Exotic Run 2 Searches from ATLAS and CMS: Midterm Report

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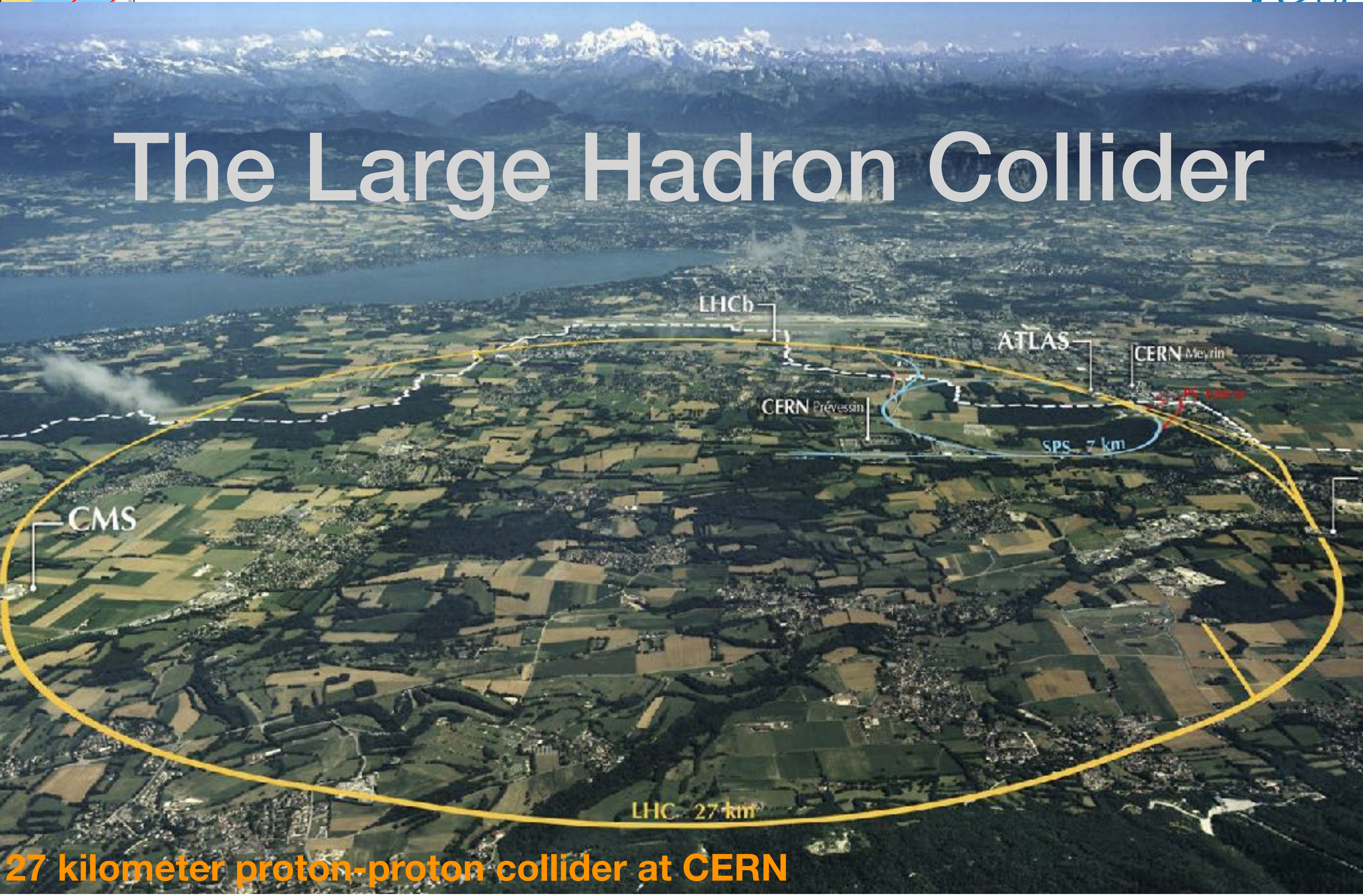
@ DESY
April 17/18, 2018

