Looking for Dark Photons with the ATLAS experiment

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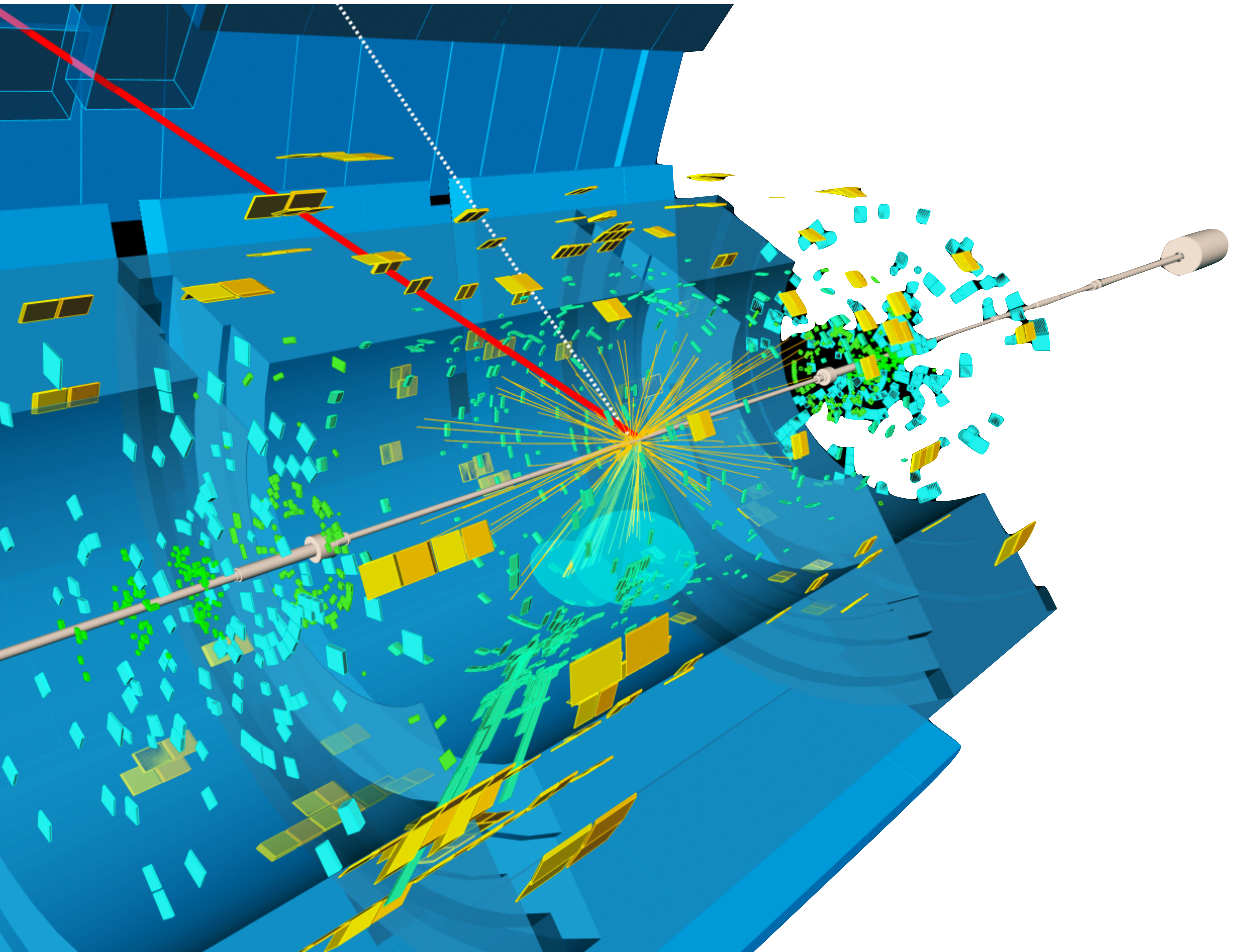
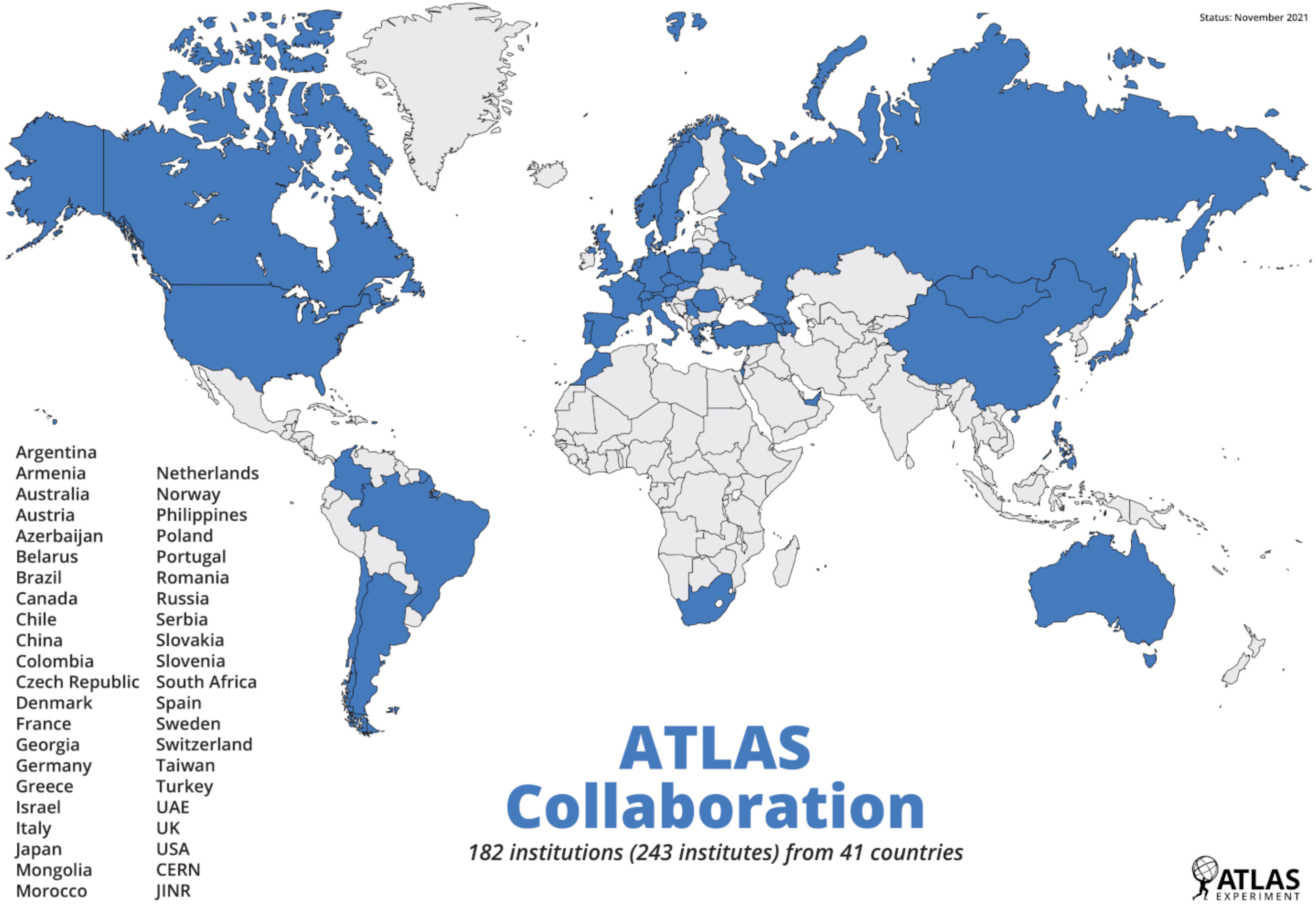


Outline

- The ATLAS experiment at LHC
- Dark matter evidences and the Dark Sector
- Prompt, displaced and very displaced dark photons searches at the ATLAS experiment
- Conclusions



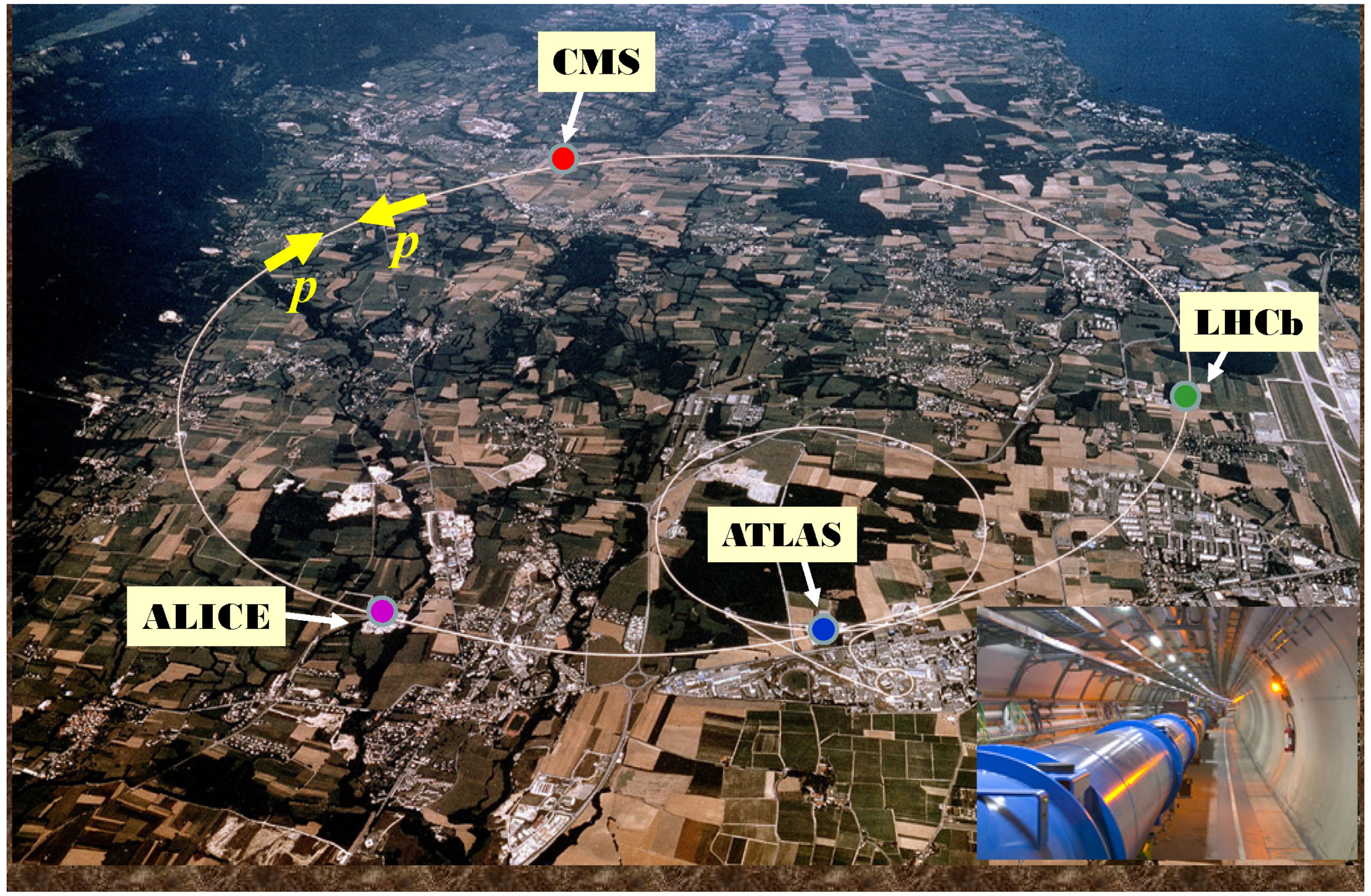
Getting to know LHC (Large Hadron Collider)

LHC is a 27km pp synchrotron collider ($f_{rev} = 11\text{kHz}$), sited 100m underground near Geneva.

Around each of the four Interaction Points (IPs) there is an experiment: ALICE, ATLAS, CMS and LHCb.

Three fundamental machine parameters for LHC discovery potential:

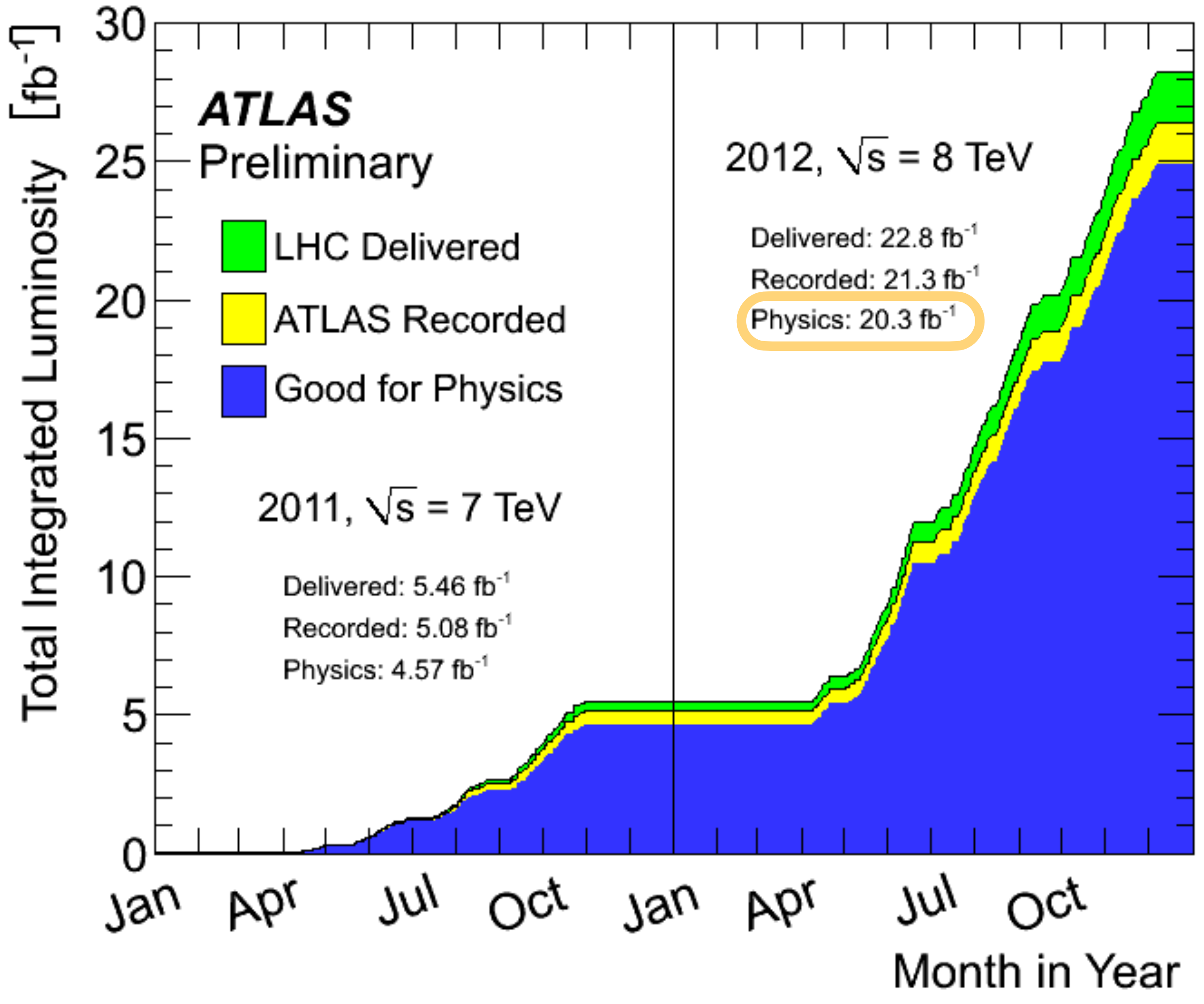
- The **luminosity** $\mathrm{L} \sim$ total number of pp collision has to be maximised
- The **center of mass energy** $\sqrt{s} = 2E_f$ (E_f beam energy)
- **Pile-Up** (PU) (multiple interactions occurring "at the same time" in the IP) has to be minimised.

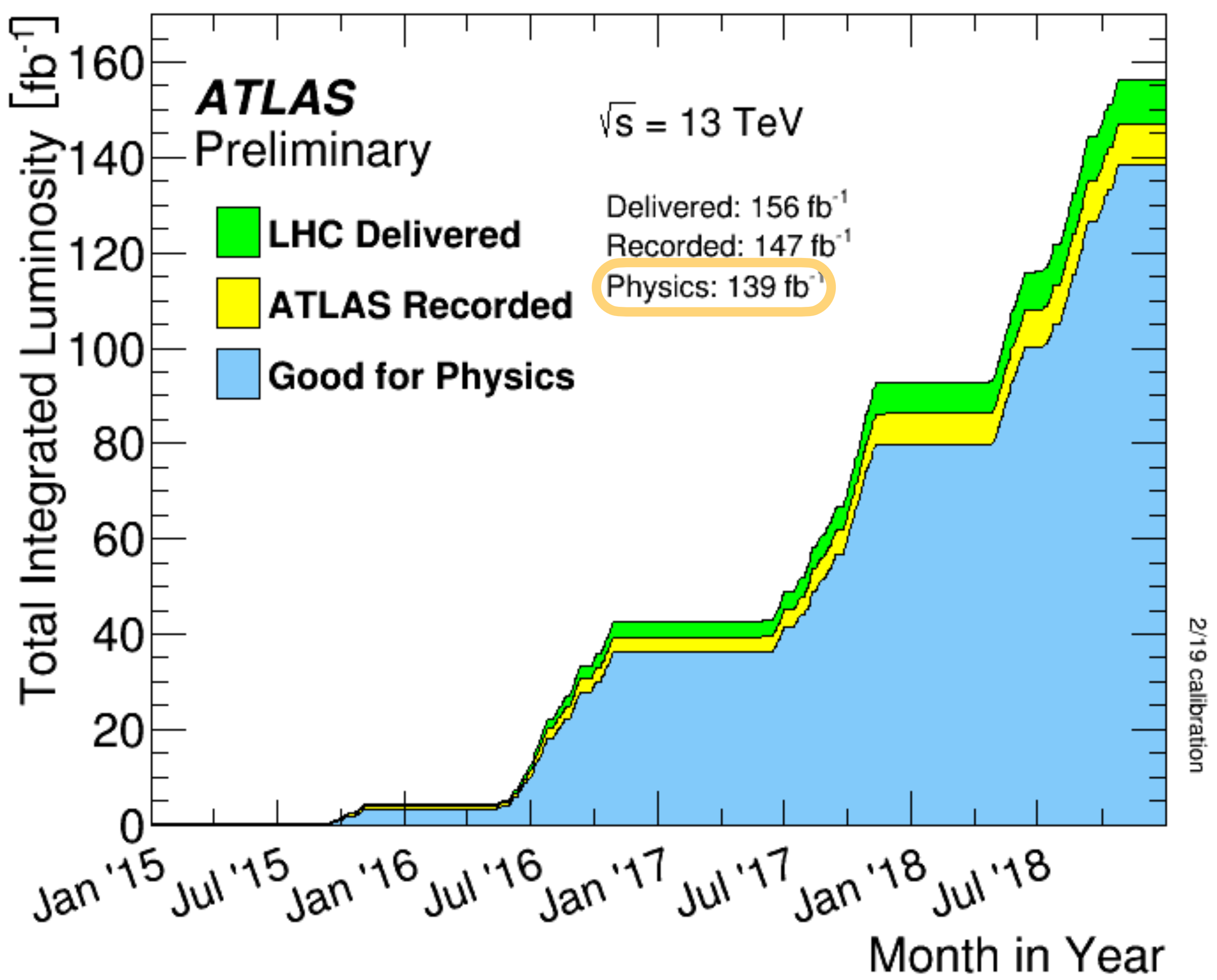


Important to maximise $\mathscr{L}$ without increasing PU too much!!

How LHC worked during the years

	Run 1			LS1		Run 2				LS2
	2010	2011	2012	2013	2014	2015	2016	2017	2018	→ Now
$\sqrt{s}$ [TeV]	7	7	8			13	13	13	13	
$N_{B_{max}}$	368	1380	1380			2232	2300	2450	2500	
$N_{P_{max}} \times 10^{11}$	1.2	1.45	1.7			1.1	1.2	1.2	1.2	
BS [ns]	150	75/50	50			25	25	25	25	
$\mathcal{L}_{max}$ $[10^{33}\text{cm}^{-2}\text{s}^{-1}]$	0.21	3.7	7.7			5	15	20	20	10^2 x 2010
PU	4	17	37			30	30	50	50	10 x 2010



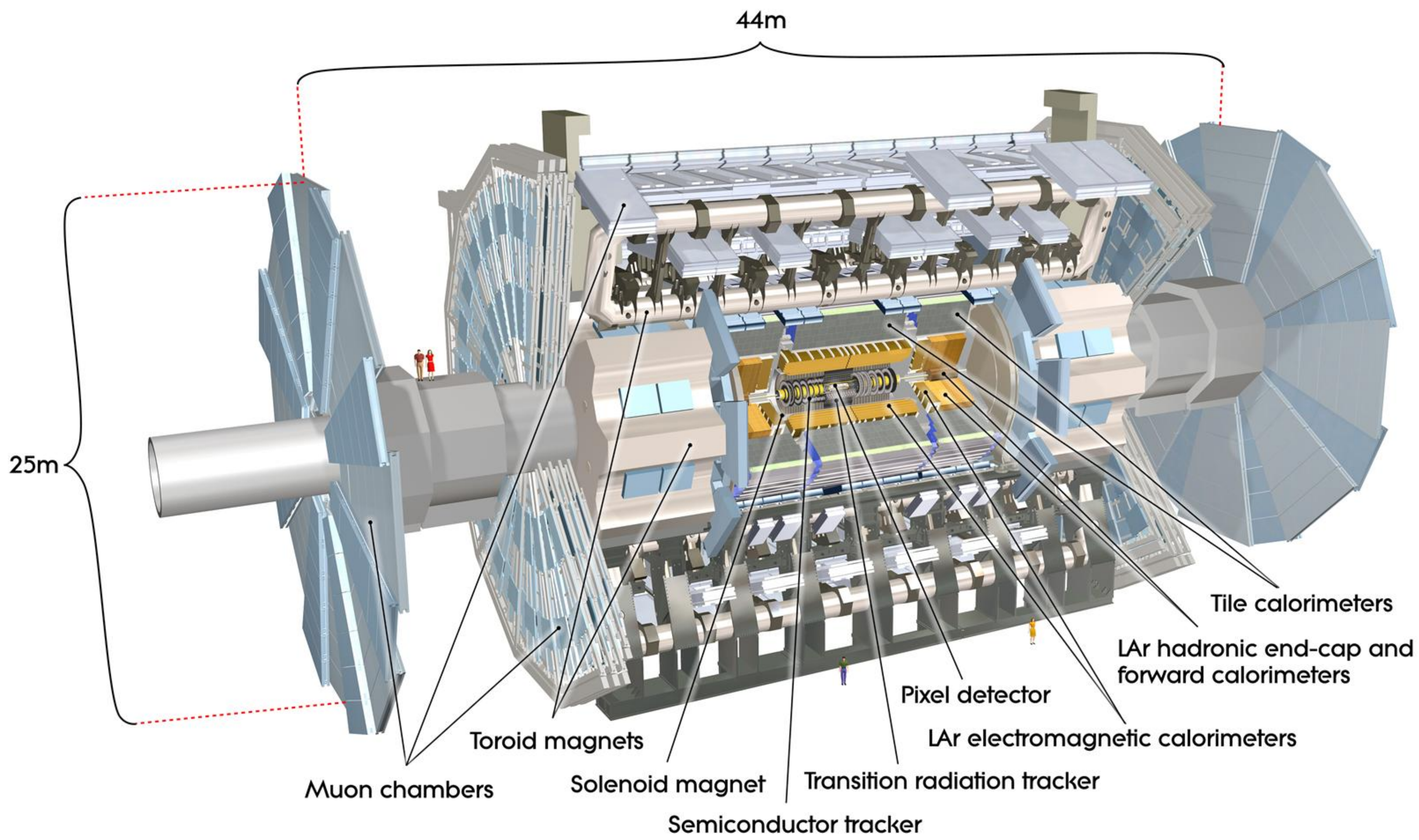


$L = 20.3\text{fb}^{-1}$ and $L = 139\text{fb}^{-1}$ of data have been collected respectively during Run 1 and Run 2 by the **ATLAS experiment.**

A closer look of ATLAS (A Toroidal LHC ApparatuS)

ATLAS: multi-purpose barrel-shaped detector with a backward-forward cylindrical symmetry with respect to the IP.

It is 44 m long, 25 m high and weights more than 7000 tons.



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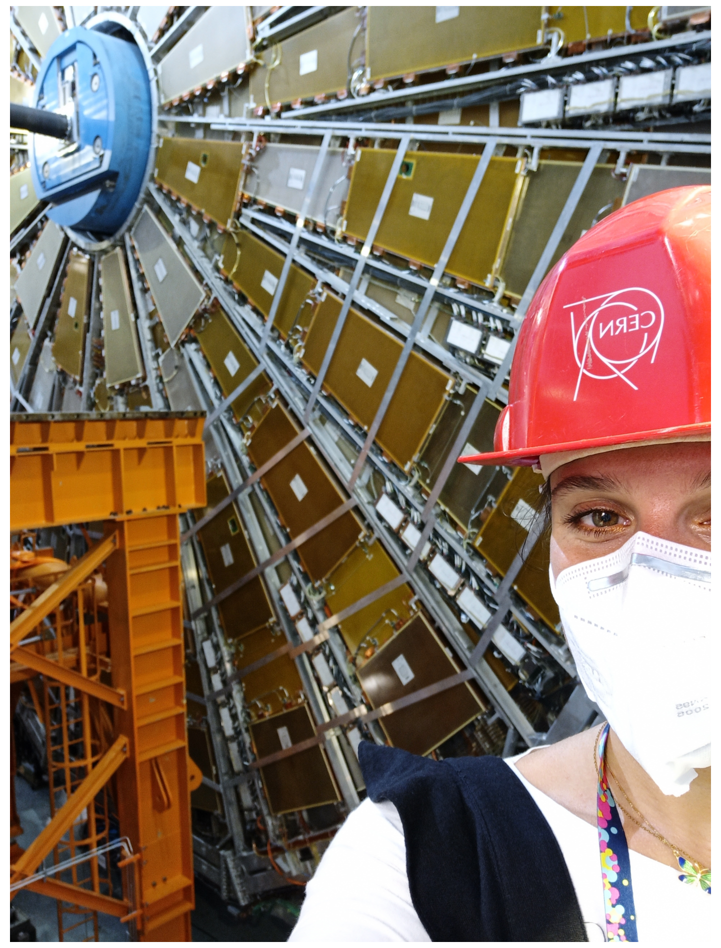

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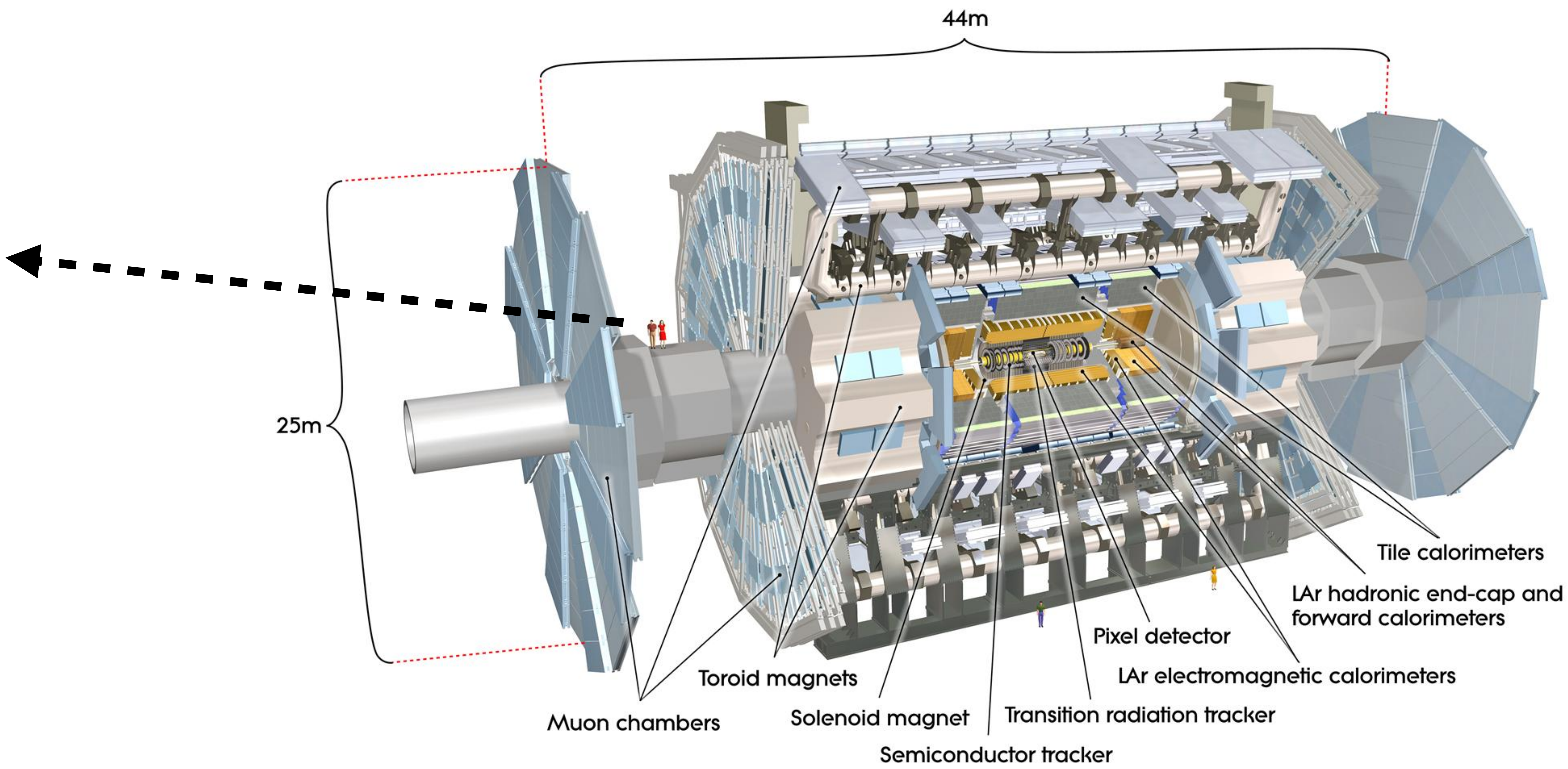

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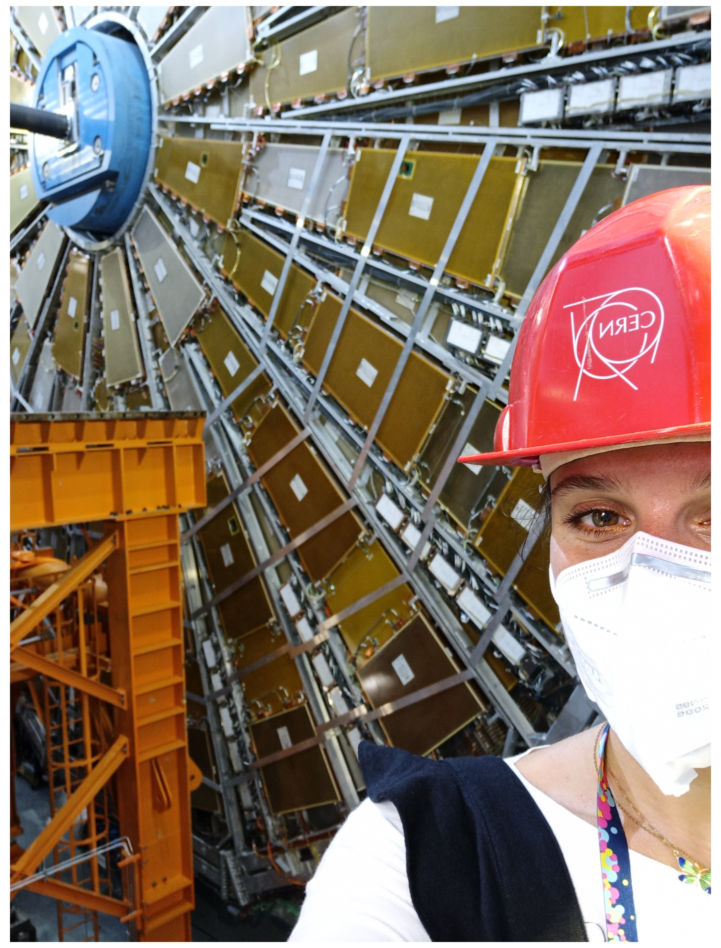

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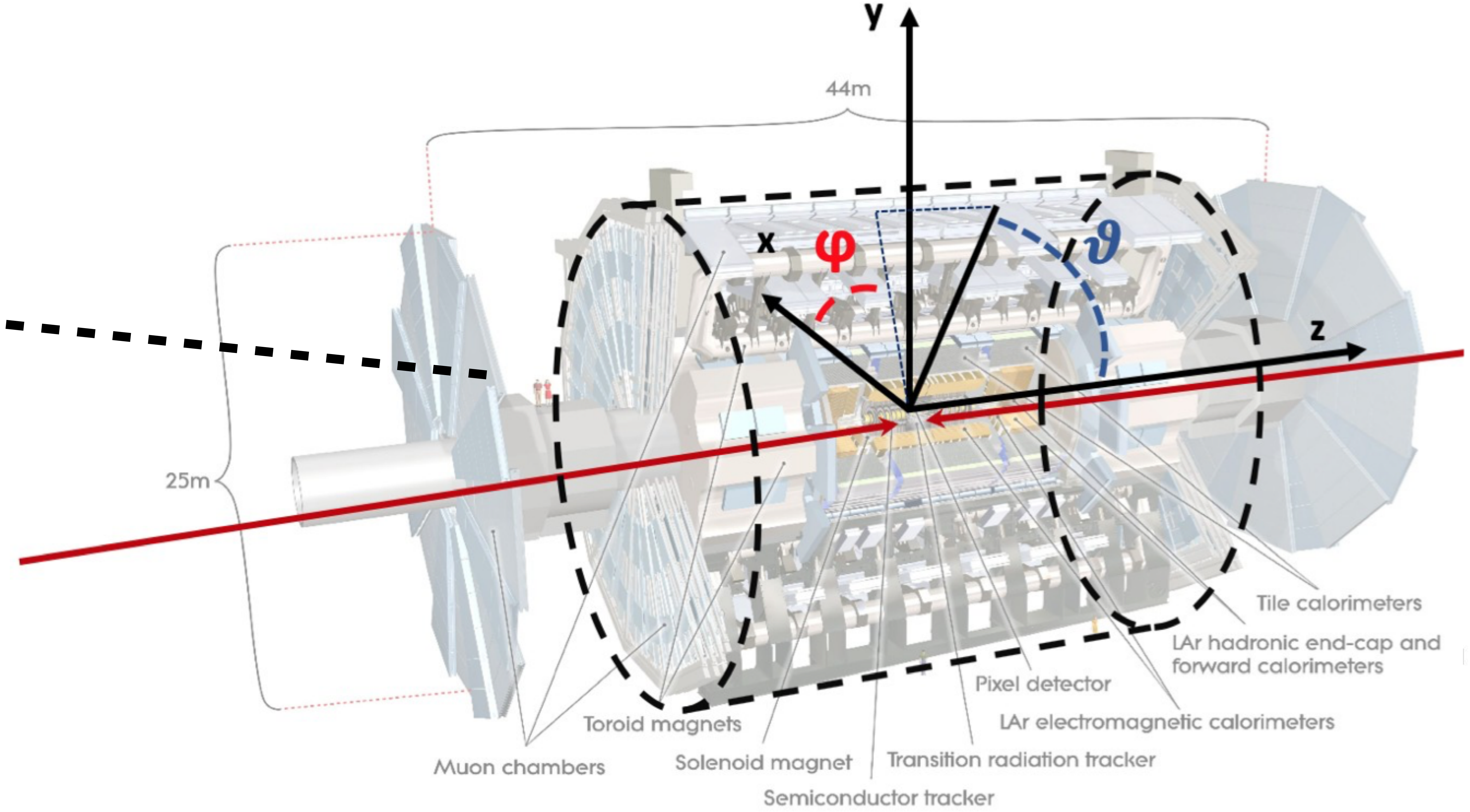

