Physics Beyond Standard Model : Exotics Chapter 1

HASCO Summer School 2023

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whoami

I am an experimental physicist, senior staff researcher at INFN (Istituto Nazionale Fisica Nucleare) – Sezione di Bologna

I am ATLAS member since looong time. Previously I was member of the CDF experiment at Fermilab (top quark discovery!) → Hadron collider physics

Current Research interests:

- Exotic physics (mainly leptonic signatures)
- ITk (Inner Tracker Phase2 Upgrade for ATLAS High-Lumi LHC)
- Missing Energy Trigger

Focus on experimental and practical aspects (with examples) of Beyond Standard Model searches at Hadronic colliders.

I will be ~~probably~~ biased towards ATLAS experiment

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Forewords

I would like to **thank** lecturers of previous HASCO schools (M. Verducci, C. Doglioni, and many others) since their previous lectures were a source of “inspiration”

Many slides have been elaborated from CERN seminars, public presentations in ATLAS, etc.. I have tried to reference properly and acknowledge authors when possible.

I apologize in advance if I have missed some of the authors

Outline

- Why looking for physics Beyond Standard Model ?
- “So, you want to look for Beyond Standard Model physics”
  - Ingredients of a search: strategy, background estimation, statistics,...
- Few searches
  - Leptoquarks
  - Dark Matter
  - Long Lived Particle searches

Outline

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Beyond Standard Model

Look for example on CMS Publication web page

CMS Physics Publications

- Forward and Small-x QCD Physics
- B Physics and Quarkonia
- Standard Model Physics
- Top Physics
- Higgs Physics
- Supersymmetry
- Exotica
- Beyond 2 Generations
- Heavy-Ion Physics

C. Merlassino lecture

Exotica Publications

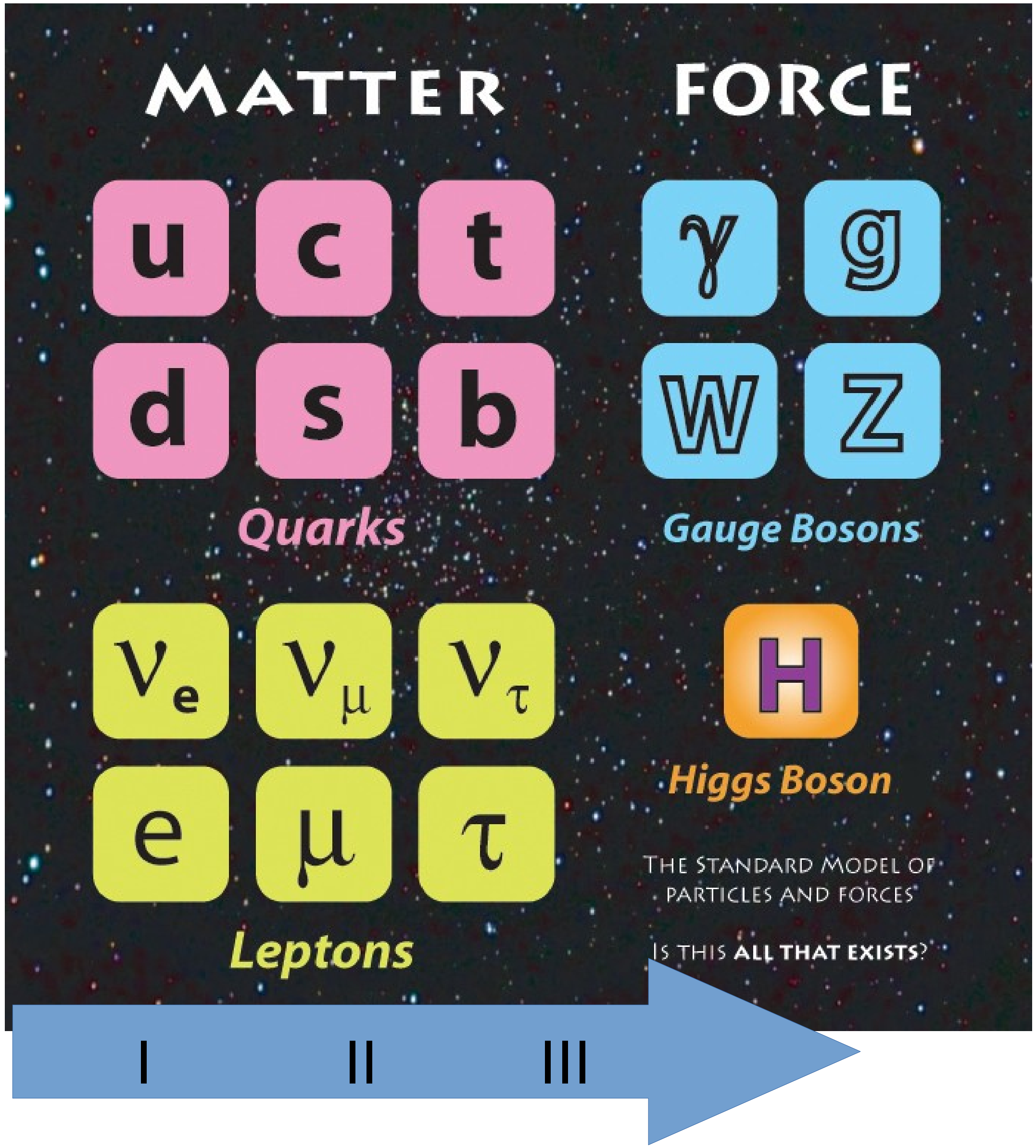
- Leptoquarks
  - First-Generation Leptoquarks
  - Second-Generation Leptoquarks
  - Third-Generation Leptoquarks
- Randall--Sundrum Gravitons
- Heavy Gauge Bosons
  - Sequential Standard Model
  - Superstring-Inspired Models
- Long-Lived Particles
- Dark Matter
- Large Extra Dimensions
  - Arkani-Hamed--Dimopoulos--Dvali Model
  - Semiclassical and Quantum Black Holes
- Compositness
- Contact Interactions
- Excited Fermions
- Heavy Fermions, Heavy Righ-Handed Neutrinos
- Colorons, Axigluons, Diquarks
- Supersymmetry
- Resonances
  - Multijets
  - Dijets
  - Dileptons
  - $t\bar{t}$
  - Dibosons, VV and VH
  - Boosted Topologies

There are more things in ~~heaven and earth~~ your experiment, Horatio,
Than are dreamt of in your ~~philosophy.~~ model

William Shakespeare

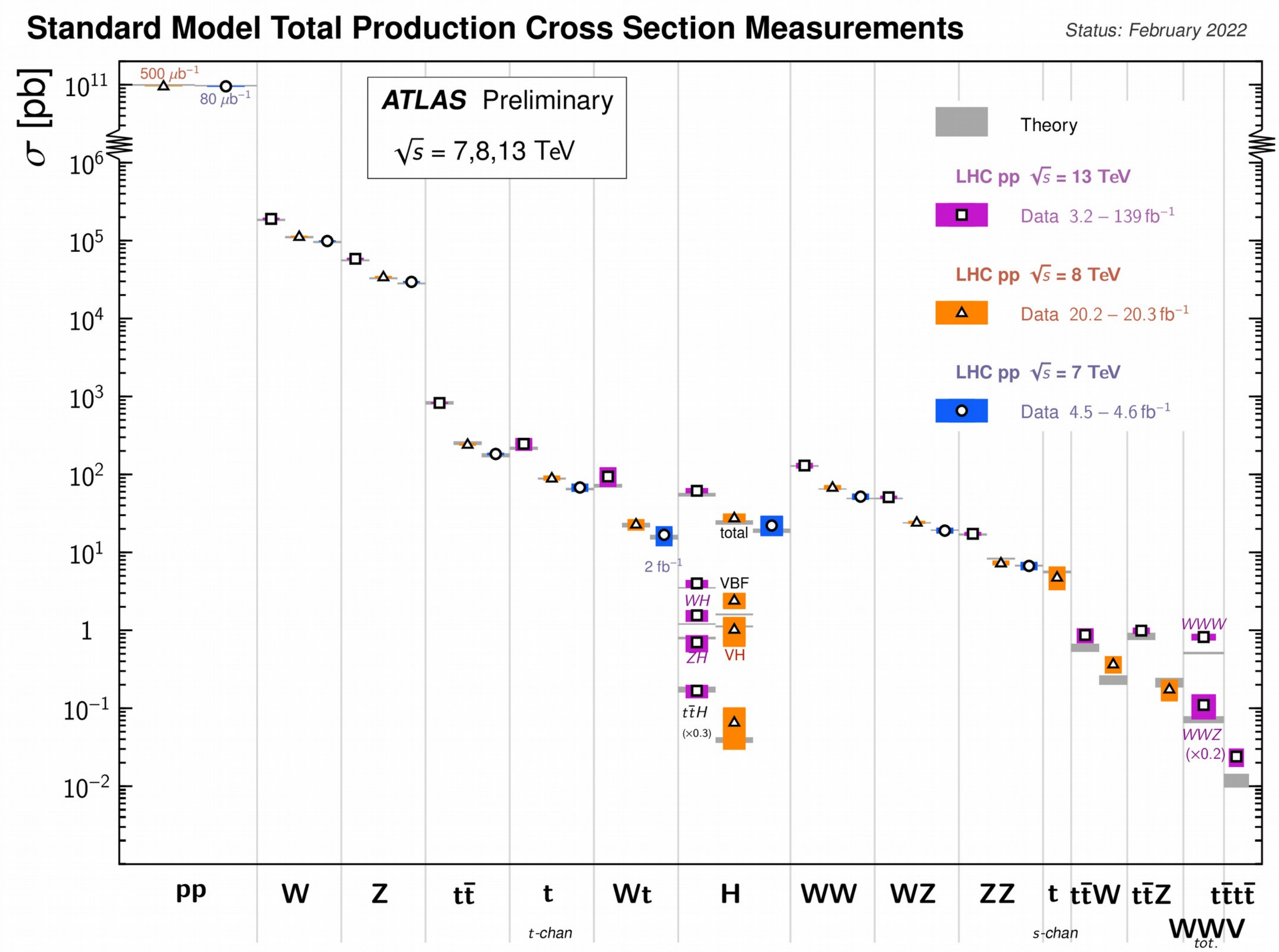
The Tragedy of Hamlet, Prince of Denmark
Act 1, Scene 5

The Standard Model



Matter Generations

The Standard Model



Impressive theory providing predictions valid over **7 orders** of magnitude!

Why BSM?

Theoretical/Aesthetic Motivations

- Too many free SM parameters (masses, mixing, couplings)
- Hierarchy problem (huge gap between fundamental particles masses)
- Fine tuning of Higgs mass (Higgs boson is the only fundamental scalar particle)
- and counting ...

Experimental Motivations

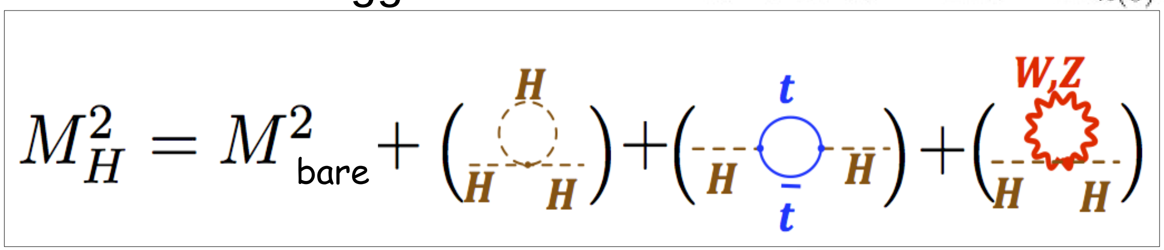
- Dark Matter
- Dark Energy
- Gravity
- Matter vs Anti-Matter
- and counting...

Hierarchy Problem

17 orders of magnitude between Eelectroweak scale and Planck scale

$$m_h = 125 \text{ GeV} \ll M_{Planck} = 10^{19} \text{ GeV}$$

Corrections to Higgs mass $\quad (125\text{GeV})^2 = m_h^2 = m_{h(0)}^2 + \delta m_h^2$



$$\delta m_h^2 = -\frac{3y_t^2}{8\pi^2}\Lambda_{UV}^2$$

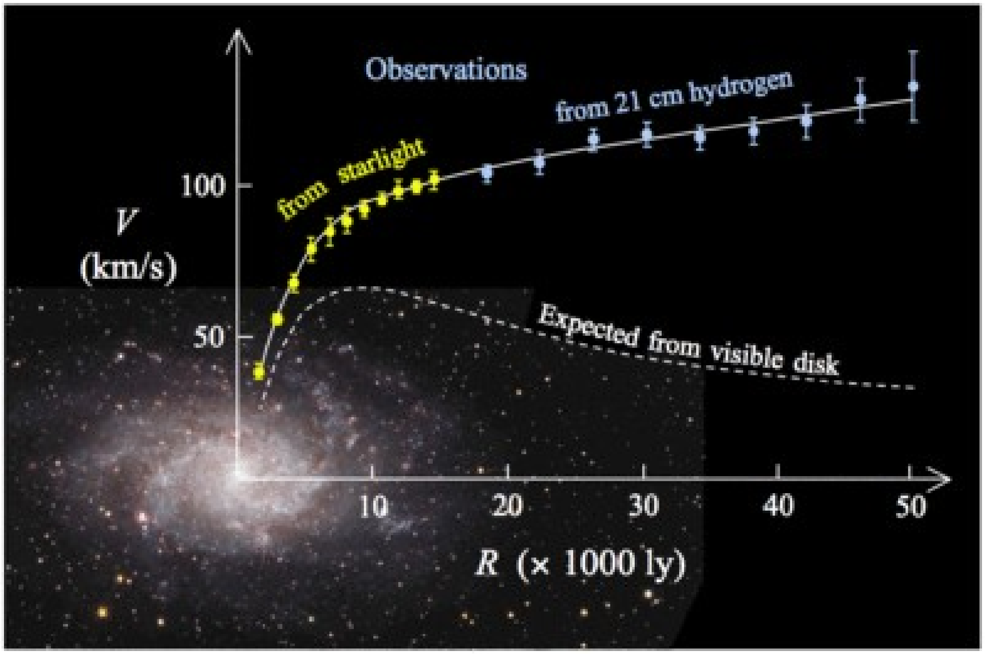
If $\quad \Lambda_{UV} = M_{Planck} \quad \Rightarrow \quad \dfrac{\delta m_h^2}{(125 \text{ GeV})^2} \simeq 10^{32}$ $\quad$ Fine Tuning !

If no fine-tuning $\quad \dfrac{\delta m_h^2}{(125 \text{ GeV})^2} \simeq 1 \quad \Rightarrow \quad \Lambda_{UV} \simeq 650 \text{ GeV}$

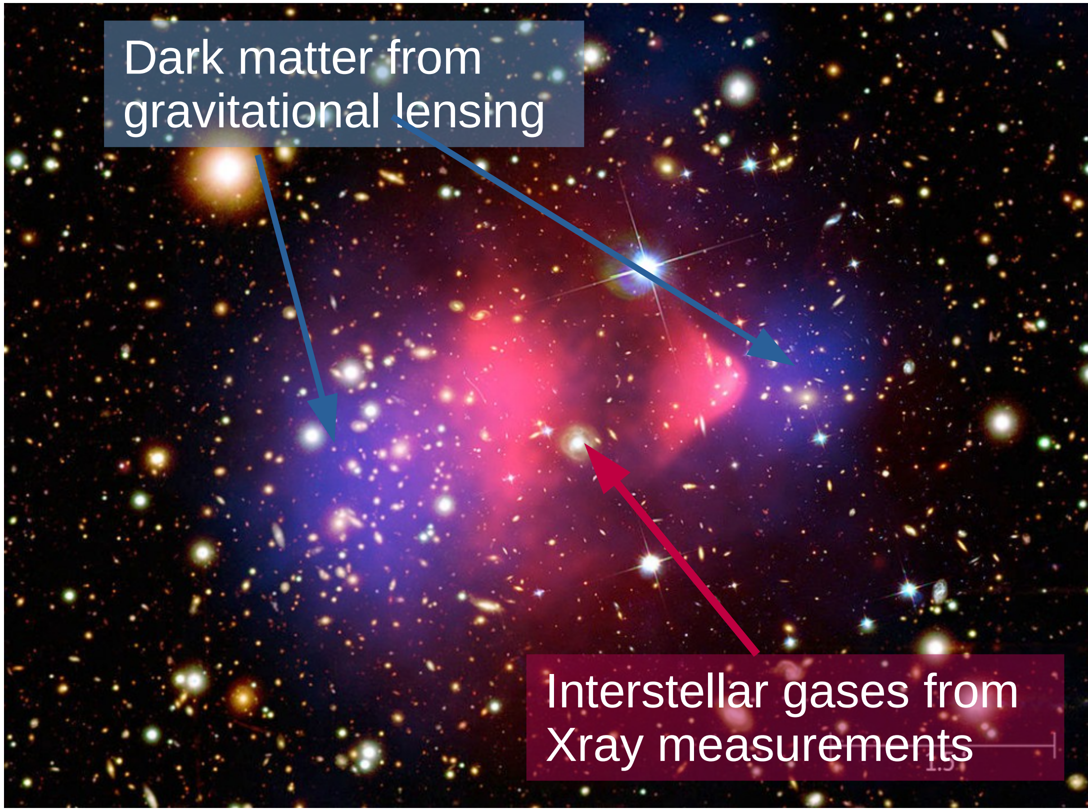
How to solve Hierarchy?

- Λ_{UV} is not at the Planck scale (in the reach of LHC?) → **BSM**
- Higgs is composite → **BSM** (It happens for π^0 and $\pi^\pm$)
- Additional particles cancel divergences → SUSY → cf lecture from C. Merlassino tomorow
- Anthropic scenario → Multiverse (not sure how to test that...)
- Something else …. (Intriguing….)

Dark Matter



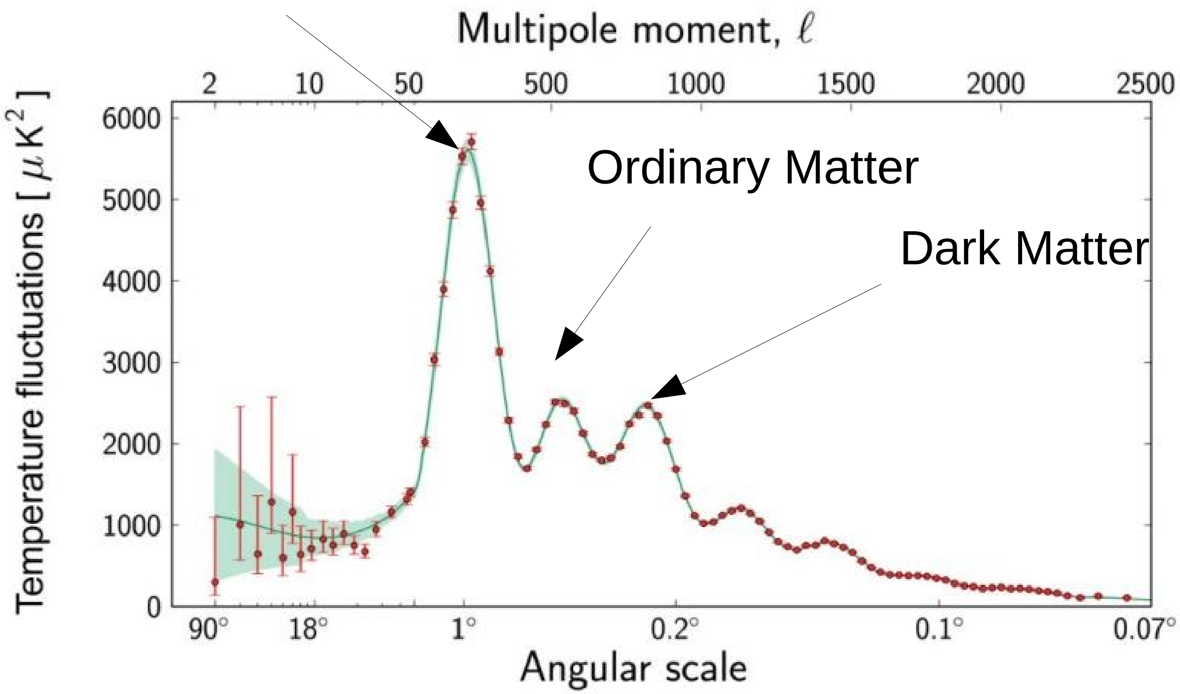
Dark Matter from galactic rotational curves



Dark matter from cluster (Bullet Cluster)
galaxies collisions

Dark Matter

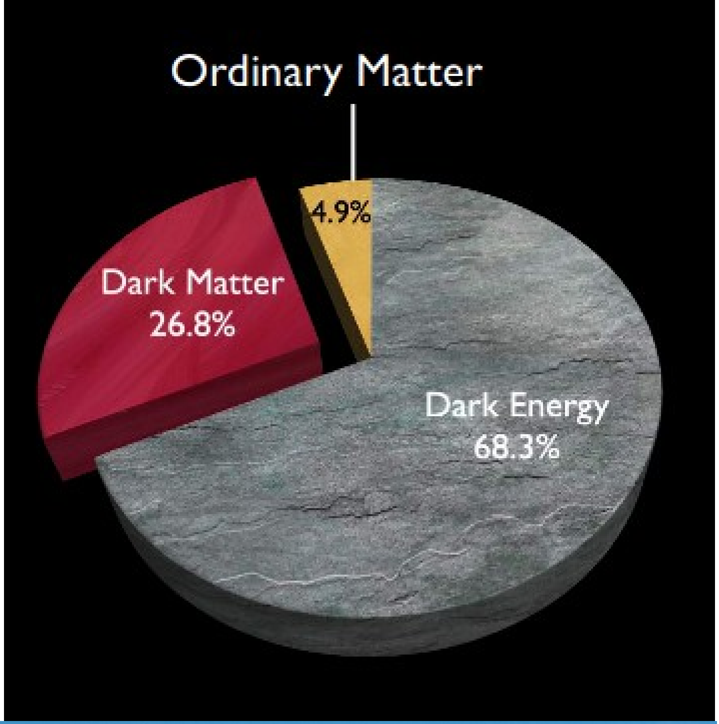
Flat universe



Ordinary Matter

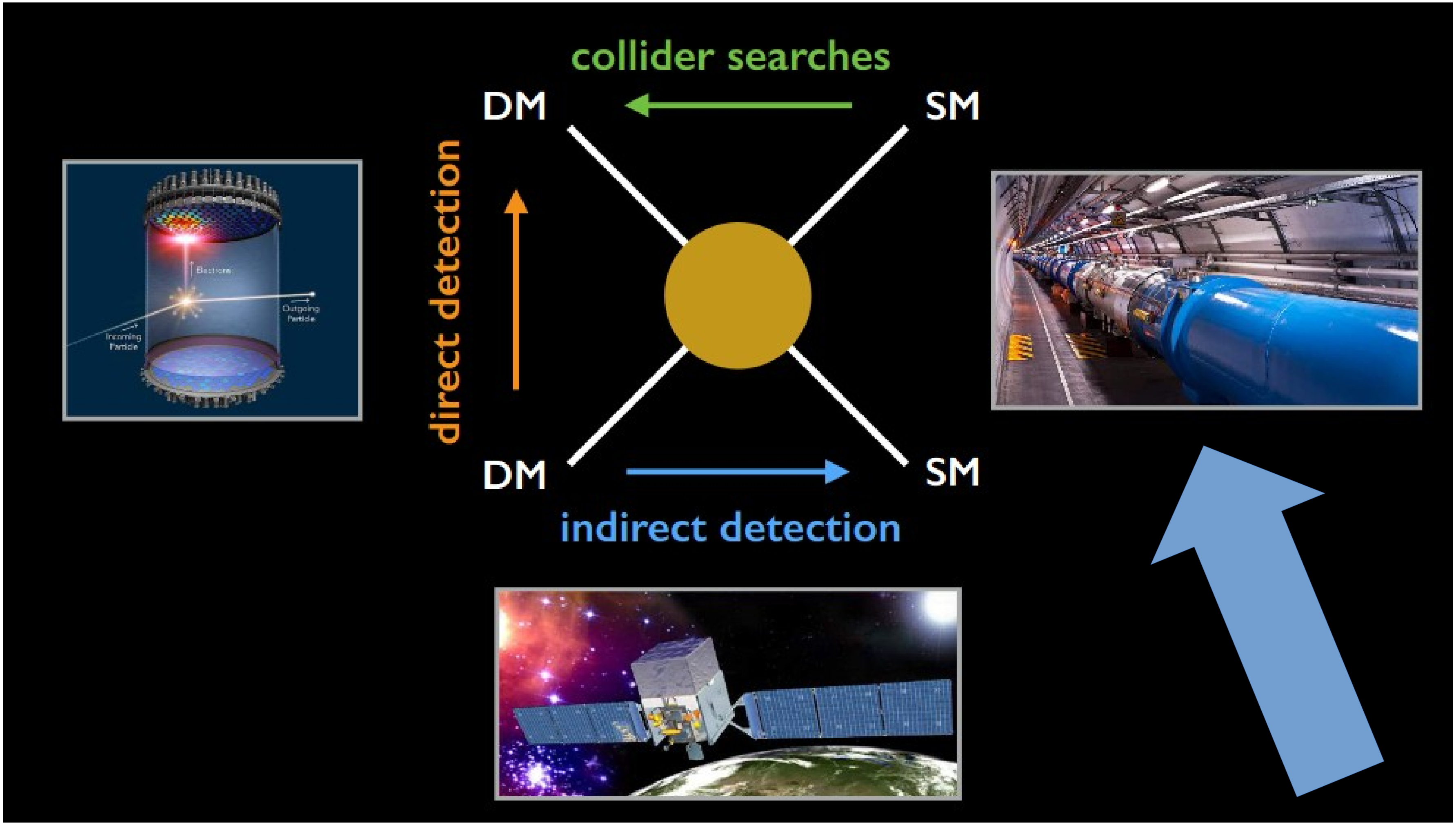
Dark Matter

From Cosmic Microwave Background power spectrum



Will Euclid be a game changer? (launched on 01/07/2023) ?

Direct searches of Dark Matter



- Why looking for physics Beyond Standard Model ?
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How to search for BSM?

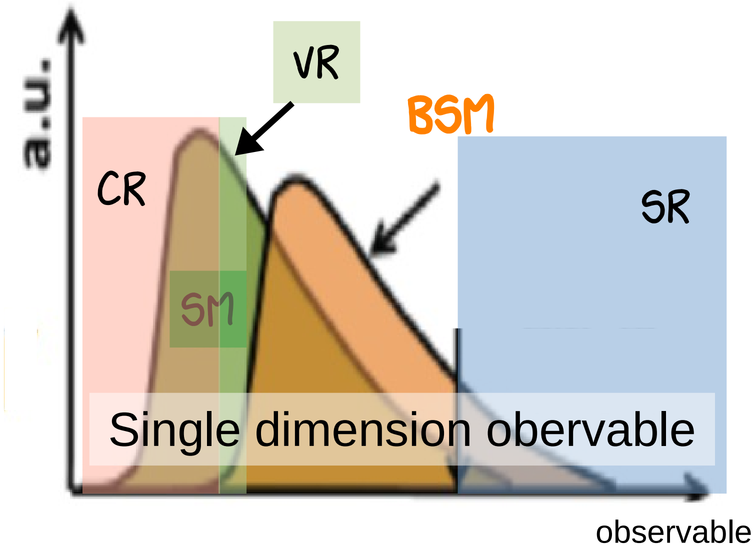
- From theory to data
  - Use principles/conjectures to postulate a theory
  - Derive phenomenology
  - Design an “experiment” to prove or reject it
- From data to theory
  - Observe phenomena
  - Postulate a theory that explains data
  - Design an “experiment” to prove or reject it

SUSY for example. cf Lecture of C. Merlassino tomorrow

Data driven searches **Signature** based

Use theoretical models to interpret results

Where to look for BSM?

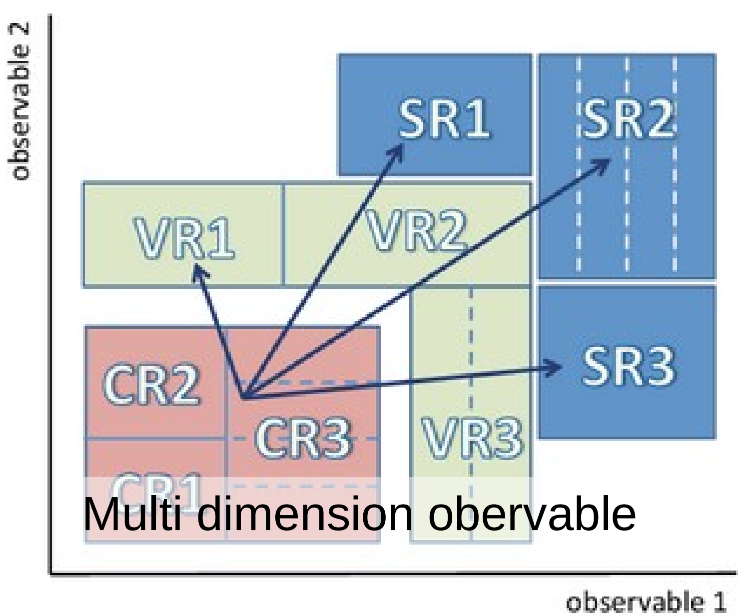


Single dimension obervable

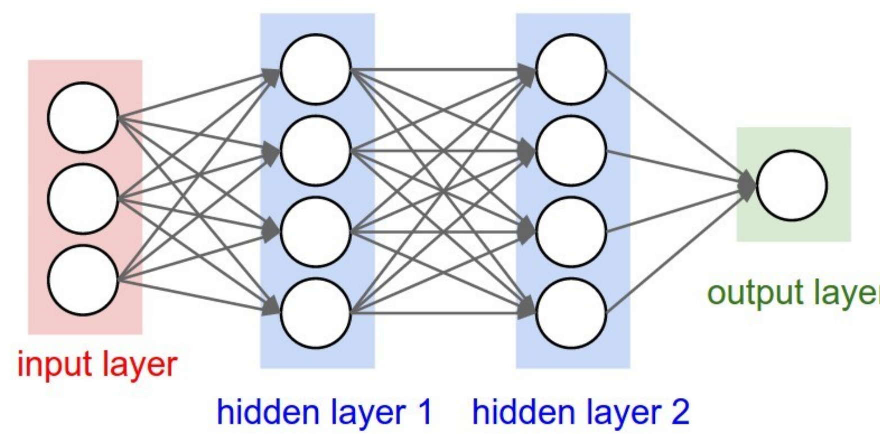
- **Excess** of events wrt expectations
- **Deficit** of events wrt expectations

Expectations → SM predictions
→ Better you know well your SM expectations

Observables → Physics reconstructed variables with discriminant power (could be provided by ML *cf* F. Meloni lecture)



Multi dimension obervable



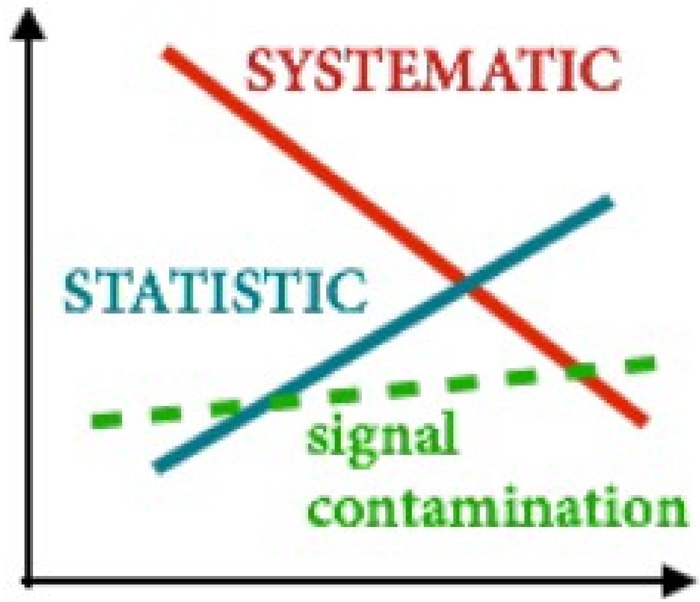
Machine Learning observable

Where to look for BSM?

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 kinamatical 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!



CR → VR → SR

Example: TypeIII seesaw heavy leptons searches in ATLAS

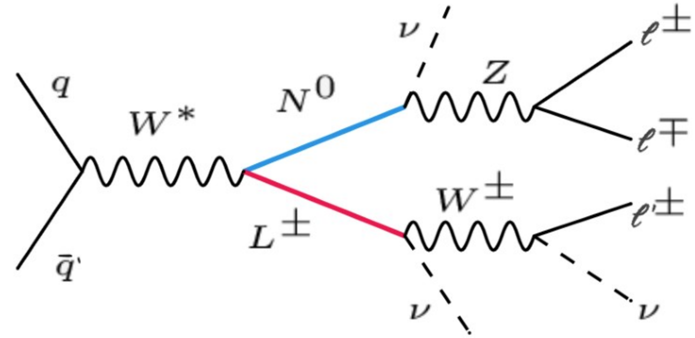
Three and four leptons final state

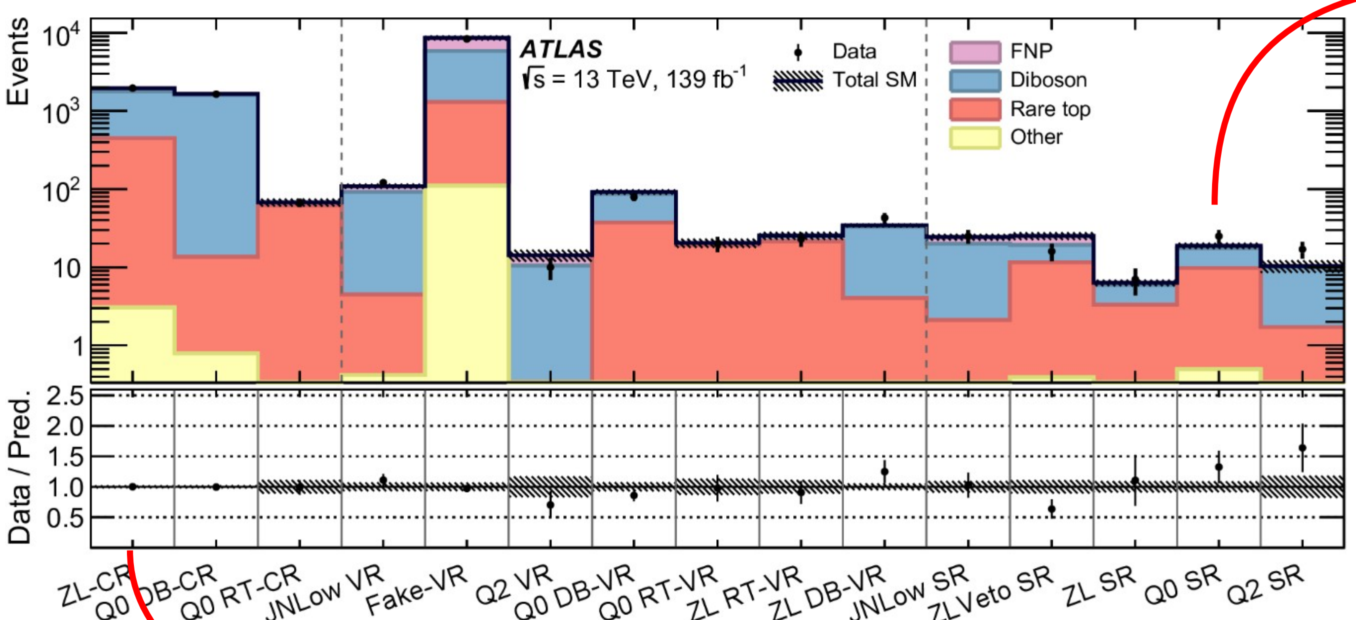
Neutrino mass by SeeSaw: $m_\nu = y\frac{v^2}{M}$

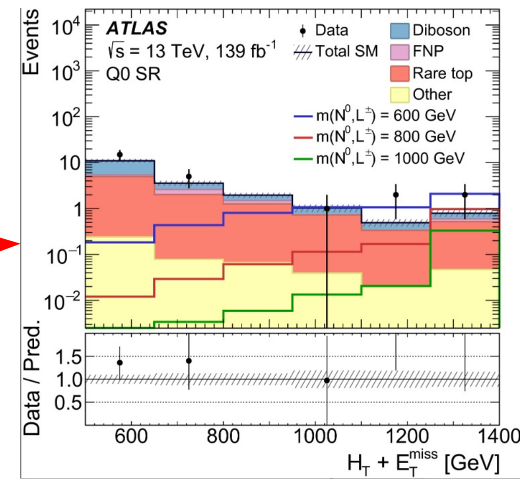
$y \rightarrow$ Yukawa coupling

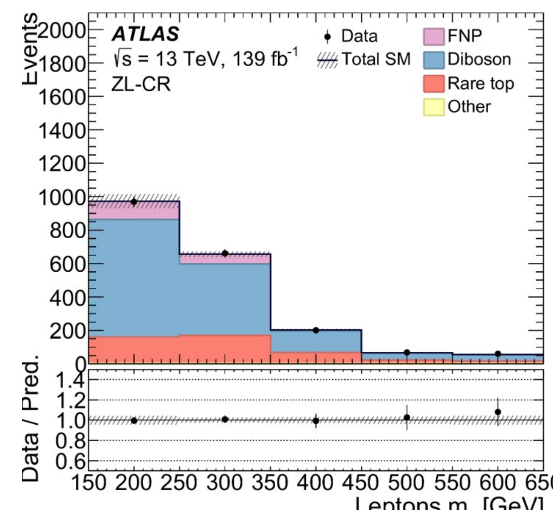
$v \rightarrow$ vacuum expected value

$M \rightarrow$ Heavy particles mass









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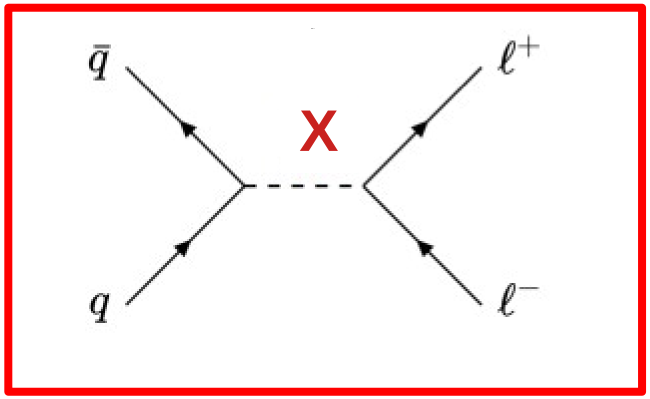
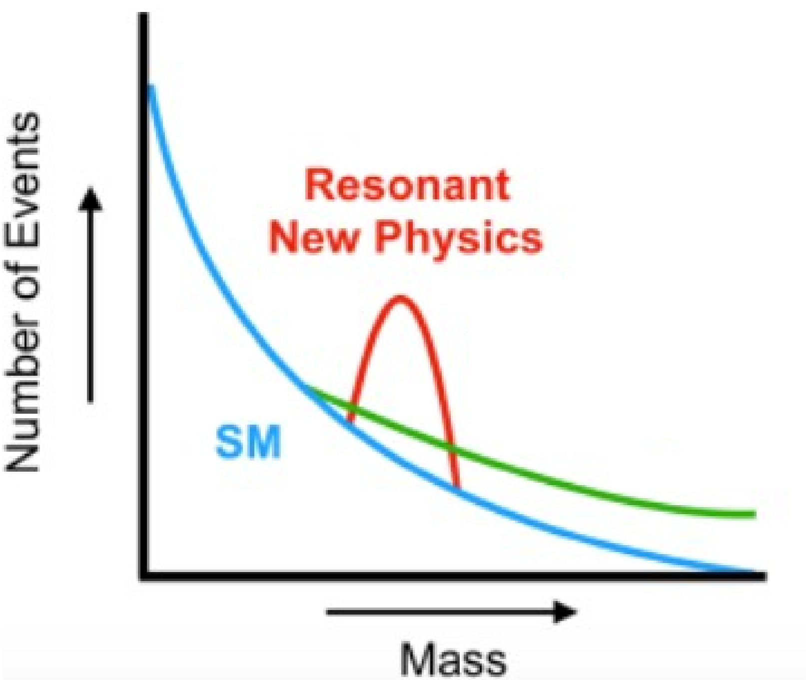
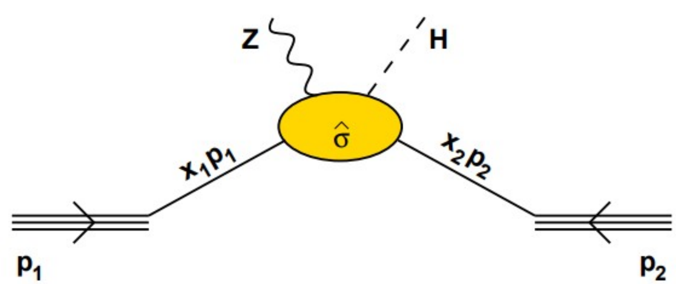
Where to look for BSM?

