Physics Beyond the Standard Model (Exotics)

HASCO Summer School
Gottingen 28th July - 5th August 2024

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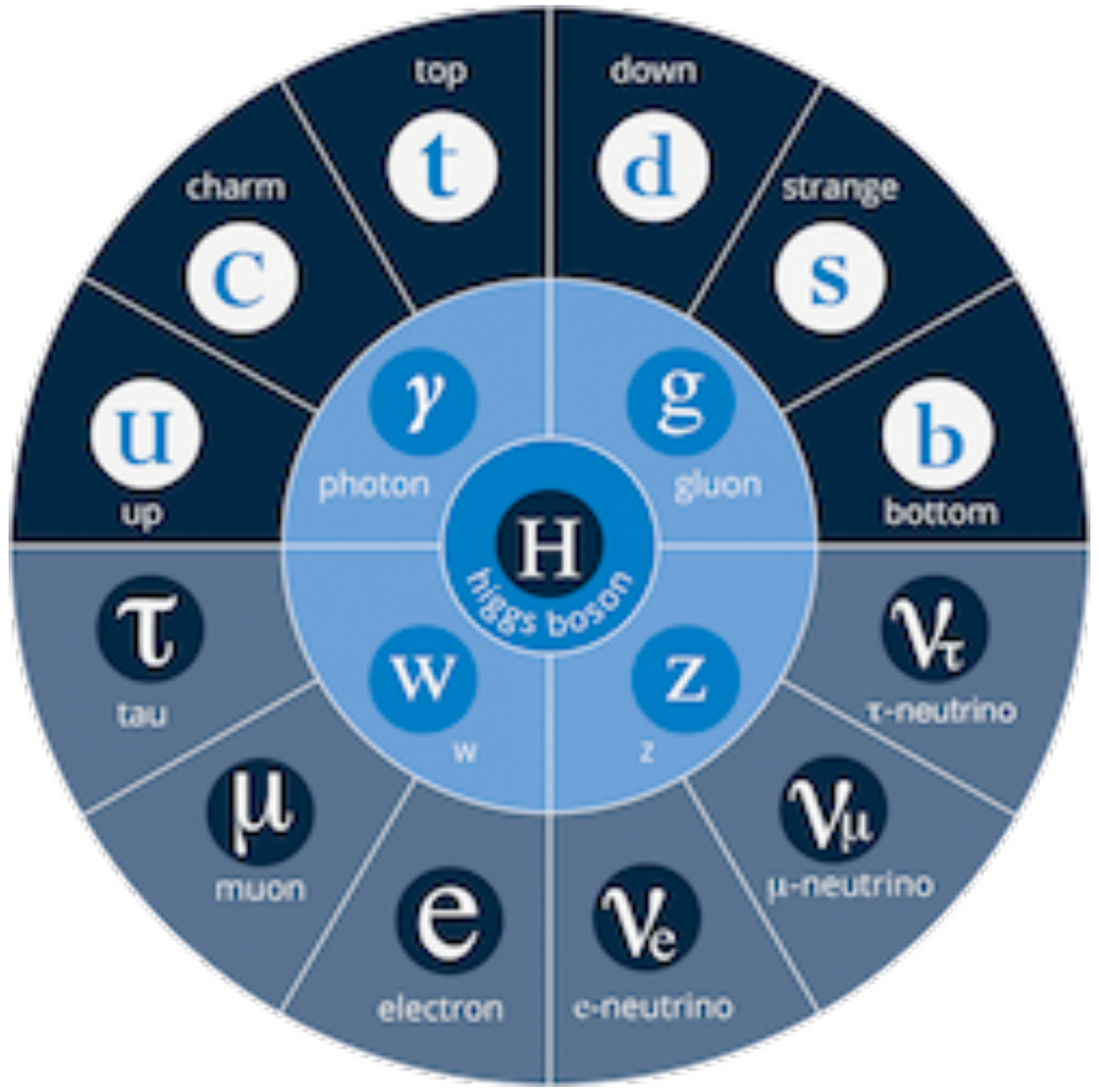
Outline of the lecture

- Intro to LHC and its detectors. (See Simone and Maxim lectures)
- High Energy Physics Experiment Strategies
- Motivation for non Standard Model analyses/searches.
    - The Standard Model (see Ulla's lecture) has some problems that could be solve by supersymmetry or Physics beyond the Standard Model (BSM - Exotics models).
- Organise an exotics search:
    - Overview of the exotics searches at ATLAS
- Outline of some analyses:
    - Lepton Jets and displaced jets
    - Di-jets resonance
    - Precision measurements



Caveat:

- very broad subject, impossible to cover all constantly changing
- personal bias unavoidable
- very diverse subjects come together here

stop me if you get lost!

Introduction to myself

Experimental particle physicist on the ATLAS experiment at the LHC since 2000. My research focuses on the physics of fundamental particles and their interactions.

I participated to the **detector construction and commissioning** of the ATLAS Muon Spectrometer, including the muon reconstruction and identification software development. Contribution to R&D studies for the Muon Spectrometer.

Main physics topics: Higgs into 4 leptons, Standard Model measurements as b-jets cross section and a_{tau} measurements with heavy ions, Exotics Searches as Hidden Valley models (Higgs decays into non Standard Model particles), Dark matter candidates (lepton jets), long-lived searches.

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Past experience:

@ CERN Fellow

@ University of Wuerzburg (Germany)

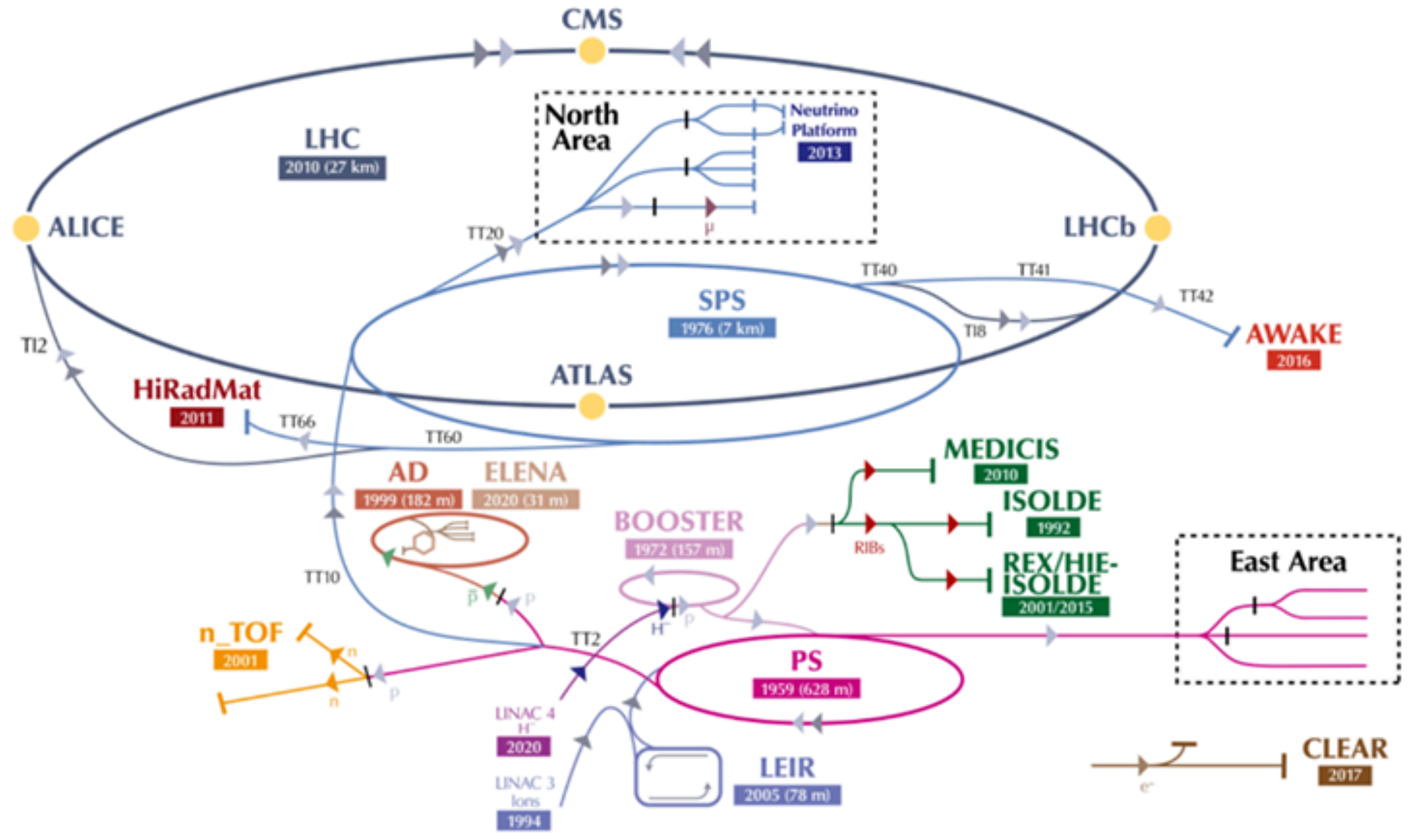
@ University of Washington (USA)

@ University of La Sapienza Roma (Italy)

@ University of Roma III (Italy)

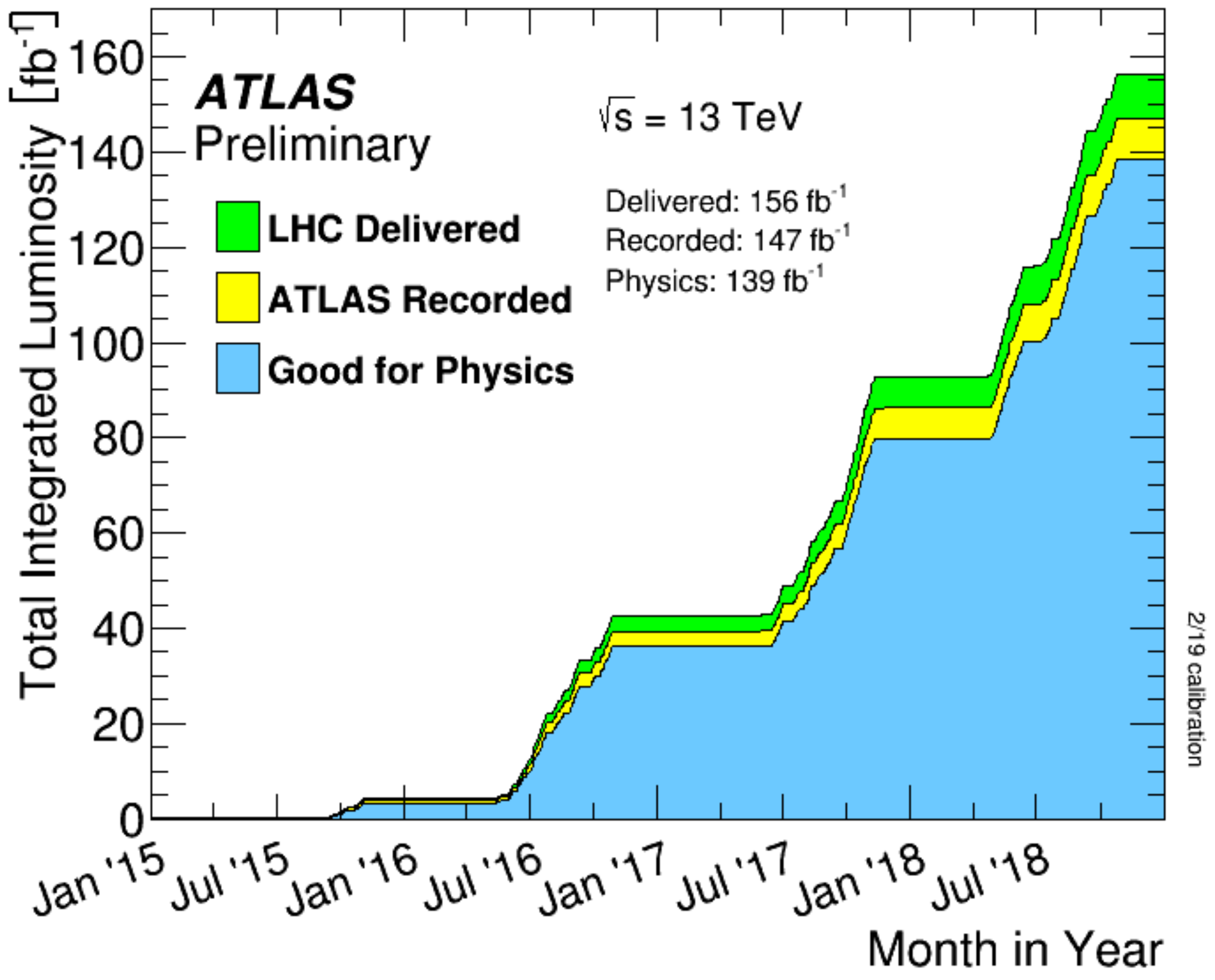
I will definitely give an experimental point of view to the subjects of this course.
The theoretic aspects will be covered in a qualitative way.
ATLAS Point view!

LHC Operation and HEP Experiments



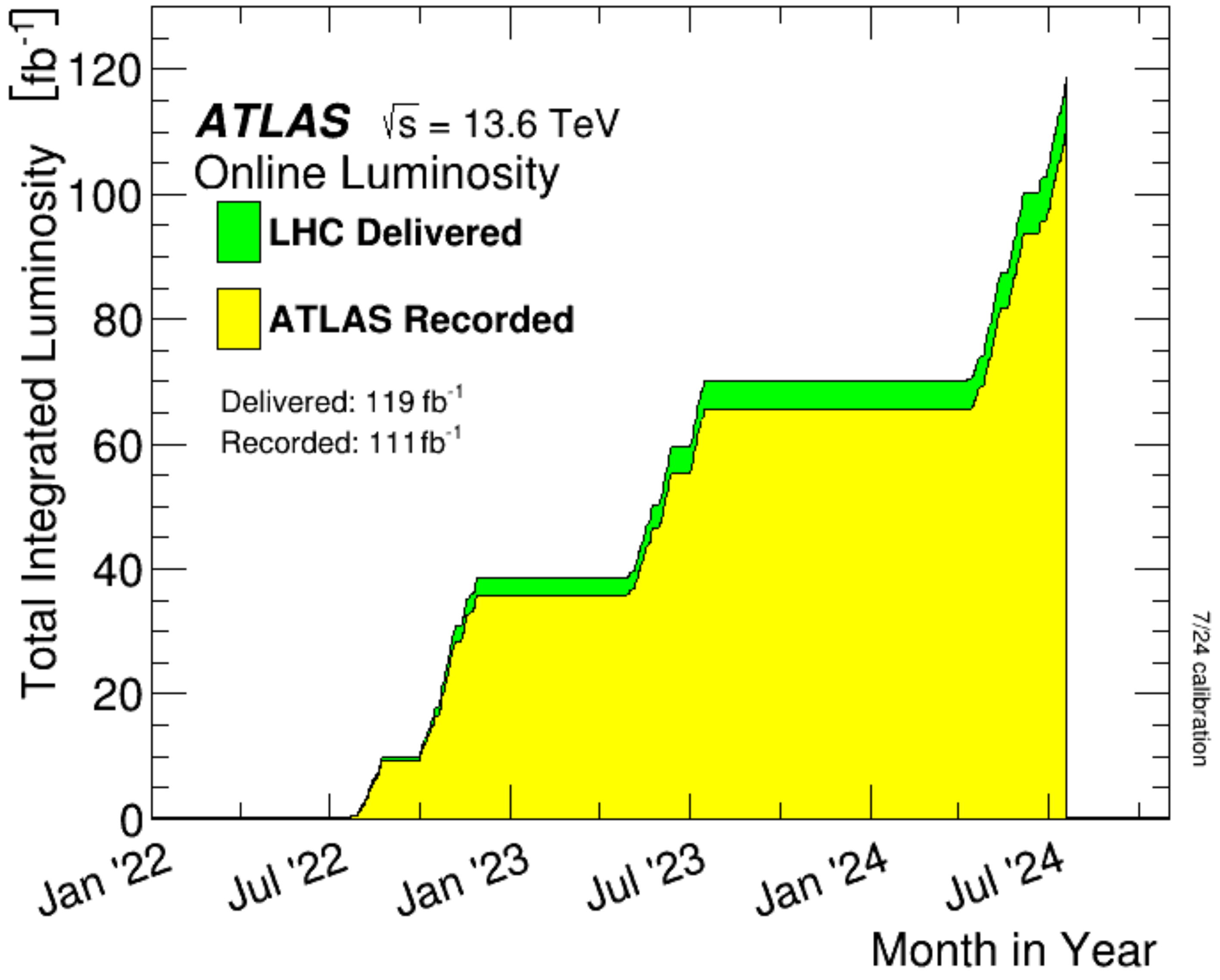
LHC Operation

- pp Run-2 was finished on 24/10/2018 6:00 am
- ATLAS @ Full Run-2 recorded 139 fb^{-1} (year 2015-2018), 13 TeV CM energy (ATLAS @ 2015-2016 about 36 fb^{-1})
- Run-1 2010-2012 at 7/8 TeV CM energy. Collected ~ 25 fb^{-1}

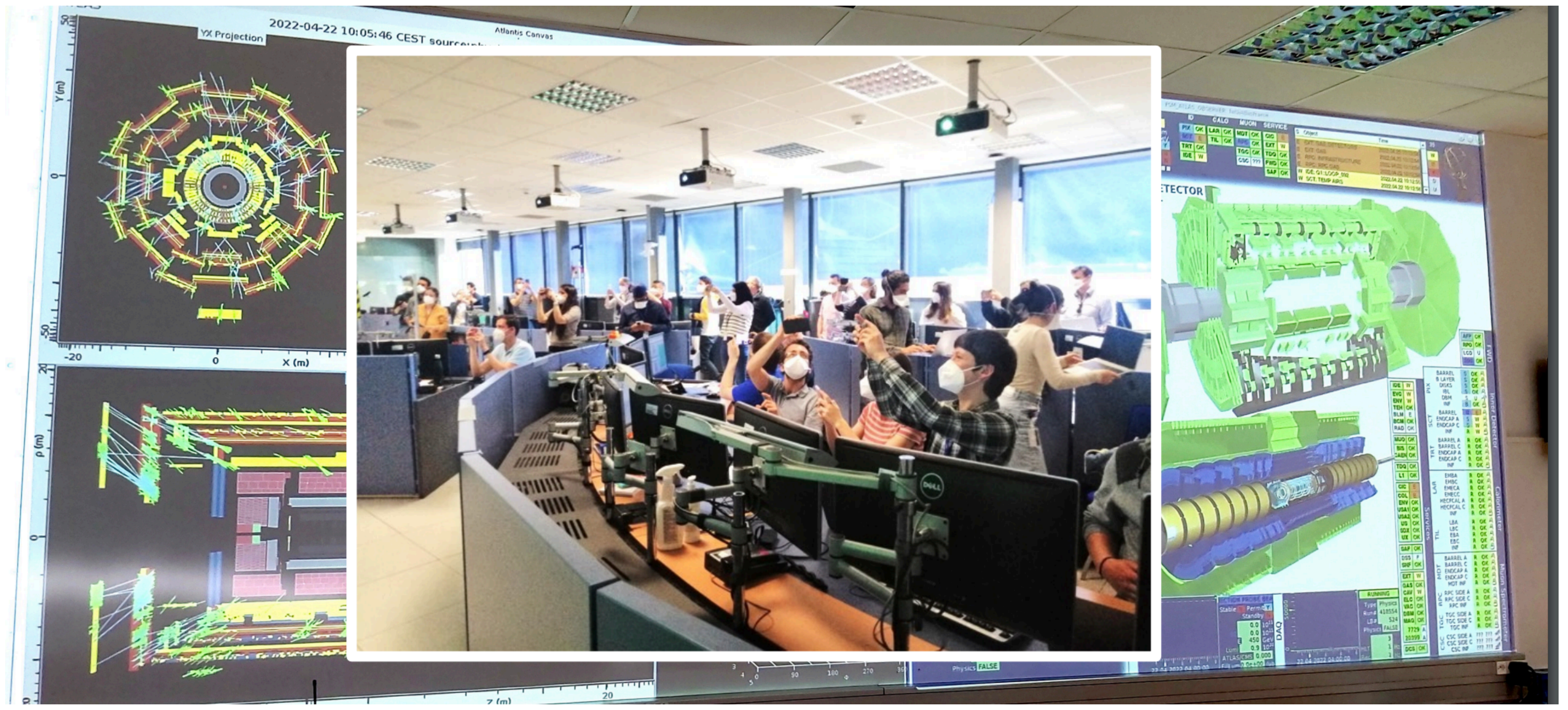


Both LHC and the detectors performed extremely well in Run-2.

- Maintained ~94% data-taking and data-quality efficiency despite harsh pileup conditions.



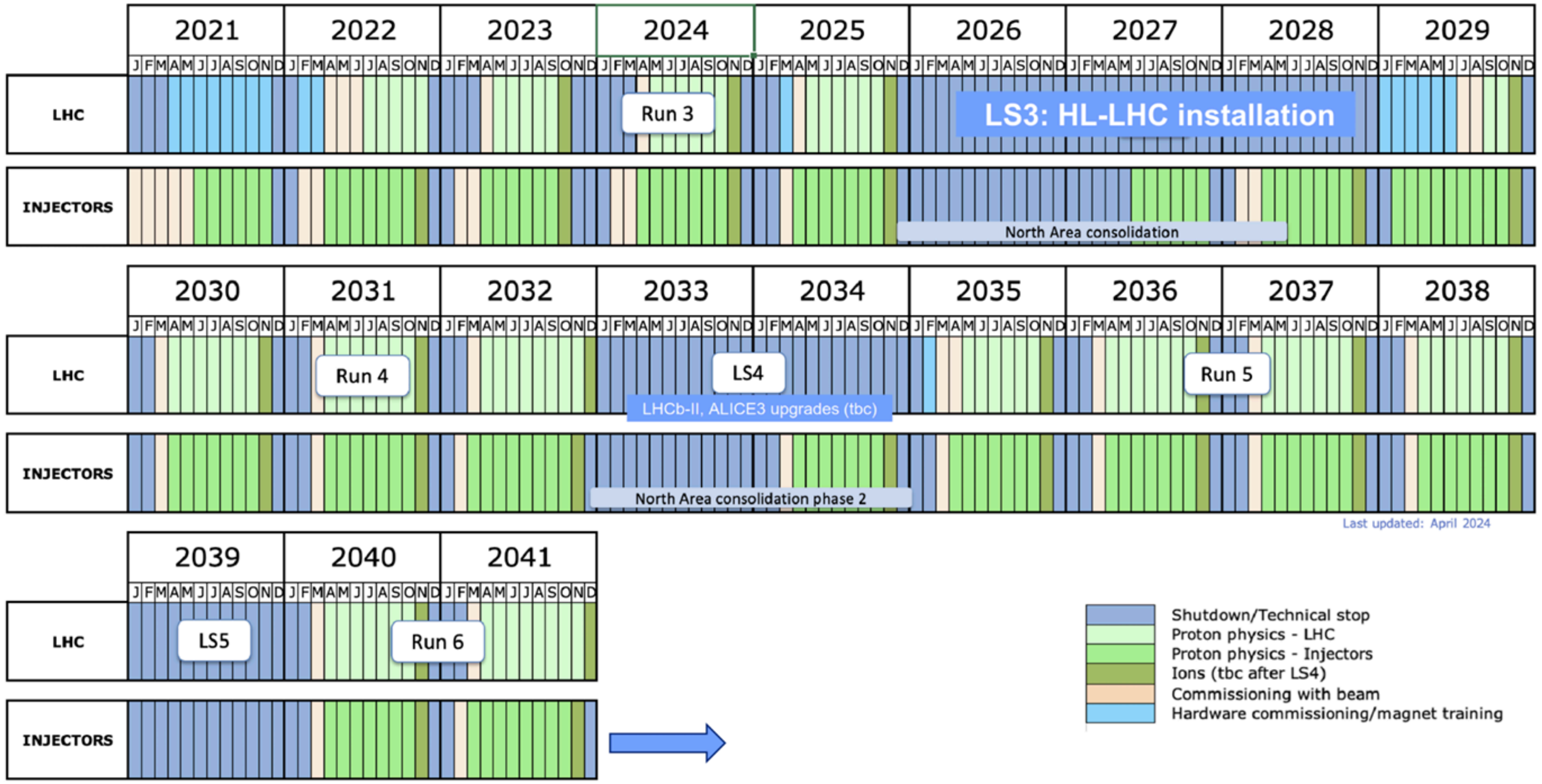
Run-3 started on the 5th of July 2022

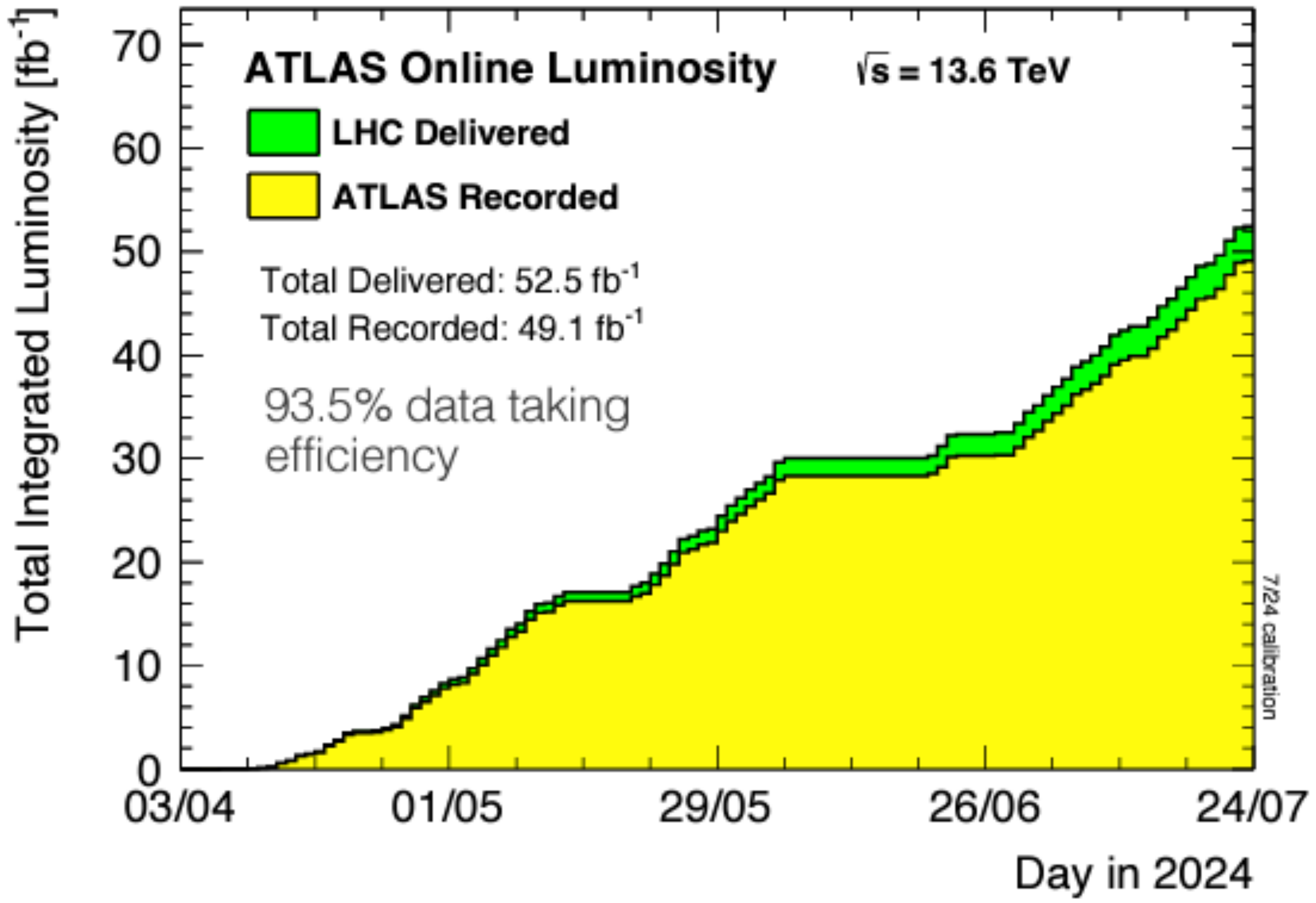


Run-3: Total recorded (delivered) integrated luminosity: 114 (123) fb^{-1}

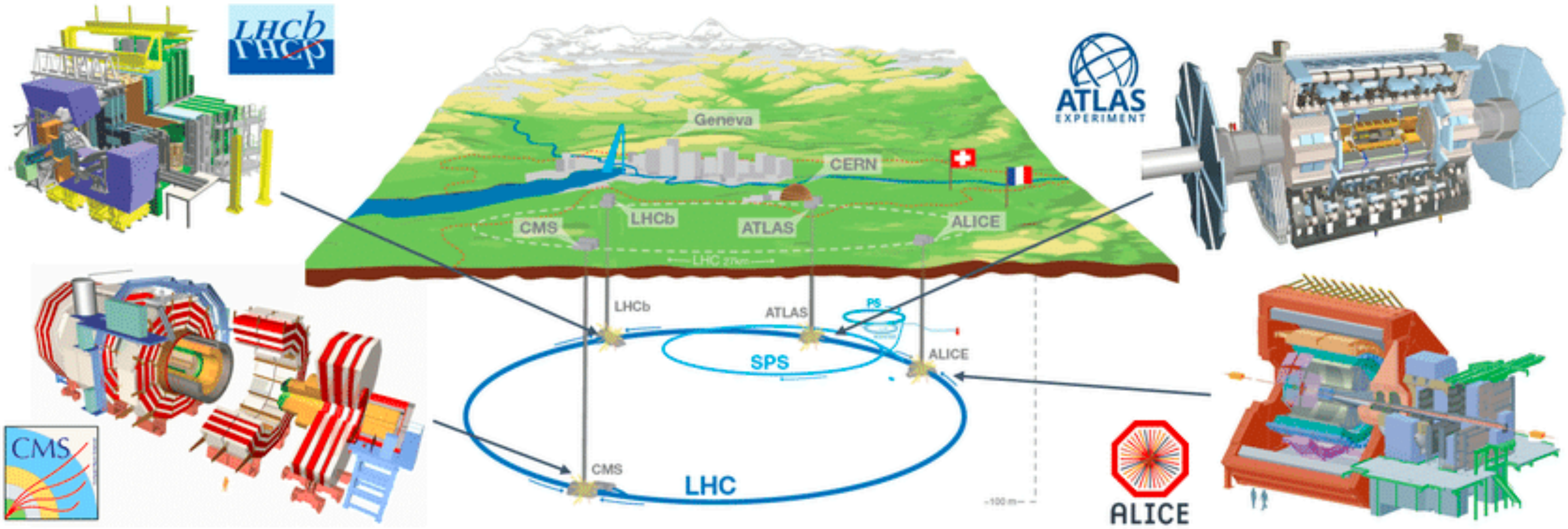
After HL-LHC: will be installed in Long Shutdown 3.

- In 2029 the HL-LHC will begin operations.
- Three Runs are planned of 4, 4 and 2 years respectively.

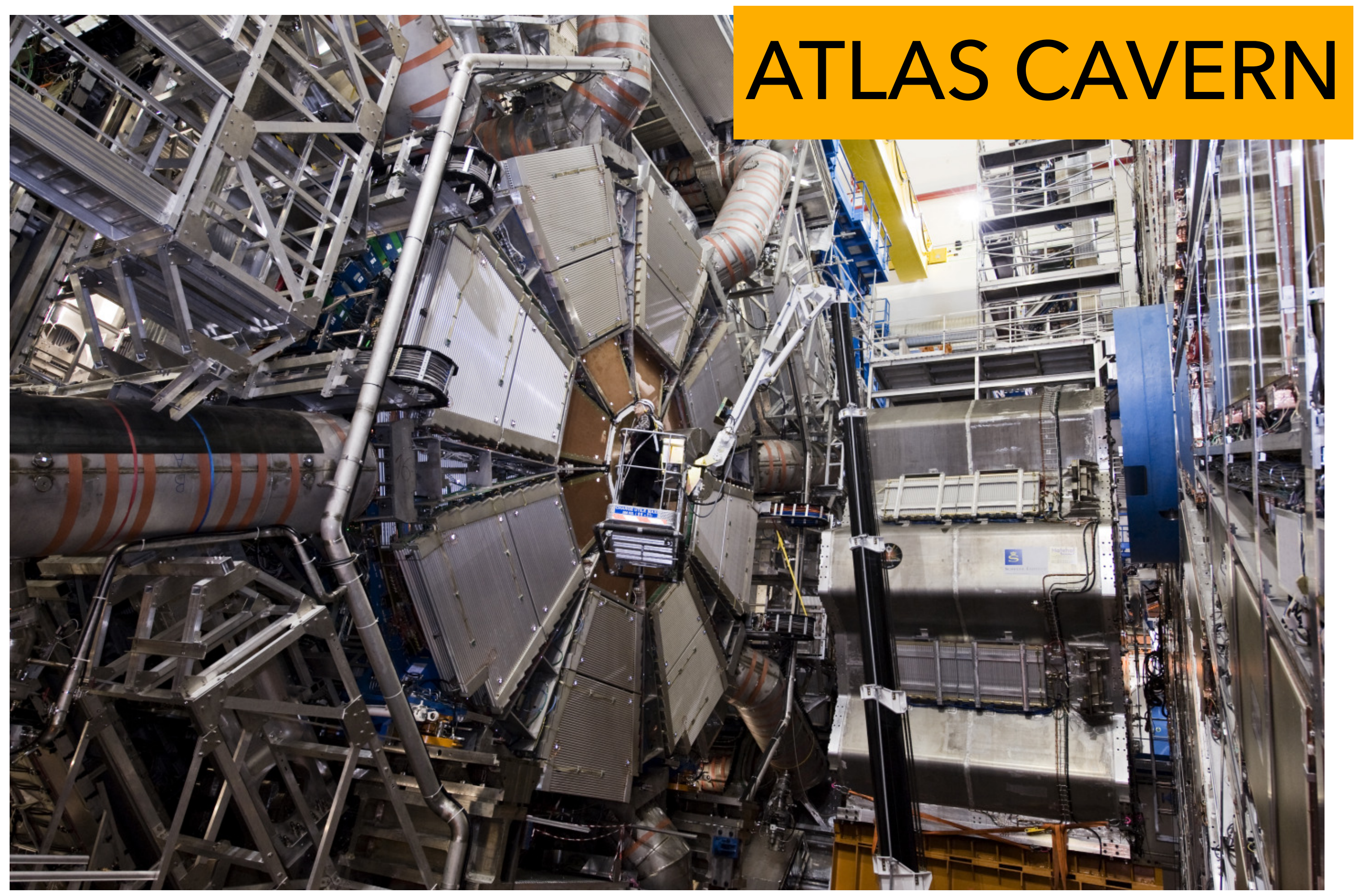




Experiments @ LHC




ATLAS CONTROL ROOM


ATLAS CAVERN

Luminosity

Rate $= \sigma L$

Number of Events $= \sigma L_{int}$

- σ – cross-section
  - units of barn $= 10^{-24}$ cm^2
    probability for a physics interaction
- L – luminosity
  - measure of density of colliding particles

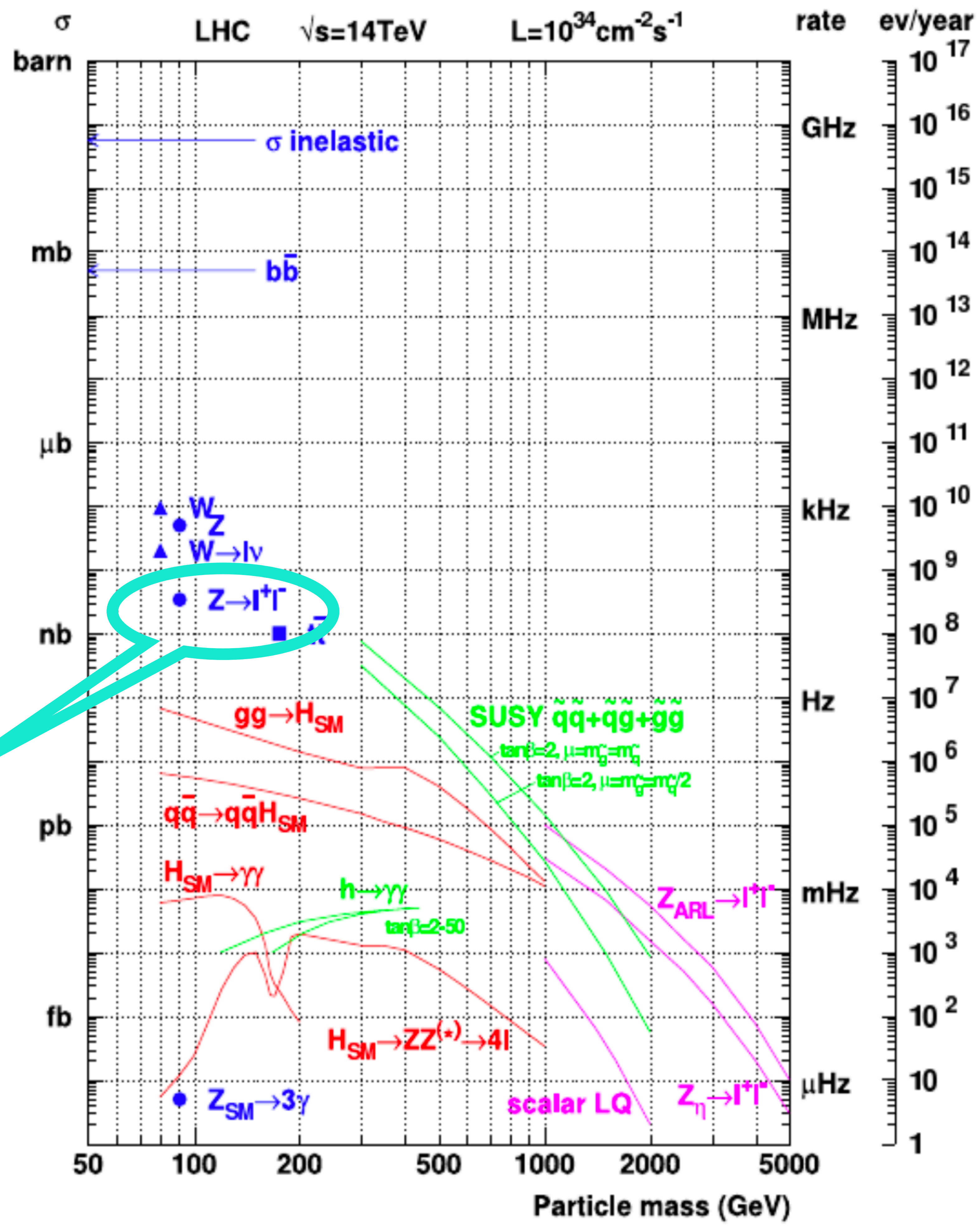
$$L = \frac{f N_1 N_2}{4\pi\sigma_x\sigma_y}$$

$\sigma = 3$ nb

$L = 10^{34}$ cm^{-2} s^{-1}

Rate $= \sigma L$

Rate $= 30$ Hz



The **integrated luminosity** (L_{int}), which is the integral of the luminosity with respect to time:

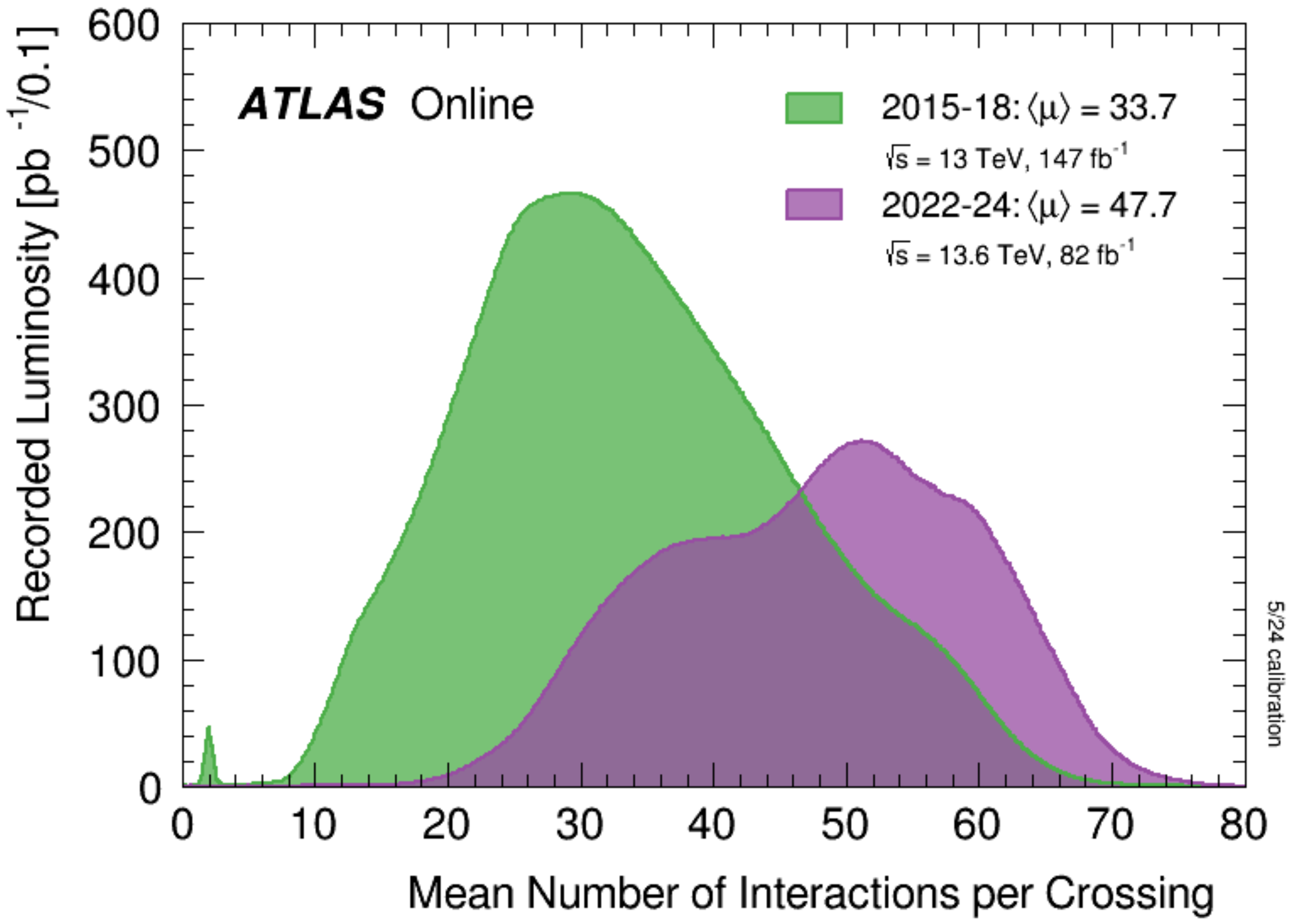
$$L_{\mathrm{int}} = \int L \, dt. \qquad L = \frac{1}{\sigma}\frac{dN}{dt}$$

$$\mathcal{L} = \frac{N^2 n_b f \gamma}{4\pi\epsilon_n\beta^*}F$$

- N is the number of protons per bunch.
- n_b is the number of bunches
- f is the revolution frequency of the LHC (11.245 kHz)
- γ is relativistic Lorentz factor
- ϵ_n is the *normalized emittance*
- β^* is the beta function at the interaction point
- F is the geometrical factor encoding the overlap between the beams

Luminosity vs Pile-up

- Every collision produces up to 80 interactions. Extremely challenging environment to identify and reconstruct the interesting event!
  - Mean Number of Interactions depends on the luminosity of the machine LHC.
- **Number of interactions per crossing calculated for each colliding bunch pair.**
  - $\mu = L_{bunch}\, \sigma_{inel}$ / frequency
  - where L_{bunch} is the per bunch instantaneous luminosity, σ_{inel} is the inelastic cross section which we take to be 80 mb for both 13 TeV and 13.6 TeV collisions, and frequency is the LHC revolution frequency.

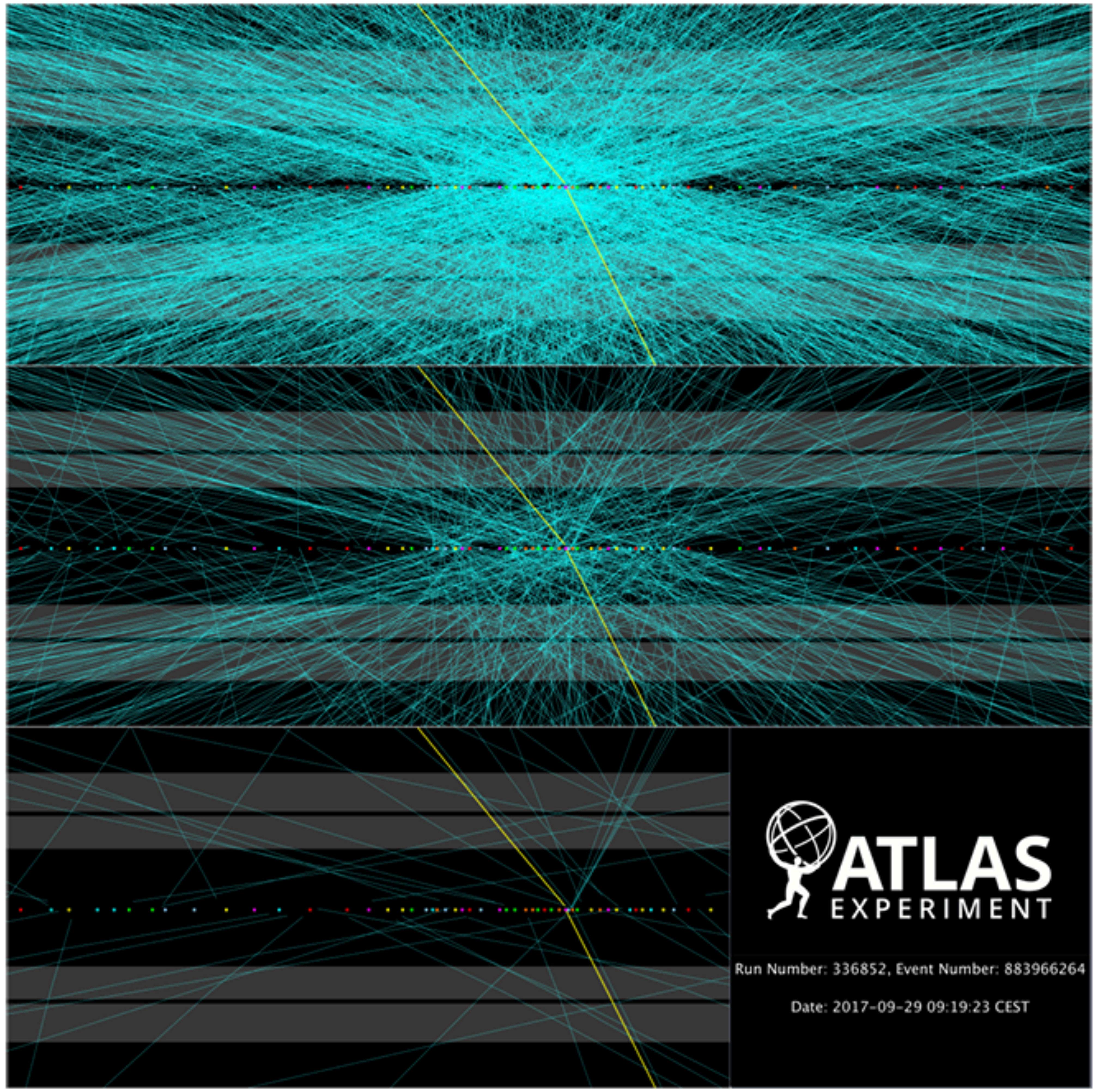


Pile Up Challenge vs Luminosity

Track p_T > 100 MeV

Track p_T > 1 GeV

Track p_T > 5 GeV

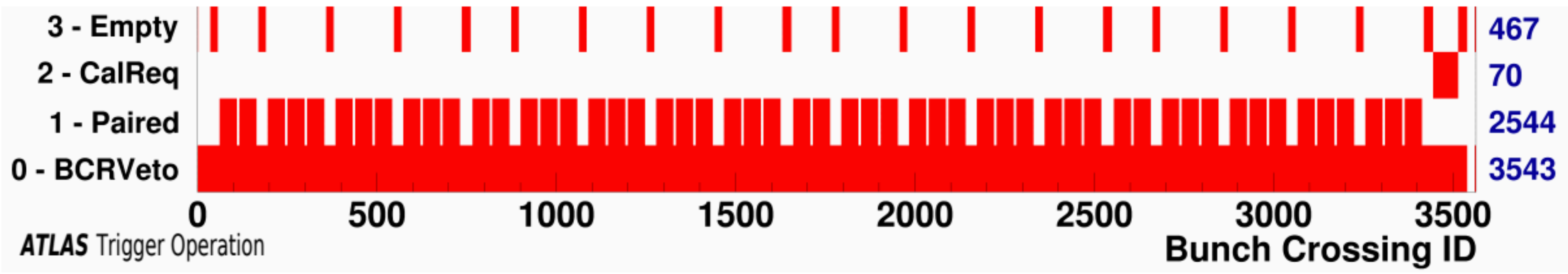


- Challenge with high pile up:
  - Example of a Z boson decays to 2 muons in an event with 65 additional pile-up collisions.

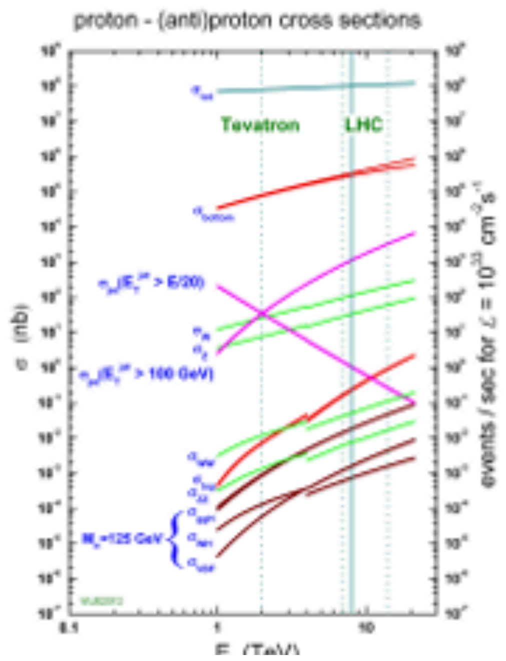
Trigger Selection: Online selection

ATLAS Lectures

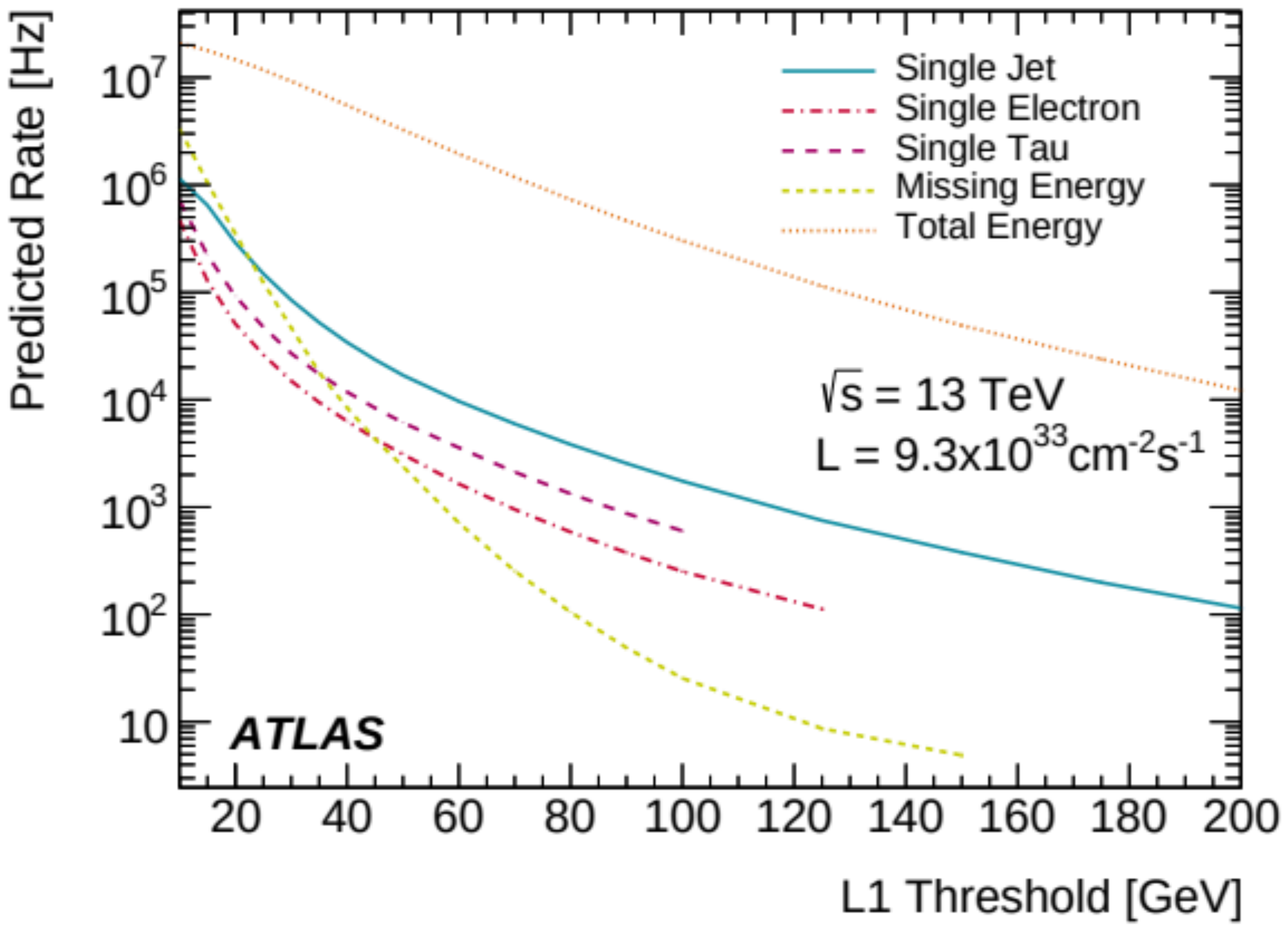
The protons are contained in BUNCH, each bunch have 10^{11} protons for 25 ns of time width. On average we have 3500 bunches per beam. They are not all filled!

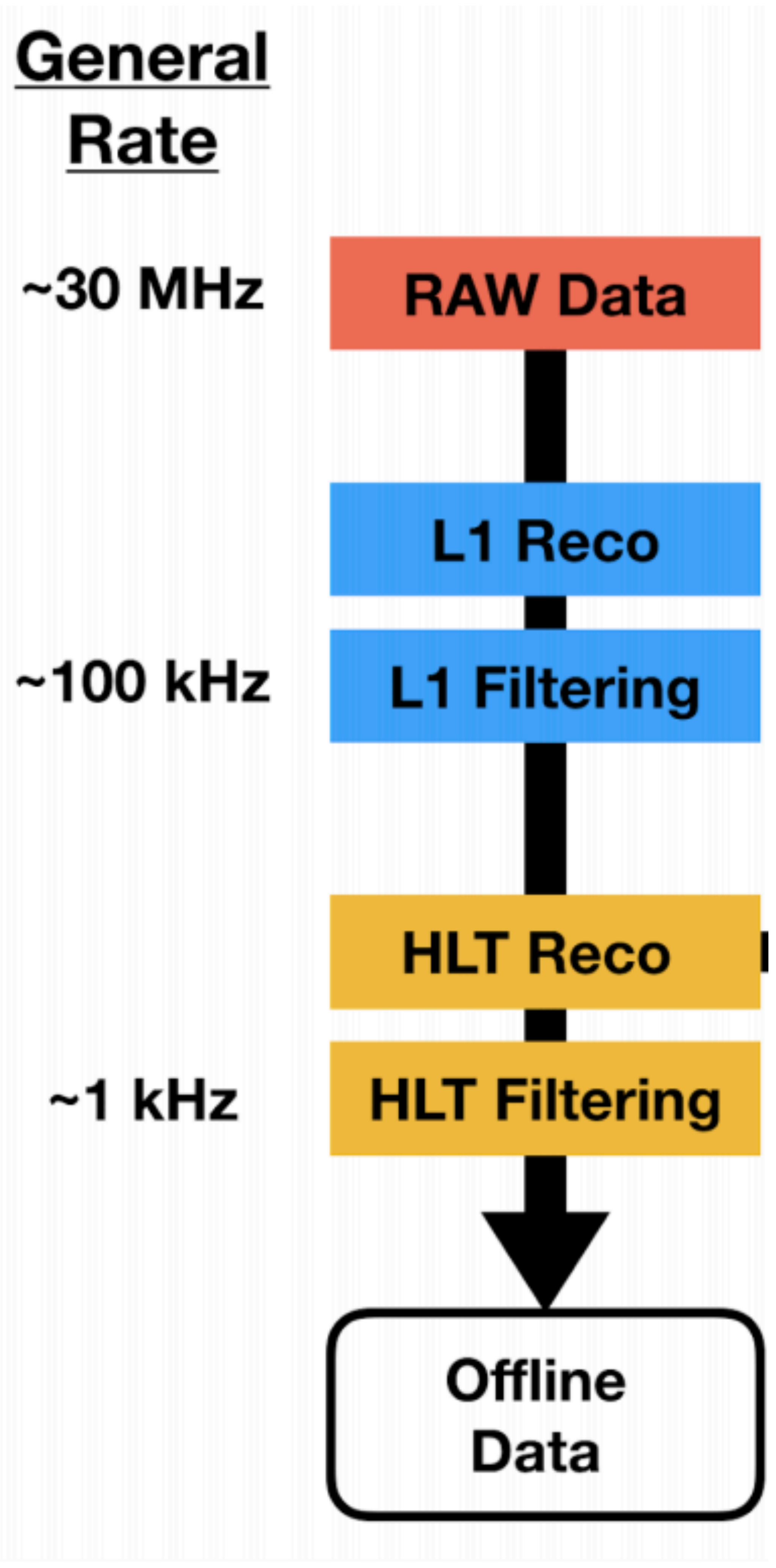


A **two-level trigger system** records data at an average rate of **1 kHz from physics collisions**, starting from an initial bunch crossing rate of 40 MHz.



Trigger system



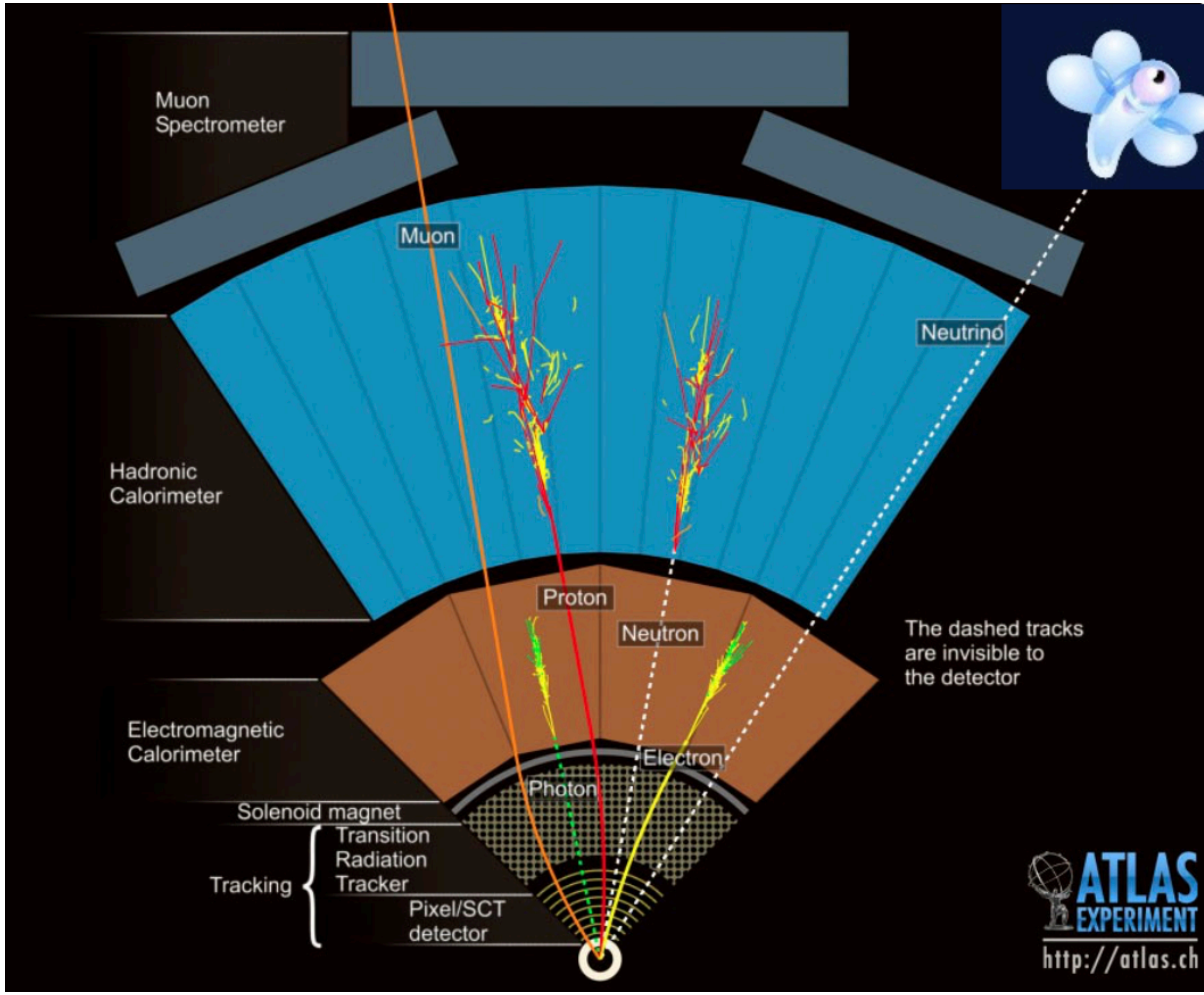


“Main” Stream

Design of High Energy Physics Experiments

HEP experiment usually consist of different detecting subsystems wrapped concentrically in layers around the collision point.

- The trajectory, momentum, and energy of particles are individually identified and measured.
- A huge magnet system bends the paths of the charged particles so that their momenta can be measured as precisely as possible.



