Search for emerging jets in the ATLAS detector and reinterpretation of the LHC results

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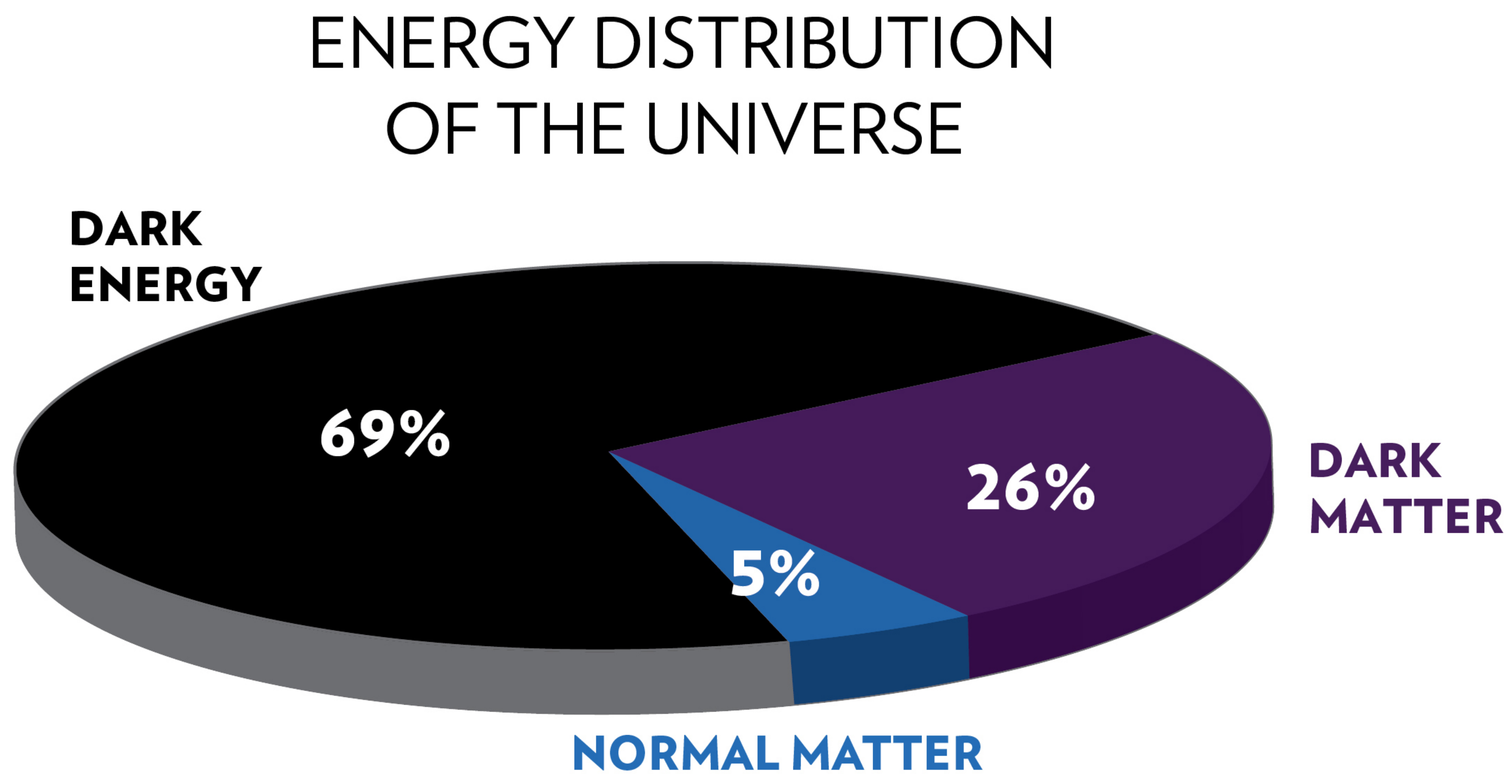
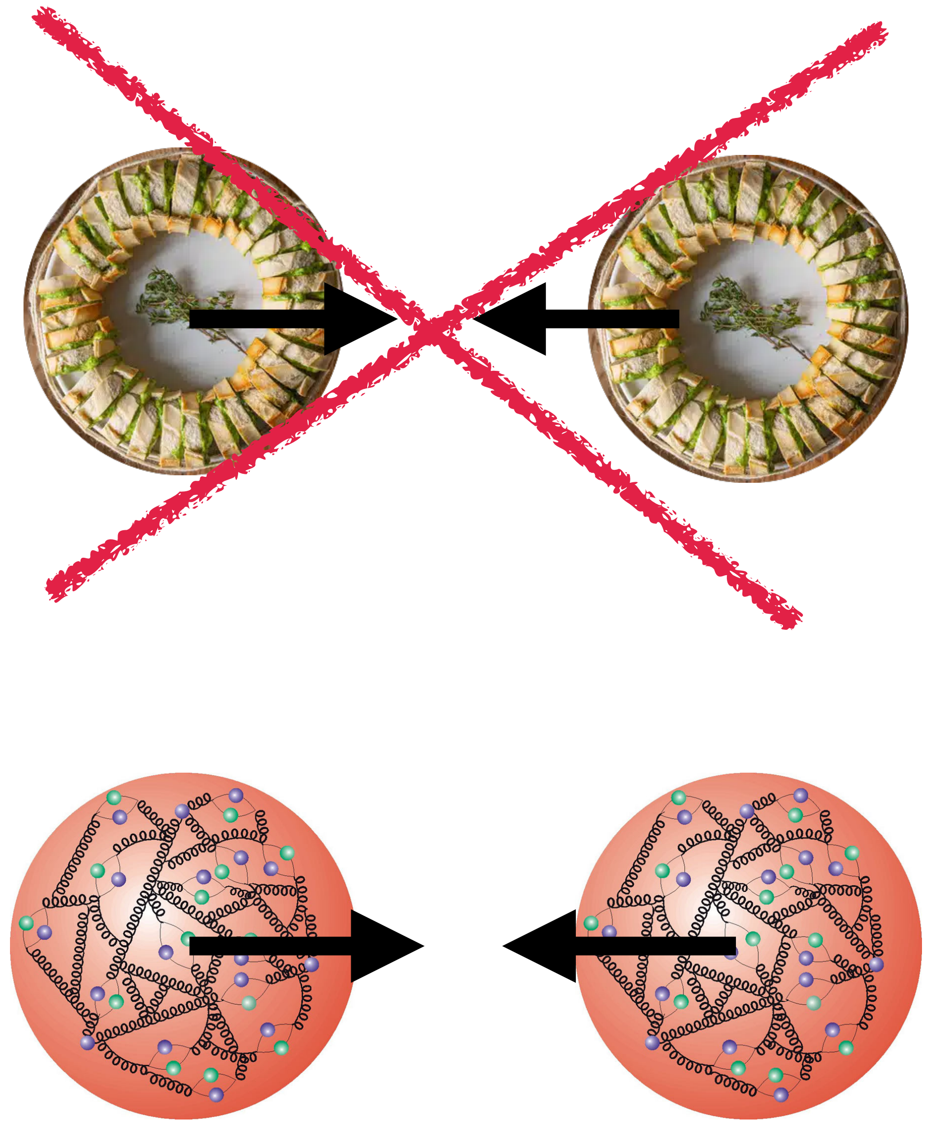
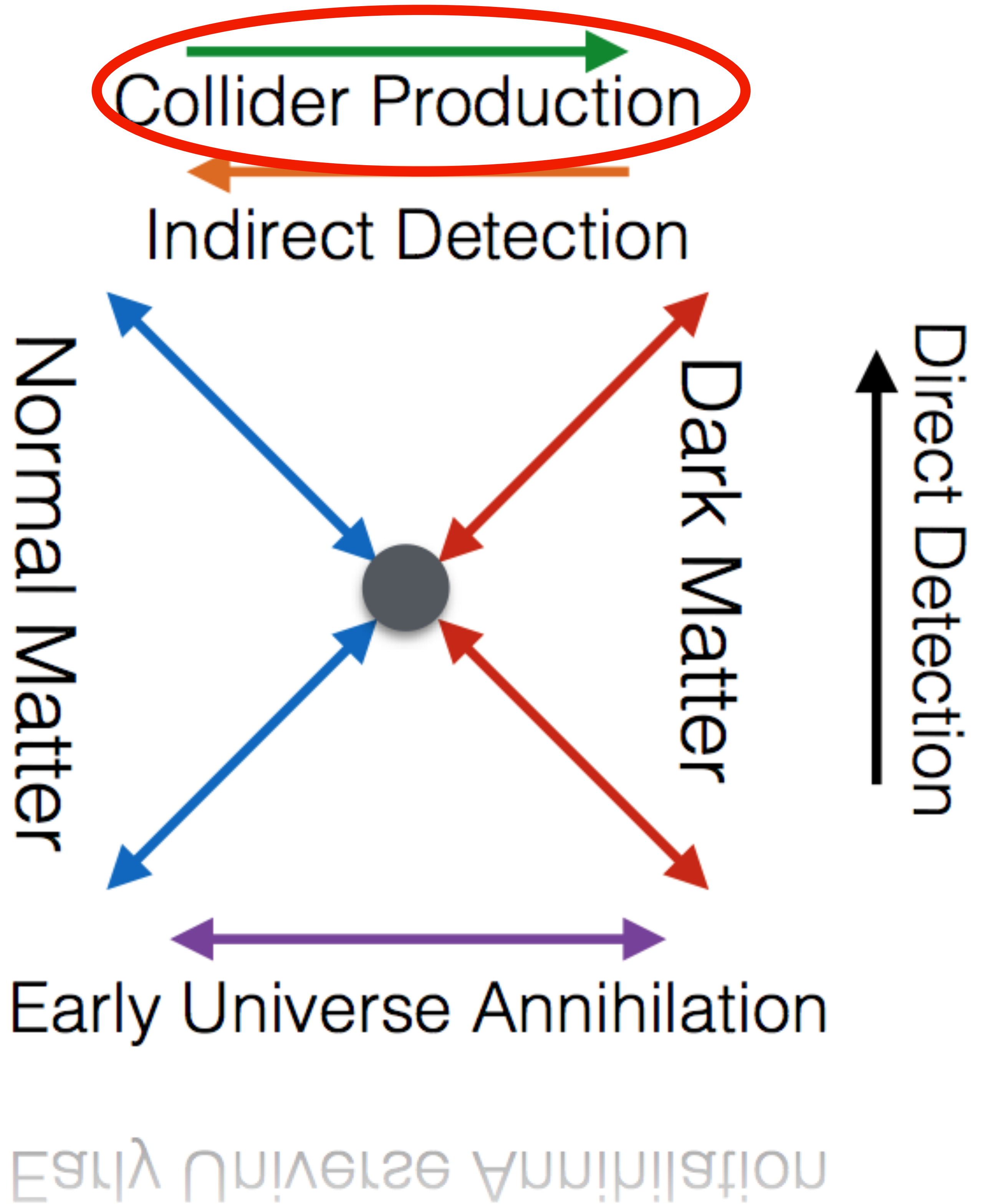
Search for emerging jets

Context

- 85 % of the matter in the Universe not composed of Standard Model particles : *Dark Matter*
- Several hypothesis to explain its nature : could be made of *new particles weakly interacting* with Standard Model ones
- Proton - proton (not préfou - préfou) collisions at the LHC to possibly produce such particles, before observing them thanks to detector like ATLAS