Resonant searches





- **Resonant** searches are "**golden**" searches at collider experiment
- Final states: leptons, jets (light or b-jets), photons
- Accessible mass of **X** BSM particle depends on available √s
- Mind the Parton Distribution Functions !



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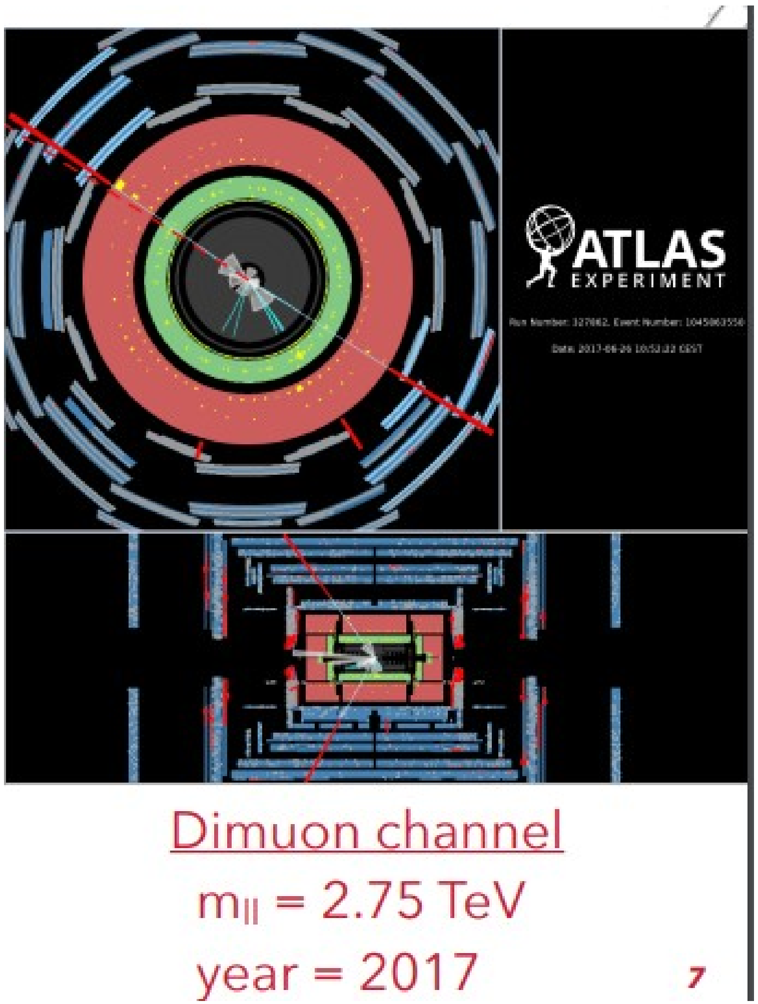
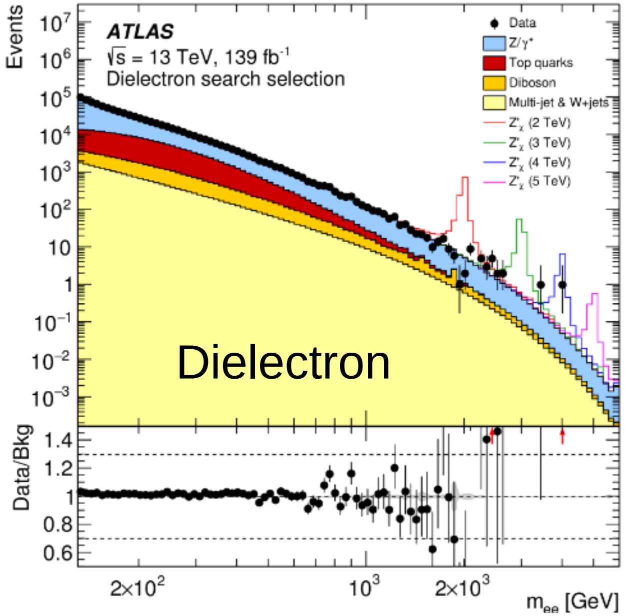
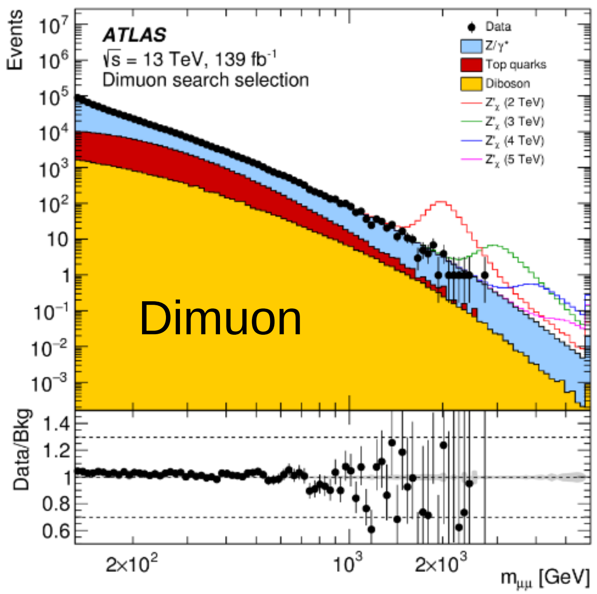
Resonant Searches

Dileptonic final states: Dielectron and Dimuons







Where to look for BSM?

Non-Resonant searches

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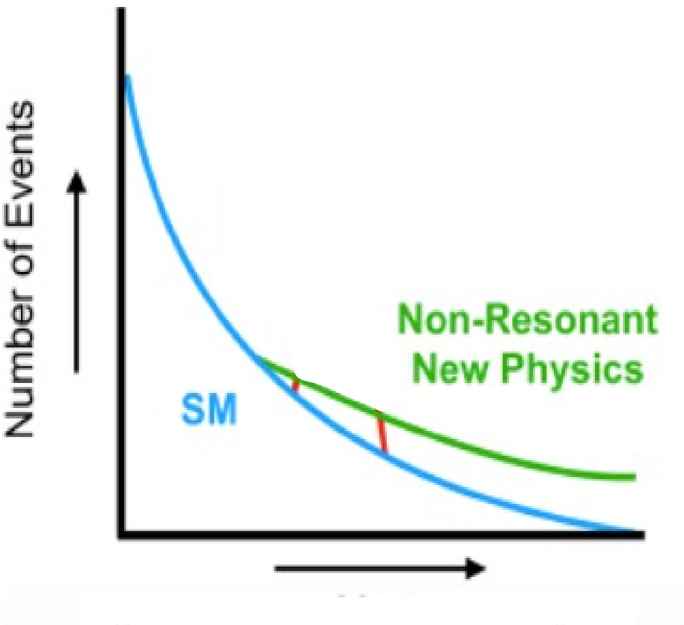
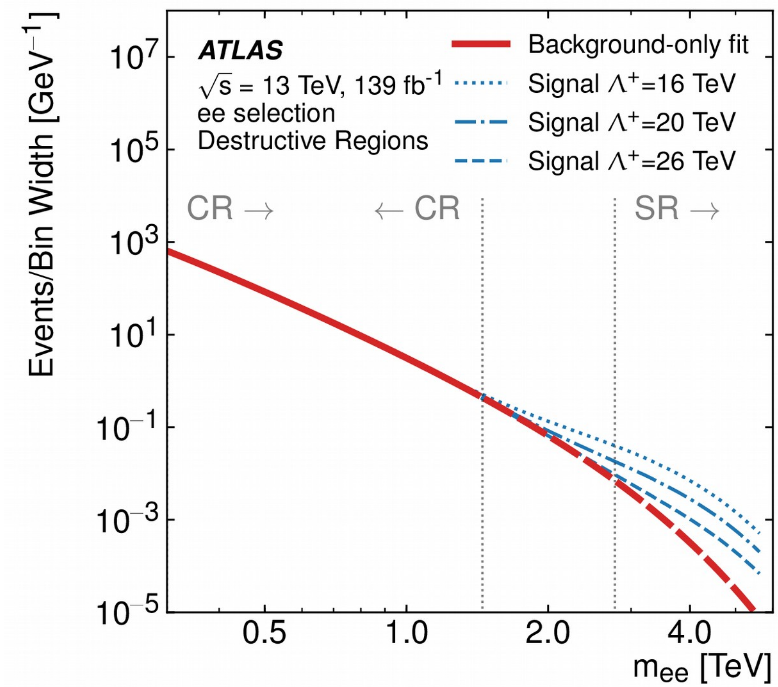
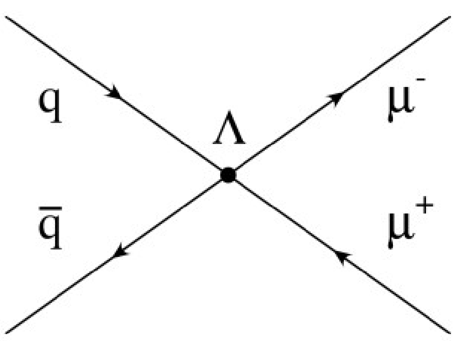


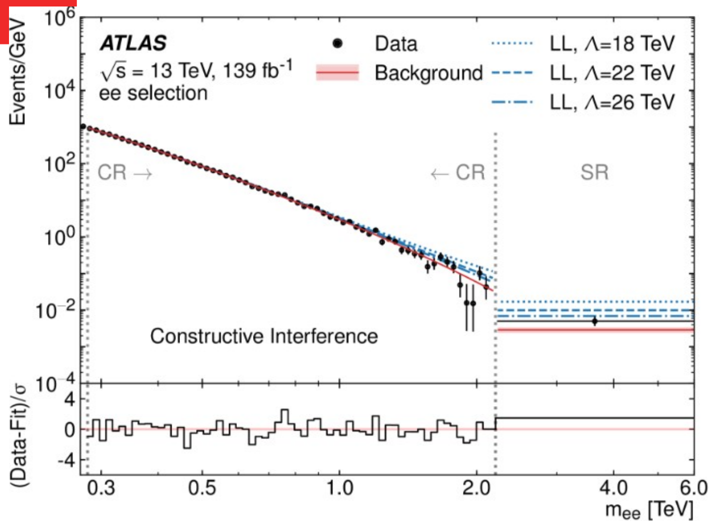
Non-Resonant searches
Look for deviations in tails of the distributions
Larger physics reach
(Λ larger than √s)



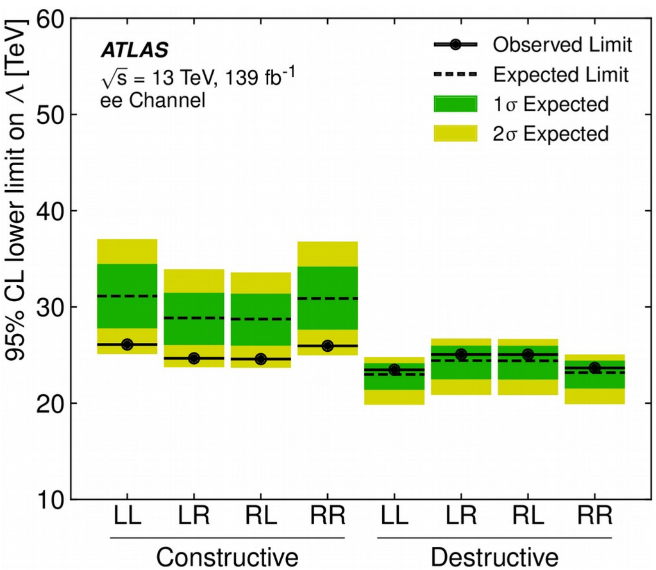


$$\mathcal{L} = \frac{g^2}{\Lambda^2}\Big[\ \eta_{LL}\,(\bar{q}_L\gamma_\mu q_L)(\bar{\ell}_L\gamma^\mu\ell_L) + \eta_{RR}\,(\bar{q}_R\gamma_\mu q_R)(\bar{\ell}_R\gamma^\mu\ell_R) + \eta_{LR}\,(\bar{q}_L\gamma_\mu q_L)(\bar{\ell}_R\gamma^\mu\ell_R) + \eta_{RL}\,(\bar{q}_R\gamma_\mu q_R)(\bar{\ell}_L\gamma^\mu\ell_L)\Big]$$

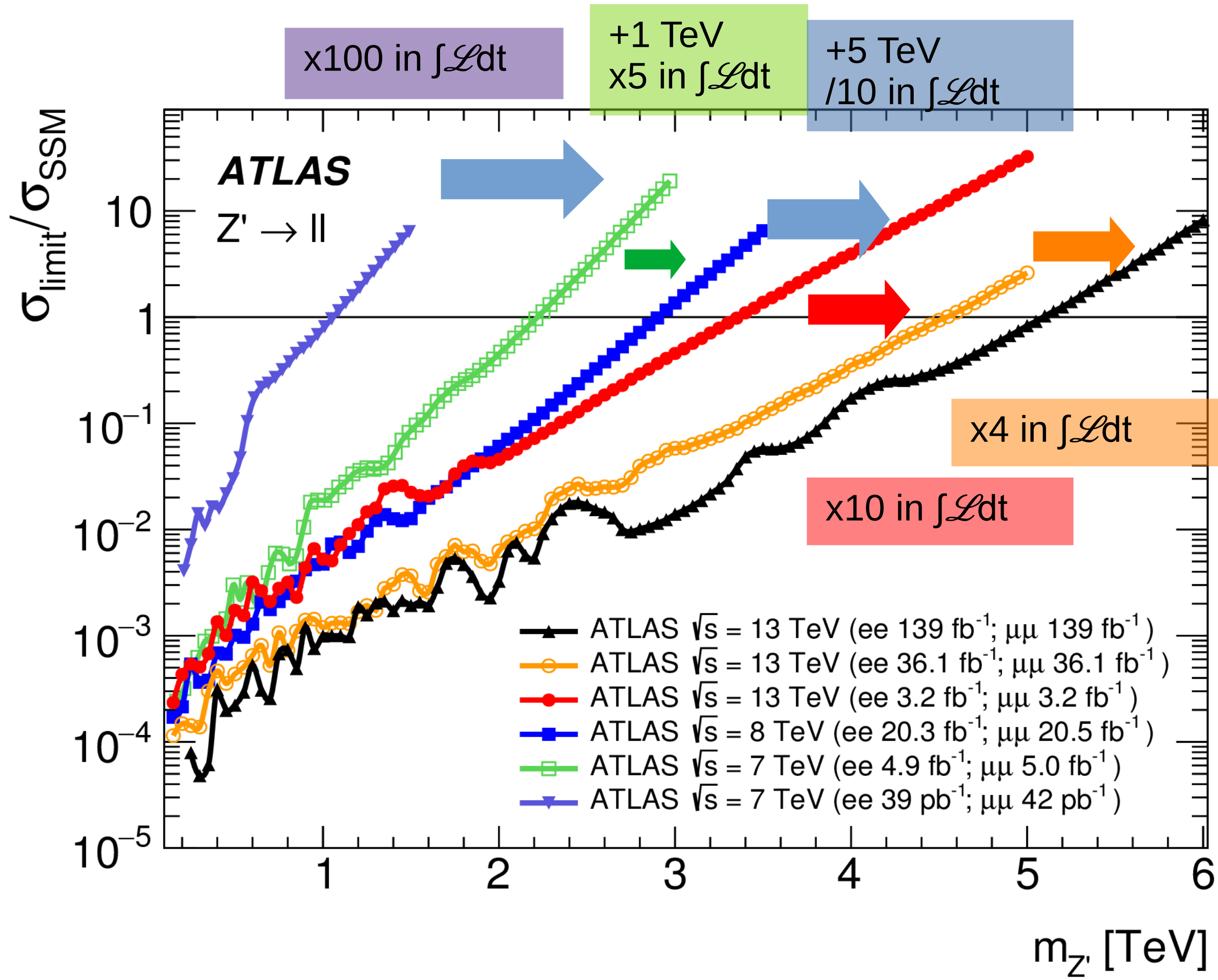
Resonant vs Non Resonant



Non Resonant searches

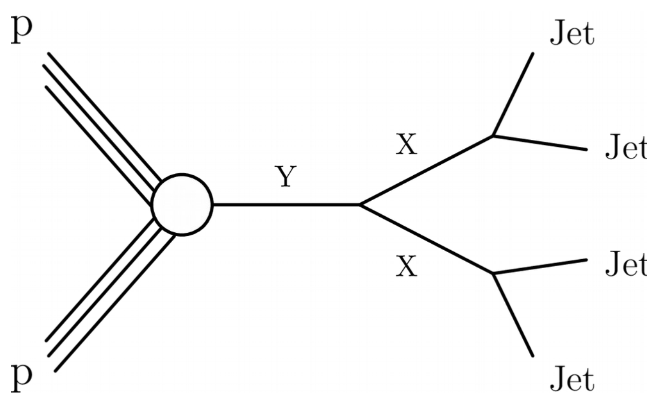


Resonant searches

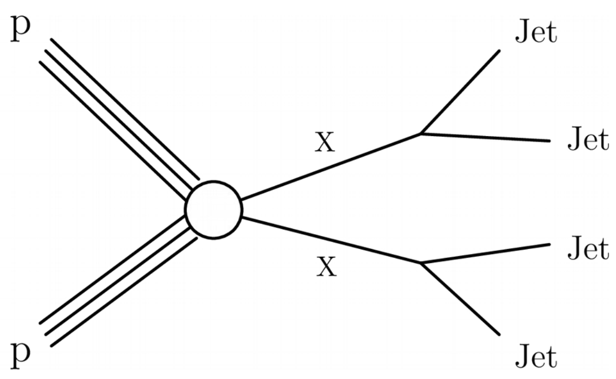


Jet Resonances

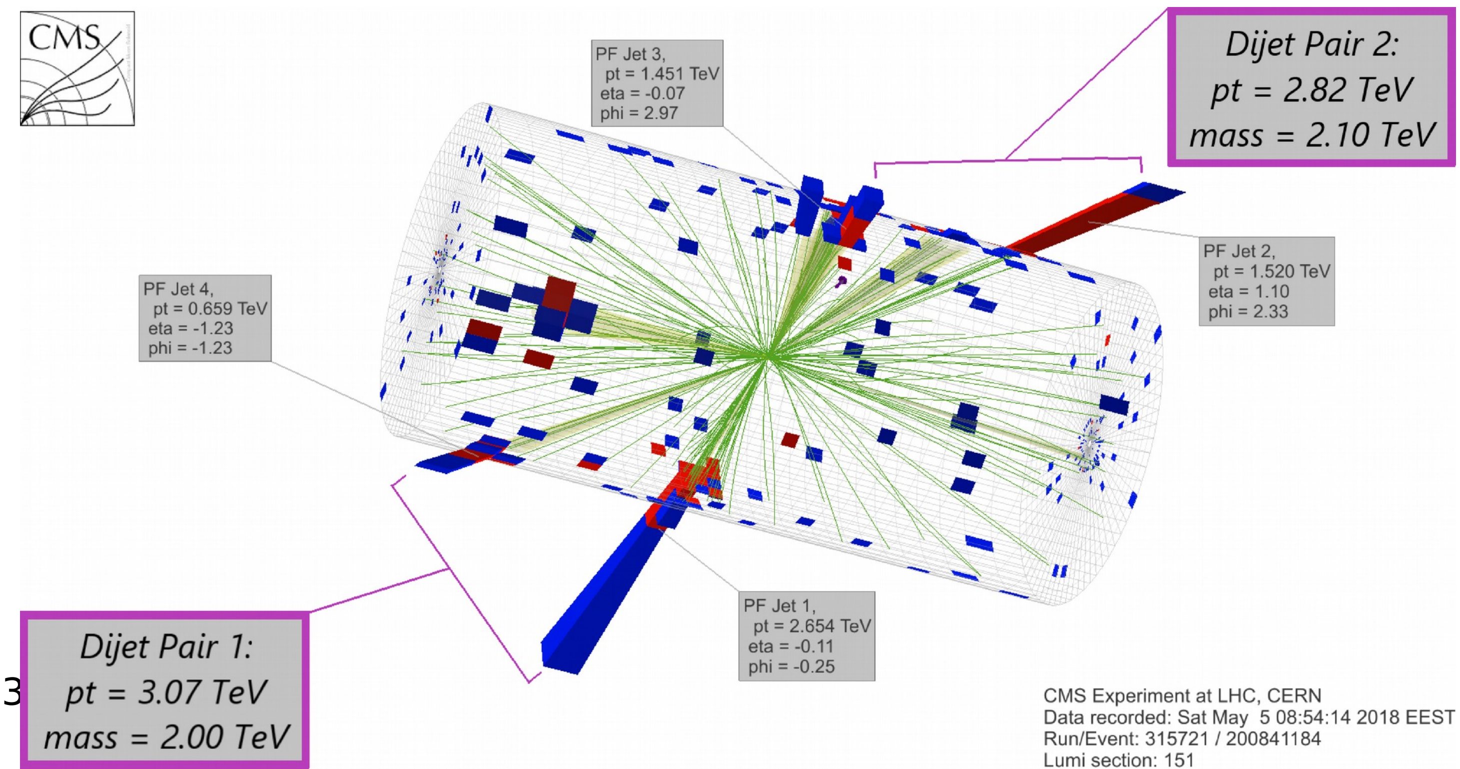
Jets final states

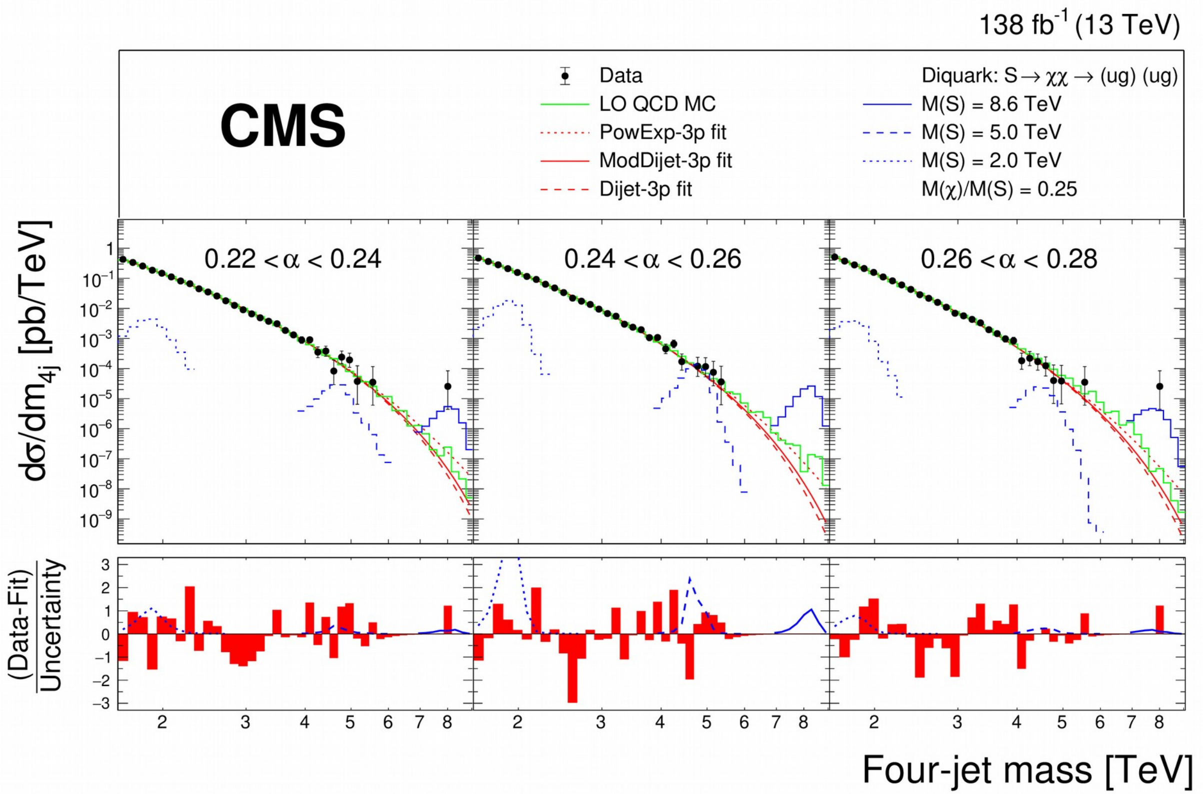


Resonant - Resonant



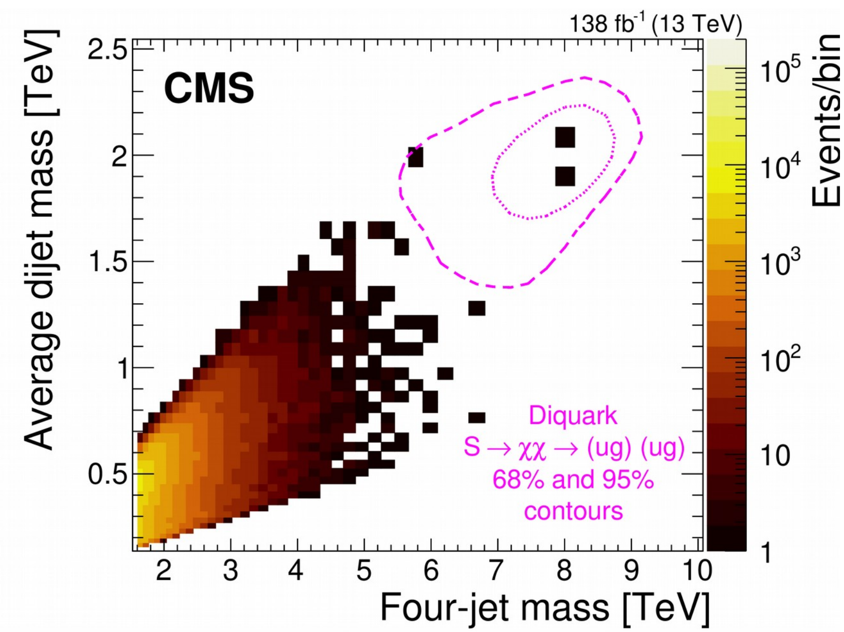
Non Resonant - Resonant





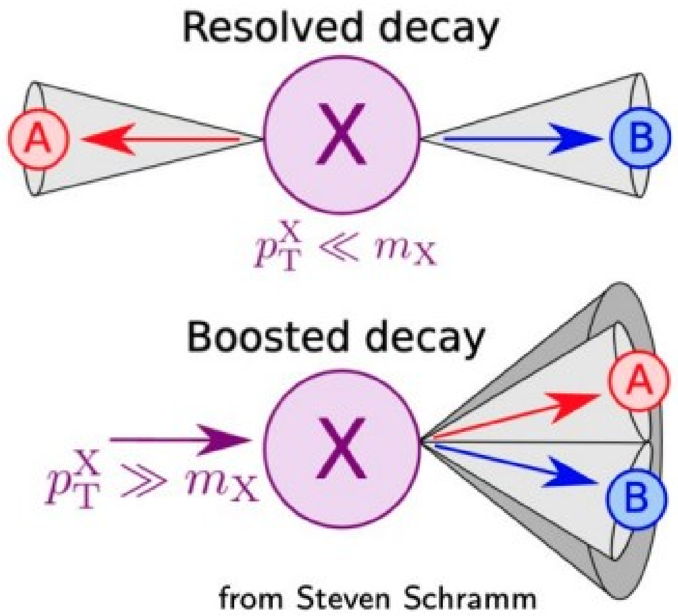
$$\alpha = \frac{\bar{m}_{jj}}{m_{4j}}$$

How much significant are these 2 or 3 events?



arxiv:2206.09997

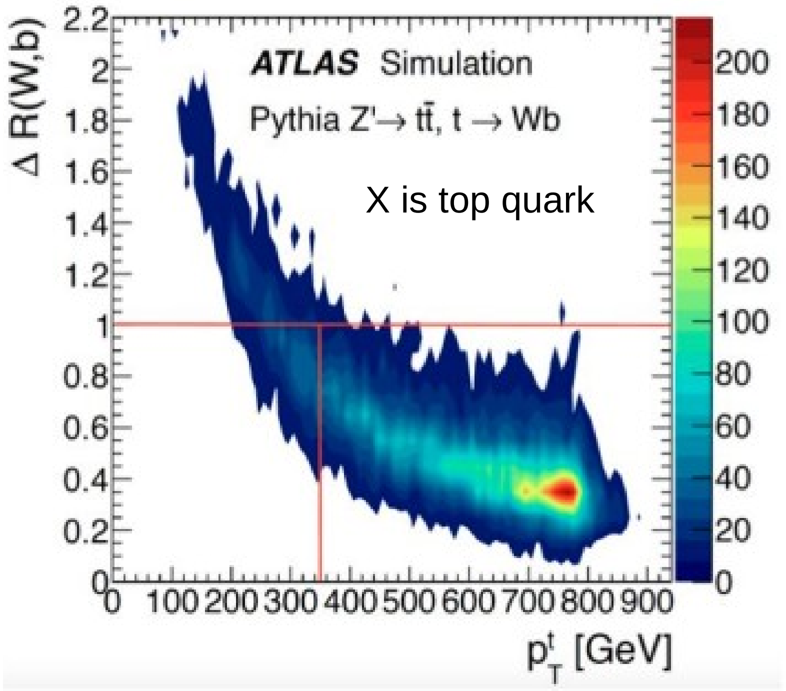
Boosted Regime



"Standard" jets have Radius R=0.4

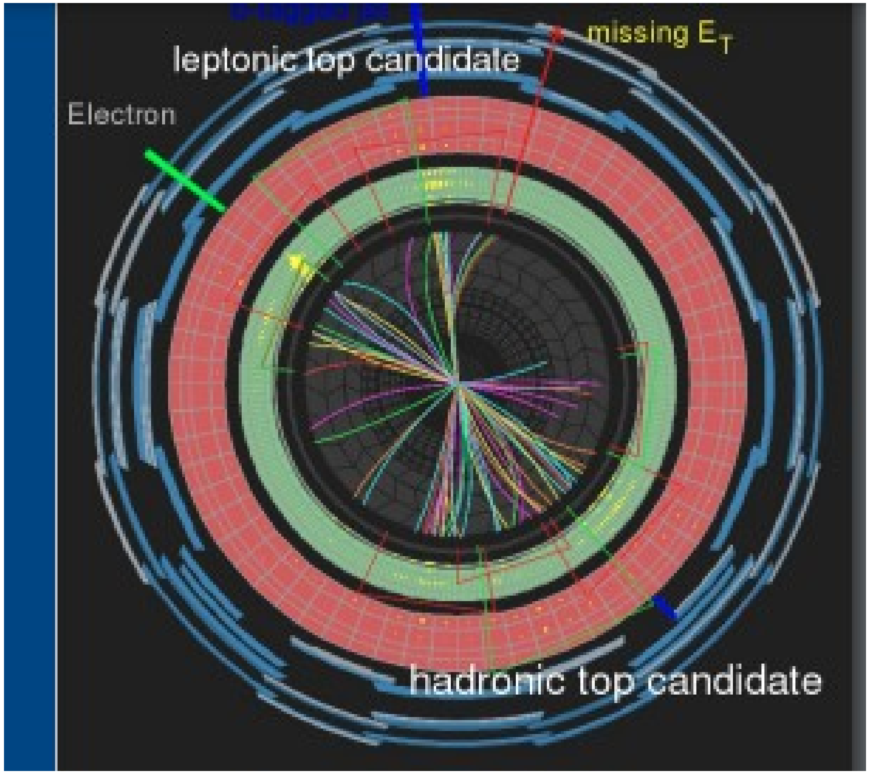
$$R = \sqrt{\Delta\Phi^2 + \Delta\eta^2}$$

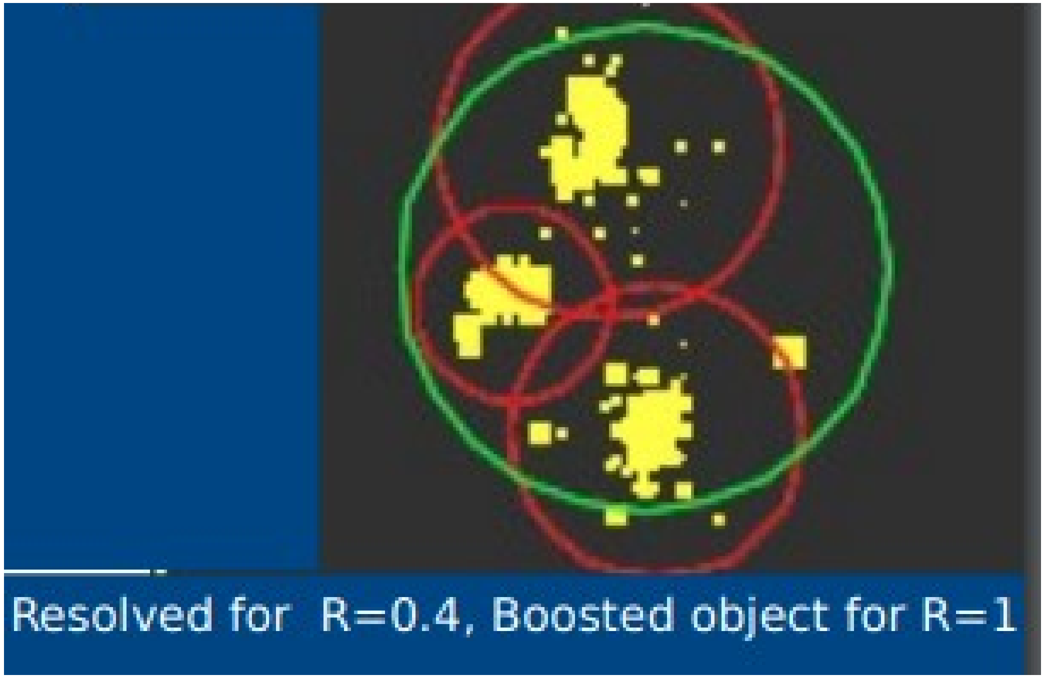
$$\Delta R = 2\frac{M_X}{P_{T,X}}$$



Hadronic decays usually with larger branching ratio → Statistics increase
If X is boosted → A and B decays become closer and closer
→ Jet multiplicity decreases, jets become larger (fat jets)
Peeking inside the jets to identify product decays from top, Z, W or Higgs (taggers)