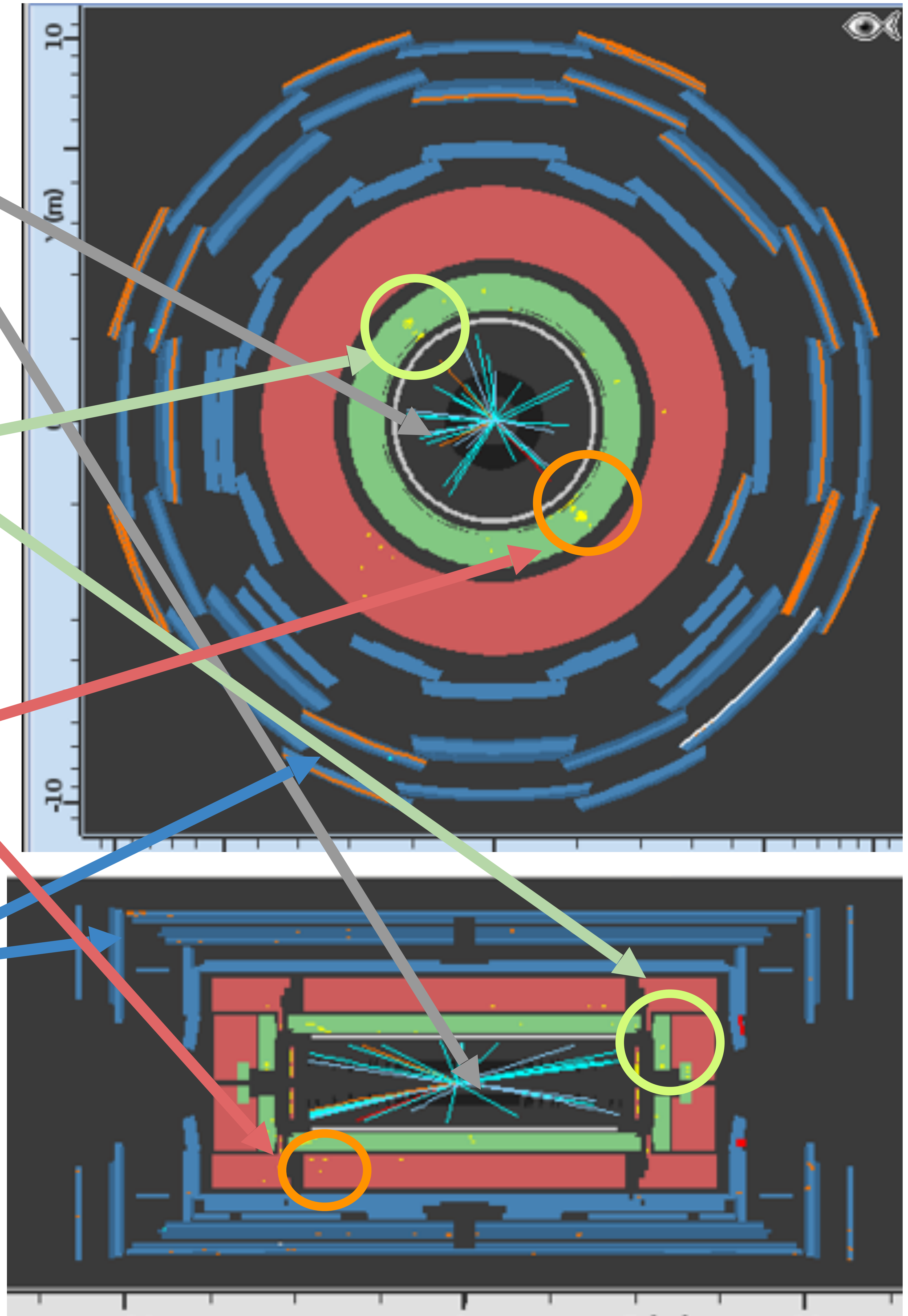
Particle Reconstruction

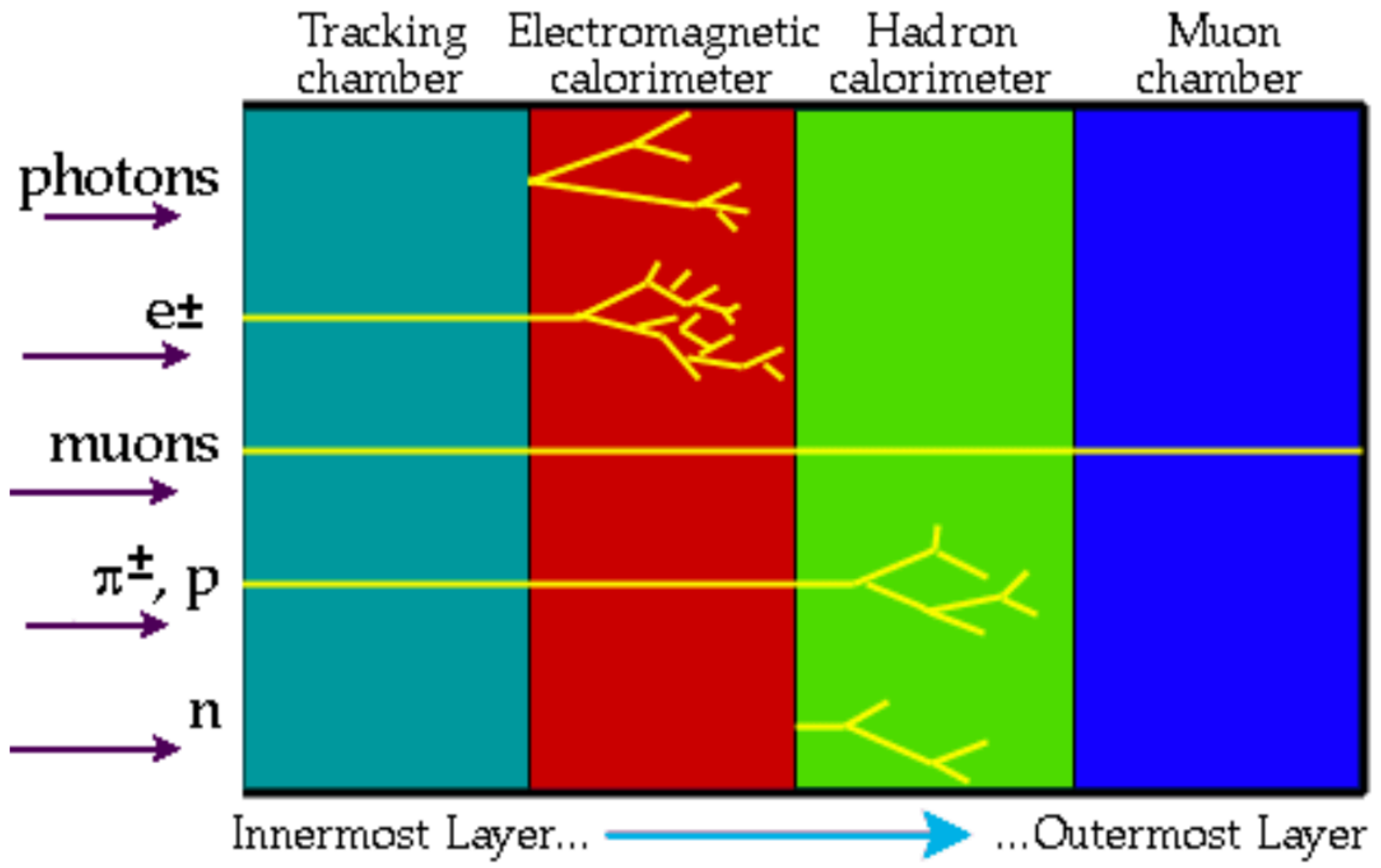
Tracking system:
Charged particles

Electromagnetic Calorimeter:
electrons (e-), positrons (e+)
and photons.

Hadronic Calorimeter:
hadrons (es: protons,
neutrons, pions…)

Muons Spectrometer





Neutrinos and any neutral light particle escapes from the detector with no signature.

Missing Energy in the event is a clue of the presence of these particles

Why Exotics Searches?

The Standard Model

The Standard Model (SM) describes the **elementary subatomic particles** of the universe which have been experimentally seen.

The SM includes the **electromagnetic, strong and weak forces** and all their carrier particles, and **explains well how these forces act on all of the matter particles.** The Higgs boson does not carry a force but instead gives the elementary particles mass.

Elementary Particles:

- quarks (u,c,t,d,s,b)
- leptons (e,mu,tau, neutrino)

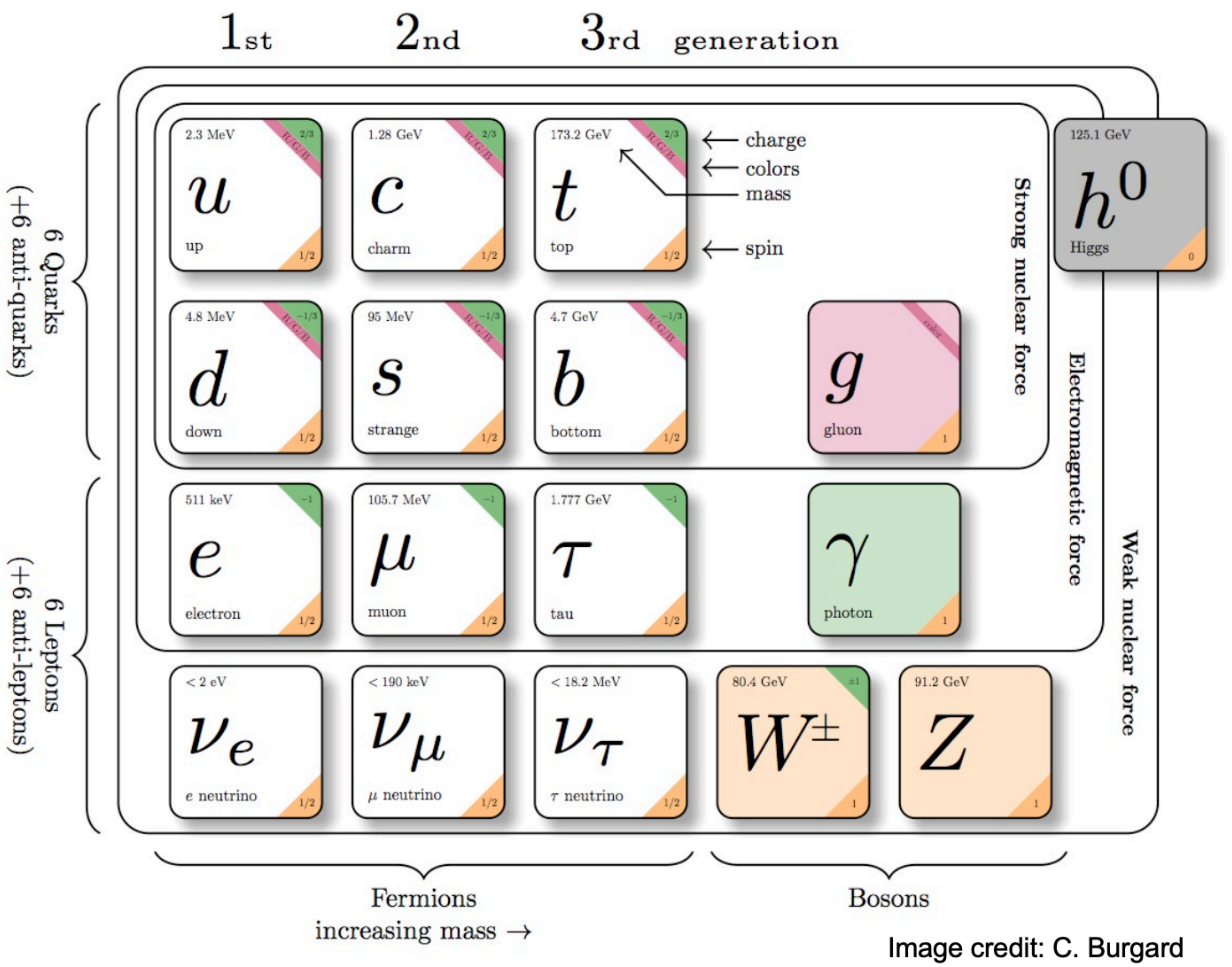


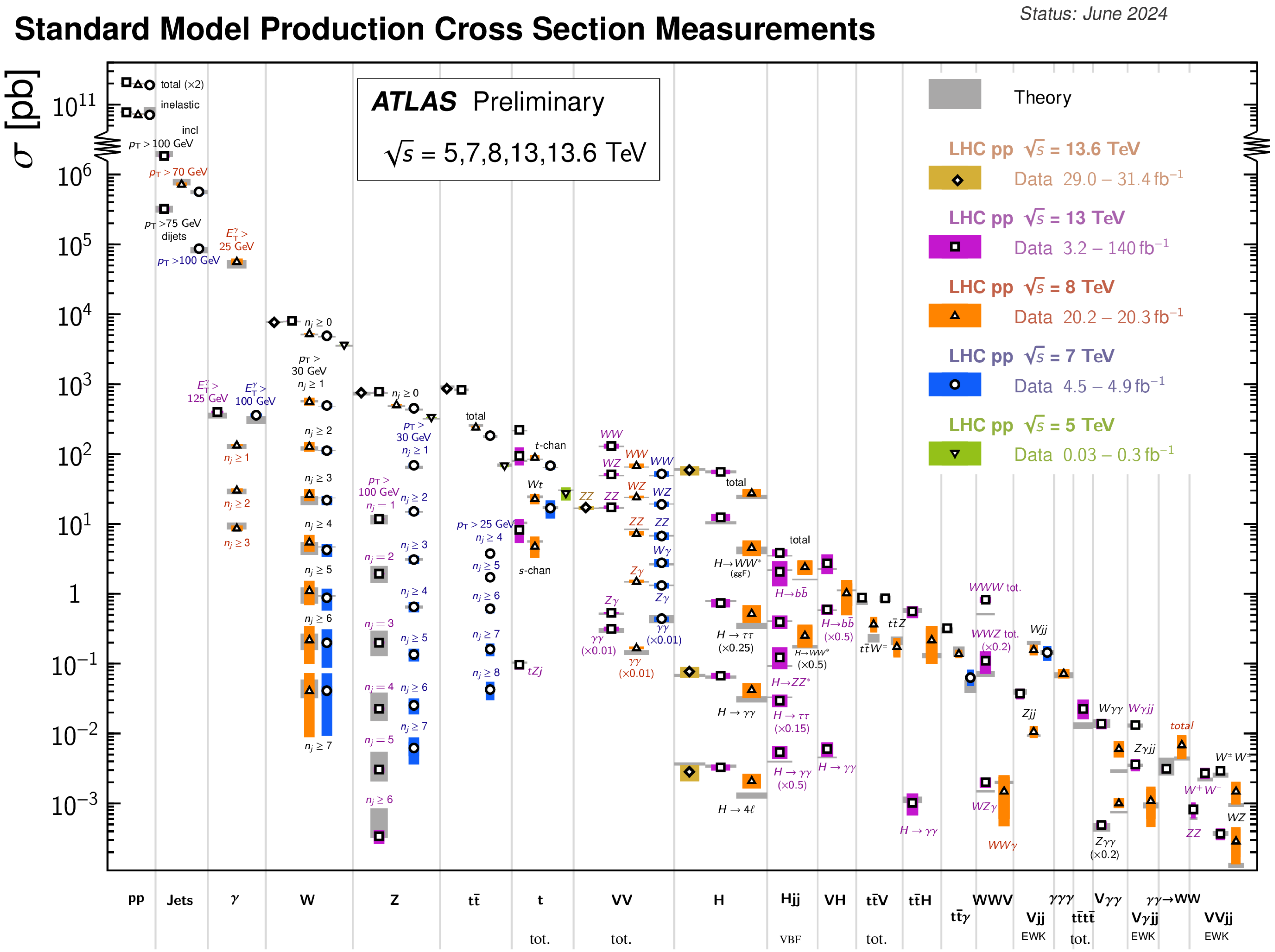
Image credit: C. Burgard

Fundamental forces

- Strong force
- Weak force
- Electromagnetic force
- Gravitation force non included!

The Standard Model success

The SM theory has successfully explained almost all experimental results and precisely predicted a wide variety of phenomena!



Why beyond SM?

The SM is currently the best description there is of the subatomic world, but it does not explain the complete picture! The theory incorporates only three out of the four fundamental forces, omitting gravity and doesn't not answer to some important questions.

Large difference in scales of forces (hierarchy problem)

Fine-tuning needed for Higgs mass

Neutrino masses

Free SM parameters

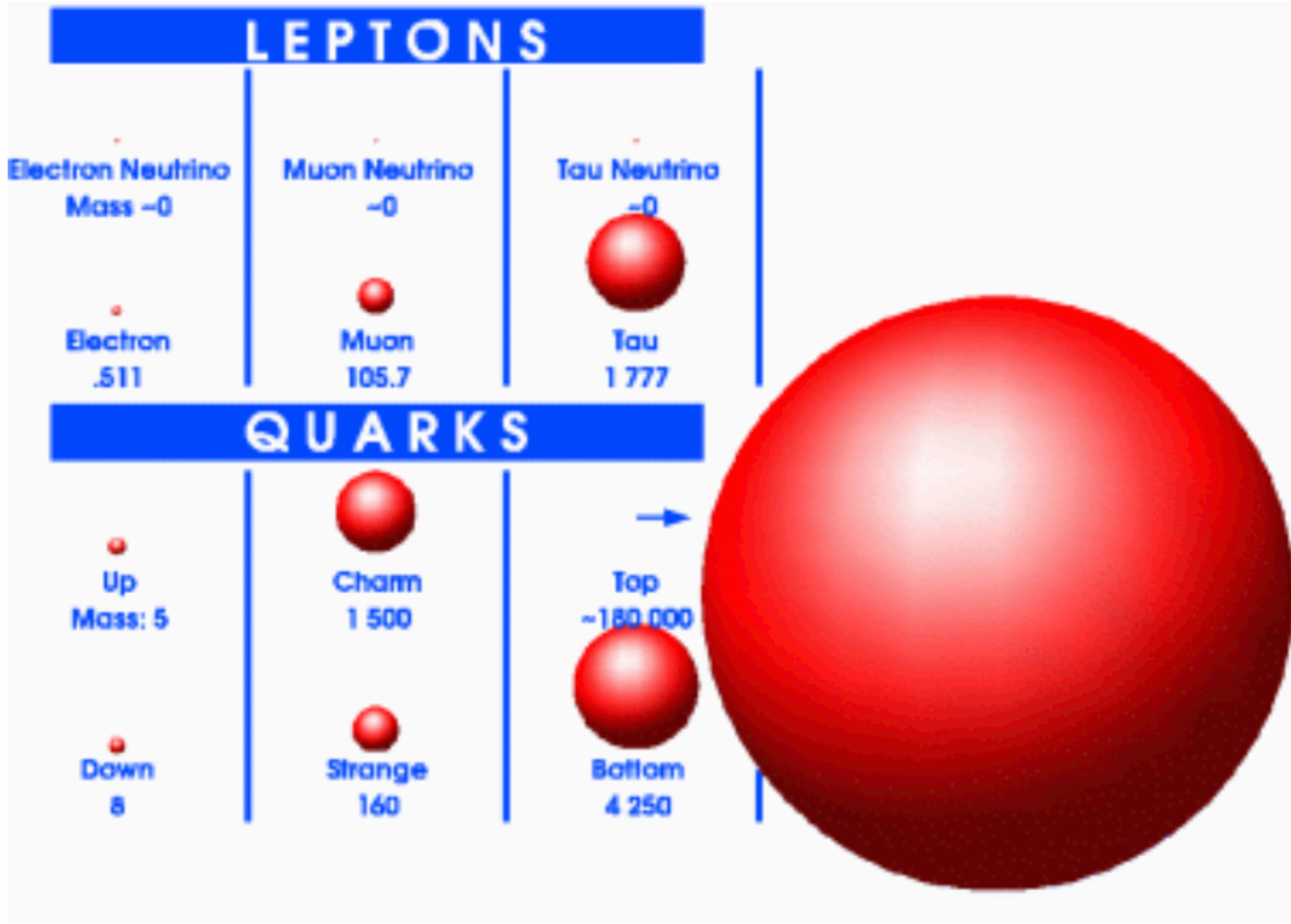
Dark matter (DM)
Dark energy
Matter vs antimatter

Gravitation force and its Weakness

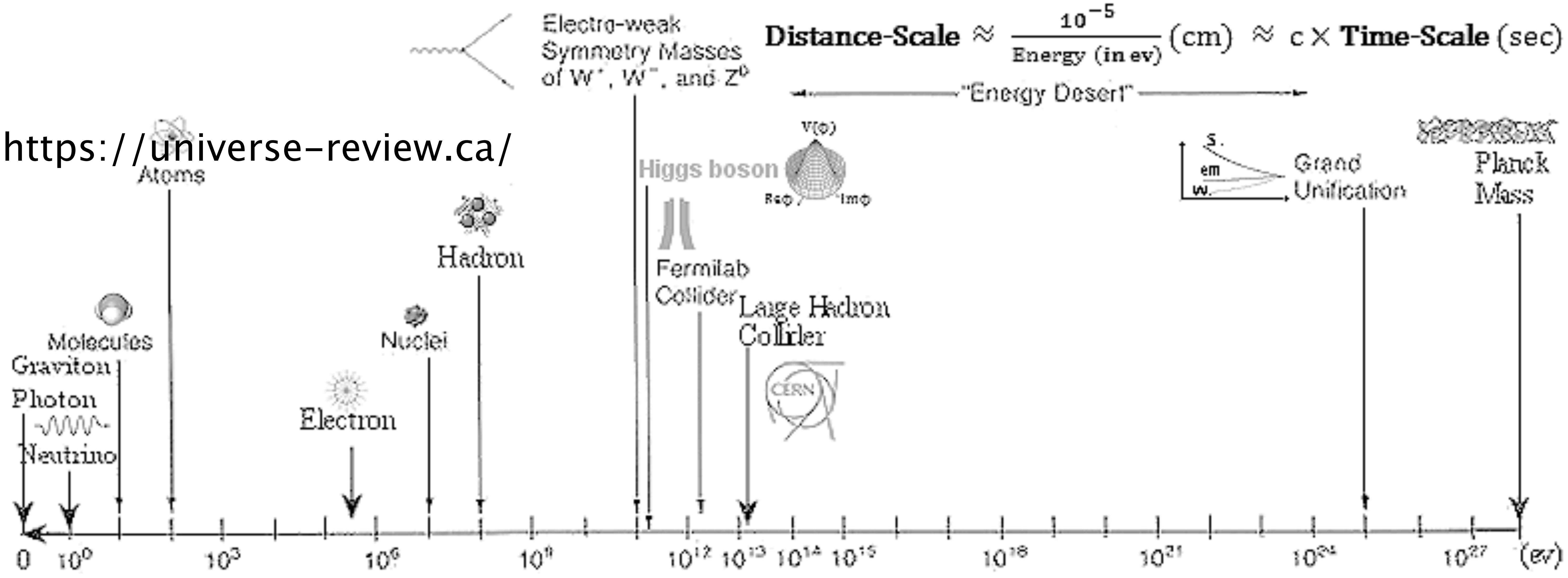
Hierarchy Problem

The hierarchy problem occurs because the fundamental parameters of the Standard Model don't reveal anything about the scales of energy.

The theorists have to put the particles and their masses into the theory by hand, so they had to construct the energy scales by hand.



https://universe-review.ca/

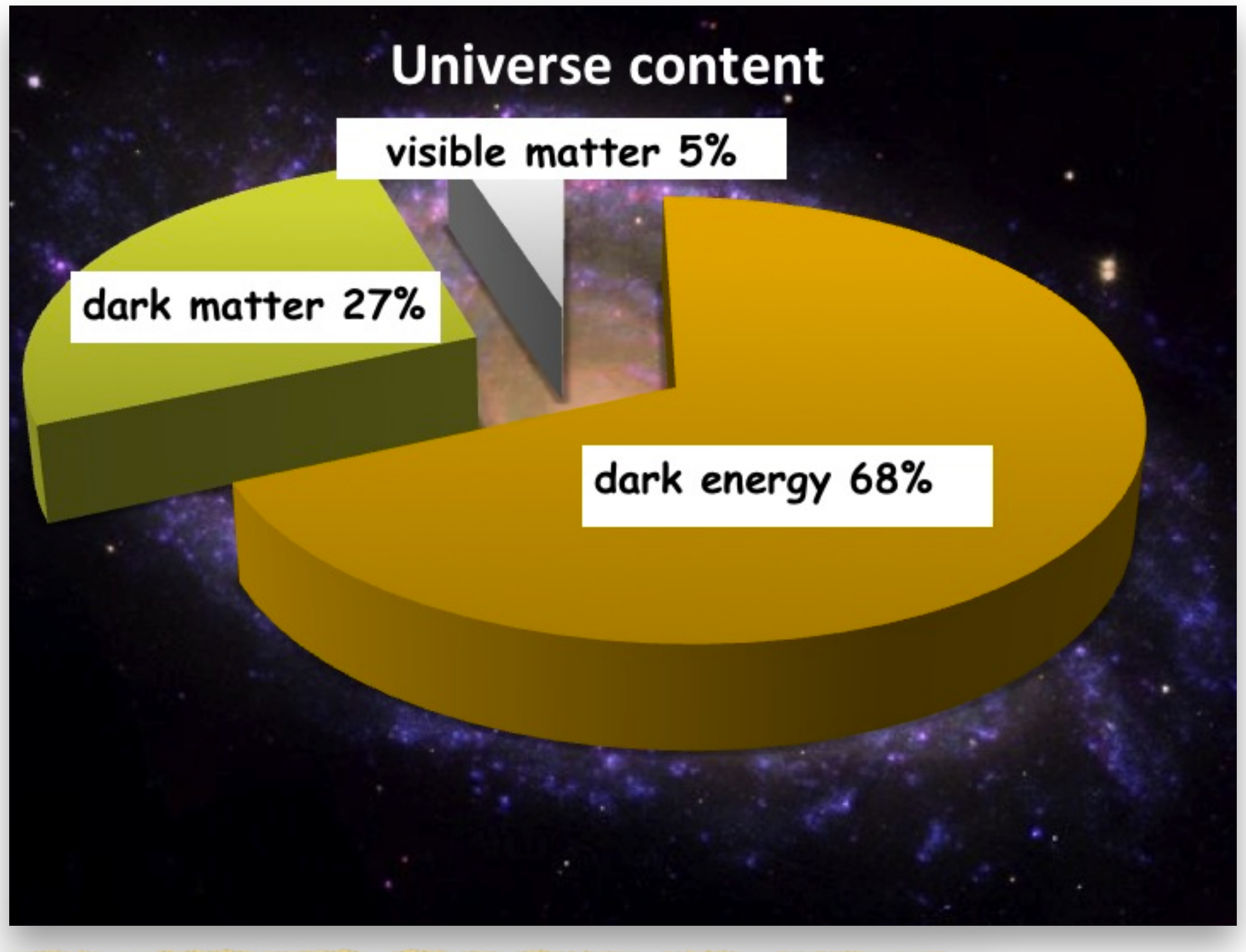


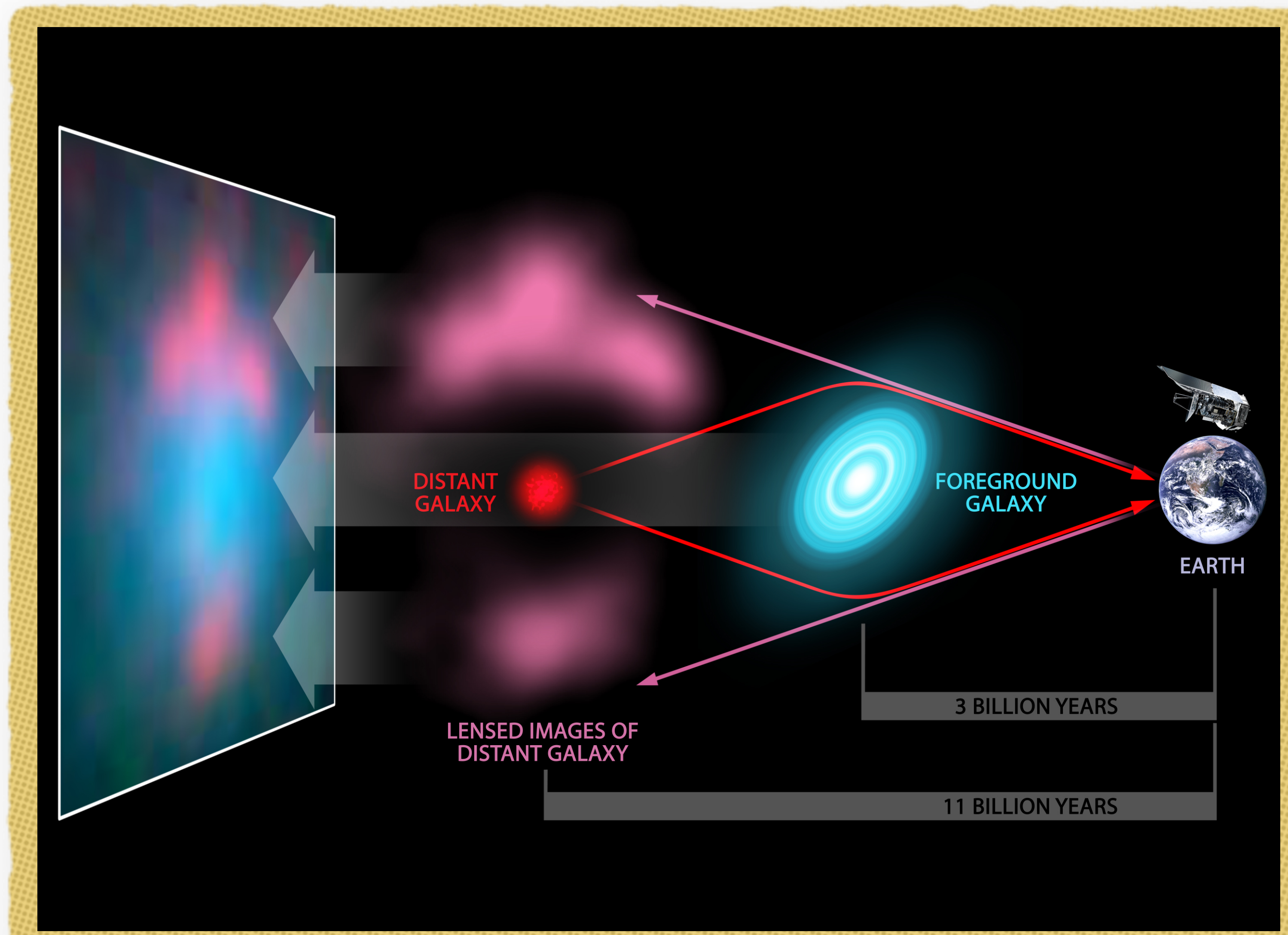
Need of a single theory that could be **applied at all scales**, without the need for renormalization (removing infinities), and understands the properties of nature and its rules **working for different scales**.

Dark Matter and Dark Energy

Visible matter makes up just 5 percent of the universe. The rest is dark matter DM—which makes up about 23 percent—and dark energy, a whole other story—which claims the remaining 72 percent.

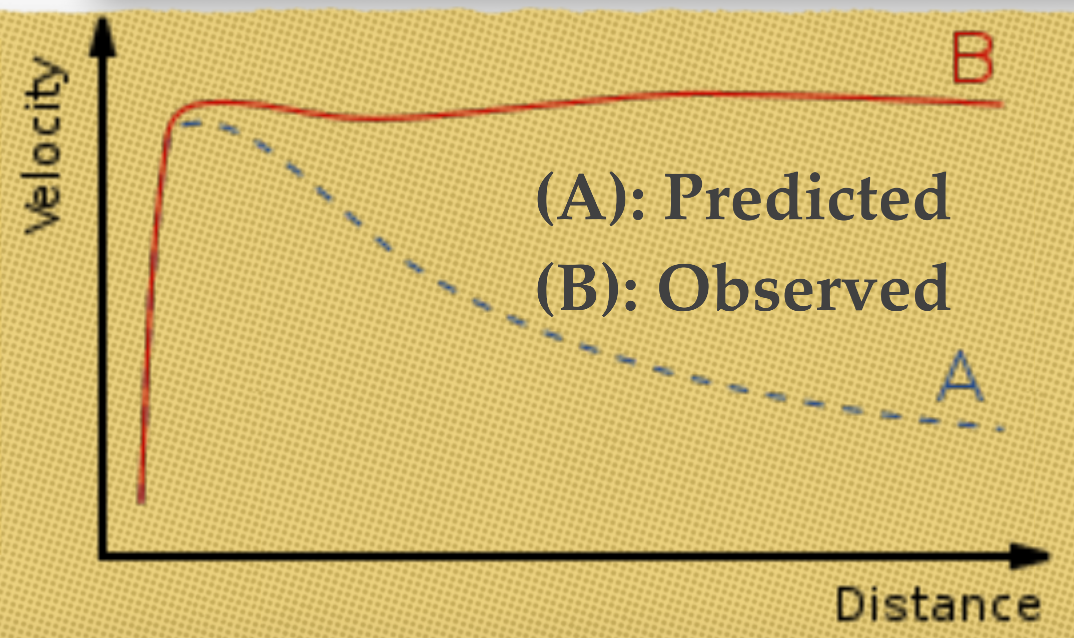
The existence of a non-baryonic component in the universe can be inferred by its gravitational interactions.

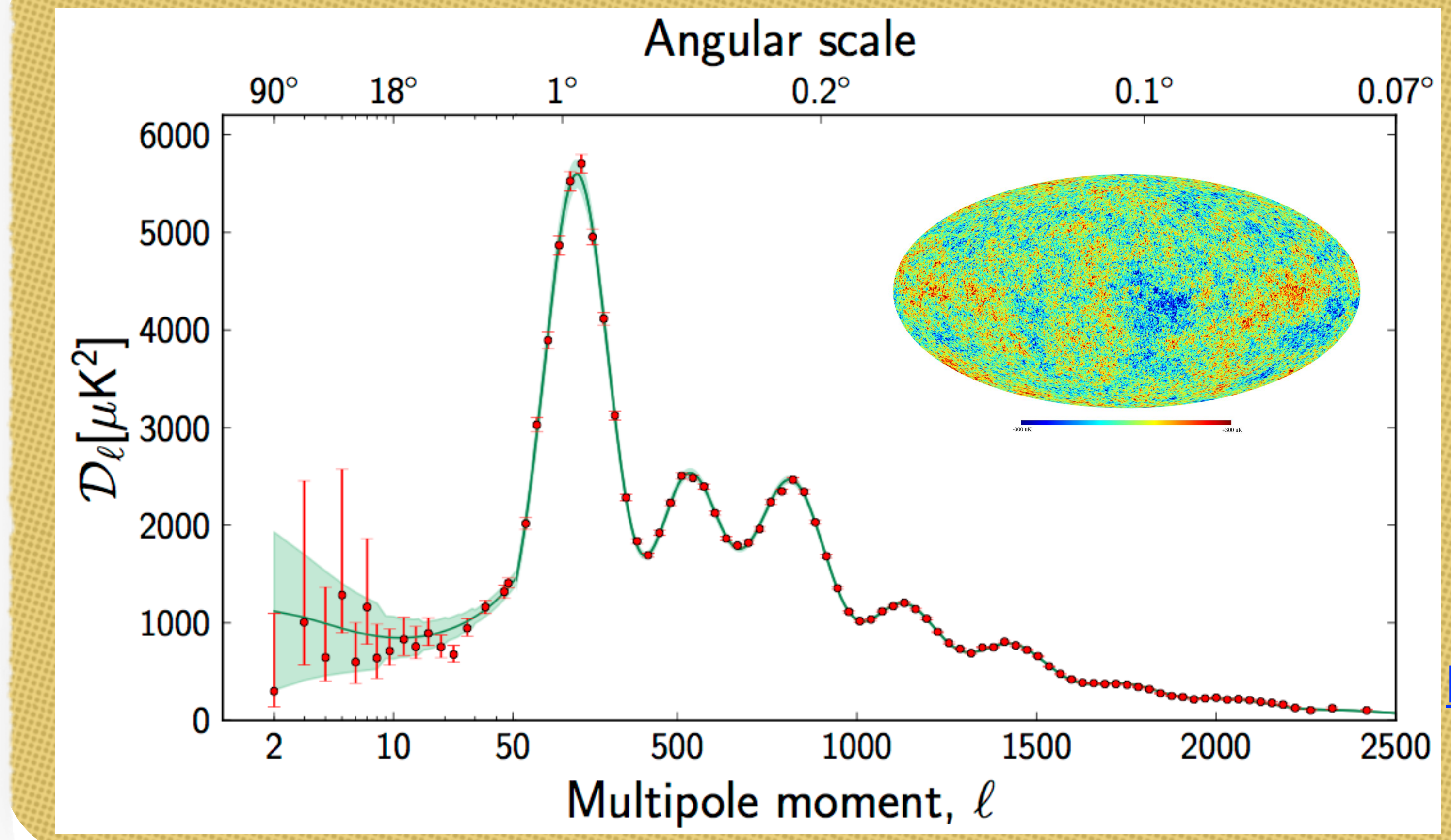




Visible mass not sufficient to explain observed lensing effect

Velocity found to be flat, consistent with ~10x as much "dark" mass for more than one galaxy



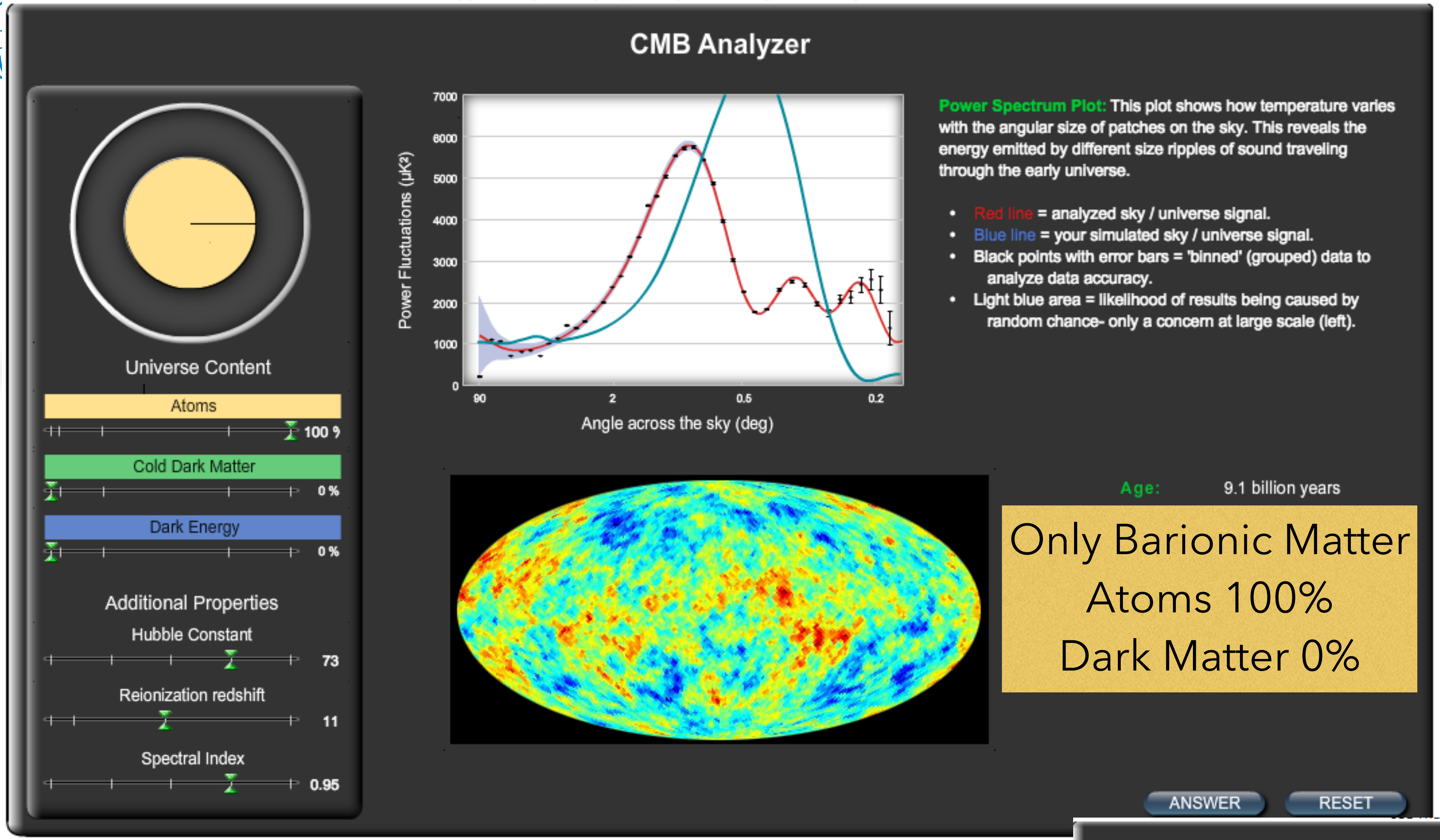


Baryonic matter alone can't produce the Cosmic Microwave Background CMB spectrum

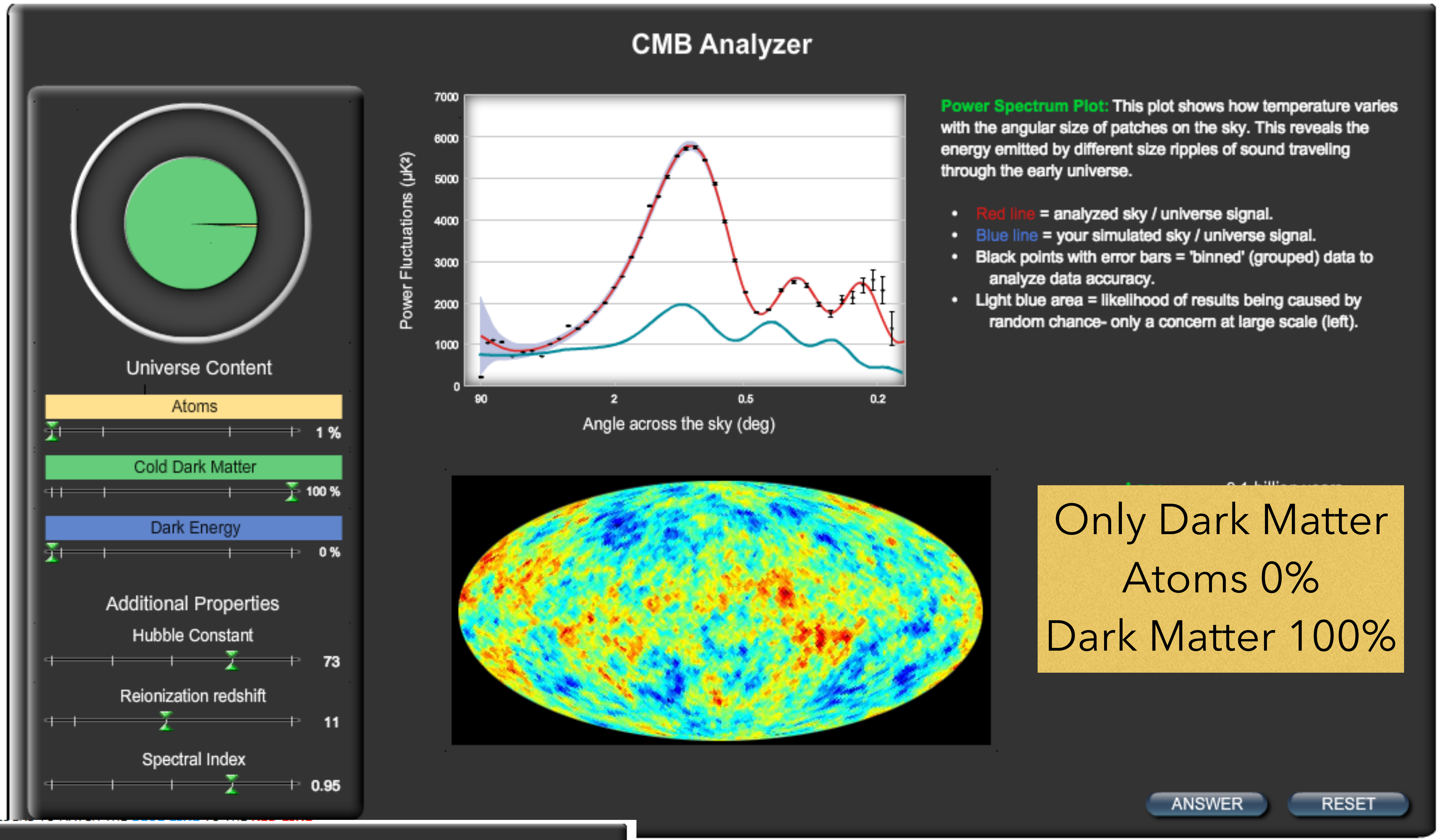
hjp://lambda.gsfc.nasa.gov/educaUon/cmb_plojer/

CMB exercise

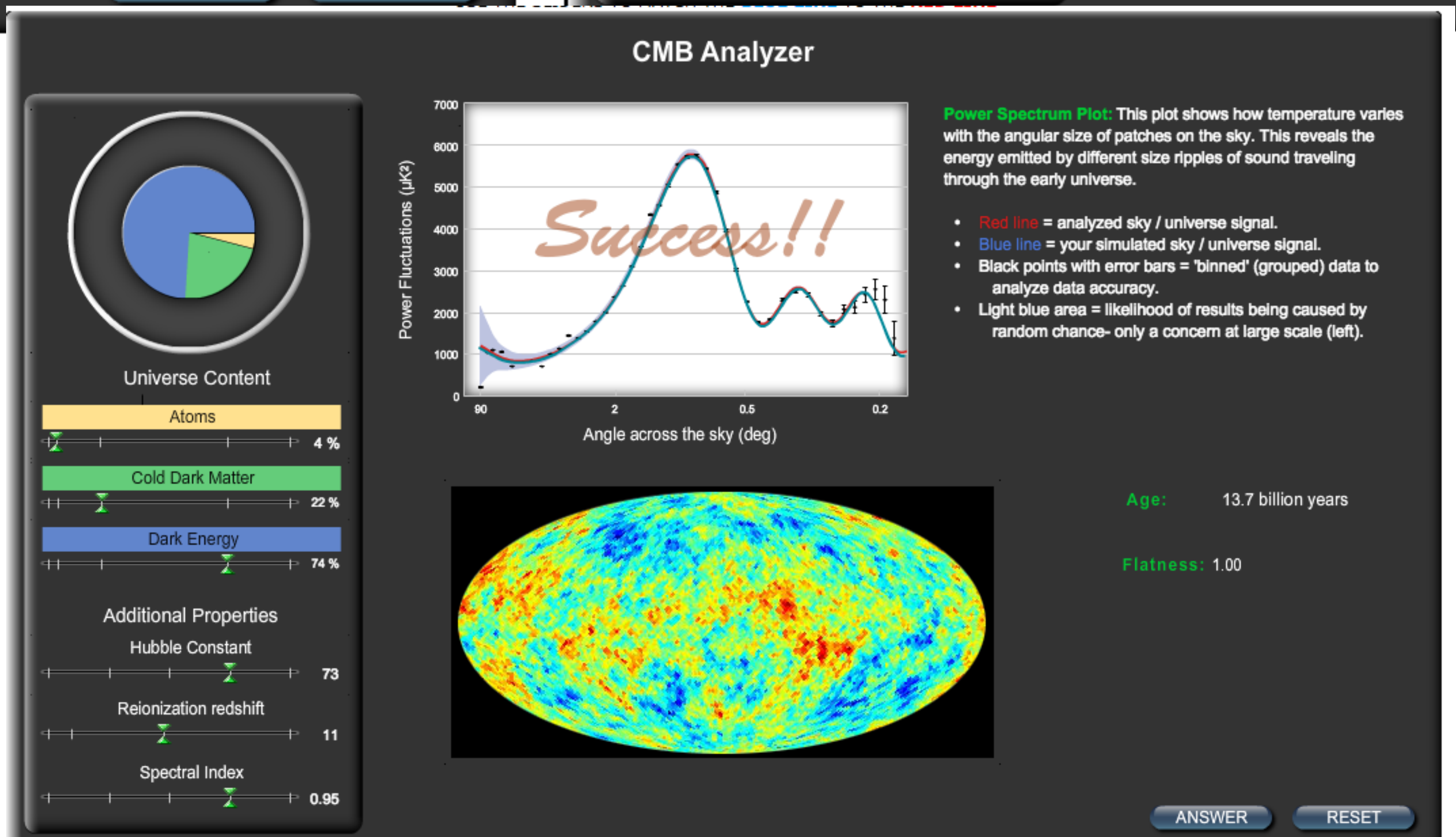
hjp://lambda.gsfc.nasa.gov/educaUon/cmb_plojer/



Only Barionic Matter
Atoms 100%
Dark Matter 0%

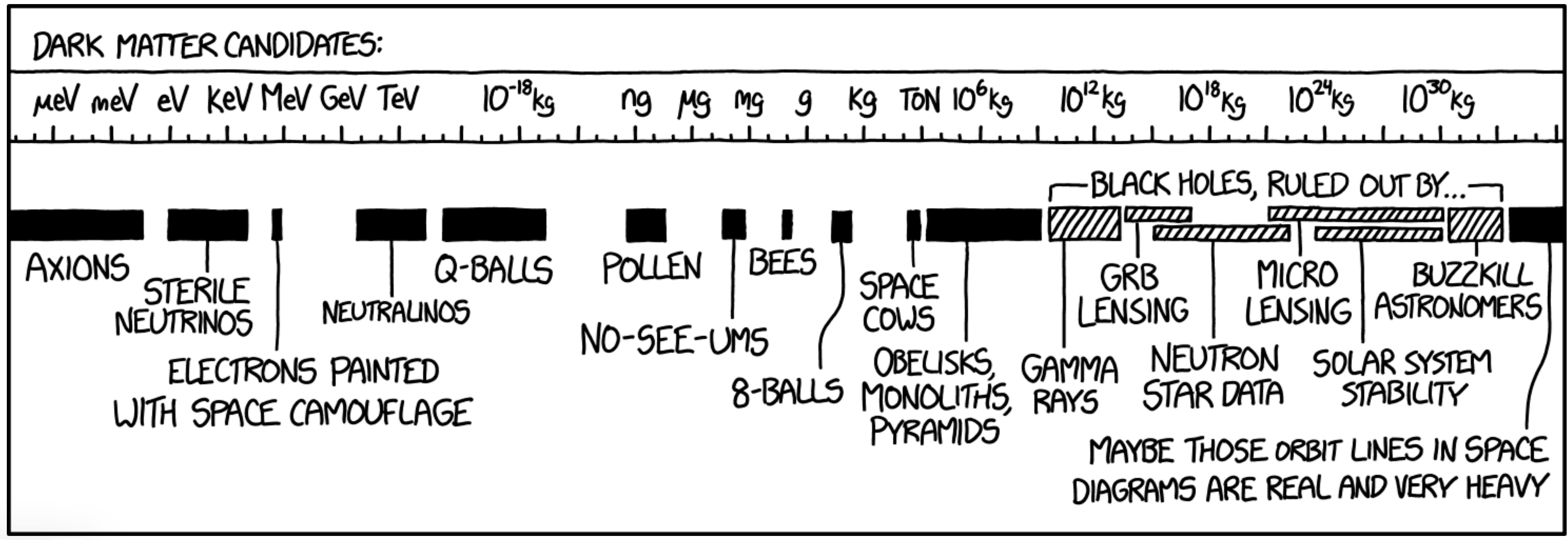


Only Dark Matter
Atoms 0%
Dark Matter 100%

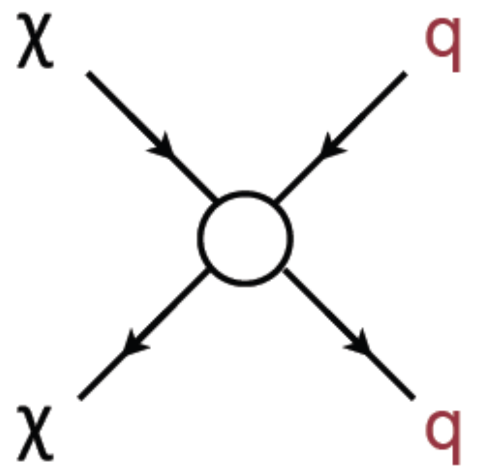


Better Agreement
Atoms 4%
Dark Matter 22%
Rest Dark Energy

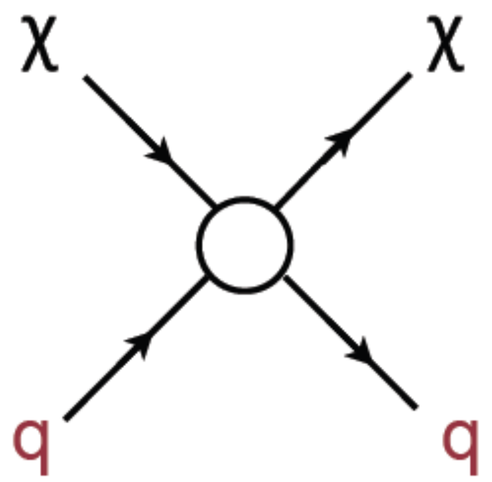
Dark Matter Searches



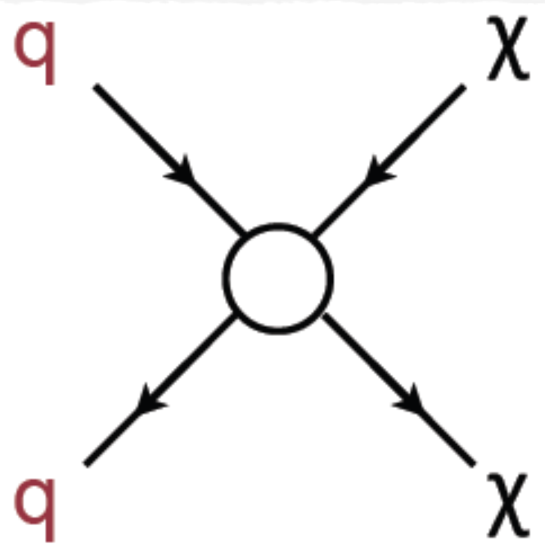
Indirect Detection:
Detection Annihilation DM, space-experiments (AMS, Ice-Cube, Fermi, KM3NET…).

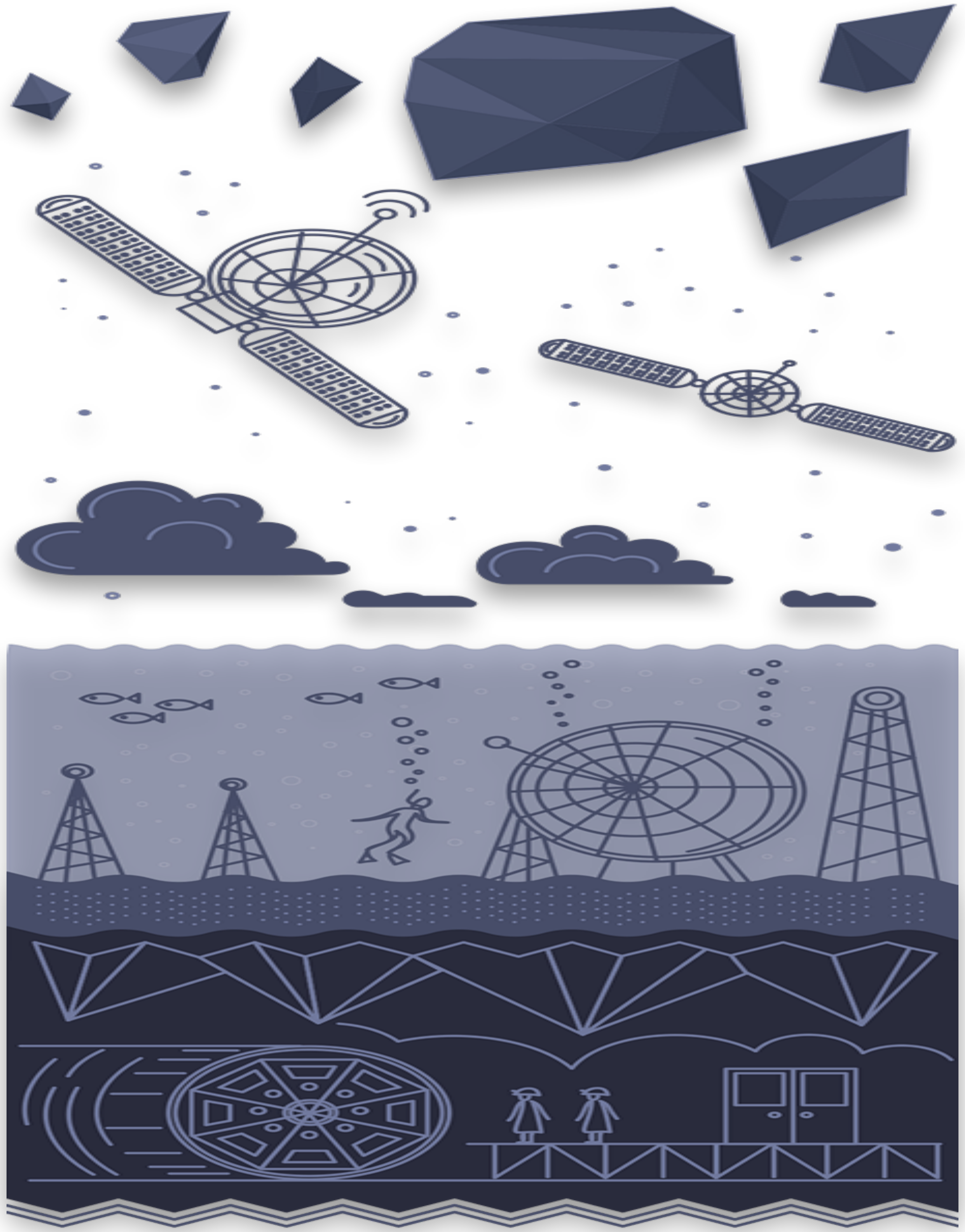


Direct Detection:
DM hits nuclei of the apparatus, those recoil. Study on the excess wrt radioactivity (DAMA, DarkSide, LUX, CDMS…).

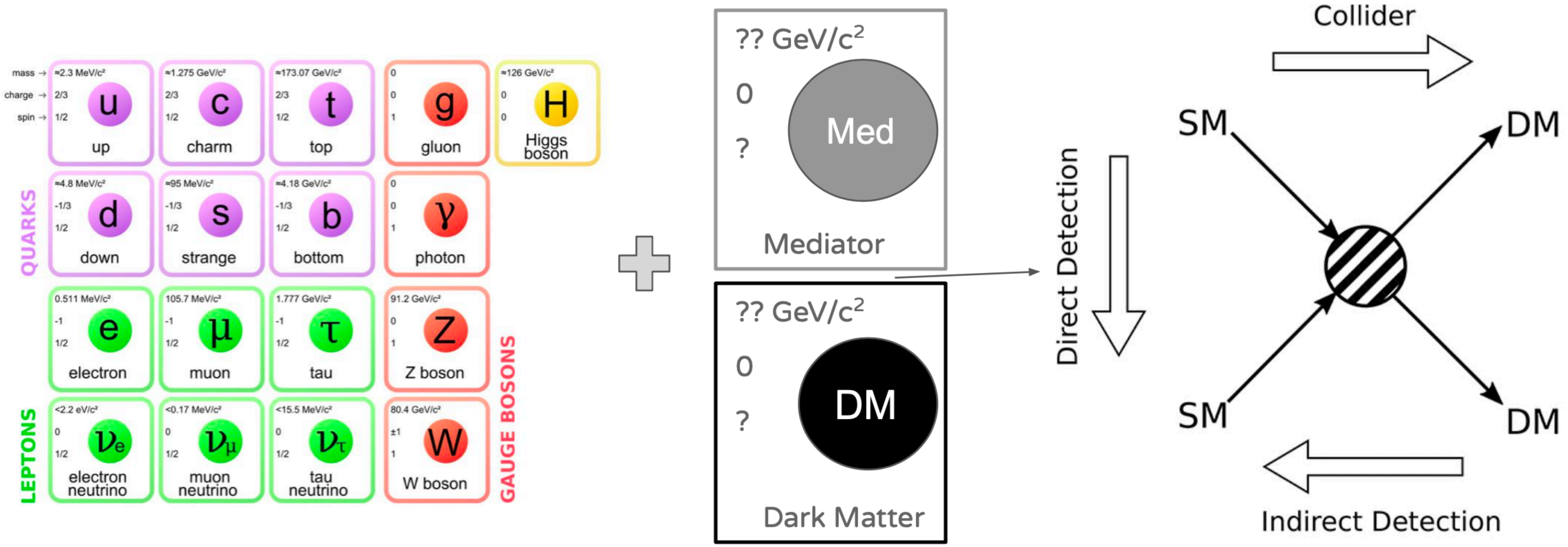


Production of DM:
Pair production at LHC. Weird signatures with large missing ET (**ATLAS**,CMS)



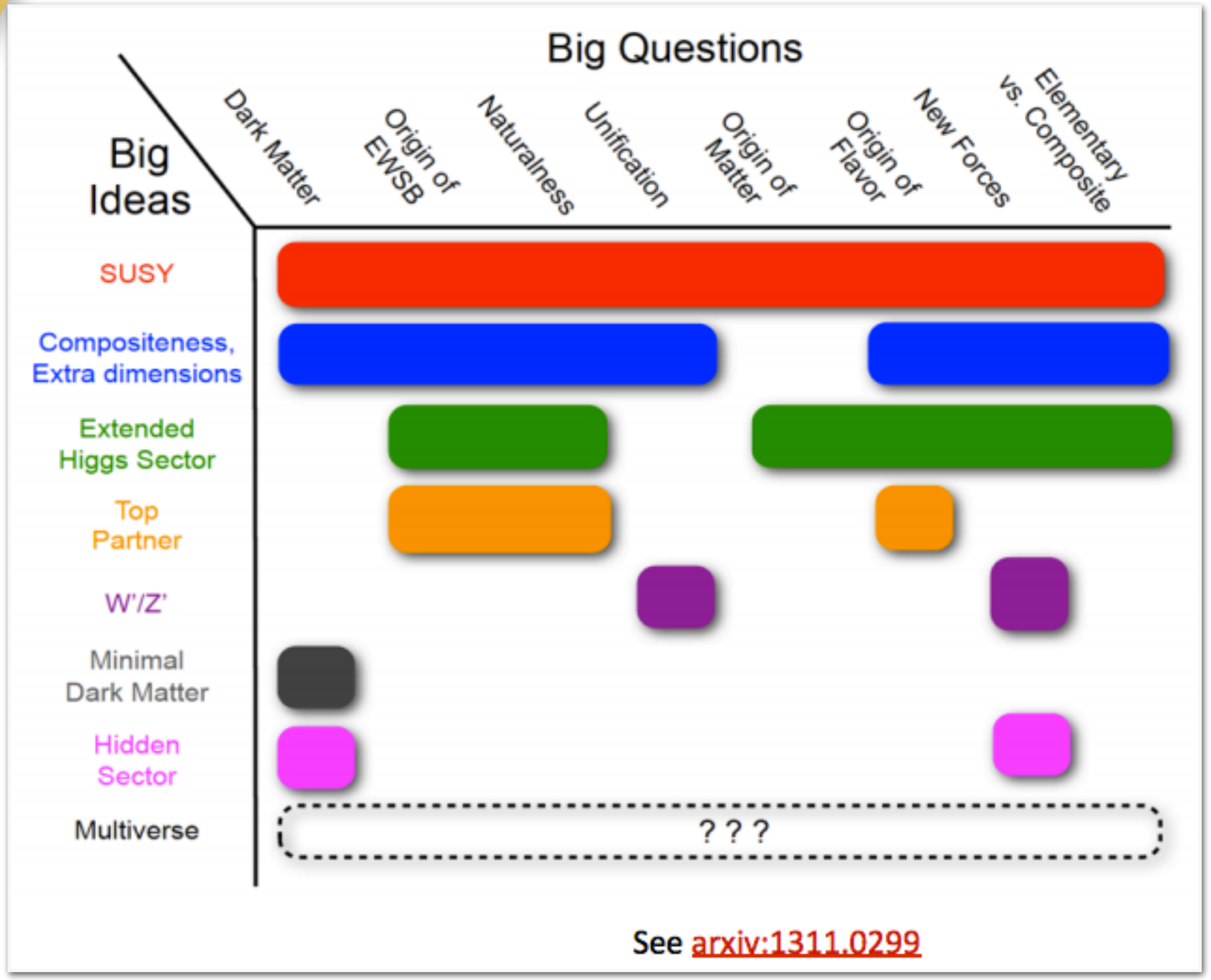


Dark Matter Searches @ Colliders



- DM couples to SM: This can be studied at colliders ! For example at LHC in pp → SM + DM
- Many theories predicting DM + SM interactions (DM searches widely use simplified models).
- Assuming an interaction between dark matter and SM particles through mediators (either SM or new as Higgs, Higgs-like, Z′, neutrino…).

