Chasing dark matter with ATLAS at the Large Hadron Collider

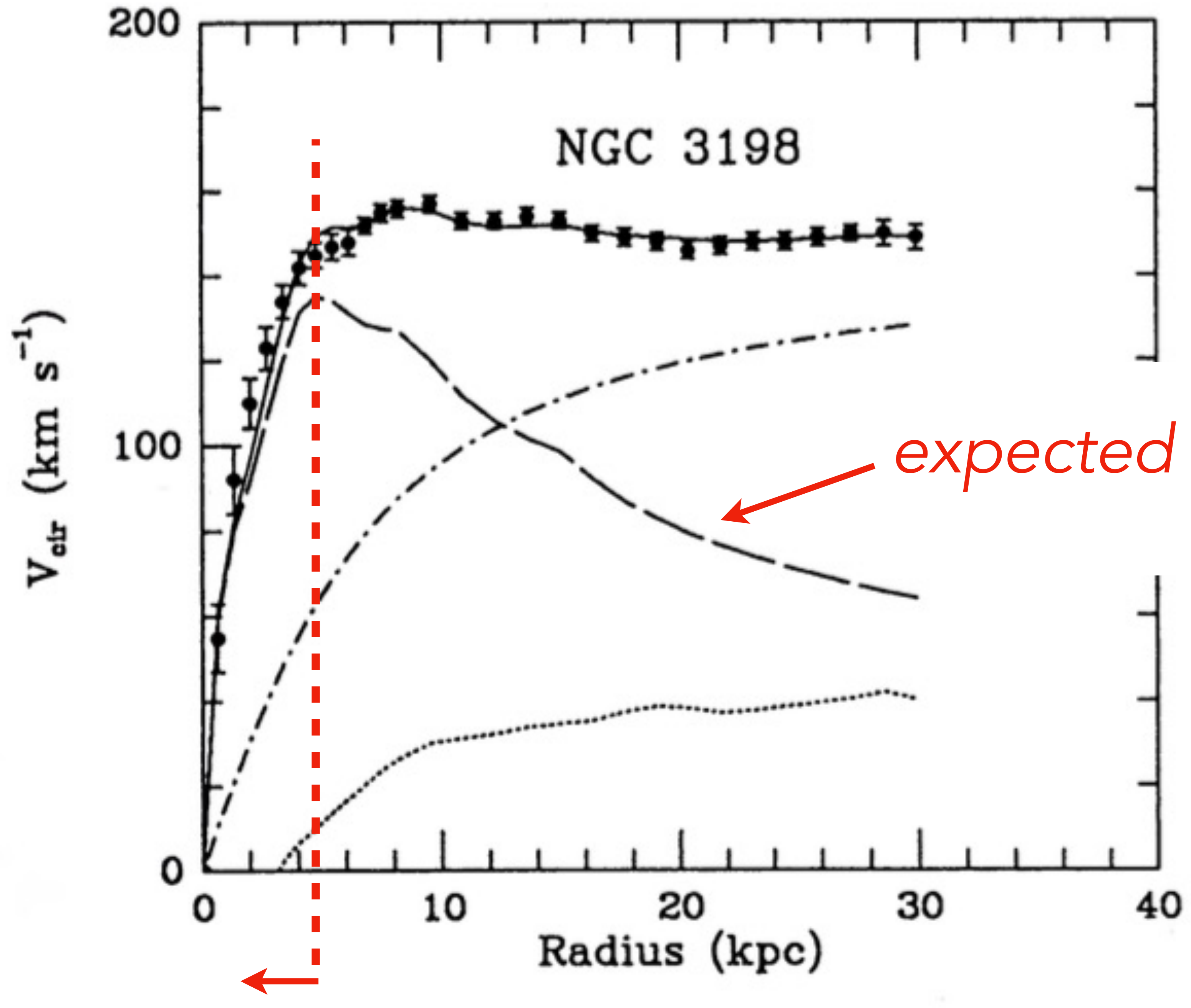
Guglielmo Frattari, PhD seminar series, 5 May 2021

TOM GAULD for NEW SCIENTIST

A bit of context

- Standard Model (SM) particles cannot fully explain structure & dynamics of the universe
- 4 main observations which hint at the existence of *dark matter* (DM)

1. rotation curves of galaxies

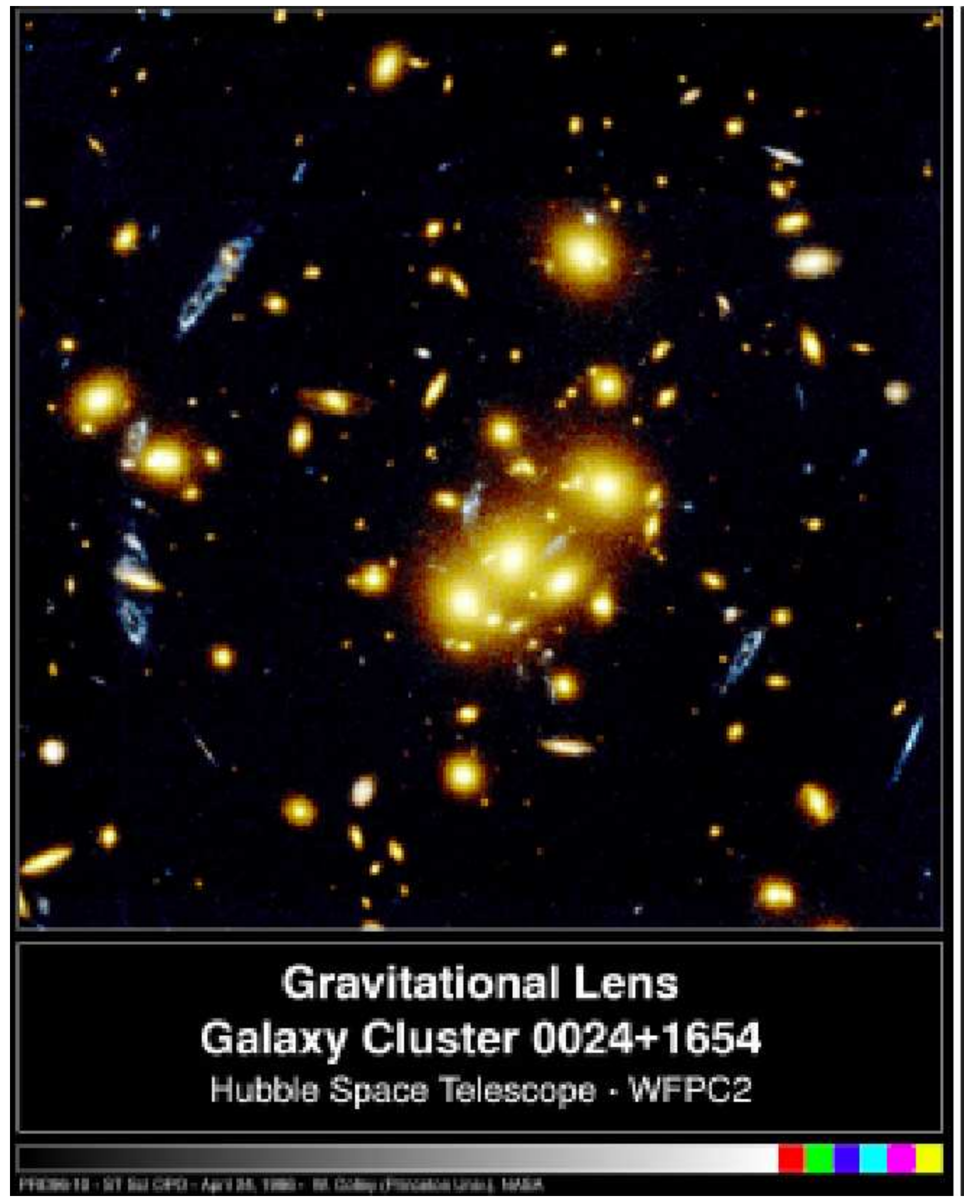


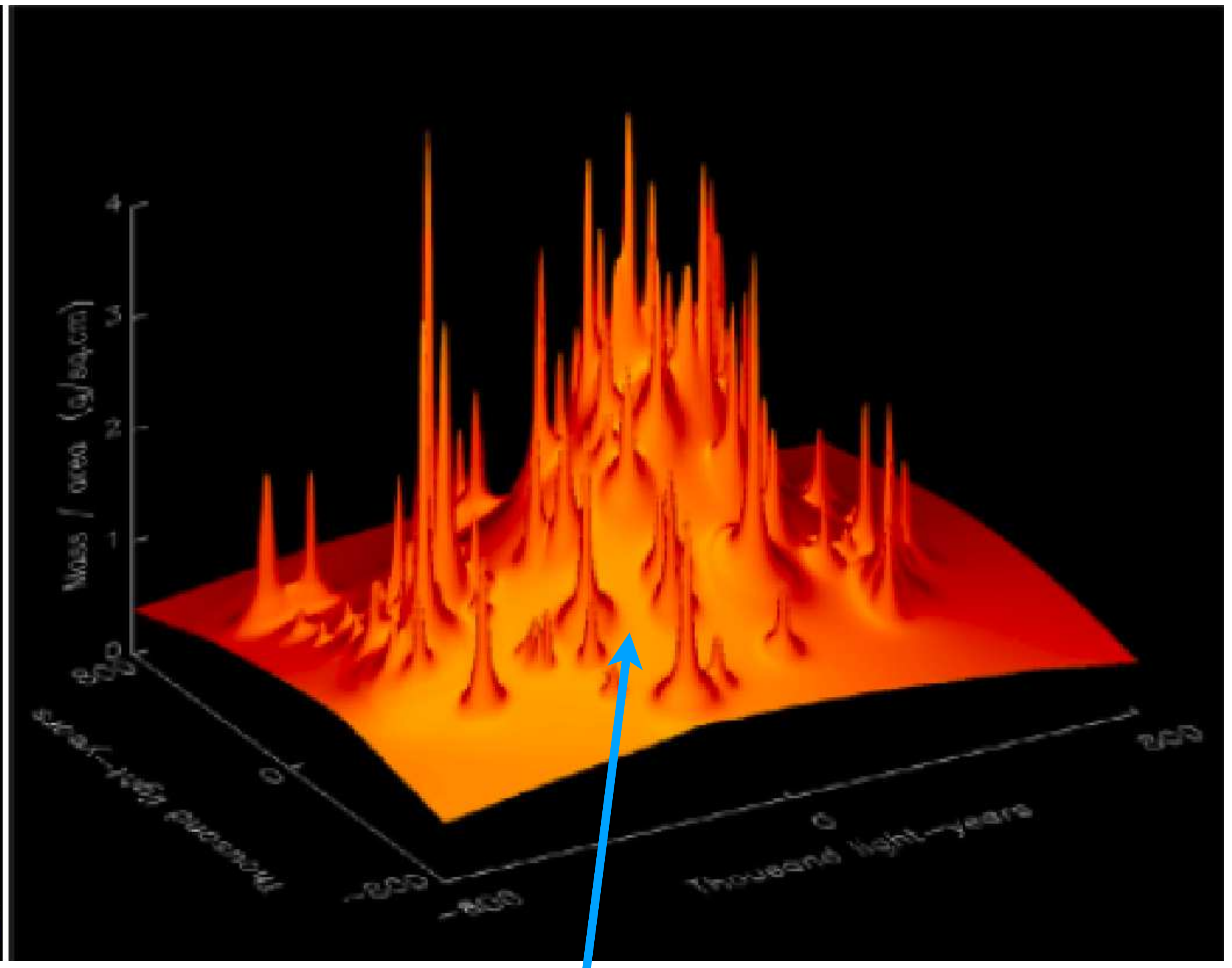
expected $\sim \dfrac{1}{\sqrt{r}}$

~99% of observed matter

$$v_{rot}(r) = \sqrt{\frac{GM(r)}{r}}\,,\;\; M(r) = 4\pi \int \rho(r) r^2 \, dr$$

2. Strong gravitational lensing

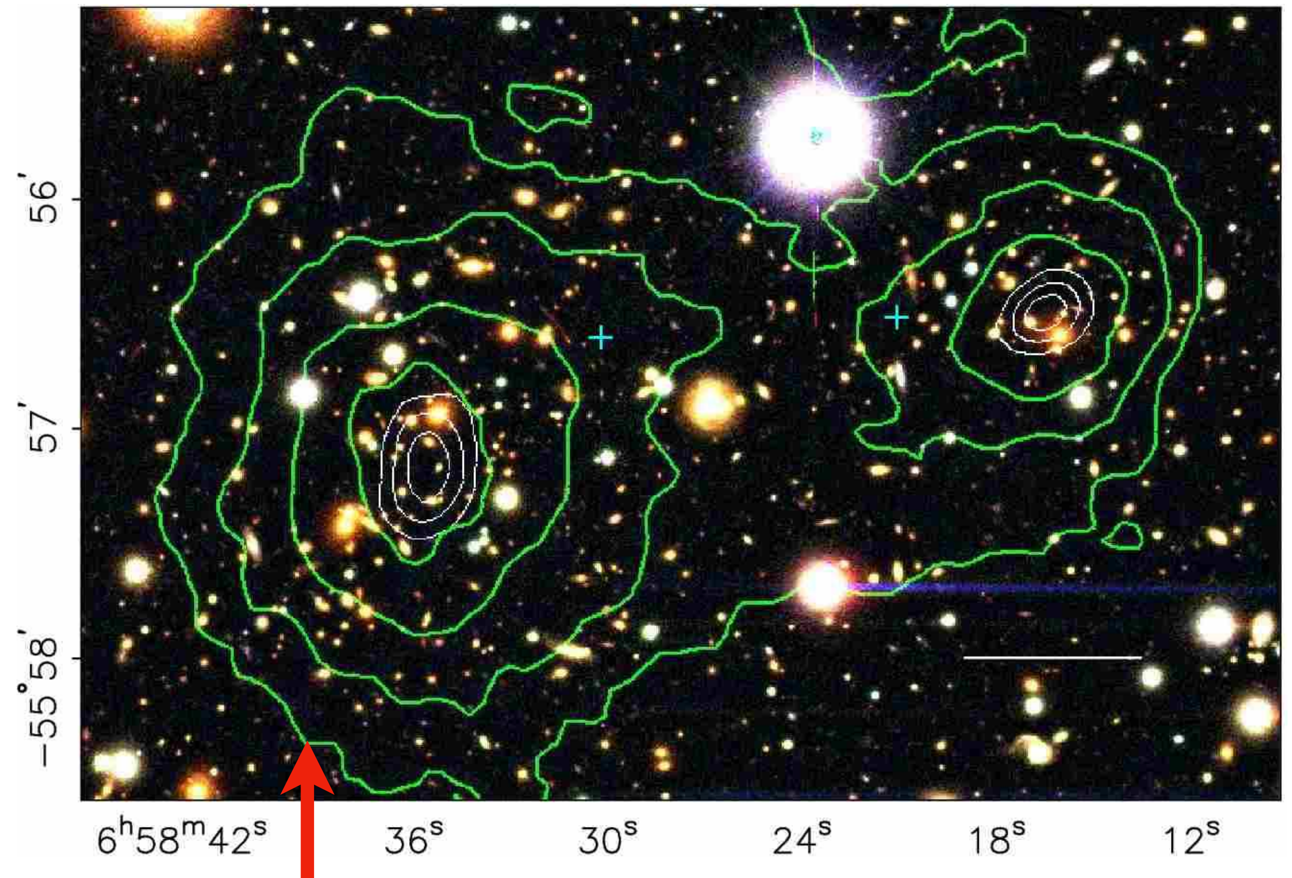




additional contribution from non-luminous matter

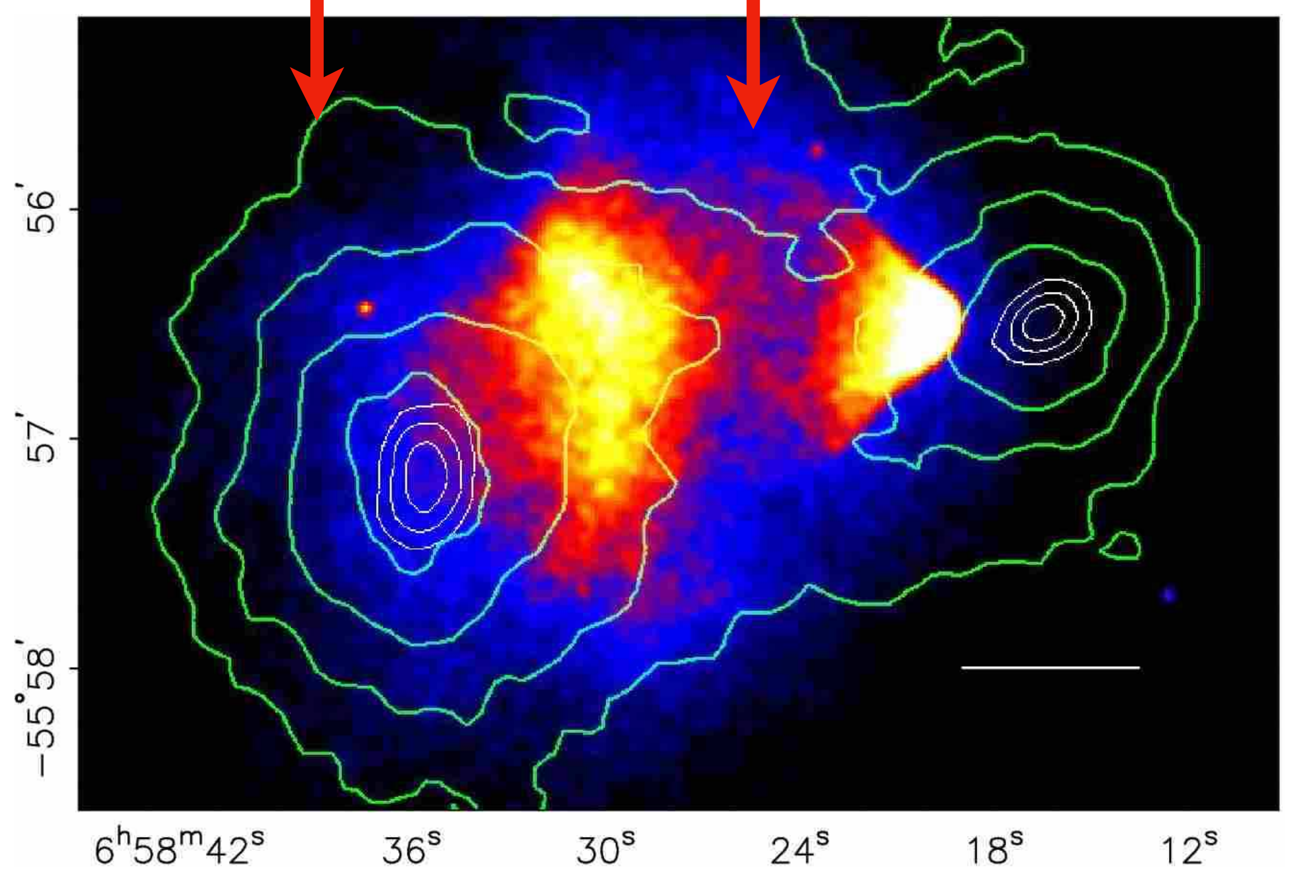
Hints at the existence of a dark matter

3. *bullet cluster* collision

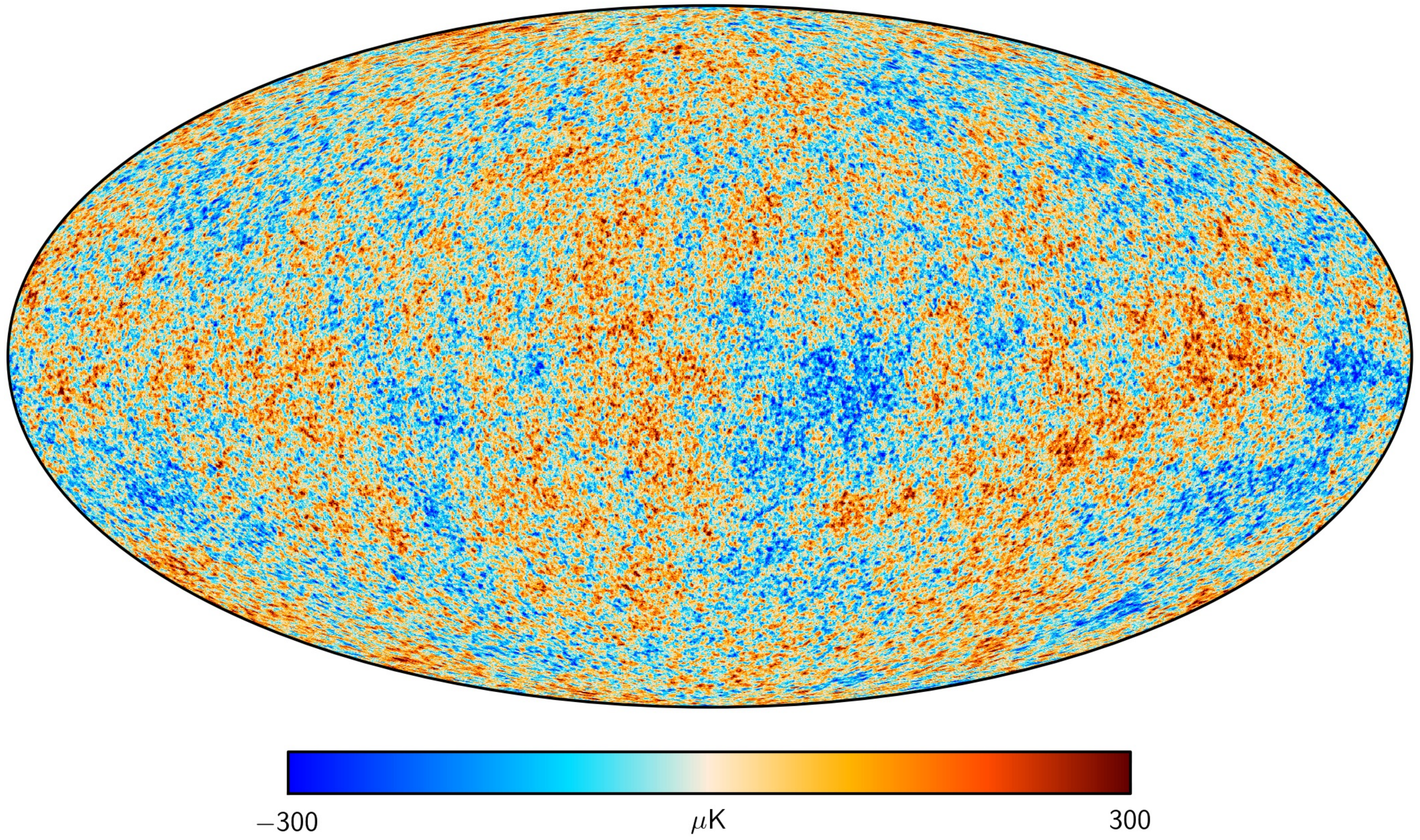


gravitational lensing map

X-ray emissions of high temperature matter



4. *Cosmic Microwave Background spectrum*

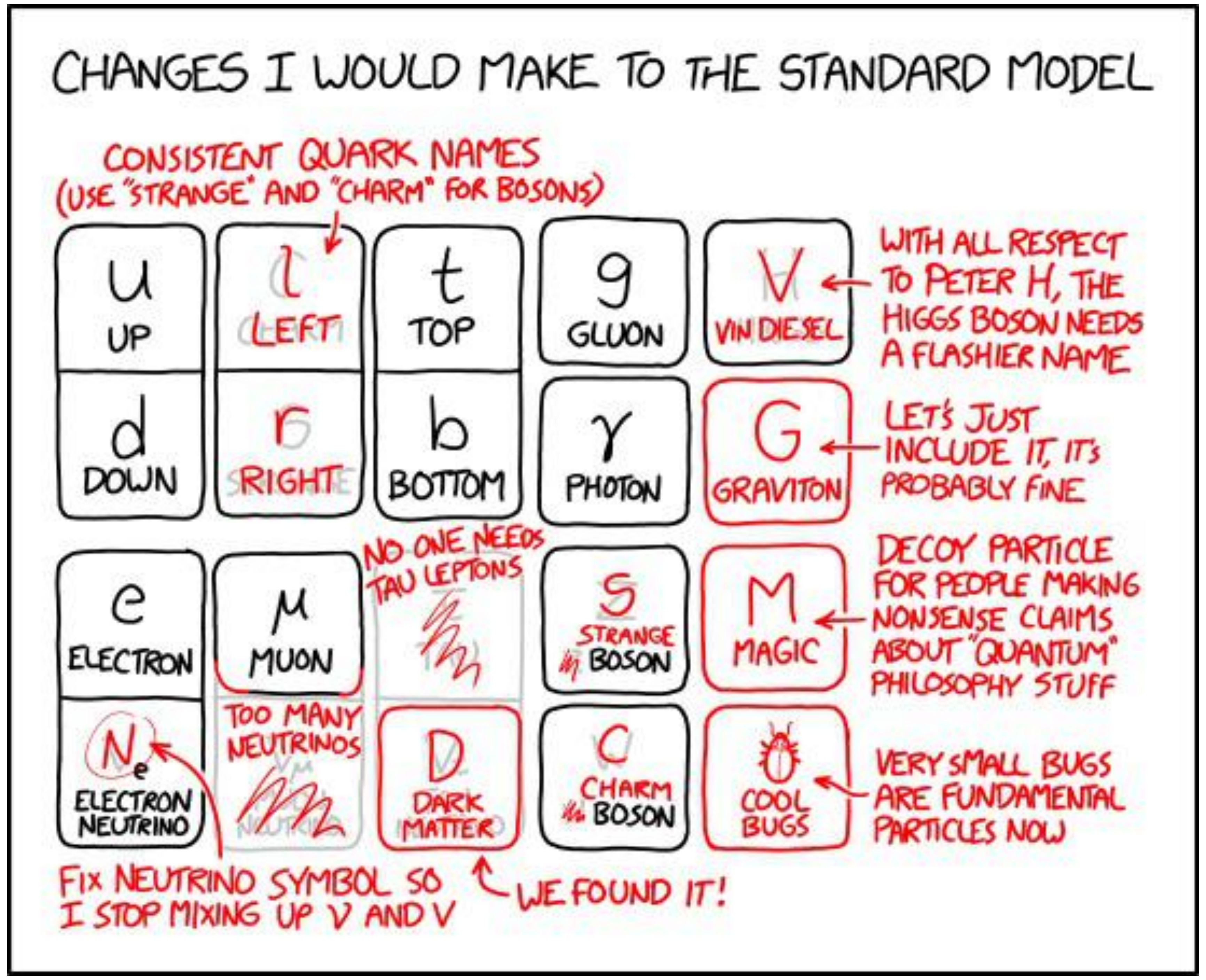


- allows for a quantitative estimate of different energy densities in the universe

normal matter	dark matter	dark energy
5%	26%	69%

Weakly Interacting Massive Particles

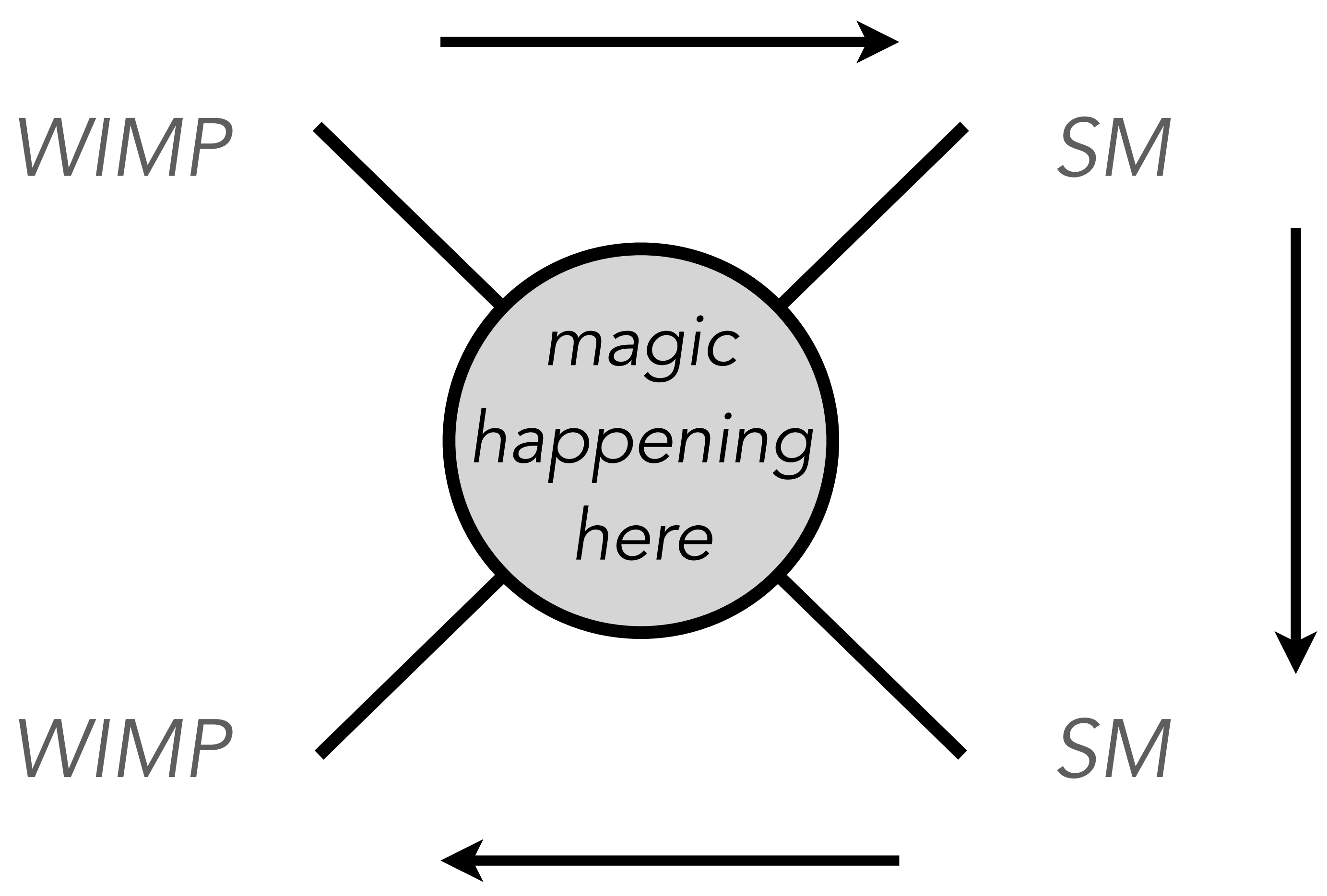
- under the hypothesis of a particle nature for dark matter, it must:
  - be stable → it survived from the early stages of the universe
  - no strong, weak or EM, only gravitationally interacting with ordinary matter → hence **dark**
  - fulfil the observed relic density
- neutrinos ruled out



