Searching for exotic new phenomena with ATLAS

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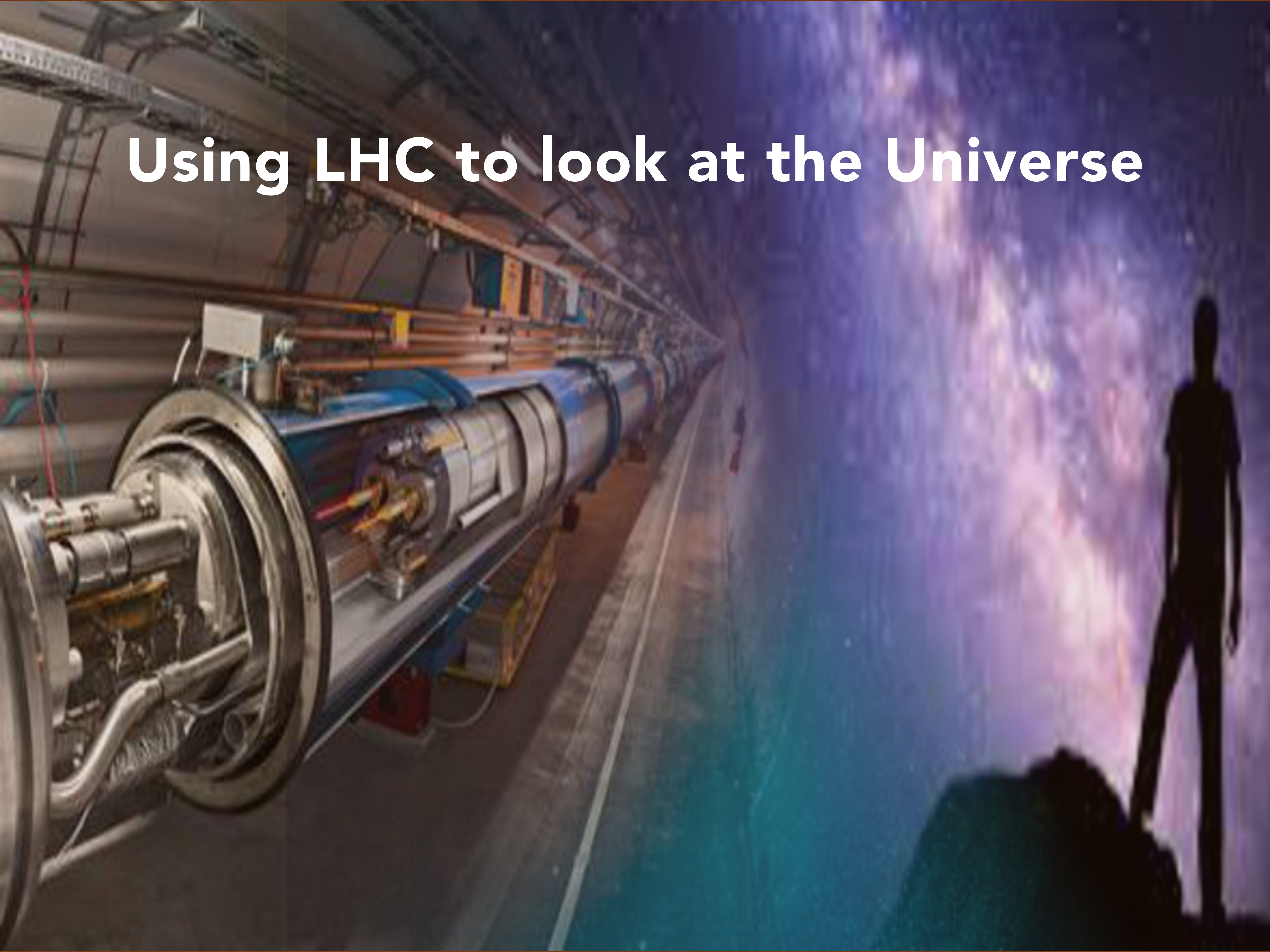
Using LHC to look at the Universe



If something is unclear

feel free to interrupt and ask questions!

How to make discoveries - The CMB example

The Cosmic Microwave Background radiation was discovered in 1964/5 by Arno Penzias & Bob Wilson using the Homdel horn antenna at Bell labs (Nobel 1978)

Luck or result of collective scientific effort?

Instruments Science policy

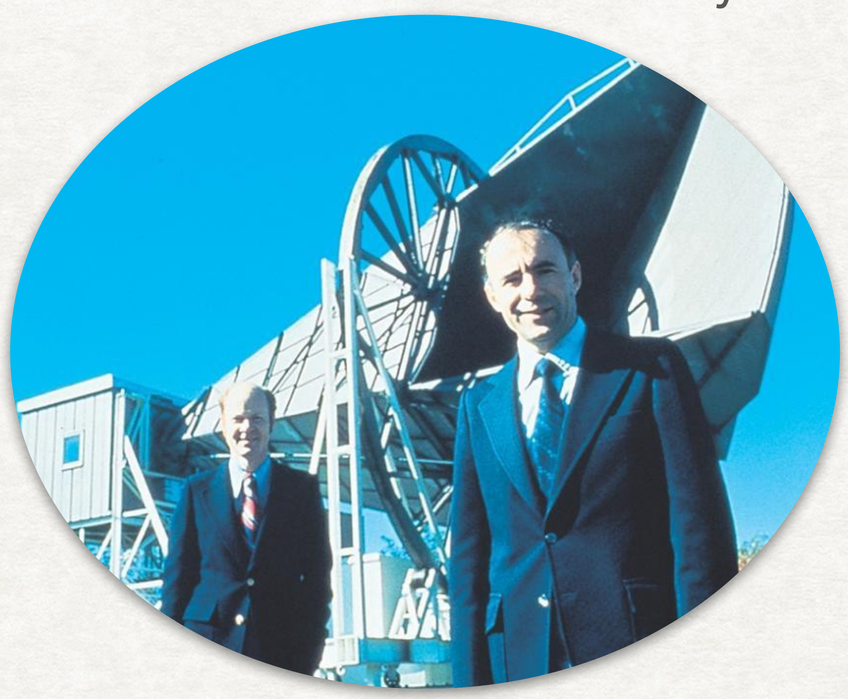
- Horn antenna was the **best instrument of the time**
- Penzias & Hogg **convinced management** to use the antenna for radio astronomy research

Knowledge of scientific status quo

- Burke brought to Penzias' attention pre-print by Peebles discussing possibility to discover microwave radiation from Big Bang

Experimentalists (measurements)

- Penzias & Wilson experts in microwave radio astronomy



Theorists (interpretation)

- Dicke, Peebles, Wilkinson, Roll interpret measurement as evidence for Big Bang

Deviations

- measurements showed **temperature 3K higher than expected**
- after careful examination they established that it was a real effect (not due to "white dielectric"=pigeon droppings)

Open mind

- "study of the early universe not the sort of thing to which a respectable scientist would devote his time" (Weinberg)
- steady-state Universe was prevailing at the time

What we will focus on in these lectures

Status quo:

- what do we know?
- open questions: why we need new physics?

Instruments & methods: how to look for new physics @ colliders

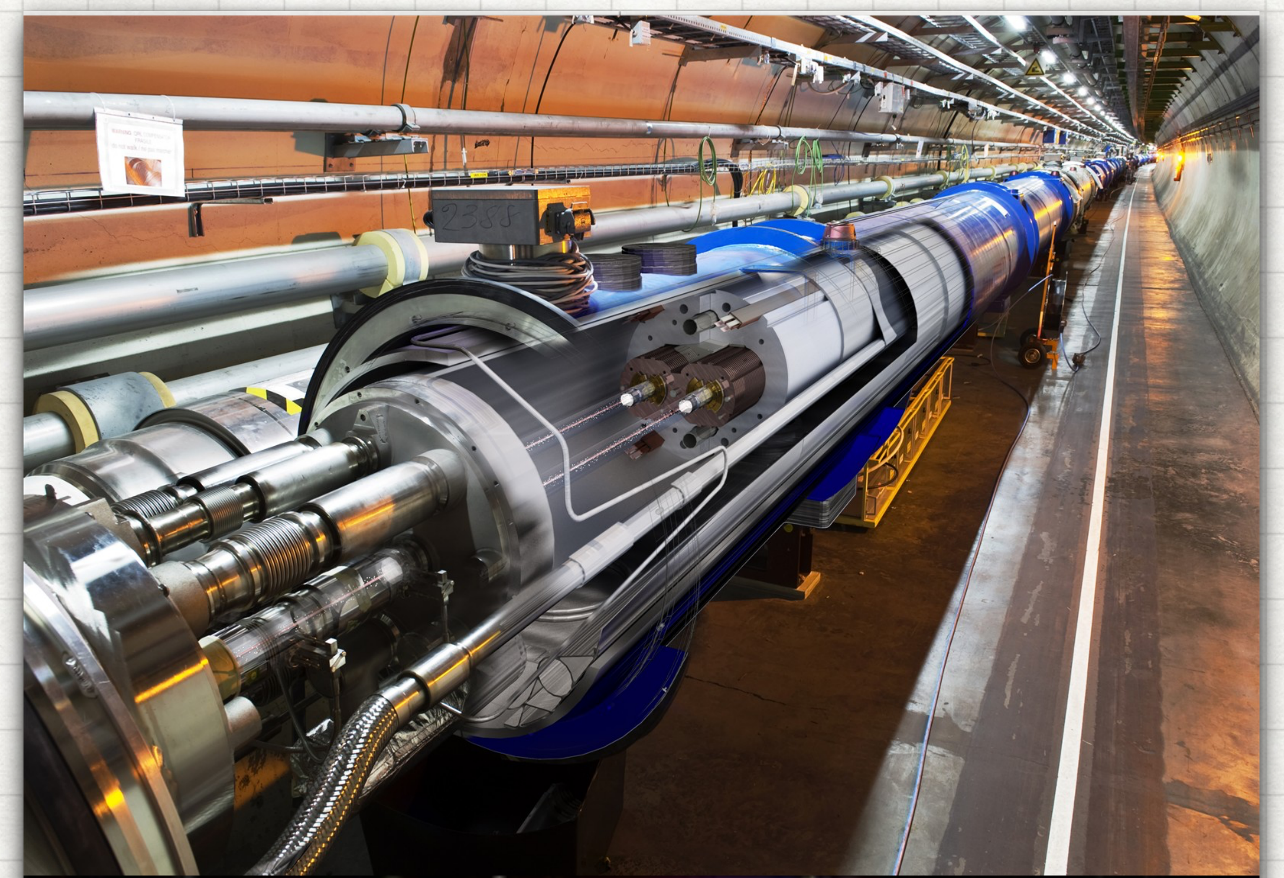
- LHC & ATLAS design
- Anatomy of an ATLAS analysis
- Hypothesis testing

Measurements & Interpretations

- What to look for in the data and how?
- Recent ATLAS results and their interpretation

HEP

STATUS QUO

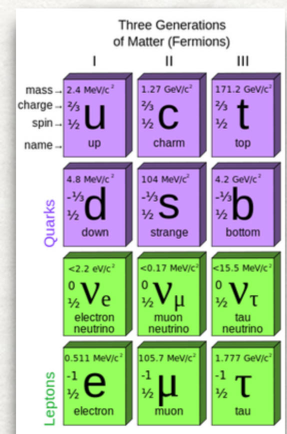


2 Standard Models

Standard Model (particle physics)

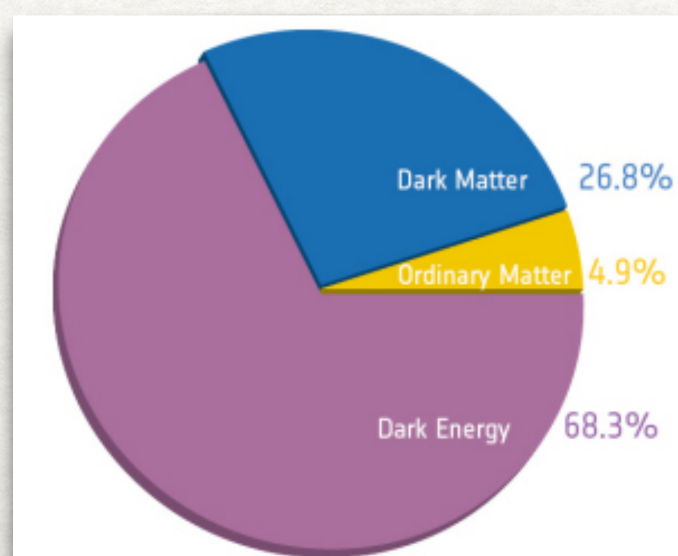
Gauge symmetries + particle content

$$SU(3) \times SU(2)_L \times U(1)_Y$$



Describes (almost) all phenomena that we observe in high energy physics

ΛCDM (Cosmology)



"Matter"

+

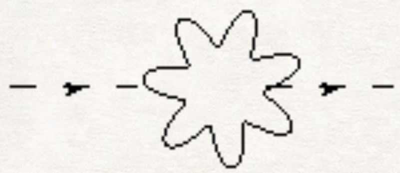
General relativity

Describes (almost) all cosmological observations

Open problems in the 2 Standard Models

Theoretical

Hierarchy problem/Naturalness



$$\delta m_H^2 = \frac{C}{16\pi^2}\Lambda_{UV}^2$$

Naturalness: dimensionless ratios or free parameters should be O(1)

Large hierarchy between mass scales makes the theory "unnatural"

Solution requires new physics

- Higgs mass - quadratic divergence $m_H/m_{Planck} = O(10^{-17})$ ⇒ SUSY/ compositness/…
- Cosmological constant: $\rho(\Lambda_{meas})/\rho(\Lambda_{EWPT})=(10^{-12}\text{ GeV}/10^2\text{ GeV})4=10^{-56}$
- Strong-CP problem: why CP violation in strong interactions is so small? ⇒ axion

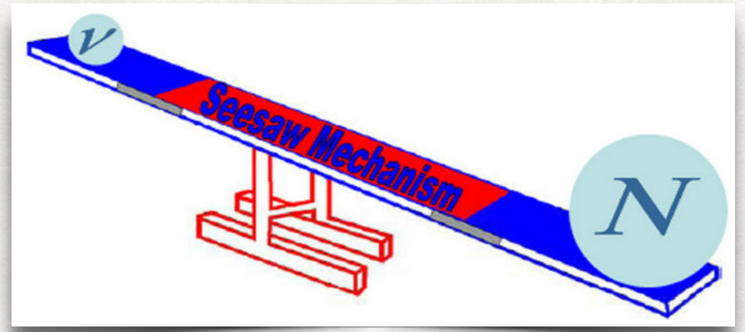
+ many others

- no explanation for values of free parameters
- charge quantisation
- flavour structure
- unification of quantum gravity with SM
- gauge coupling unification
- …

Open problems in the 2 Standard Models

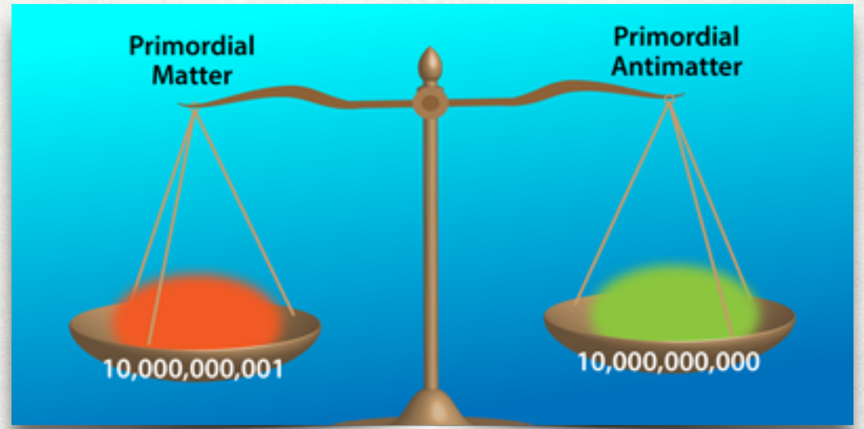
Experimental facts

Neutrinos have mass

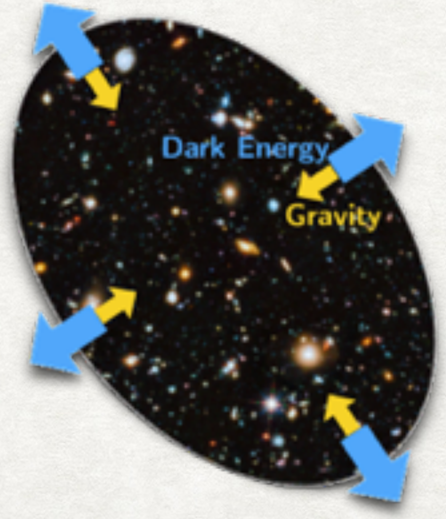


Galaxies have more matter than what we see

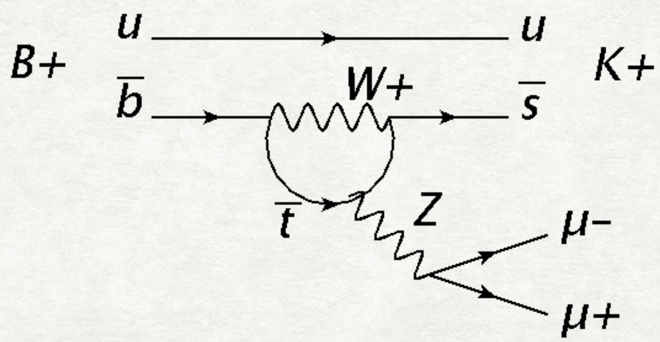
We don't see any anti-matter in the universe



The universe accelerates



Other measured anomalies



Dark matter

- Hypothetical matter with no EM or strong interactions
- Vast observational evidence:

Galaxy clusters

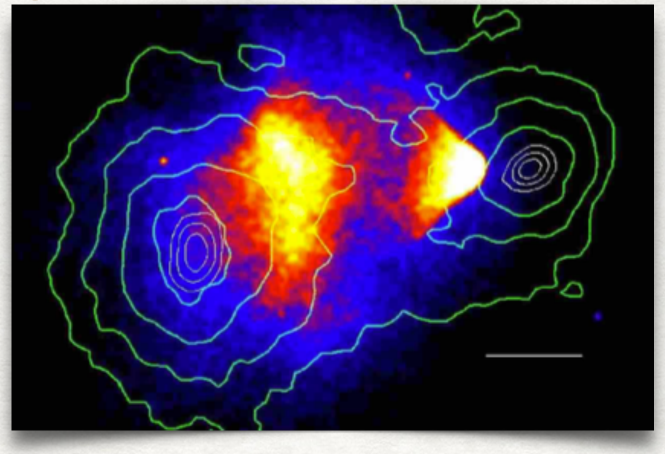
Fritz Zwicky applied virial theorem to Coma cluster

$$T = U/2$$

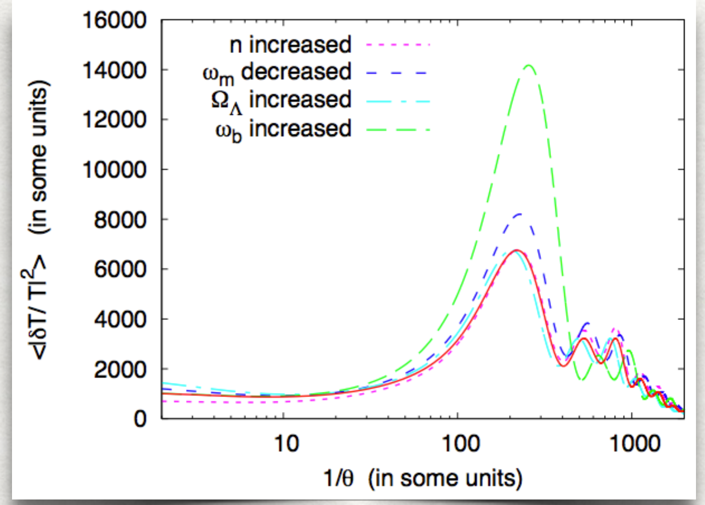
$$M_{\mathrm{virial}} = \frac{3R < v_{\parallel}^2 >}{G} > M_{\mathrm{lum}}$$

Gravitational lensing/Bullet cluster

Lensing observations of bullet cluster show separation between gravitational potential and baryonic matter ⇒ invisible matter is dominant



Cosmic Microwave Background and Large Scale Structure



- Gravitational attraction (DM+baryons) vs photon pressure ⇒ acoustic oscillations
- DM behaves differently than baryons: it does not interact with photons
- Amount of DM and baryonic matter determine the amplitude of the CMB peaks

- Vast array of models (see hep-ph/0404175, 1003.0904, 1605.04909, PDG review)
- All of them *involve new physics*

Matter-antimatter asymmetry

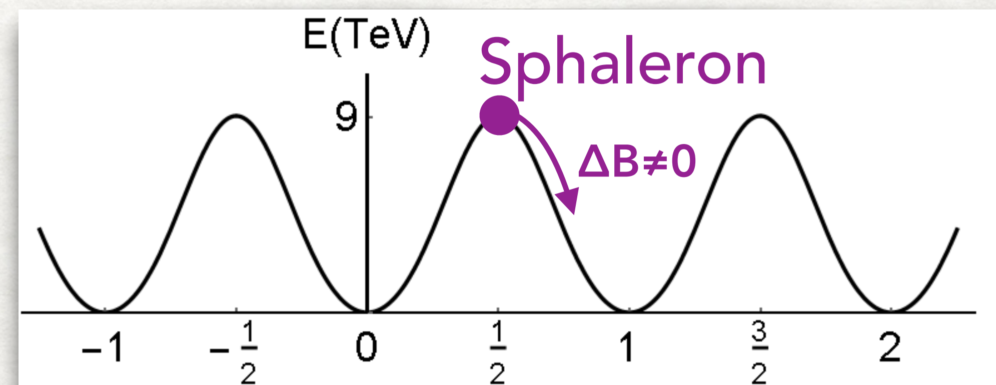
Из эффекта С. Окубо
при большой температуре
для Вселенной сшита шуба
по ее кривой фигуре
А. Сахаров

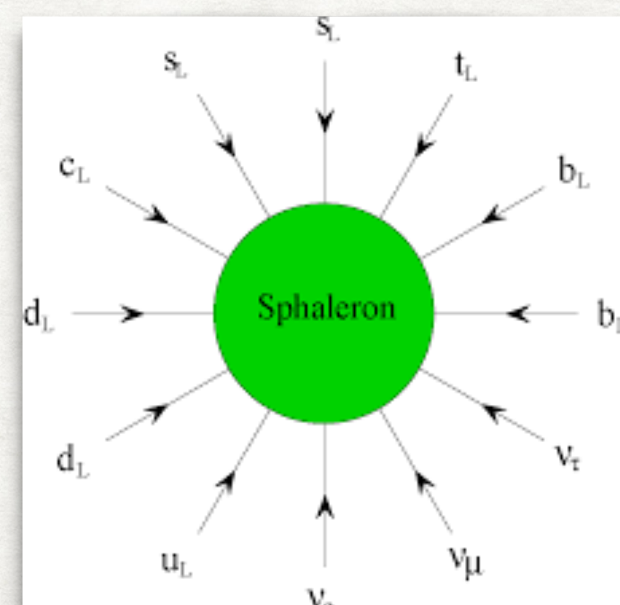
Sakharov requirements for baryogenesis:

- **B violation** (creating baryon excess)
- **C, CP violation** (ensuring transitions that create baryons have higher rate than transitions creating anti-baryons)
- **out-of-equilibrium conditions** (otherwise X↔Y+B)

Baryogenesis in SM

- **C, CP violation:** EW interactions both C and CP violating - but it is argued that the amount of CP violation is too small
- **B violation:** non-perturbative sphaleron process can induce Δ**B**=3,6,9,… transitions (spectacular signatures, e.g. 3 leptons + 7 jets)
- **Out-of-equilibrium:** 1st order phase transition: EW symmetry breaking (but this is not possible with m_H=125 GeV)



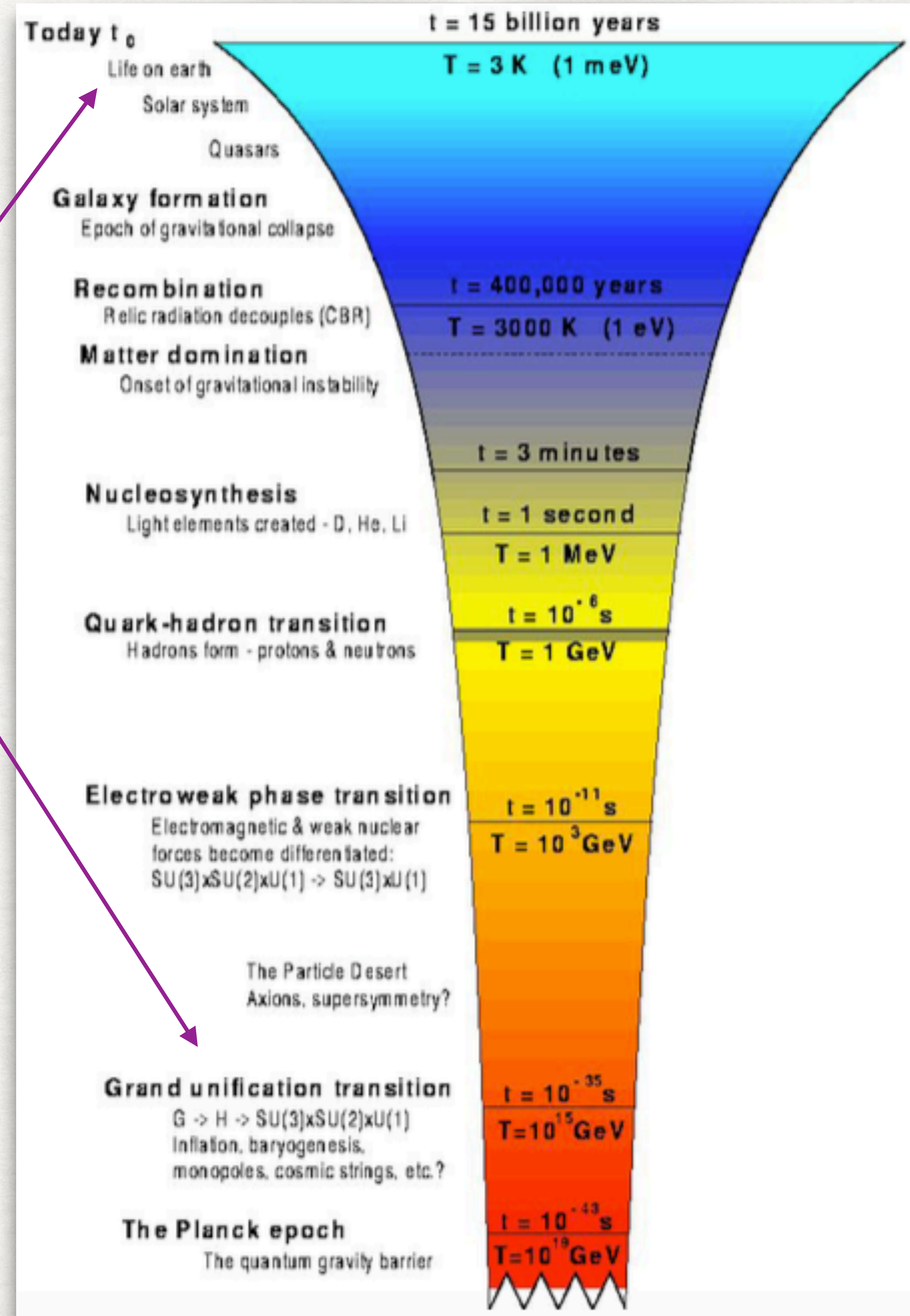


Baryogenesis in BSM models

- **extra sources of CP violation and 1st order PT**

Inflation/Dark energy

- 2 periods of exponential expansion during the evolution of the universe
  - dark energy domination (now)
  - inflation

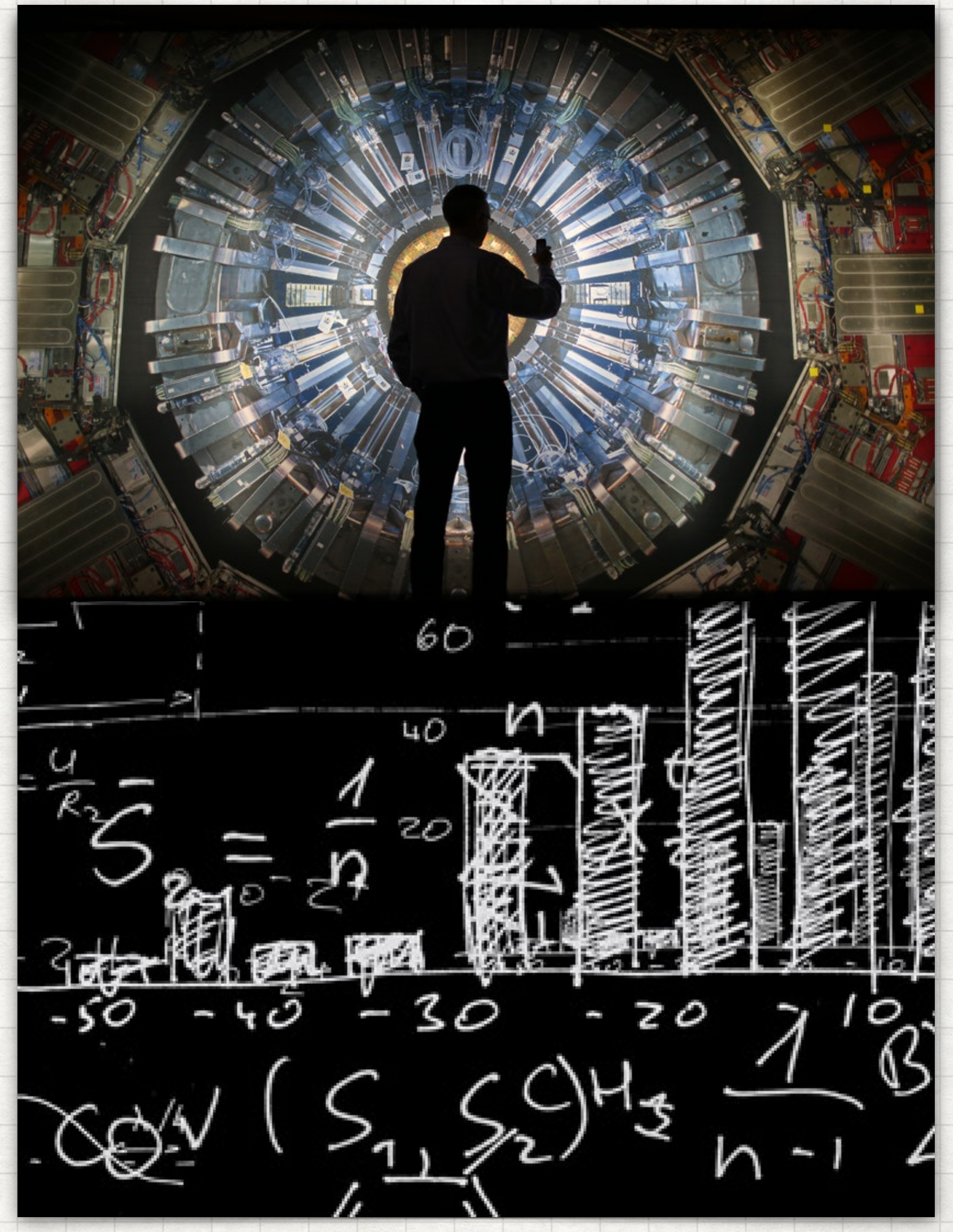


- nature of field which drives acceleration is completely unknown
- several models in the market - most of them involve new BSM fields

Several problems require new physics

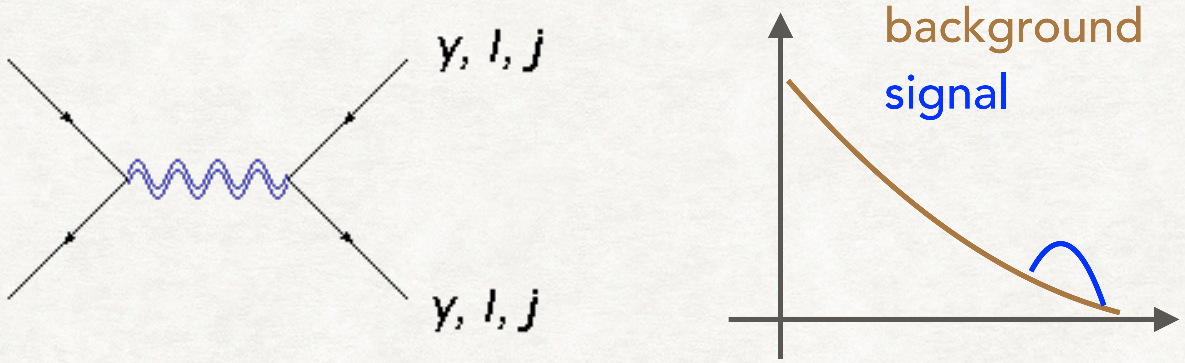
How/where can we look for signs of new physics?

INSTRUMENTS
&
METHODS



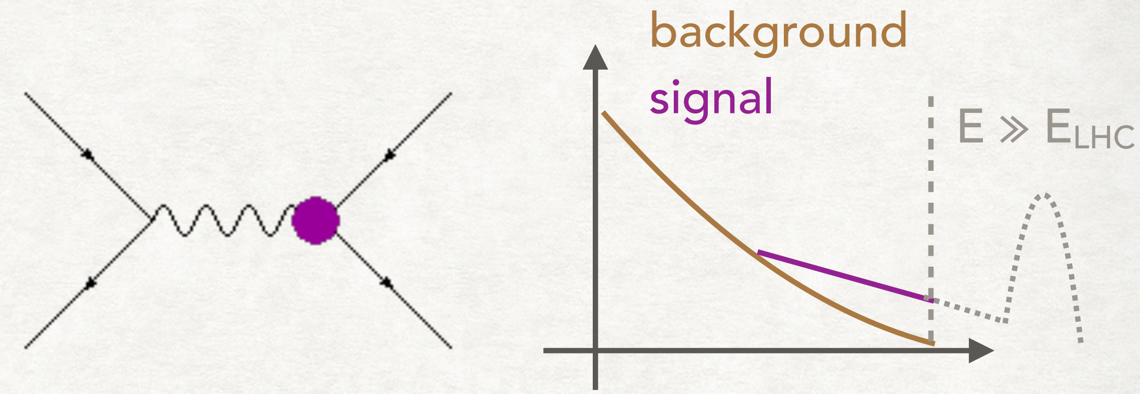
How new physics might show up

New resonances



resonance ⇒ **good resolution**

Deviations in tails



tails ⇒ **good containment** (detect) and resolution (measure) **for highly energetic objects**

- resonances will be **heavy** (otherwise we would have seen them already
  ⇒ **high center-of-mass energy**
- tails ⇒ small cross-sections
  ⇒ **need high luminosity**

The LHC accelerator

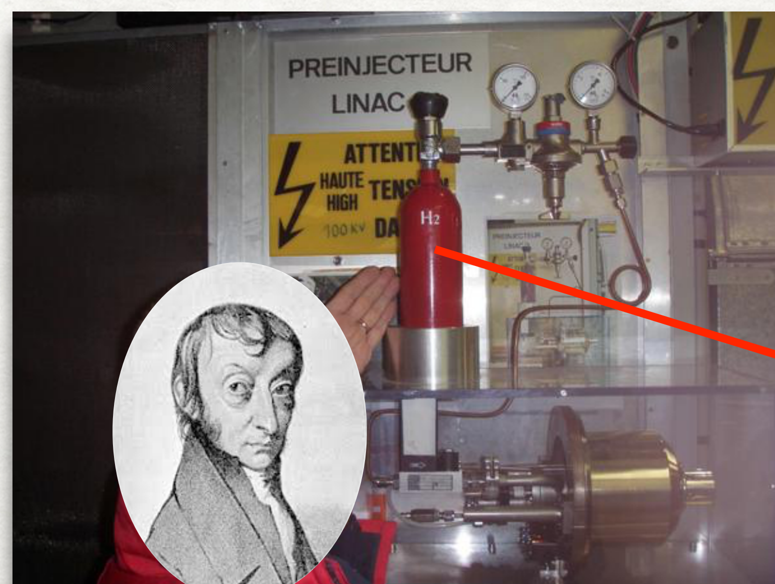
Needs

- high energy ⇒ large collider ($E=cBR=0.3 * B[T] * N_{mag} * L[m]/2\pi$)
- new physics discovery ⇒ several experiments for cross-checking ⇒ circular (many interaction points - many detectors)
- need high luminosity ⇒ protons (easy to get, less Brehmsstrahlung $P_{BS} \propto m^{-4}$)

Limitations

- technology: B = 8.4T (NbTi)
- real estate: LEP tunnel: R=27km

⇒ $\sqrt{s}=14$ TeV

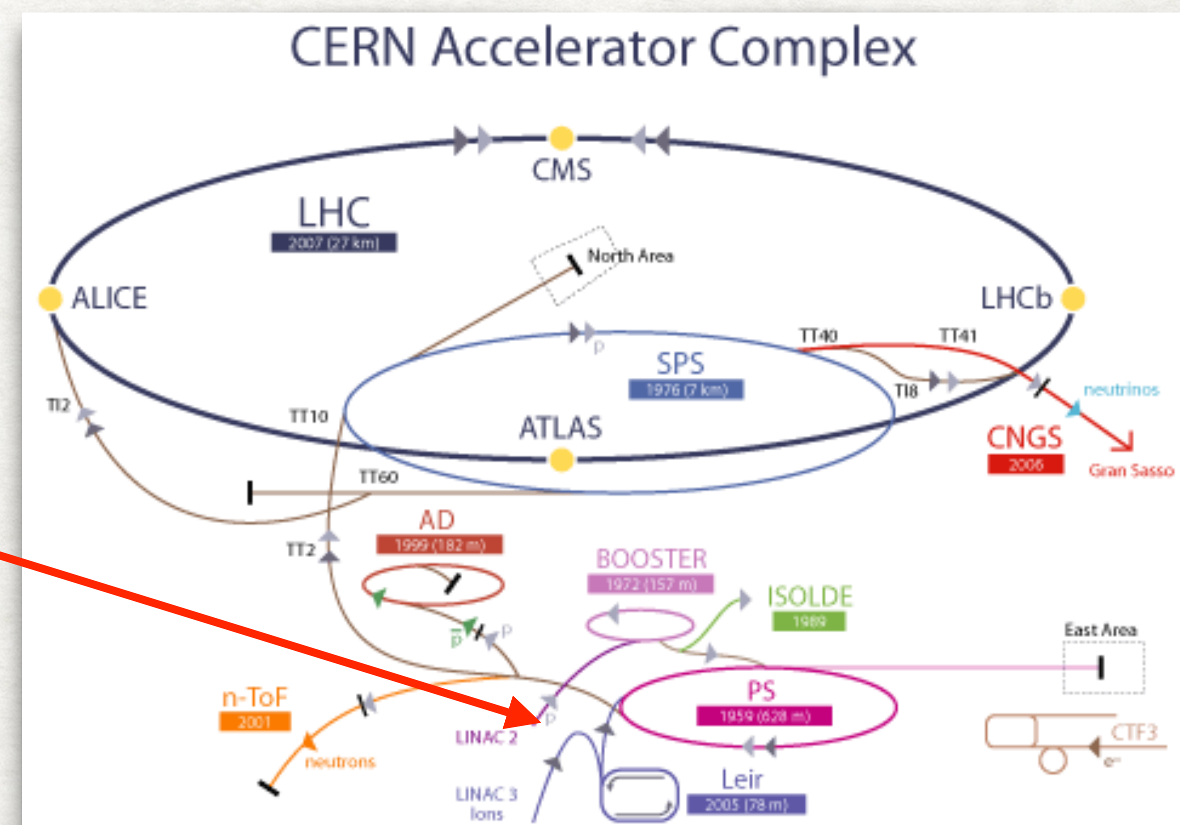


1 cm^3 of H_2 gas: 140 years of beam

room temperature, pressure

$5 \cdot 10^{19}$ atoms of hydrogen

LHC needs $6 \cdot 10^{14}$ protons per fill

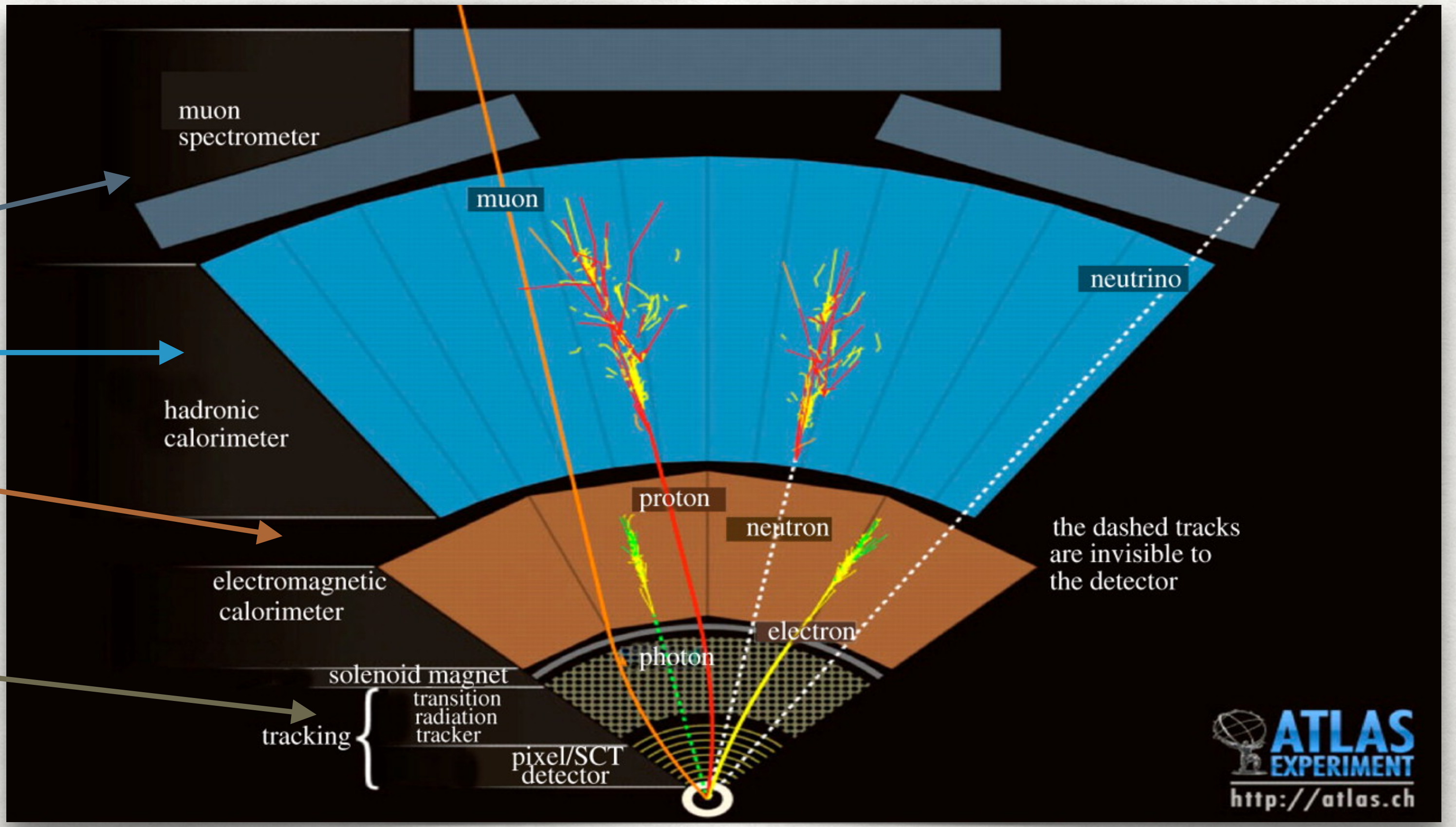


The ATLAS detector

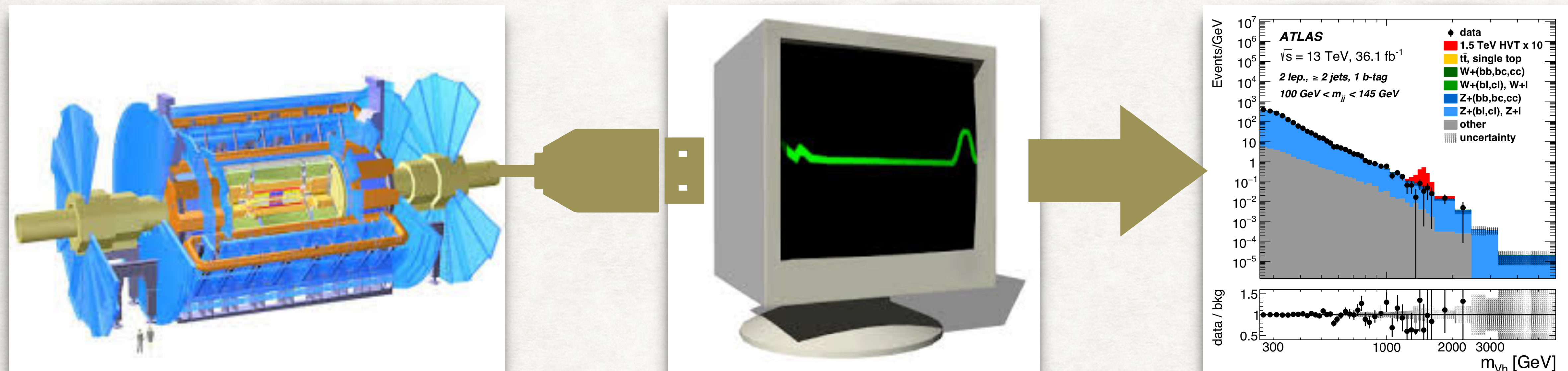
- main goals:
  - discovery of Higgs boson (H→γγ, H→ZZ(4l), H→WW(2l2ν))
  - discovery of new physics (new resonances decaying to leptons, jets, b-jets)
- signatures:
  - leptons, photons, jets missing energy ⇒ **multi-purpose hermetic detector**
  - highly energetic particles ⇒ **dense calorimeters for shower containment**
  - b-jets ⇒ **high granularity inner tracker for secondary vertex reconstruction**