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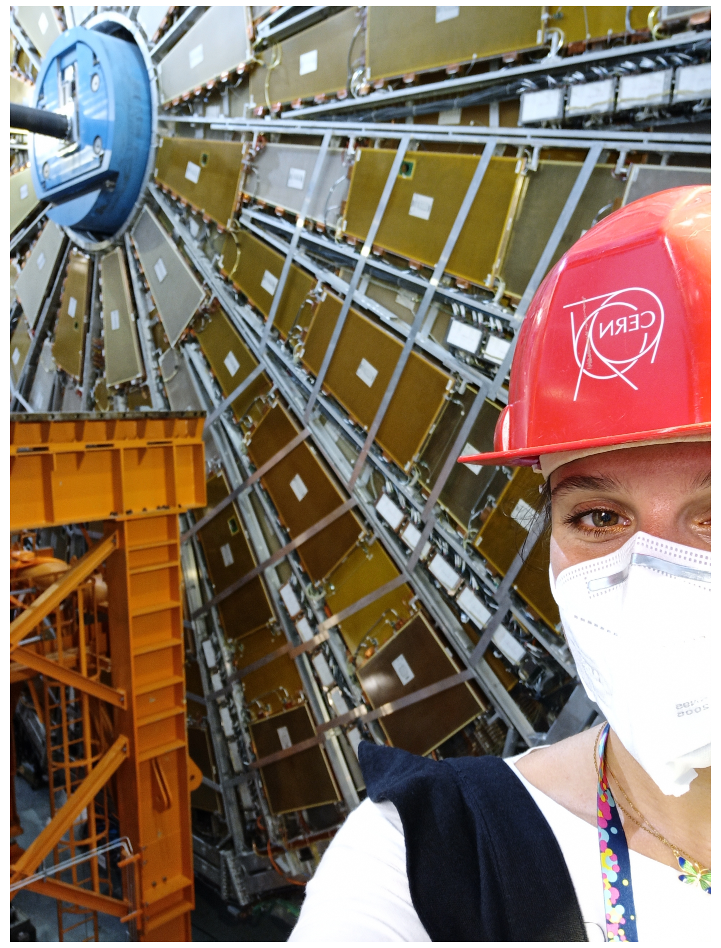
- $p_{\mathrm{T}} = \sqrt{p_x^2 + p_y^2}$
- φ
- $E_{\mathrm{T}}^{\mathrm{miss}}$



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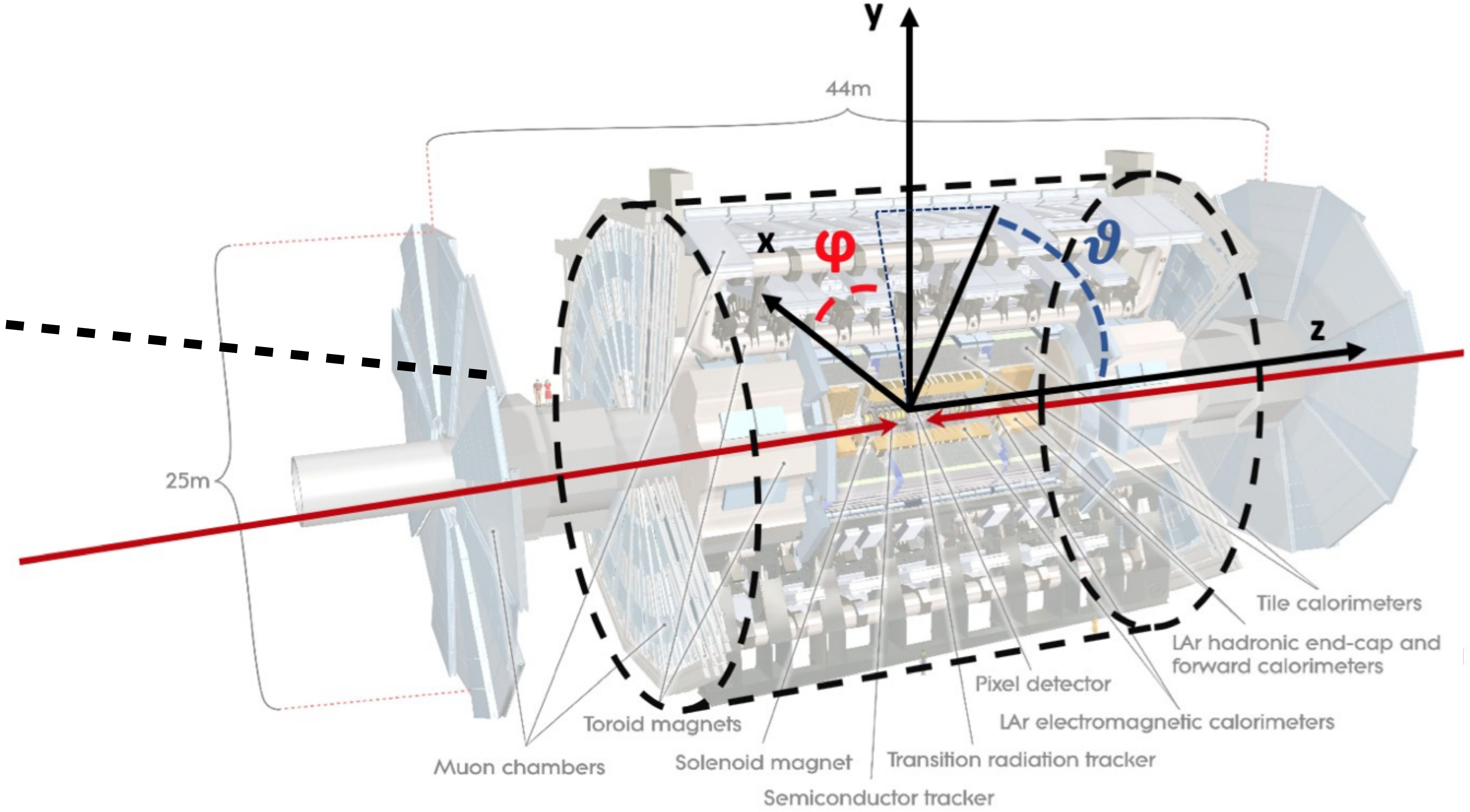

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Main purpose for its construction?

The **discovery of the Higgs boson!**

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And they did it (in 2012)!

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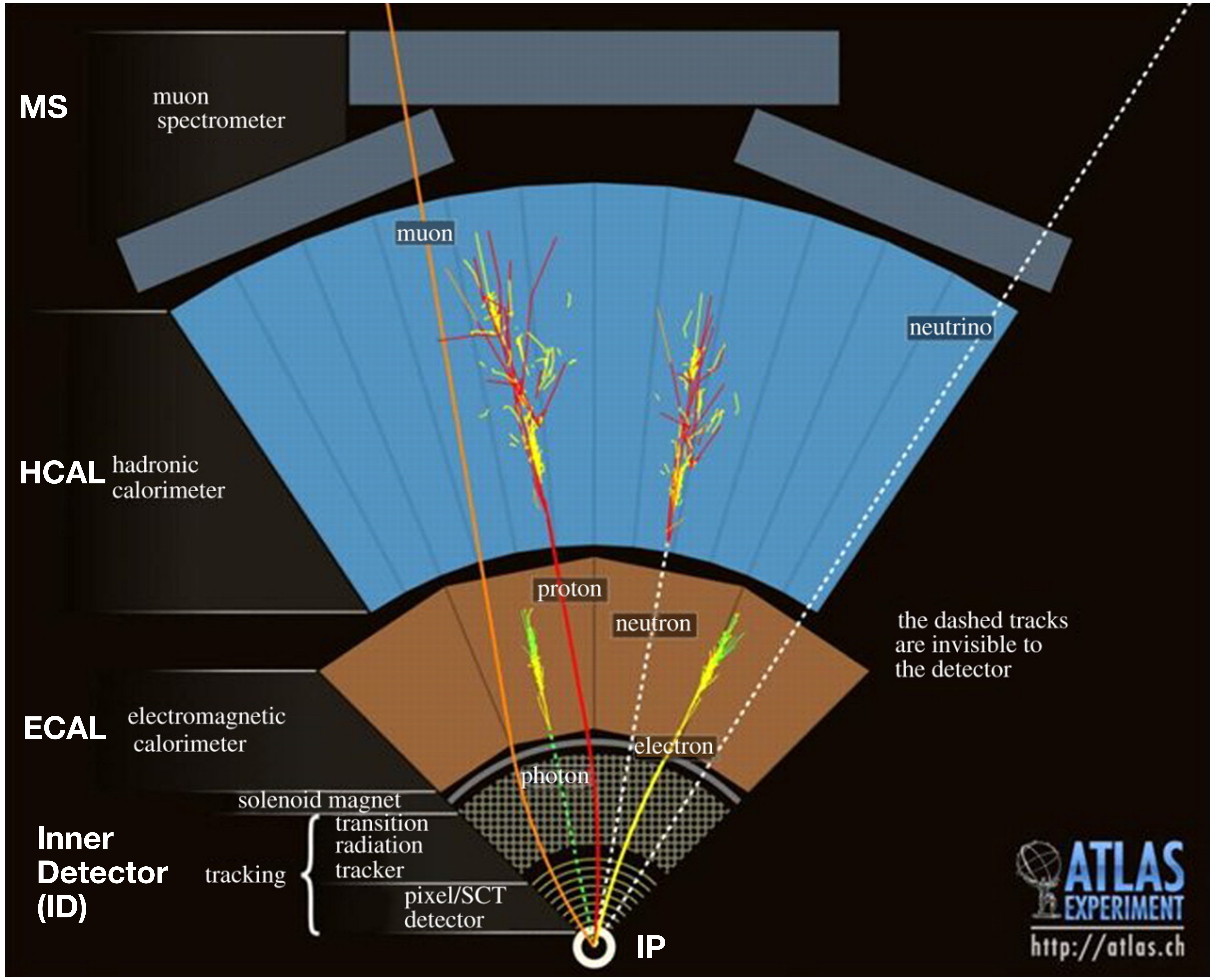
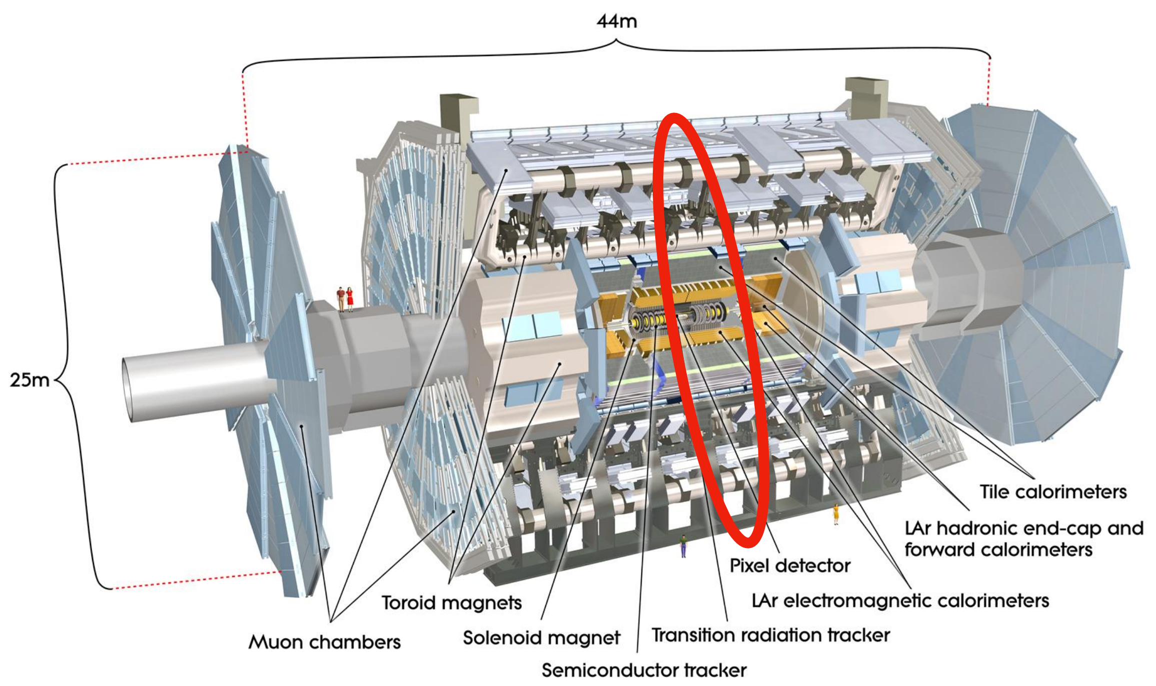
A detector that detects almost everything?





Set of sub-detectors devoted to a precise kind of particles, distinguished according to their interaction with the detectors.

Naive examples:

An electron interacts mostly with the ID and with the ECAL → a particle that interacts mostly with the ID and with the ECAL is reconstructed as an electron!

Attention: **jets :=** groups of highly collimated hadrons and other particles (reconstructed as energy deposits in the calorimeters).

What do we do in ATLAS?

5500 members (**<u>1200 PhD students</u>**!)

We don't work all on the same search. ATLAS is a multi-purpose detector → various searches are carried out. Two macro-categories:

- Precision measurement → it is looked for deviations on SM predicted values (such as Γ_H)
- New Physics searches → it is looked for events that could be interpreted in terms of BSM

1. Collect data
2. How the desired event will look (what signature) in ATLAS? → knowing the background processes
3. MC simulation both for background and signal
4. Find discriminating variables between signal and background

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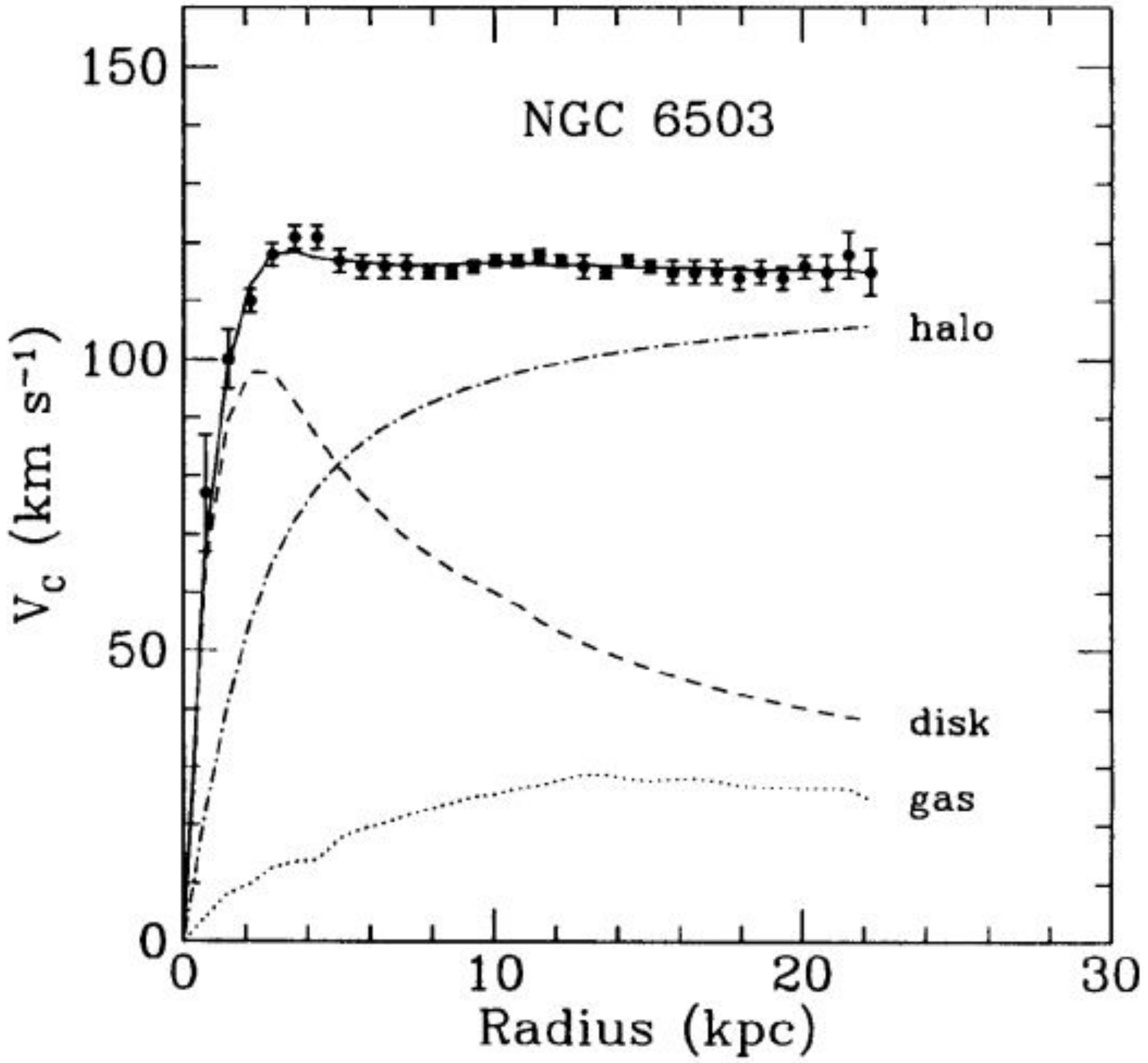
<u>New Physics</u>:

5. Look in data for excess of events wrt to SM MC prediction that can be interpreted in terms of new physics

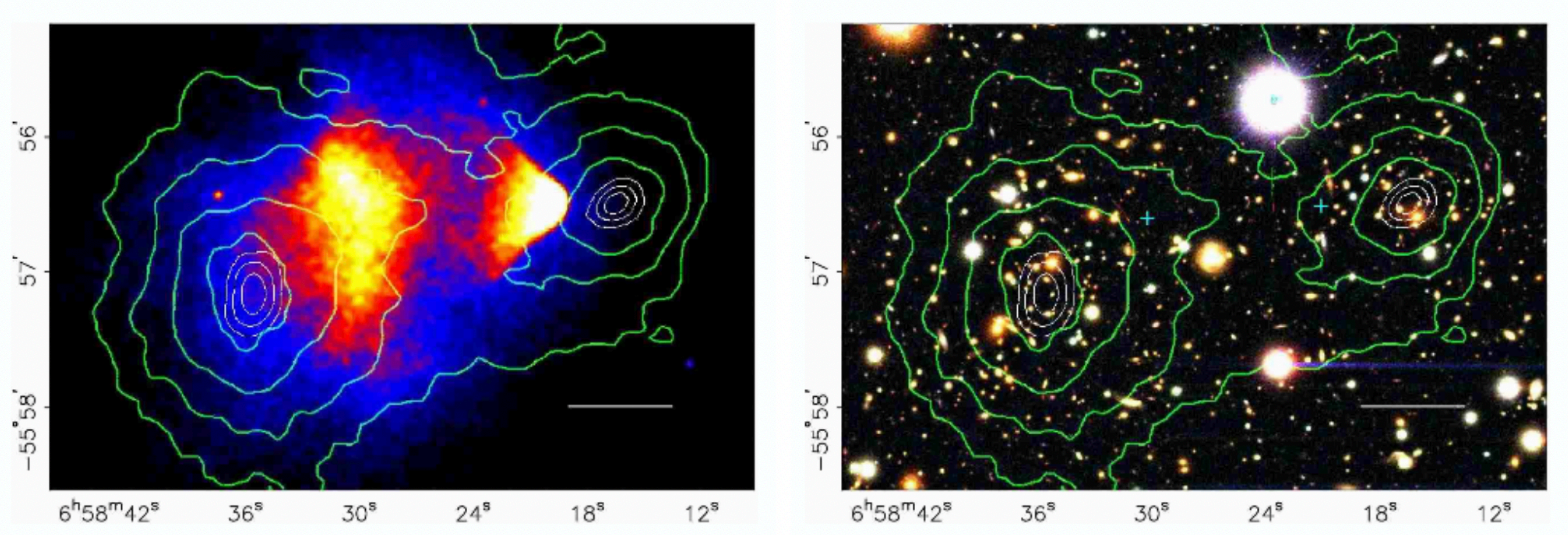
Dark matter evidence in a nutshell

Evidence that "something is not working" ranges from the galactic to the cosmological scale.

Galactic scale



Cluster of galaxy scale



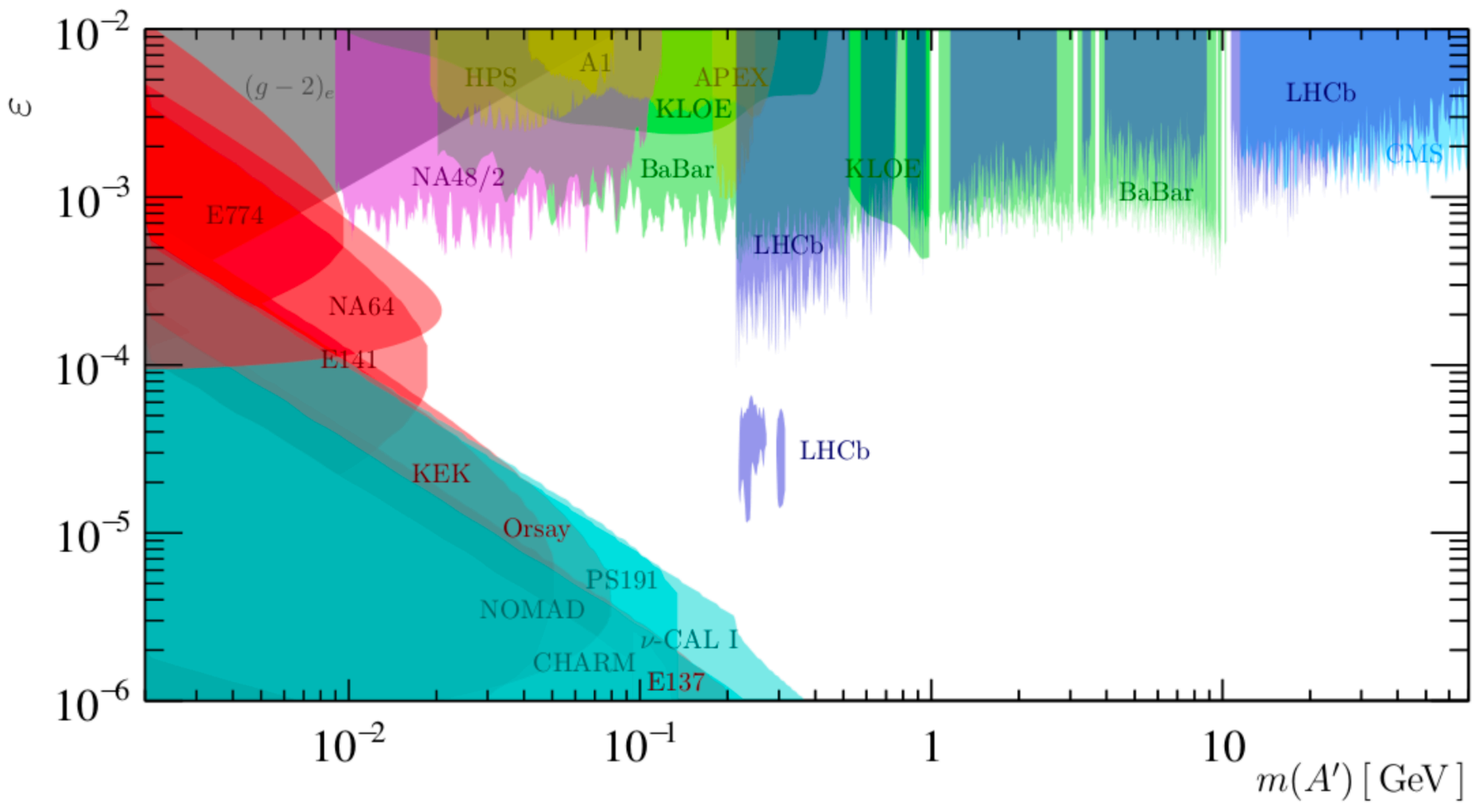
All this evidence points to the existence of a Dark Matter that interacts gravitationally (and hopefully "weakly") with ordinary matter → $81\ \%$ of matter is Dark Matter!!!

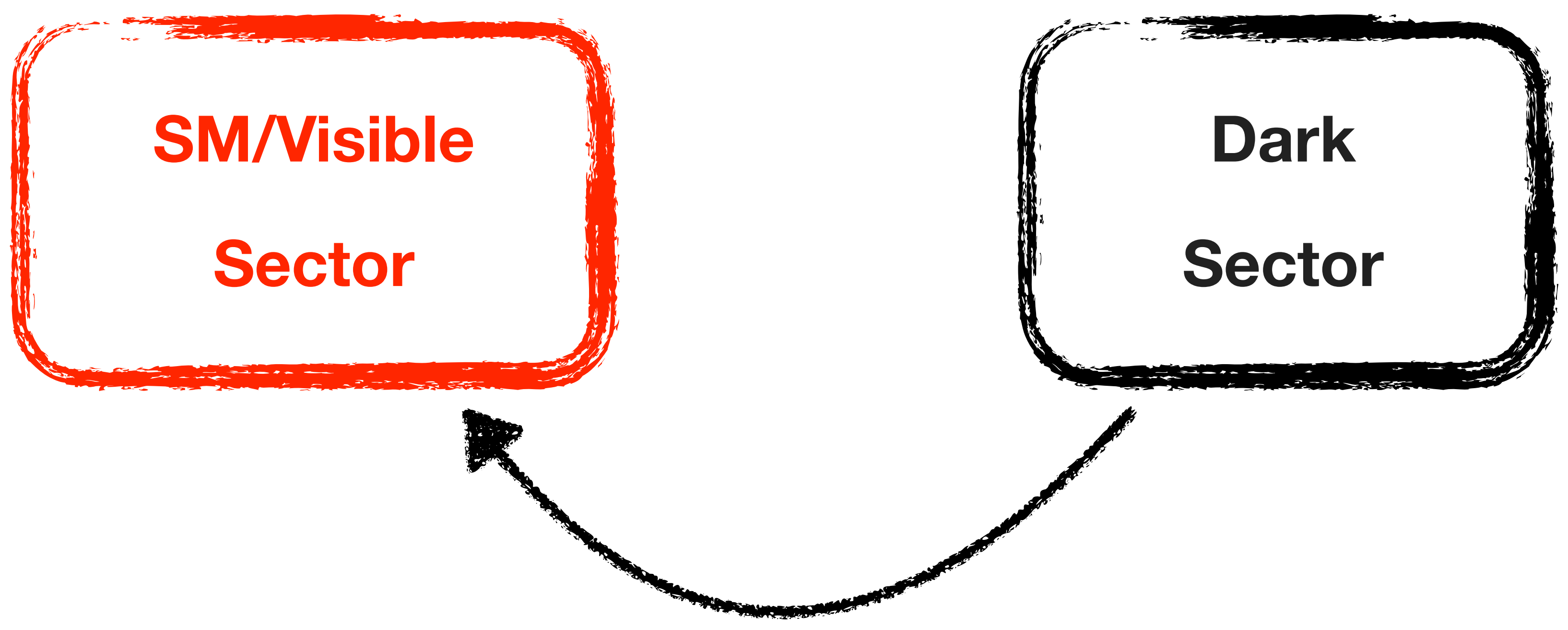
Accessing the Dark Sector through portals

Investigated possibility: Dark Matter could constitute a whole new **Dark Sector** of particles.

Minimal Dark Sector model: $\mathrm{U}(1)_\mathrm{d}$ symmetry spontaneously broken by a Dark Higgs (S) mechanism → the interaction is short range, the γ_d is massive and decays.

Minimal assumption: "portal" between the dark and the visible sector is needed → vector portal (mixing between γ_d and γ).





Vector portal ε
γ_d decay

Gauge Sector

Dark Higgs Sector

$$\mathscr{L} = -\frac{1}{4}V_{d_{\mu\nu}}V_d^{\mu\nu} - \frac{\varepsilon}{2}V_{d_{\mu\nu}}F_d^{\mu\nu} - \mu_S^2|S|^2 + \lambda_S|S|^2$$

Interaction term
ε mixing parameter

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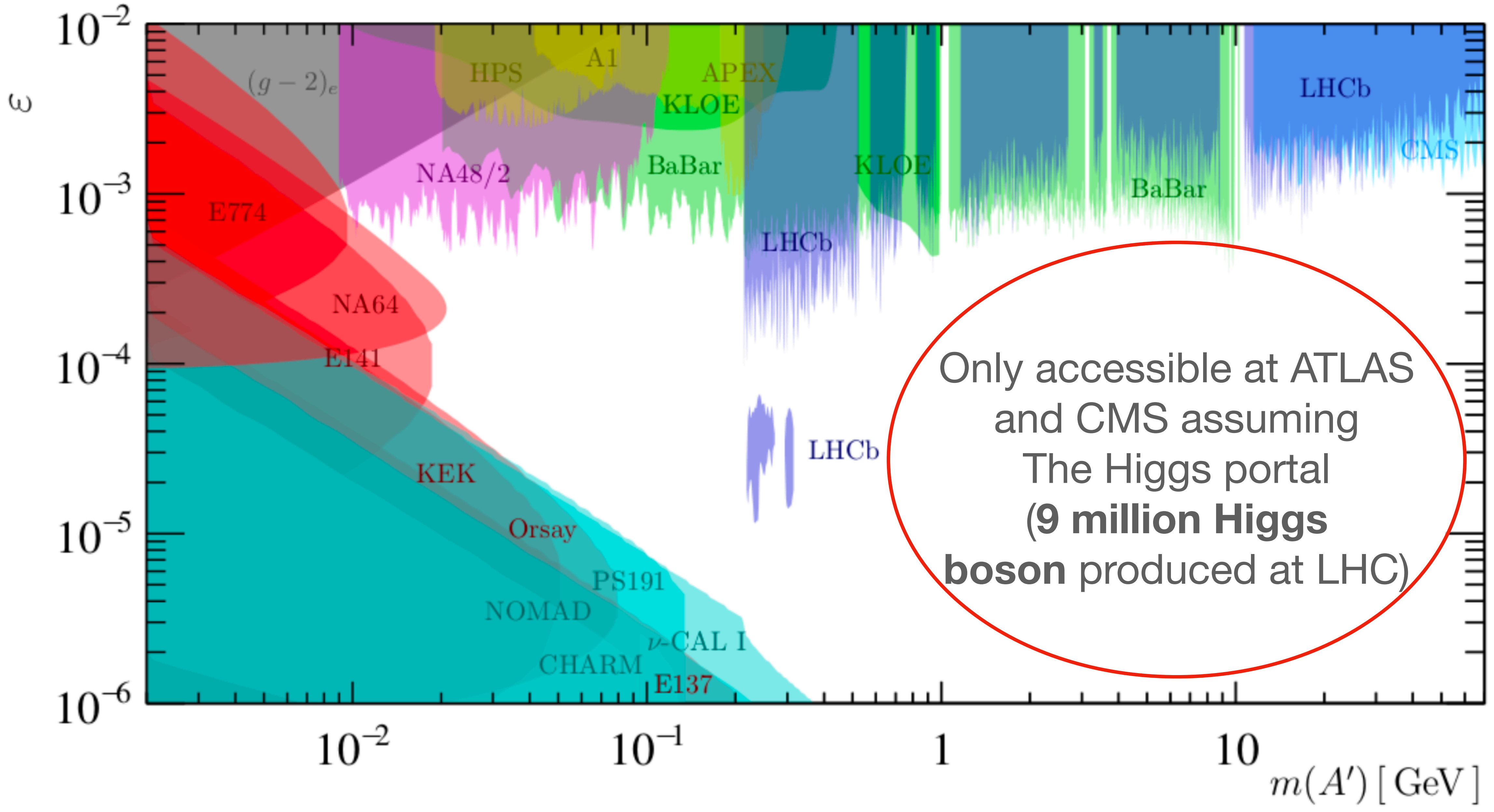

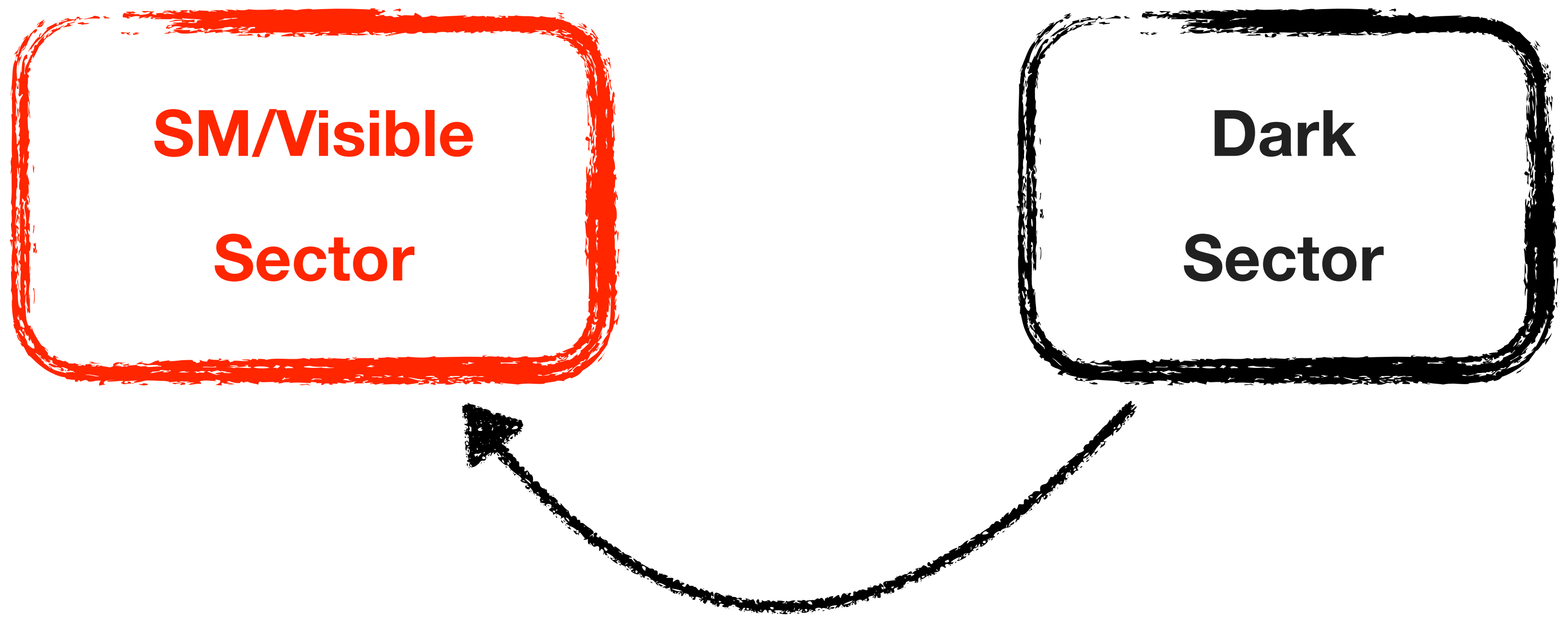

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Can the Higgs decay into Dark Matter?