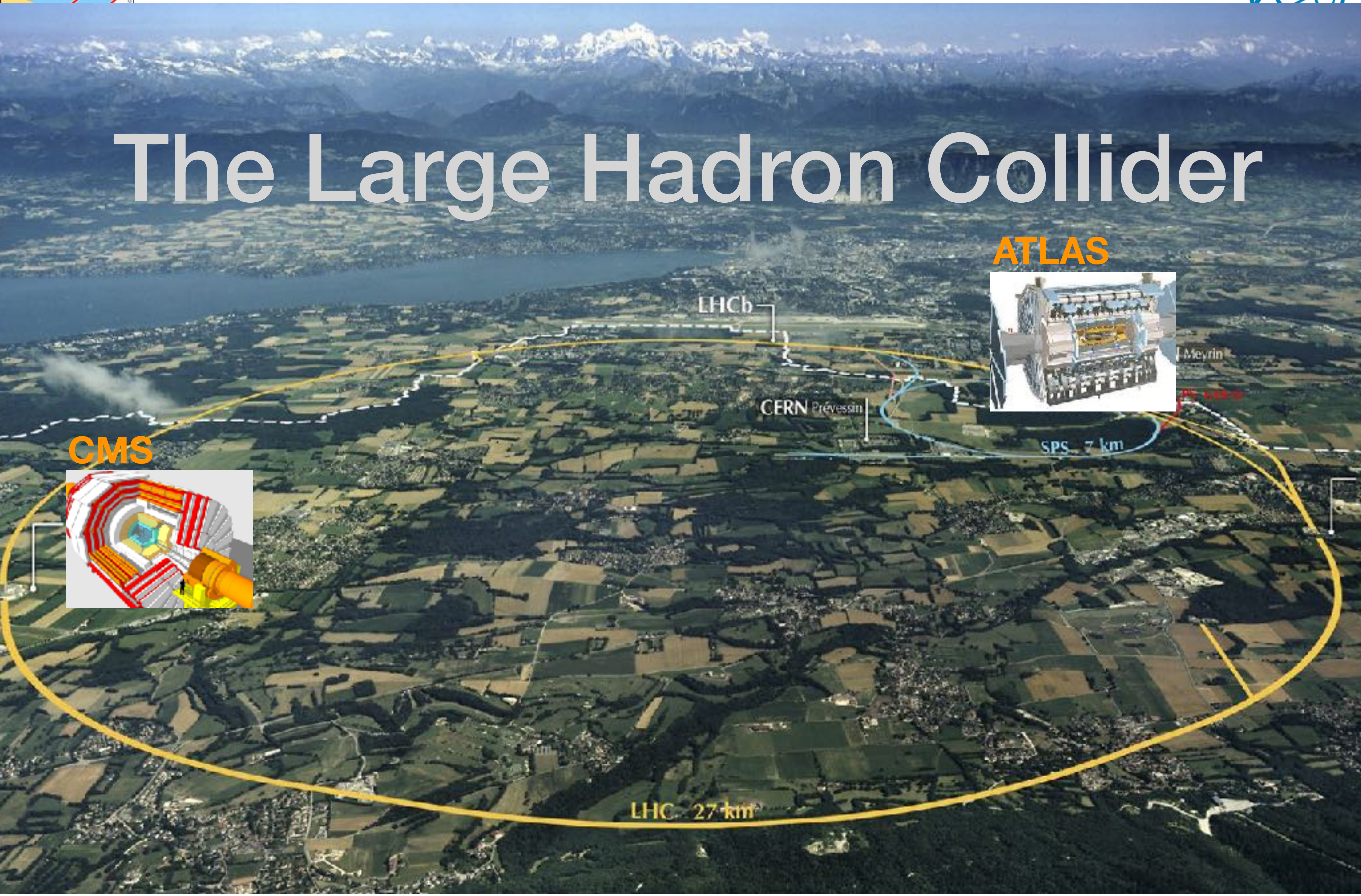
The Large Hadron Collider



27 kilometer proton-proton collider at CERN

A big machine to probe small distances

The Large Hadron Collider



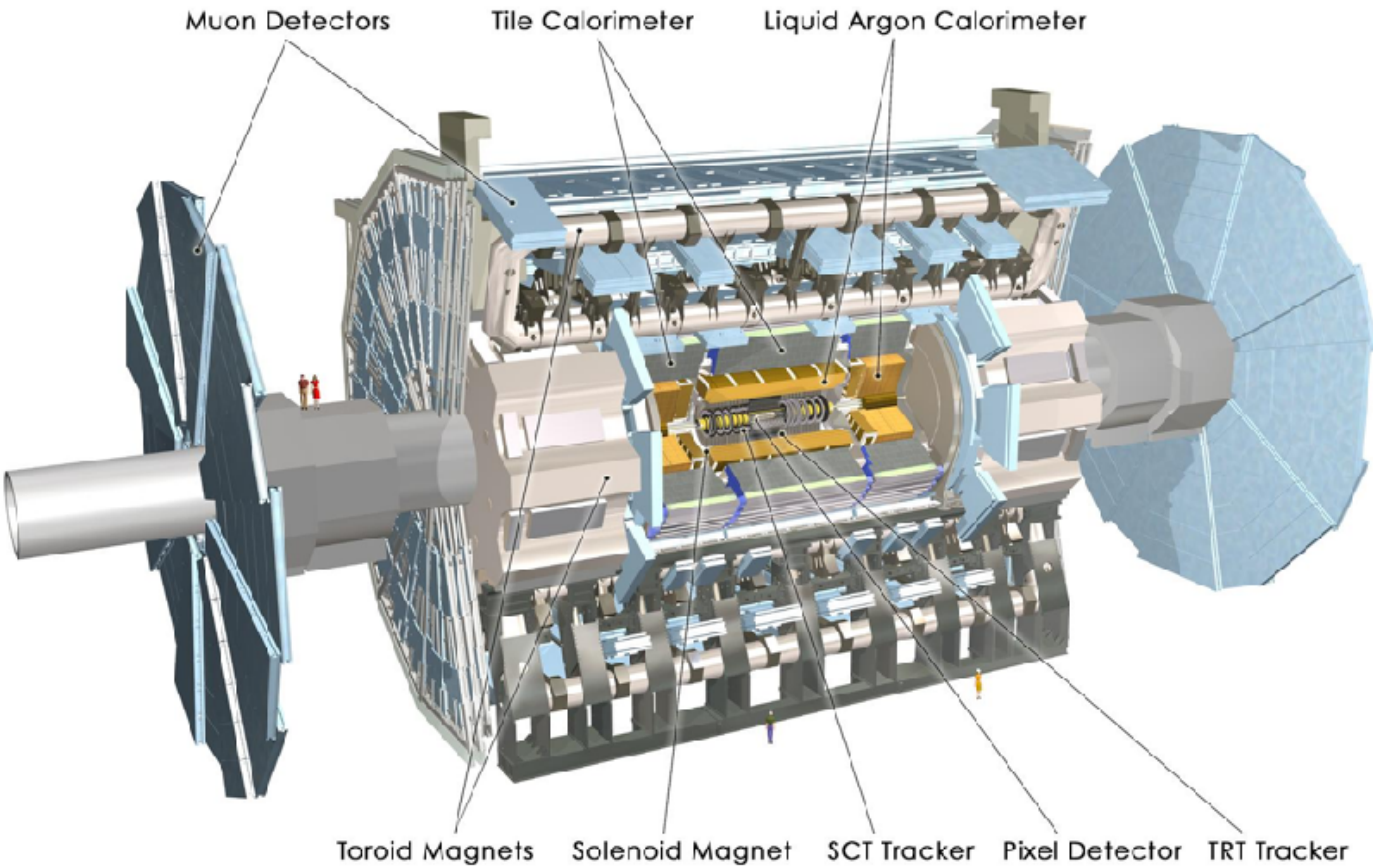
Two general purpose detector, two specialized detectors

The ATLAS Detector

Doing science bigly!