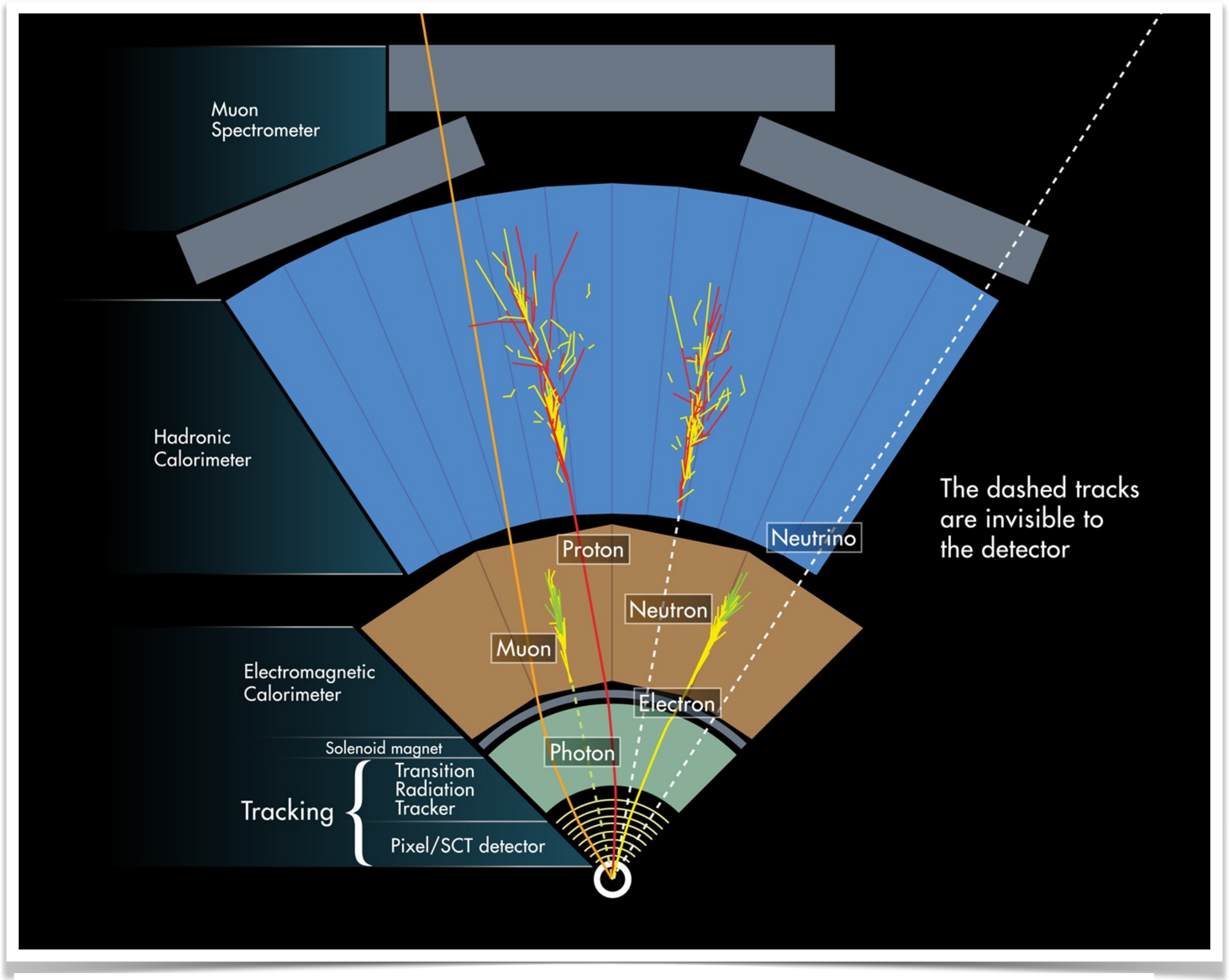


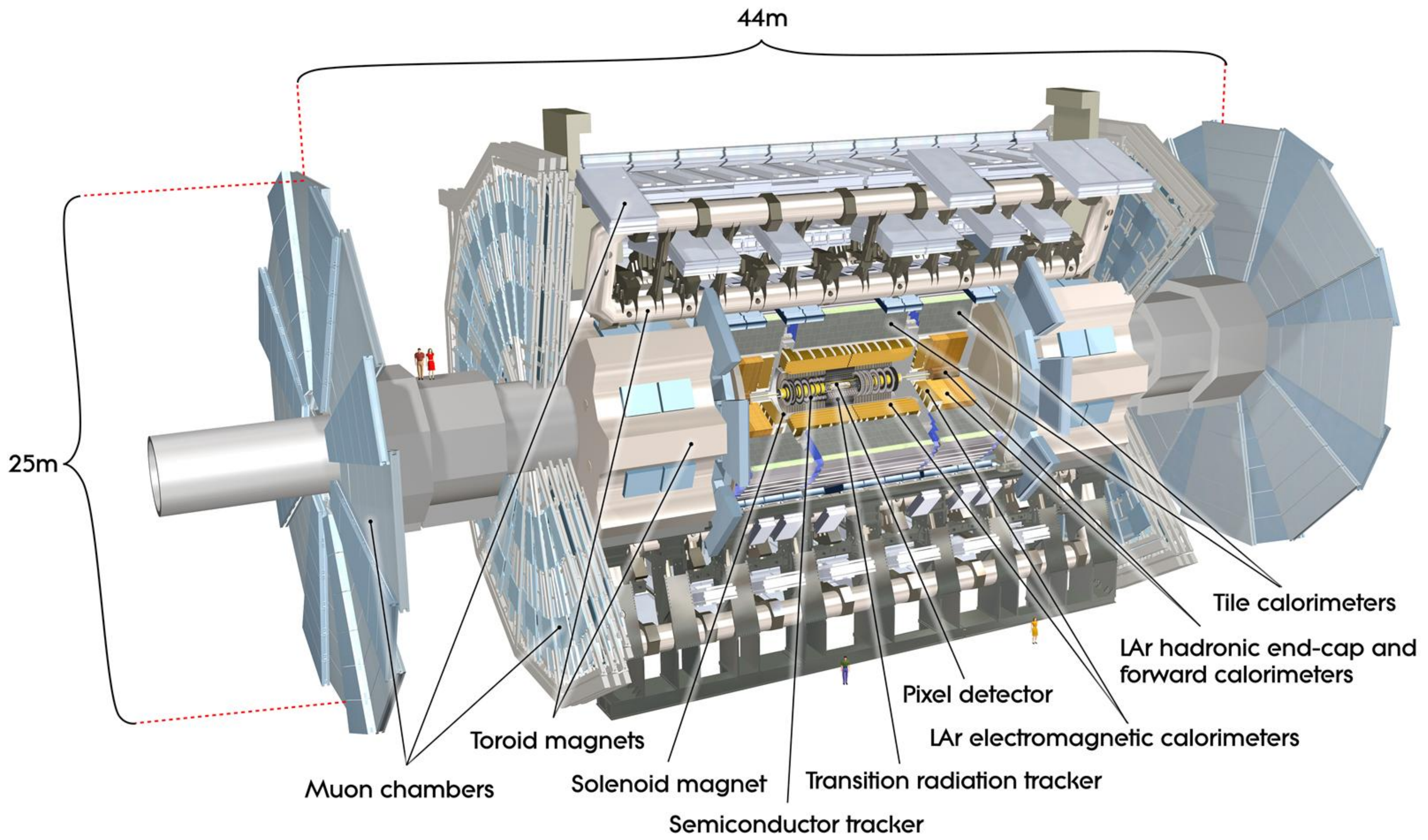


The ATLAS detector

- ATLAS : general-purpose detector at the LHC, study of Standard Model and *search for new physics*
- Designed in different layers :
  - the **inner detector**, reconstruct the trajectory of a charged particle (curved by a magnetic field) and measure its momentum with a « *track* »
  - the **calorimeters,** stop the particle and measure the deposited energy ; an energy deposition is called a « *cluster* »
  - the **muon spectrometer,** measure the muon momentum and trajectory
- 40.10^6 beam crossings per second in the center of the detector :

  → **trigger system** reduces it to 1000 events per second that are stored for analysis
- Offline event reconstruction performed on all the recorded events : signals from the detector turn into physical objects like jets, leptons, photons …





Hadronic jets

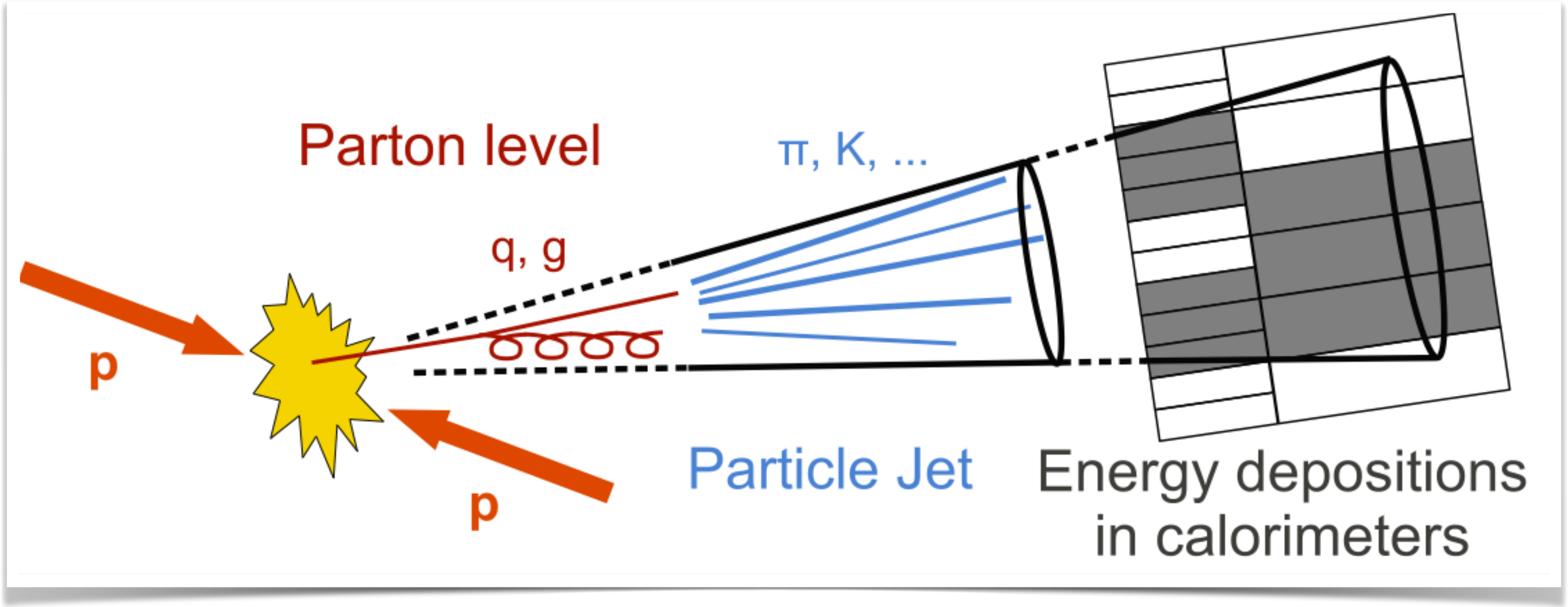
- *QCD processes* :

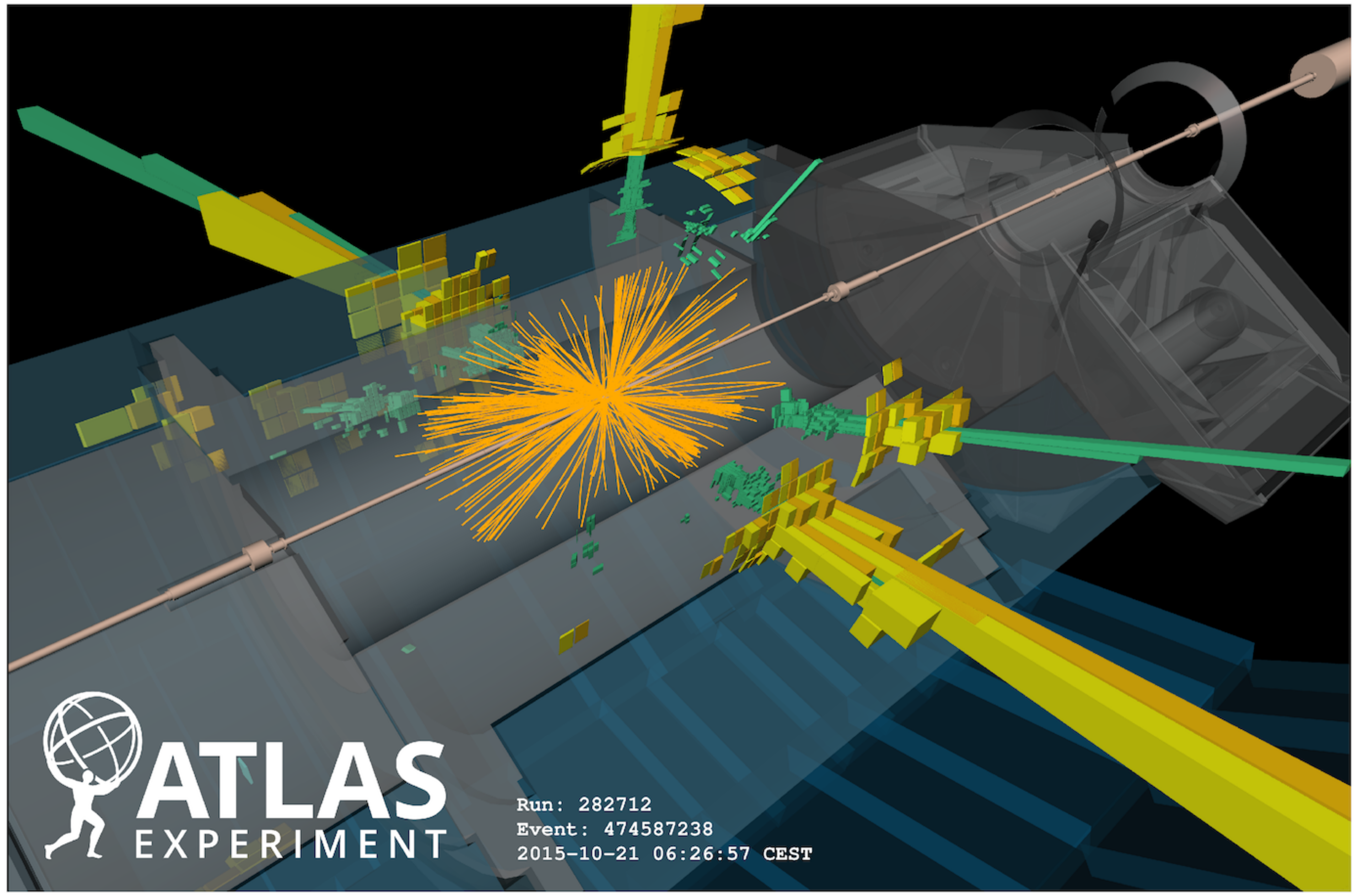
  - During *p-p collisions*, interaction between the partons composing the protons : *emission of a high energy parton*