ATLAS layout

- Muon spectrometer (muons)
- HCal (jets)
- ECal (jets, electrons, photons)
- Inner tracker (charged particles, B-decays)



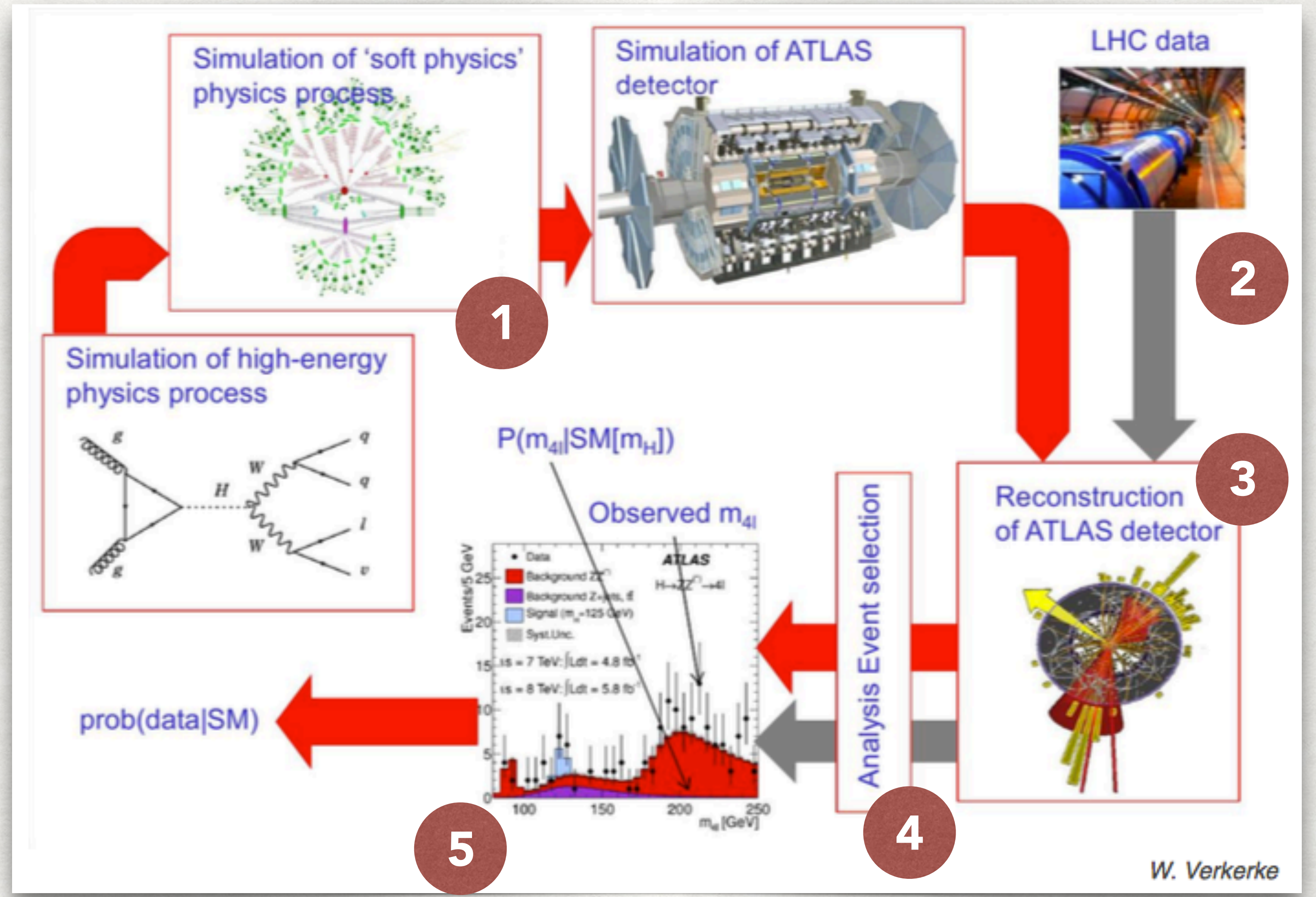
How we do an analysis



?

Anatomy of an ATLAS analysis

1. Modelling of physics processes
   - perturbative calculations (QFT)
   - non-perturbative models + tuning
   - detector simulation (billion CPU hours/year)
2. Data collection
   - optimisation of triggers
   - understanding of sub-detectors (good data)
3. Reconstruction
   - calibration of detector signals
   - correcting for detector effects
   - at least one method per object
4. Data analysis
   - optimisation of event selection (physics)
   - analysis implementation (software)
5. Interpretation
   - Comparison of data and SM predictions
   - Hypothesis testing/Unfolding

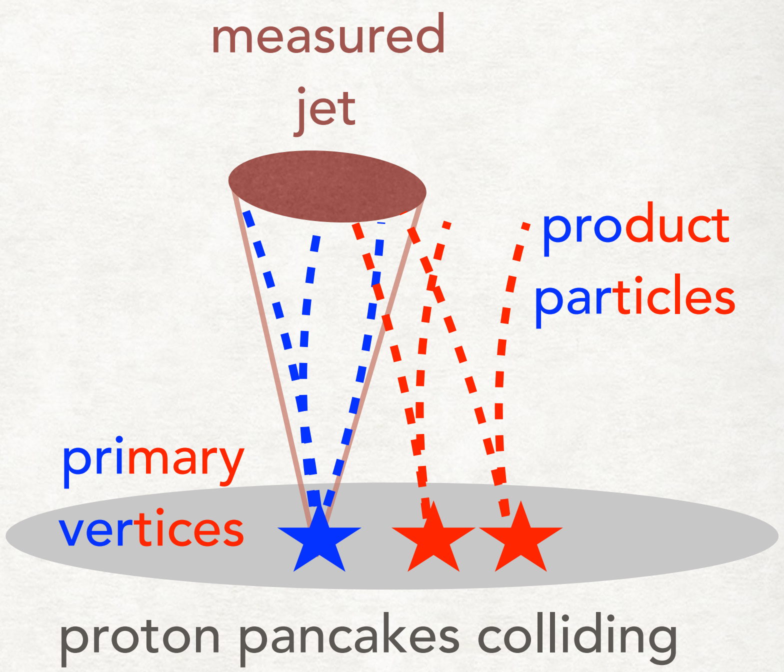


Each bullet corresponds to work of O(10-100) people

An example: measuring jets with many pp collisions

- **problem: ~40 pp interactions per bunch crossing (pile-up)**
  ⇒ measured jet energy will contain contributions from many pp collisions
  ⇒ only 1 collision is interesting - have to subtract the rest
- **pile-up correction:**

$$p_T^{\text{true}} = p_T^{\text{meas}} - \rho_{\text{PU}} A_{\text{jet}} - \alpha(N_{PV} - 1) - \beta\langle\mu\rangle$$



Had to

- determine how to best measure PU density **ρ**
- determine how to best measure jet area A
- determine the values of **α**, **β**
- see how the method performs using real data (2 separate data analyses)

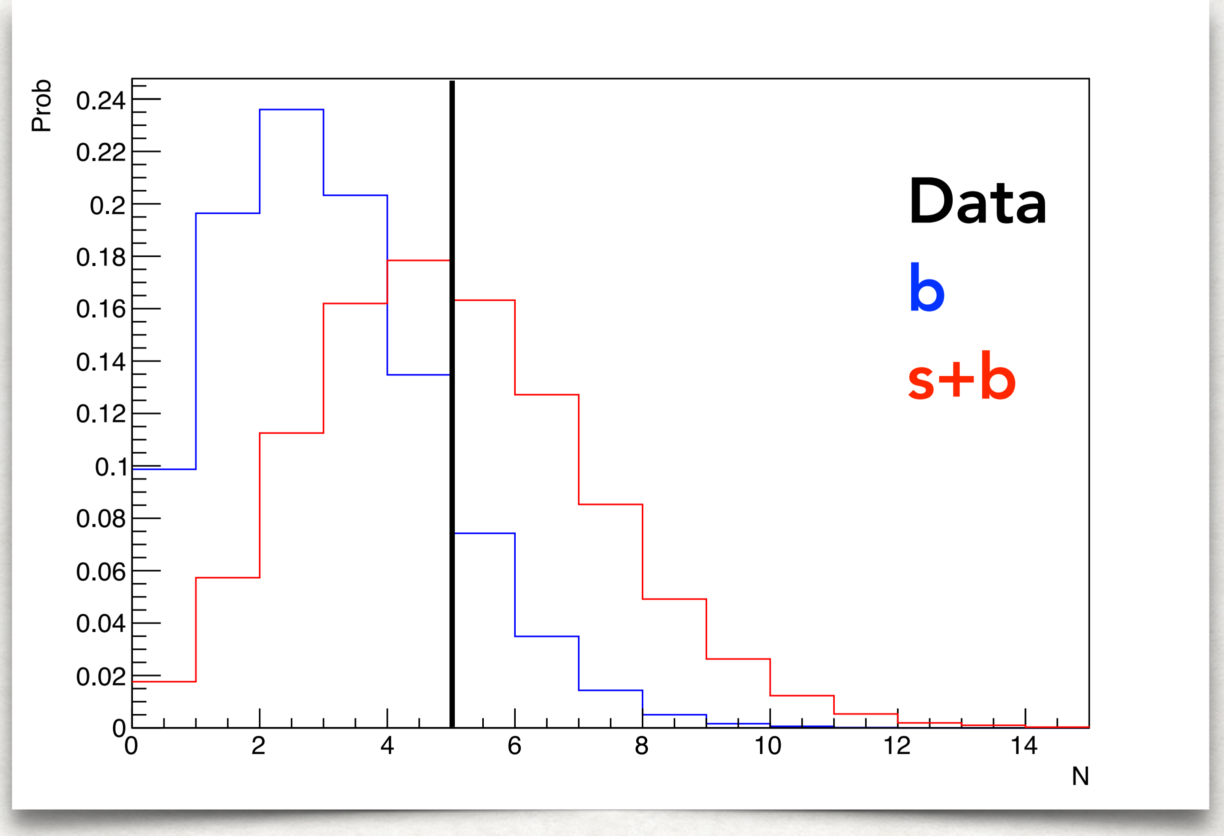
Work in collaboration with Pavel Starovoitov and ~10 more people took ~1 whole year

Hypothesis testing

- What's the probability of observing N_{obs} events if we expect b events? (simple counting experiment)

$$Pois(N_{\rm obs}|b) = \frac{b^{N_{\rm obs}} e^{-b}}{N_{\rm obs}!}$$

- Example: N_{obs} = 5, b = 3, s = 2
  - P(5|b)=10%, P(5|s+b)=18% *("N=5 is more likely under s+b hypothesis")*
  - **Does that mean there is signal in the data?**
  - To answer that we would need to calculate



$$P(s+b|5) = \frac{P(5|s+b)P(s+b)}{P(5)}$$

Bayes Theorem

$$P(5) = P(5|b)P(b) + P(5|s+b)P(s+b)$$

$$P(s+b|5) = \frac{P(5|s+b)P(s+b)}{P(5|b)P(b) + P(5|s+b)P(s+b)}$$

- with P(b)=P(s+b)=0.5 we get P(b|5)=36%, P(s+b|5)=64%
  - **"s+b is more likely given the measurement"**
  - **but to answer this we had to inject prior "degree of belief" P(b), P(s+b)**

Interpreting probabilities

- **Two schools** of interpreting probabilities:
  - Bayesian: probability of hypothesis (*"what's the probability that new physics exists based on our measurement?"*)
  - Frequentist: probability of given measurement in repeated identical experiments (*"NP either exists or not. I can only tell you the probability of getting this result **assuming** that NP exists (or not)"*)
  - Frequentist interpretation more widely used in HEP

Frequentist statements are about the data not the model!

- **So when do we declare that we found new physics?**
  - assume 2 competing hypotheses b, s+b
  - p_b = probability of observing as least N_{obs} events in data if bg-only hypothesis is true
  - **declare discovery when p_b is very small**

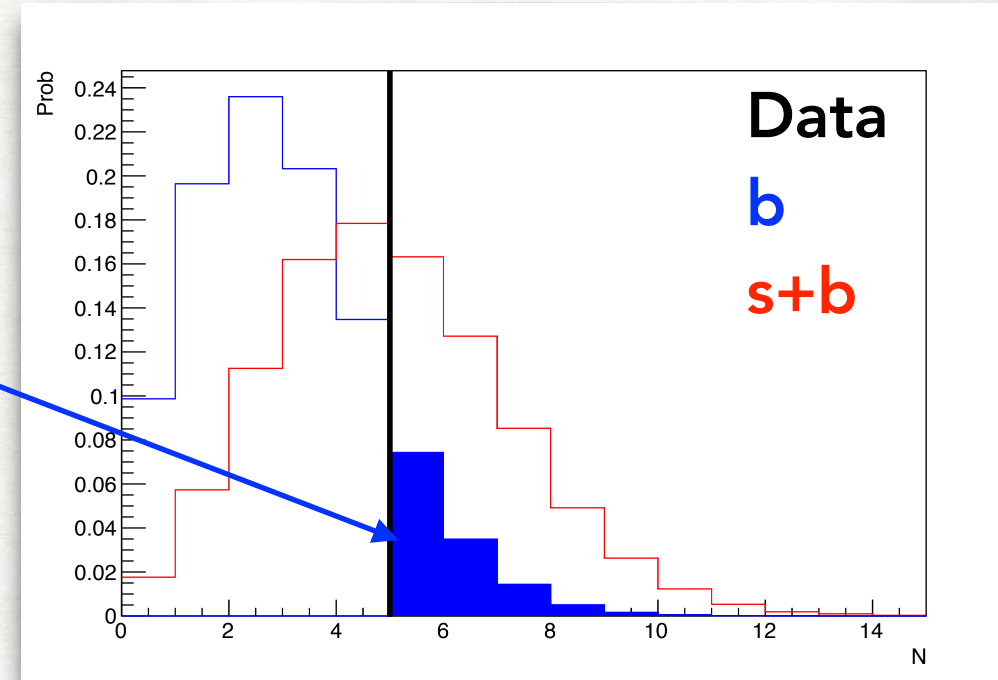
$$p_b = \int_{N_{obs}}^{\infty} Pois(N|b)dN$$

$$z = \sqrt{2}\,\mathrm{erf}^{-1}(1 - 2p_b)$$

z-score ("sigma")	p-value
3	0.135%
5	$2.87 \cdot 10^{-7}$

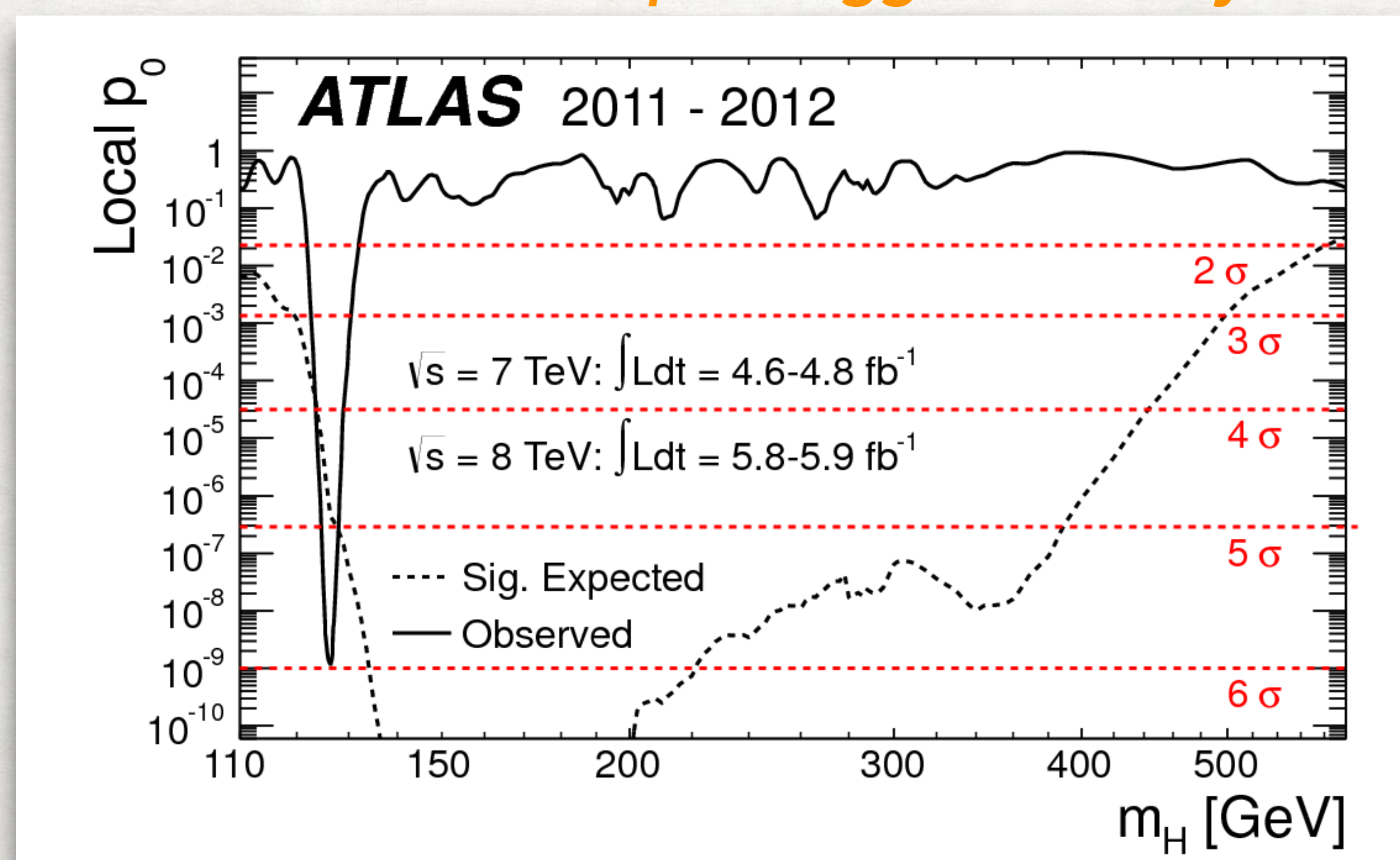
Discovery - p_b

$$p_b = \int_{N_{obs}}^{\infty} Pois(N|b)dN$$



- Going back to our example:
  - $p_b = 0.13$, 1.1σ
  - we would need 10 observations to get 3σ evidence and 15 to get 5σ discovery

A real life example: Higgs discovery



The probability of observing the measured number of events with a mass of 125 GeV if there is no Higgs boson is 10^{-9}

For other m_H no significant excess of events

Look Elsewhere Effect

- The more trials we do the more likely it is to observe a big fluctuation
  - e.g. a 2σ fluctuation is expected to occur after ~44 trials
- When looking for an effect in a given parameter range we should take into account the probability of observing this effect anywhere in the parameter range

Simple corrections for trials with same expected significance:

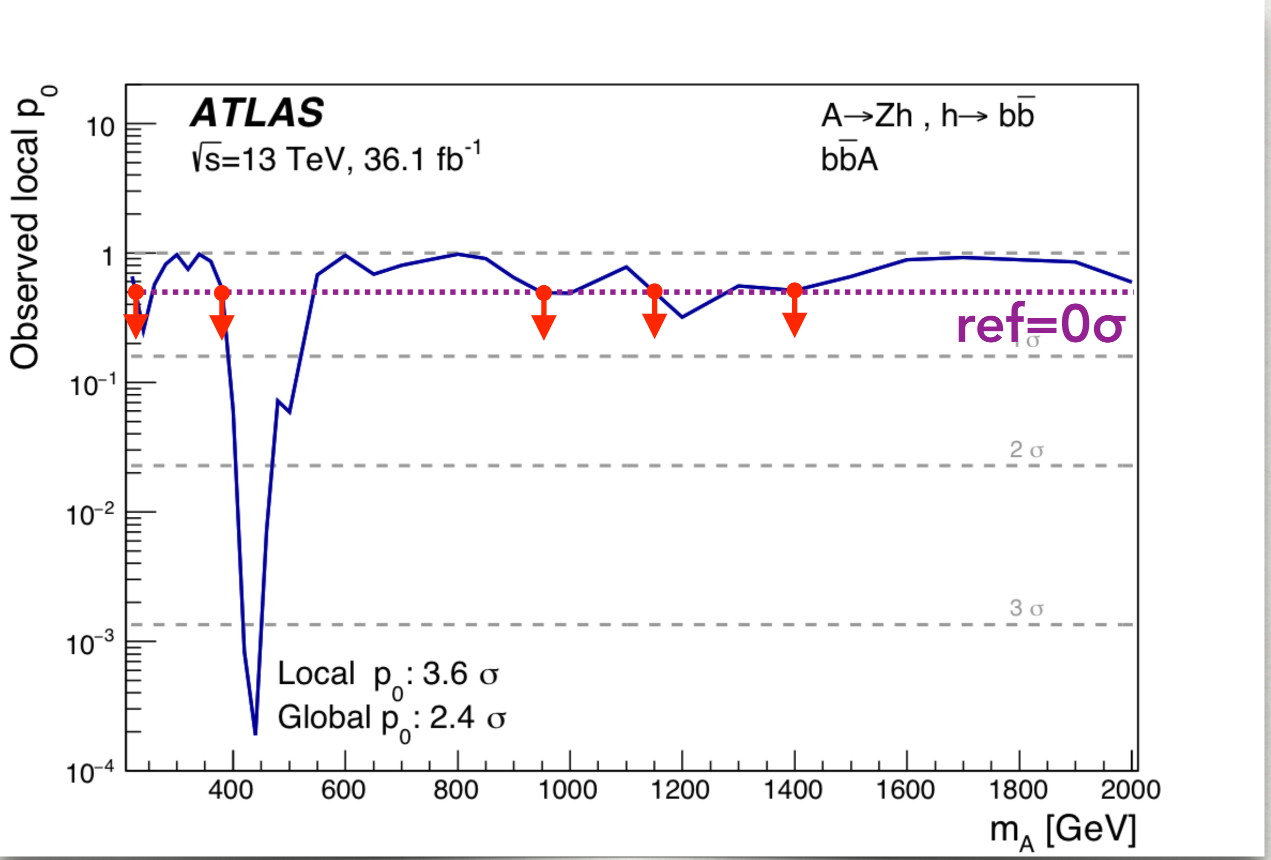
- Bonferonni correction: $p_{\text{glob}} = p_{\text{local}}^{\text{min}} N_{\text{trials}}$
- Dunn-Sidak correction: $p_{\text{glob}} = 1 - (1 - p_{\text{local}}^{\text{min}})^{N_{\text{trials}}}$