How to fix them?



A new theory has to:

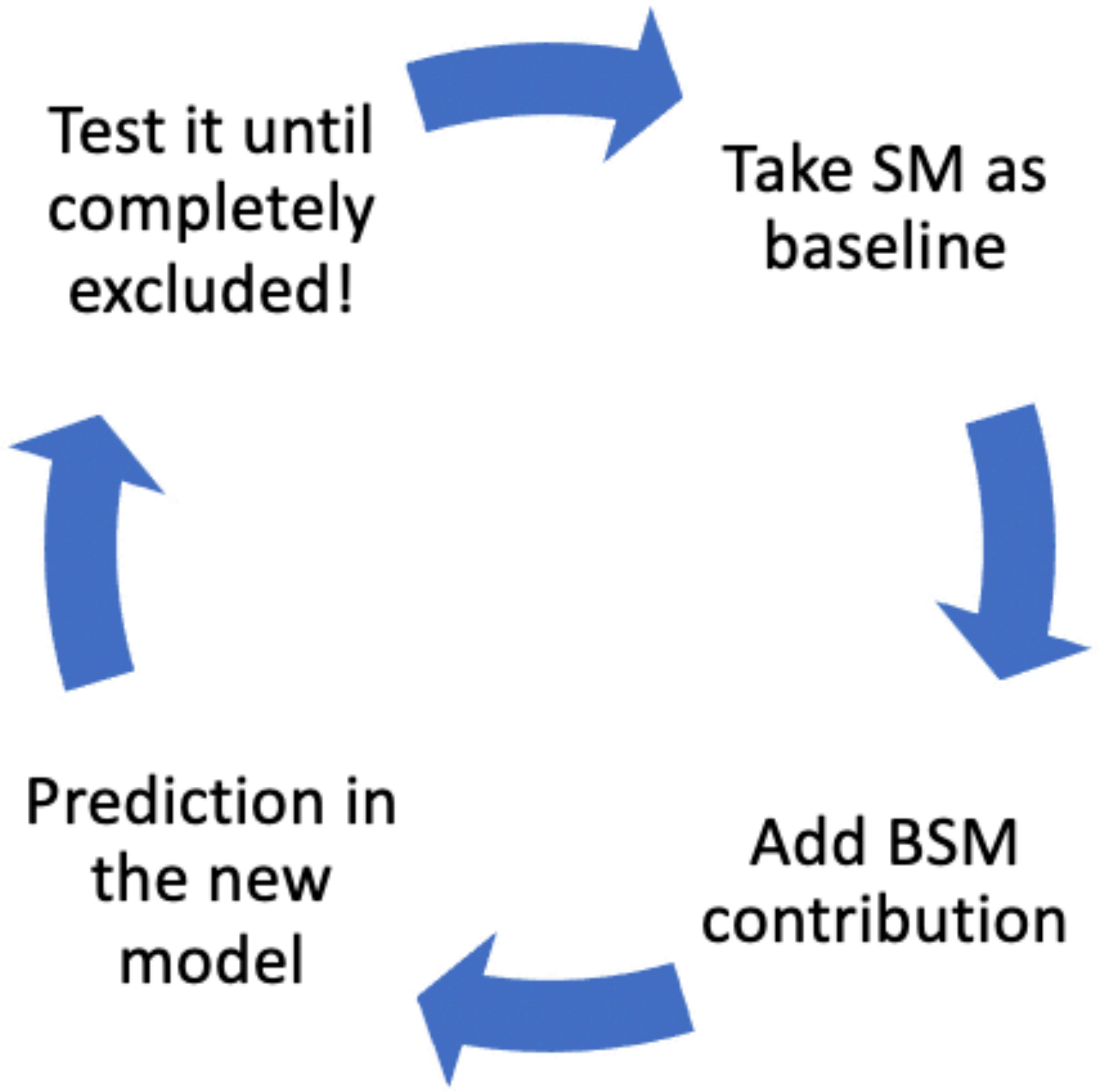
A. Contain SM (its symmetries and mass spectra)
B. Respect the actual phenomenologies
C. Be free from anomalies (current should be conserved)
D. Langrangian density of the order of E^4

$$\mathscr{L} = \mathscr{L}_{SM} + \mathscr{L}_{NON-SM} + \mathscr{L}_{INT}$$

We have to look at "beyond the Standard Model" to solve the observations that not fit the theory or not explained by the theory! SUSY or Exotics models can fix some of these problems. (See Sara lecture for SUSY model)

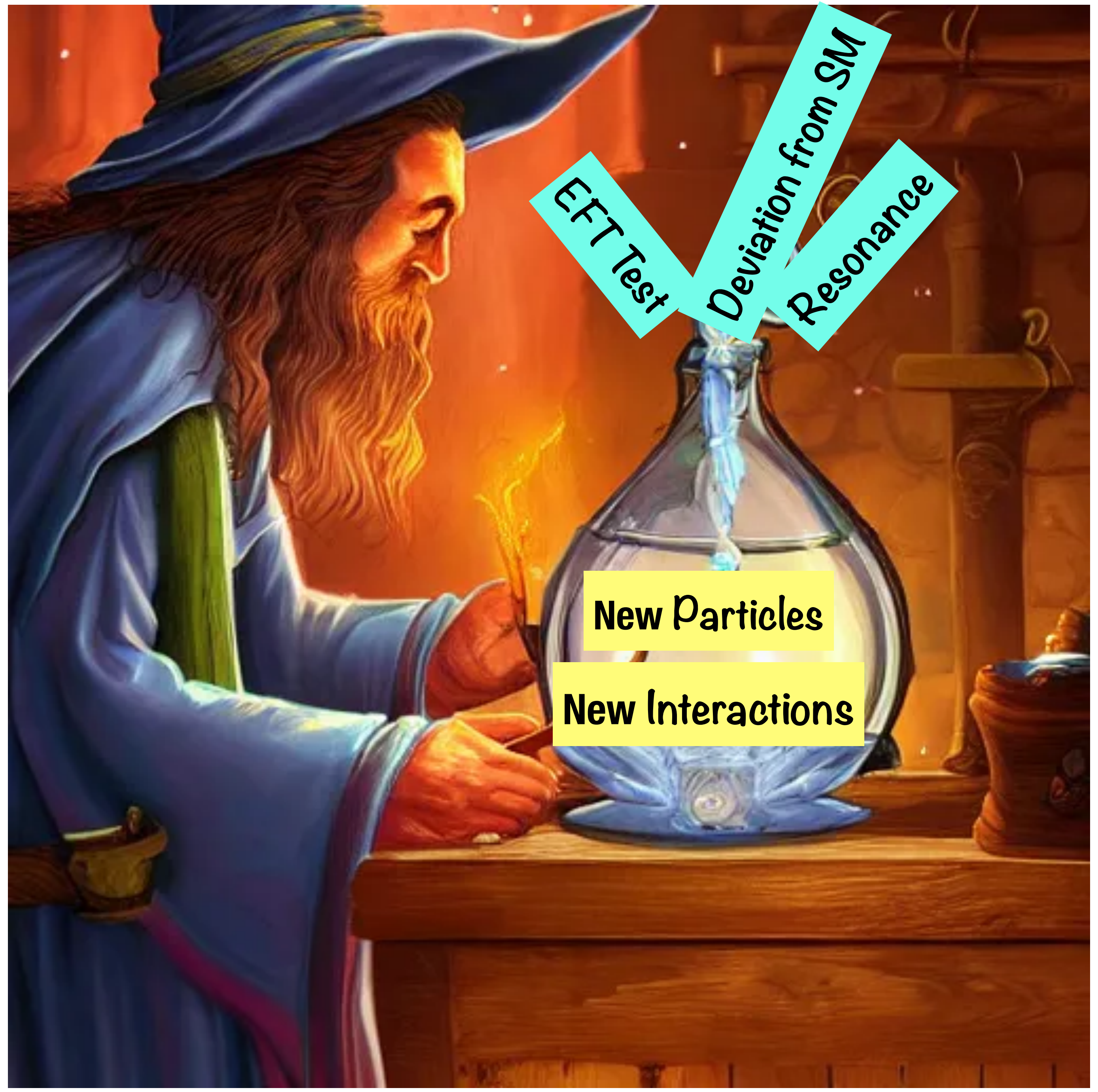
From SM to BSM

- **Research action**
  - take the SM as the baseline model
  - add BSM ingredients to solve one or more problems
  - make predictions in new BSM phase space
  - test experimentally with existing data, new data, or new experiments and repeat



- **Potential BSM ingredients**
  - new particles
  - new interactions: portals, mixing,…, new signatures

- **Potential observables**
  - high-mass / low-mass resonances
  - cross section or branching ratio deviations
  - shape deviations / interference



Interpretation of the Result

Questions on the meaning of the results, the methodology, unexpected findings and limitations and shortcomings of the study.

Top-down: Starting from the Theory….

- Mostly before LHC (LEP, Tevatron)
- Start from a theoretical principle to address SM problems: (mostly) fully consistent BSM models
- Huge parameter space, describing new phenomenology
- Make the experimental tests
- Hard to re-interpret in other context

Bottom-up: Arriving to a Theory….

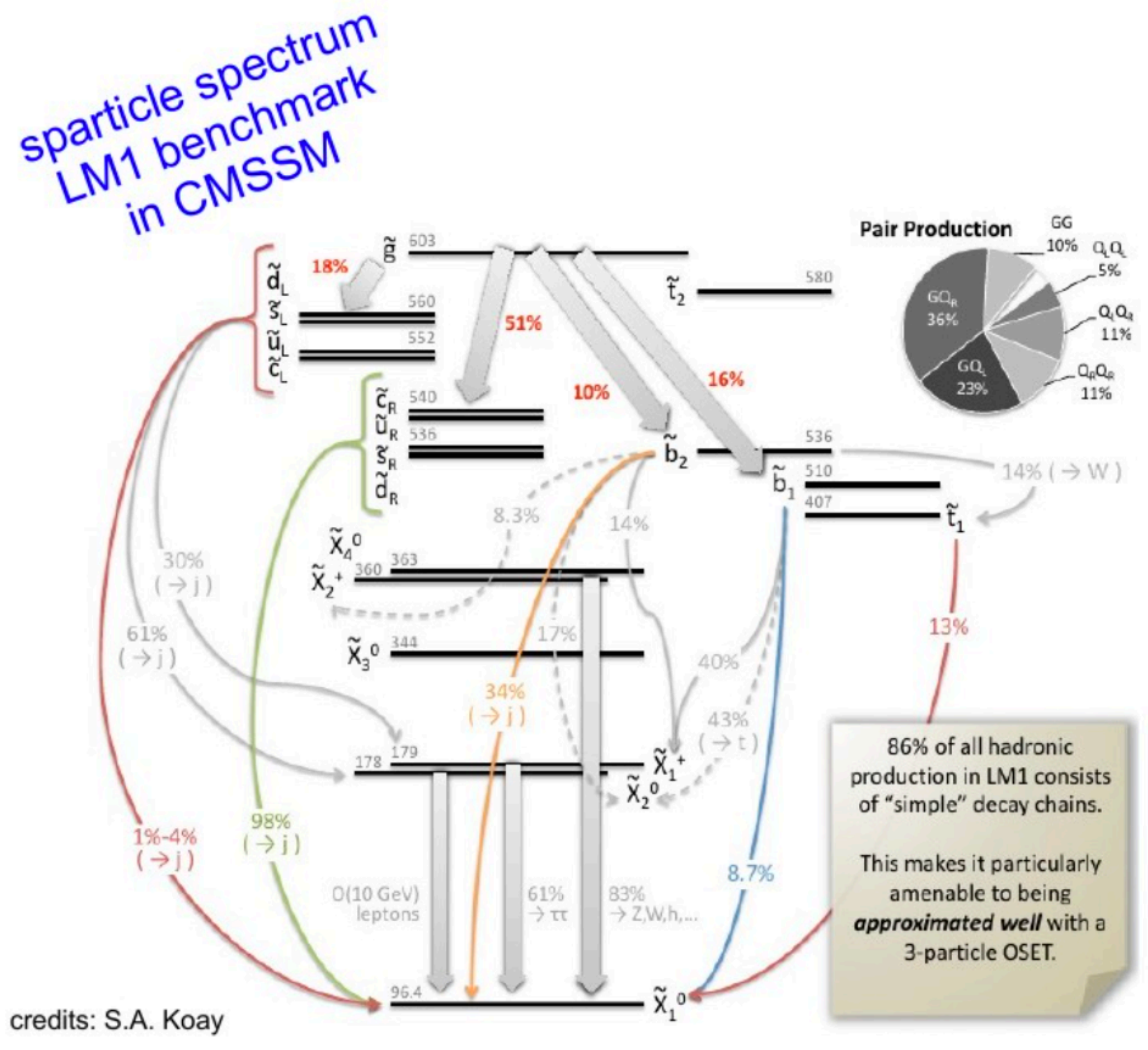
- Limit to the essence of the BSM aspect of interest
- Focus on experimental signatures
- Easier to re-interpret
- actually expands the phase space
- Simplified Model and Effective Field Theory

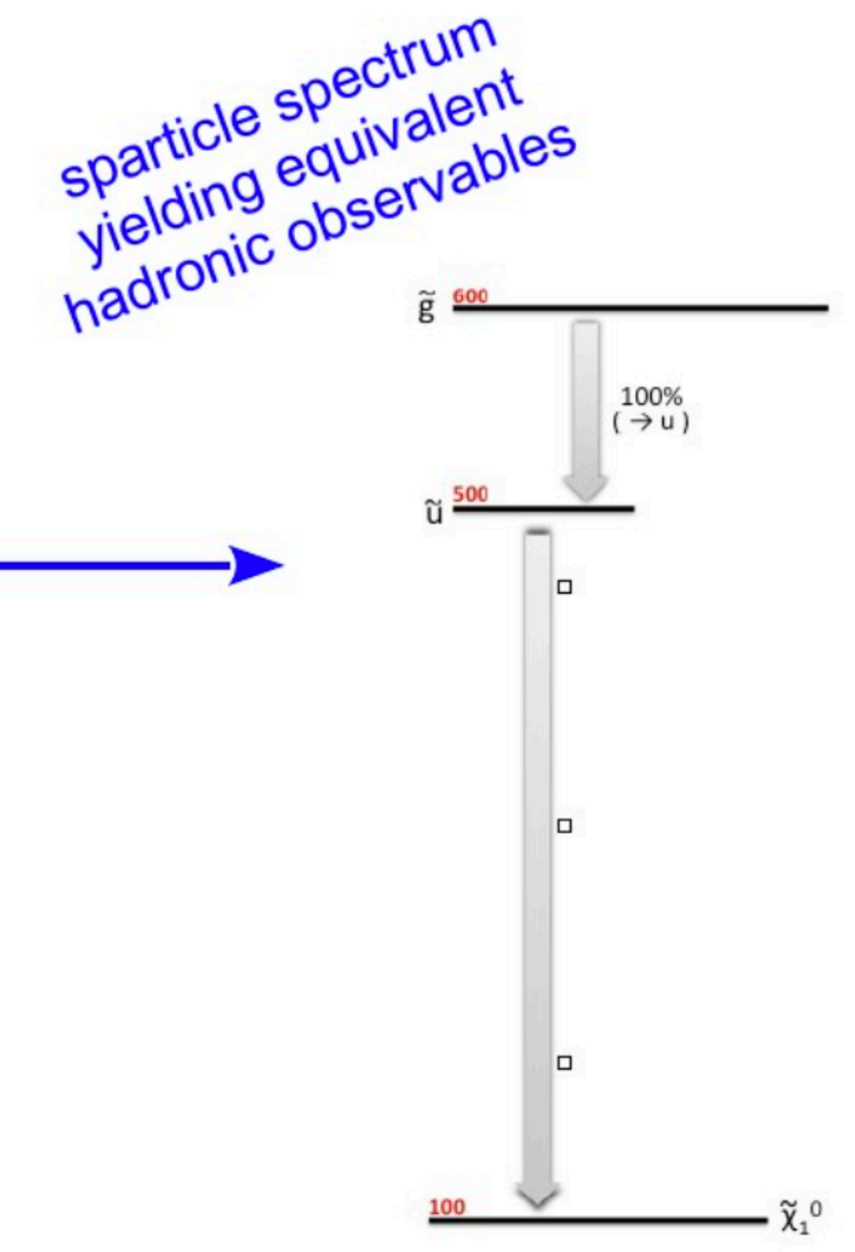
If there is not a discovery….set a limit on the theory parameter!

Bottom-up Method

Transition to simplified models in 2010 (SUSY) and 2015 (dark matter)

Simplified Models for LHC New Physics Searches
LHC New Physics Working Group • Daniele Alves (SLAC) et al. (May, 2011)
Published in: *J.Phys.G* 39 (2012) 105005 • e-Print: 1105.2838 [hep-ph]





- Nowadays strong emphasis on Effective Field Theory (EFT)
  - parametrize our ignorance of the full theory at high energies in "effective" low-energy "operators"

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda}\sum_i c_i \mathcal{O}_i + \frac{1}{\Lambda^2}\sum_j c_j \mathcal{O}_j + \cdots$$

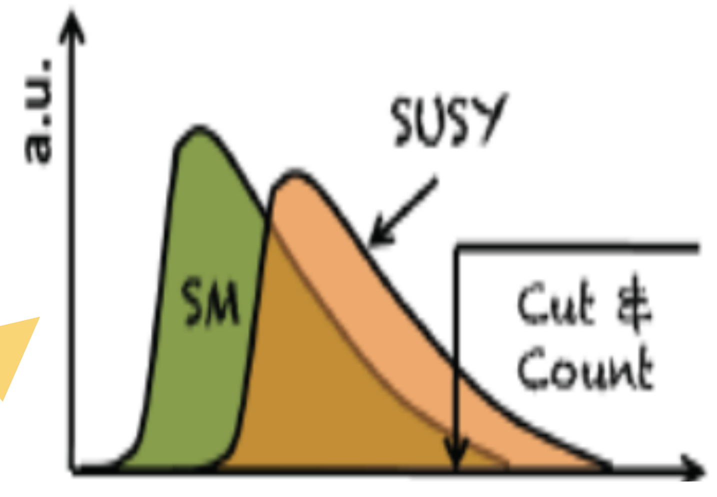
  - these operators are non-renormalizable, so they cannot be Lagrangian terms in a fully consistent renormalizable theory that works at all energies.

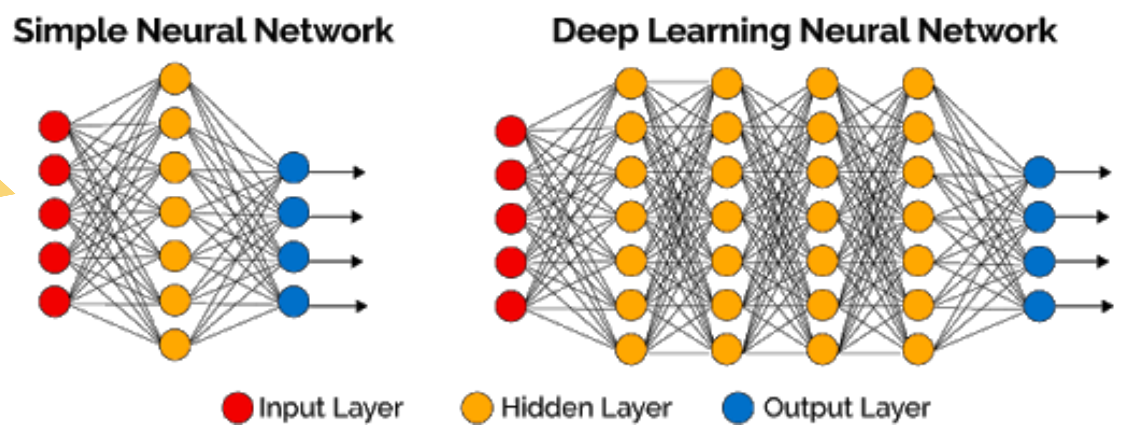
example: the non-renormalizable Fermi theory with 4-fermion vertices could describe observations because the W mass was at that time still a very high energy scale

Organize the “search”

1. Find good discriminant(s) to identify the signal region SR (be blind in data)

Cut and Count or Neural Network, Multivariate analyses (**)





2. Determine background events and define the systematics uncertainties

Background samples possible from data or taken from theory Simulation

3. Statistical analysis of the events selected (*)

Likelihood fit to determine if your data are statistically consistent with a background only hypothesis in the signal region

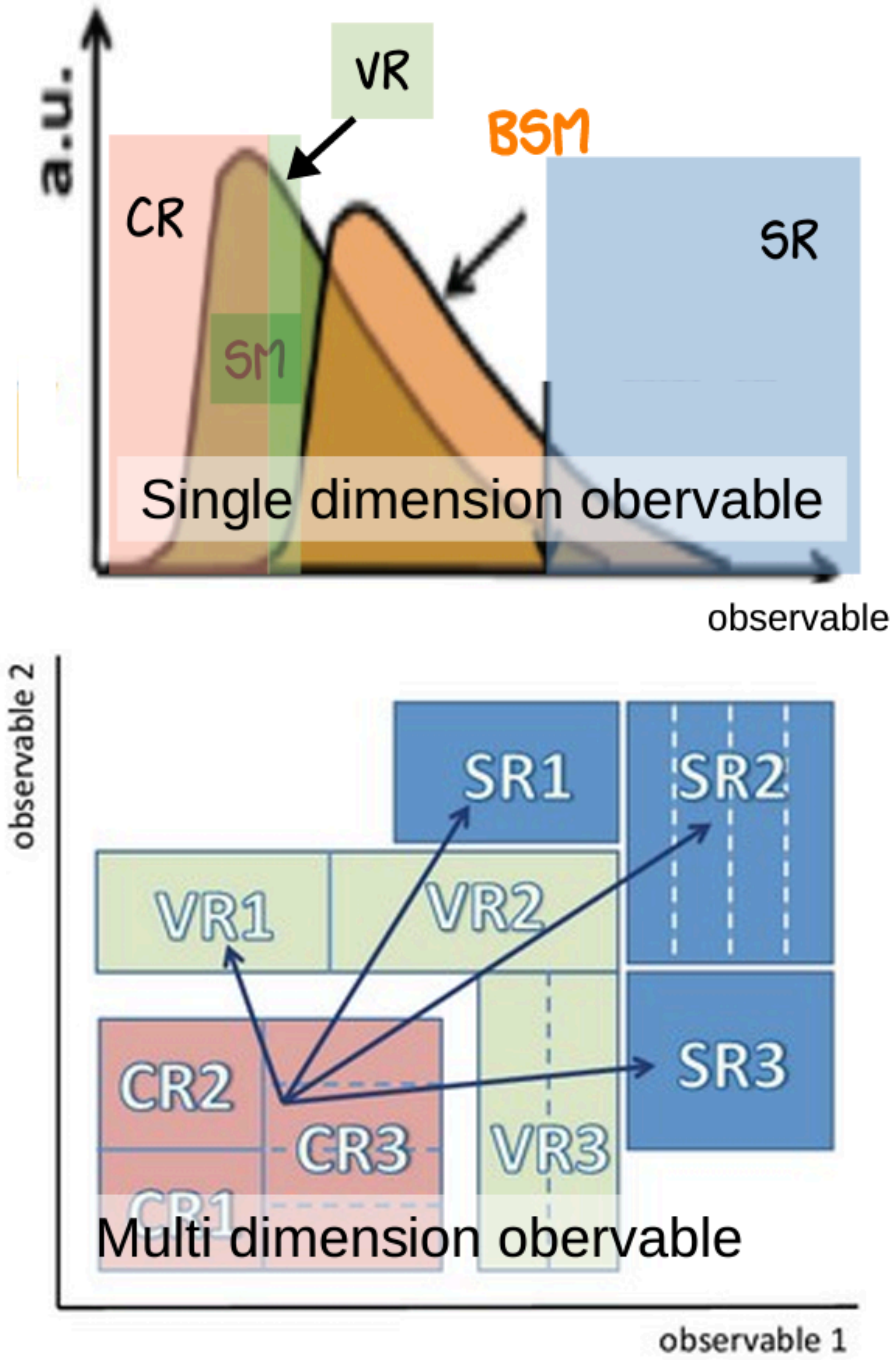
(*) see Tomas lecture
(**) see Jonas and Stefanie lectures.

Definition of Regions

- **CR → Control Regions.** Background dominated. No (or very small) BSM signal contamination. Likelihood fit to control background and evaluate systematic. Ideally at least one CR per background process

- **VR → Validation Regions.** Still depleted in BSM signal events. To assess validity of background estimation on a kinematical region "closer" to SR

- **SR → Signal Regions.** Usually "blinded" at the beginning. It's where we expect to see BSM signal. When you are sure about your background estimation, fit procedure etc. you can open the box!

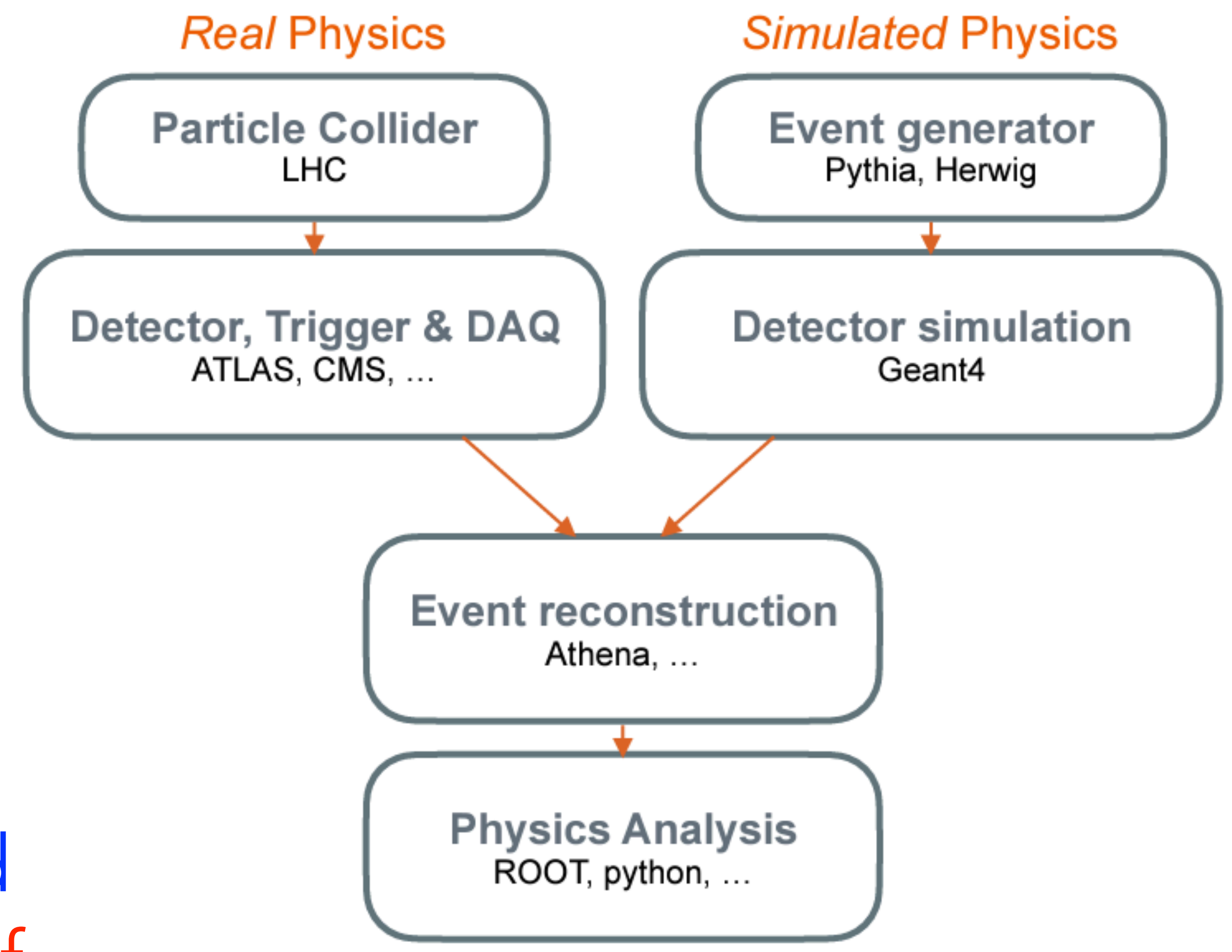


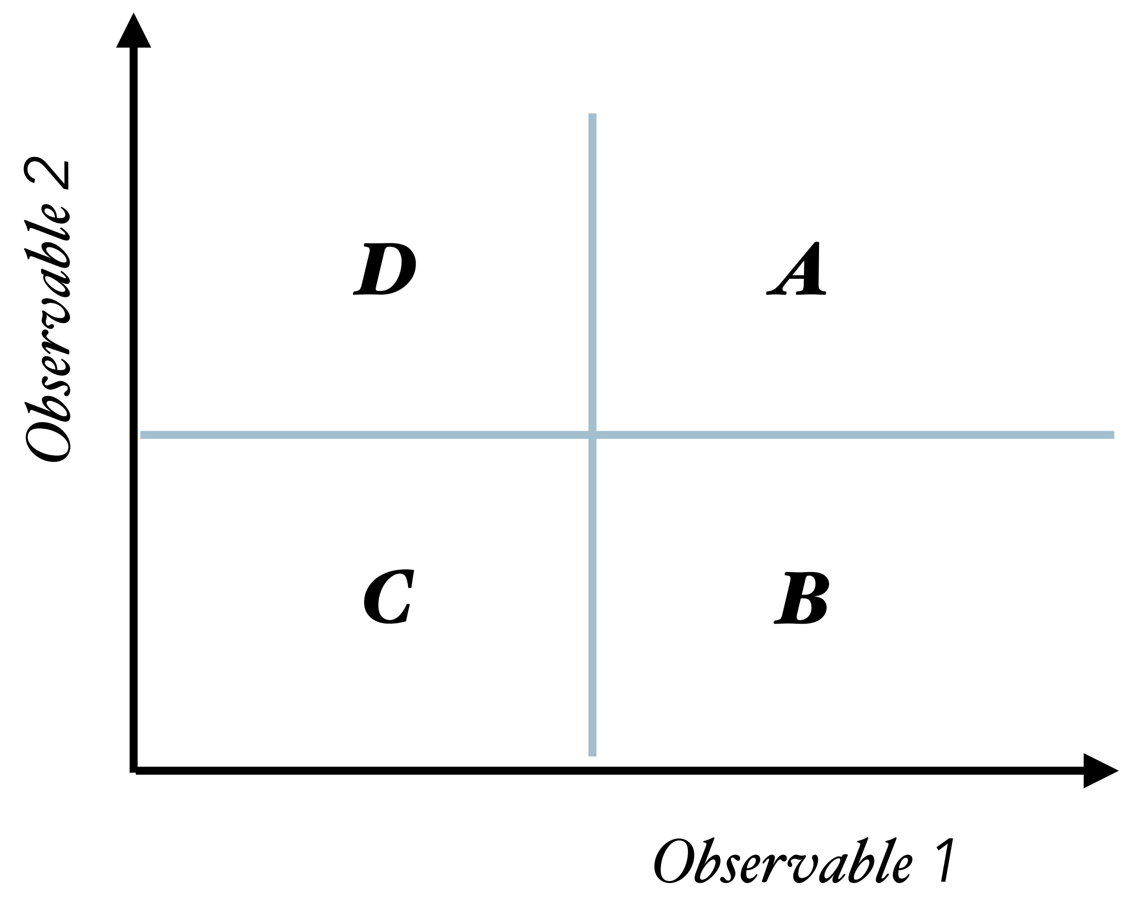
Background Events

- **SM Models Background:** twin set of collision data to compare to the real collisions obtained by simulation.

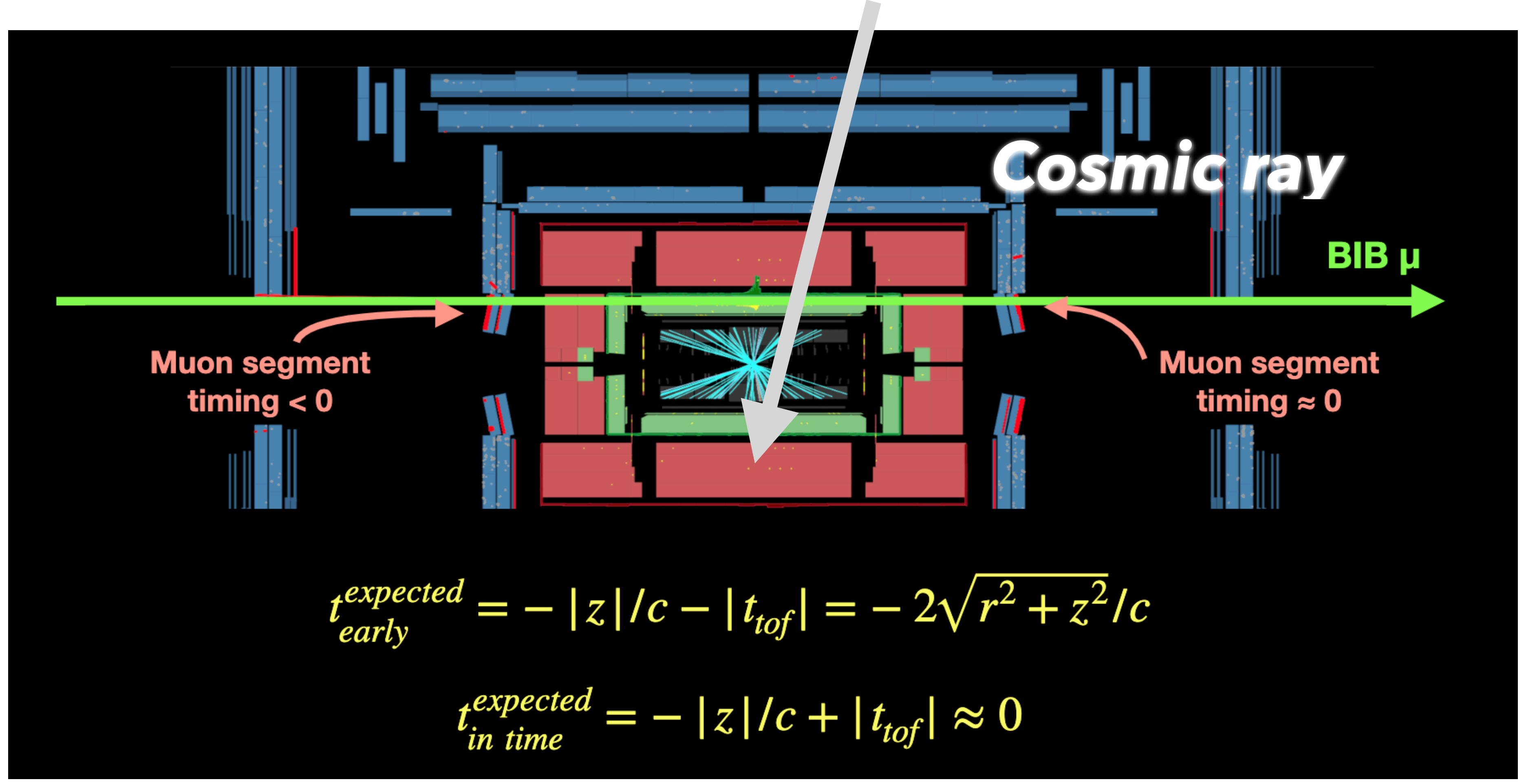
- **Data Driven Background:** samples obtained from real data due to the limitation of CPU/storage resources. ABCD Extrapolation Method using with 2 independent observables. Three of these regions, called B, C, and D, are background dominated. The fourth, A, is the signal region, the background in the signal region can be predicted from the other three regions.

- **Non Standard Background:** Beam Induced background and cosmic-rays muons could represent a “non-standard” background for SUSY and Exotics searches. Main from data.



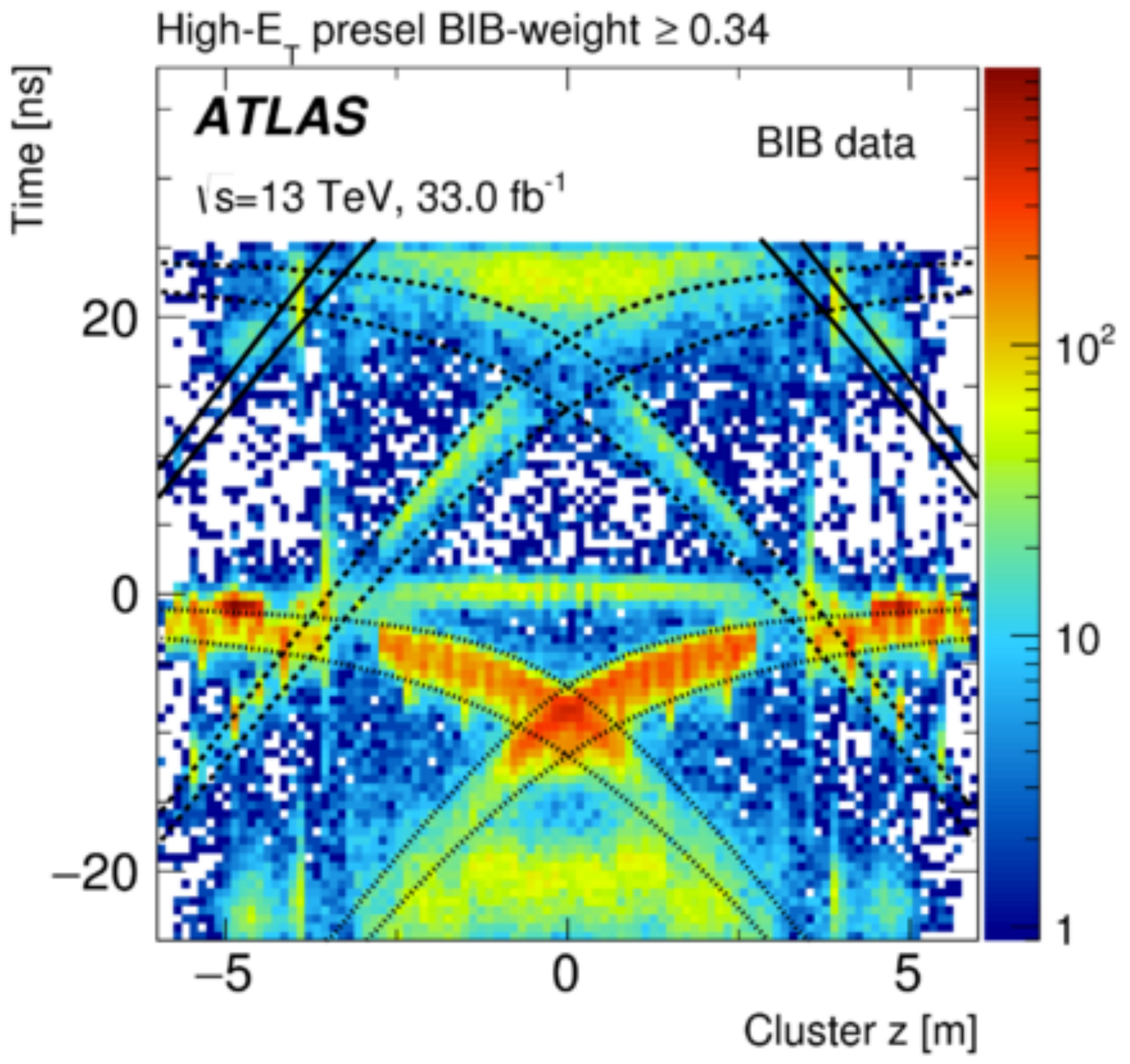


$$N_A = \frac{N_B N_C}{N_D},$$



Non-Collisions Background

- The term **non-collision backgrounds (NCB)** refers to signals seen in the ATLAS detector which have not been produced by normal collisions of the LHC beams. The main components are beam-induced backgrounds (BIB) and cosmic-ray muons :
    - Beam halo: protons with high transverse amplitude hitting tertiary collimators (TCT)
    - Beam gas: small-angle deflections of the protons originated by elastic beam-gas scattering (adds to TCT loss) or inelastic hits of protons with residual gas molecules
    - Cosmic rays: predominantly muons travelling downward due to atmospheric cosmic-rays showers
- Motivation for these studies:
    - **Beam condition feedback** to LHC and **monitoring tool** to ensure good data quality
    - These events are an important **background source for searches** with mostly displaced objects as:
        - SUSY and Exotics long-lived particles searches. Most of the studies are done with a tight synergy with the physics groups involved.



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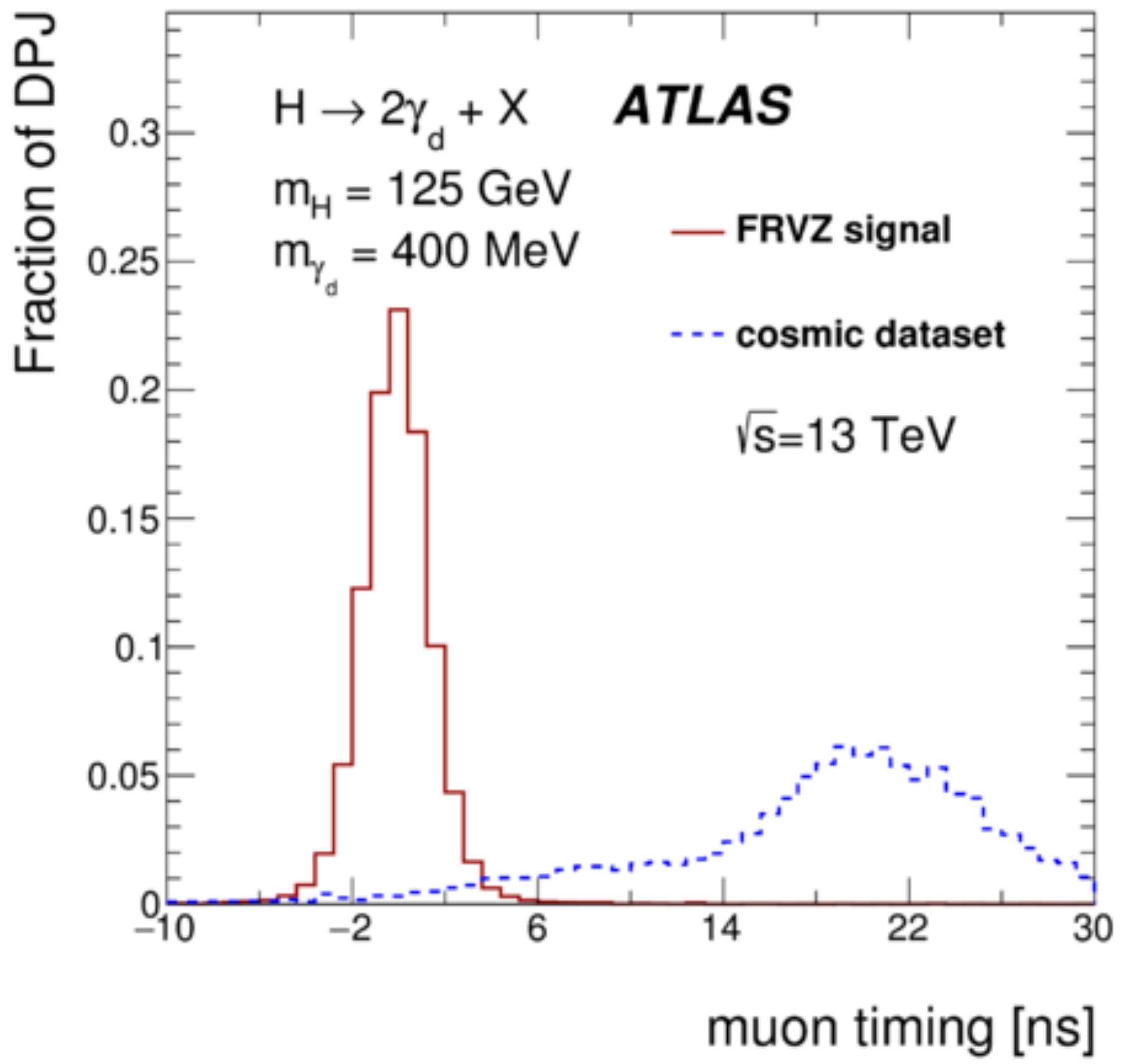

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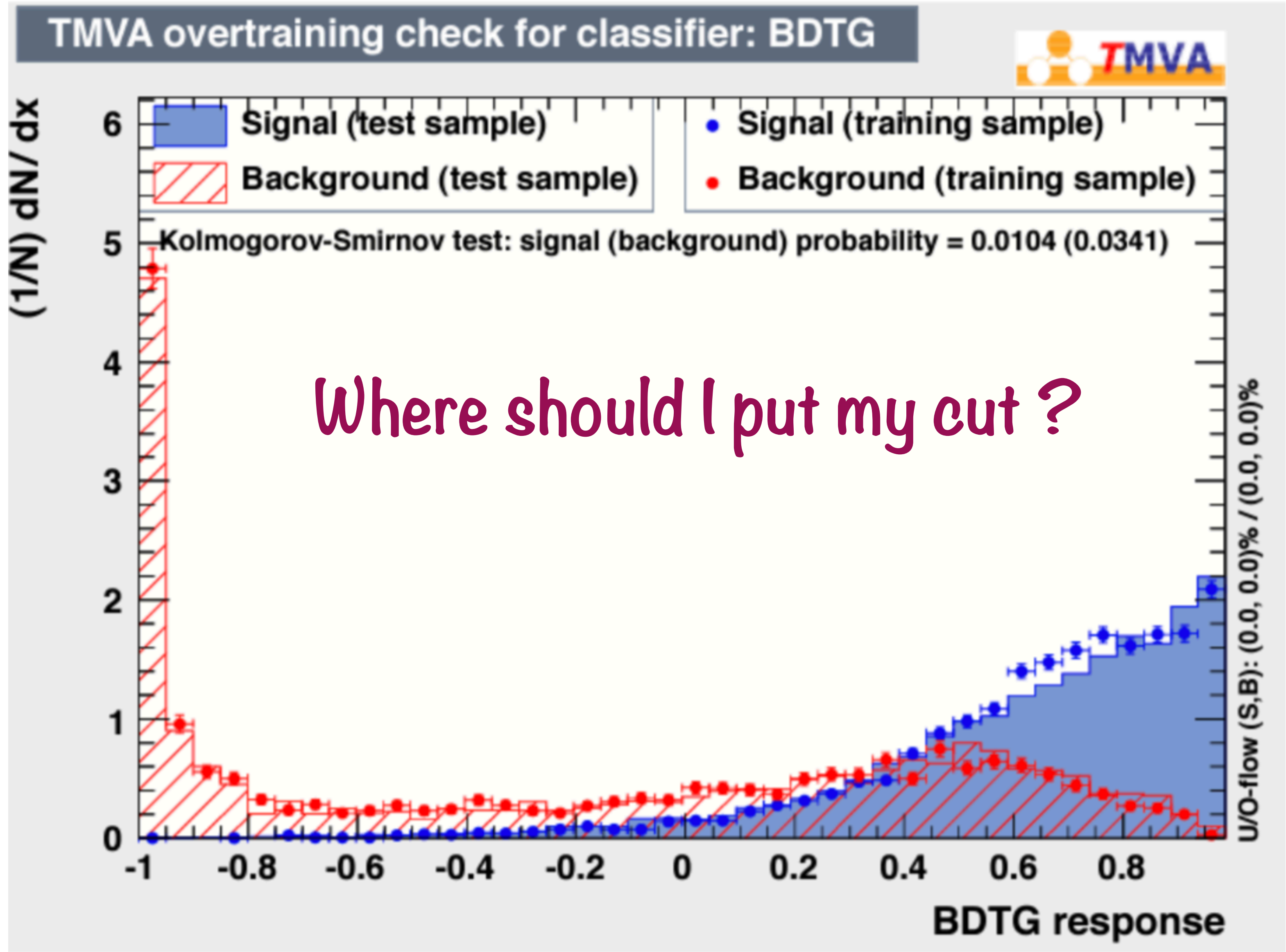
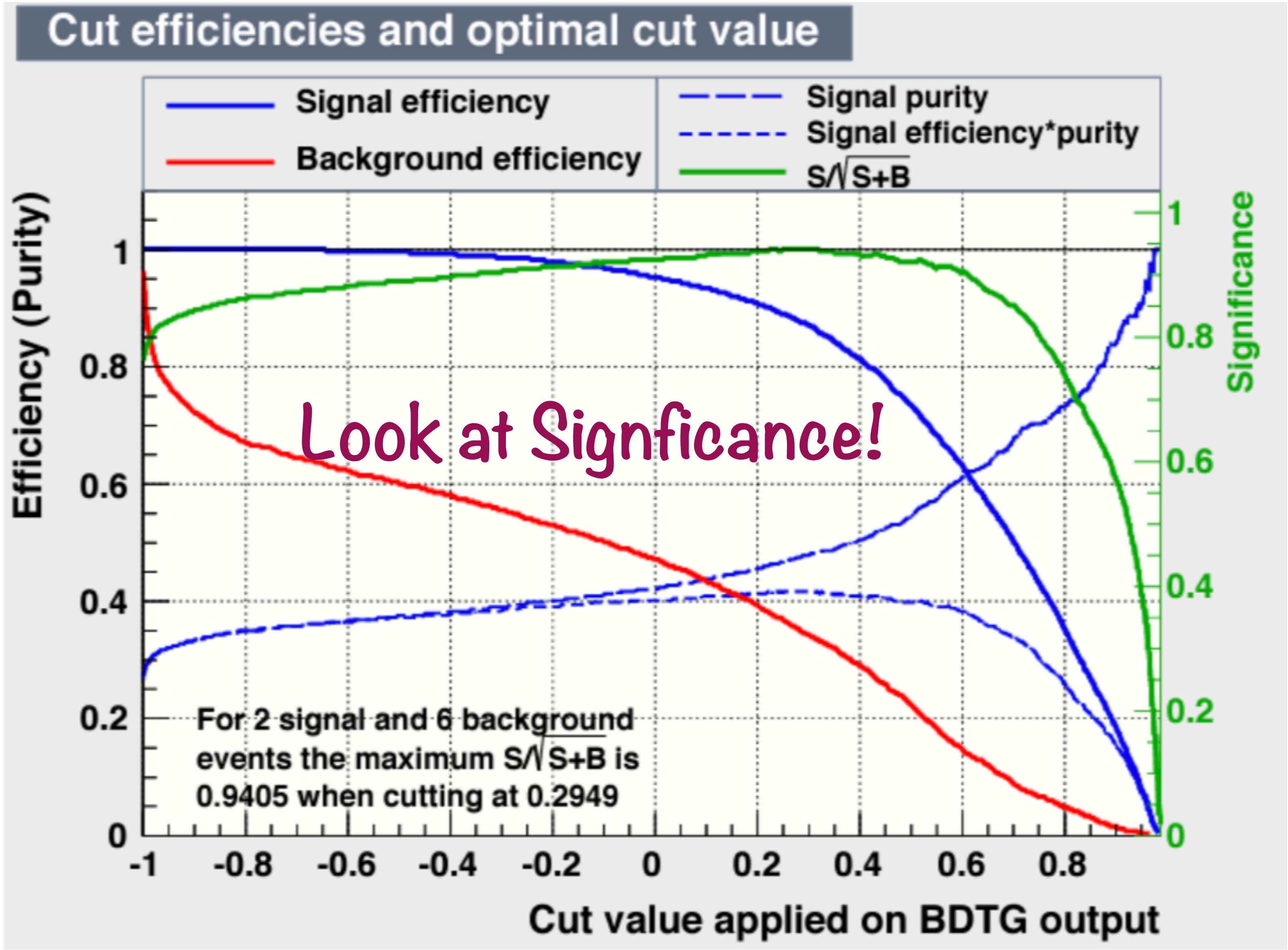
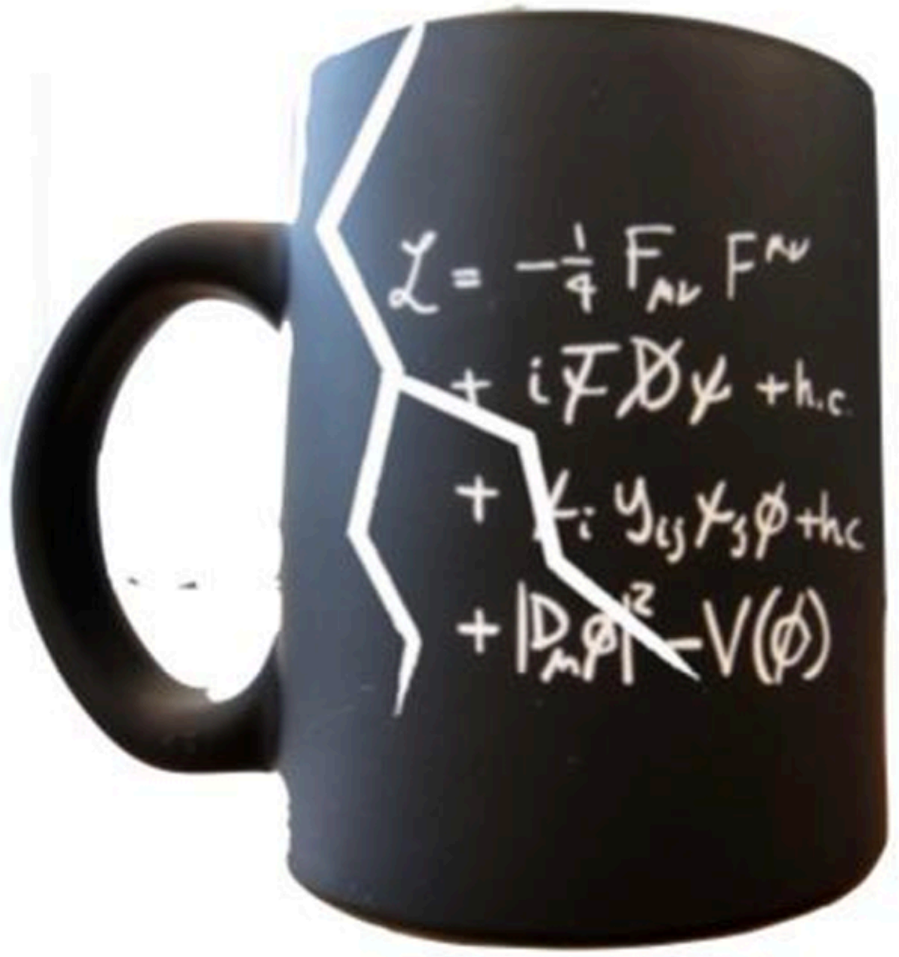
How do we optimise the selection?

- **Score Function: Significance** $S/\sqrt{(S+B)}$
  - Number of signal events S in a selected event sample is estimated by subtracting the estimated background B from the total number of events N:
    - S = N-B
- Statistical uncertainty in the signal estimate:
  - $S = \sqrt{N} = \sqrt{(S+B)}$
  - Poisson statistics
  - ignore systematic uncertainties, and consider B large enough
- goal: maximize significance
  - by keeping signal events
  - while suppressing background
- Additional score function based on likelihood test:
  - $\sqrt{2(S+B)ln(1+S/B) - 2S}$





Now what are we looking for?



- Search for cracks in the Standard Model that will indicate us what/where is beyond…
  - Precision Measurements of SM and/or rare processes – limited by luminosity and data-taking capabilities
    - low-mass resonances with large background
    - small couplings
    - rare decays
  - Direct searches for new particles or phenomena due to high energies – limited by colliders' center of mass energies
    - New bosons new fermions…
    - Heavy neutrinos, ….
  - unusual processes – limited by detectors and our ingenuity:
    - invisible signatures
    - long-lived particles
    - unusual charges

Motivation for Long-Lived Particles

- A wide variety of BSM and SUSY models (Hidden Sectors, RPV violating decays, Split-SUSY, AMSB, GMSB, etc.) predict the existence of Long Lived Particles (LLP), *new particle with long life-time*, enabling direct measurements.
  - **Small Coupling** (R-Parity Violation SUSY, Dark Photons…)
  - **Limited/Compressed spectra** (for example Compressed SUSY…)
  - **Large mediator mas**s, i.e. decays via Heavy Particle (Heavy Neutral particle - Neutrinos…)

	Signature	Scenario	decay-length sensitivity
1	Late decaying	split SUSY, Hidden Valley	—
2	low β, large dE/dx	GMSB, Split-SUSY, Stealth SUSY, Multi-charged	>1000mm
3	Disappearing track	AMSB (wino-LSP)	O(100-1000)mm
4	Non-pointing γ	GMSB	O(100-1000)mm
5	Displaced vertex, Lepton-jet	RPV, GMSB, Hidden Valley	O(10-100)mm

Example: Charged pion lifetime:

$$\frac{1}{\tau_{\pi^+}} = \frac{f_\pi^2}{256\pi m_\pi}\left[\frac{g^2}{M_W^2}\frac{m_\mu}{m_\pi}(m_\pi^2 - m_\mu^2)\right]^2$$

Large decay lengths:

Small couplings → Hidden sectors

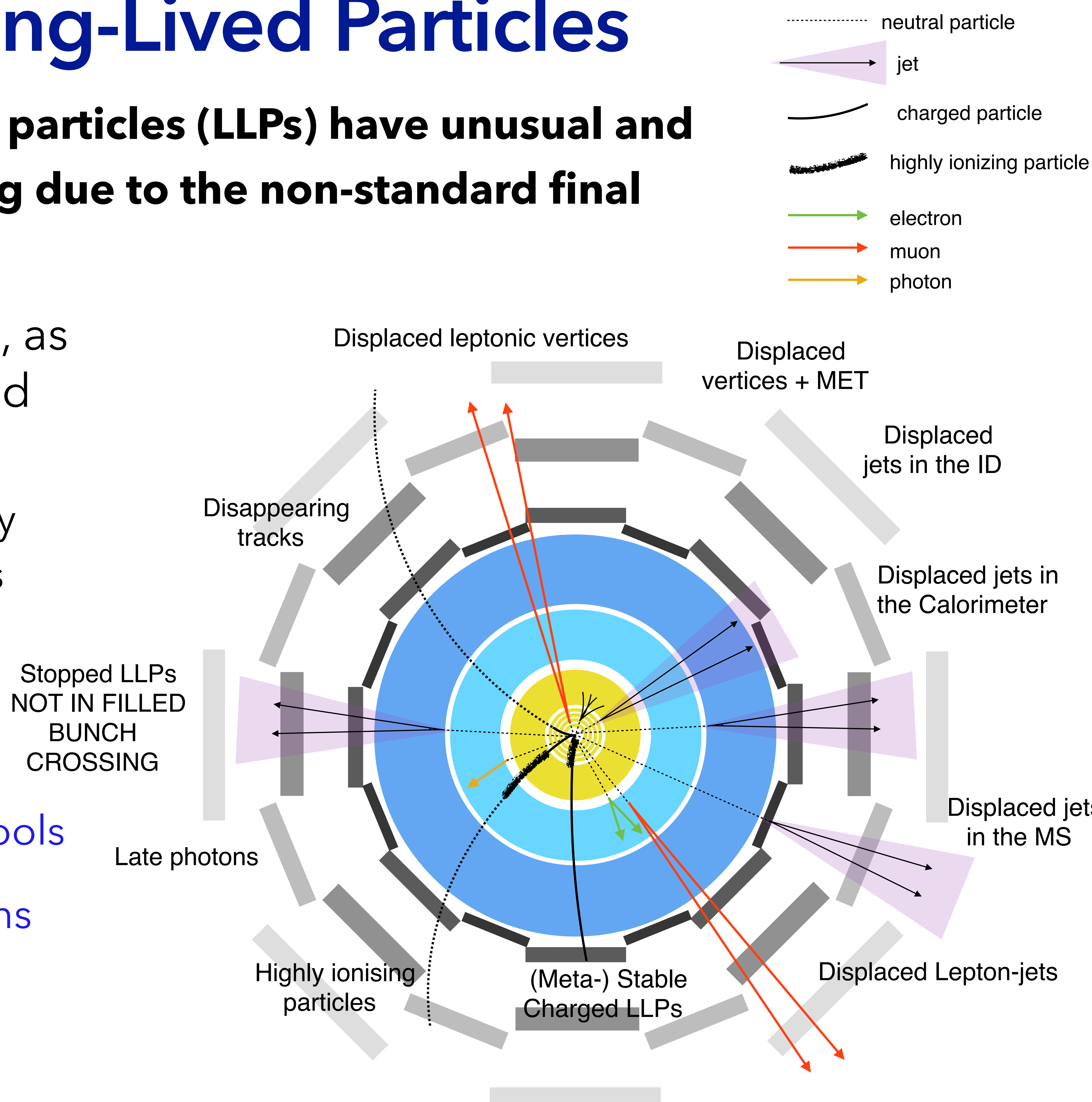
Large mediator mass → BSM mediators

Compressed spectra → Approximate symmetries

Unusual signatures: Long-Lived Particles

- **Unconventional signatures as long-lived particles (LLPs) have unusual and unique signatures, extremely challenging due to the non-standard final topologies.**

- The signal event reconstruction and selection, as the background estimation, use dedicated and very specialised techniques.
  - Detector-signature based search. Experimentally very diverse, depending on particles' properties (dE/dx, Time-of-flight, displaced vertex)
  - May require customised trigger and self-made objects reconstruction algorithm
  - Requires non-standard analysis strategies and tools
    - Non-standard background (cosmic-ray muons and Beam Induced background), generally data-driven estimation



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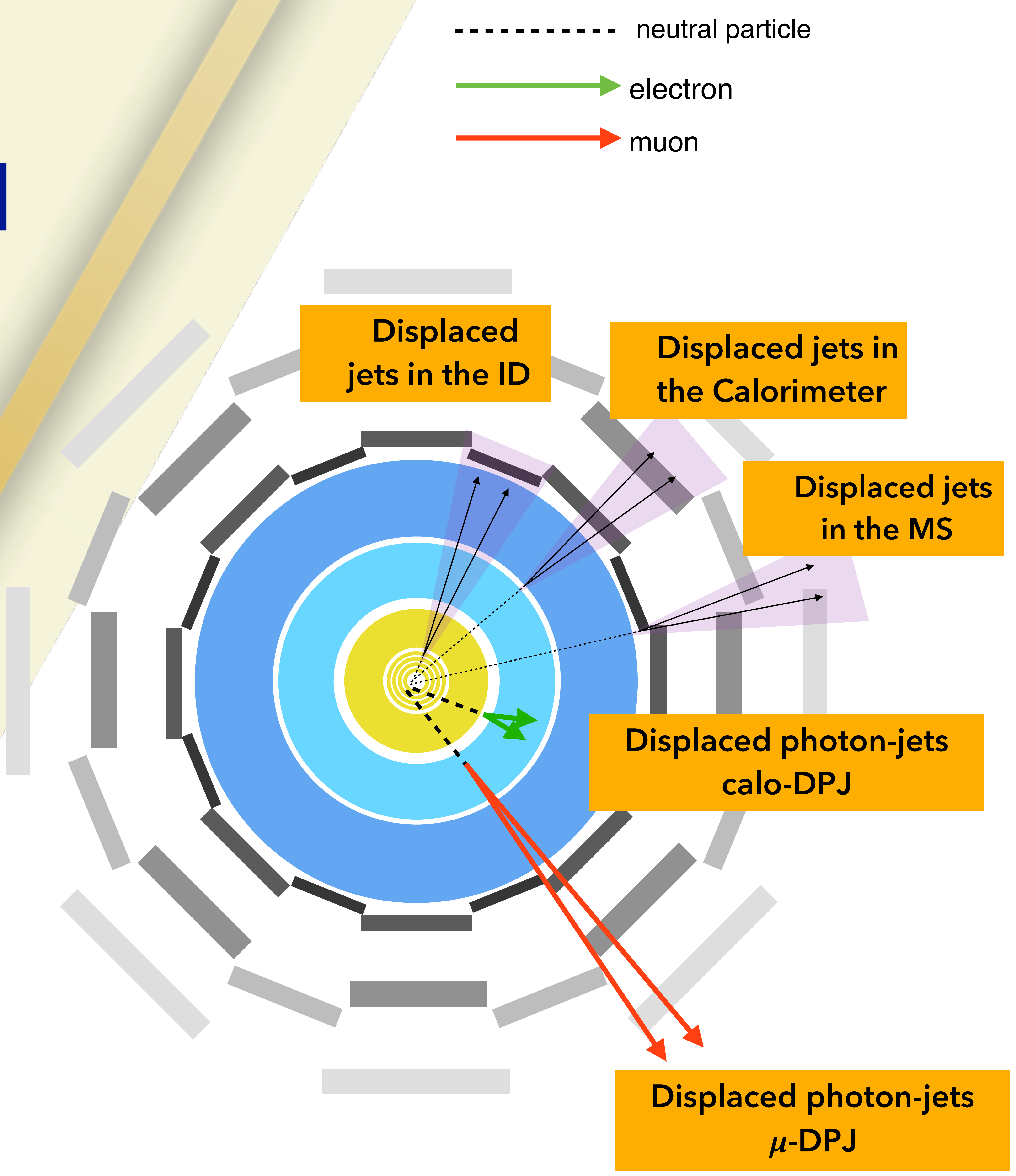
Dark Matter candidates: Hidden Sector and Dark Photons

Excellent Example of:

A. Dedicate trigger algorithm
B. Non-standard Background
C. Application of NN and BDT selection
D. Estimation of expected background via ABCD method

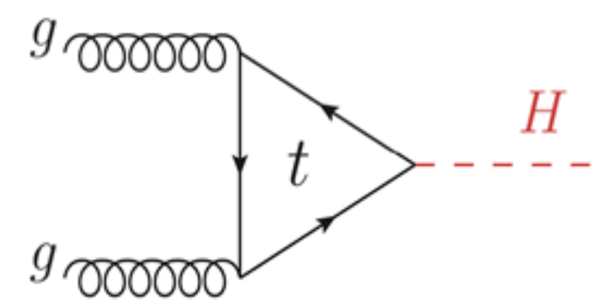


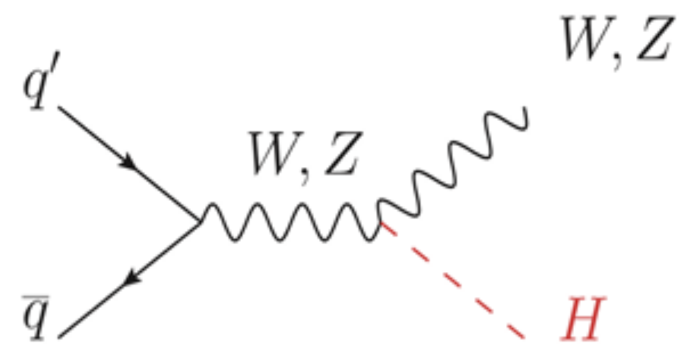
Dark Photon

These analyses explore the existence of a dark sector weakly coupled to the SM. The theory introduced a dark Higgs H_d that decays in dark particles.