In ATLAS $B(H \rightarrow und) \leq 19\,\%$ has been measured → there is room for the Higgs boson to decay into Dark Matter!

Dark Sector Model with both a vector and an Higgs portal is studied in ATLAS.

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Gauge Sector

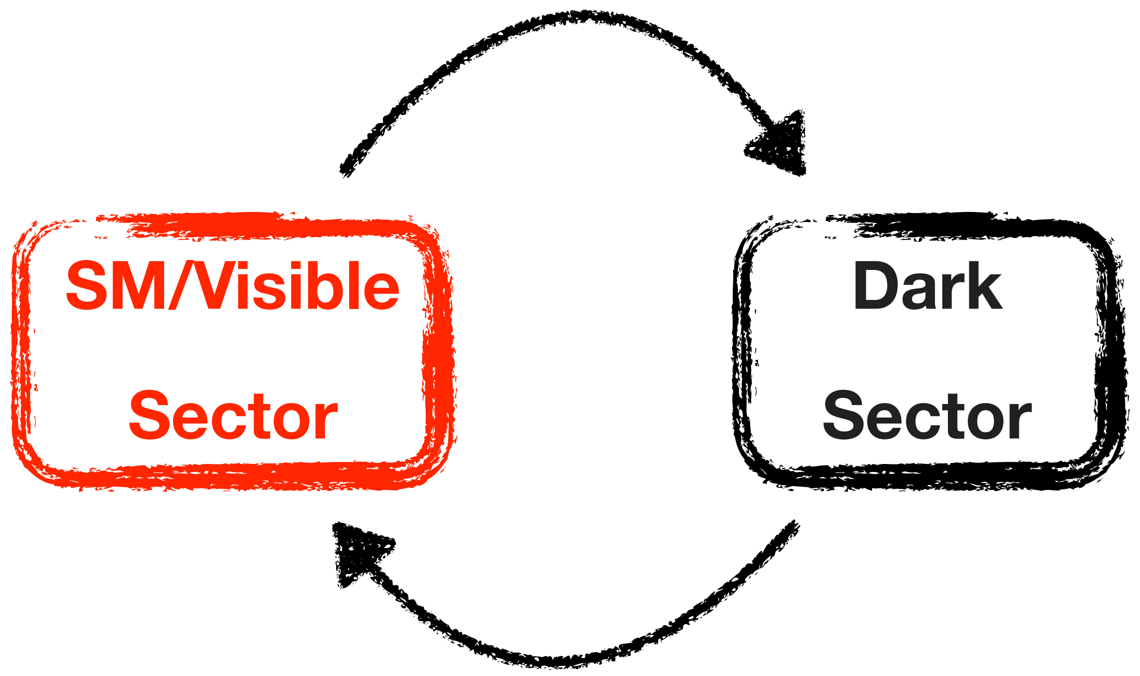
Interaction term
ε mixing parameter

Dark Higgs Sector

Higgs Sector

Higgs mixing term
$k \leftrightarrow B(H \rightarrow und)$ mixing parameter

Higgs Portal $B(H \rightarrow und)$
Higgs decay to DM



Vector portal ε
γ_d decay to SM

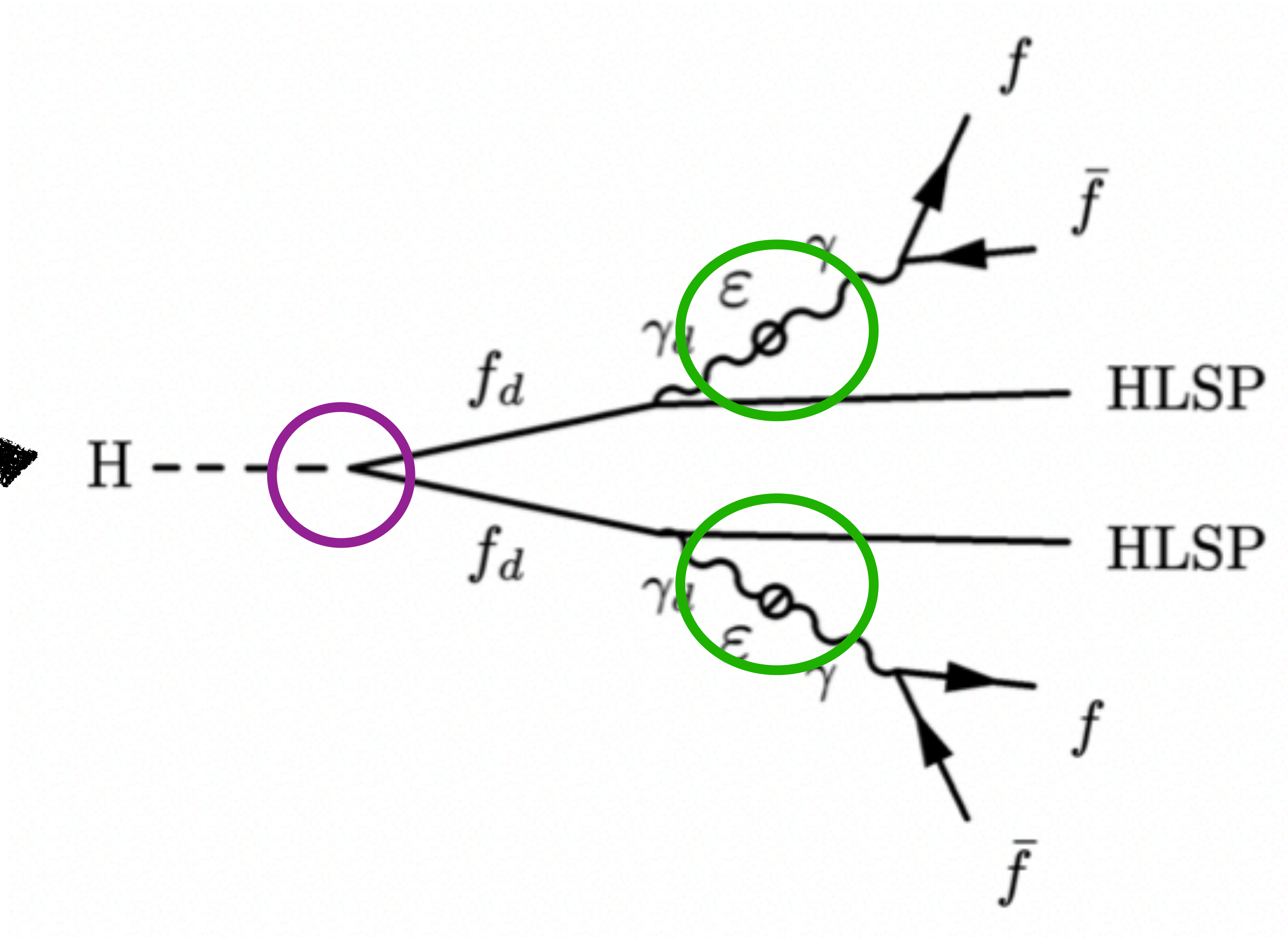
The benchmark signature

The free parameters of the Dark Sector model that we want to probe are:

- $B(H \to und)$ (which is constrained by other measurements);
- ε $(\tau_{\gamma_d} \propto \varepsilon^{-2})$;
- m_{γ_d}.

In ATLAS a benchmark signature (**FRVZ**) is studied to investigate this model.

If no evidence of Dark Photons is found this would translate in excluded regions in the 3D free parameters space.



Hidden Lightest Stable Particle

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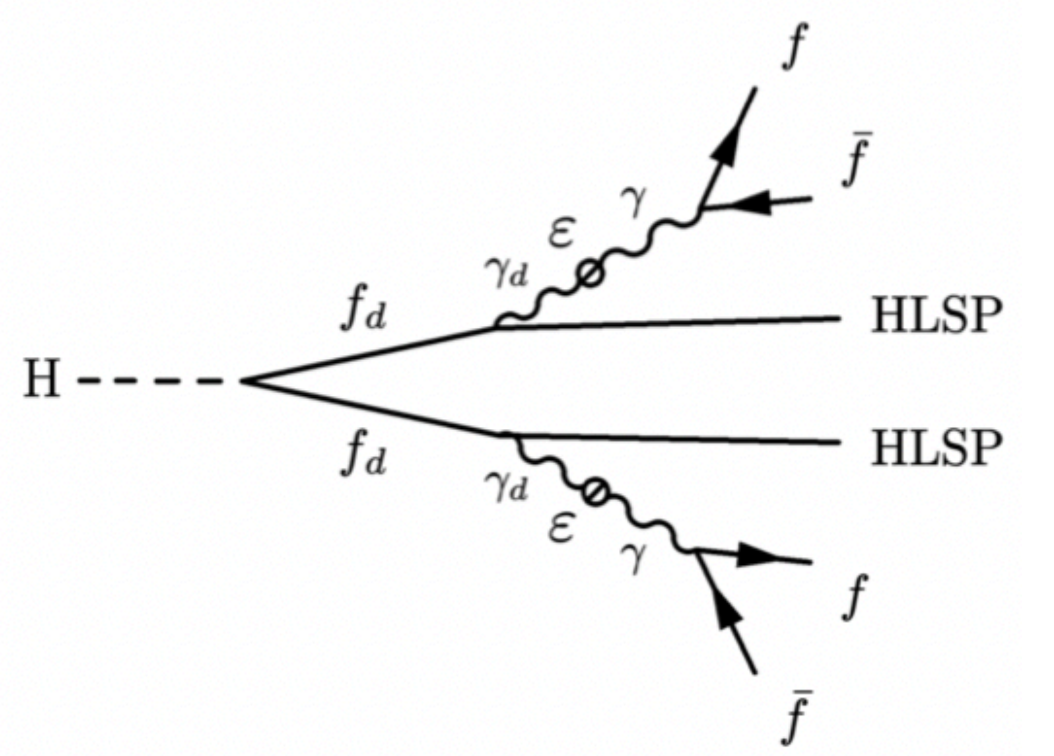
Interaction term
ε mixing parameter

Higgs mixing term
parameter

Dark Photon signatures at ATLAS



The values of the free parameters what influence what we would see:

$B(H \rightarrow und)$ determines the number of events that we would observe;

$m_{\gamma_d} \in [0.1, 10]\text{GeV} + p_T^{\gamma_d} \approx \frac{p_T^H}{4} \rightarrow$
γ_d decay products highly collimated → DP Jets
m_{γ_d} determines γ_d BRs;
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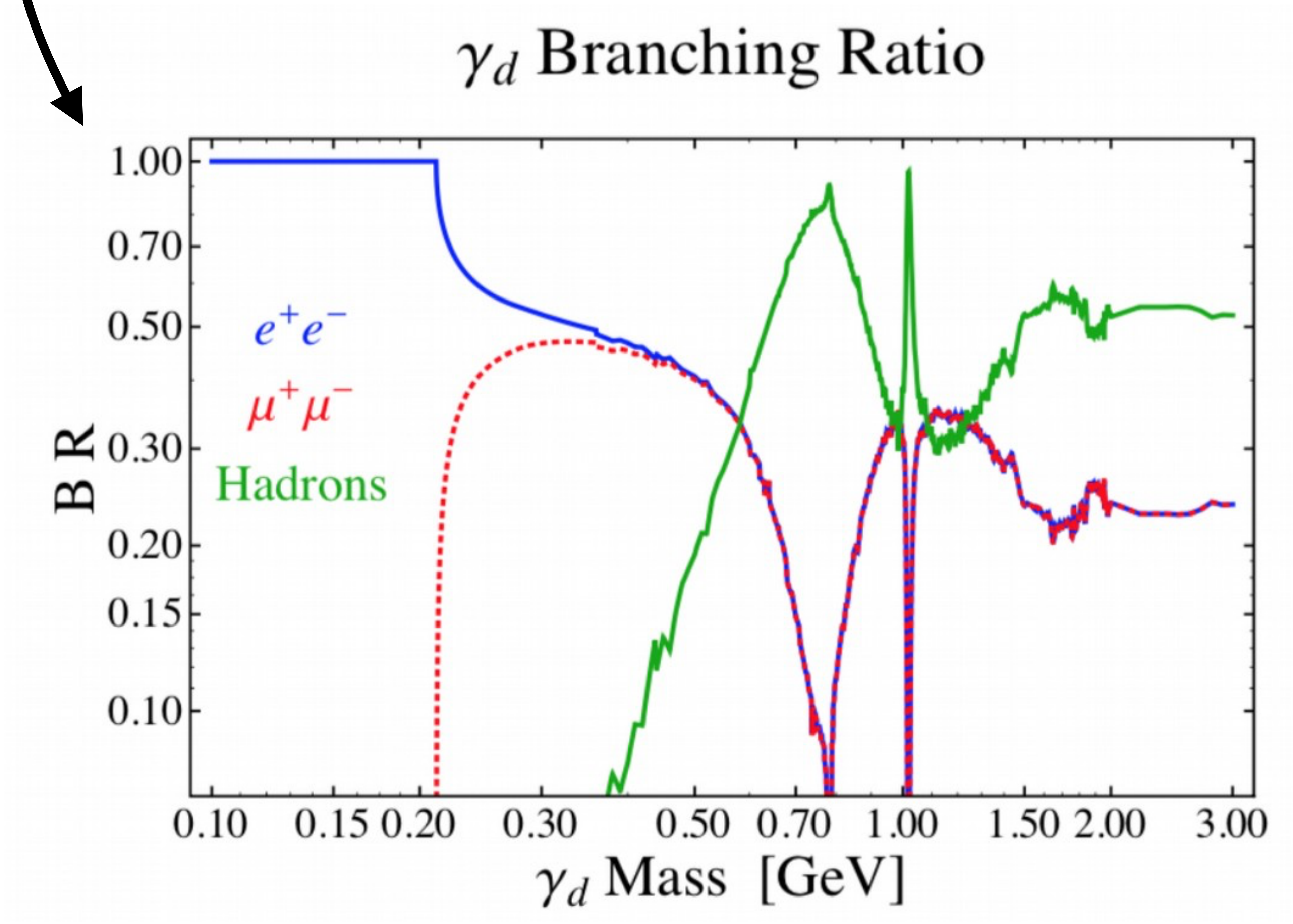
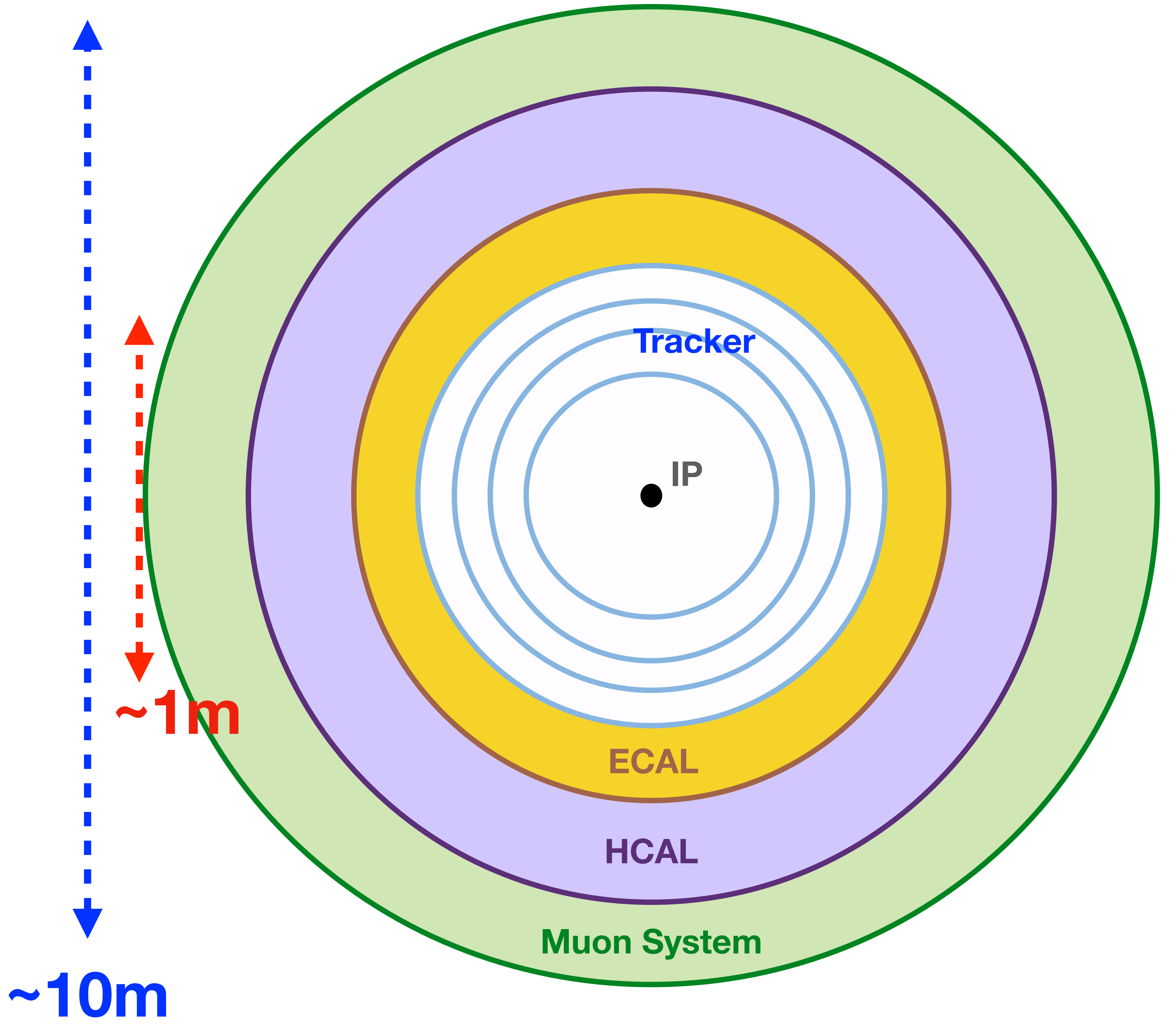
Impact on the signatures in the ATLAS detector!





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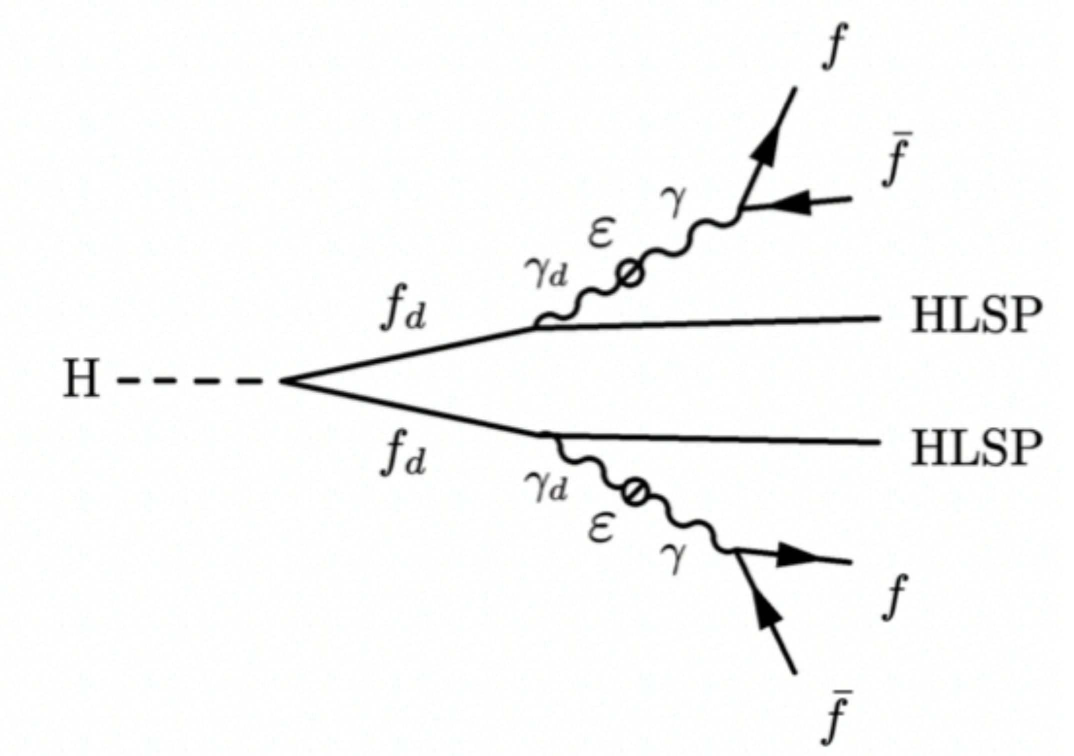

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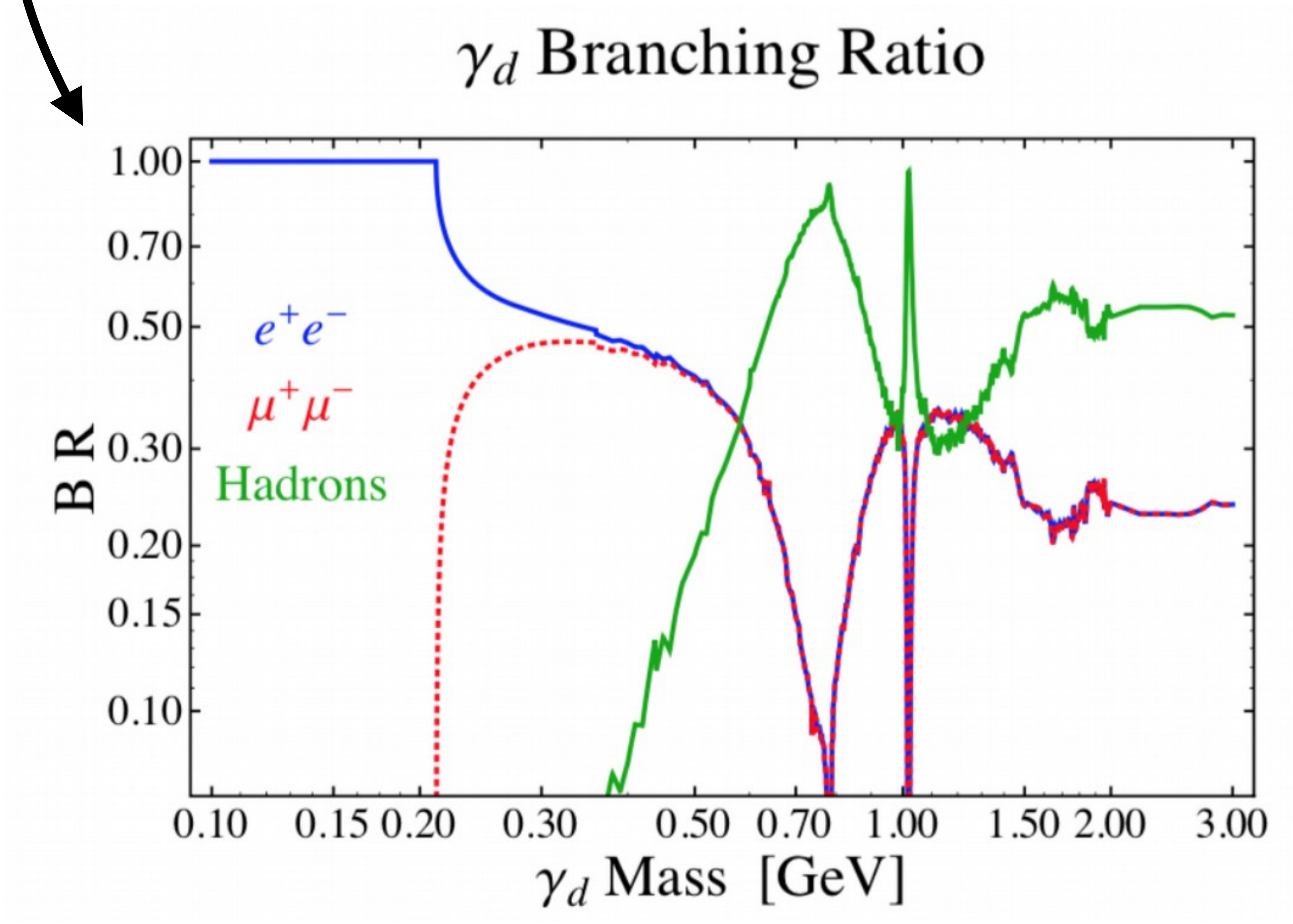

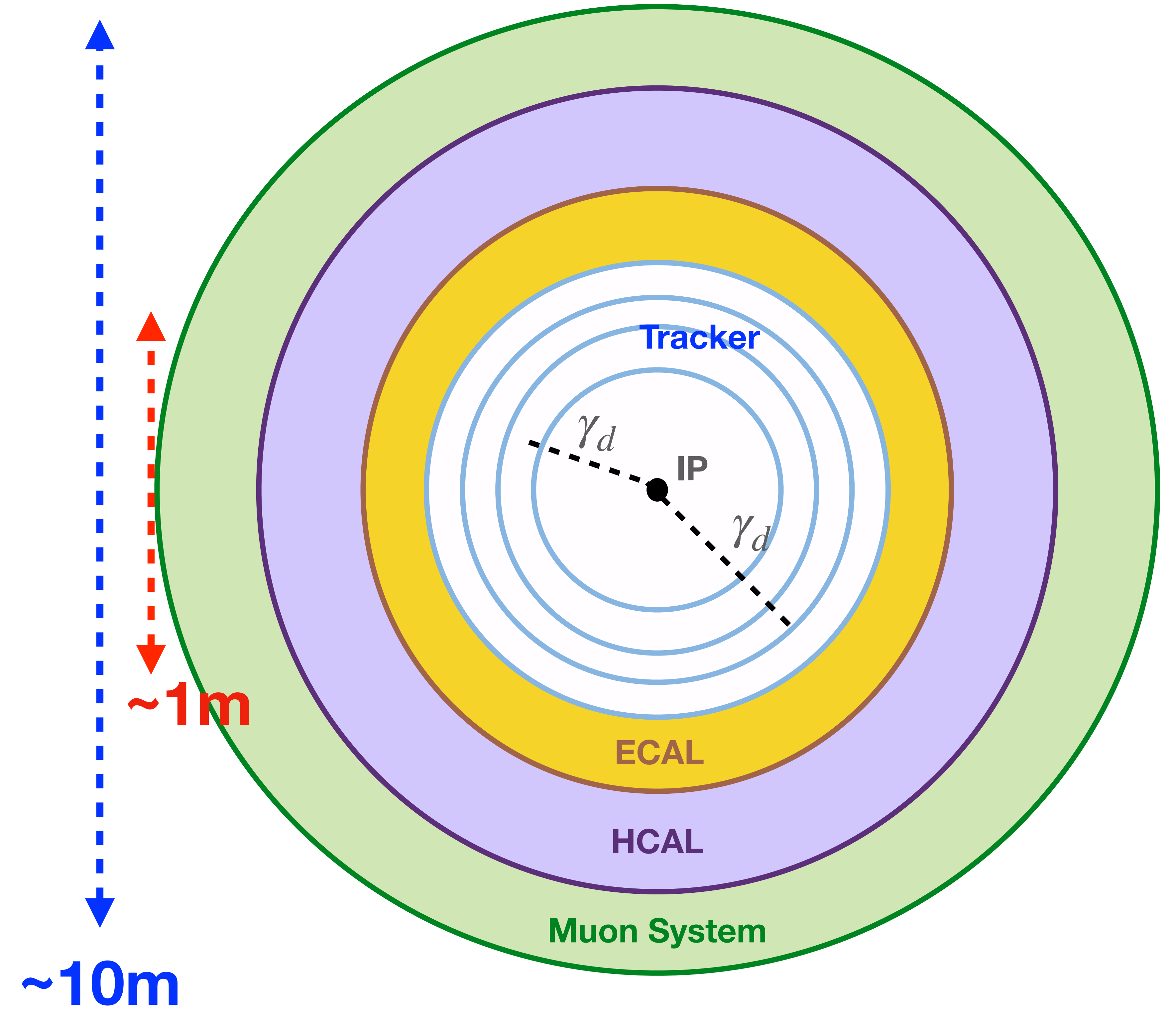

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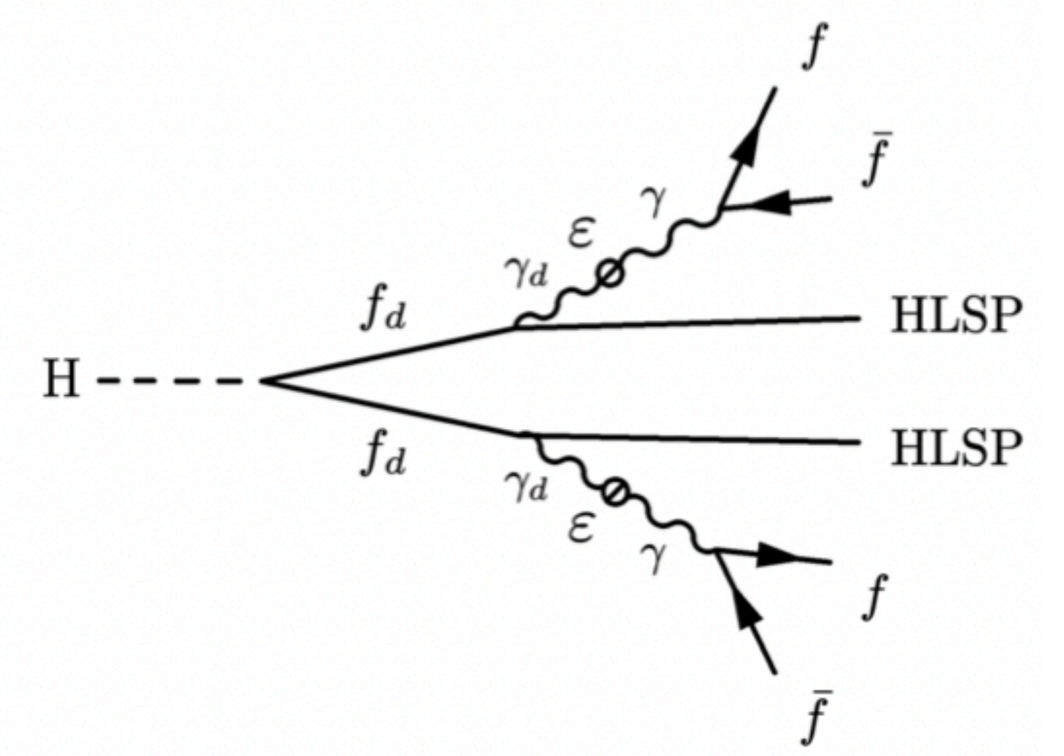

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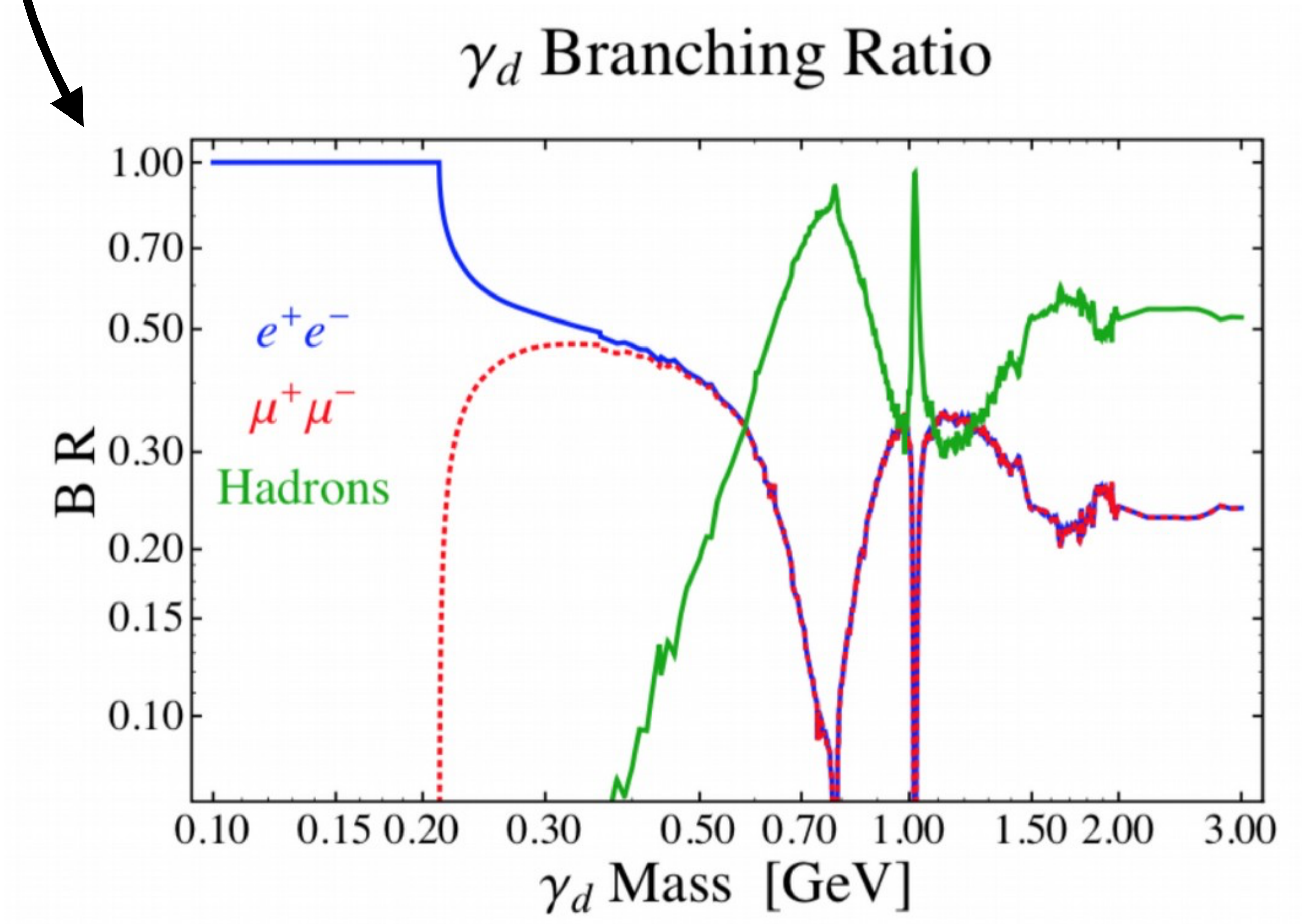