For searches with falling background:

- use asymptotic trials factor:

$$p_{\text{glob}} = p_{\text{local}} + N_{\text{down}} \mathrm{e}^{-\frac{1}{2}(z_{\text{local}}^2 - z_{\text{ref}}^2)}$$

- with z_{ref}=0σ
- N_{down}: number of times p-value crosses zref from above
- e.g. p_{local}=3.6σ with N_{down}=5 gives p_{global}=2.4σ

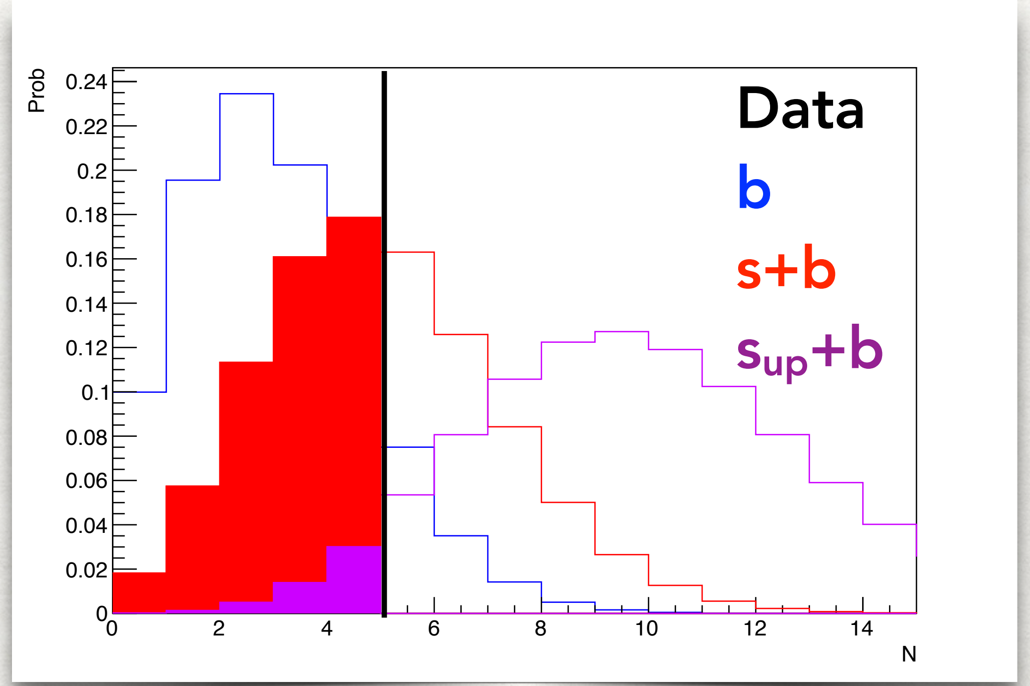


Exclusion - p_{s+b}

- Most of the times when we search for NP we find nothing
  - we want a similar metric to say when a signal hypothesis can be excluded
  - define p_{s+b} = probability of observing at most N_{obs} evens if s+b hypothesis is true
  - In our example p_{s+b}=53%

$$p_{s+b} = \int_0^{N_{obs}} Pois(N|s+b)dN$$

- By convention consider signal excluded if p_{s+b}=5%
- *"95% CL upper limit" = "signal for which p_{s+b}=0.05"*
  - in our example we exclude s>6.85

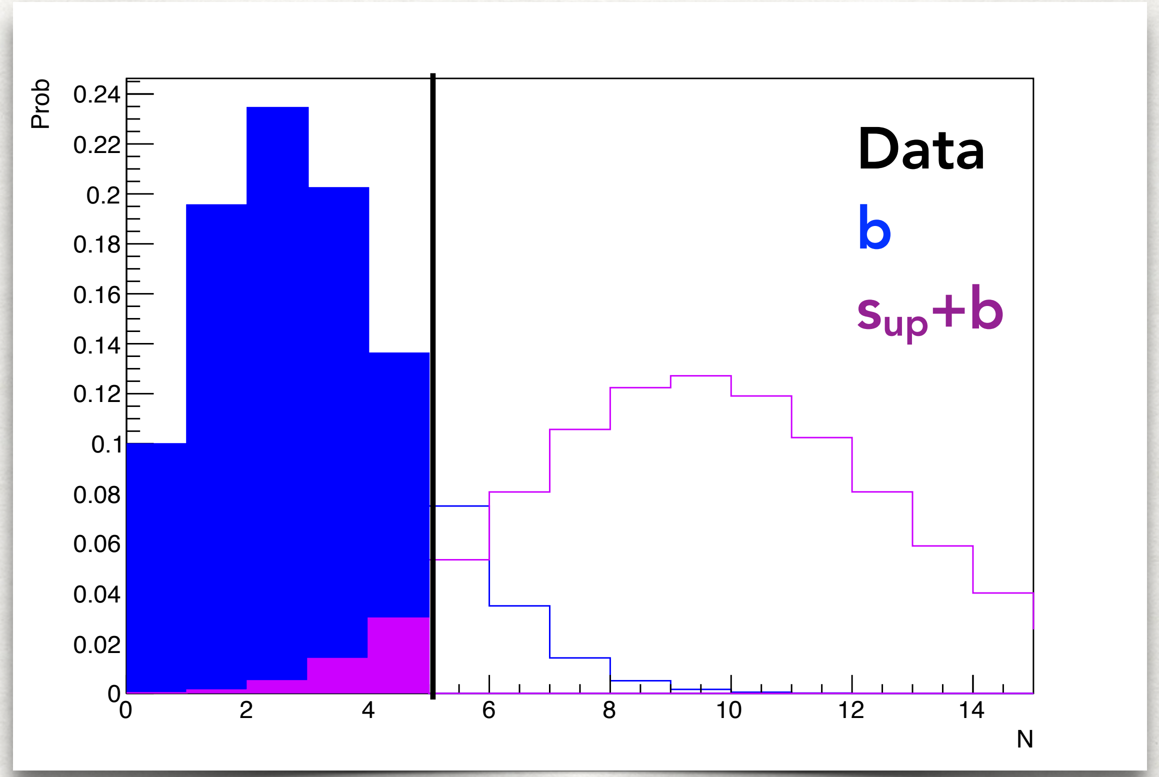


- What happens if N_{obs}=0?
  - p_{s+b}=0 means we exclude all values of s?

Exclusion - CLs limits

- Modify p_{s+b} to take into account that it's difficult to distinguish small b values from the s+b hypothesis
- 95% CLs exclusion limit: CLs=0.05

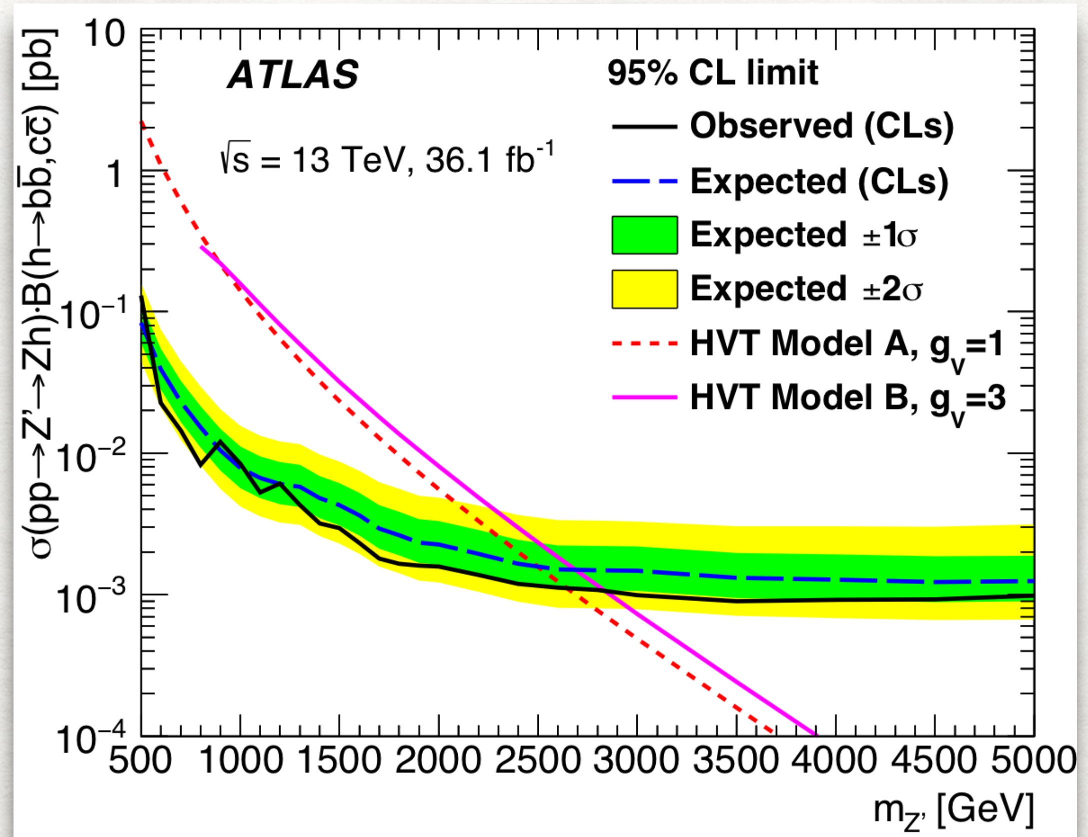
$$CL_s = \frac{p_{s+b}}{1 - p_b}$$



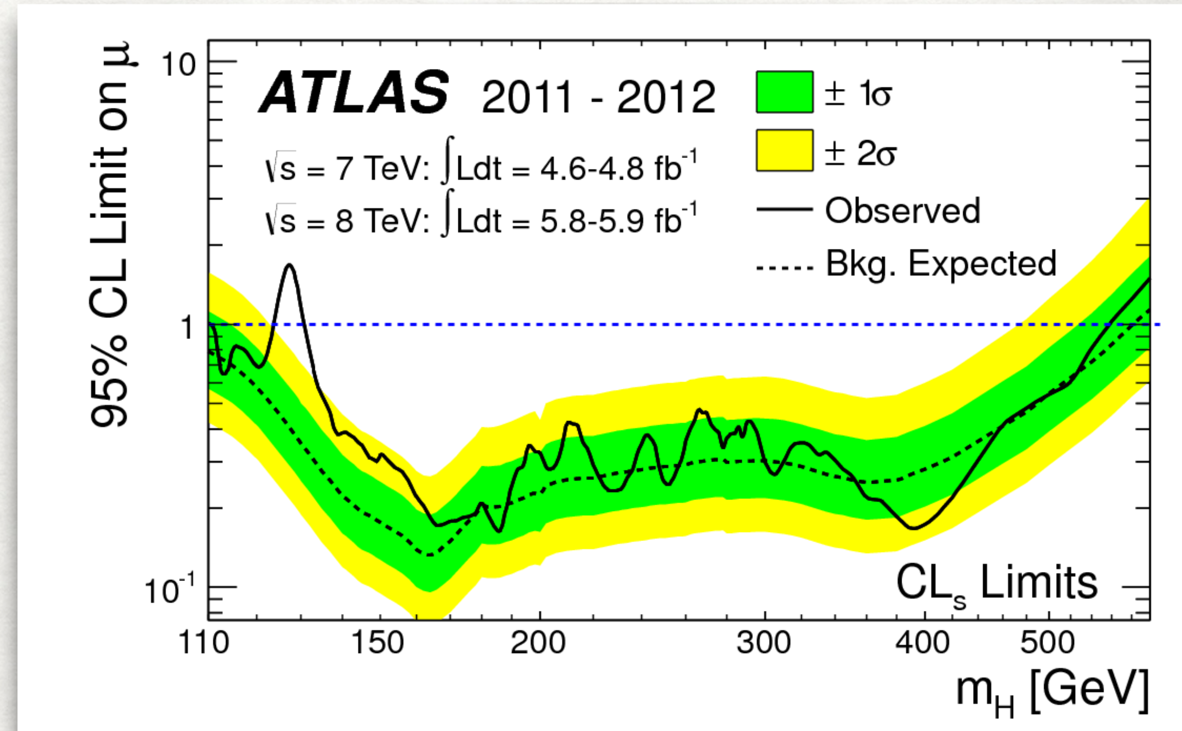
- In our example
  - for N_{obs}=0,
    - CLs(s=0)=0.052
    - CLs exclusion for N_{obs}=0: s>2.46
  - for N_{obs}=5
    - p_{s+b}(s=6.85)=0.05
    - CLs(s=6.85)=0.38
    - **CLs limits are more conservative than p_{s+b} limits**

How to read exclusion plots

Search for Z′→Zh



Search for SM Higgs



- Upper limits on cross-section = **we can exclude $\sigma > \sigma_{obs.\ imit}$ @ 95% CL**
- σ_{exp}: upper limit you expect to set assuming s=0
- If $\sigma_{obs.\ imit} < \sigma_{theory}$ the model is excluded (left: $m_{Z'}$<2.5 TeV is excluded)
- If $\sigma_{exp.\ imit} > \sigma_{theory}$ the experiment is not sensitive yet to this model - can't exclude it (left: we can't exclude mZ′>3 TeV)
- If $\sigma_{obs.\ imit}$ >(<) $\sigma_{exp.\ limit}$ there is an excess (deficit) in the data with respect to the b-only hypothesis
- Right: we have sensitivity to exclude m_H=125 GeV and we can't

Likelihood fits

- Likelihood in a real experiment is more complicated
  - several bins, several regions
  - systematics - incorporated as nuissance parameters **θ** that are constrained by auxiliary measurements f_{constr}

$$L(N_{obs}|\mu s + b;\theta) = \prod_i Pois(N|\mu s + b;\theta) \cdot f_{\rm constr}(\theta|\tilde{\theta})$$

- We want to compare the likelihood of the data under 2 competing hypotheses
  - **likelihood ratio**: L(N|s+b)/L(N|b) - becomes large when data is “signal-like”
  - **profile likelihood ratio**

$$\lambda(\mu) = \frac{L(\mu_{\rm fix}, \theta)}{L(\mu, \theta)} \quad \Rightarrow$$

systematics NP are constrained simultaneously

- With PL ratio we can define p-values e.g. for discovery

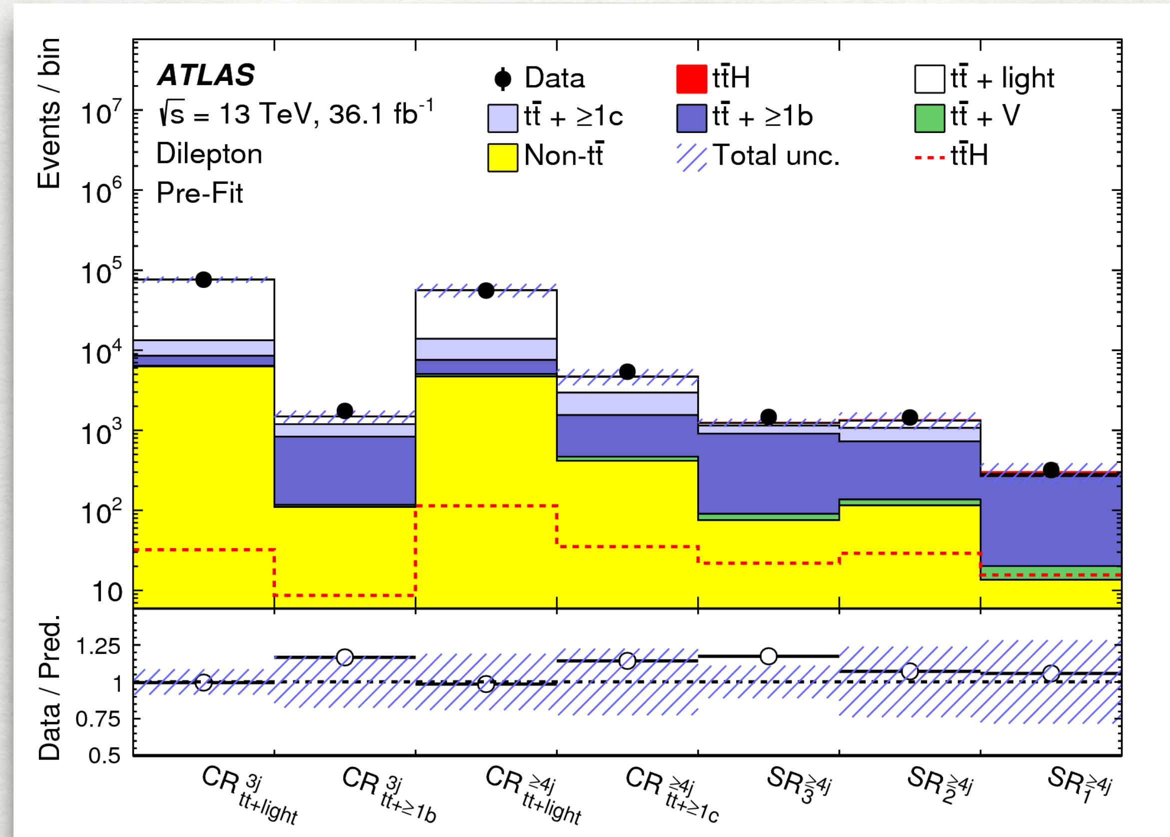
$$q_0 = -2\ln\lambda(\mu = 0)$$

$$p_0 = \int_{p_0,obs}^{\infty} f(q_0|0)\,dq_0$$

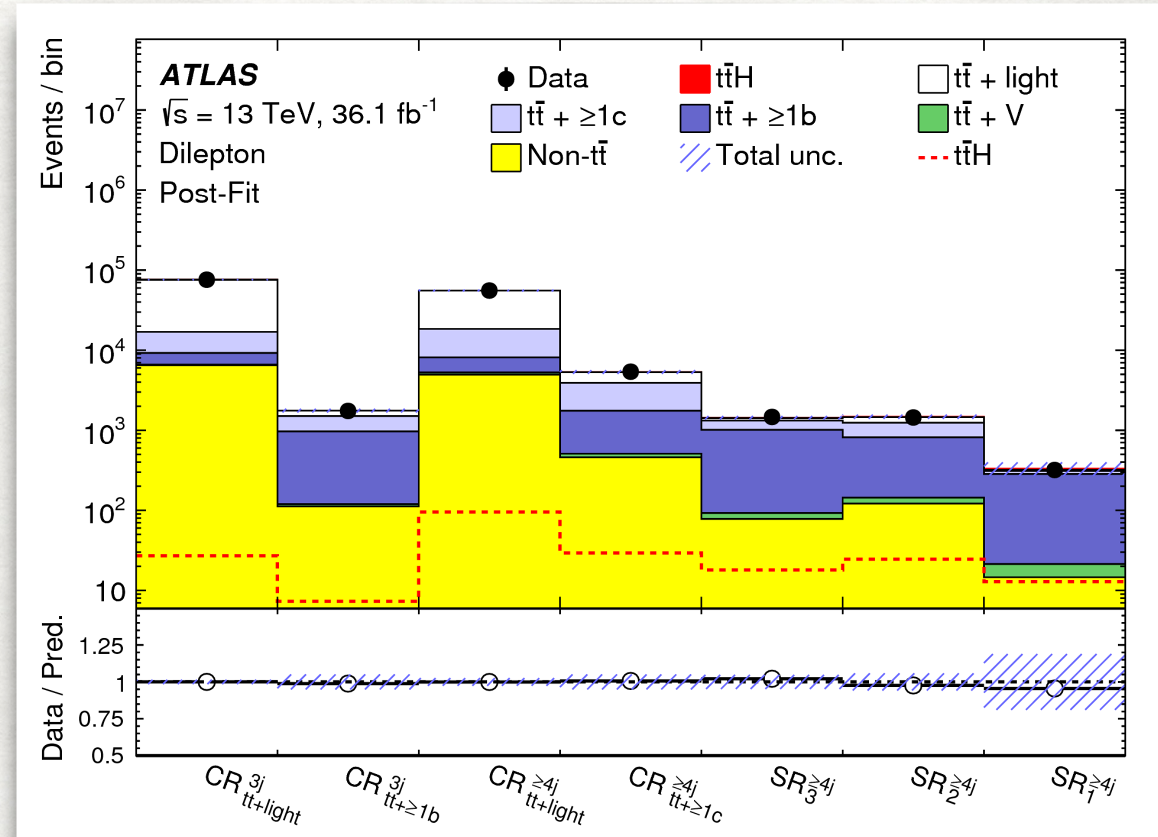
- We need to know $f(q_0|0)$ ⇒ it’s a χ^2 distribution (Wilk’s theorem) (see 1007.1727)

