SEARCH FOR DIRAC MAGNETIC MONOPOLES AND OTHER HIGHLY IONIZING PARTICLES

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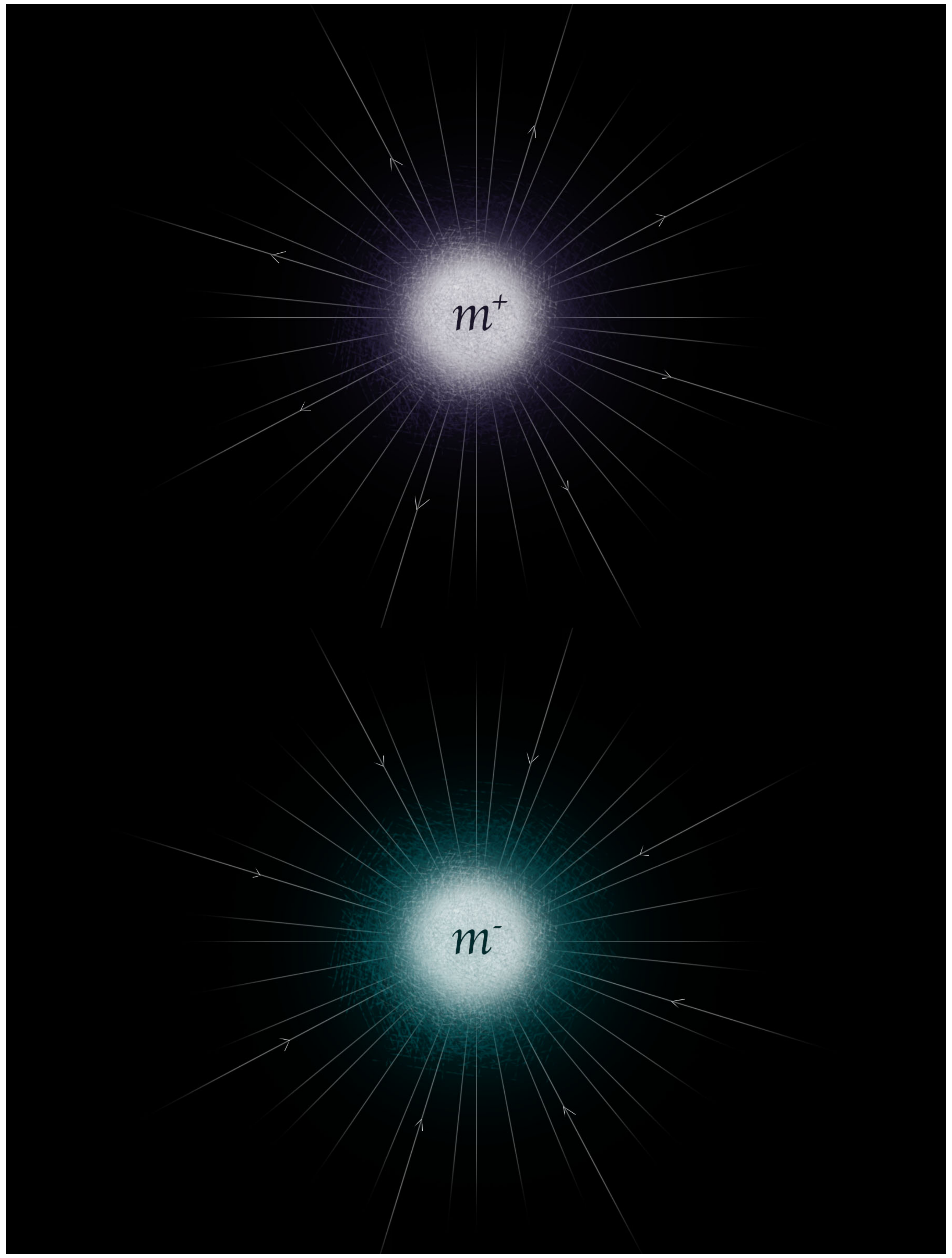
WHAT ARE WE LOOKING FOR?

MAGNETIC MONOPOLE

- Electric monopole: Fundamental particle with electric charge "e"
  - Static source of radial electric field
- **Magnetic monopole:** Fundamental particle with magnetic charge "q_m"
  - Static source of radial magnetic field
  - No substructure, point particles
  - Stable (LLP) due to magnetic charge conservation
  - Unknown mass and spin



WHY?

ELECTRIC QUANTIZATION CONDITION

- Dirac Magnetic Monopoles (Quantum electrodynamics) [see Dirac]:
  - Explain electric charge quantization

$$\frac{q_m q_e}{\hbar c} = \frac{N}{2}$$

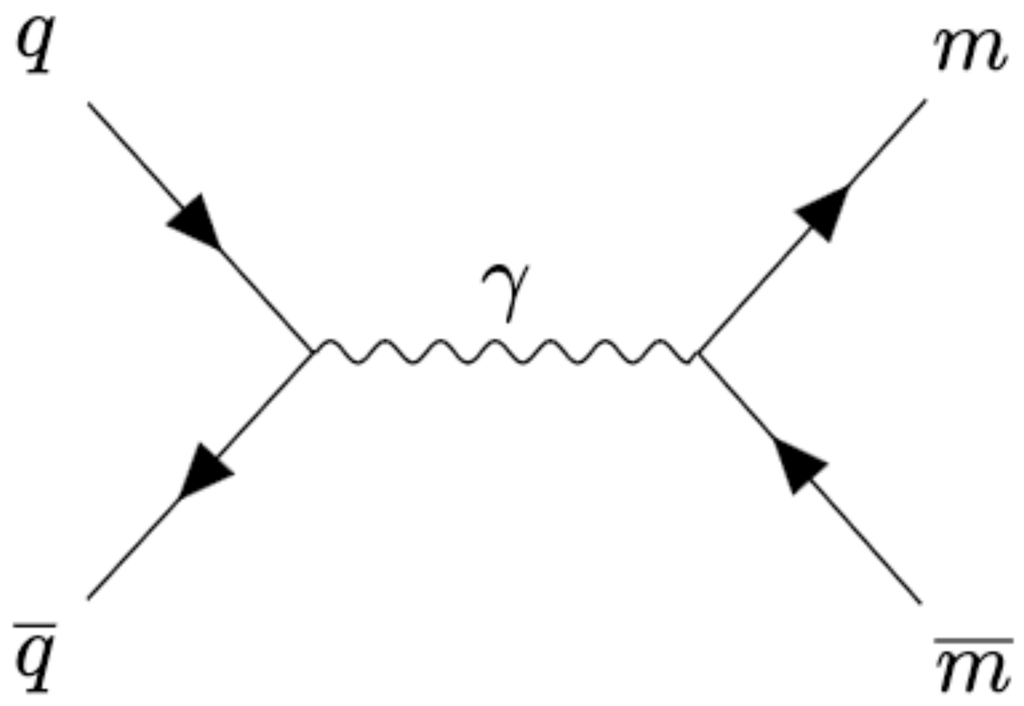
$$q_m = N g_D e c$$

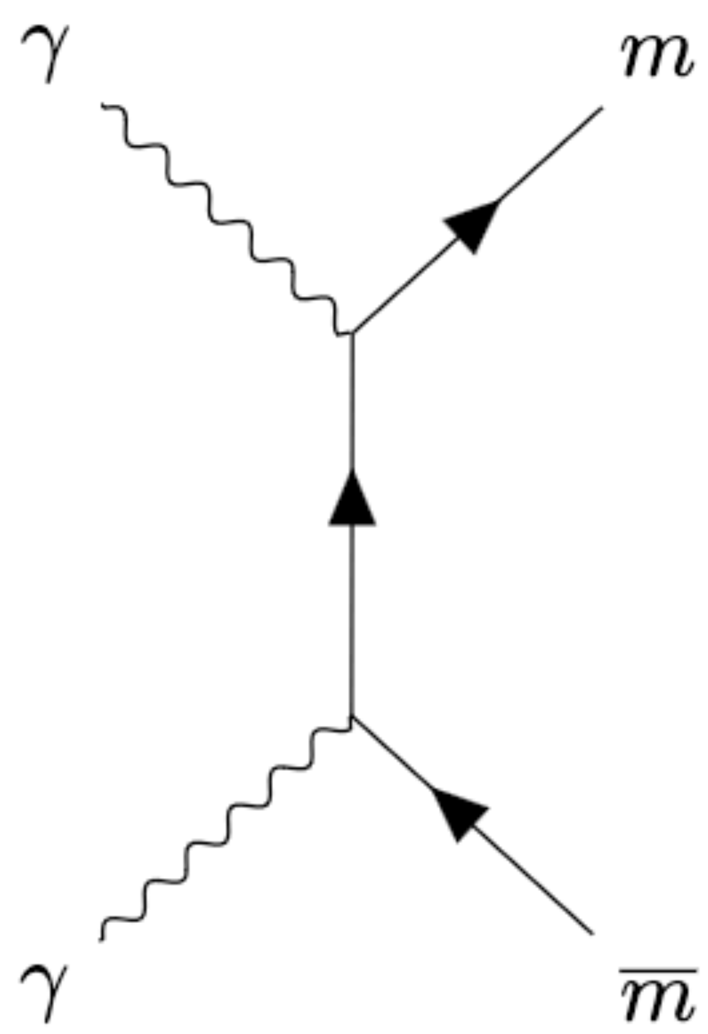
$$g_D = \frac{1}{2\alpha} = 68.5$$

HOW?

PAIR PRODUCTION

- Benchmark pair-production mechanisms
  - Drell-Yan
  - Photon Fusion
- Large magnetic coupling prohibits perturbative cross section predictions





Feynman-like diagrams for photon-mediated Drell-Yan (left) and Photon fusion (right) monopole pair production.

$$\alpha = \frac{\mu_0 e^2 c}{4\pi\hbar} \xrightarrow{e \to n g_D / c} \alpha_m = \frac{\mu_0 n^2 g_D^2}{4\pi\hbar c}$$

$$\alpha \approx \frac{1}{137} \qquad \alpha_m \approx 34.34$$

INTERACTION WITH MATTER

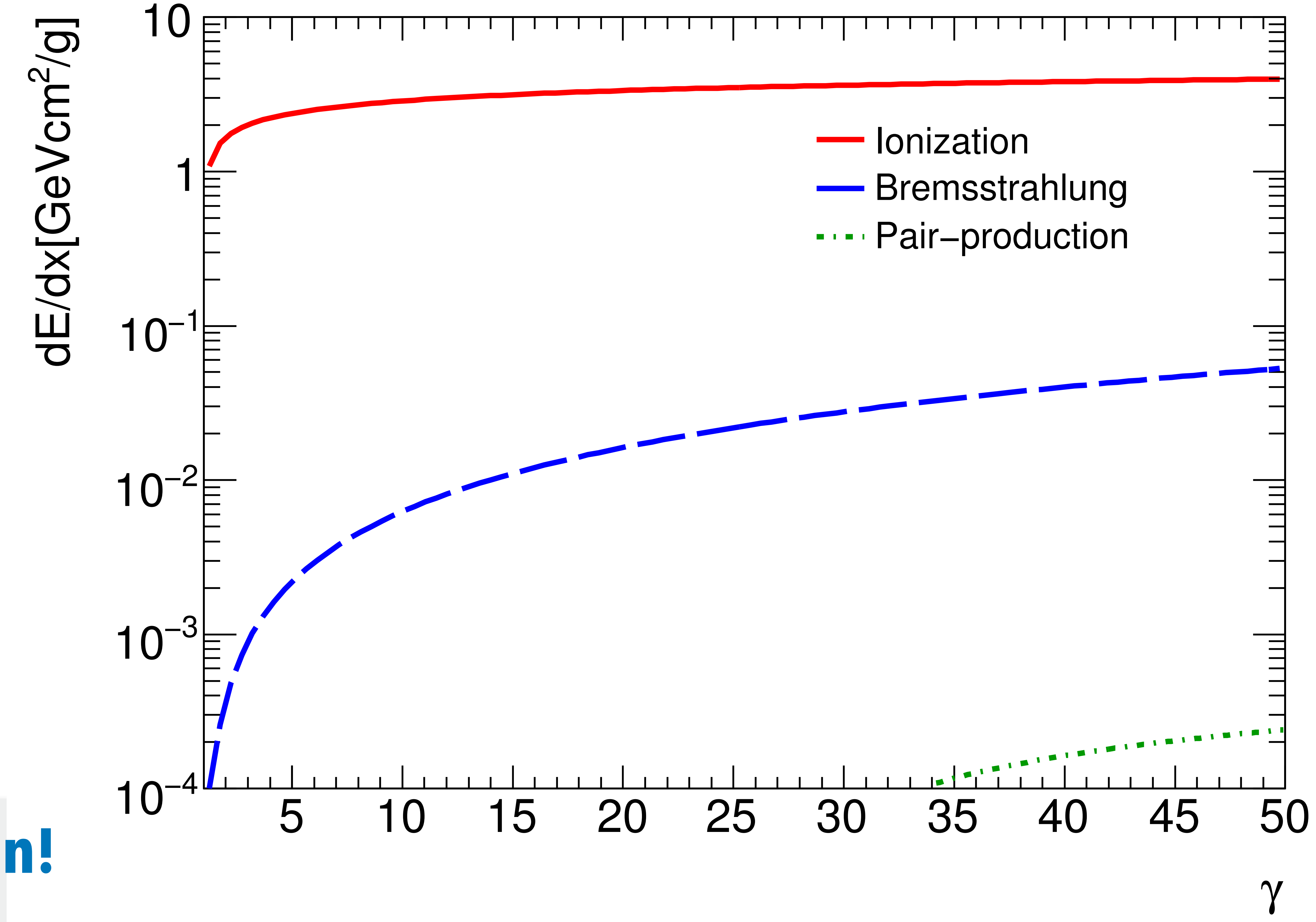
$$-\frac{dE}{dx} = \frac{4\pi e^4 z^2 N_e}{m_e c^2 \beta^2}\left[\ln\left(\frac{2m_e c^2\beta^2\gamma^2}{I}\right) - \beta^2 - \frac{\delta}{2})\right]$$