  - Emission of other collinear partons by the initial parton : *parton shower*

  - Finally, gathering of the partons to form hadrons (*hadronization*), composing an hadronic jet

  - In ATLAS, hadronic jets can be reconstructed in different ways thanks to tracks and clusters





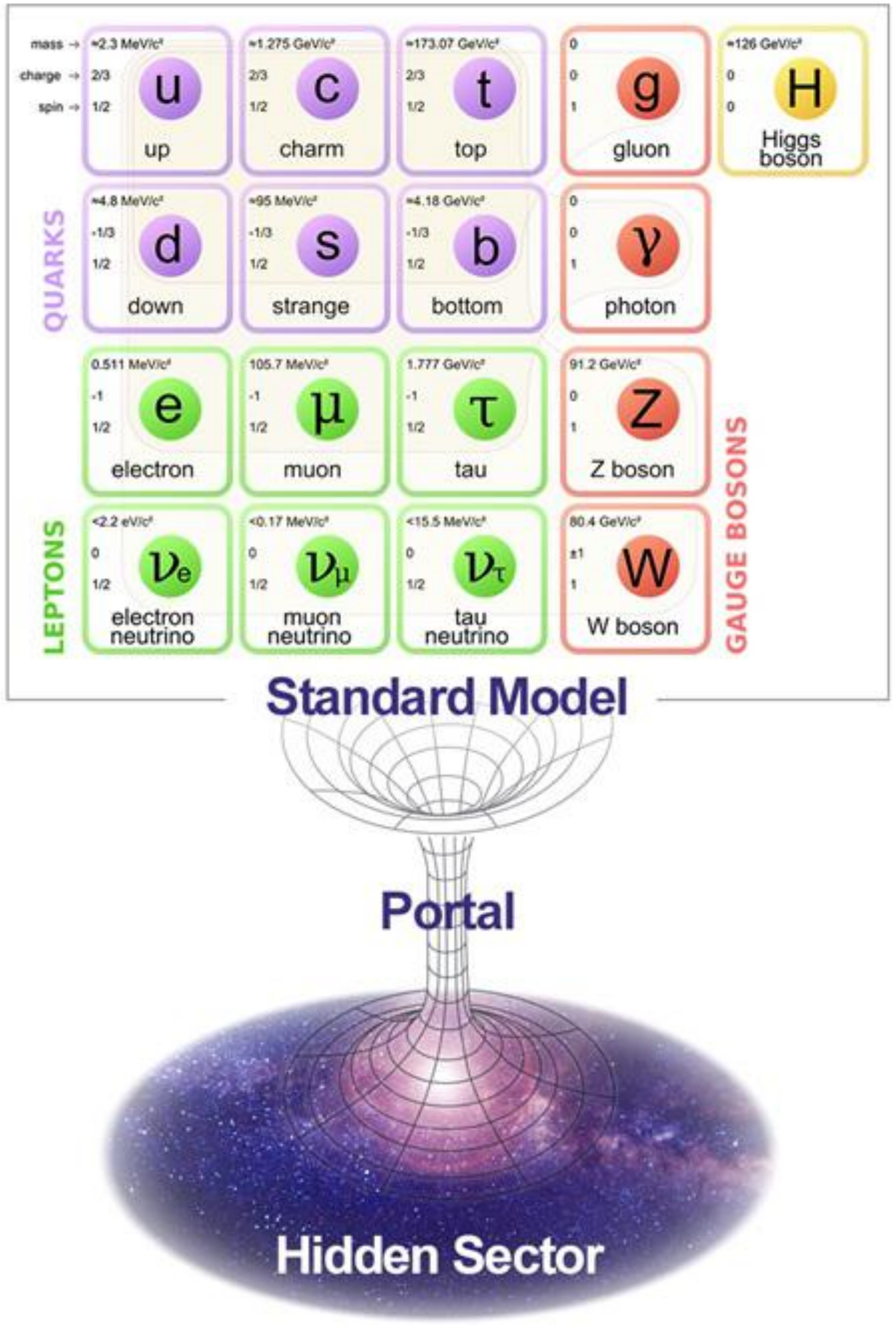
Dark QCD

- Extension to the SM predict a QCD-like hidden dark sector
  → stable particles from this hidden sector : dark matter candidates

$$\mathcal{L}_d = \bar{q}'_i (i \not{D} - m_{q'_i}) q'_i - \frac{1}{4} G'^{\mu\nu} G'_{\mu\nu}$$

q' and $G'^{\mu\nu}$: dark quarks and dark gluon field strength

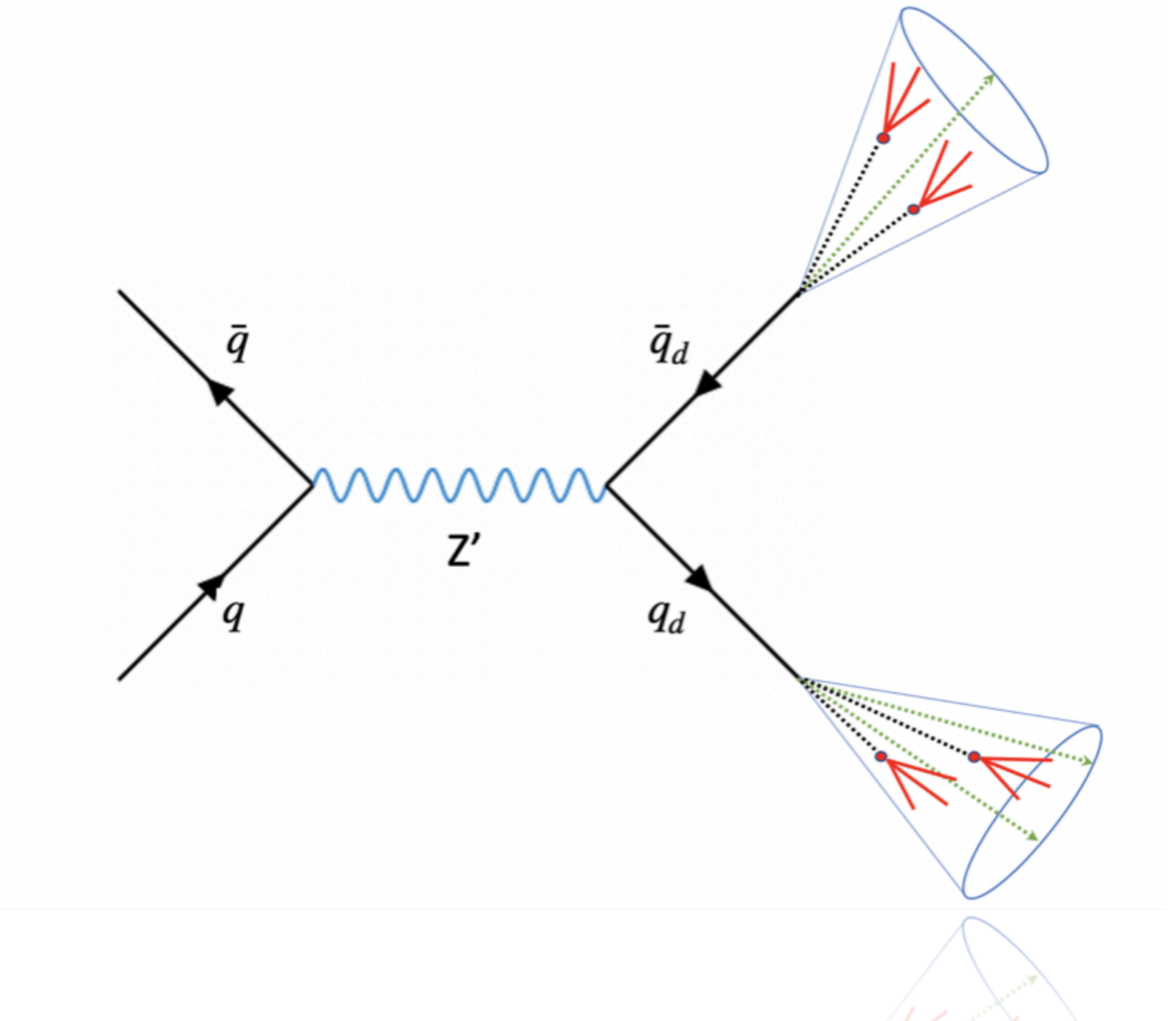
- Production of a jet of dark hadrons by a high energy dark parton in a similar process as SM partons
- New particles from this hidden sector connected to SM ones through a new mediator particle
  → production of dark partons in p-p collisions
  → dark hadrons decay to SM particles, producing dark jet in the detector



Emerging jets

- At the LHC, possible production of dark quarks q_d via a new Z' mediator

$$\mathcal{L}_{\text{med}} = -\frac{1}{4} Z'^{\mu\nu} Z'_{\mu\nu} - \frac{1}{2} M^2_{Z'} Z'^{\mu} Z'_{\mu} + Z'_{\mu}(\bar{q}'_i \gamma^{\mu} q'_i + \bar{q}_j \gamma^{\mu} q_j)$$



- q_d will form unstable dark mesons ρ_d and π_d
  $\rightarrow \rho_d$ decays to π_d
  $\rightarrow$ π_d **decays to SM quarks with a certain lifetime** τ_{π_d}
- Jets from SM quarks start to appear in the detector at some distance from the interaction point : emerging jets
- Model considered :
  Z' mass, π_d lifetime and π_d and ρ_d masses are parameters

	Model A	Model C	Model D
m_{π_d} (GeV)	5	10	20
$c\tau_{\pi_d}$ (mm)	5-50	5-50	1-50
$m_{Z'}$ (GeV)	600-1500-3000		
Decay to SM	Dark pions to quarks		
Decay in dark sector	Dark rhos to dark pions		