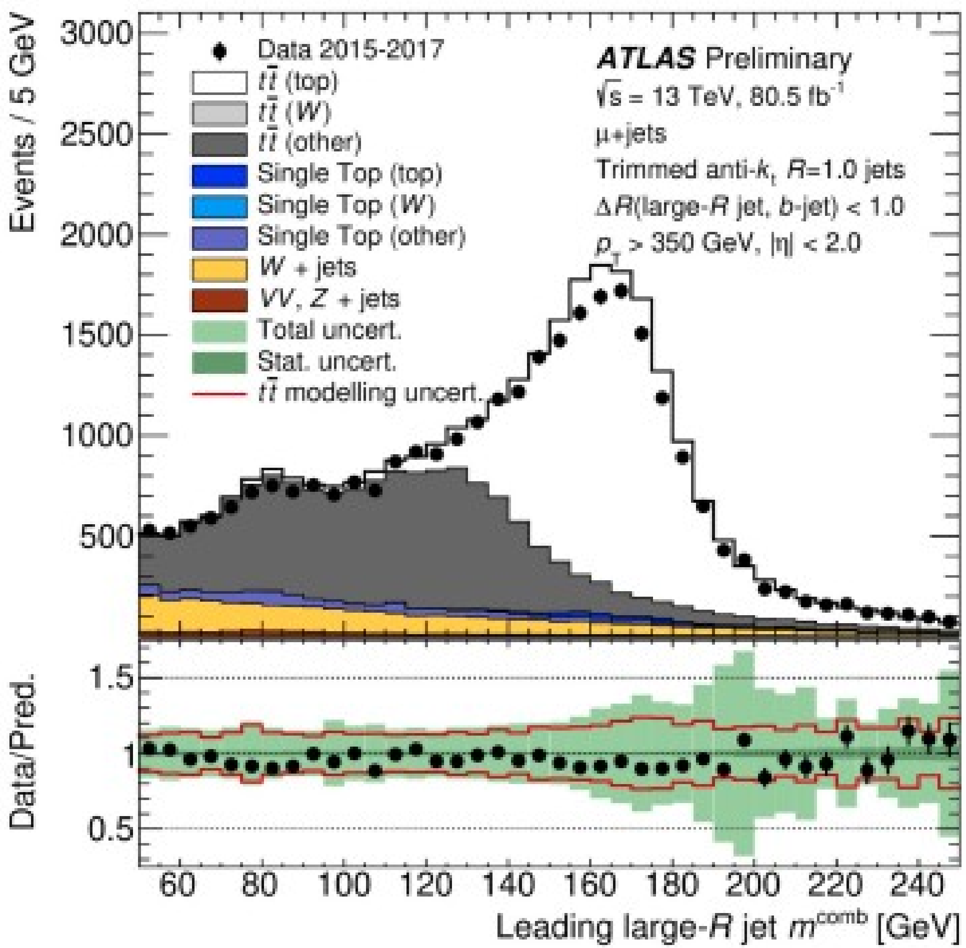
Boosted Regime

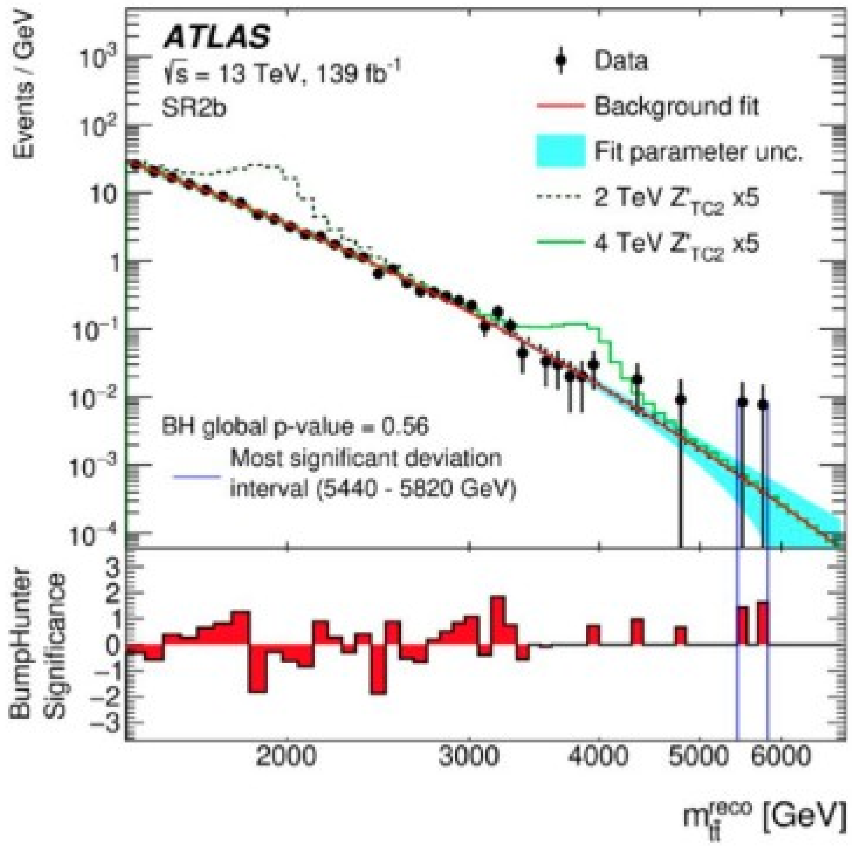




Different algorithms to look inside a fat jet → Combination with ML (DNN)

Searching for a leptophobic Z' $Z' \to t\bar{t}$

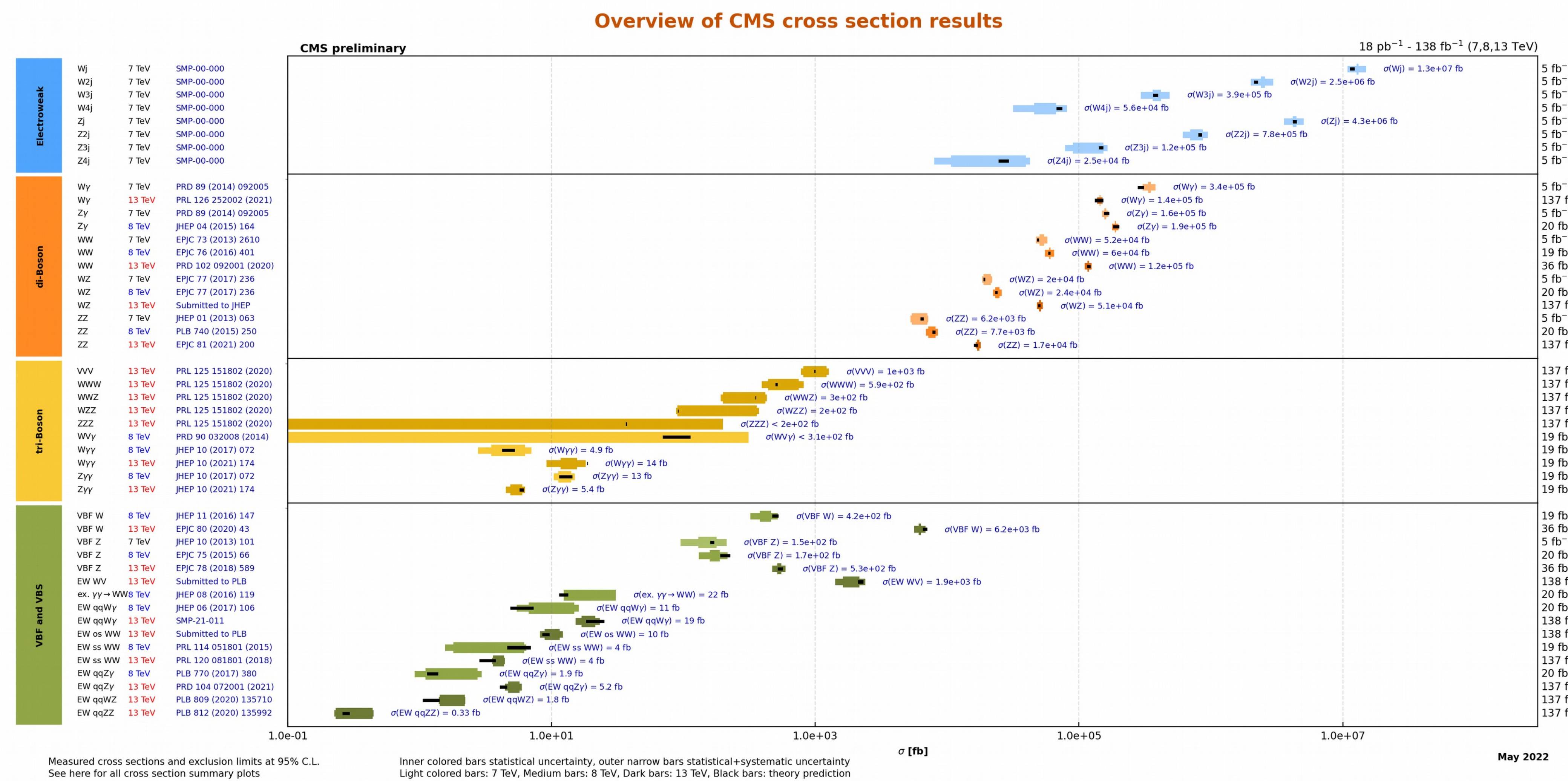




Data driven background using fit function

EXOT-2018-48

Background



Overview of CMS cross section results
CMS preliminary
18 pb⁻¹ - 138 fb⁻¹ (7,8,13 TeV)
Electroweak
di-Boson
tri-Boson
VBF and VBS
Wj 7 TeV SMP-00-000 σ(Wj) = 1.3e+07 fb
W2j 7 TeV SMP-00-000 σ(W2j) = 2.5e+06 fb
W3j 7 TeV SMP-00-000 σ(W3j) = 3.9e+05 fb
W4j 7 TeV SMP-00-000 σ(W4j) = 5.6e+04 fb
Zj 7 TeV SMP-00-000 σ(Zj) = 4.3e+06 fb
Z2j 7 TeV SMP-00-000 σ(Z2j) = 7.8e+05 fb
Z3j 7 TeV SMP-00-000 σ(Z3j) = 1.2e+05 fb
Z4j 7 TeV SMP-00-000 σ(Z4j) = 2.5e+04 fb
Wγ 7 TeV PRD 89 (2014) 092005 σ(Wγ) = 3.4e+05 fb
Wγ 13 TeV PRL 126 252002 (2021) σ(Wγ) = 1.4e+05 fb
Zγ 7 TeV PRD 89 (2014) 092005 σ(Zγ) = 1.6e+05 fb
Zγ 8 TeV JHEP 04 (2015) 164 σ(Zγ) = 1.9e+05 fb
WW 7 TeV EPJC 73 (2013) 2610 σ(WW) = 5.2e+04 fb
WW 8 TeV EPJC 76 (2016) 401 σ(WW) = 6e+04 fb
WW 13 TeV PRD 102 092001 (2020) σ(WW) = 1.2e+05 fb
WZ 7 TeV EPJC 77 (2017) 236 σ(WZ) = 2e+04 fb
WZ 8 TeV EPJC 77 (2017) 236 σ(WZ) = 2.4e+04 fb
WZ 13 TeV Submitted to JHEP σ(WZ) = 5.1e+04 fb
ZZ 7 TeV JHEP 01 (2013) 063 σ(ZZ) = 6.2e+03 fb
ZZ 8 TeV PLB 740 (2015) 250 σ(ZZ) = 7.7e+03 fb
ZZ 13 TeV EPJC 81 (2021) 200 σ(ZZ) = 1.7e+04 fb
VVV 13 TeV PRL 125 151802 (2020) σ(VVV) = 1e+03 fb
WWW 13 TeV PRL 125 151802 (2020) σ(WWW) = 5.9e+02 fb
WWZ 13 TeV PRL 125 151802 (2020) σ(WWZ) = 3e+02 fb
WZZ 13 TeV PRL 125 151802 (2020) σ(WZZ) = 2e+02 fb
ZZZ 13 TeV PRL 125 151802 (2020) σ(ZZZ) < 2e+02 fb
WVγ 8 TeV PRD 90 032008 (2014) σ(WVγ) < 3.1e+02 fb
Wγγ 8 TeV JHEP 10 (2017) 072 σ(Wγγ) = 4.9 fb
Wγγ 13 TeV JHEP 10 (2021) 174 σ(Wγγ) = 14 fb
Zγγ 8 TeV JHEP 10 (2017) 072 σ(Zγγ) = 13 fb
Zγγ 13 TeV JHEP 10 (2021) 174 σ(Zγγ) = 5.4 fb
VBF W 8 TeV JHEP 11 (2016) 147 σ(VBF W) = 4.2e+02 fb
VBF W 13 TeV EPJC 80 (2020) 43 σ(VBF W) = 6.2e+03 fb
VBF Z 7 TeV JHEP 10 (2013) 101 σ(VBF Z) = 1.5e+02 fb
VBF Z 8 TeV EPJC 75 (2015) 66 σ(VBF Z) = 1.7e+02 fb
VBF Z 13 TeV EPJC 78 (2018) 589 σ(VBF Z) = 5.3e+02 fb
EW WV 13 TeV Submitted to PLB σ(EW WV) = 1.9e+03 fb
ex. γγ→WW 8 TeV JHEP 08 (2016) 119 σ(ex. γγ→WW) = 22 fb
EW qqWγ 8 TeV JHEP 06 (2017) 106 σ(EW qqWγ) = 11 fb
EW qqWγ 13 TeV SMP-21-011 σ(EW qqWγ) = 19 fb
EW os WW 13 TeV Submitted to PLB σ(EW os WW) = 10 fb
EW ss WW 8 TeV PRL 114 051801 (2015) σ(EW ss WW) = 4 fb
EW ss WW 13 TeV PRL 120 081801 (2018) σ(EW ss WW) = 4 fb
EW qqZγ 8 TeV PLB 770 (2017) 380 σ(EW qqZγ) = 1.9 fb
EW qqZγ 13 TeV PRD 104 072001 (2021) σ(EW qqZγ) = 5.2 fb
EW qqWZ 13 TeV PLB 809 (2020) 135710 σ(EW qqWZ) = 1.8 fb
EW qqZZ 13 TeV PLB 812 (2020) 135992 σ(EW qqZZ) = 0.33 fb
1.0e-01
1.0e+01
1.0e+03
1.0e+05
1.0e+07
σ [fb]
May 2022
Measured cross sections and exclusion limits at 95% C.L.
See here for all cross section summary plots
Inner colored bars statistical uncertainty, outer narrow bars statistical+systematic uncertainty
Light colored bars: 7 TeV, Medium bars: 8 TeV, Dark bars: 13 TeV, Black bars: theory prediction

Design your analysis to look for BSM signal where you expect a good Signal over Background ratio:
S/B or better S/√B or

$$\mathcal{S} = \sqrt{2\left[(S+B)\ln\left(1+\frac{S}{B}\right) - S\right]},$$ (even better)

→ Small and/or well known background

Background usually classified in:

- **Reducible background** → Instrumental background. For example:
  - hadronic jets that are mismeasured and are confused with electrons, muons or tau.
  - Light jets tagged as jets containing b-quarks → Have excellent algorithms to reconstruct physics reconstructed objects.
  - Great purity without sacrificing too much efficiency. Estimate contamination of background events with data-driven methods or MonteCarlo methods

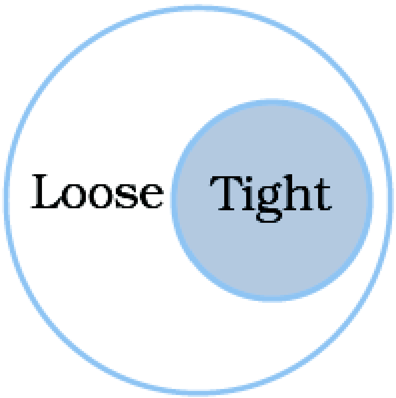
- **Irreducible background**. Standard Model events that look like your signal. Usually you are not sampling the bulk of the SM events, you concentrate more on the tails that are less known theoretically. Usually estimated using MonteCarlo methods

Fake Leptons (electrons and muons)

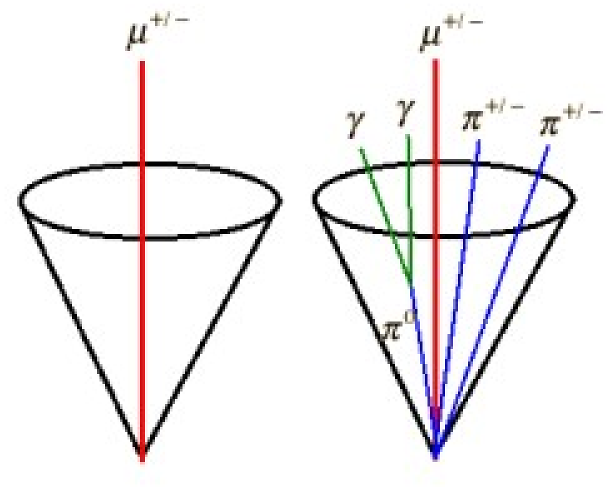
Origin: Jets misidentified as reconstructed leptons, non prompt leptons from semileptonic-decays of heavy flavour particles, photon conversions, pions/kaons decays. More detail here on the different methods used in ATLAS arXiv:2211.16178

Fake Factor (one of the many possibilities)

→ Evaluate in a kinematic region close to the one of your analysis a Fake Factor and dominated by fake leptons (for example muon + jet events)



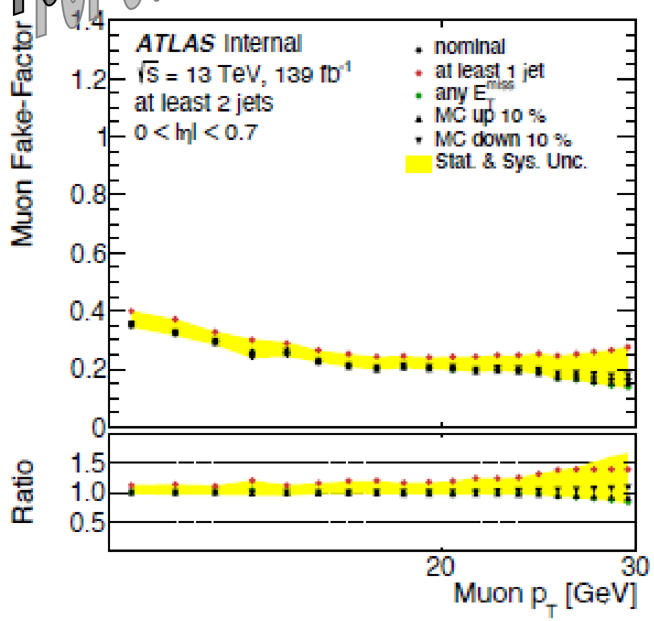
$$F = \frac{f}{1-f} = \frac{N_{\text{tight}}}{N_{\text{loose}}}$$



The difference in "**Loose**" and "**Tight**" is usually the isolation (calorimetric and/or track)

Tight corresponds the selection you are using in your search

Fake Leptons (electrons and muons)



Fake factors can be parameterized as a function of P_T, η,...

Fake Factors are applied to the events selected in your search using the Loose selection instead of the Tight one

If you have a single lepton final state:

$$N_{\mathrm{f}}^{\mathrm{t}} = \sum_{\mathrm{data},i=1}^{N^1} F_i - \sum_{\mathrm{MC},j=1}^{N^1_{\mathrm{MC}}} w_{\mathrm{MC},j} F_j,$$

For an arbitrary n lepton multiplicity

$$N_{fakes} = \left[\sum_{events}^{nloose} (-1)^{n-1} \prod_i^n f_i\right]_{data} - \left[\sum_{events}^{nloose} (-1)^{n-1} \prod_i^n f_i\right]_{MC}$$

Assumptions:

- The region where you have evaluated F is “similar” to the one you are using in your analysis
- Fake factors can be factorized (leptons are indipendent)

Irreducible Background

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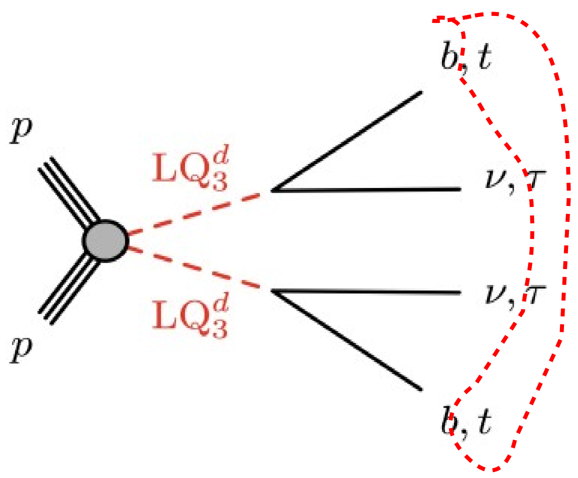
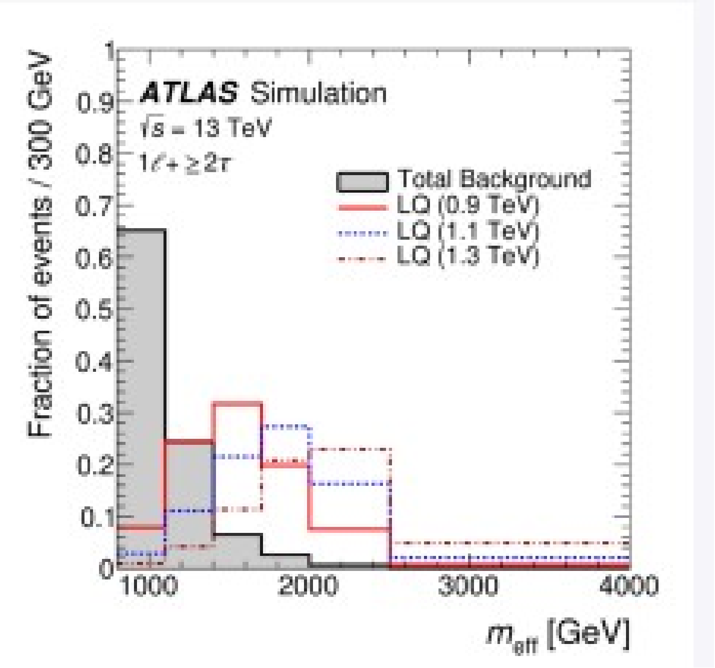
Use MonteCarlo to evaluate contribution from SM process with same final state of your analysis region. Usual SM processes $t\bar{t}$, single top, $t\bar{t}$+X, diboson, multiboson
But the theory might be **inaccurate** in the phase space you are evaluating the contribution (e.g. large jet multiplciity, kinematic tails,…)
Example: Search of leptoquark decaying in top quarks and tau leptons

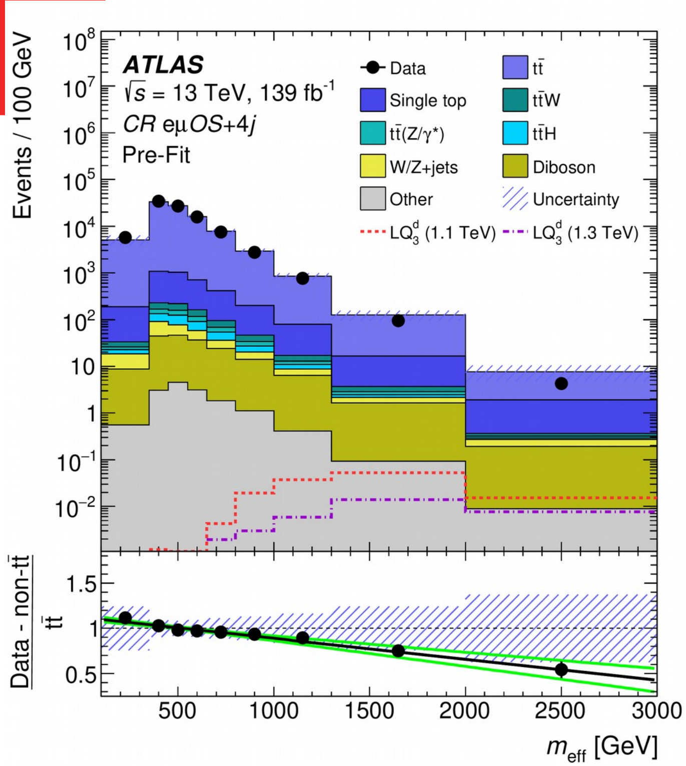




$t\bar{t}$ process is clearly the main background
The discriminating variable is M_{eff} (the scalar sum of E_T all reconstructed objects in the event)

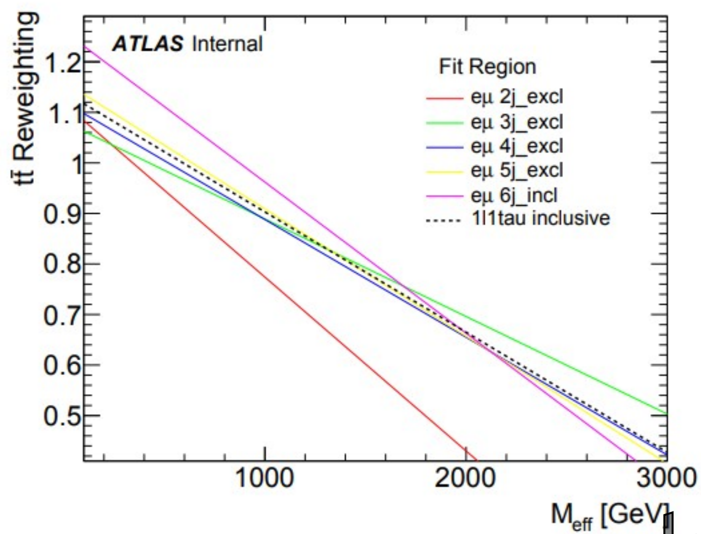
$$m_{\text{eff}} = \sum_{(\text{jet, e}, \mu, \tau)} p_{\text{T}} + E_{\text{T}}^{\text{miss}}$$

The problem

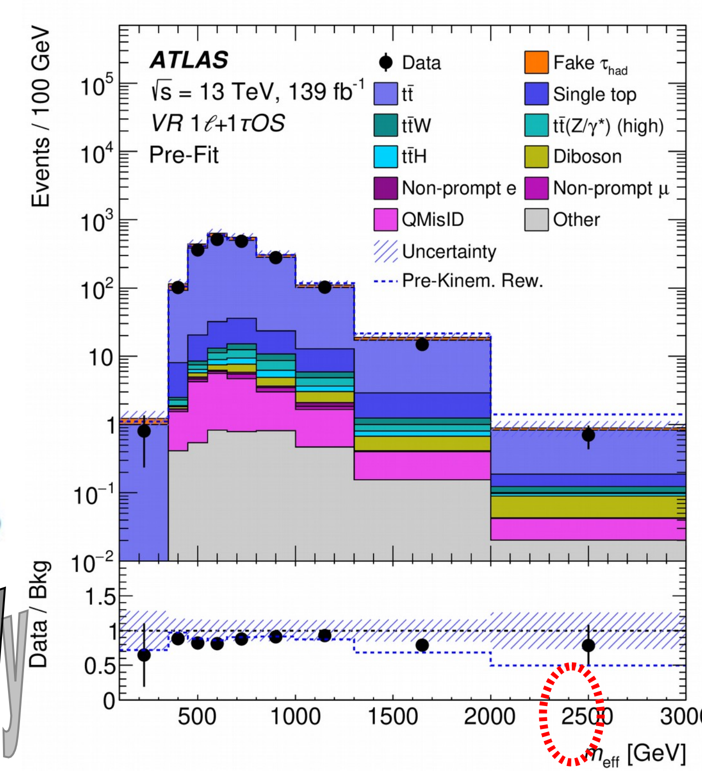


Clear mismodeling of M_{eff} for $t\bar{t}$ process

The cure:
Reweight the $t\bar{t}$ distribution as a function of M_{eff} and jet multiplicity



The result



Irreducible Background

Or use a “better” MonteCarlo (not always possible) with updated theory calculations e.g. diboson differential cross section.
NNLO QCD and NLO Electroweak corrections might be important is some kinematical regions

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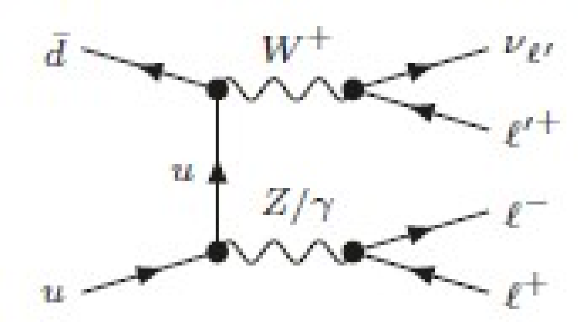
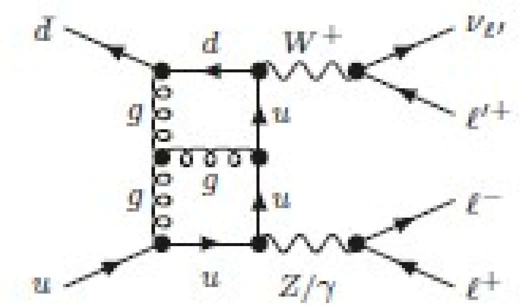
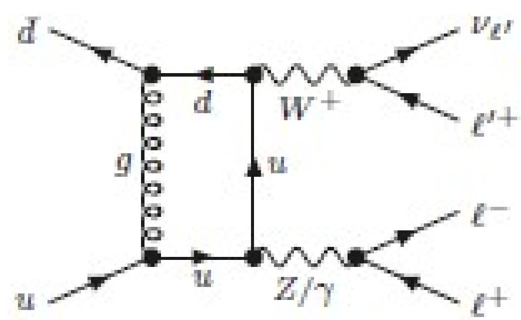


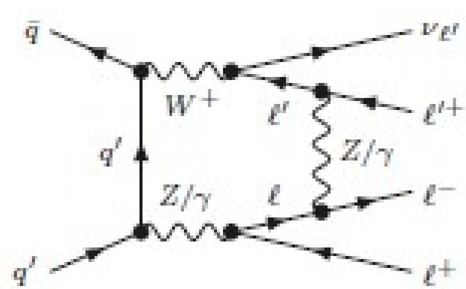
LO



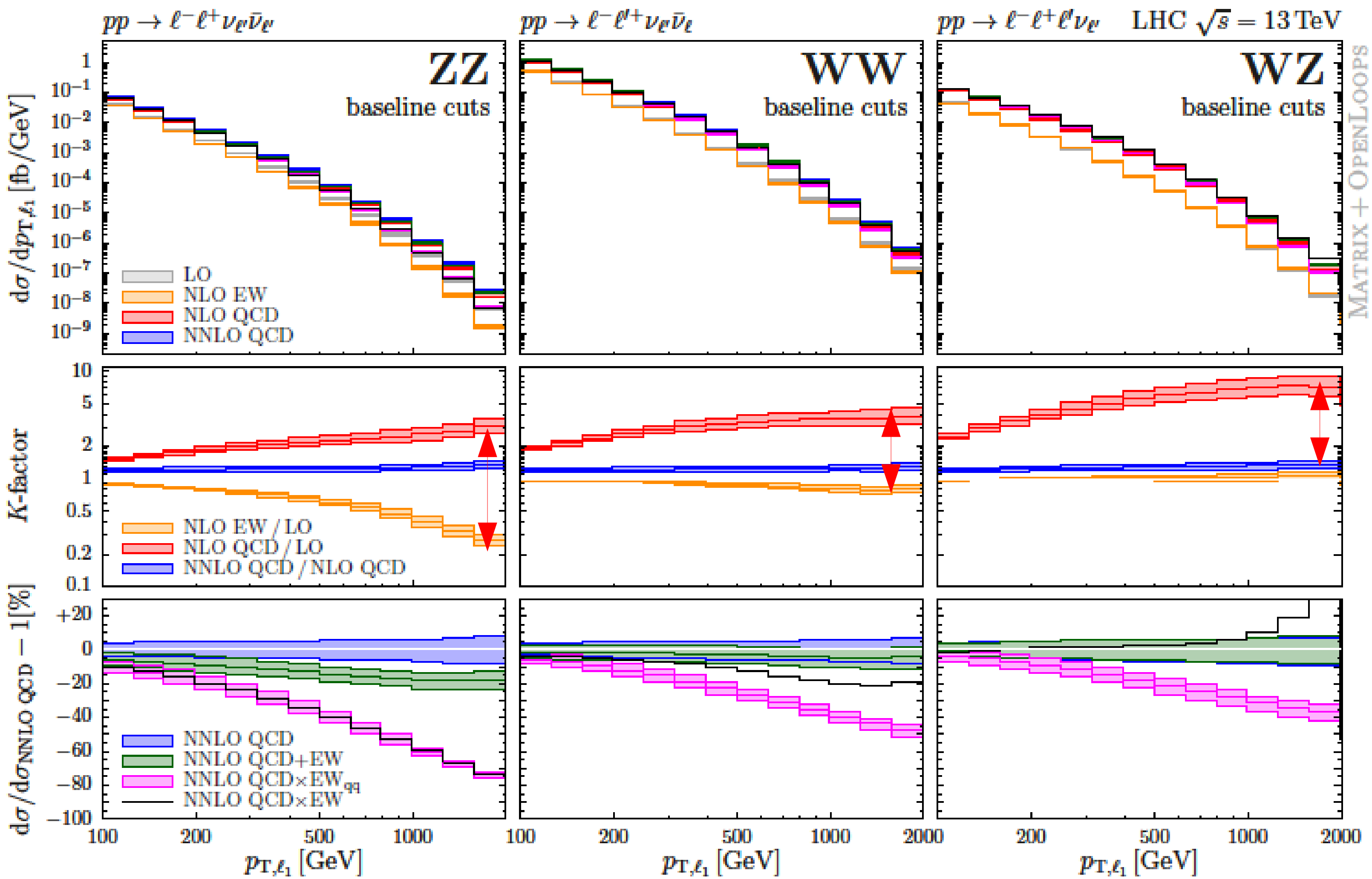
NNLO QCD



NLO QCD



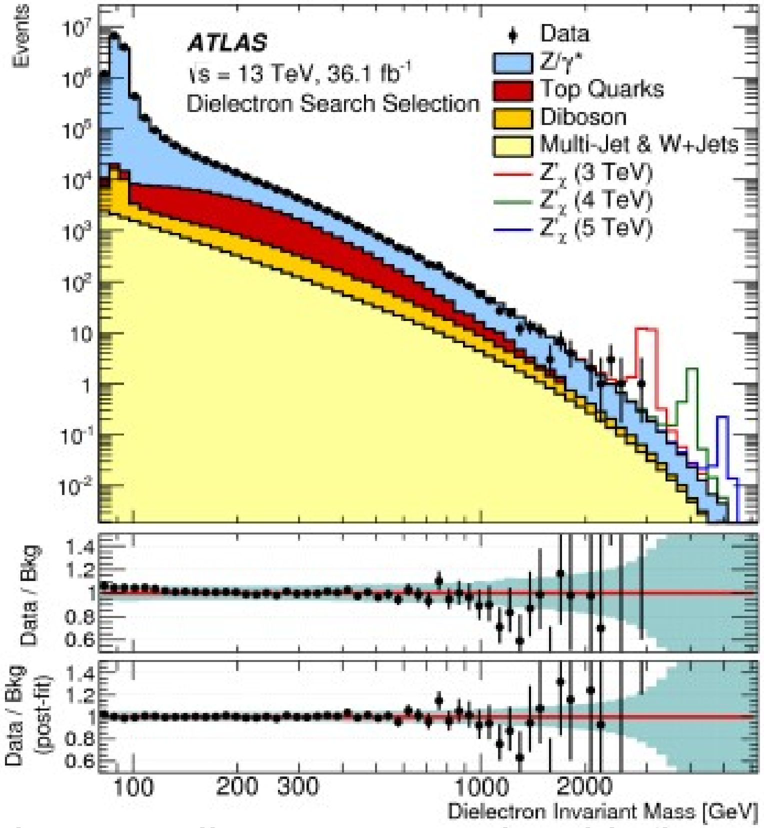
NLO EW

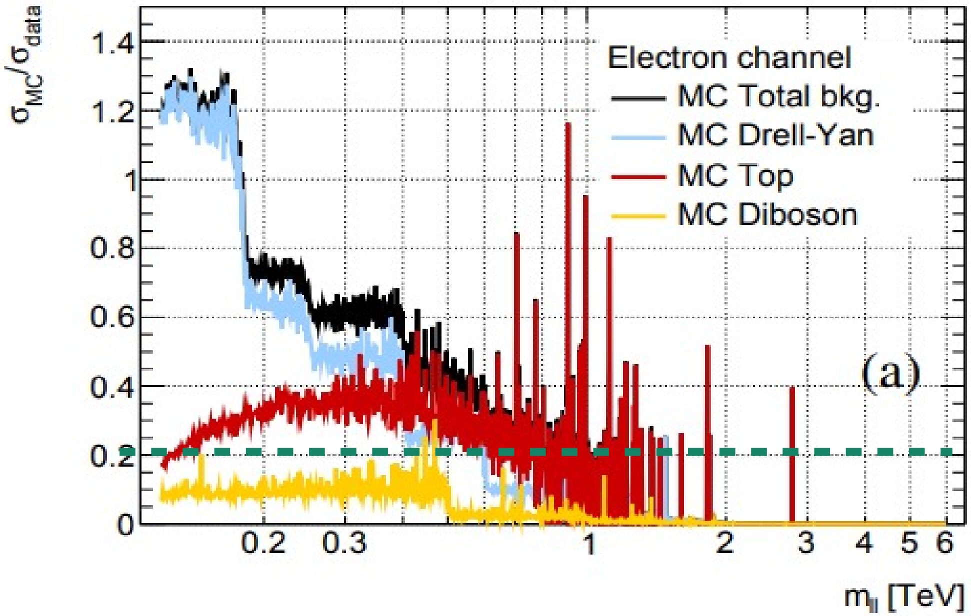


In the high P_T region (large lepton P_T) corrections can go up to a factor 2 (or down a factor 5) !