HECOS: BETHE-BLOCH

$$-\frac{dE}{dx} = \frac{4\pi e^2 g^2 N_e}{m_e c^2}\left[\ln\left(\frac{2m_e c^2\beta^2\gamma^2}{I}\right) + \frac{k(g)}{2} - \frac{1}{2} - \frac{\delta}{2} - B(g))\right]$$

MAGNETIC MONOPOLES: BETHE-AHLEN

- Energy loss ∝ charge^2 **~4700 x more ionizing than proton!**
- Electrons in the presence of a magnetic monopole would experience an interaction proportional to gβ
- HIPs also produce a lot of knock off electrons from the inner layers of the nuclei, **delta rays**, which further ionize.



Energy loss per unit distance as a function of the Lorentz factor for a 1g_D 1500 GeV monopole in LAr.

(WHAT ARE WE LOOKING FOR?)

HIGHLY IONIZING PARTICLE: HIP

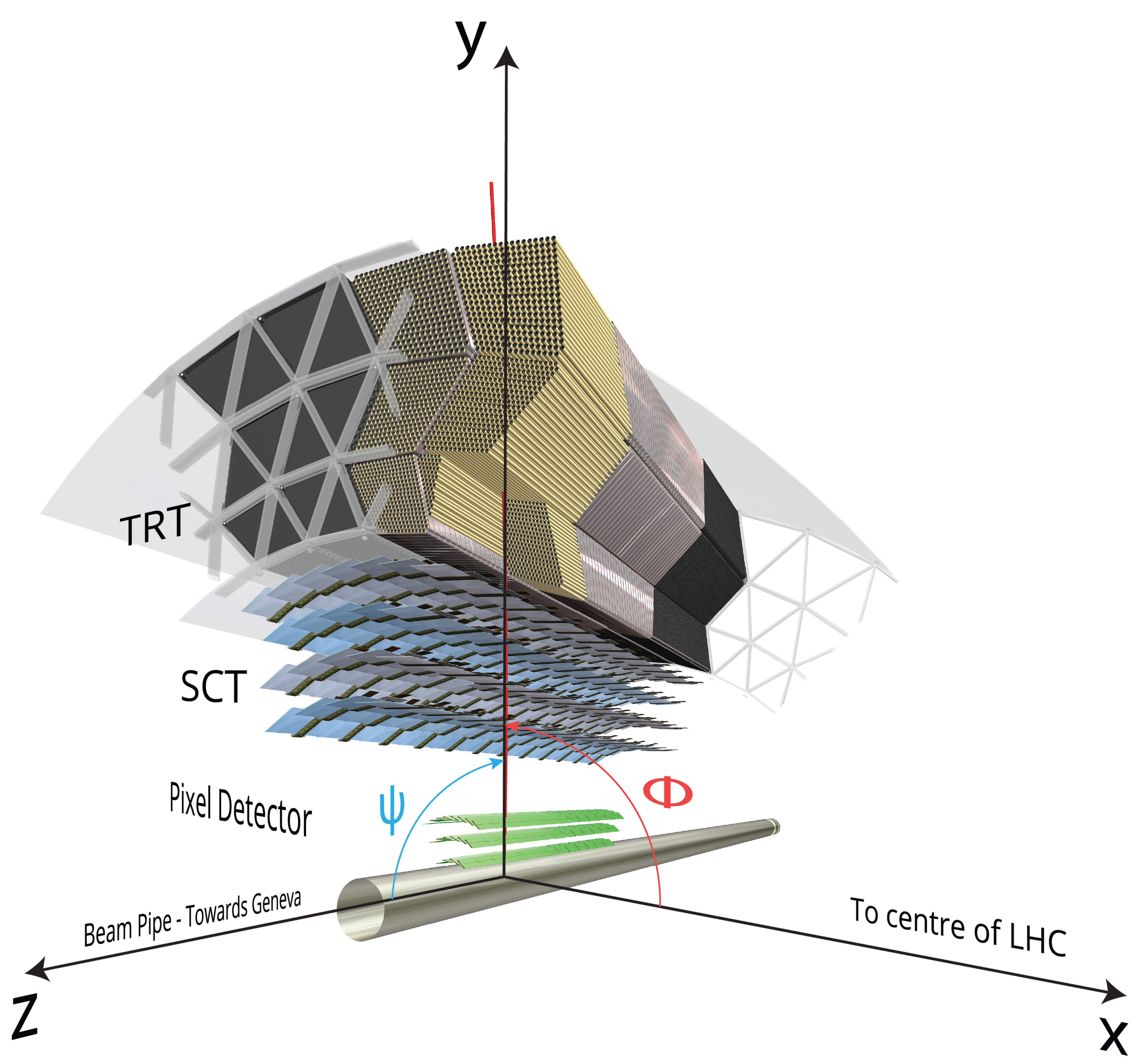
- **Magnetic monopole:** Fundamental particle with magnetic charge "q_m"
- **High Electric Charge Object (HECO):** Particle with electric charge many times *e*:
- Spin 0 or 1/2
- Mass in the range of 200 to 4000 TeV
- g = 1 or 2 gD ; |z| = 20, 40, 60, 80 or 100

HOW?

HIGHLY IONIZING PARTICLE SIGNAL

$$\mathbf{F} = \mathbf{q}(\mathbf{E} + \mathbf{v} \times \mathbf{B}) + \mathbf{g}(\mathbf{B} + \mathbf{v} \times \mathbf{E})$$

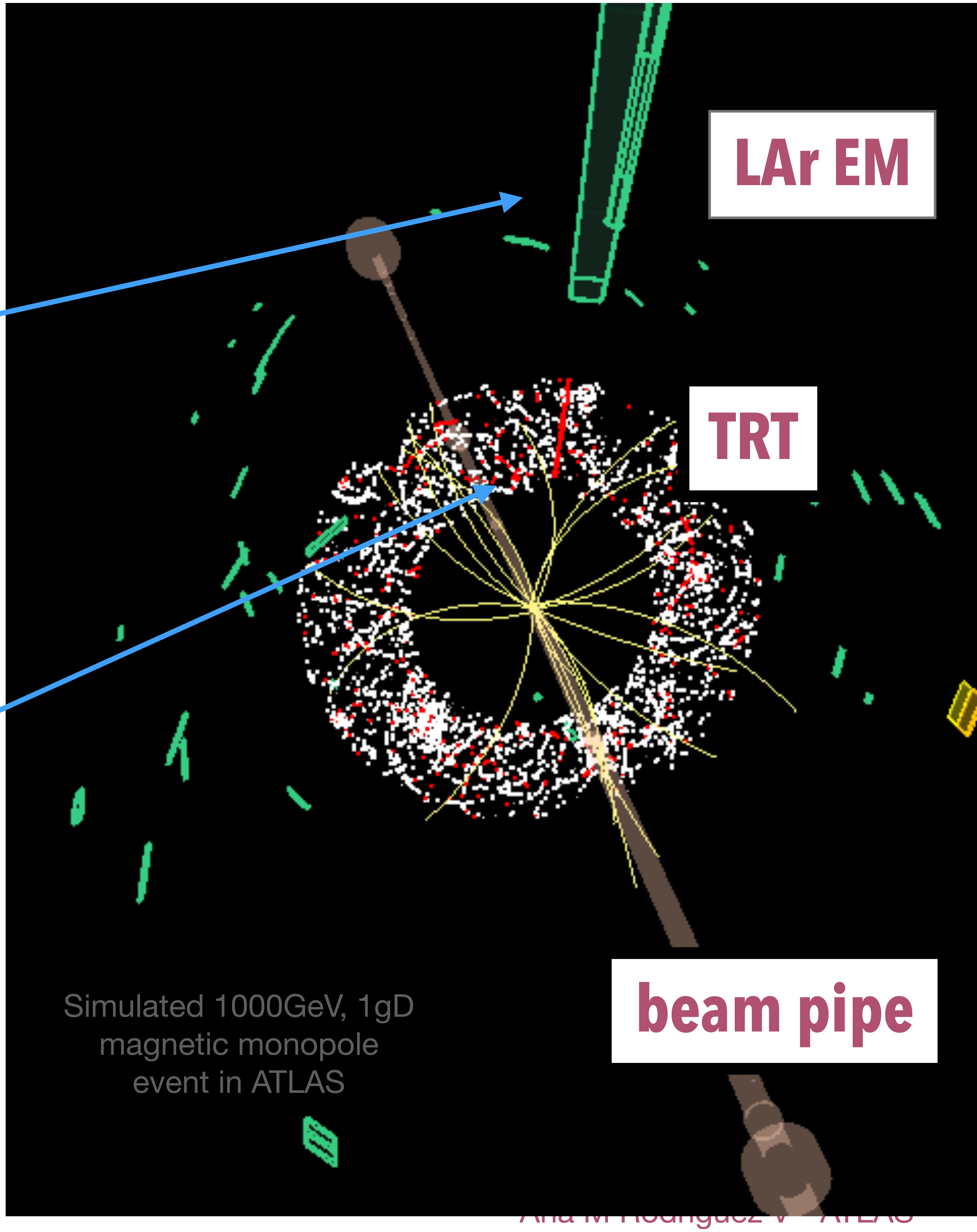
- Particle detection is non-standard:
    - Magnetic monopoles trajectories do not bend in the same plane as charged particles
  - No decay into daughter particles
    - Magnetic charge conservation