Emerging jets analysis

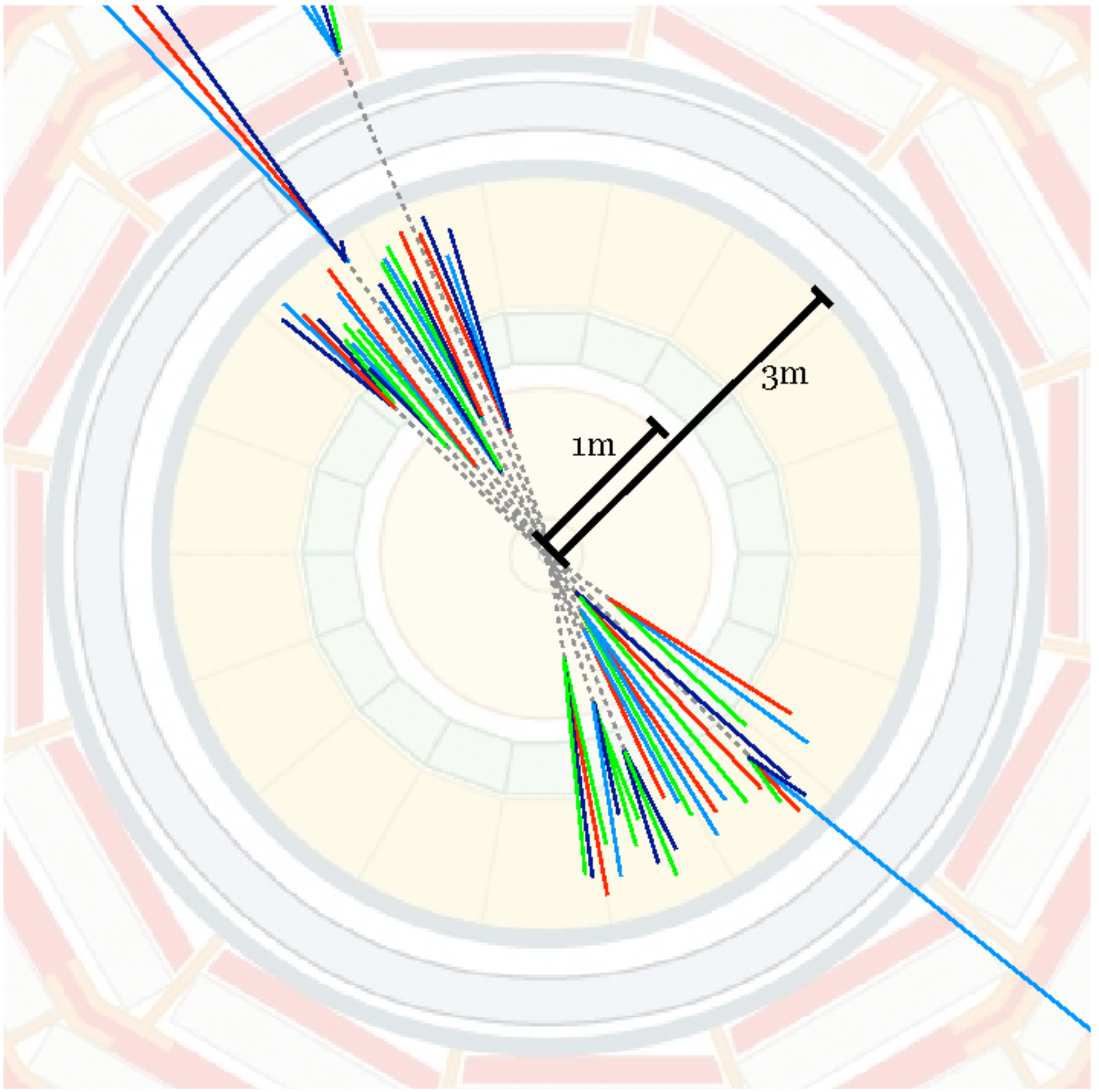
- Looking for *di-jet events,* with *large radius tracks* and *secondary vertices* displaced from the proton-proton interaction point

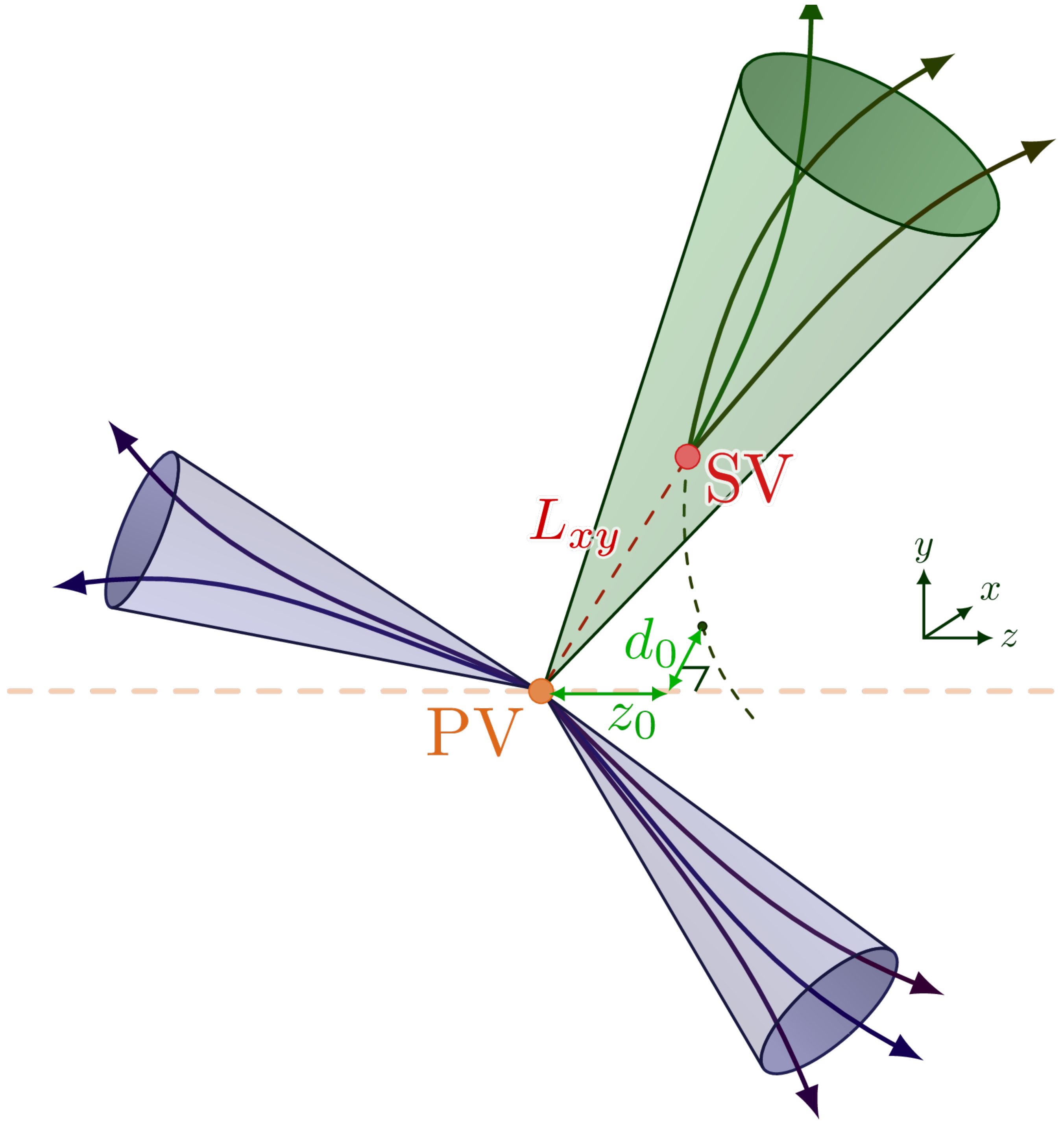
- Main background : QCD di-jet events

  → in general composed of prompt tracks, and contain more rarely secondary vertices

  → QCD jets can mimic the emerging jets signature : jets containing B-mesons

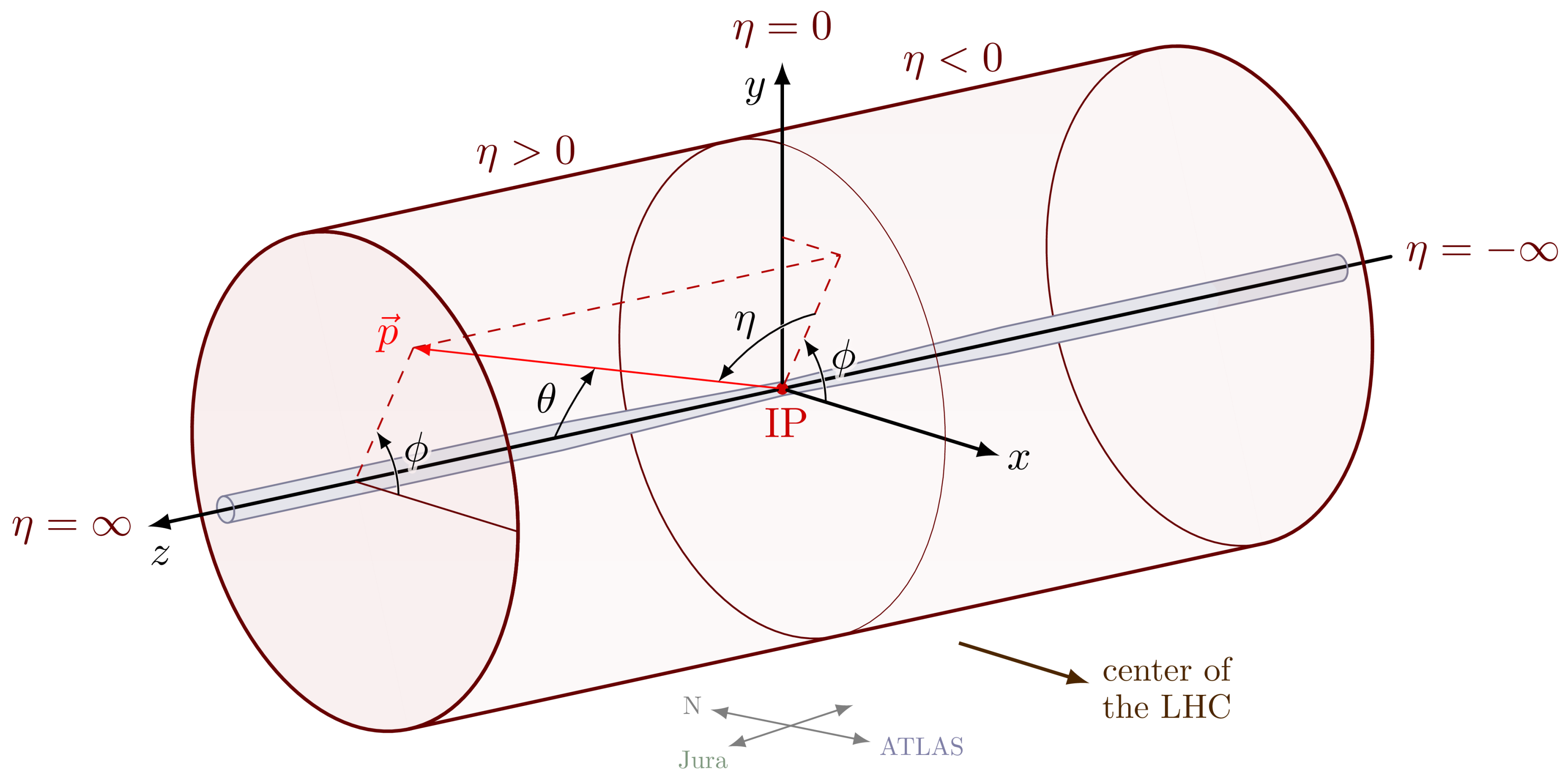
- Dark jets larger than QCD jets due to double hadronization (in dark sector and in visible sector) : substructure variables discriminating





Emerging jets analysis

- Emerging jet trigger in ATLAS :
  require one jet with $p_T > 200$ GeV, $|\eta| < 1.8$ and $PTF^{jet} < 0.08$
  (Prompt Track p_T Fraction)



$$PTF^{jet} = \frac{\sum_{trk \in jet} p_T^{trk}(d0 < 2.5\sigma_{d0,bkg}(p_T))}{p_T^{jet}}$$

$$\sigma_{d0} = \frac{0.0463}{p_T} + 0.0195$$

- Reconstruction of large jets thanks to jet algorithm grouping energy clusters together, matching of the tracks to the jet

- Possible discriminating variables :
  - number of displaced vertex inside the jet → by requiring 3 or more associated tracks to the vertex, suppression of vertex corresponding to photon conversion into e^+e^- pair in dense area of the detector
  - Energy Correlation Factor 2 (ECF2) : the more the jet has « sub-jets », the higher ECF2 will be
  - p_T fraction of prompt track in the jet (PTF) but with prompt track defined as a track associated to a primary vertex

