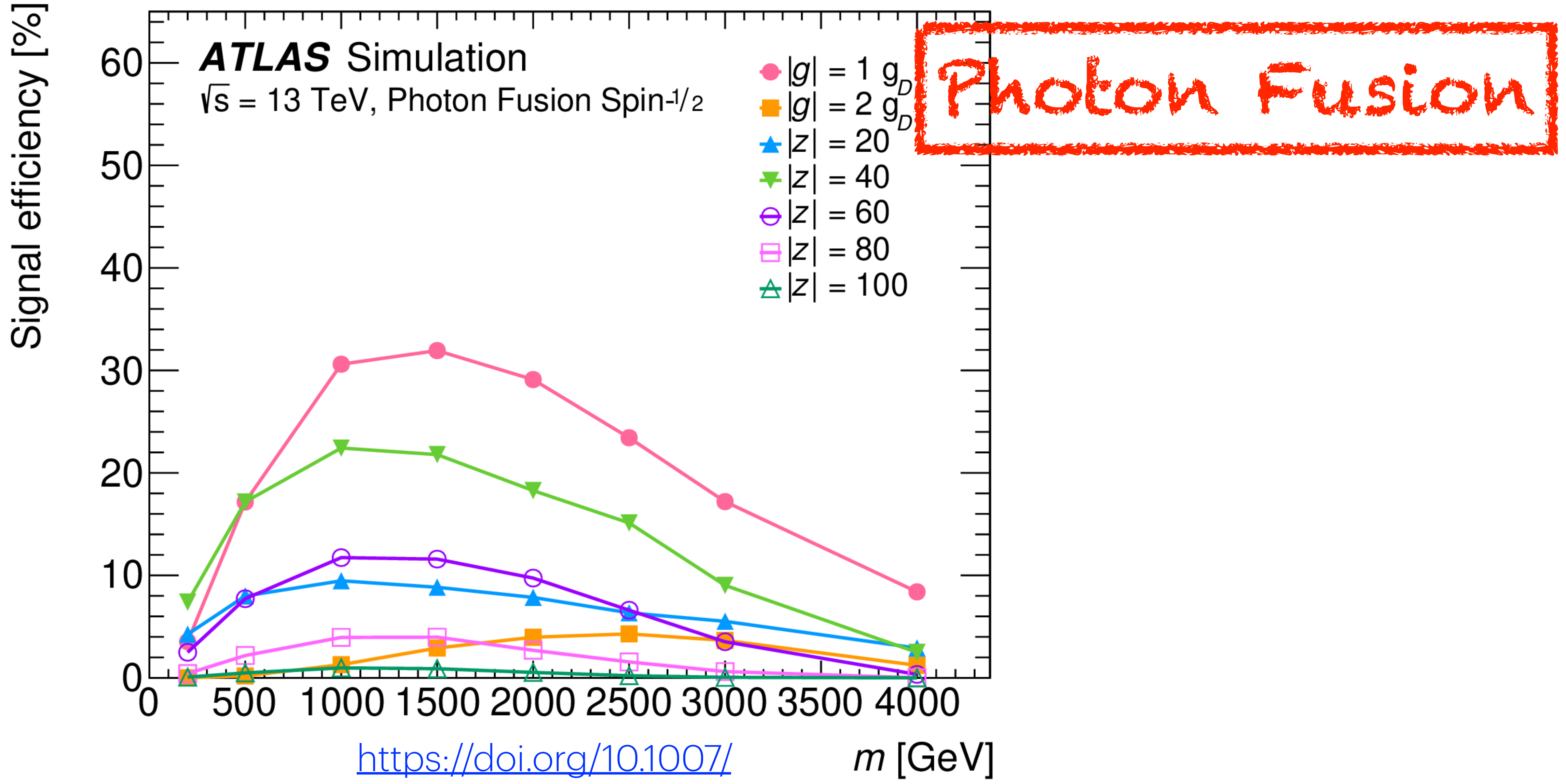




https://doi.org/10.1007/JHEP11(2023)112

Signal Efficiency





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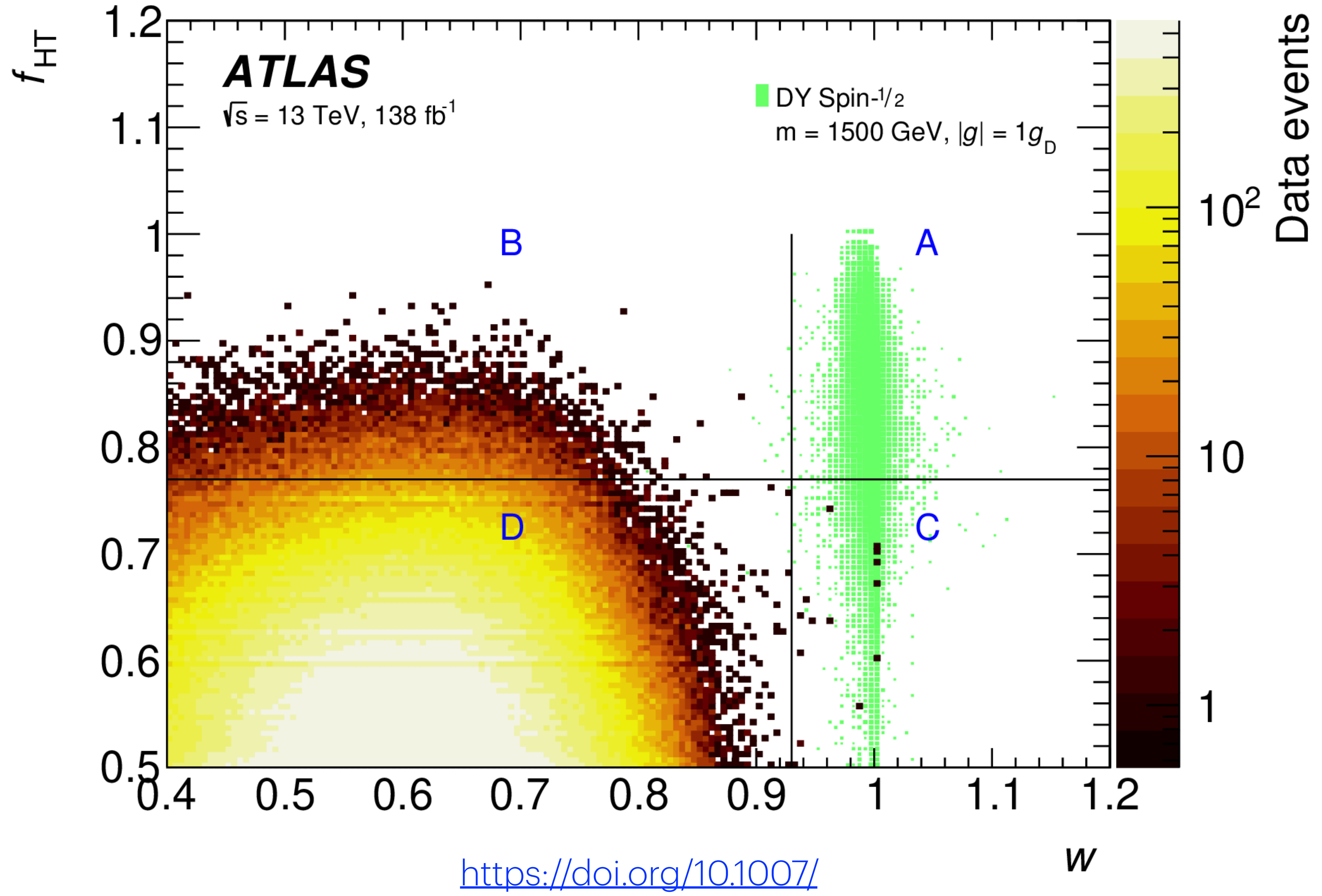
ABCD Background Estimation Method

- Two possible sources of rare backgrounds:
  - High energy electrons and jets.
- difficult to simulate a statistically significant MC sample.
- Data-driven background estimation through ABCD method:

$$N_A^{exp} = N_C \frac{N_B}{N_D}$$

= 0.15 ± 0.04 (stat) ± 0.05 (sys)