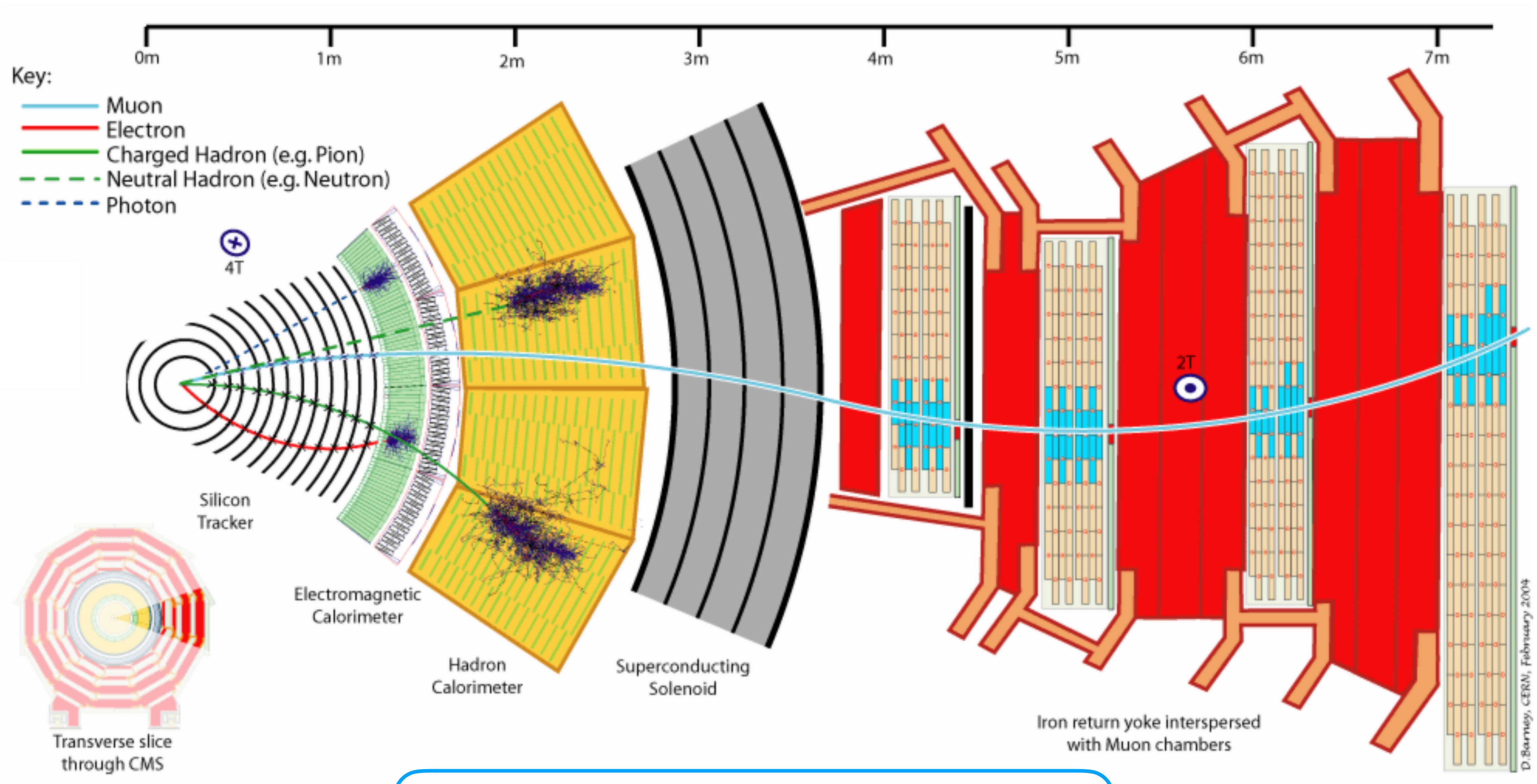
Detector Size and Weight

Diameter: 25 m
Length: 46 m
Overall weight: 7000 tonnes
3000 km of cables
Weight of ATLAS is same as a hundred 747 jets (empty)
ATLAS is half the size of Cathedral of Notre Dame de Paris