Background from Data

In some searches limited statistics of MC
→ Large statistics uncertainties associated to MC statistics
→ Using data driven approaches to fit the background





High mass dilepton analysis with first Run2 36fb⁻¹
Full Run2 analysis with x4 statistics!

Fit the background distributions with some parameterized functions to get **smooth** functions. Several possibilities:

- Functional form

$$f_{\gamma\gamma\times \mathrm{BW}}(M) = f_{\gamma\gamma}(M)\cdot \frac{\Gamma_Z}{(M_Z-M)^2+\Gamma_Z^2}$$

with $f_{\gamma\gamma}(M) = (1-(\frac{M}{\sqrt{s}})^{\kappa})^b \cdot (\frac{M}{\sqrt{s}})^{a_0+a_1\ln(\frac{M}{\sqrt{s}})+a_2\ln^2(\frac{M}{\sqrt{s}})+a_3\ln^3(\frac{M}{\sqrt{s}})}$

- $\kappa = 1$ in ee channel and $\kappa = 1/3$ in $\mu\mu$ channel

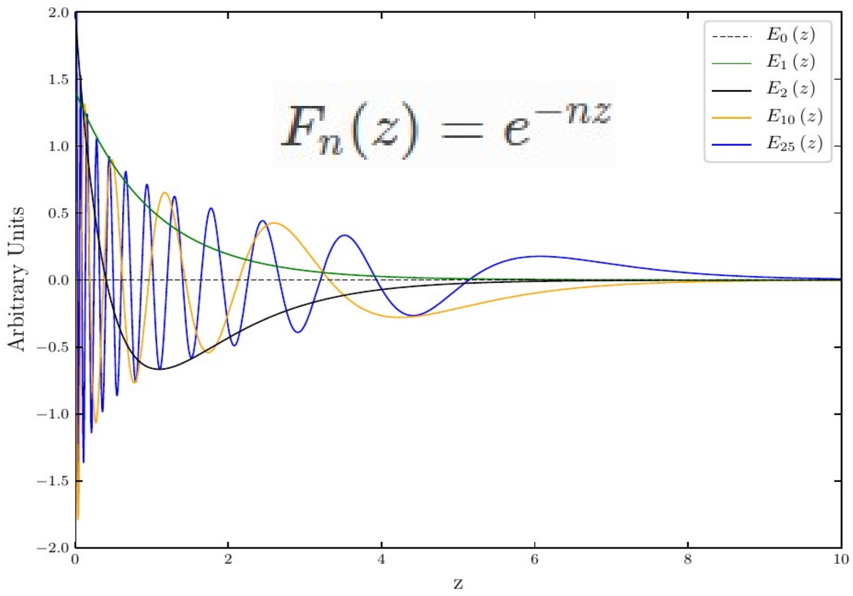
} Used for dilepton searches

3-parameter fit	$f(x) = p_1(1-x)^{p_2}x^{p_3}$
4-parameter fit	$f(x) = p_1(1-x)^{p_2}x^{p_3+p_4 ln(x)}$
5-parameter fit	$f(x) = p_1(1-x)^{p_2}x^{p_3+p_4 ln(x)+p_5 ln(x^2)}$
6-parameter fit	$f(x) = p_1(1-x)^{p_2}x^{p_3+p_4 ln(x)+p_5 ln(x^2)+p_6 ln(x^3)}$

x=(parameter of interest)/sqrt(s)

} Used for dijet or 4-jet searches

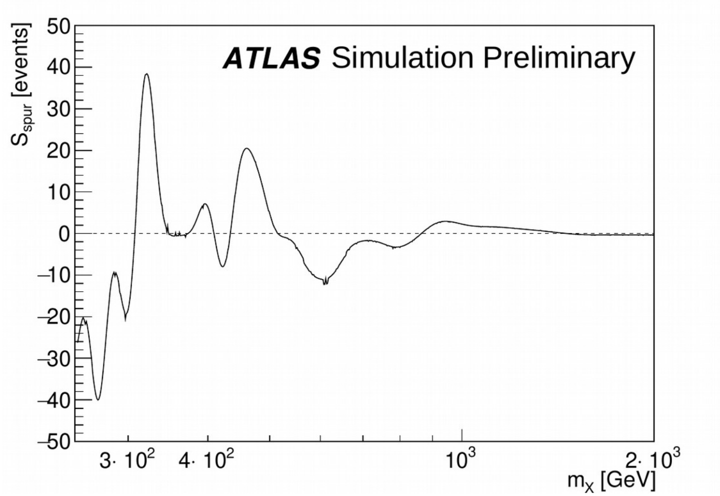
- Gaussian Process Regression link
- Functional Decomposition (link) the template shape is parameterized using a series expansion

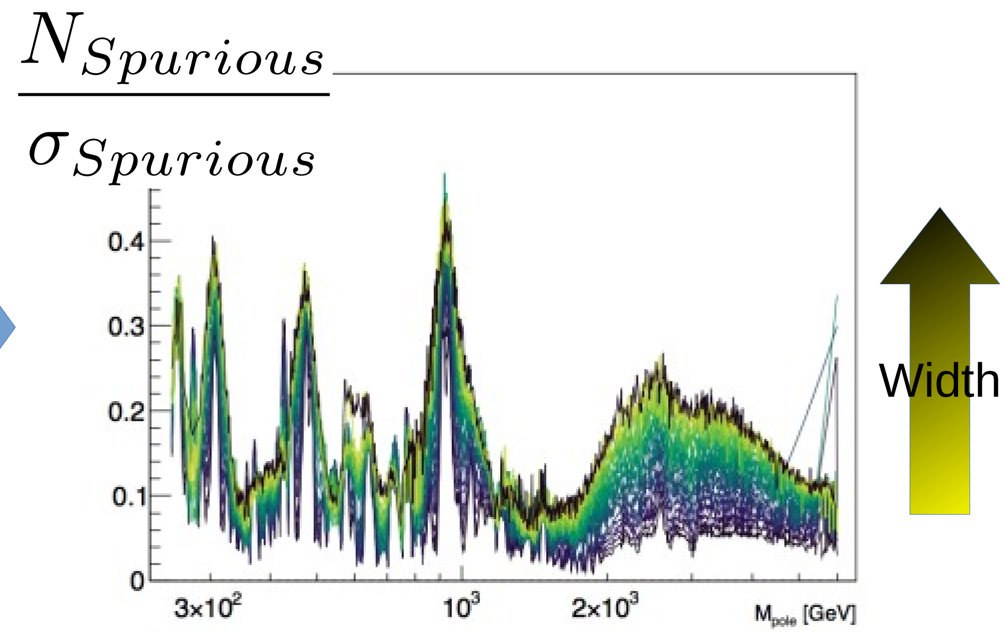


Whatever smoothing method you use, you have to be sure that:

- We do not “create” artificial excess → Spurious tests
- We can succesfully identify hypothetical signal → Injection tests

Spurious tests results on the dilepton channel





Very nice handbook here

Statistics

How to wrap up all that?

Global (binned) likelihood function

Poisson

$$\mathcal{L}(\boldsymbol{n}|\mu,\boldsymbol{\theta}) = \prod_{i\in bins} \mathcal{P}(n_i|\mu\cdot S_i(\boldsymbol{\theta}) + B_i(\boldsymbol{\theta}))$$

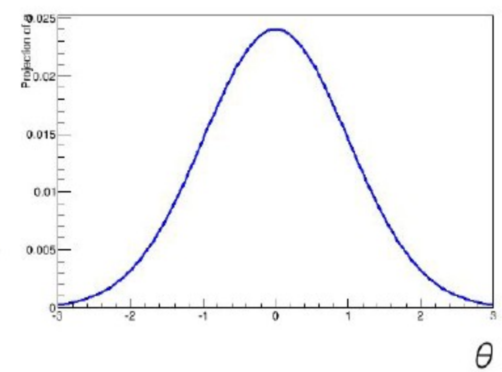
observed bin contents

parameters

S+*B* prediction in bin *i*

μ is the parameter of interest (POI)
μ = 0 → Standard Model
μ =1 → Beyond Standard Model
Also background can be normalized separately
μ_{top}, $\mu_{Diboson}$, etc.

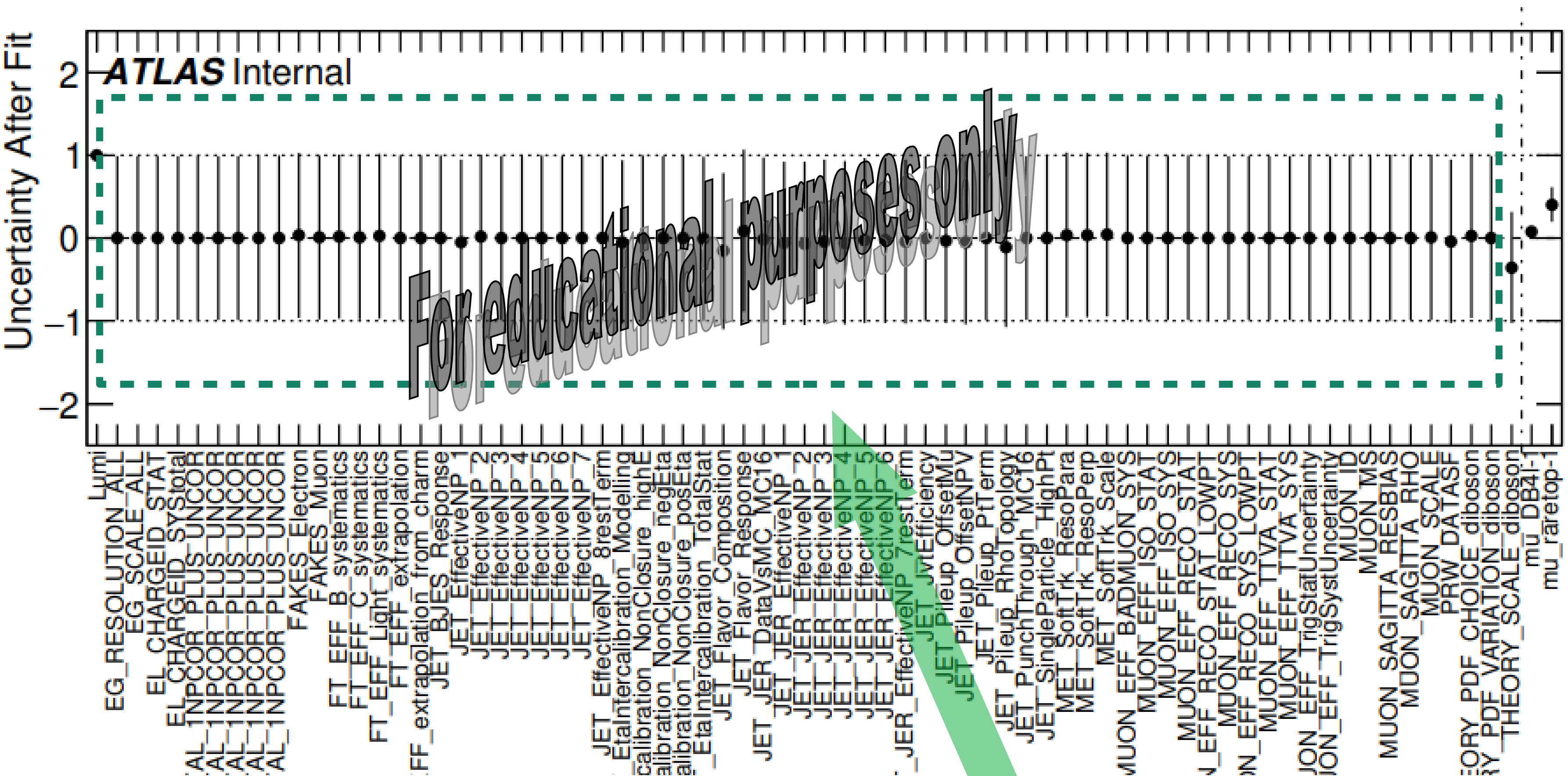
$$\times \prod_{j\in syst} \mathcal{G}(\theta_j^0|\theta_j,\Delta\theta_j)$$



But we have an imperfect knowledge of our detector, theory, … → systematics

Much more complete treatment on T. Dado lecture

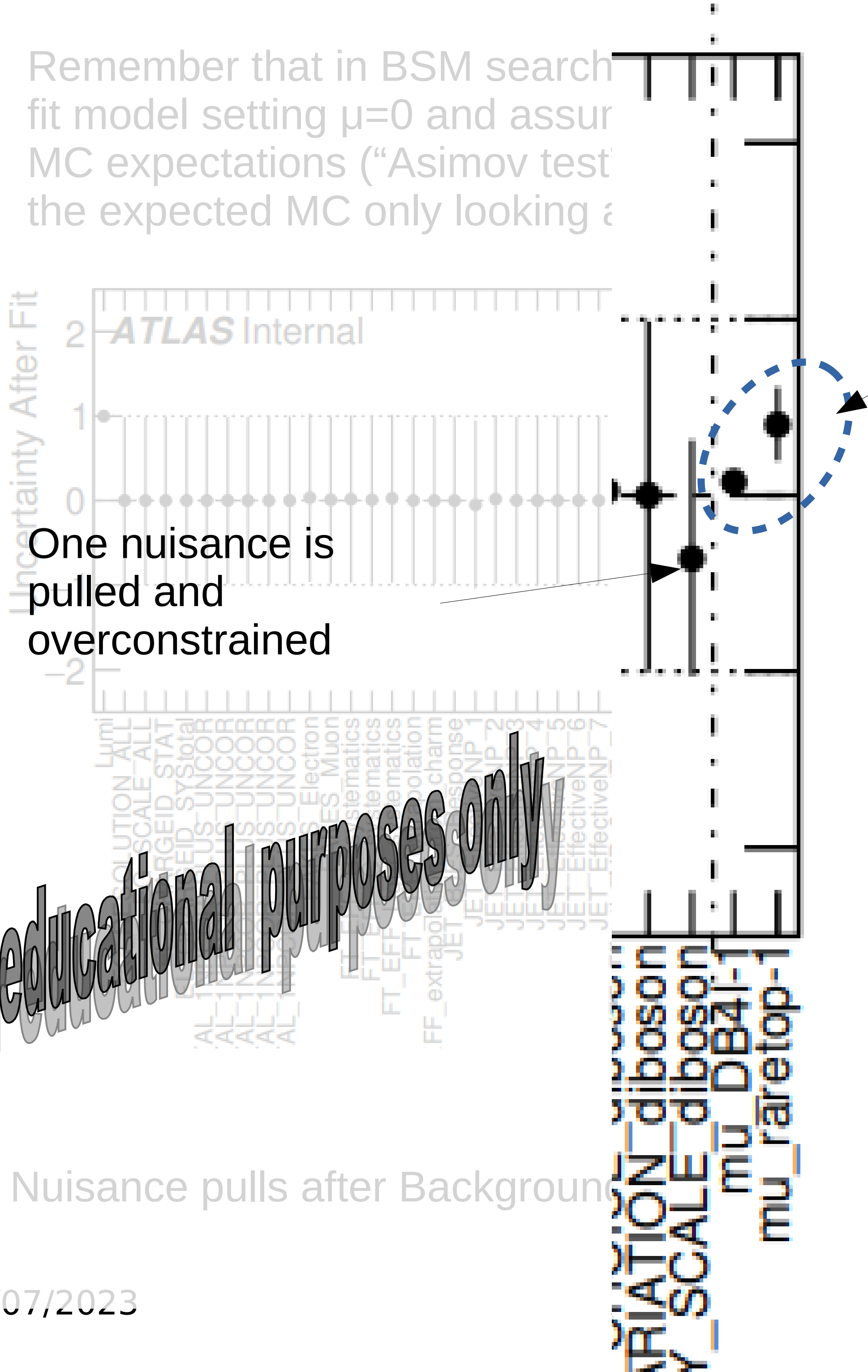
Remember that in BSM searches, data in signal regions are blinded → validate your fit model setting μ=0 and assuming the data points in your CR + SR coincide with the MC expectations ("Asimov test") or a "Background-only" fit where you fit the data with the expected MC only looking at CR

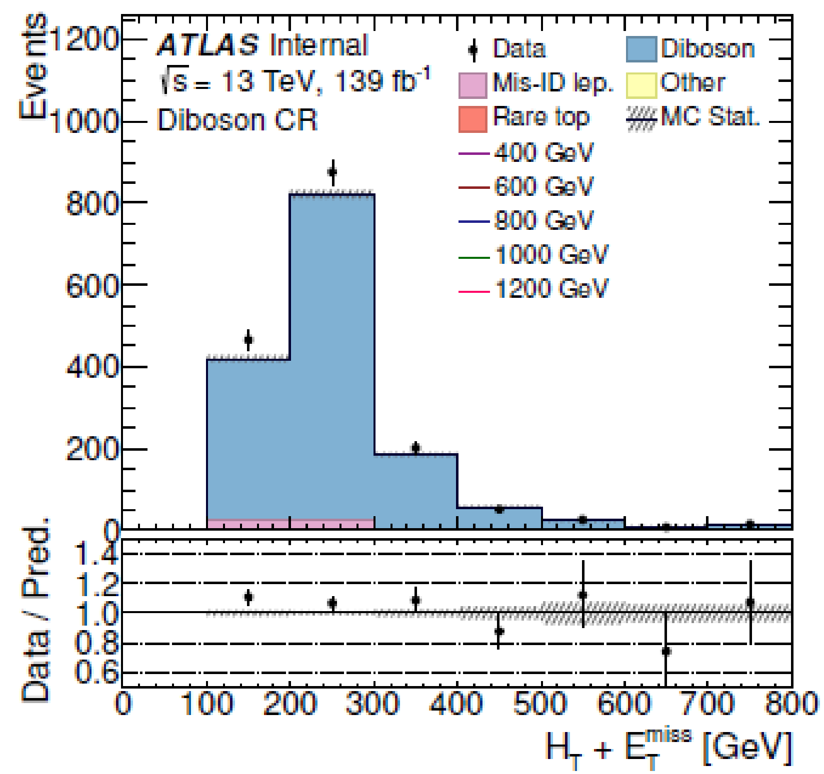


Look fine, mean ~ 0 and variance ~1

Nuisance pulls after Background fit

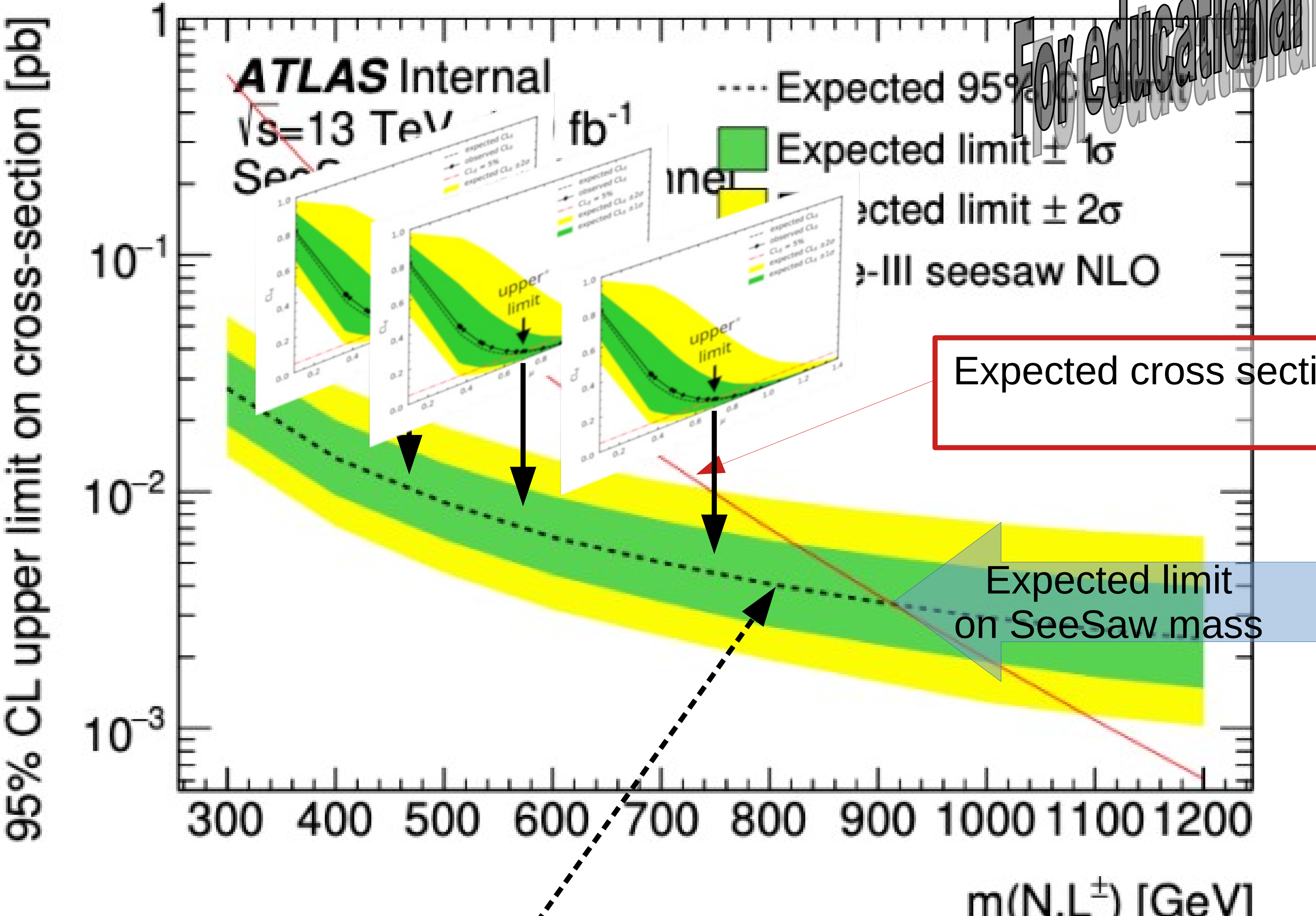
Remember that in BSM search[...]gions are blinded → validate your fit model setting μ=0 and assur[...] in your CR + SR coincide with the MC expectations ("Asimov test[...]only" fit where you fit the data with the expected MC only looking a[...]





Nuisance pulls after Backgroun[...]

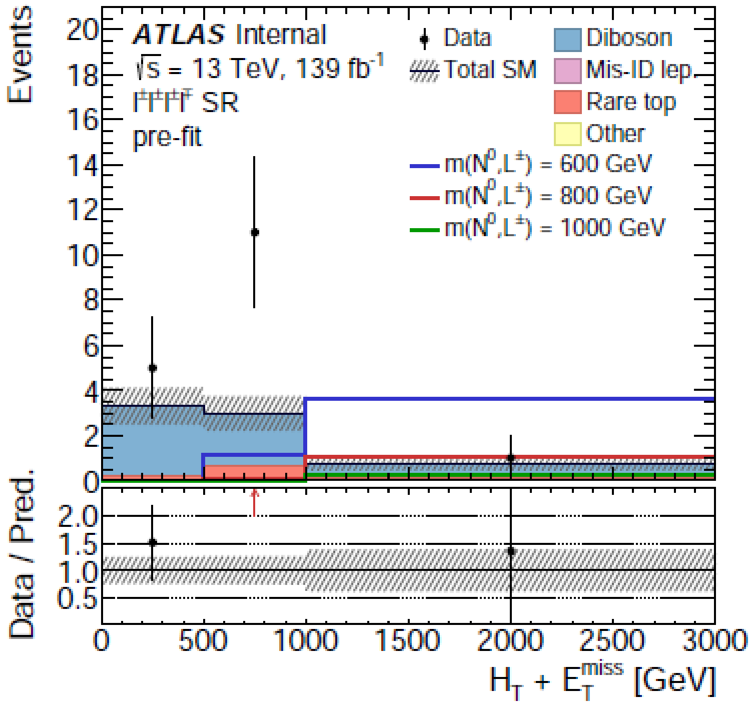
Signal Regions still **blinded**

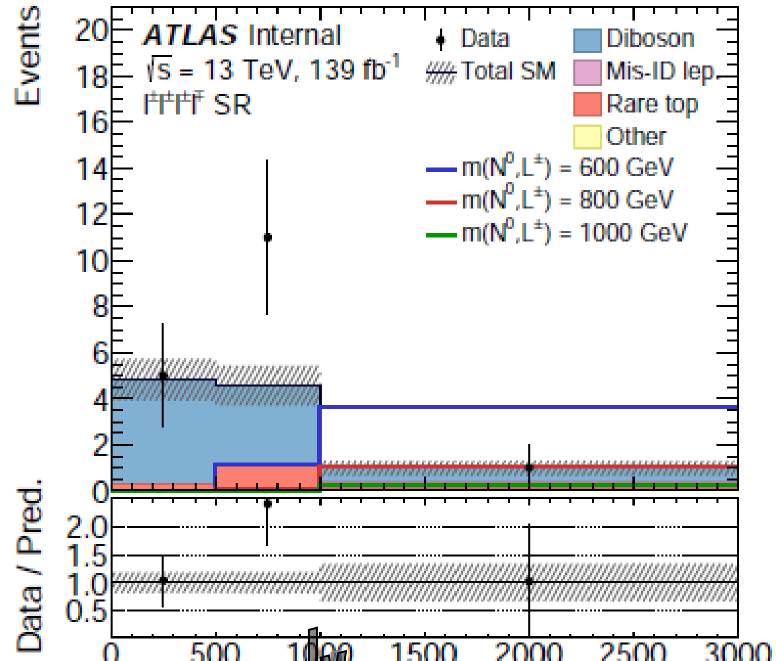


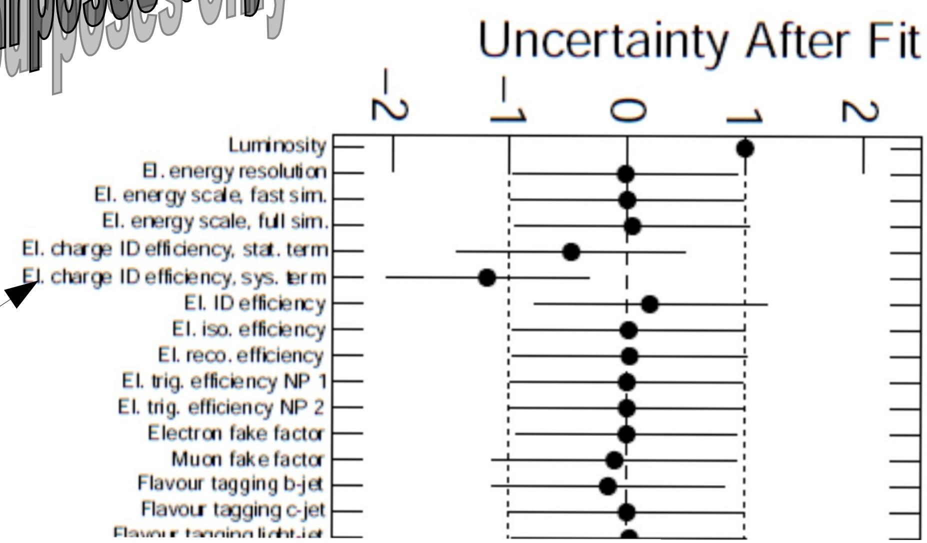
Expected exclusion limit: Given the background abundance, in CR, their normalization after the background fit, the extrapolation to the SR we can exclude at 95% CL a cross section up to …. (e.g. ~4 fb for 800 GeV)

After unblinding

Distribution of one of the four lepton signal regions

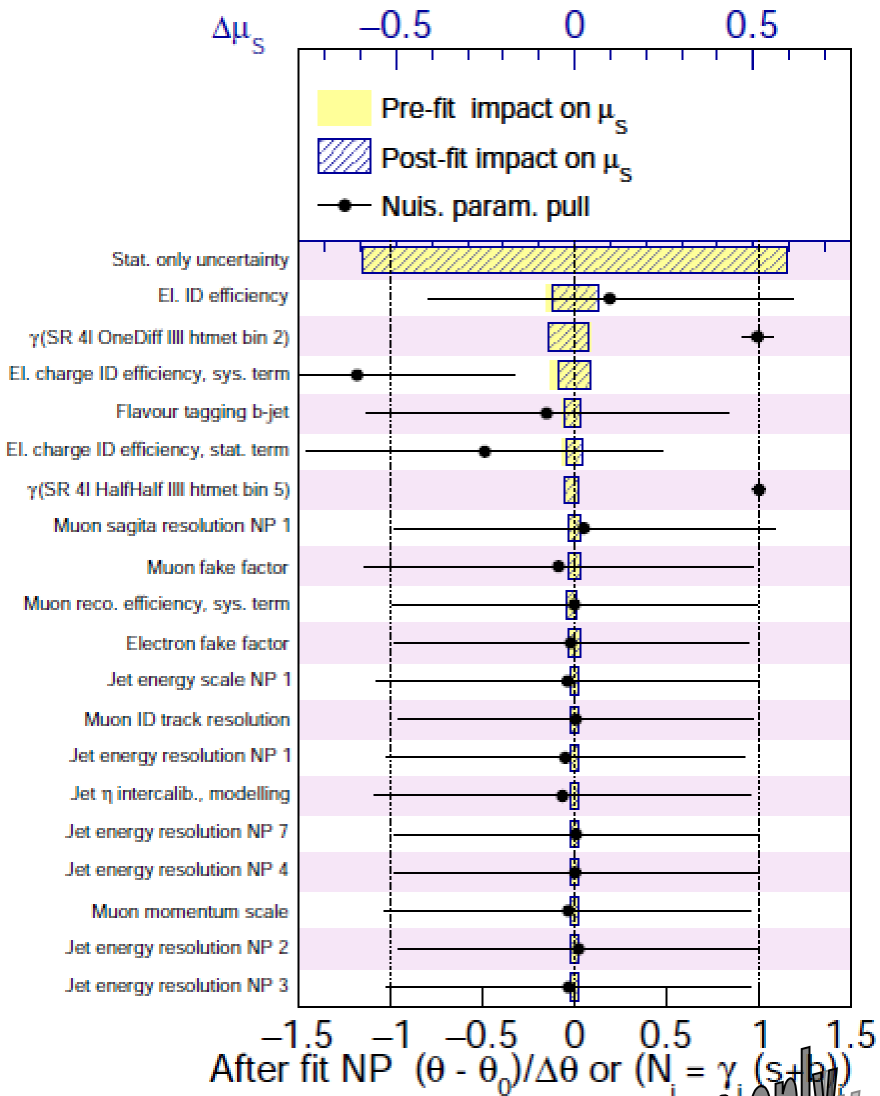






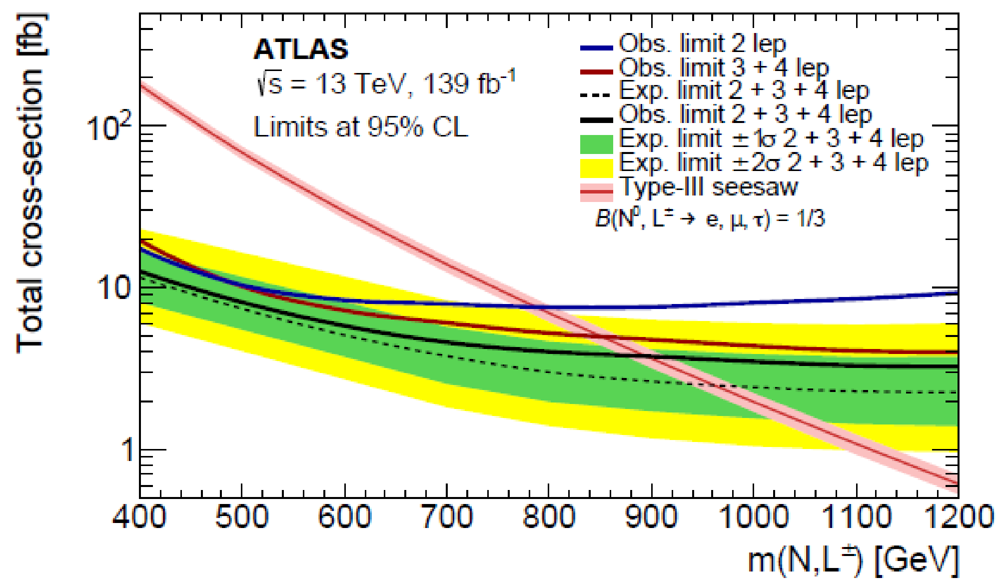
1) After fit systematic uncertainties get sensibly smaller
2) Fit tries to increase the diboson contribution to match the 2nd bin of data (in particular pulling one of the systematics)

Ranking plot of uncertainties
(statistics and systematics)



BSM searches are usually statistics limited

The final exclusion plot



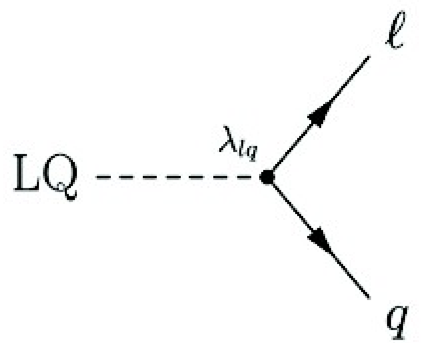
- Why looking for physics Beyond Standard Model ?
- "So, you want to look for Beyond Standard Model physics"
  - Ingredients of a search: strategy, background estimation, statistics,...
- Few searches
  - Leptoquarks
  - Dark Matter
  - Long Lived Particle searches

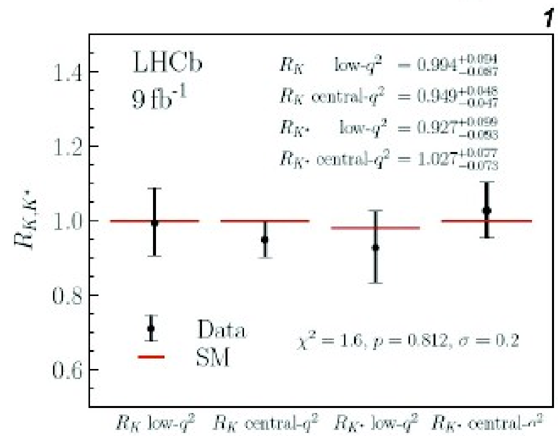
Leptoquark searches

Leptoquarks are BSM particles that couple leptons with quarks (fractional charge, color, B and L quantum numbers)
Scalar or Vectors

β=0 → neutrino (neutral lepton)
β=1 → charged lepton
Minimal model:
Couple with same generation quark-lepton
Or intra-generation mixing

$$\beta = 0\ LQ_3^u \to t\nu_\tau$$
$$\beta = 1\ LQ_3^u \to b\tau$$
$$\beta = 0\ LQ_3^d \to b\nu_\tau$$
$$\beta = 1\ LQ_3^d \to t\tau$$