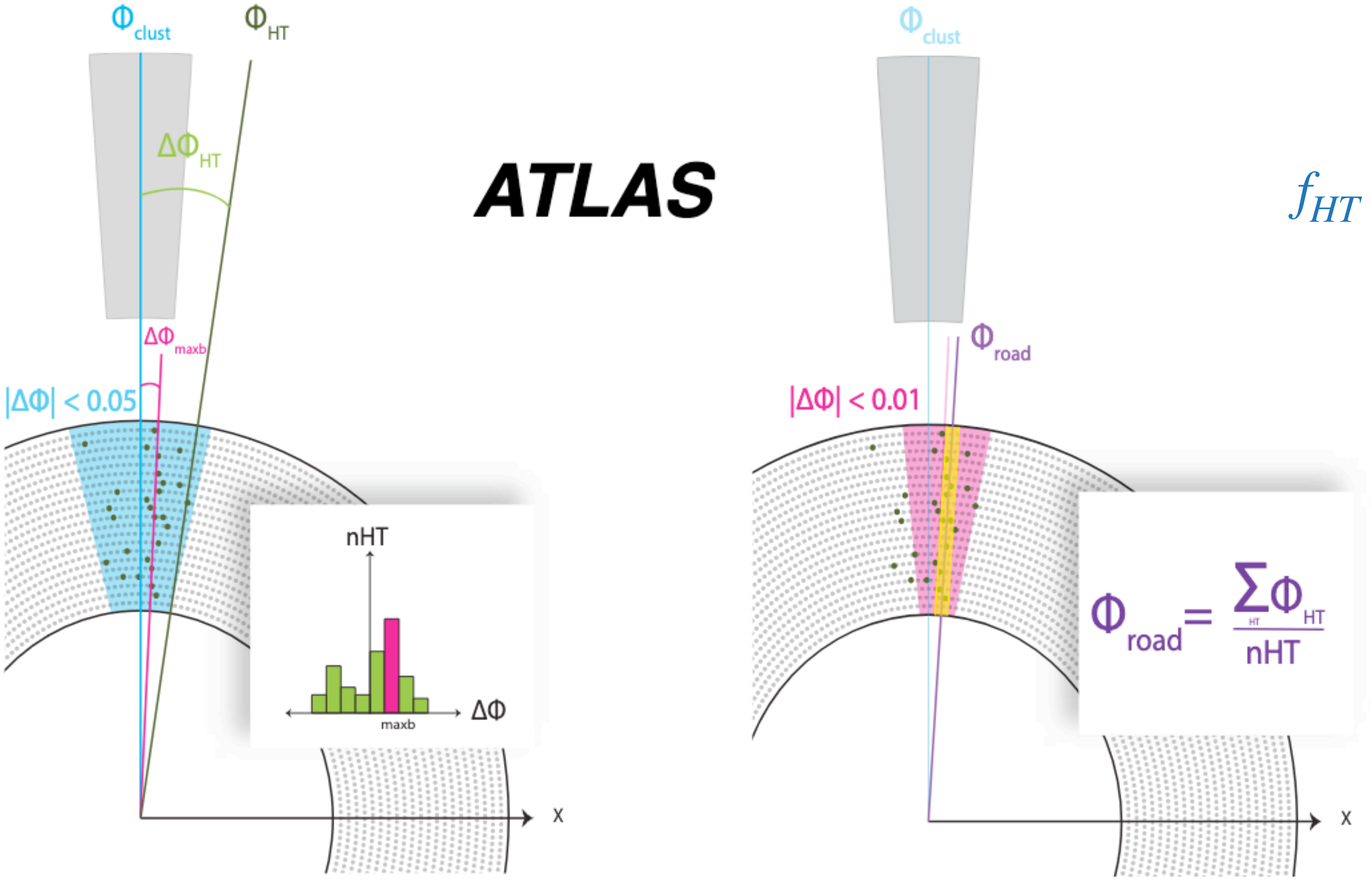
SIGNAL DISCRIMINATION:

- **Concentrated high energy** deposition in the LAr EM calorimeter.
  - No shower in the calorimeters.

- Many large energy deposits in the TRT observed as **TRT High Threshold hits**
  - Significant amounts of δ-rays,