The CMS Detector

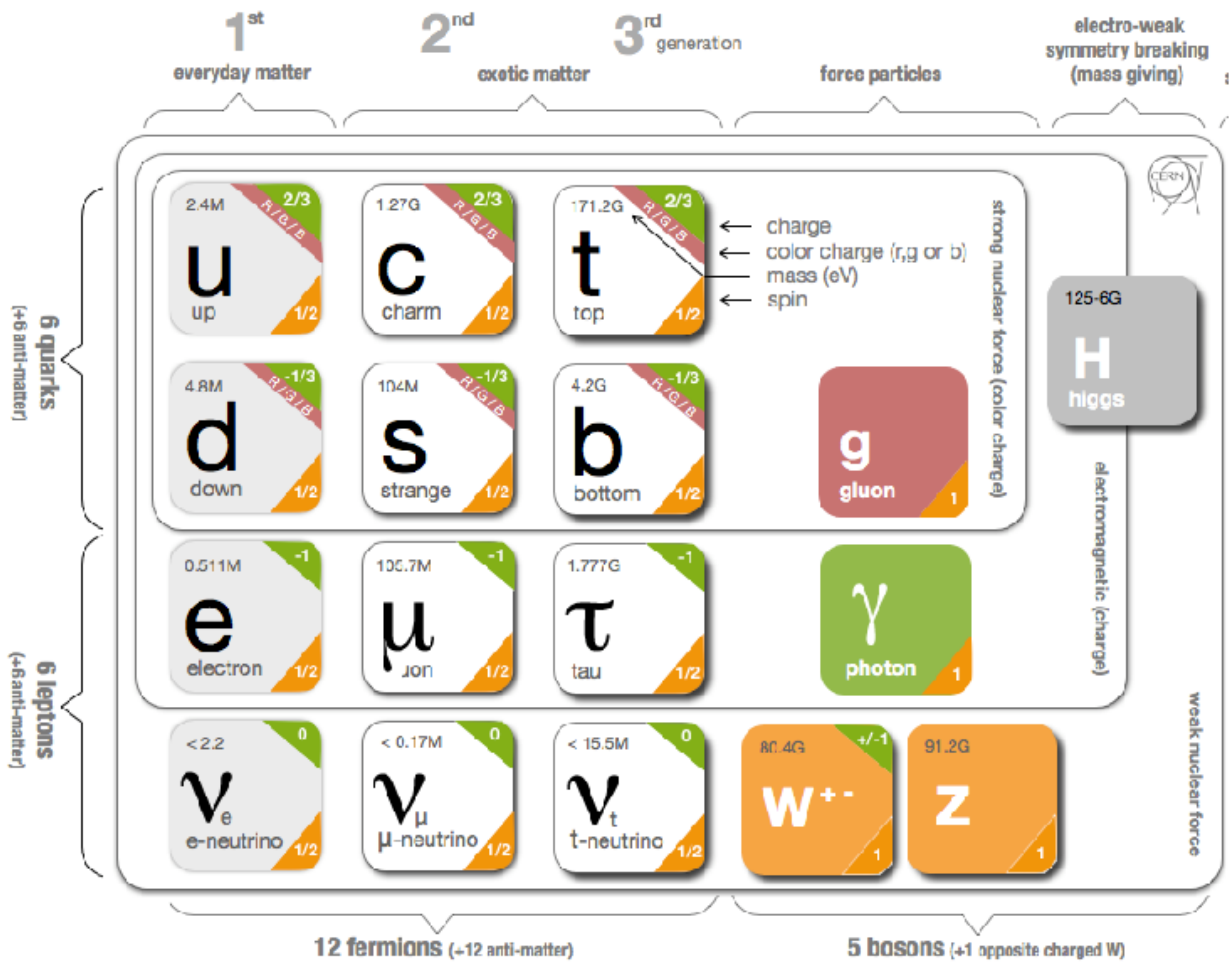
Doing science bigly!



Not shown:
Trigger system for selecting
the 0.0025% most interesting collisions

The Standard Model

At the smallest scales probed, we study the interactions of **fundamental particles**