Good candidate:

- Weakly Interacting Massive Particles - WIMPs
- searched in many different ways

Indirect detection experiments

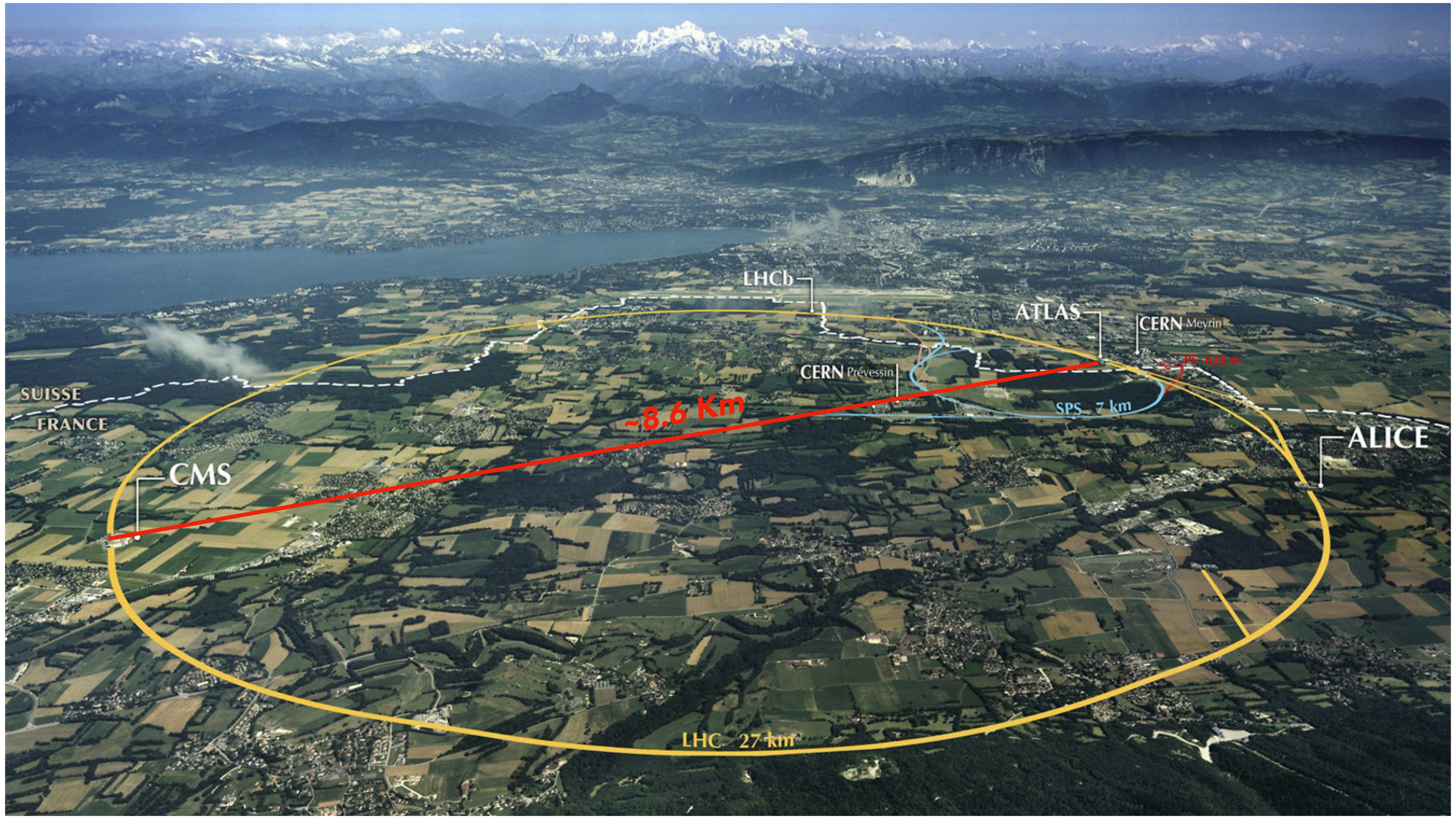


Direct detection experiments

Collider experiments

The Large Hadron Collider

- the hottest & one of the coolest place in the universe!
  - proton-proton collisions at up to 13 TeV supplemented by superconducting magnets working at 1.9 K
  - features 4 main experiments, ATLAS, ALICE, CMS & LHCb



Why Large?

- to reach high energy with limited bending power: $$p \propto B \cdot R$$
- to reduce bremsstrahlung energy loss:

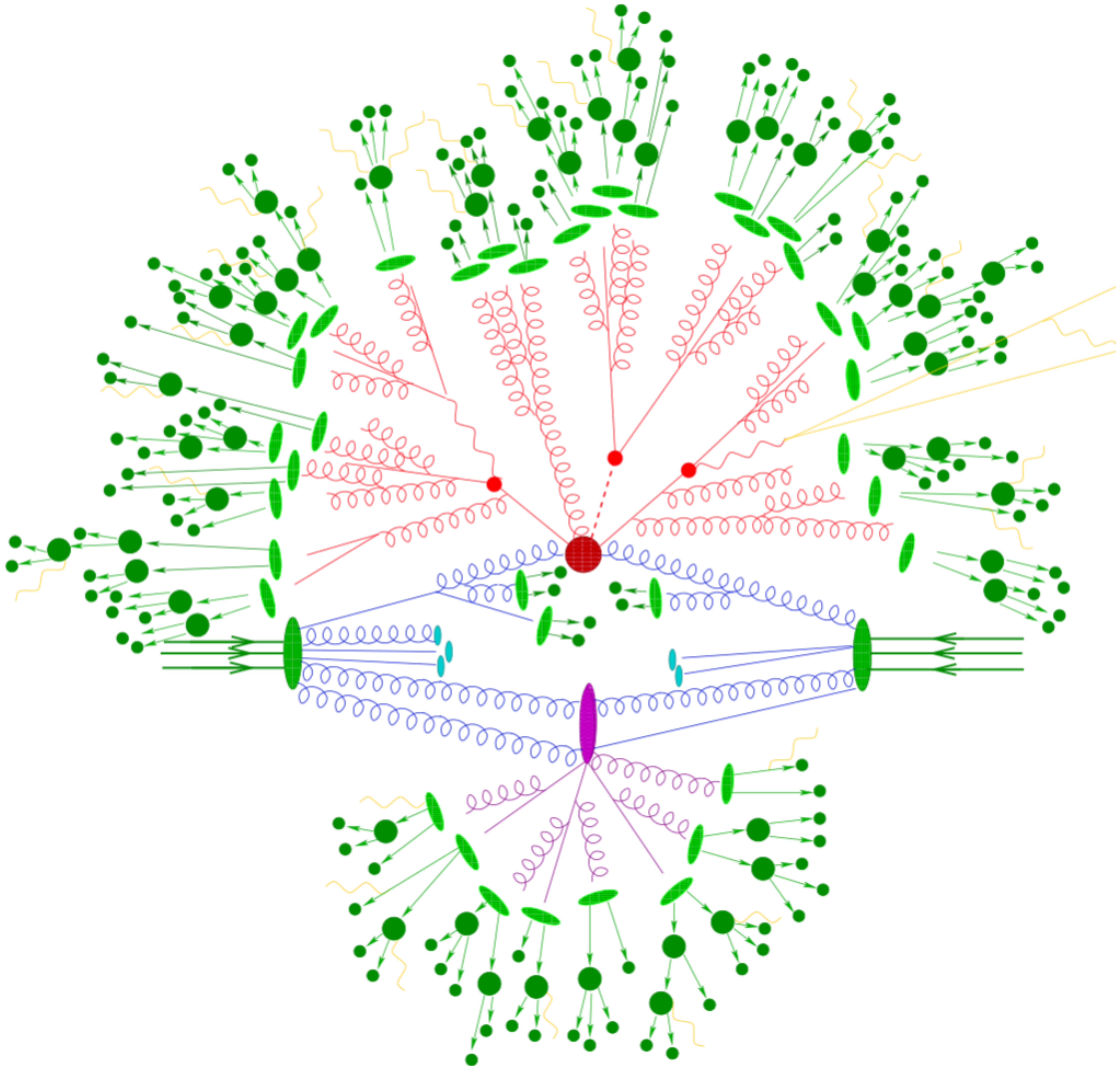
$$W \propto \frac{E^4}{R^2 m^4}$$

Why Hadrons?

- further suppress bremsstrahlung:

$$W_e \simeq 10^{13} \cdot W_p \quad \text{for fixed E}$$

Hadron-hadron collisions 101



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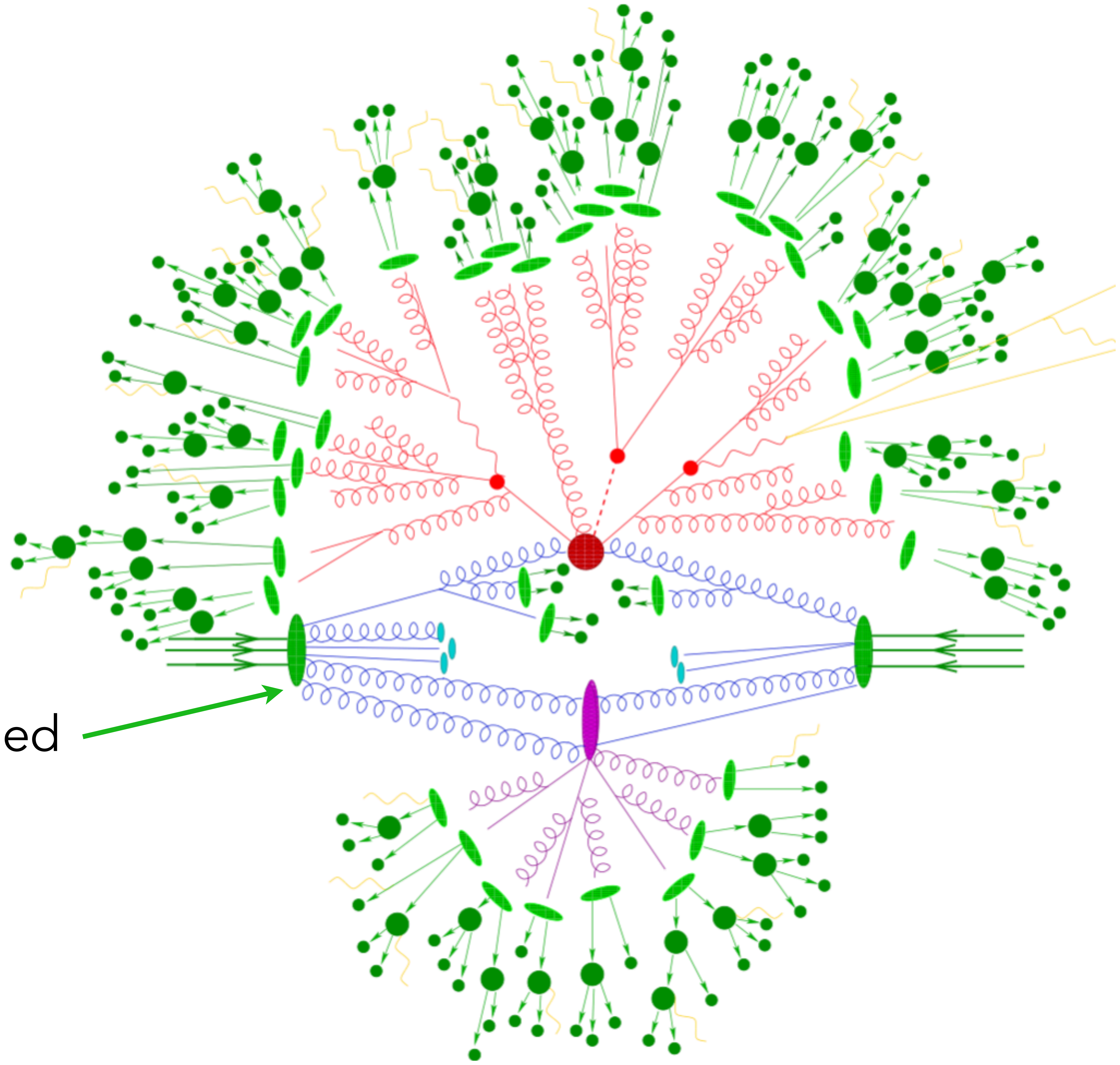
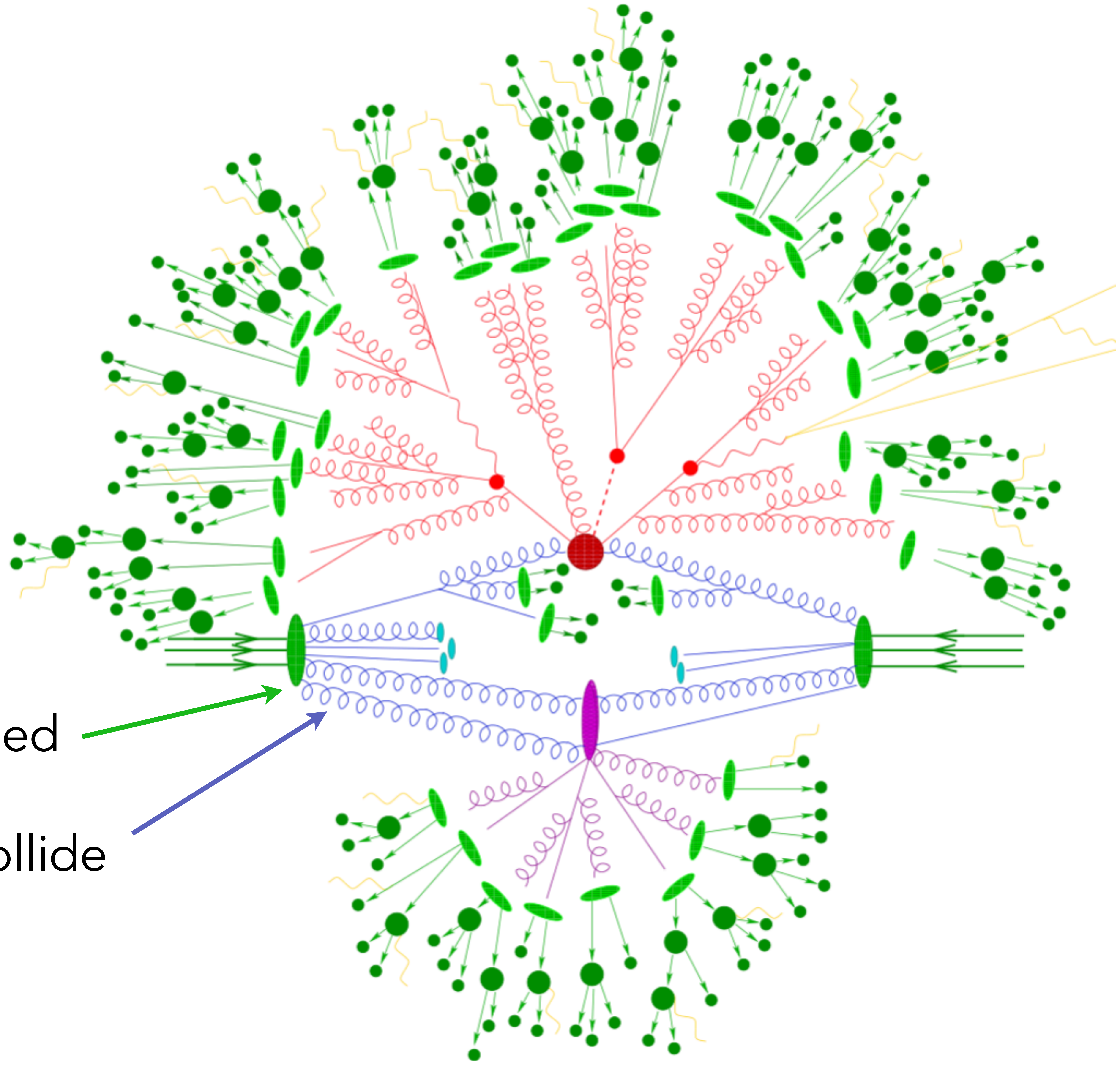


protons are collided

Hadron-hadron collisions 101

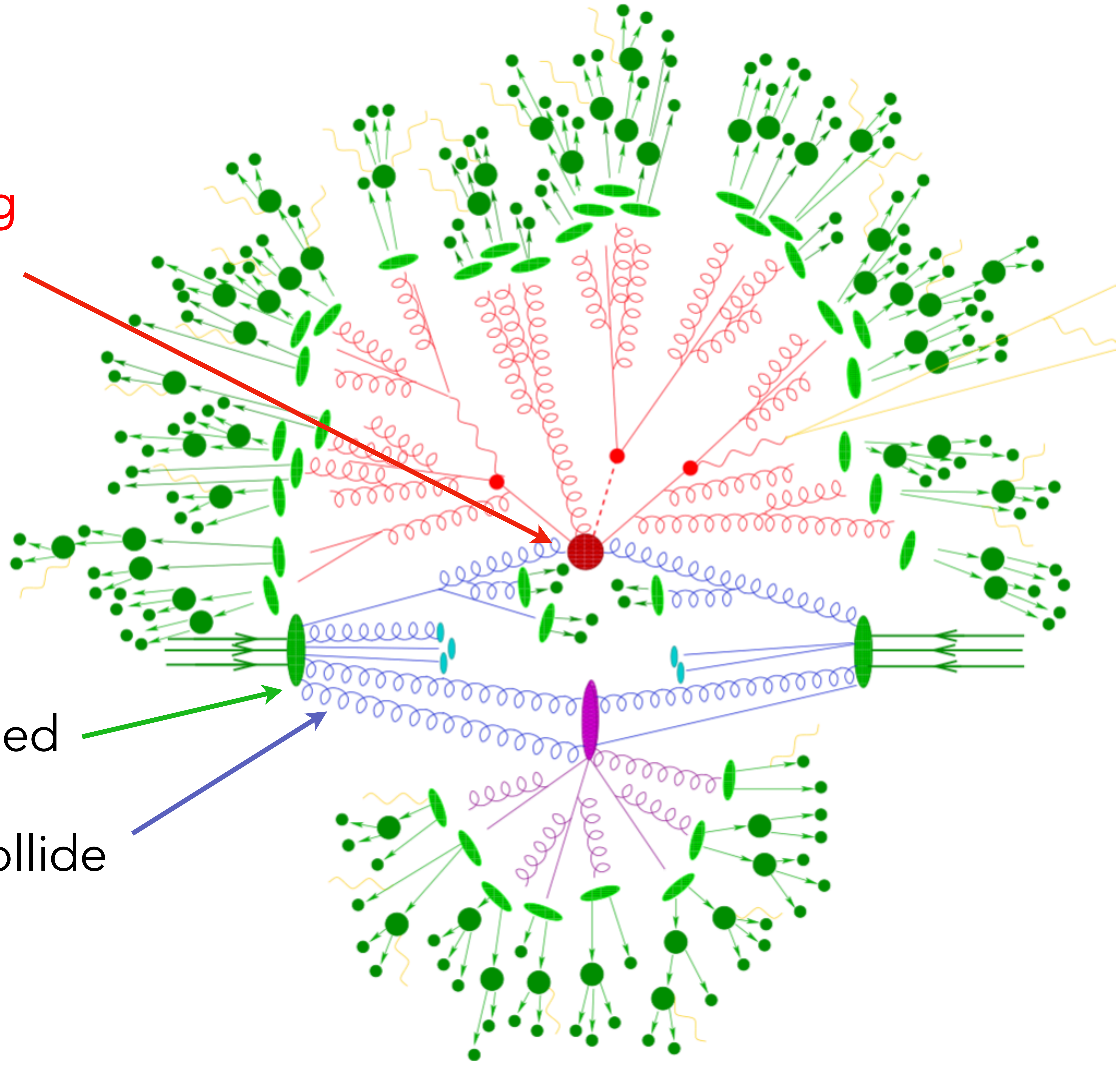


protons are collided

partons actually collide

Hadron-hadron collisions 101

hard scattering
interaction



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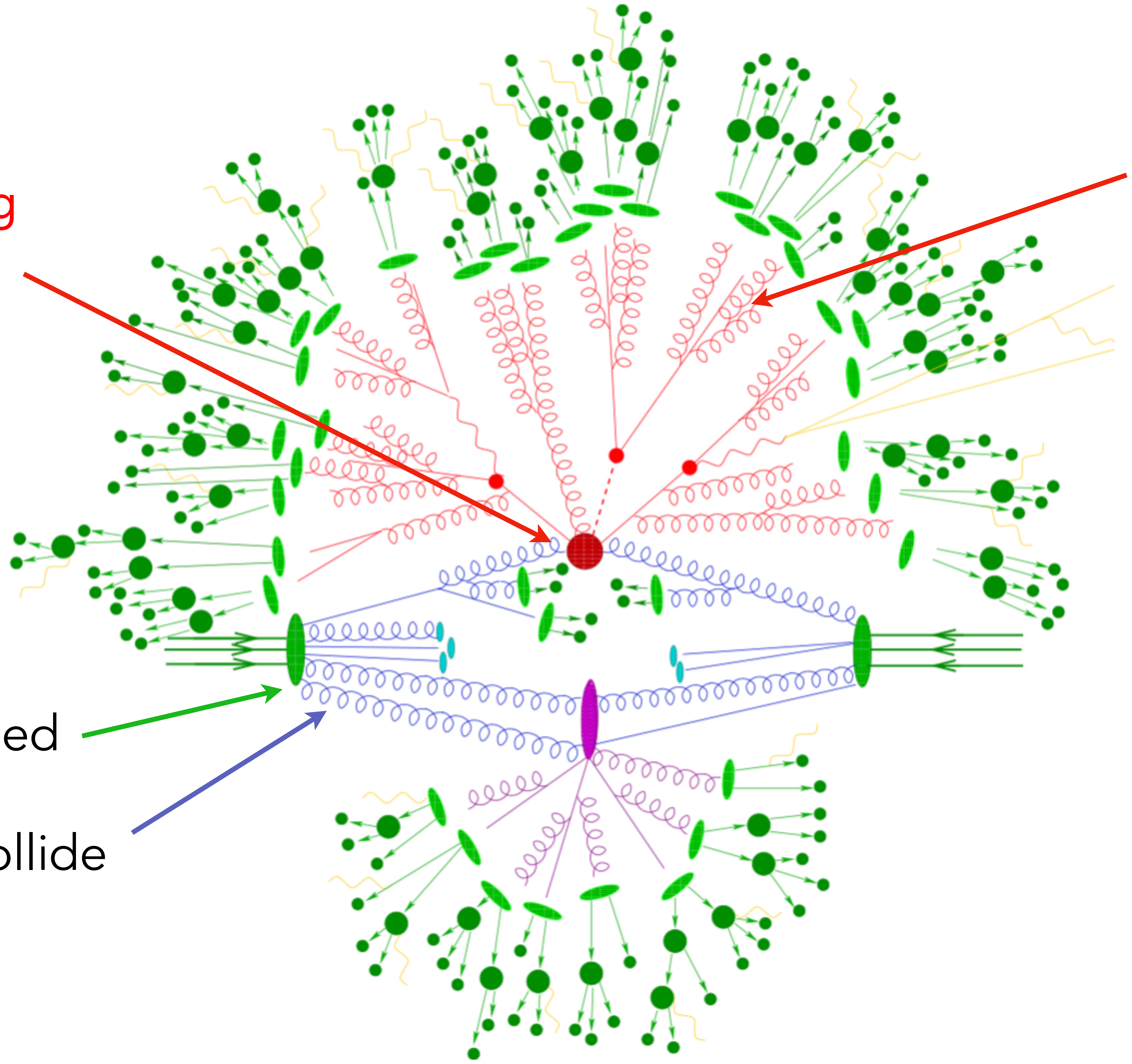
Hadron-hadron collisions 101

hard scattering
interaction

partons emit QCD
radiaton & hadronize



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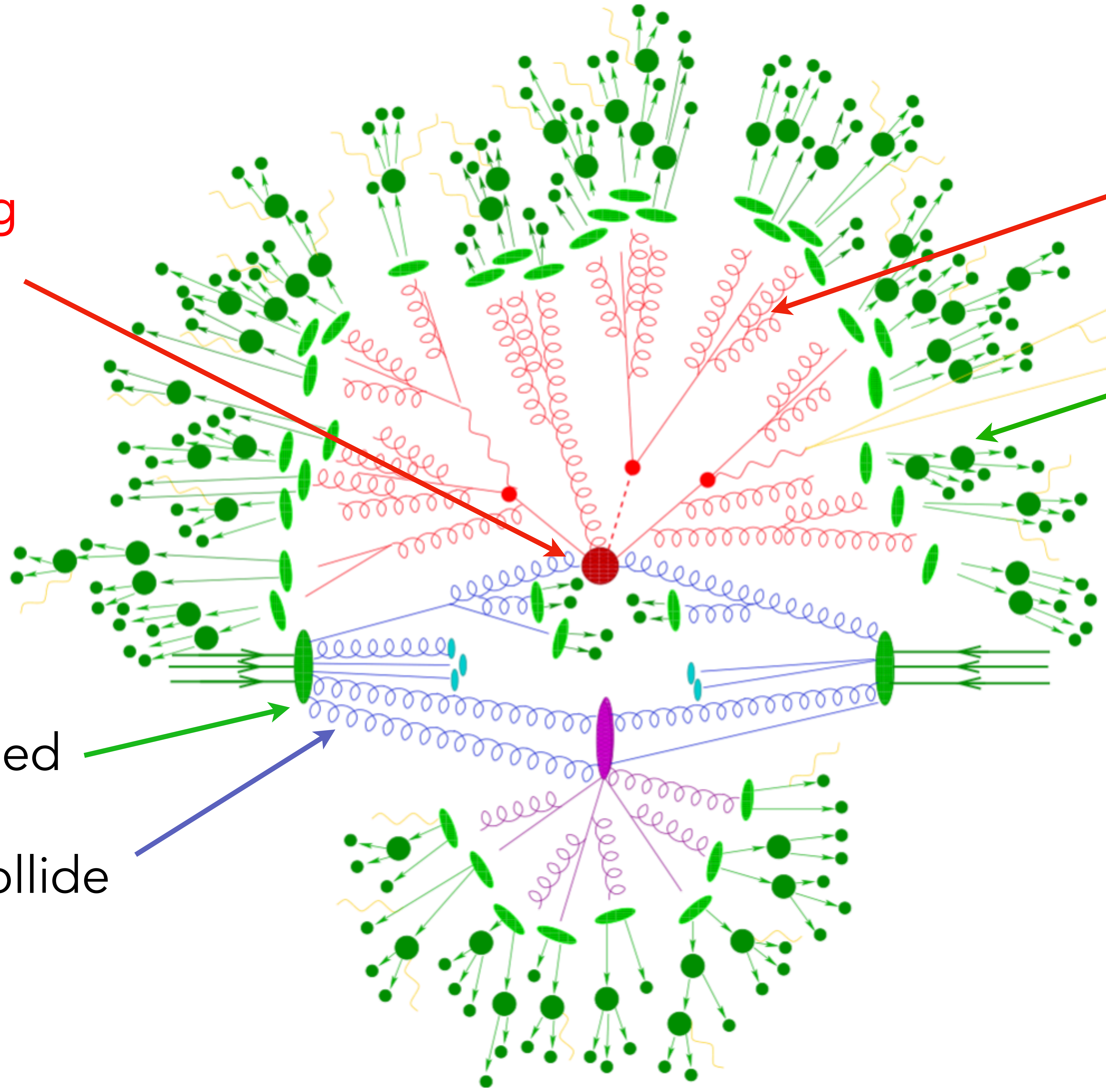
unstable hadrons decay