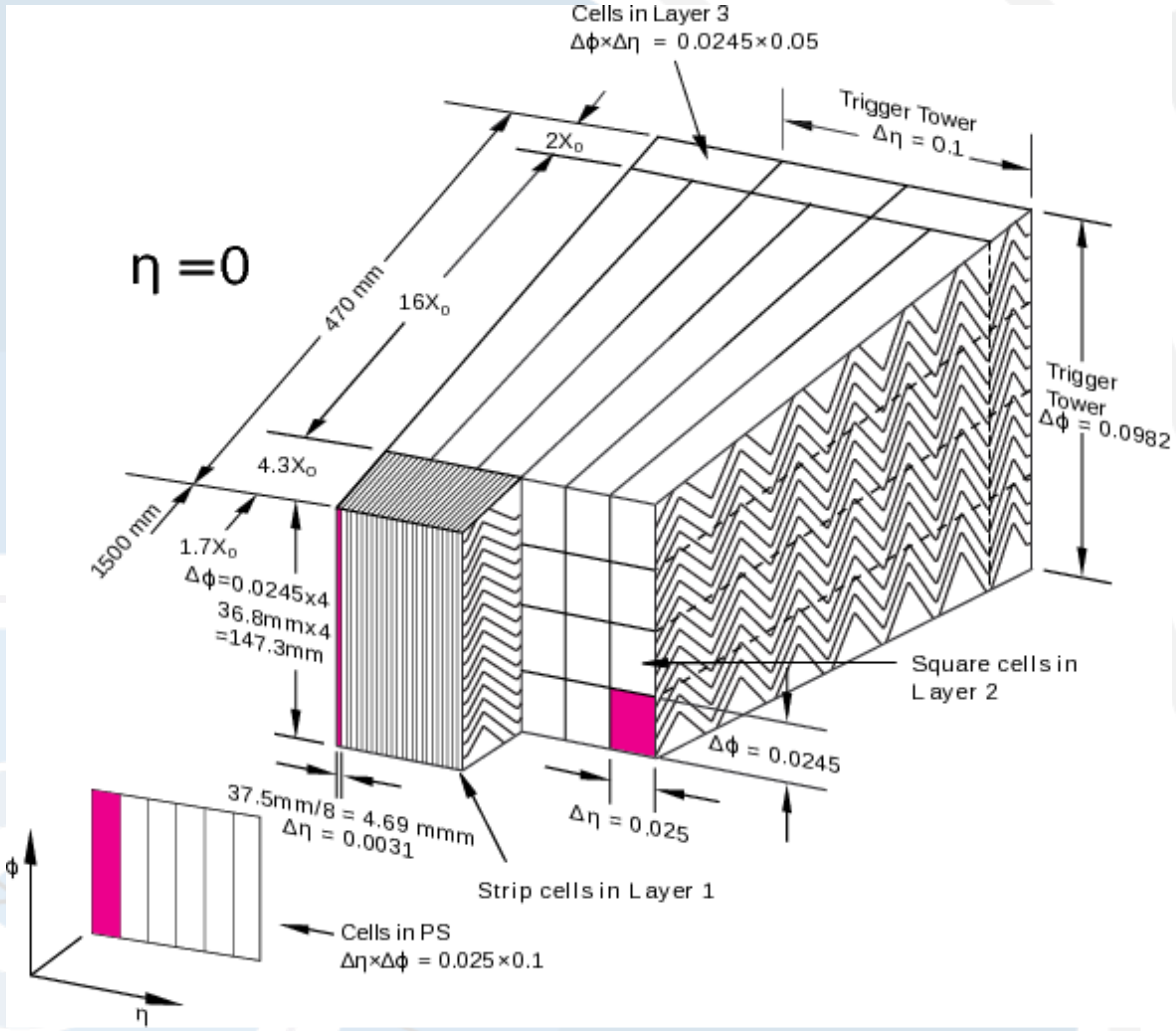


FRACTION OF HIGH-THRESHOLD HITS

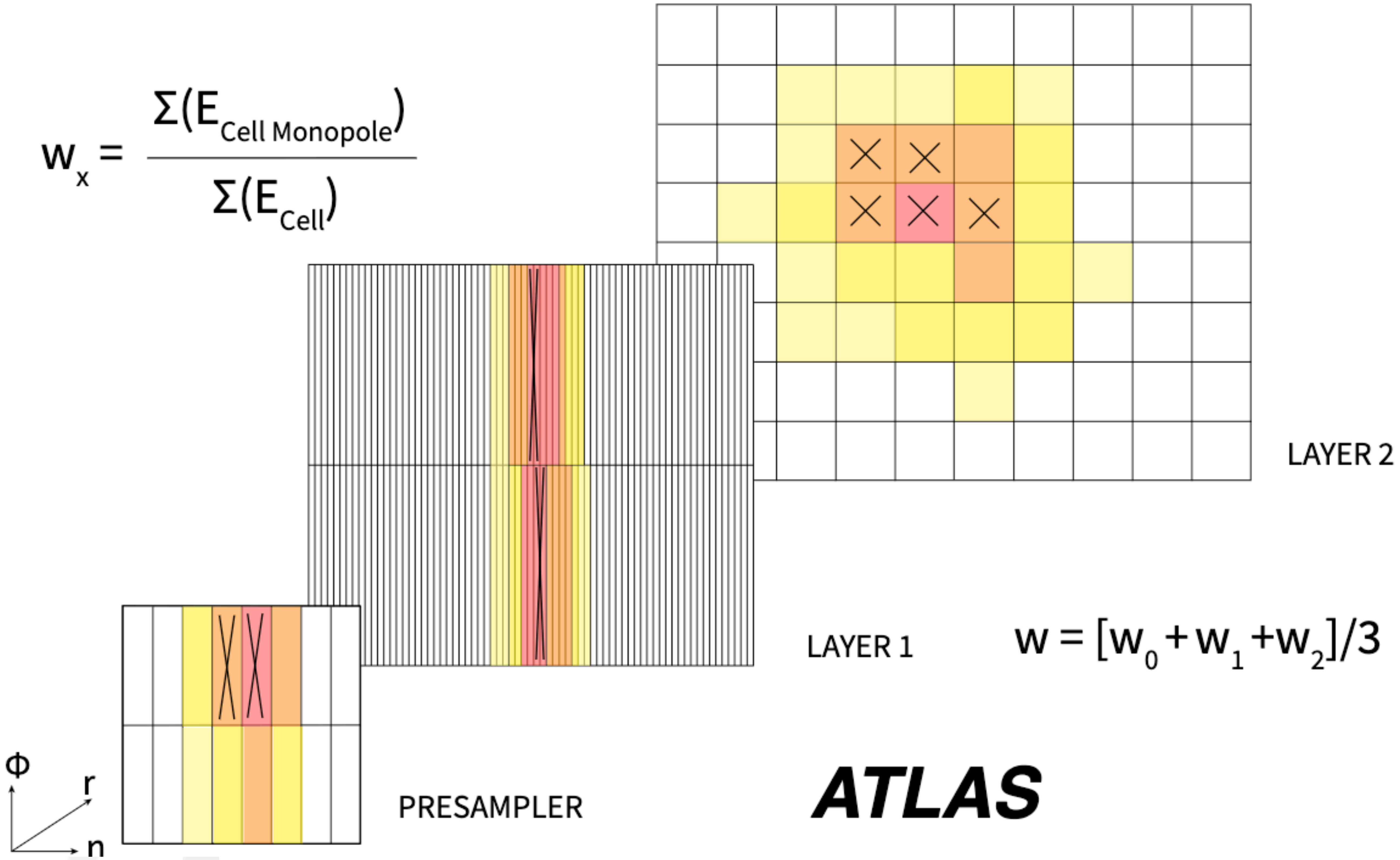


$$f_{HT} = \frac{HT_{hits}}{HT_{hits} + LT_{hit}}$$

CALORIMETER ENERGY DISPERSION – W

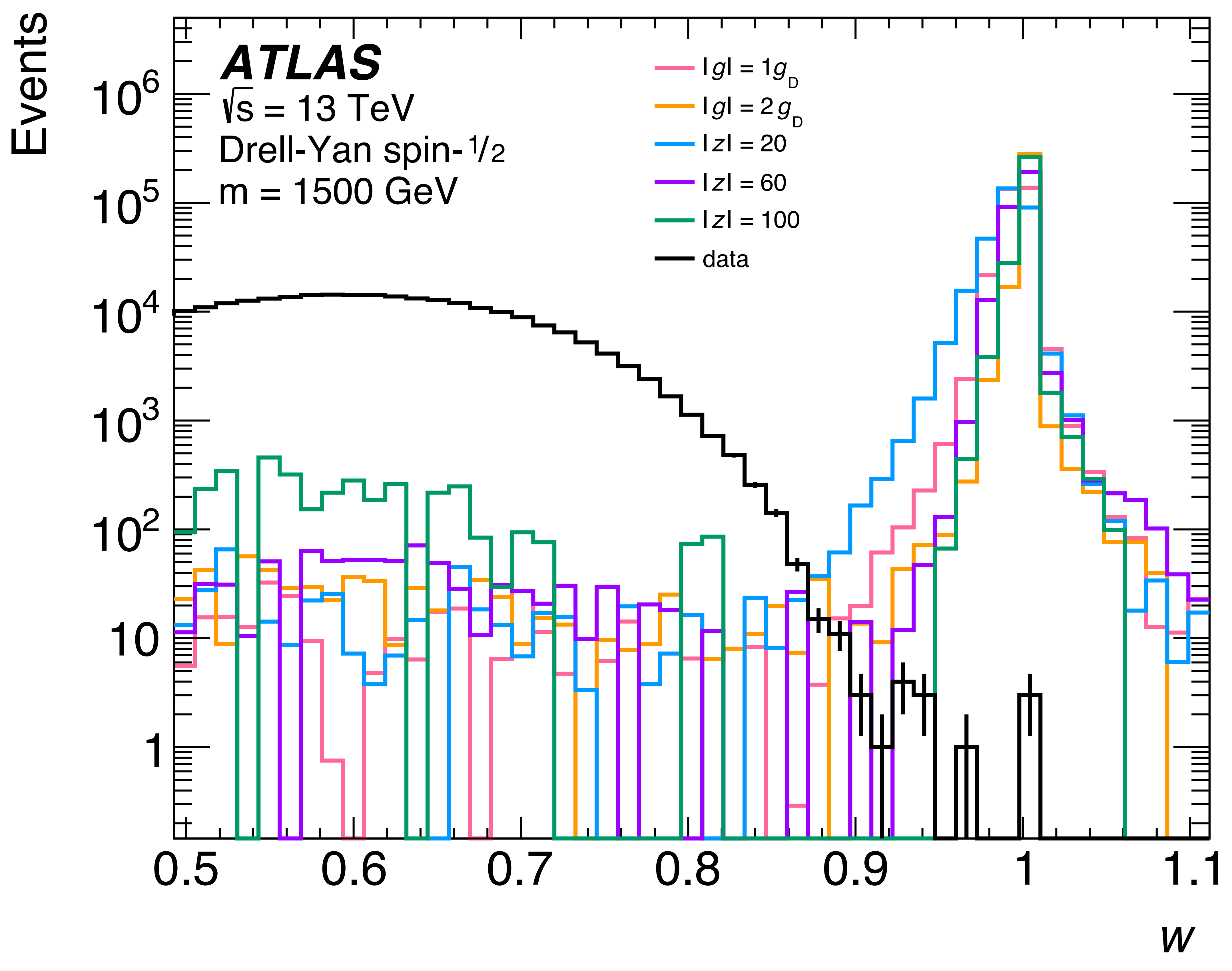


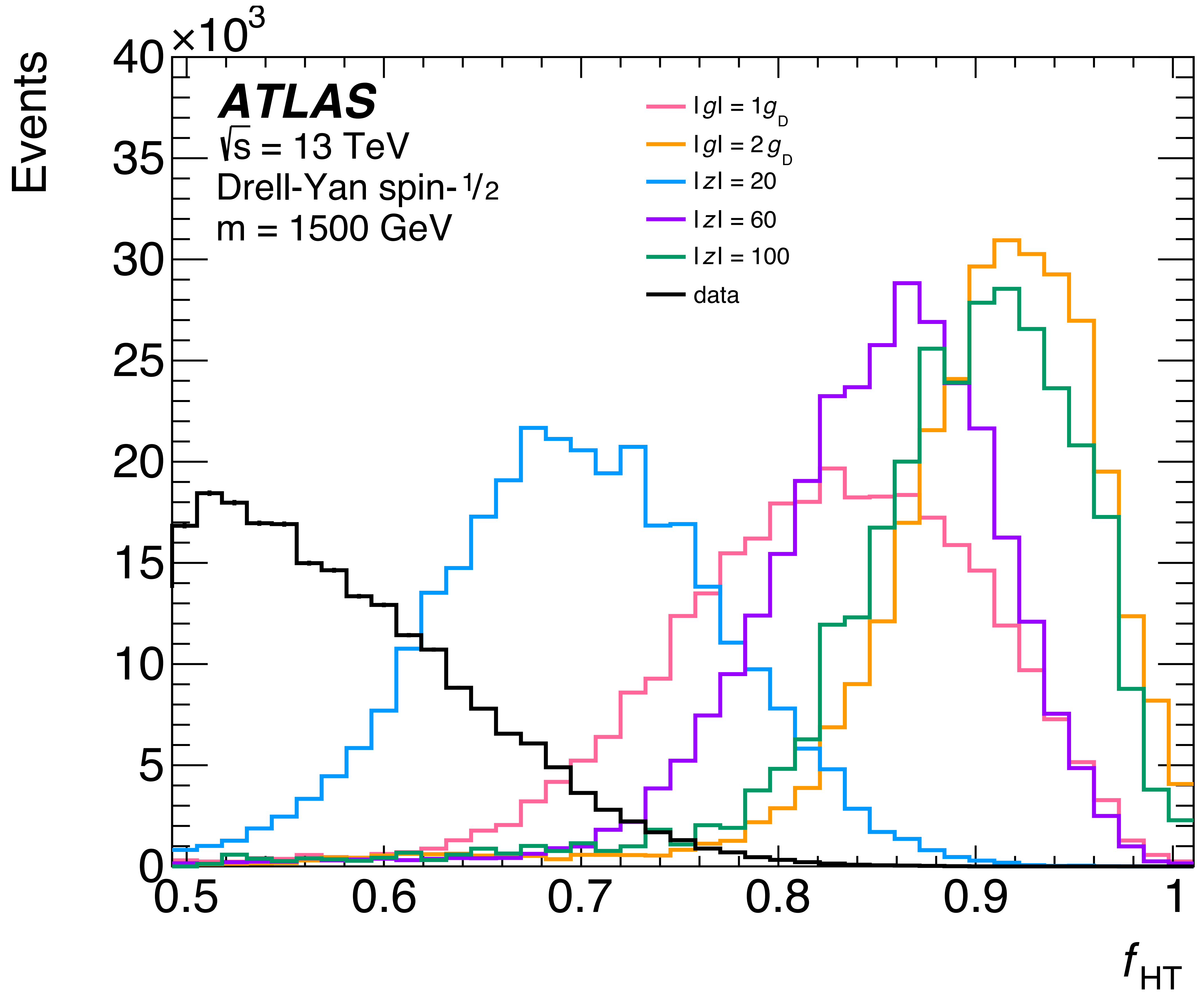
$$w_x = \frac{\Sigma(E_{\text{Cell Monopole}})}{\Sigma(E_{\text{Cell}})}$$



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

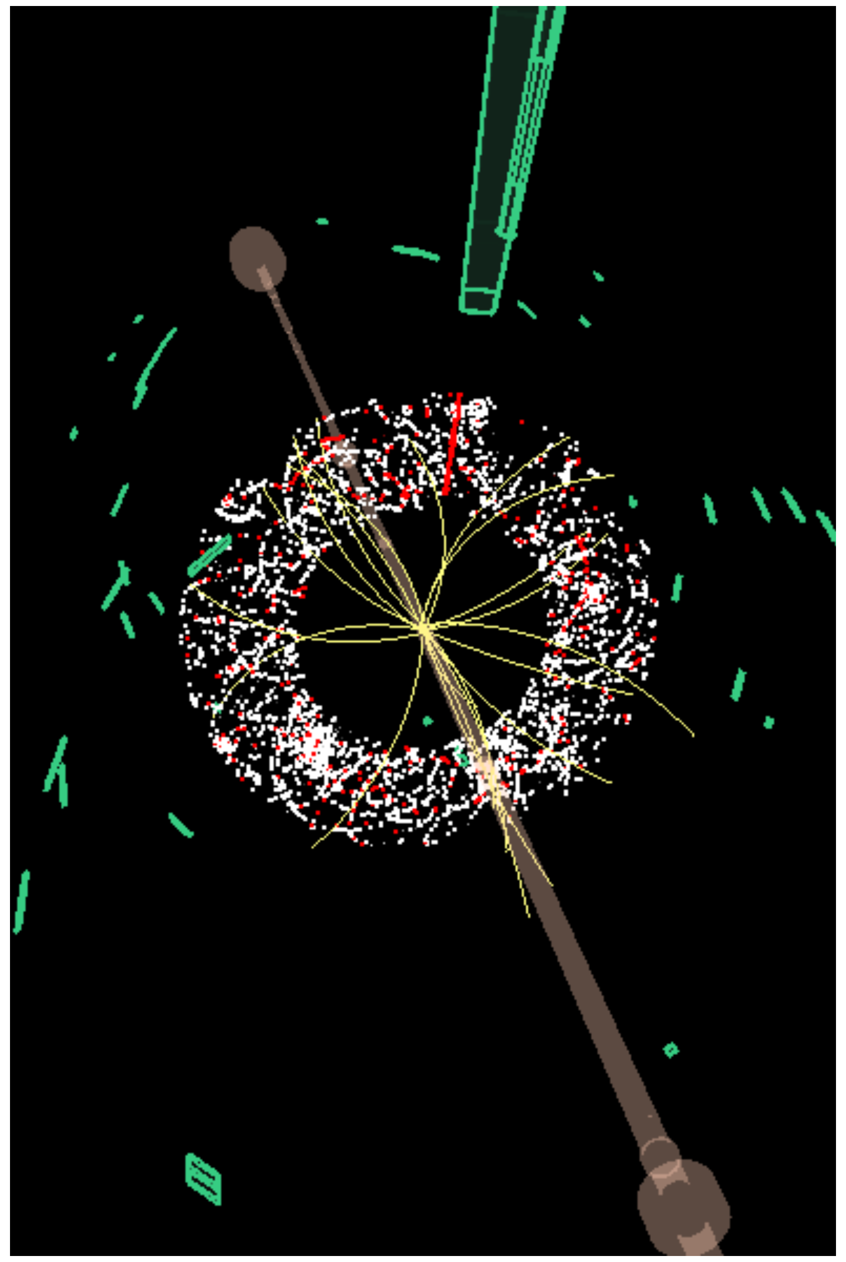
SIGNAL DISCRIMINATING VARIABLES:



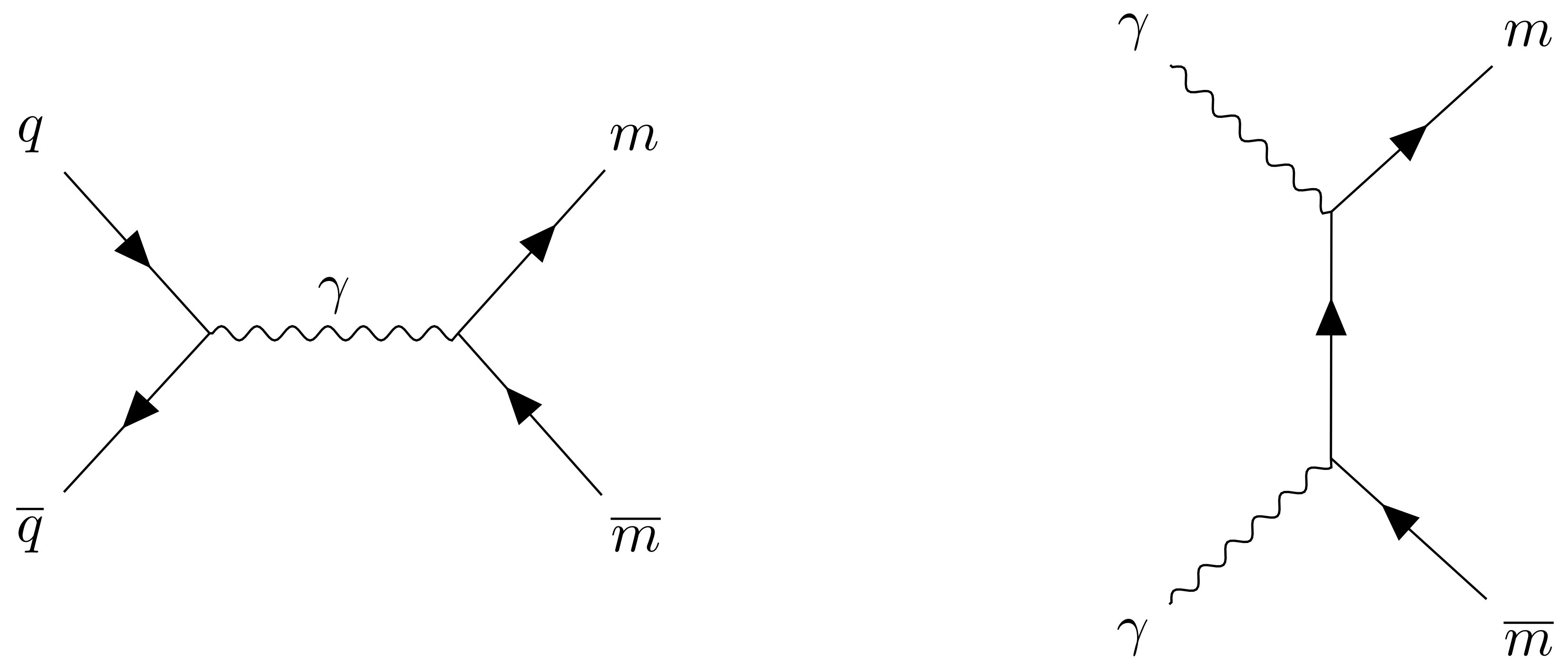


METHOD:

- Search for **Highly Ionizing Particles (HIPs)**: Monopoles or HECOs (High electric charge objects)
  - LHC (Run 2) 13 TeV pp collisions, ~138 fb^{-1} (DESDM_EXOTHIP)
- Highly ionizing particles produce **significant amounts of δ-rays**, creating a large number of **High Threshold Hits** (N_{HT}) in the TRT.
  - **Dedicated trigger** imposing requirements on the N_{HT} and fraction of TRT HT hits (f_{HT}) in a narrow region around the L1 calorimeter Region of Interest (ROI)
- No shower in the calorimeters.
  - Large+narrow energy deposition in the LAr Calorimeter *(w)*
- *PAIR PRODUCTION* mechanisms considered: **Drell-Yan (including Z exchange) and Photon Fusion** (new!)
- Charges: monopoles |g| = 1, 2 gD, HECOS |z| = 20 - 100
- Masses: 200, 500, 1000, 1500, 2000, 2500, 3000 and 4000 GeV
- Estimate background through ABCD method



Event display for 1500 GeV 1gD monopole.