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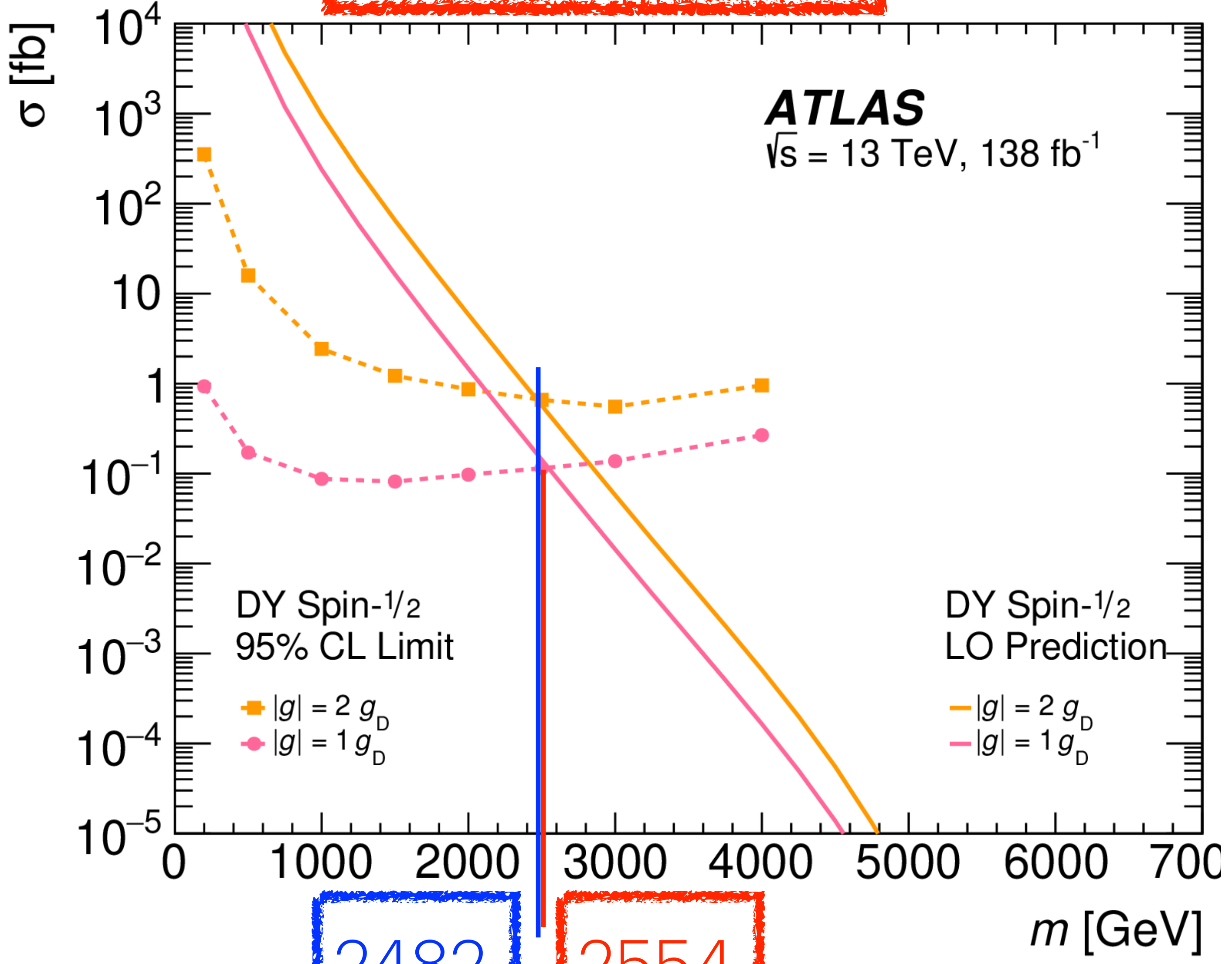
Results and Interpretation

- No excess of events over SM backgrounds in signal region.
- Imposes 95% CL upper cross-section limits on both Drell-Yan and Photon-fusion production.
- We have set highest-to-date mass limits on 1gD and 2gD monopoles.
- Our results for $1g_D$ and $2g_D$ are competitive with the MoEDAL experiment which is dedicated for monopole searches.