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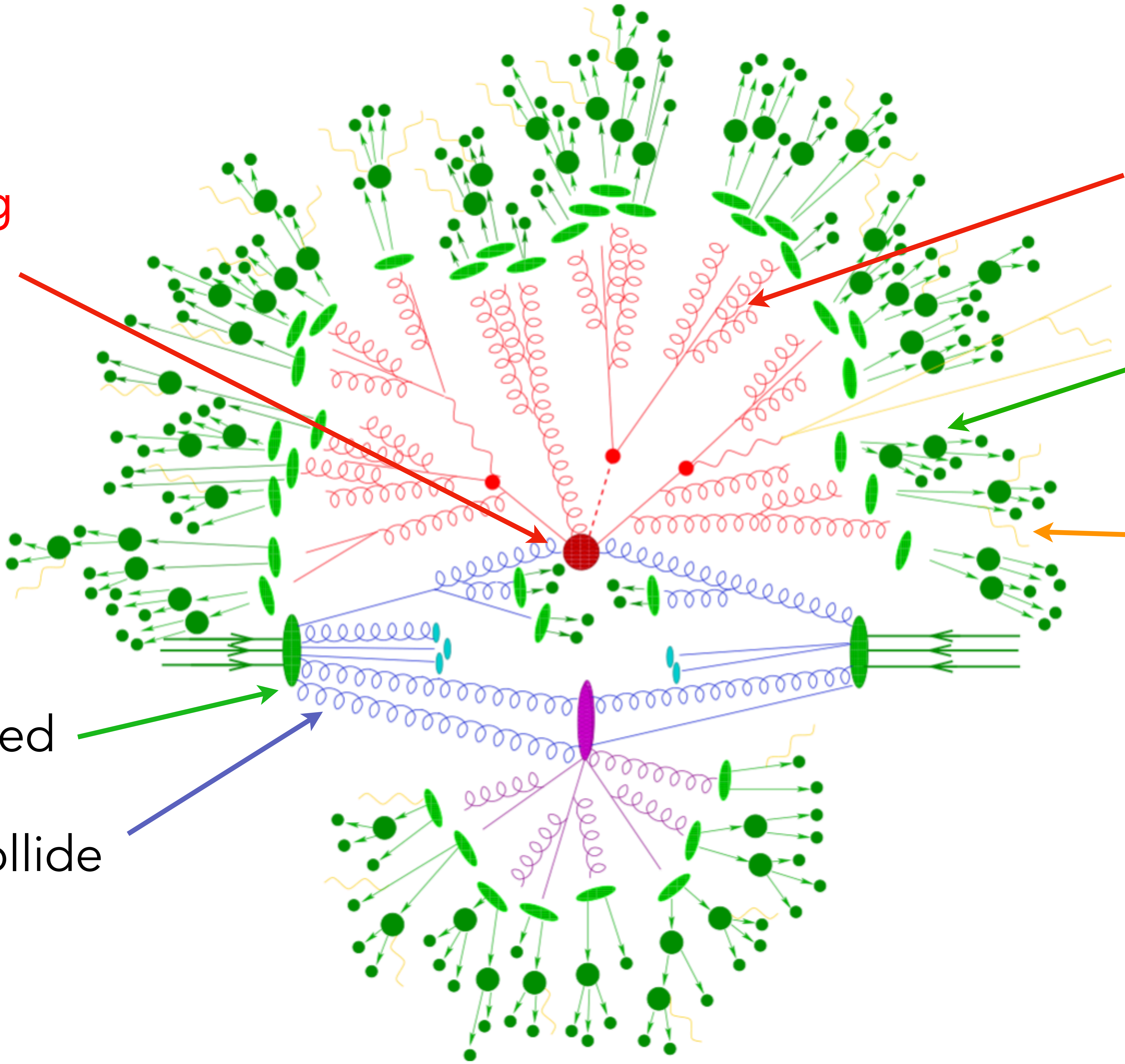
EM radiation (photons!)



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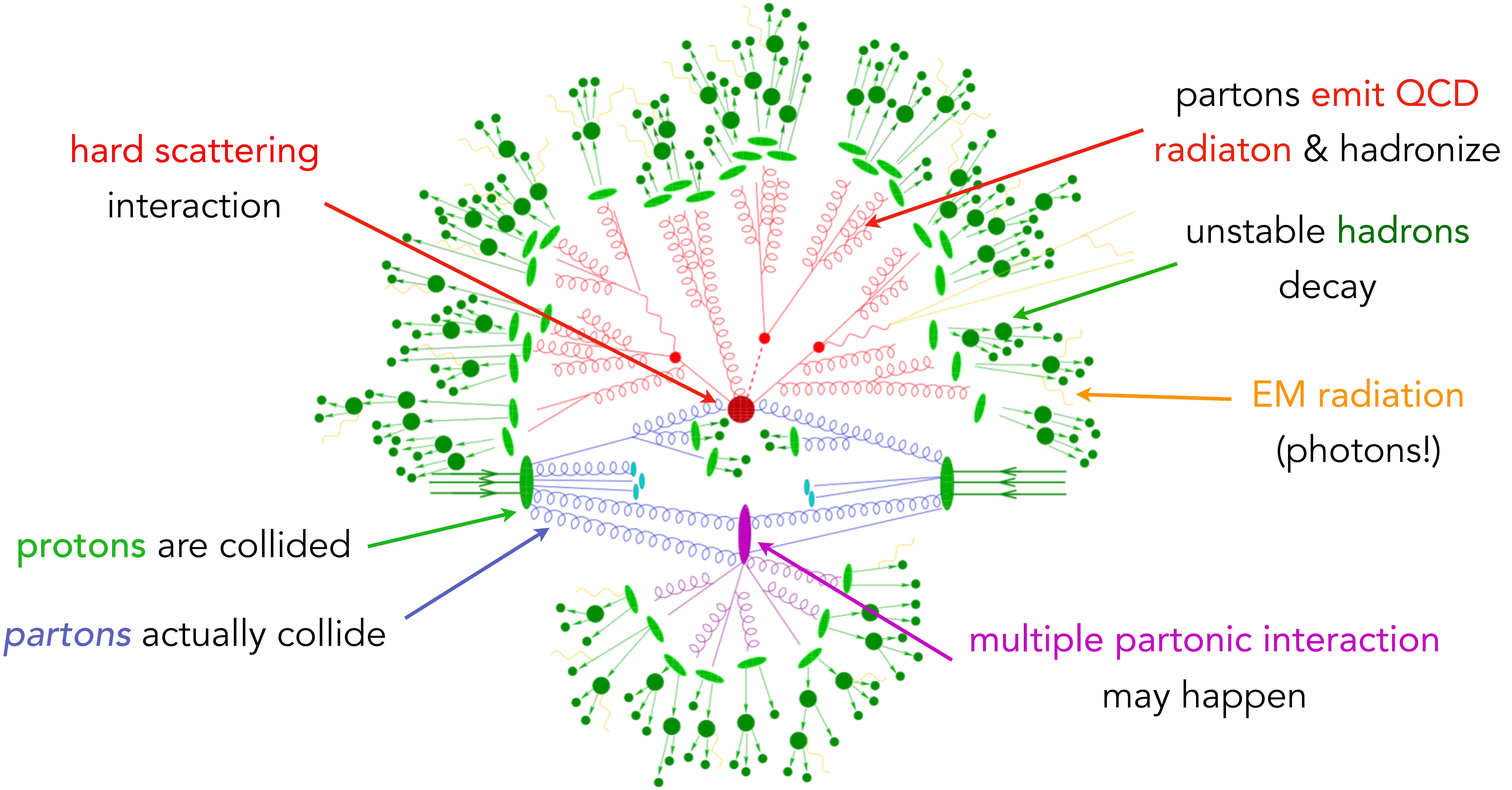
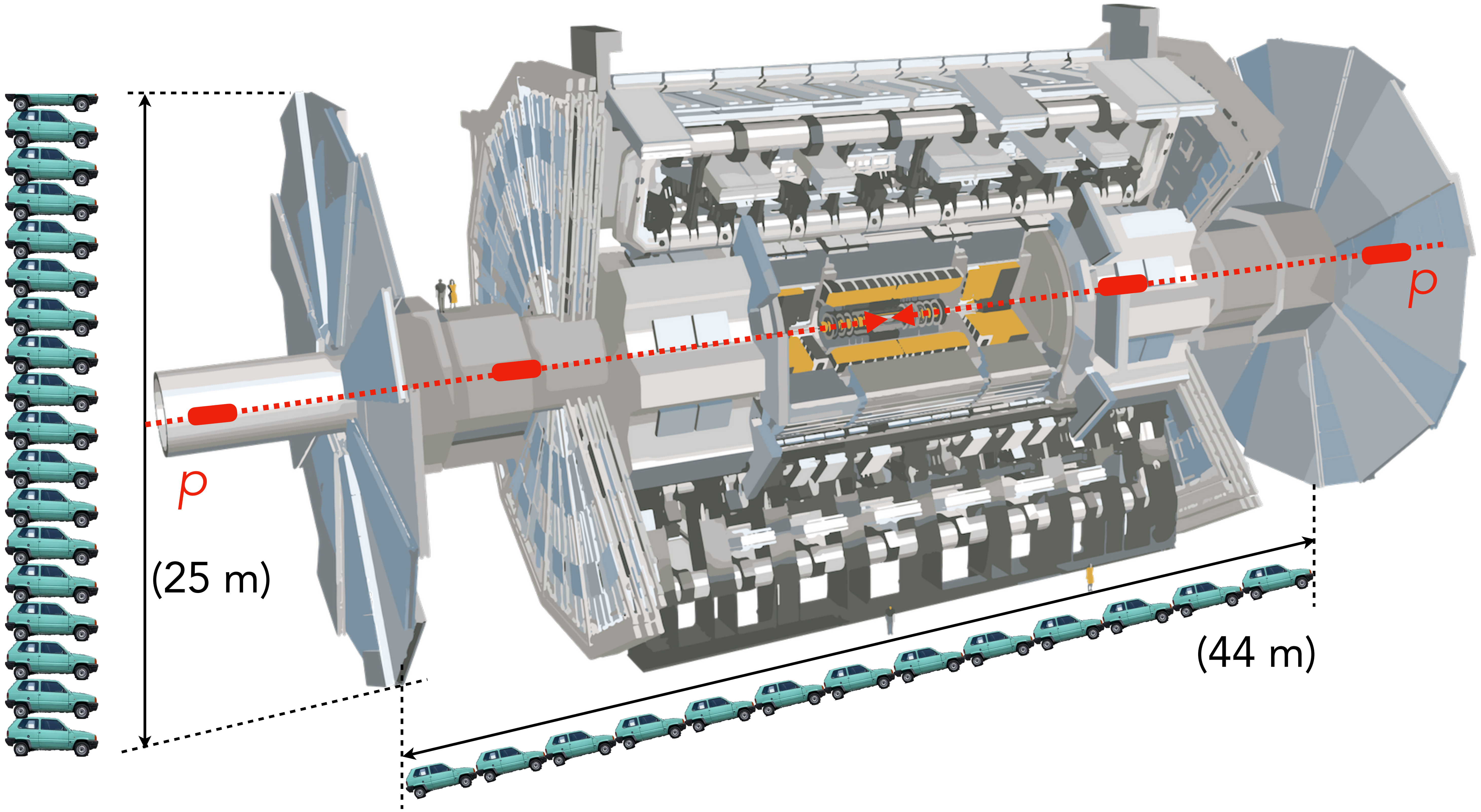


Our microscope: the ATLAS experiment

- A Toroidal Lhc ApparatuS is big, but how much big?

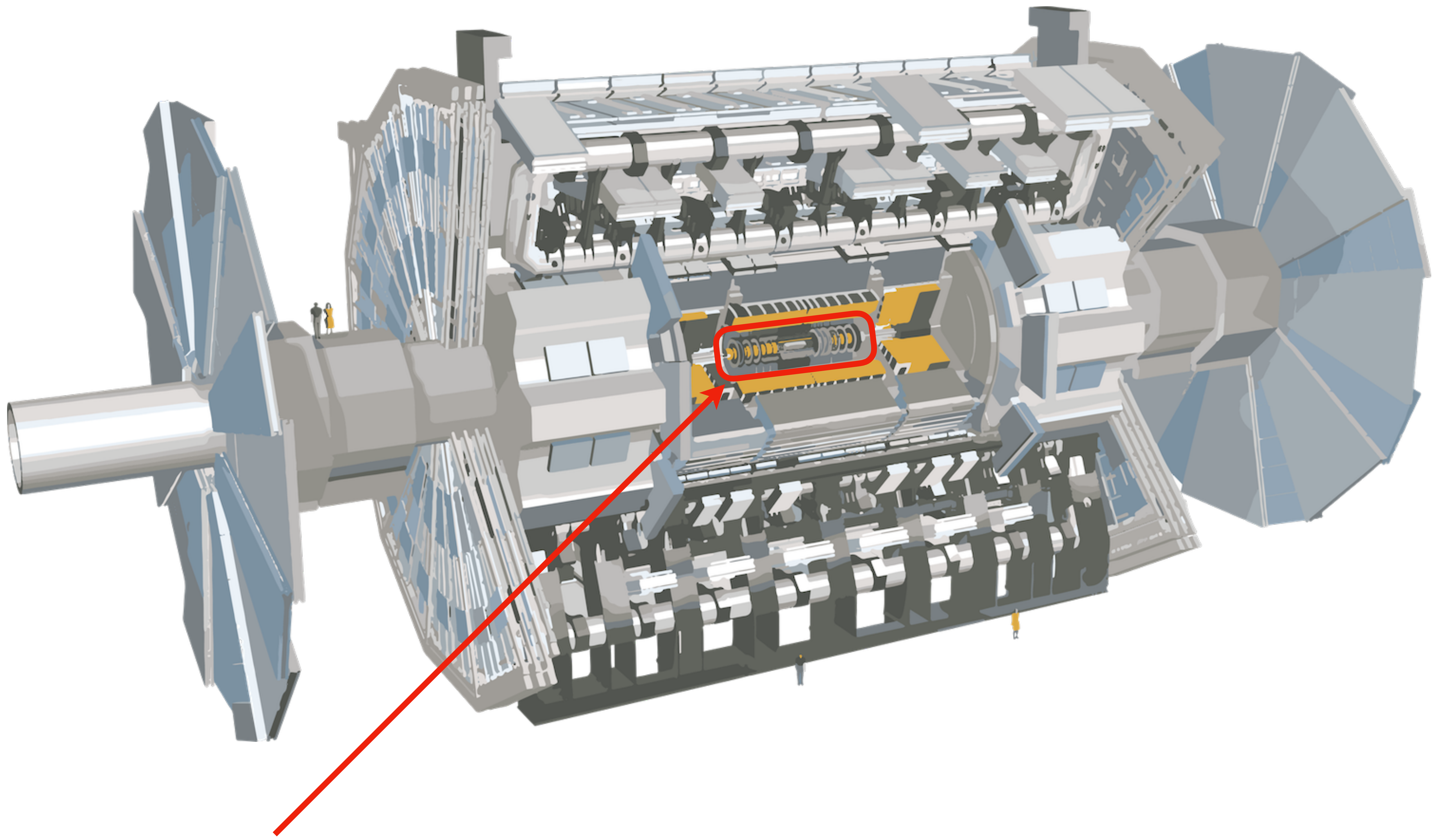
  ~ 13 x 17.3 Fiat Panda Young, 1998

- one blink of eye (~150 ms) ~ 6 million collisions between *pp* bunches (one every 25 ns)
  - trigger system selects events to be written to disk (rate ~1 kHZ)



- several sub-detectors covering almost the full solid angle around the interaction point (IP)

ATLAS in a nutshell



Inner detector

- inside a 2 T axial magnetic field
- position of the IP determined up to ~5 μm

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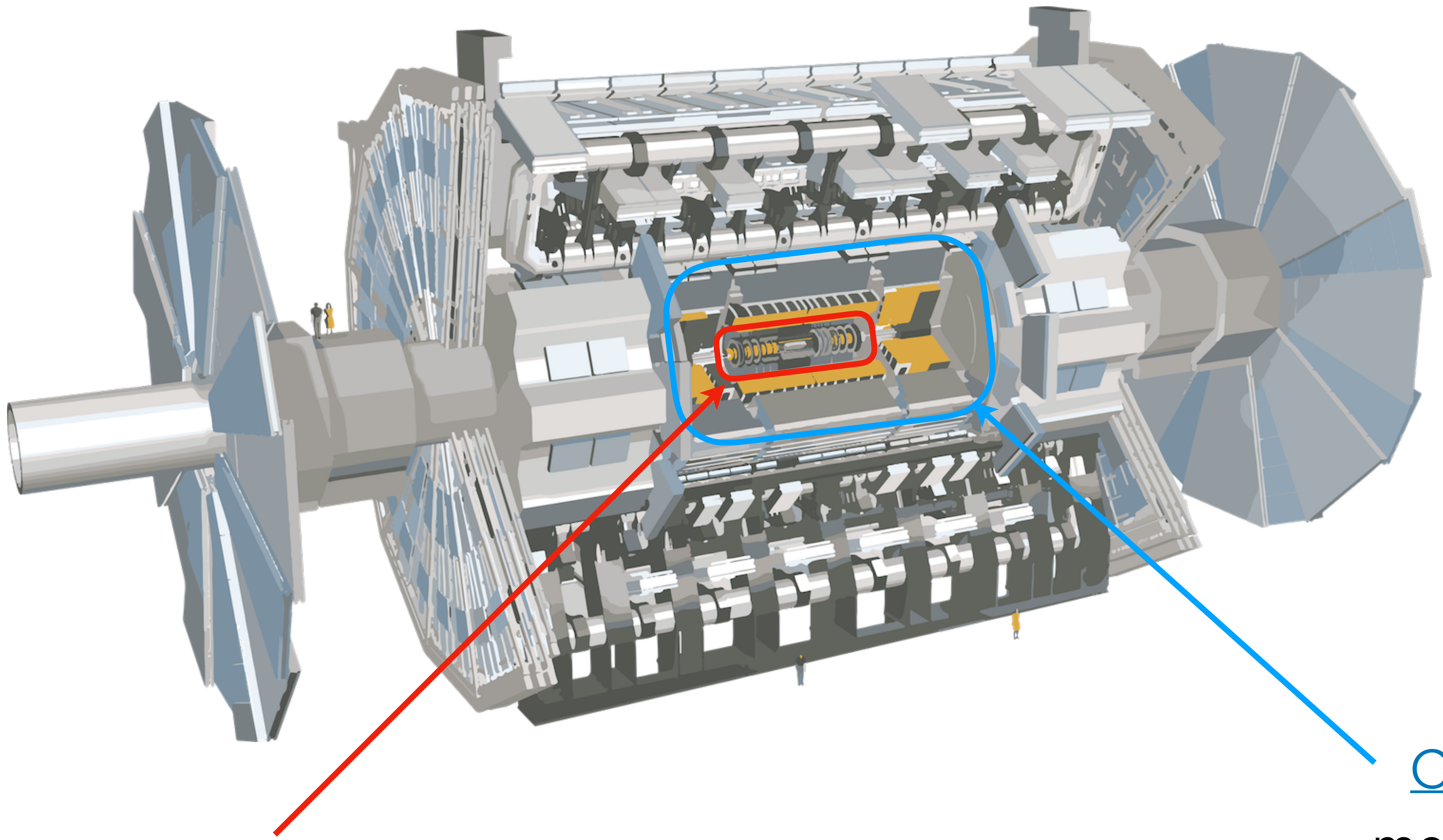

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Calorimetric system

- measure the energy of particles in a destructive way
- only muons & neutrinos do not interact with it

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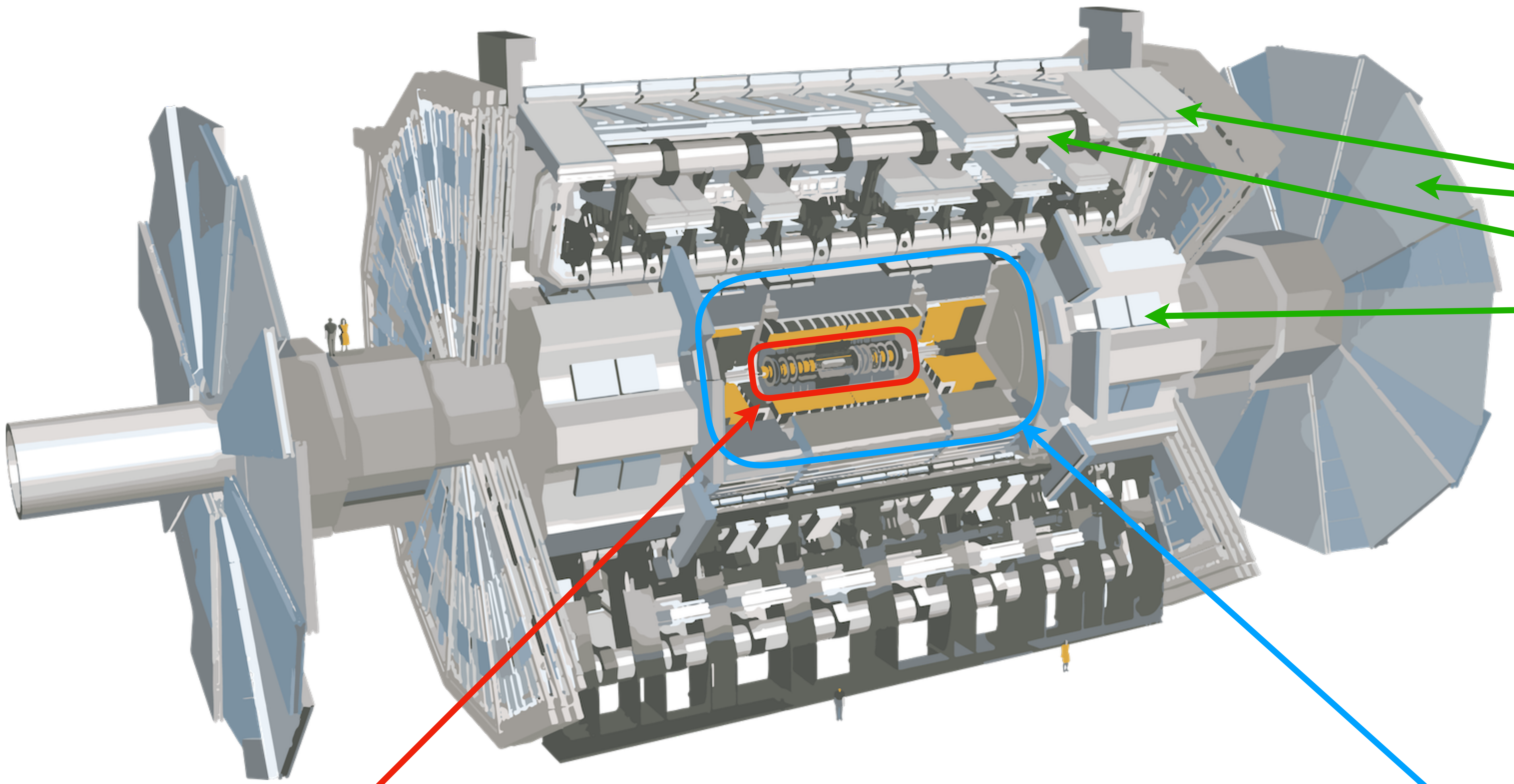

Muon spectrometer

- 3 big toroidal magnetic fields to bend & measure most penetrating charged particles, muons!