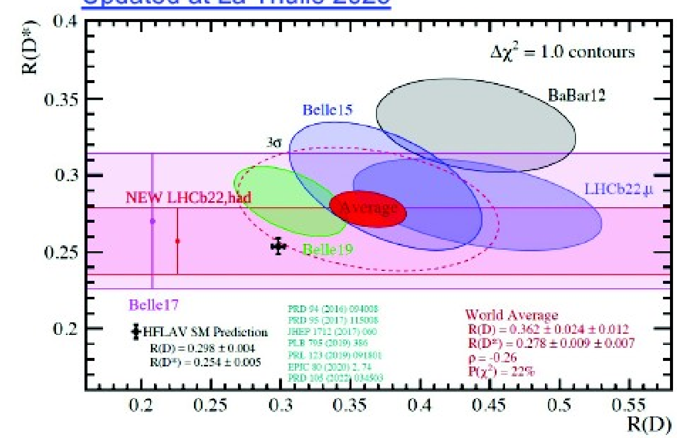


No longer evidence of μ/e universality violation

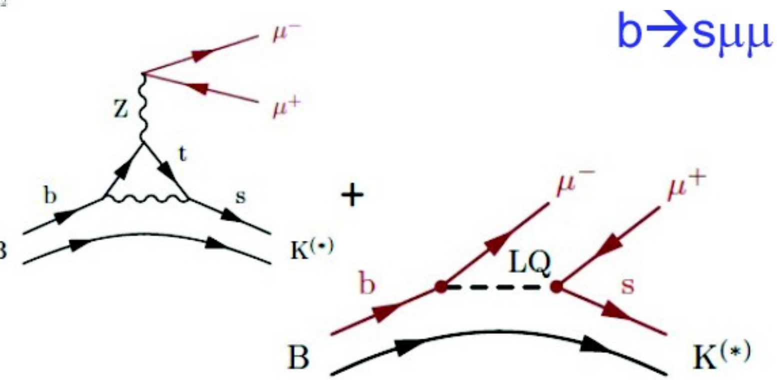
Broad search program

Resurgence of LQ because of lepton universality violation (now no more) and other tensions in flavor sector (b → sμμ) (still there)

Updated at La Thuile 2023

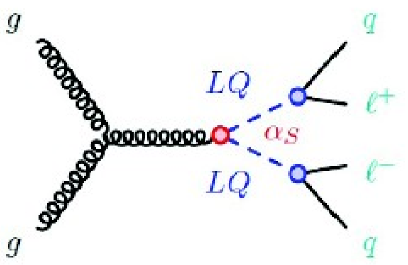


b→sμμ



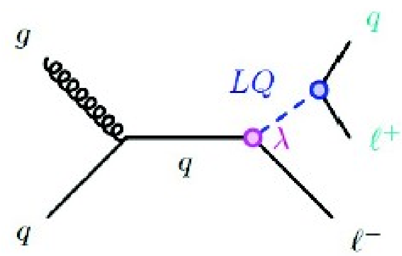
From A. Juste slides

Pair production



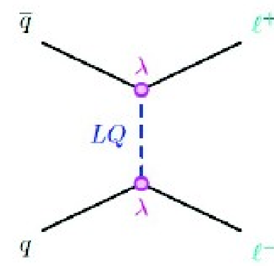
QCD production (universal mode)
σ only depends on m_{LQ}
Sensitivity to low m_{LQ}

Single production

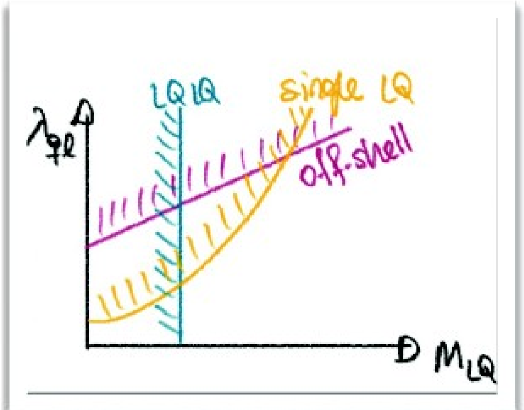


Depends on q PDF
$\sigma \sim \lambda^2$
Sensitivity to higher m_{LQ}
if λ sufficiently large

Off-shell production

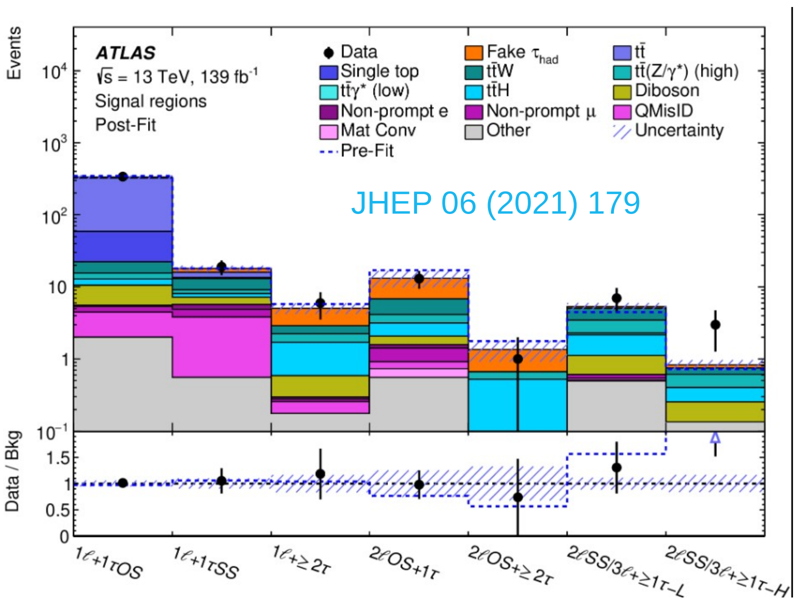


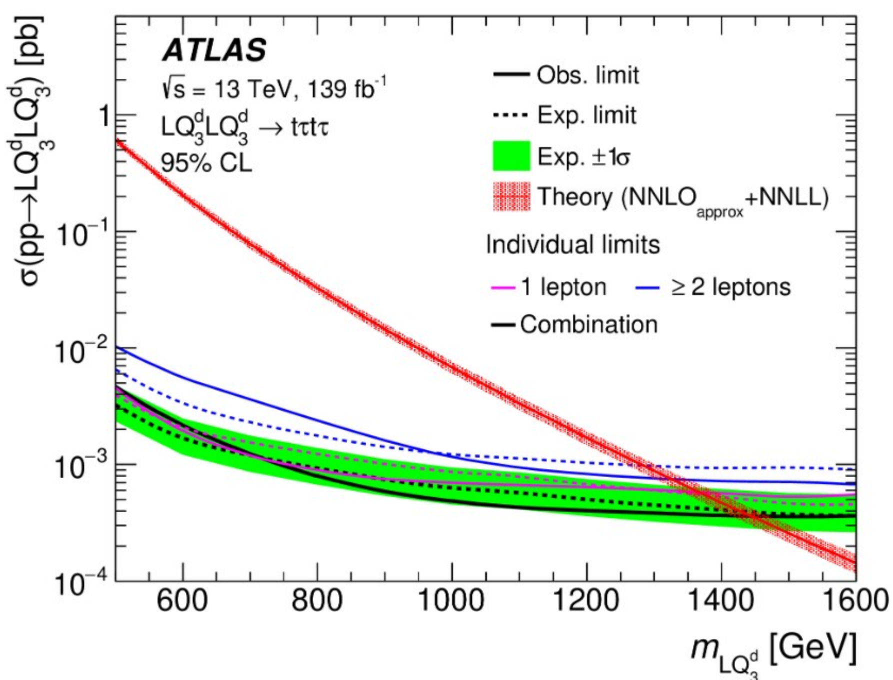
(Depends on q PDF)^2
$\sigma \sim \lambda^4$
Sensitivity to very high m_{LQ}
if λ sufficiently large

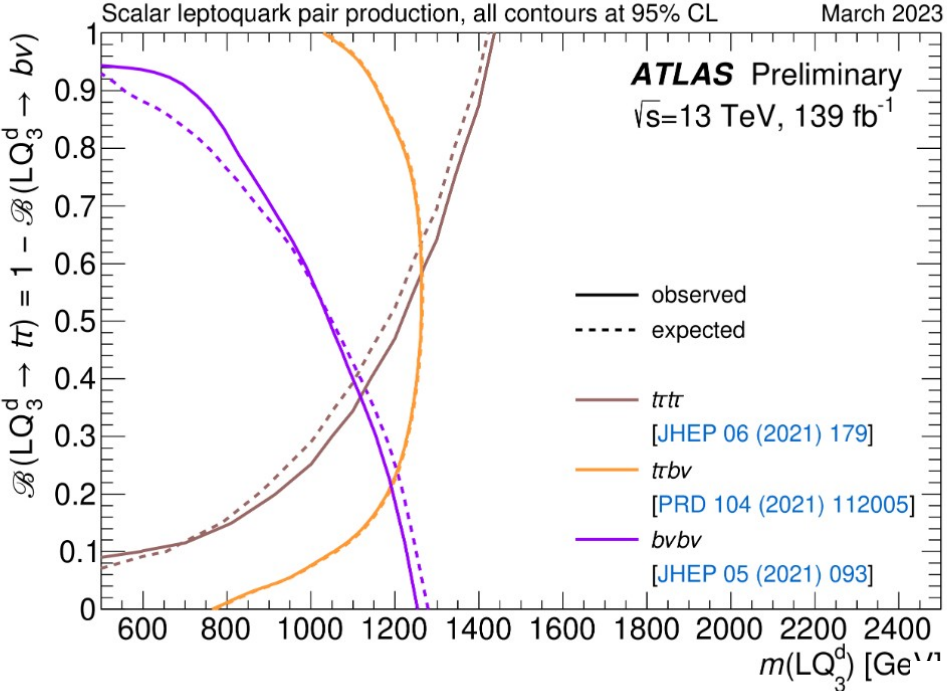


Very similar to contact interaction we discussed before

$$LQ_3^d LQ_3^d \to t\tau t\tau$$ search

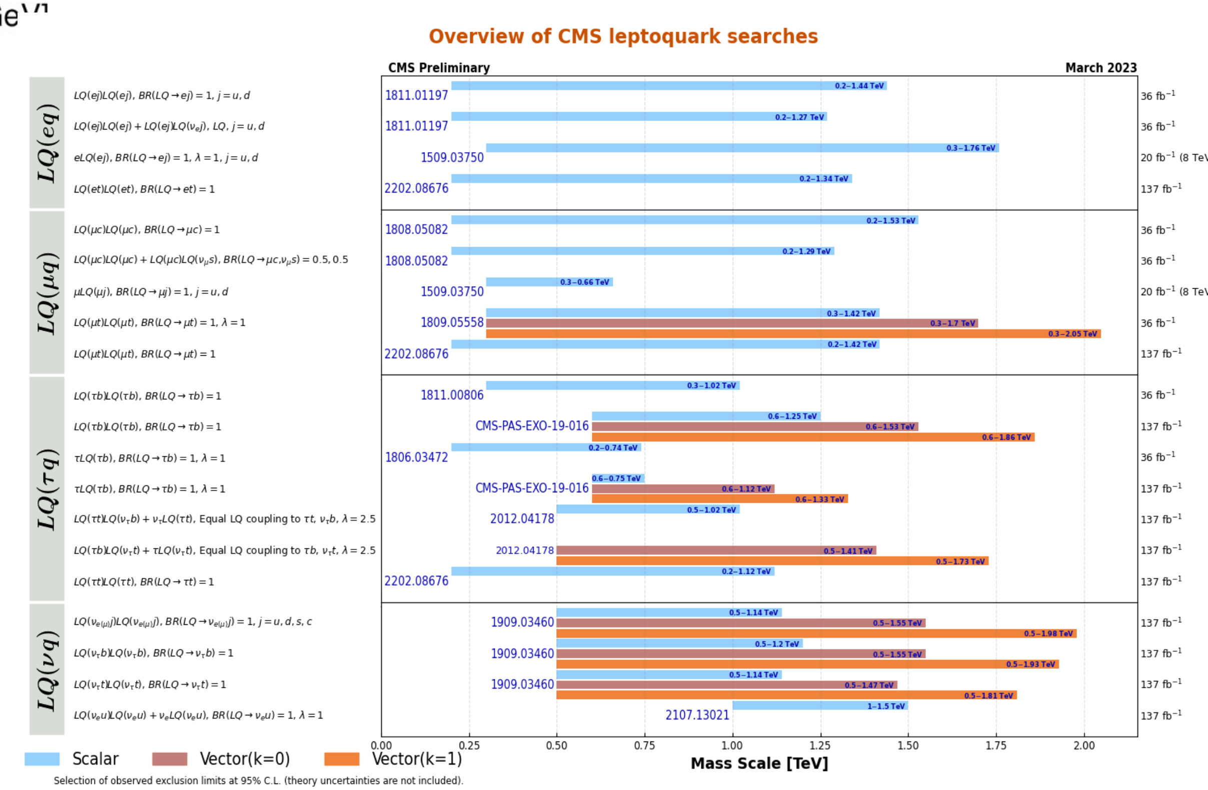






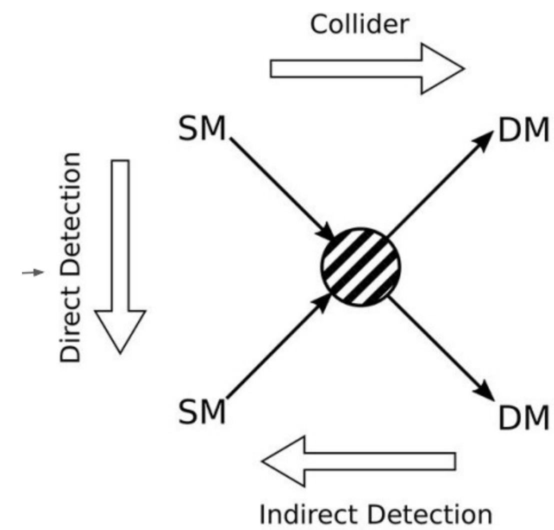
ATL-PHYS-PUB-2023-006

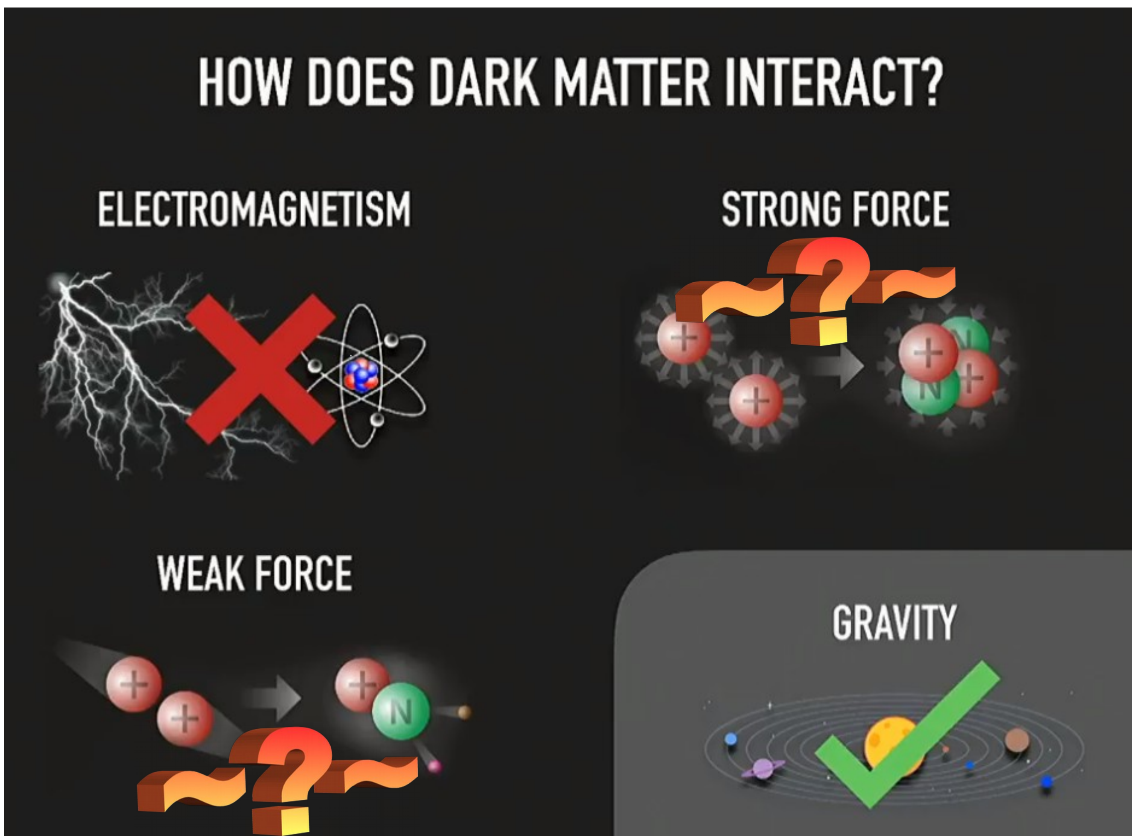
CMS Summary plot

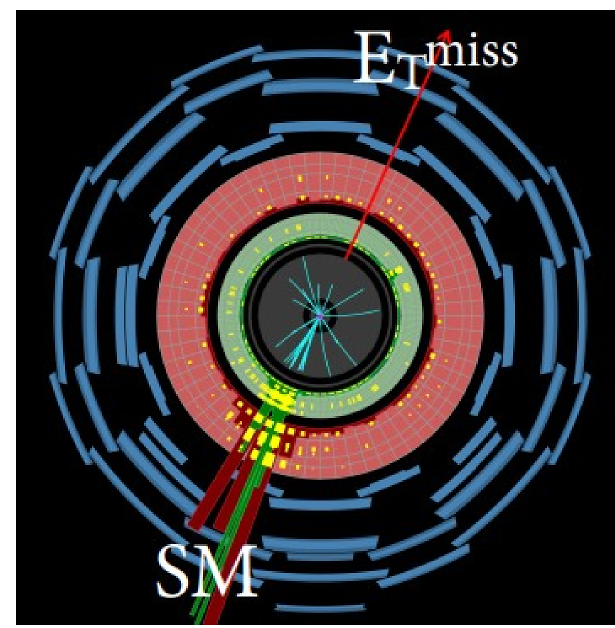


Dark Matter Searches

Dark Matter can be observed at LHC only under the WIMP hypothesis
May be we can produce DM at LHC
But cannot observe it ➡ Missing Transverse Energy!

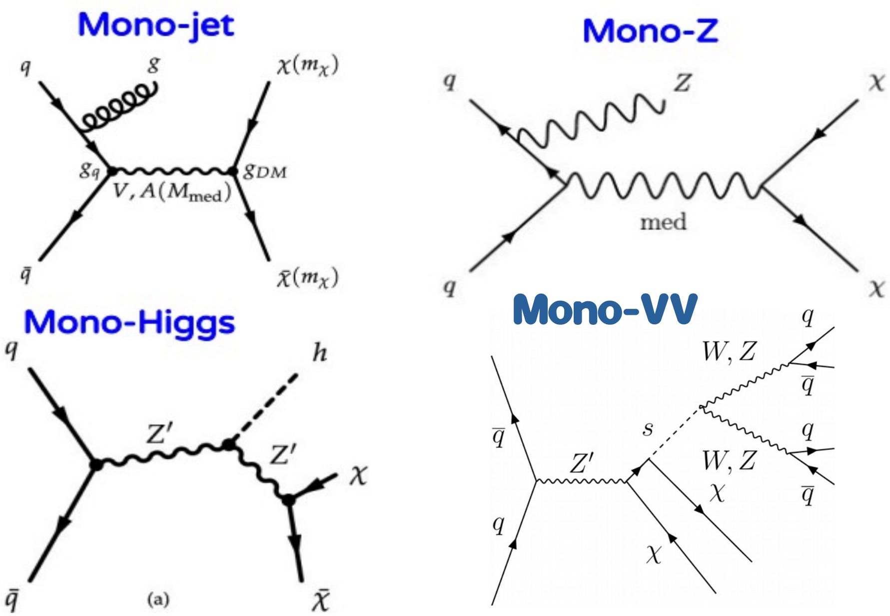


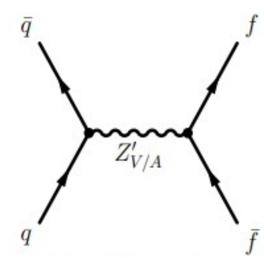




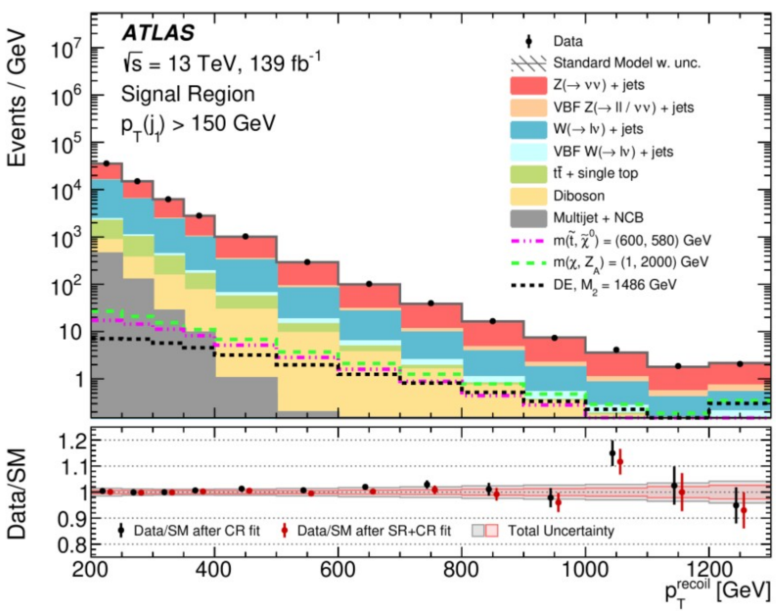
DM Signatures coulde be:

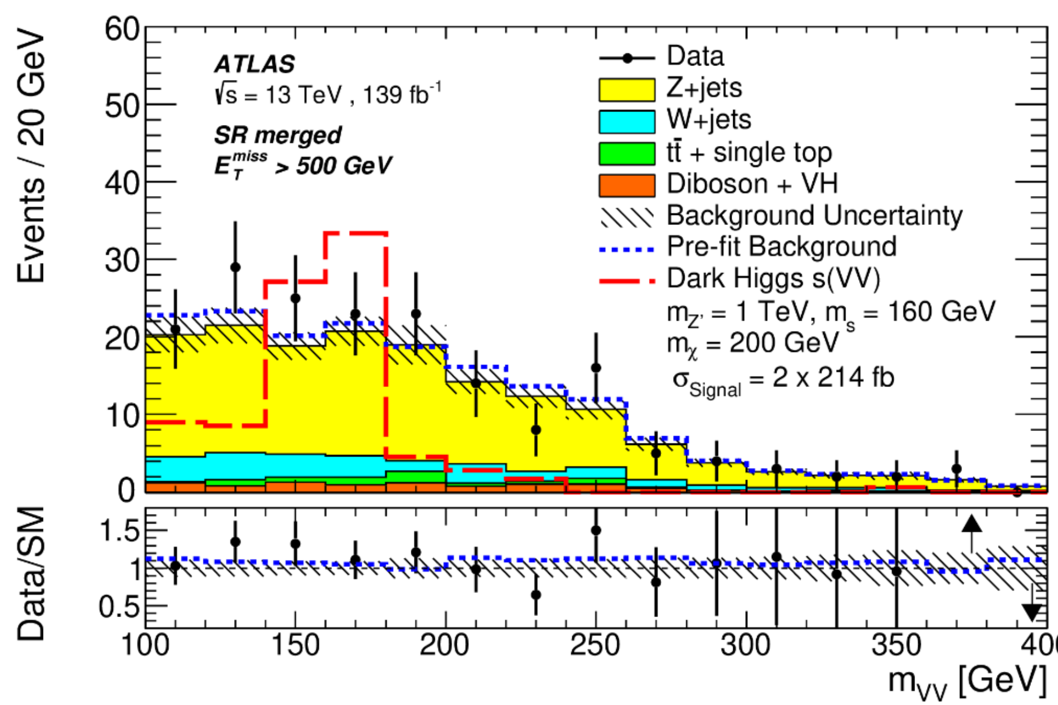
- Mono-objects: mono-jet, mono-Z, mono-Higgs, mono-tt/bb → object recoiling against DM
- Resonances searches
- Long lived Particles





Example mono-jet





Phys Rev D 103 (2021) 112006

PRL 126 (2021) 121802

Mono-objects, dijet, ditops, (dilepton), Long Lived particles final states can be interpreted with:

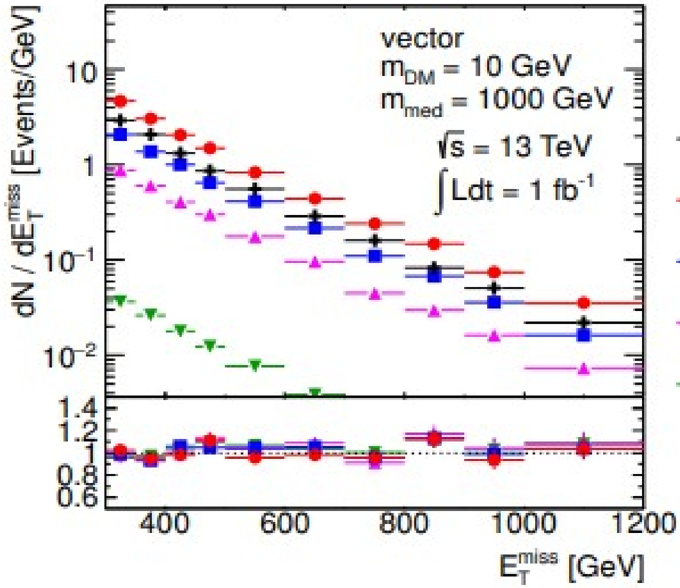
1) Effective Field Theories (→ not here cf U. Bumenschein and H. Mildner lectures)
2) **Simplified** Models
3) Complete Models (e.g. 2HDM+**α** Two Higgs Doublet Model)

Simplified model parameters:

- Mass of the mediator Z'
- Mass of the DM M**χ**
- Coupling (universal) of Z' with quarks g_q
- Coupling (universal) of Z' with leptons g_l
- Coupling (universal) of Z' with Dark Matter g_χ
- Spin of mediator (Scalar/Pseudo-Scalar or Vector/Axial-Vector)

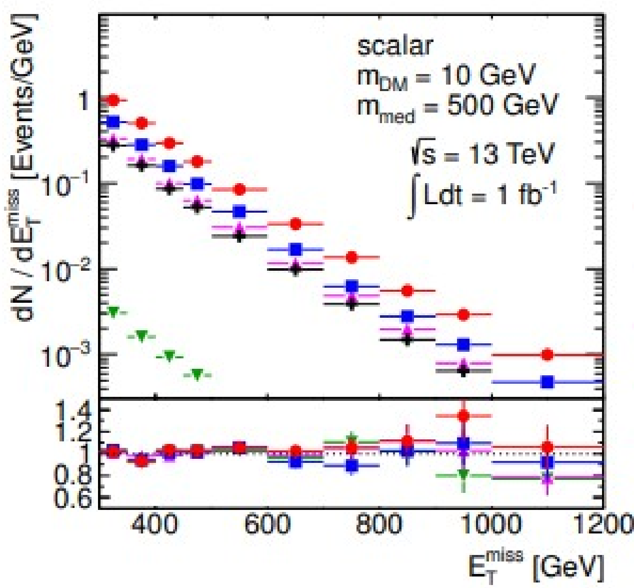
Typical benchmark points (agreed between ATLAS and CMS):
g_{DM}=1 g_q=0.25 → Vector or Axial-Vector Mediator
g_{DM}=1 g_q=1 → Scalar or Pseudo-Scalar
Leptophobic (g_l=0) or Leptophilic (g_l=0.1)

How couplings affect ETMiss Distribution



g_{SM}	g_{DM}	Γ/m_{med}	$\sigma \times A_{300}$ [fb]	$\sigma \times A_{500}$ [fb]
1.00	1.00	0.504	4.8e+02	1.2e+02
1.45	1.45	1.059	7.5e+02	1.8e+02
0.25	1.00	0.056	3.5e+02	9.0e+01
0.50	0.50	0.126	1.5e+02	3.8e+01
0.10	0.10	0.005	6.3e+00	1.6e+00

Vector Mediator



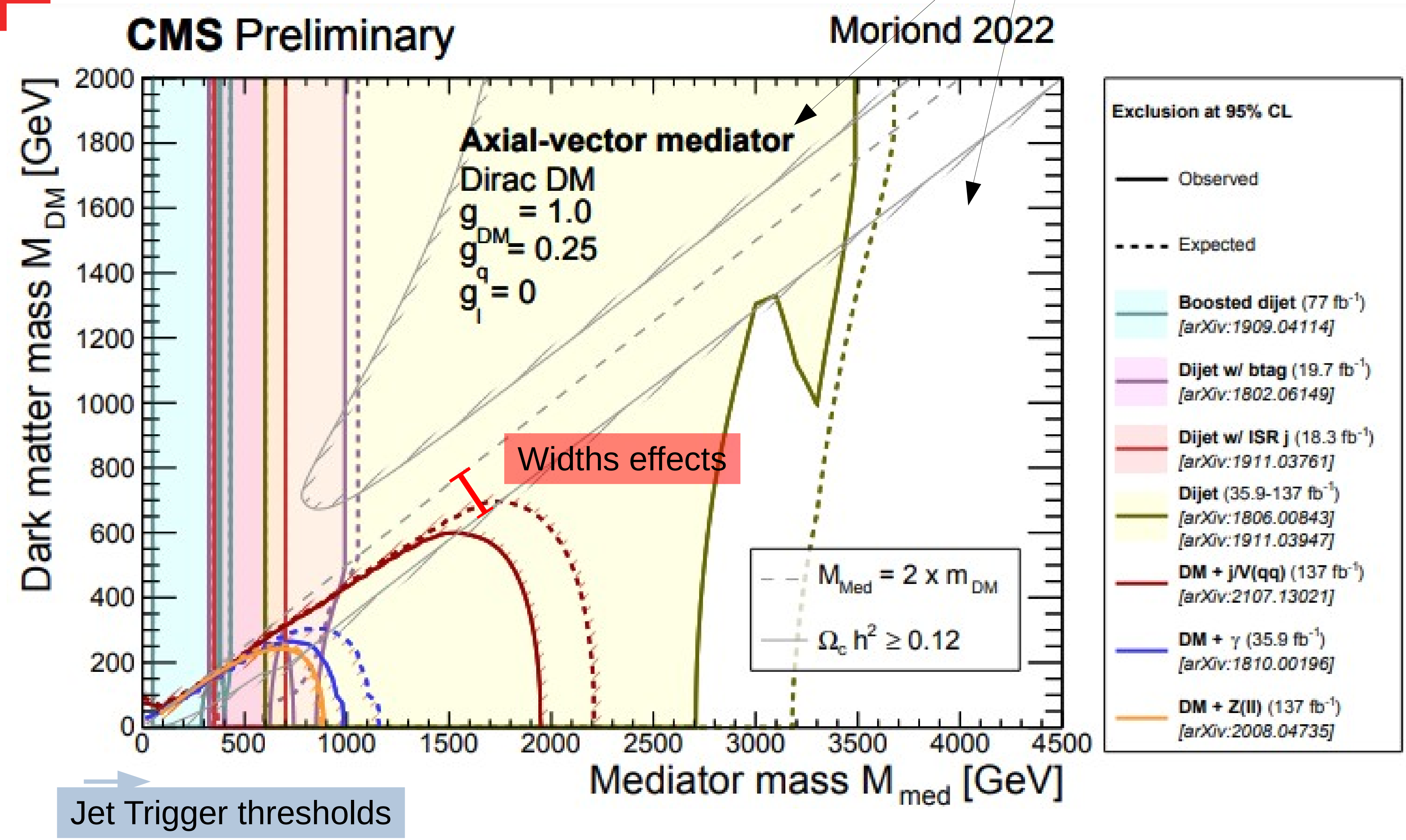
g_{SM}	g_{DM}	Γ/m_{med}	$\sigma \times A_{300}$ [fb]	$\sigma \times A_{500}$ [fb]
1.00	1.00	0.062	3.3e+01	4.0e+00
2.00	2.00	0.248	1.1e+02	1.4e+01
2.00	1.00	0.129	6.0e+01	7.5e+00
1.00	2.00	0.181	3.9e+01	5.0e+00
0.10	0.10	0.001	3.5e-01	4.4e-02