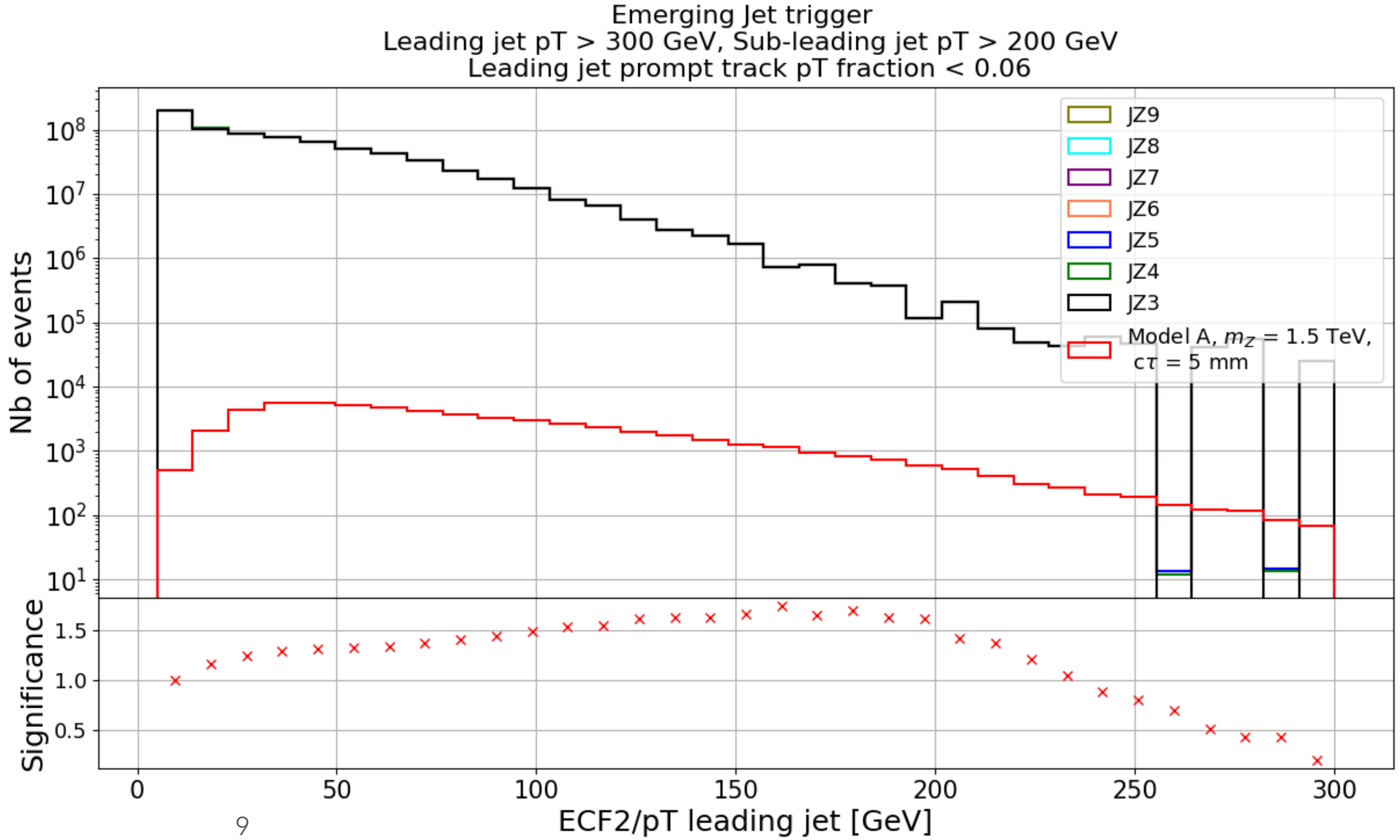
Discriminating variables

- Study on background and emerging jet signal events from MC simulation to find the *best cut values* to apply on discriminating variables
  → *maximize the significance* $S(c) = \dfrac{N_s(c)}{\sqrt{N_b(c)}}$ with N_s (N_b) the number of signal (background) events that remain after a cut c on a variable
  → compromise to find between signal acceptance and background rejection

- Baseline selection :
  - Emerging jet trigger
  - leading jet $p_T > 300$ GeV
  - sub-leading jet $p_T > 200$ GeV
  - leading jet prompt track p_T fraction < 0.06

  → to be in a region where the trigger is maximally efficient for all the events

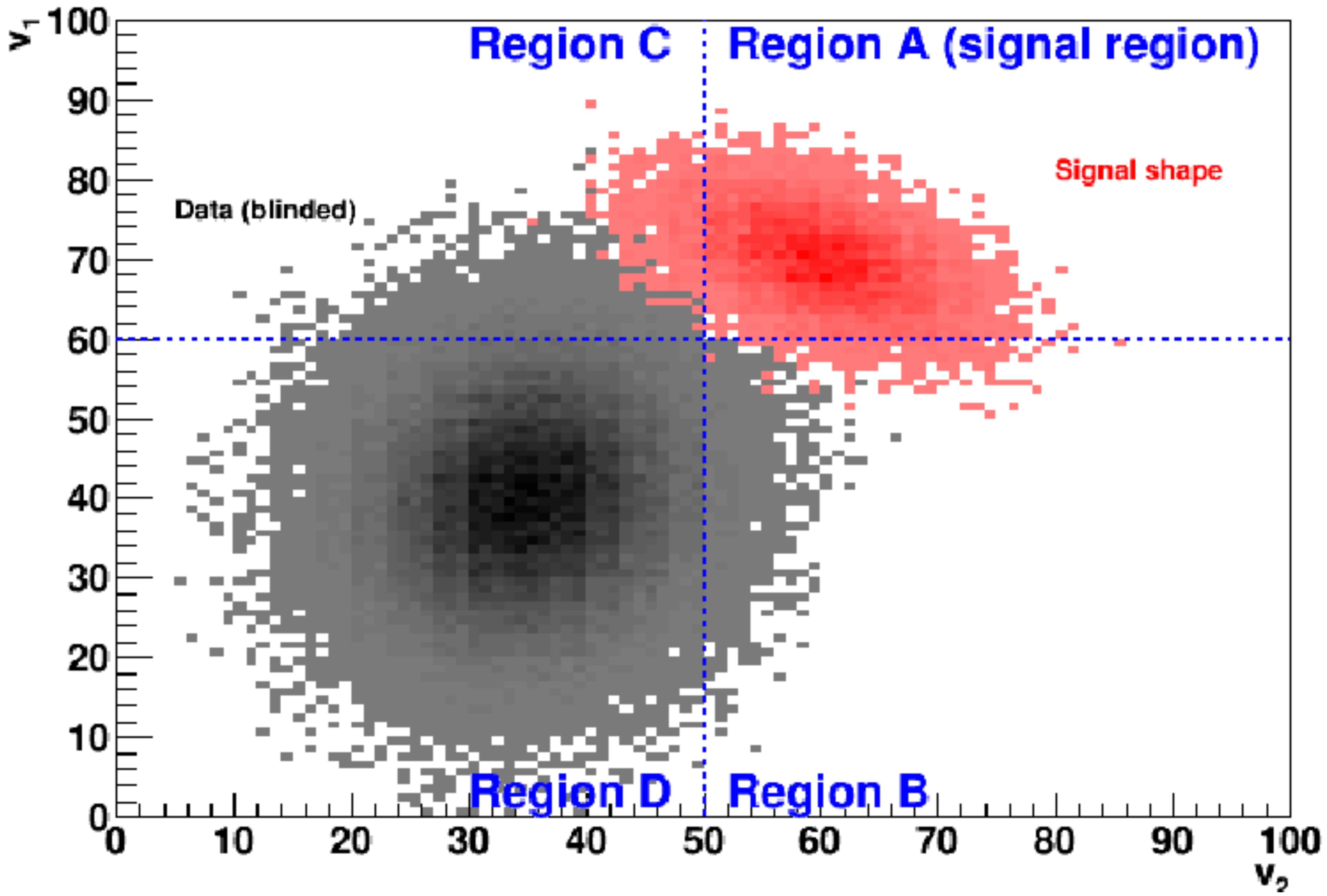
  Number of background event normalized to an integrated luminosity of 30 fb-1



Background estimation : ABCD method

- MC simulated events not reliable enough to estimate QCD background contribution
- Use 2 uncorrelated discriminating variable
  → Based on the cut values of these variables, definition of 4 regions on a 2D plan with these variables as x and y axis
- Use real data in the region B, C and D to estimate background contribution in the signal region A (i.e the region containing the events passing the 2 cuts) based on :

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



Recasting LHC analyses with MadAnalysis

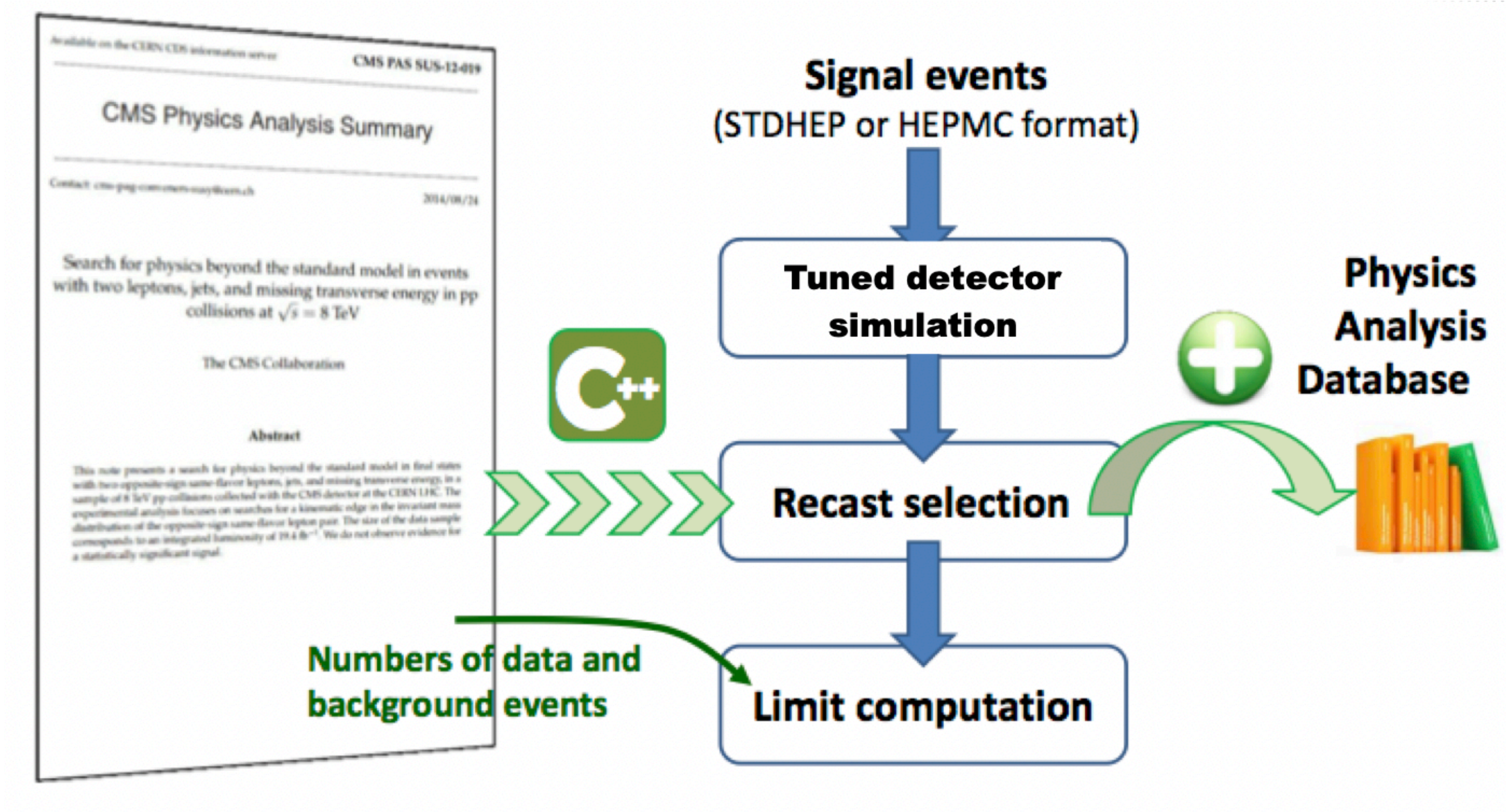
- A given LHC analysis cannot test all related theoretical models : **MadAnalysis** allows to constrain new models that have not been explicitly tested by analysis

- Based on a simplified detector simulation and on a C++ code reproducing the cutflow of an analysis