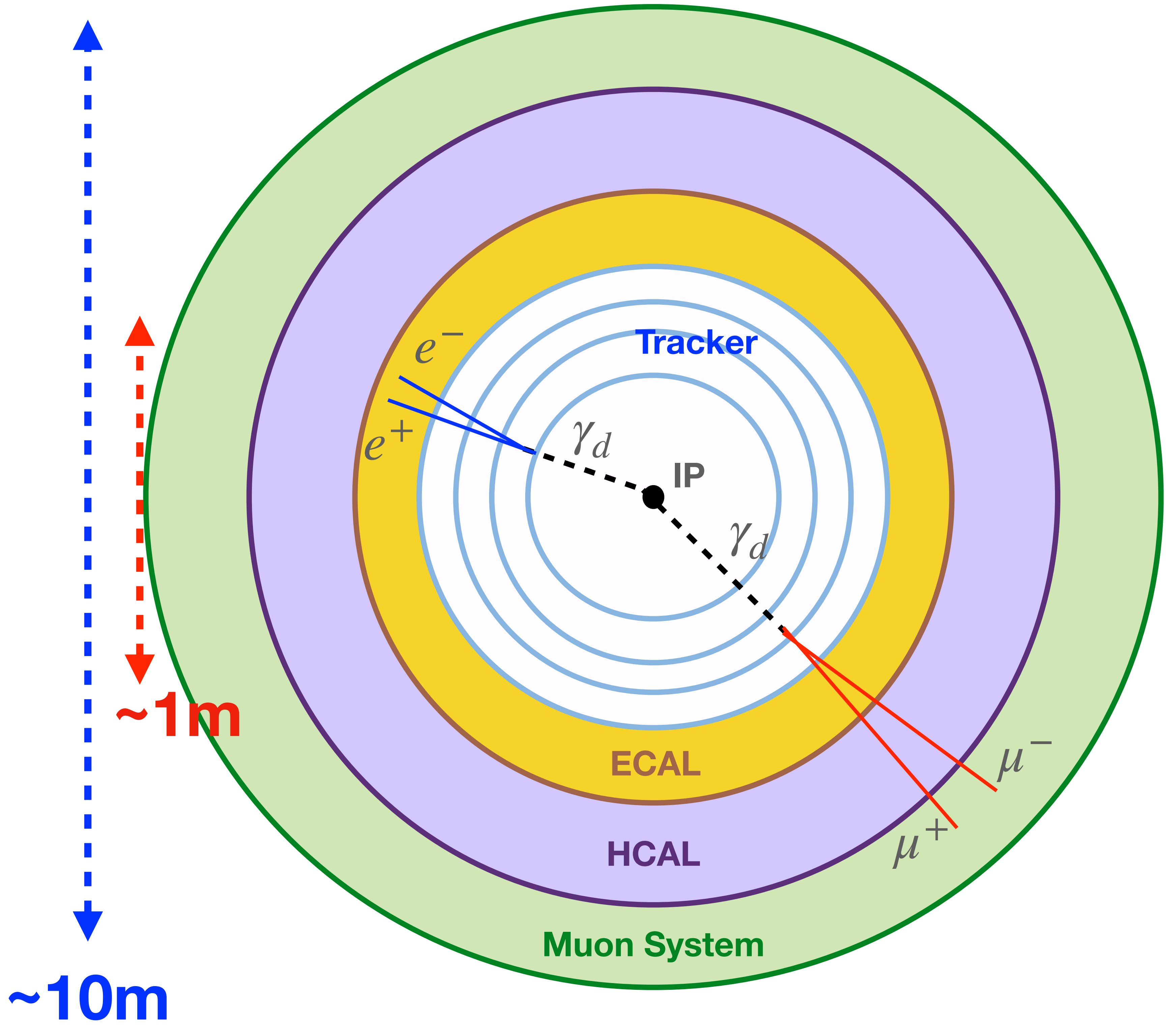

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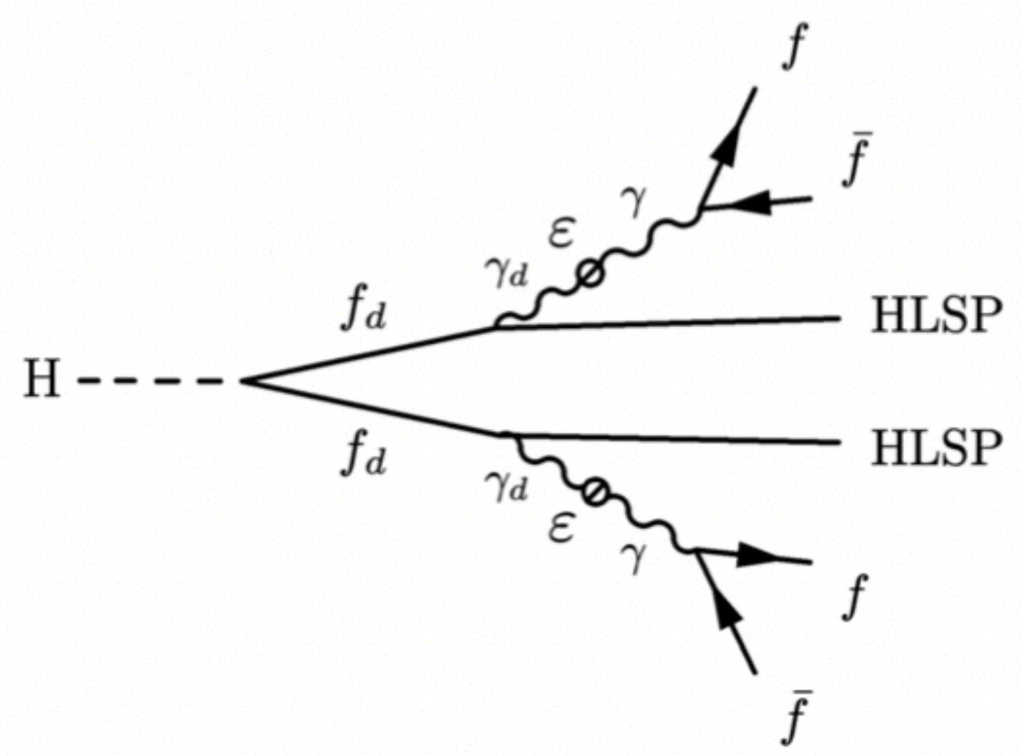

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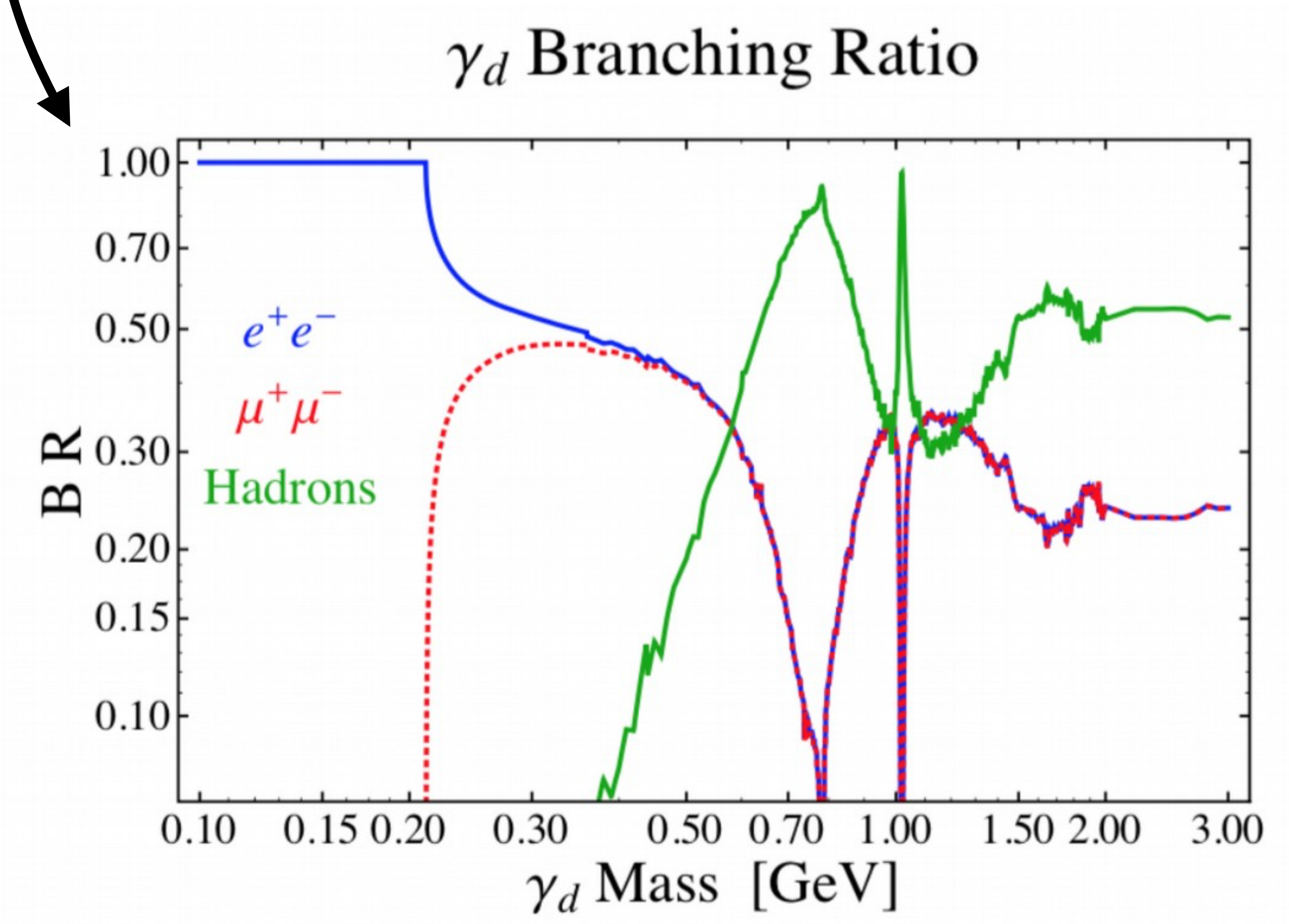

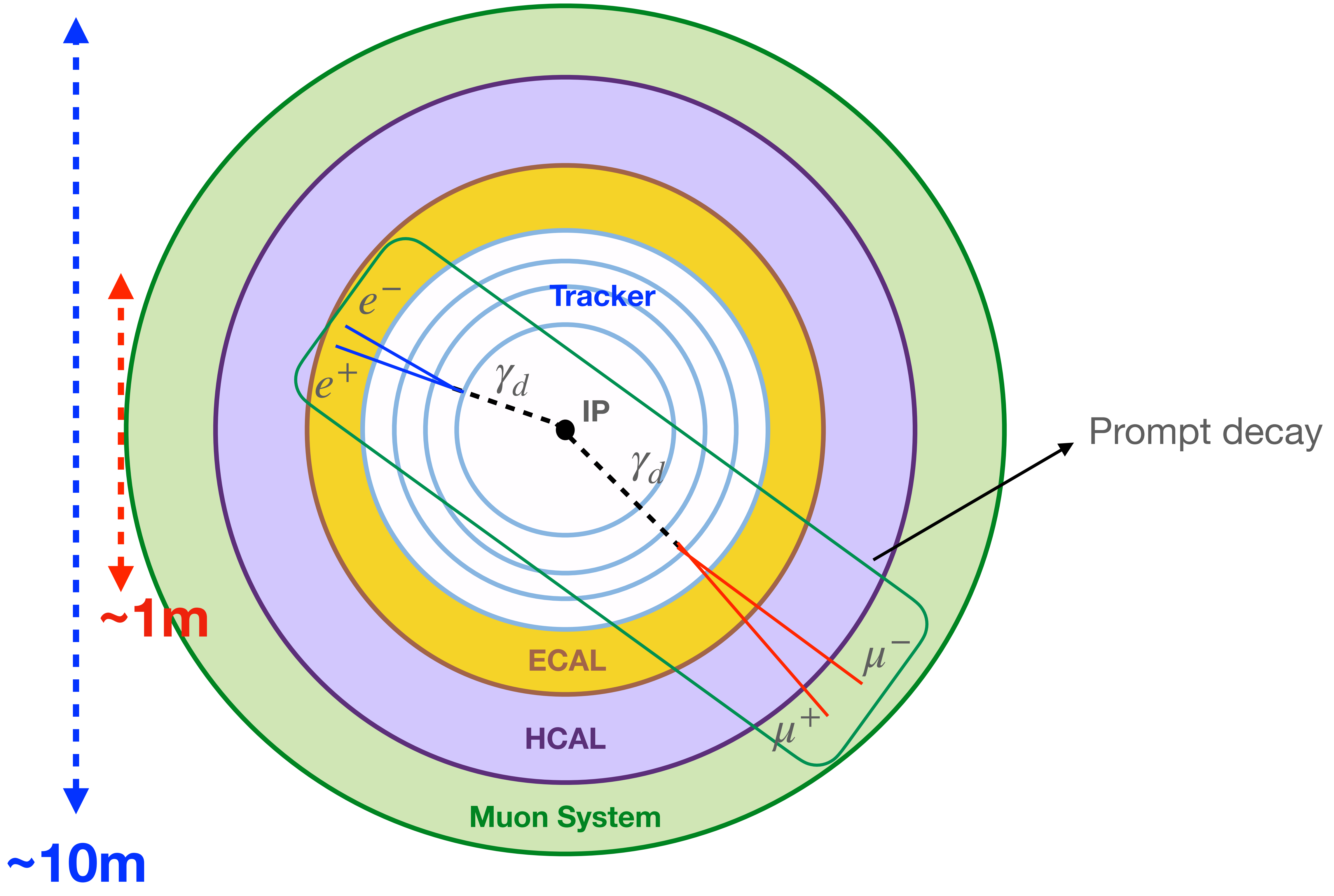

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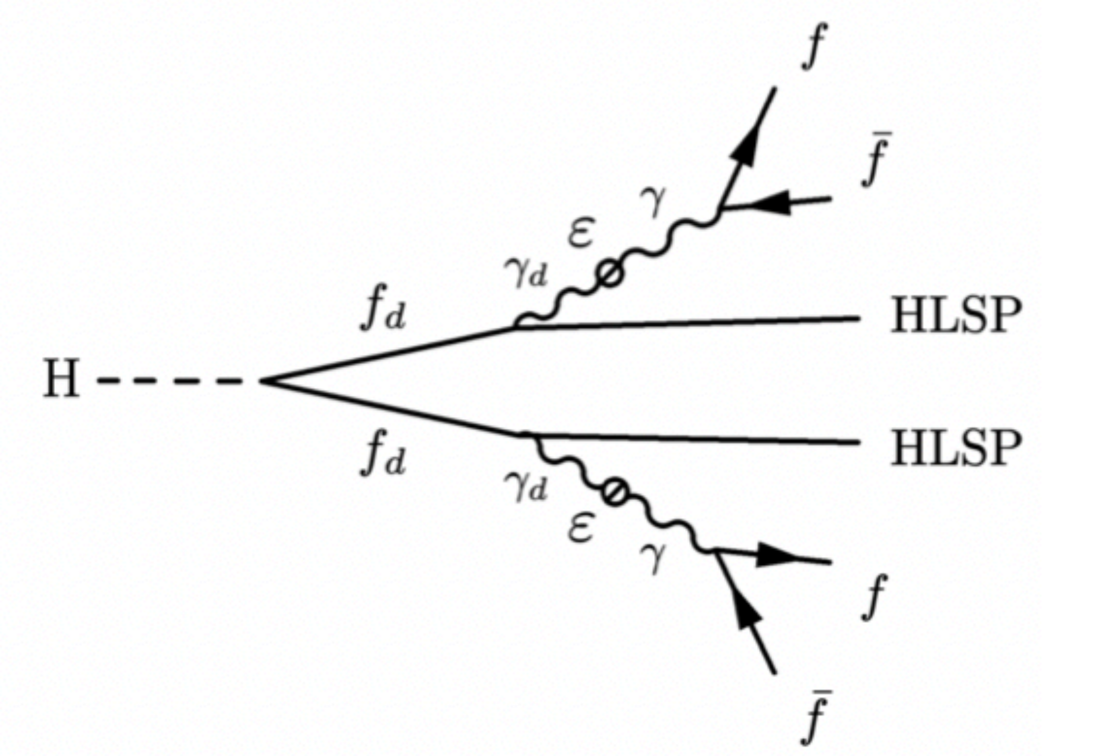

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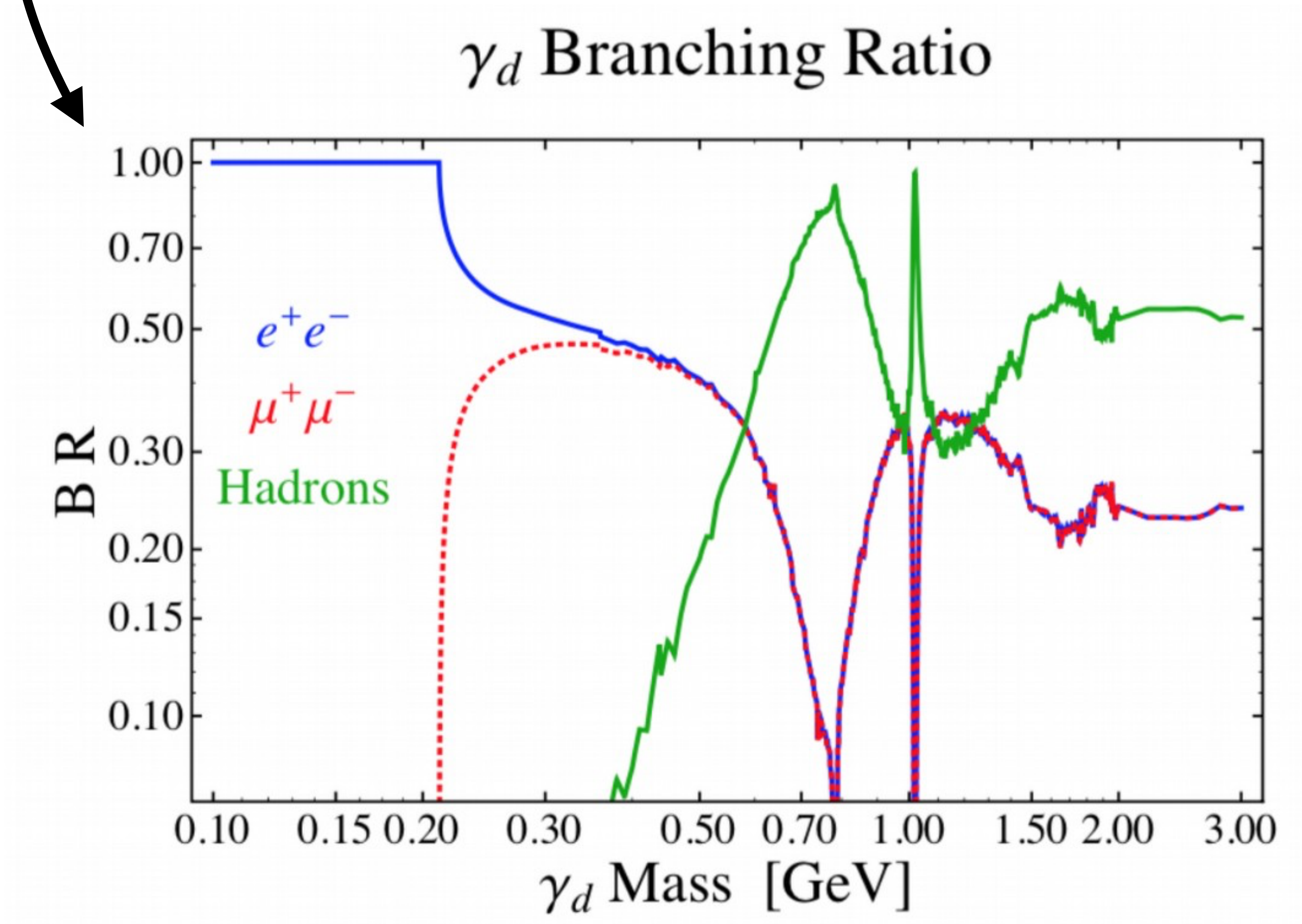

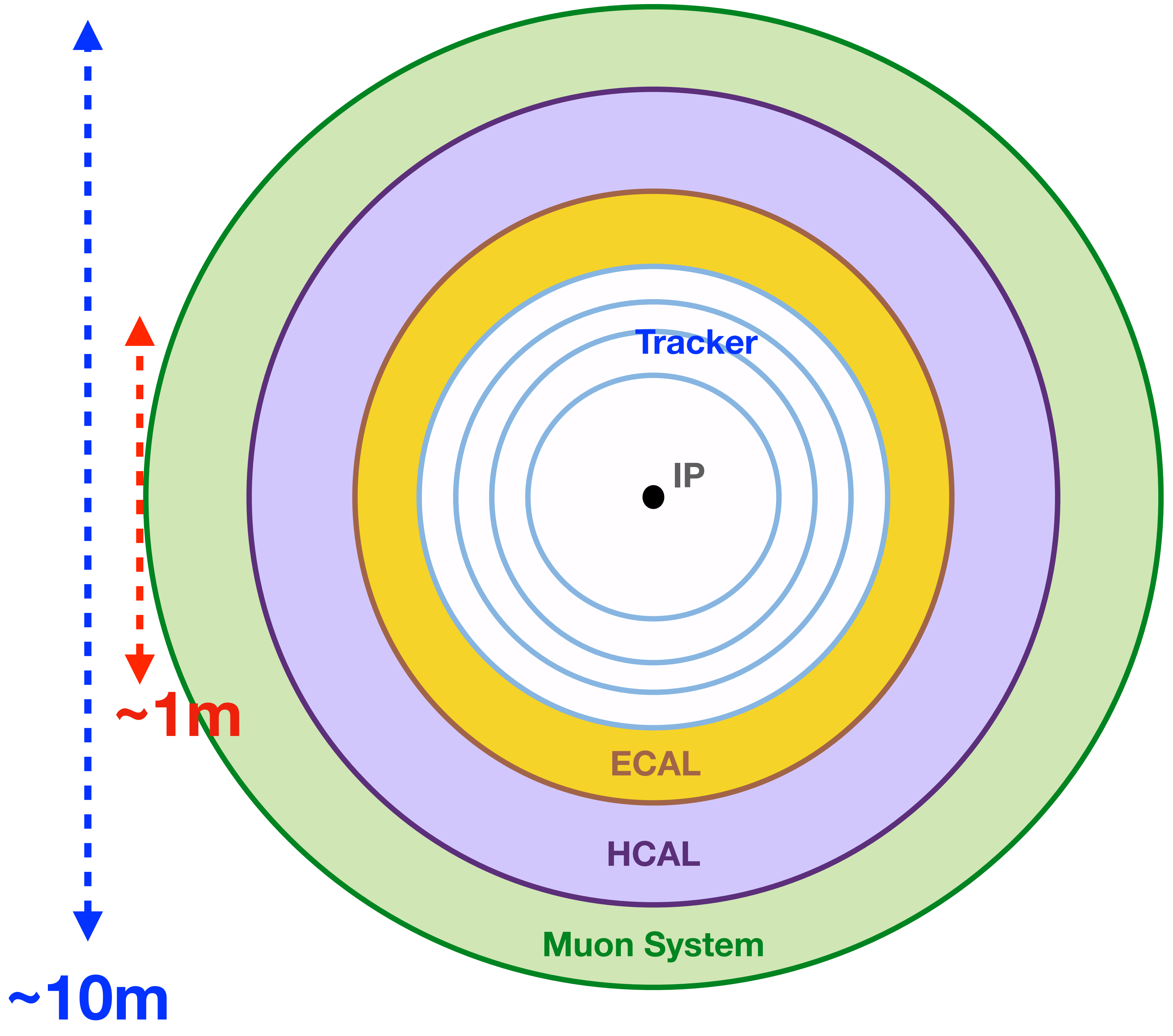

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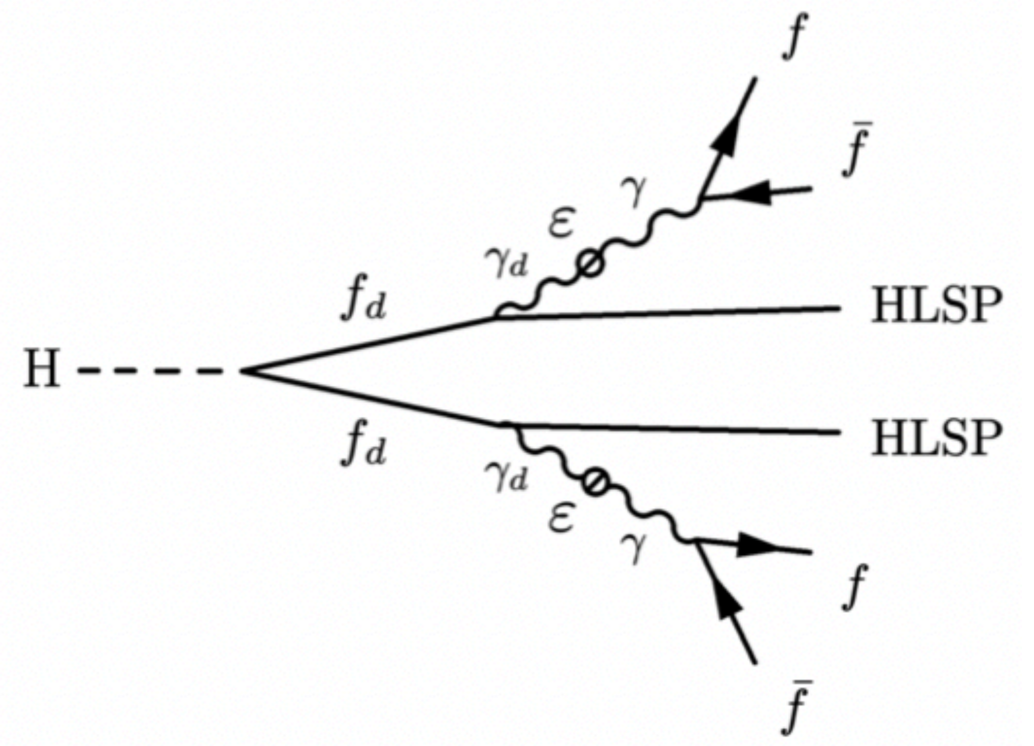

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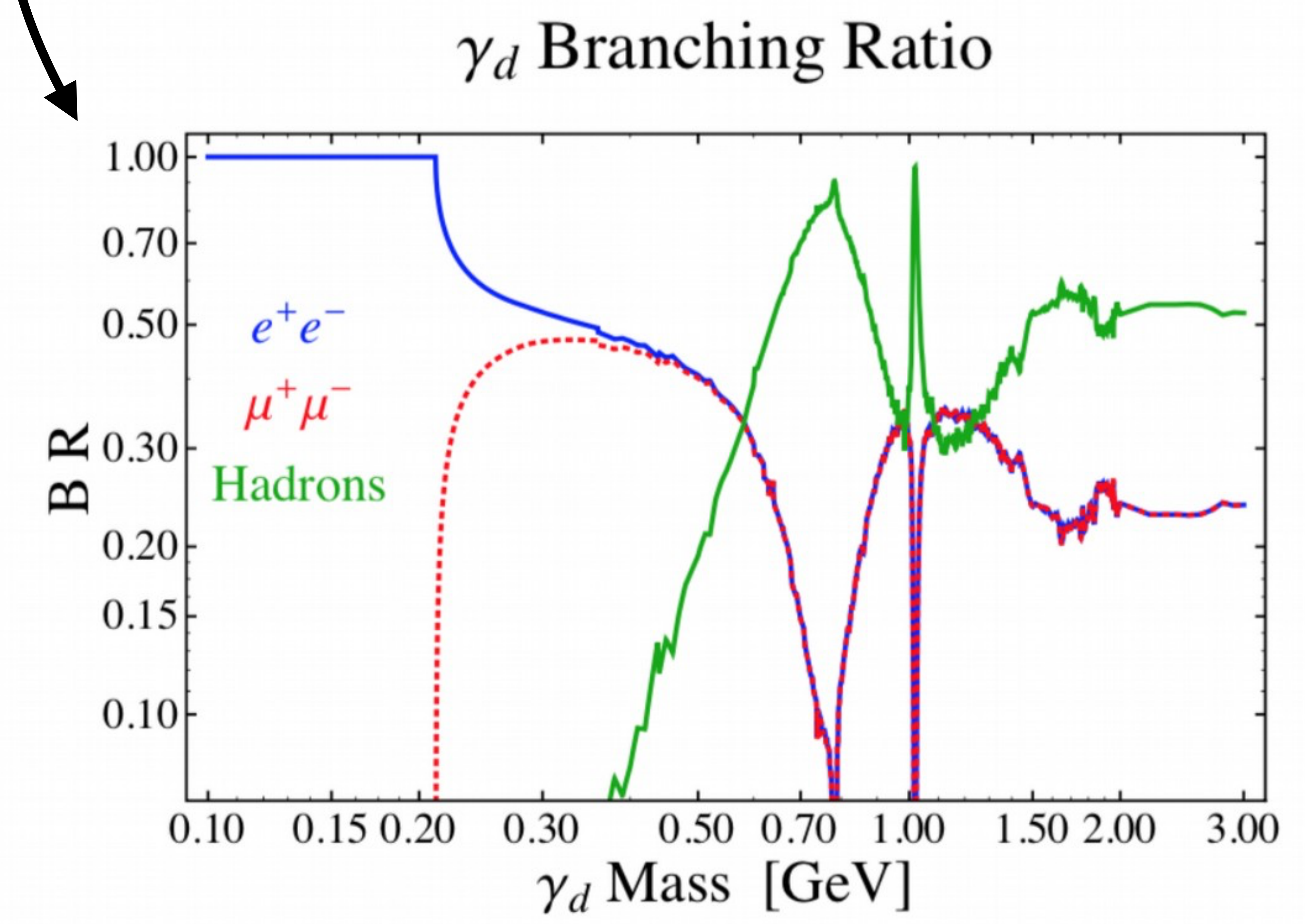

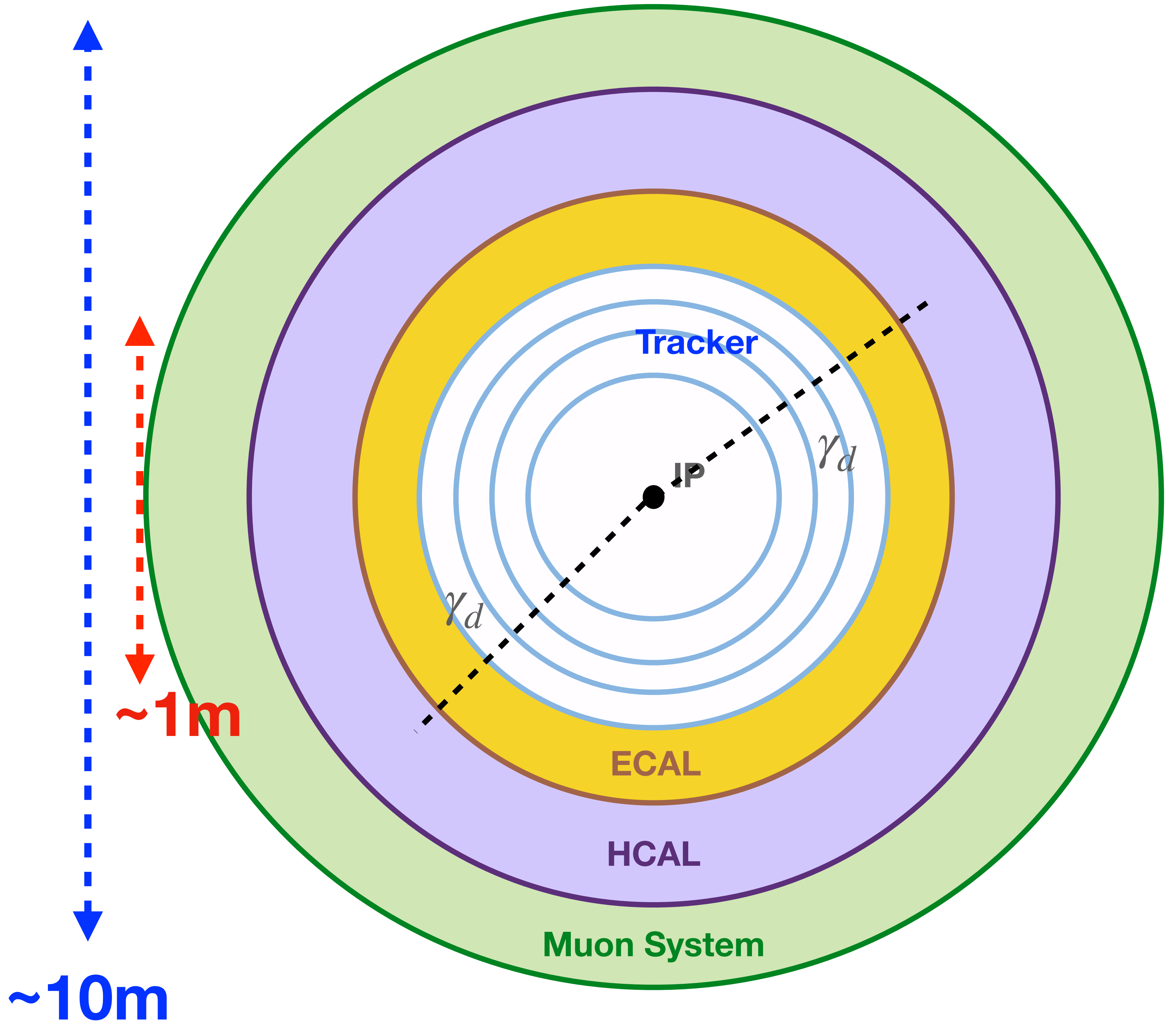

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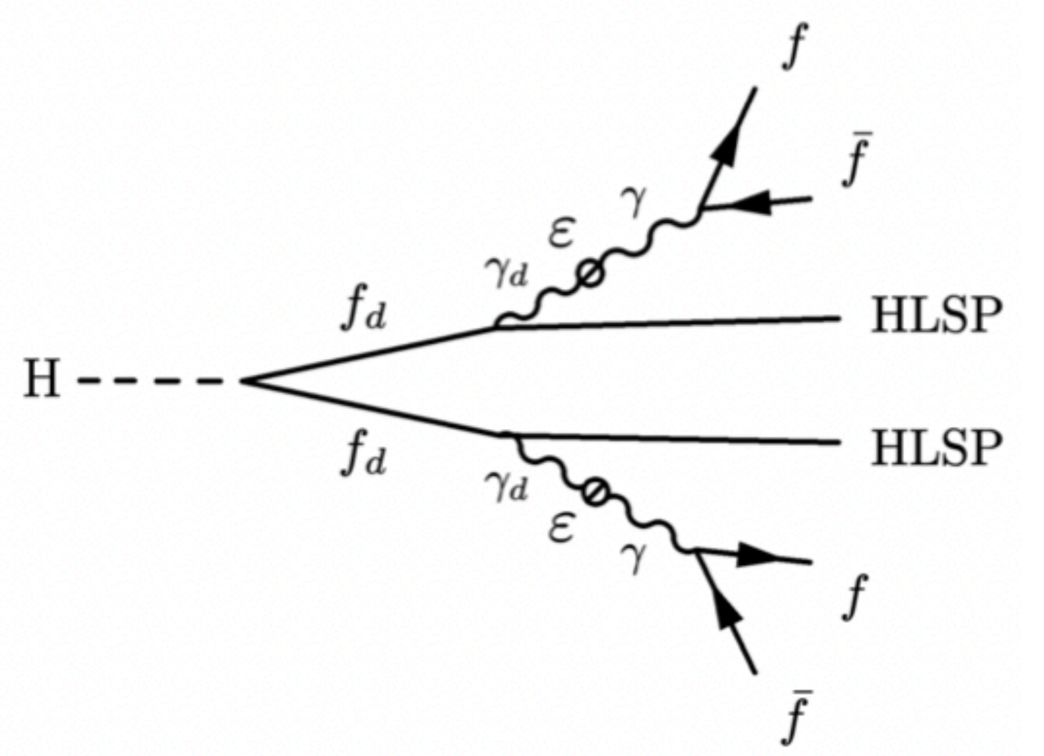