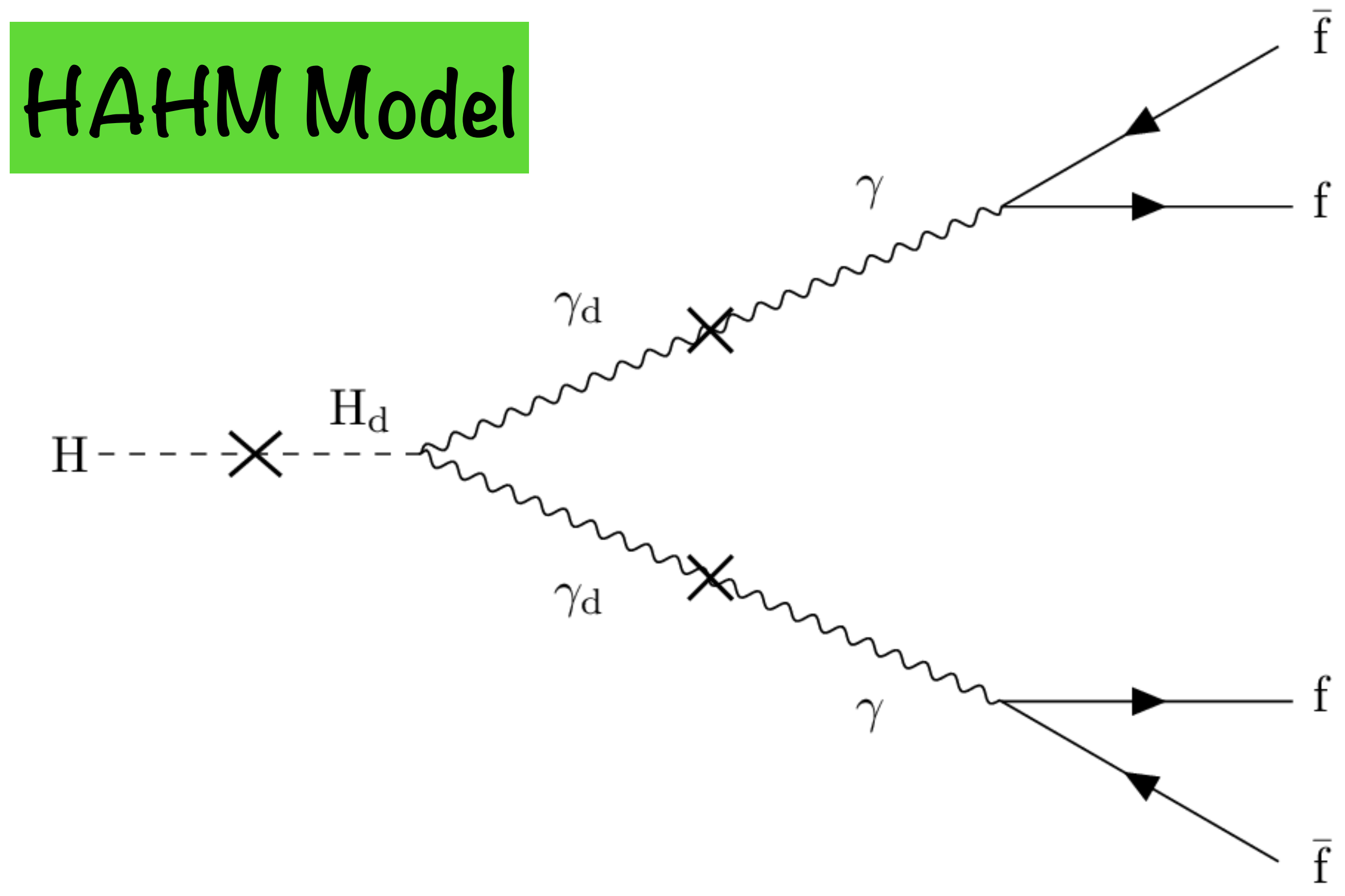
- Higgs boson can be produced via ggF and/or WH processes.
- The benchmark models used in these analyses are the **Falkowski-Ruderman-Volansky-Zupan (FRVZ) model and Hidden Abelian Higgs Model (HAHM)**, where a pair of dark fermions f are produced via a Higgs boson (H) decay or dark photons are directly produced by Higgs boson.

Higgs production

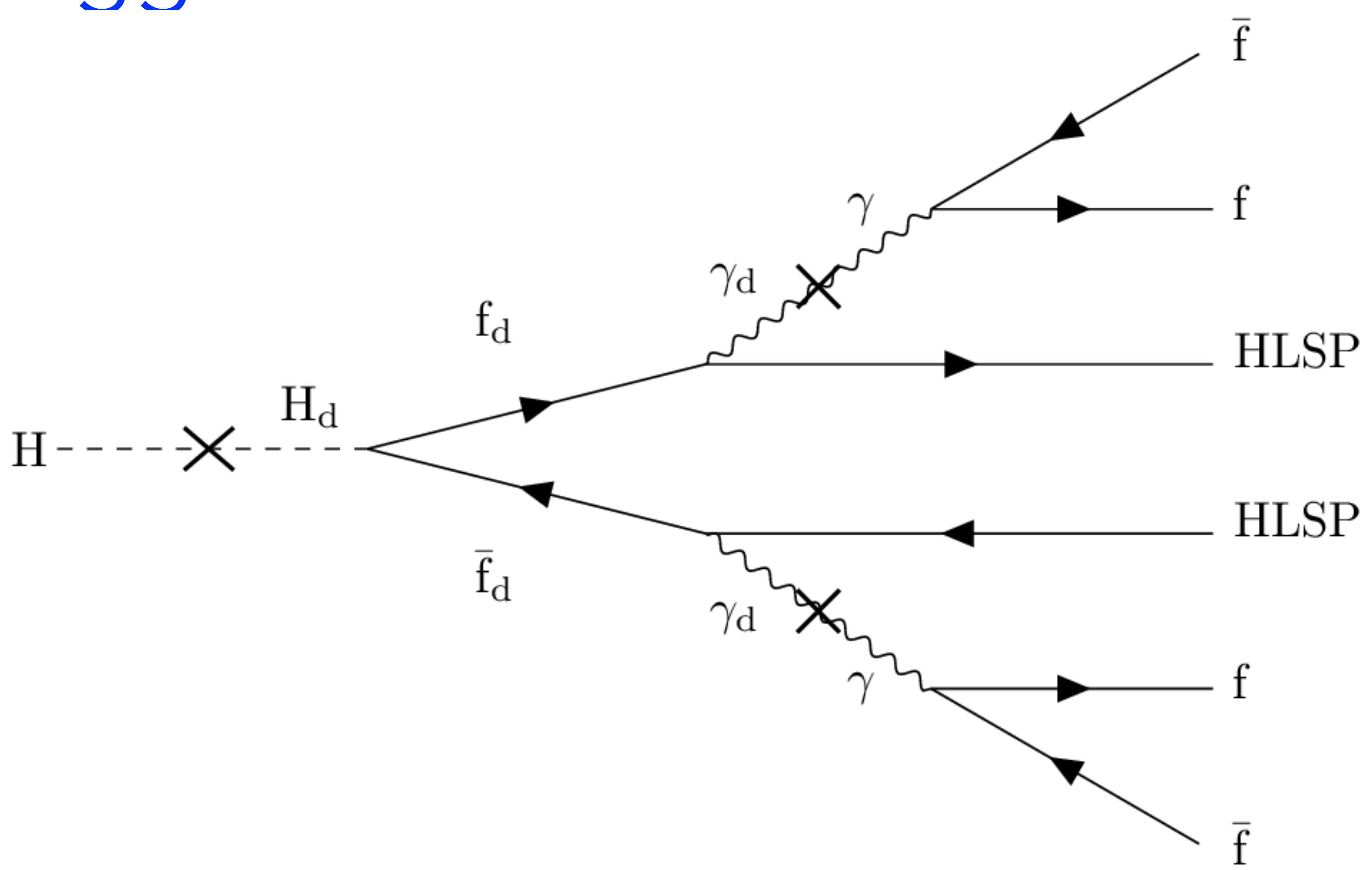




HAHM Model



FRVZ Model



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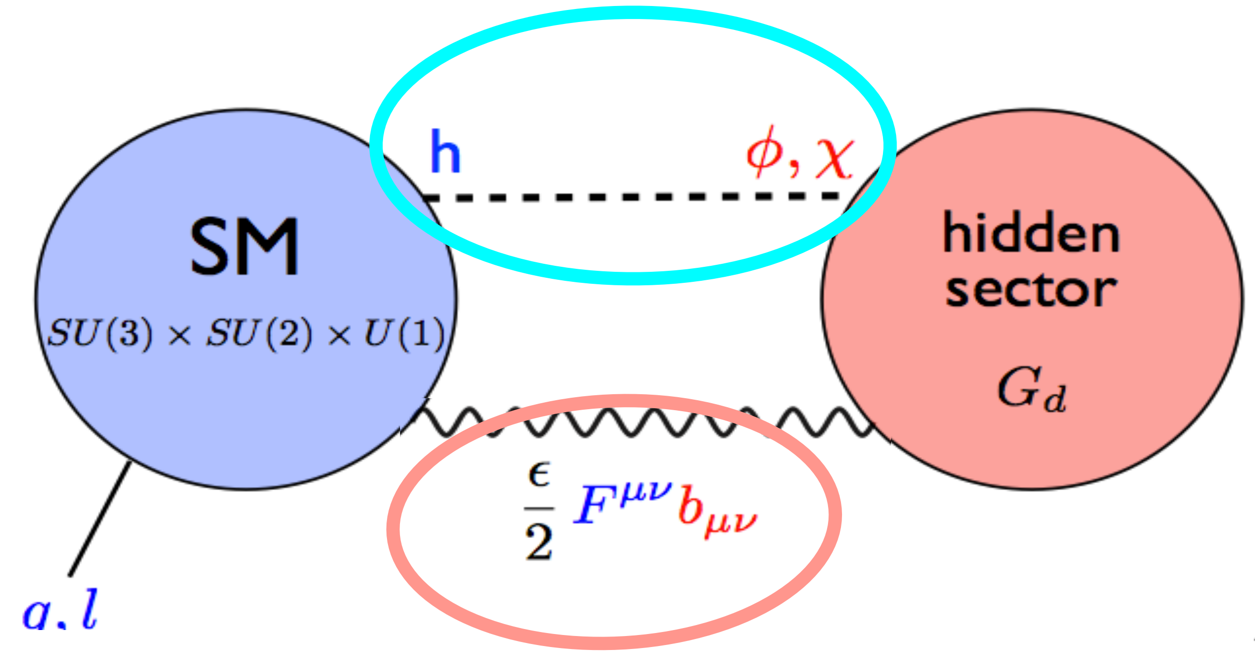
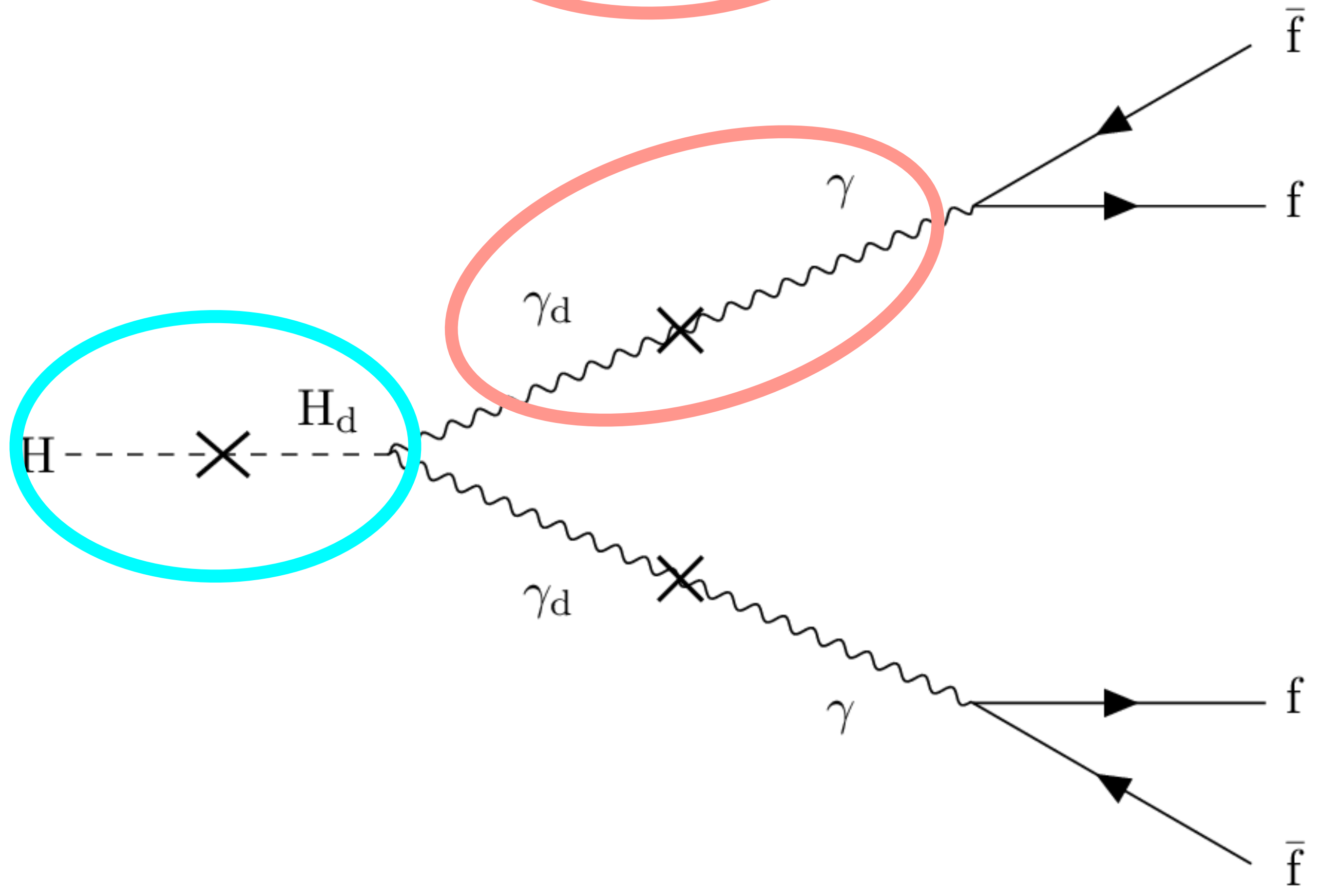
Lifetime of the Dark Photon

The communication of the dark sector with the SM is through kinetic mixing of the dark photon and the standard photon



$$\mathcal{L}_{\text{gauge mixing}} = \frac{\epsilon}{2} B_{\mu\nu} b^{\mu\nu},$$

where $B\mu\nu$ and $b\mu\nu$ denote the field strengths of the electromagnetic fields for the SM and dark sector respectively, and ε is the kinetic mixing parameter.



The kinetic mixing term ε, which can vary over a wide range of values, 10^{-11}- 10^{-2} , determines the lifetime of the dark photon. For a small kinetic mixing value, the f_d has a long lifetime, so that it decays at a macroscopic distance from its production point.

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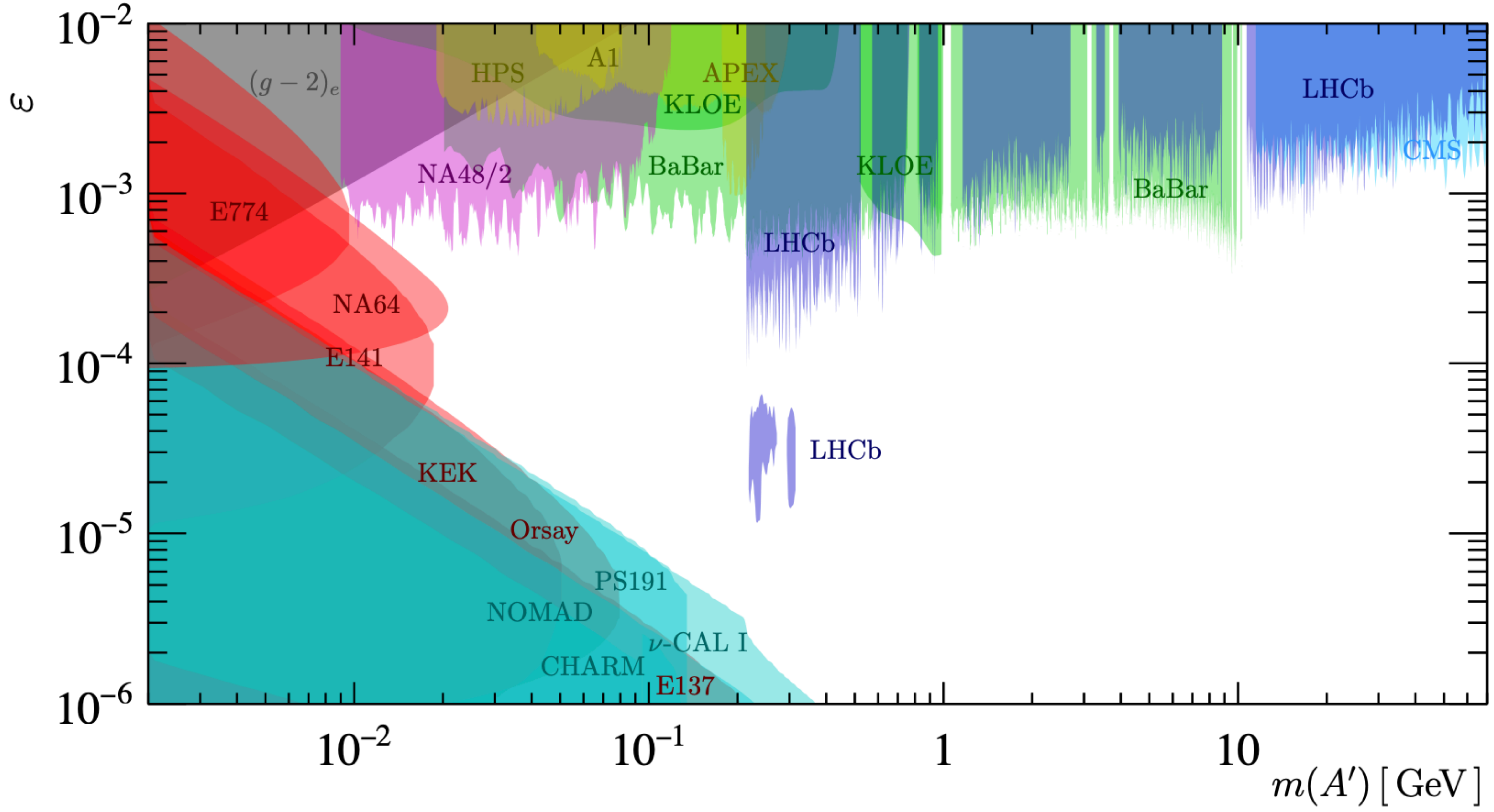
Dark Photon Life Time

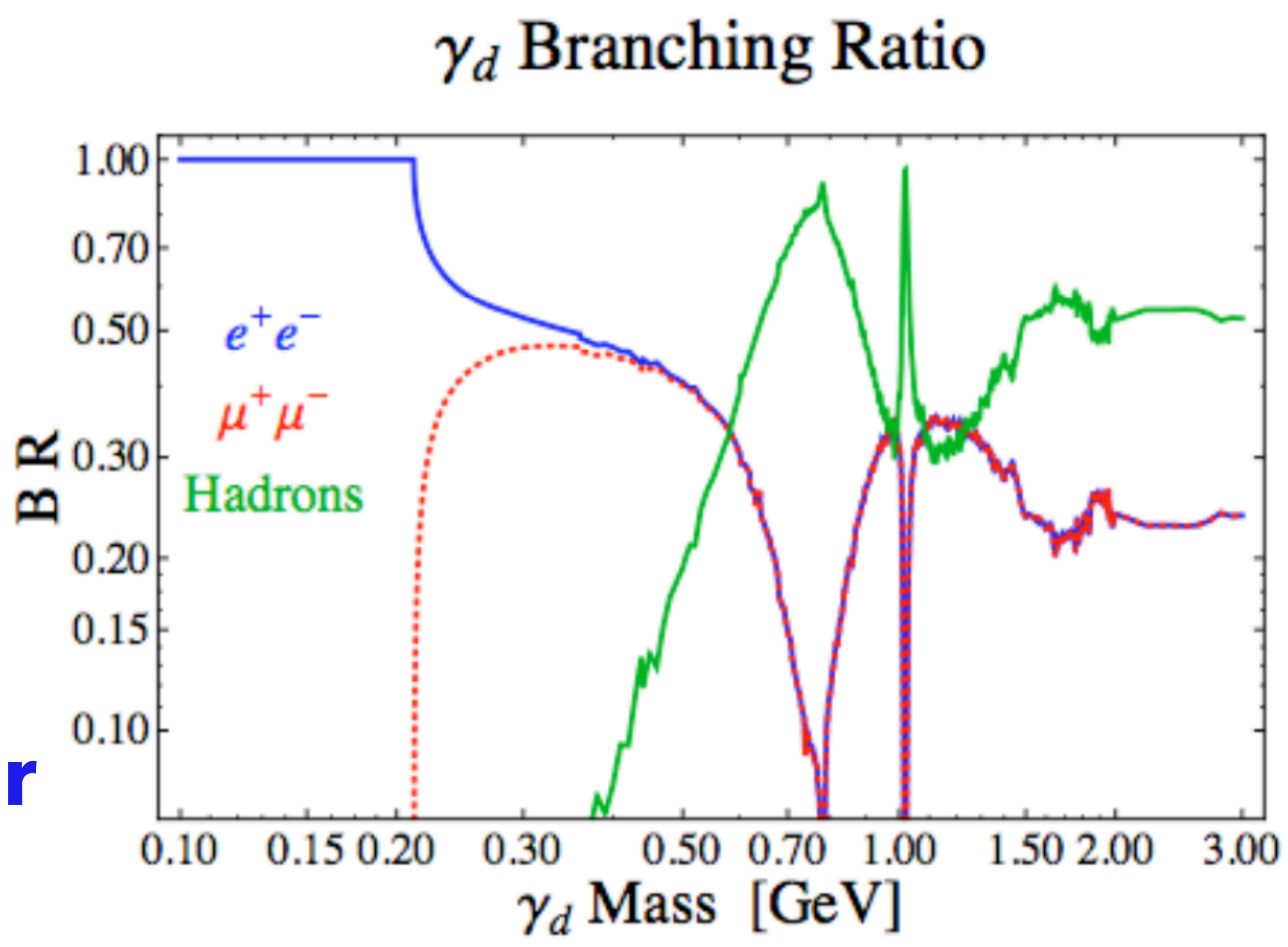


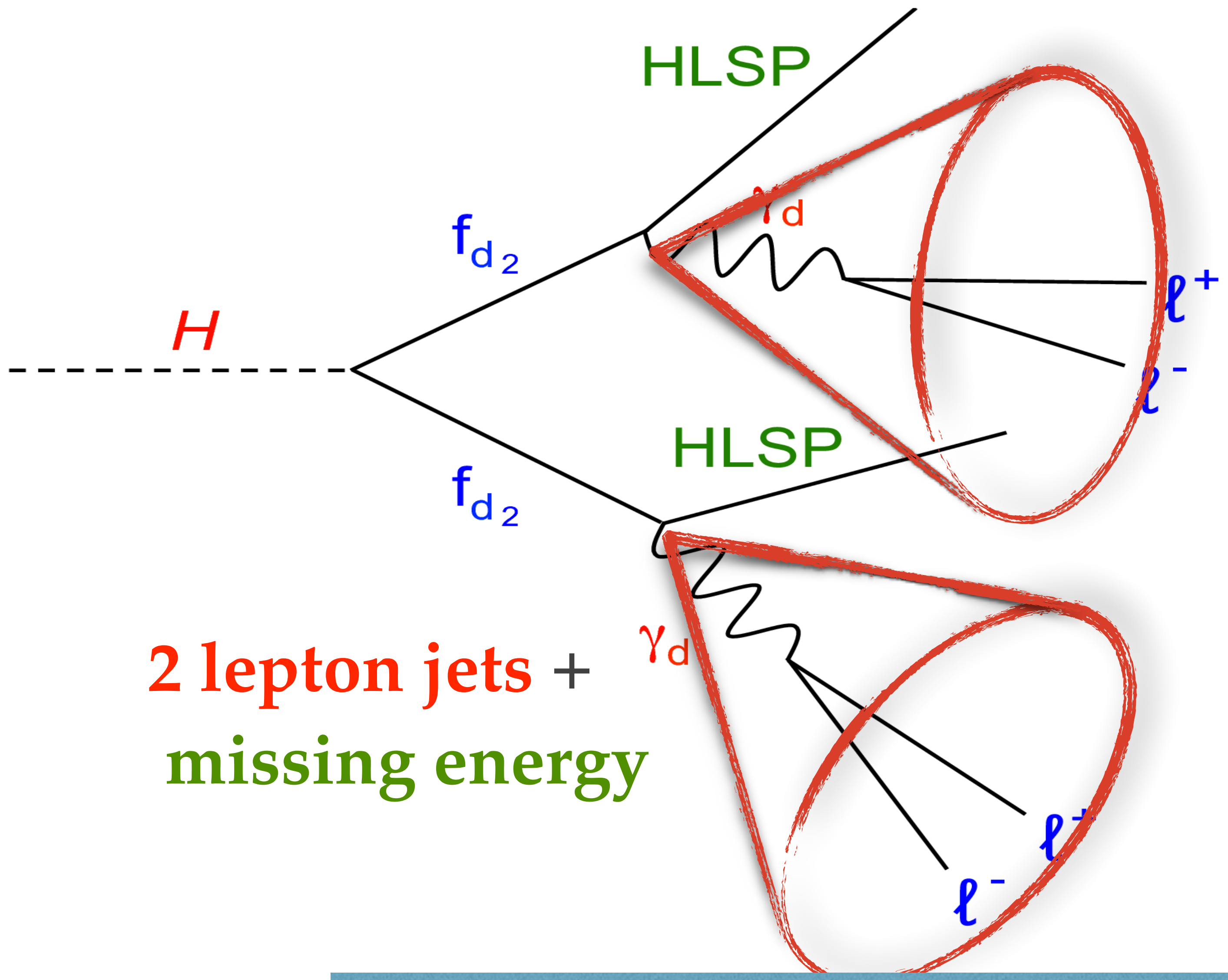
$$\tau \propto \left(\frac{10^{-4}}{\epsilon}\right)^2 \left(\frac{100\ \mathrm{MeV}}{m_{\gamma_d}}\right)^2 \ [\mathrm{s}]$$

The mean life time τ of the dark-photon is inversely proportional to the kinetic mixing parameter ε.

Phenomenology Displaced Photon Jets (DPJ)

- These models predict the existence of **dark photons, light neutral particles decaying into collimated leptons or light hadrons**.
  - This search looks for **long-lived dark photons (small coupling) produced from the decay of a Higgs boson or a heavy scalar boson and decaying into displaced collimated Standard Model fermions.**
- DPJ **is a cluster of highly collimated charged particles**: electrons, muons and pions originated by N neutral light dark photons produced with large boosts → **lepton/hadron pairs in a narrow cone ΔR**
- **DPJ with long-lived γ_d's (small ε) → displaced decays highly isolated in the detector.**





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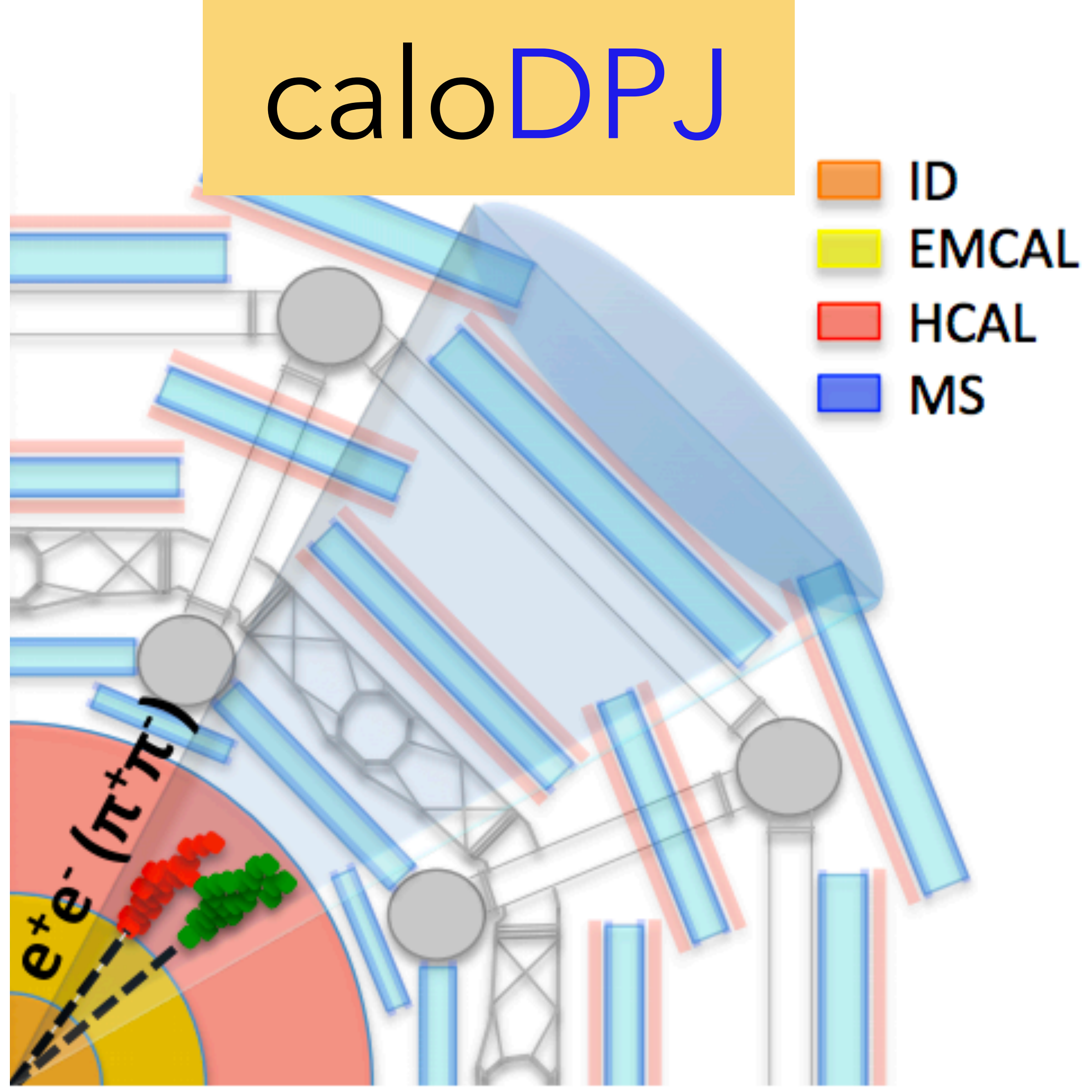
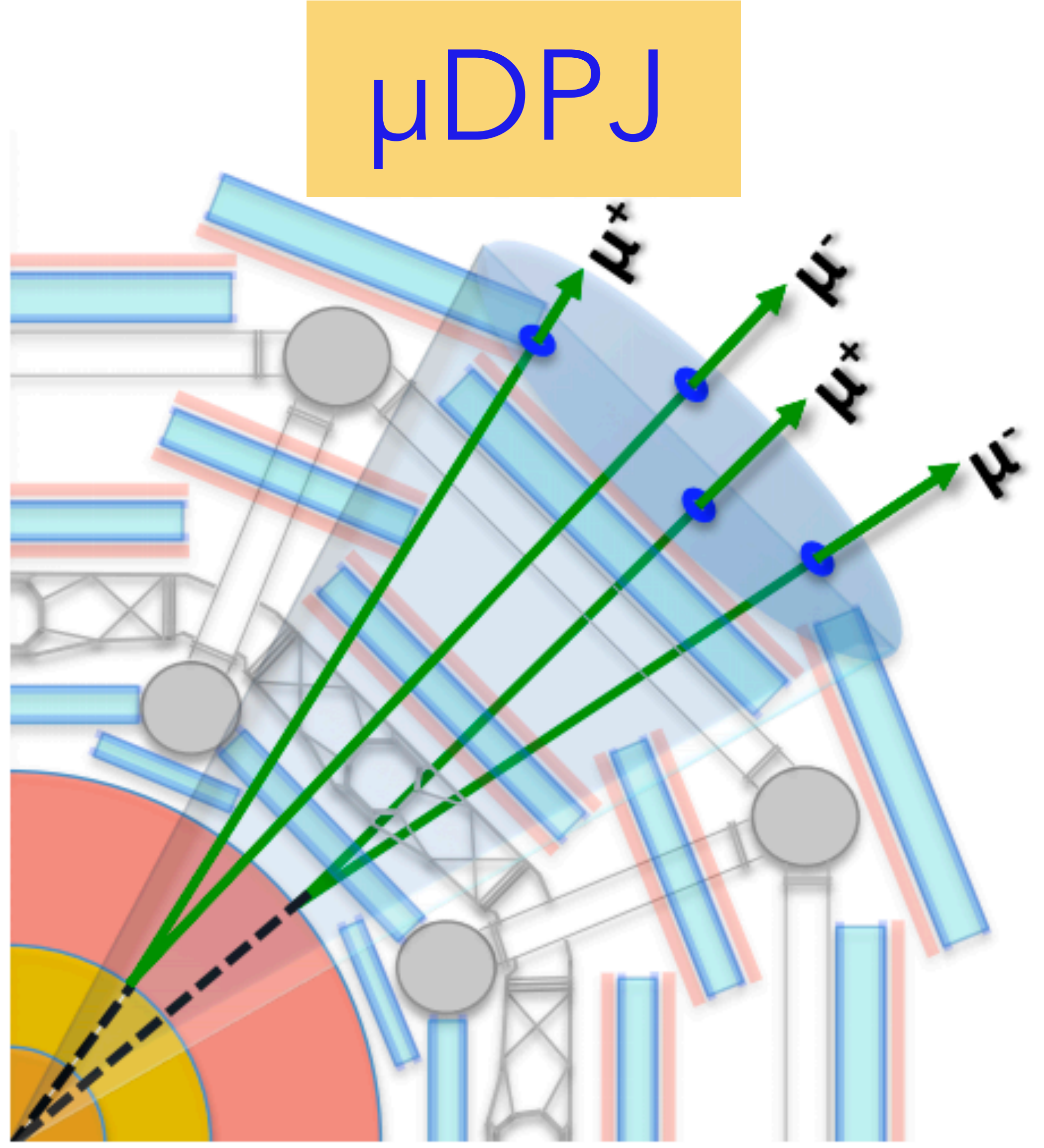
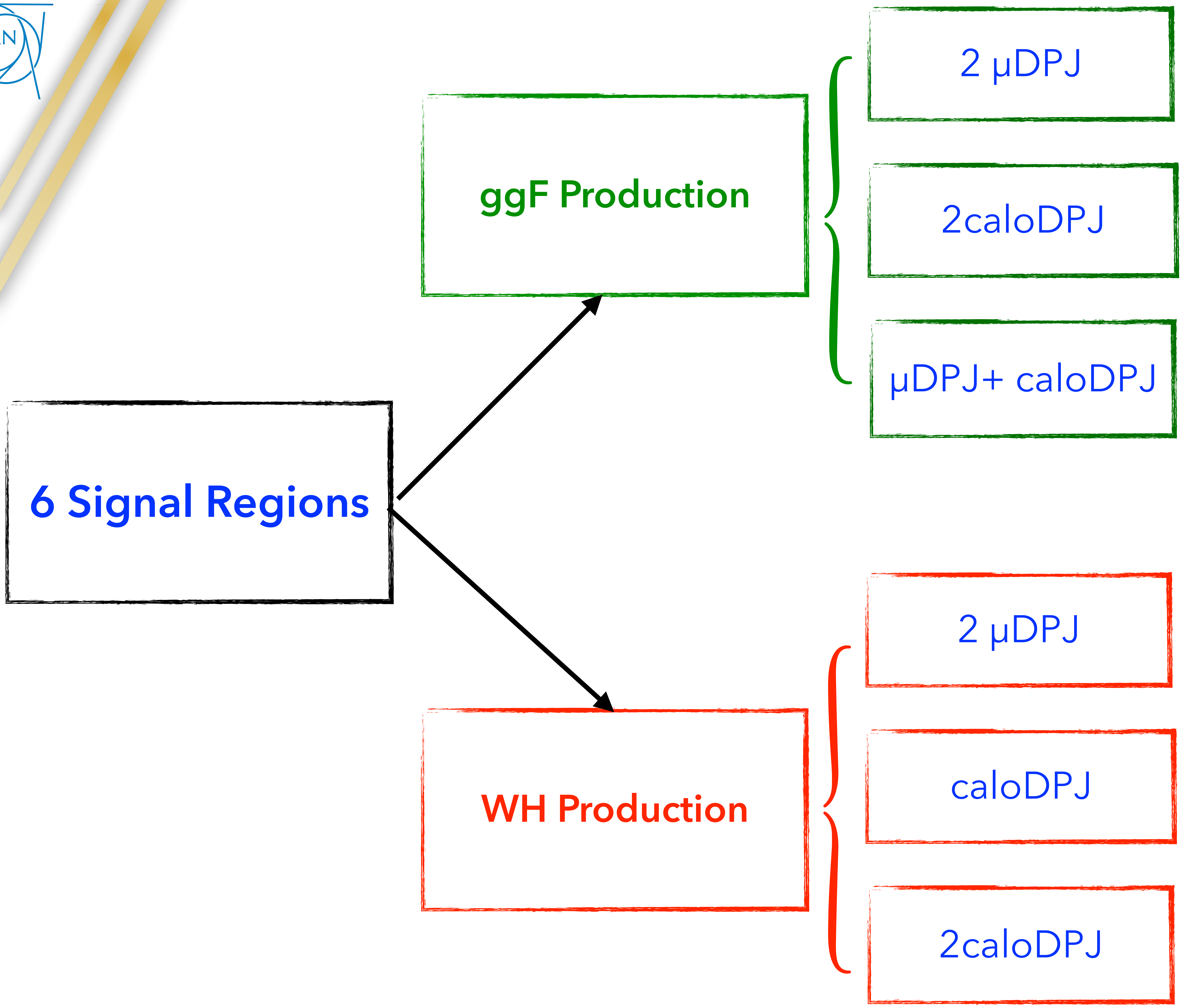
Strategy for Displaced Photon Jets

- The DPJ are characterised into two classes depending on the dark photon decays:
  - muonic-DPJ (μDPJ) – DPJs decays into muons, at least **two muons are required and no jets are allowed in the cone.**
  - calo-DPJ (caloDPJ) – DPJs decays into electron or pion pairs in the HCAL, **one jet is required and no muons are allowed to be in the cone**.
- The analysis exploits **multivariate techniques for the suppression of the main multi-jet background**, optimised for the different DPJ channels
  - **Main Background multijets**, additional background from **non standard collisions events (Cosmic-rays and Beam Interaction)**
  - **Dedicated trigger selection is applied.**





Signal Regions definition for DPJ



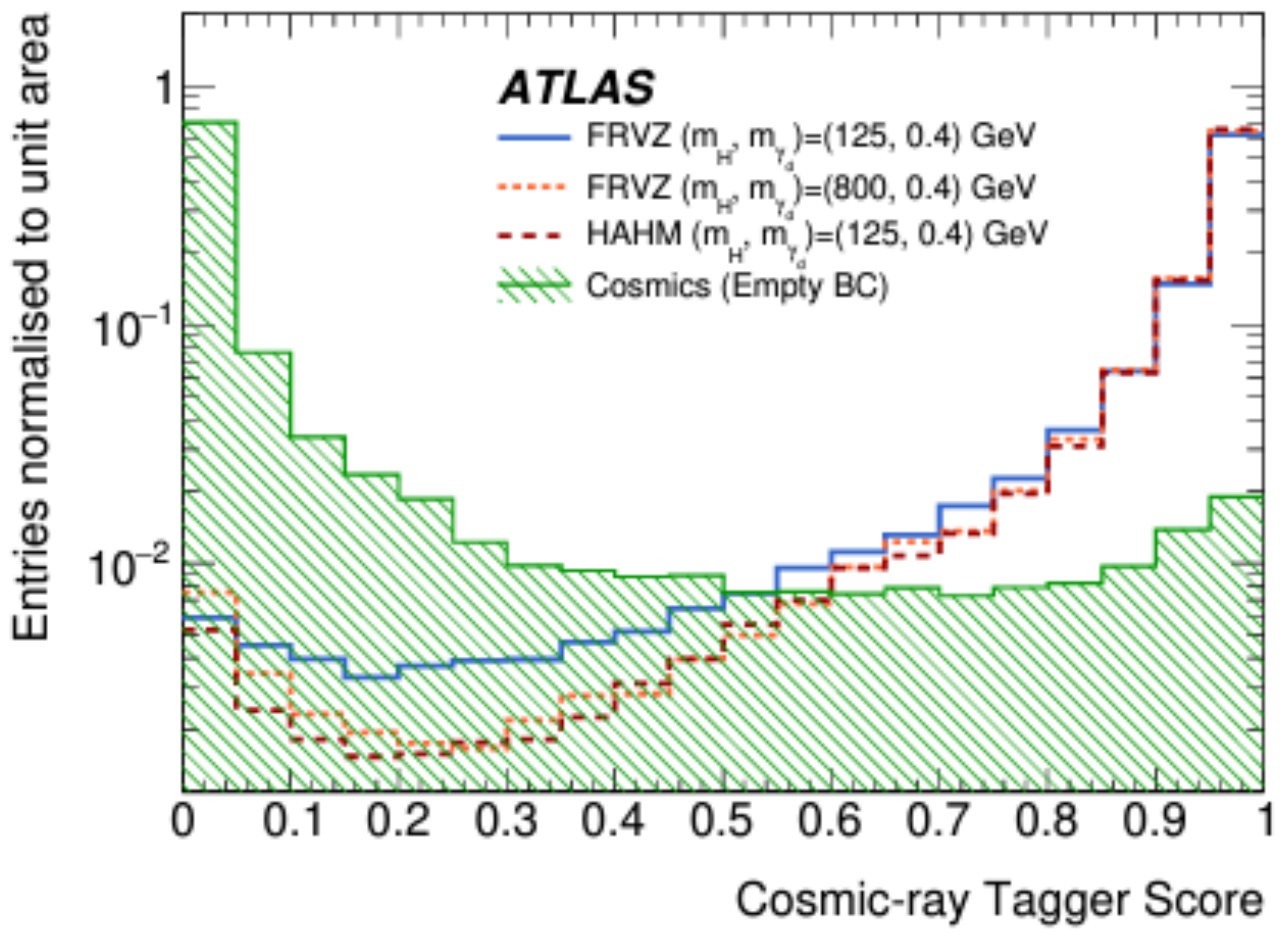
Special trigger

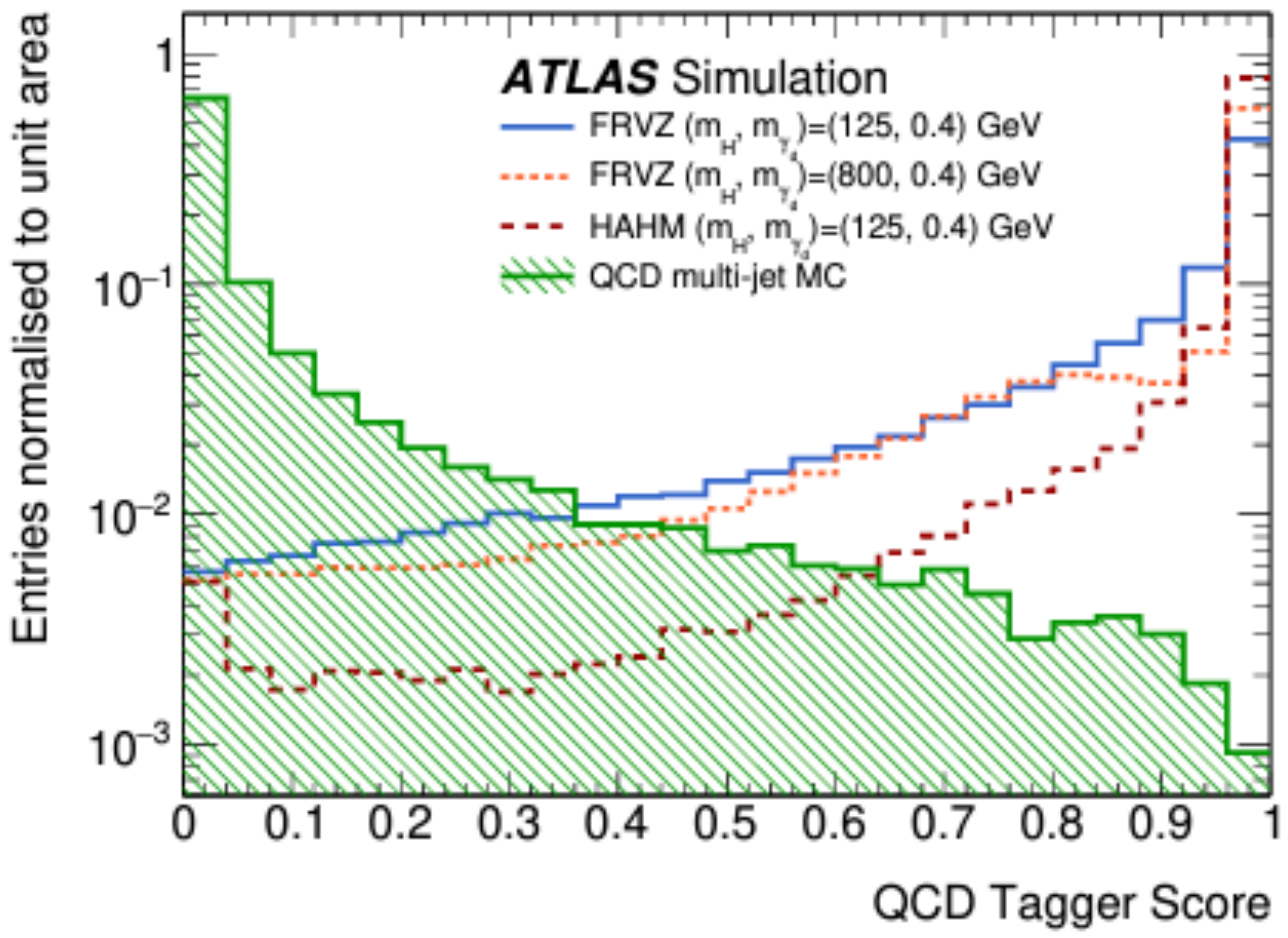
Requirement / Region	$SR^{ggF}_{2\mu}$	SR^{ggF}_{2c}	$SR^{ggF}_{c+\mu}$
Number of μDPJs	2	0	1
Number of caloDPJs	0	2	1
Tri-muon MS-only trigger	yes	—	—
Muon narrow-scan trigger	yes	—	yes
CalRatio trigger	—	yes	—
$\lvert\Delta t_{\mathrm{caloDPJs}}\rvert$ [ns]	—	< 2.5	—
caloDPJ JVT	—	< 0.4	—
$\Delta\phi_{\mathrm{DPJ}}$	$> \pi/5$	$> \pi/5$	$> \pi/5$
BIB tagger score	—	> 0.2	> 0.2
$\max(\sum p_{\mathrm{T}})$ [GeV]	< 4.5	< 4.5	< 4.5
$\prod$ QCD tagger	—	> 0.95	> 0.9

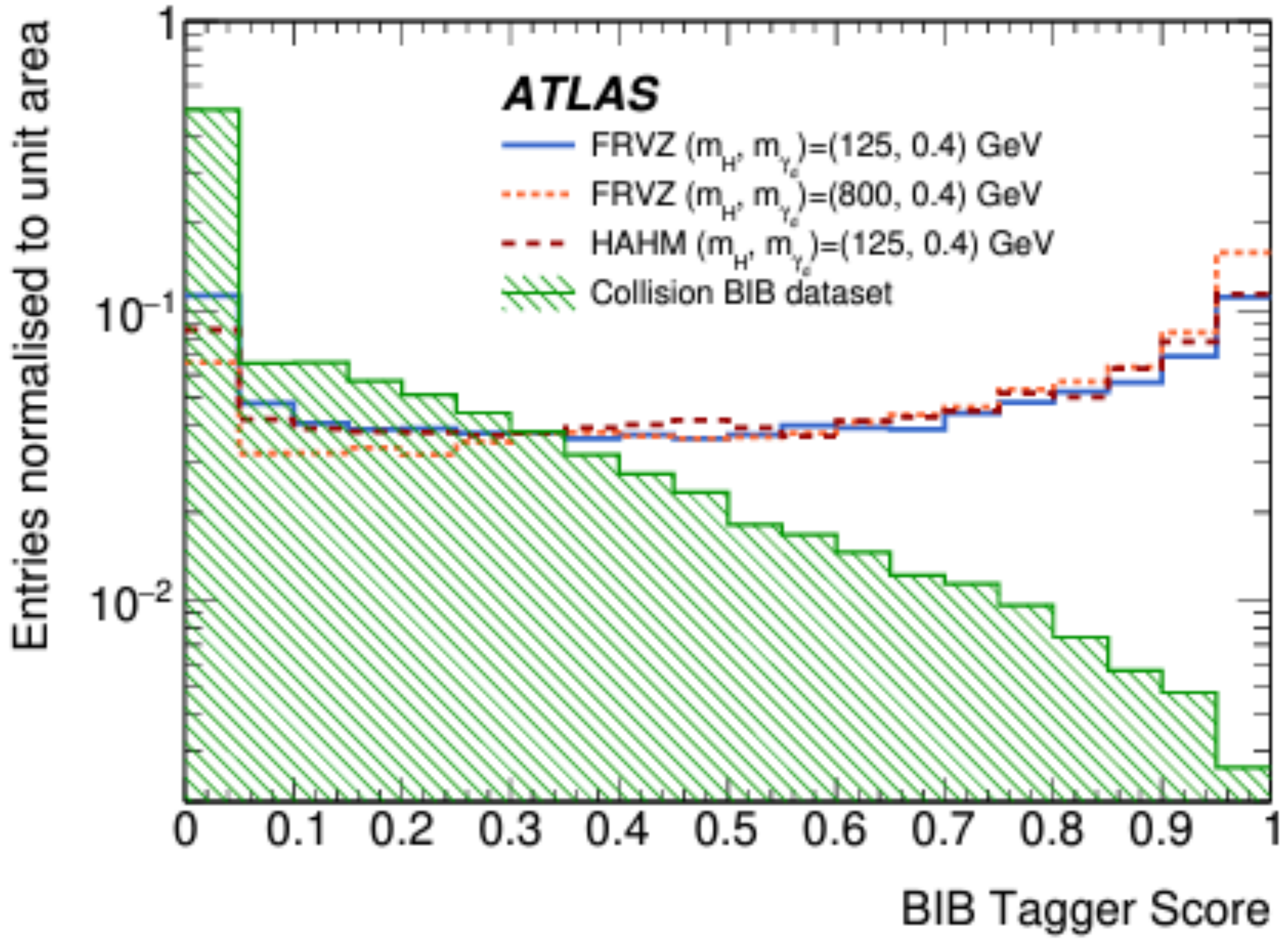
Requirement / Region	SR^{WH}_{c}	SR^{WH}_{2c}	$SR^{WH}_{c+\mu}$
Number of μDPJs	0	0	1
Number of caloDPJs	1	2	1
Single-lepton trigger (μ, e)	yes	yes	yes
m_{T} [GeV]	> 120	—	—
$\lvert t_{\mathrm{caloDPJ}}\rvert$ [ns]	< 4	< 4	< 4
Leading (far) caloDPJ width	< 0.08	< 0.10 (0.15)	< 0.1
caloDPJ p_{T} [GeV]	> 30	—	—
JVT	< 0.6	< 0.6	< 0.6
$\min(\Delta\phi)$	$< 3\pi/5$	$< 3\pi/10$	$< 7\pi/20$
min(QCD tagger)	> 0.99	> 0.91	> 0.9

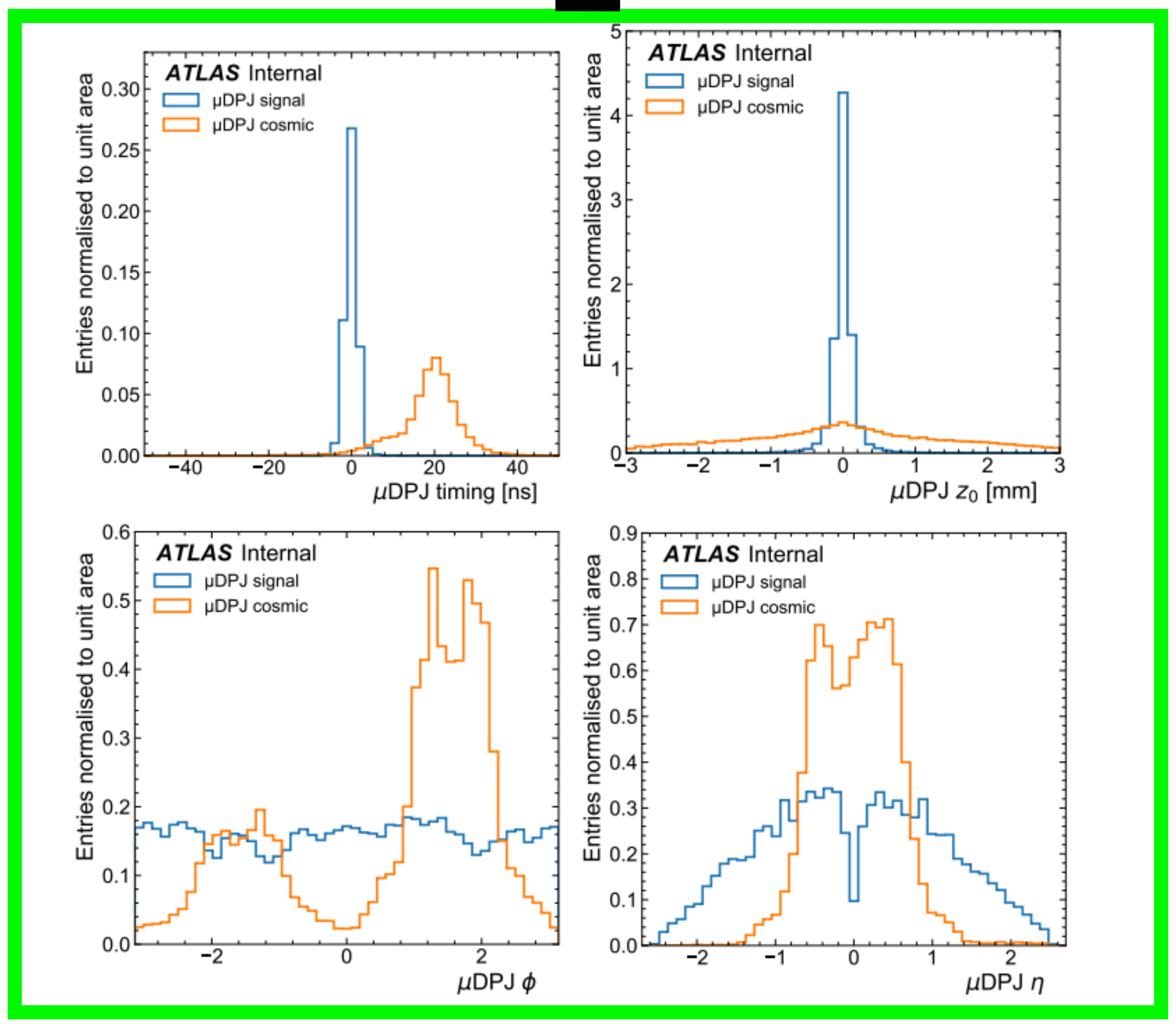
Multi Variate Tagger

- Muonic DJ :cosmic-ray tagger output score > 0.5
- Calo DJ: QCD tagger >0.9 and BIB Tagger >0.2
  - Validation of the background in the ABCD Plane by using SumPt and QCD Tagger





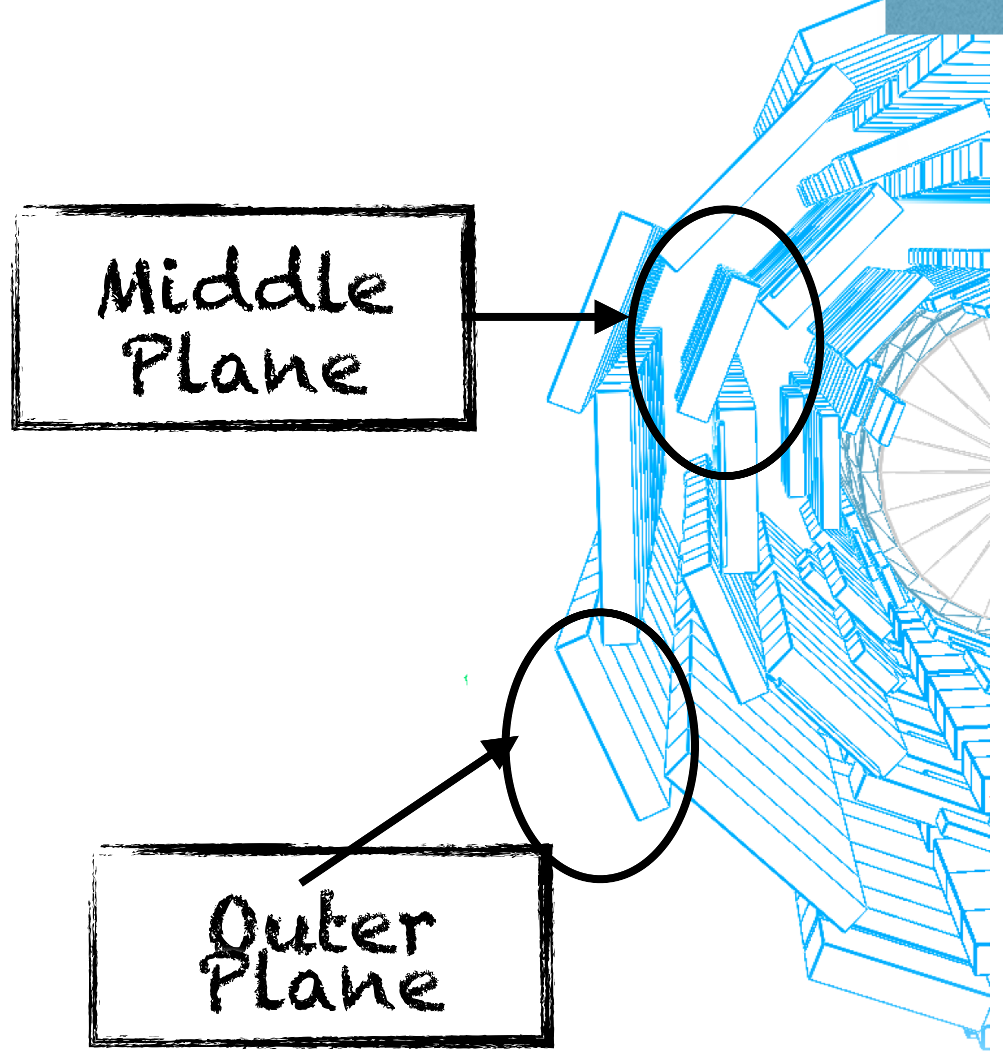


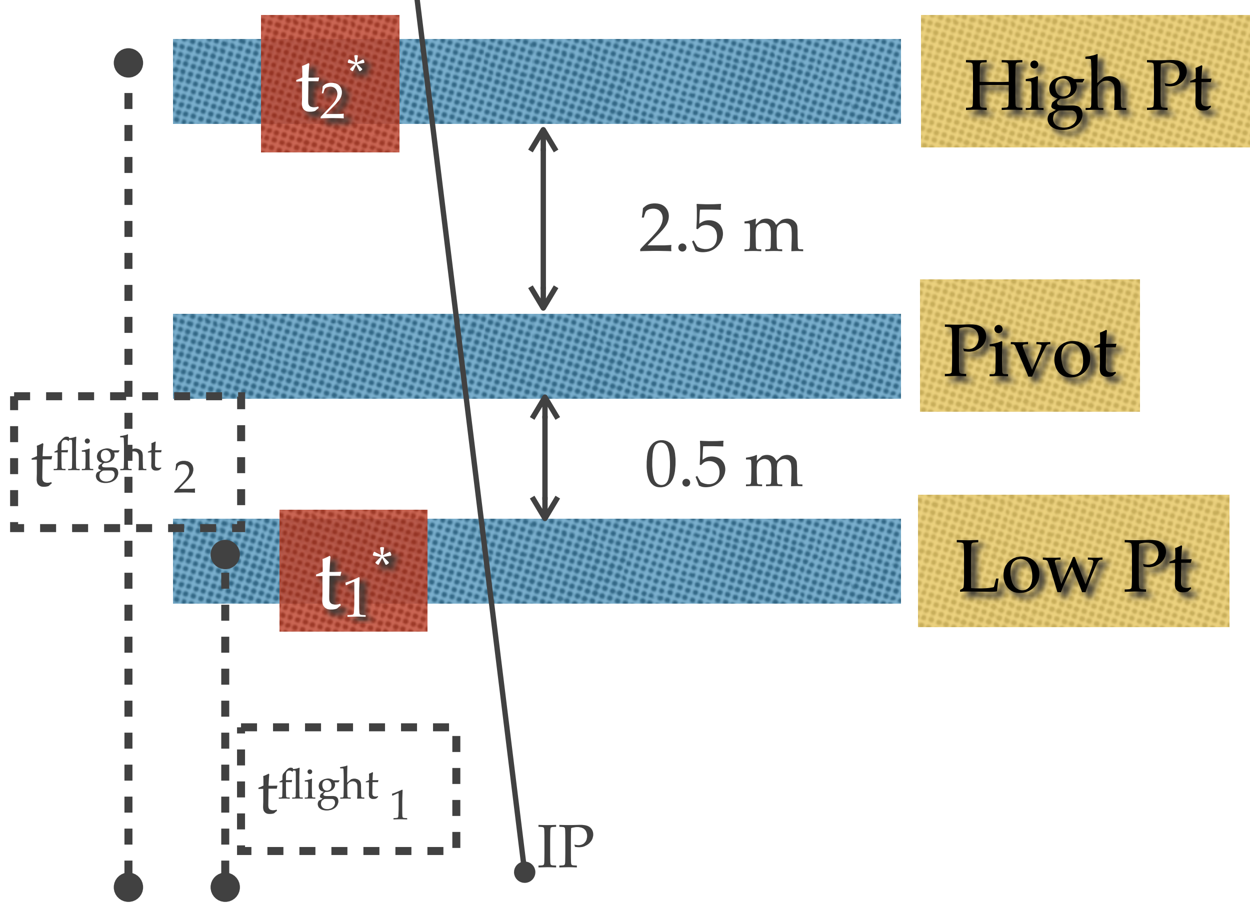


Cosmics ray muons

Eur. Phys. J. C 80 (2020) 450 and arXiv:2206.12181

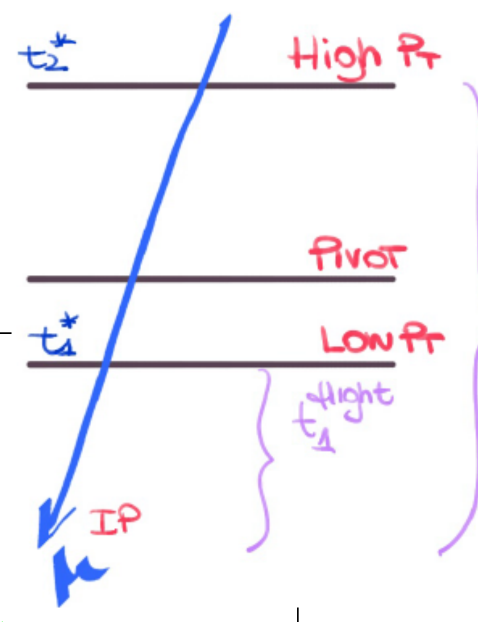
- The Trigger chamber RPC measures the time that is corrected by the time of flight of the muon assuming the IP as the origin of the muon. On each layer the corrected time for a mu from IP is centred zero.
- Looking at the Delta T between Outer and Middle layers is possible to identify the direction of flight of the muon.
- If the muon is a cosmics muon the Delta T corresponds to a defined value :~- 18 ns.
  - the difference is proportional to twice time of flight.