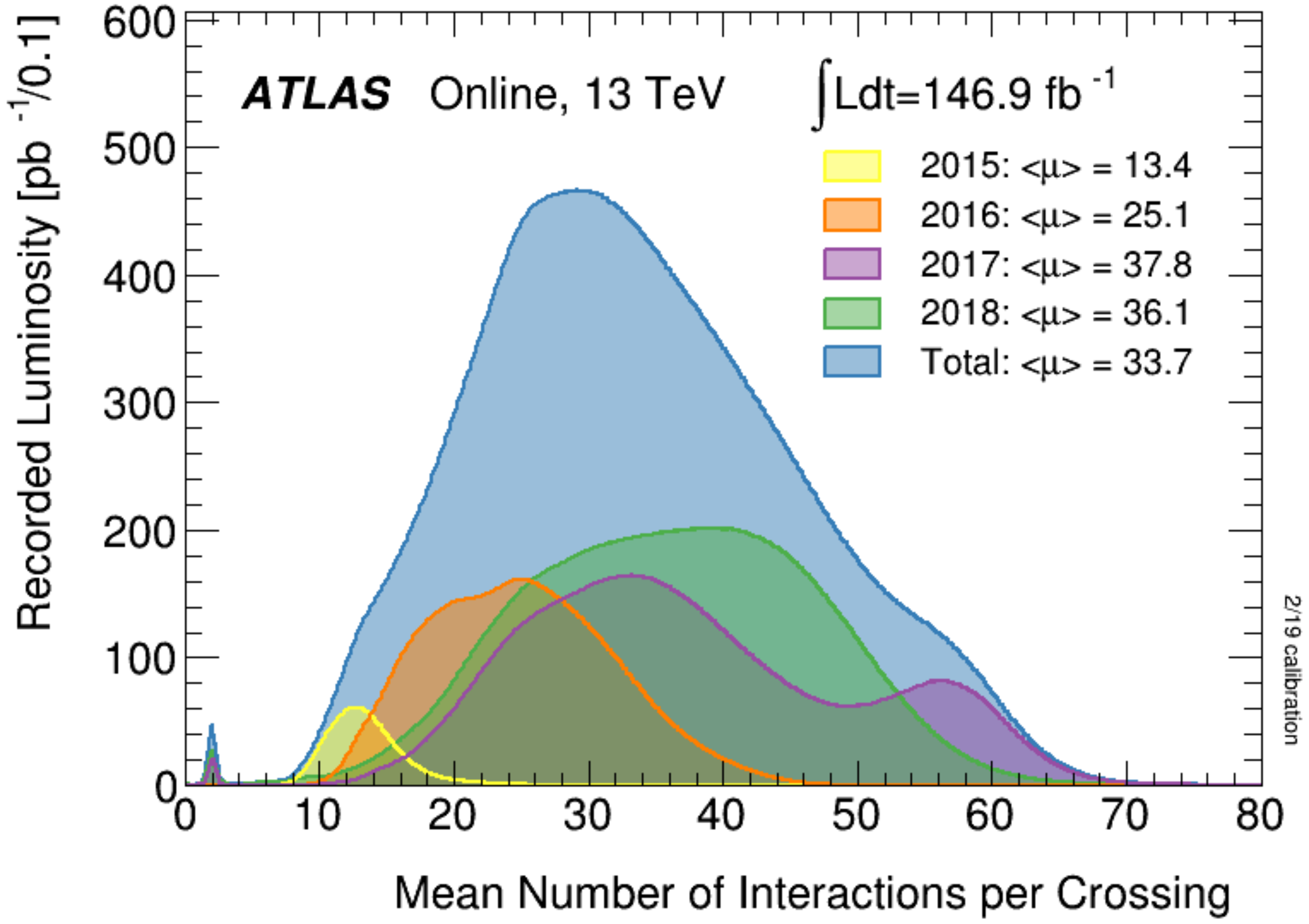


Feynman-like diagrams for photon-mediated Drell-Yan (left) and Photon fusion (right) monopole pair production.

SIGNAL DEFINITION

DATA COLLECTION AND PRESELECTION

- Hardware EM trigger (or Level 1)
- Software HIP trigger
  HLT_g0_hiptrt_L1EM22VHI
  - Based on TRT fHT fraction
- CaloCalTopoCluster calorimeter cluster candidate
- Candidate associated with highest fHT

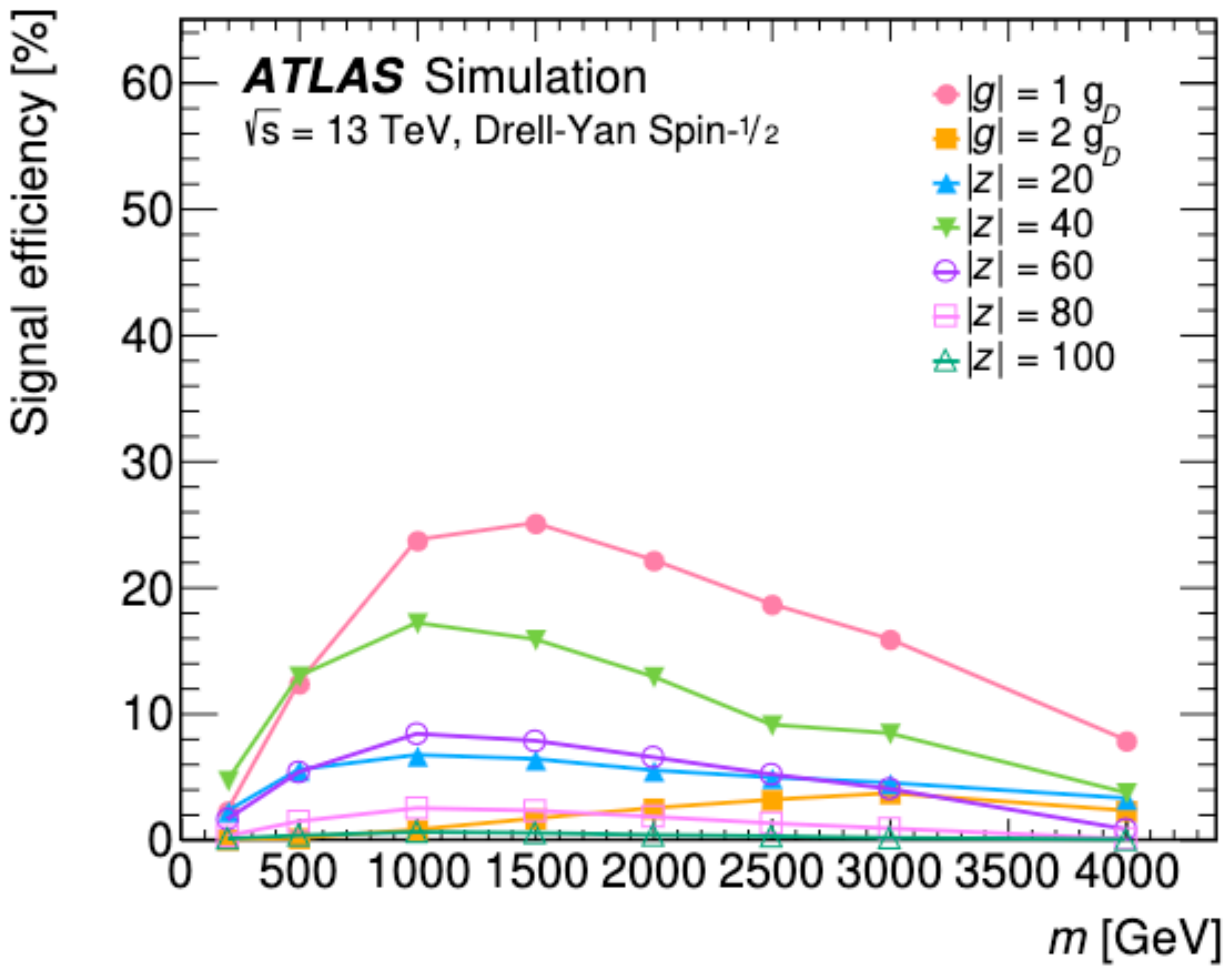


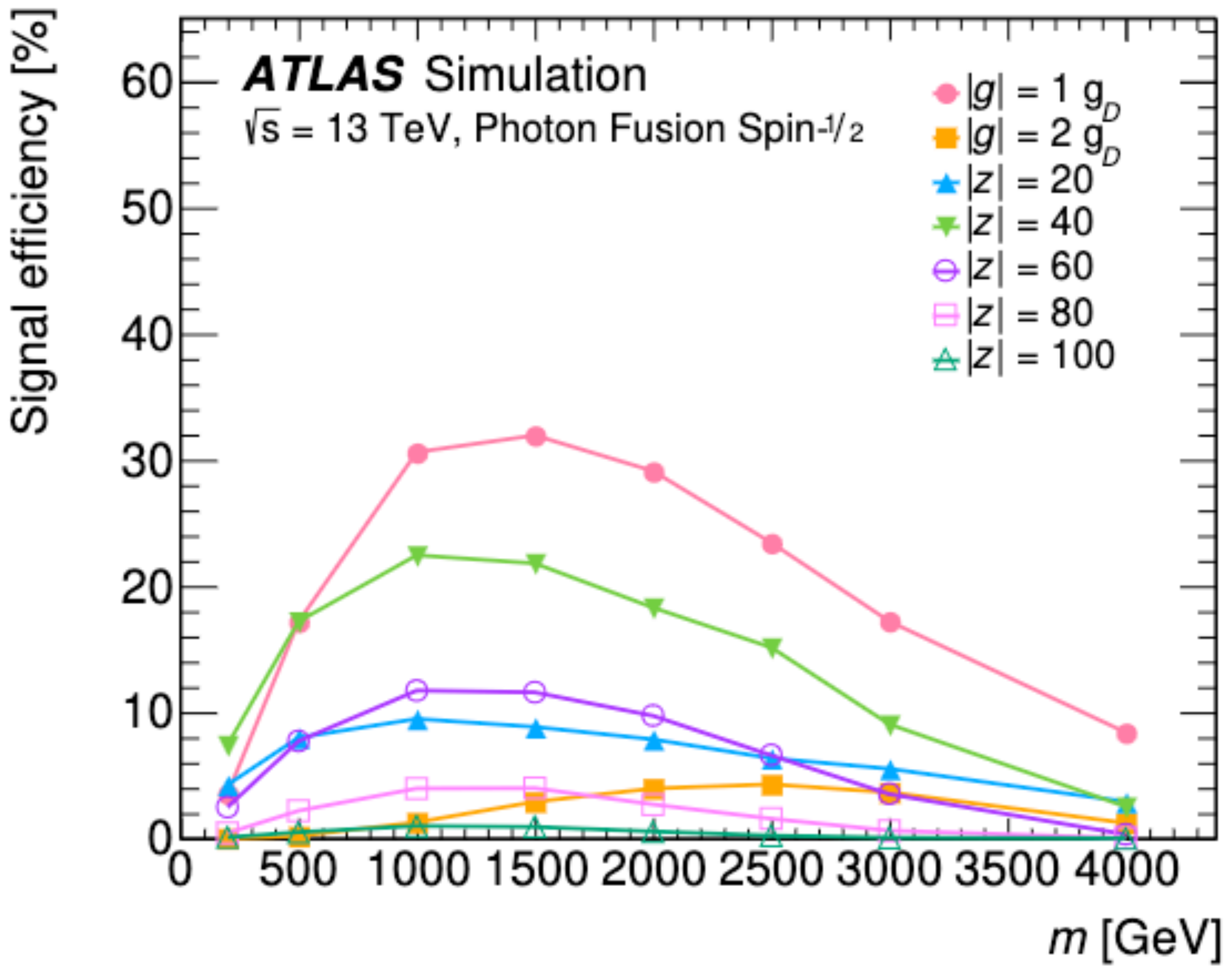
		Total	p_T cut eff.	L1	HLT	Pres.
data	counts	11088272	-	10966159	10961601	1509234
	rel. eff.	1		0.99	1.00	0.14