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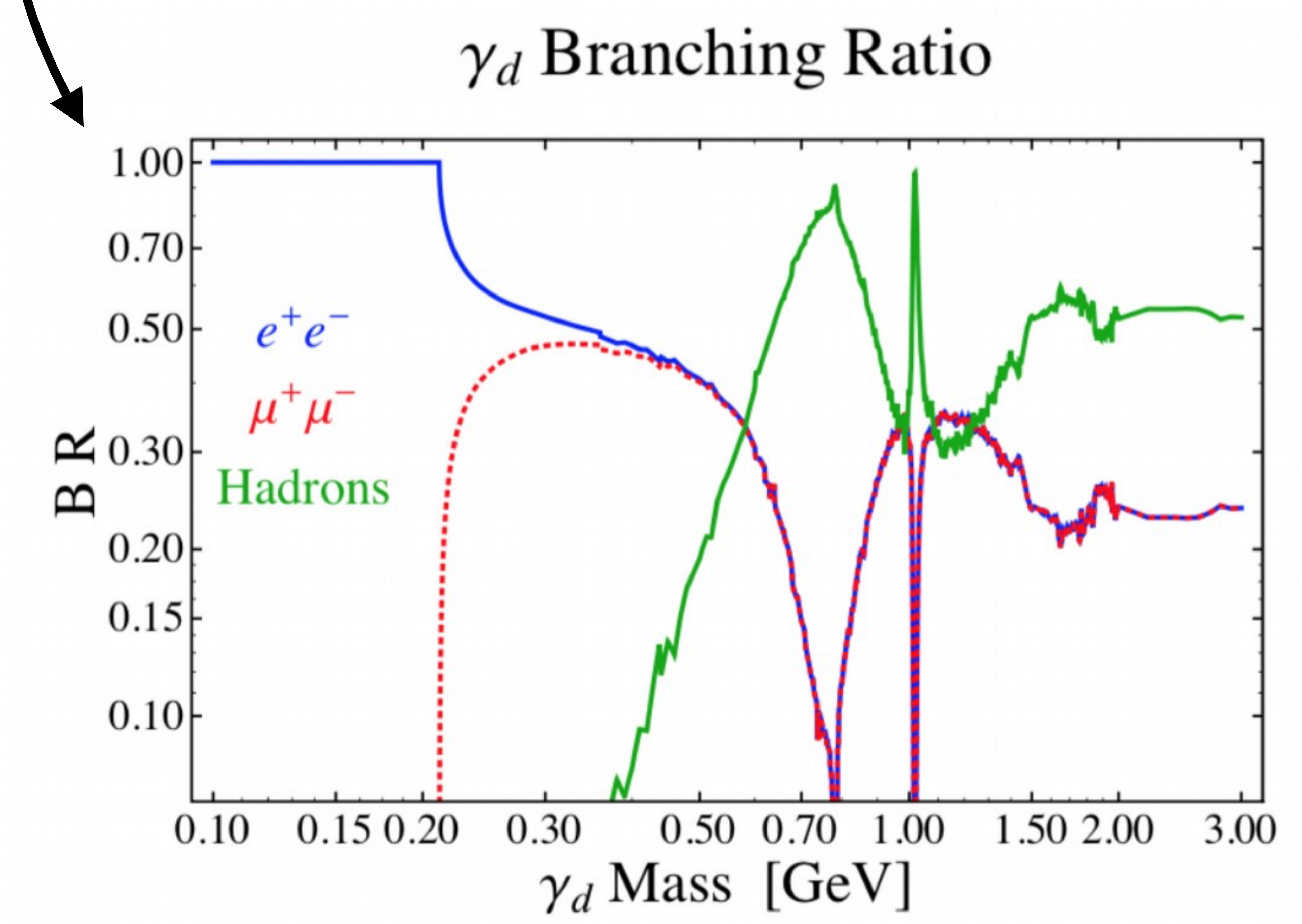
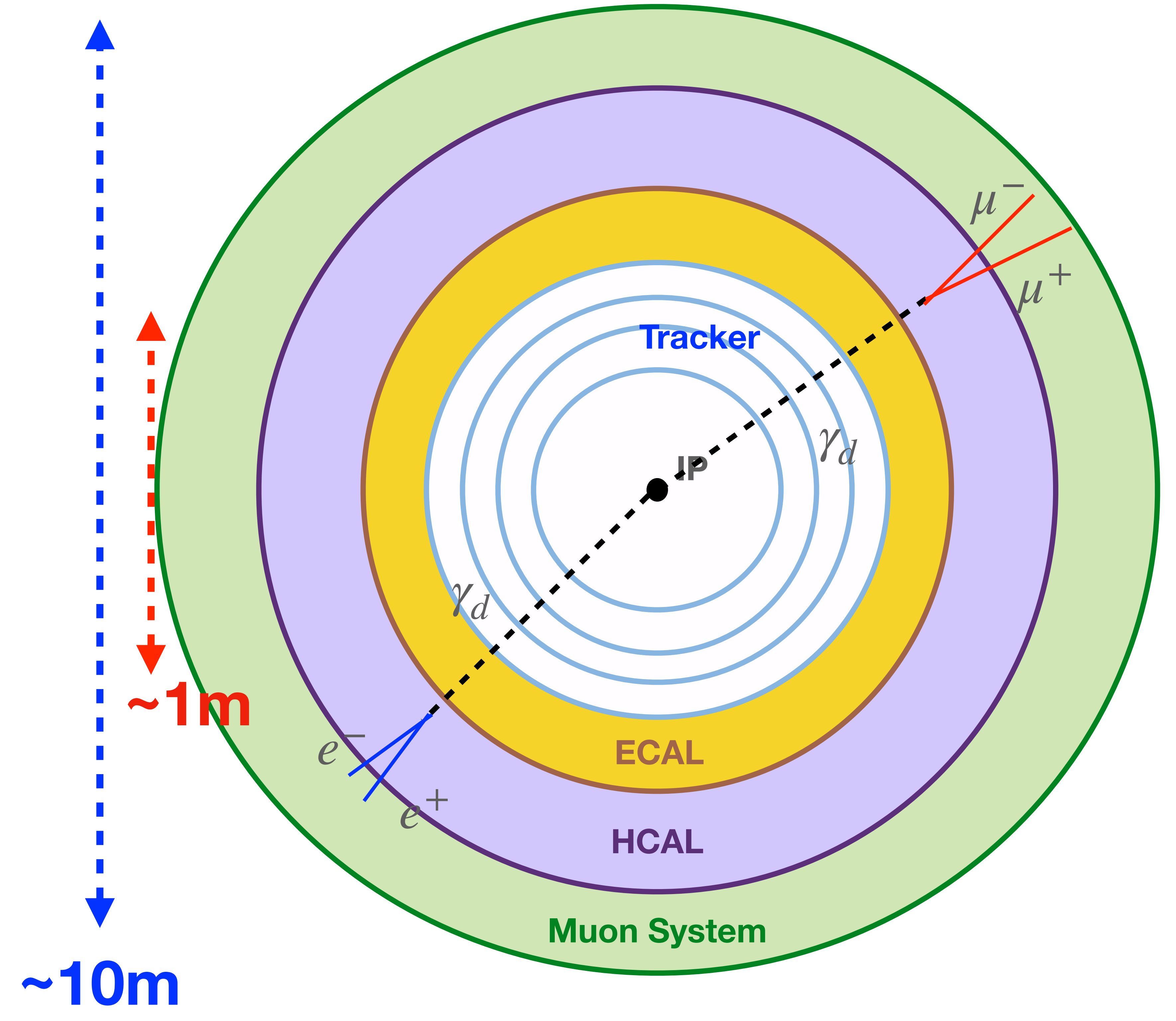
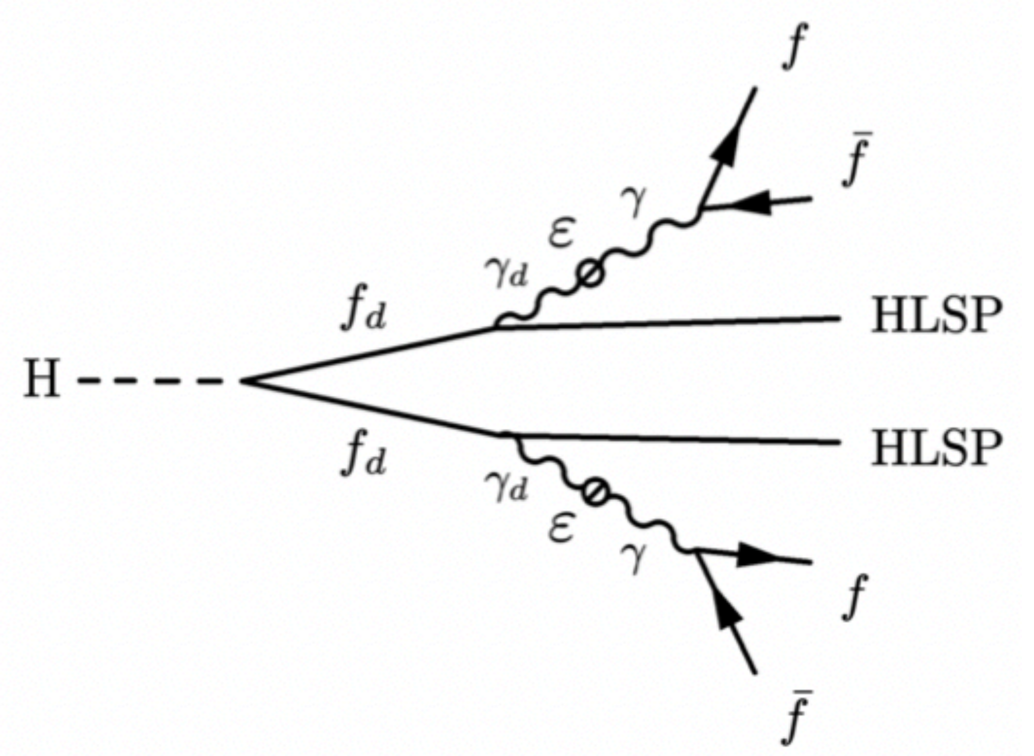




Dark Photon signatures at ATLAS



The values of the free parameters what influence what we would see:

$B(H \to und)$ determines the number of events that we would observe;

$m_{\gamma_d} \in [0.1, 10]\text{GeV} + p_T^{\gamma_d} \approx \frac{p_T^H}{4} \to$
γ_d decay products highly collimated → DP Jets
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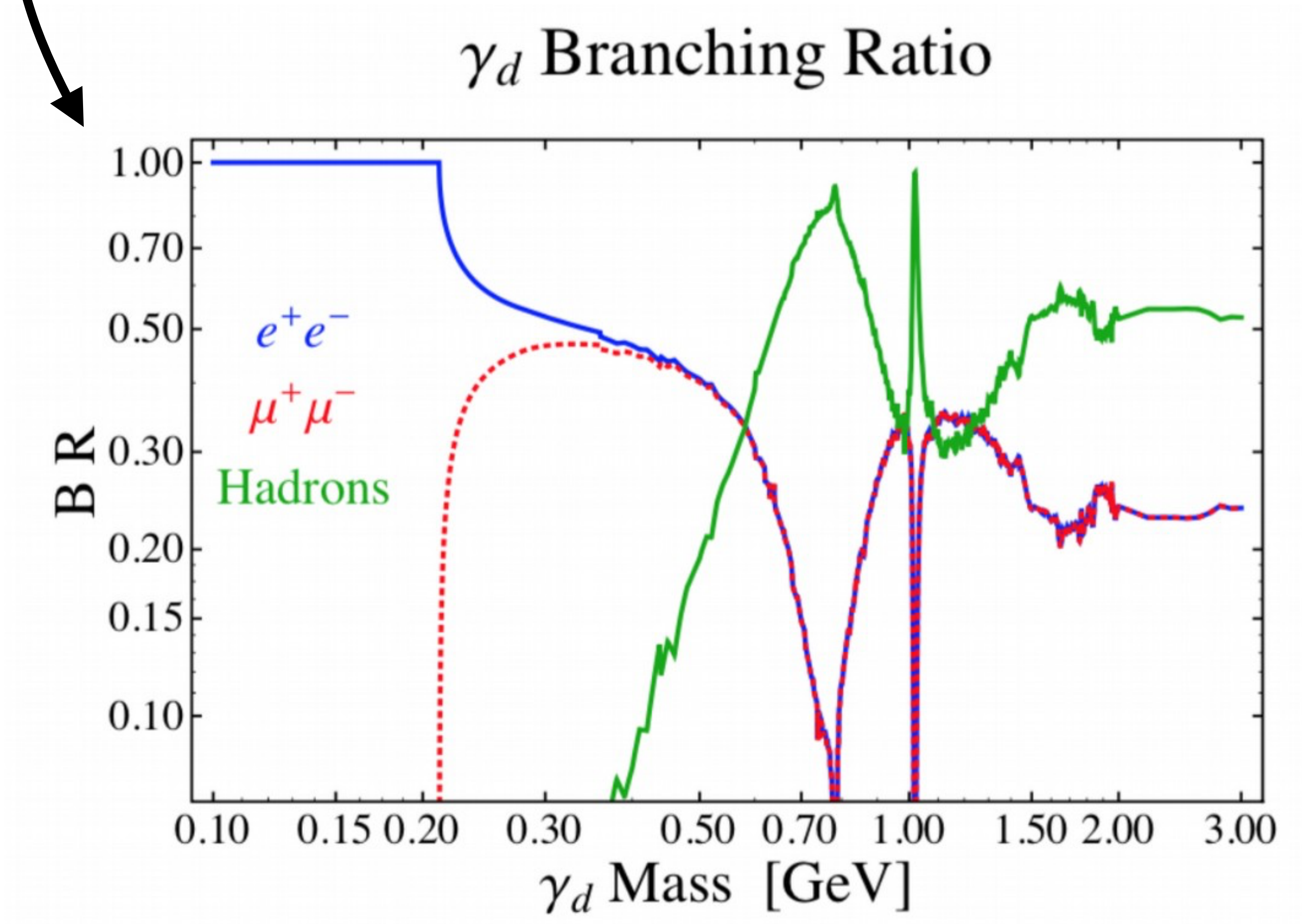

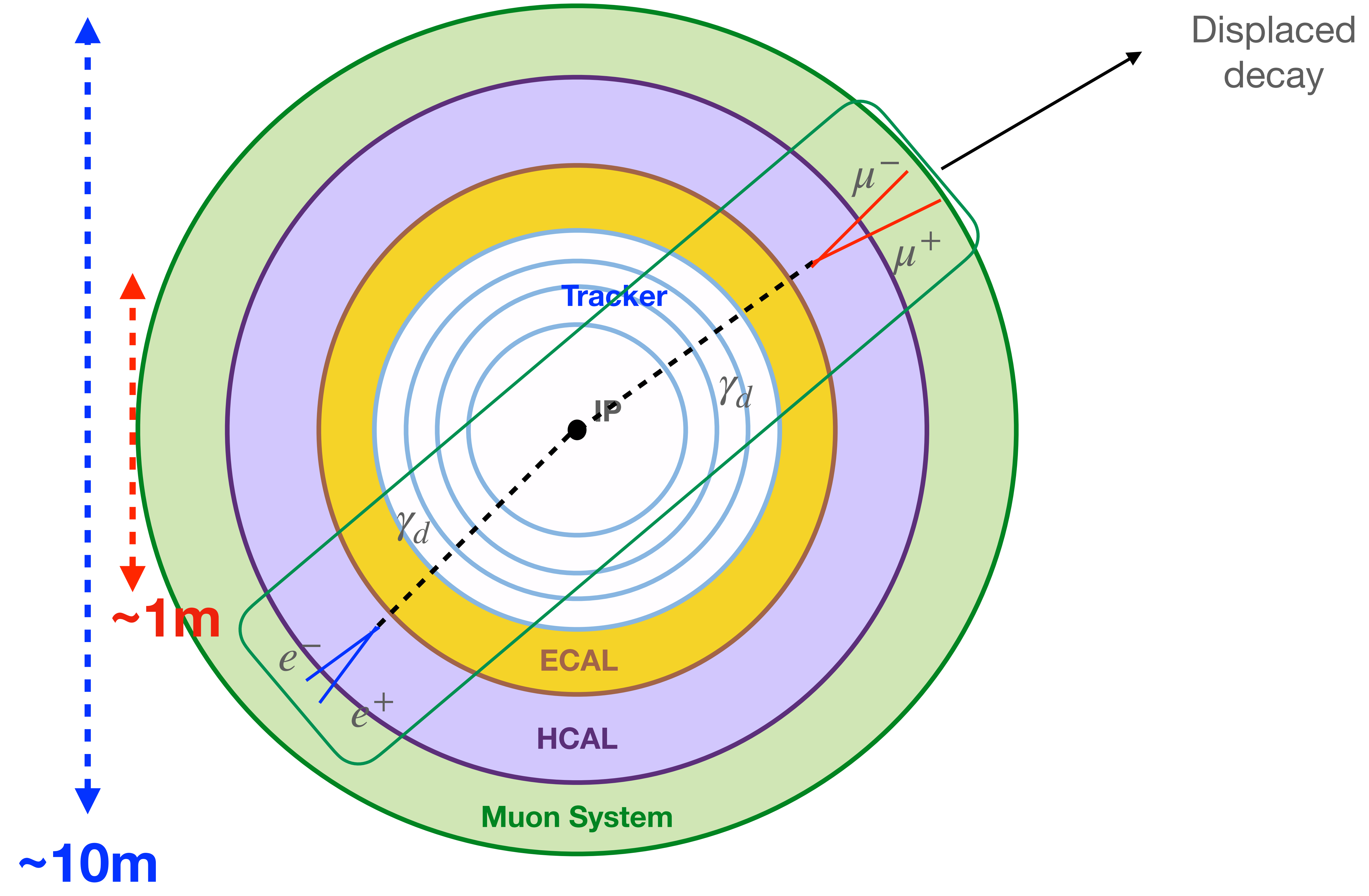

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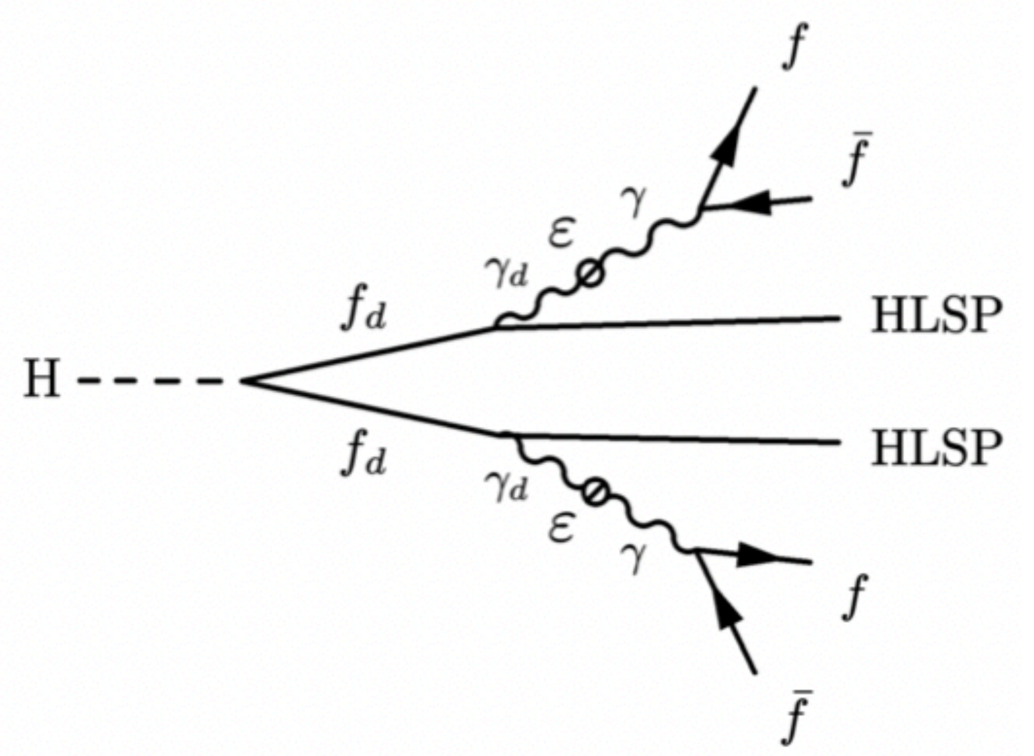

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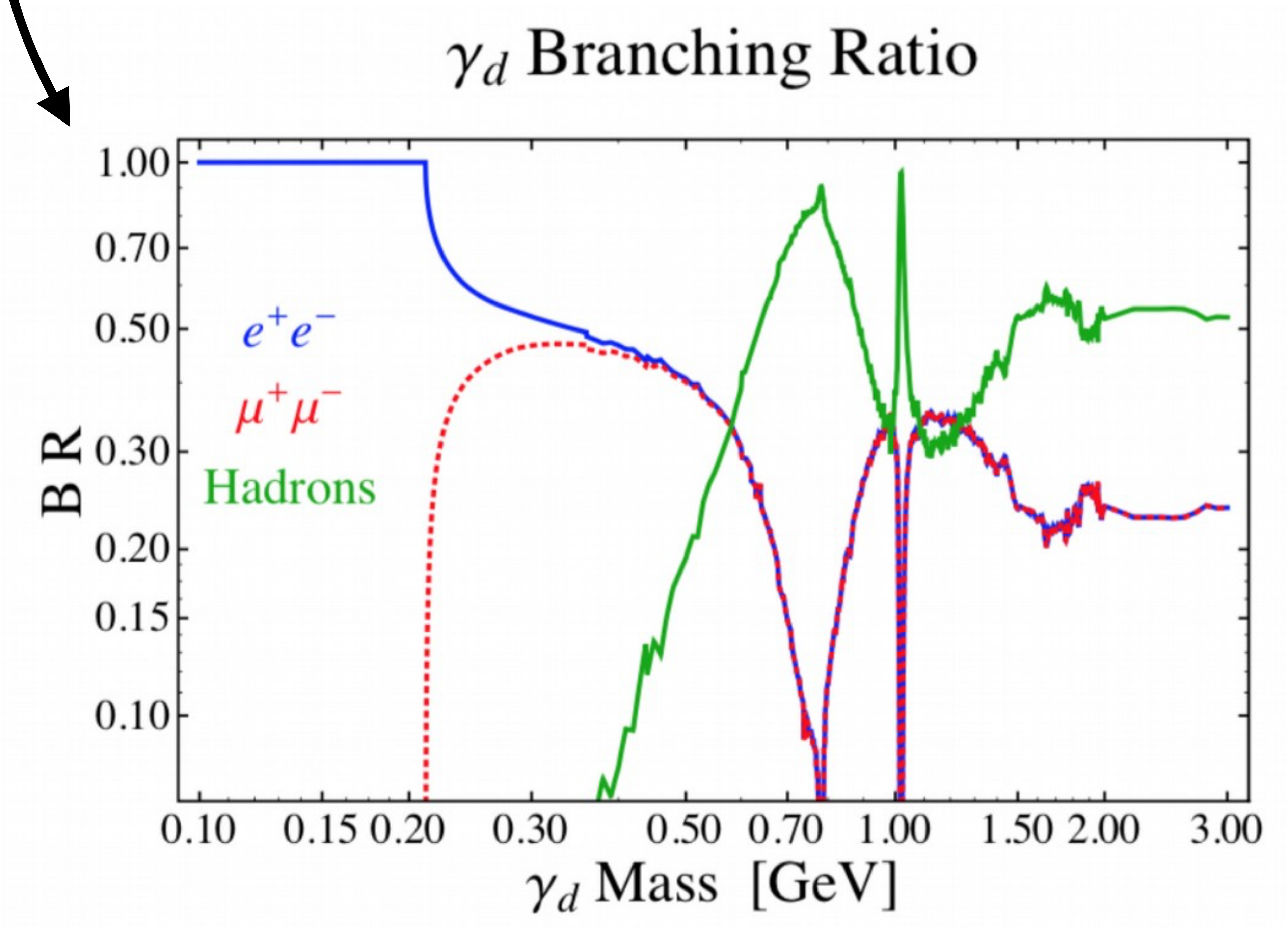

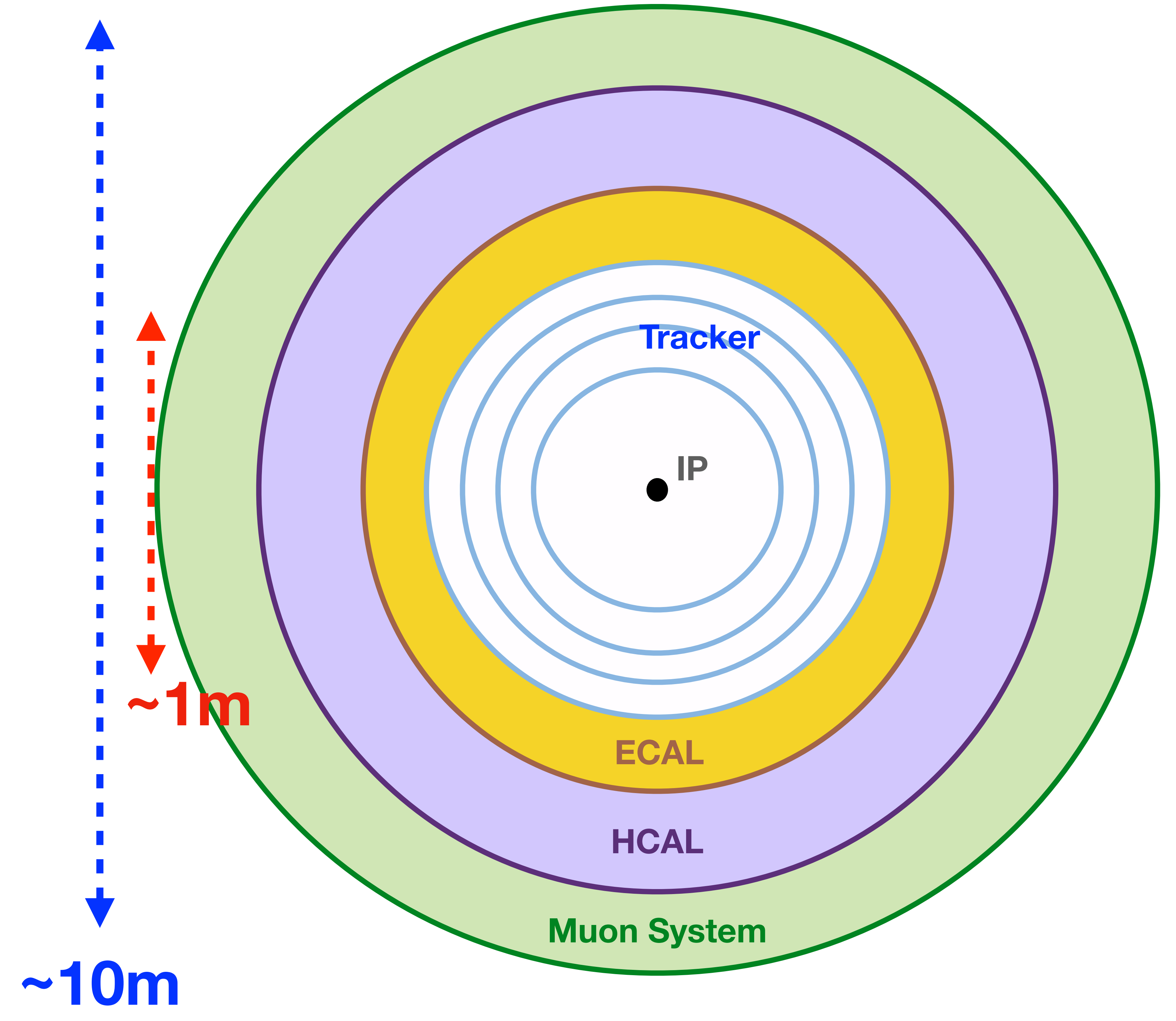

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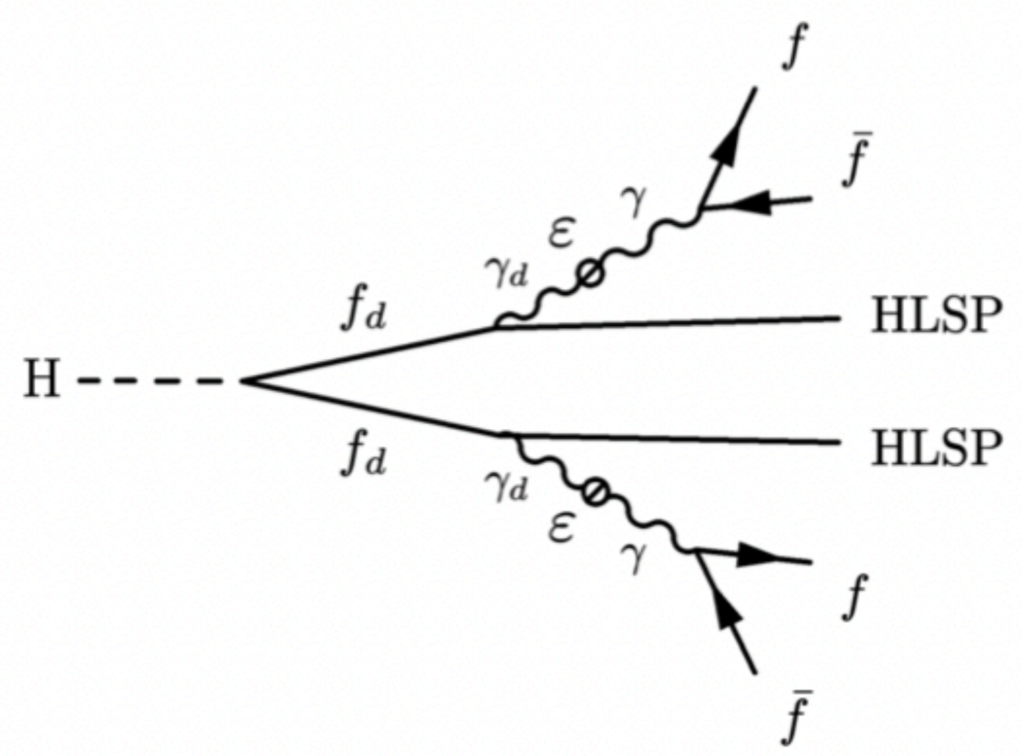

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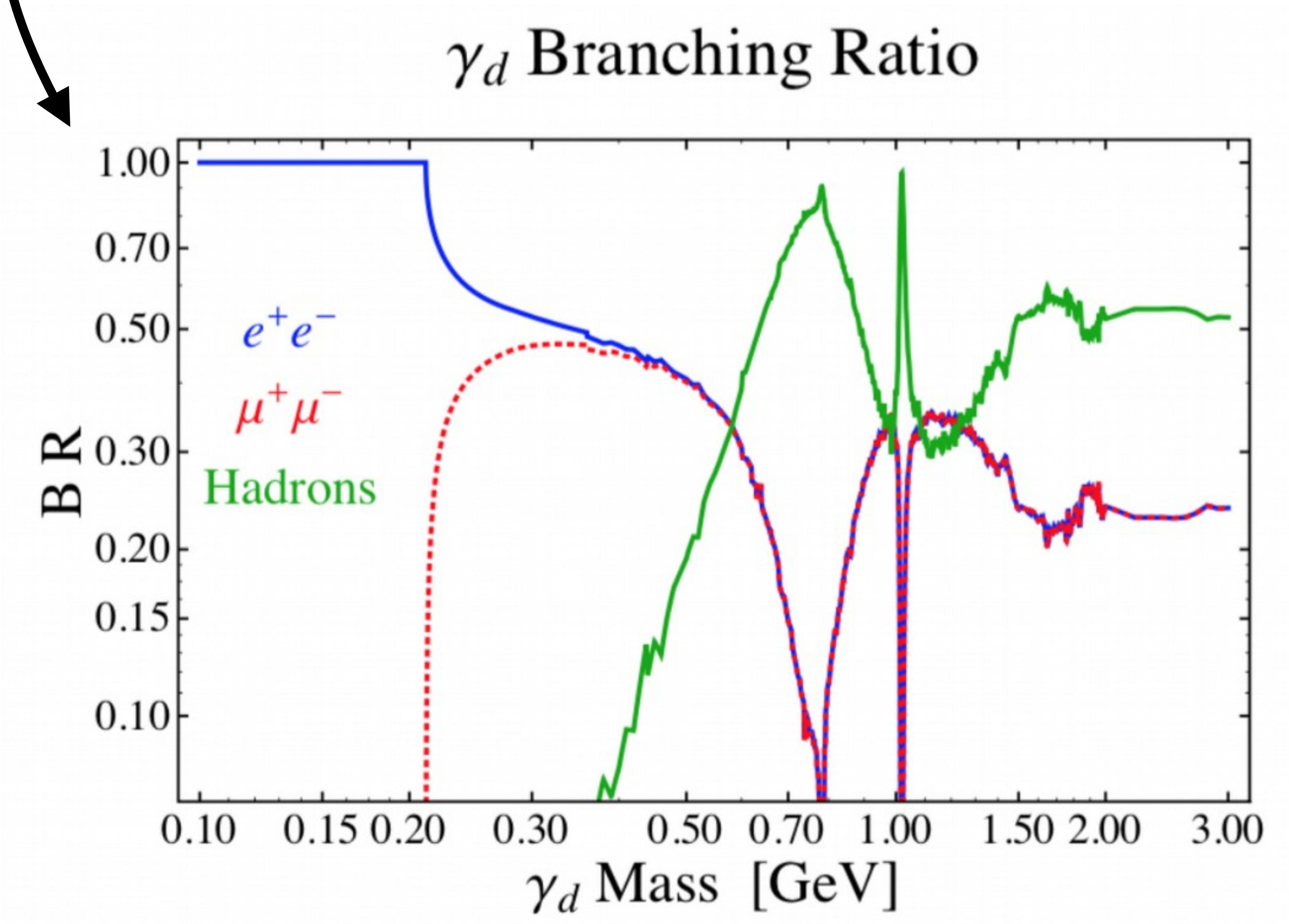