High Pt: BOS +BOL Lxy>9000 mm
Pivot: BML 7750<Lxy<9000 mm
Low Pt: BMS Lxy<7750 mm

t_1^* and t_2^* are the un-corrected RPC time in low and high pt stations



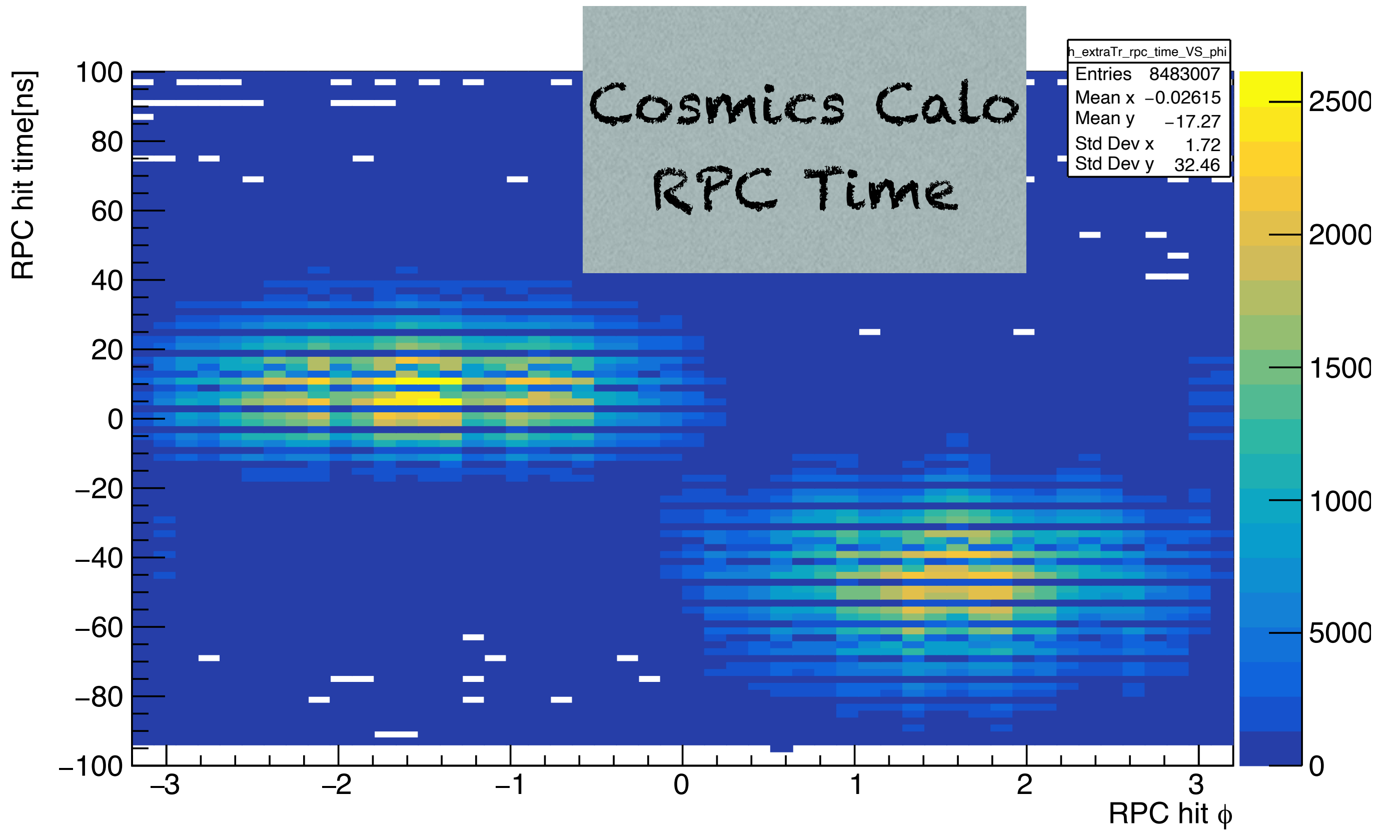
μ from Cosmics

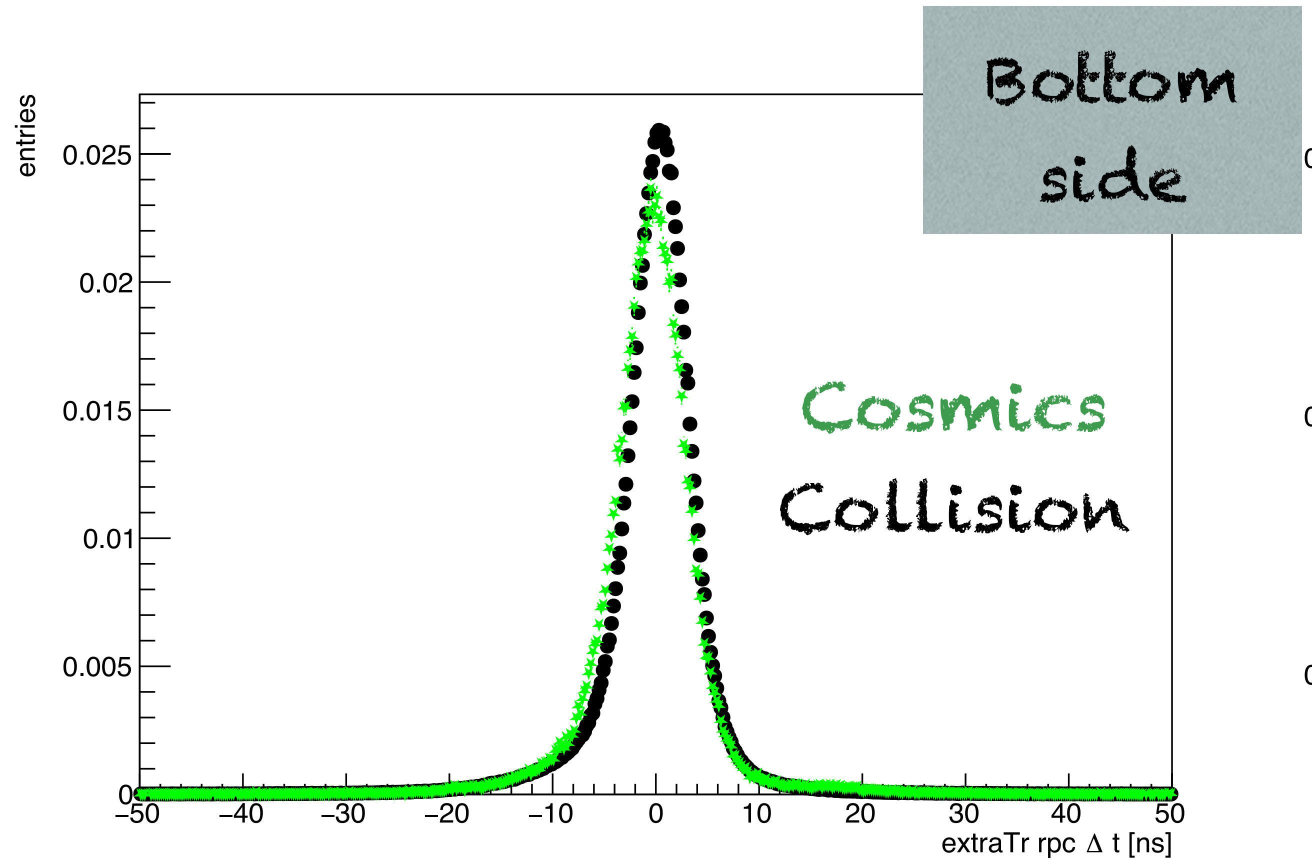
$\Delta T = t_2^* - t_2^F - t_1^* + t_1^F$

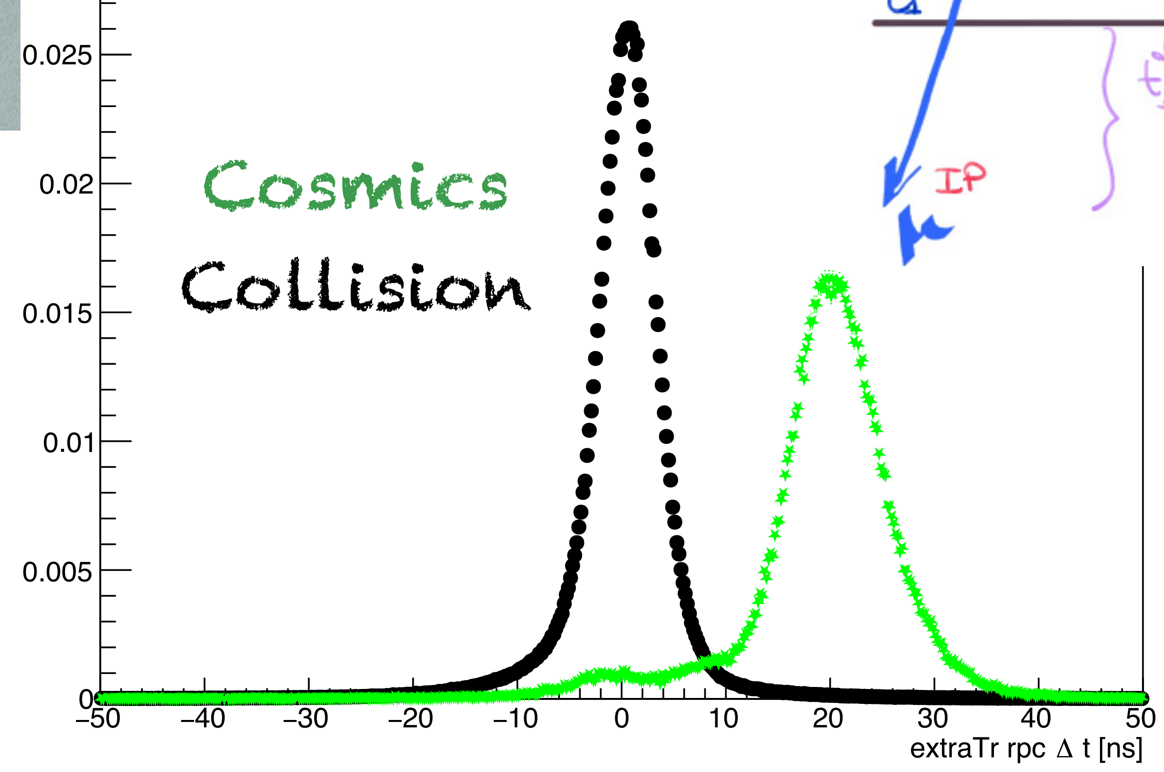
being $t_1^* = t_2^* + (t_2^F - t_1^F)$

$t_2^* - t_2^F - t_2^* - t_2^F + t_1^F + t_1^F$

$= -2(t_2^F - t_1^F)$







Results : Exclusion Limits

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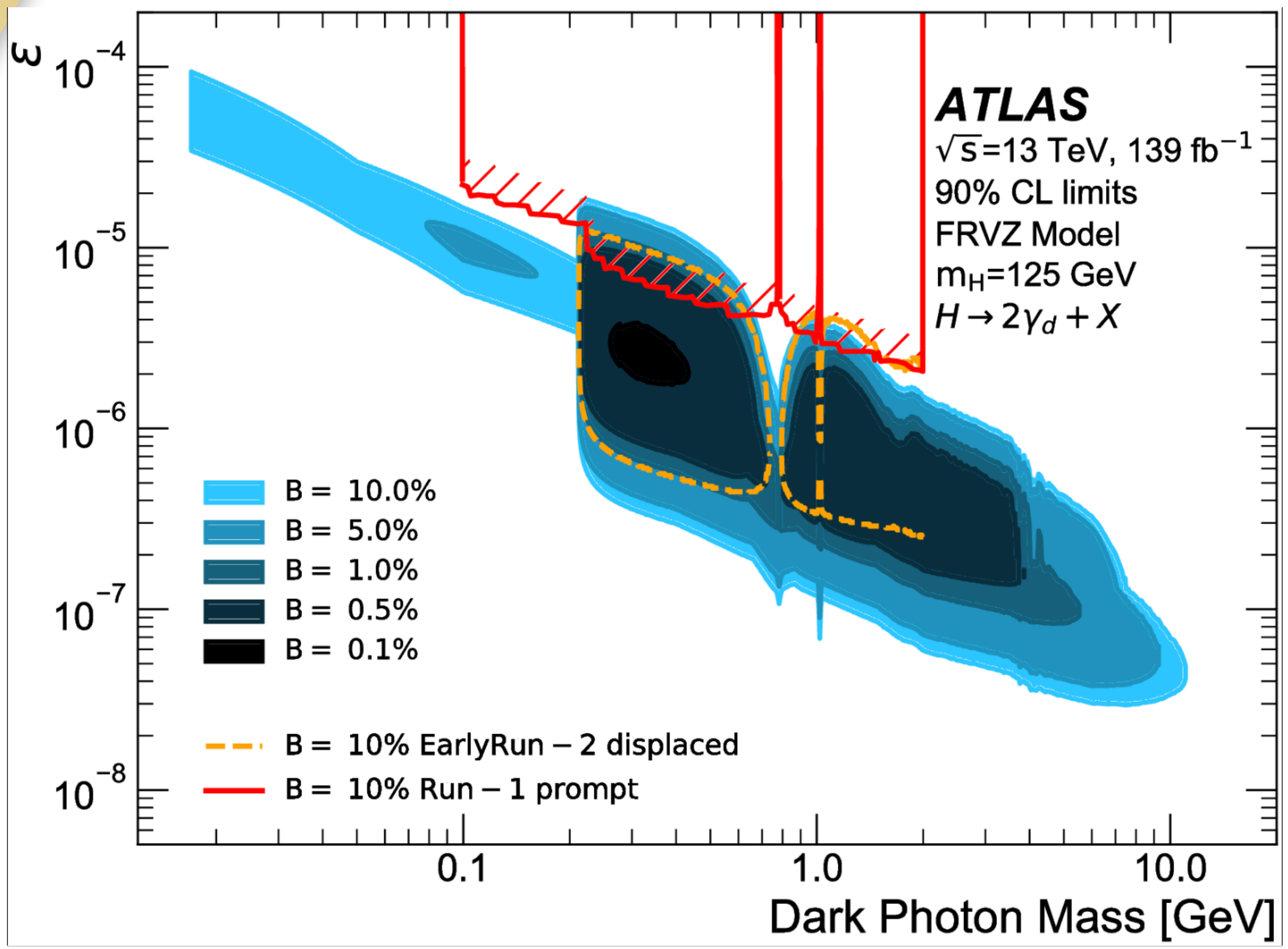
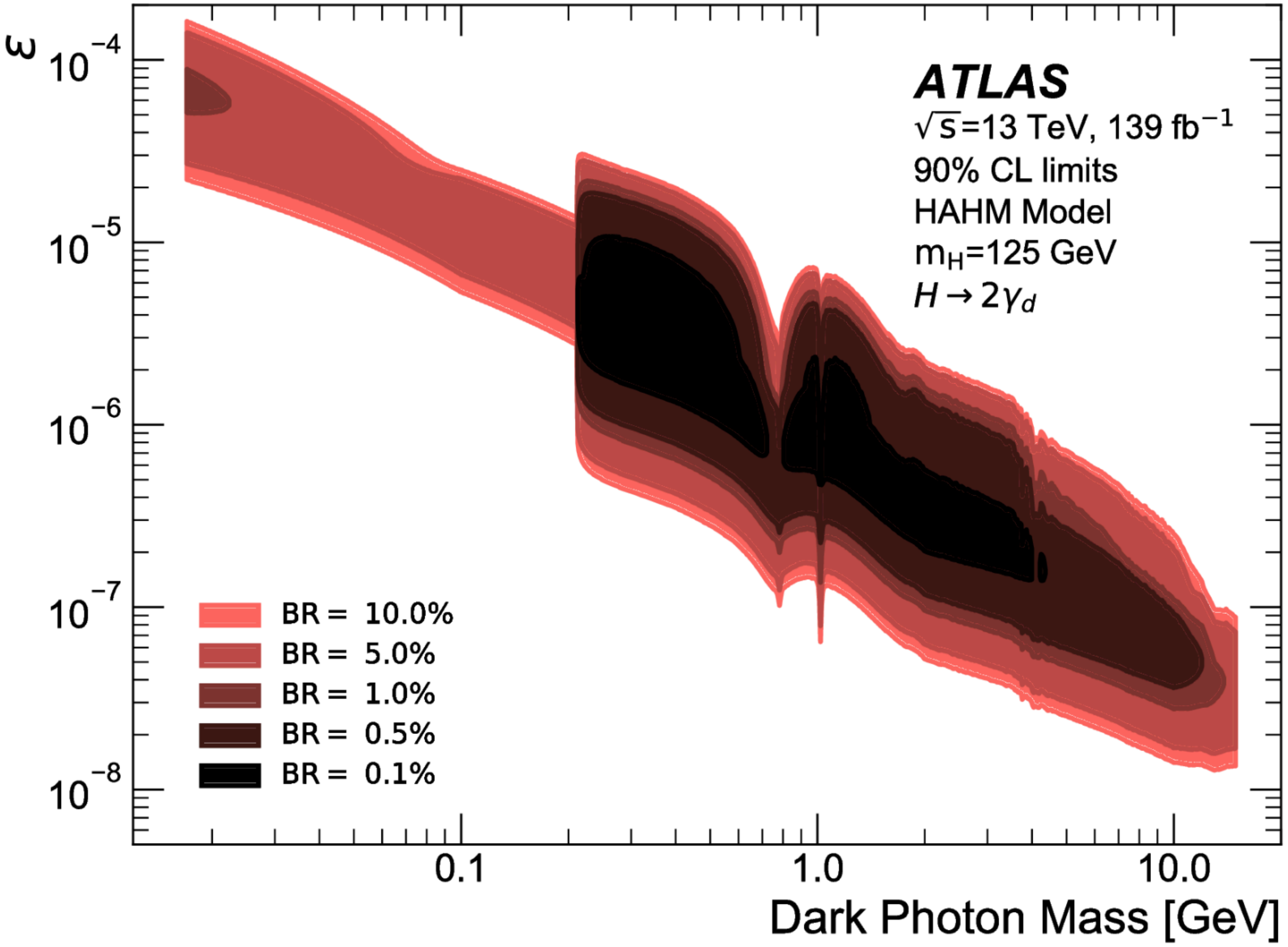




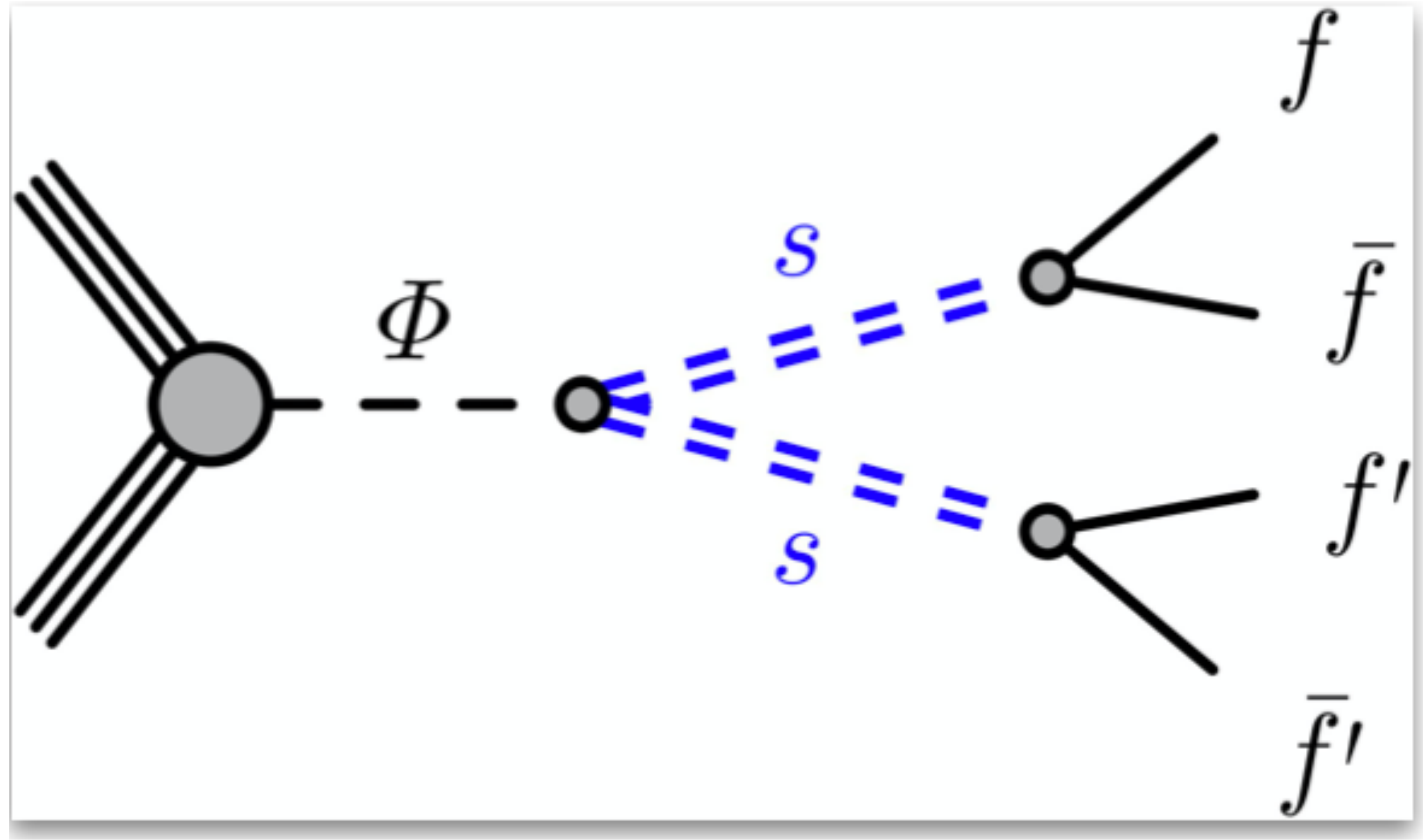
LLP Displaced Hadronic Jets

JHEP 06 (2022) 005

Model Interpretation: Weakly coupled Hidden Sector (HS) communicates with the SM via neutral LLP that decays within the ATLAS detector.

- Scalars decaying to SM fermions (quarks,leptons)

- This analysis explores signature, **where both neutral LLPs decaying in the hadronic calorimeter**, resulting in an atypical jet topology:
  A. Produce narrower cone than typical SM jets originating from the IP
  B. Ratio of energy in the HCal (E_H) to the energy in the ECal (E_{EM}) is large (large $log(E_H/E_{EM})$)
  C. No associated ID tracks to the jet –large ΔRmin between the jet direction and the tracks



Background

- **QCD jets**
  - Jets usually deposits in all subsystems.
  - Large QCD cross-section in pp collisions
- **Beam-induced background (BIB):**
  - LHC beam-gas and beam-halo interactions upstream detector
- **Cosmic backgrounds:**
  - Cosmic rays and external radiation to detector

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Event Selection

- Dedicated signature-driven trigger: **"CalRatio Trigger".**
  - Although the jets from neutral LLP decays pass standard jet triggers, the high prescales of these triggers and the high multijet and other background-process cross-sections required a dedicated trigger

Cuts optimised for models:

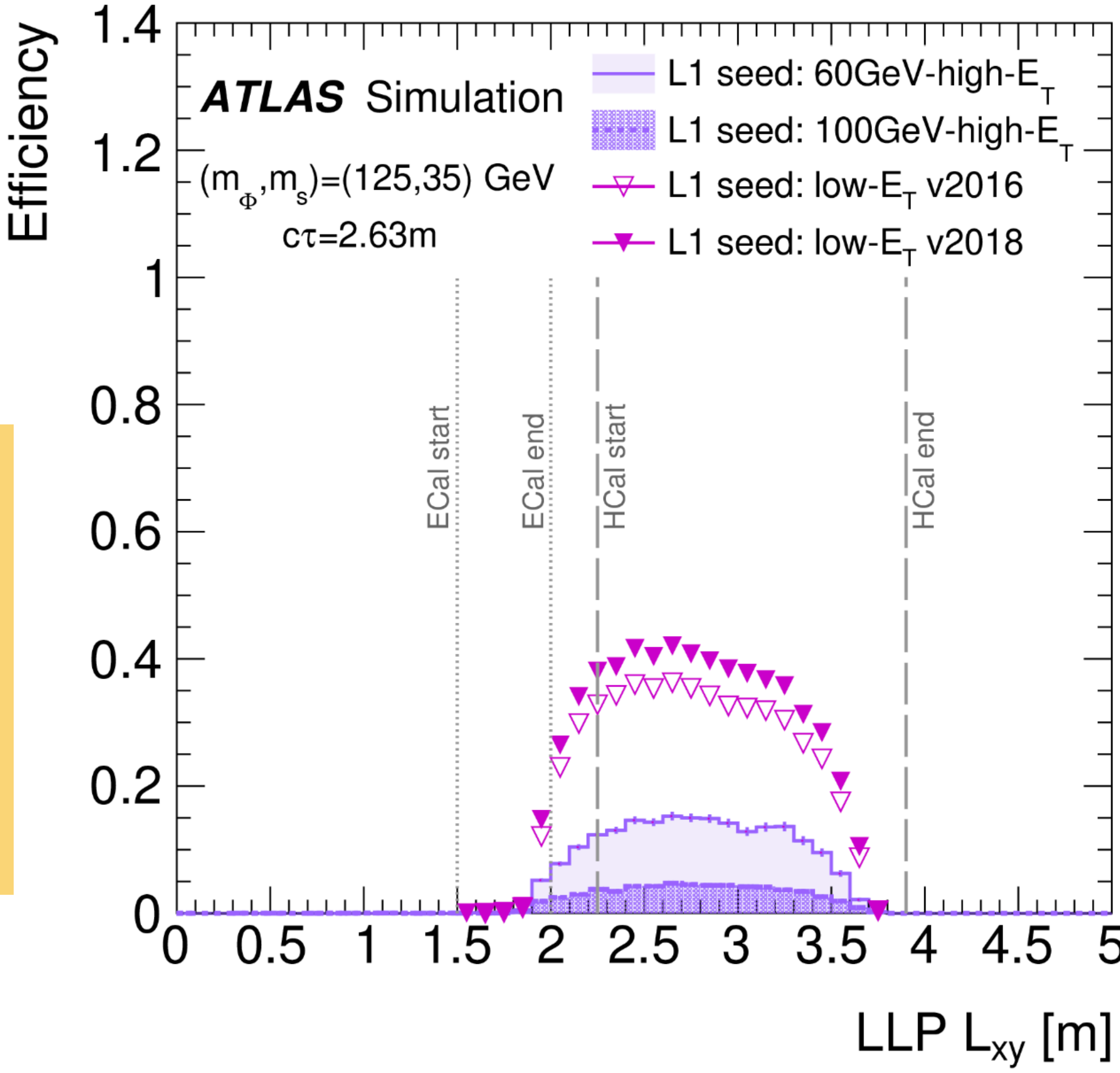
High E_T, mass(Φ)>200GeV

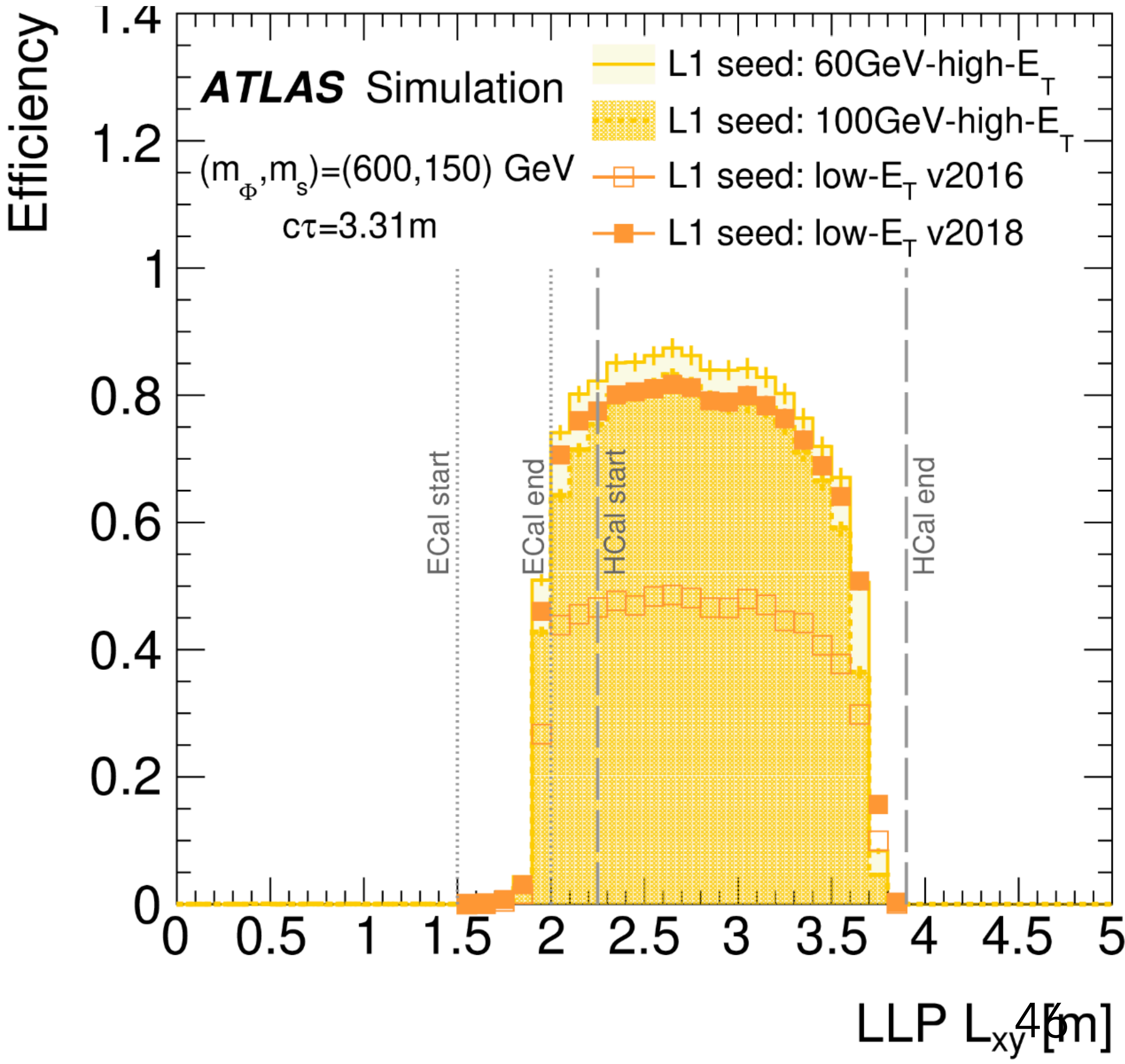
Low E_T, mass(Φ)≤200GeV

- **Select displaced jets : Jet tagging NN.** Distinguish signal vs BIB and QCD
- **Event Selection: BDT per event**
  - Boosted Decision tree (BDT) is used to select signal based on jet-NN signal and BIB score of two leading E_T T jets and event variables
- **ABCD method to define SR and CRs.**

Low-E_T selection
$H_T^{miss}/H_T < 0.6$
$(\sum_{jet^{sig_{1l}}, jet^{sig_{2l}}} \log_{10}(E_H/E_{EM})) > 2$
$p_T(jet^{sig_{1l}}) > 80GeV$
$p_T(jet^{sig_{2l}}) > 80GeV$
low-E_T NN product > 0.7

High-E_T selection
$H_T^{miss}/H_T < 0.6$
$(\sum_{jet^{sig_{1h}}, jet^{sig_{2h}}} \log_{10}(E_H/E_{EM})) > 1$
$p_T(jet^{sig_{1h}}) > 70GeV$
$p_T(jet^{sig_{2h}}) > 80GeV$
high-E_T NN product > 0.5





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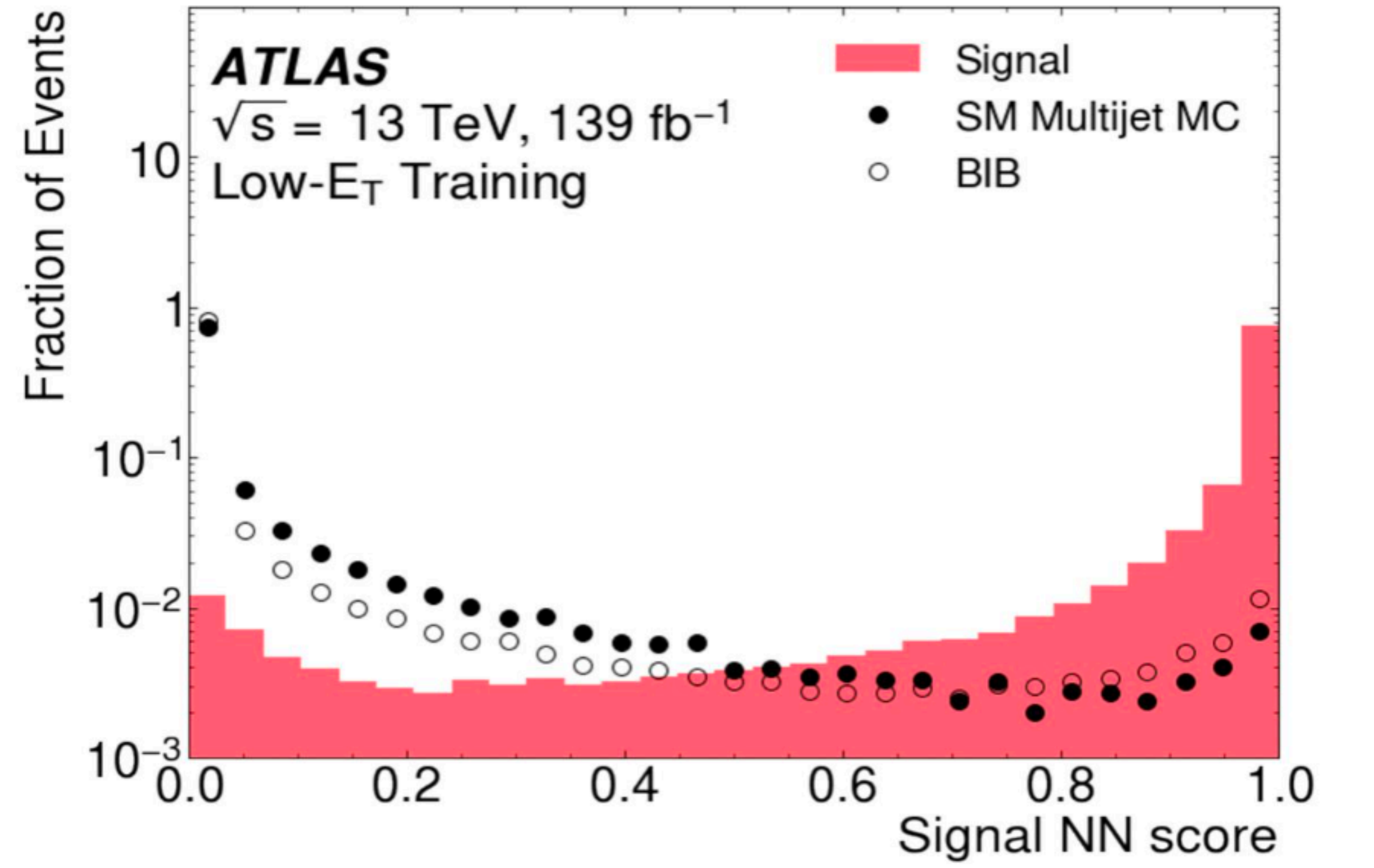
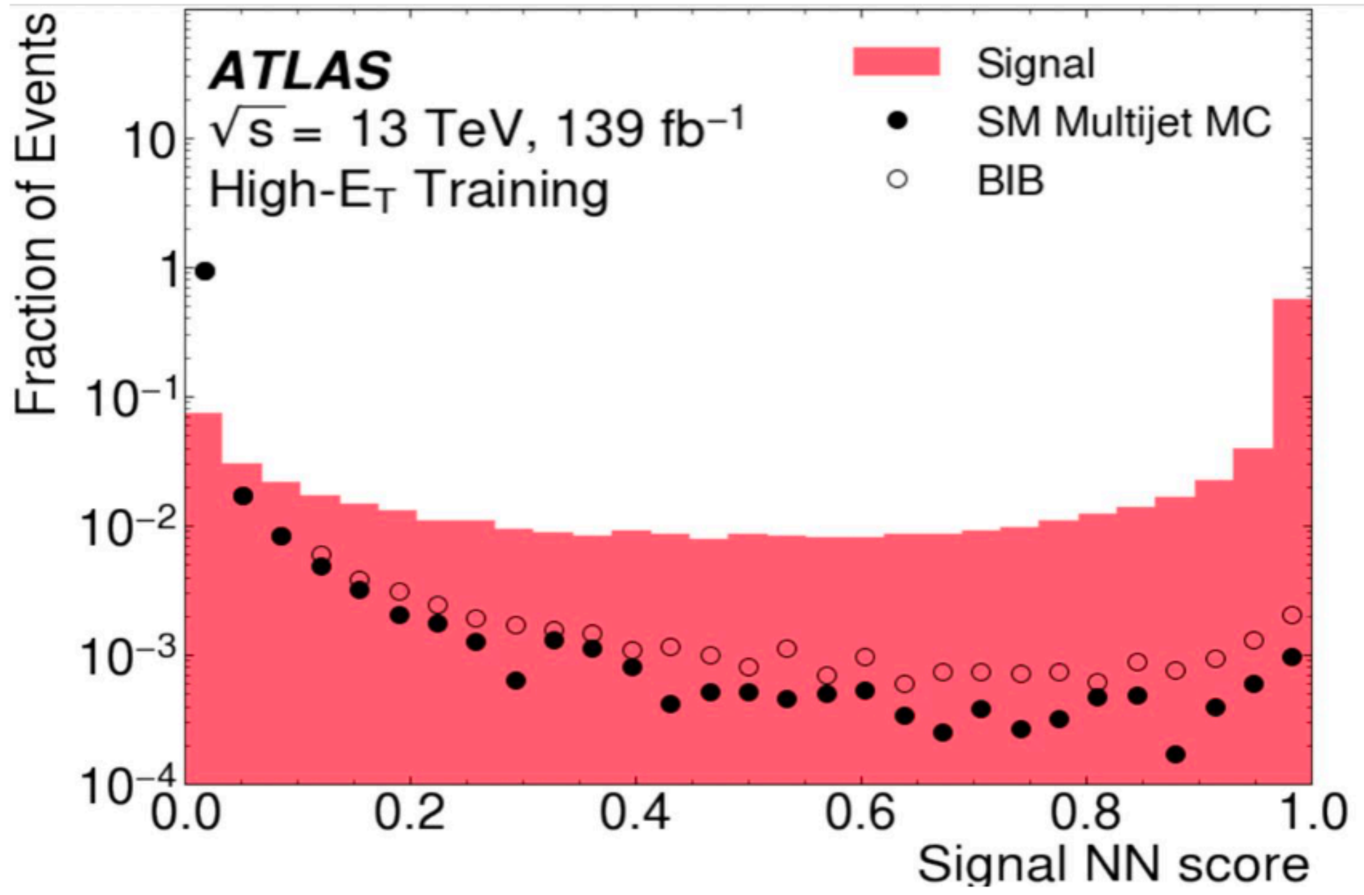
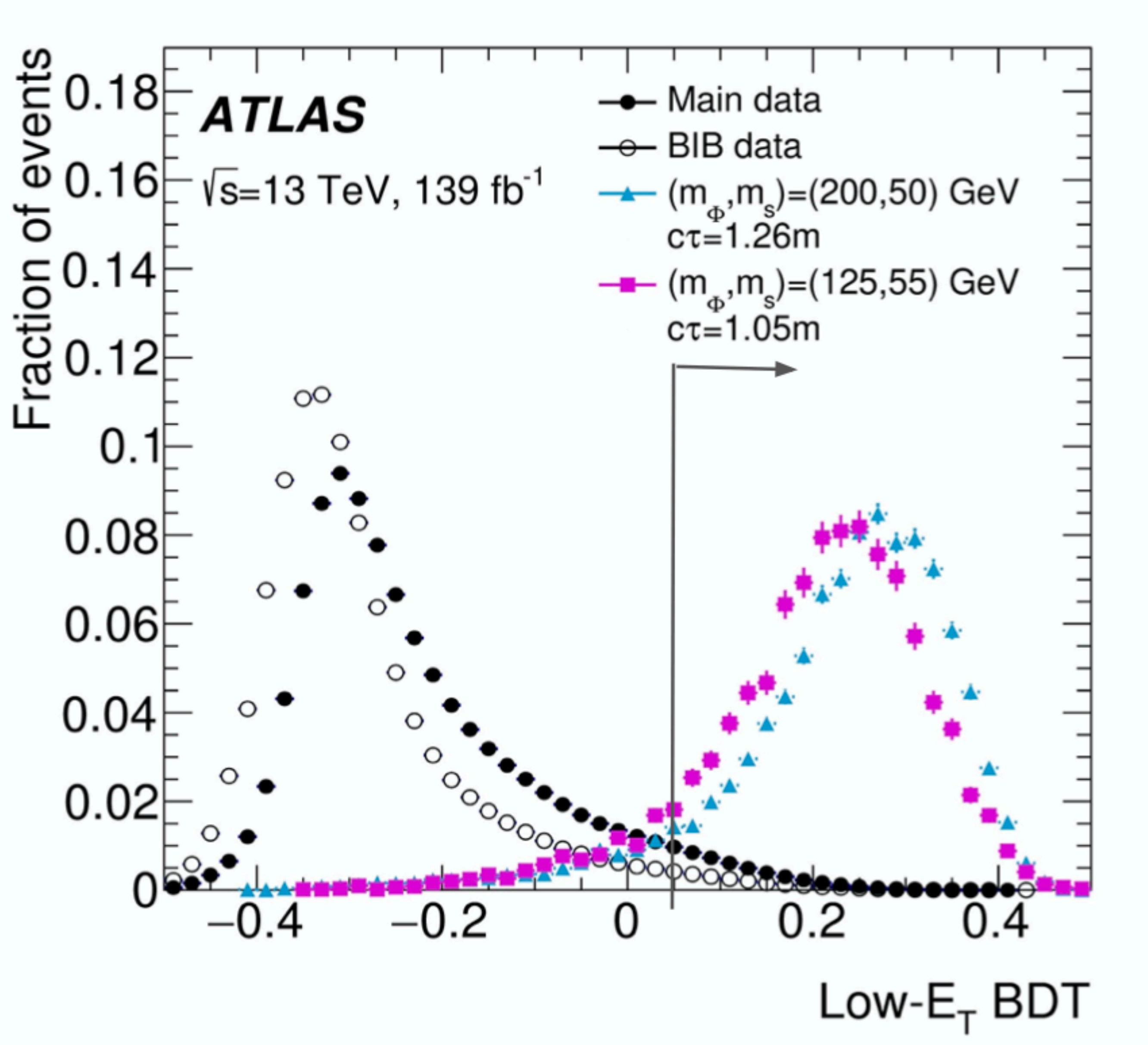
Jet NN and BDT Selection

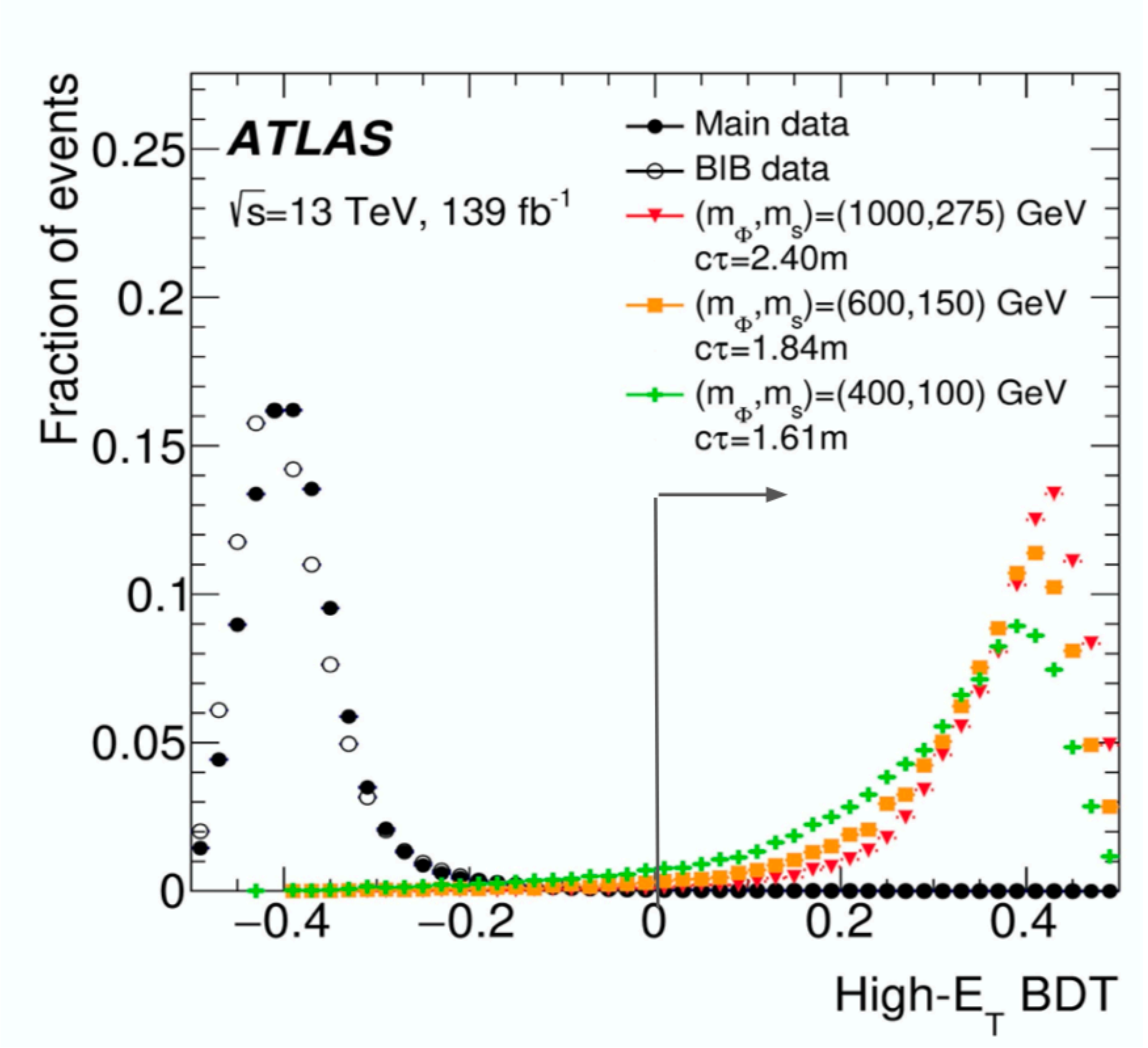
Neural network to distinguish signal, BIB and QCD.

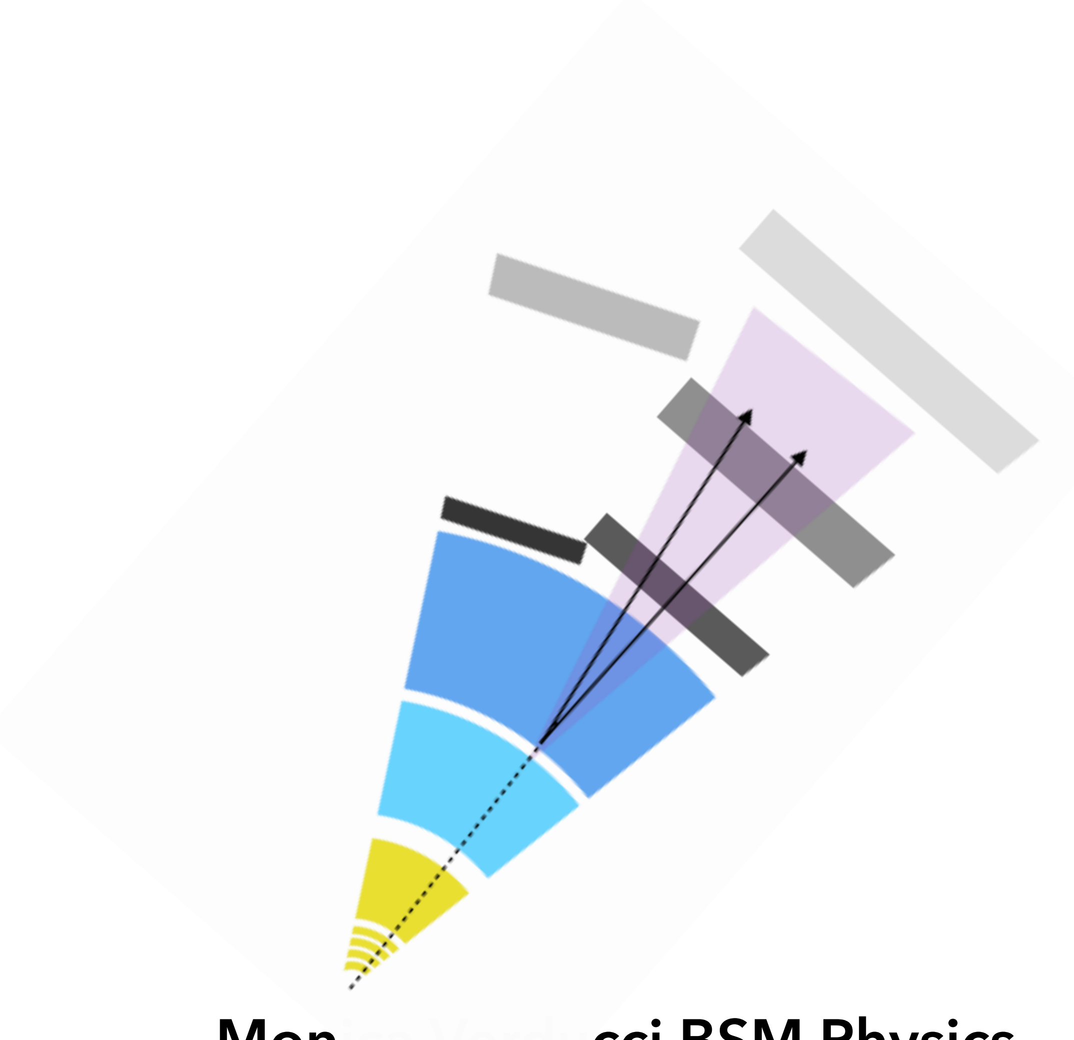
- Quality, momenta, Interaction Point IP of tracks around candidate jets
- Momenta, timing, energy fraction in ECAL and HCAL cluster of jets.
- Spatial and timing info of muon-tracks arounds jets. Jet variables.











Displaced Jet Characteristics

JHEP 06 (2022) 005

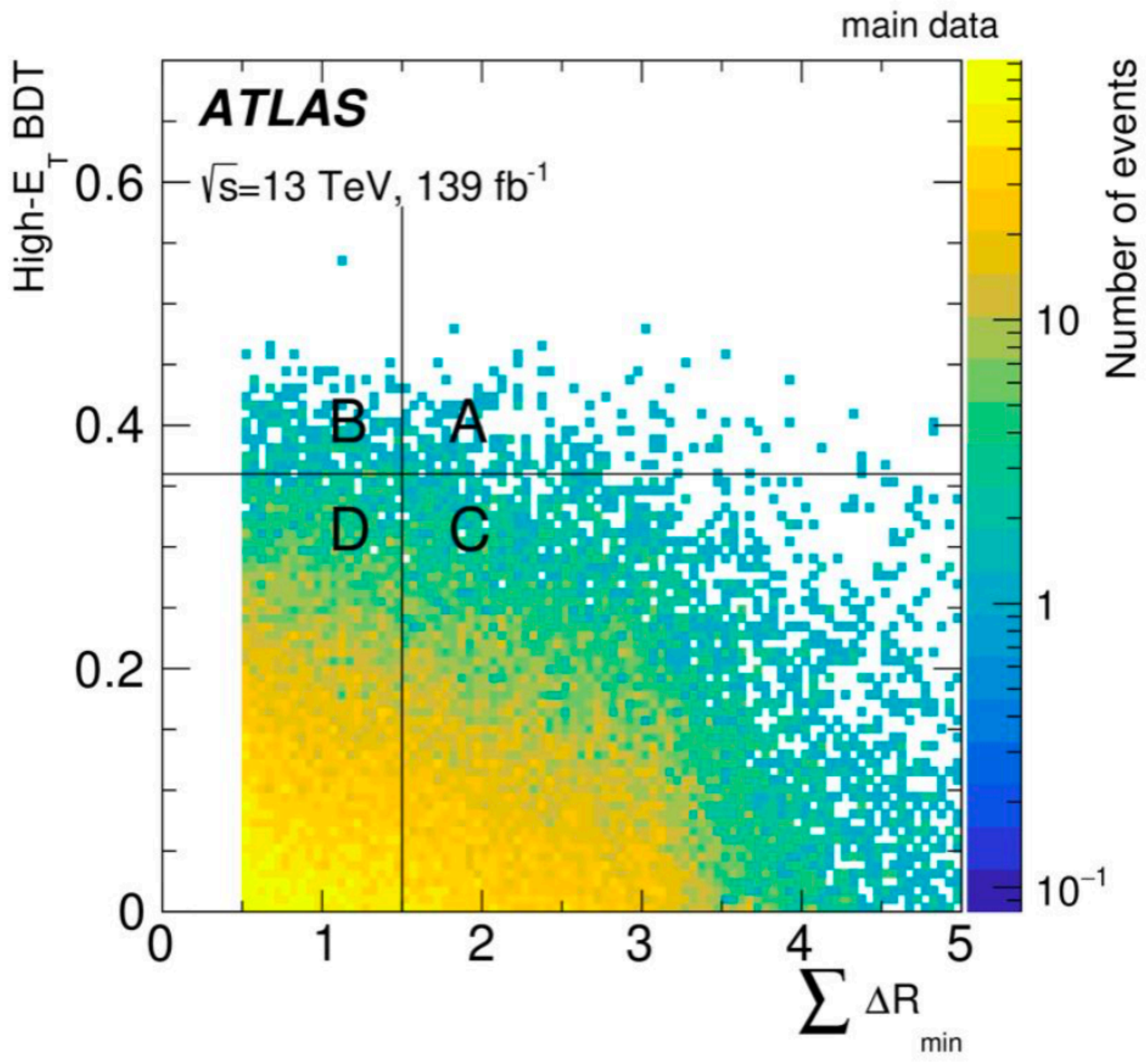
Background Estimation

After event selection, main background is multi-jet. Modified ABCD method to estimate multi-jet background.

- Combined fit of multi-jet background following relation of ABCD method.

Define SR (A) and CRs (B,C, D) based on event selection with: BDT score and ΣΔRmin(jet,tracks)

Agreement between data and SM prediction!