Calorimetric system

- measure the energy of particles in a destructive way
- only muons & neutrinos do not interact with it

Inner detector

- inside a 2 T axial magnetic field
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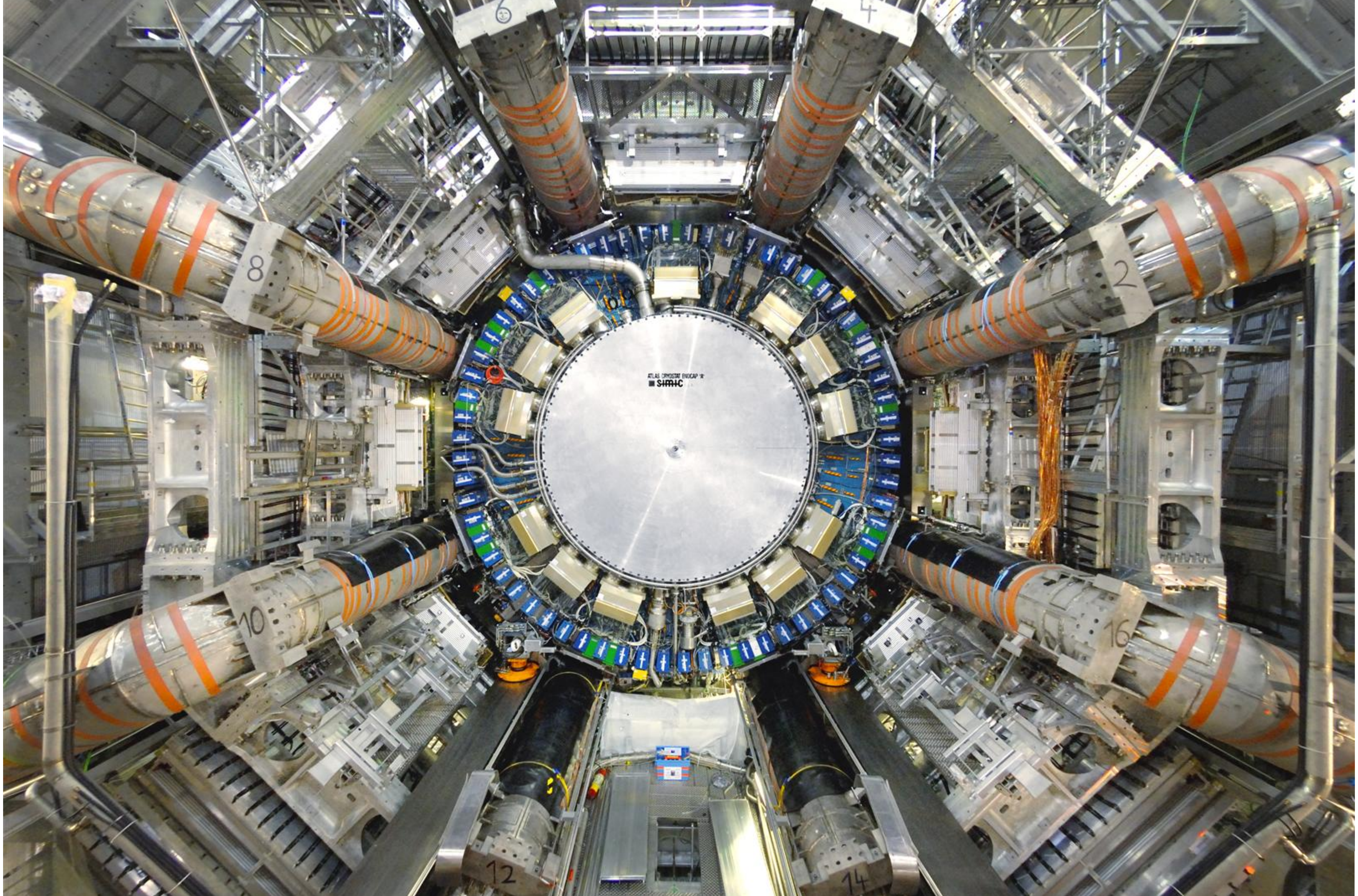
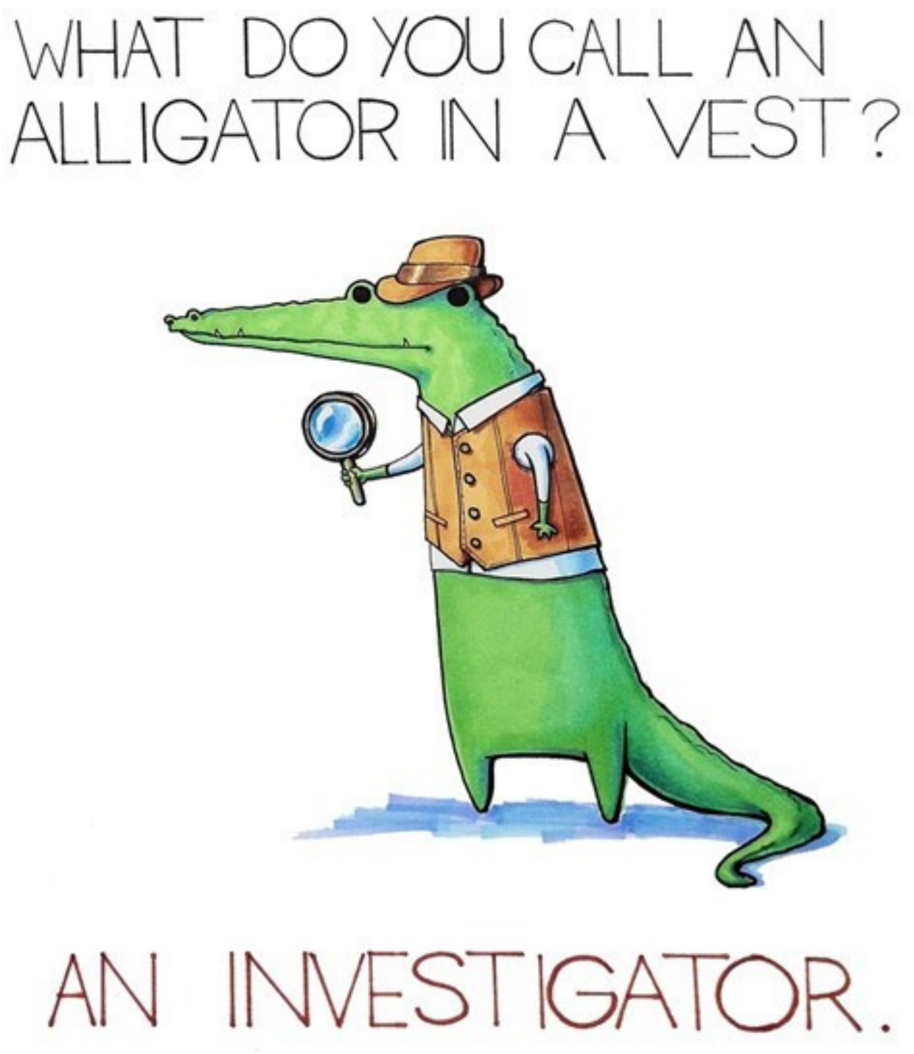

8
2
10
16
12
14

Hunting dark matter

- if produced in collisions, dark matter would not interact with ATLAS detectors
  - produce *missing energy* in the final states

- fundamental property of the collisions:
  - happen along one axis → total momentum in the transverse plane = 0
  - we can search an object X recoiling against *missing transverse momentum* (MET)



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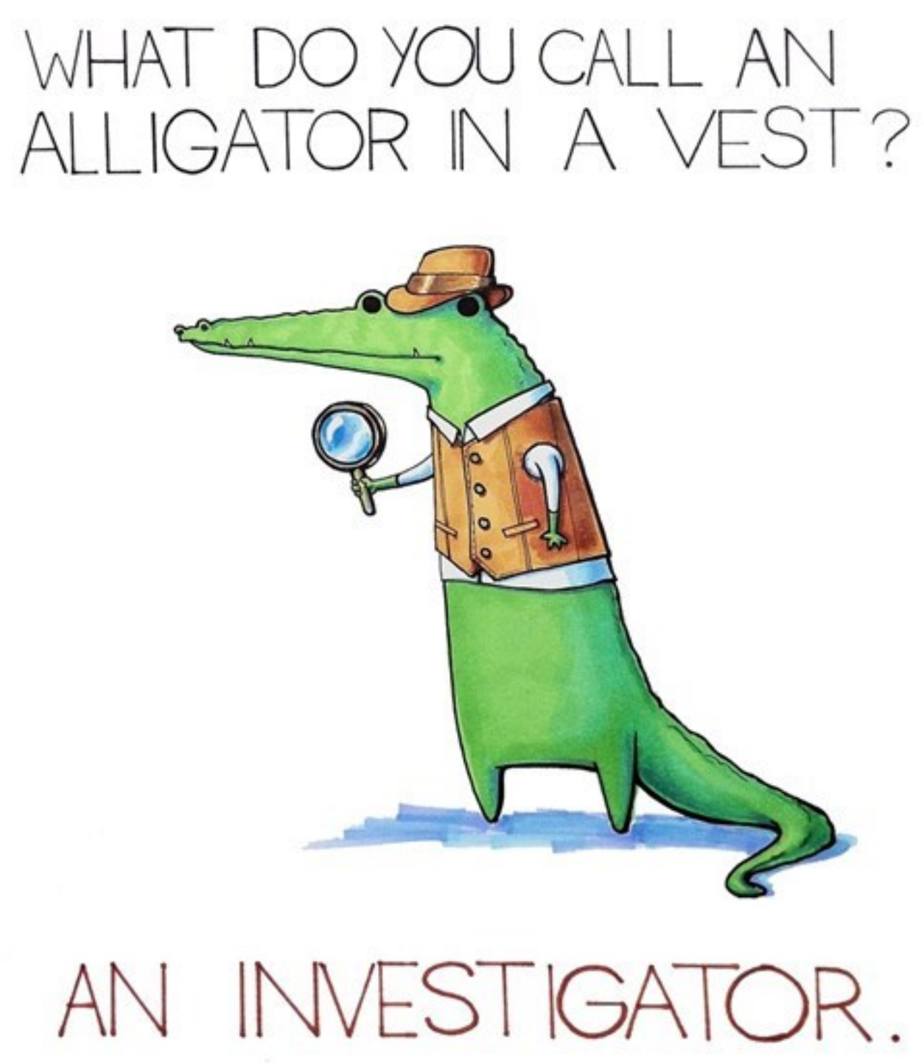
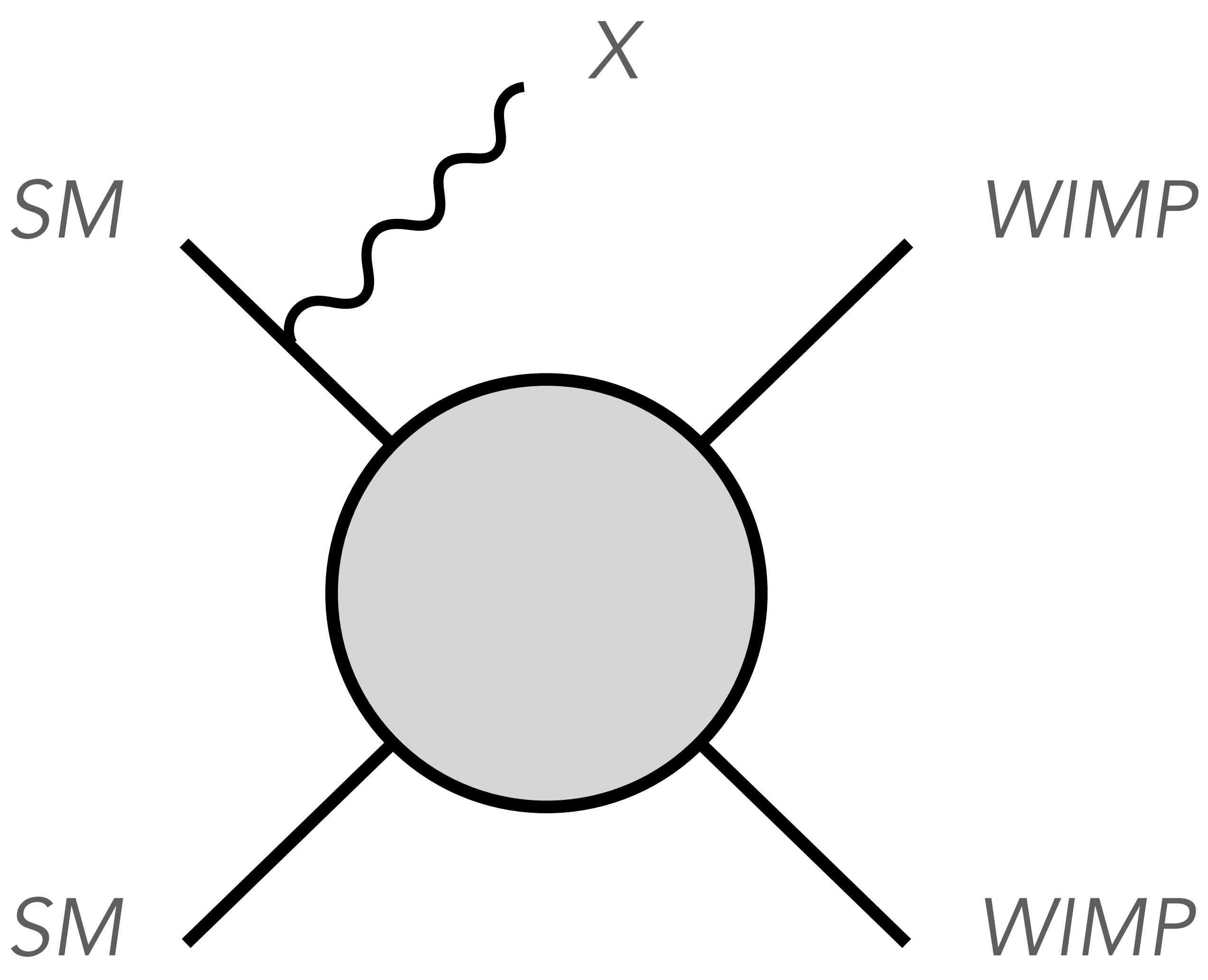




- different final states investigated
  - mono-jet
  - mono-photon
  - mono-V (W or Z boson)
  - mono-Higgs

largest cross-section ↓ lowest cross-section

- mono-jet most sensitive search to WIMPs

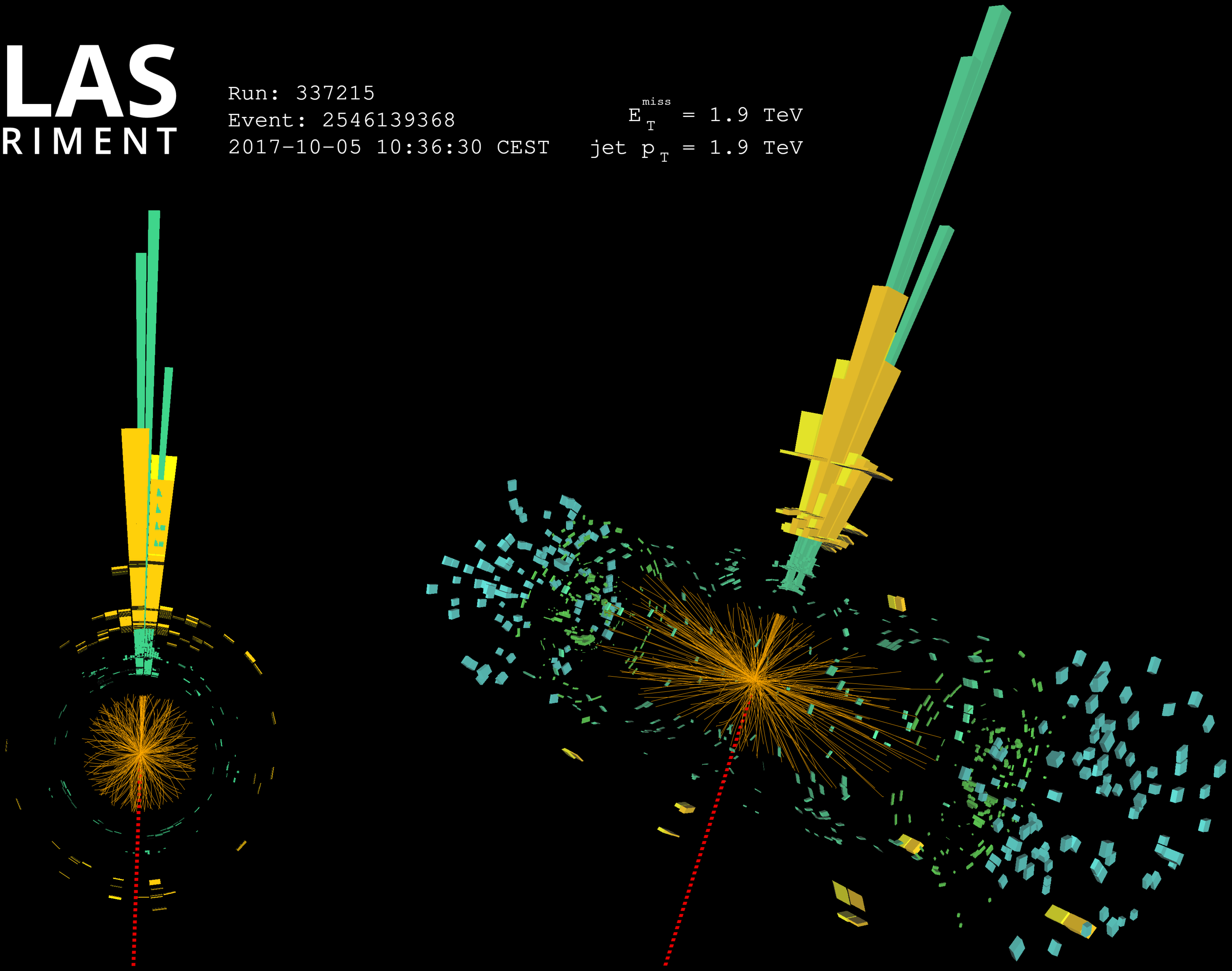

ATLAS
EXPERIMENT
Run: 302393
Event: 738941529
2016-06-20 07:26:47 CEST


ATLAS
EXPERIMENT
p
Run: 302393
Event: 738941529
2016-06-20 07:26:47 CEST

ATLAS EXPERIMENT

Run: 337215
Event: 2546139368
2017-10-05 10:36:30 CEST

E_T^{miss} = 1.9 TeV
jet p_T = 1.9 TeV




ATLAS
EXPERIMENT
Run: 337215
Event: 2546139368
2017-10-05 10:36:30 CEST
E_T^{miss} = 1.9 TeV
jet p_T = 1.9 TeV

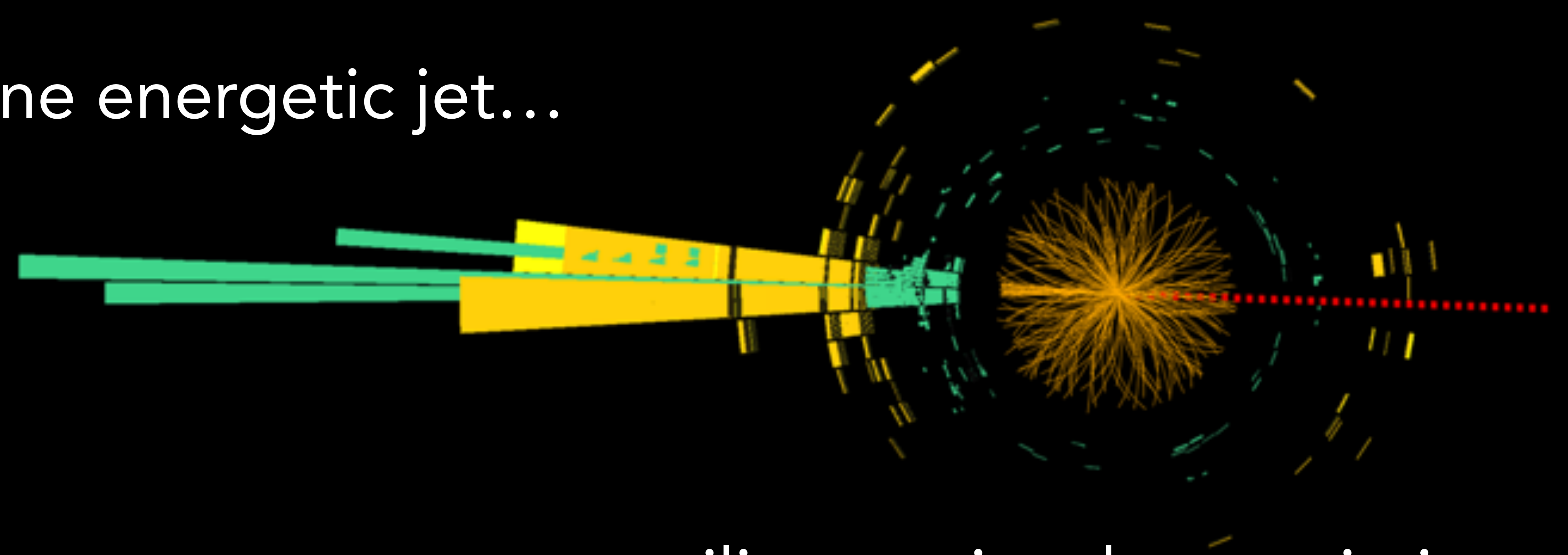
Mono-jet analysis strategy

- goal: look for an excess of events with large imbalance in the transverse plane

1st. identify candidate events online
(i.e. while collisions are running @40 MHz) → MET trigger w. threshold to cope with available bandwidth

2nd. apply offline an event selection to isolate candidate signal events

at least one energetic jet…

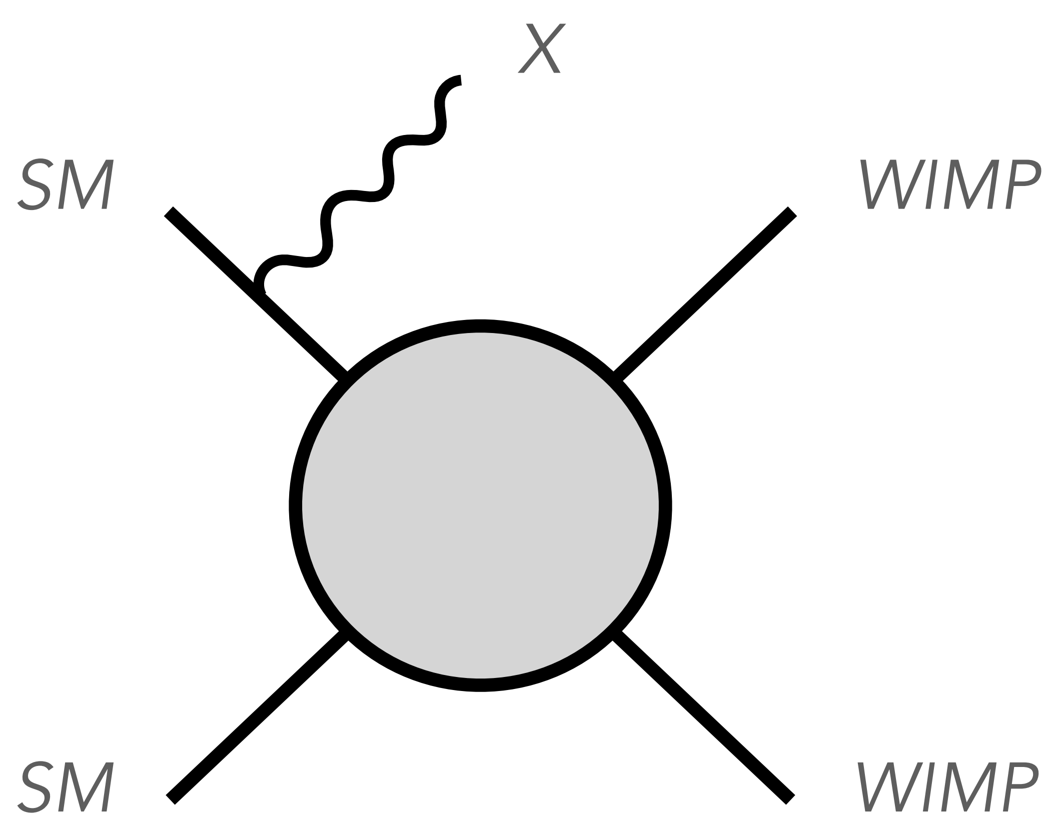


…recoiling against large missing transverse momentum

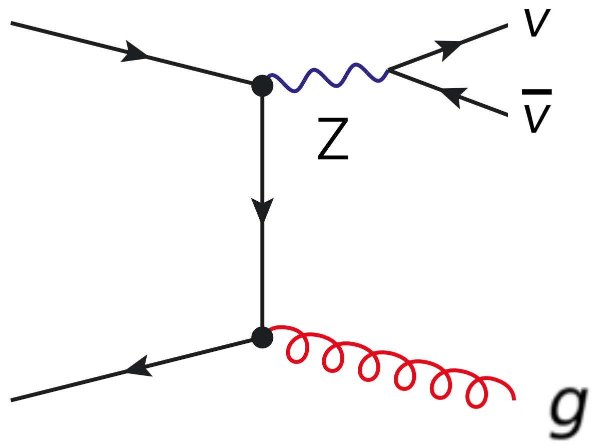
& many more

→ events mimicking the signal signature will still *sneak* into the Signal Region

Signal vs backgrounds

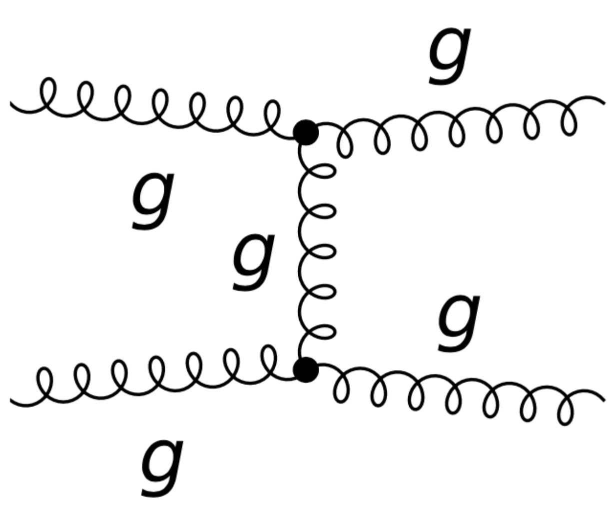


Irreducible backgrounds

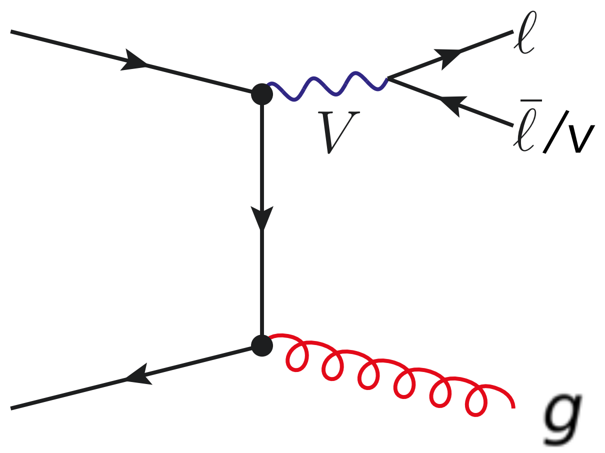


Z(νν) + jets
exactly the same signature of the signal we search!