Drell-Yan



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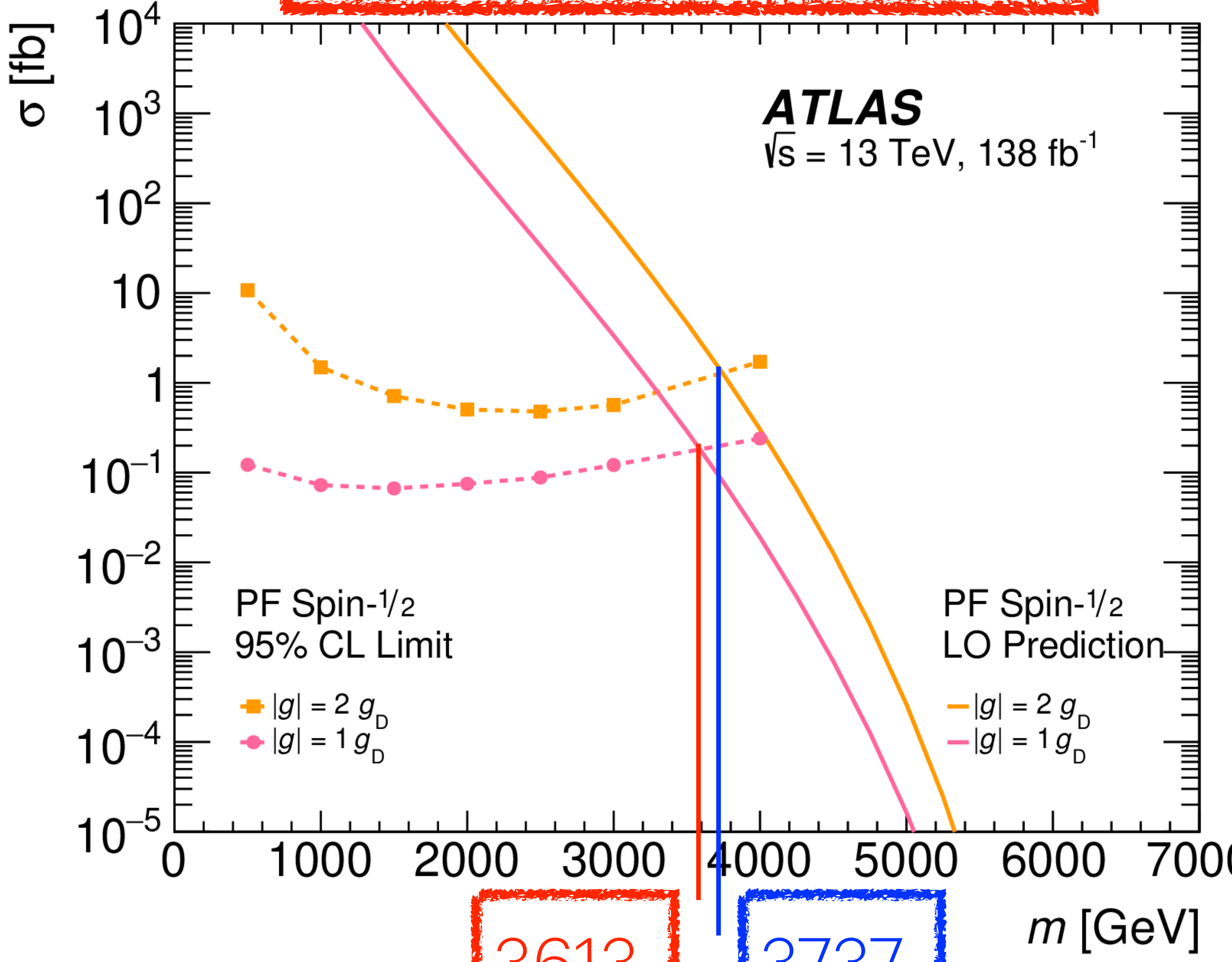
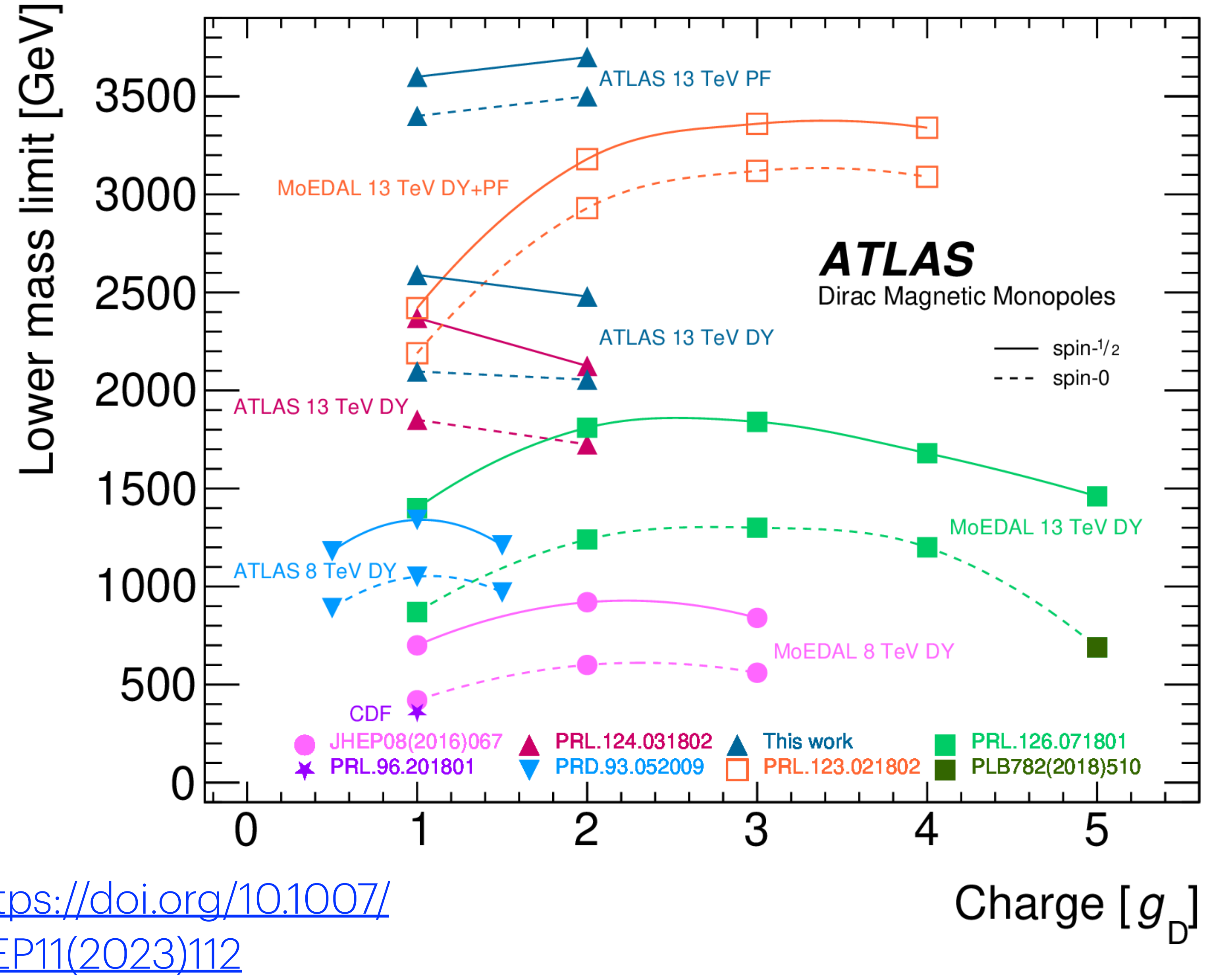
Photon Fusion