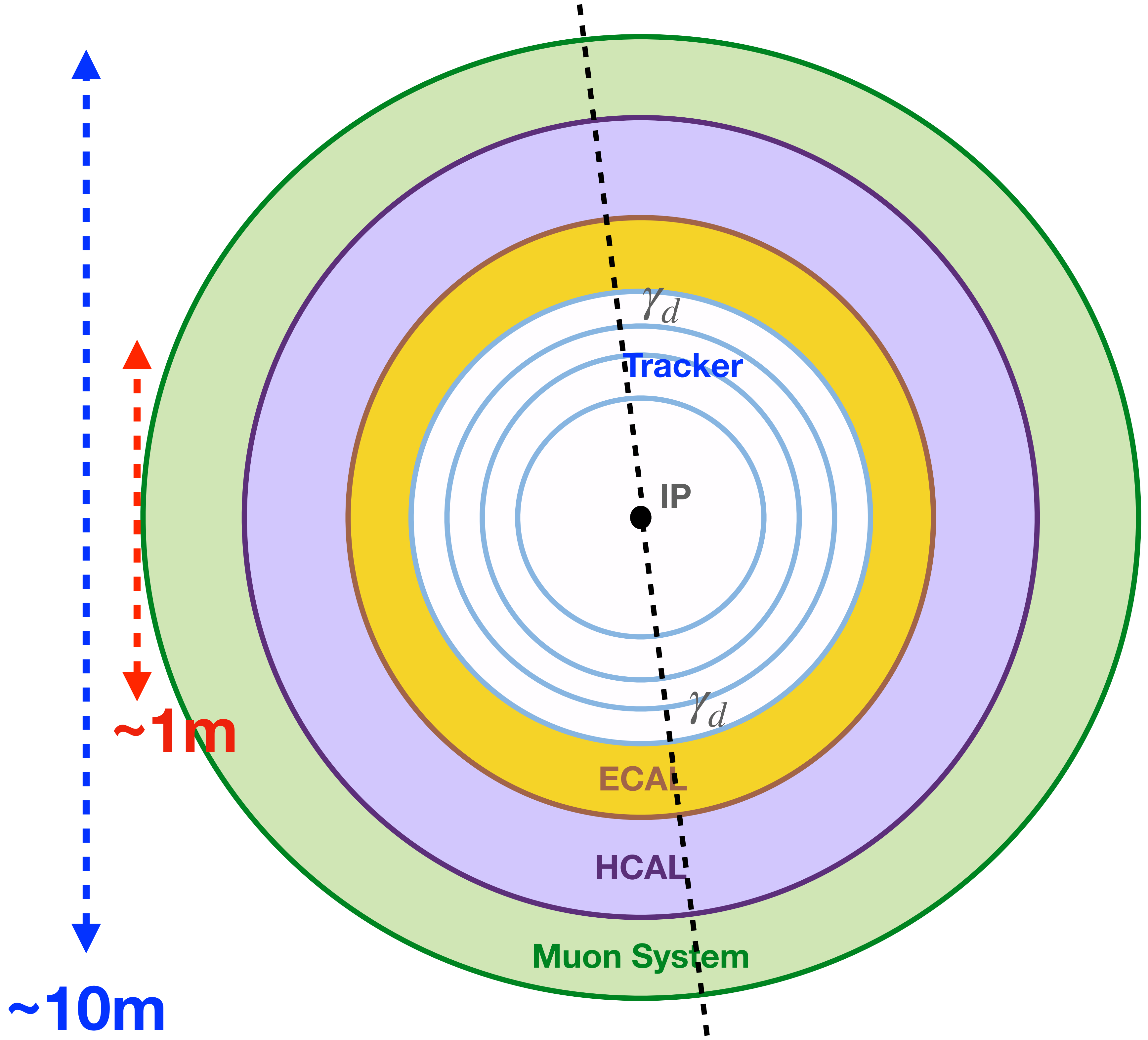

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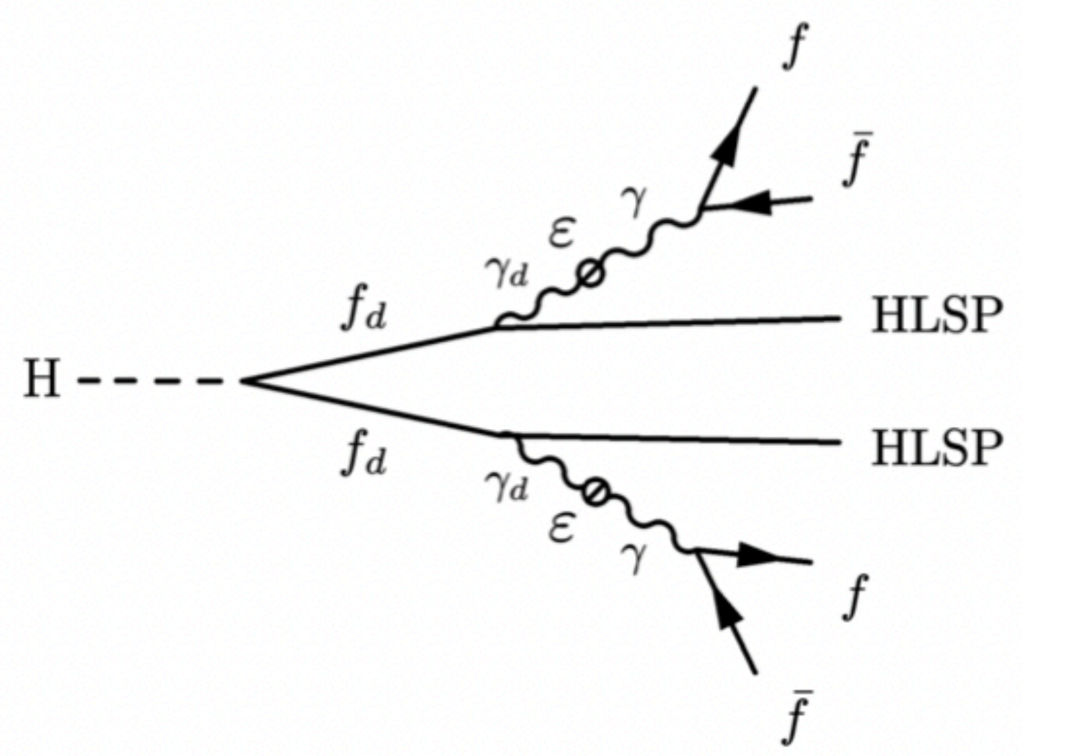

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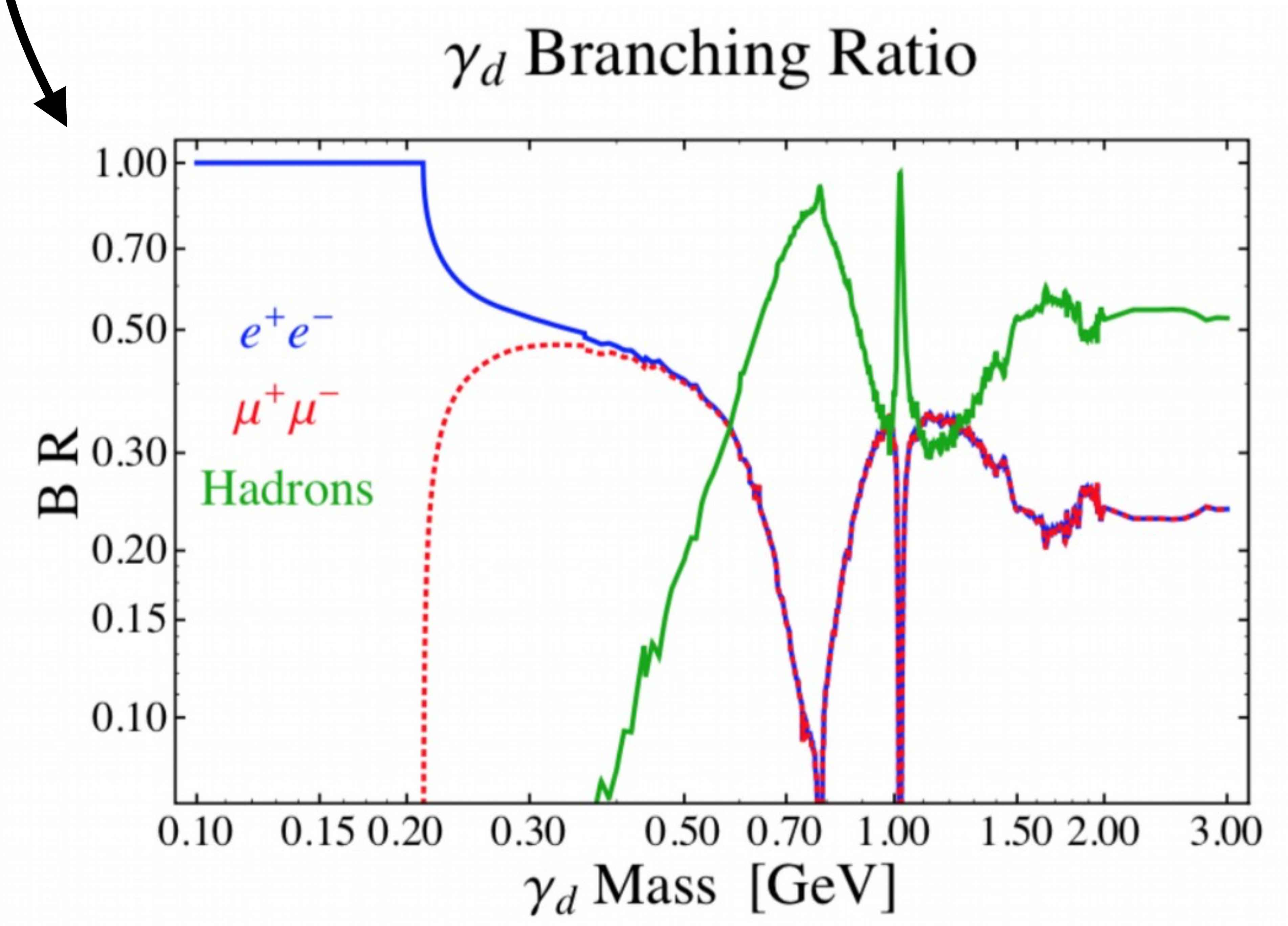

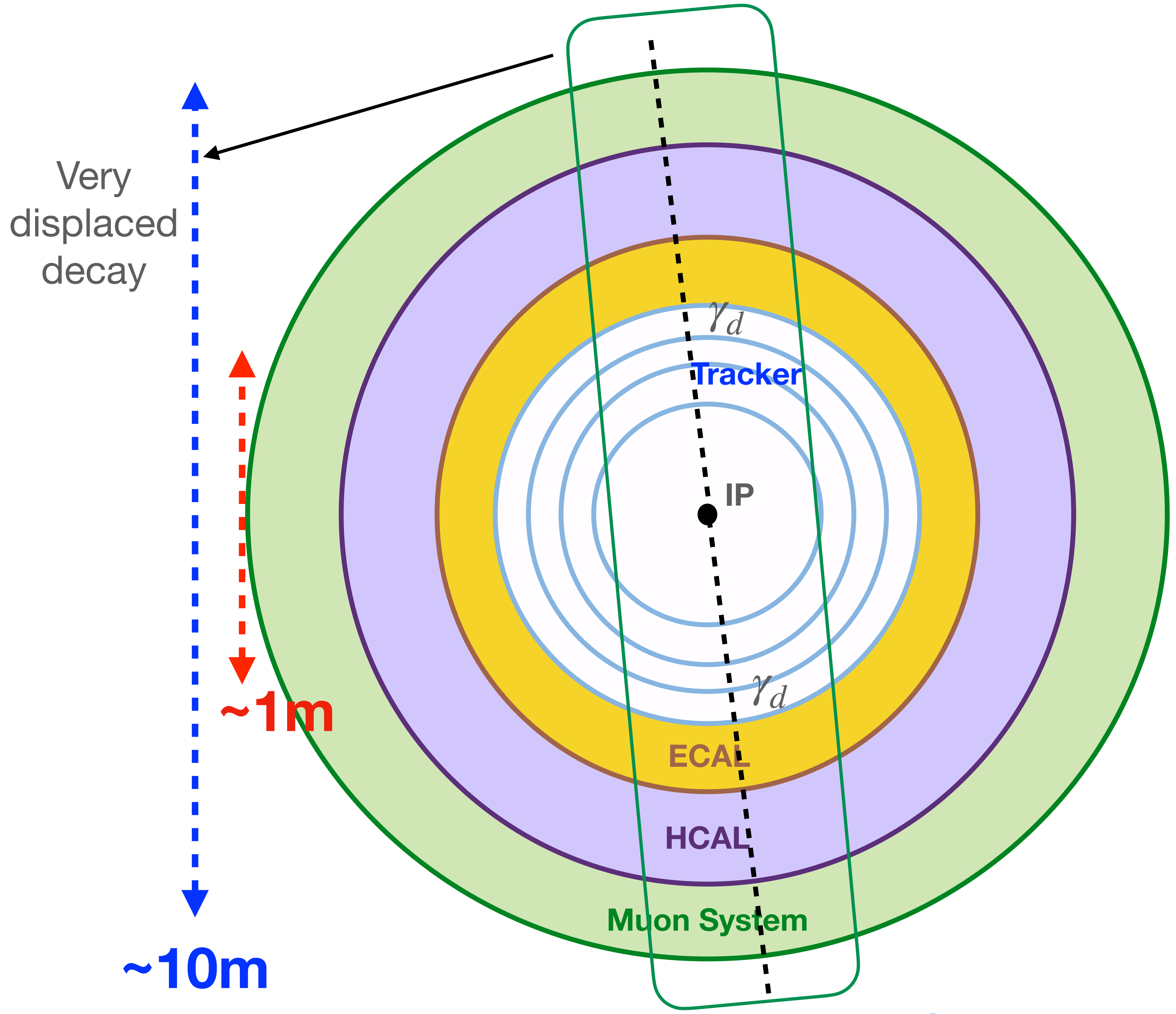

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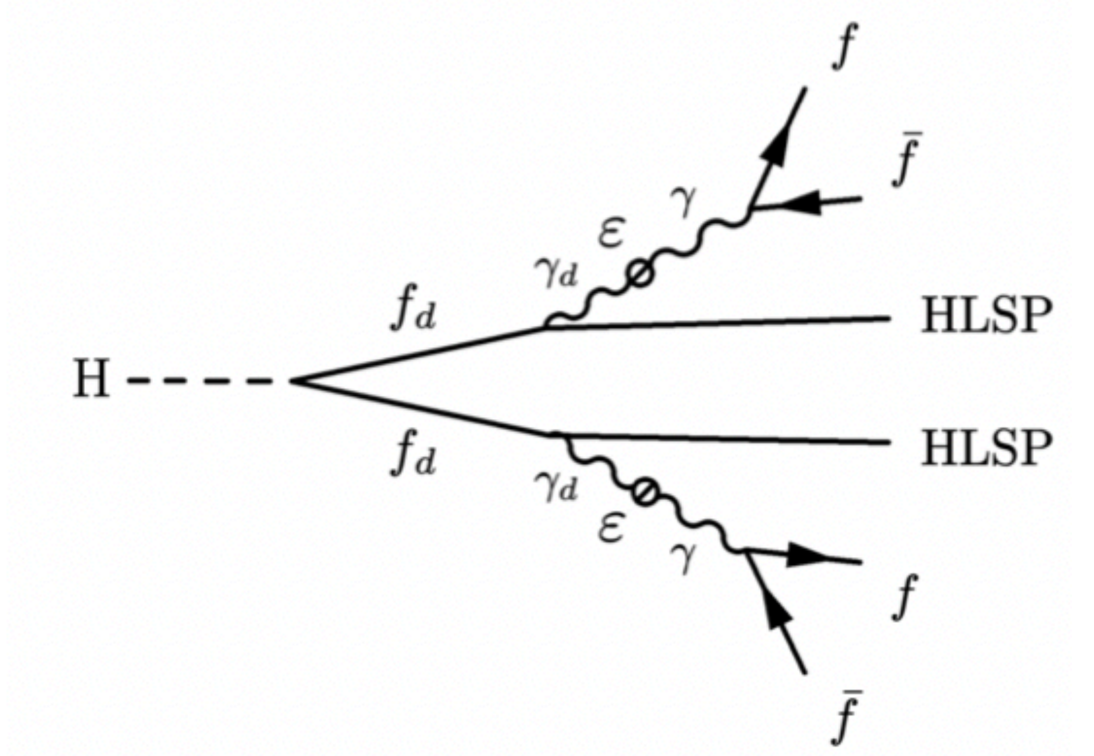

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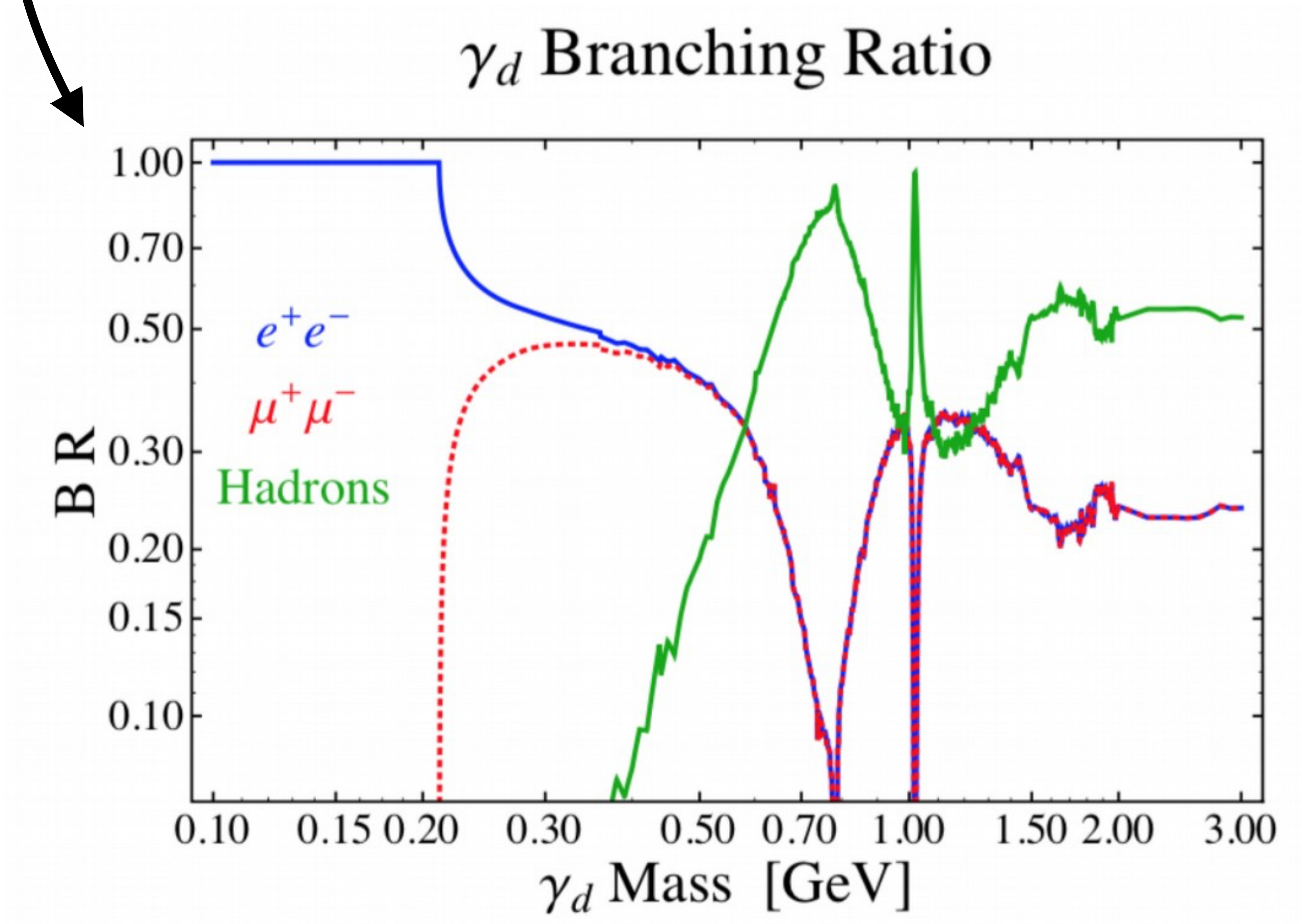

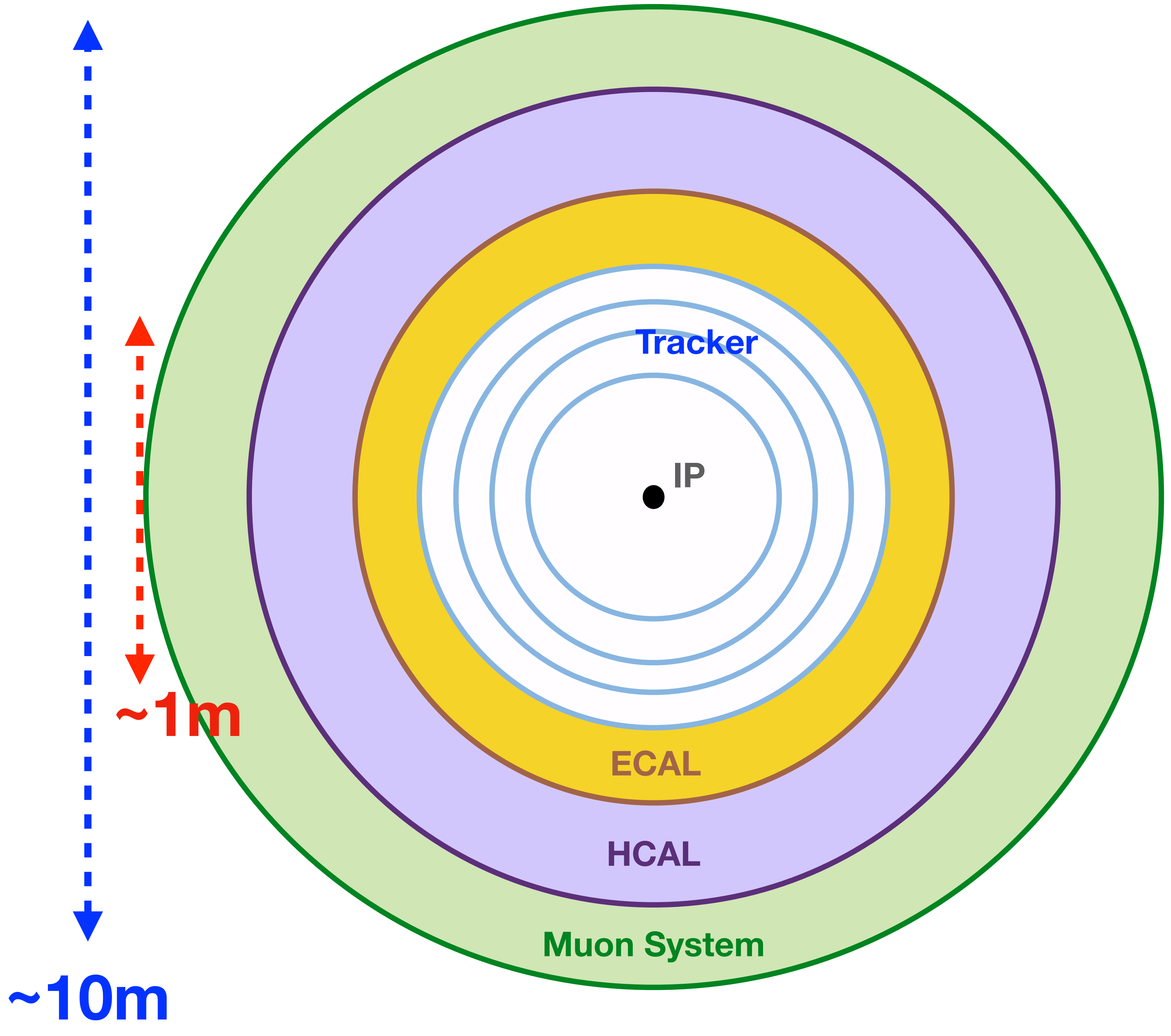

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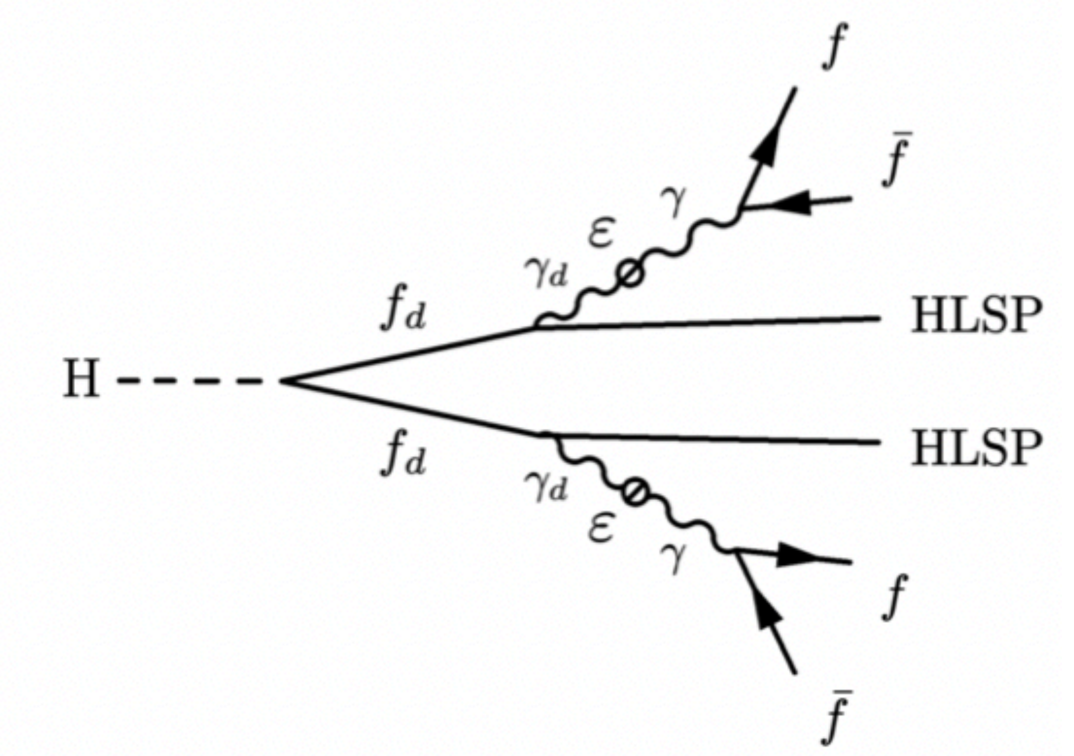

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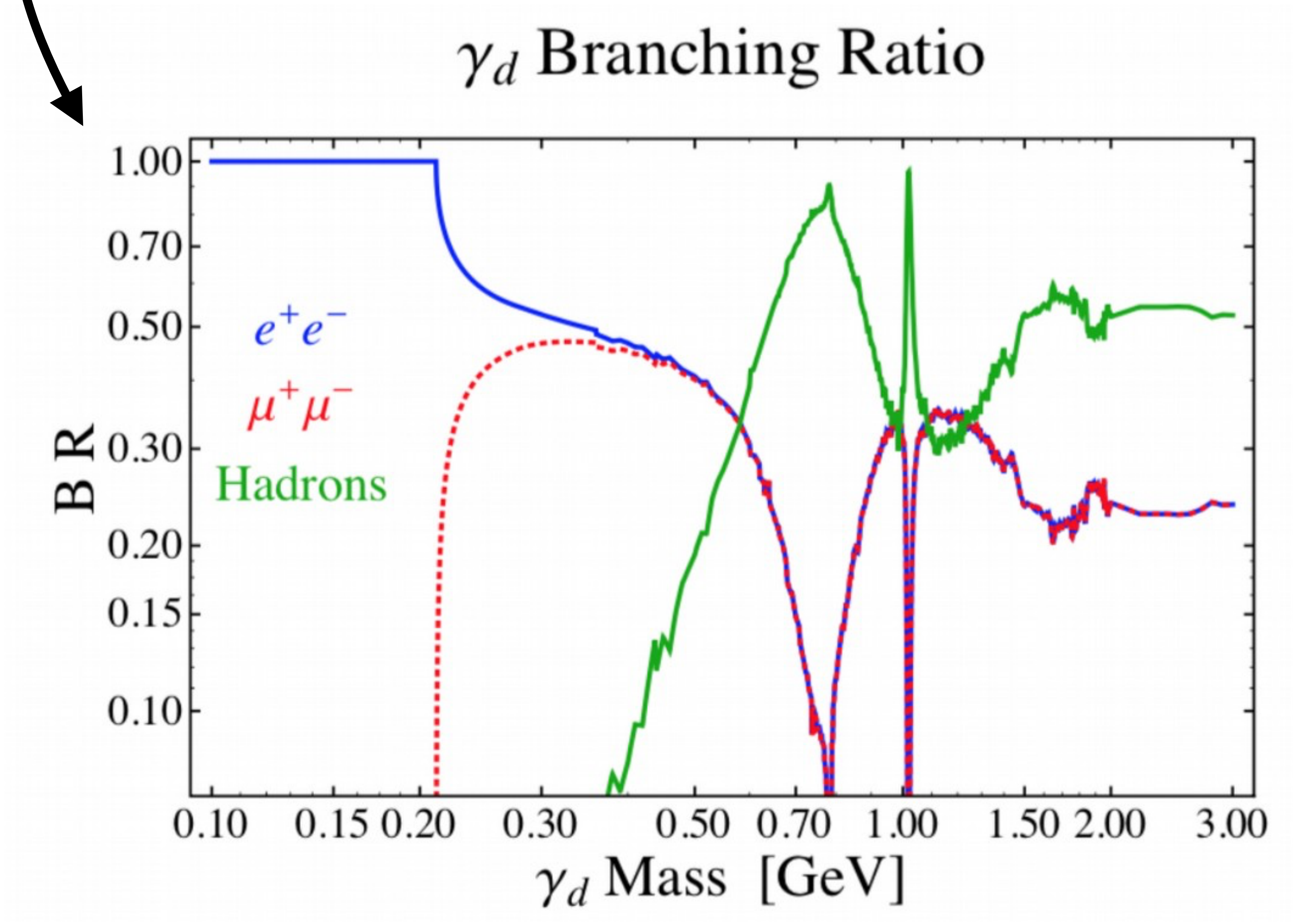
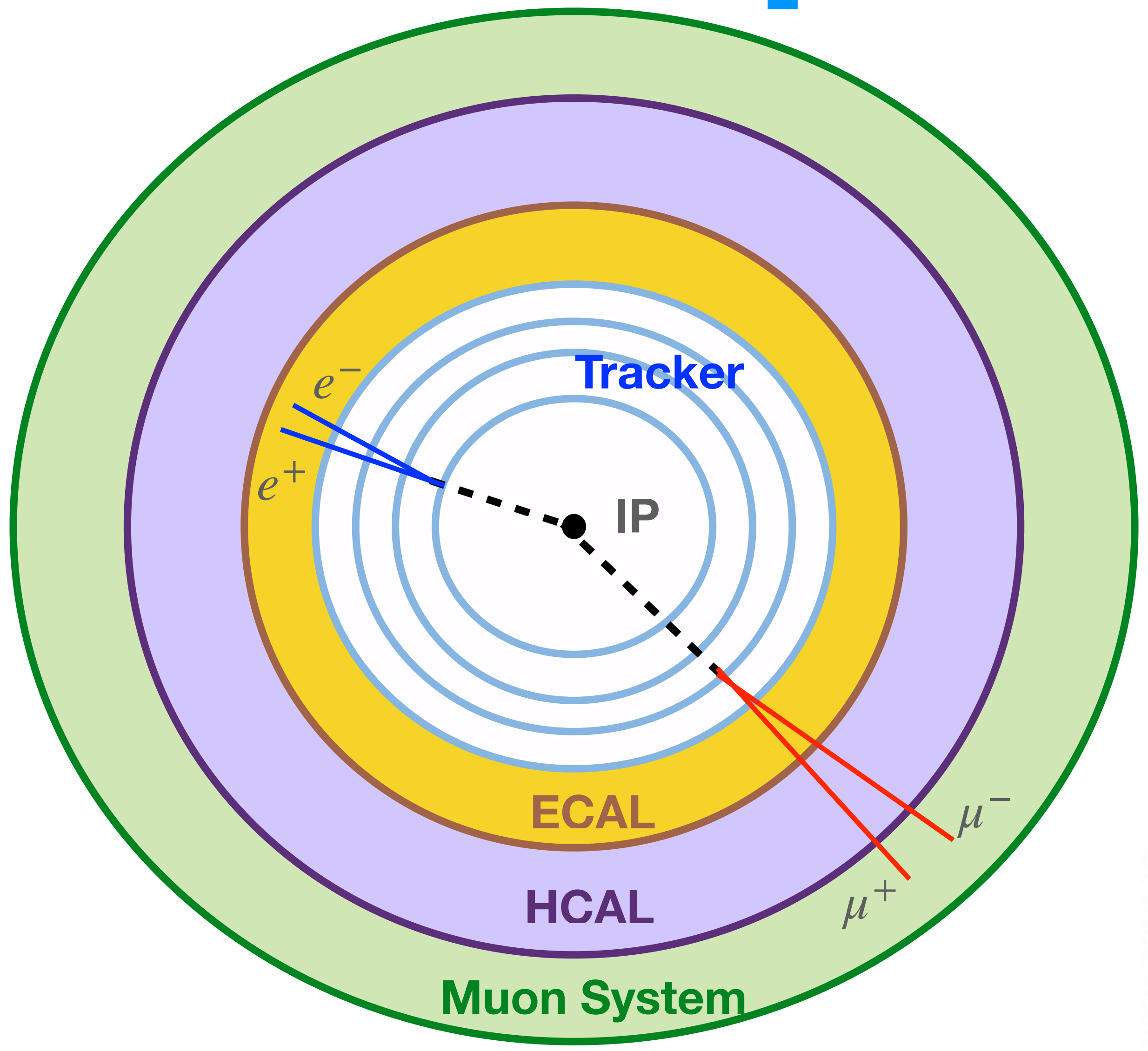


According to τ_{γ_d} completely different signatures arise! → Searches are divided in:

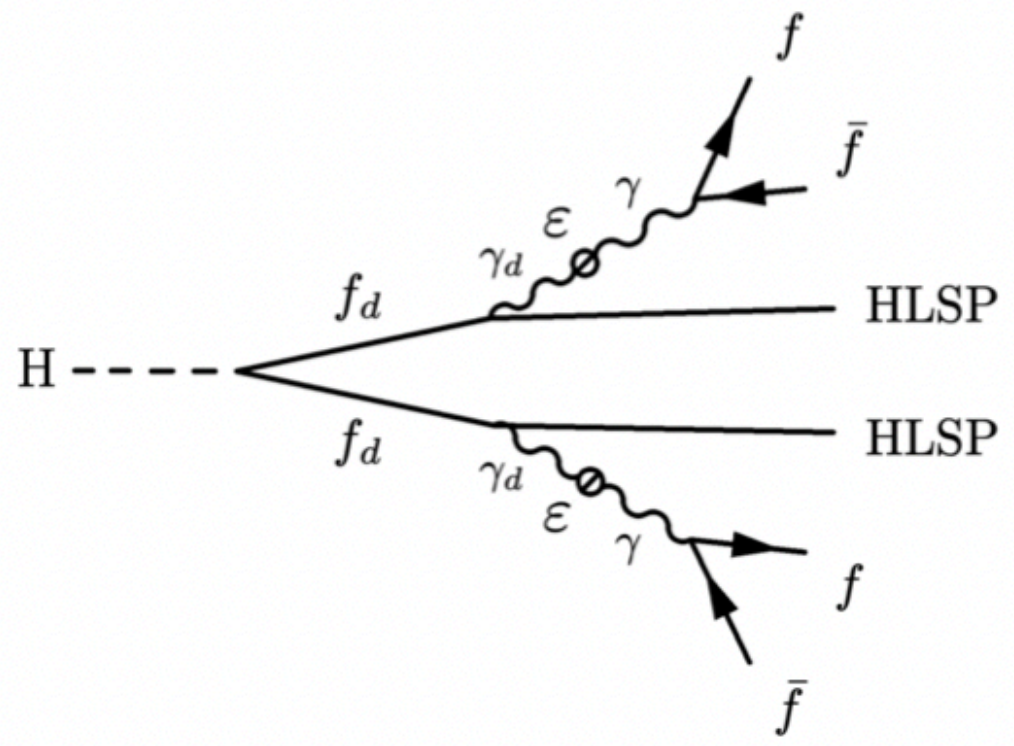
- **Prompt** searches;
- **Displaced** searches;
- **Very displaced** searches.