- Signal candidates defined by

  $w \geq 0.93$ and $f_{HT} \geq 0.77$

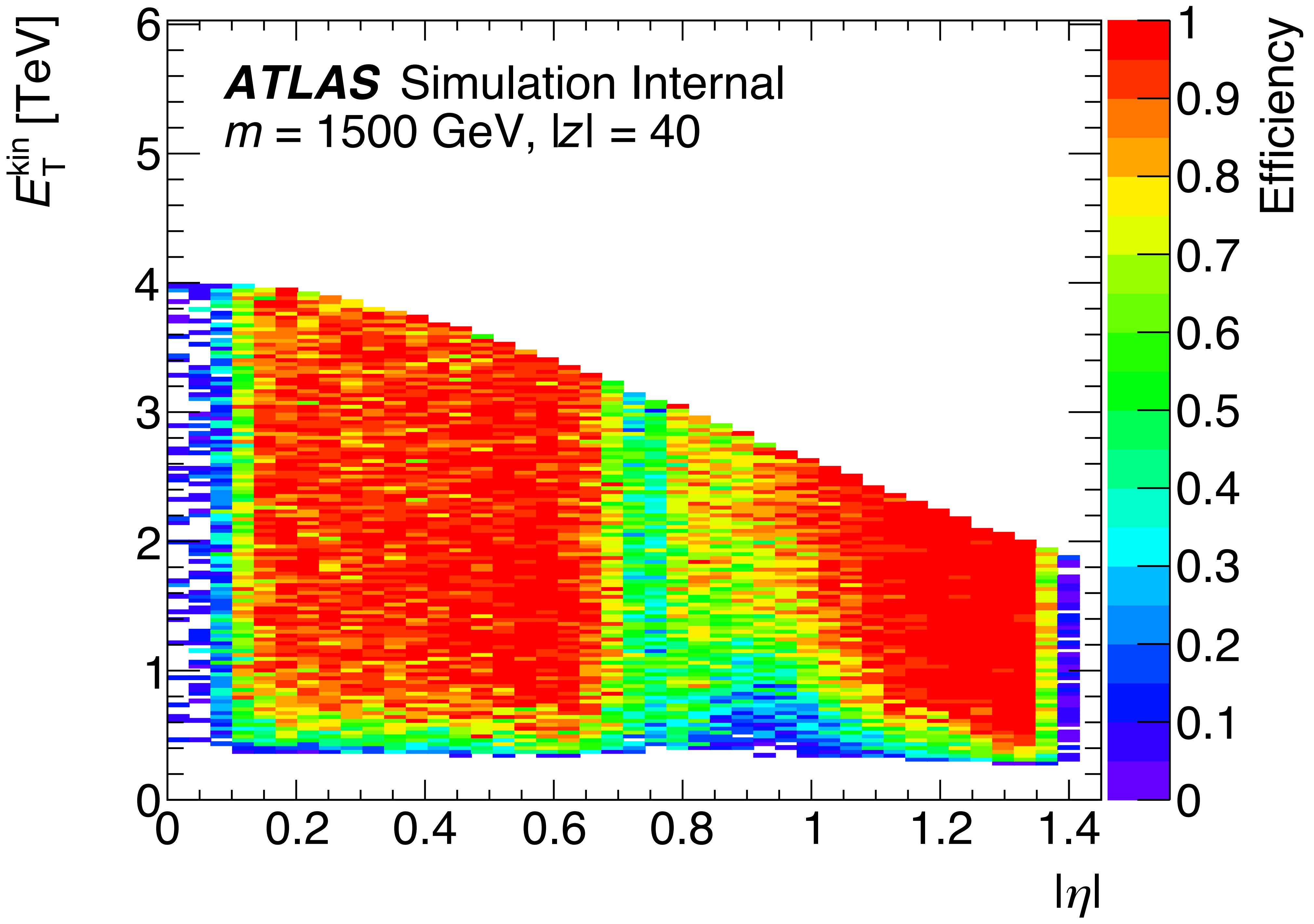
		Total	p_T cut eff.	L1	HLT	Pres.	w	f_{HT}
data	counts	11088272	-	10966159	10961601	1509234	[redacted]	
	rel. eff.	1		0.99	1.00	0.14		
$1g_D$	eff [%]	100	63.9	47.9	40.7	35.9	35.8	22.1
	rel. eff.	1	0.64	0.75	0.85	0.88	1.00	0.62
$2g_D$	eff [%]	100	8.2	3.4	2.64	2.58	2.57	2.49
	rel. eff.	1	0.08	0.41	0.78	0.98	1.00	0.97
$\|z\| = 20$	eff [%]	100	73.11	57.67	44.61	40.08	39.93	5.46
	rel. eff.	1	0.73	0.79	0.77	0.90	1.00	0.14
$\|z\| = 60$	eff [%]	100	23.99	10.98	8.25	7.33	7.31	6.51
	rel. eff.	1	0.24	0.46	0.75	0.89	1.00	0.89
$\|z\| = 100$	eff [%]	100	3.23	0.82	0.39	0.37	0.37	0.35
	rel. eff.	1	0.03	0.25	0.48	0.95	1.00	0.95





EFFICIENCY IN SIMULATION RESOURCES EXTRAPOLATION METHOD

- Model independent samples
  - Reduce *fully simulated samples*
    - 7 charges, 8 masses, 4 models (DY, PG, spin 0, 1/2)
    - **17 million pair - events!**
  - Model independent efficiency maps
    - 7 charges, 8 masses, model independent+1 model
    - **~4.5 million pair-events and 2.8 single events**
- **Extrapolation:**
  - Extrapolation of efficiency based on kinematic conditions

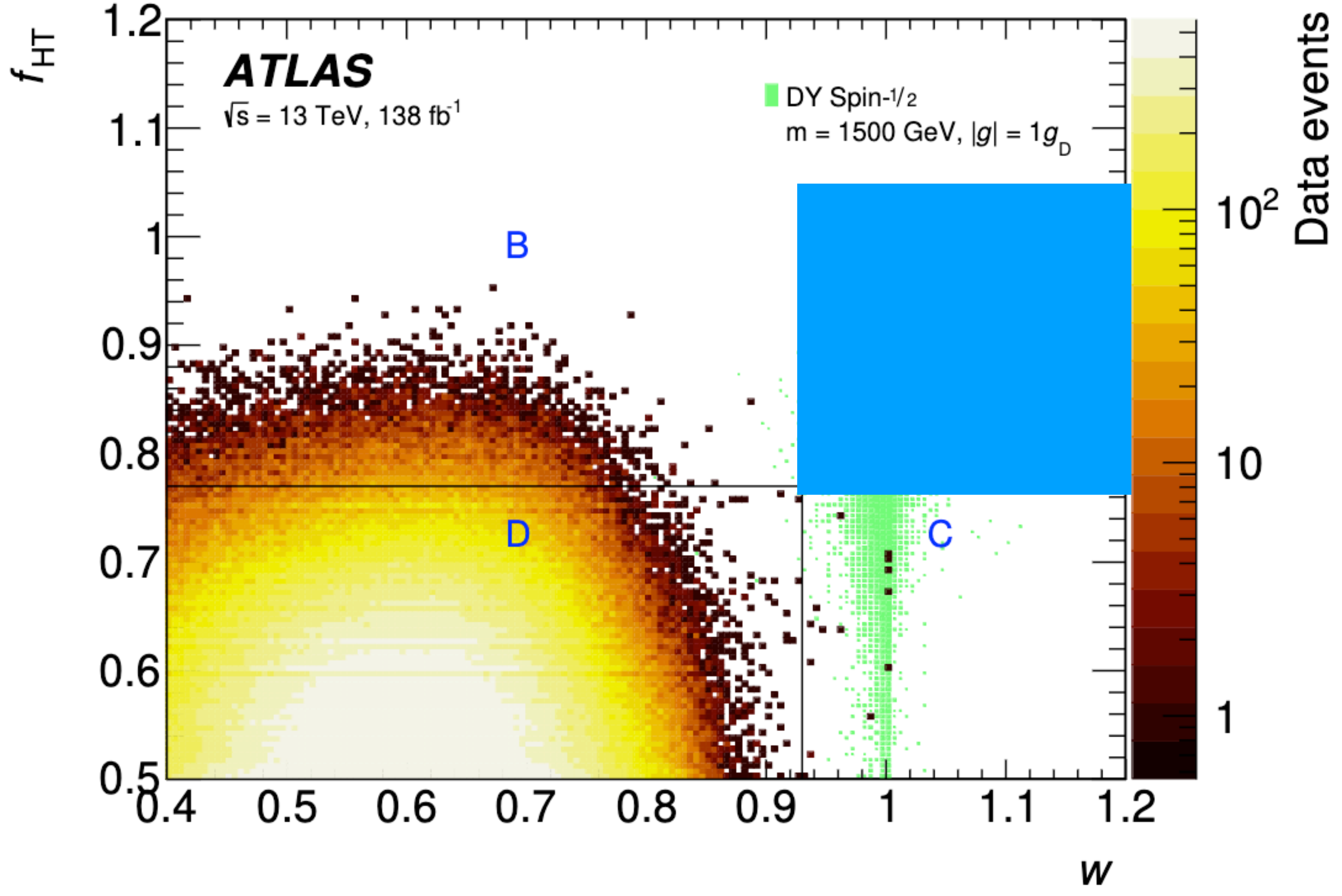


BACKGROUND ESTIMATION

BACKGROUND ESTIMATION:

- Two possible sources of background (Jets and high energy electrons)
- Too computationally intensive to have statistically significant MC samples
- Data driven background estimation:

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



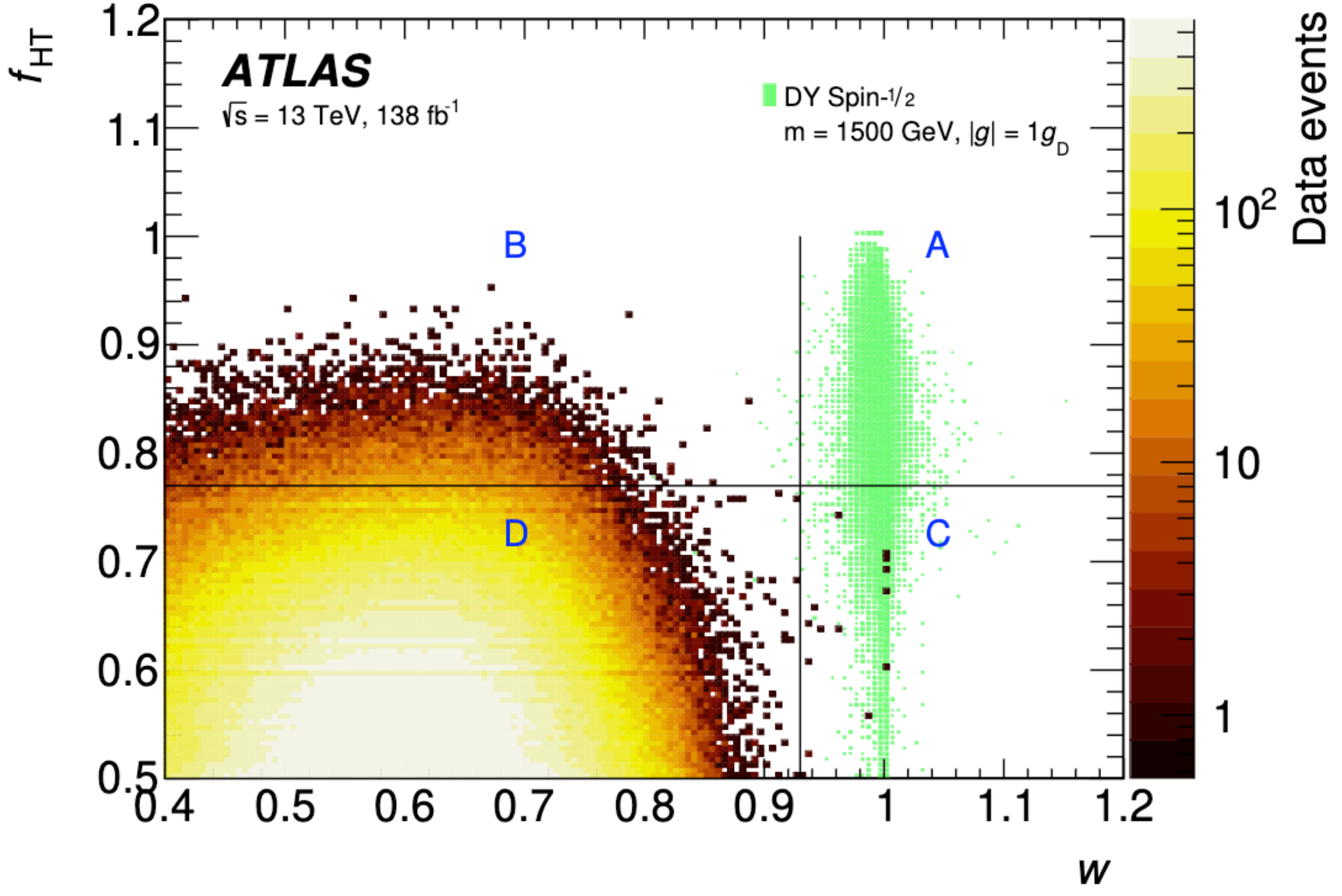
η- sliced ABCD BACKGROUND ESTIMATE

- Create 3D ABCD background estimate by slicing ABCD plane in TF-uniform η regions
- Systematic uncertainty of ~30% (root mean square of the deviation of the fit for the TF)