3613 3737

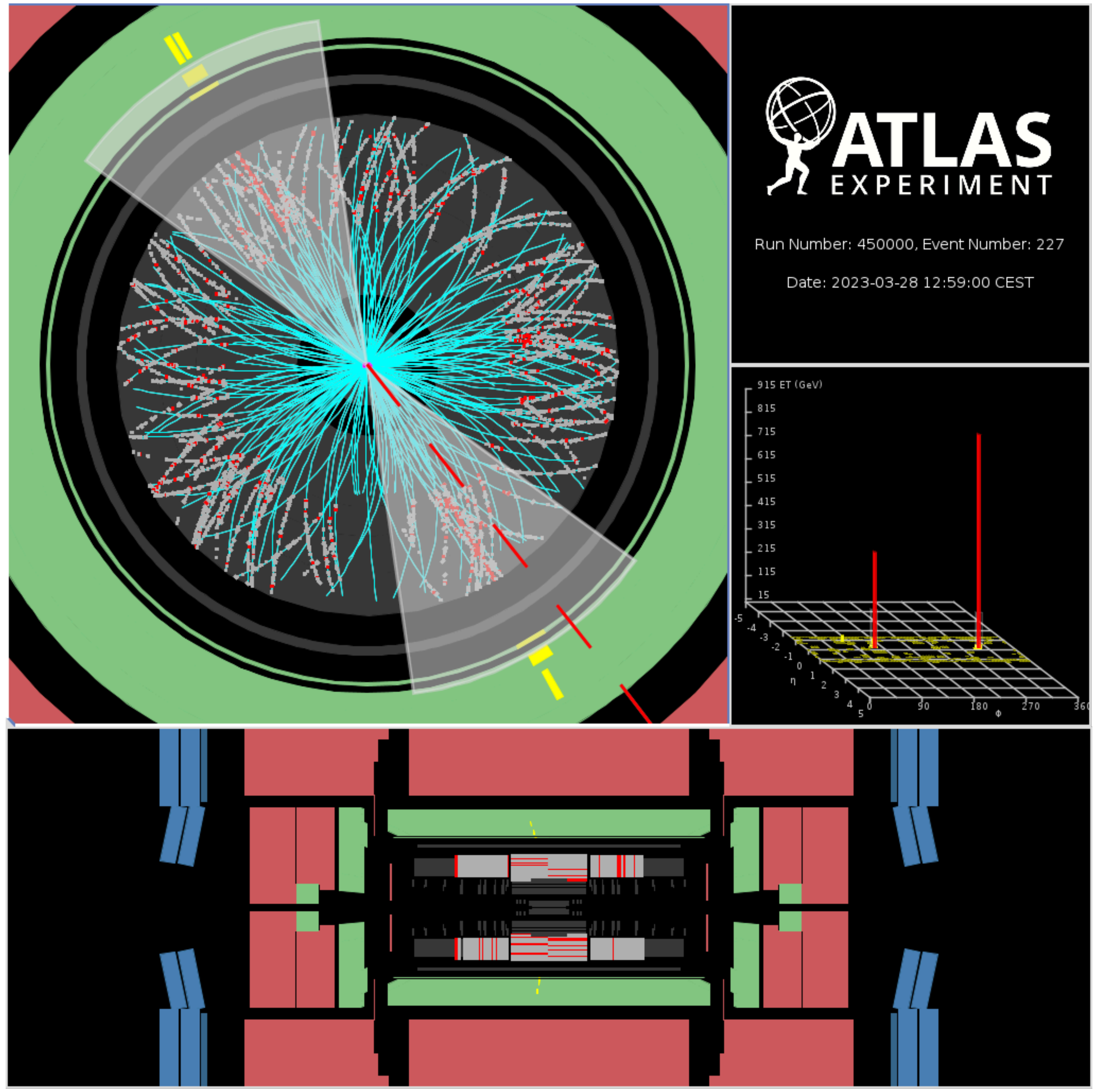
Comparison plot



[All plots:https://doi.org/10.1007/JHEP11(2023)112](https://doi.org/10.1007/JHEP11(2023)112)

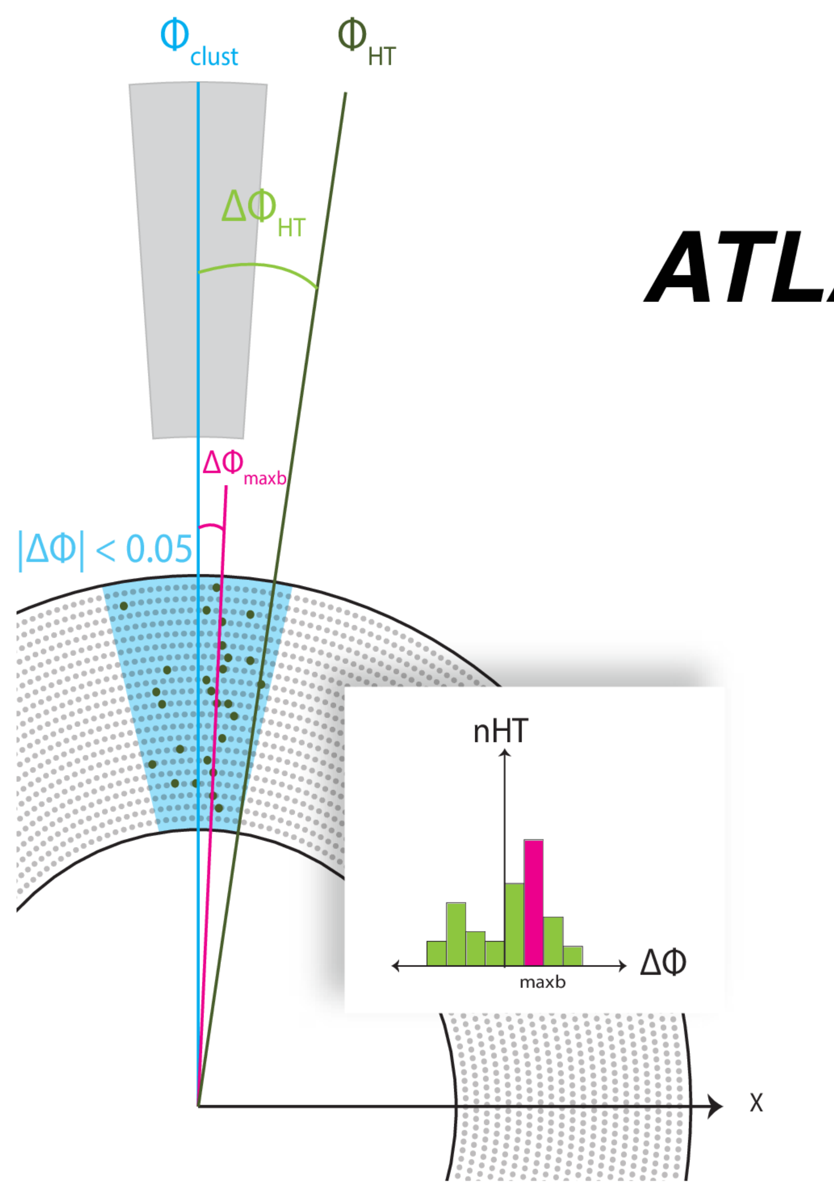
Overview of Run 2 + Run 3 Combined Analysis

- We are aiming for combined analysis with Run 2 and Run 3 data.
- Recently, a search for magnetic monopole pair production in Run 3 ultra-peripheral Heavy ion collisions with ATLAS detector has been published. (https://arxiv.org/abs/2408.11035)
- To extend our analysis we hope to include Dyons (particle with both magnetic and electric charge).