Remind : ABDC Method

Three of these regions, called B, C, and D, are background dominated. The fourth, A, is the signal region.

$$N_A = \frac{N_B N_C}{N_D},$$

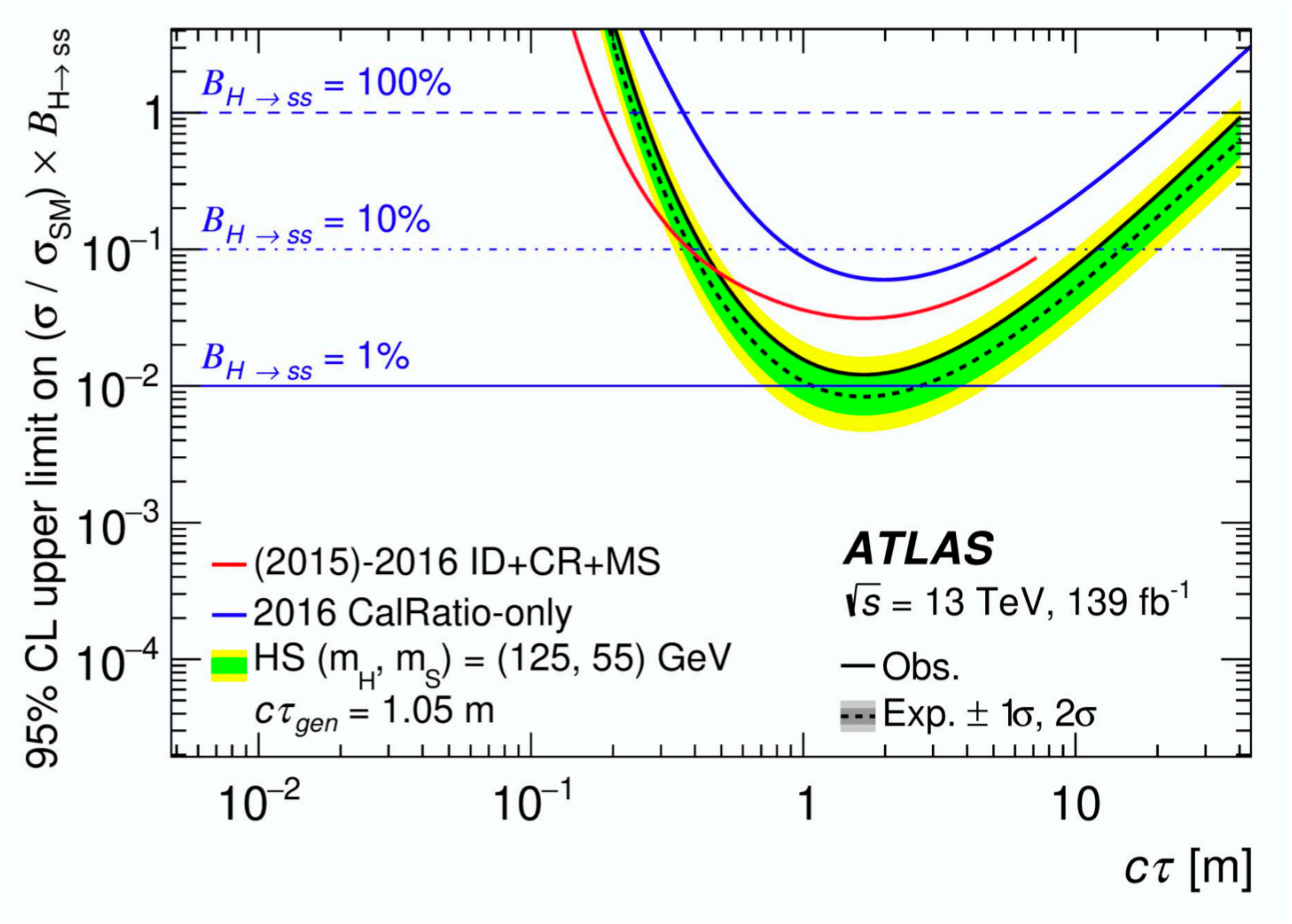
Results

Sensitivity to BR(H → ss) down to 1%

Better sensitivity than previous CalRatio:

- **Better trigger.**
- **Better displaced jet-NN.**

Less sensitive limit from 2016 combination at low *cτ* due to not inclusion of Inner Detector analysis.



arXiv:1910.08447

Di-Jets Resonance

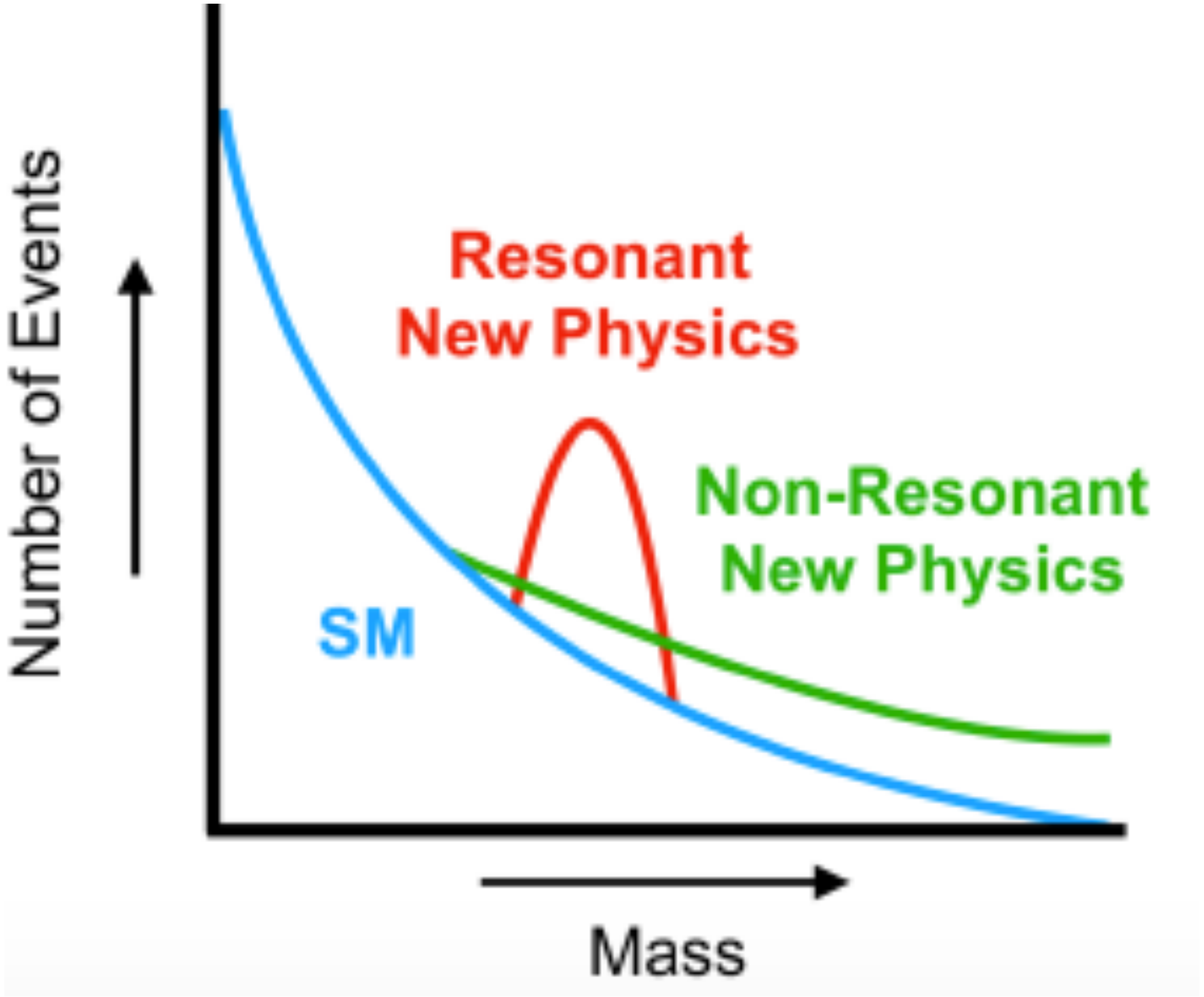
Excellent Example of:

A. Bump Search
B. Scan for resonance

Di-Jets Resonance

arXiv:1910.08447

- The results are interpreted in the context of several new physics scenarios:
  - excited quarks q^* (q = (u, d, c, s, b)) from compositeness models,
  - heavy Z^0 and W^0 gauge bosons,
  - a chiral excitation of the W boson, denoted W^*
  - a leptophobic Z^0 dark-matter mediator model,
  - quantum black holes,
  - and Kaluza-Klein gravitons.
- In addition, limits on generic Gaussian-shaped narrow-resonance signals are derived.

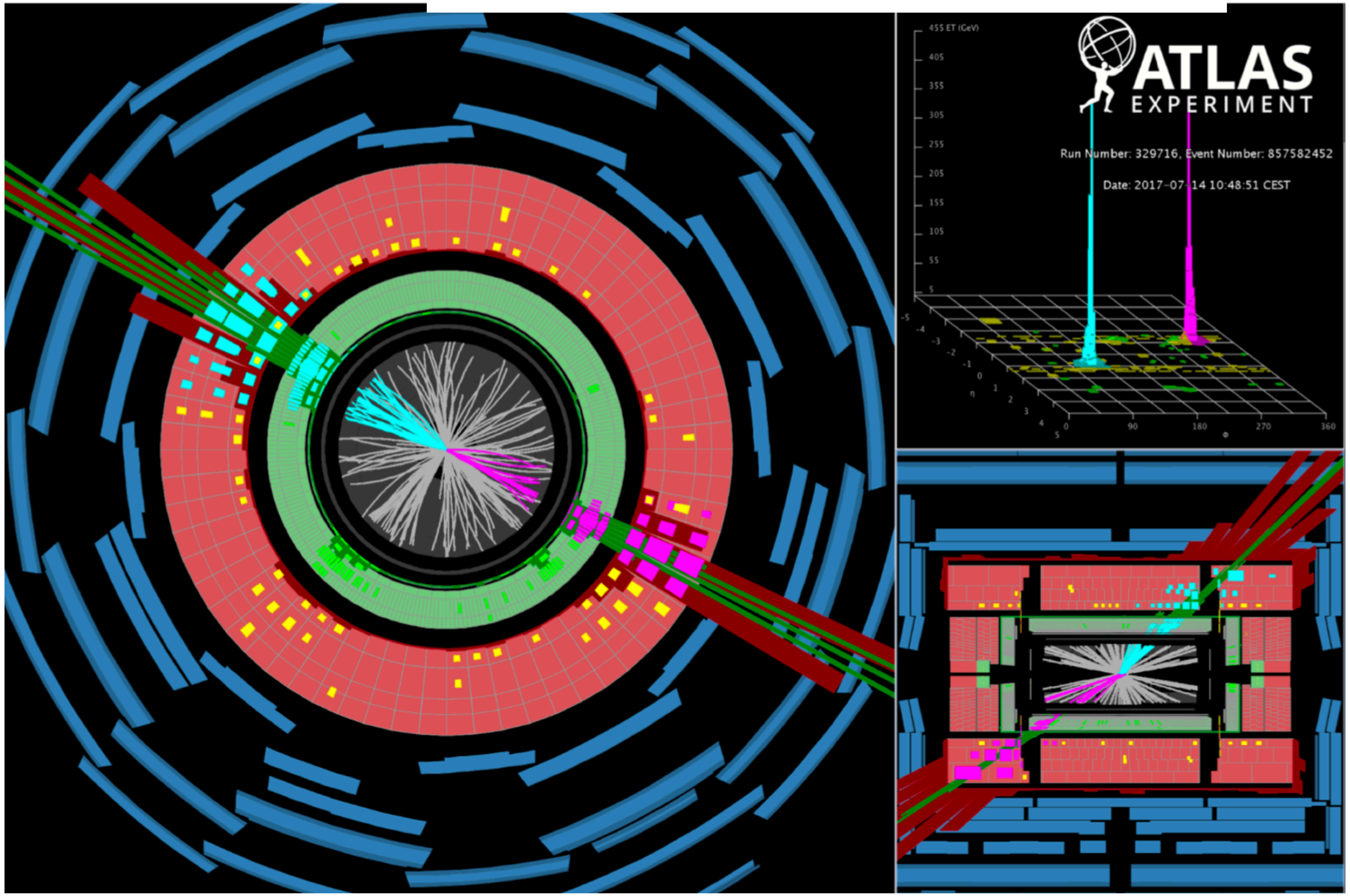


Di-Jets Resonance Search

arXiv:1910.08447

- Search for di-jet resonances.
- Full Run-2 data- set: 139 fb^{-1}
- Inclusive di-jet search and dedicated di-b-jet signature.

dijet event with mjj=9.5 TeV



Event Selection

arXiv:1910.08447

Event Selection: single-jet trigger that requires at least one jet with p_T >420 GeV, the lowest p_T unprescaled single-jet trigger. At least two jets with p_T >150 GeV and the azimuthal angle between the two leading jets must be greater than 1.0.

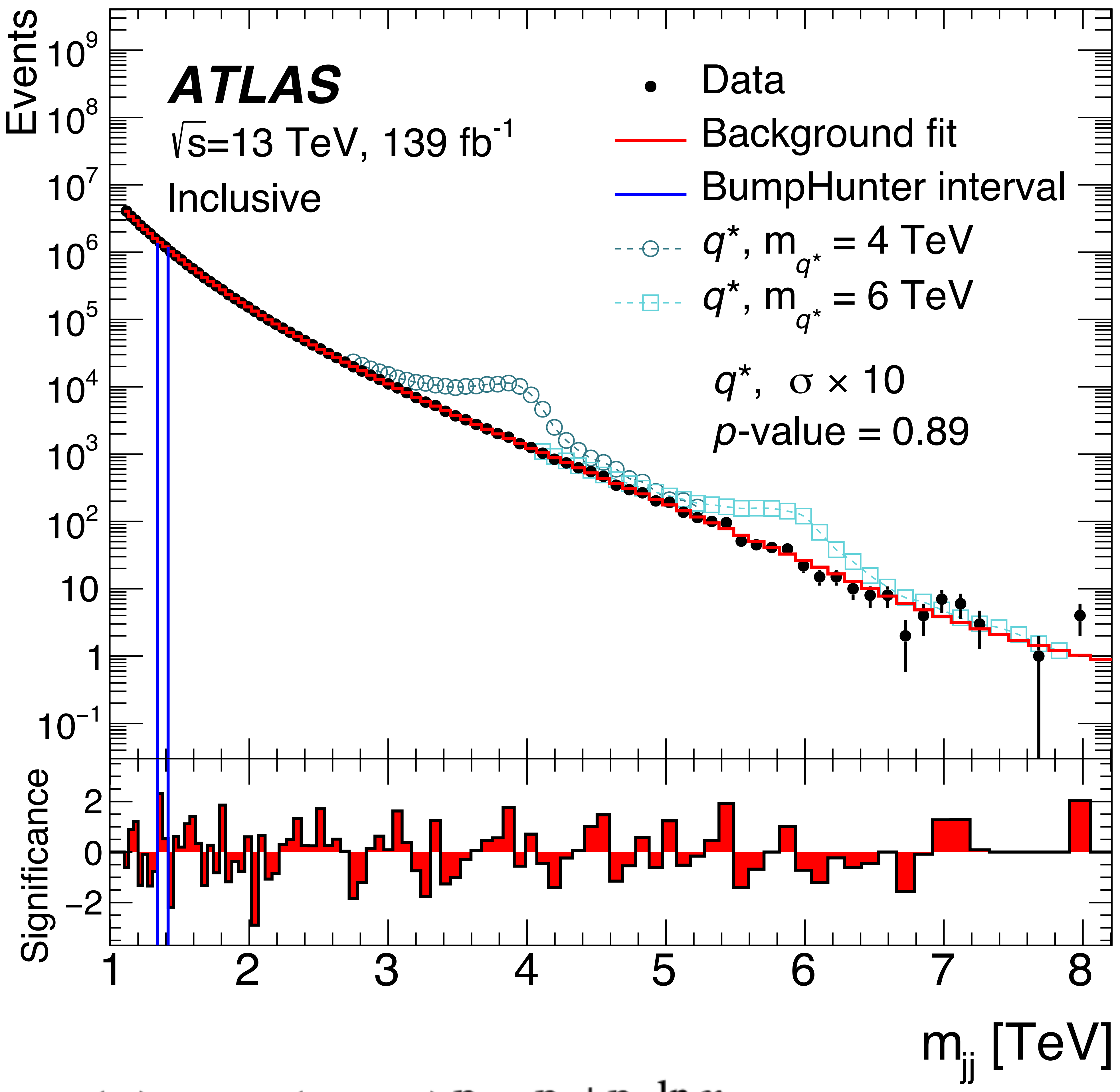
Category	Inclusive		1b	2b
Jet p_T	> 150 GeV			
Jet ϕ	$\lvert\Delta\phi(jj)\rvert > 1.0$			
Jet $\lvert\eta\rvert$	-		< 2.0	
$\lvert y^*\rvert$	< 0.6	< 1.2	< 0.8	
m_{jj}	> 1100 GeV	> 1717 GeV	> 1133 GeV	
b-tagging	no requirement		$\geqslant$ 1 b-tagged jet	2 b-tagged jets
Signal	DM mediator Z' W' q^* QBH Generic Gaussian	W^*	b^* Generic Gaussian	DM mediator Z' ($b\bar{b}$) SSM Z' ($b\bar{b}$) graviton ($b\bar{b}$) Generic Gaussian

- In addition to an **inclusive dijet search**, events with **jets identified as containing b-hadrons** are examined specifically (one or exactly two b-jets).
  - **Improved b tagging:**
    b-jets identified with deep-learning neural networks, operating point ε_b (efficiency of b-selection)=77% (for $t\bar{t}$ events).

Invariant Mass Fit

arXiv:1910.08447

- SM Di-jet mass spectrum described with parametric function and validated with data-driven methods.
  - The **distribution of the invariant mass of the two leading jets** is examined for local excesses above a data-derived estimate of the Standard Model background.
  - For b-tagged jets Control Regions CR are defined with inverted b-tag requirements.
  - **Quantify significance of any access with bump-hunter.**



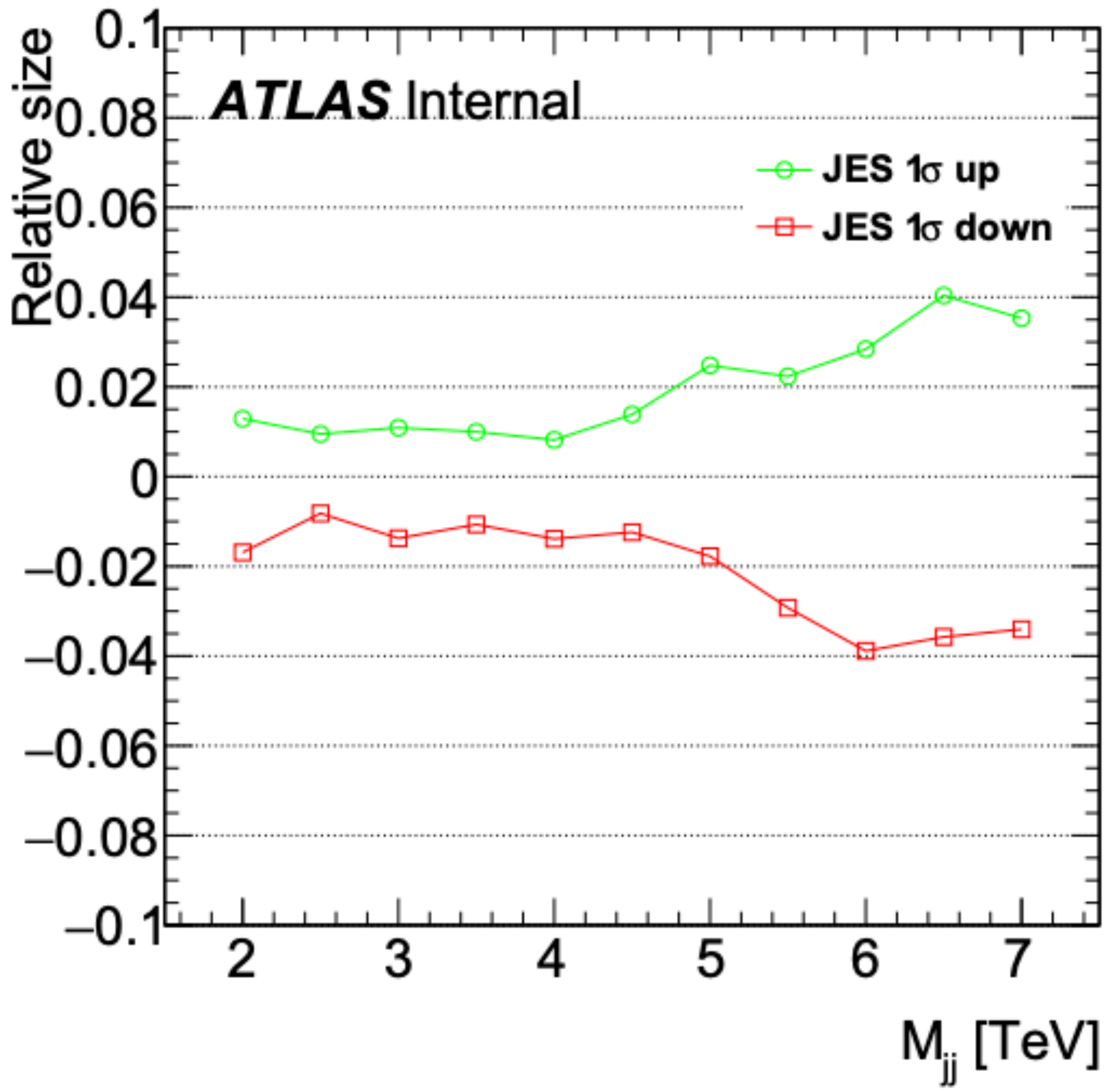
$$f(x) = p_1(1-x)^{p_2} x^{p_3 + p_4 \ln x}$$

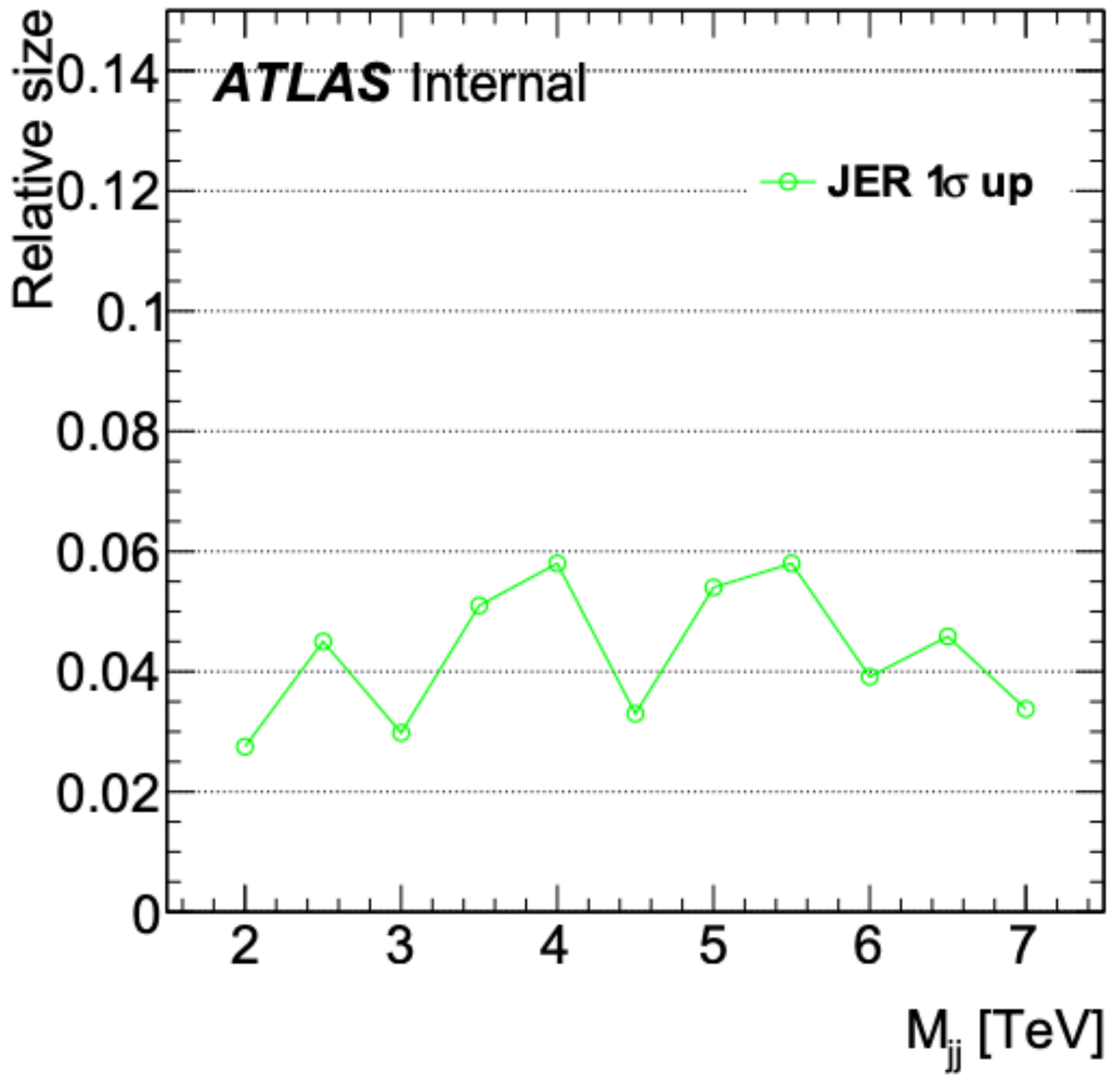
Systematics

arXiv:1910.08447

The statistical uncertainty of the fit due to the **limited size of the data** sample and the uncertainty due to the **choice of fit function** are considered as systematic uncertainties affecting the data-driven background determination.

The main systematic uncertainties in the MC signal samples include those associated with the modelling of the jet energy scale (JES), the jet energy resolution (JER) and the b-tagging efficiency.

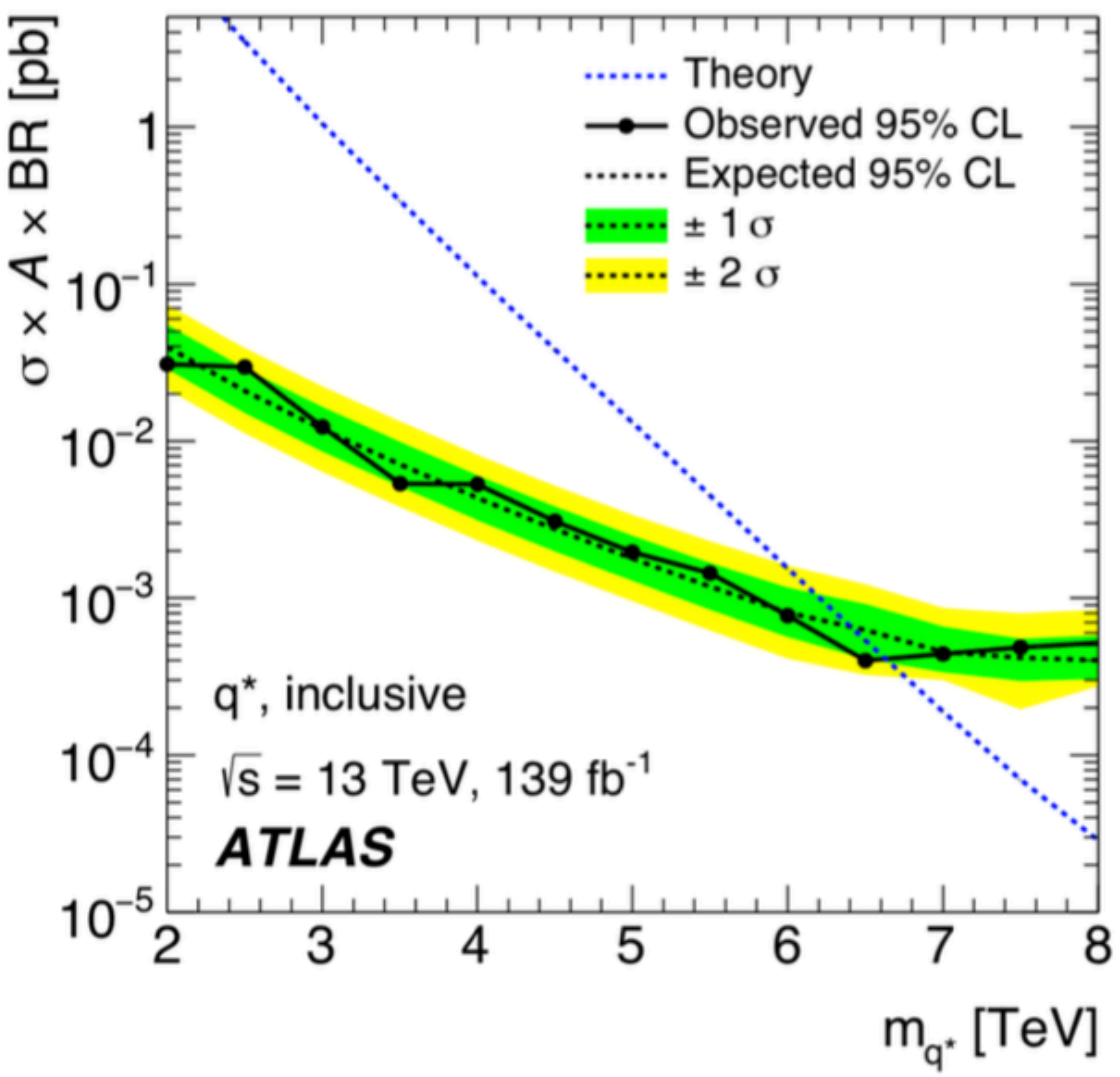




Results

arXiv:1910.08447

No excess found!



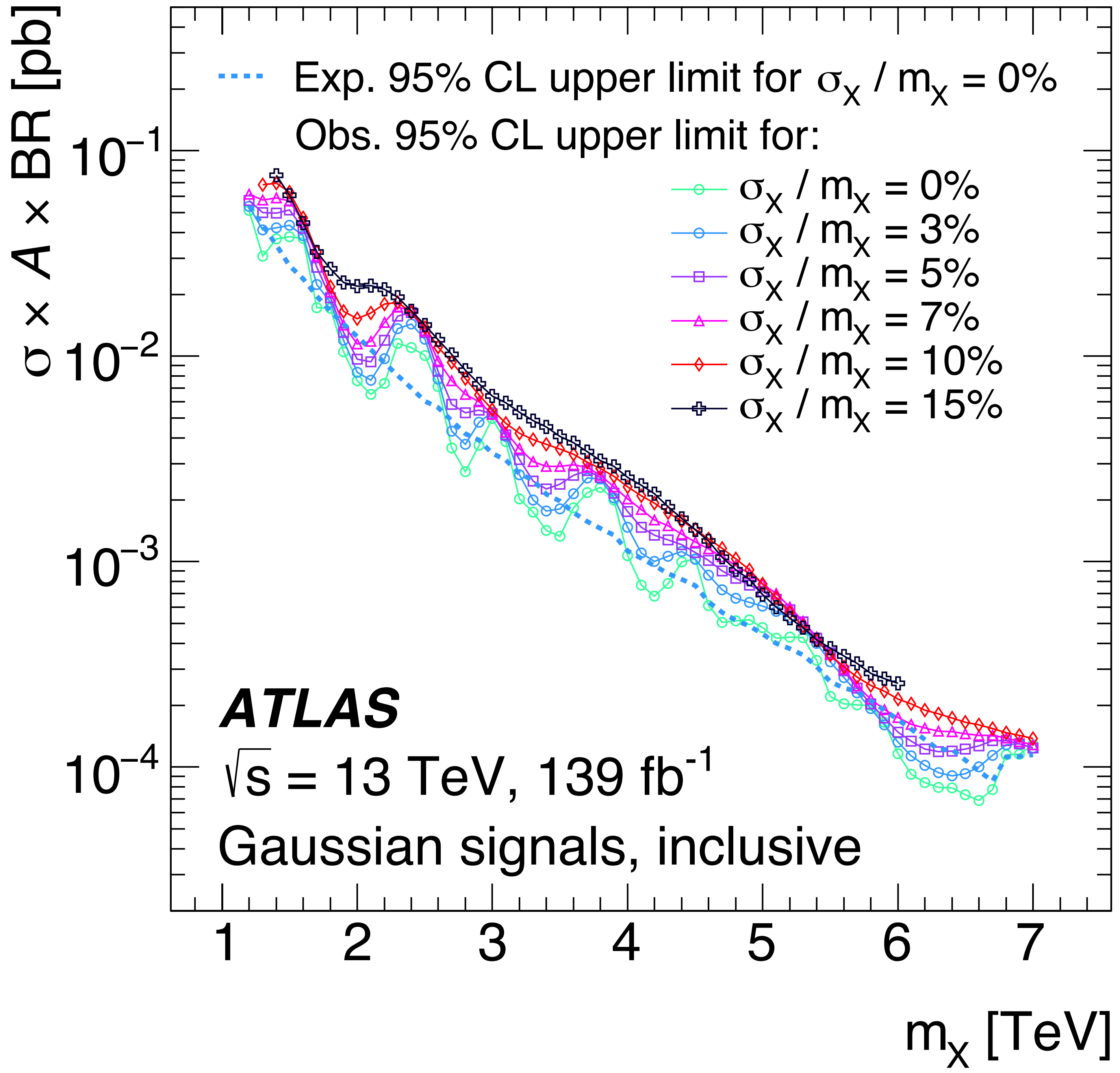


Table 2: The lower limits on the masses of benchmark signals at 95% CL.

Category	Model	Lower limit on signal mass at 95% CL	
		Observed	Expected
Inclusive	q^*	6.7 TeV	6.4 TeV
	QBH	9.4 TeV	9.4 TeV
	W'	4.0 TeV	4.2 TeV
	W^*	3.9 TeV	4.1 TeV
	DM mediator Z', $g_q = 0.20$	3.8 TeV	3.8 TeV
	DM mediator Z', $g_q = 0.50$	4.6 TeV	4.9 TeV
$1b$	b^*	3.2 TeV	3.1 TeV
$2b$	DM mediator Z' $g_q = 0.20$	2.8 TeV	2.8 TeV
	DM mediator Z', $g_q = 0.25$	2.9 TeV	3.0 TeV
	SSM Z',	2.7 TeV	2.7 TeV
	graviton, $k/\overline{M}_{PL} = 0.2$	2.8 TeV	2.9 TeV

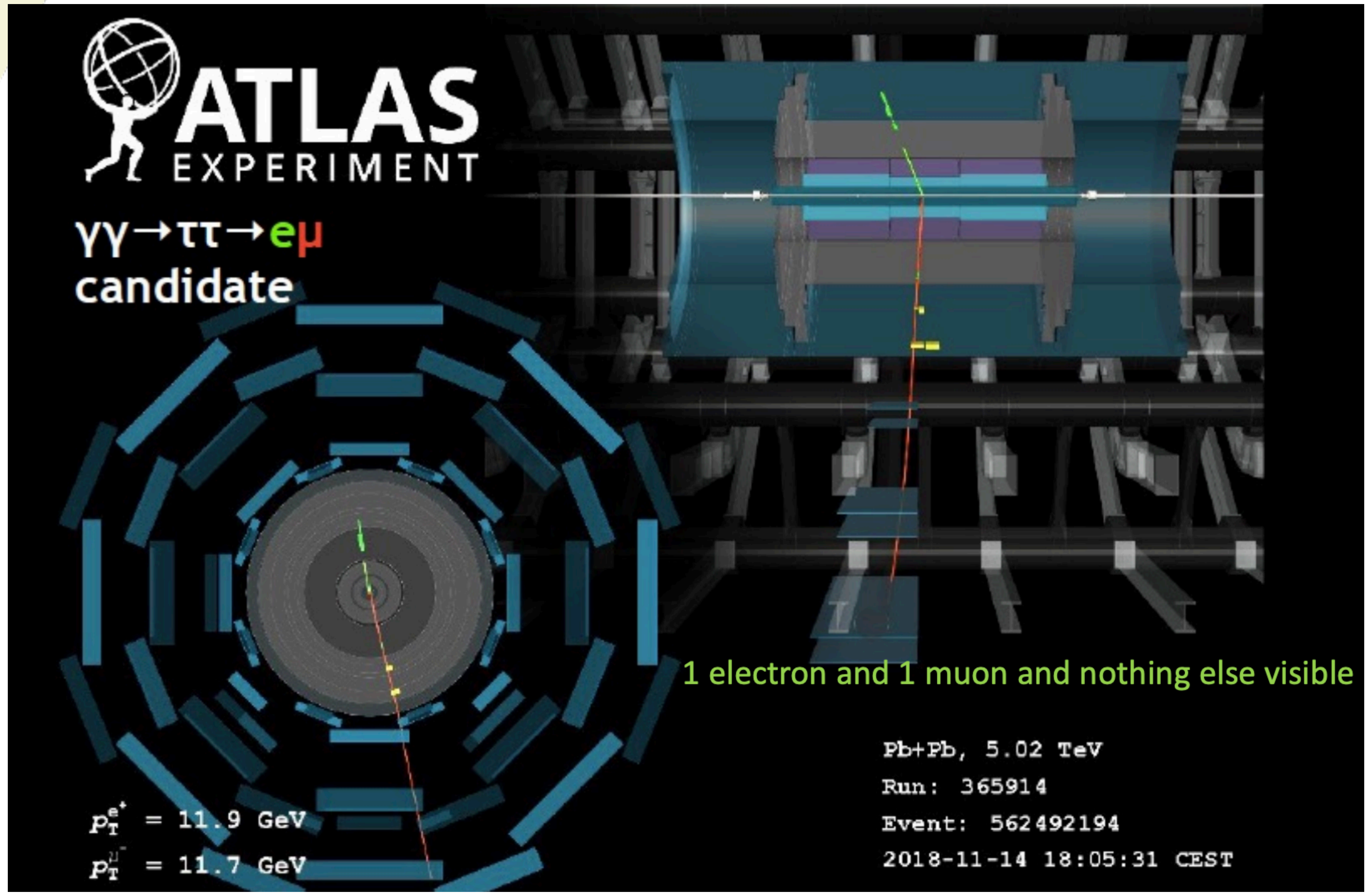
JHEP 03 (2021) 243

Precision Measurements in Heavy Ion Program

Excellent Example of:

A. Lead - Lead Data

B. Anomalies searches



Exotics in Pb-Pb Collisions

JHEP 03 (2021) 243

- Pb-Pb collisions can be used to :
  - Set limits on the production of axion-like particles.

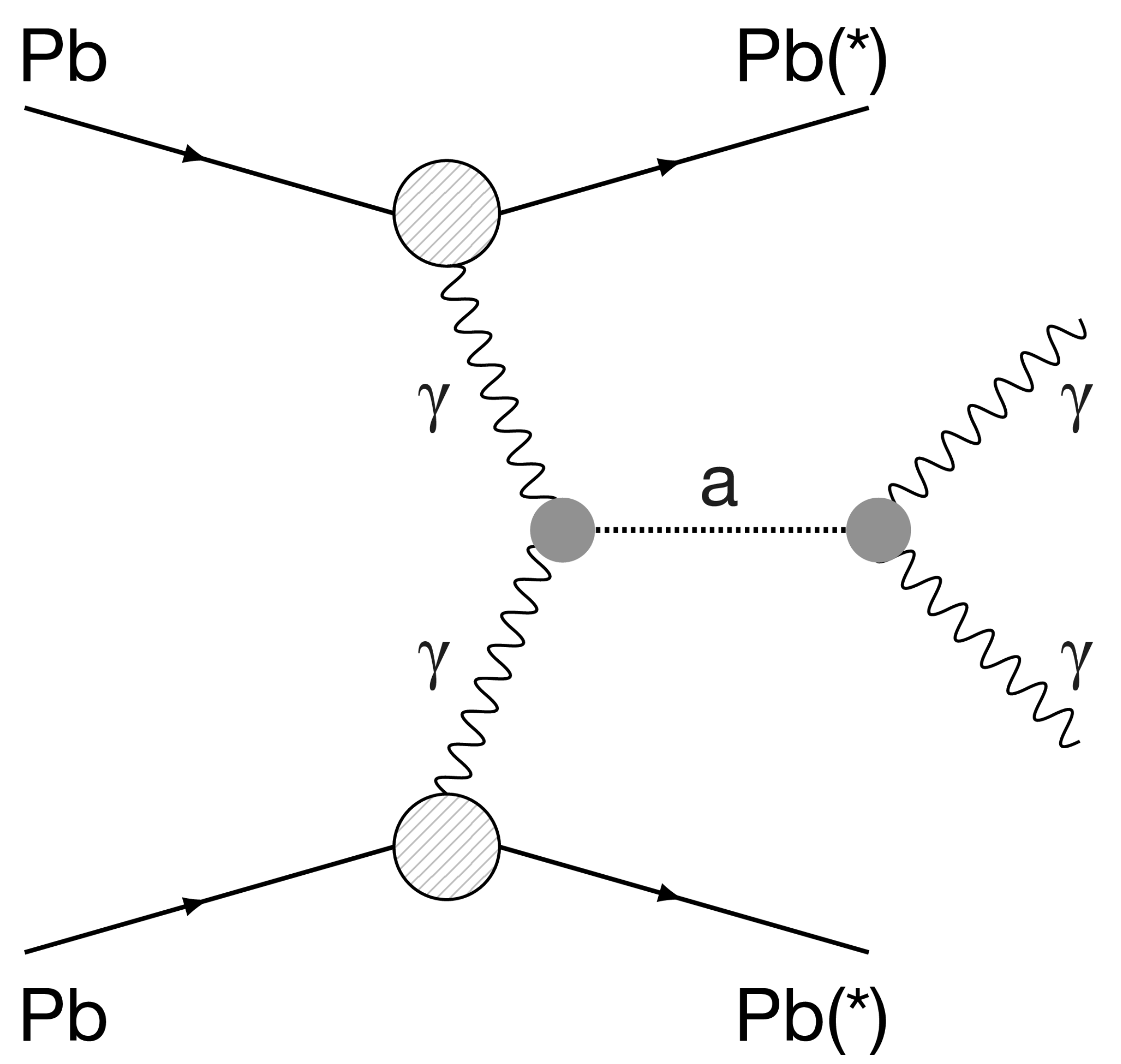
    Pb+Pb ($\gamma\gamma$) → Pb$^{(*)}$+Pb$^{(*)}\gamma\gamma$

  - Explore electromagnetic properties of the τ lepton

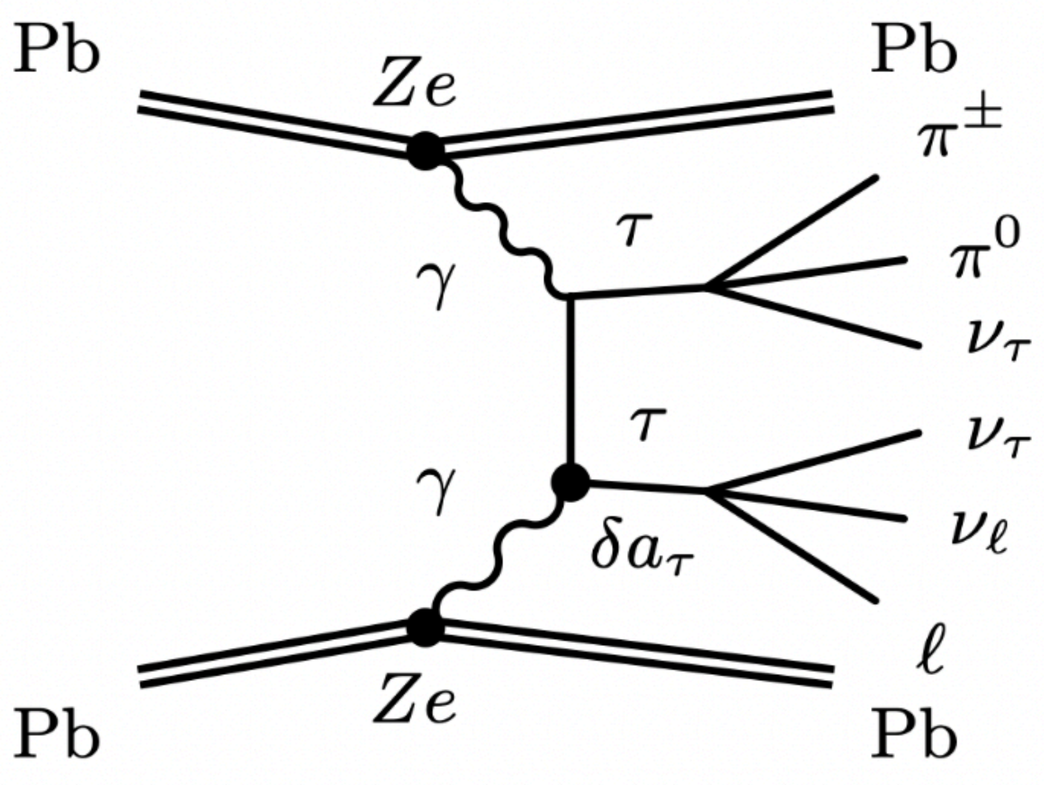
    Pb+Pb ($\gamma\gamma$) → Pb$^{(*)}$+Pb$^{(*)}$ tau tau

    - **The Standard Model analysis explores the possibility to measure g-2 of the tau leptons**
- These studies use 2.2 nb^{-1} of integrated luminosity collected in 2015 and 2018 at sqrt(s) = 5.02 TeV.

Axion production



Tau g-2 study



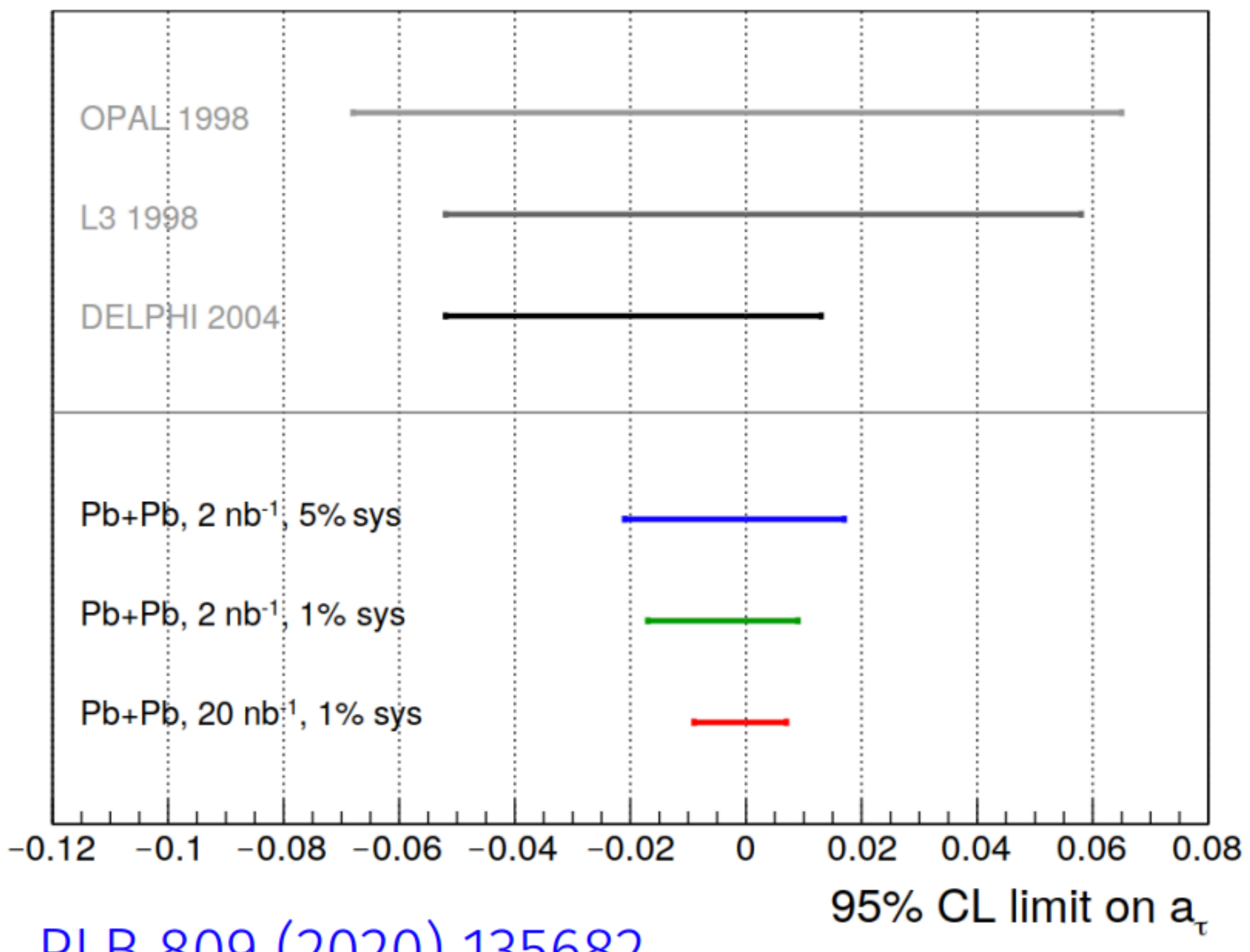
Current status of a_{tau} measurement

2204.13478

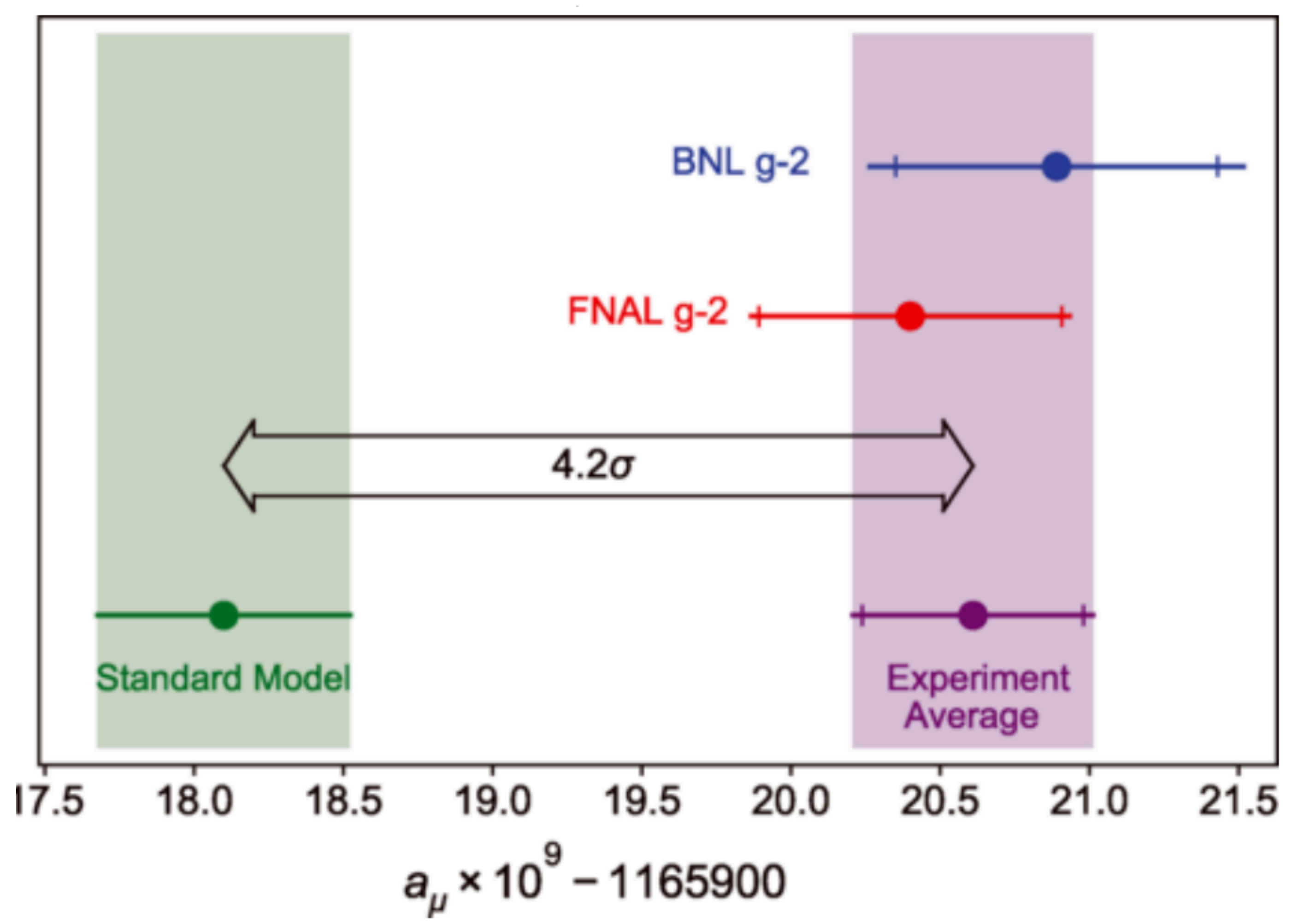
- **Anomalous magnetic moment:**

$$a_\tau = \frac{(g-2)_l}{2}$$

- **Standard Model prediction (Mod. Phys. Lett. A 22 (2007) 159):**
  - **a_τ = 0.00117721 ± 0.00000005**
- **Best experimental limits on a_τ set by DELPHI at LEP (EPJ C 35 (2004) 159):**
  - **$-0.052 < a_\tau < 0.013$ (95% CL)**
- Relevant for precision measurement of QED, electroweak, and QCD
- **Many BSM models predict modifications of a_τ:**
  - lepton compositeness where corrections are of O(m_{lepton}/ $m_{constituent}$)
  - SUSY models O($\delta a_\tau \sim m^2_\tau / M^2_S$)
  - a_τ can be $m^2_\tau / m^2_\mu \approx 280$ times more sensitive to BSM than a_μ



PLB 809 (2020) 135682

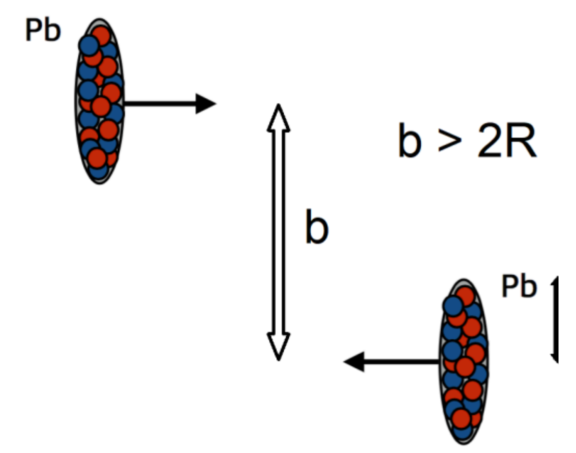


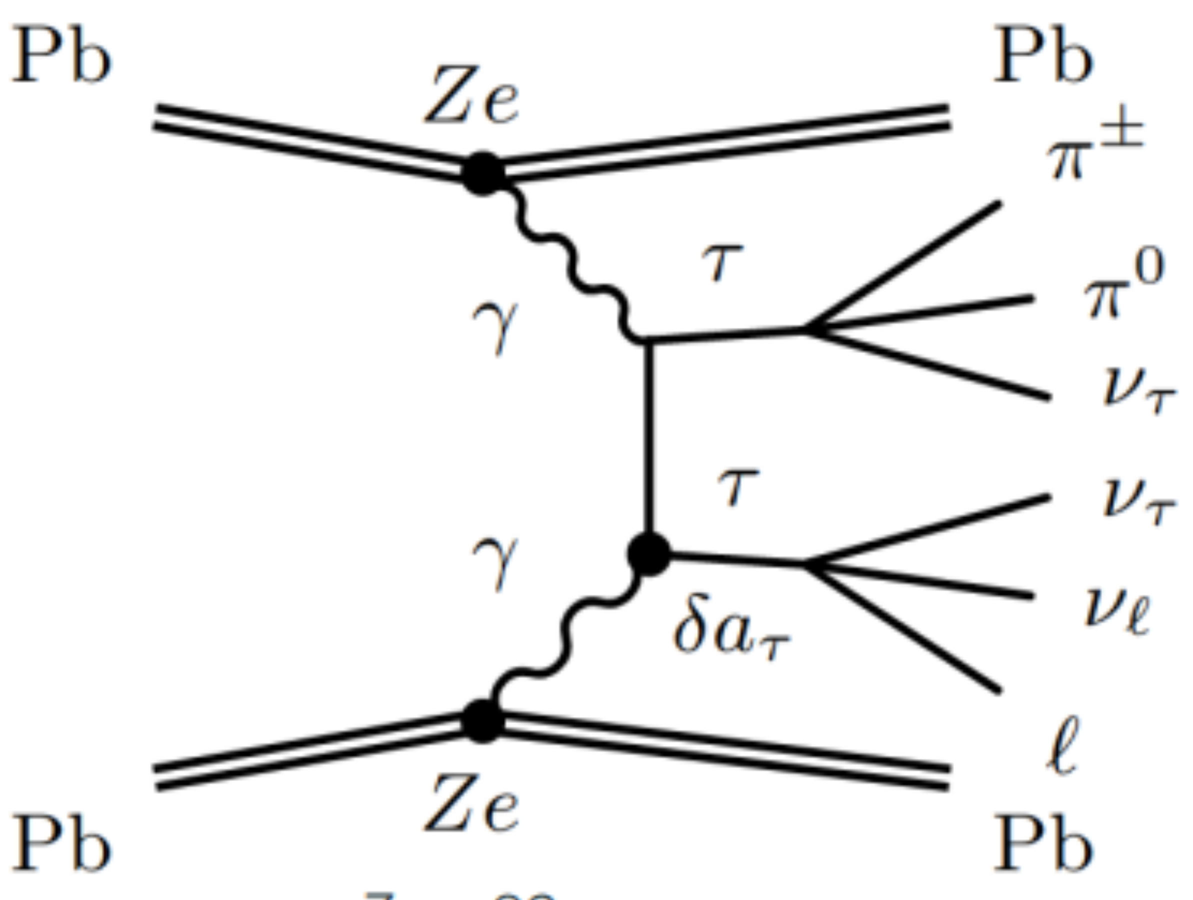
PhysRevLett.126.141801

Constraining atau with LHC

[2204.13478](2204.13478)

- ATLAS and CMS analyses aim to improve existing constraints on $a_\tau = (g-2)/2$ using $\gamma\gamma \to \tau\tau$ events produced in ultraperipheral Pb+Pb collisions.
  - **Why Ultraperipheral Pb+Pb collisions?**
    - **Z^4 cross-section enhancement** balancing out lower luminosity
    - **essentially no pile-up** from hadronic interactions → exclusivity selections
    - **low trigger and reco object thresholds**
  - Main Background
    - $\gamma\gamma \to ll$
    - $\gamma\gamma \to qq$
    - photo-nuclear events





$Z = 82$

$Z^4 \approx 4.5 \cdot 10^7$

$\tau^\pm \to \nu_\tau + \ell^\pm + \nu_\ell \; (\ell = e,\ \mu)$	1 Lepton
$\tau^\pm \to \nu_\tau + \pi^\pm + n\pi^0$	1 Charged Pion
$\tau^\pm \to \nu_\tau + \pi^\pm + \pi^\mp + \pi^\pm + n\pi^0$	3 Charged Pions

- Analysis idea from:
  - L. Beresford, J. Liu, PRD 102 (2020) 113008
  - M. Dyndal, M. Schott, M. Klusek-Gawenda, A. Szczurek, PLB 809 (2020) 135682

$$\mathcal{B}(\tau^\pm \to \ell^\pm \nu_\ell \nu_\tau) = 35\%,$$
$$\mathcal{B}(\tau^\pm \to \pi^\pm \nu_\tau + \text{neutral pions}) = 45.6\%,$$
$$\mathcal{B}(\tau^\pm \to \pi^\pm \pi^\mp \pi^\pm \nu_\tau + \text{neutral pions}) = 19.4\%.$$

Analysis Strategy @ ATLAS

2204.13478

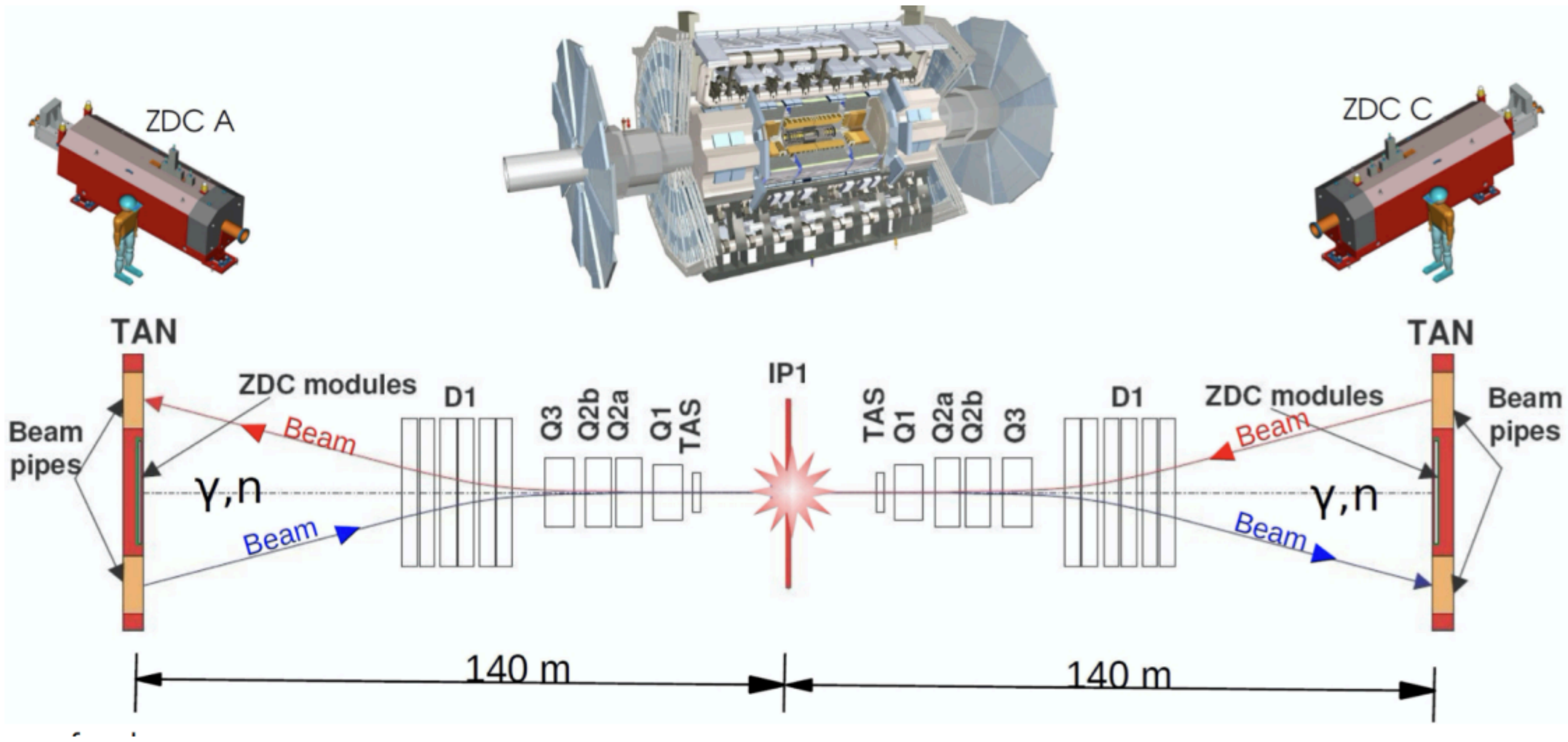
Analysis Strategy:

- 3 periods of heavy ion collisions during Run2
- Ultraperipheral Collisions (UPC) of PbPb at $\sqrt{s_{NN}}$ = 5.02 TeV
  - Order of 1.44 nb^{-1} data sample
  - Elastic & diffractive
  - Small energy deposit in the forward detector system

Both ATLAS and CMS use muon to trigger the event.
Vetoing Forward activity to separate UPCs from inelastic Pb+Pb collisions

- Constraints on a_τ from total $\gamma\gamma \rightarrow \tau\tau$ cross-section / yield and differential distributions (e.g. leading lepton p_T)
- Categorise di-τ events:
  - lepton + 1 track (ℓ/pion)
  - lepton + 3 tracks (3pions)
  - μ + e

Zero Degree Calorimeter



Analysis Strategy @ ATLAS

2204.13478

ATLAS

Event Preselection

- **Trigger:** HLT_mu4 + FCal-based forward gap + total E_T at L1 < 50 GeV
- E_{ZDC} <1TeV: reduce neutral particles in the forward region helps to separate UPCs from inelastic Pb+Pb collisions. Reduce photo-nuclear background

Region Selection

- Exclusivity selections: no tracks except signal leptons/tracks - no clusters unmatched to signal leptons/tracks
- Cuts on system p_T help to suppress $\gamma\gamma \to \mu\mu$ background in 1M1T SR

Observable	Preselection			
GRL	Pass			
$E_{\text{ZDC}}^{A,C}$	< 1 TeV			
Trigger	HLT_mu4_hi_upc_FgapAC3_L1MU4_VTE50 fired			
Region	1M1T SR	1M3T SR	1M1E SR	2M CR
N_μ^{baseline}	= 1	= 1	—	—
N_μ^{sig}	= 1	= 1	= 1	2
N_e^{sig}	= 0	= 0	= 1	—
$N_{\text{trk}}\,\Delta R > 0.1$ from μ^{sig}	= 1	= 3	—	—
$N_{\text{trk}}\,\Delta R > 0.1$ from ℓ^{sig}	—	—	= 0	= 0
Unmatched clusters	= 0	= 0	—	—
$\sum$ charge	= 0	= 0	= 0	—
$p_{\text{T}}^{(\mu,\text{trk})}$	> 1 GeV	—	—	—
$p_{\text{T}}^{(\mu,\text{trk},\gamma)}$	> 1 GeV	—	—	—
$p_{\text{T}}^{(\mu,\text{trk},\text{cluster})}$	> 1 GeV	—	—	—
m_{trks}	—	< 1.7 GeV	—	—
$A_\phi^{\mu,\text{trk(s)}}$ (*)	< 0.4	< 0.2	—	—
$m_{\mu\mu}$	—	—	—	> 11 GeV

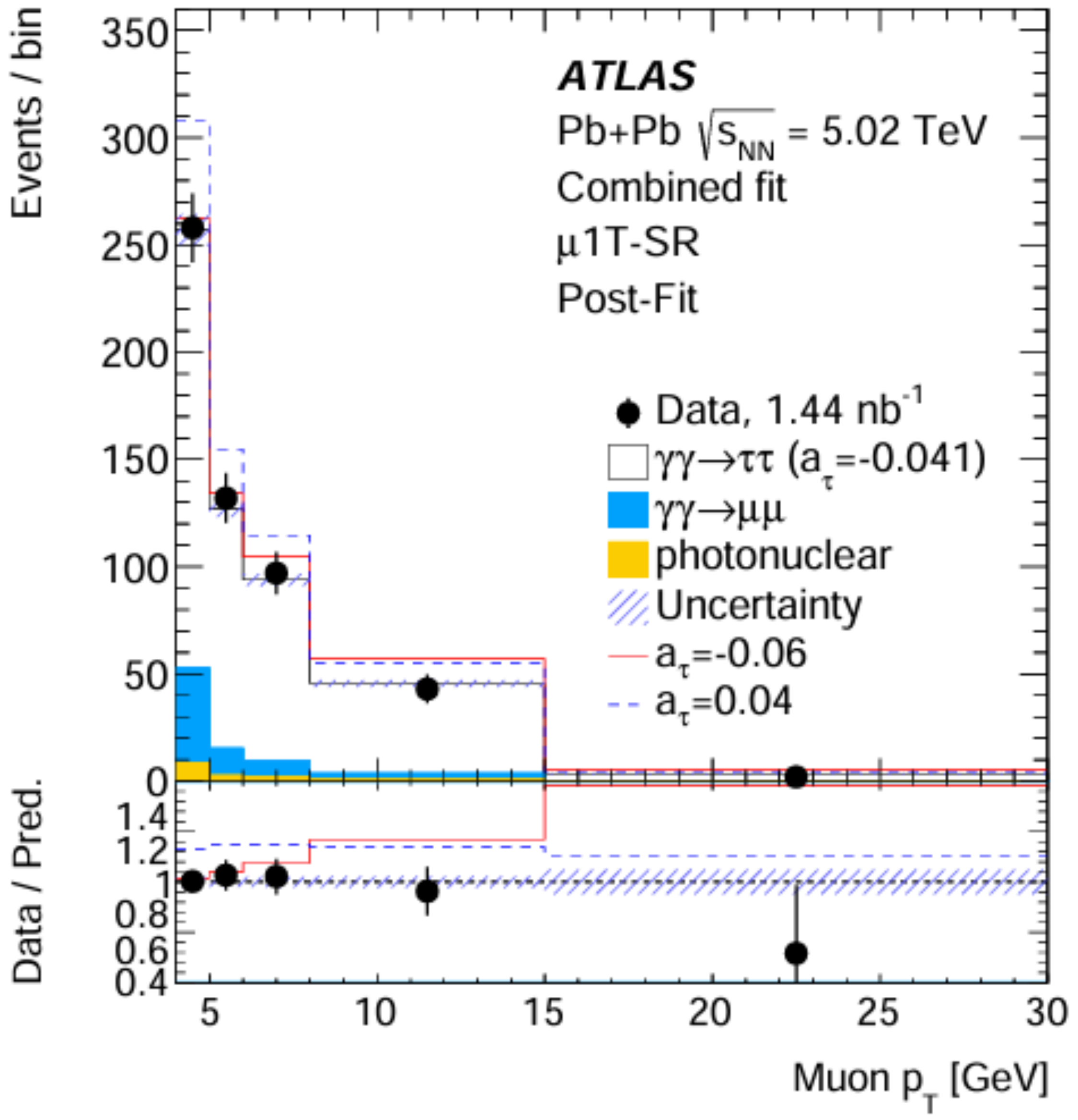
1Muon+ 1Track | 1Muon+ 3Tracks | 1Muon+ 1Electron

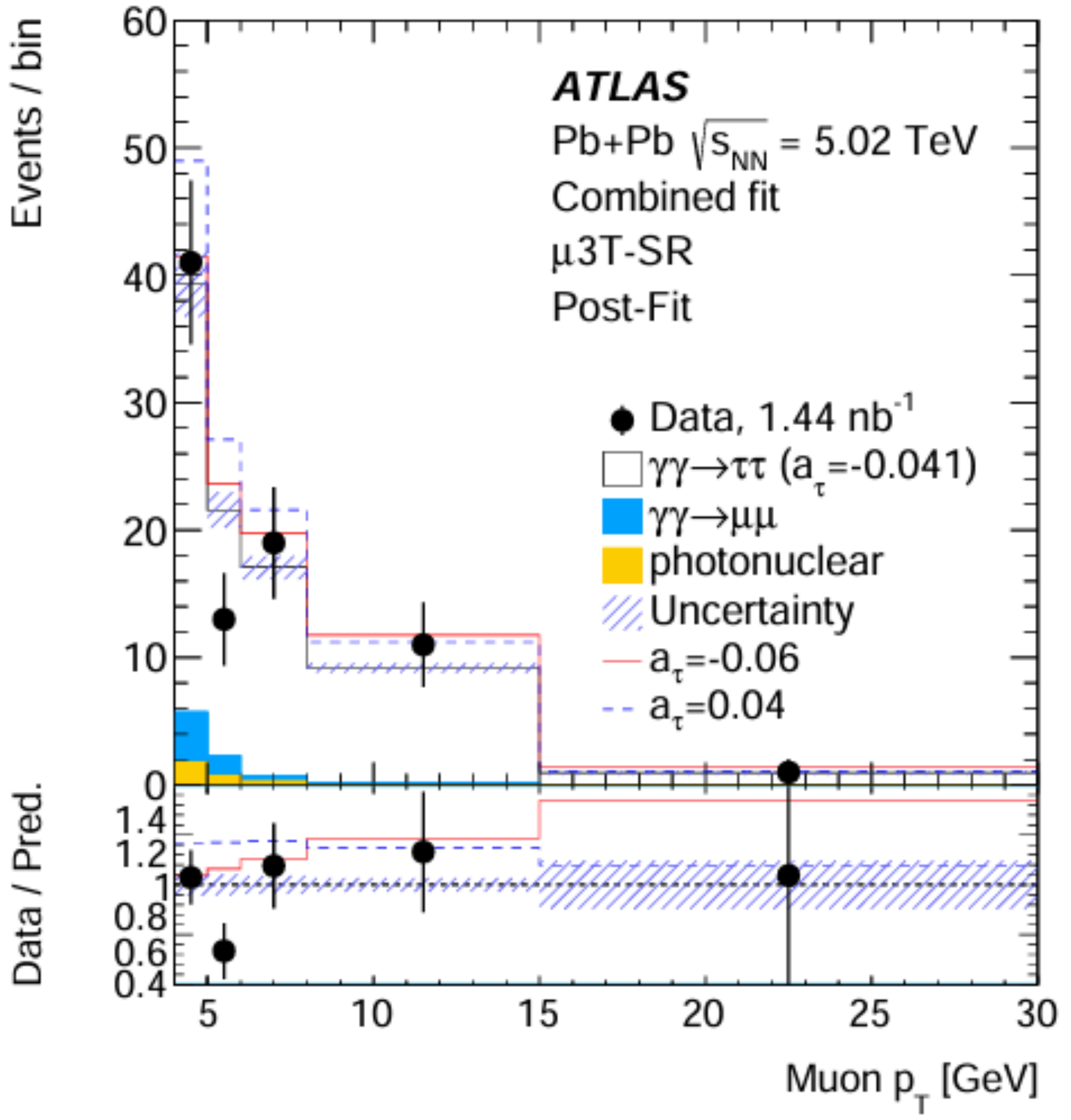
Region	Data	Signal $\gamma\gamma \to \tau\tau$	Background $\gamma\gamma \to \mu\mu(\gamma)$	Background $\gamma\gamma \to ee$	Background $\gamma\gamma \to$ jet	Background photonuclear
1M1T SR	532.0	497.1	70.2	0.0	0.1	13.5
1M3R SR	85.0	90.2	6.7	0.0	0.3	2.8
1M1E SR	39.0	35.2	2.8	0.0	0.0	0.0

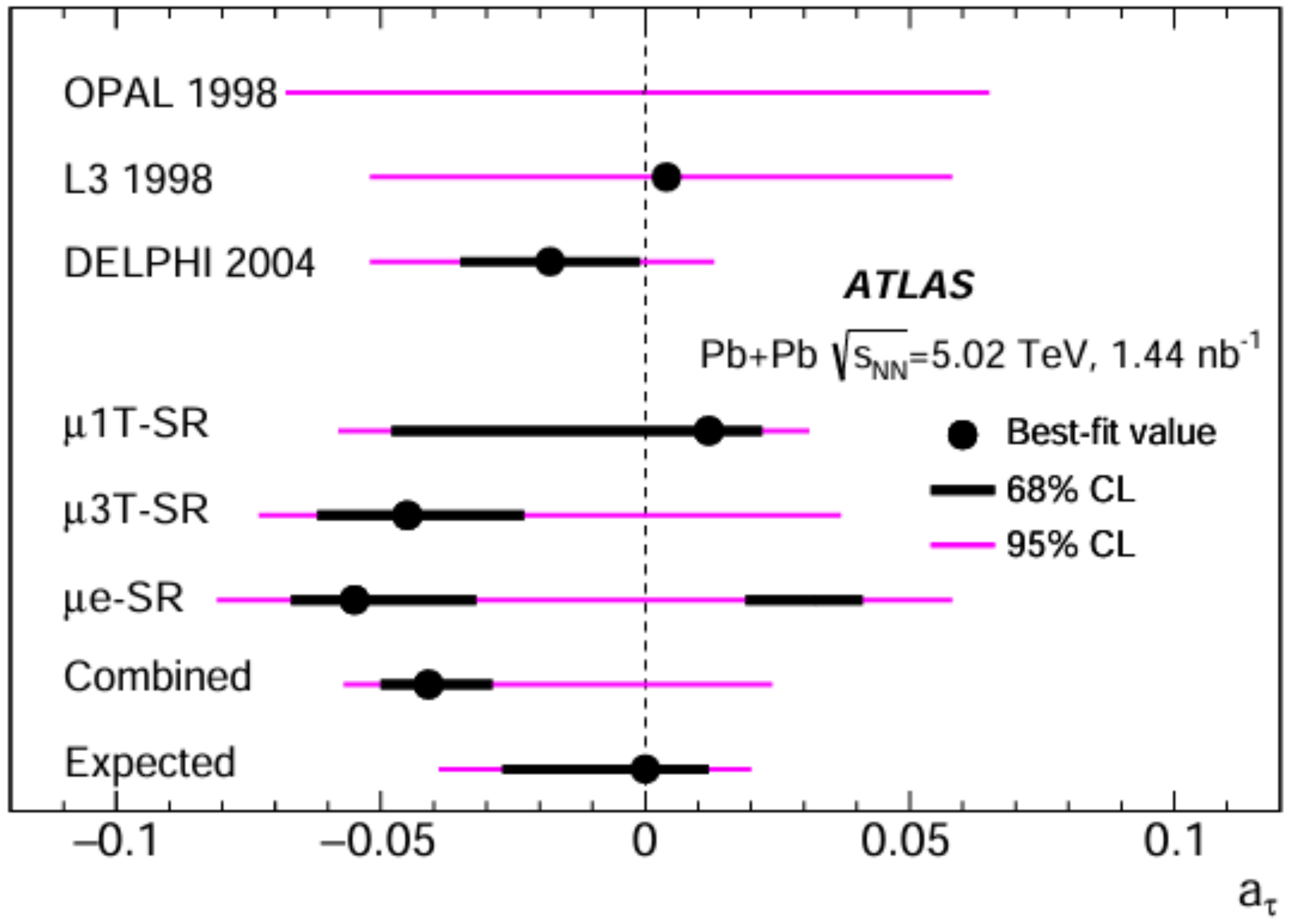
(*) $A_\phi^{\mu,\text{trk(s)}} \equiv 1 - |\Delta\phi_{\mu,\text{trk(s)}}|/\pi$

Results

- Muon transverse momentum used to extract the limits
  - Limits sets to anomalous magnetic momentum of tau
  - Limits set to signal strength $\mu_{\tau\tau} = 1.03^{+0.06}_{-0.05}$ (tot)







$-0.057 < a_\tau < 0.024$ at 95% CL.

ATLAS Long-lived Particle Searches* - 95% CL Exclusion

Status: May 2020

ATLAS Preliminary

$\int\mathcal{L}\,dt = (18.4 - 136)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV

	Model	Signature	$\int\mathcal{L}\,dt\ [\mathrm{fb}^{-1}]$	Lifetime limit			Reference
SUSY	RPV $\tilde{t} \to \mu q$	displaced vtx + muon	136	$\tilde{t}$ lifetime	0.003-6.0 m	$m(\tilde{t})$= 1.4 TeV	2003.11956
	RPV $\chi_1^0 \to ee\nu/e\mu\nu/\mu\mu\nu$	displaced lepton pair	32.8	χ_1^0 lifetime	0.003-1.0 m	$m(\tilde{q})$= 1.6 TeV, $m(\chi_1^0)$= 1.3 TeV	1907.10037
	GGM $\chi_1^0 \to Z\tilde{G}$	displaced dimuon	32.9	χ_1^0 lifetime	0.029-18.0 m	$m(\tilde{g})$= 1.1 TeV, $m(\chi_1^0)$= 1.0 TeV	1808.03057
	GMSB	non-pointing or delayed γ	20.3	χ_1^0 lifetime	0.08-5.4 m	SPS8 with Λ= 200 TeV	1409.5542
	AMSB $pp \to \chi_1^\pm\chi_1^0, \chi_1^+\chi_1^-$	disappearing track	20.3	$\chi_1^\pm$ lifetime	0.22-3.0 m	$m(\chi_1^\pm)$= 450 GeV	1310.3675
	AMSB $pp \to \chi_1^\pm\chi_1^0, \chi_1^+\chi_1^-$	disappearing track	36.1	$\chi_1^\pm$ lifetime	0.057-1.53 m	$m(\chi_1^\pm)$= 450 GeV	1712.02118
	AMSB $pp \to \chi_1^\pm\chi_1^0, \chi_1^+\chi_1^-$	large pixel dE/dx	18.4	$\chi_1^\pm$ lifetime	1.31-9.0 m	$m(\chi_1^\pm)$= 450 GeV	1506.05332
	Stealth SUSY	2 MS vertices	36.1	$\tilde{S}$ lifetime	0.1-519 m	$\mathcal{B}(\tilde{g} \to \tilde{S}g)$= 0.1, $m(\tilde{g})$= 500 GeV	1811.07370
	Split SUSY	large pixel dE/dx	36.1	$\tilde{g}$ lifetime	$>$ 0.9 m	$m(\tilde{g})$= 1.8 TeV, $m(\chi_1^0)$= 100 GeV	1808.04095
	Split SUSY	displaced vtx + E_T^{miss}	32.8	$\tilde{g}$ lifetime	0.03-13.2 m	$m(\tilde{g})$= 1.8 TeV, $m(\chi_1^0)$= 100 GeV	1710.04901
	Split SUSY	$0\,\ell$, $2-6$ jets $+E_T^{miss}$	36.1	$\tilde{g}$ lifetime	0.0-2.1 m	$m(\tilde{g})$= 1.8 TeV, $m(\chi_1^0)$= 100 GeV	ATLAS-CONF-2018-003
Higgs BR = 10%	$H \to s\,s$	ID/MS vtx, low EMF/trk jets	36.1	s lifetime	0.12-116 m	$m(s)$= 25 GeV	1911.12575
	FRVZ $H \to 2\gamma_d + X$	2 $e-, \mu-$jets	20.3	γ_d lifetime	0-3 mm	$m(\gamma_d)$= 400 MeV	1511.05542
	FRVZ $H \to 2\gamma_d + X$	2 $\mu-$jets	36.1	γ_d lifetime	1.5-307 mm	$m(\gamma_d)$= 400 MeV	1909.01246
	FRVZ $H \to 4\gamma_d + X$	2 $\mu-$jets	36.1	γ_d lifetime	3.7-178 mm	$m(\gamma_d)$= 400 MeV	1909.01246
	$H \to Z_d Z_d$	displaced dimuon	32.9	Z_d lifetime	0.009-24.0 m	$m(Z_d)$= 40 GeV	1808.03057
	$H \to ZZ_d$	2 e, μ + low-EMF trackless jet	36.1	Z_d lifetime	0.21-5.2 m	$m(Z_d)$= 10 GeV	1811.02542
Scalar	VH with $H \to ss \to bbbb$	$1-2\ell$ + multi-b-jets	36.1	s lifetime	0-3 mm	$\mathcal{B}(H \to ss)$= 1, $m(s)$= 60 GeV	1806.07355
	Φ(200 GeV) $\to s\,s$	low-EMF trk-less jets, MS vtx	36.1	s lifetime	0.41-51.5 m	$\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 50 GeV	1902.03094
	Φ(600 GeV) $\to s\,s$	low-EMF trk-less jets, MS vtx	36.1	s lifetime	0.04-21.5 m	$\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 50 GeV	1902.03094
	Φ(1 TeV) $\to s\,s$	low-EMF trk-less jets, MS vtx	36.1	s lifetime	0.06-52.4 m	$\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 150 GeV	1902.03094
HNL	$N \to W\ell$	displaced vtx ($\mu\mu$ or μe) + μ	36.1	N lifetime	0.44-37 mm	$m(N)$= 5 GeV, LNC	1905.09787
	$N \to W\ell$	displaced vtx ($\mu\mu$ or μe) + μ	36.1	N lifetime	0.64-22 mm	$m(N)$= 5 GeV, LNV	1905.09787

$c\tau$ [m]: 0.01, 0.1, 1, 10, 100

τ [ns]: 0.01, 0.1, 1, 10, 100

$\sqrt{s}$ = 8 TeV | $\sqrt{s}$ = 13 TeV partial data | $\sqrt{s}$ = 13 TeV full data

*Only a selection of the available lifetime limits is shown.

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2020

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 139)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ	1 – 4 j	Yes	36.1	M_D 7.7 TeV	$n = 2$	1711.03301
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	M_{th} 8.9 TeV	$n = 6$	1703.09127
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	36.7	G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	1707.04147
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	1808.02380
	Bulk RS $G_{KK} \to WV \to \ell\nu qq$	1 e, μ	2 j / 1 J	Yes	139	G_{KK} mass 2.0 TeV	$k/\overline{M}_{Pl} = 1.0$	2004.14636
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 3 j	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	139	Z' mass 5.1 TeV		1903.06248
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z' mass 2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass 2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	0 e, μ	≥ 1 b, ≥ 2 J	Yes	139	Z' mass 4.1 TeV	$\Gamma/m = 1.2\%$	2005.05138
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	139	W' mass 6.0 TeV		1906.05609
	SSM $W' \to \tau\nu$	1 τ	–	Yes	36.1	W' mass 3.7 TeV		1801.06992
	HVT $W' \to WZ \to \ell\nu qq$ model B	1 e, μ	2 j / 1 J	Yes	139	W' mass 4.3 TeV	$g_V = 3$	2004.14636
	HVT $V' \to WV \to qqqq$ model B	0 e, μ	2 J	–	139	V' mass 3.8 TeV	$g_V = 3$	1906.08589
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V' mass 2.93 TeV	$g_V = 3$	1712.06518
	HVT $W' \to WH$ model B	0 e, μ	≥ 1 b, ≥ 2 J		139	W' mass 3.2 TeV	$g_V = 3$	CERN-EP-2020-073
	LRSM $W_R \to tb$	multi-channel			36.1	W_R mass 3.25 TeV		1807.10473
	LRSM $W_R \to \mu N_R$	2 μ	1 J	–	80	W_R mass 5.0 TeV	$m(N_R) = 0.5$ TeV, $g_L = g_R$	1904.12679
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV	η_{LL}^-	1703.09127
	CI $\ell\ell qq$	2 e, μ	–	–	139	Λ 35.8 TeV	η_{LL}^-	CERN-EP-2020-066
	CI $tttt$	≥ 1 e,μ	≥ 1 b, ≥ 1 j	Yes	36.1	Λ 2.57 TeV	$\lvert C_{4t}\rvert = 4\pi$	1811.02305
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med} 1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi) = 1$ GeV	1711.03301
	Colored scalar mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med} 1.67 TeV	g=1.0, $m(\chi) = 1$ GeV	1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
	Scalar reson. $\phi \to t\chi$ (Dirac DM)	0-1 e, μ	1 b, 0-1 J	Yes	36.1	m_ϕ 3.4 TeV	$y = 0.4$, $\lambda = 0.2$, $m(\chi) = 10$ GeV	1812.09743
LQ	Scalar LQ 1st gen	1,2 e	≥ 2 j	Yes	36.1	LQ mass 1.4 TeV	$\beta = 1$	1902.00377
	Scalar LQ 2nd gen	1,2 μ	≥ 2 j	Yes	36.1	LQ mass 1.56 TeV	$\beta = 1$	1902.00377
	Scalar LQ 3rd gen	2 τ	2 b	–	36.1	LQ_3^u mass 1.03 TeV	$\mathcal{B}(LQ_3^u \to b\tau) = 1$	1902.08103
	Scalar LQ 3rd gen	0-1 e, μ	2 b	Yes	36.1	LQ_3^d mass 970 GeV	$\mathcal{B}(LQ_3^d \to t\tau) = 0$	1902.08103
Heavy quarks	VLQ $TT \to Ht/Zt/Wb + X$	multi-channel			36.1	T mass 1.37 TeV	SU(2) doublet	1808.02343
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass 1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3}T_{5/3}\lvert T_{5/3} \to Wt + X$	2(SS)/≥ 3 e,μ	≥ 1 b, ≥ 1 j	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1	1807.11883
	VLQ $Y \to Wb + X$	1 e, μ	≥ 1 b, ≥ 1j	Yes	36.1	Y mass 1.85 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B \to Hb + X$	0 e,μ, 2 γ	≥ 1 b, ≥ 1j	Yes	79.8	B mass 1.21 TeV	κ_B= 0.5	ATLAS-CONF-2018-024
	VLQ $QQ \to WqWq$	1 e, μ	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	139	q^* mass 6.7 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1910.08447
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	36.1	b^* mass 2.6 TeV		1805.09299
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	1 e, μ	≥ 2 j	Yes	79.8	N^0 mass 560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	2 μ	2 j	–	36.1	N_R mass 3.2 TeV	$m(W_R) = 4.1$ TeV, $g_L = g_R$	1809.11105
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production	1710.09748
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Multi-charged particles	–	–	–	36.1	multi-charged particle mass 1.22 TeV	DY production, $\lvert q\rvert = 5e$	1812.03673
	Magnetic monopoles	–	–	–	34.4	monopole mass 2.37 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1905.10130

$\sqrt{s} = 8$ TeV | $\sqrt{s} = 13$ TeV partial data | $\sqrt{s} = 13$ TeV full data

10^{-1} 1 10 **Mass scale [TeV]**

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

Conclusions

- I did not present any discovery or very precise measurement published but I hope you enjoy anyway the lecture and find some interest for BSM studies!

- The list of searches presented is not complete, but please check the links below for having a complete overview:
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
  - https://cms-results.web.cern.ch/cms-results/public-results/publications/EXO/index.html

- For any comments or questions you can send me an email to **monica.verducci@cern.ch**

BackUp

ABCD Method

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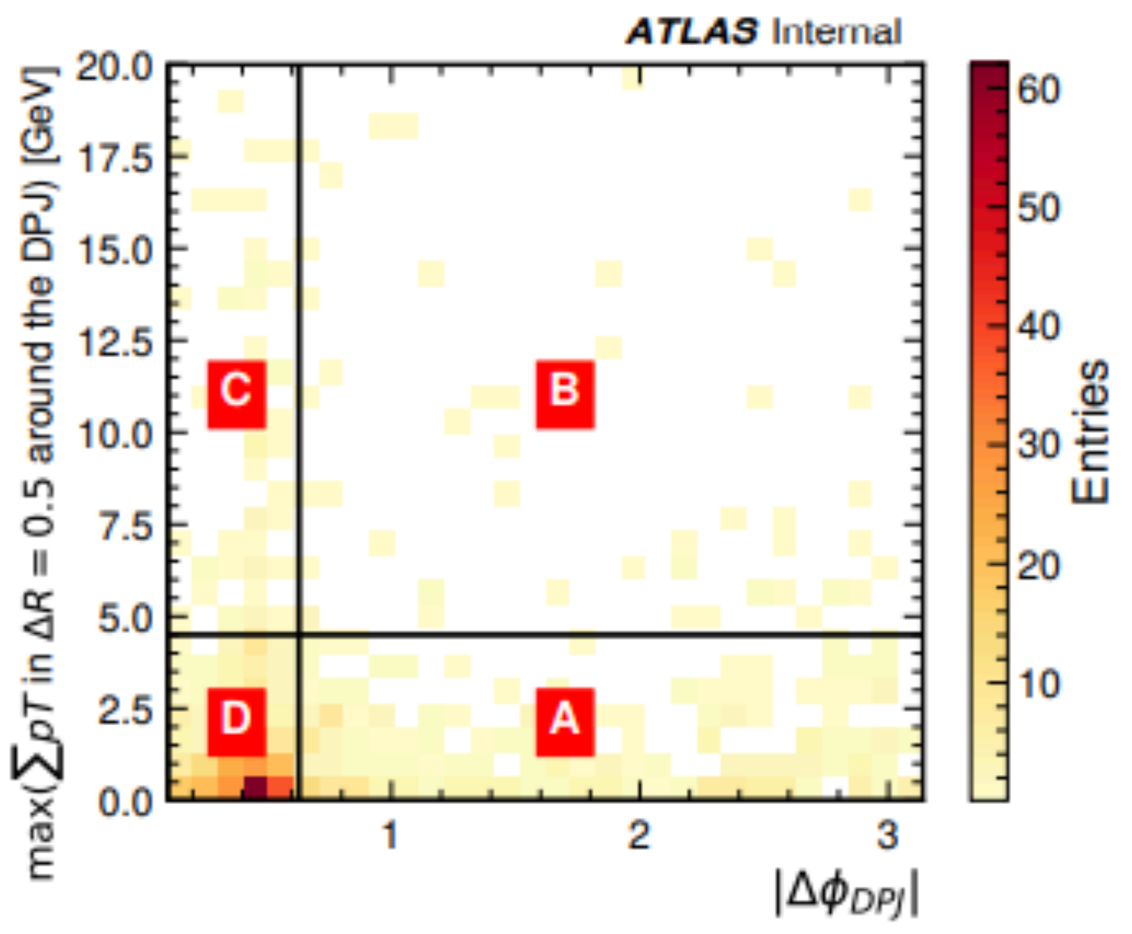
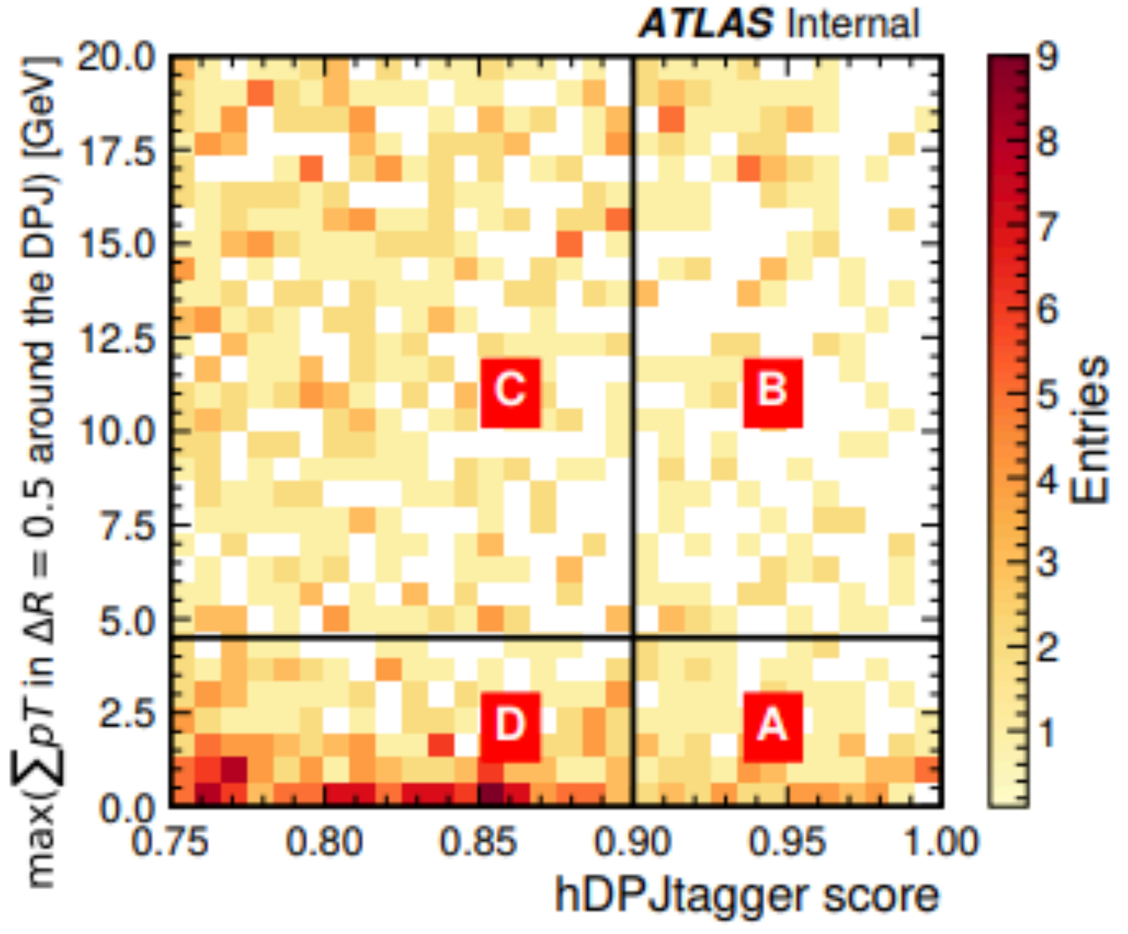
- A data-driven ABCD method is used to estimate the multi-jet background in each of the three channels
  - The number of background events are computed by knowing the number of events in the other three regions:
    - NA = ND × NB/NC

	B	C	D	expected in A	A observed
2 μDPJ	55	61	389	357 ± 67	269
μDPJ– hDPJ	169	471	301	108 ± 12	110
2 hDPJ	97	1113	12146	1065 ± 112	1045

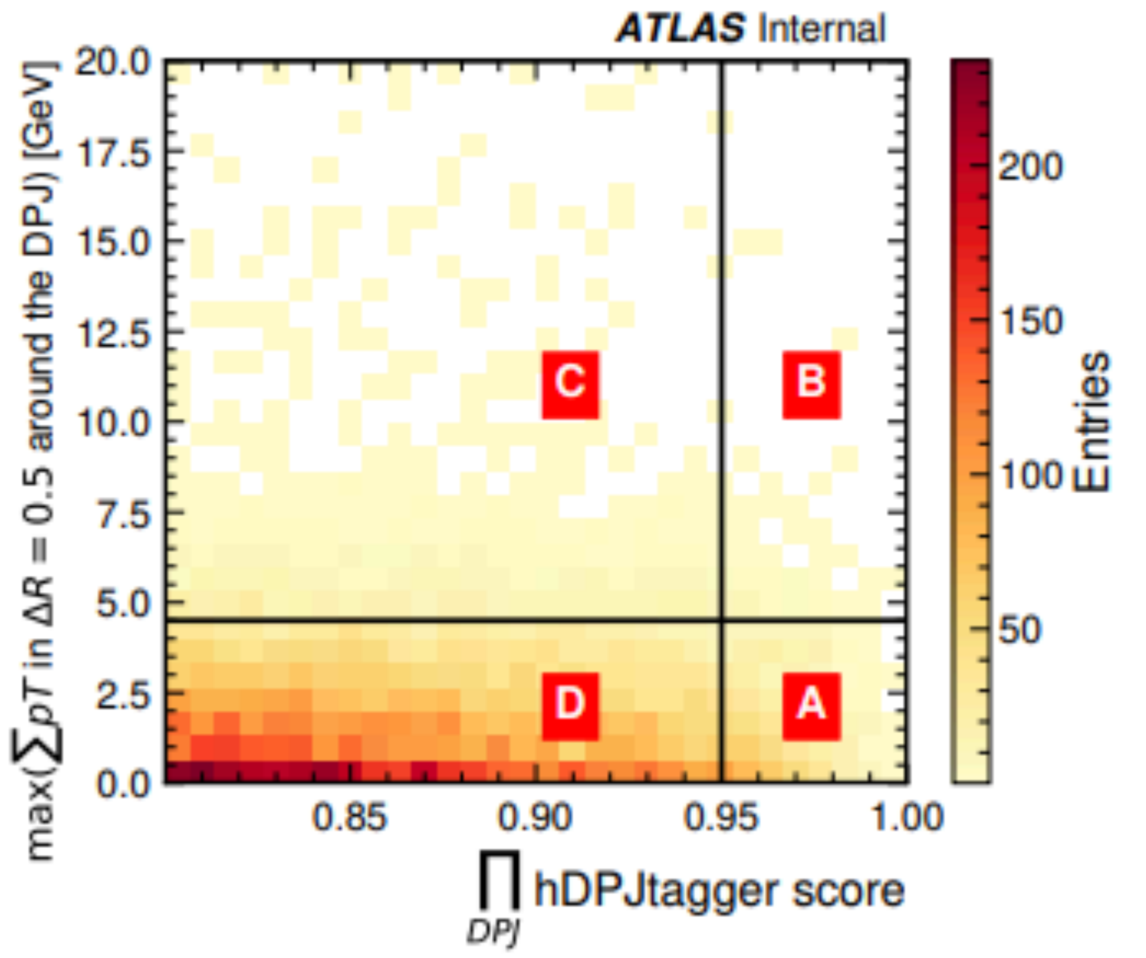


(a) muonic–muonic



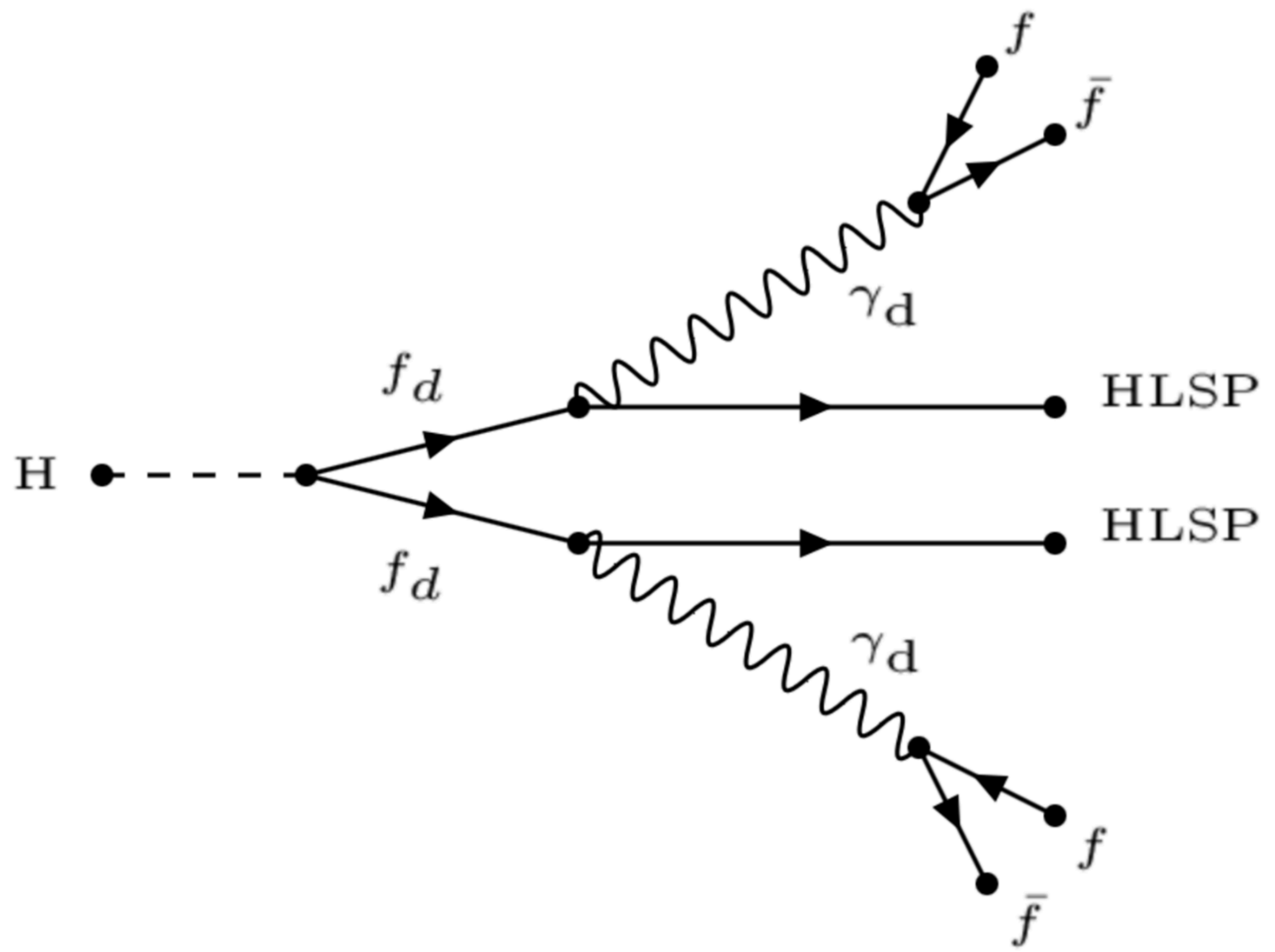
(b) muonic–hadronic

Signal Region A

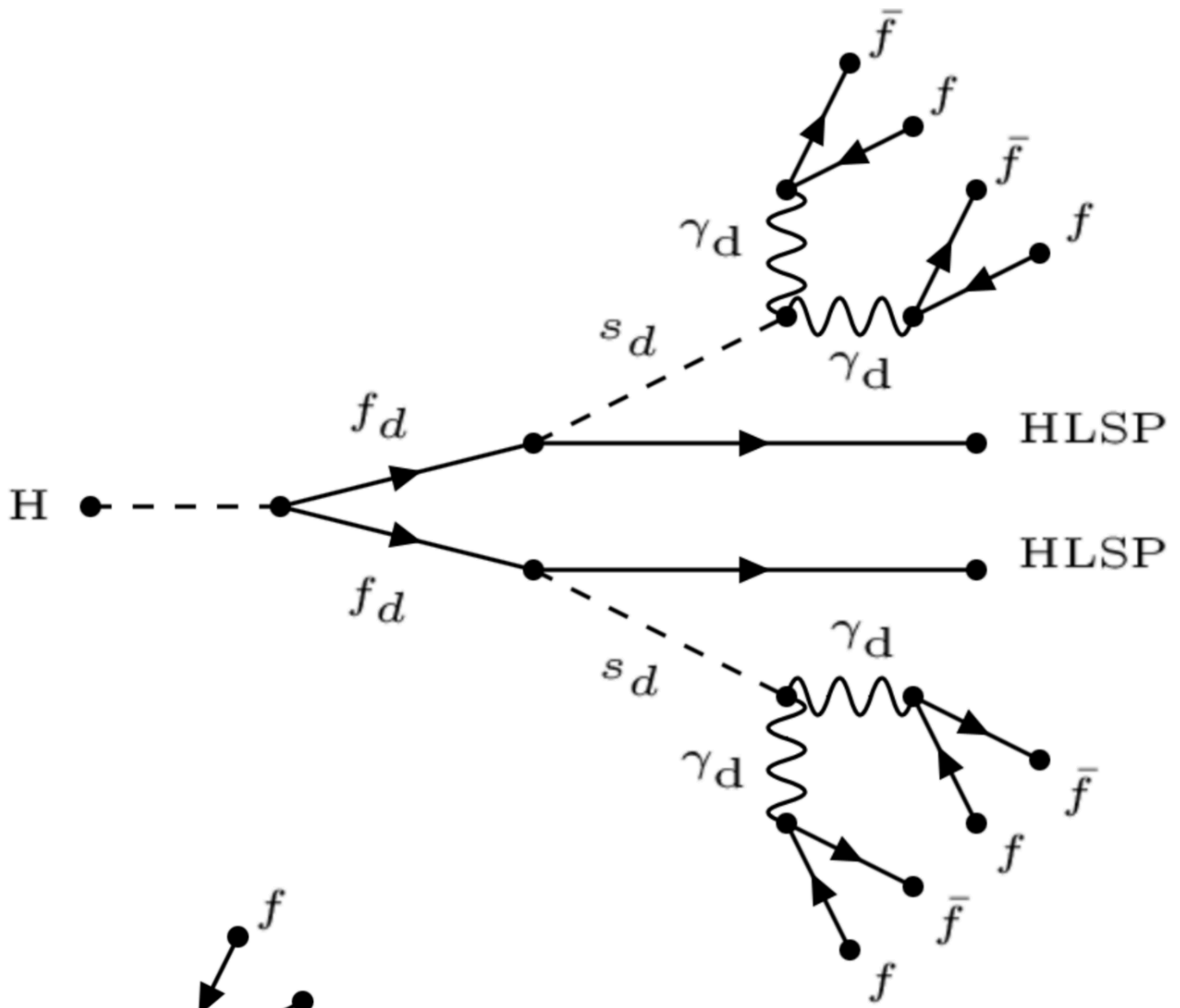


(c) hadronic–hadronic

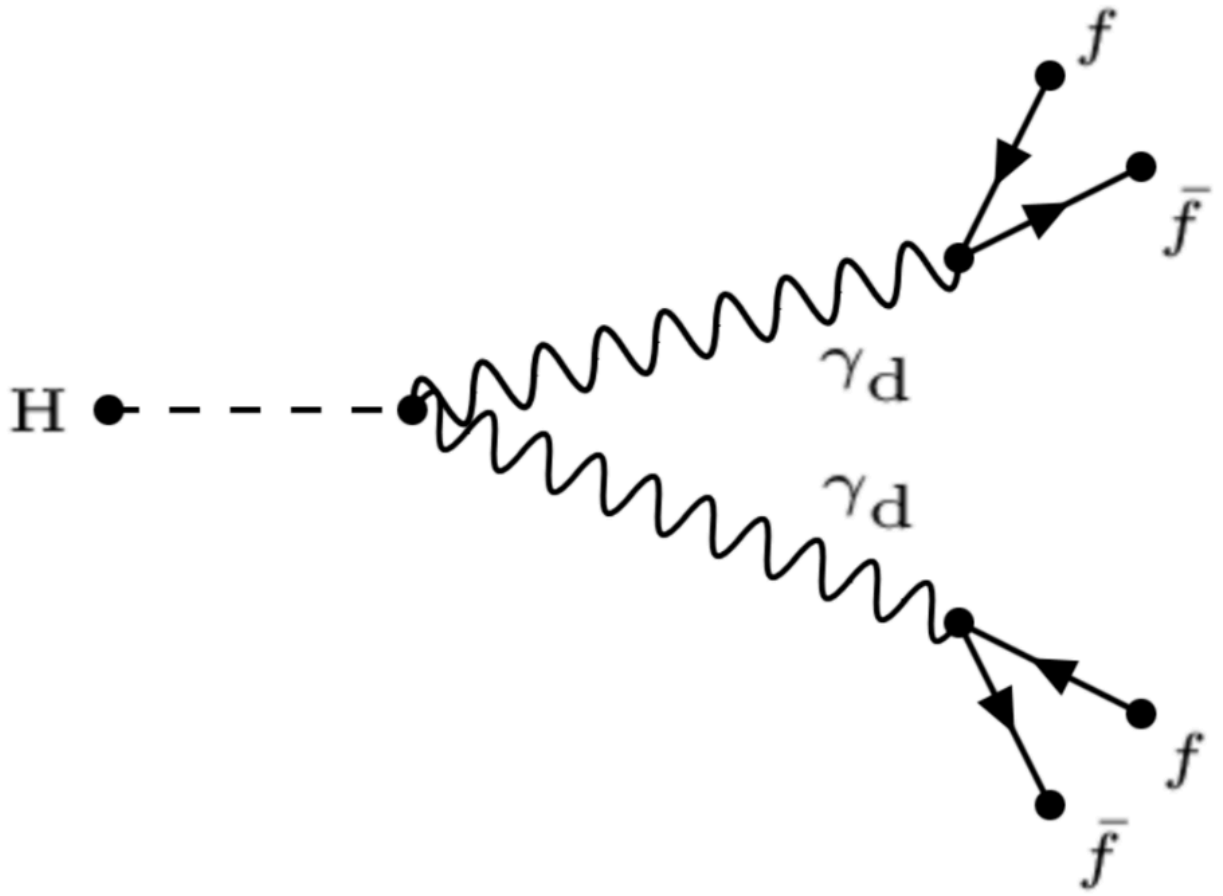
Dark Photon



H
f_d
f_d
γ_d
γ_d
HLSP
HLSP
f
$\bar{f}$
f
$\bar{f}$

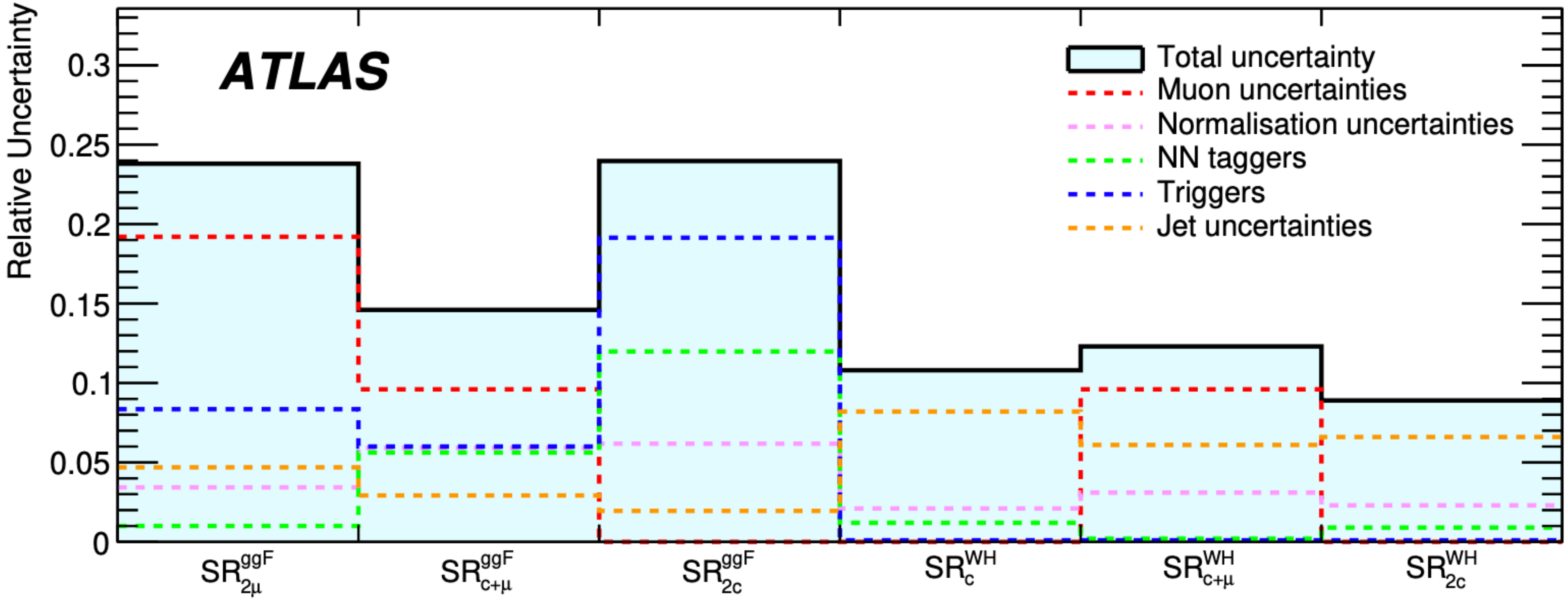


H
f_d
f_d
s_d
s_d
γ_d
γ_d
γ_d
γ_d
HLSP
HLSP
f
$\bar{f}$



H
γ_d
γ_d
f
$\bar{f}$
f
$\bar{f}$

Systematics Displaced Dark Photons



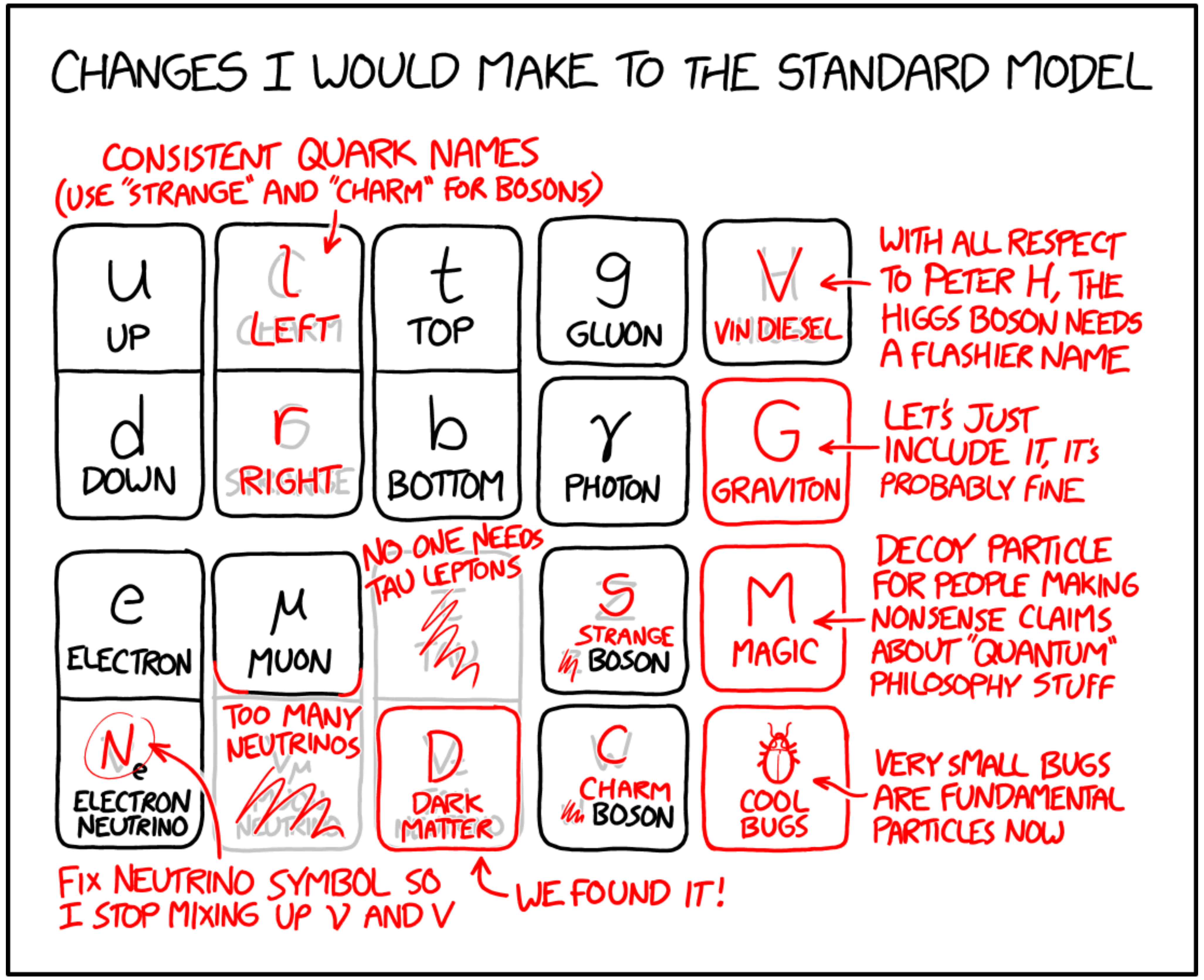
Beyond the Standard Model

We start from the base guide of any theory: new symmetry for new models.
Preserve gauge invariance (SU(3) x SU(2)L x U(1)Y)

- do not introduce too large sources of breaking of the accidental / approximate symmetries of the SM classical Lagrangian

Remind: Quantum Mechanics any global transformation induces a quantity conserved.

1. Translation Invariance -> Linear Momentum Conservation
2. Rotation Invariance -> Angular Momentum Conservation
3. Translation in Time Invariance -> Energy Conservation



E. Noether's Theorem: Symmetries Invariances naturally lead to conserved quantities!

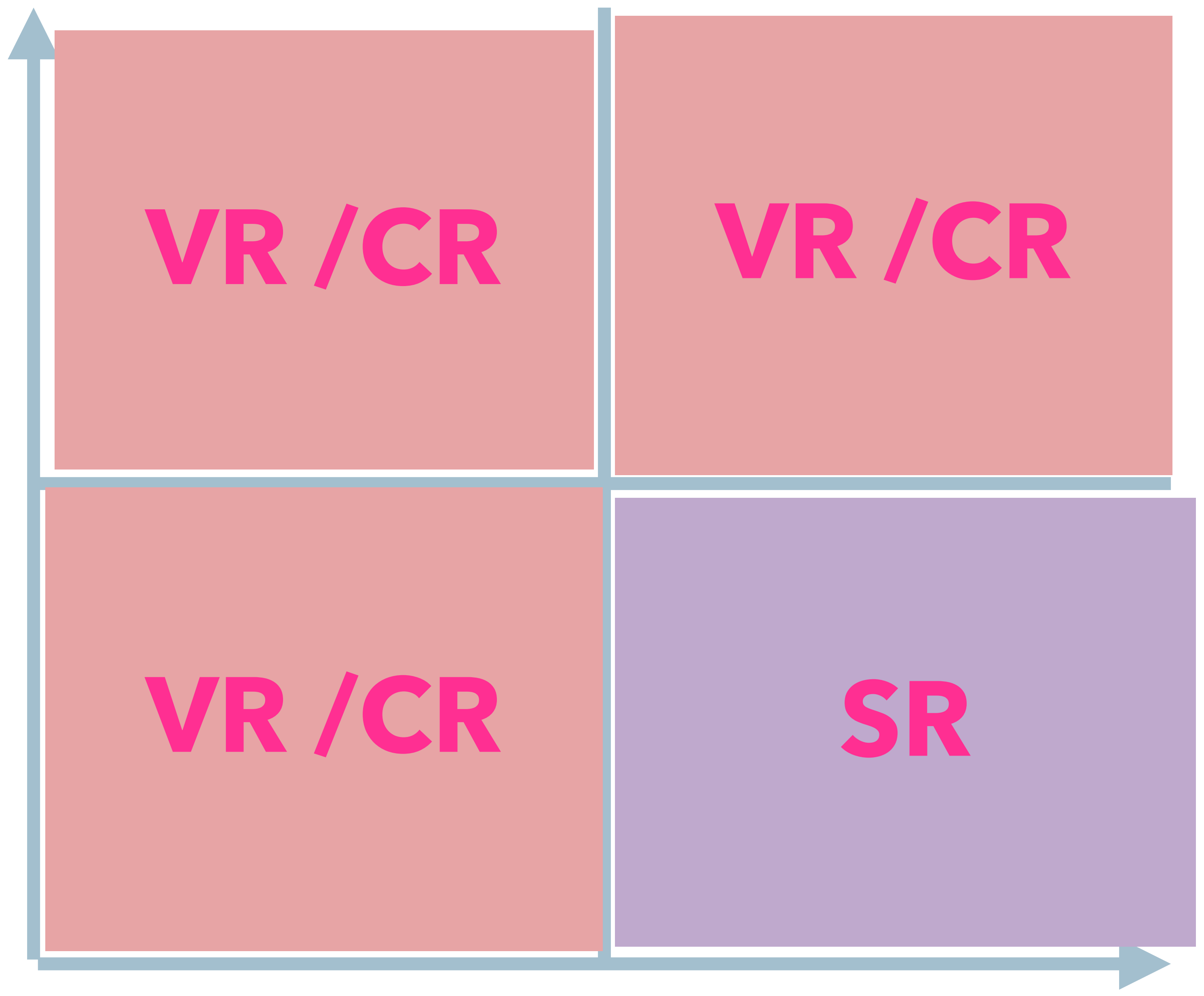
Definition of Regions

Signal Region SR
Cuts defined to maximise the signal events.

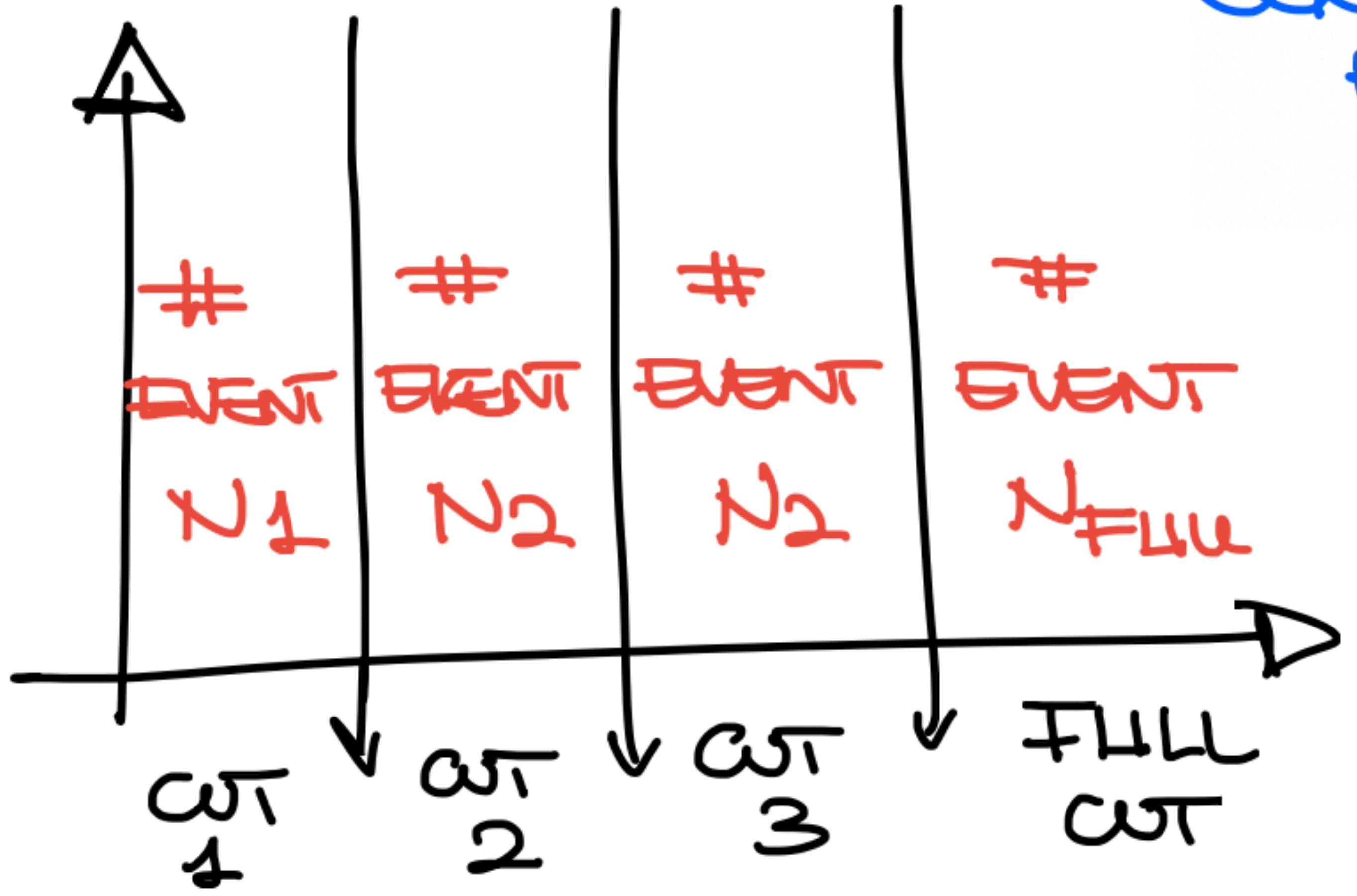
Validation Region VR
Orthogonal Cuts to the one used for the SR, the signal events should be negligible.