Scalar Mediator

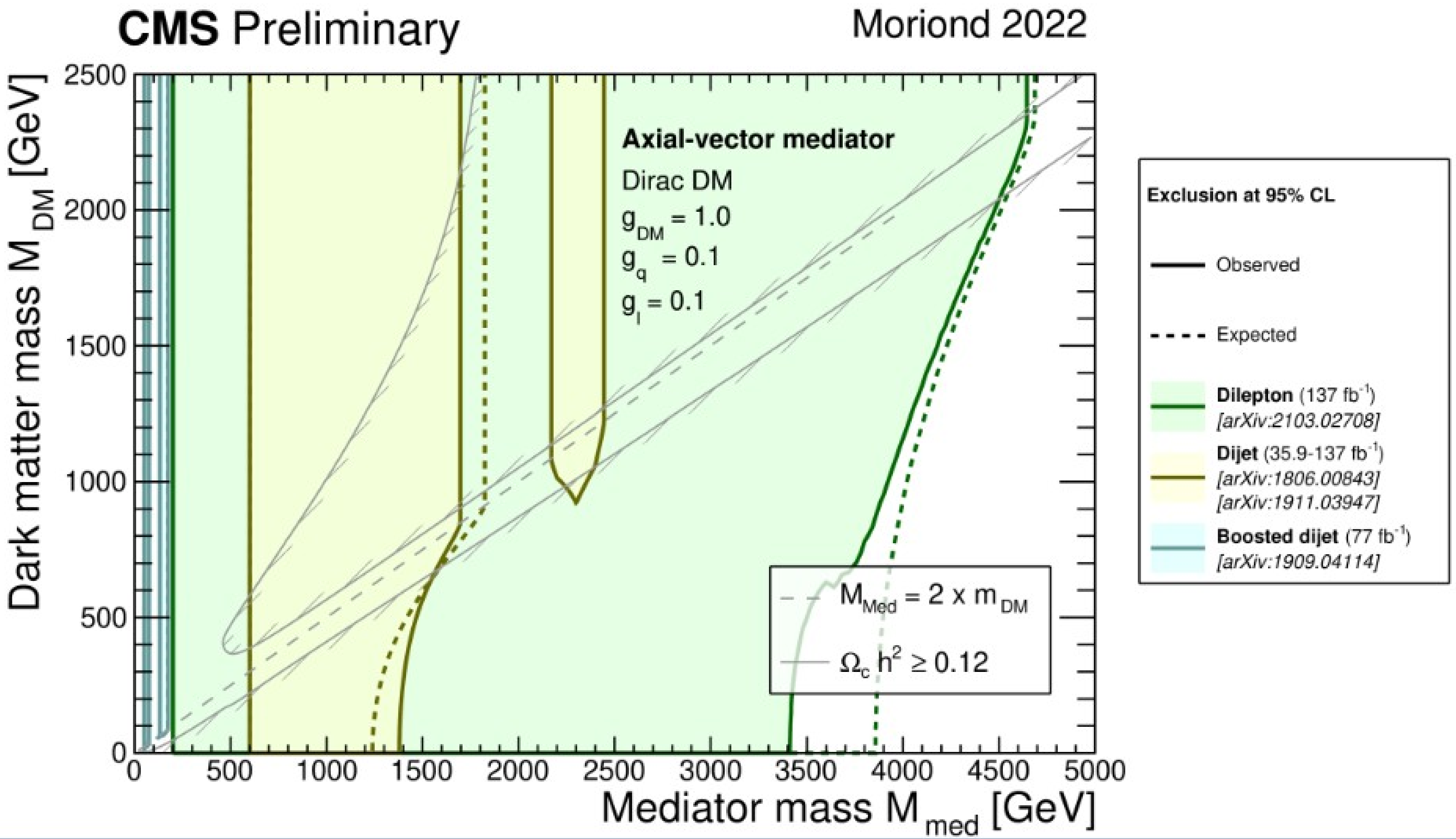
arxiv:1507.00966

Leptophobic

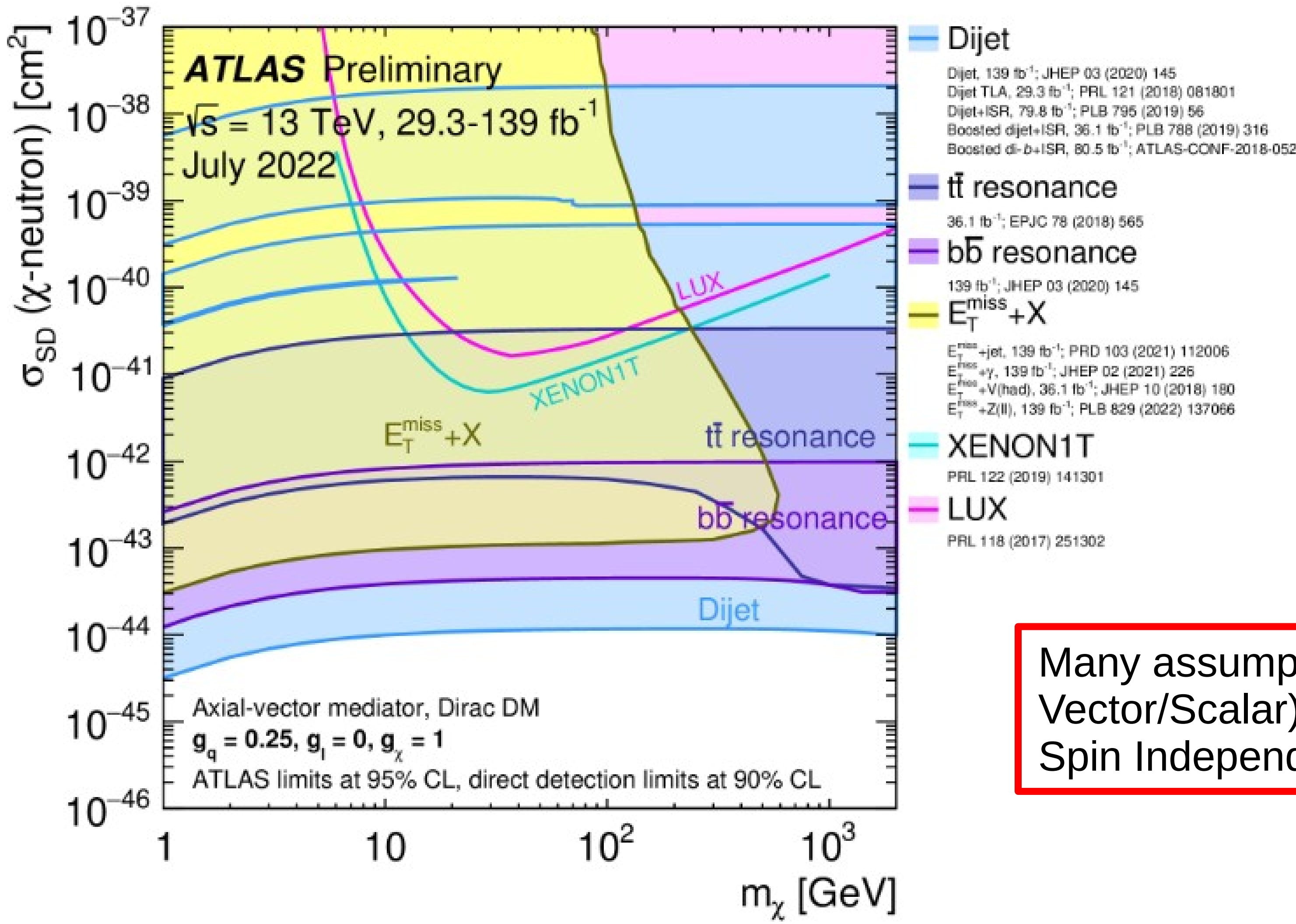
Relic density



Leptophilic



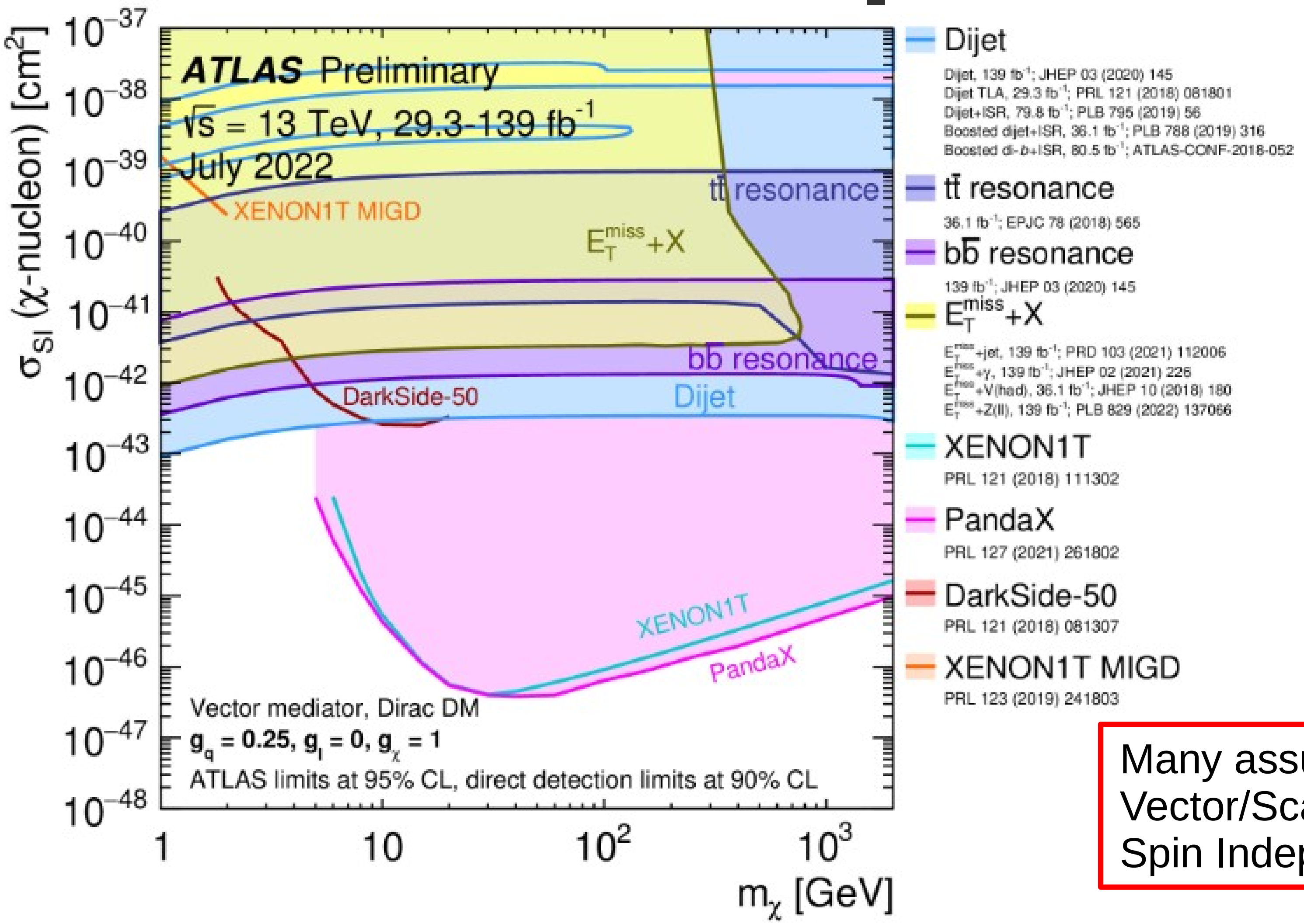
Comparison with Direct Detection Experiments



Spin Dependent

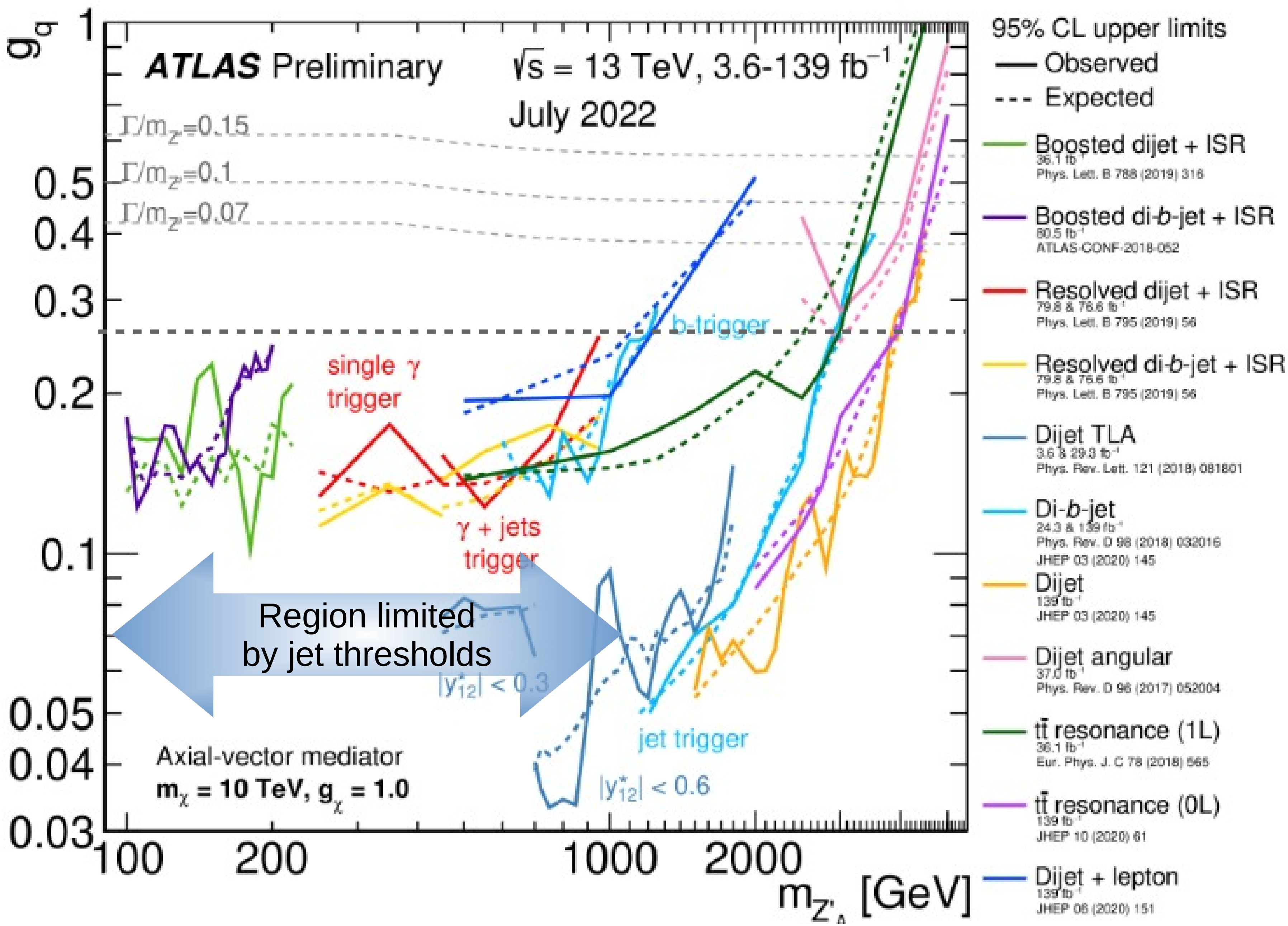
Many assumptions (couplings, Vector/Scalar), Spin Dependent vs Spin Independent Interactions

Comparison with Direct Detection Experiments



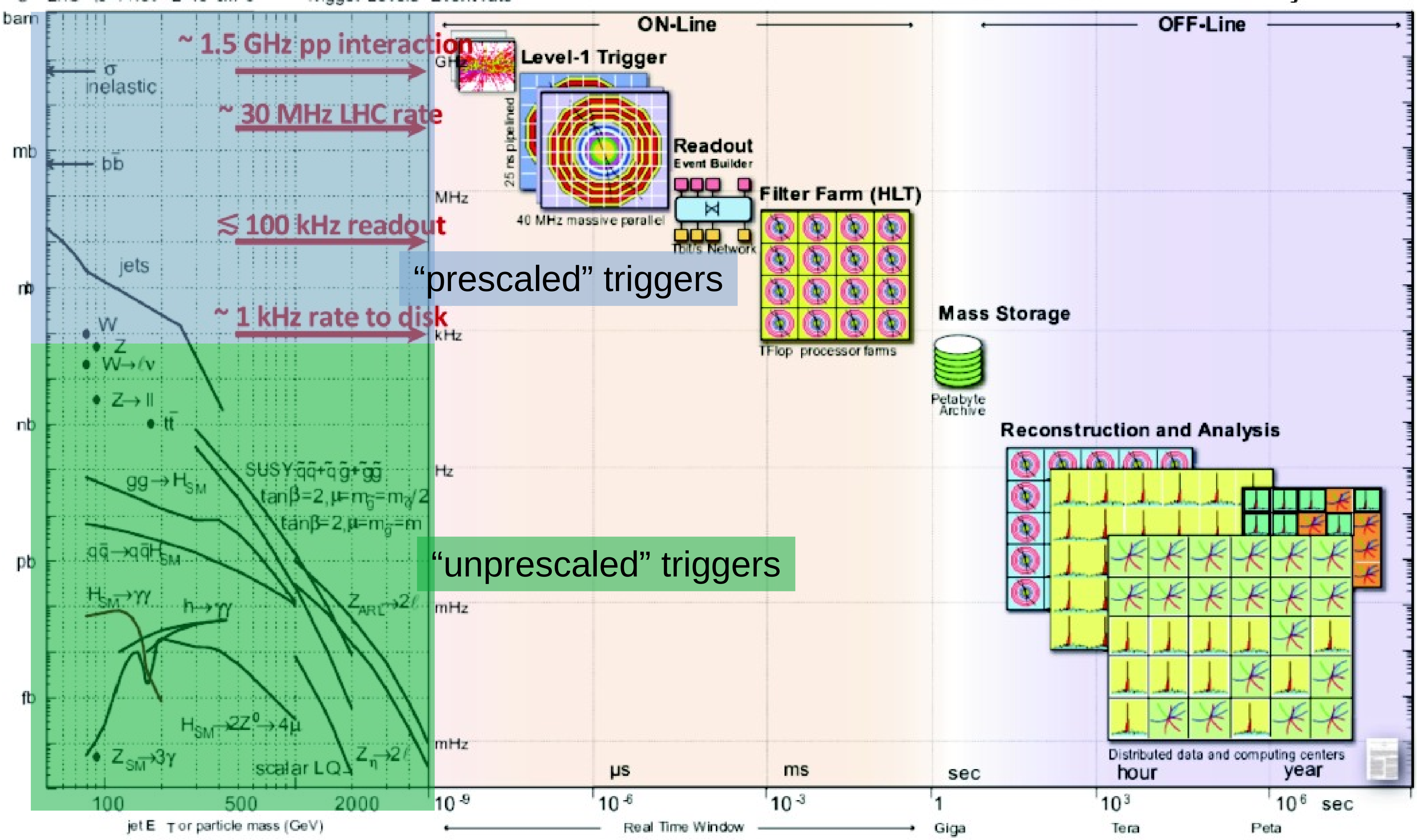
Spin Independent

Many assumptions (couplings, Vector/Scalar), Spin Dependent vs Spin Independent Interactions

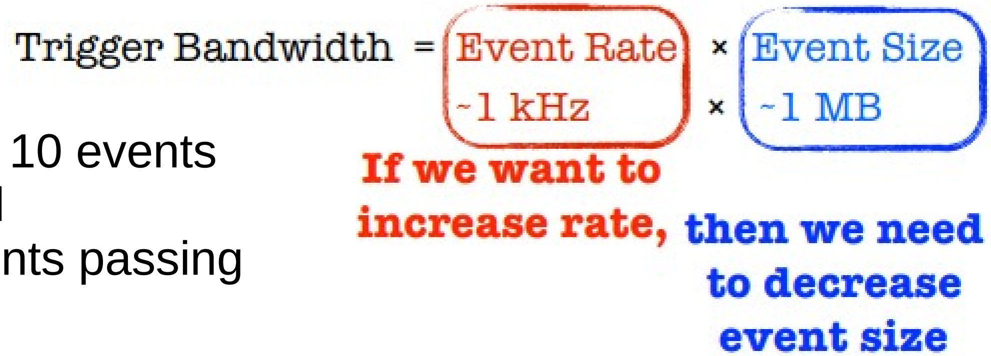


ATLAS Preliminary
√s = 13 TeV, 3.6-139 fb⁻¹
July 2022
Γ/m_Z=0.15
Γ/m_Z=0.1
Γ/m_Z=0.07
single γ trigger
γ + jets trigger
b-trigger
jet trigger
|y*12| < 0.3
|y*12| < 0.6
Region limited by jet thresholds
Axial-vector mediator
m_χ = 10 TeV, g_χ = 1.0
g_q
m_Z'A [GeV]
95% CL upper limits
Observed
Expected
Boosted dijet + ISR
36.1 fb⁻¹
Phys. Lett. B 788 (2019) 316
Boosted di-b-jet + ISR
80.5 fb⁻¹
ATLAS-CONF-2018-052
Resolved dijet + ISR
79.8 & 76.6 fb⁻¹
Phys. Lett. B 795 (2019) 56
Resolved di-b-jet + ISR
79.8 & 76.6 fb⁻¹
Phys. Lett. B 795 (2019) 56
Dijet TLA
3.6 & 29.3 fb⁻¹
Phys. Rev. Lett. 121 (2018) 081801
Di-b-jet
24.3 & 139 fb⁻¹
Phys. Rev. D 98 (2018) 032016
JHEP 03 (2020) 145
Dijet
139 fb⁻¹
JHEP 03 (2020) 145
Dijet angular
37.0 fb⁻¹
Phys. Rev. D 96 (2017) 052004
tt̄ resonance (1L)
36.1 fb⁻¹
Eur. Phys. J. C 78 (2018) 565
tt̄ resonance (0L)
139 fb⁻¹
JHEP 10 (2020) 61
Dijet + lepton
139 fb⁻¹
JHEP 06 (2020) 151

From a talk by Mia Tosi

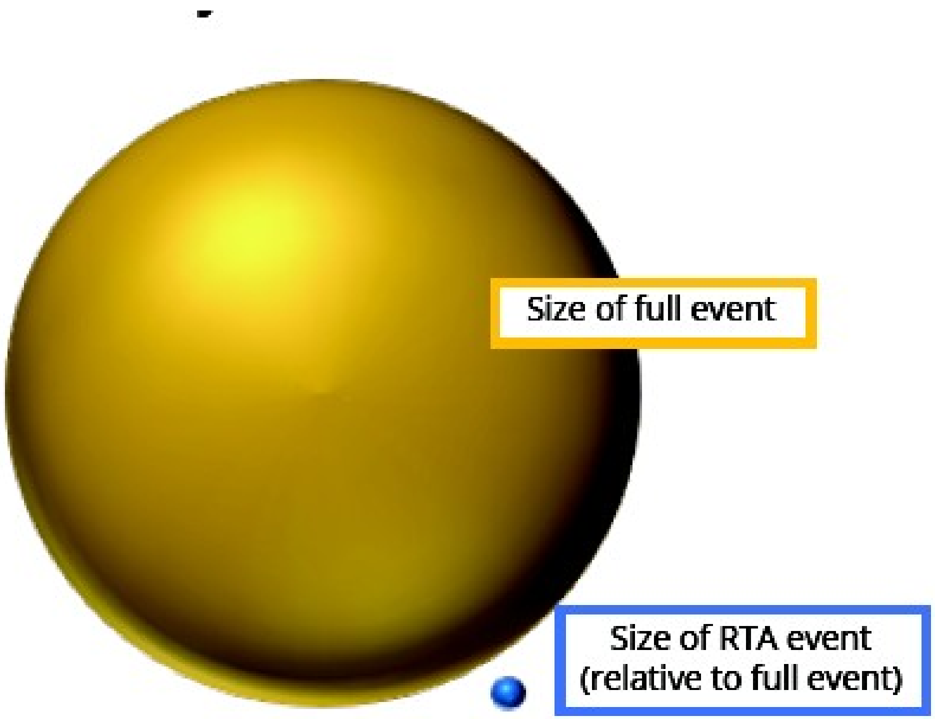


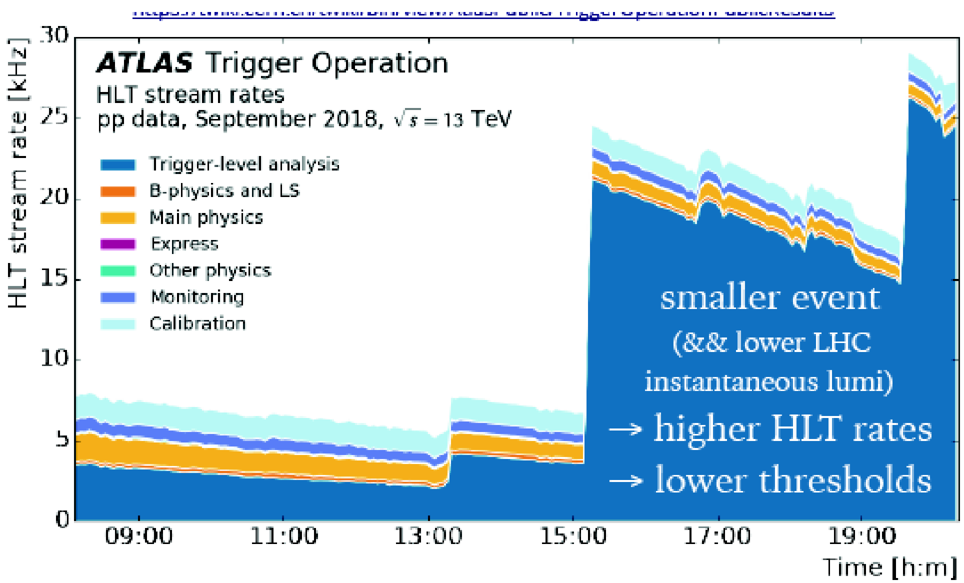
The "true" limit is



e.g. prescale (ps=10) → 1 every 10 events passing that trigger are recorded
Unprescaled (or ps=1) → all events passing that trigger are recorded

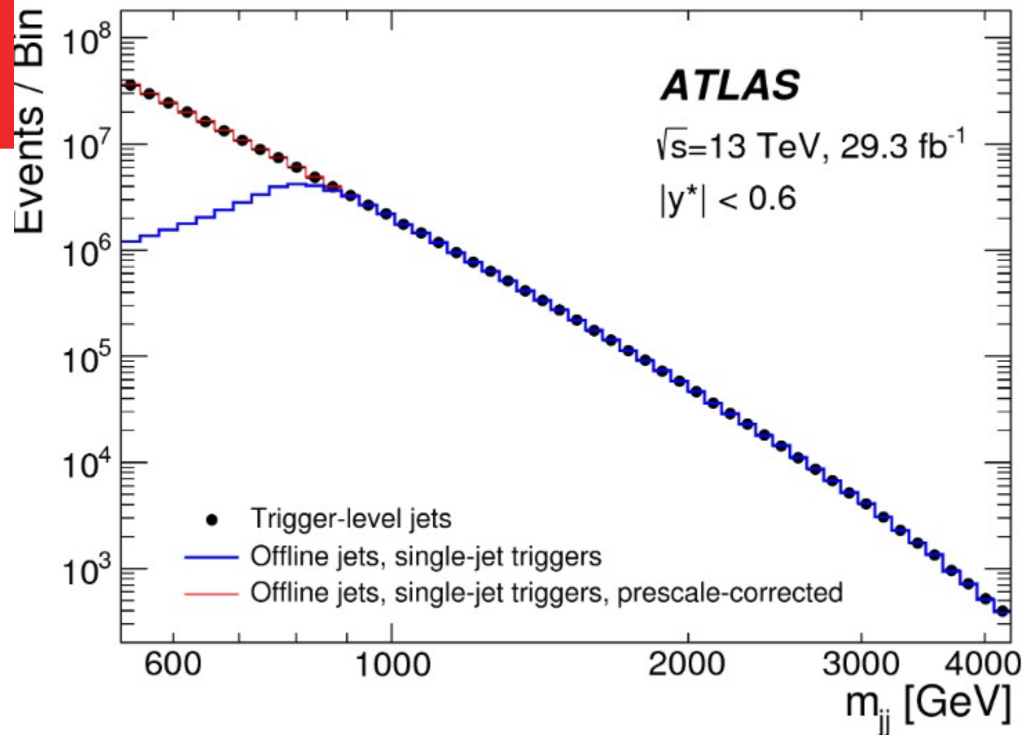
Prescaled triggers → pay too much in terms of statistics (for exotic analysis)
→ Reduce the event size



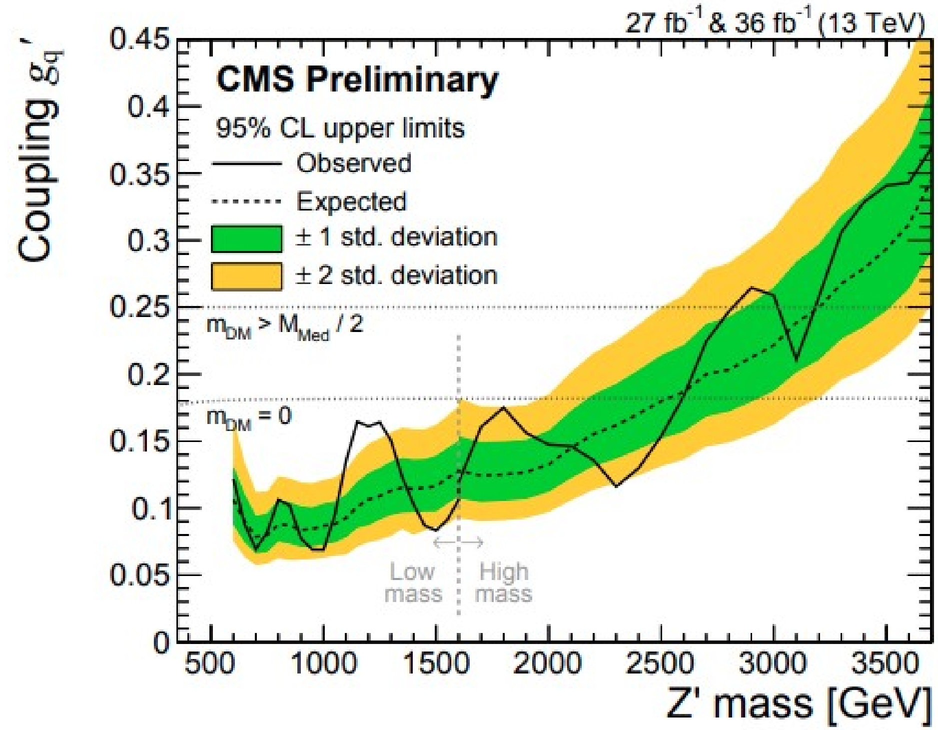


From C. Doglioni talk

PRL 121 (2018) 081801



JHEP 08 (2018) 130



Hadronic jets need to be calibrated (offline)

EM-scale jets → **Jet-area based pileup correction** → **Absolute MC-based calibration** → **Global sequential calibration**

- **EM-scale jets**: *Jet finding applied to topological clusters at the electromagnetic scale*
- **Jet-area based pileup correction**: *Applied as a function of event pileup p_T density and jet area only*
- **Absolute MC-based calibration**: *Corrects the jet 4-momentum to the particle-level energy scale. Both the energy and direction are calibrated*
- **Global sequential calibration**: *Reduces flavor dependence and energy leakage using calorimeter variables only*

→ **Eta intercalibration** → **Trigger-to-offline data-derived correction** → **Residual *in-situ* calibration**

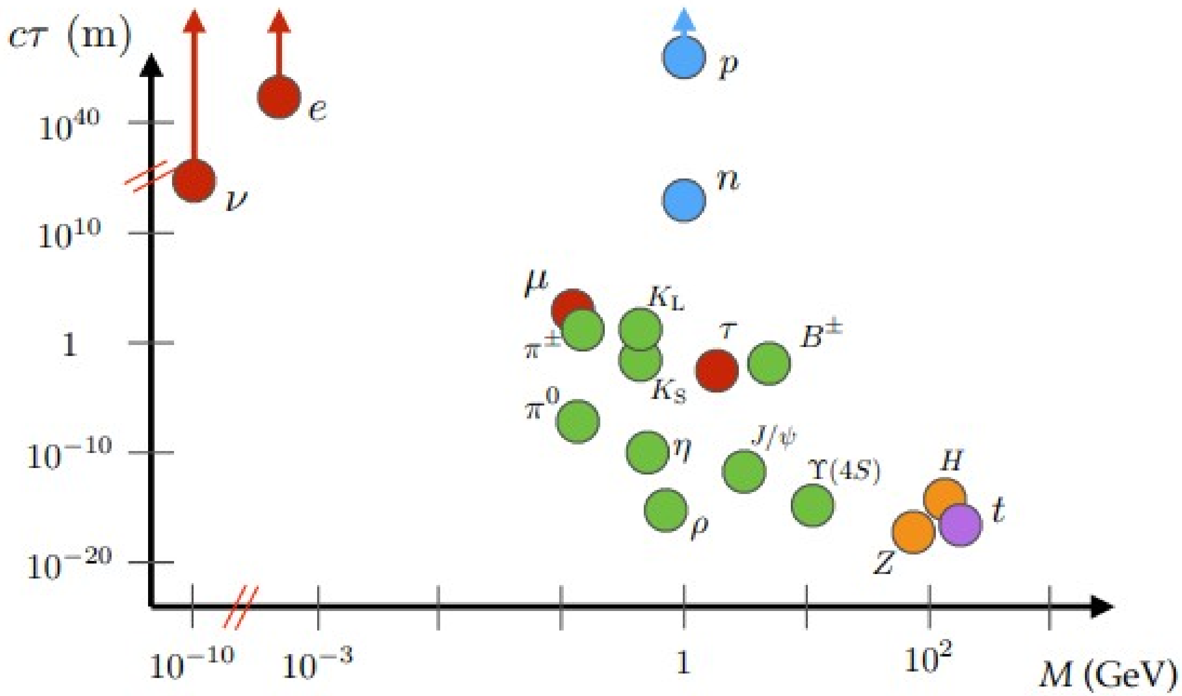
- **Eta intercalibration**: *Corrects the scale of forward jets in data to that of central jets, using the p_T balance ratio between data and simulation, applied only to data*
- **Trigger-to-offline data-derived correction**: *Corrects trigger-level jets to the scale of offline jets, applied only to data*
- **Residual *in-situ* calibration**: *A smooth residual calibration is derived by fitting in-situ measurements and applied only to data*

——— *Derived for offline jets*

······ *Derived specifically for trigger jets*

Long Lived Particles

A possible third signature for Dark Matter



Alimena et al. (eds. Beacham, Shuve) (2019)

Example: Charged pion lifetime:

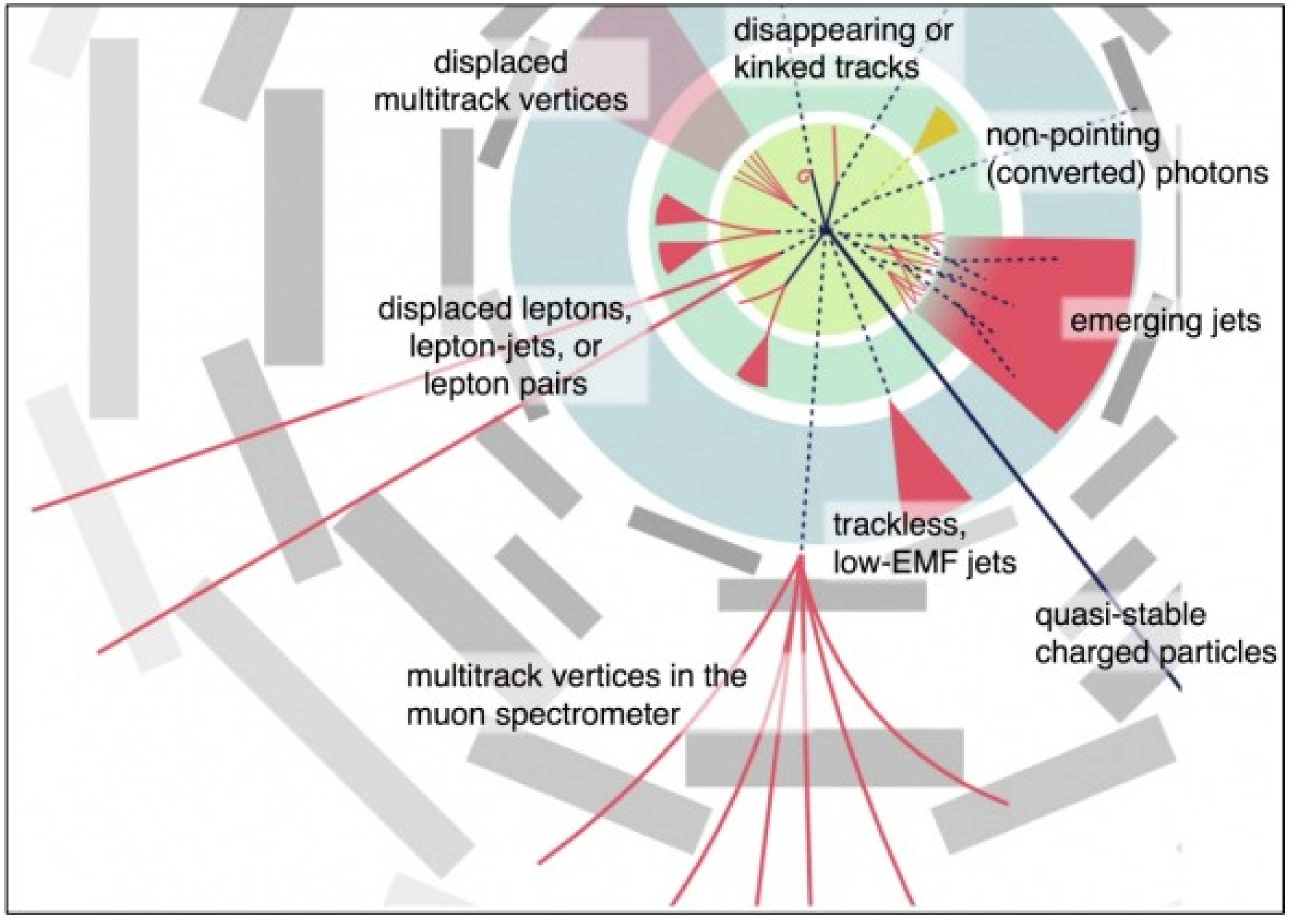
$$\frac{1}{\tau_{\pi^+}} = \frac{f_\pi^2}{256\pi m_\pi}\left[\frac{g^2}{M_W^2}\frac{m_\mu}{m_\pi}(m_\pi^2 - m_\mu^2)\right]^2$$

Large decay lengths:

Small couplings → Hidden sectors

Large mediator mass → BSM mediators

Compressed spectra → Approximate symmetries



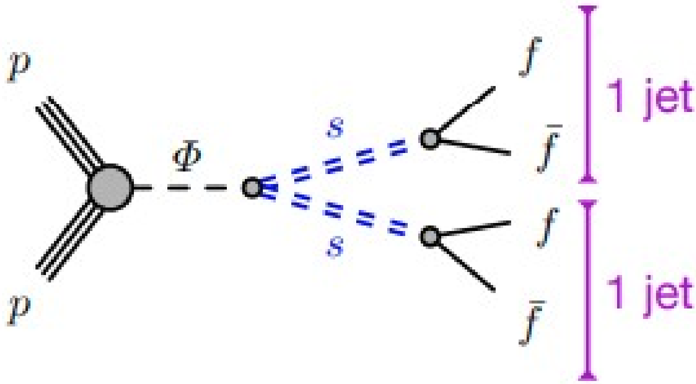
Russell (see, e.g., LLP White Paper 2019)

ATLAS detector have been designed primarily requiring high efficiency detection for “prompt” (or issued by b,c and τ decays) particles →

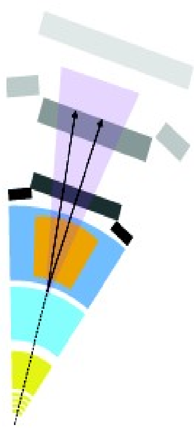
Modified algorithms for Long Lived Particles:

- Trigger selection
- Tracking and particle ID
- Background estimation
  - Non collision Background (Beam Induced Background)
  - Material interactions
  - Cosmic Muons

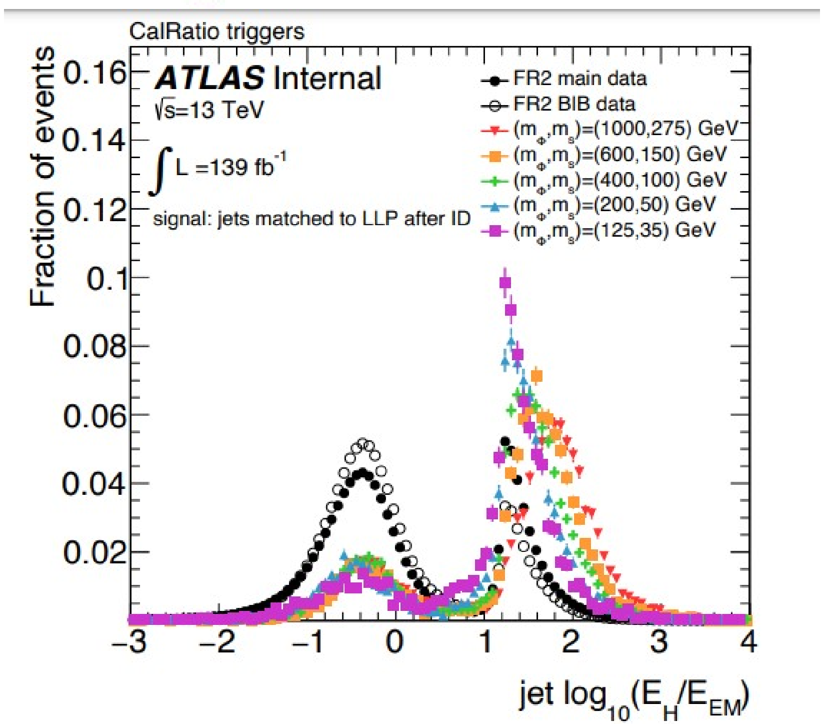
Trigger Selection

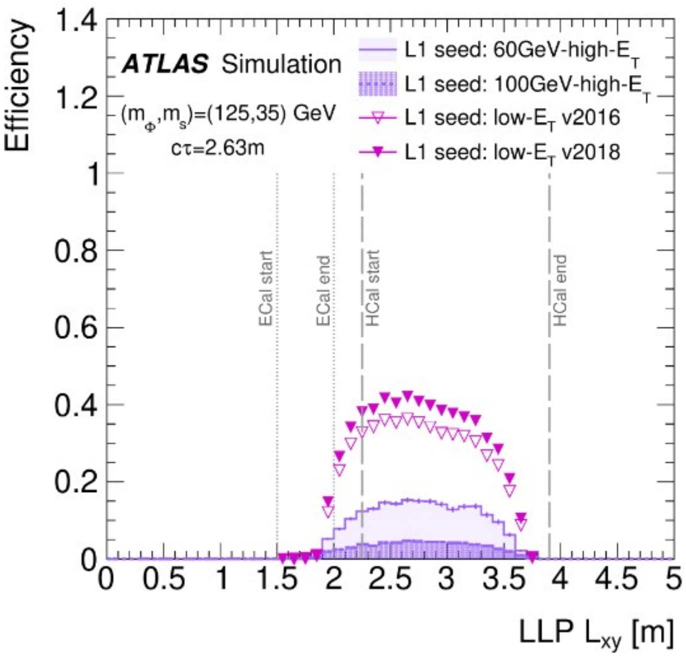


Too large single or dijet trigger thresholds (~400 GeV)
→ Exploit peculiar energy deposition in calorimeter→ lower jet trigger thresholds ~100 GeV