Likelihood fits

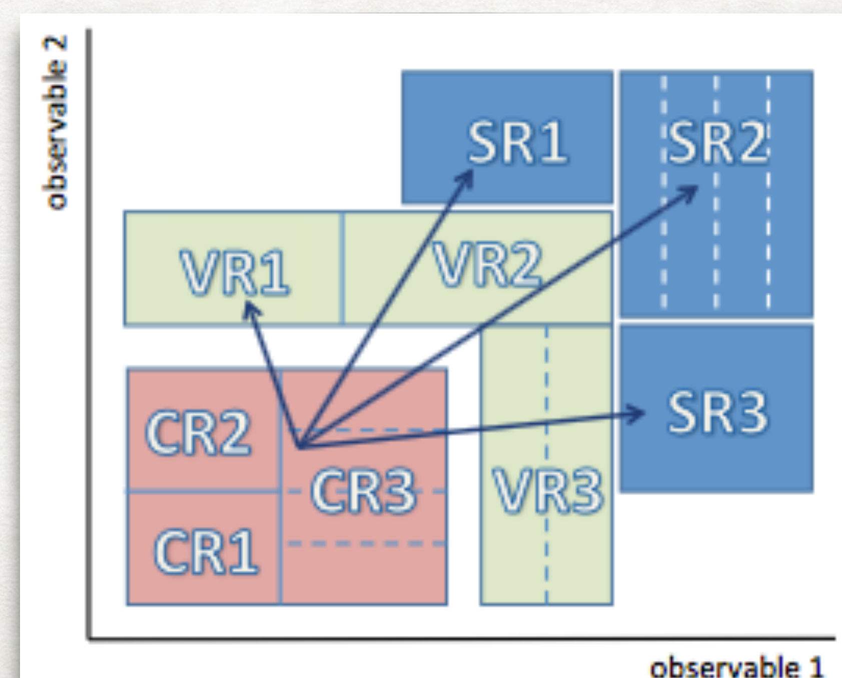
Before fit



After fit



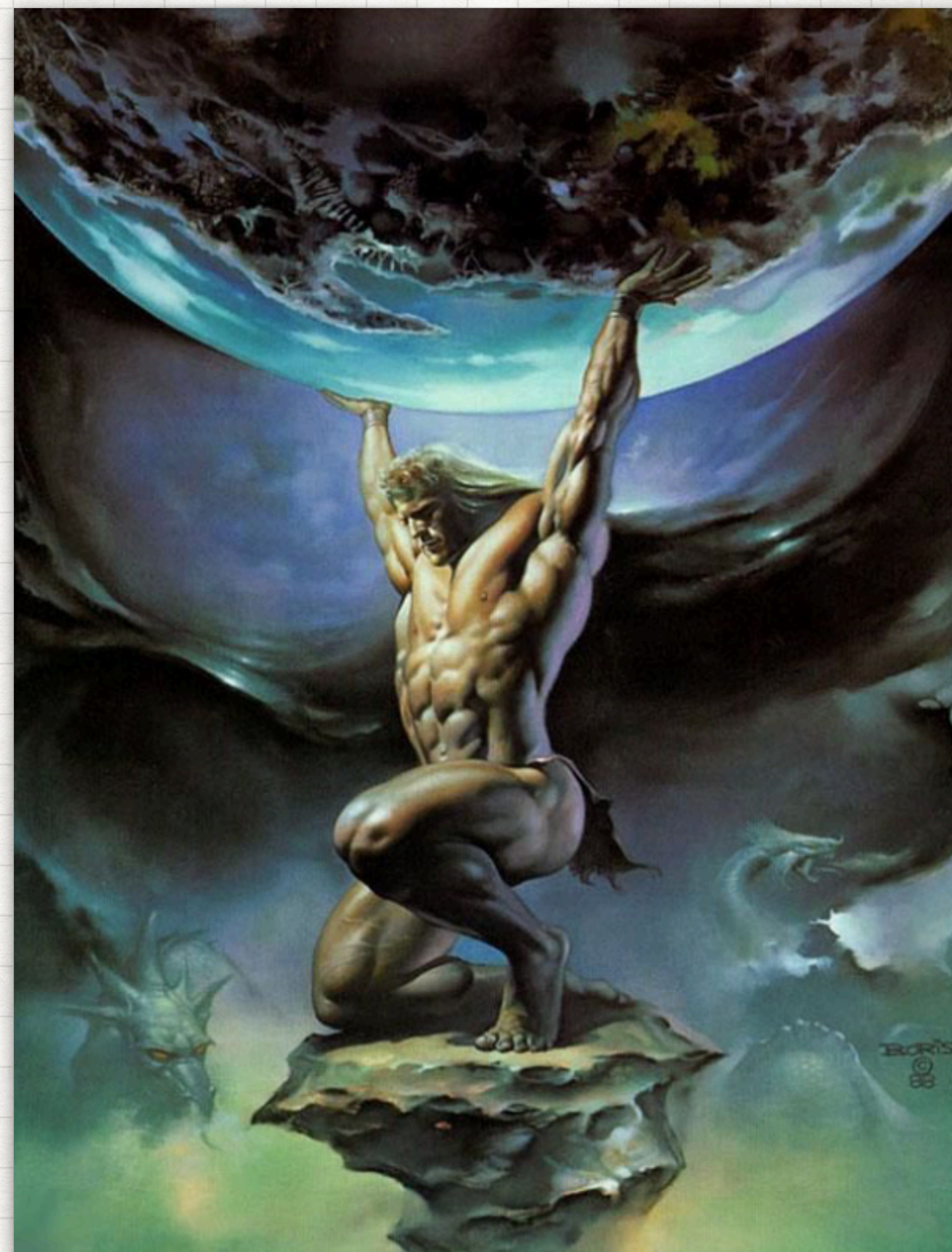
- searches usually split into many regions
  - Signal Regions: signal-enriched - allows to constrain μ
  - Control Regions: low signal - allows to constrain background normalisations and systematics
  - Validation regions can be used to study behaviour of fit



- ✓ We now know which observations point to the existence of new physics
- ✓ We have some ideas where these might show up
- ✓ LHC and ATLAS great instruments to search for new physics
- ✓ We know how to look for new physics

Now let's look at some ATLAS results…

ATLAS SEARCHES FOR
NEW PHYSICS



What we are looking for - some examples

Theory	Addresses	Lagrangian	Signature	Resonant	References
New resonances (gauge bosons)	Hierarchy problem	Simplified	W′→lν, Z′→ll W′, Z′ → WW,ZZ,WZ W′, Z′ → Wh, Zh	✔	Theory/ATLAS
Extended Higgs sector	Baryogenesis	Full model	A→ZH→llbb	✔	Theory/ATLAS
	Motivated by SUSY, axion, …	Full model	A→tt	x	Theory/ATLAS
Dark Matter	Galaxy rotation, CMB, etc	Simplified	X+E_T^{miss}	✔/x	Theory/ATLAS
Dark Energy	Accelerated expansion of universe	EFT	tt+E_T^{miss} jet+E_T^{miss}	x	Theory/ATLAS

Here we will only focus on some basic concepts:

- how a **resonant/non-resonant** search looks like
- **simplified models** and **EFTs**
- **physics**: baryogenesis/dark matter/dark energy

RESONANT SEARCHES

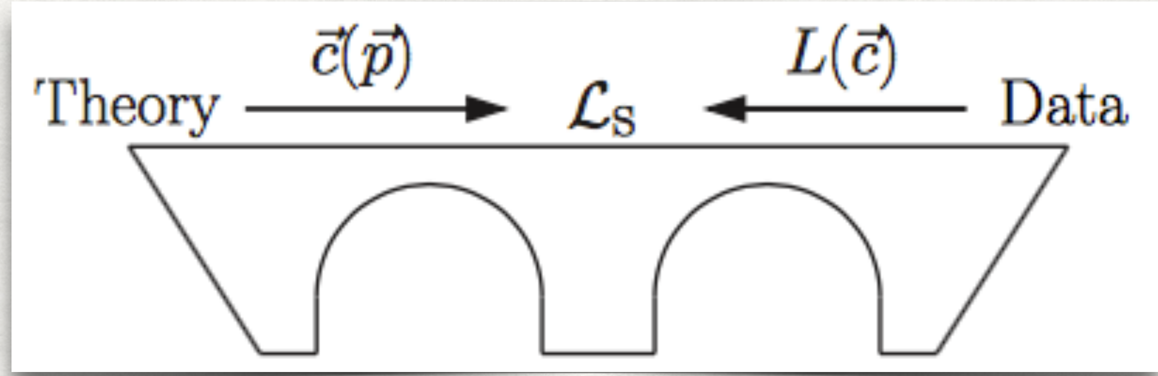
WITH SIMPLIFIED MODELS

Heavy vector bosons - simplified models

- For every new gauge symmetry there is a new gauge boson
  - new gauge bosons arise in many extensions of the SM
  - can we **search for those bosons in a ~model-independent way?**

Simplified model approach

- phenomenological Lagrangian that can describe on-shell production and decay
- only dependent on few parameters (mass, width)
- measurement easy to interpret and can be mapped analytically to a complete theory

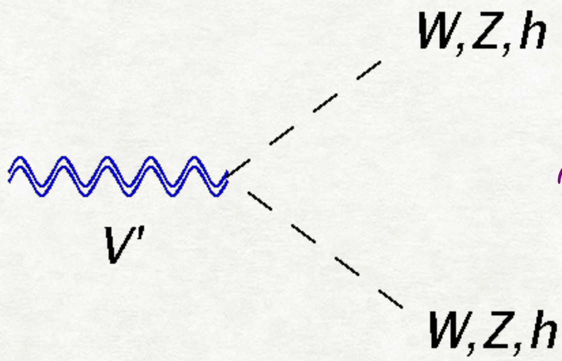


1402.4431

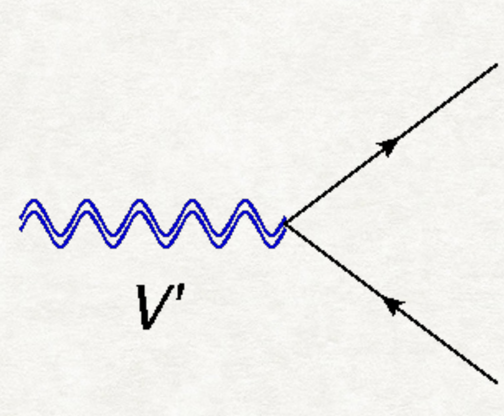
- Now used in many cases where many models are available in the market:
  - Dark matter - replacing EFT models which have limited validity @ LHC
  - Electroweak-charged new bosons

HVT model - signatures

$$\mathcal{L}_{V'} = -\frac{1}{4}F^a_{\mu\nu}F_a^{\mu\nu} + \frac{m_{V'}}{2}{V'}^a_\mu {V'}_a^\mu + i g_H {V'}^a_\mu H^\dagger \tau^a \overleftrightarrow{\nabla}^\mu H + g_l {V'}^a_\mu \bar{l}_L \gamma^\mu \tau^a l_L + g_q {V'}^a_\mu \bar{q}_L \gamma^\mu \tau^a q_L$$



$\sim g_H$



$\sim g_l / g_q$

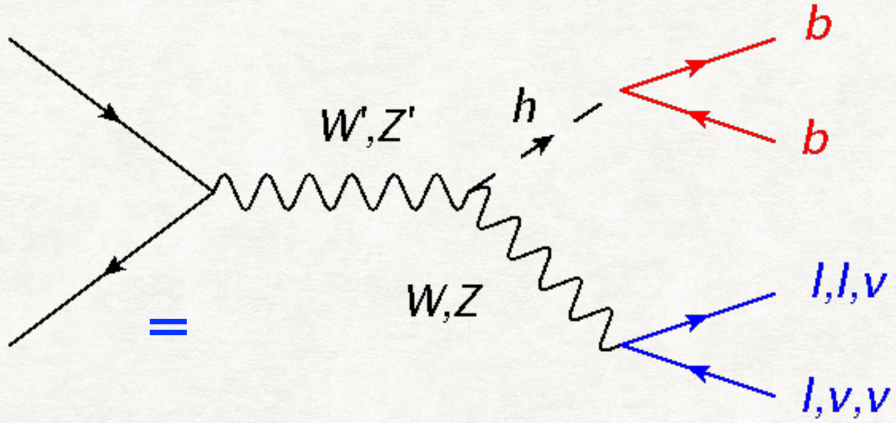
- **Four main signatures**
    - V'→Vh→(qqbb, llbb, lvbb, vvbb)
    - V'→VV→(llll, lllv, lvlv, llqq, lvqq, qqqq)
    - V'→leptons→ll, lv
    - V'→jj

⇒ 13 different final states

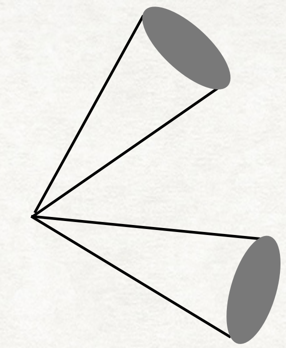
⇓

a lot to gain by combined analysis

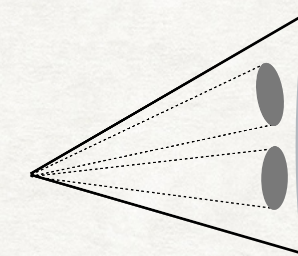
VH resonance search



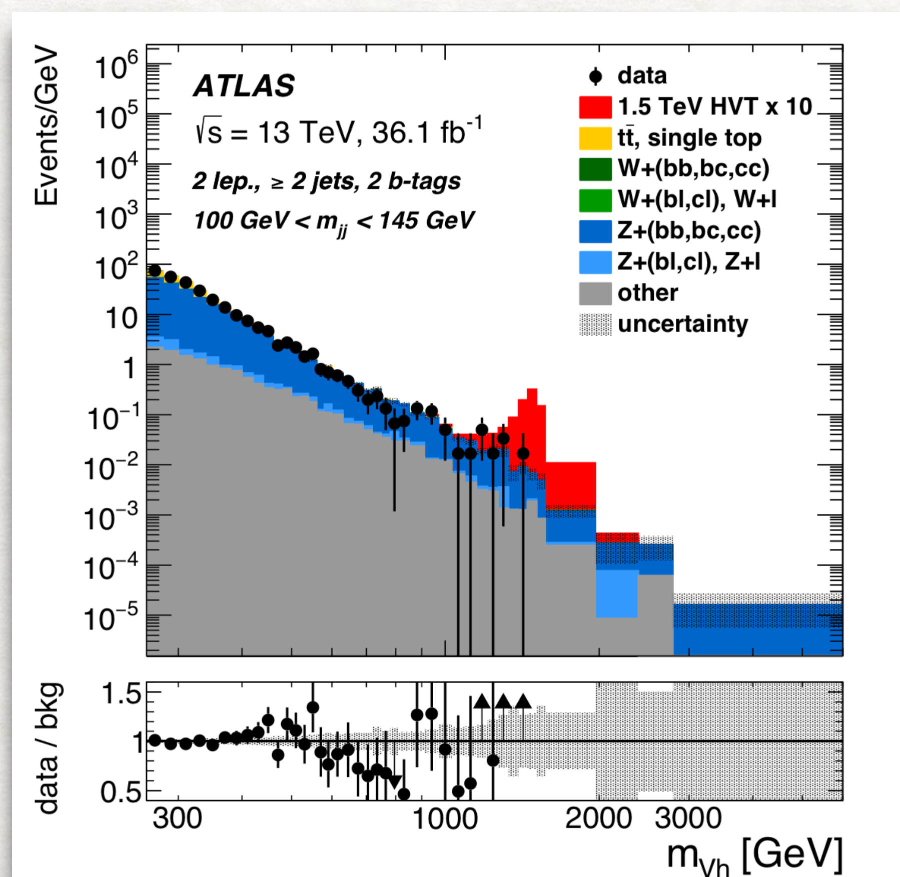
Resolved
R=0.4
calorimeter jets



Merged
R=1 calorimeter jet
+ ghost associated
R=0.2 track-jets



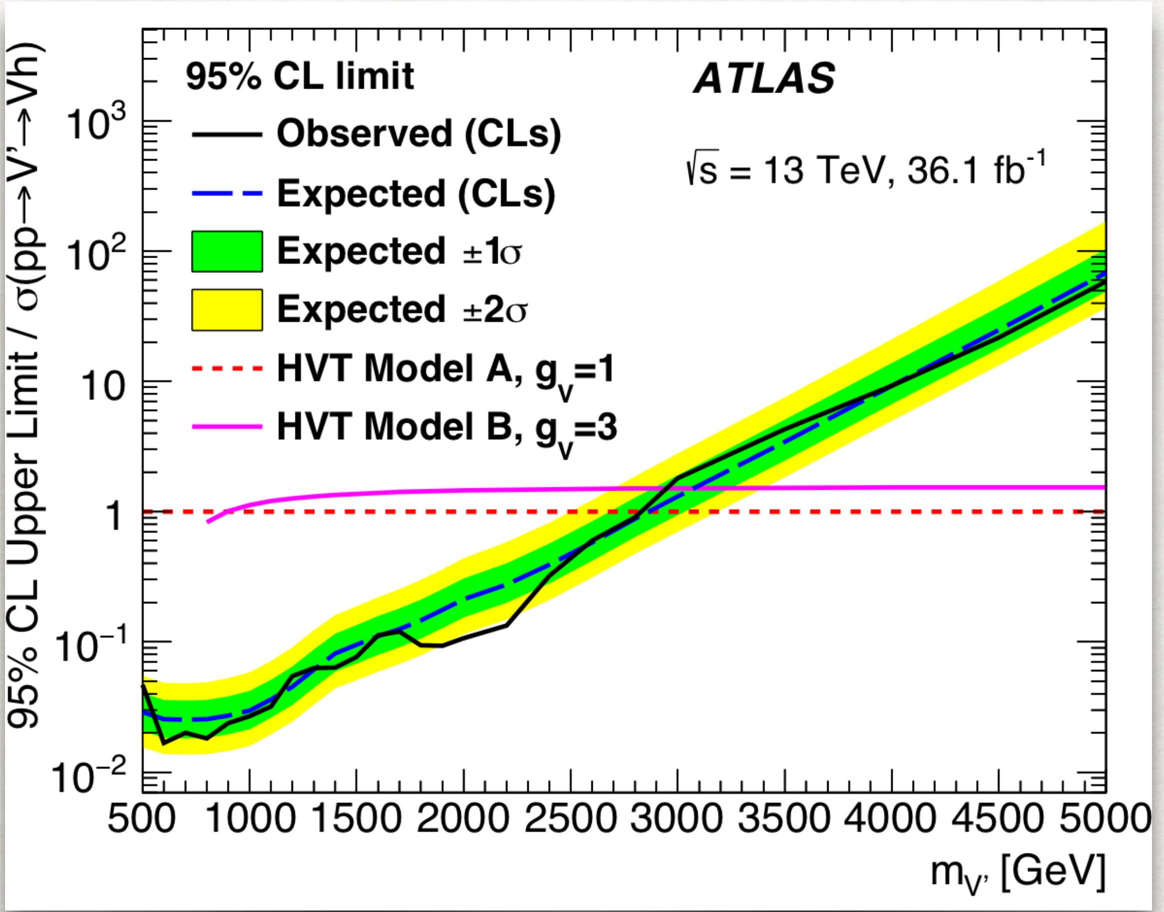
m_{llbb} distribution



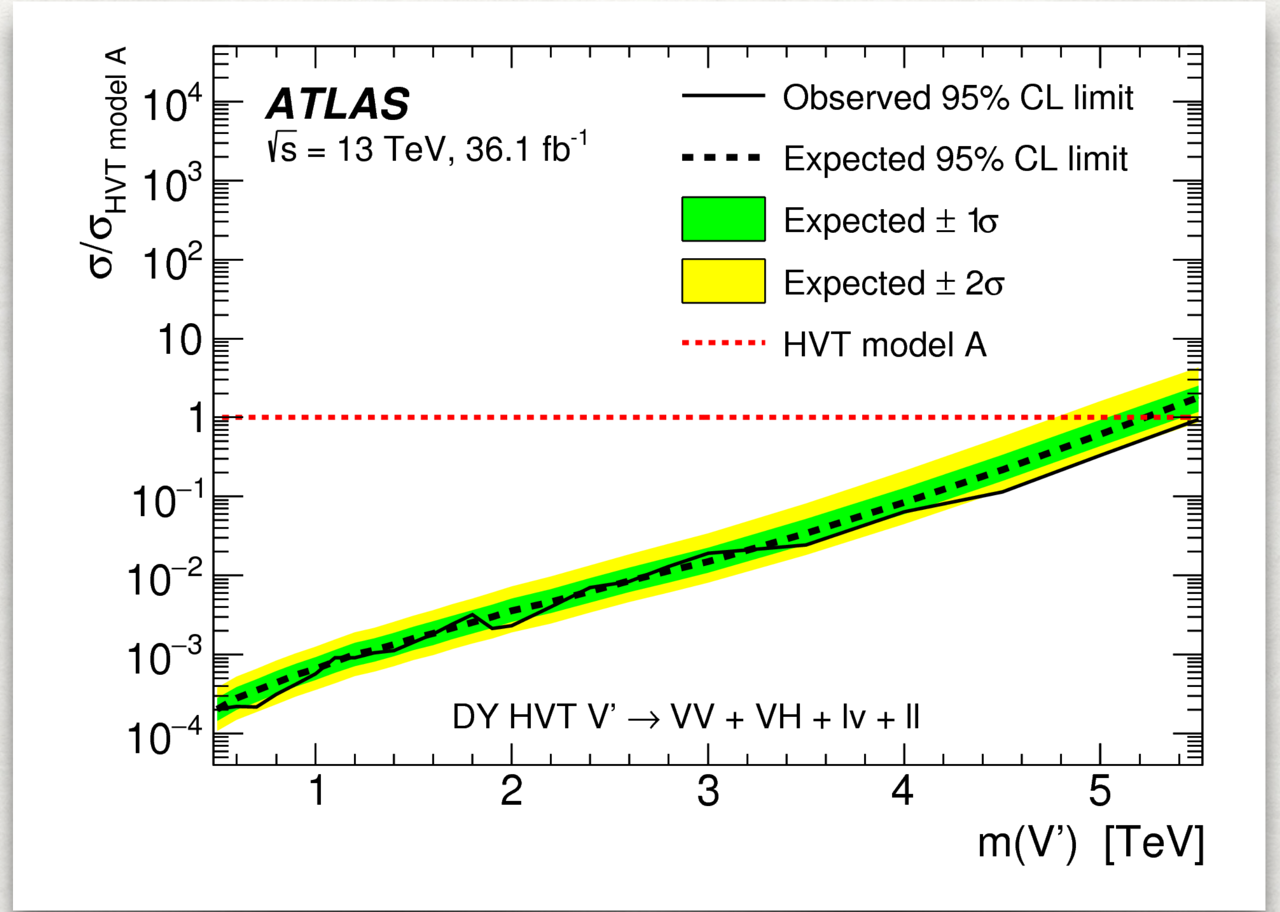
- Fit to m(Vh) or m_T(Vh)
- Several regions used
  - resolved & merged regions to gain sensitivity in different kinematic regimes
  - 3 channels: 0, 1, 2-lepton
  - m_{bb} side-band regions used to control Z/W+heavy flavour background
  - eμ region in 2-lepton used to control top bg
  - further splitting according to $N_{b\text{-jets}}$

The effect of a combined fit

Only VH channels



Combination: VV+VH+V

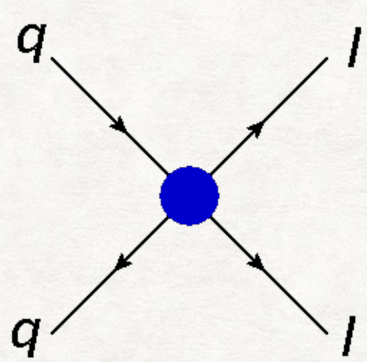


- Combined fit: much more data ⇒ much more constraining power
- Before combination: exclude $m_{V'} < 2.8$ TeV
- After combination: exclude $m_{V'} < 5.5$ TeV

NON- RESONANT SEARCHES

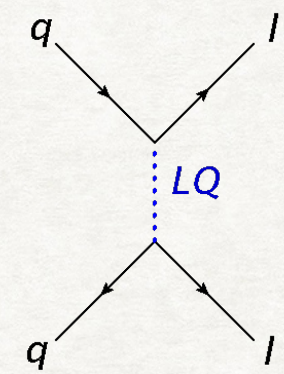
What is a non-resonant search?