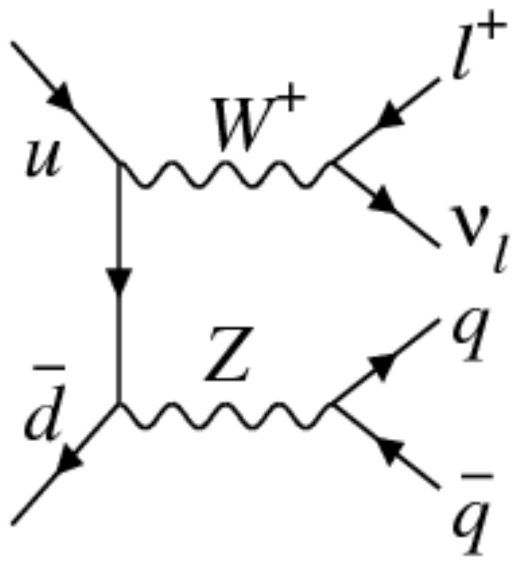
Reducible backgrounds



multi-jet production



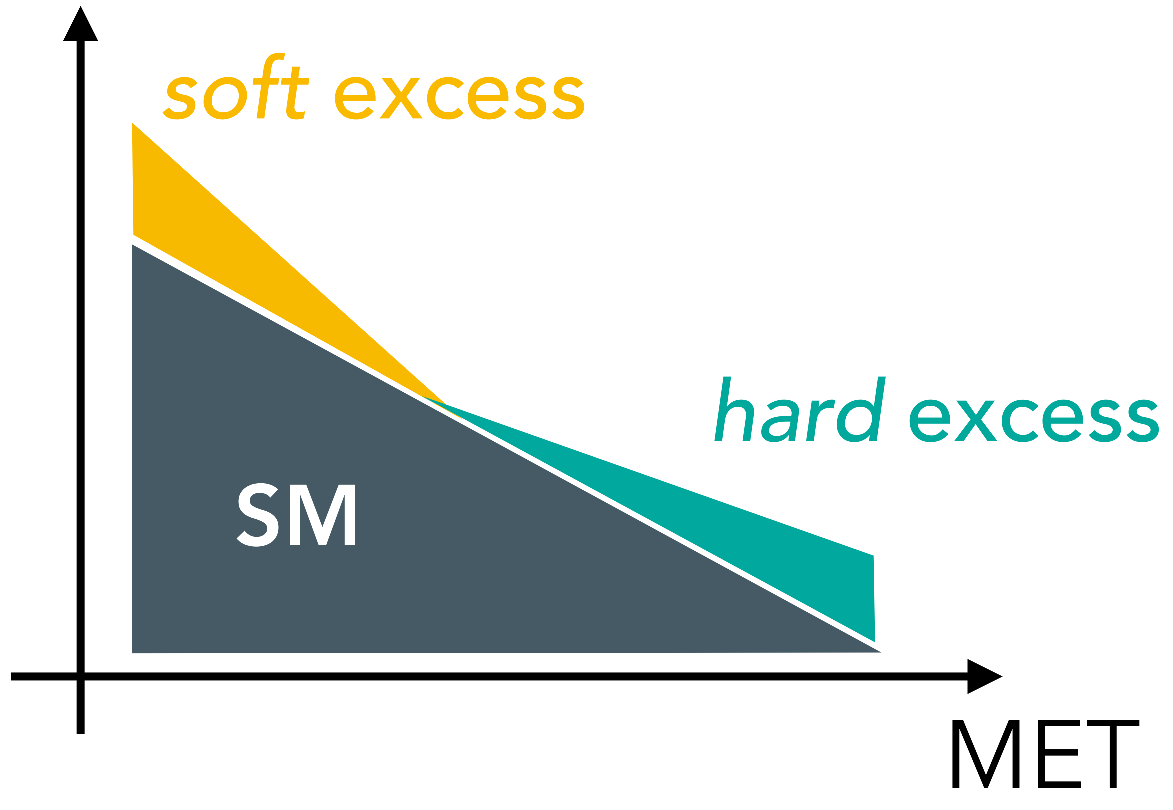
V+jets



dibosons production

V = $W^{\pm}$ or Z_0 weak boson

- MET distribution shape helps in identifying any excess - precise prediction of backgrounds is needed



- rely on state of the art Monte Carlo generators & theoretical calculations
- data-driven estimates if MC predictions are not reliable
  - e.g. QCD processes

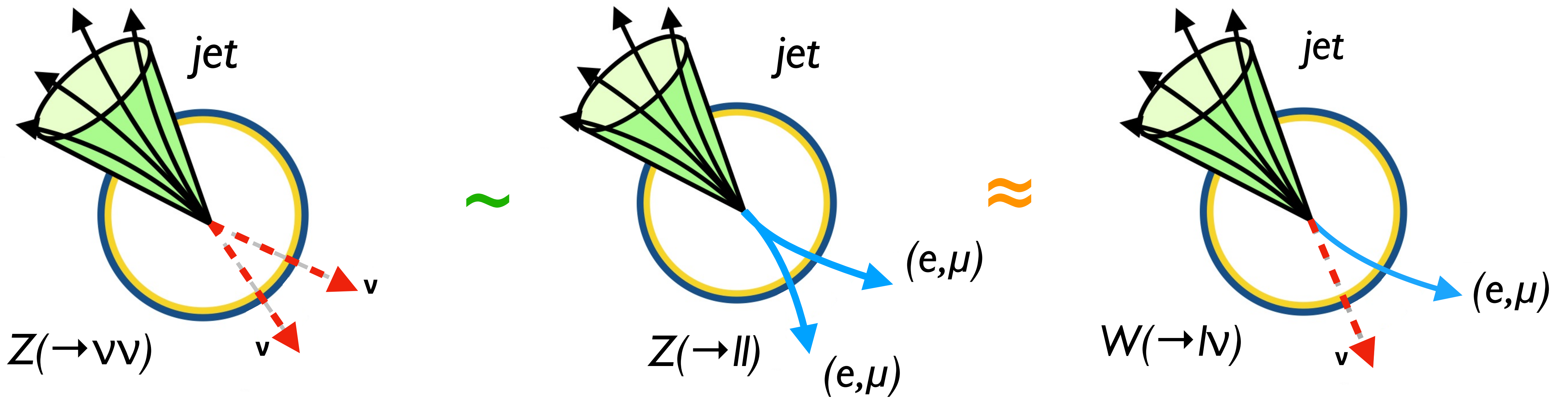
The need for *Control Regions*

- data is N$^\infty$LO in both QCD and EW, MC predictions are not
  - predictions are corrected in regions orthogonal to the SR using data

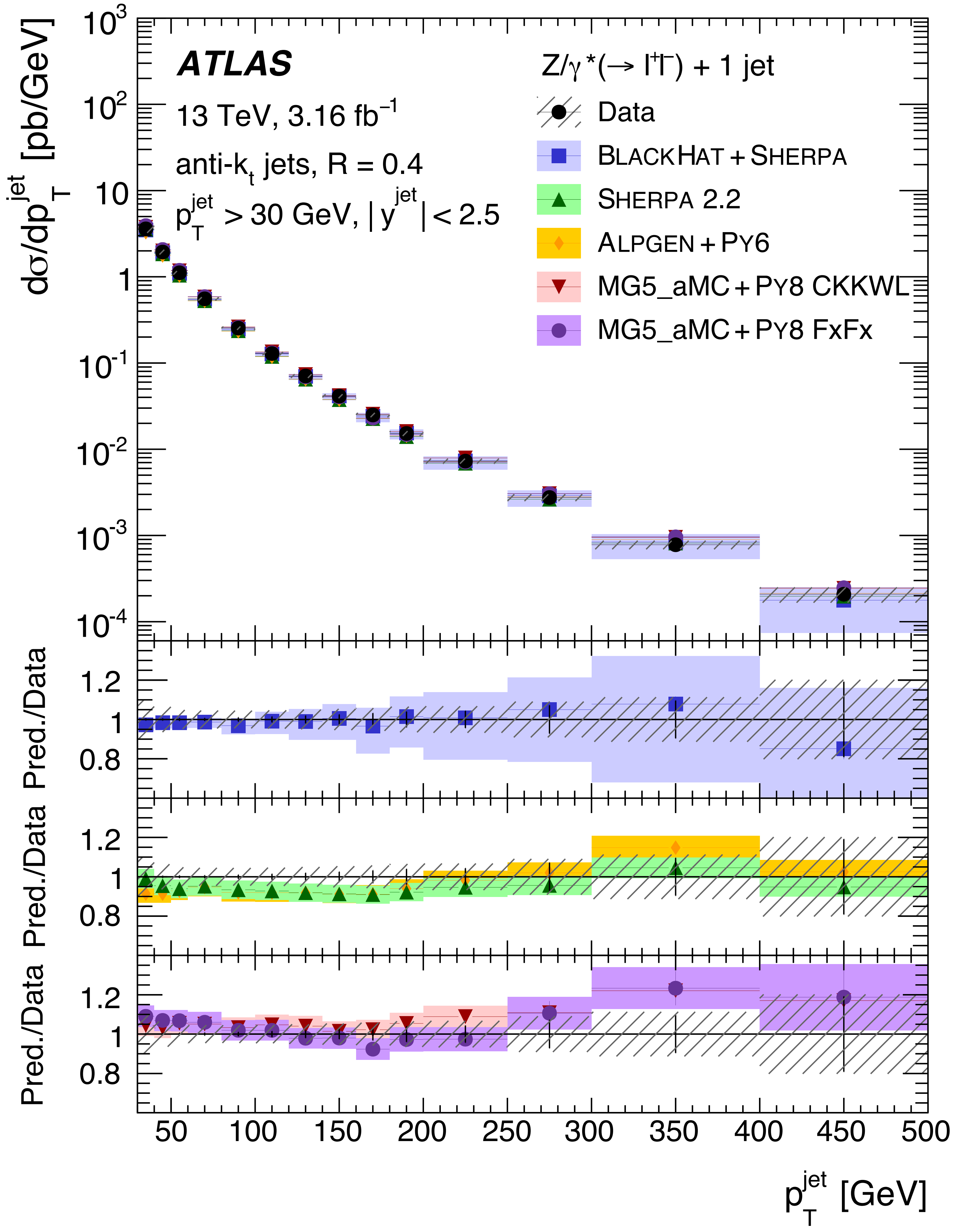
$$N^{\mathrm{SR}}_{\mathrm{BG}_i} = \boxed{\frac{\left(N^{\mathrm{CR}_j}_{\mathrm{data}} - N^{\mathrm{CR}_j}_{\text{non-BG}_j,\ \mathrm{MC}}\right)}{N^{\mathrm{CR}_j}_{\mathrm{BG}_j,\ \mathrm{MC}}}} \cdot N^{\mathrm{SR}}_{\mathrm{BG}_i,\ \mathrm{MC}}$$

corrected predictions = data-driven correction factor x original predictions

- ratio of MC predictions reduce associated uncertainties too!
- minor extrapolation effects if keeping kinematics selections similar:
  - treating leptons as invisible particles in the CRs!



example of ATLAS measurement of the cross-section of the Z+jets process



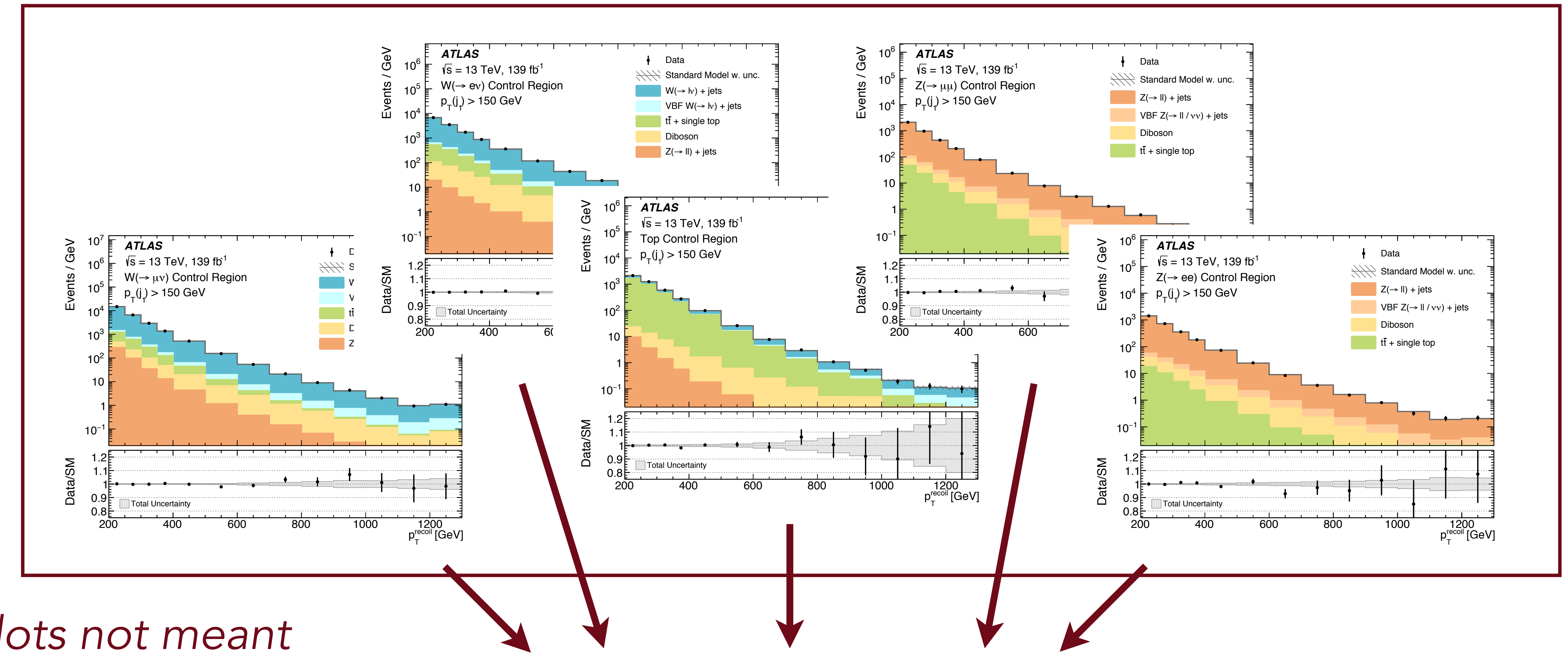
Likelihood model and fit strategy

Fit strategy

1. estimate the backgrounds in the SR with only the CRs
   → unbiased way to check for any excess in the SR

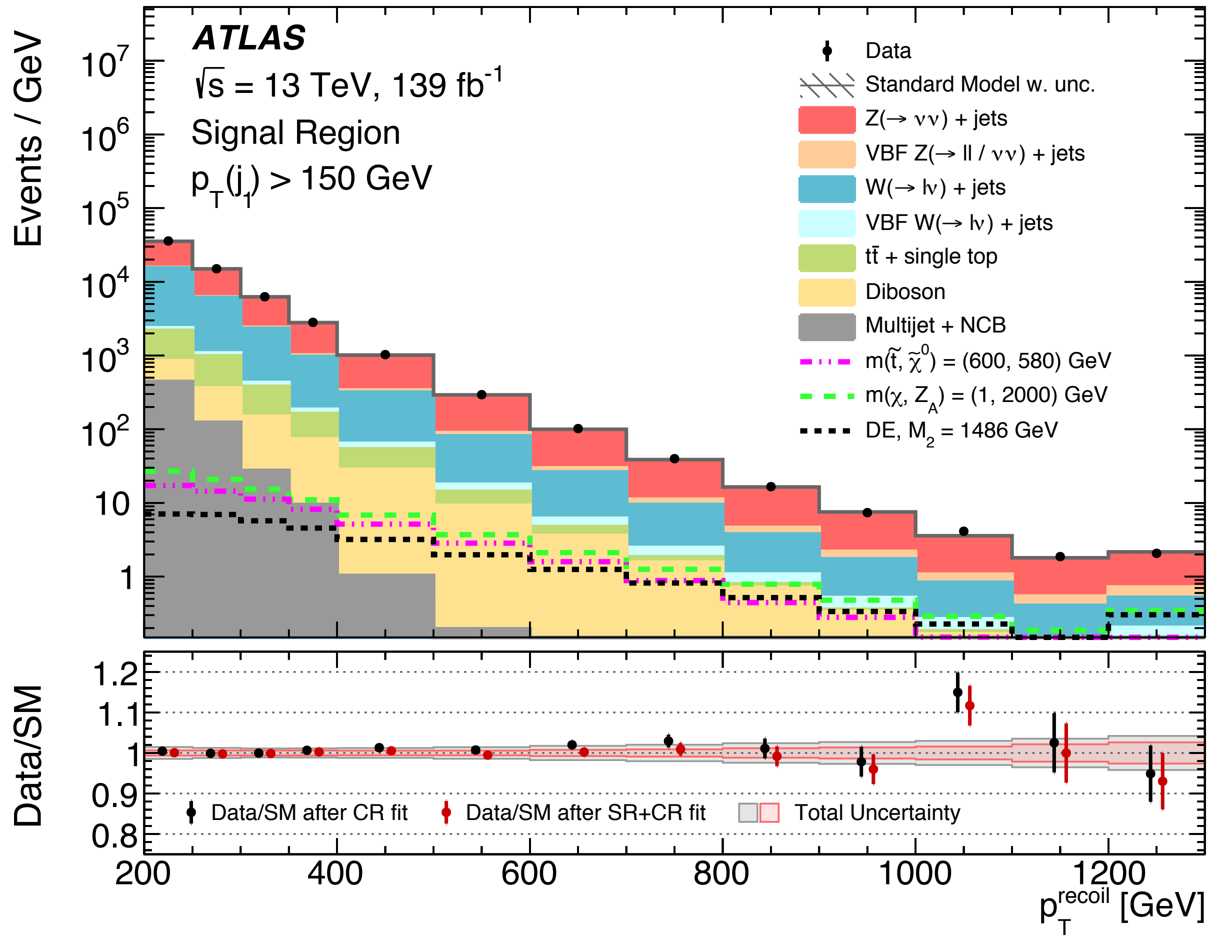
2. include the SR in the fit and derive:
   - model independent limits on the number of possible signal events
   - limits on the parameters of new physics models

Orthogonal control regions

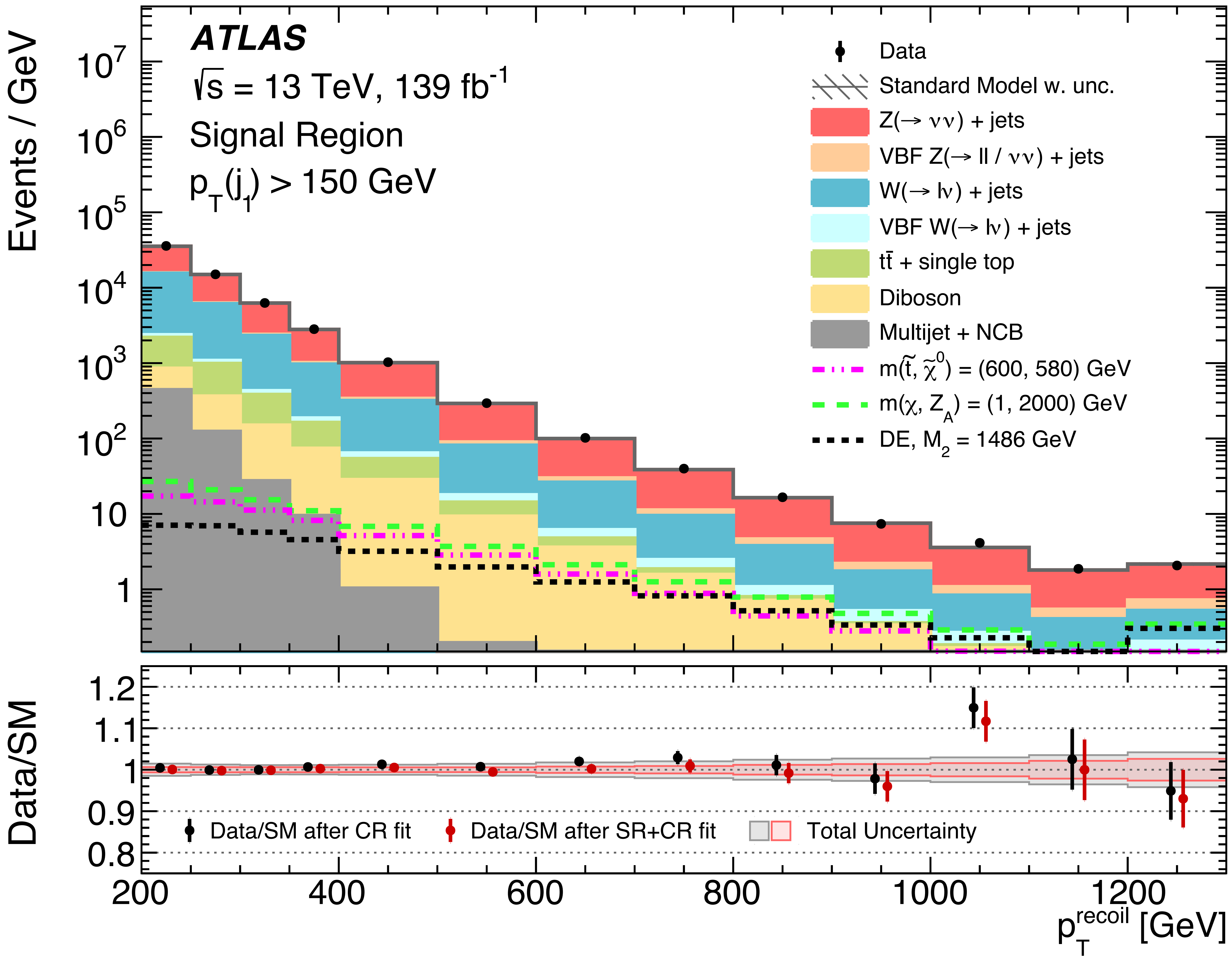


(plots not meant to be read)

Signal region



The money plot



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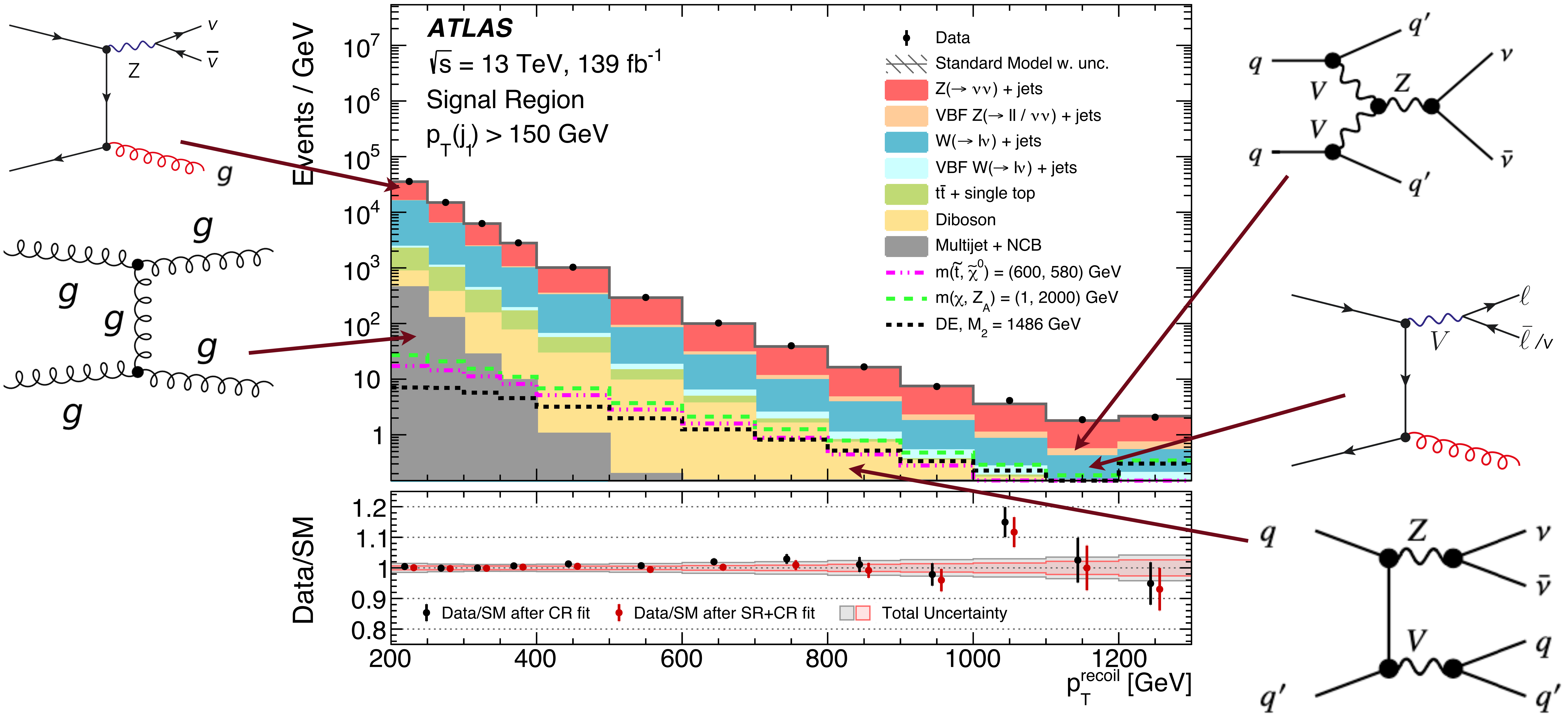
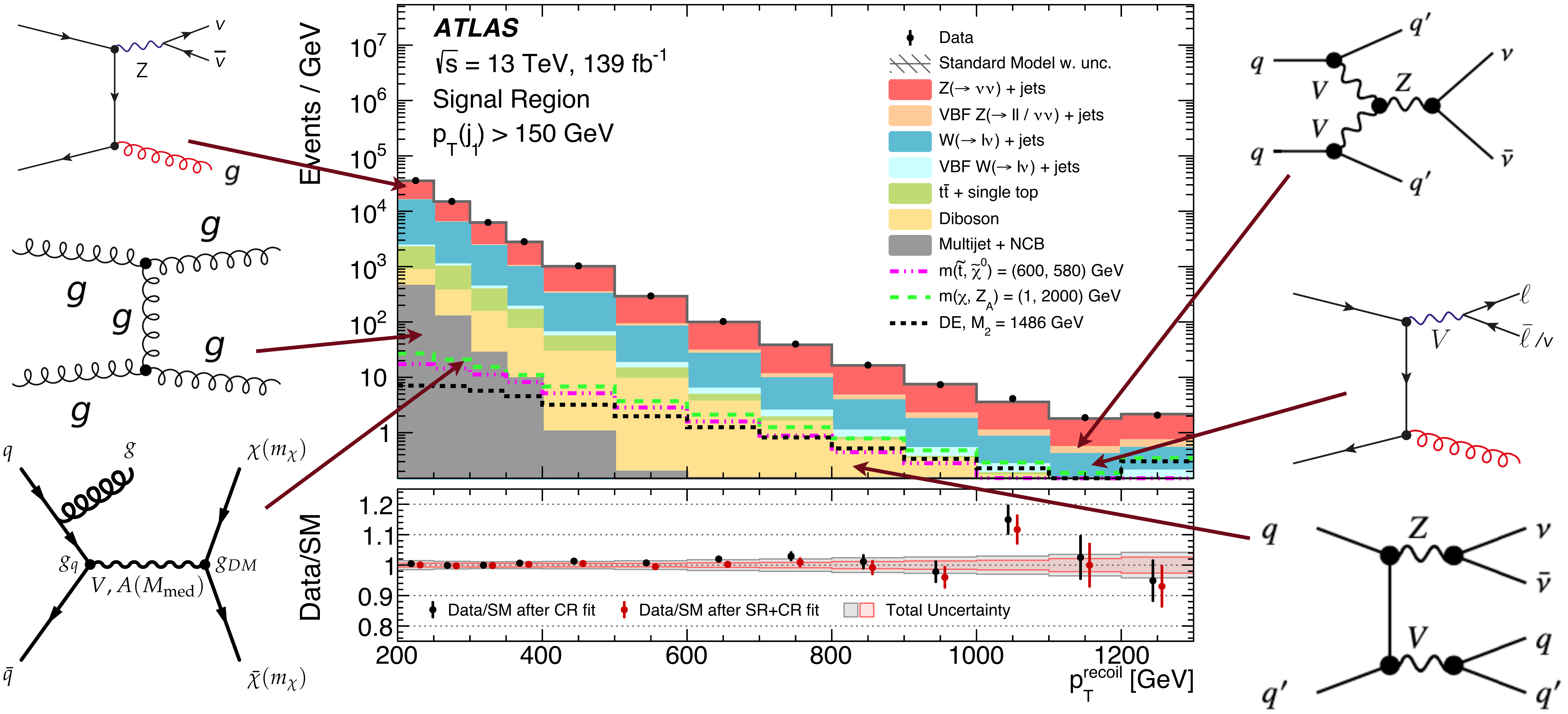


Total uncertainty between 1.2% and 4%!