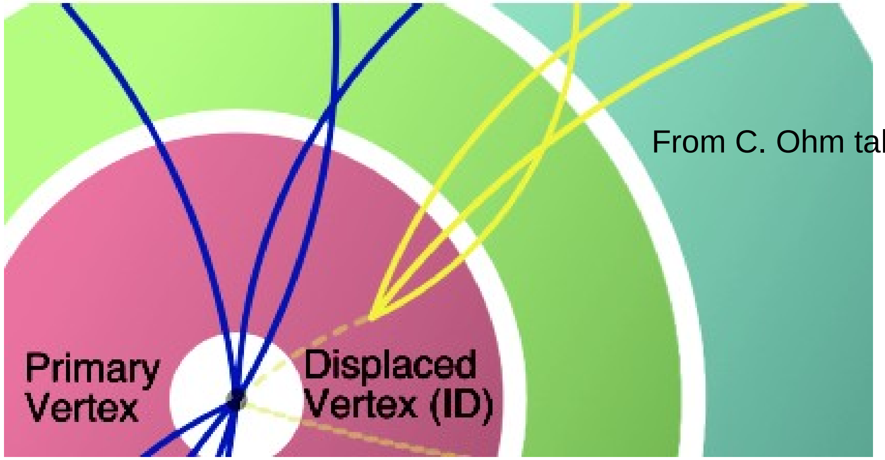
JHEP 06 (2022) 005





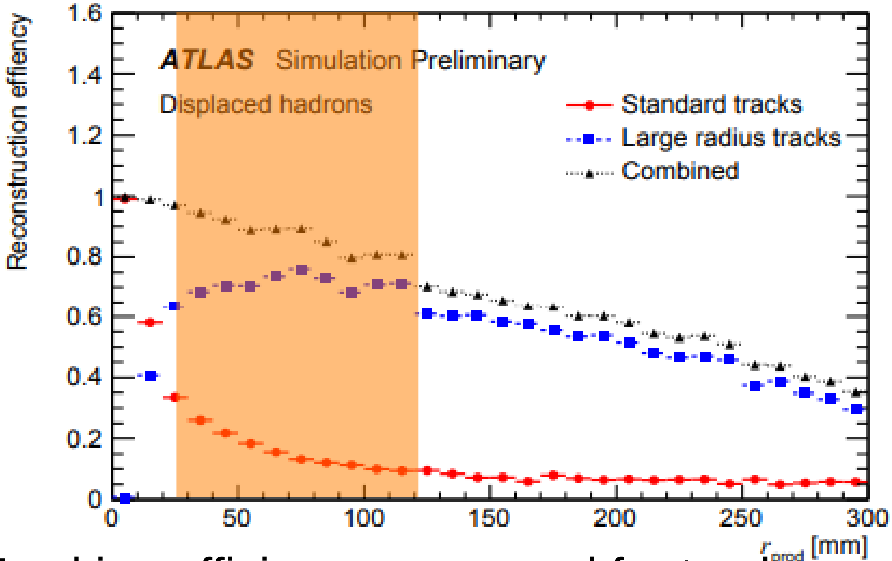
Reconstruction

- Removes constraints on d_0, z_0 and number of hits → larger efficiency on tracks from large radius
- "Slow" tracking algorithms → Runs only on ~1% of hits (TRT, SCT and PIX)



From C. Ohm talk

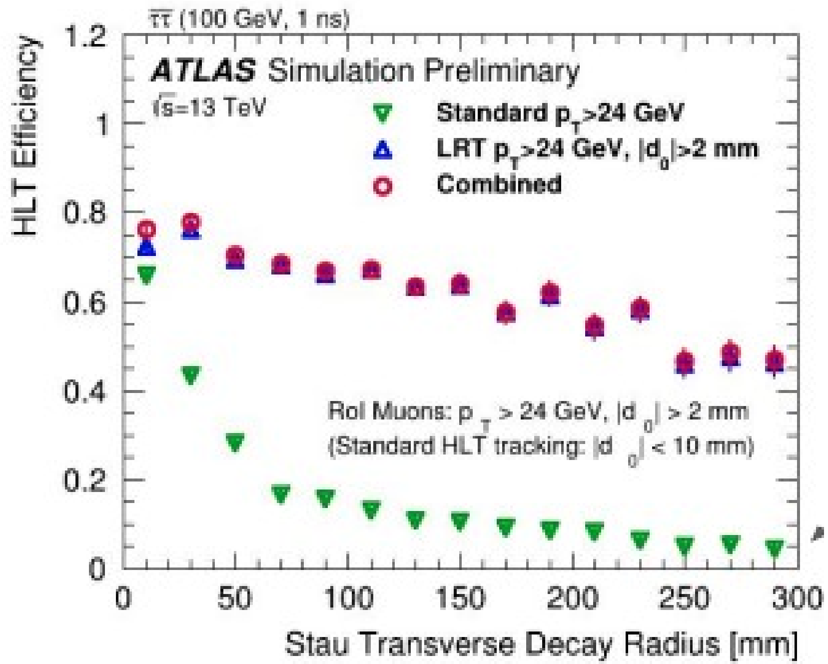
Beam pipe Pixel

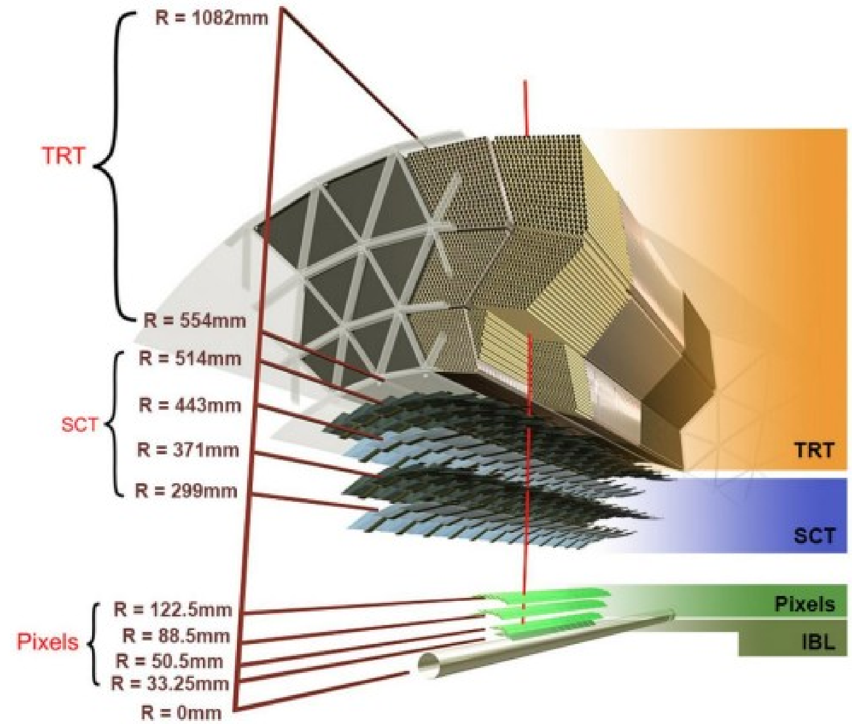


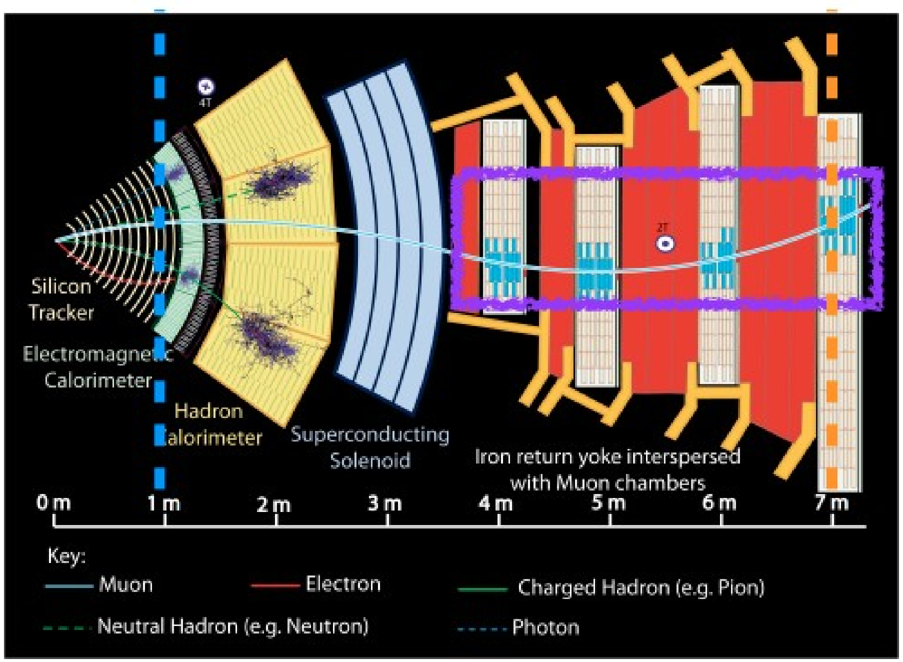
Tracking efficiency recovered for tracks produced at large radius

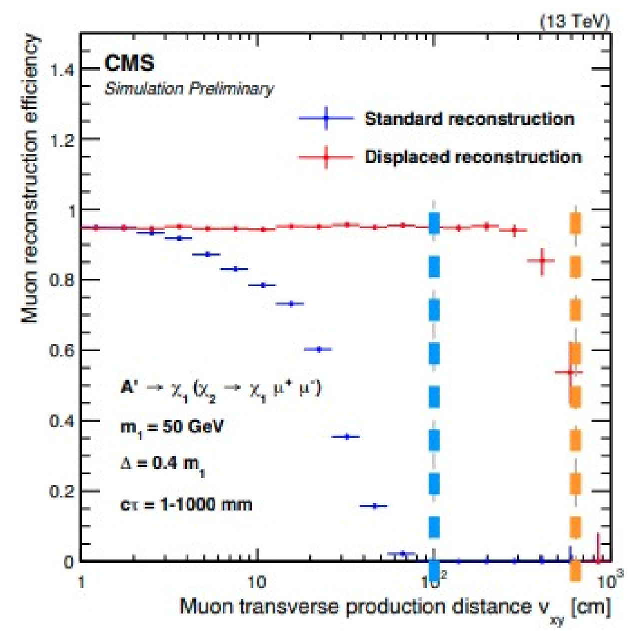
ATL-PHYS-PUB-2017-014

Displaced tau triggers in ATLAS

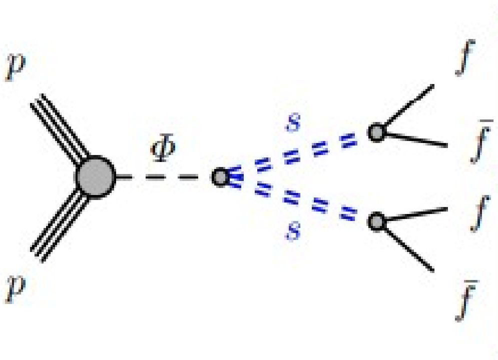








LLP in Calorimeter

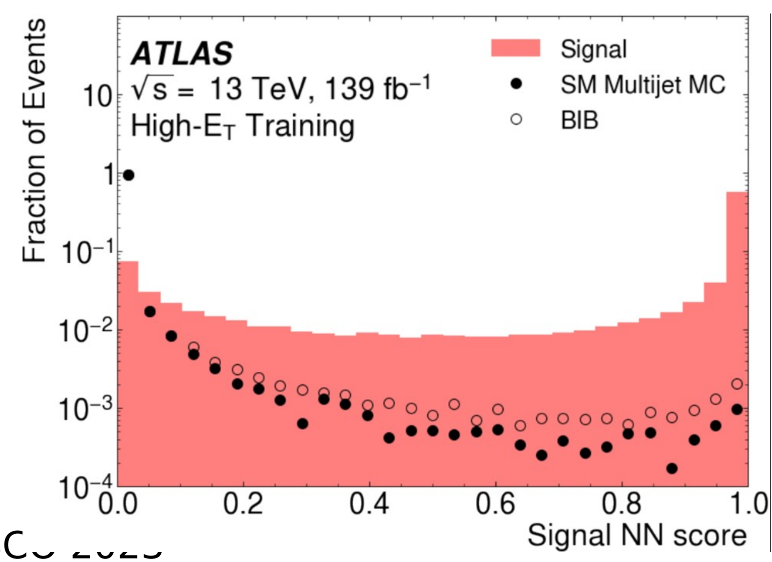


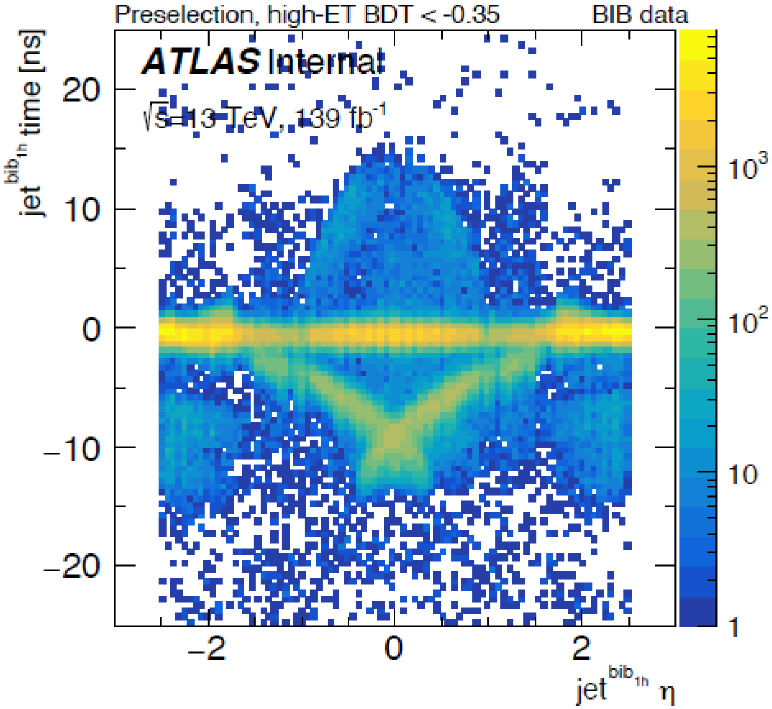
Hidden Sector model
ϕ is the portal
M_ϕ from 400 GeV to 1 TeV and M_s from 50 to 475 GeV → High E_T
M_ϕ from 60 GeV to 200 GeV and M_s from 5 to 55 GeV → Low E_T

- Three BDT trained to distinguish between:
  - Signal
  - Beam Induded Background ← Specific to LLP searches → LHC beam-gas and beam-halo interactions upstream detector
  - Multijet

Signal characteristics:
- ✓ Narrower cone than typical SM jets
- ✓ No associated tracks to the “jets”
- ✓ Larger energy deposit in Had calorimeter than Em (alreay used for triggering)

JHEP 06 (2022) 005

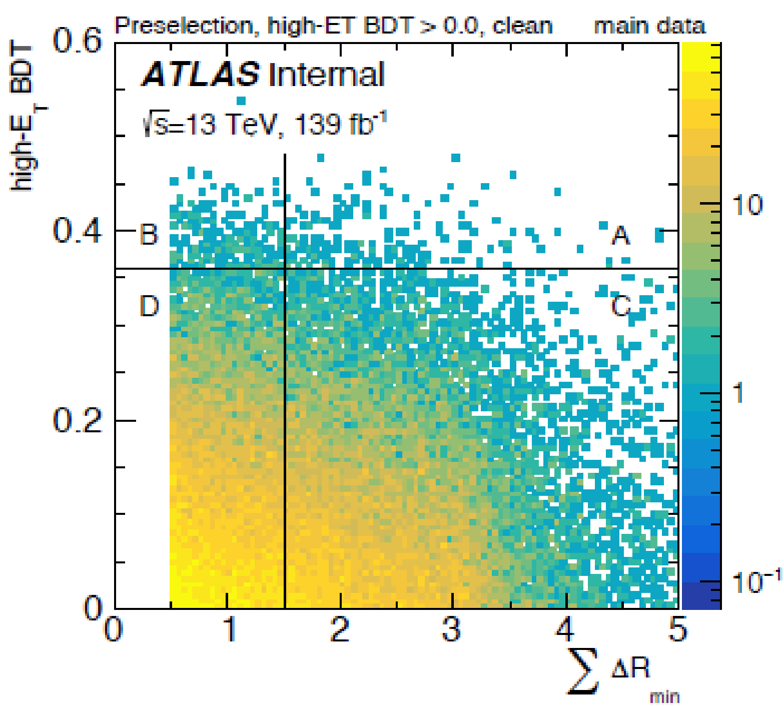


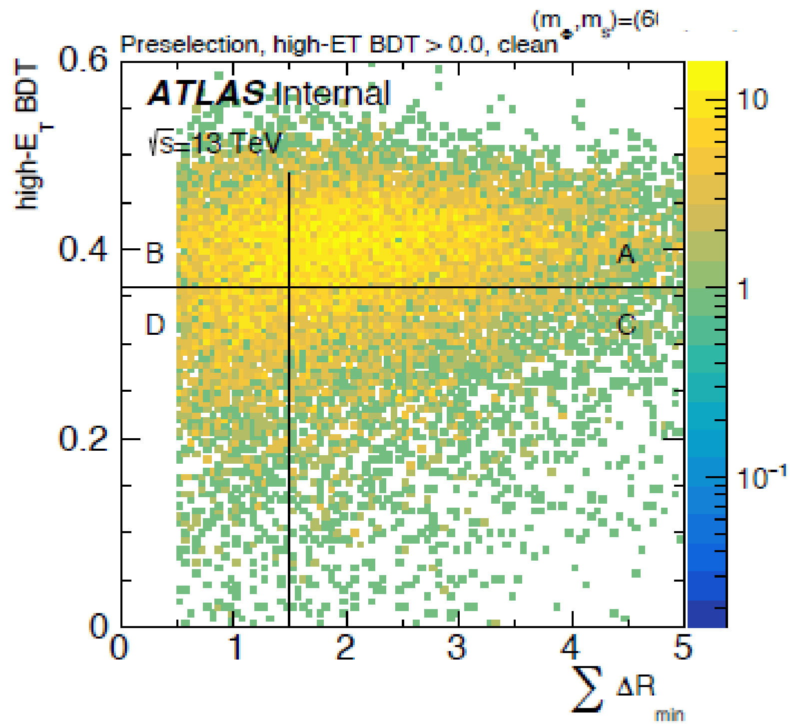


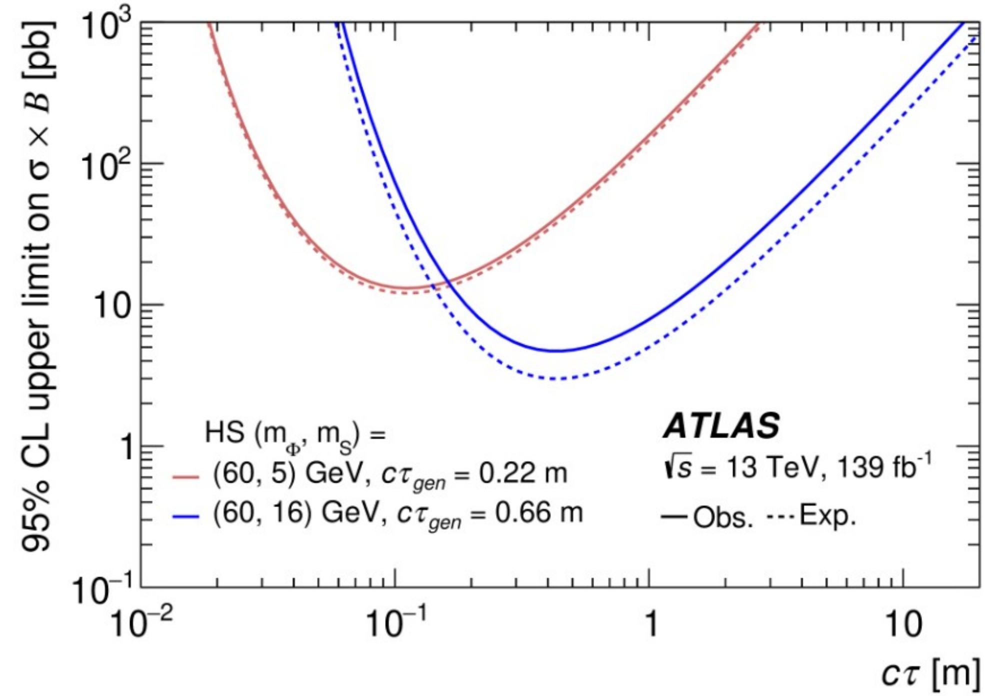
Beam Induced Background dataset
Small BDT score (unlikely to be signal)

After cleaning BIB
→ ABCD method with two variables (BDT score vs ΔR_{min}(track,jet))

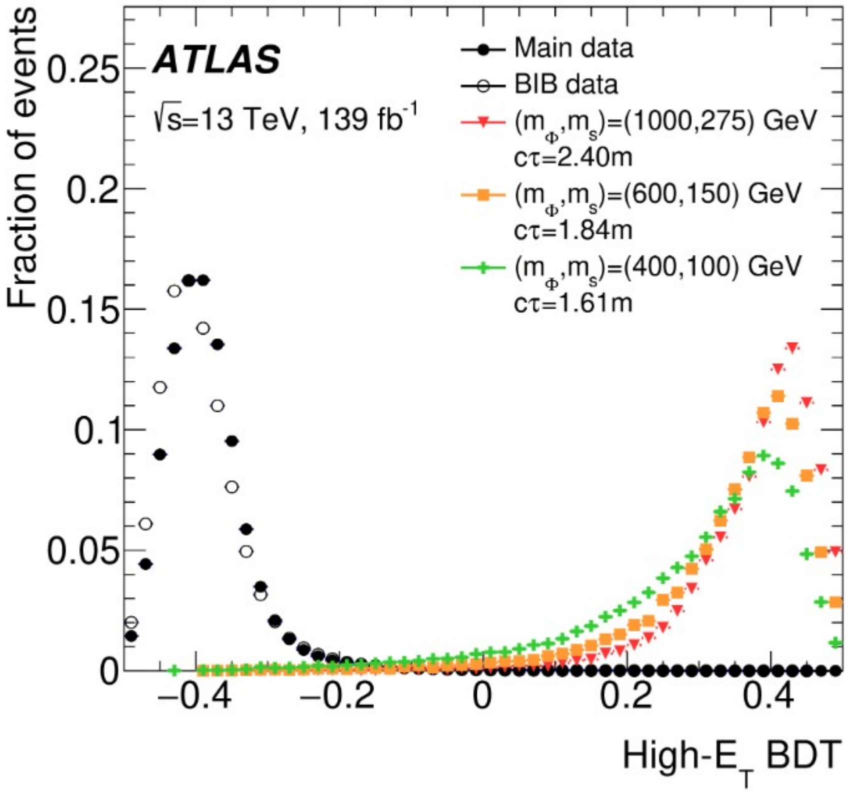
$$N_A = \frac{N_B \times N_C}{N_D}$$

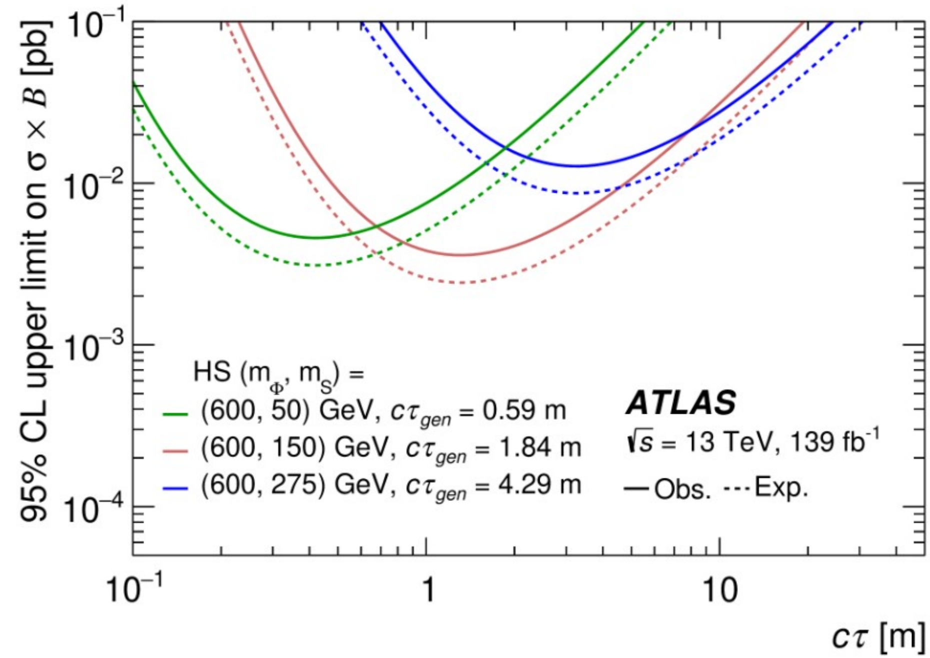






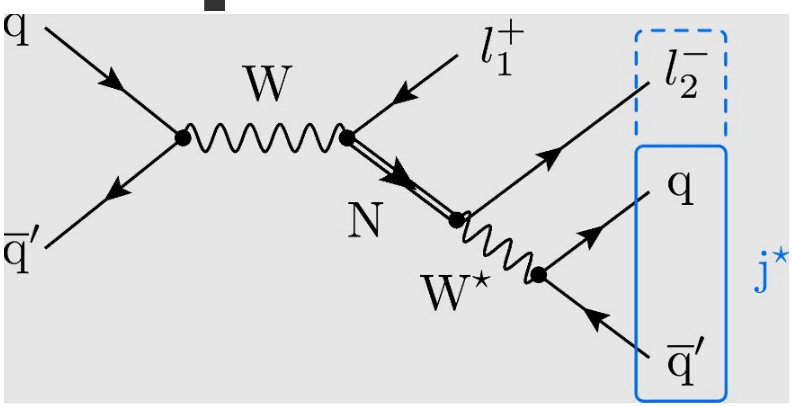
Exclusion limit vs lifetime





BDT output for data, signal, background

Search for Heavy Neutrino Lepton



CMS-PAS-EXO-21-013

Address both Dirac and Majorana Heavy neutrino (N) searches

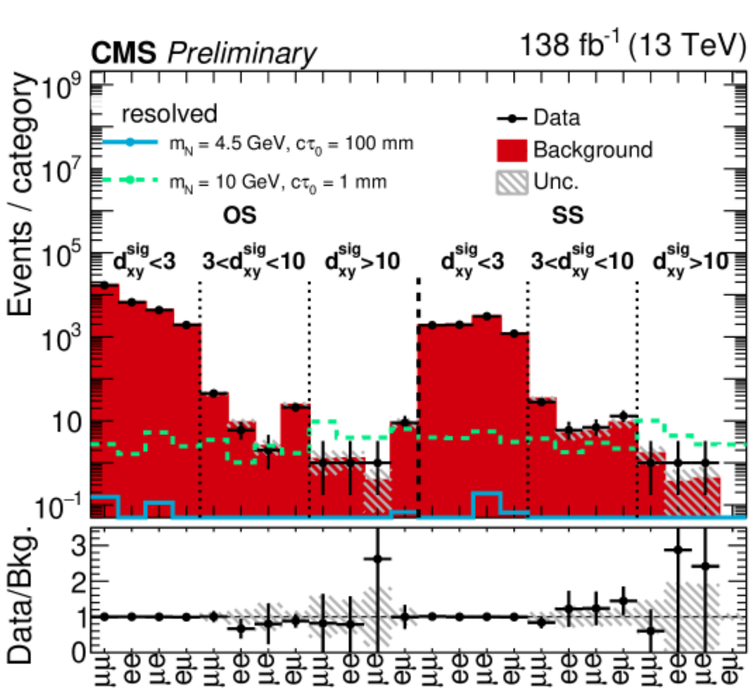
Dirac → neutrino and antineutrino are different → outgoing leptons have opposite sign (OS)

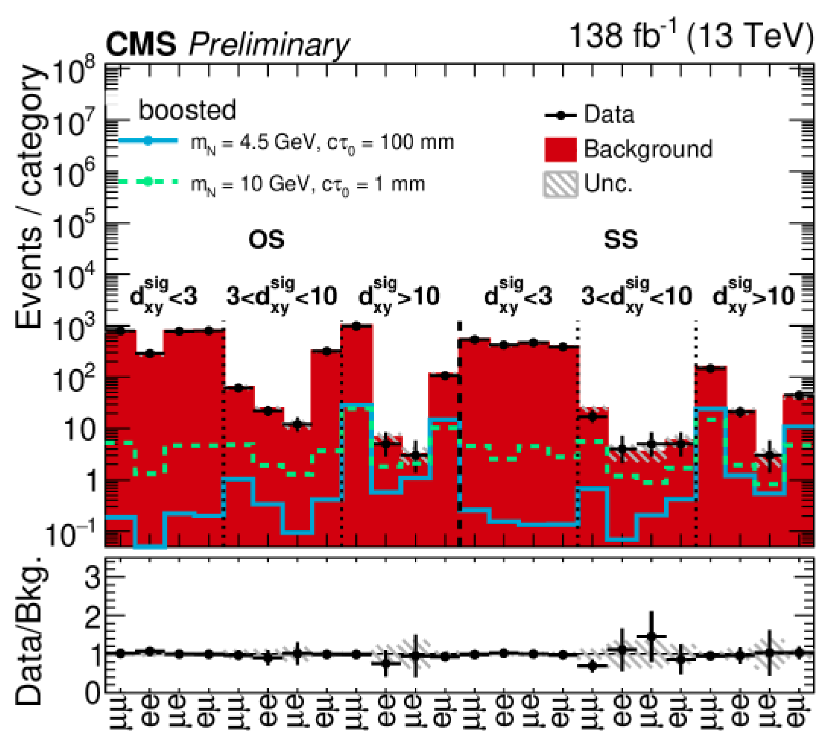
Majorana → neutrino and antineutrino are the **same** particle → leptons have same sign (SS)