$$N_A^{\text{bkg}} = 0.15 \pm 0.04 \ (\text{stat.}) \pm 0.05 \ (\text{syst.})$$

UNBLINDING SIGNAL REGION

- No excess over SM prediction



RESULTS & INTERPRETATION

LIMIT SETTING VIA CLS METHOD

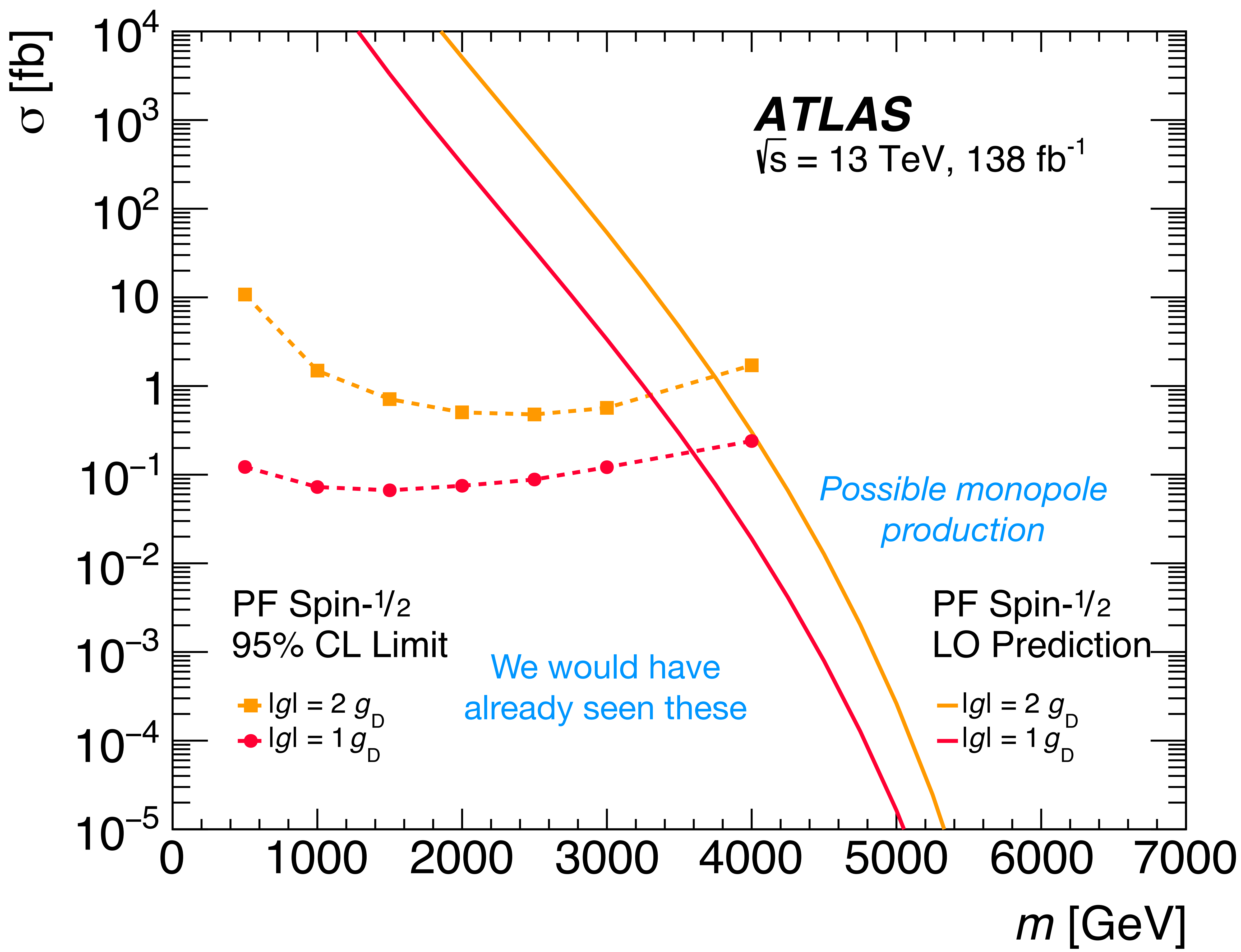
- Find the set of free parameters (q) for which CLs ≤ α
- The fit will result in a value of the signal strength μ_{sig}

$$\sigma = \frac{\mu_{\text{sig}}}{\epsilon \mathcal{L}}$$

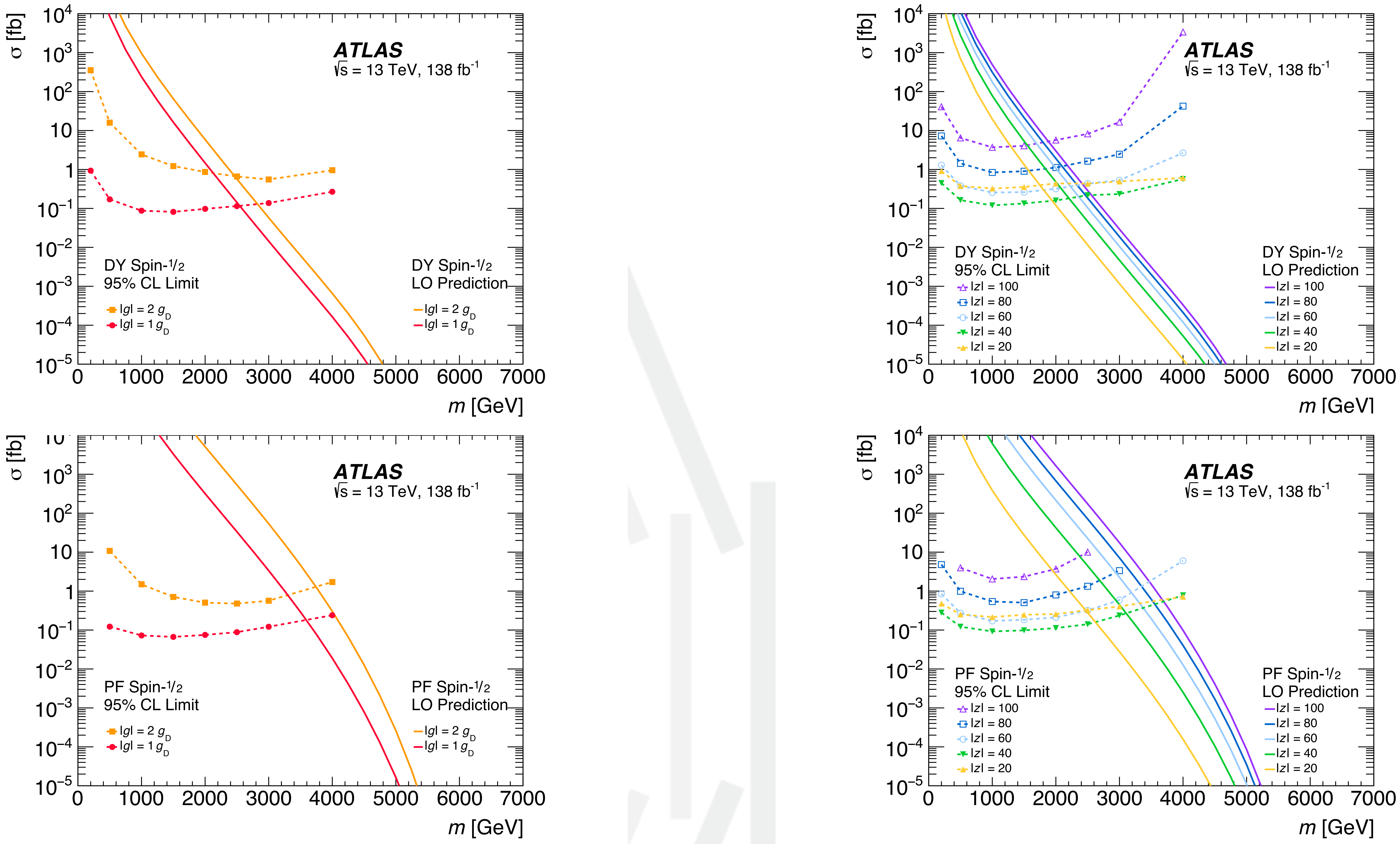
Signal selection efficiency for MC sample

L = integrated luminosity

- Lower mass limits are set in the intersection between theoretical and production