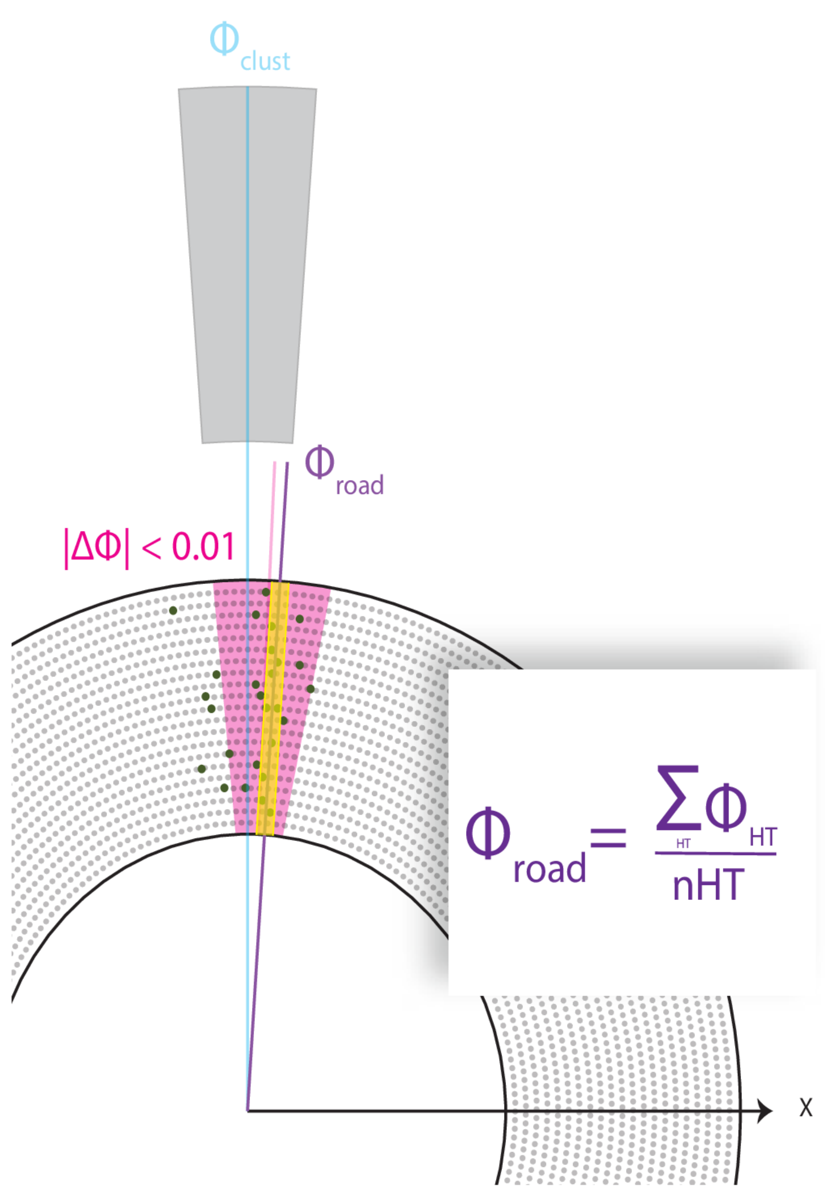
Thank you!