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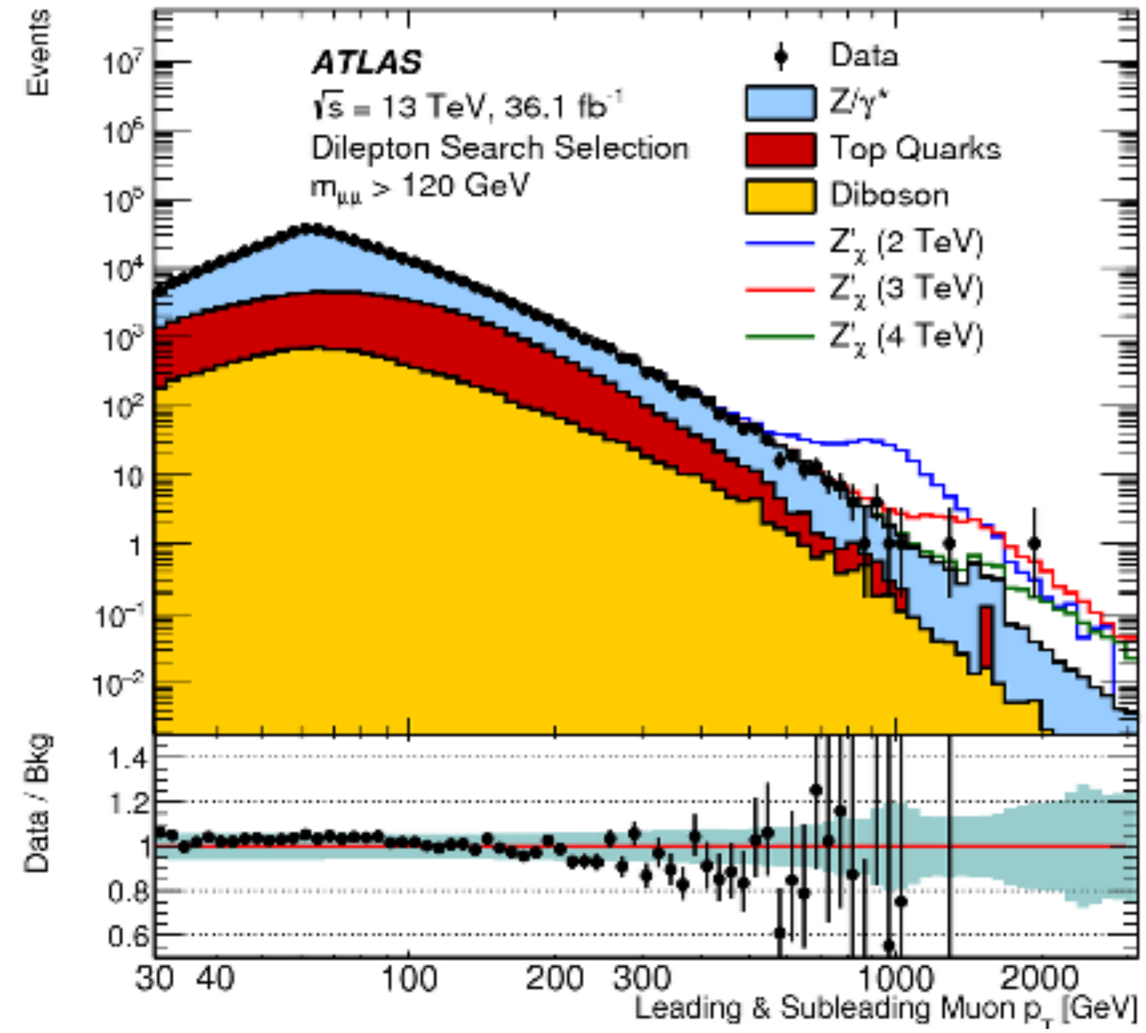
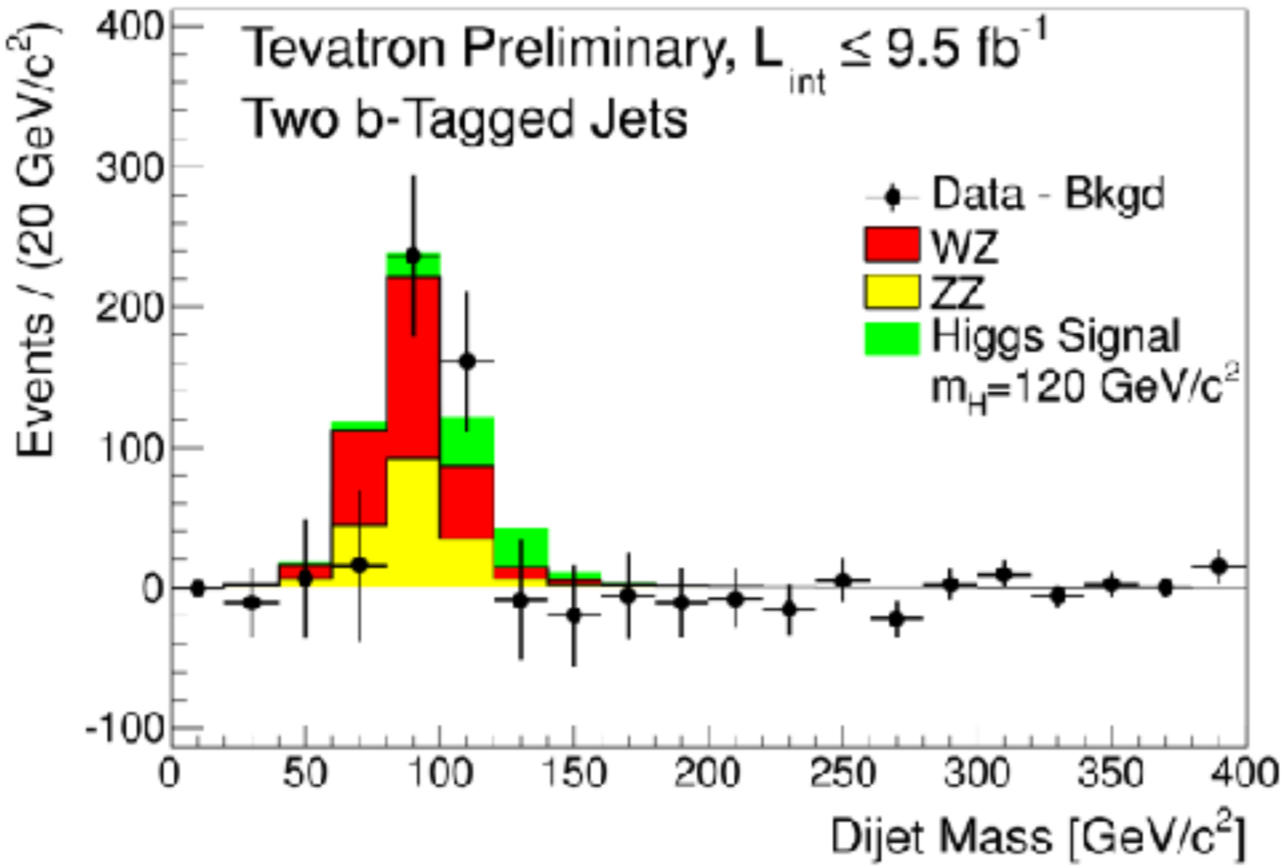
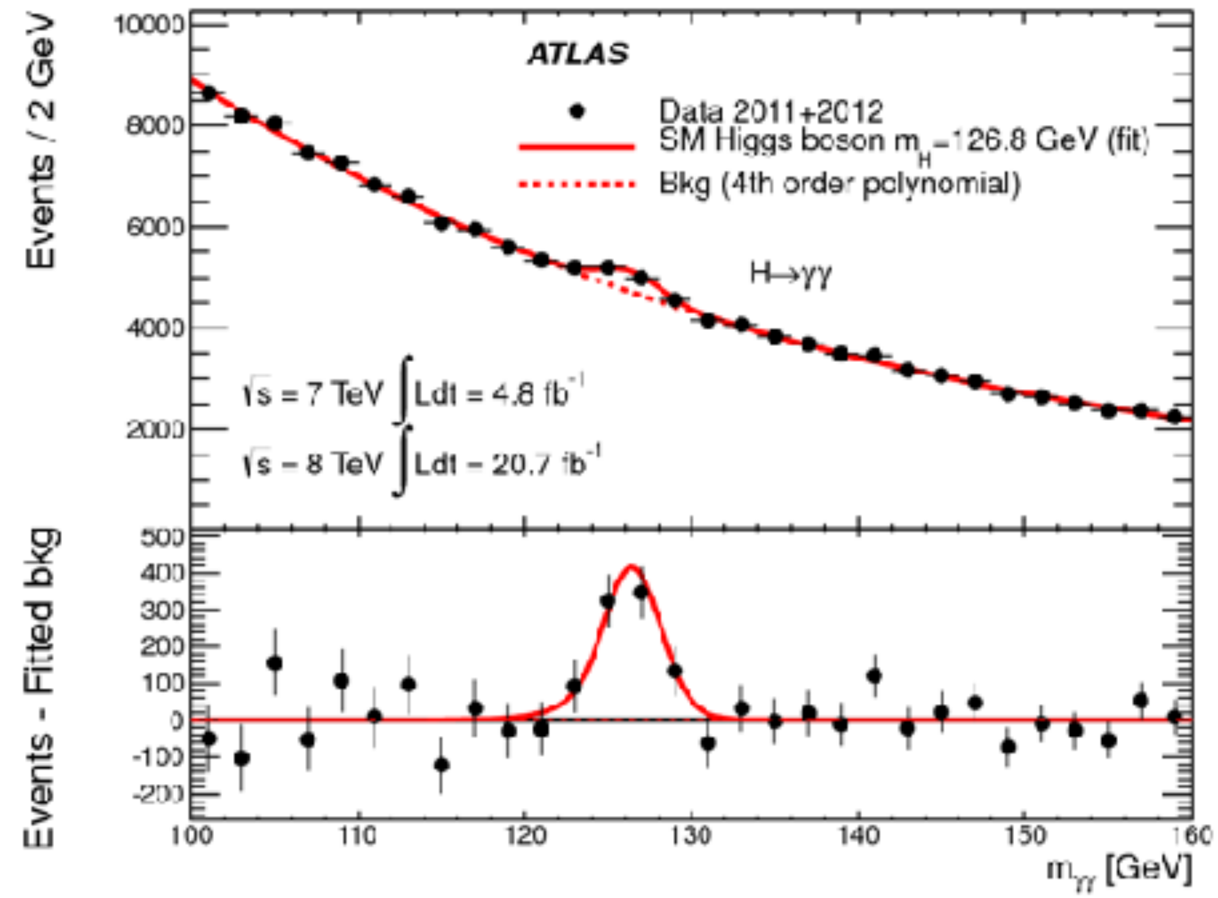
“Simulation”