  → computation of signal efficiencies and cross-section upper-limits

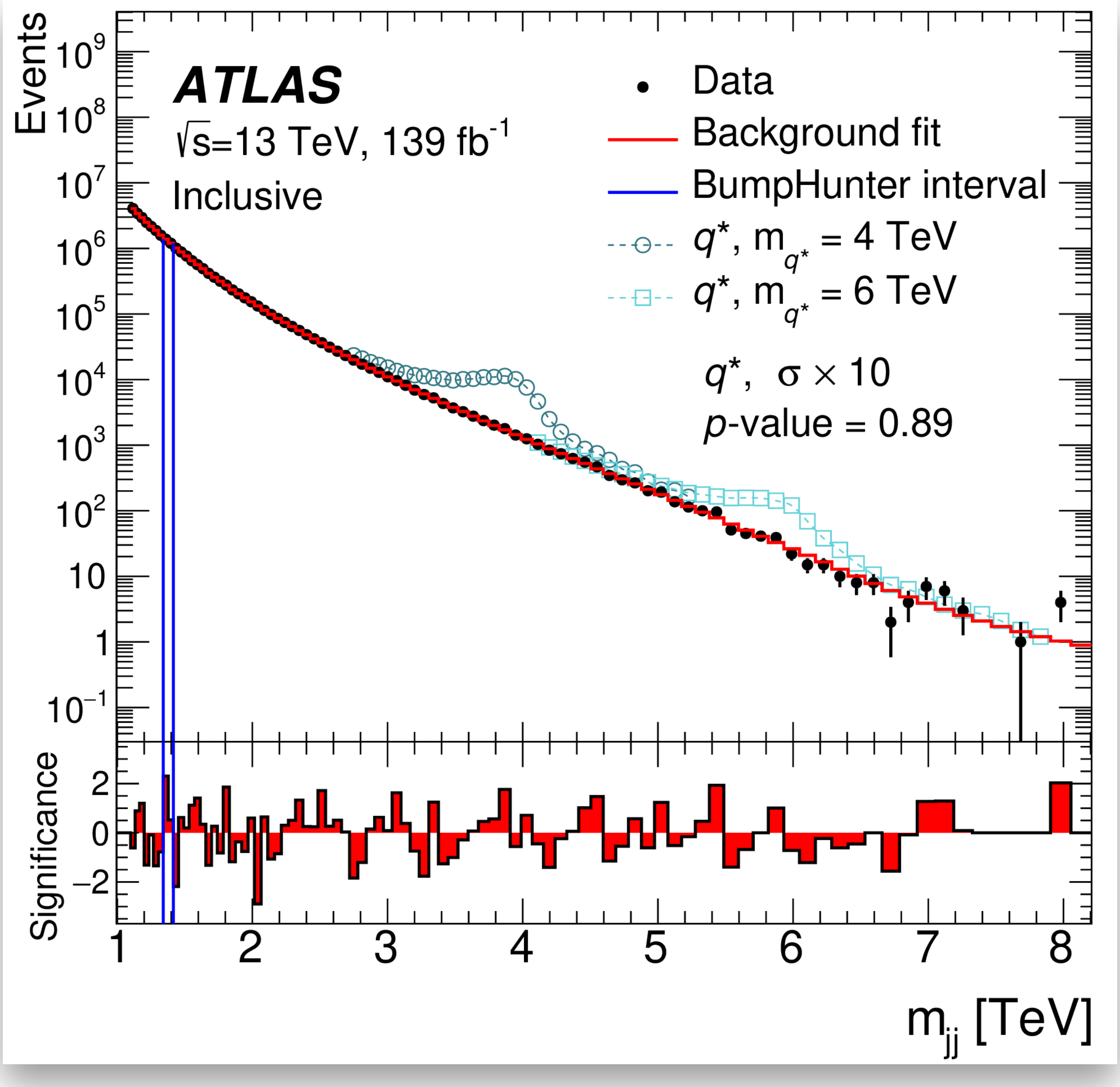
- To implement a published analysis and add it to the MA public database, *several steps* :

  - write the analysis code in the MA internal language (event selection, cuts)
  - configure the detector card (reconstruction, tagging efficiencies)
  - obtain the number of data and background events in each signal regions
  - validate the implementation by reproducing the analysis results in terms of signal acceptance and cross-section upper-limit for the models studied in the analysis



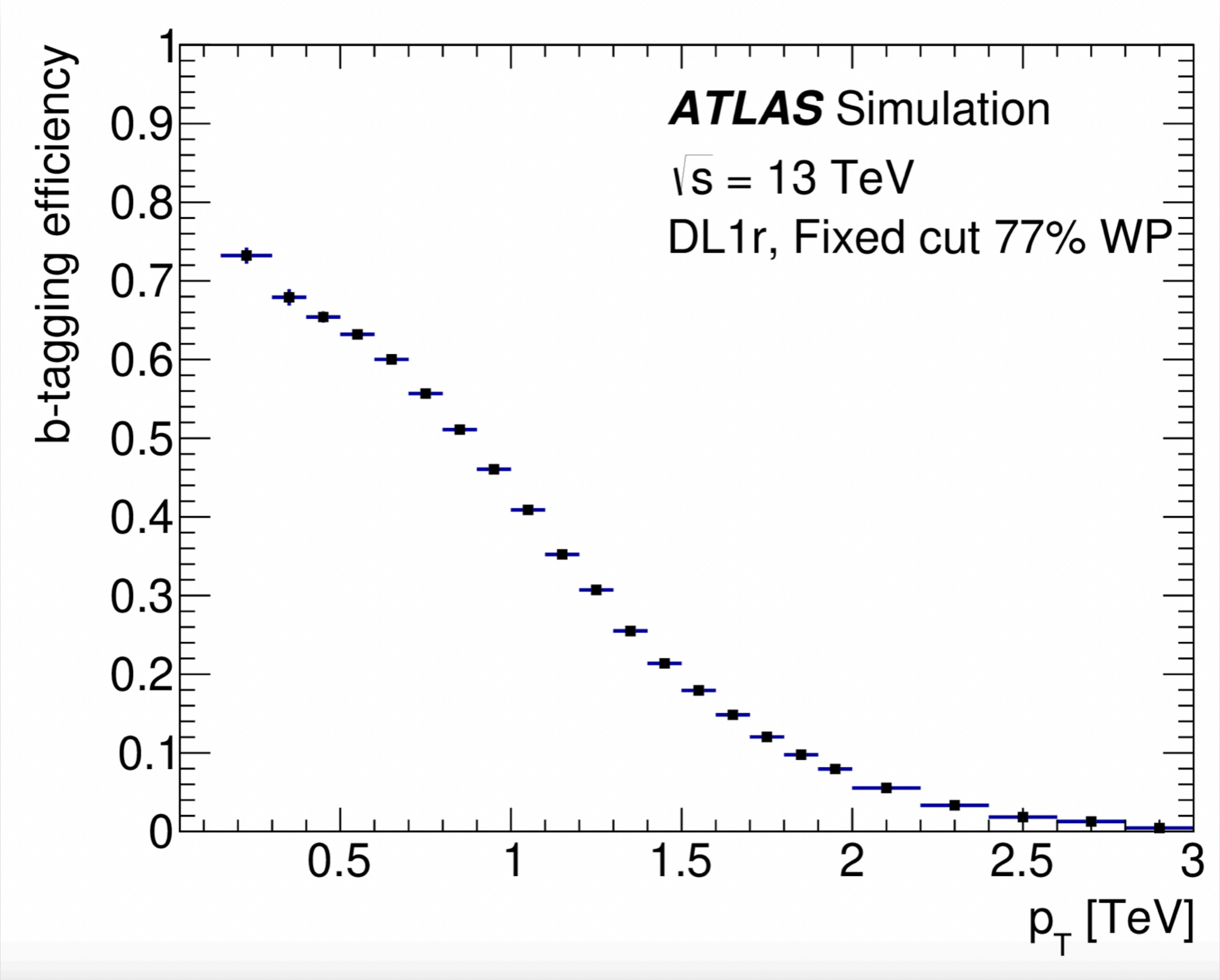
→ Once the analysis is implemented in MA, new models with a similar final state can be constrained i.e exclusion limits on production cross-section can be computed

Search for new resonances in mass distributions of jet pairs using 139 fb^{-1} of pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector



- Implementation of this ATLAS analysis : search for new heavy particles decaying into quarks and gluons and producing 2 energetic jets in the detector :
  → excited quark q^*, new mediator Z', W' ...
- Search for local excess in the distribution of the invariant mass of the 2 leading jets above Standard Model background
- Trigger : At least one jet with $p_T > 420$ GeV
- Inclusive jet selection, and separate regions with at least one or exactly 2 b-tagged jet (1b and 2b resp.)

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		⩾ 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