The money plot

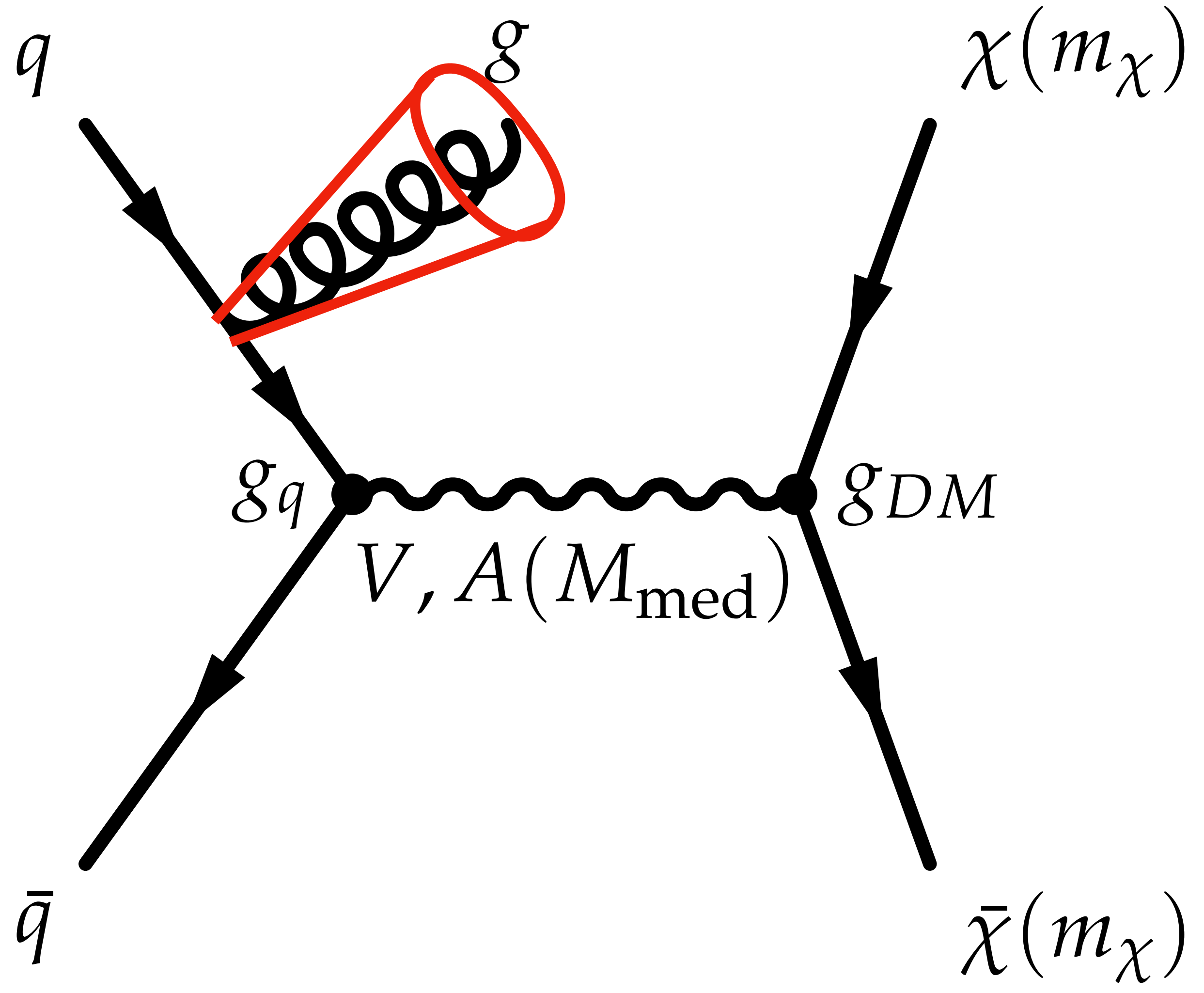


Total uncertainty between 1.2% and 4%!

Simplified dark matter models

- simple extension of SM, depending on few parameters
  - introduce a lepto-phobic new mediator and fermionic WIMPs, χ
  - can be compared to limits obtained in Direct Detection (DD) experiments

$$\mathscr{L} = \mathscr{L}_{SM} + \mathscr{L}_{DM}(m_\chi, M_{med}, g_q, g_{DM})$$



- limits obtained in different mediator nature hypotheses
- fixed coupling chosen for benchmark models

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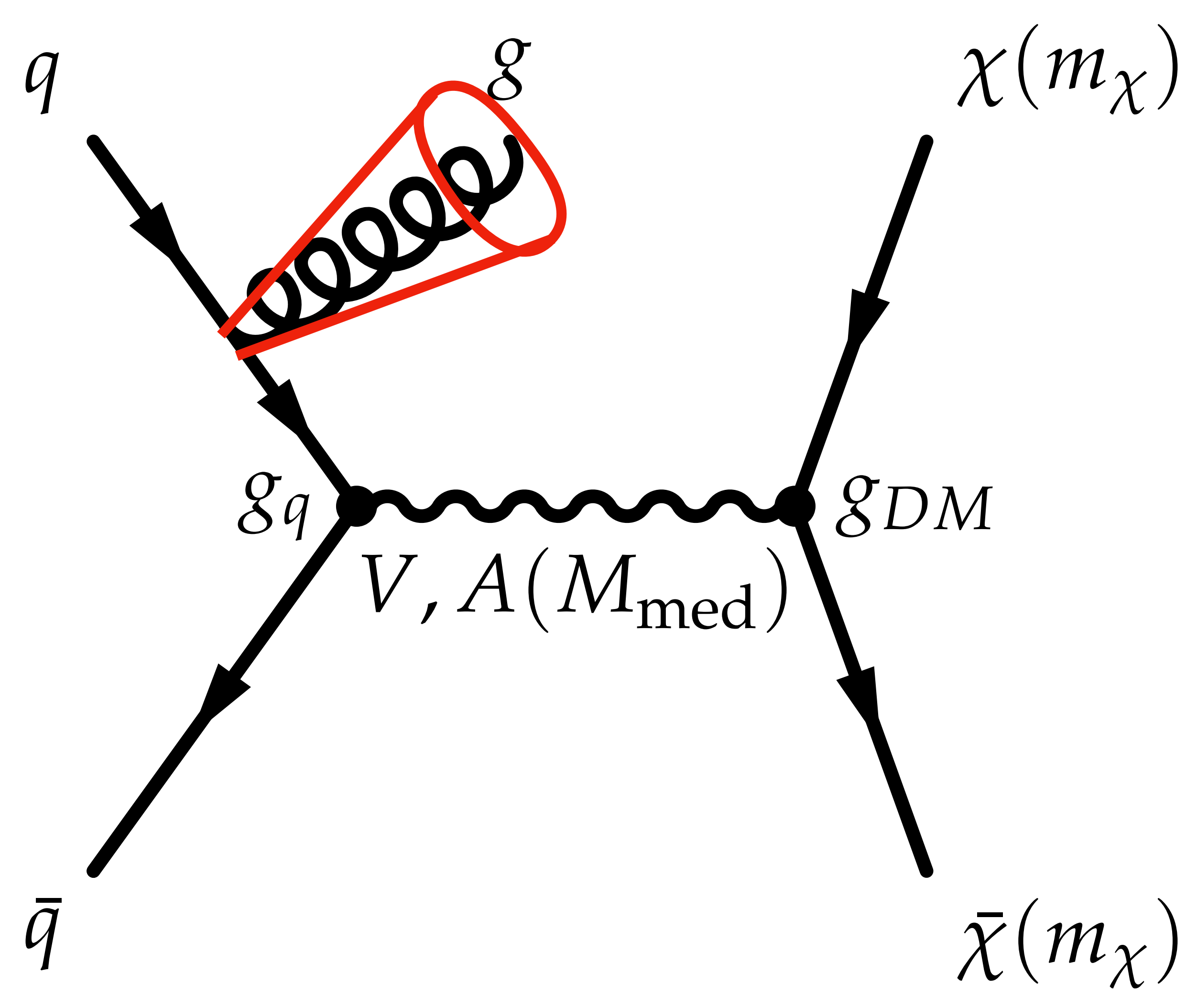

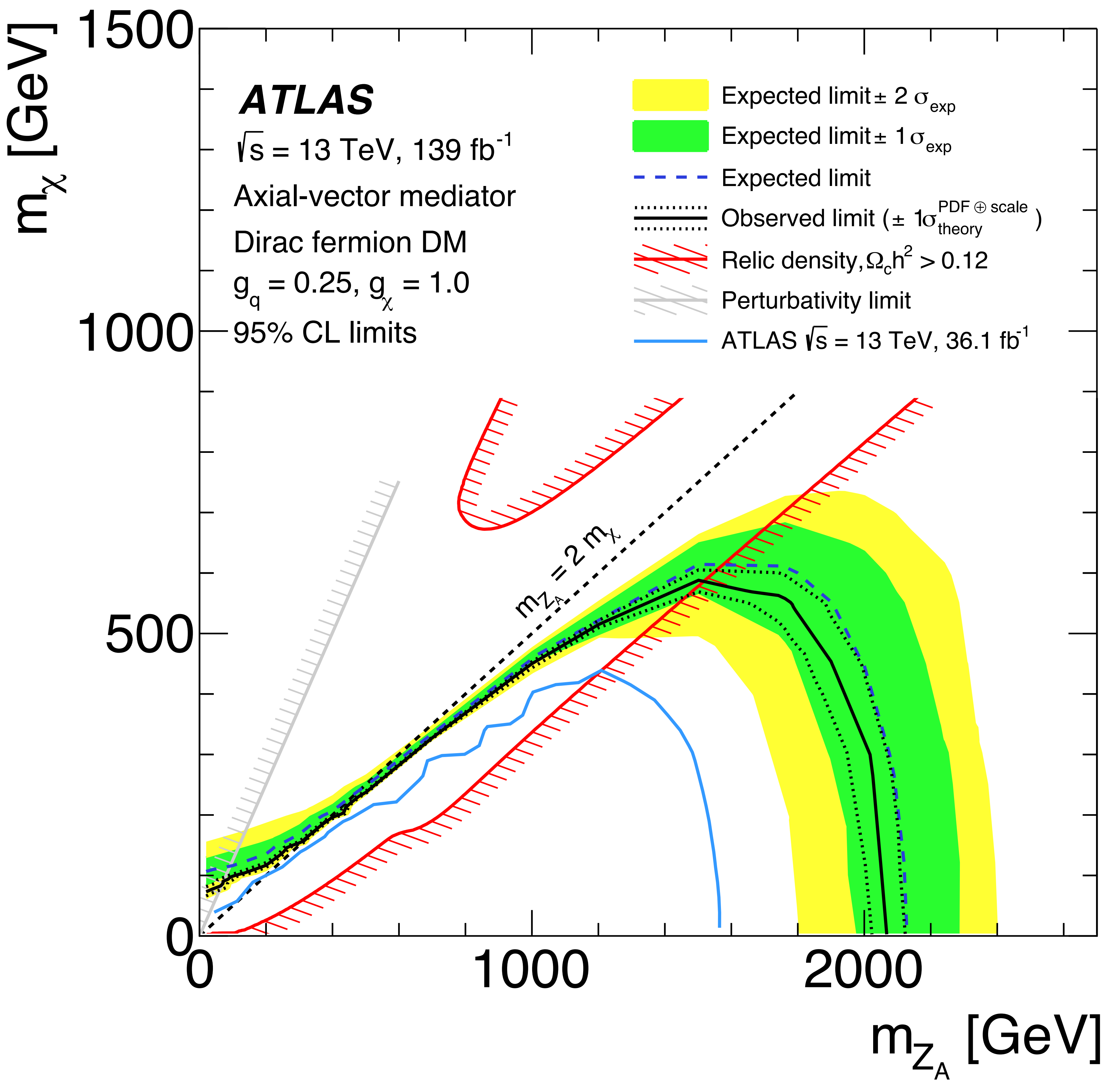

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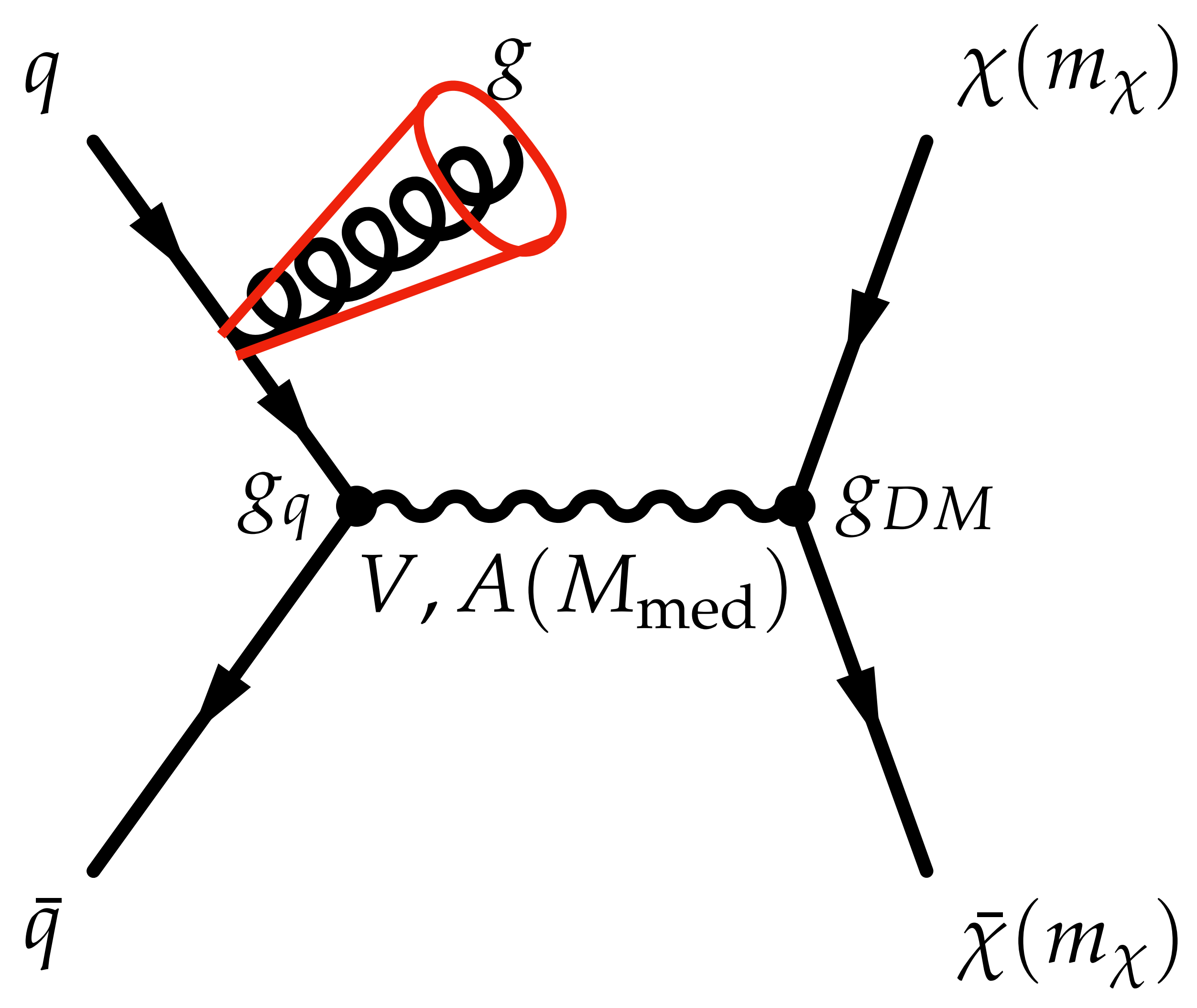

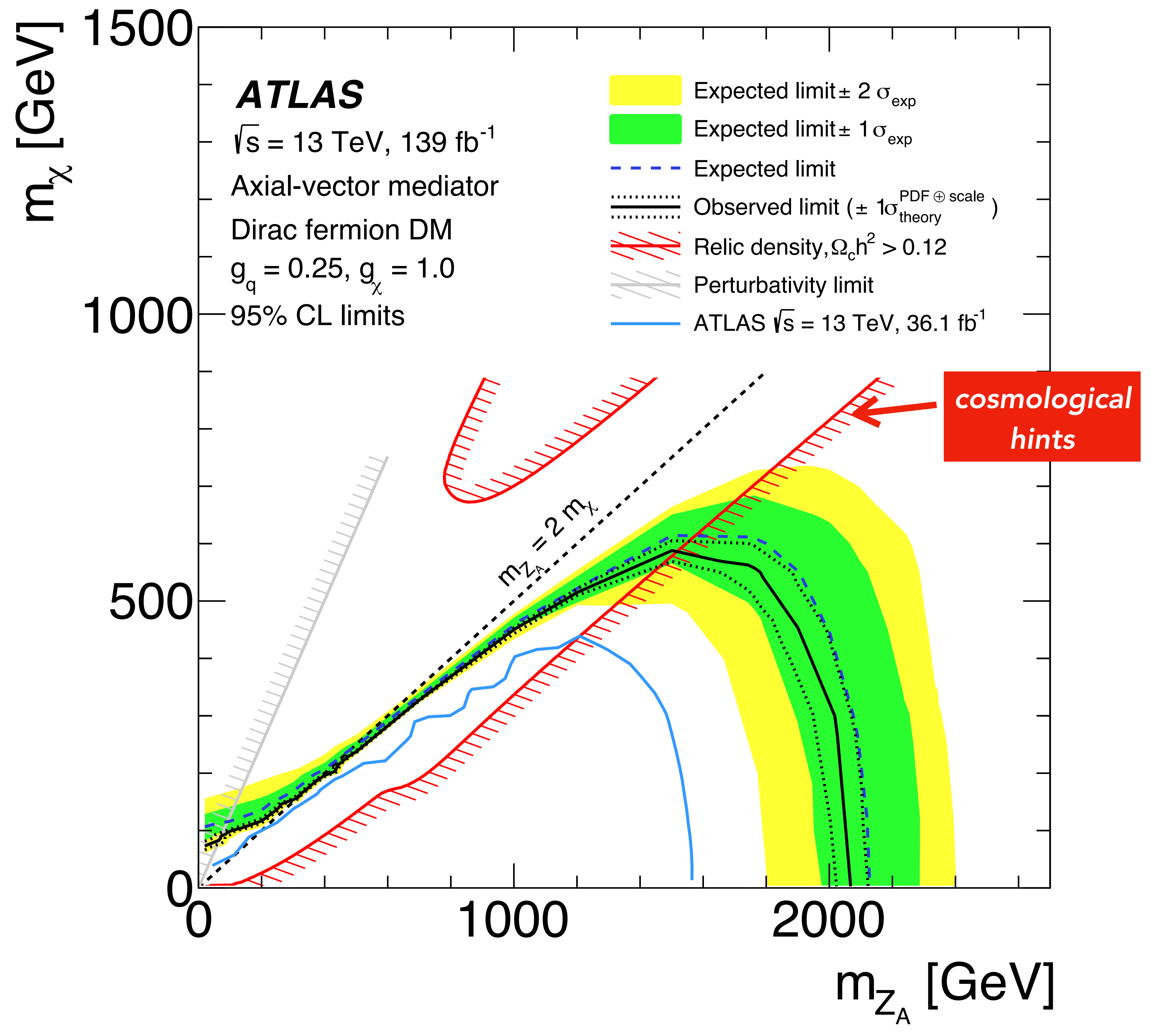

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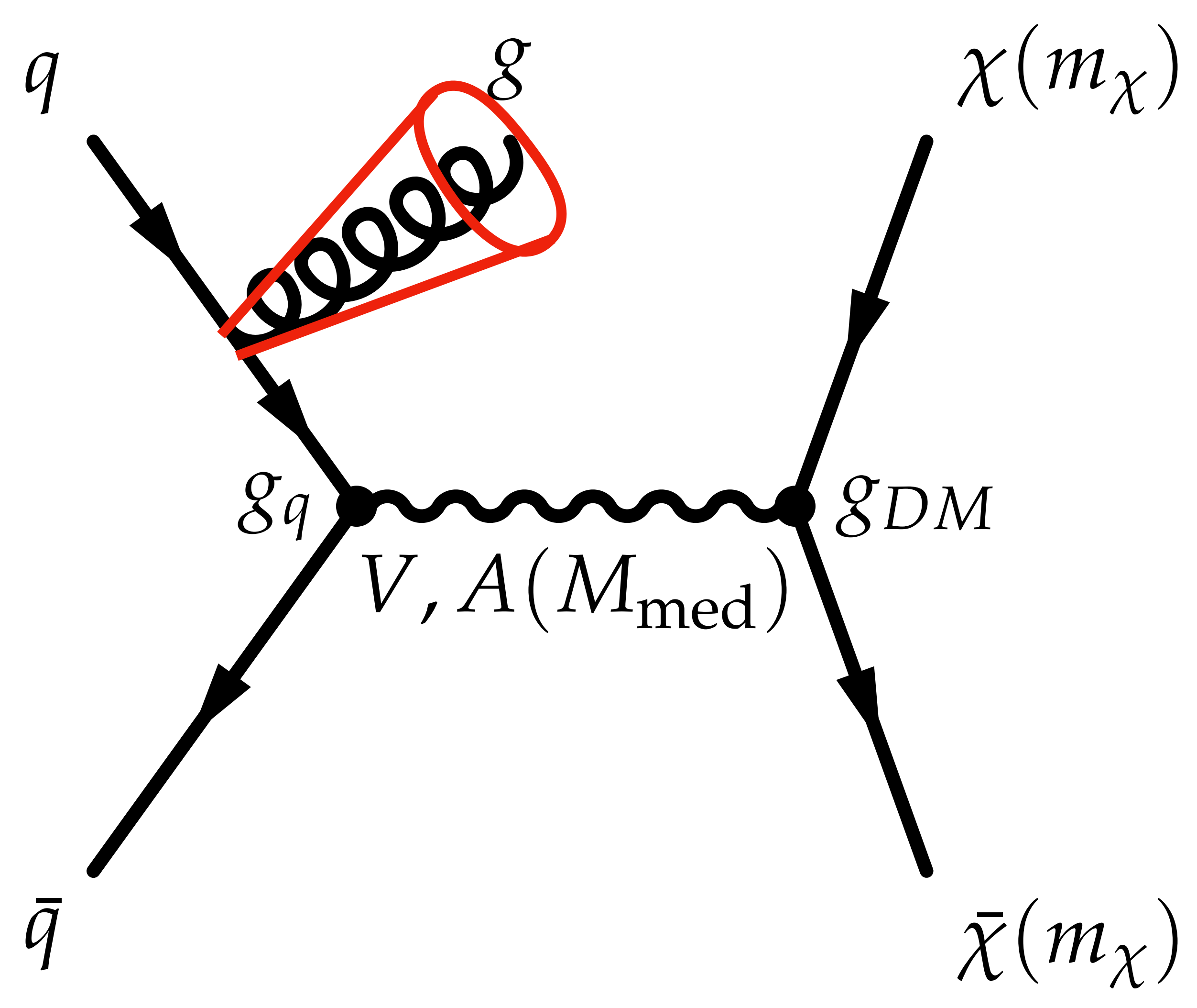

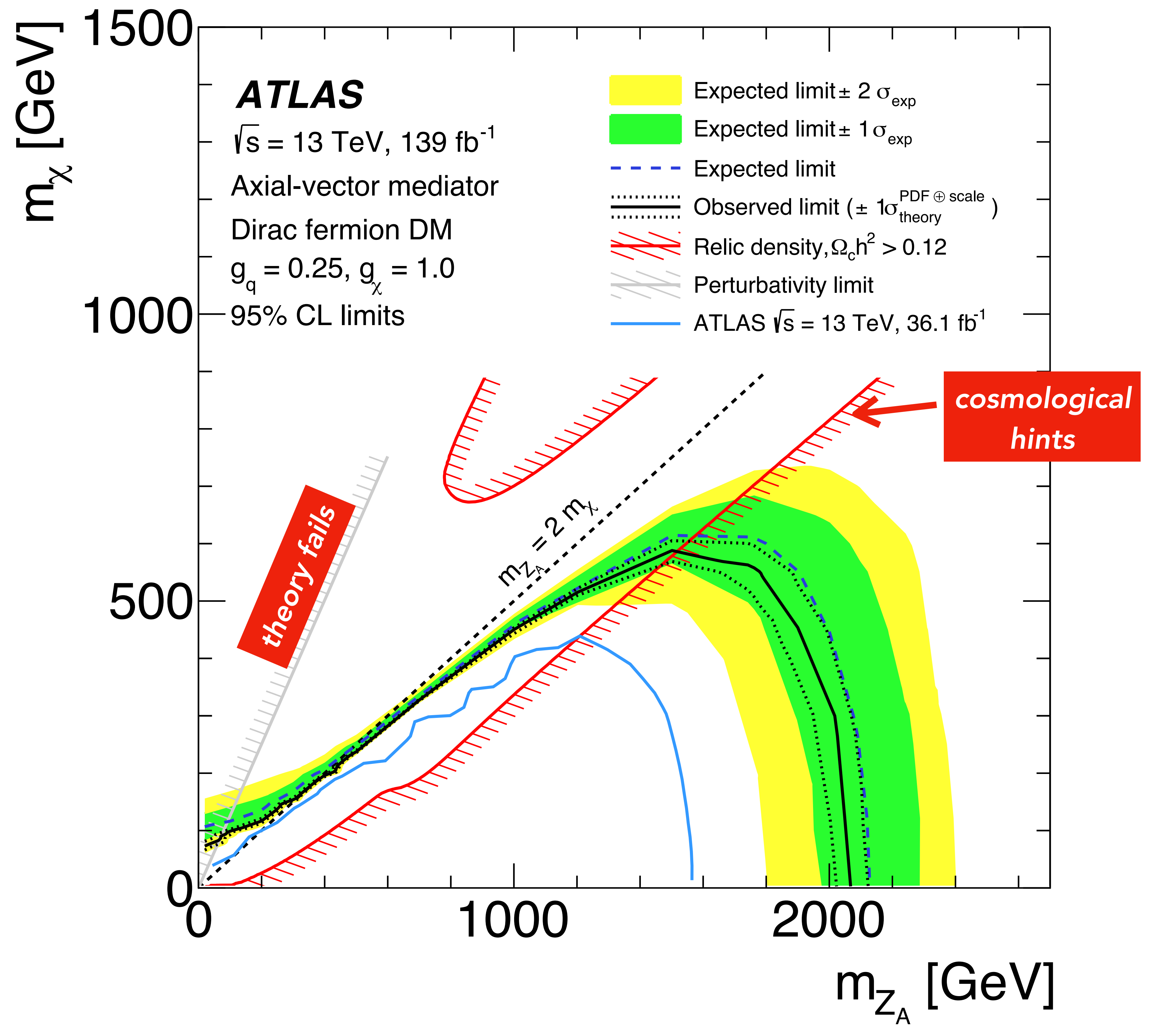

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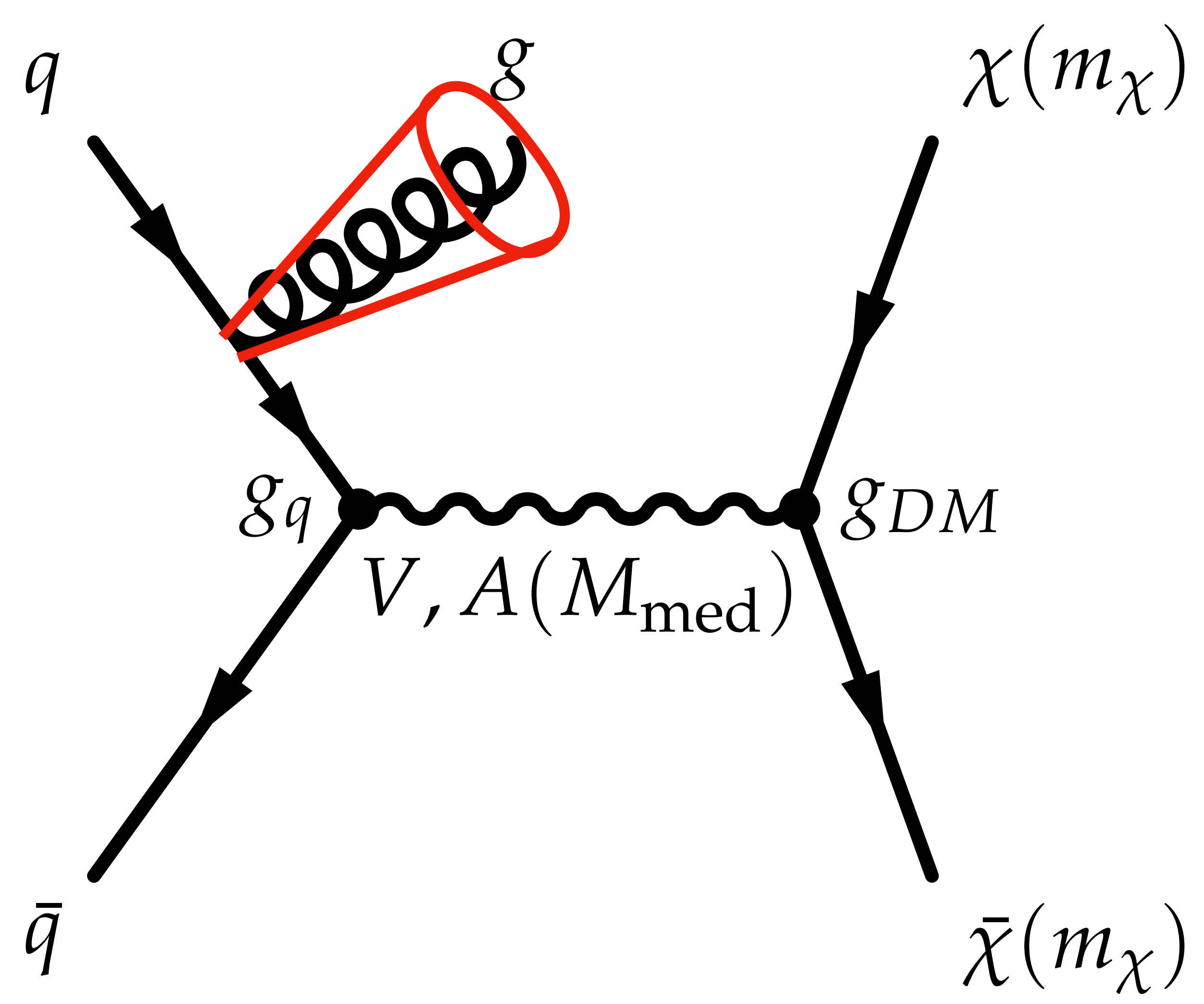