No resonance



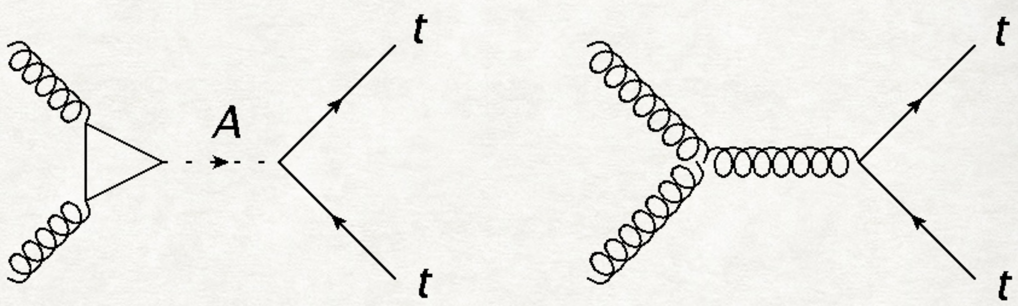
EFT interactions

Resonance not in s-channel

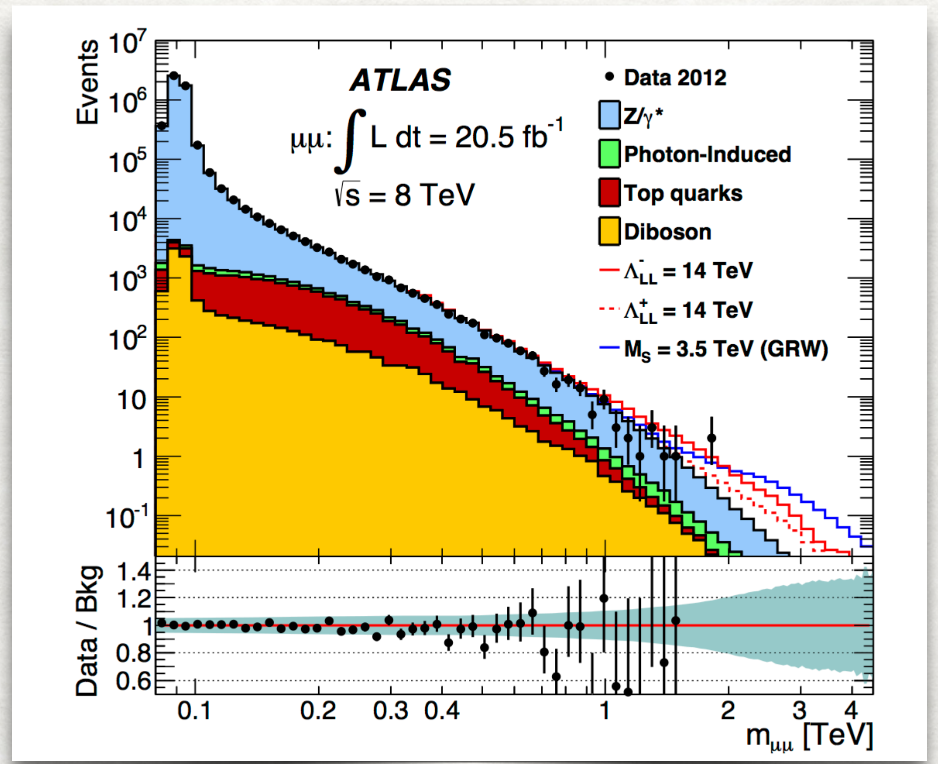


t-channel leptoquark

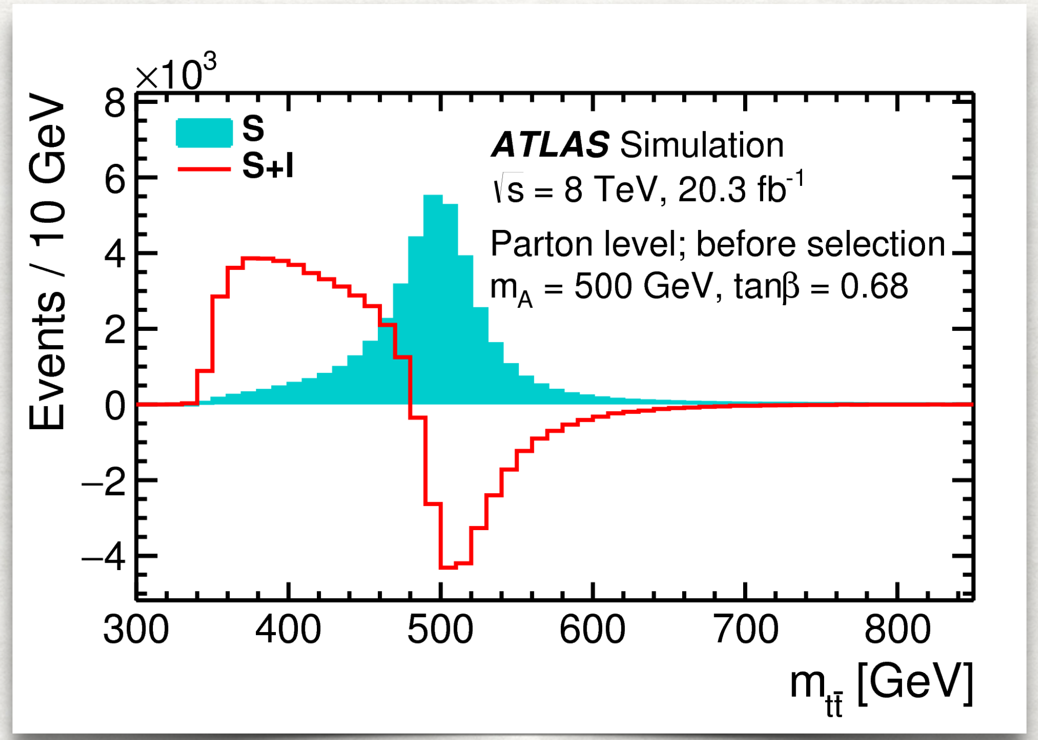
s-channel resonances interfering with SM background



A→tt

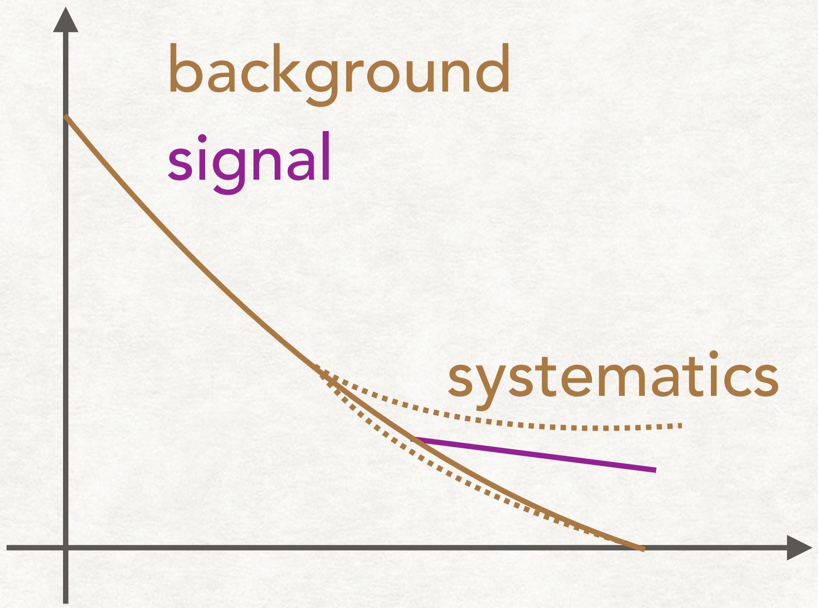


Tails



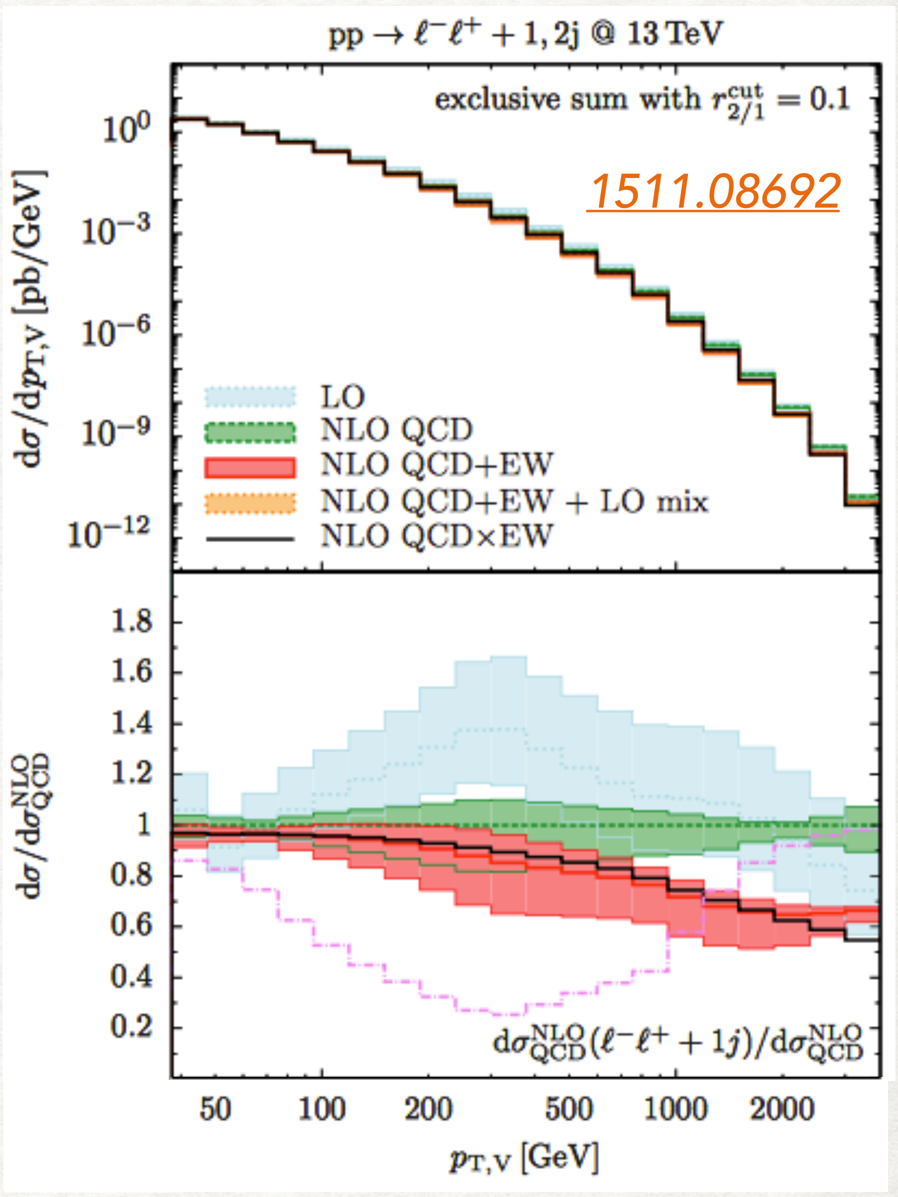
Dip in invariant mass

Challenges



- Shape analysis
  - Requires understanding and good control of the systematic errors - many effects can create a shape distortion (unlike a bump search)
- High-pT regime
  - Usually requires extrapolation from low p_T ⇒ increased uncertainties can bury signal
  - New effects/uncertainties become important, e.g. NLO EW corrections

NLO EW corrections



BARYOGENESIS

Electroweak baryogenesis

- Extensions of SM scalar sector can provide all ingredients for baryogenesis:
  - sphaleron mechanism (SM)

  \+ more CP violation than SM

  \+ 1st order phase transition (not possible in SM with m_H=125 GeV)

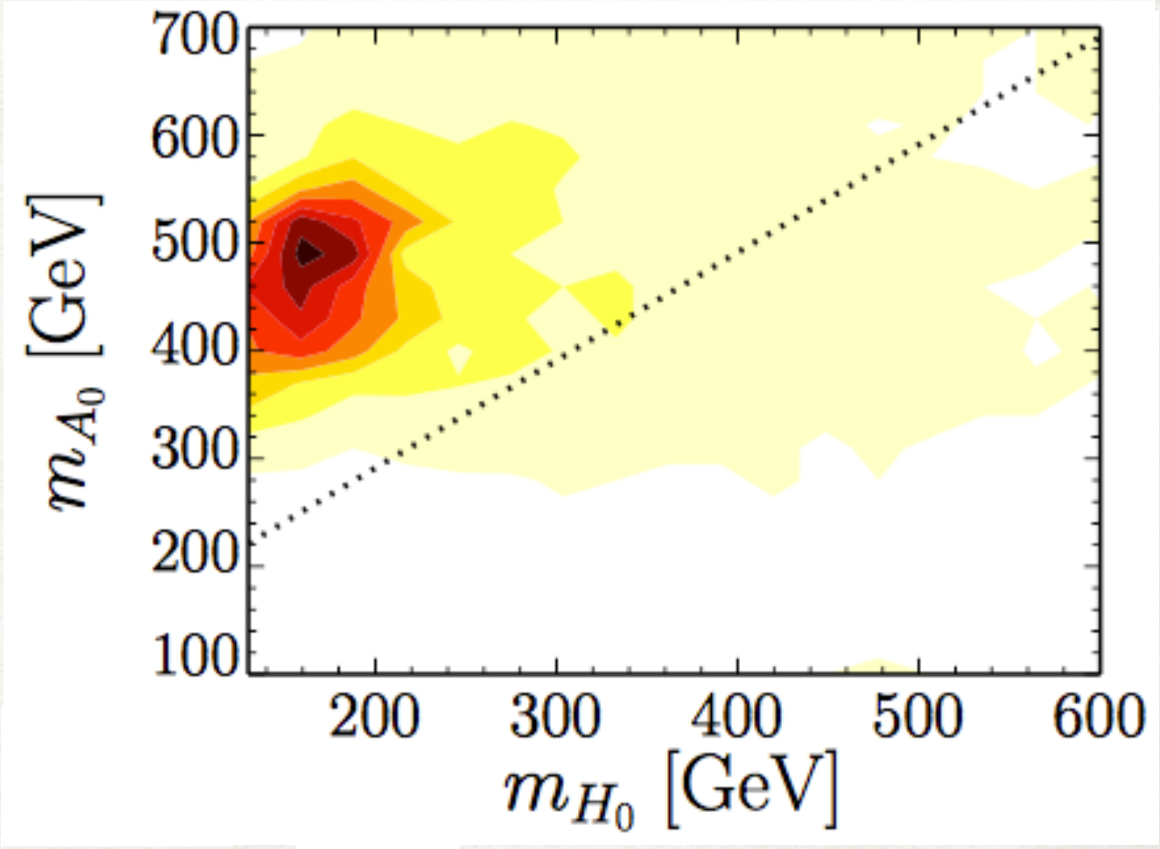
  ➡ the question is: under which conditions we have FOPT?

- 5 Higgses: A, H, h, H^+, H^-
- the conditions for FOPT are
  - $m_A > m_H$
  - large mass splitting

- then dominant decays are
  - A→ZH
  - H→bb

A→ZH→llbb is the smoking gun signal for electroweak baryogenesis

Favoured m_A,m_H values for FOPT



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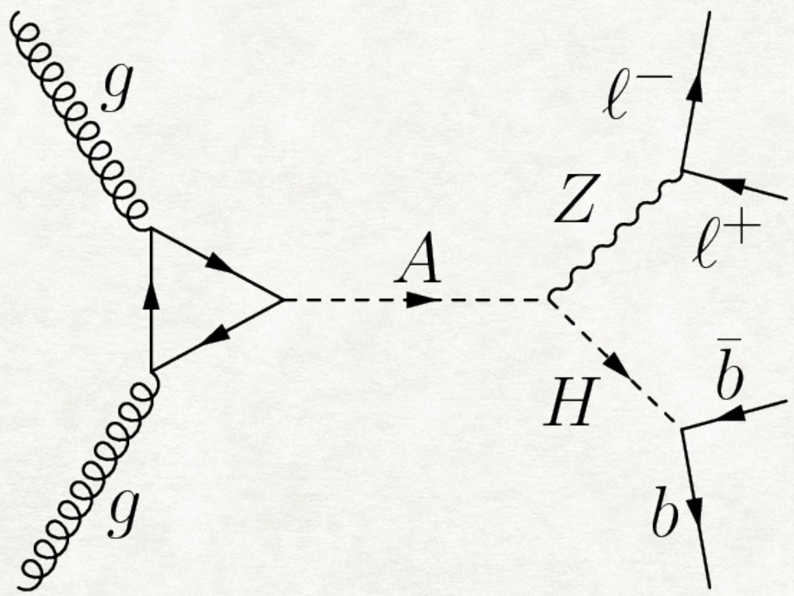
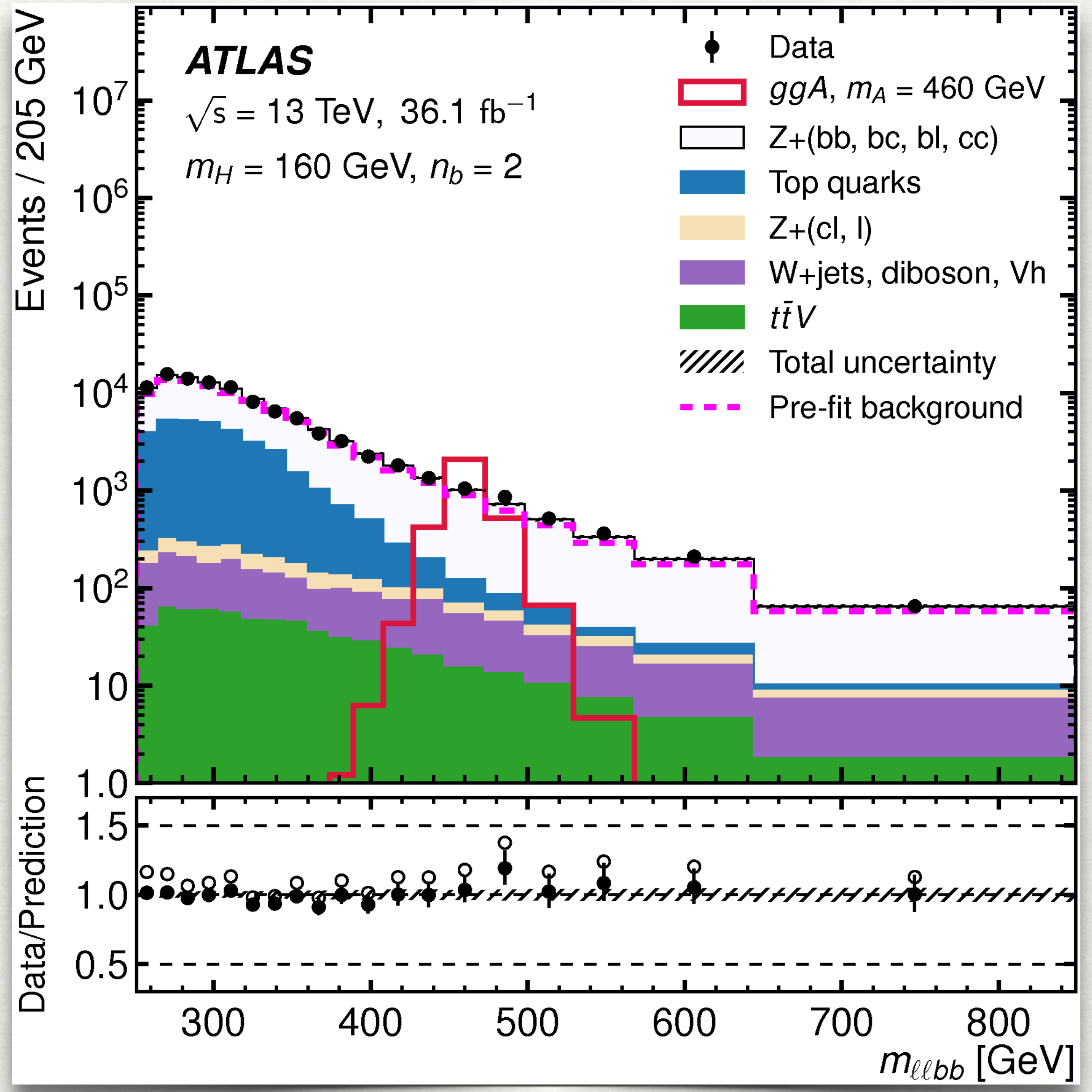
ATLAS search



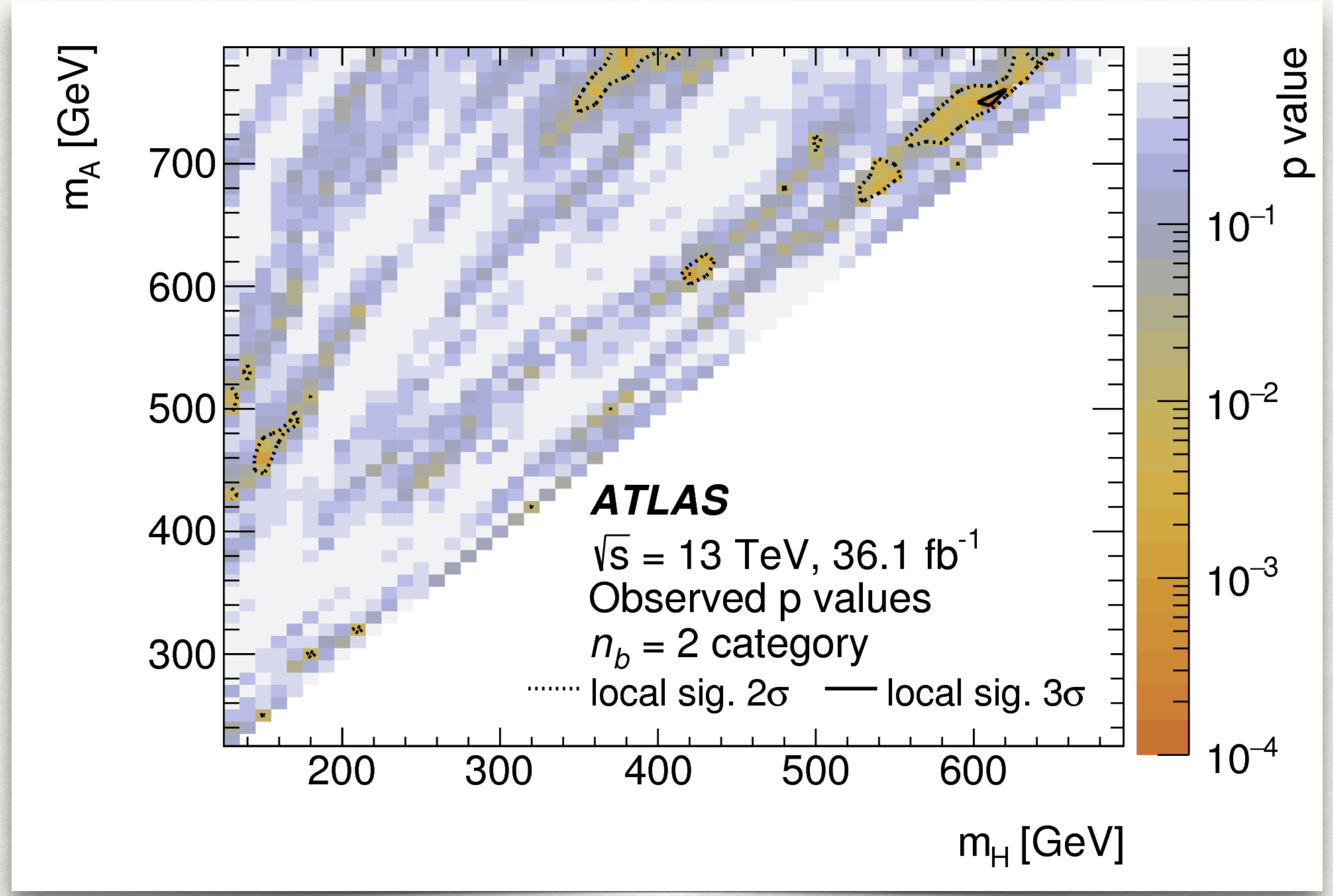
m_{llbb} distribution



- Look for bumps in m_{llbb}=m_A
- m_H is unknown so we also have to search in windows of m_{bb}
  - ➡ 2D resonance search
  - ➡ m_{llbb} fitted in windows of m_{bb}