Validation of the implementation

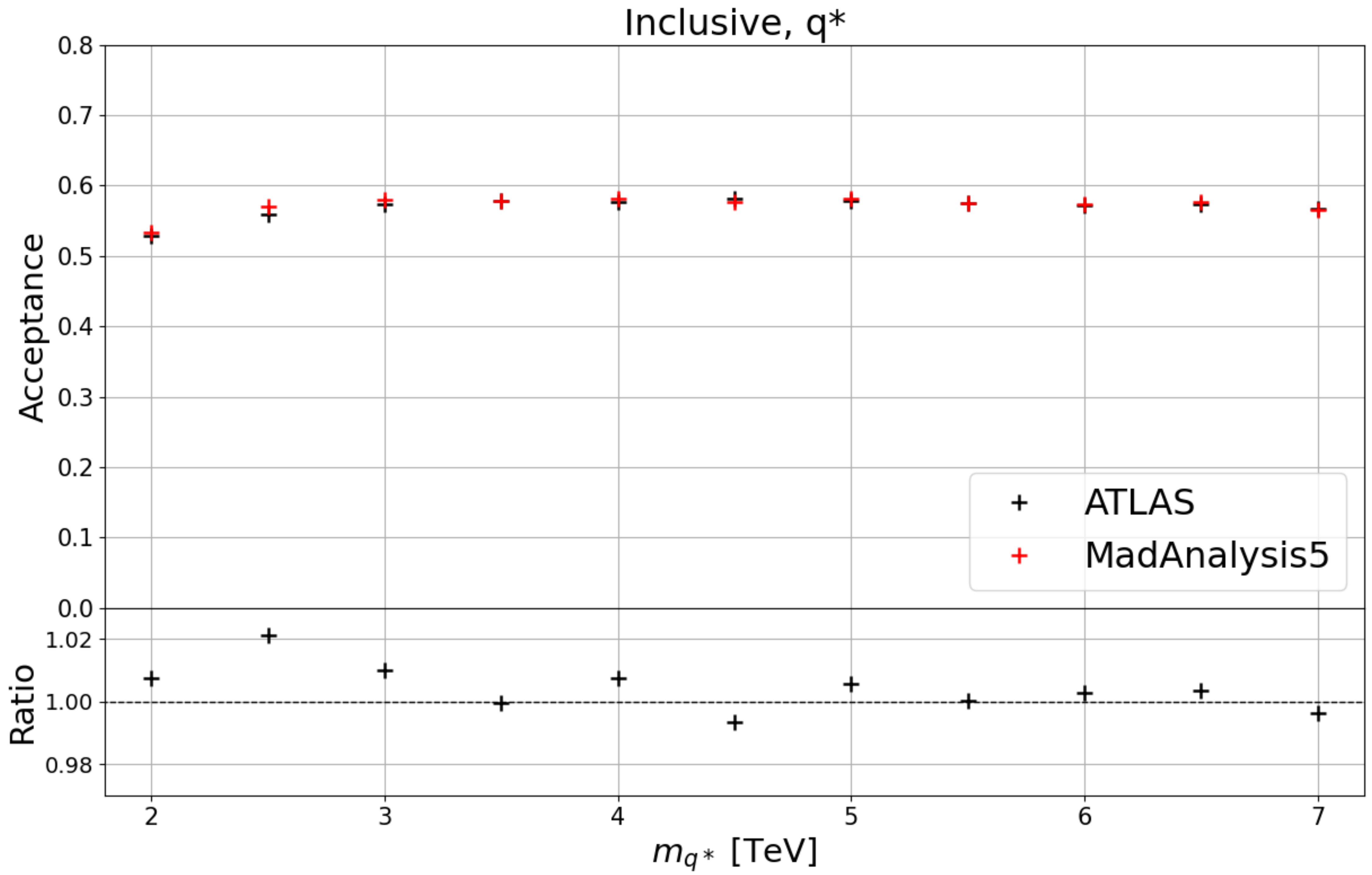
Acceptance

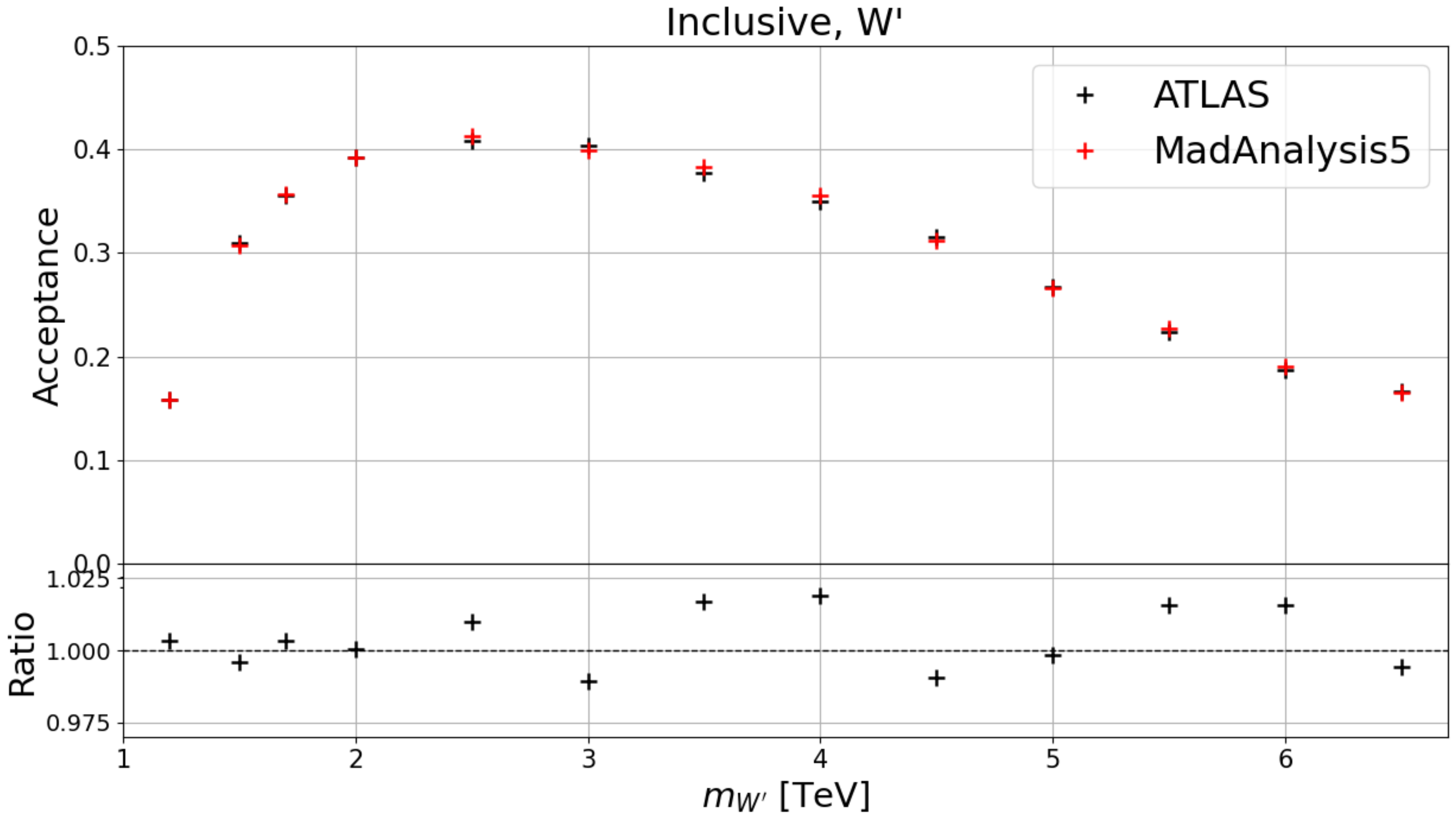
- Generation of signal events corresponding to models tested by ATLAS in the analysis
- With MadAnalysis, computation of the signal acceptance (fraction of events passing all the cuts) in the signal region and comparison with ATLAS results
- Excellent agreement for 2 models in the inclusive region :

  - $q\bar{q} \to q* \to q\bar{q}$

  - $q\bar{q} \to W' \to q\bar{q}$

Relative errors below 3%

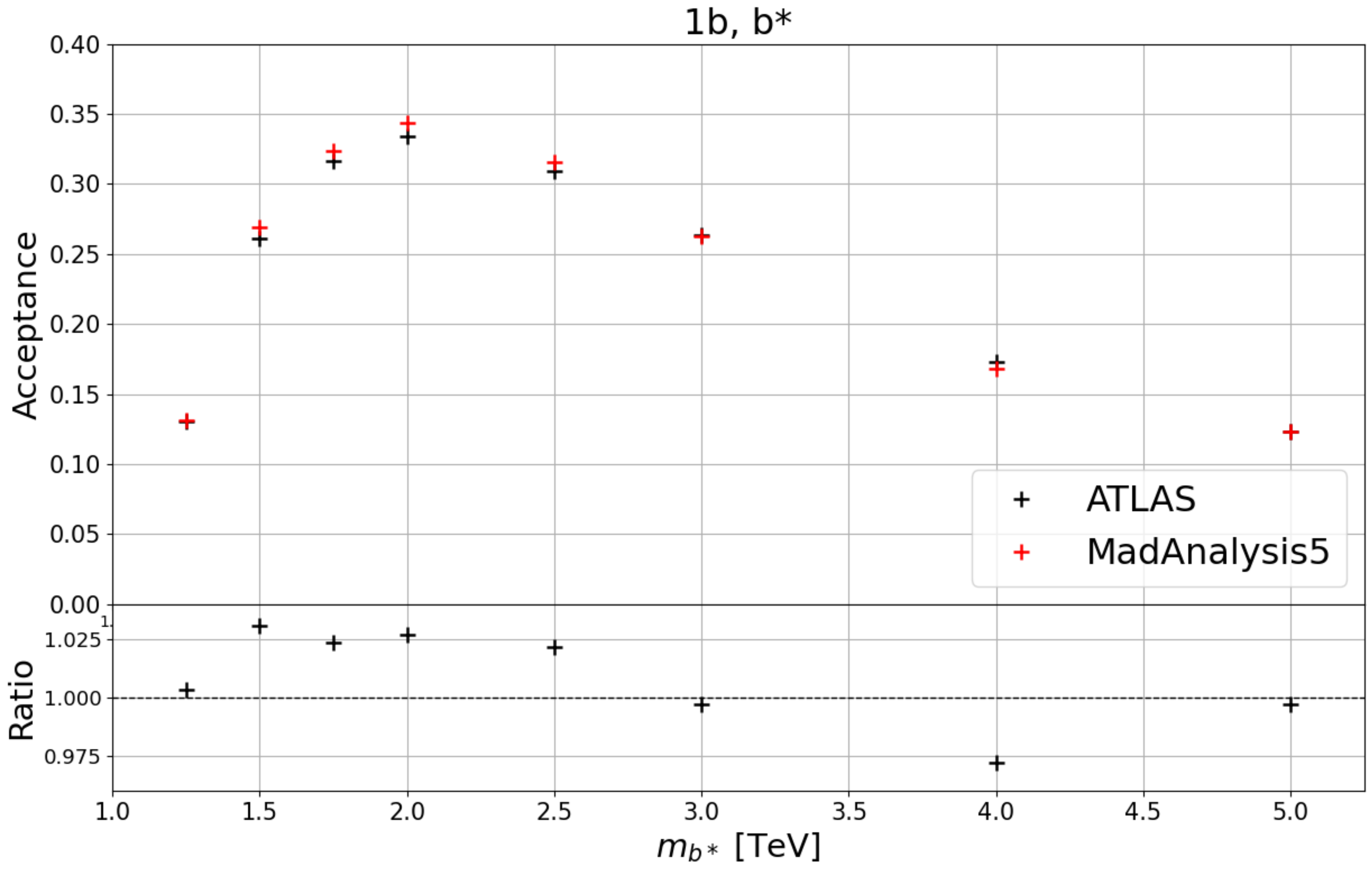


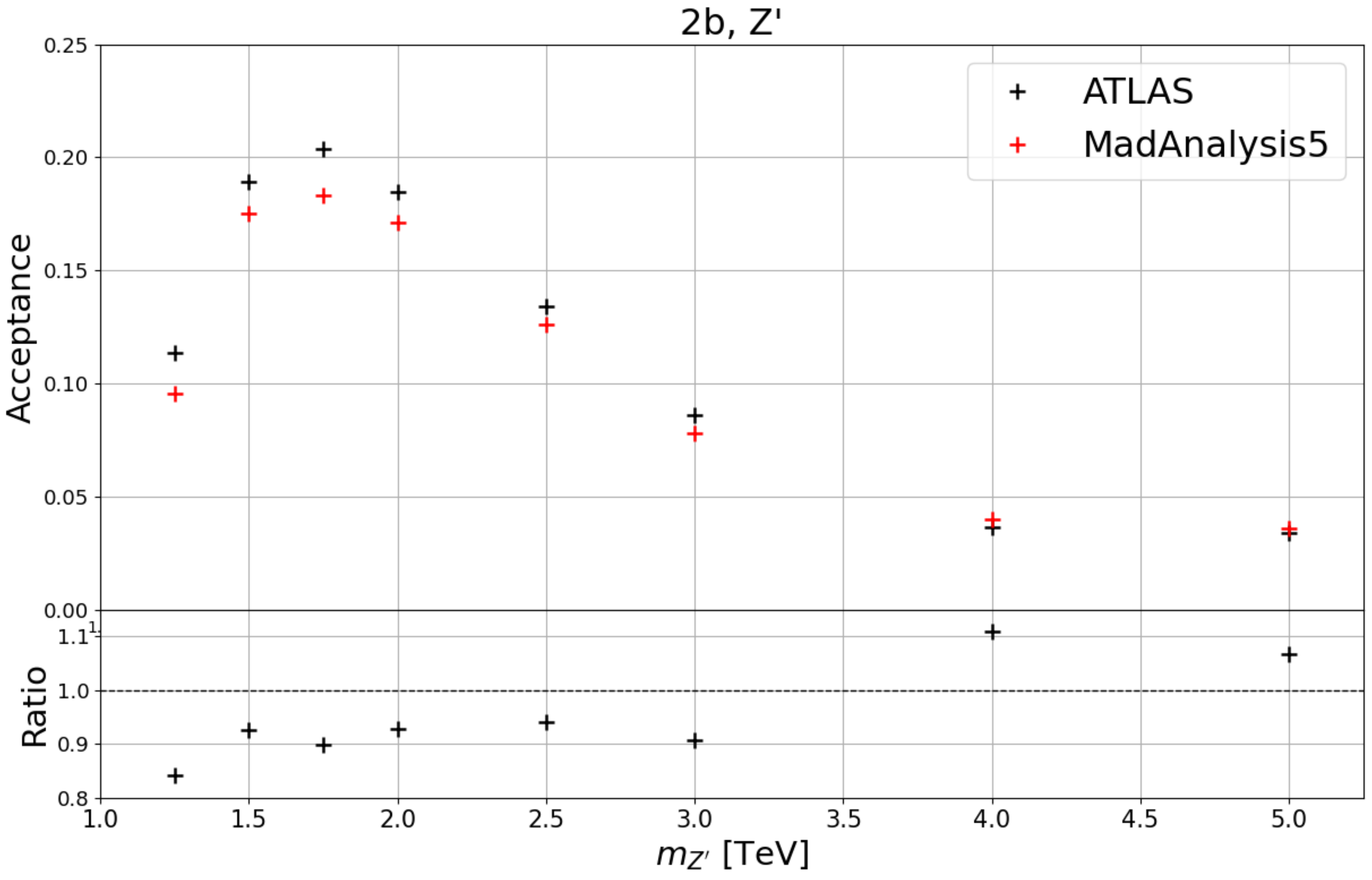


Validation of the implementation

Acceptance

- Also an excellent agreement for the model in the 1b region : $q\bar{q} \to b* \to bg$
- Satisfying agreement (relative errors below 15%) for one model in the 2b region : $q\bar{q} \to Z' \to b\bar{b}$