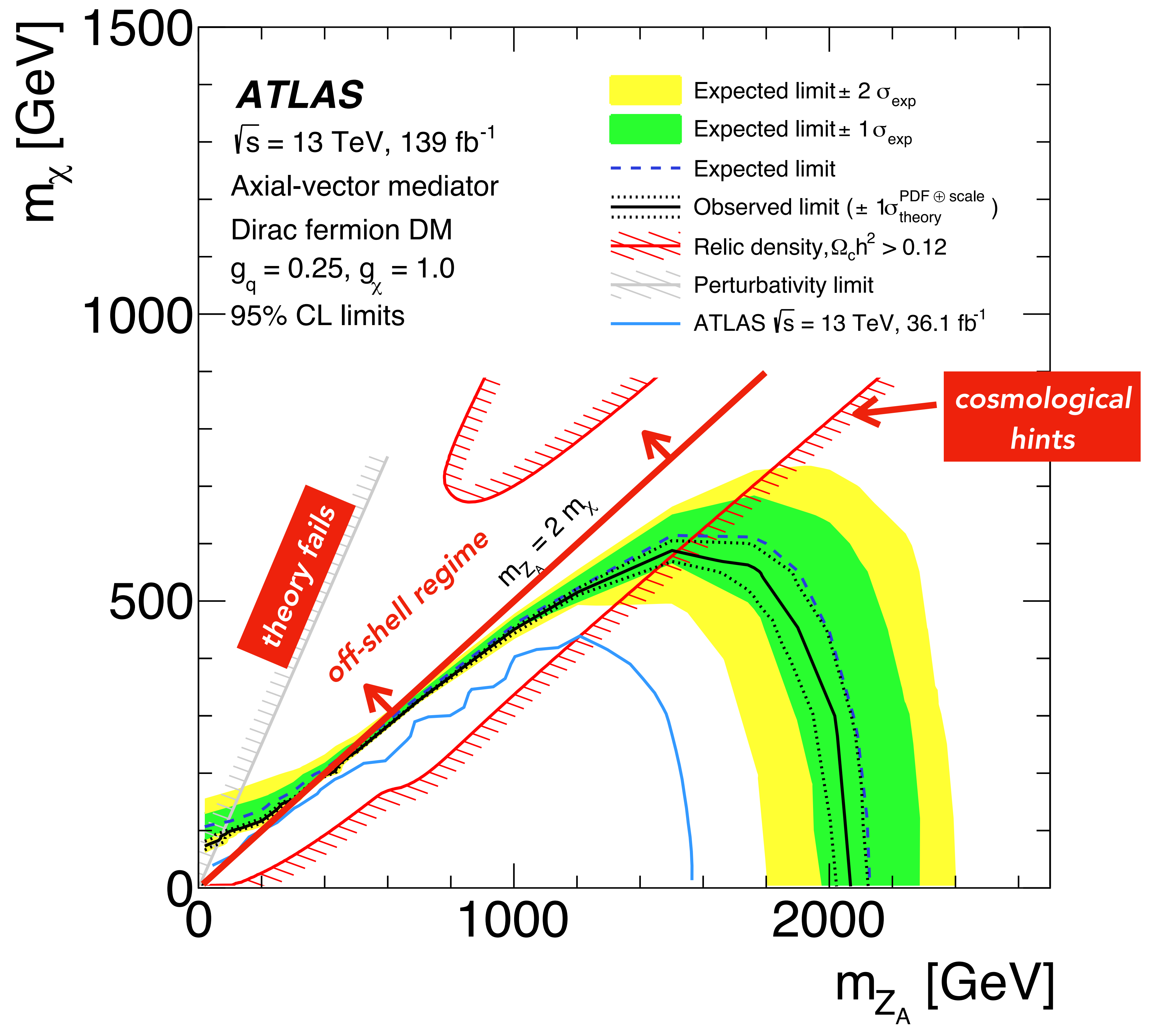

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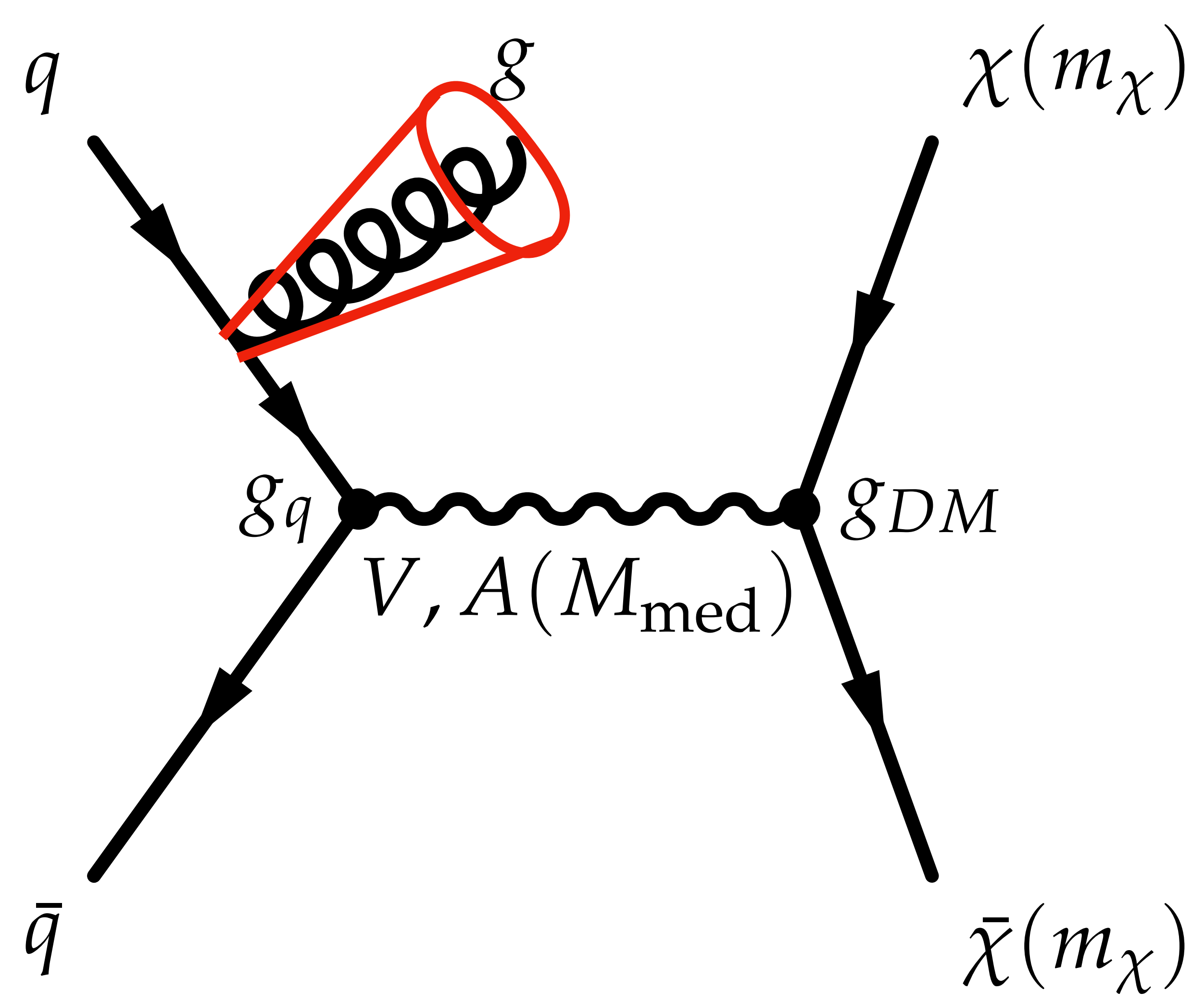

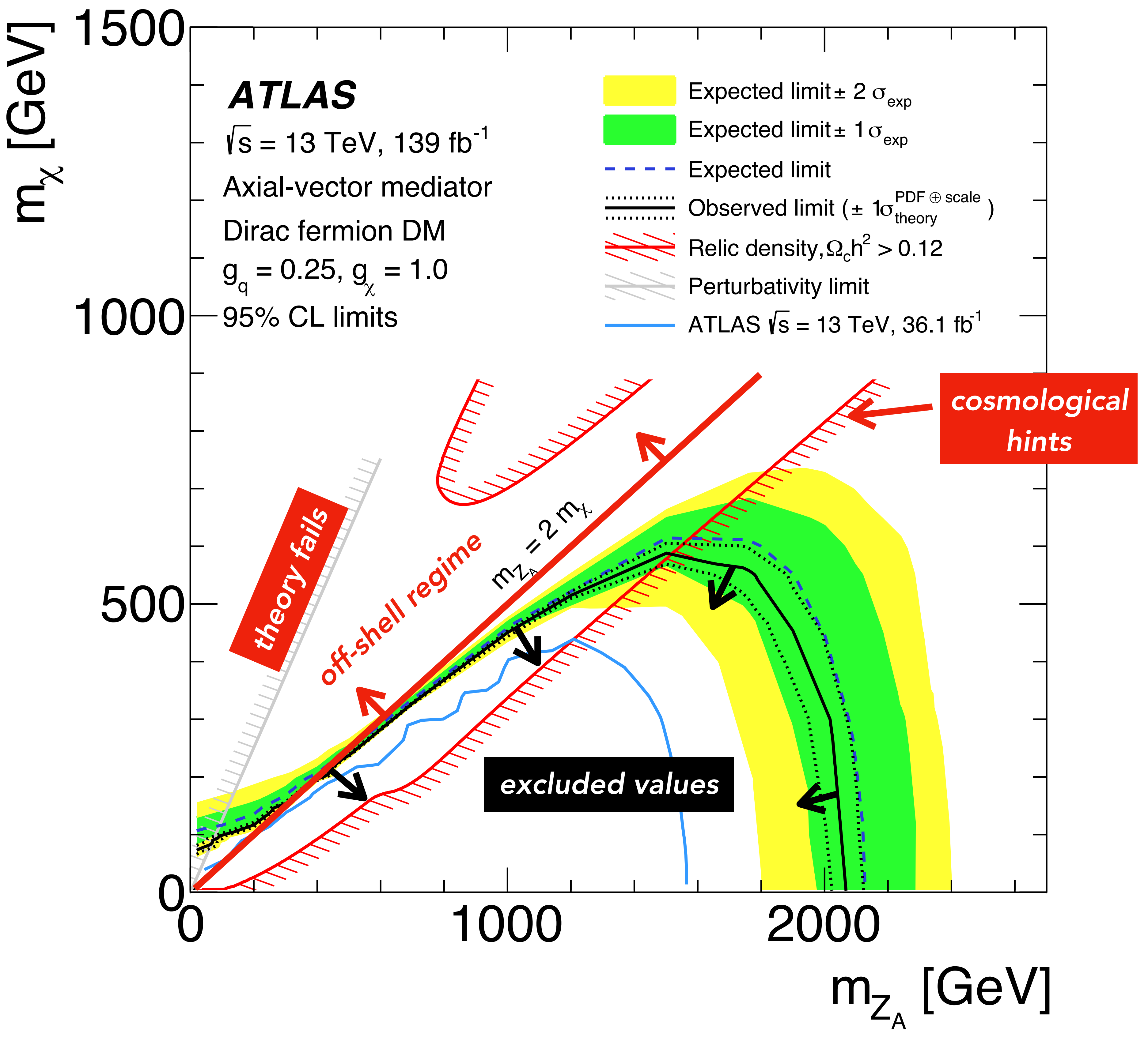

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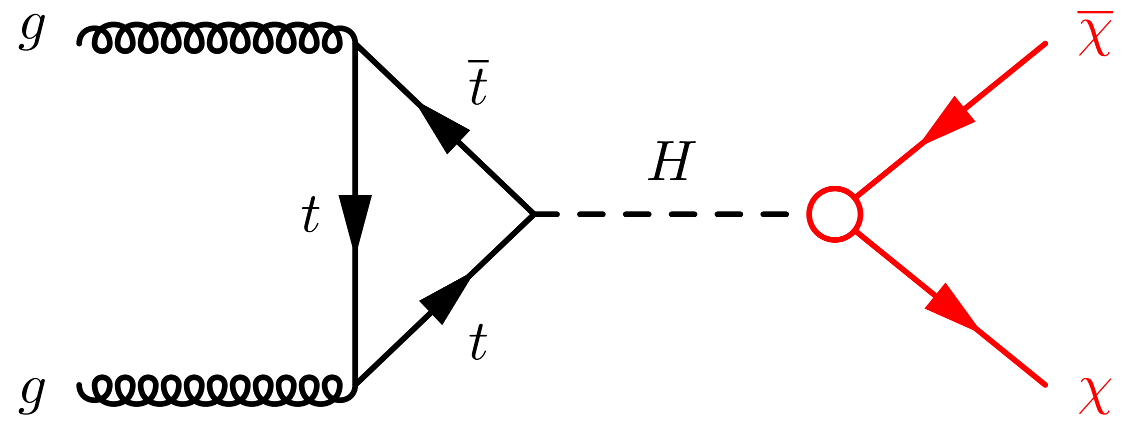
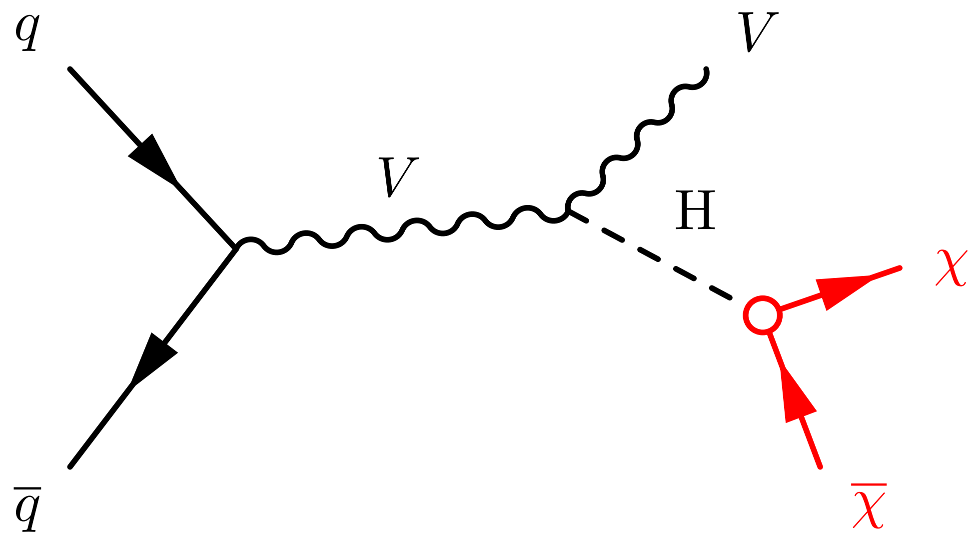
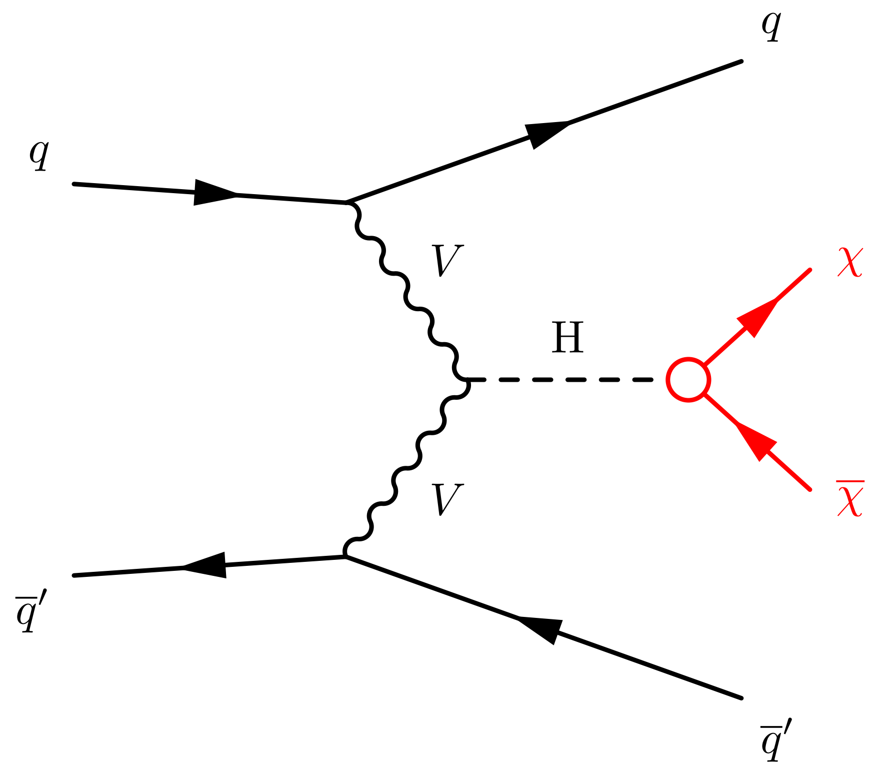
Dark matter from Higgs boson decays

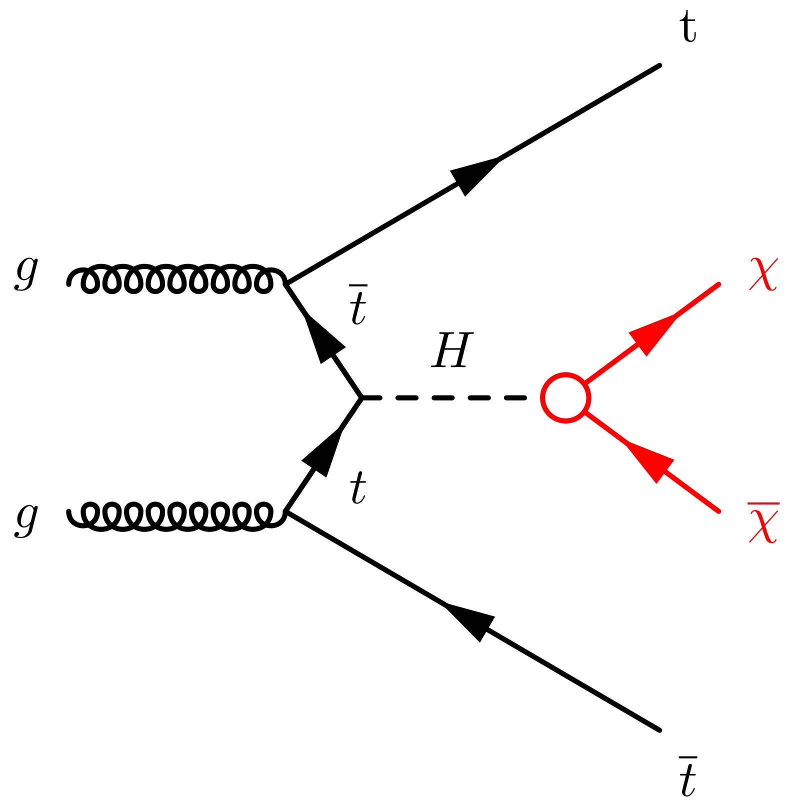
- decay width of Higgs boson is predicted to be < 1% from the Standard Model
- yet no sensitivity from collider experiments, only upper limits set

  → still possible to find decays of the Higgs boson to new particles, like DM particles!









- mono-jet search upper limit:

  BR(H→inv) < 34% @95% CL
  - second most stringent limit set by a single ATLAS analysis!

- current most stringent upper limit:

  11% obtained combining 3 different ATLAS analyses

Conclusions

- mono-jet is a gold channel to probe new physics at the Large Hadron Collider
  - general signature: can be used to test several different hypothesis which provide a WIMP candidate