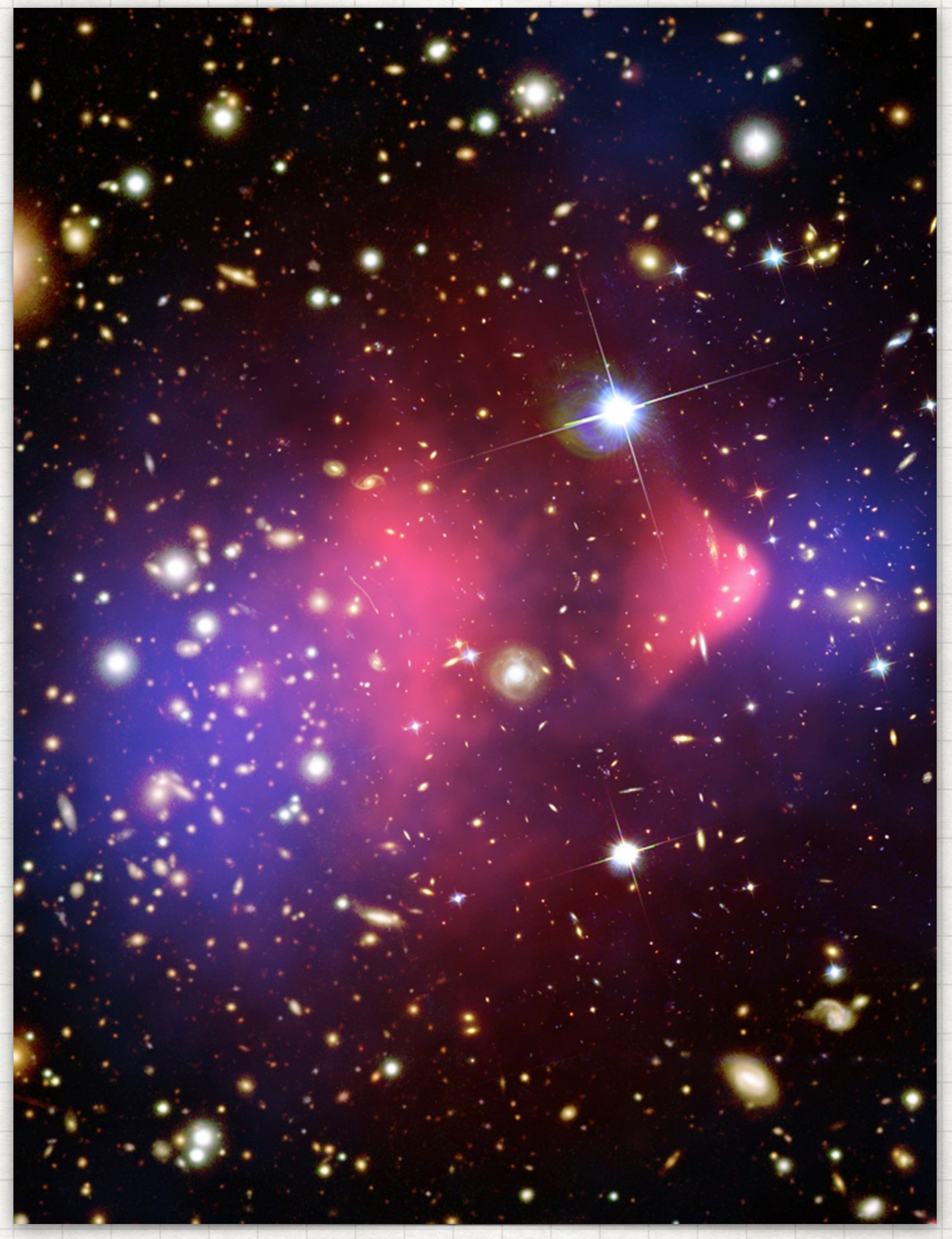
Results

Local p_0 plot



- **search performed in >1500 regions!**
- No significant excess found
- Still large phase space that remains viable for EW baryogenesis

DARK MATTER



What could DM be?

Characteristics:

- stable
- doesn't interact with EM or strong interactions

WIMPs

- mass ~m_W
- $\sigma \sim \alpha^2/m_W^2 \sim 1$pb
- arise in many BSM theories such as SUSY, extra dimensions, ...

Axions

- postulated to resolve strong CP problem
- unstable but lifetime can be O(10Gyr)

Sterile neutrinos

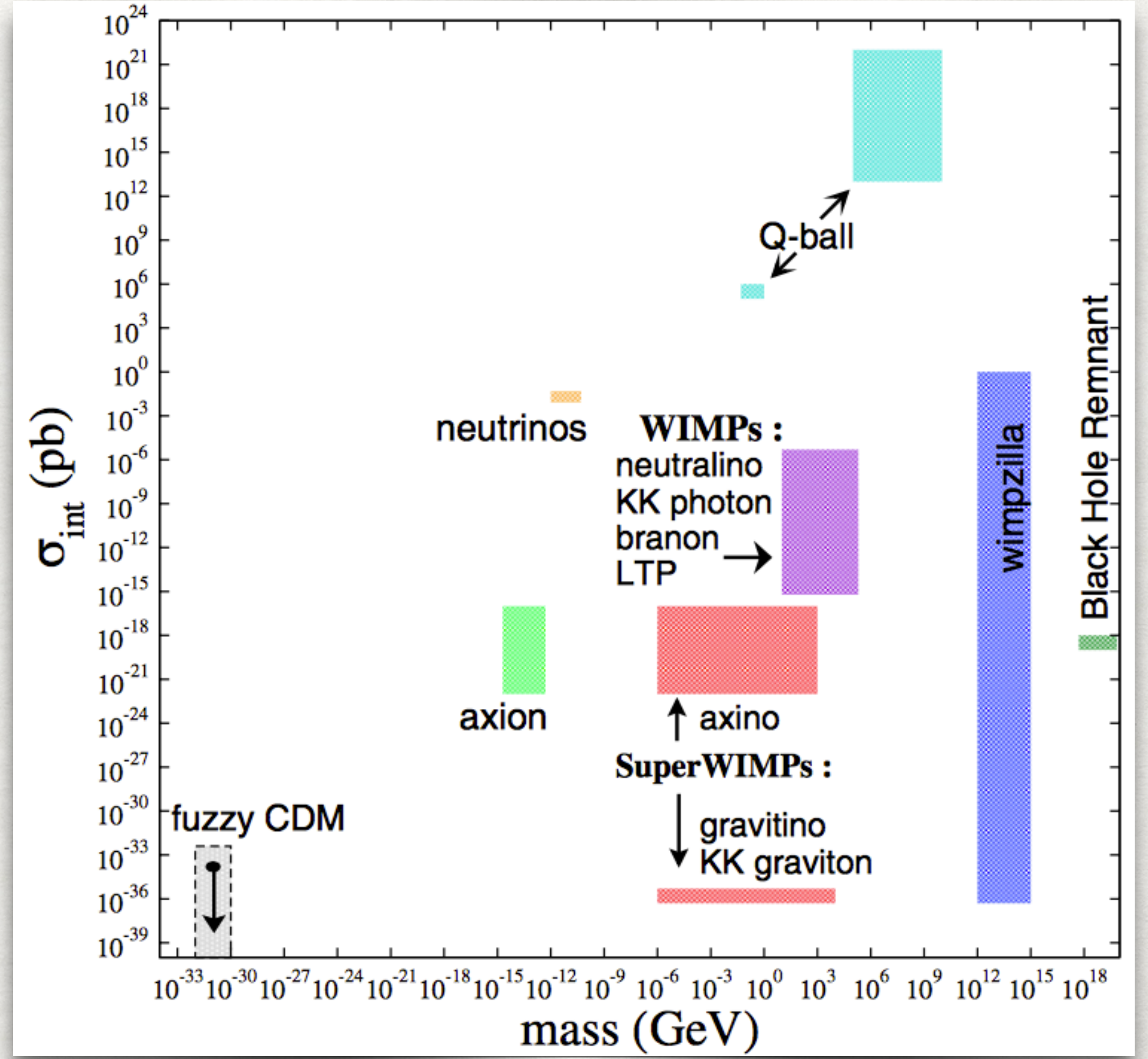
- related to neutrino mass problem

MACHOs

- primordial black holes, brown dwarfs, ...

or a combination of the above!

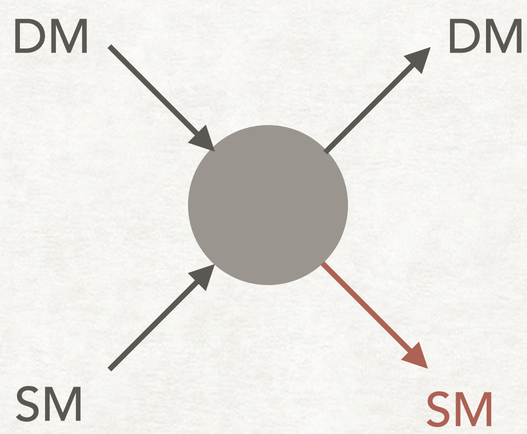
Immense zoo of DM candidates



Detection

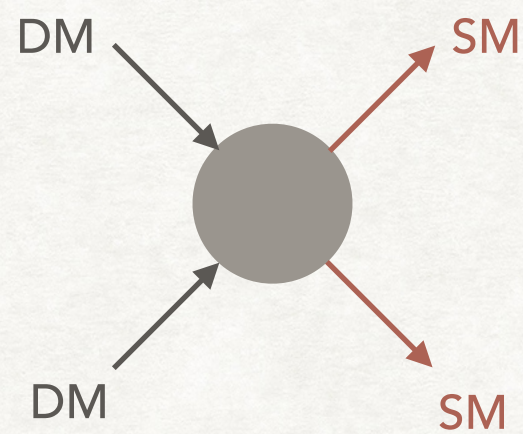
3 ways of detection

Direct detection



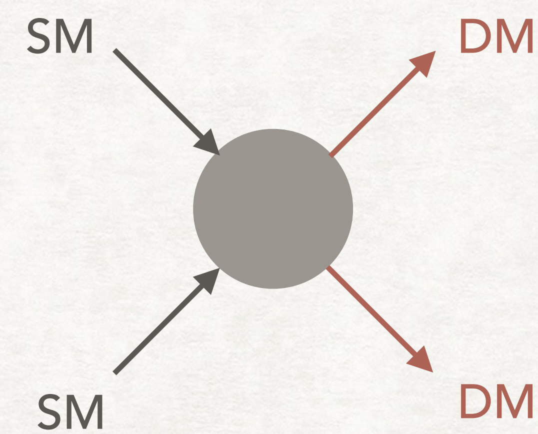
- Principle: detect recoil from interaction of DM with detector medium
- recoil detected via phonons/electrons/photons
- DM has to arrive to detector and interact
- Very low signal cross-section must have very low backgrounds
  - ➡ large volume
  - ➡ underground

Indirect detection



- Principle: detect DM annihilation products
- photons/neutrinos/$e^{\pm}$,p
- Earth-based (e.g. Fermi-LAT, IceCube) and space-based (e.g. AMS)

Colliders

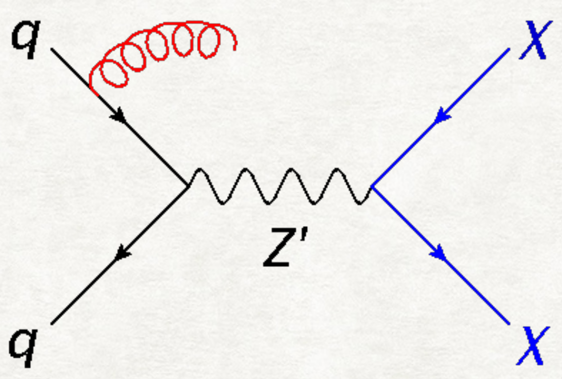


- Principle: DM is produced and its presence is inferred by momentum imbalance (missing energy)
- we can't measure missing energy - need X+E_T^{miss} signature
- X: jets, leptons, photons, top quarks, bottom quarks

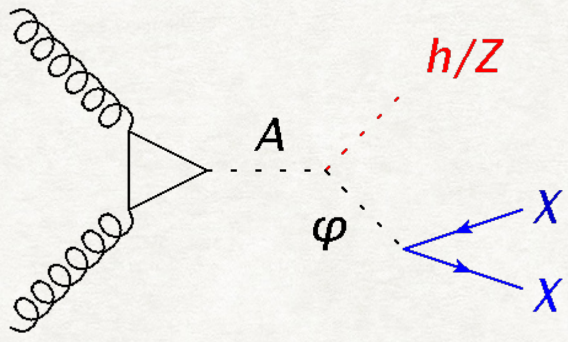
Collider signatures

Some examples

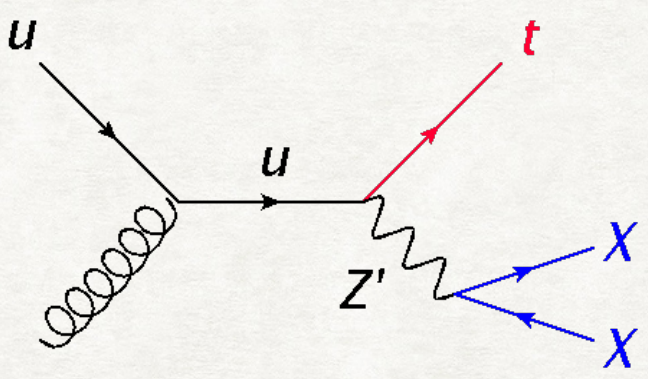
Mono-jet



Mono-H/Z



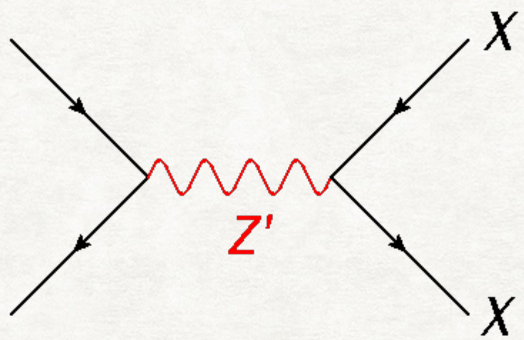
Mono-top



- General characteristic: missing energy (DM) + X (visible)
- In the past used EFT models: agnostic of UV details
  - limited validity especially for Q_{tr} ⇒ now use simplified models (UV complete)
- BSM particle (spin 0 or 1) mediates SM-DM interaction
- mediator properties determine signatures
  - e.g. FCNCs, part of extended Higgs sector, …

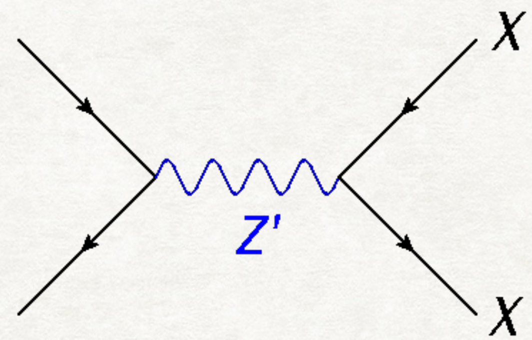
EFT vs simplified models

Off-shell



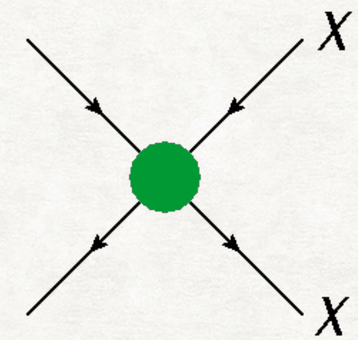
- $Q_{tr} \gg M_{med}$
- EFT limit too aggressive

On-shell

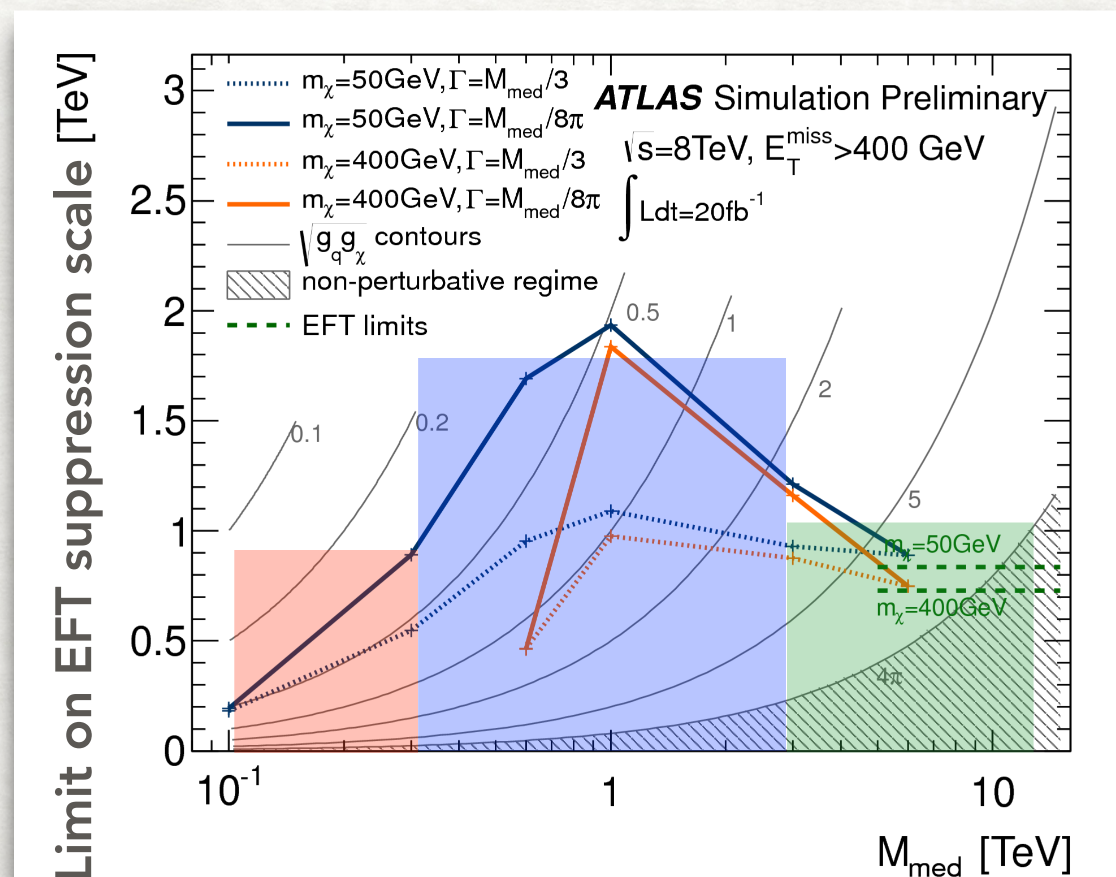


- $Q_{tr} \sim M_{med}$
- EFT limit too pessimistic
  (not sensitive to resonant enhancement)

Contact Interaction



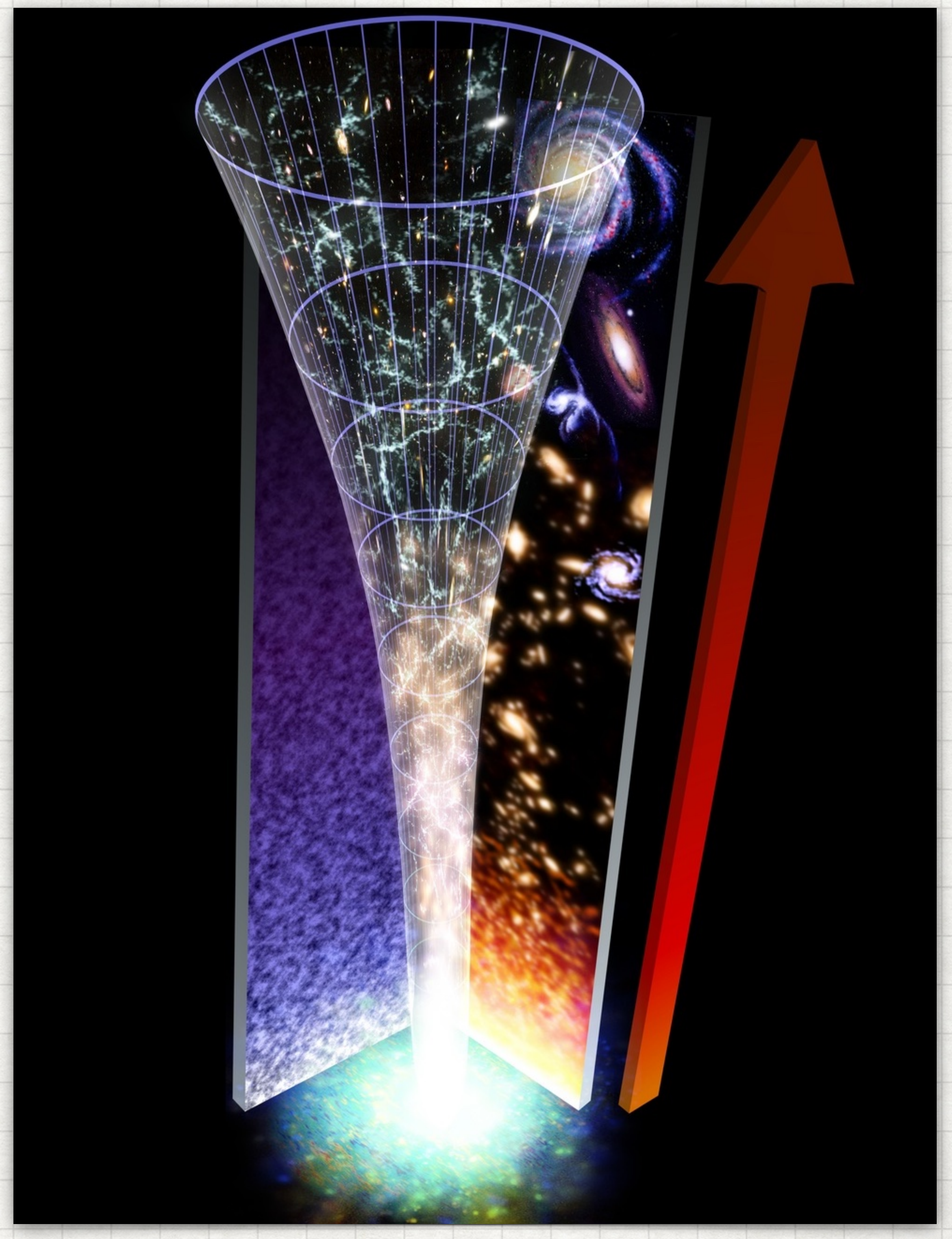
- $Q_{tr} \ll M_{med}$
- "mediator too heavy to propagate"
- EFT limit correct



- EFT validity: $Q_{tr} \ll M_{med}$
- EFTs may have limited validity at colliders
  - EFT limits have to be rescaled outside their validity range
- Simplified (UV complete) valid for all Q_{tr} - more widely used

DARK ENERGY

AND EFTs



What is Dark Energy?