Prompt Dark Photon searches

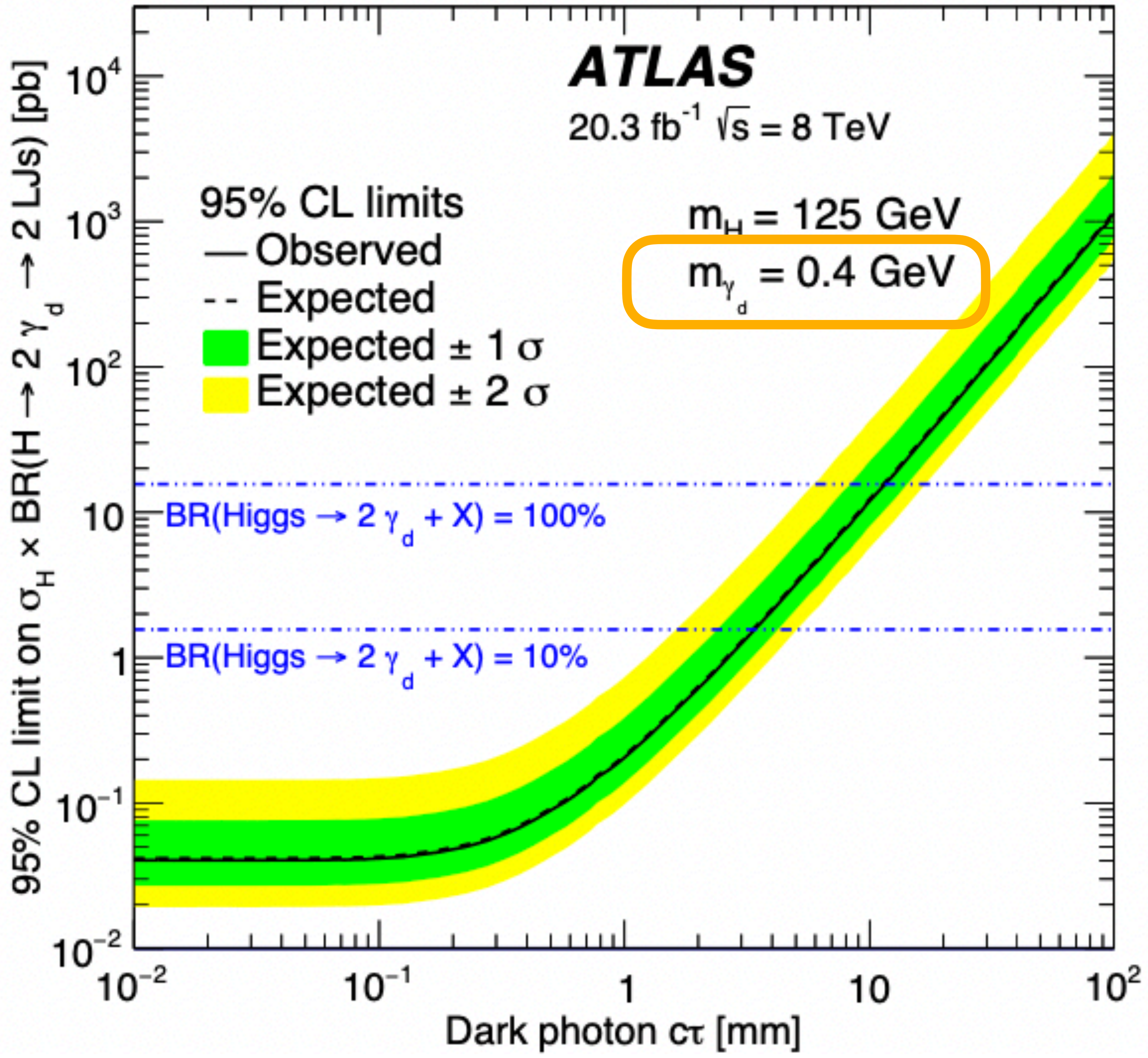


Electrons and muons reconstructed in the **conventional way** (electrons interact with ECAL and ID while muons with MS and ID)

- Only $\gamma_d \to \mu^+\mu^-$ or $\gamma_d \to e^+e^-$ considered;
- Results based on data collected in Run 1 $\mathrm{L} = 20.3\mathrm{fb}^{-1}$;
- Signature: at least **2 Dark Photon Jets** (μDPJ, at least 2μ, and eDPJ, at least $1e$);



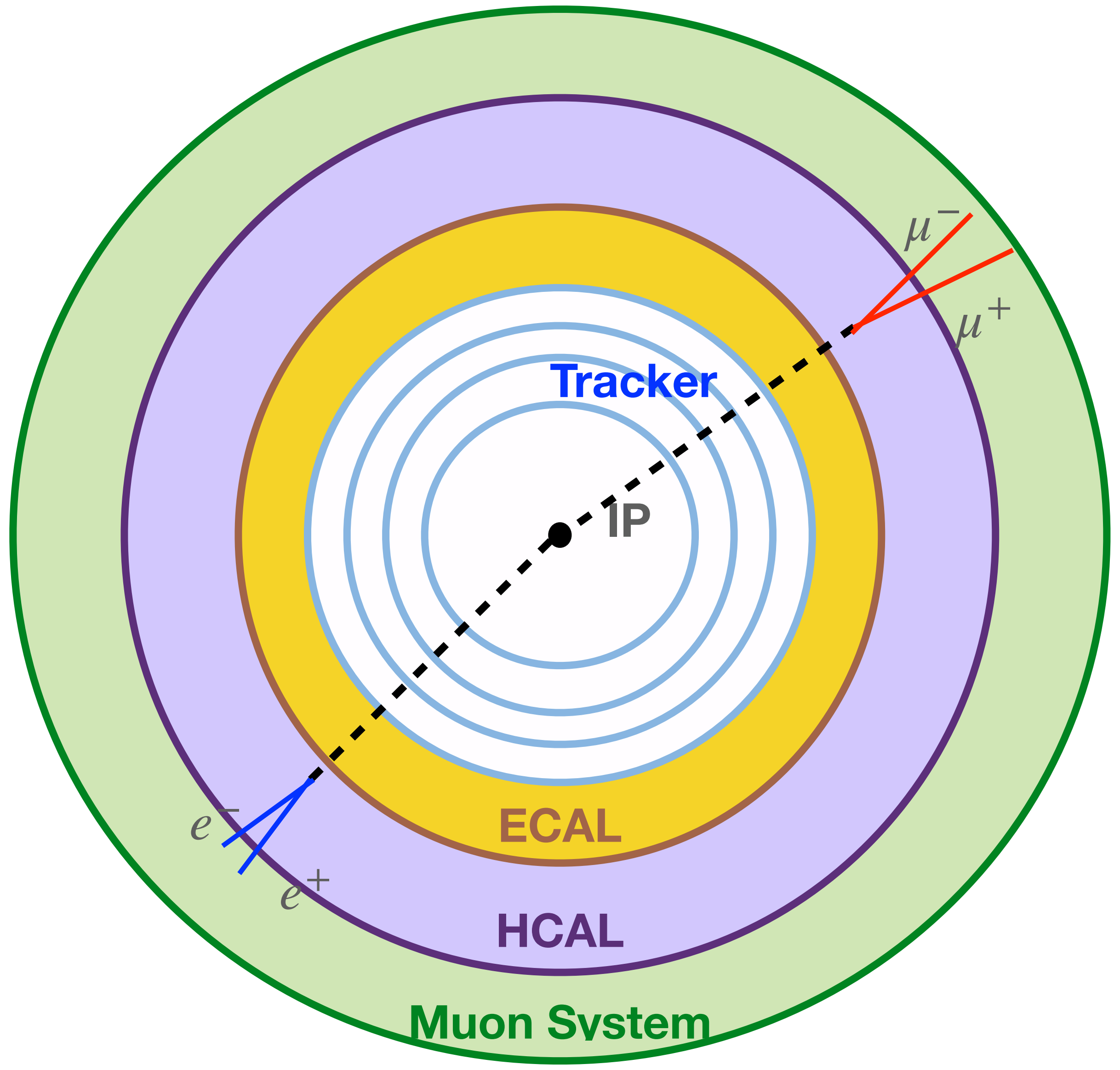
Main background: multi-jets and $Z(\to l^+l^-) + jets \to$ variables (such as f_{EM}, E_{T}^{had}) to distinguish S and B.



Look for excess in data wrt residual SM background → no excess is found, results in terms of excluded region in the parameter space.

Assuming $B(H \to 2\gamma_d + X) = 10\,\%$
$c\tau_{\gamma_d} < 3\mathrm{mm}$ **is excluded!**

Displaced Dark Photon searches

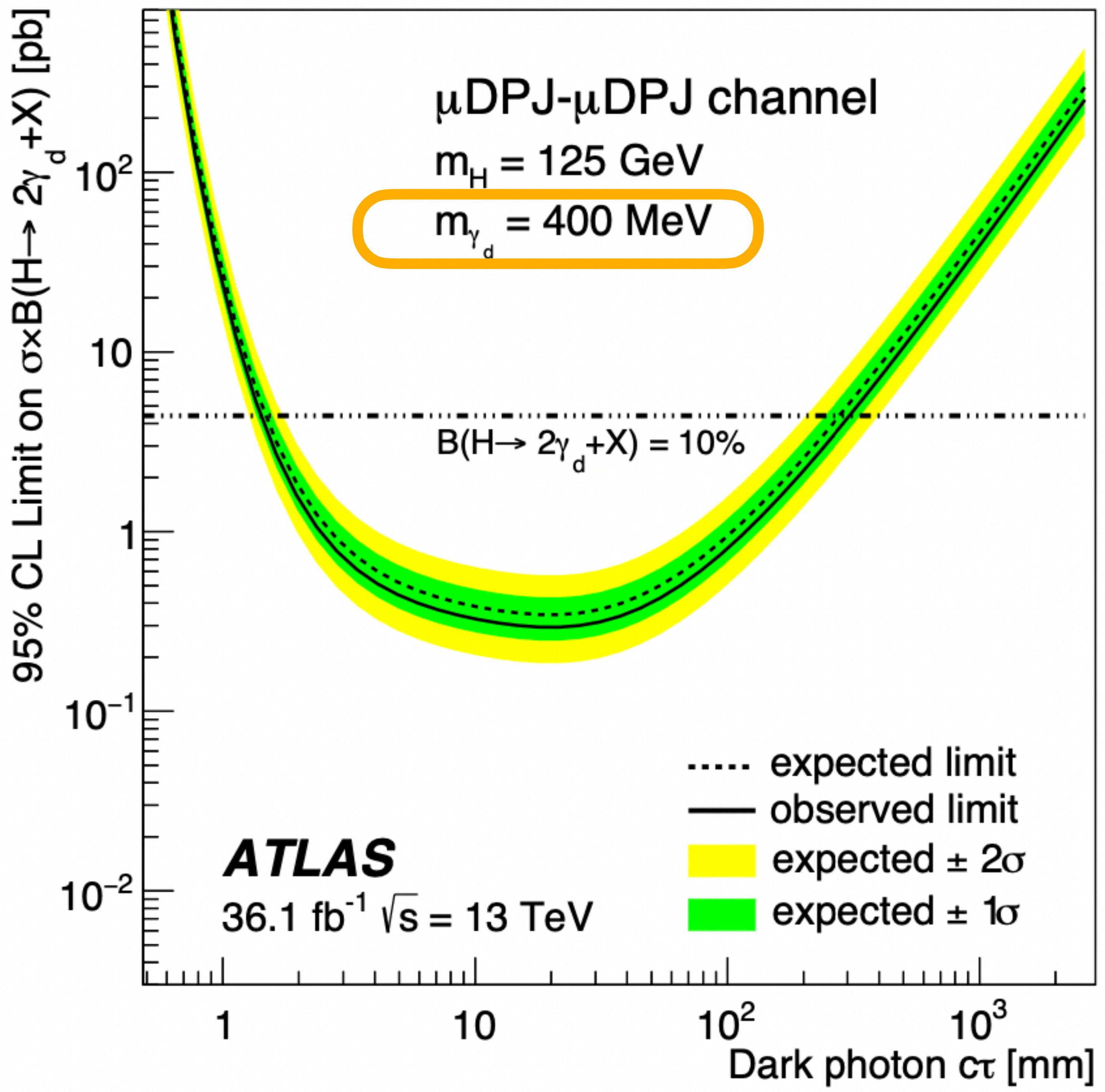


Electrons and muons reconstructed **NOT in the conventional way** (electrons interact with ECAL and **not** ID → reconstructed as jets, while muons with MS and **not** ID)

- All γ_d decay modes are considered;
- Results based on data collected in early Run 2 (2015-2016) $\mathrm{L} = 36.1 \mathrm{fb}^{-1}$;

Signature: at least **2 Dark Photon Jets** (μDPJ, at least 2μ, and hDPJ, at least 1 jet);

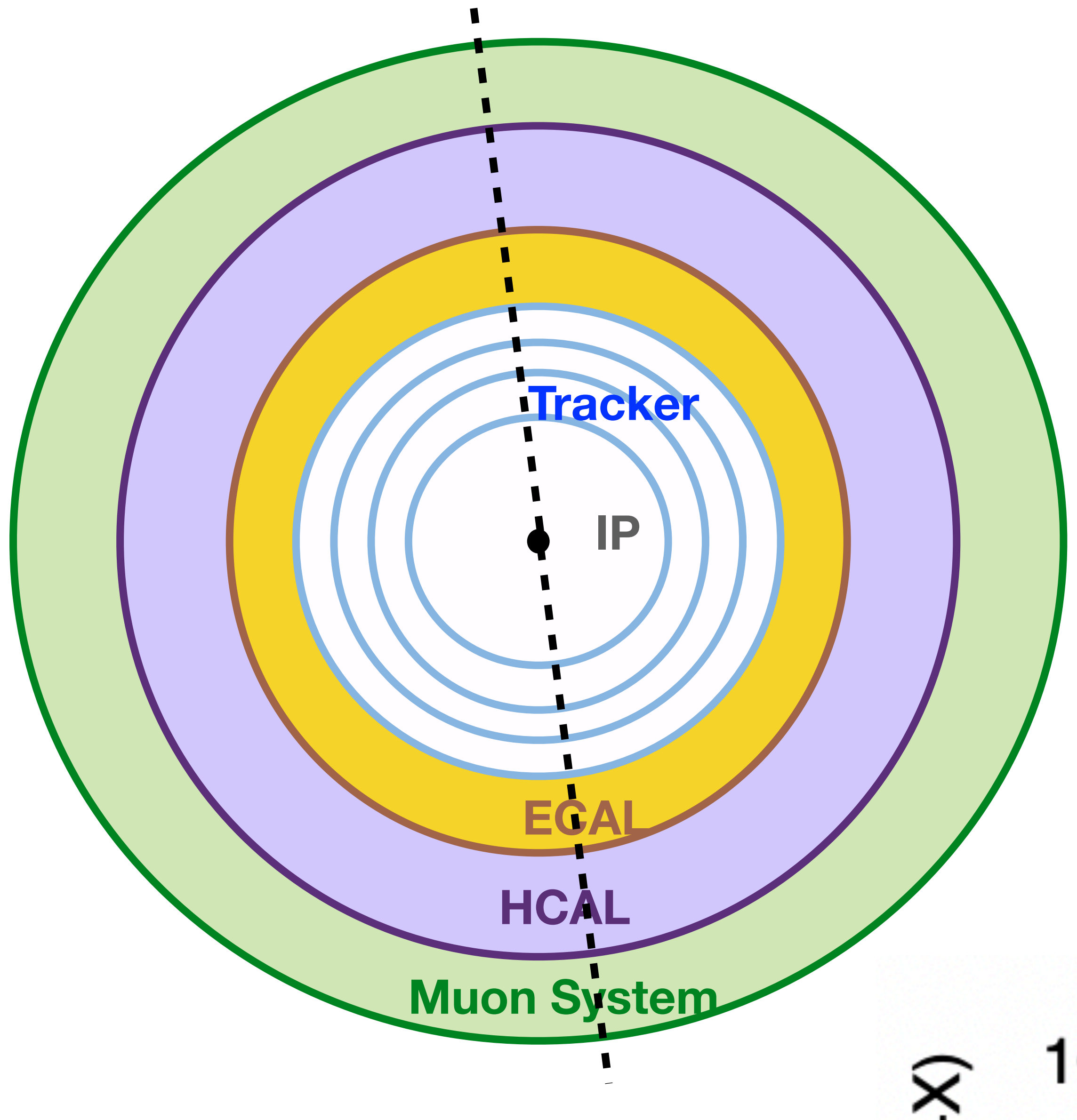
Main background: multi-jets (jets mistaken as hDPJ) Beam Induced Background (BIB) and cosmic rays (μ not from PV mistaken as μDPJ) → variables (such as $\frac{E_{ECAL}}{E_{tot}}$, $\Delta t_{jet-collision}$) to distinguish S from B.



Look for excess in data wrt residual SM background → no excess is found, results in terms of excluded region in the parameter space.

Assuming $B(H \to 2\gamma_d + X) = 10\,\%$ $2\mathrm{mm} < c\tau_{\gamma_d} < 200\mathrm{mm}$ **is excluded!**

Very displaced Dark Photon searches

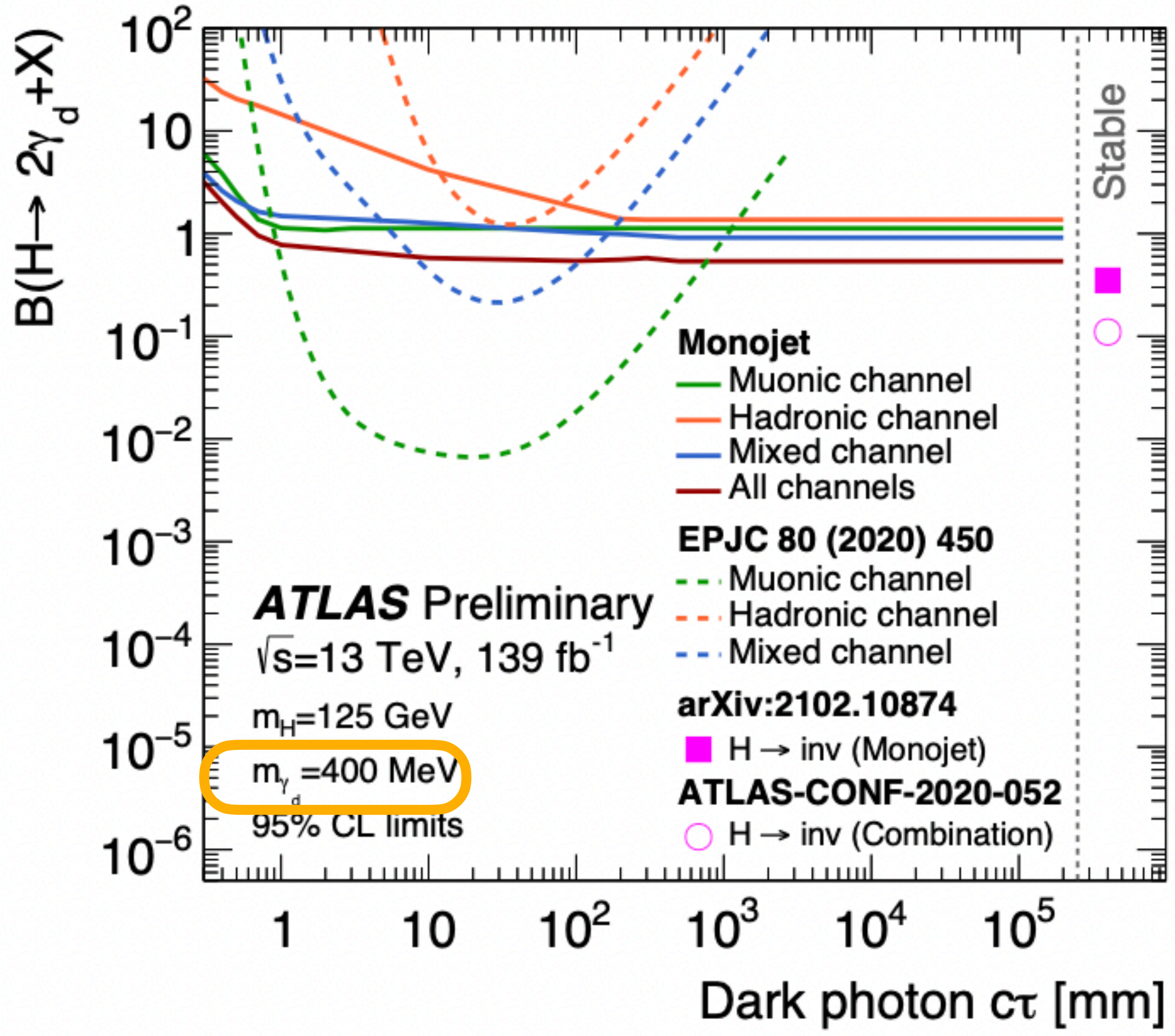


Electrons and muons not reconstructed, γ_d decay outside ATLAS

- All γ_d decay modes are considered;
- Results based on data collected in Run 2 $\mathrm{L} = 139\mathrm{fb}^{-1}$;

Signature: $E_{\mathrm{T}}^{\mathrm{miss}}$ **as γ_d decay outside ATLAS (+ jet with high p_{T});**

Main background: multi-jets (low $E_{\mathrm{T}}^{\mathrm{miss}}$, jets not properly reconstructed) $Z(\nu\bar{\nu}) + jets$ (ν is invisible for ATLAS, irreducible) → low number of jets $+\Delta\varphi^{min}_{jet-E_{\mathrm{T}}^{\mathrm{miss}}}$ required to reduce multi-jets, $Z(\nu\bar{\nu}) + jets$ can only be evaluated through MC.

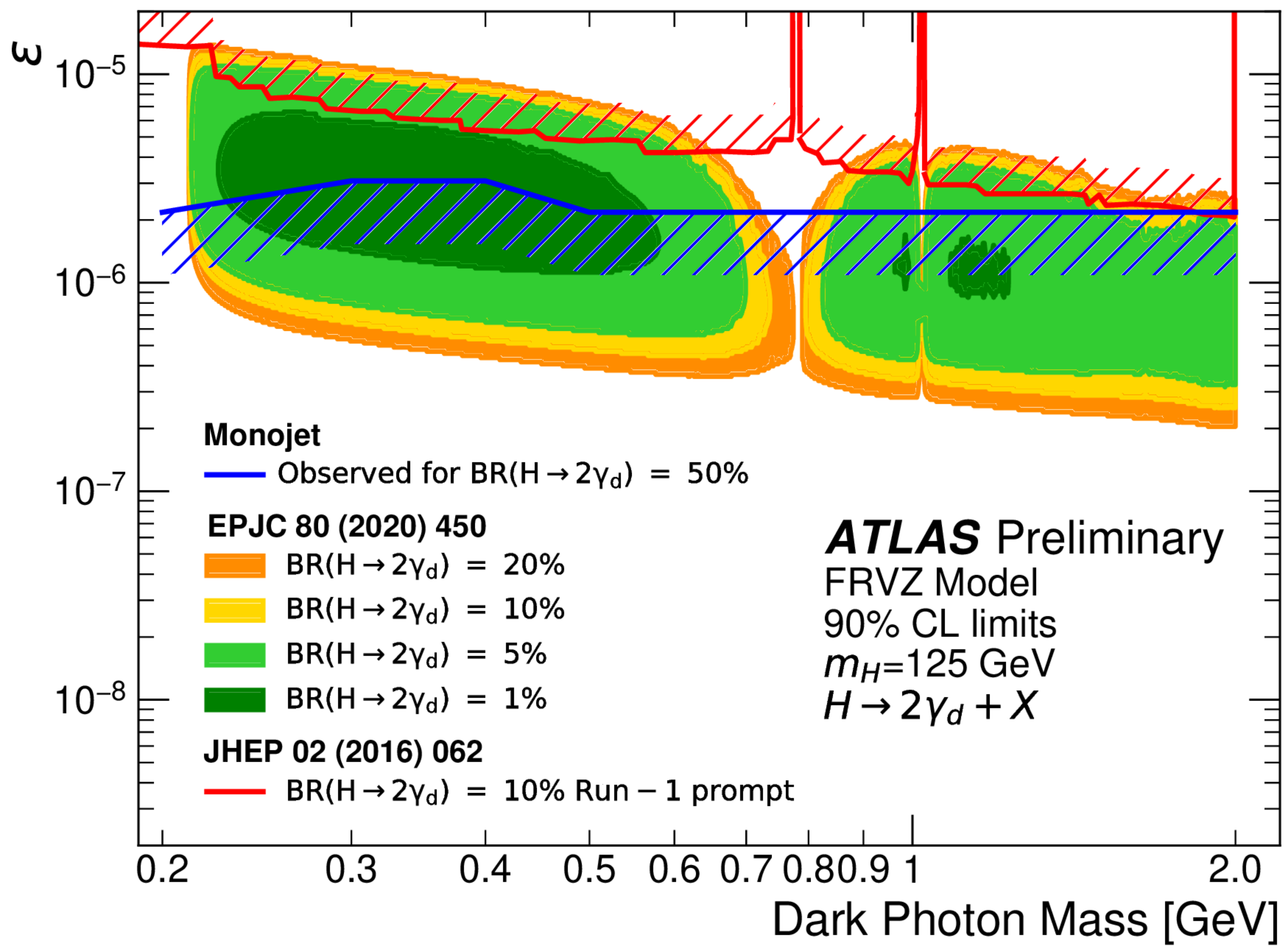


Look for excess in data wrt residual SM background → no excess is found, results in terms of excluded region in the parameter space.

Assuming $B(H \to 2\gamma_d + X) = 50\,\%$
$c\tau_{\gamma_d} > 100\mathrm{mm}$ is excluded!

What are we able to exclude at ATLAS then?

Previous results shown separately for the various searches and for $m_{\gamma_d} = 0.4\mathrm{GeV}$ can be seen altogether in the $(\varepsilon, m_{\gamma_d})$ plane, where assuming a $B(H \to 2\gamma_d + X)$ excluded regions are found.



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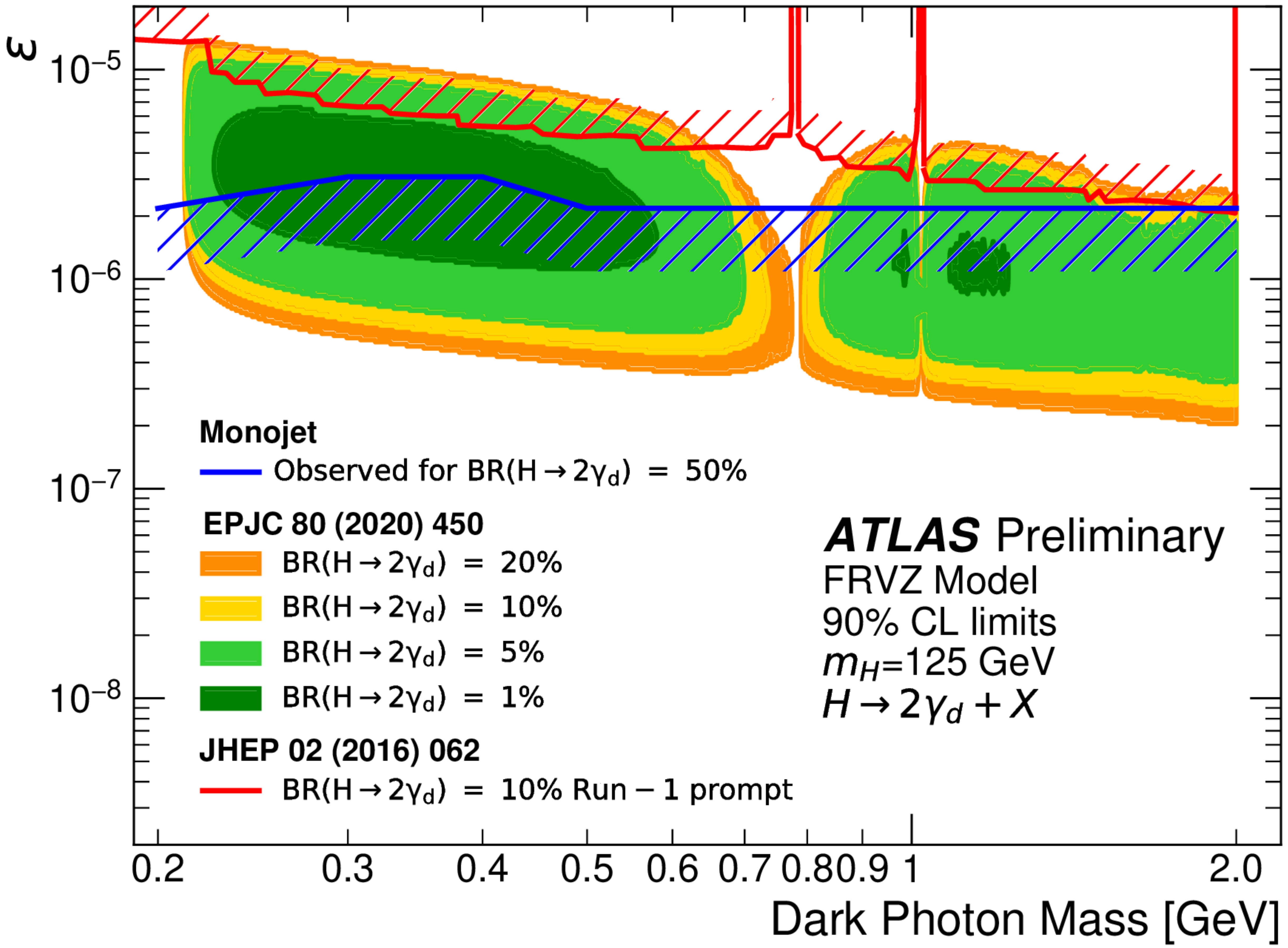
Remembering that $\tau_{\gamma_d} \propto \varepsilon^{-2}$ excluded area found by the searches which look for:



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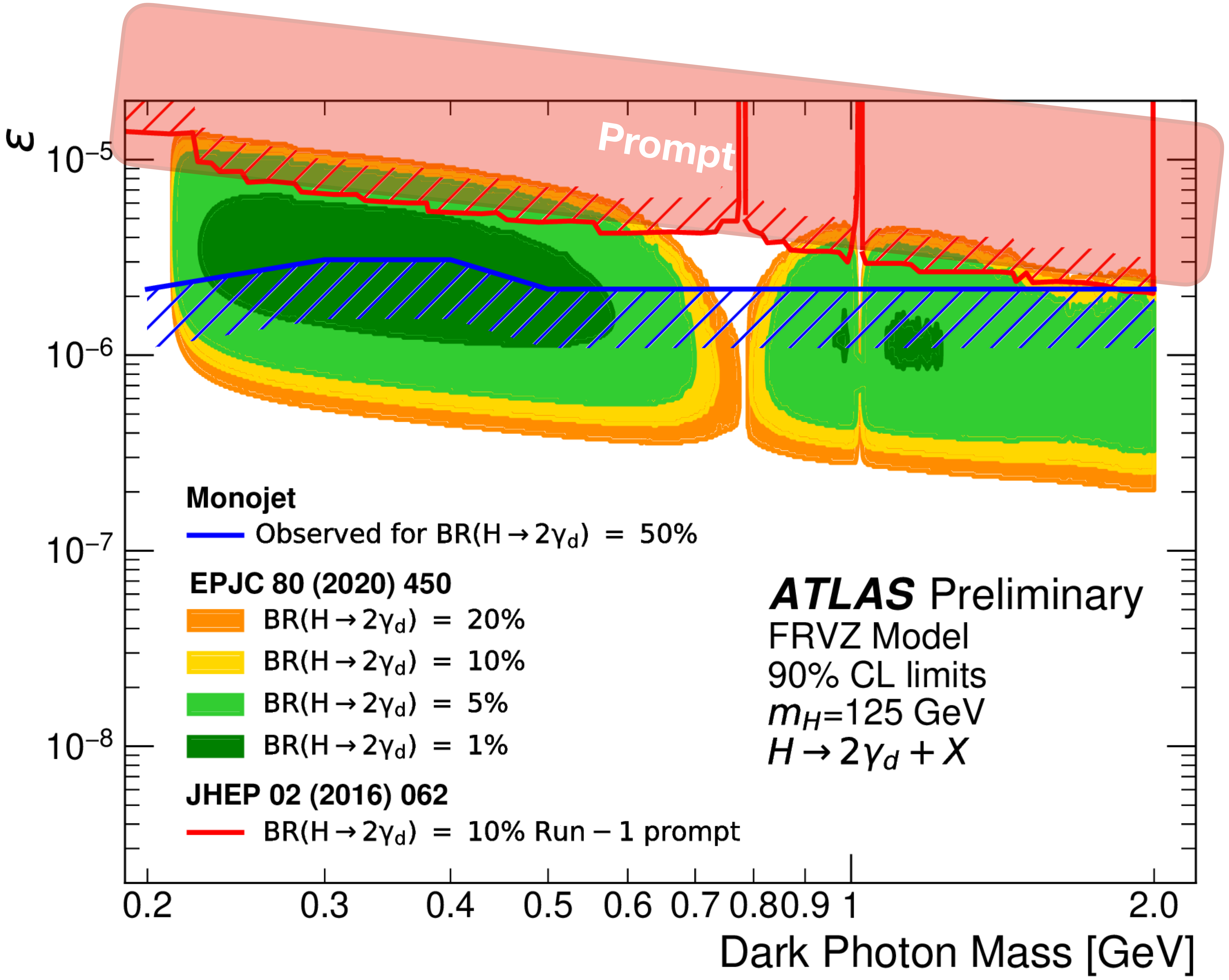