Trigger on prompt lepton $\mathbf{l_1}$

Hadronic or leptonic decay of W boson

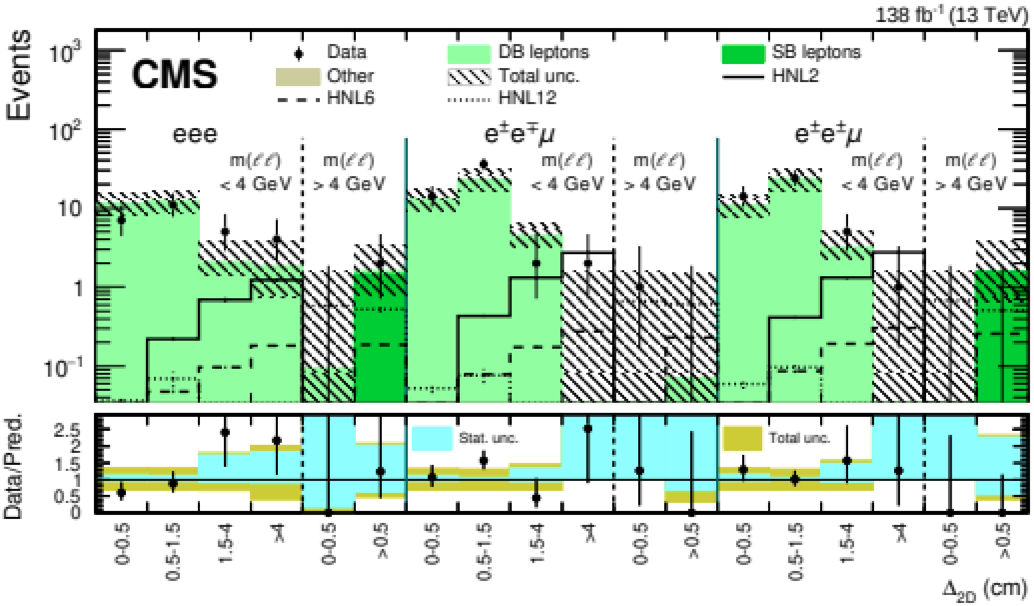
For lower M_N → boosted configuration

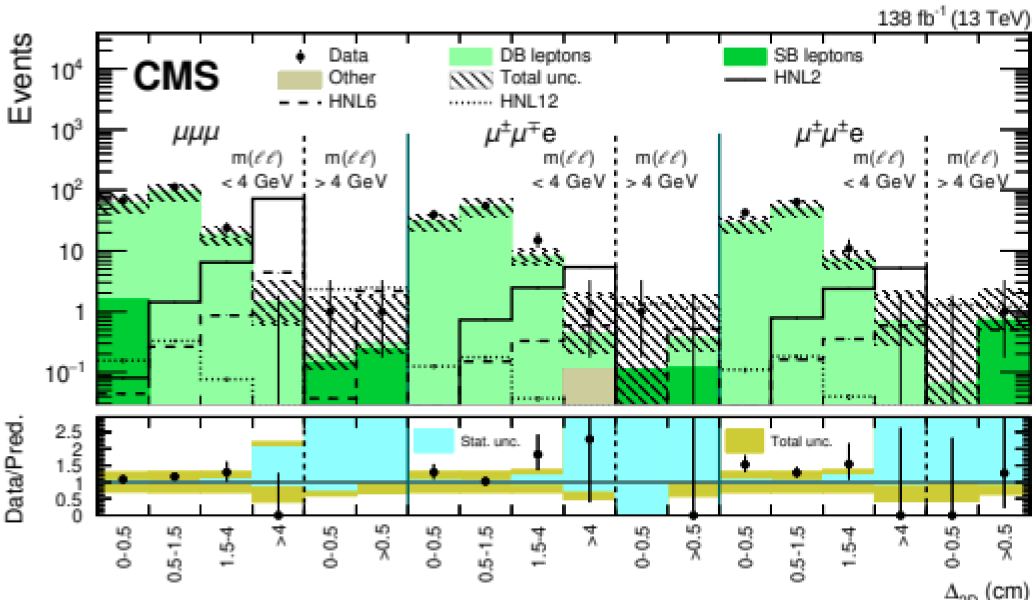




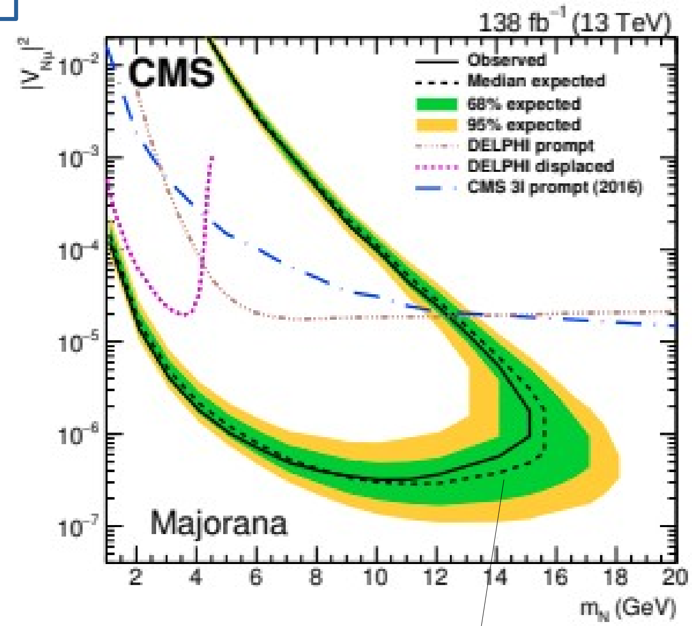
Tri-lepton

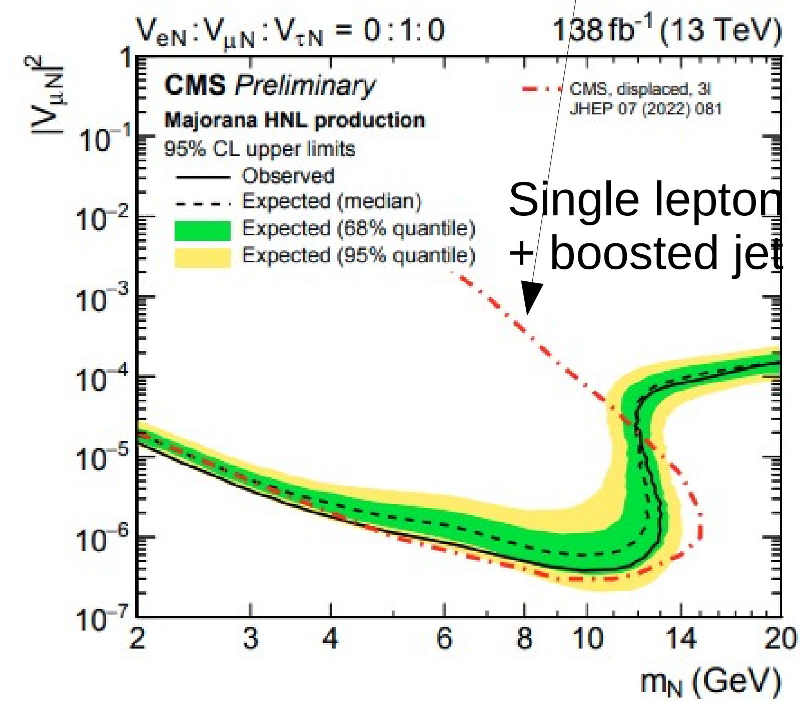
JHEP 07 (2022) 081





	M_N (GeV)	$\|V_{Nl}\|^2$
HNL2	2	0.8×10^{-4}
HNL6	6	1.3×10^{-6}
HNL12	12	1.0×10^{-6}



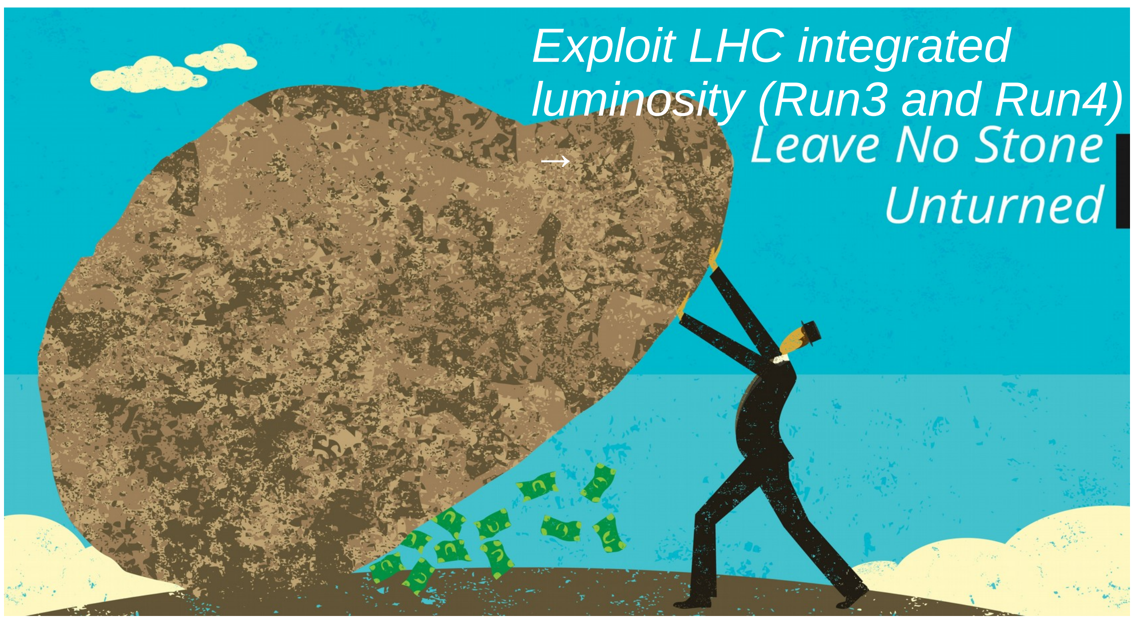


Single lepton + boosted jet

Recover sensitivity with boosted configuration

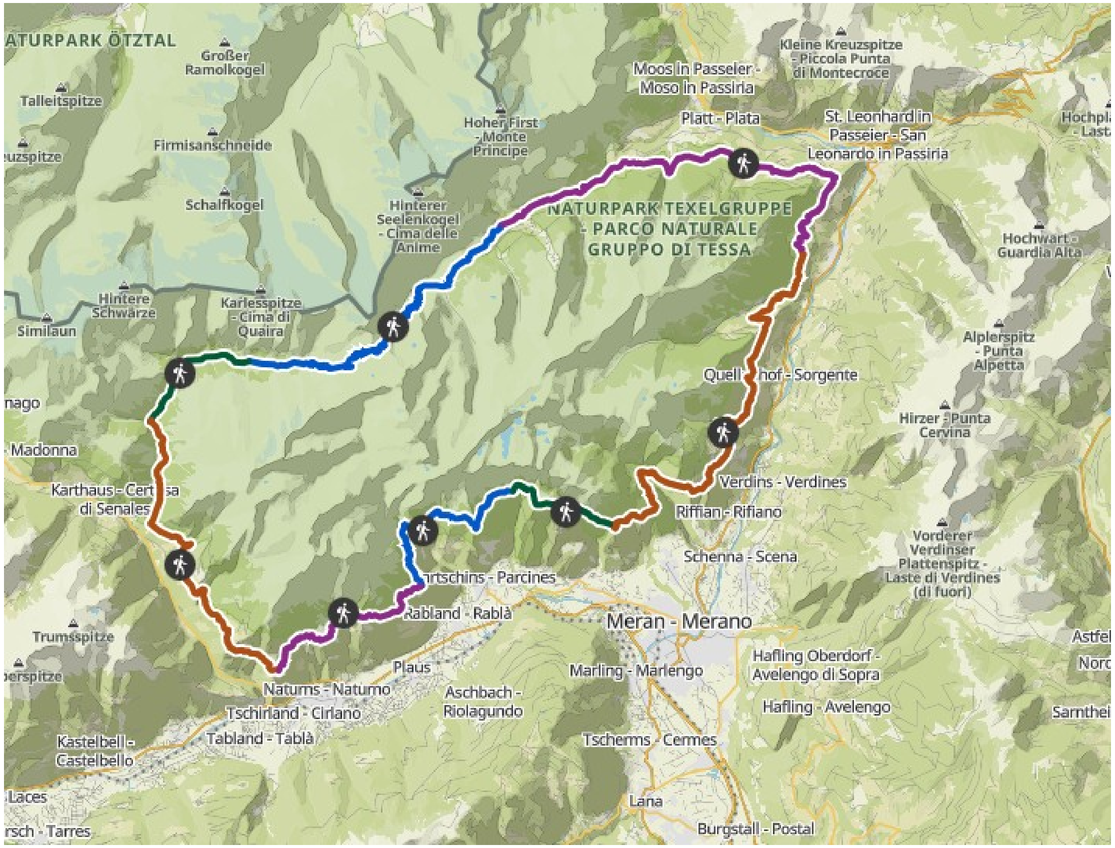
Conclusions and Outlook

After Higgs discovery, we are entering an era of BSM searches guided by experimental results rather than theory → More similar to other experimental sciences



Ask questions ! There are no stupid questions !

It will be difficult for me to connect at the Q&A session on Monday



Since I will be trekking here ….

BackUp

ATL-PHYS-PUB-2014-004

Splitting scale: $\sqrt{d_{ij}} = min(p_{Ti}, p_{Tj}) \times \Delta R_{ij}$ *Butterworth, Cox, Forshaw, PRD65*

Momentum balance: $\sqrt{y} = \sqrt{d_{ij}} / m_{ij}$

BDRS, PRL100

Mass drop: $\mu_{ij} = \frac{max(m_i, m_j)}{m_{ij}}$

Jet width: $w = \frac{\Sigma_i \Delta R_{iJ}\, p_{Ti}}{\Sigma_i\, p_{Ti}}$

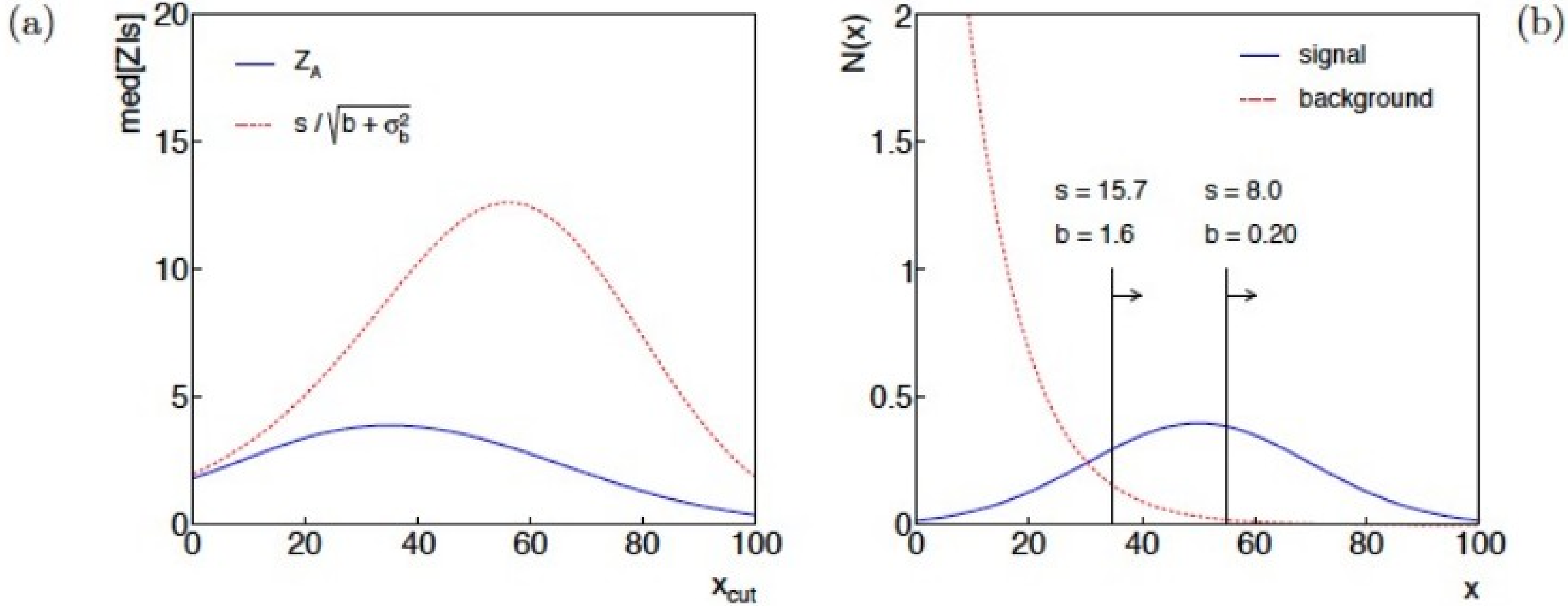
N-subjettiness: $\tau_N = \frac{\Sigma_k\, p_{Tk} (min(\Delta R_{1k}, \Delta R_{2k}, \ldots, \Delta R_{Nk}))^\beta}{\Sigma_k\, p_T\, R_0^\beta}$ *Thaler, van Tilburg, JHEP03*

More sophisticated:

+ inject "physics", shower deconstruction *(Soper & Spannowsky)*, templates *(Perez et al.)*
+ quantify uncertainty inherent in the decision making process, e.g. volatility *(Krohn et al.)*

From M. Vos lectures (2014)

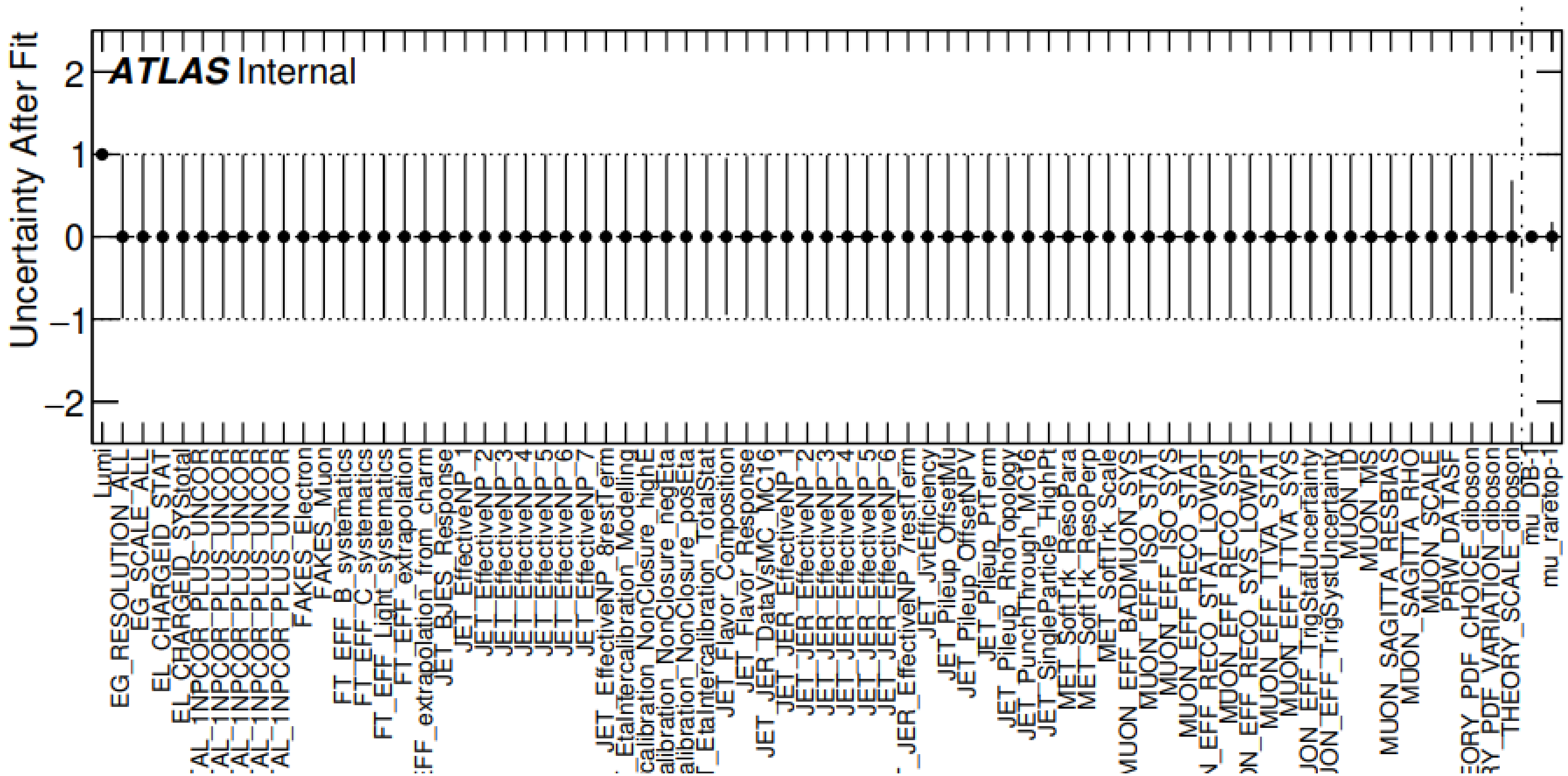
From G. Cowan lectures for CERN Summer Students



Maximixing sensitivity with

$$\frac{s}{\sqrt{b}}$$

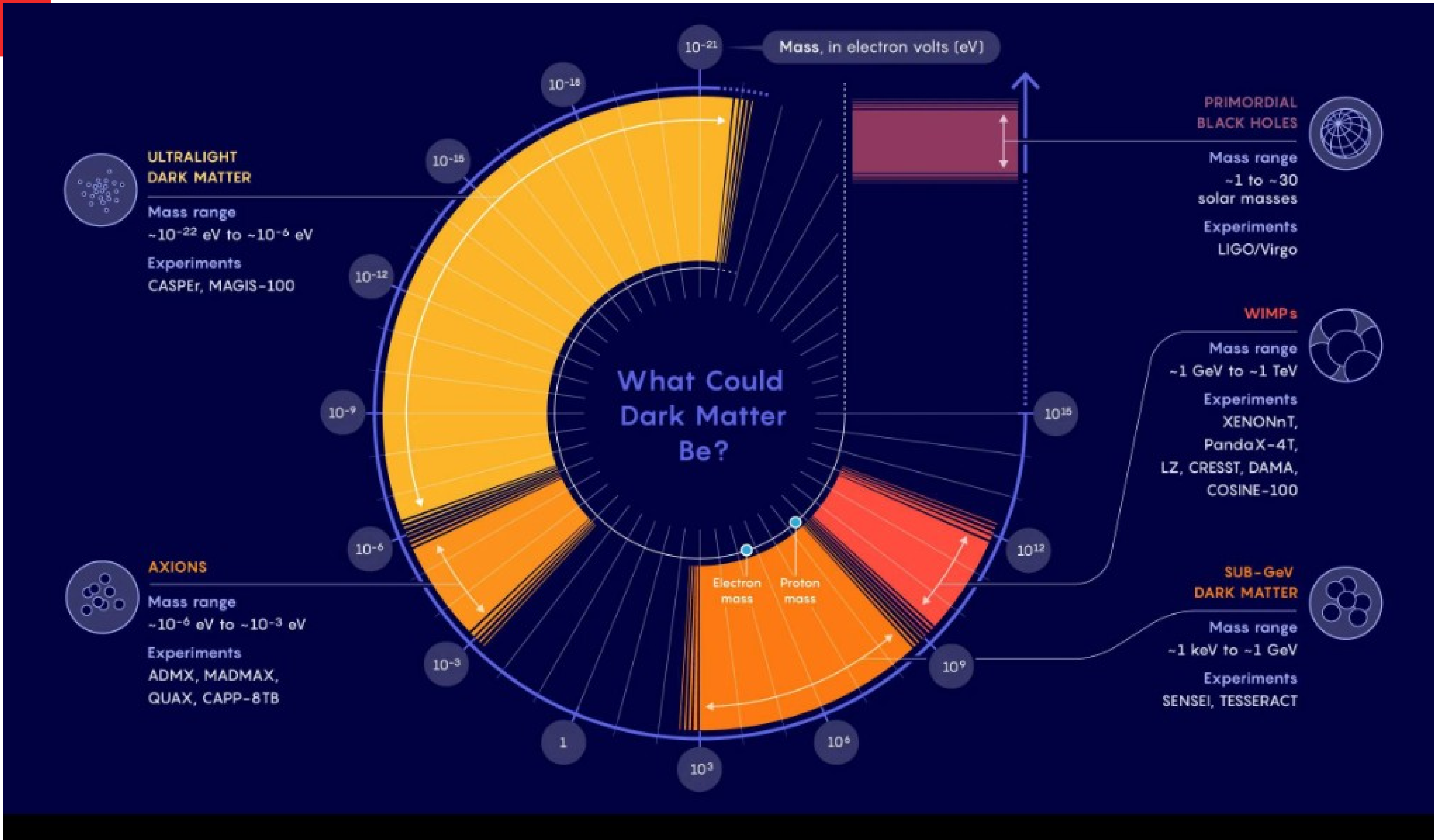
$$Z_A = \sqrt{2\left((s+b)\ln\left(1+\frac{s}{b}\right)-s\right)}$$



(b)

Nuisance pulls for Asimov tests for 4-lep region

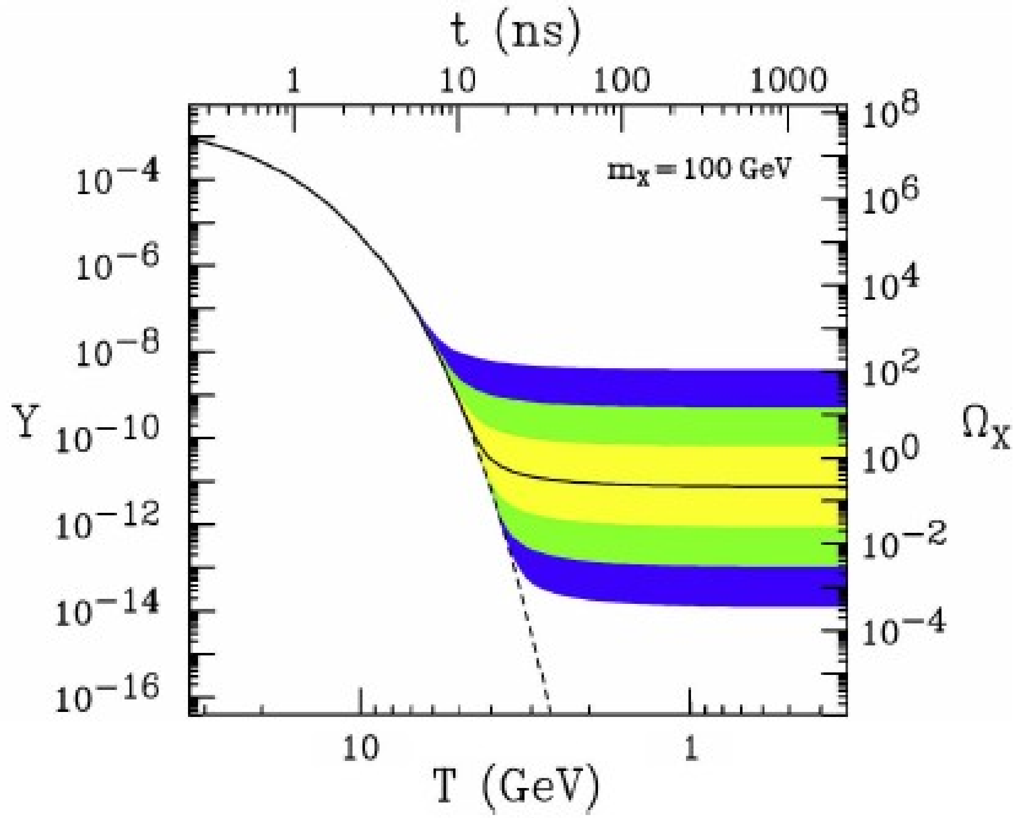
Possible Dark Matter Candidates



Credit: Samuel Velasco/Quanta Magazine

Example: TypeIII seesaw heavy leptons searches in ATLAS Eur. Phys. J C81 (2021) 218

	OS ($\ell^+\ell^- = e^+e^-, e^\pm\mu^\mp, \mu^+\mu^-$)			**SS** ($\ell^\pm\ell^\pm = e^\pm e^\pm, e^\pm\mu^\pm, \mu^\pm\mu^\pm$)		
	Top CR	m_{jj} VR	SR	Diboson CR	m_{jj} VR	SR
N(jet)	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2
N(b-jet)	≥ 2	0	0	0	0	0
m_{jj} [GeV]	$(60, 100)$	$(35, 60) \cup (100, 125)$	$(60, 100)$	$(0, 60) \cup (100, 300)$	$(0, 60) \cup (100, 300)$	$(60, 100)$
$m_{\ell\ell}$ [GeV]	≥ 110	≥ 110	≥ 110	≥ 100	≥ 100	≥ 100
$\mathcal{S}(E_{\mathrm{T}}^{\mathrm{miss}})$	≥ 5	≥ 10	≥ 10	≥ 5	≥ 5	≥ 7.5
$\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \ell)_{\mathrm{min}}$	—	—	≥ 1	—	—	—
$p_{\mathrm{T}}(jj)$ [GeV]	—	—	≥ 100	—	—	≥ 60
$p_{\mathrm{T}}(\ell\ell)$ [GeV]	—	—	≥ 100	—	—	≥ 100
$H_{\mathrm{T}} + E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	≥ 300	≥ 300	≥ 300	$(300, 500)$	≥ 500	≥ 300



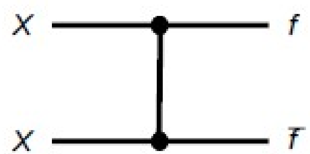
$$\Omega_{\rm DM} h^2 \approx 0.1 \left(\frac{3 \times 10^{-26}\ {\rm cm}^3/{\rm s}}{\langle \sigma v \rangle} \right)$$

$$\approx 0.1 \times 0.3 \left(\frac{\alpha^2/m_W^2}{\langle \sigma v \rangle\, \hbar^2/c} \right)$$

- The resulting relic density is

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

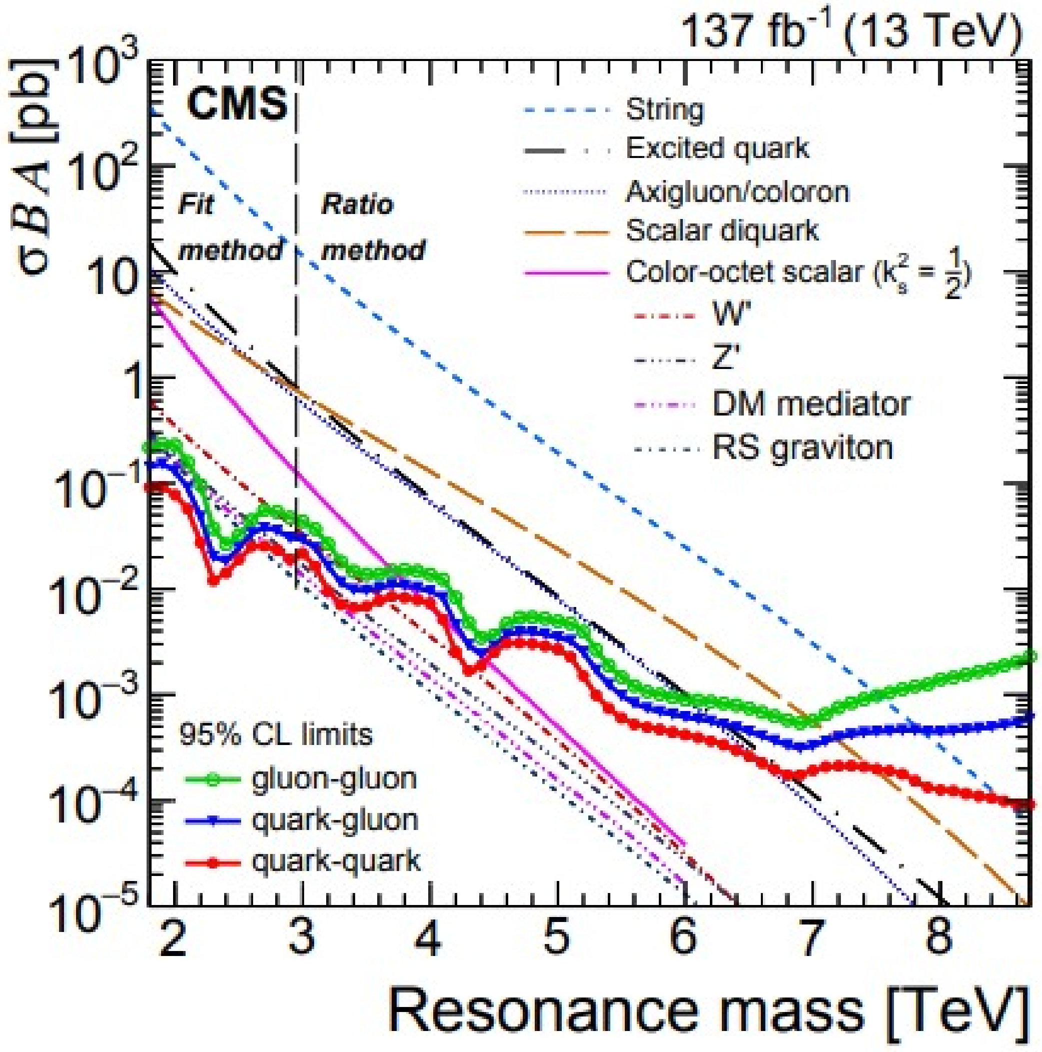
Ω_X



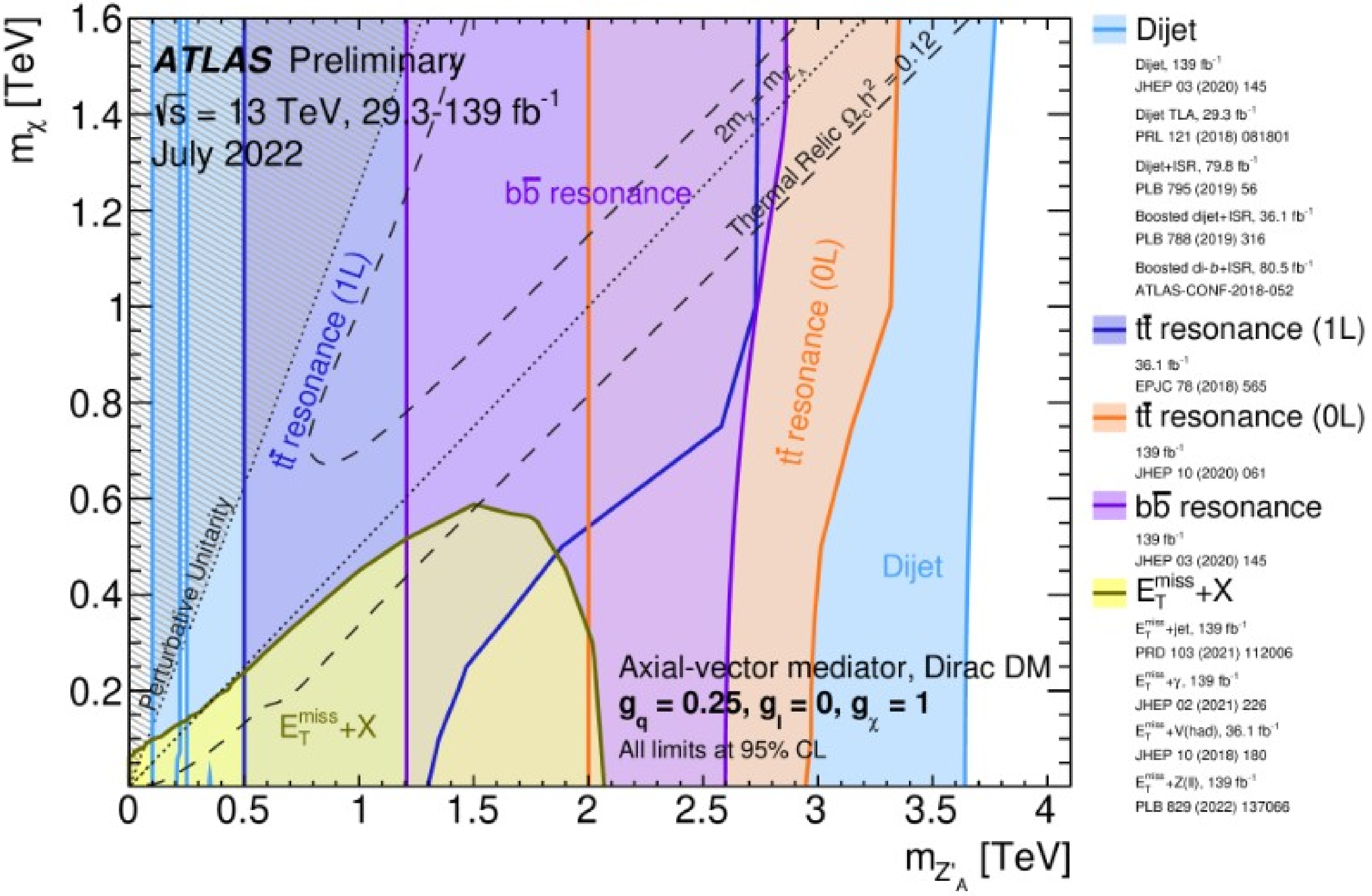
- For a WIMP, $m_X \sim 100$ GeV and $g_X \sim 0.6$ → $\Omega_X \sim 0.1$

WIMP miracle: Thermal Freeze out

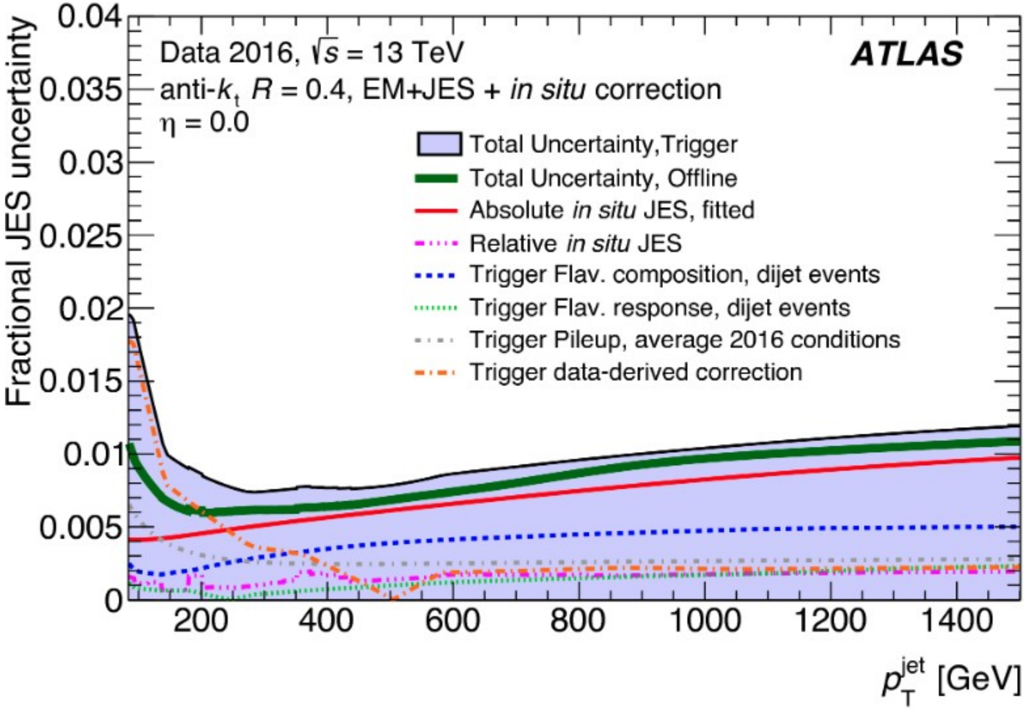
From J. Feng CERN Colloquium

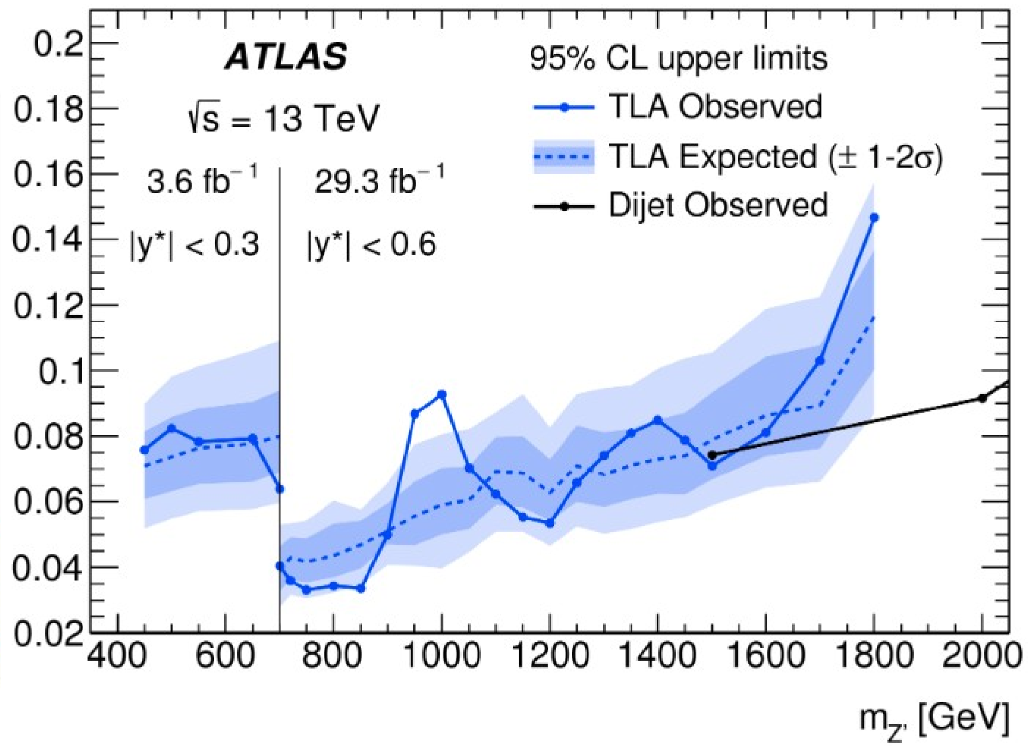


https://arxiv.org/pdf/1911.03947.pdf



ATL-PHYS-PUB-2022-036


Fractional JES uncertainty
Data 2016, $\sqrt{s}$ = 13 TeV
ATLAS
anti-k_t, R = 0.4, EM+JES + *in situ* correction
η = 0.0
Total Uncertainty,Trigger
Total Uncertainty, Offline
Absolute *in situ* JES, fitted
Relative *in situ* JES
Trigger Flav. composition, dijet events
Trigger Flav. response, dijet events
Trigger Pileup, average 2016 conditions
Trigger data-derived correction
p_T^{jet} [GeV]


g_q
ATLAS
$\sqrt{s}$ = 13 TeV
3.6 fb^{-1}
29.3 fb^{-1}
|y*| < 0.3
|y*| < 0.6
95% CL upper limits
TLA Observed
TLA Expected (± 1-2σ)
Dijet Observed
$m_{Z'}$ [GeV]