Cosmology

observations
+
assumptions
(cosm. principle)

⇒ FLRW **metric**

+

General Relativity

$$G_{\mu\nu} = 8\pi G \, T_{\mu\nu}$$

⇒ **Friedmann equations**

matter governs evolution of space-time

Types of matter

- Radiation: p=ρ/3 ⇒ decelerating expansion
- (Baryonic/Dark) Matter: p=0 ⇒ (more slowly) decelerating expansion
- **"Dark Energy"**: p < -ρ/3 ⇒ **accelerating expansion**
  - Cosmological constant Λ: p=-ρ ⇒ exponentially accelerating expansion

Particle Physics

- Cosmological constant = **vacuum energy density** (120 orders of magnitude off)
- Many **new BSM fields** can also reproduce EOS of Dark Energy

Why to search for DE at colliders

- **Interaction of DE with SM particles arises naturally in many models**
  - Screening of 5th forces: escape detection at high density regions $\rightarrow$ DE must "feel" the density of SM matter $\rightarrow$ non-zero DE/SM interaction

$\Rightarrow$ **DE can be produced and constrained at colliders** [1]

- **Dark degeneracy**
  - modified gravity models can lead to same phenomenology as DE

$$\tilde{G}_{\mu\nu} = 8\pi G \, \tilde{T}_{\mu\nu}$$

$\Rightarrow$ need **particle physics to distinguish modified gravity from dark energy** [2]

- **Complementarity with non-collider experiments**

  $\Rightarrow$ collider experiments sensitive to multitude of signatures

  $\Rightarrow$ access different parts of parameter space

  $\Rightarrow$ investigate microscopic nature of DE

So far no direct search by collider experiments

Model & Signatures

- **DE scalar field φ** - **EFT couplings** (1604.04299)

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{M_i^{(d-4)}} \mathcal{O}_i^{(d)} + \frac{1}{2} m^2 \phi^2$$

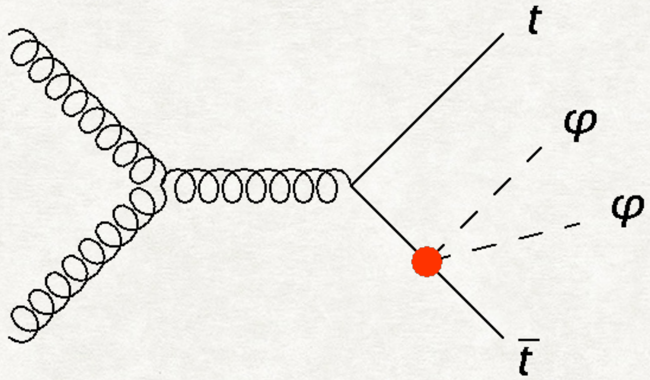
- Study two lowest-dimension operators:

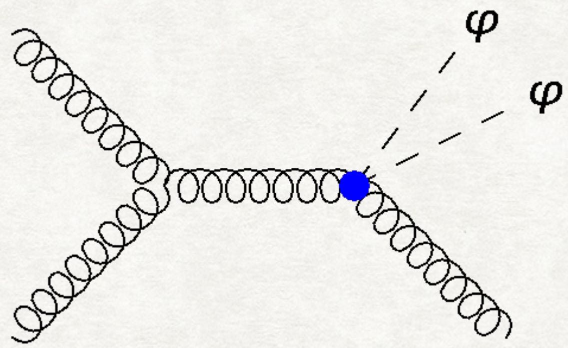
$$\mathcal{L}_1 = \frac{\partial_\mu \phi \partial^\mu \phi}{M^4} T^\nu_\nu$$

(kinetic) **conformal coupling**
⇒ enhanced for **heavy final states**

$$\mathcal{L}_2 = \frac{\partial_\mu \phi \partial_\nu \phi}{M^4} T^{\mu\nu}$$

disformal coupling
⇒ enhanced for **high momentum**



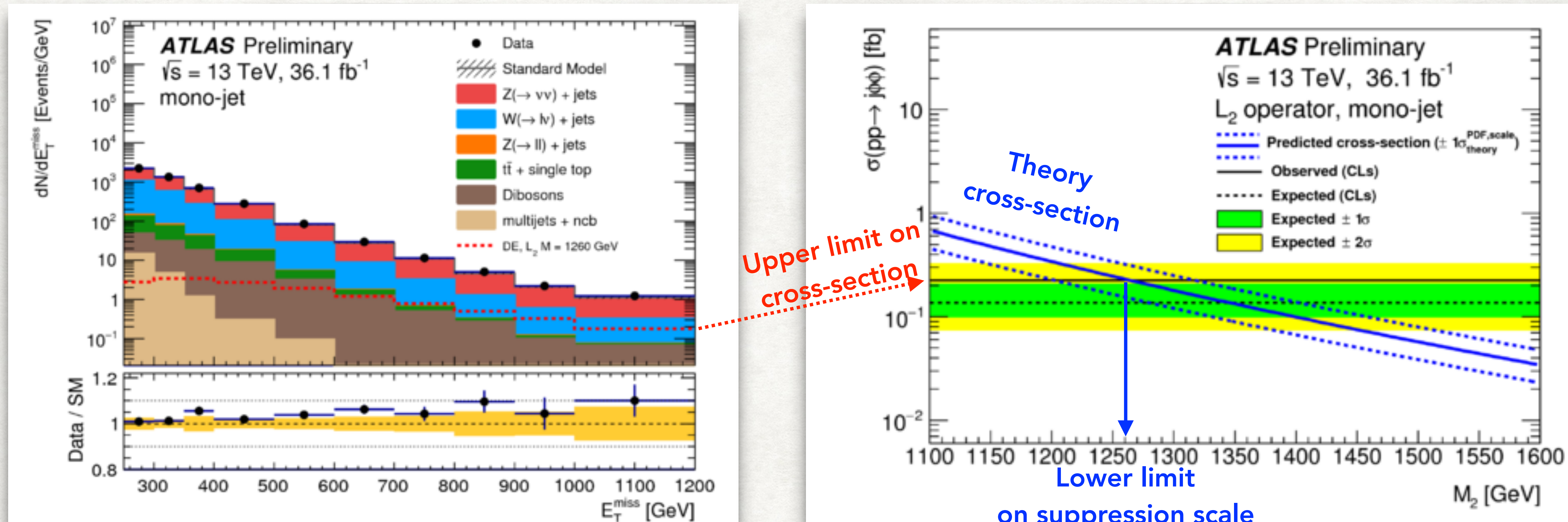


- Top final states: enhanced sensitivity to L_1 due to high top mass
- Mono-jet final states: enhanced sensitivity to L_2 due to high momentum transfers
- **DE particle φ** stable and non-interacting ⇒ seen as **missing energy** in the detector

⇒ **Signatures: tt+ E_T^{miss} , jet+ E_T^{miss}**

How we constrain it

Measure X+E_T^{miss} | *Evaluate upper limit*



- Measure E_T^{miss} (or E_T^{miss}-like) spectra and **look for deviations in the high E_T^{miss} tail**
- Fit signal template to data+background and evaluate maximal cross-section **(upper limit) compatible with data**
- **Use theory to translate it into a lower limit on the suppression scale**

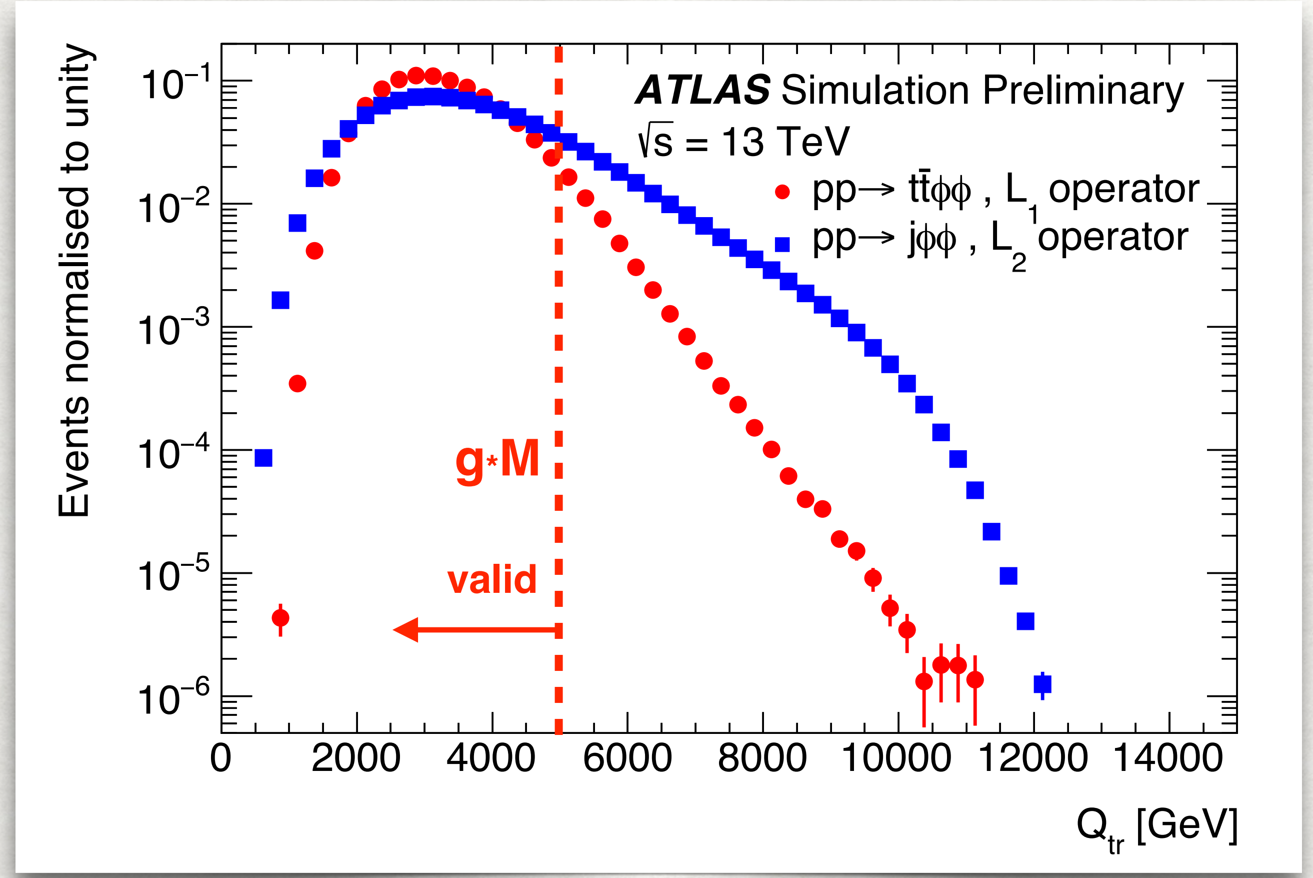
Rescaling EFT limits

- EFT approximation valid when momentum transfer not enough to resolve the interaction: $Q_{tr} \ll M$
- In practice use

$$\boxed{Q_{\rm tr} < g_* M}$$

$g_\star$: effective coupling related to UV completion of EFT ($g_\star < 4\pi$)
M : lower limit on EFT suppression scale

Momentum transfer

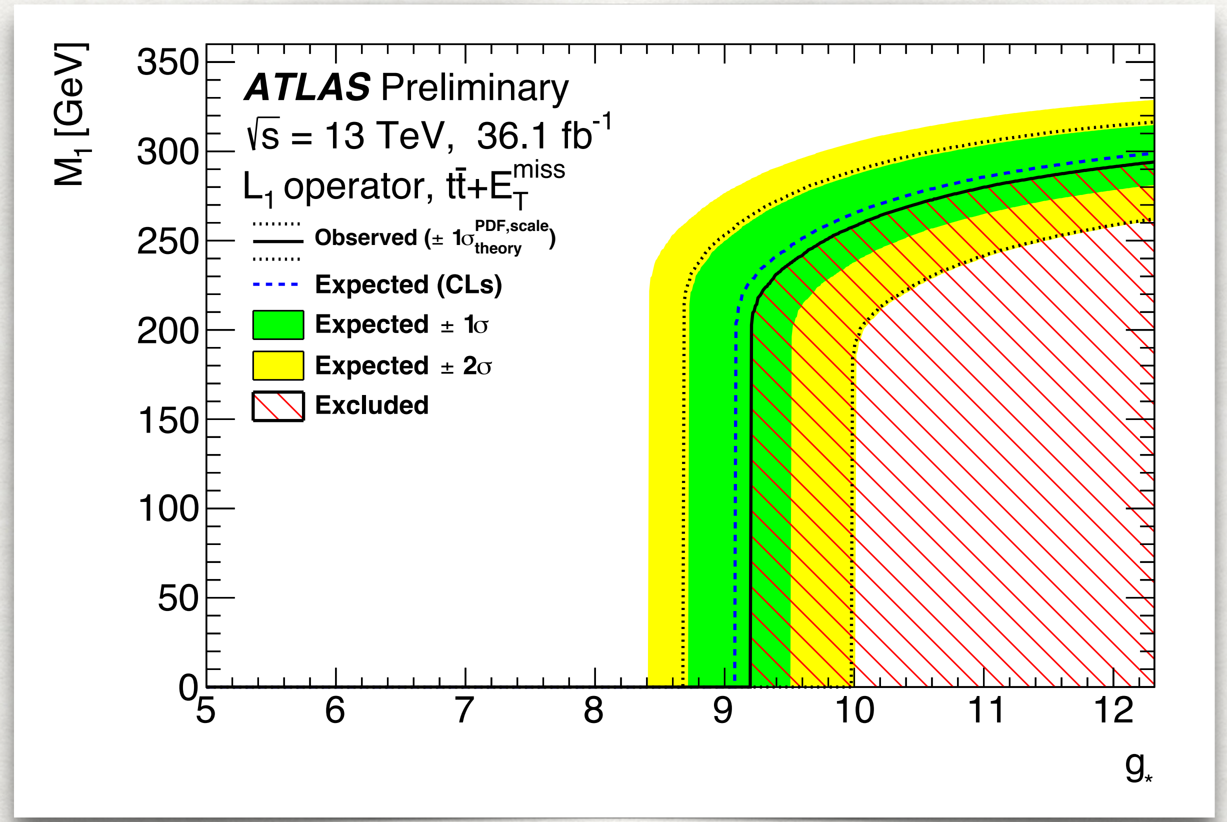


- UV completion unknown ⇒ use partonic c.o.m. energy $Q_{\rm tr} = \sqrt{\hat{s}}$
- Scan $g_\star$ and evaluate R: fraction of events that satisfy validity criterion
- Rescale limit using (1402.1275)

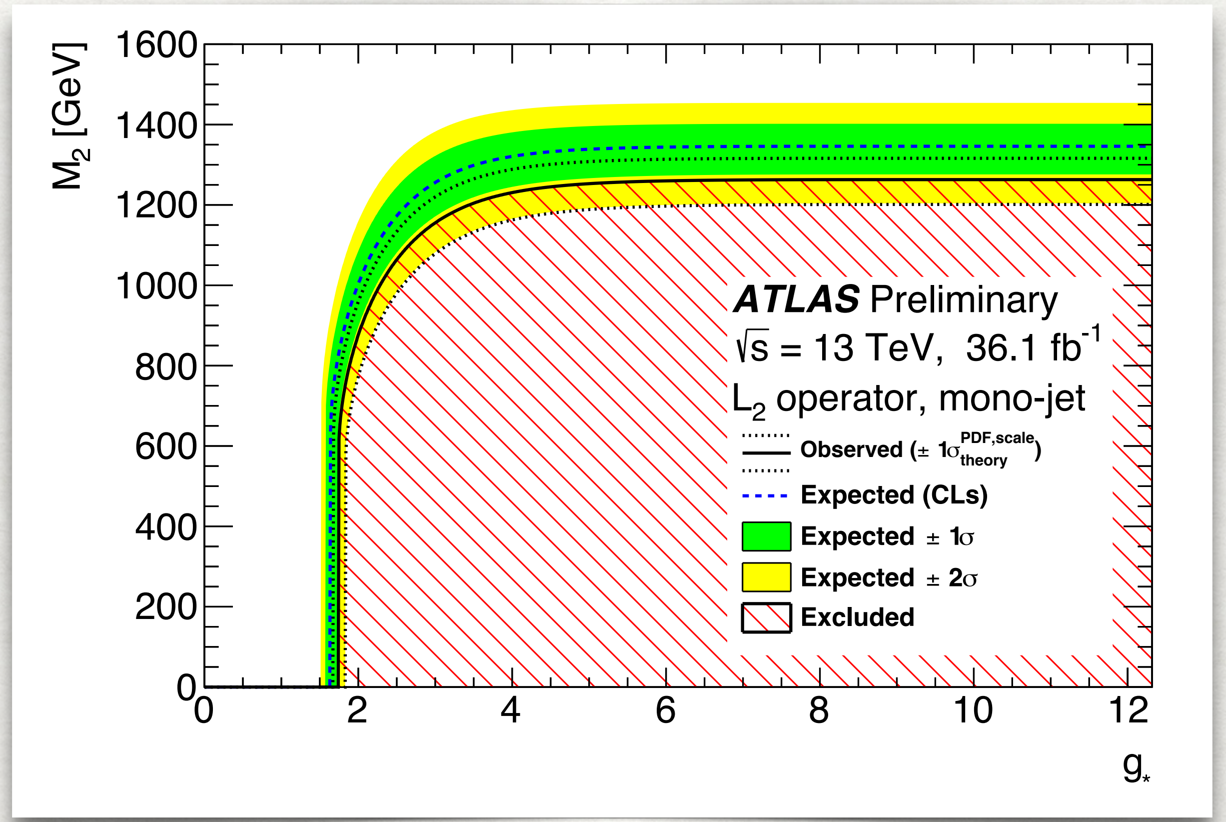
$$M_{\rm resc} = R^{1/2(d-4)} M$$

Interpretation

Exclusion limit vs coupling for L_1



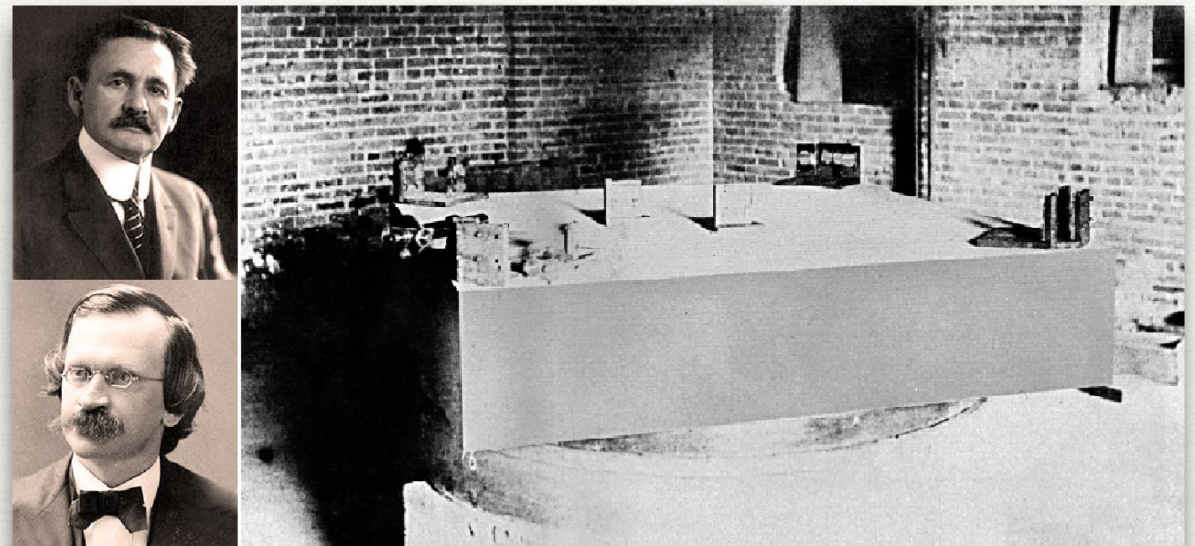
Exclusion limit vs coupling for L_2



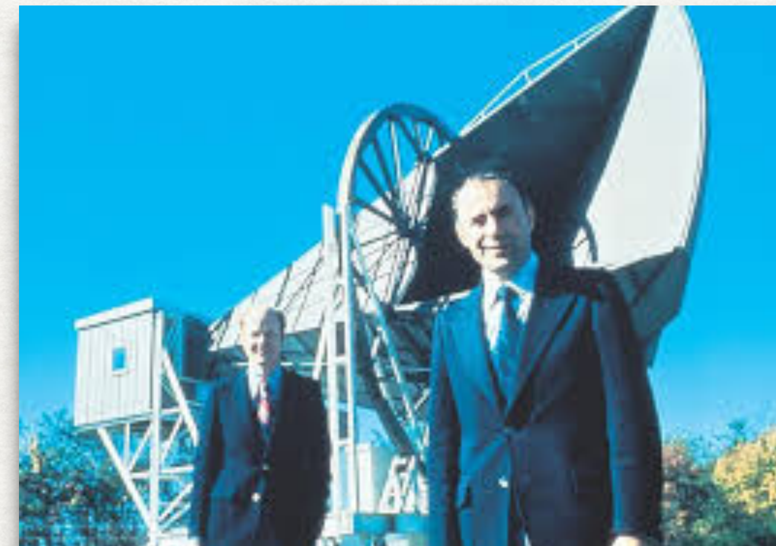
ATLAS is the first experiment to probe all forms of matter in the observable universe!

Why haven't we found anything yet?

Michelson-Morley: the most famous "failed" experiment



CMB: a standard measurement turned into a revolution



Keep eyes and mind open and nature will surprise us!

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