- How do we understand what is happening in the collisions and in the detector?
- *Monte Carlo Generators*: programs calculate the rate processes occur and the energies of the resultant particles according to the SM
- *Detector Simulation*: another program simulates how these particles would interact with the detector
- *Reconstruction*: take the energy signatures in the detector and group them to reconstruct the particles which were created
    - same code for data and for detector simulation



The Higgs Boson

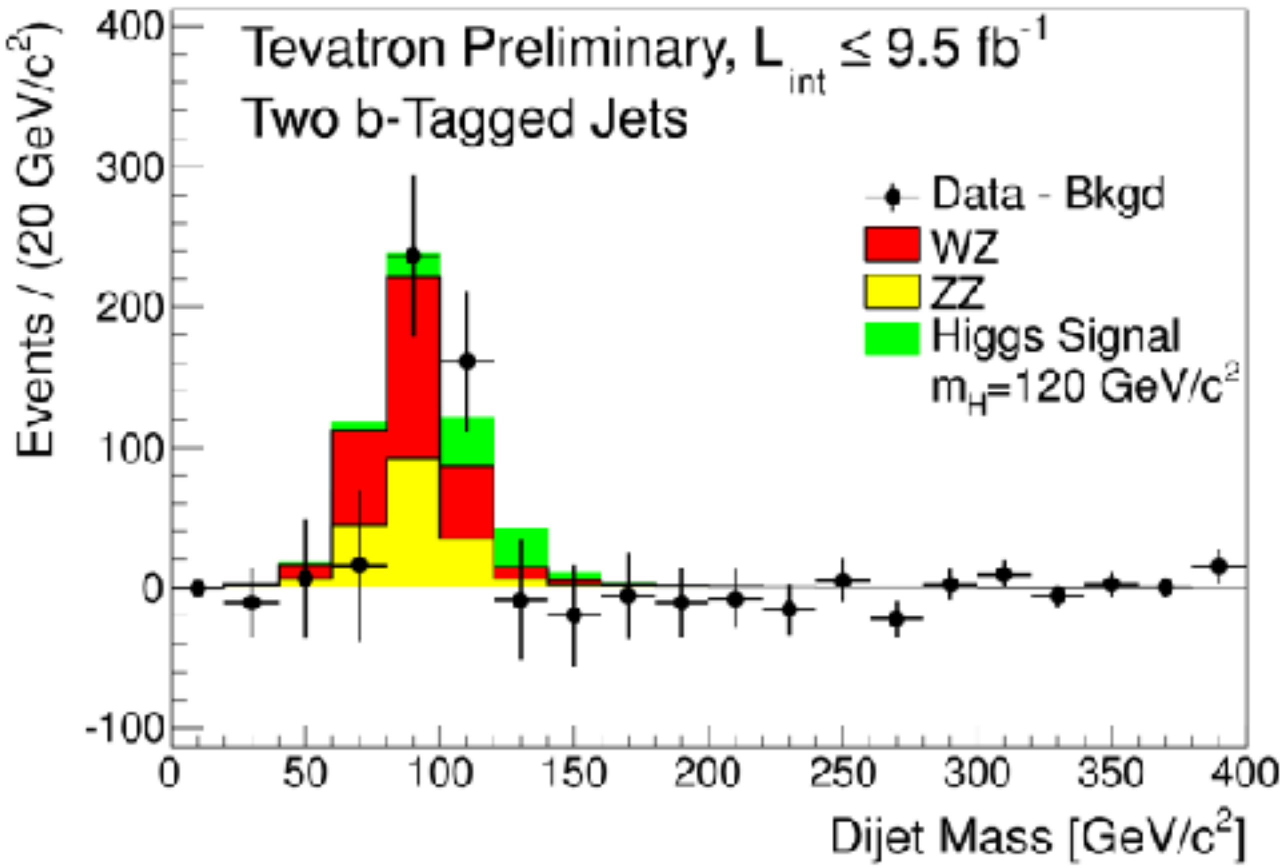


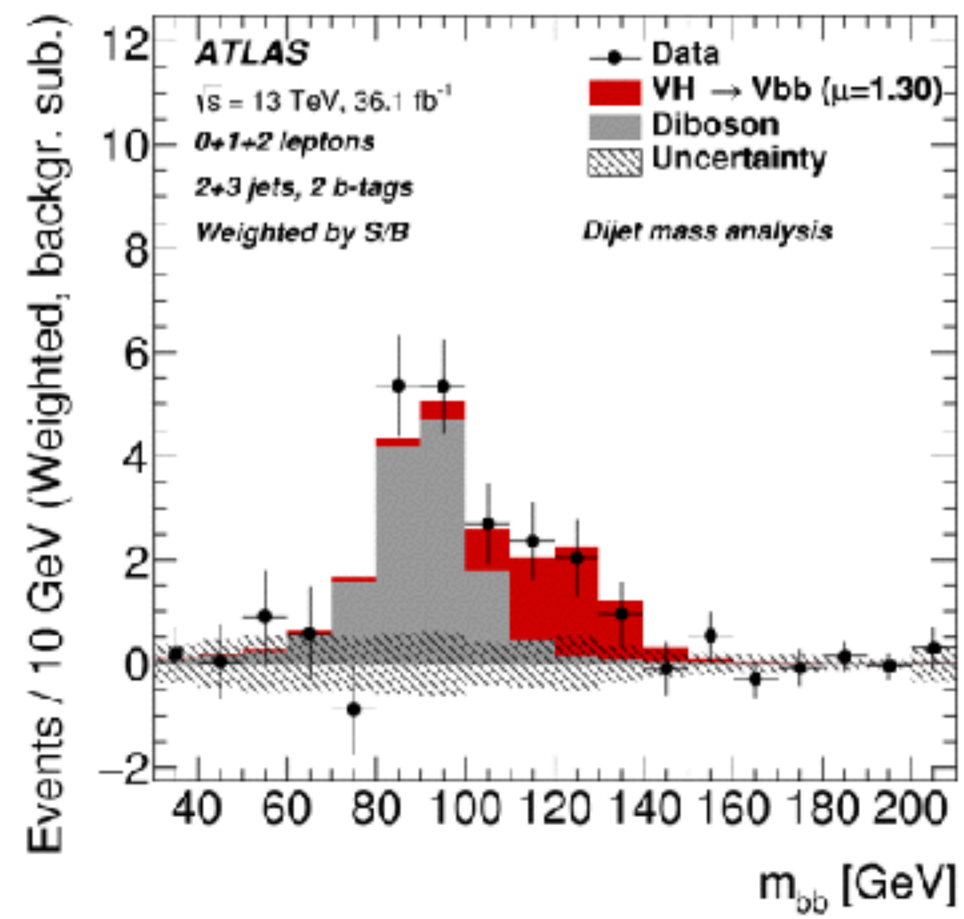


July 02, 2012

July 04, 2012

The Higgs Boson





July 02, 2012

August 10, 2017

The Higgs Boson

Abstract

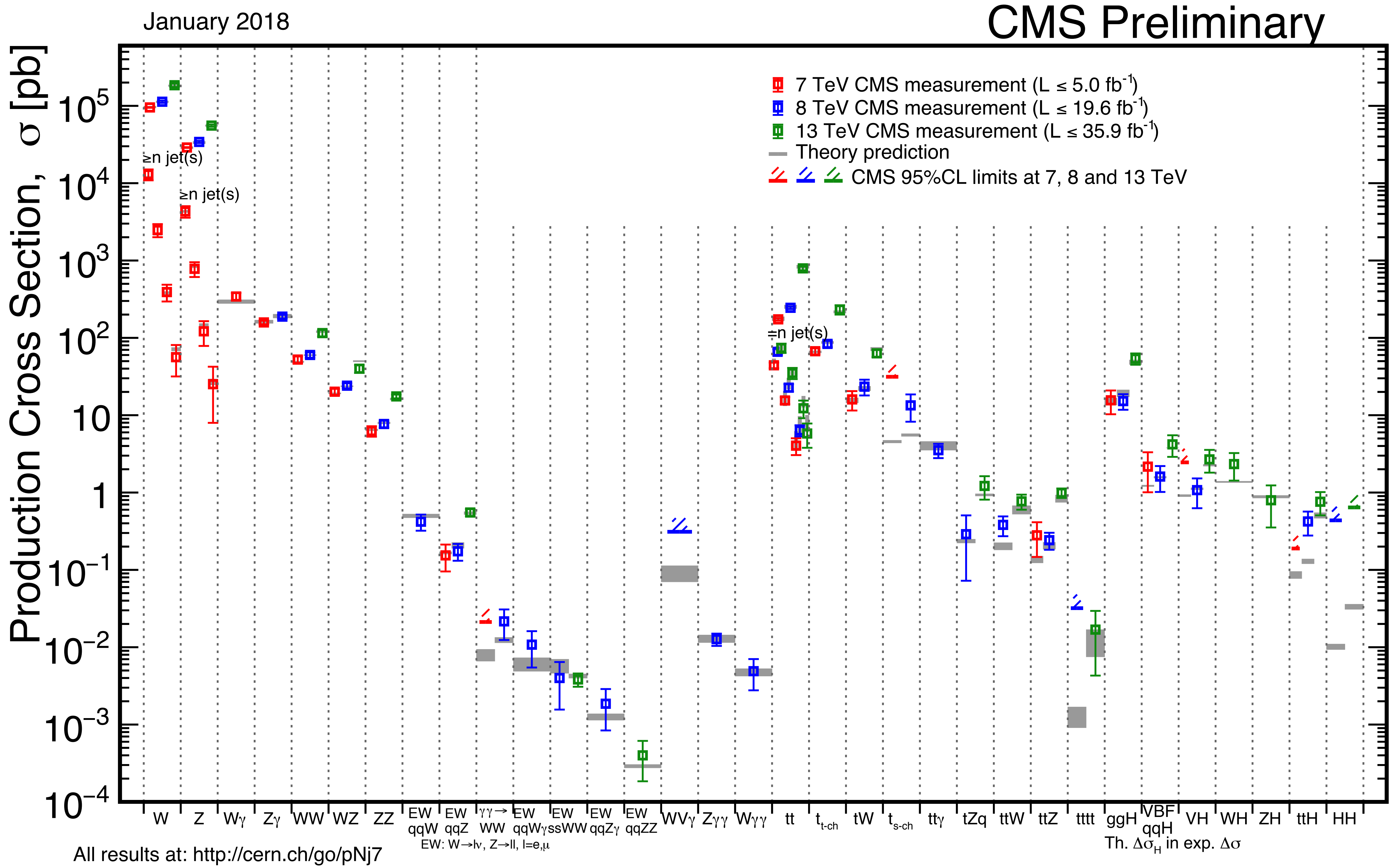
A detailed study of associated Standard Model Higgs production (WH and $t\bar{t}H$) at the LHC (or a possible upgraded Tevatron collider), where the Higgs boson decays to $b\bar{b}$ pairs, is reported for $80 < m_H < 120$ GeV. Even for optimistic b-tagging performances of the detector, the signal cannot be cleanly extracted from the background. For an integrated luminosity of $10^4\ pb^{-1}$ and $m_H = 100$ GeV, one can expect at best ~ 110 reconstructed $H \to b\bar{b}$ decays from WH production, above a resonant background of ~ 150 WZ events and a non-resonant background of ~ 4800 events, and ~ 100 reconstructed $b\bar{b}$ pairs (of which ~ 50 from $H \to b\bar{b}$ decay) from $t\bar{t}H$ production, above a background of ~ 4000 events. The main difficulty in extracting these two channels is in the expected low signal rate after reconstruction, the need for accurate control of all the background sources and for extremely good b-tagging performance. Nevertheless, for a few years of running at a luminosity of $10^{33} cm^{-2}s^{-1}$, the $H \to b\bar{b}$ channel may be the best way to probe the region $80 < m_H < 100$ GeV.