Back up

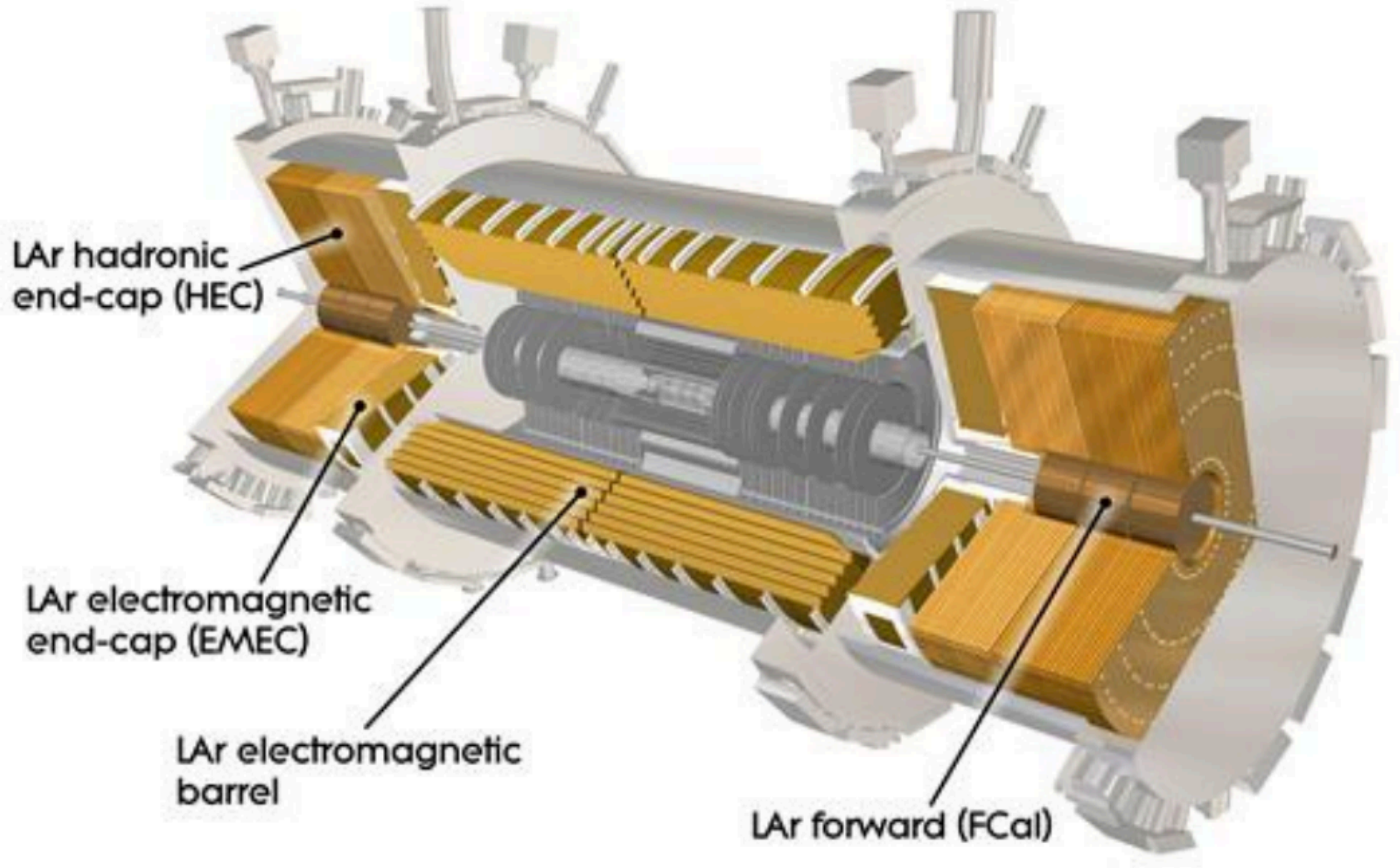


Φclust
ΦHT
ΔΦHT
ΔΦmaxb
|ΔΦ| < 0.05
nHT
maxb
ΔΦ
x

ATLAS



Φclust
Φroad
|ΔΦ| < 0.01
$\Phi_{road} = \frac{\sum_{HT} \Phi_{HT}}{nHT}$
x



LAr hadronic
end-cap (HEC)
LAr electromagnetic
end-cap (EMEC)
LAr electromagnetic
barrel
LAr forward (FCal)

Final Event Selection

- Firing the L1 EM22VHI trigger
- Firing the HLT (g0 hiptrt L1 EM22VHI) trigger
- CaloCalTopoCluster EM cluster with E_T > 22 GeV and $|\eta|$ < 1.375
- Number of high threshold hits HT > 30
- $f_{HT} \geq 0.77$ and $w \geq 0.93$

SYSTEMATIC UNCERTAINTIES

- Extrapolation Comparison with fully simulated MC samples (1%)
- Detector Geometry dependence on the square of the charge from the ionization stopping power (9%)
- Correction to Birks' Law overestimates the recombination effects at high dE/dx (8%)
- Delta ray production theoretical uncertainties of about 3% (2%)
- Luminosity ATLAS standard value (0.83%)
- Background estimate Non-uniformity of mean transfer factor (30%)
- TRT Occupancy mis-modelling affects the fraction of TRT HT hits (2%)
- Pileup variations of the nominal pileup distribution within its uncertainty (2%)
- Slow-moving HIPs ($\beta < 0.37$) trigger efficiency loss is determined by rejecting the slow-moving HIPs at truth level (2%)

Run 2 Methodology and HLT Dedicated Trigger

- Luminosity for Run 2 with p-p collisions at 13 TeV - 138 fb^{-1}
- Dedicated HIP Trigger : HLT_g0_hiptrt_L1EM22VHI. -
- The trigger uses a region of interest from the EM calorimeter at level 1 and counts the low and high threshold TRT hits in the region.
- ABCD method is used to estimate the backgrounds (explained in coming slides).