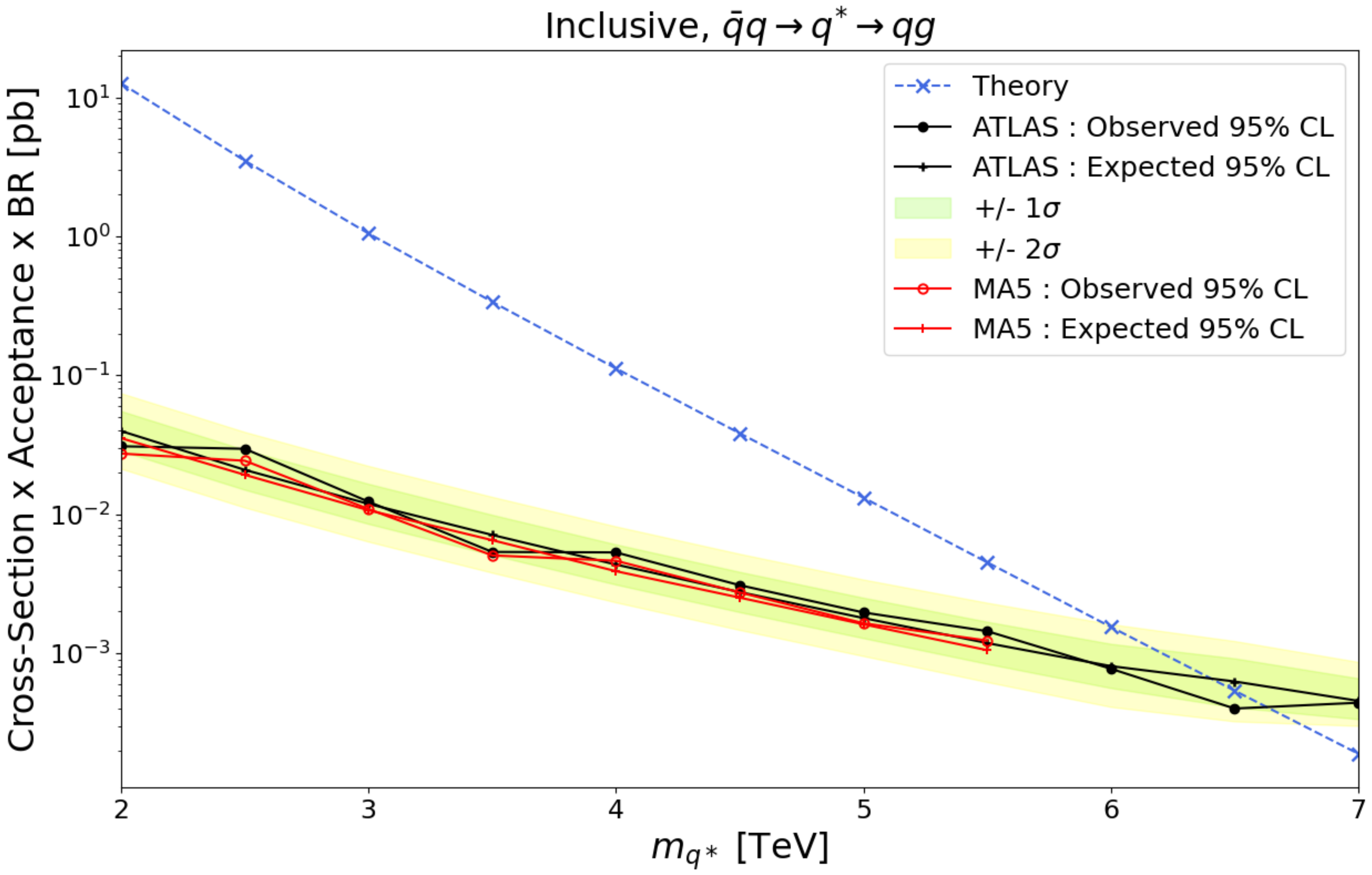


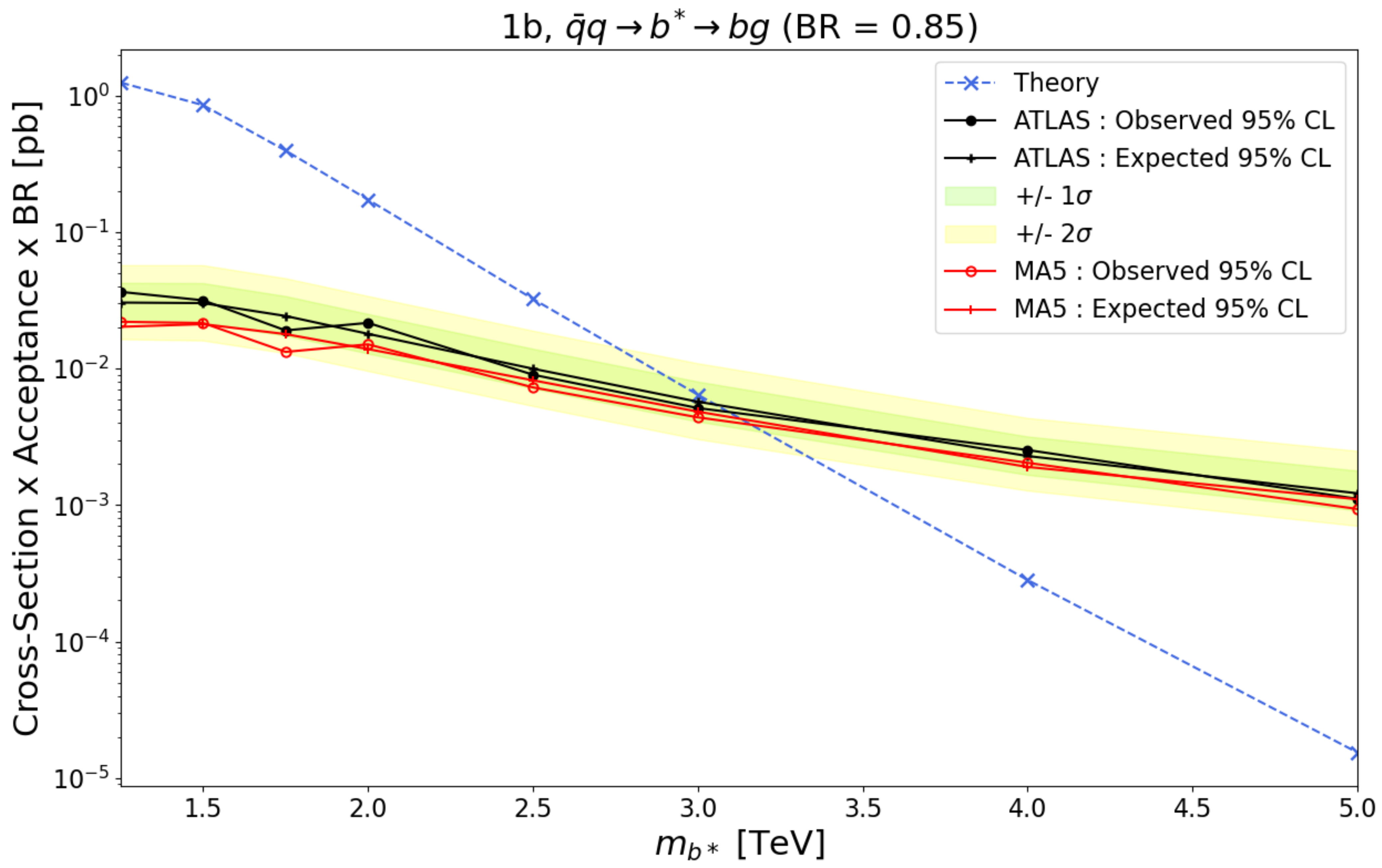


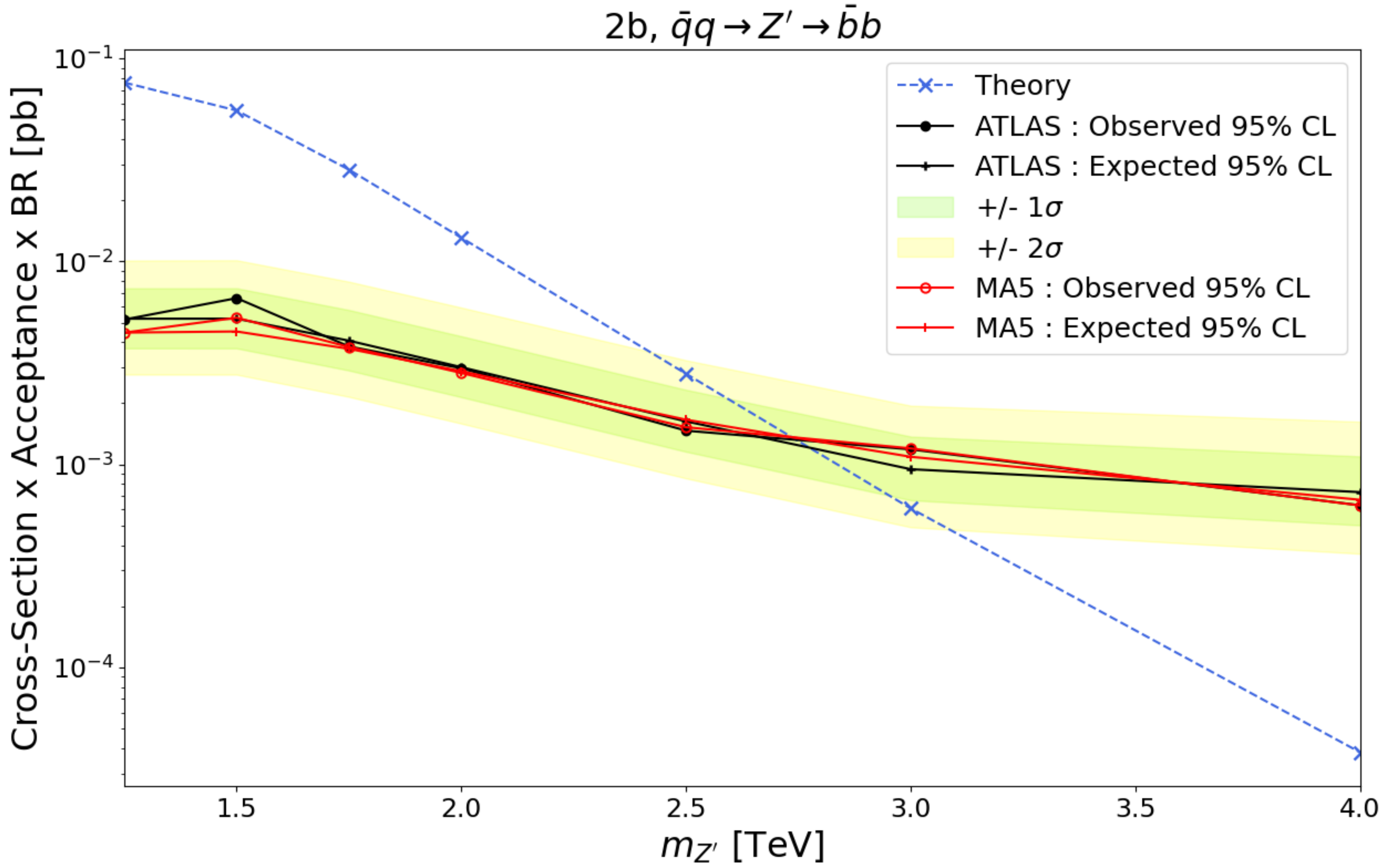
Validation of the implementation

Upper limits on cross-section

- Based on the number of observed events, and expected background in each m_{jj} bin given by ATLAS, I compute statistical exclusion limits on $\sigma \times A \times \mathrm{BR}$ (branching ratio into 2 jets) (CLs method) for the precedent models and compare the values to the ATLAS ones
- Limits obtained with MadAnalysis very similar to the ATLAS ones







Prospects

- The ATLAS di-jet resonance analysis added to the MadAnalysis database (http://madanalysis.irmp.ucl.ac.be/wiki/PublicAnalysisDatabase), can be used to study other models with a di-jet final state

  - ATLAS semi-visible jets analysis in validation

  Search for non-resonant production of semi-visible jets using Run 2 data in ATLAS

  → The goal is to recast various analyses that can be sensitive to dark QCD and see what each excludes of the parameter space

- Emerging jet analysis : determination of a signal region and background estimation in it

  → the aim is to be able to perform the most sensitive statistical interpretation of the data in the signal region, and get the better contraints on dark QCD parameters (if no excess found)

Thanks for your attention