Transfer factor

Control Region CR
the signal events should be negligible, used to estimate the background events.



An example: Estimation of Cosmics Muons Background



CONTROL REGION FOR COSMICS

↓

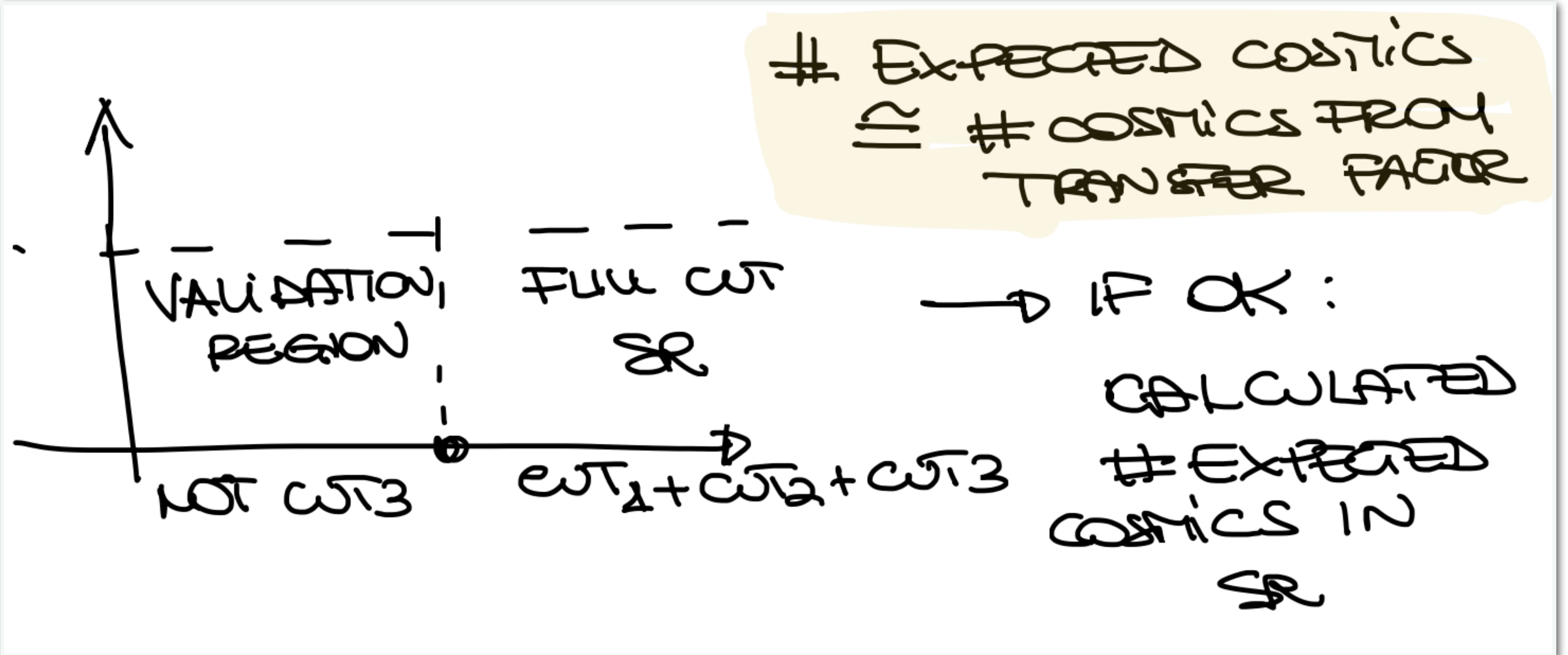
ORTHOGONAL SELECTION OF COSMICS VETO.

The cosmics muons are removed by applying a cut on the events which have activity in the MS on the side opposite to the muon are rejected.

$\Rightarrow N_{FULL}$ = # COSMIC AFTER THE FULL SELECTION BUT ON A SAMPLE ENRICHED OF COSMIC

- Now I need to know the number of cosmics in the SR, where the comics veto is applied.
- I calculated the expected number of cosmics in a VR and compare this with the effective number of cosmics via a **transfer factor.**

$$f_{Cosmics} = \frac{Events\ in\ CR\ that\ pass\ Muon\ Cosmics\ VETO}{Events\ in\ CR\ that\ do\ not\ pass\ Muon\ Cosmics\ VETO}$$

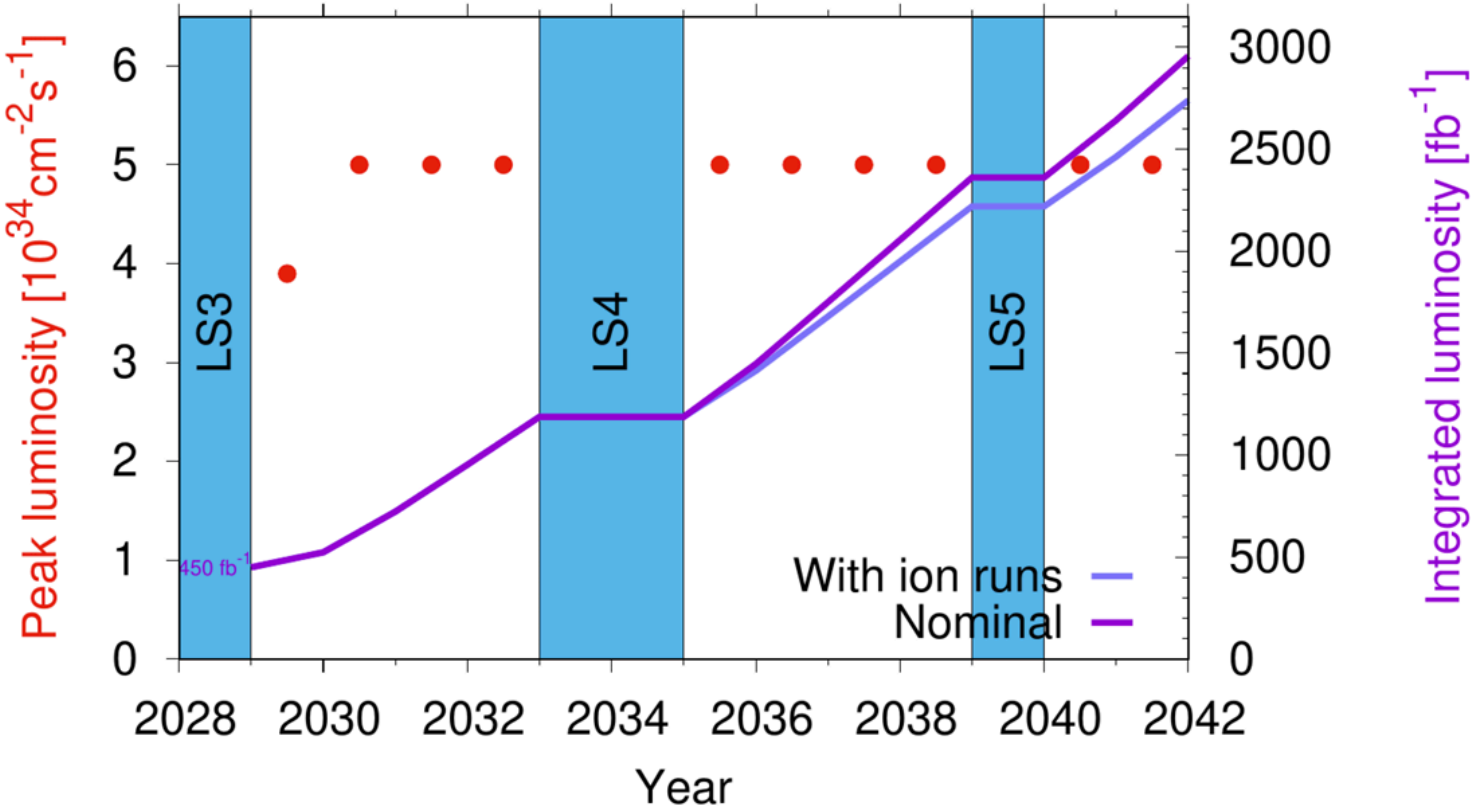


$$N_B^{SR} = \sum_i N_i^{CR} \times f_i.$$

HL-LHC

ATLAS Week slides

Chris Young showed in his LHC talk at the ATLAS Week the following HL-LHC luminosity profile presented by Mike Lamont at LHCP 2024

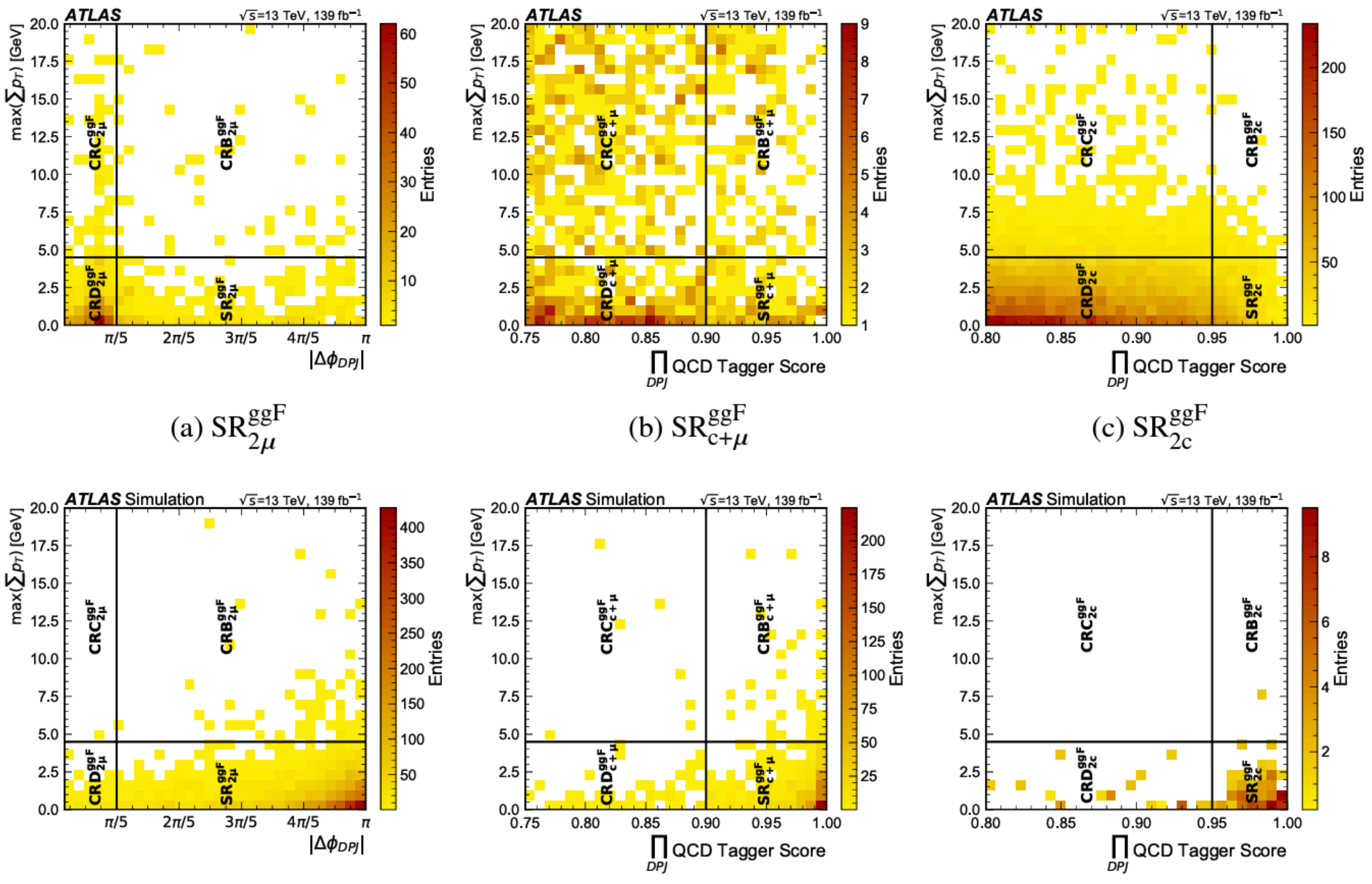


The profile features only the *baseline* scenario (5×10^{34} cm^{-2}s^{-1}, $\mu = 132$), but not the ultimate one (7.5×10^{34} cm^{-2}s^{-1}, $\mu = 200$)

Information by Mike:

- The baseline scenario was found to deliver the required 3000 fb^{-1}, which is why it was chosen
- The ultimate scenario is **not** excluded (Mike will request the corresponding simulation in that scenario)
- Mike also promised to check whether the relatively small ion effect is correct

ABCD Plane



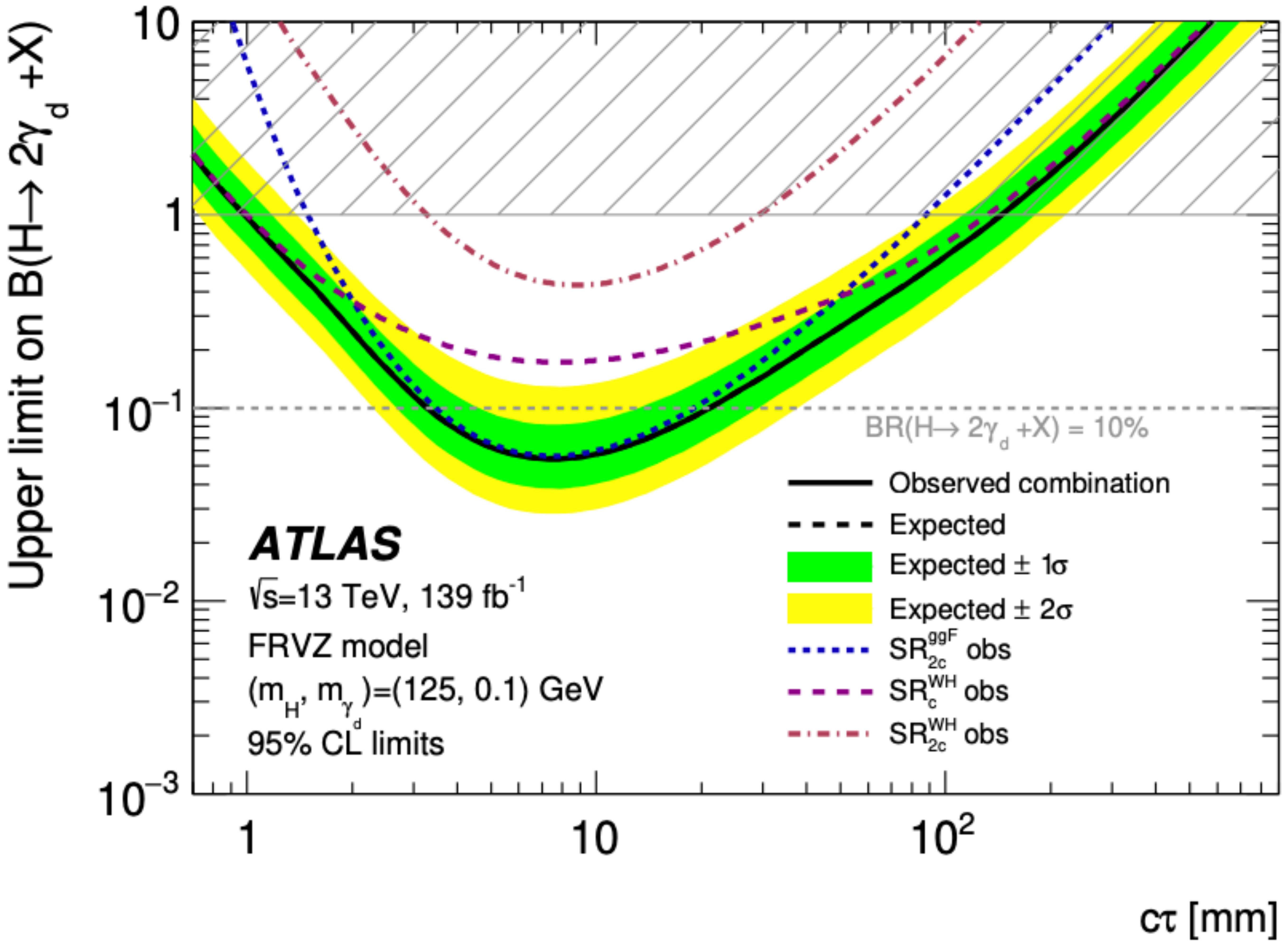
(a) $SR^{ggF}_{2\mu}$ (b) $SR^{ggF}_{c+\mu}$ (c) SR^{ggF}_{2c}

(d) $SR^{ggF}_{2\mu}$ (e) $SR^{ggF}_{c+\mu}$ (f) SR^{ggF}_{2c}

Figure 6: The per-event distributions in the ABCD planes defined for the ggF search channels. Figures (a, b, c) show data events, while Figures (d, e, f) show simulated signal events. FRVZ signal samples assuming a 125 GeV Higgs boson with a decay branching fraction of 10% to the dark sector and a γ_d mass of 400 MeV are shown.

Results

- Great Improvement due to the combination of the Higgs production modes.



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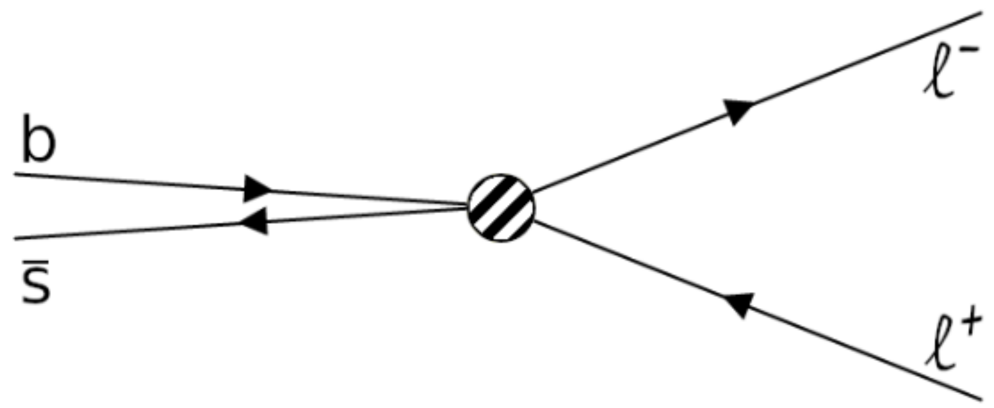
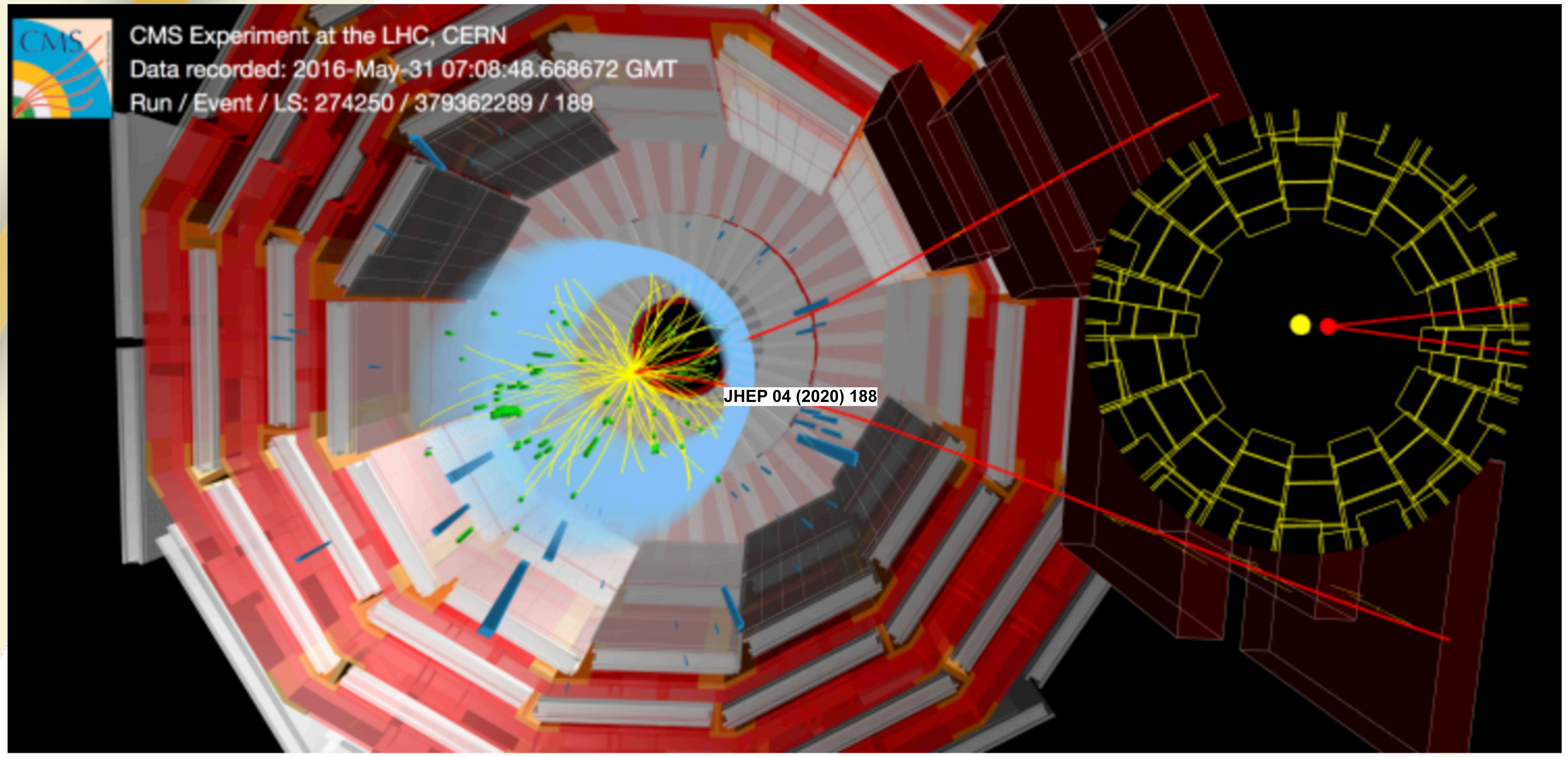
Rare decays: Bs→μμ and B→μμ (CMS)

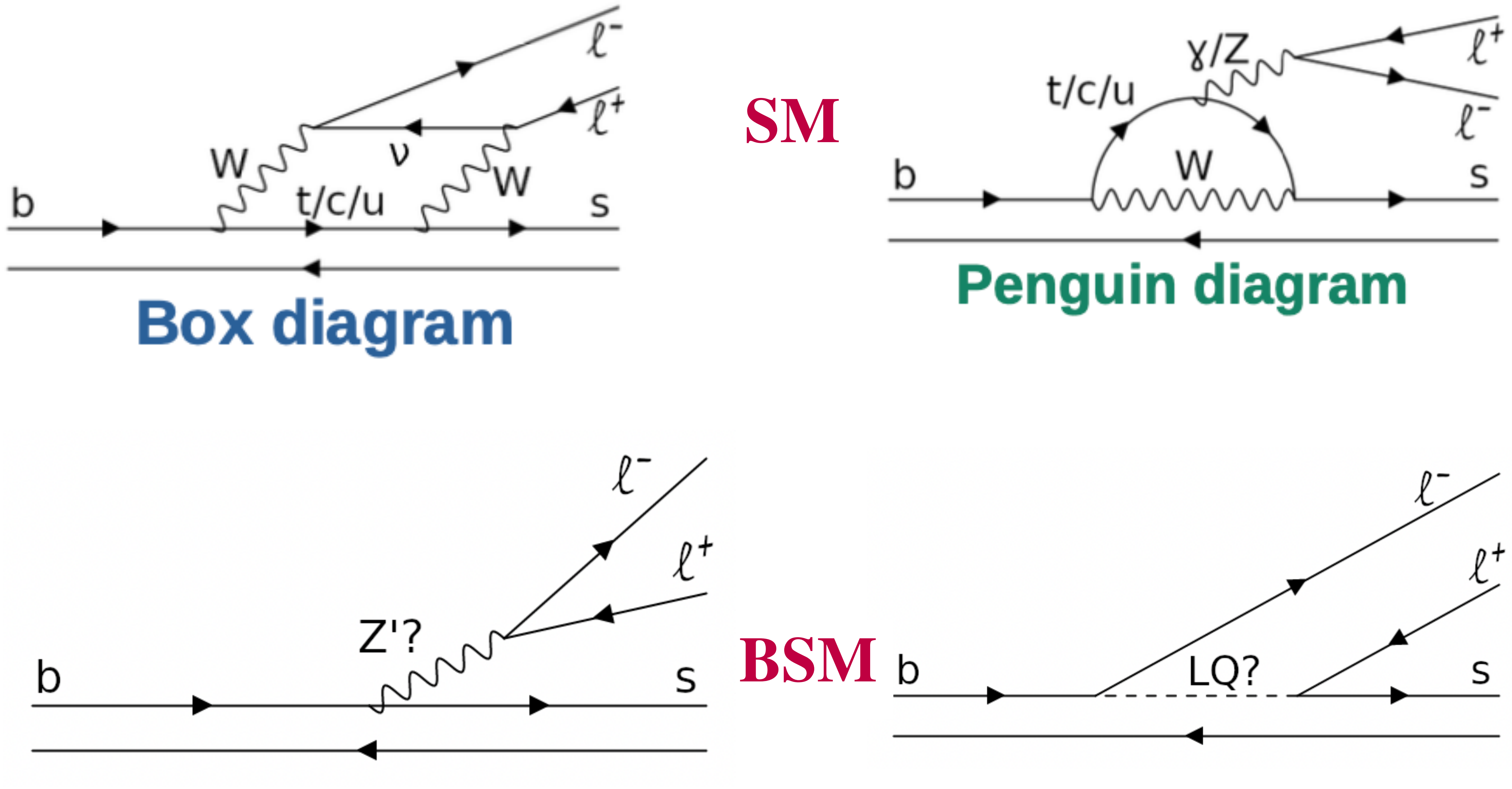




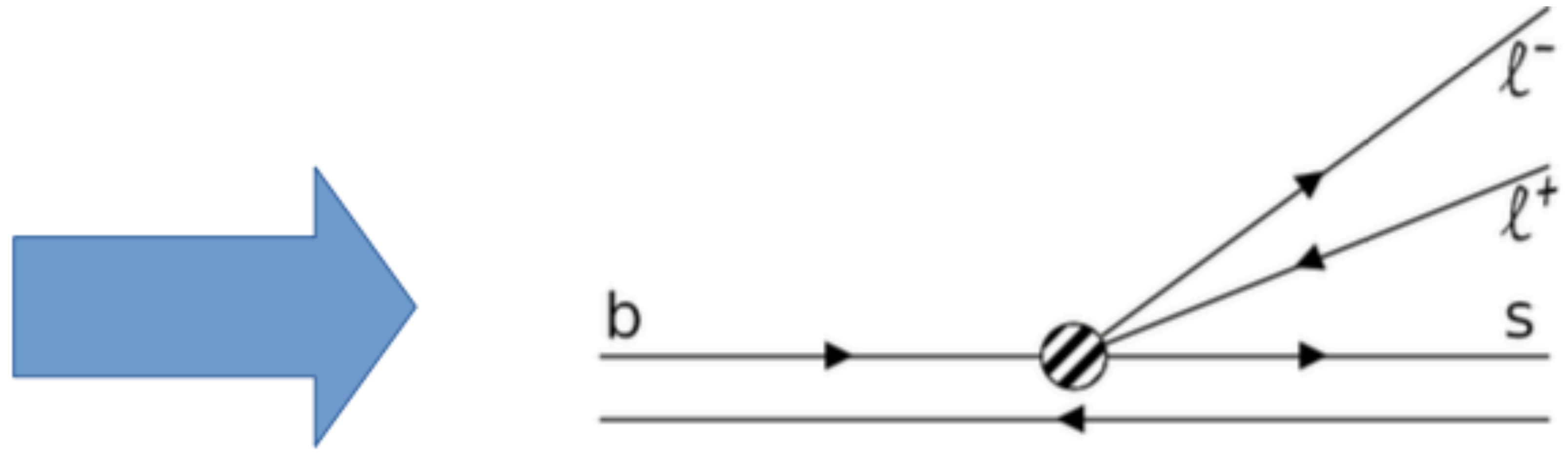
Rare Decays

Indirect BSM searches

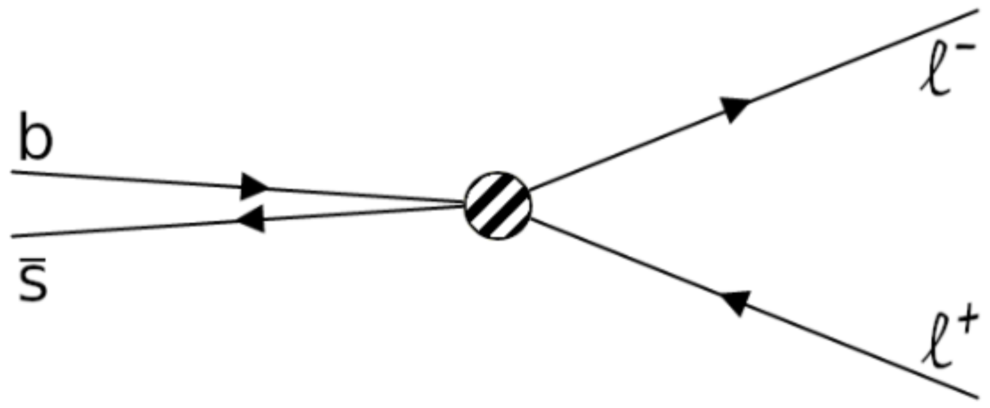
- Aim at precise measurements of SM processes, to compare them with theory predictions.
  - BSM effects can interfere with the SM processes and produce visible differences
- Best environment to indirectly search for new physics is in **rare decays** of SM particles
  - sensitive to new particles with lower couplings or higher mass
  - One of the most promising category is **flavour-changing neutral currents** decays $b \to sl^+l^-$



Decays described in the framework of Effective Field Theory degrees of freedom at weak energy scale or higher are integrated out additional 6th-dimensional terms added to the effective Lagrangian



Bs→μμ and B→μμ



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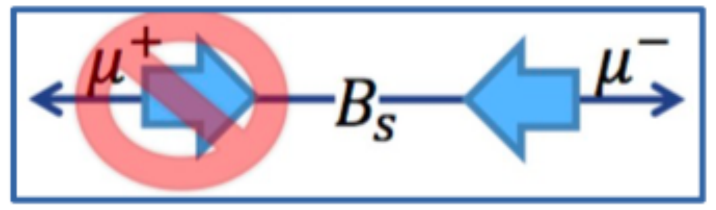
Bs→μμ double suppress in SM

- No tree-level diagram
- Helicity suppression
- BF prediction ~3.6 10^{-9}

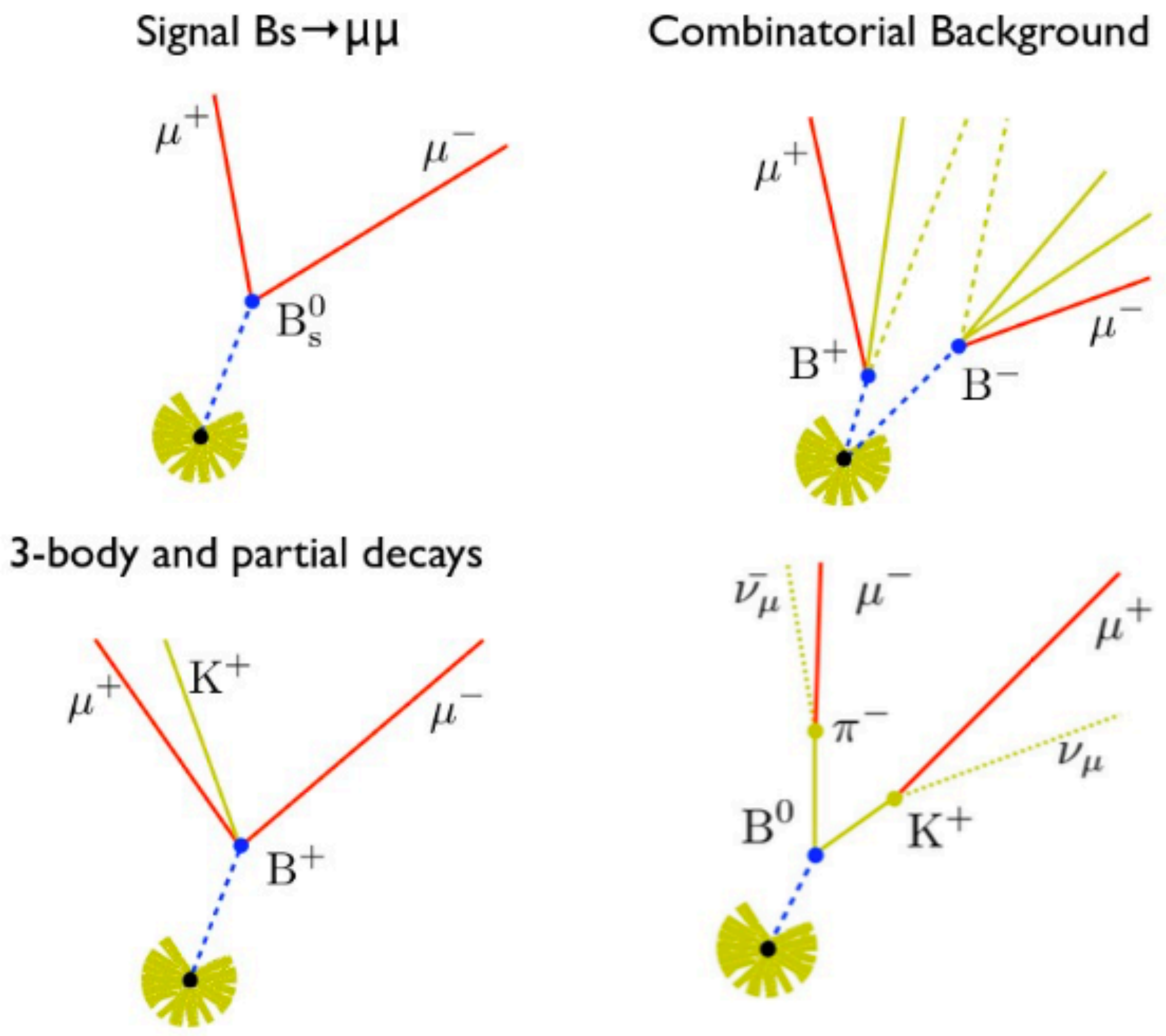


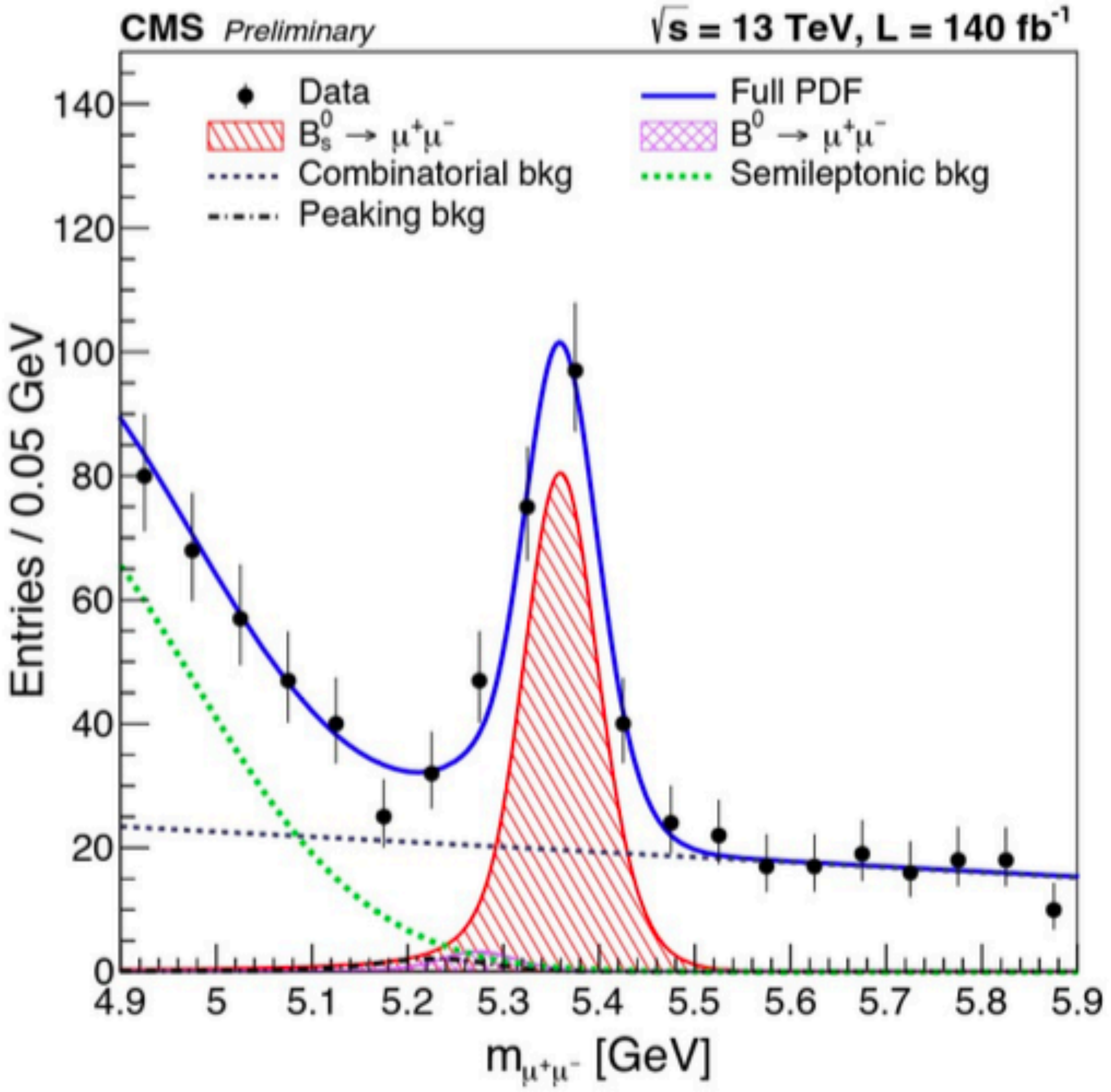
B→μμ as **Bs→μμ +**

- Additional suppression from CKM
- BF prediction ~ 10^{-10}

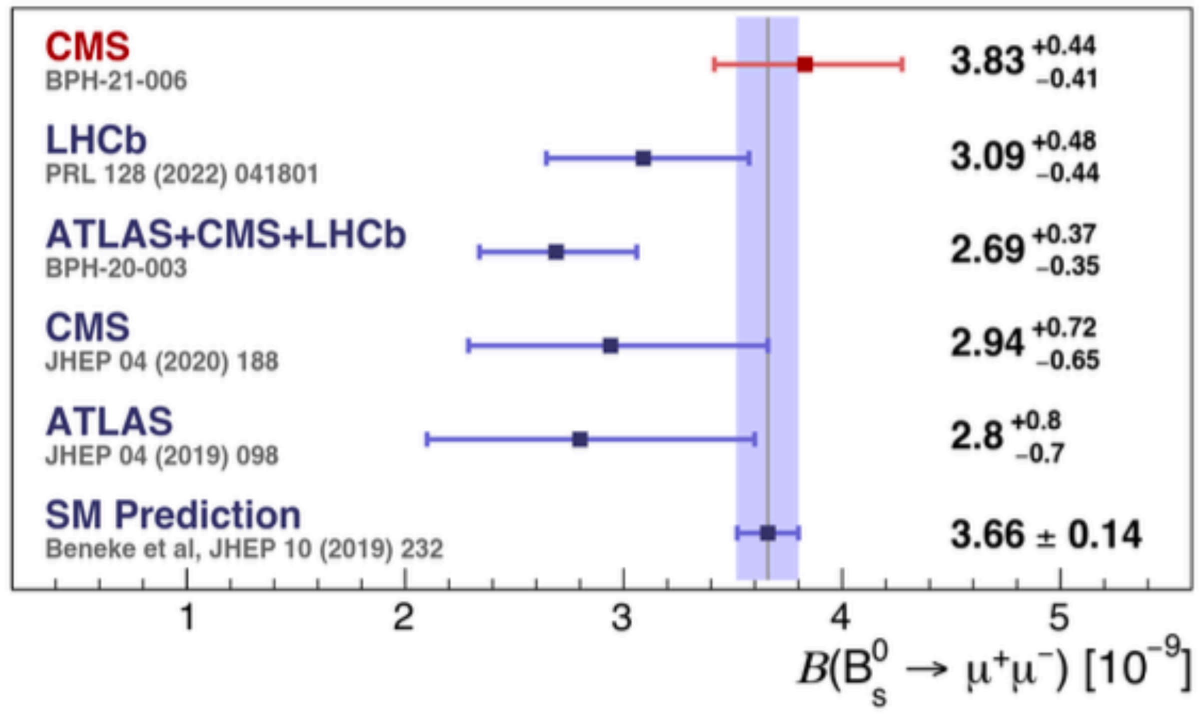
Analysis:

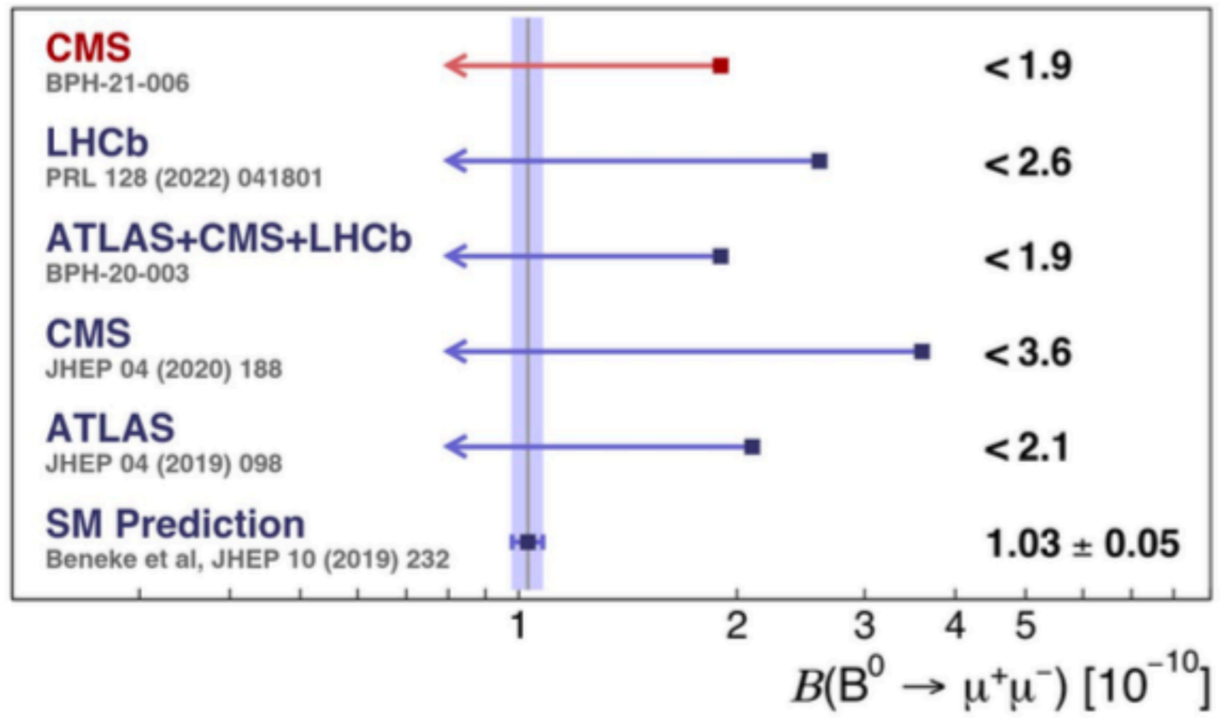
- Very clean signature
- MVA Analysis on muon identification





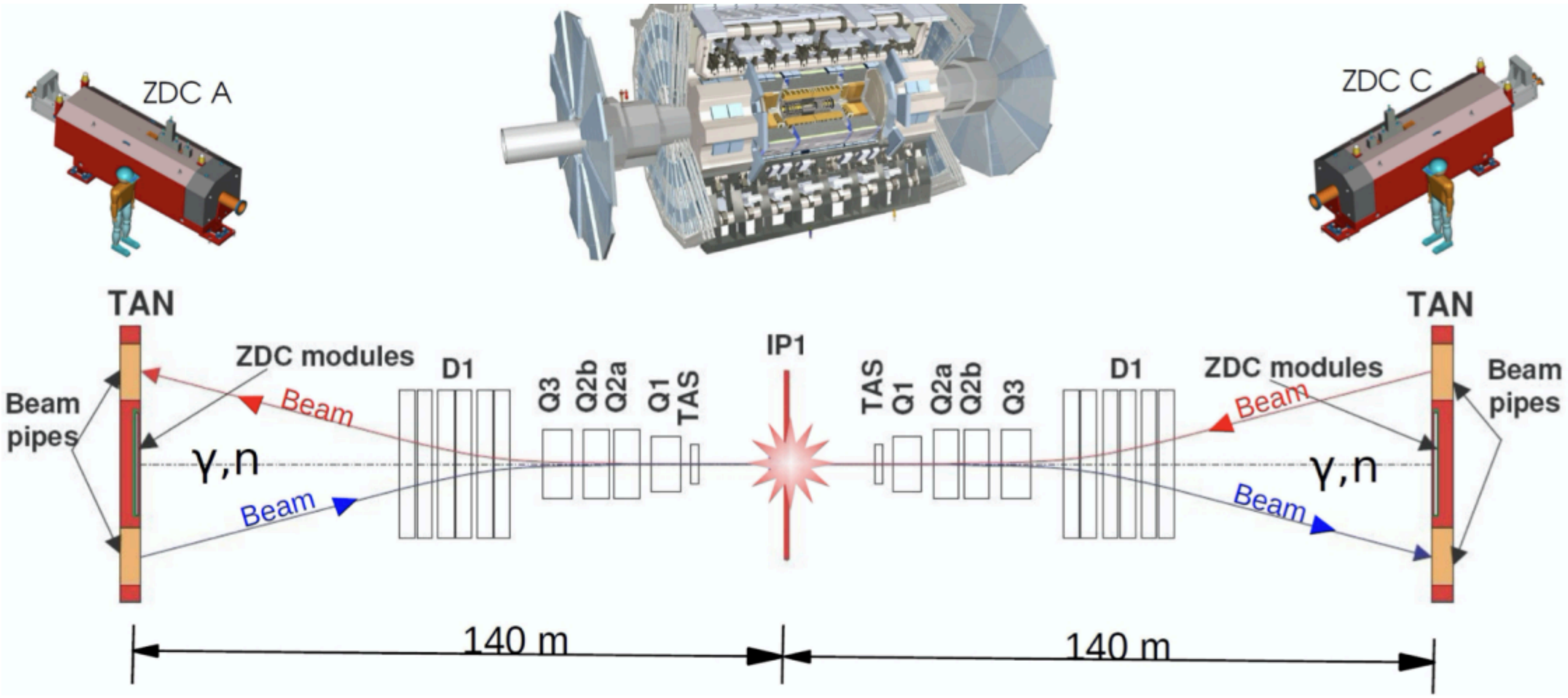
No tensions with SM predictions

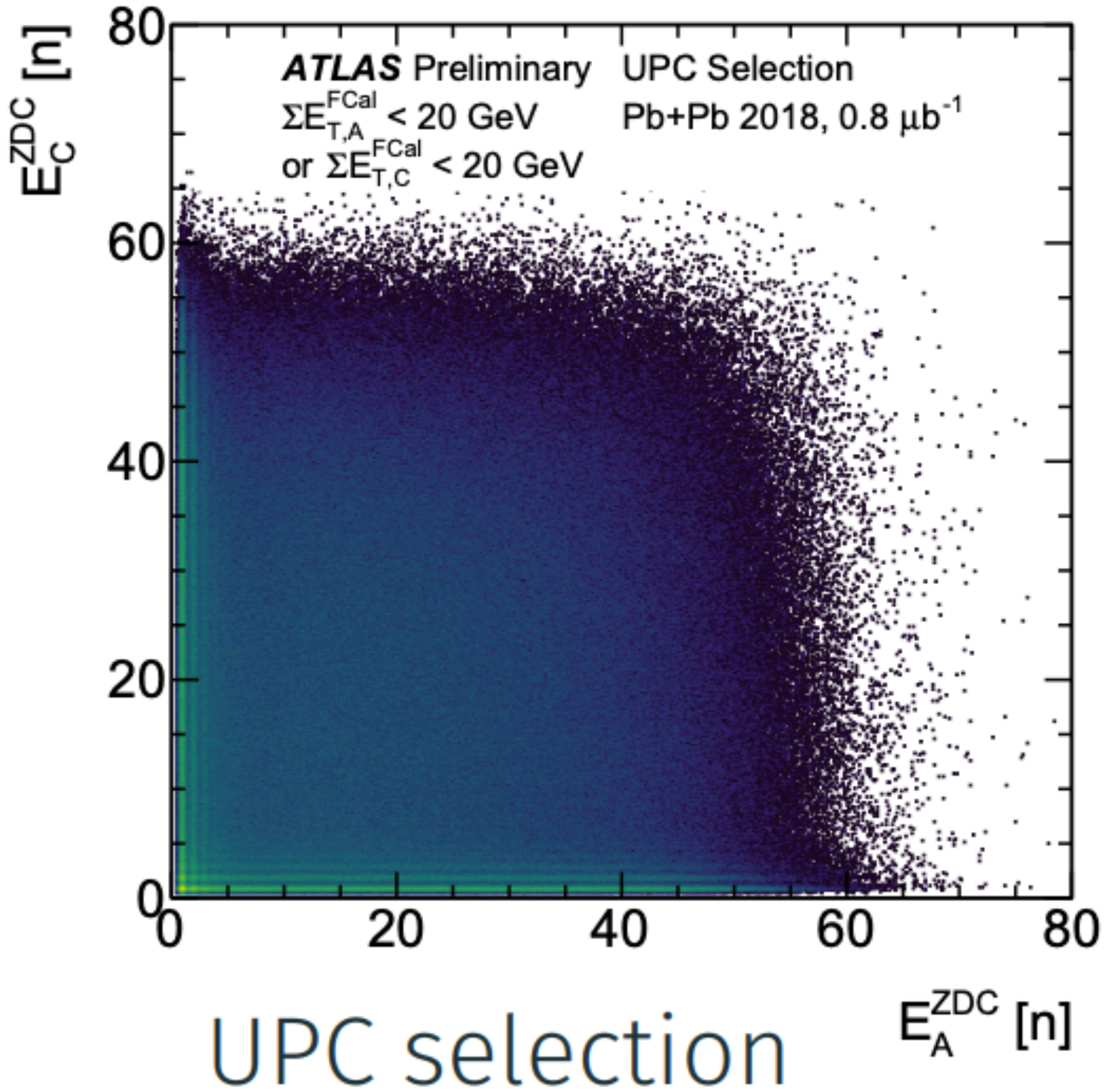




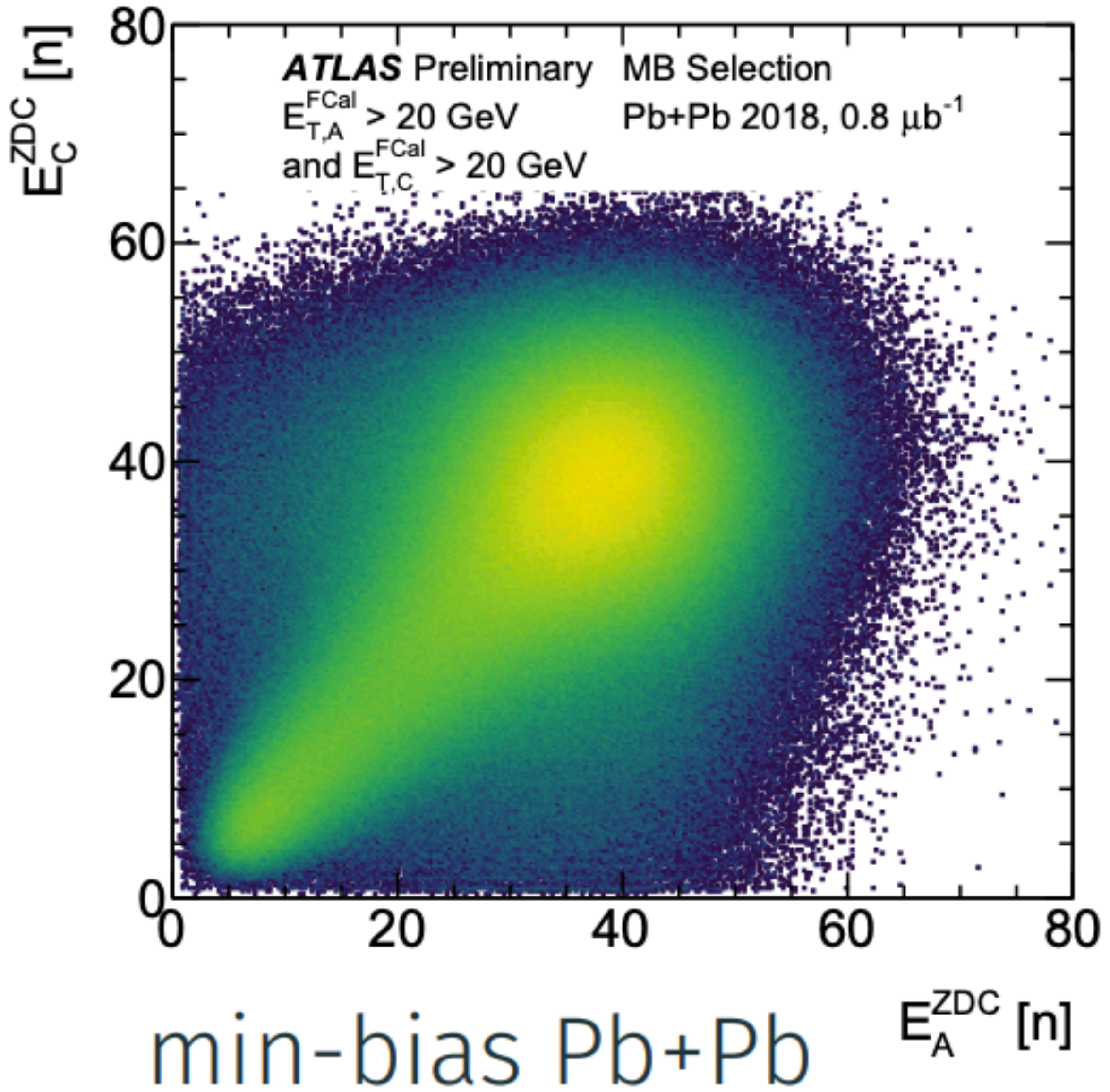
Zero Degree Calorimeter ZDC

- Energies of forward neutral particles (photons, **neutrons**) measured in two ZDC arms.
- Important for ATLAS heavy-ion program, e.g. helps to separate UPCs from inelastic Pb+Pb collisions.
- For $\gamma\gamma \to \tau\tau$ or $\gamma\gamma \to \ell\ell$ production expect $60-70\%$ of events to have no neutrons on either side (**0n0n topology**).
- ZDC is not simulated in MC, so ZDC selections can only be applied in data $\to$ **simulation reweighted to 0n0n topology**.





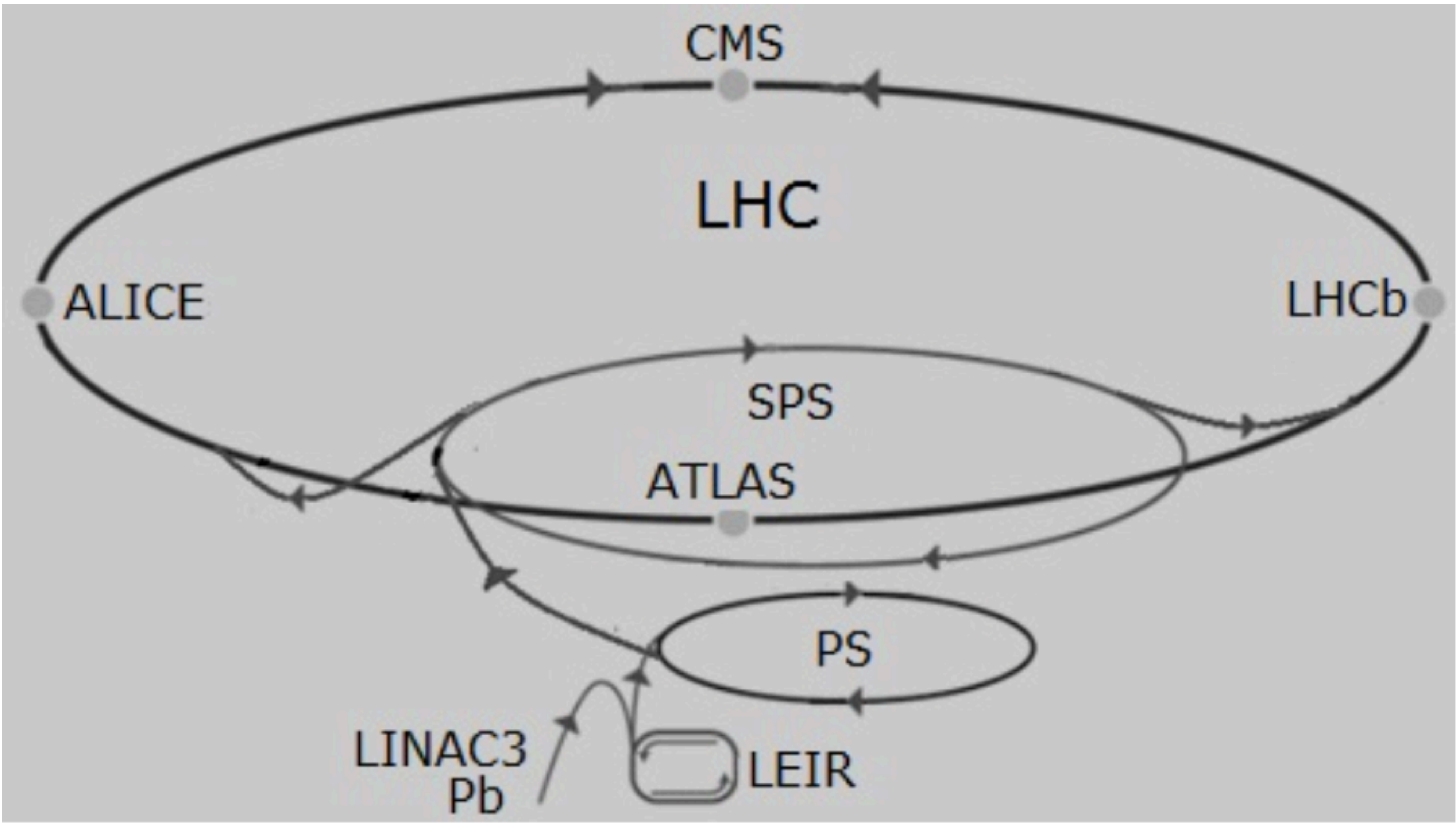
UPC selection



min-bias Pb+Pb

LHC with Lead Lead Collisions

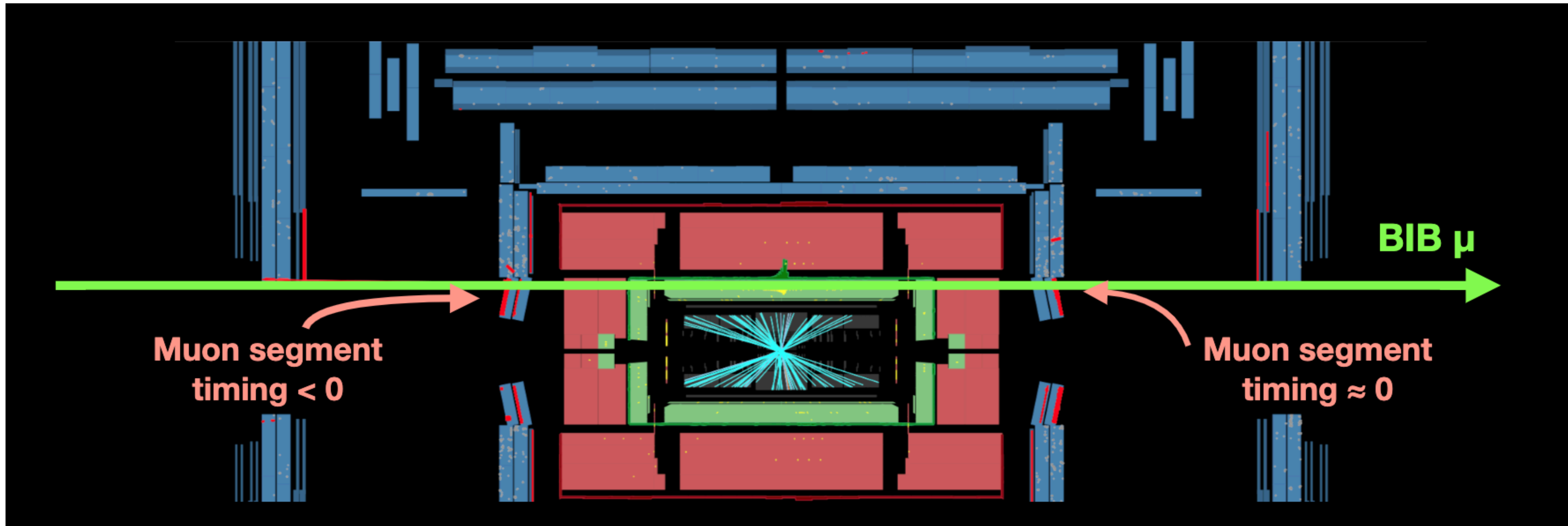
The ions first travel through a linear accelerator called **Linac3**, picking up a small amount of energy (4.5 MeV per nucleon). Next, the ions are accumulated and accelerated to 72 MeV per nucleon in the **Low Energy Ion Ring, or LEIR**. Then they move to **SPS**.



Each LHC ring will be filled in 10 min by almost 600 bunches, each of $7\times10_{7}$ lead ions. Central to the scheme is the Low Energy Ion Ring (LEIR), which transforms long pulses from Linac3 into highbrilliance bunches.

BIB Analysis in Muon and Calorimeters systems

- **A typical beam halo muon enters the detector on one side, deposits energy in the calorimeter and leaves on the other side.**
  - **Result: muon segments and calorimeter clusters parallel to the beam pipe.**
- BIB Study already performed during Run-1 with tagging flags included in the event definition.



$$t_{early}^{expected} = -|z|/c - |t_{tof}| = -2\sqrt{r^2 + z^2}/c$$

$$t_{in\ time}^{expected} = -|z|/c + |t_{tof}| \approx 0$$