- suggested readings:
  - ATLAS collaboration physics briefing - link

Physics Briefing

Tags:
physics results,
ICHEP 2020,
ICHEP,
dark matter

Jetting into the dark side: a precision search for dark matter

27th July 2020 | By ATLAS Collaboration

  - paper on the arXiv, submitted to Physical Review D for publication
    link

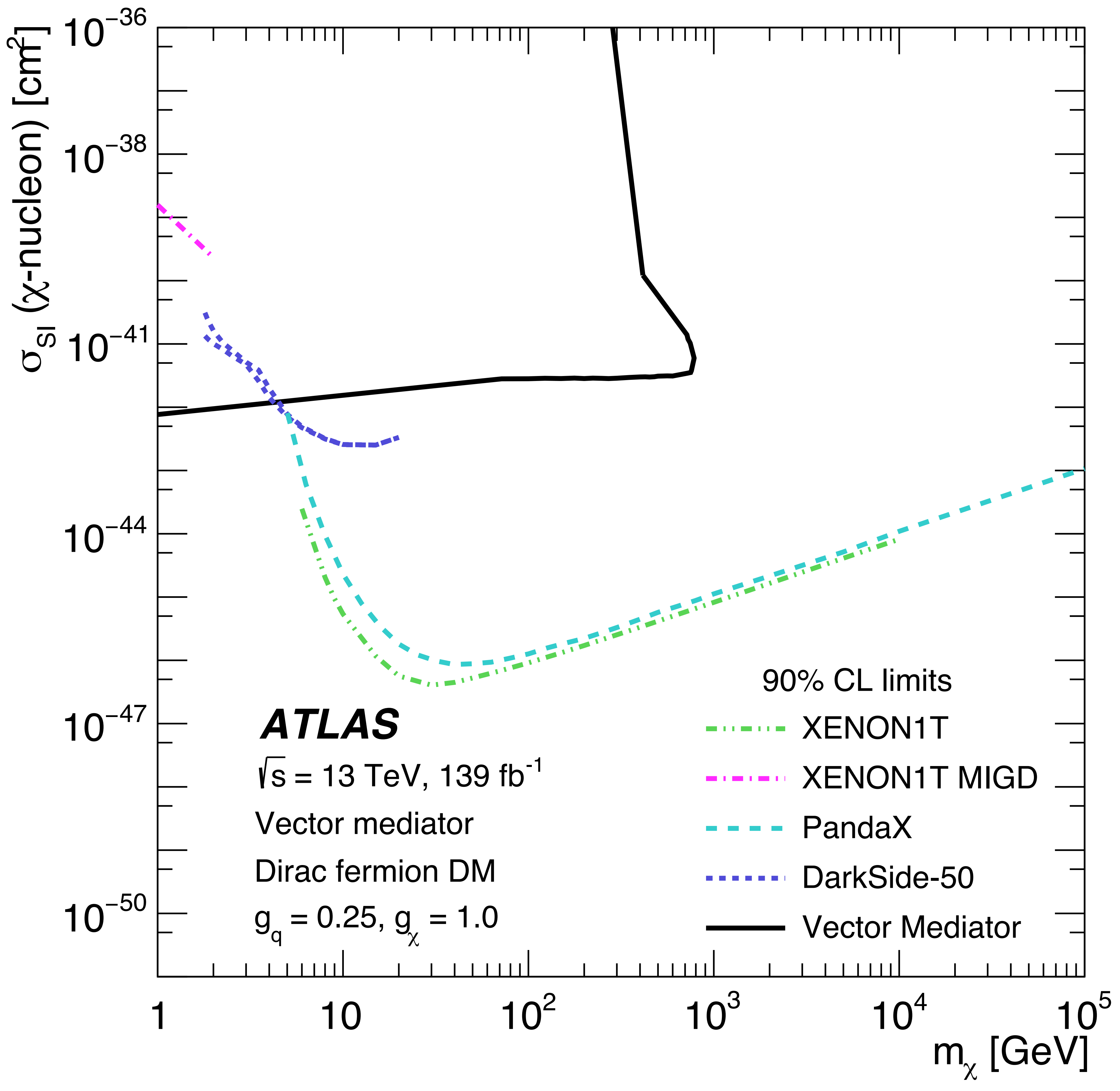
DID

NOT FIND

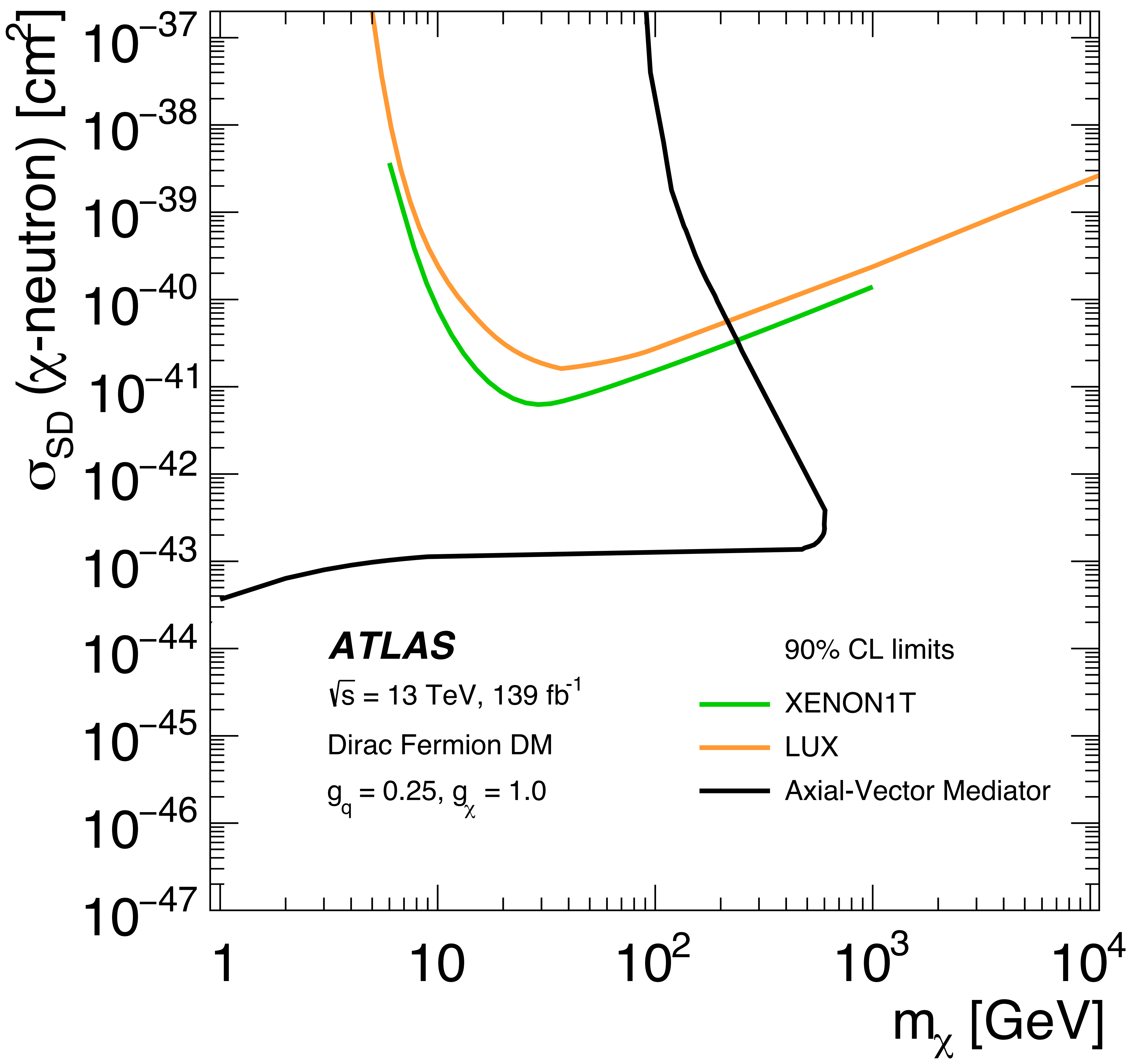
Backup slides

Comparison to Direct Detection DM searches

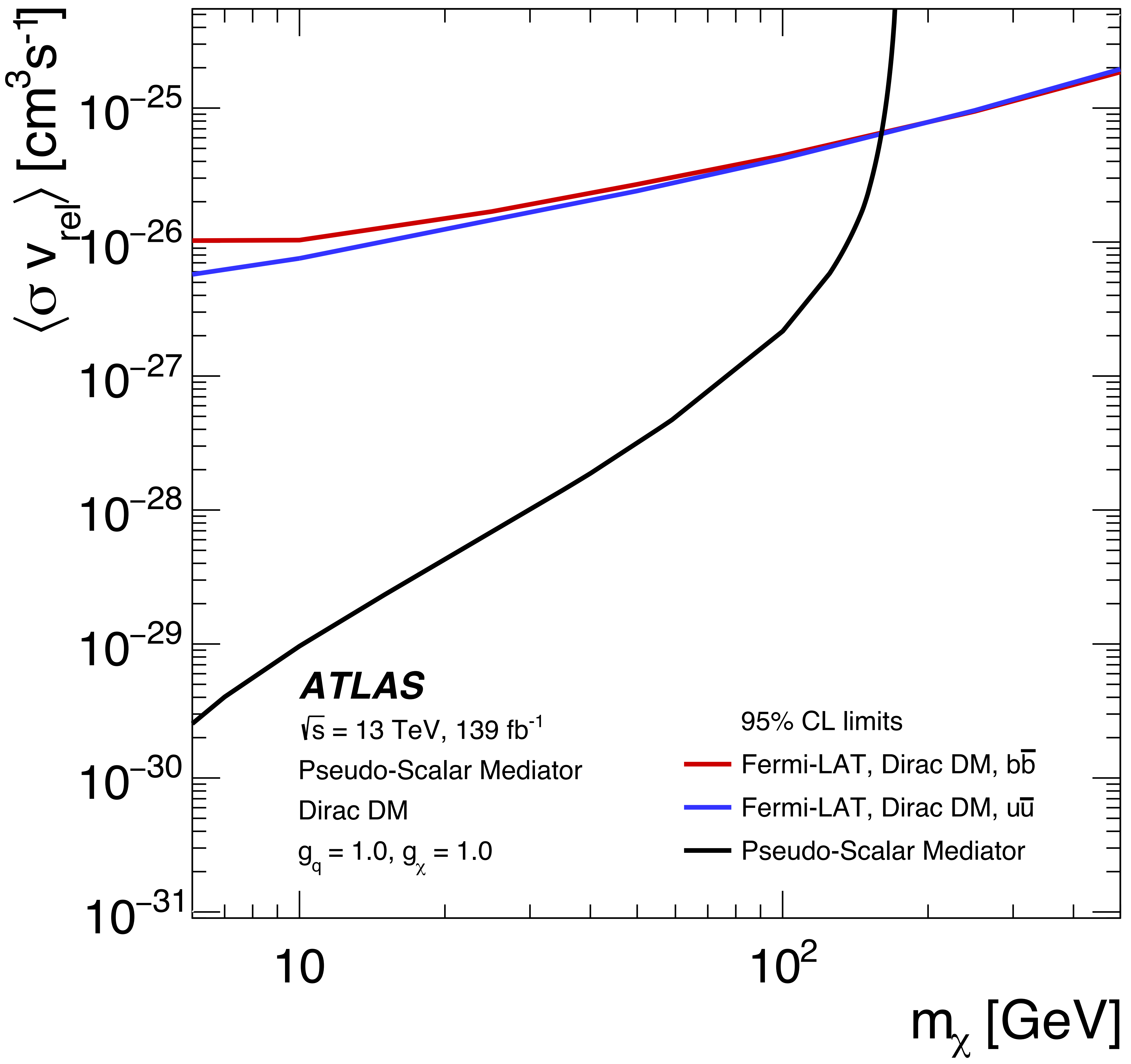
Spin independent interaction



Spin dependent interaction



Comparison to Indirect Detection DM searches



Likelihood model

$$\mathcal{L}(\mu, \kappa, \theta) = \prod_r \prod_i \text{Poisson}\left(N_{ri}^{\text{obs}} \mid \mu N_{ri}^{\text{sig}}(\theta) + N_{ri}^{\text{bkg}}(\kappa, \theta)\right) f_{\text{constr}}(\theta)$$

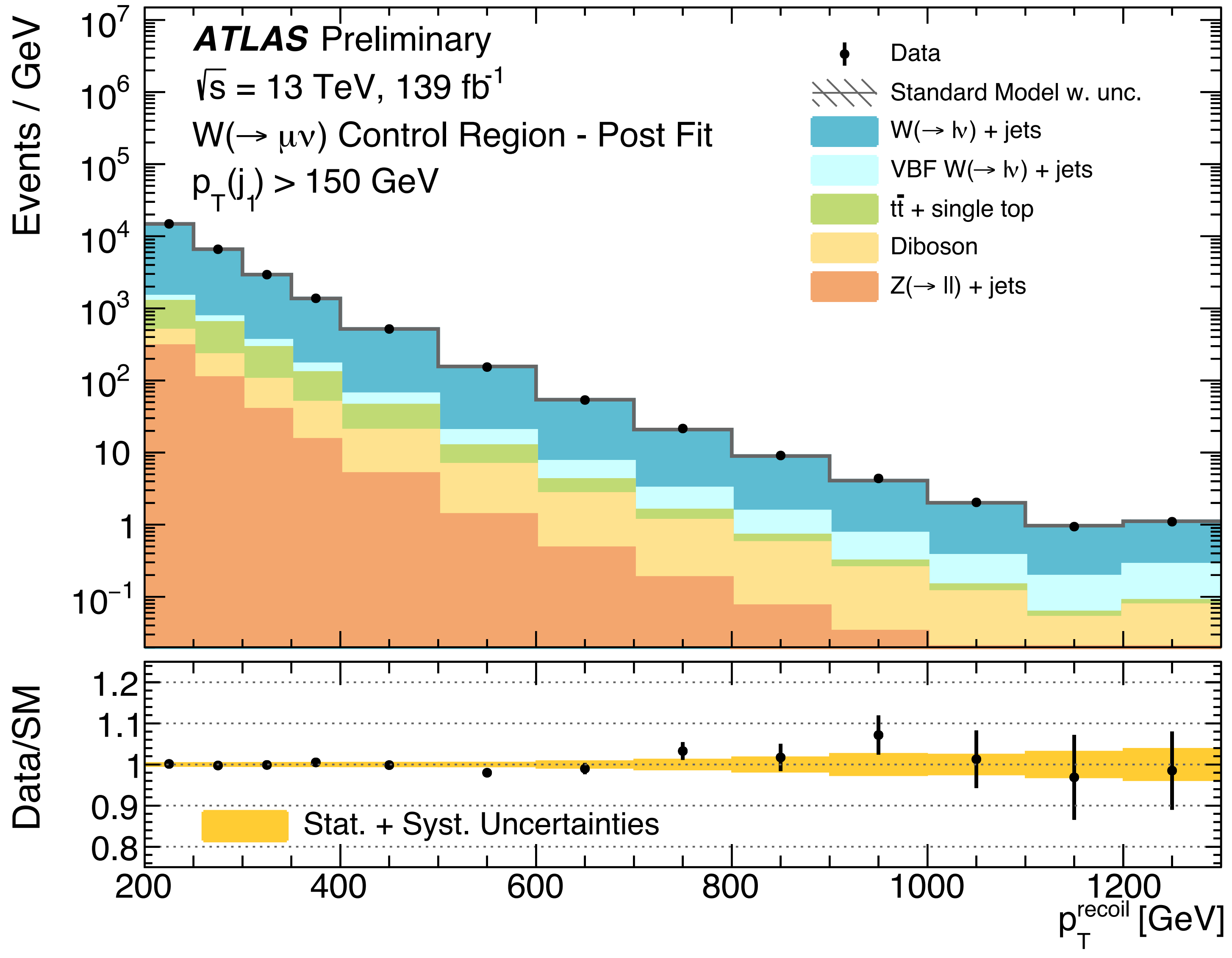
r: regions; i: MET bins; N_{ri}^{obs}: data; $\mu N_{ri}^{\text{sig}}(\theta)$: expected signal; $N_{ri}^{\text{bkg}}(\kappa, \theta)$: expected bkg.; $f_{\text{constr}}(\theta)$: parametrisation of systematic uncertainties

$$N_{ri}^{\text{bkg}} = \boxed{\kappa_V}\left(N_{ri}^{\text{Z+jets}} + N_{ri}^{\text{W+jets}}\right) + \boxed{\kappa_{t\bar{t}}} N_{ri}^{t\bar{t}} + \boxed{\kappa_t} N_{ri}^{\text{single}-t} + \boxed{N_{ri}^{\text{diboson}} + N_{ri}^{\text{VBF W/Z+jets}}} + \boxed{N_{ri}^{\text{multijet+NCB}}}$$

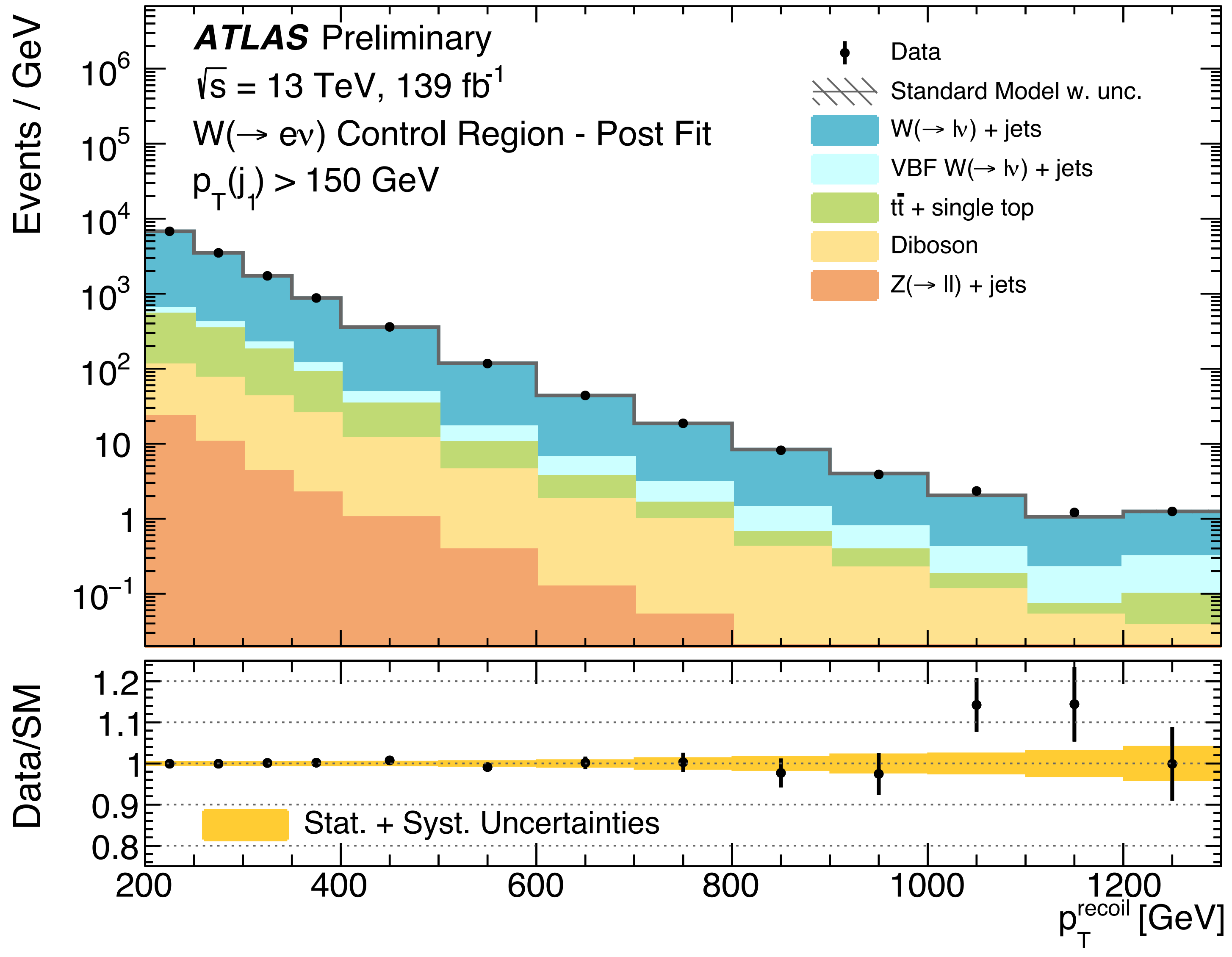
- three free floating Normalisation Factors
- diboson and VBF W/Z+jets bkgs. taken directly from MC simulation
- multijet and Non-Collision Background: data driven estimate

Control regions modelling

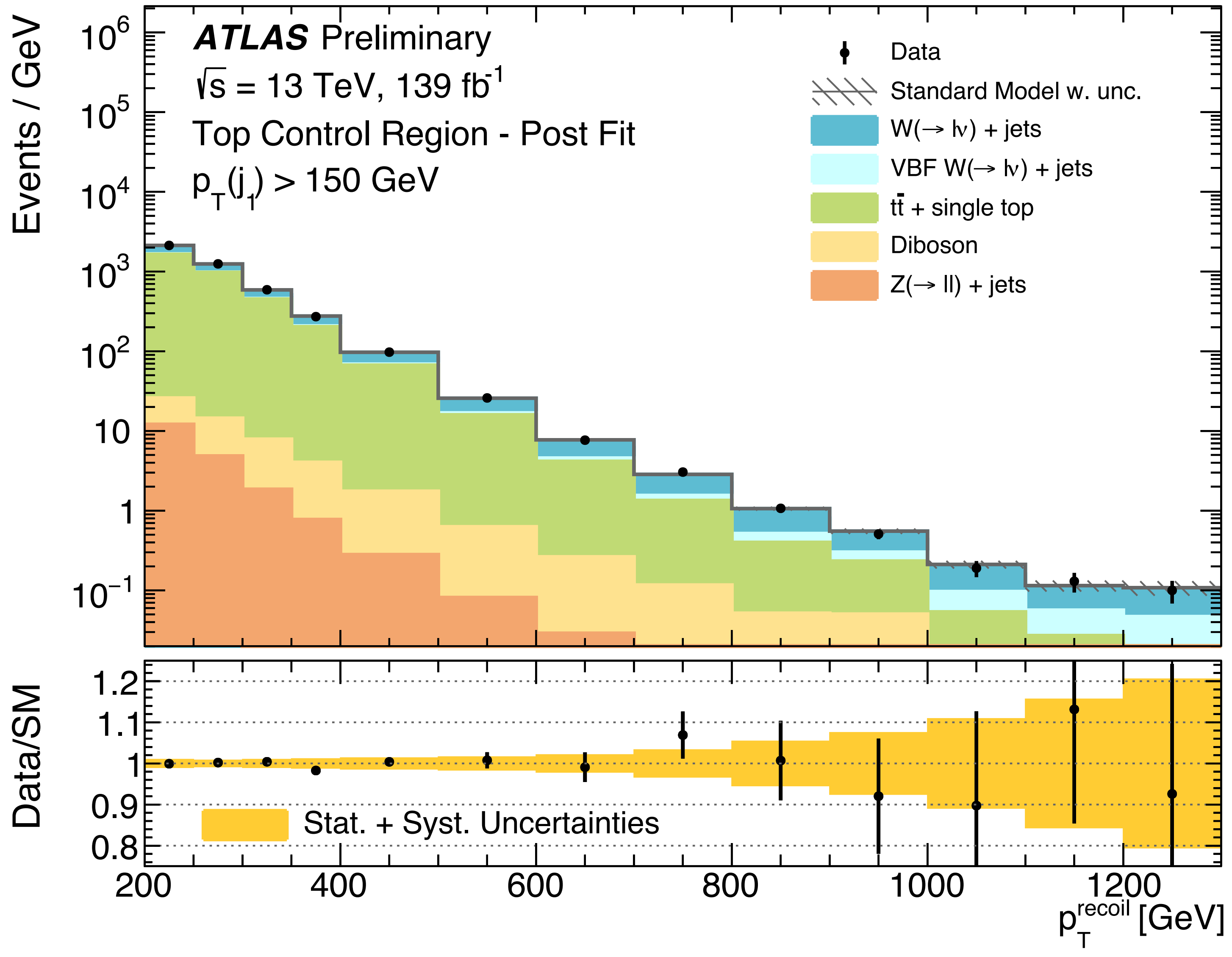
One muon control region



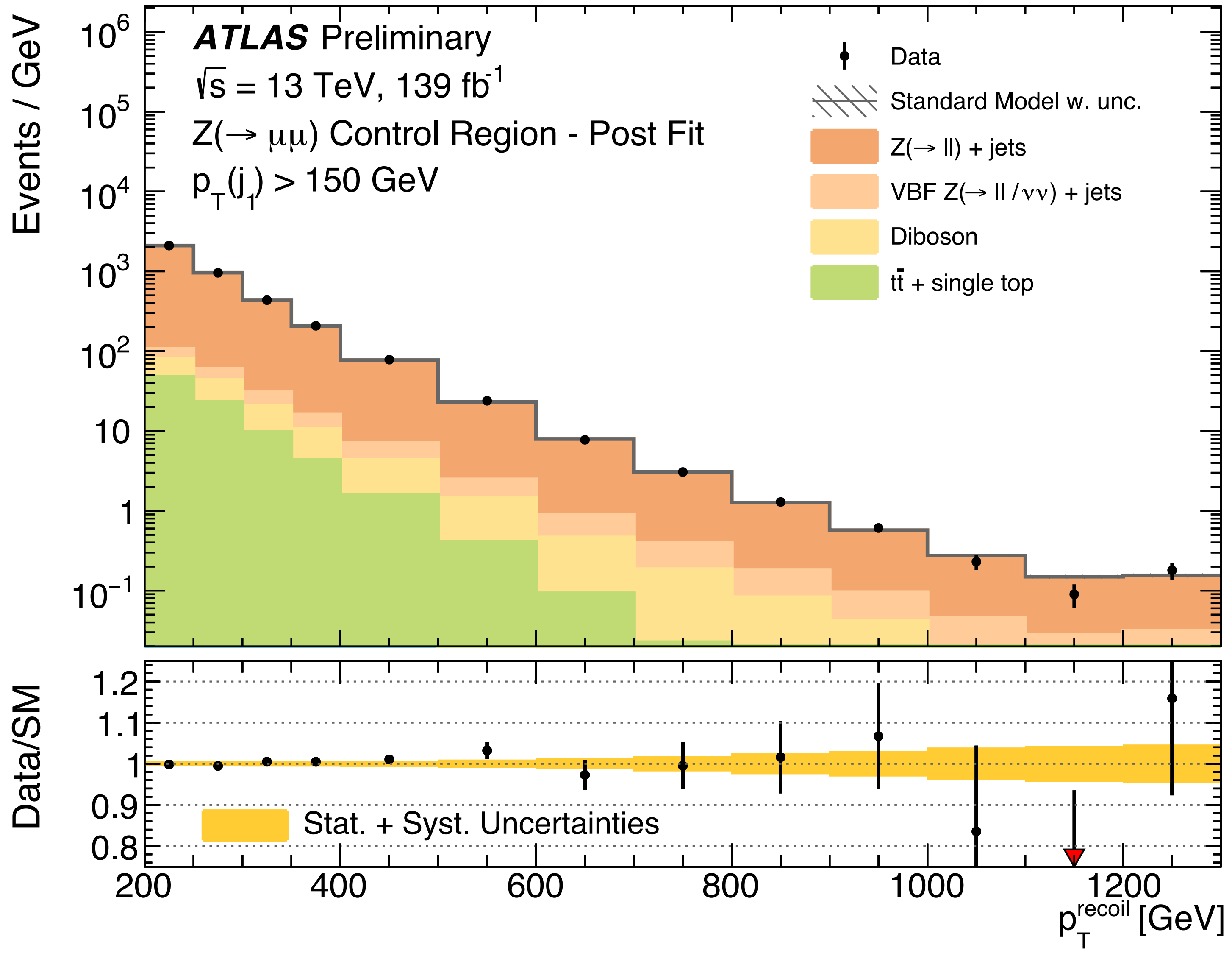
One electron control region



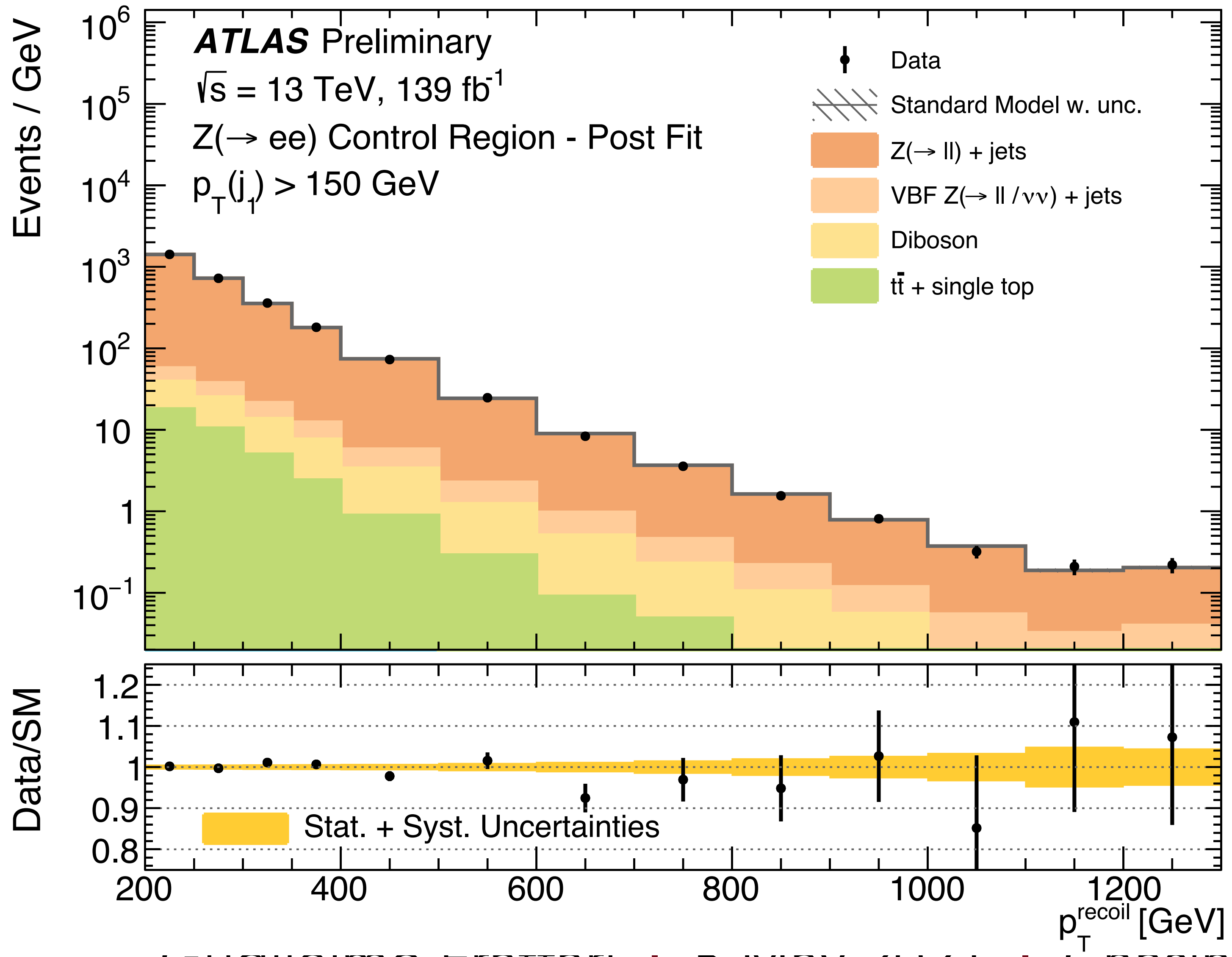
Top control region



Two muon control region



Two electron control region



Control-regions-only fit

- over 10^6 events in Control Regions to constrain Signal Region backgrounds
- excellent modelling of data in all regions