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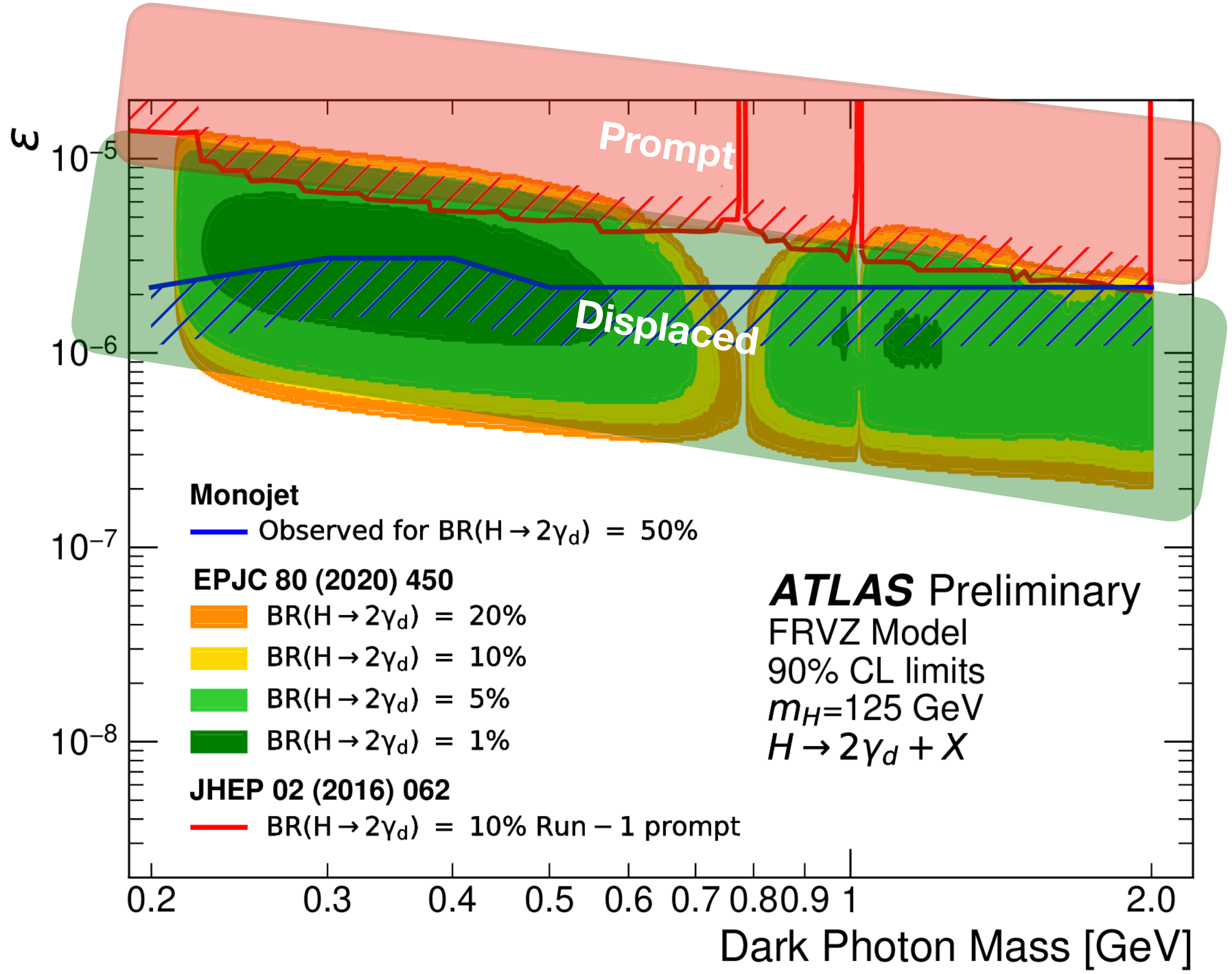

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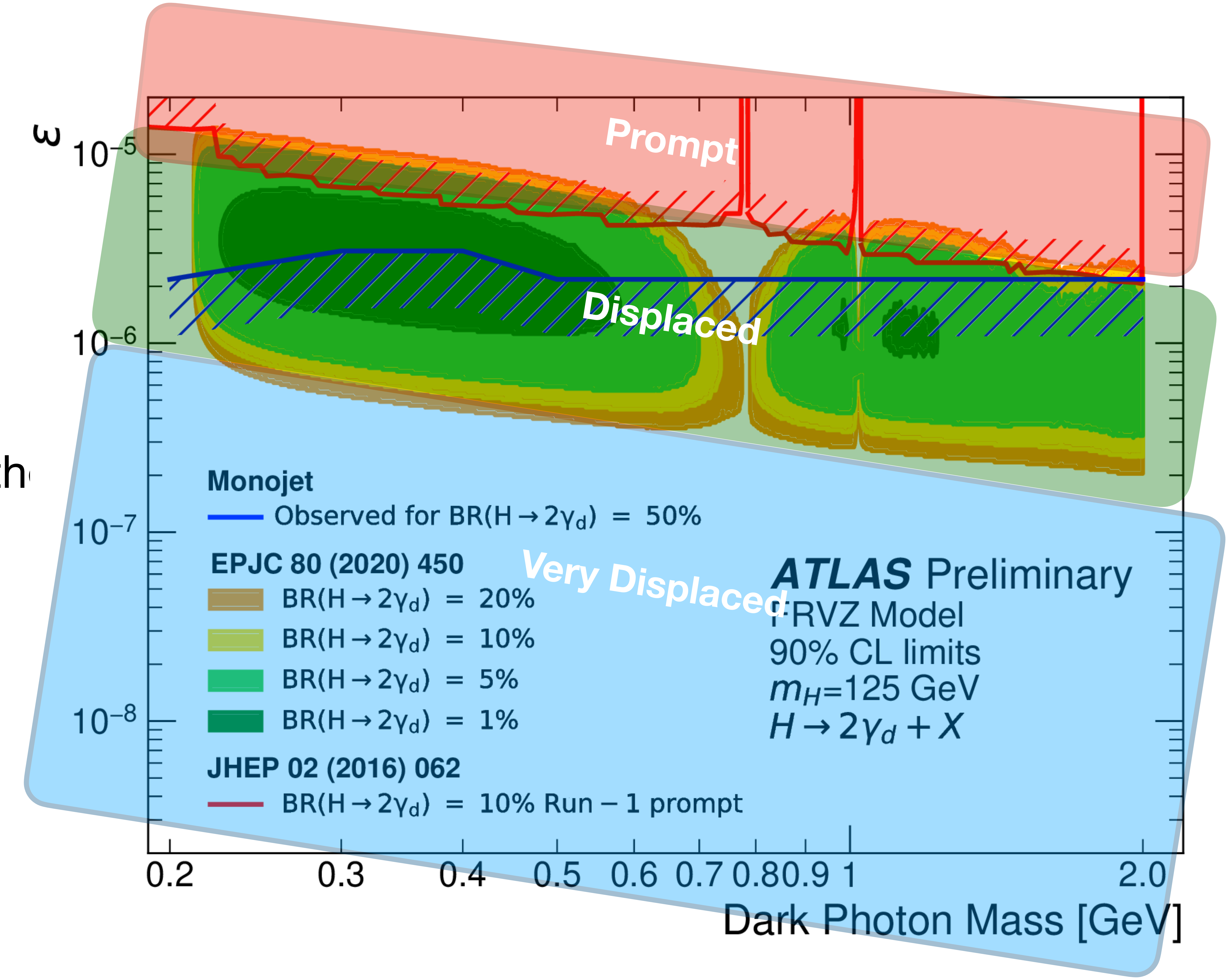


Conclusions and outlook

The possibility that Dark Matter constitutes a new Dark Sector is investigated by various experiments, like ATLAS at the LHC.

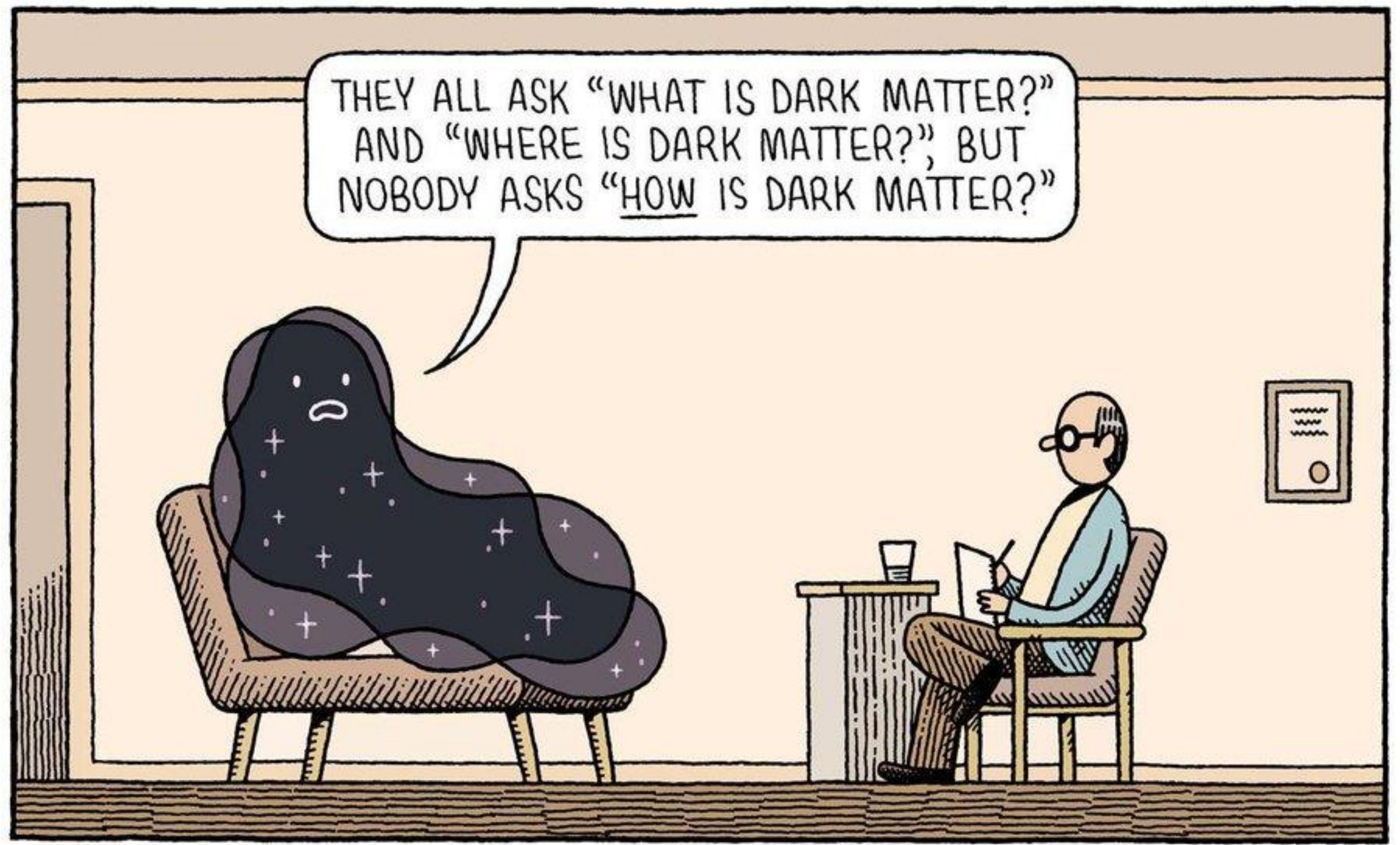
The minimal model of the Dark Sector foresees an interaction similar to the EM one mediated by the γ_d which is massive and decays into SM particles.

In ATLAS γ_d could have been produced through Higgs boson decays as $B(H \to und) \leq 19\,\%$, so three searches for γ_d exist, according to its τ_{γ_d}: prompt, displaced and very displaced searches.

No deviations of SM predictions are observed → constraints on the free parameters of the model.

What is next?

New results from the displaced group are about to come (brace yourself!) and a **new group has taken over the prompt searches** (hopefully exciting news from my side ;))



To dig deeper:
https://arxiv.org/abs/1511.05542
https://cds.cern.ch/record/2772627?ln=it
https://arxiv.org/pdf/1909.01246.pdf

Thank you for your attention!

Backup slides

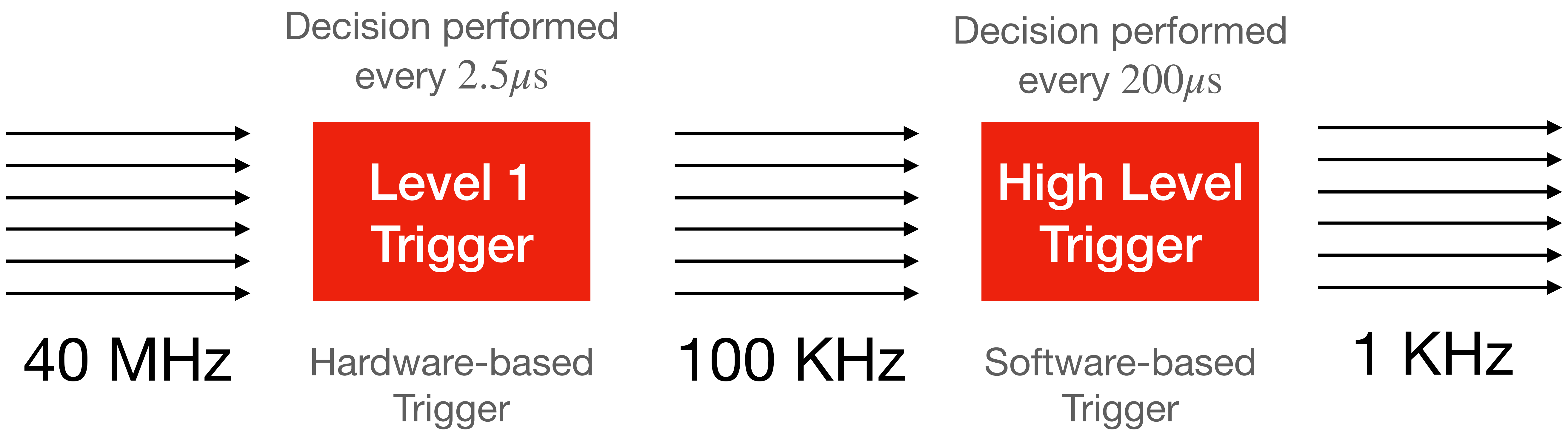
Expression of the **luminosity** $\mathrm{L} = \int \mathscr{L} dt = \int \frac{N_P^2 N_B f_{rev} F}{4 \pi \sigma_x \sigma_y} dt$

Is every event stored?

During Run 2 bunches injected every 25 ns → bunches collisions rate was 40MHz rate → ~ 1.7 billions proton-proton collisions per second → **60 TB** per second!

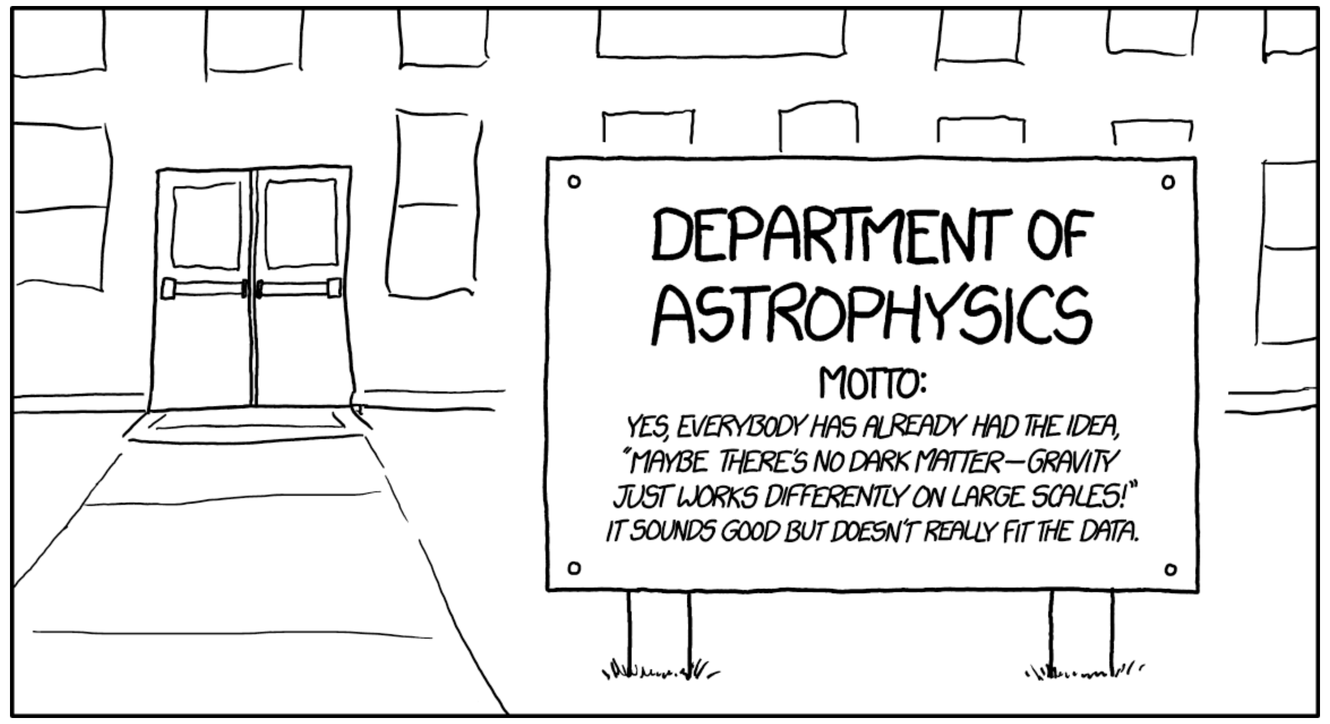
Not possible storing this amount of data + and often events are not physically interesting → some data thrown away.

The decision about keeping/throwing events is made by the **trigger system (L1 + HLT).**

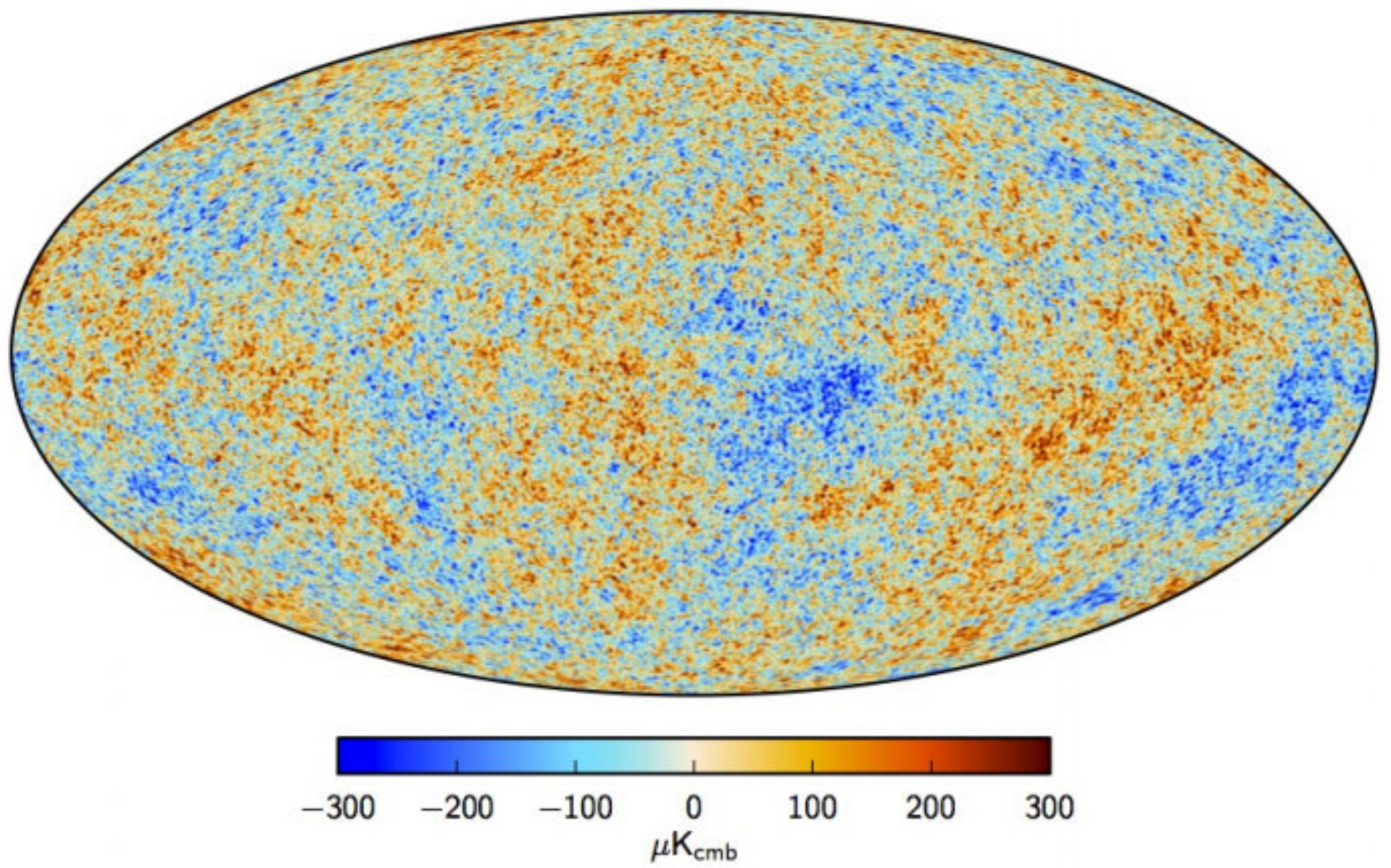


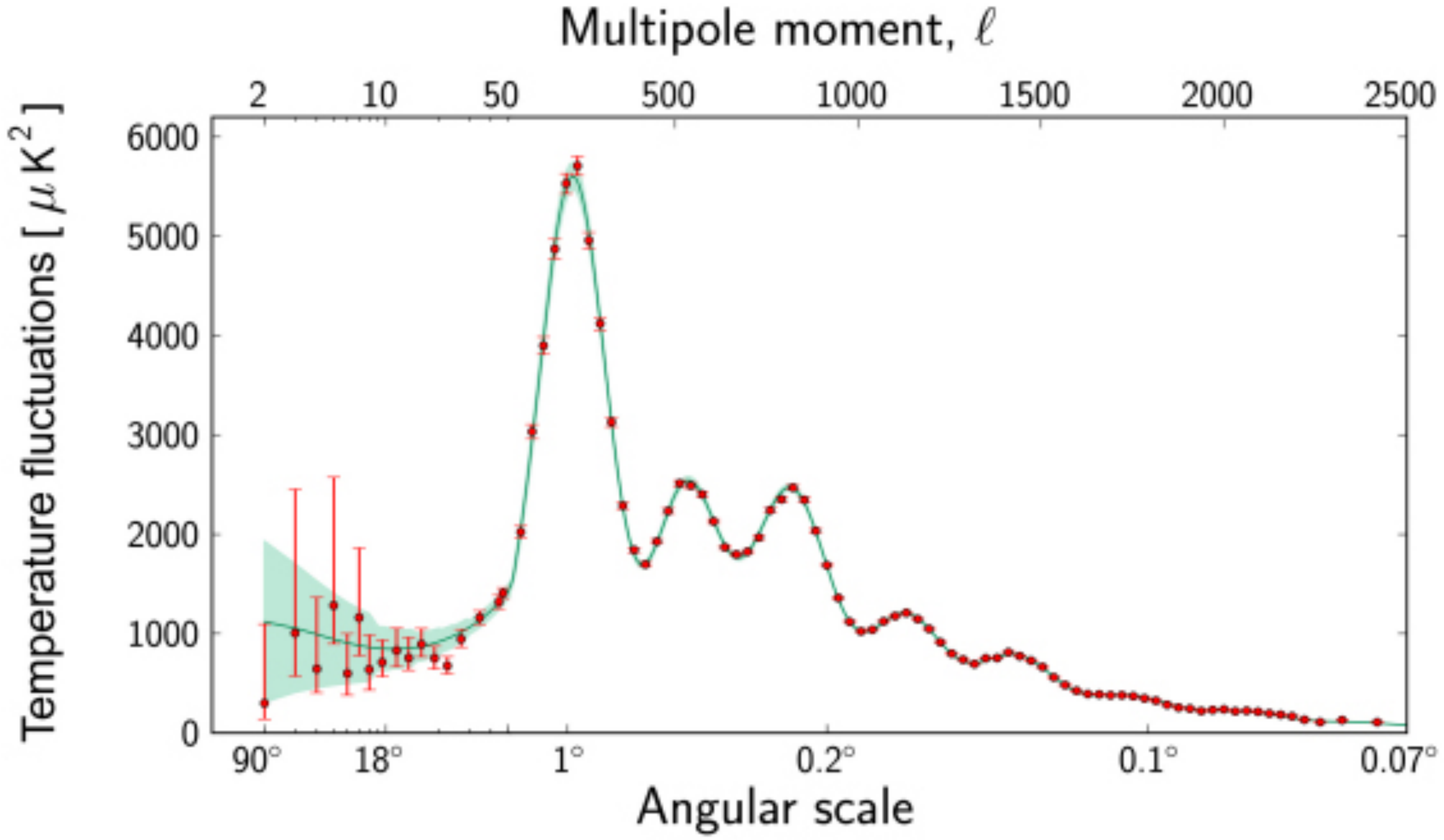
Triggers are defined to select events with particular characteristics (for example HLT_mu50 requires at least one HLT muon with $p_{\mathrm{T}} > 50\mathrm{GeV}$).

How much Dark Matter there is?



Cosmological scale





From the CMB power spectrum it is possible to derive the matter content of the Universe:

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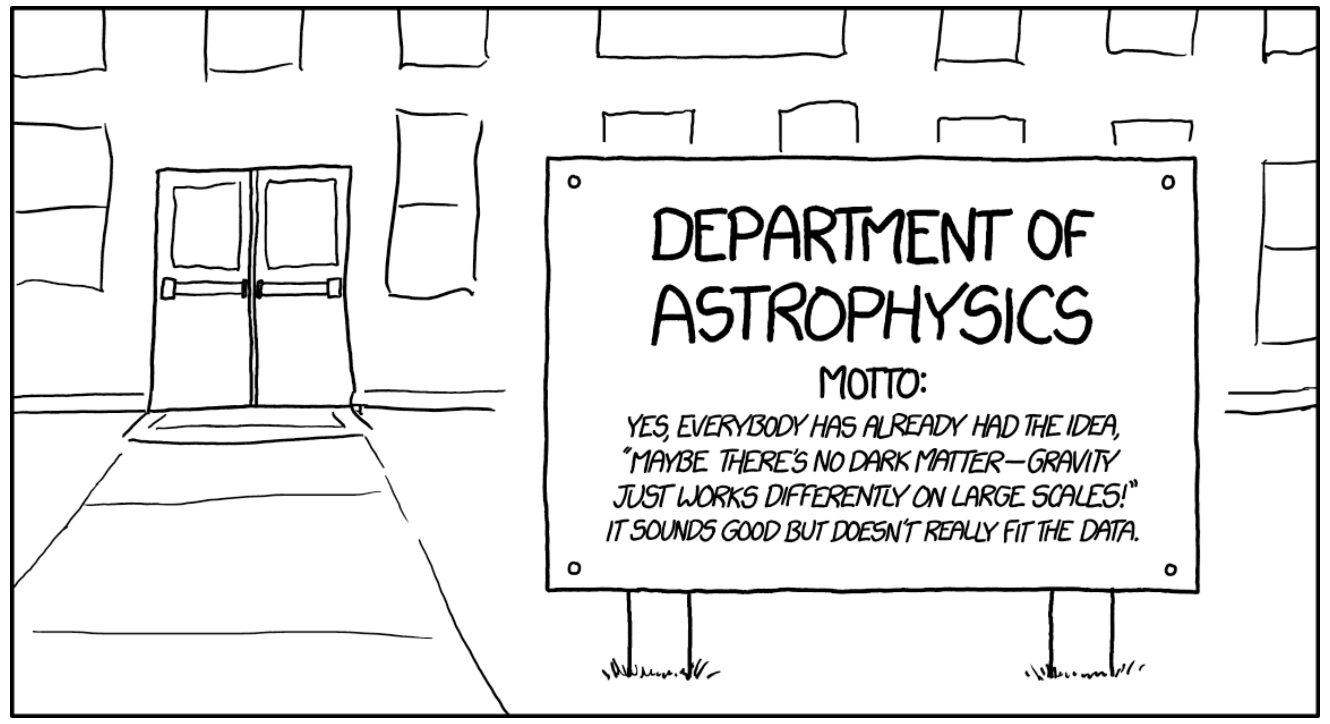

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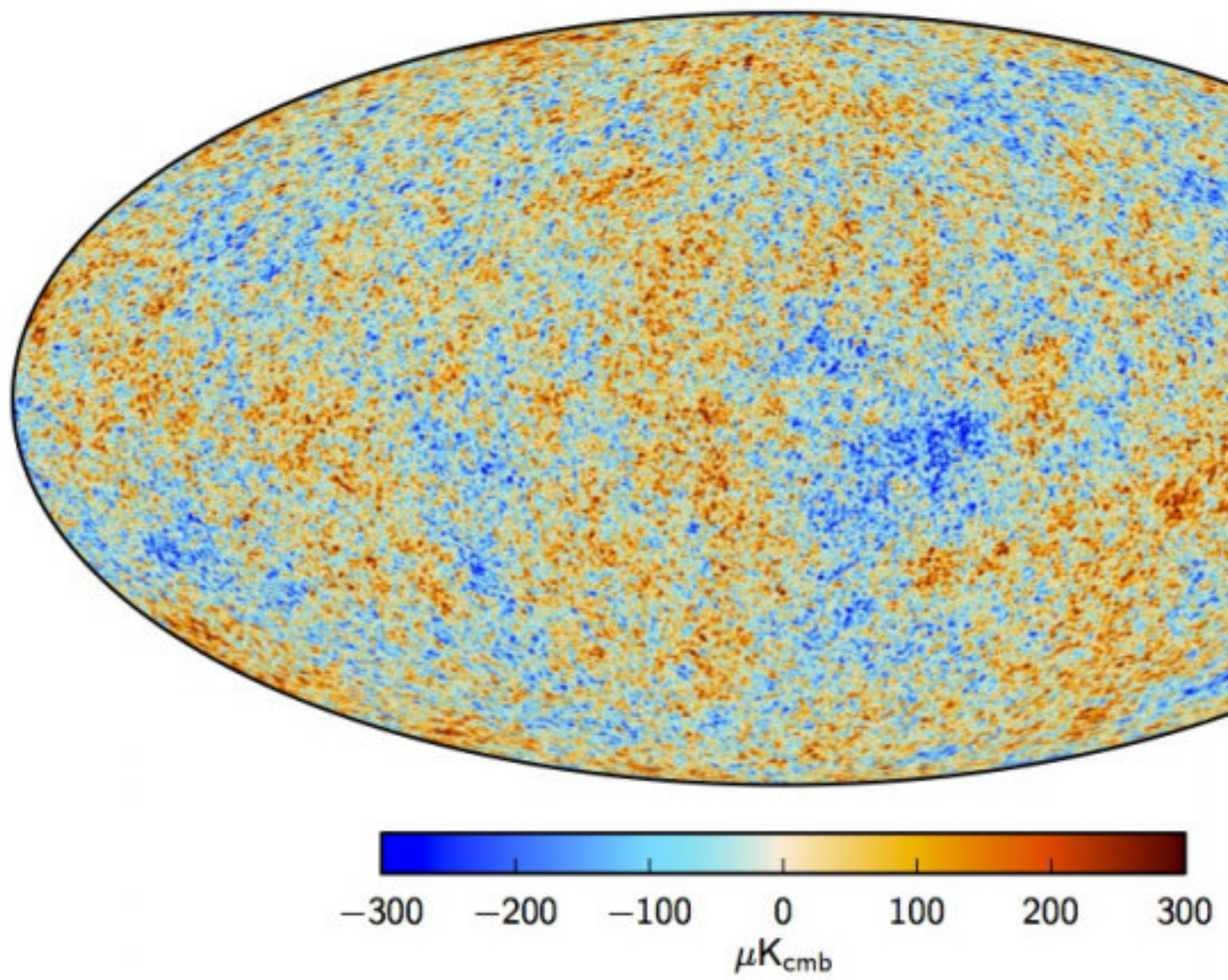

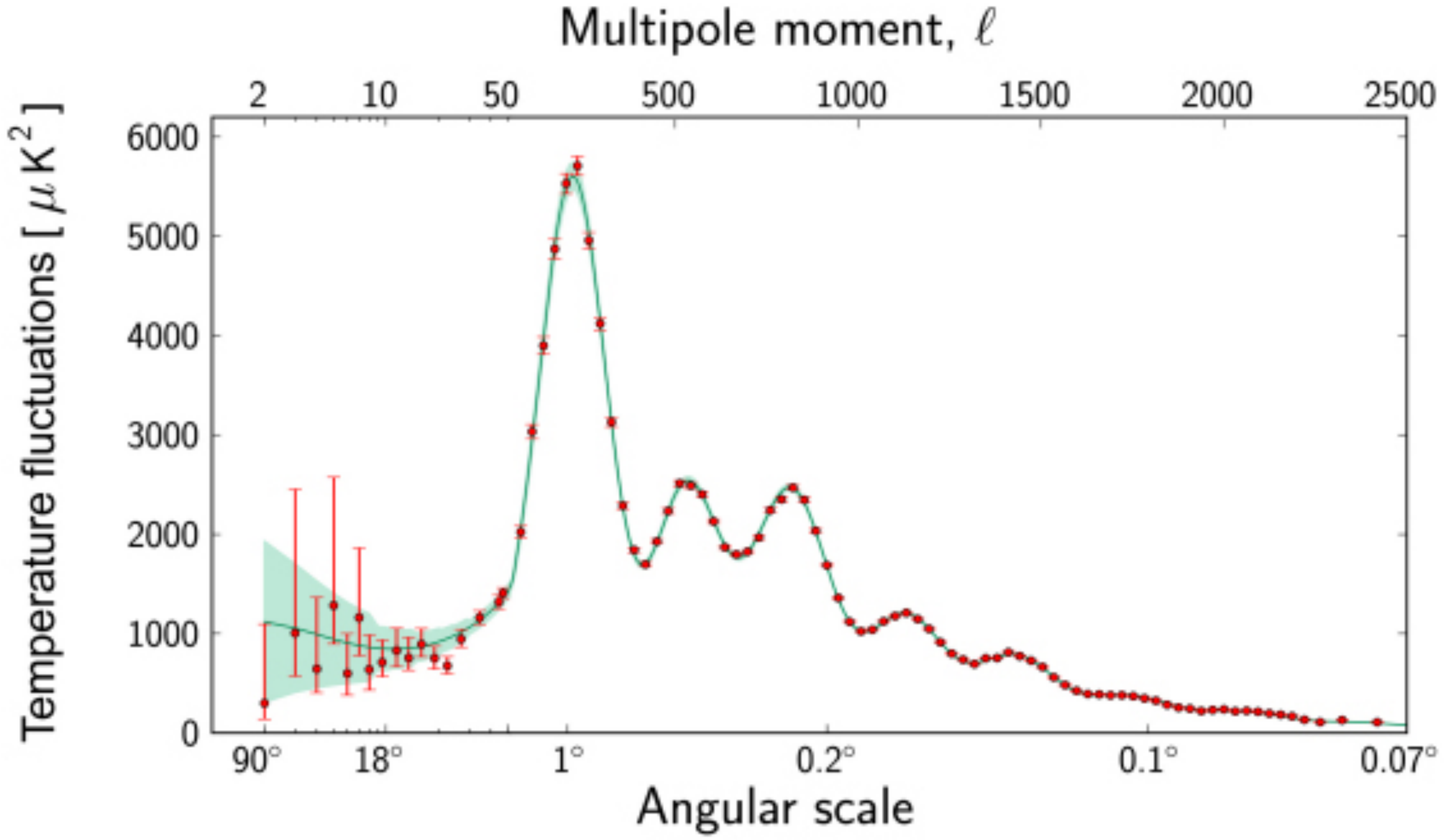

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