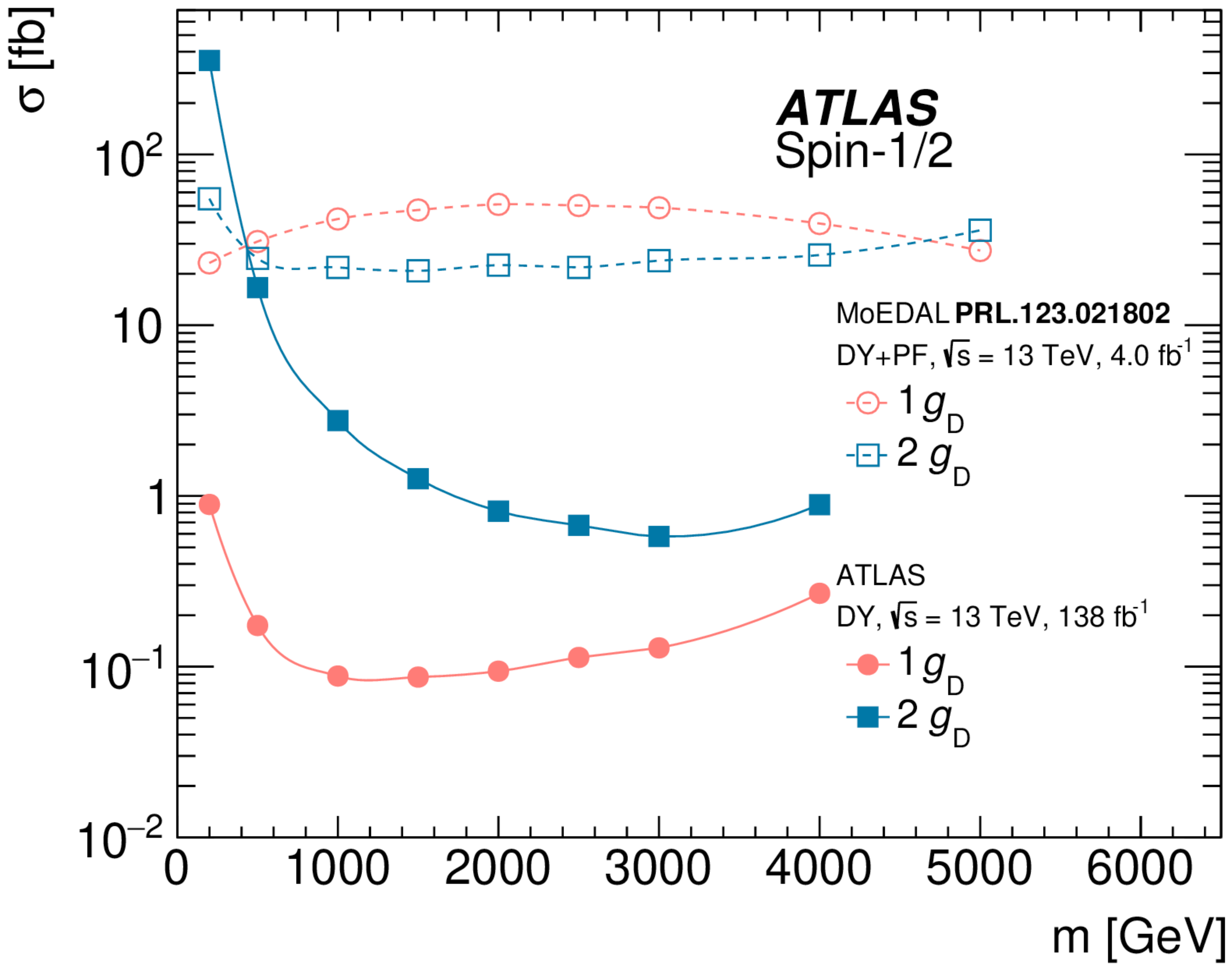


95% CL UPPER CROSS SECTION LIMITS

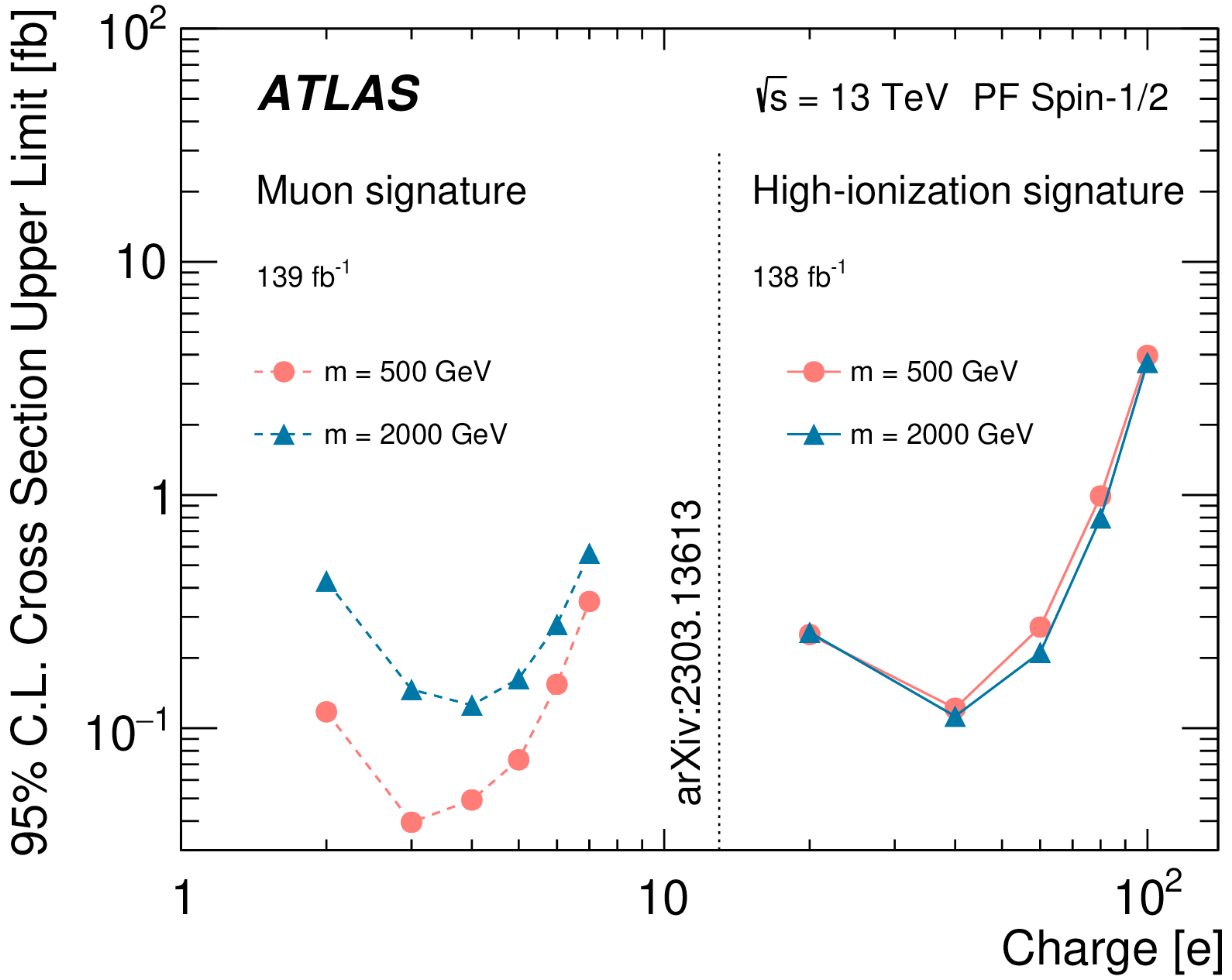


HOW DID WE DO?

COMPARISON TO OTHER STUDIES: MOEDAL

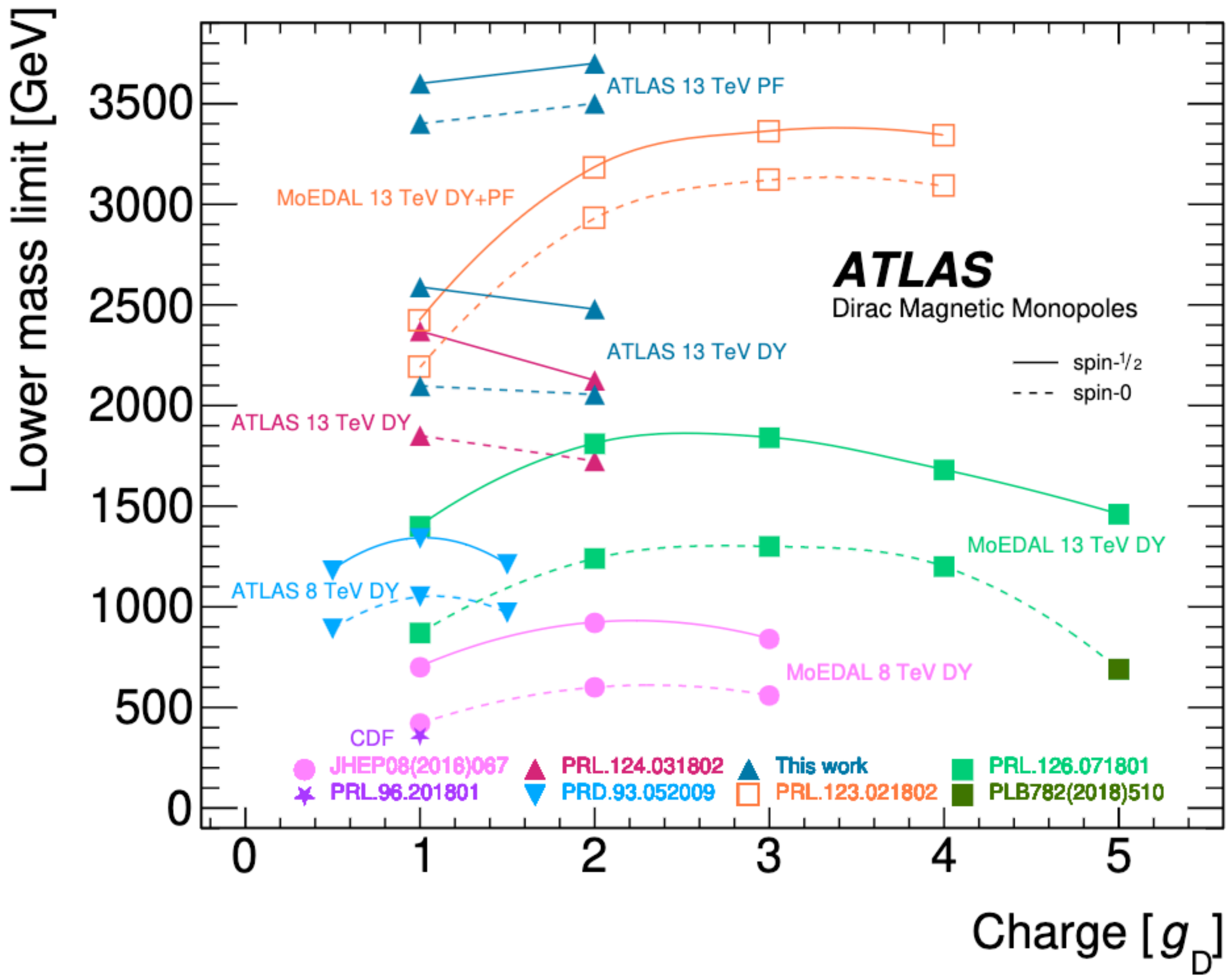


COMPLEMENTING MULTI-CHARGED PARTICLE SEARCH



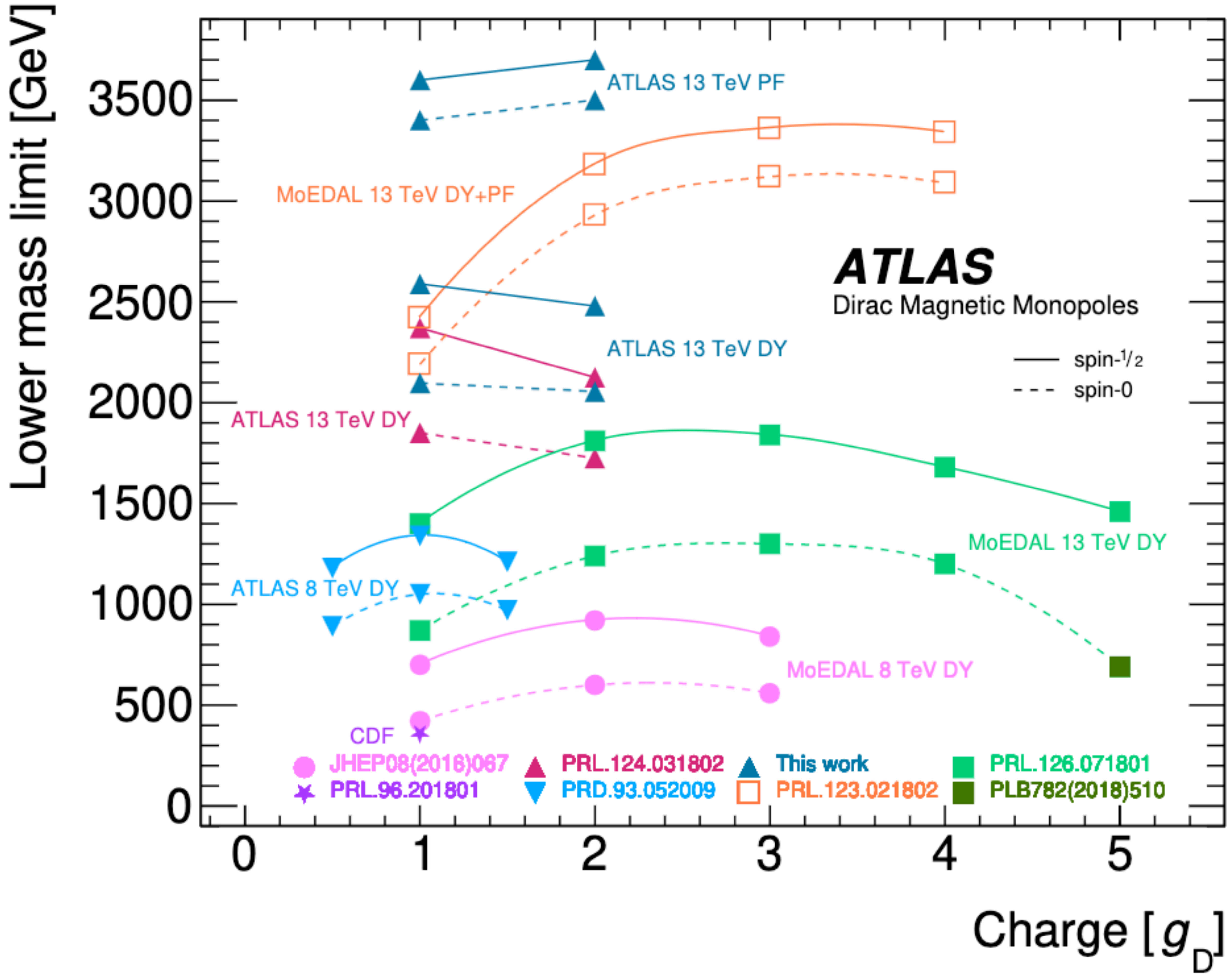
LOWER MASS LIMIT COMPARISON WITH MOEDAL

- MoEDAL covers larger charge range
- ATLAS has set highest-to-date mass limits in 1 and 2 gD monopoles



FINAL REMARKS AND OUTLOOK

- Run 2 full HIP search set most stringent cross section and mass limits to date
- Robust study of background correlations and limit setting framework performed in this analysis



THANK YOU!

BACKUP SLIDES

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%)