The Standard Model

Very successful theory

Precise measurements in great agreement with predictions.

Think rate at which processes occur in pp collisions



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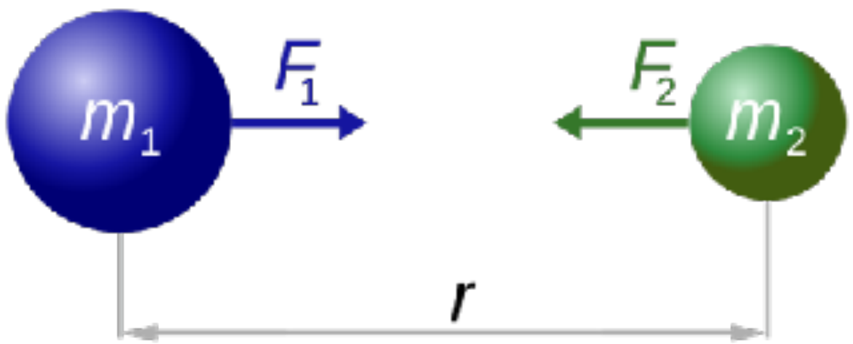
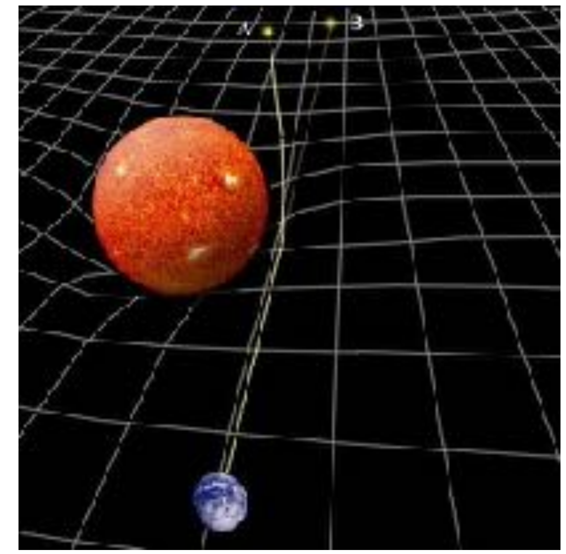
An Effective Theory



$$F_1 = F_2 = G\frac{m_1 \times m_2}{r^2}$$

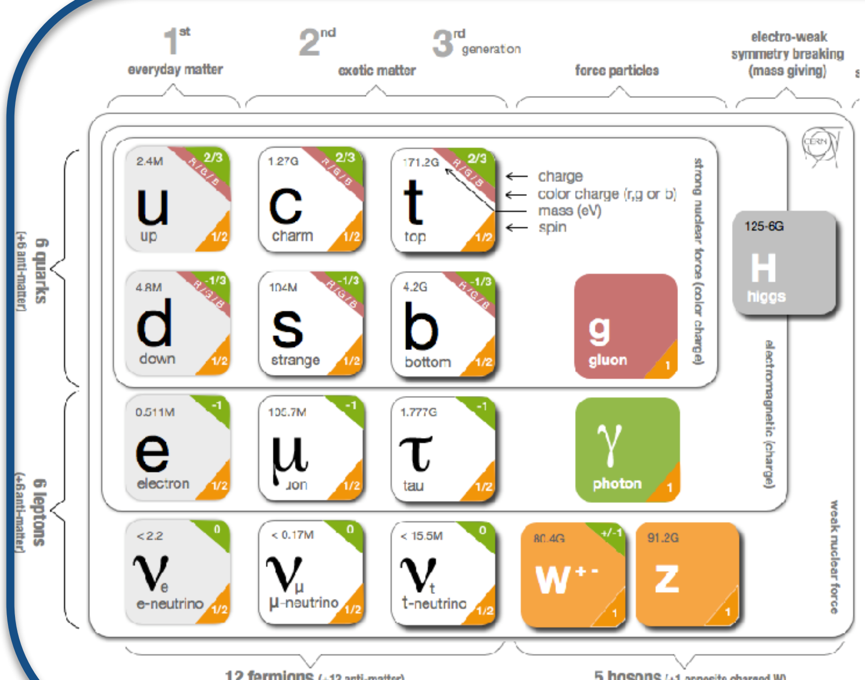
Φ/c^2 & $v^2/c^2 << 1$

is to



$$G_{\mu\nu} \equiv R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

as



$>\sim 10^{-19}$ m

is to

? @ 10^{-34} m

(many potential solutions exist)

Where to Next?

The Standard Model is an ***effective theory***

Empirical

- Does not include gravity
- Does not include Dark Matter/Energy (95% of universe)
- Why does the universe have more matter than antimatter?
- ….

Aesthetic

- stability relies the difference of big numbers to be very small (fine tuning)
- large scale differences of forces
- ….

Direct Searches

Taylor searches to a ***given theory***

- Motivated by belief or disbelief?
- **Powerful** but limited to model of choice

Look more **generally** for a **signature**

- motivated by ***minimal or general*** arguments
- Correlation of channels is limited

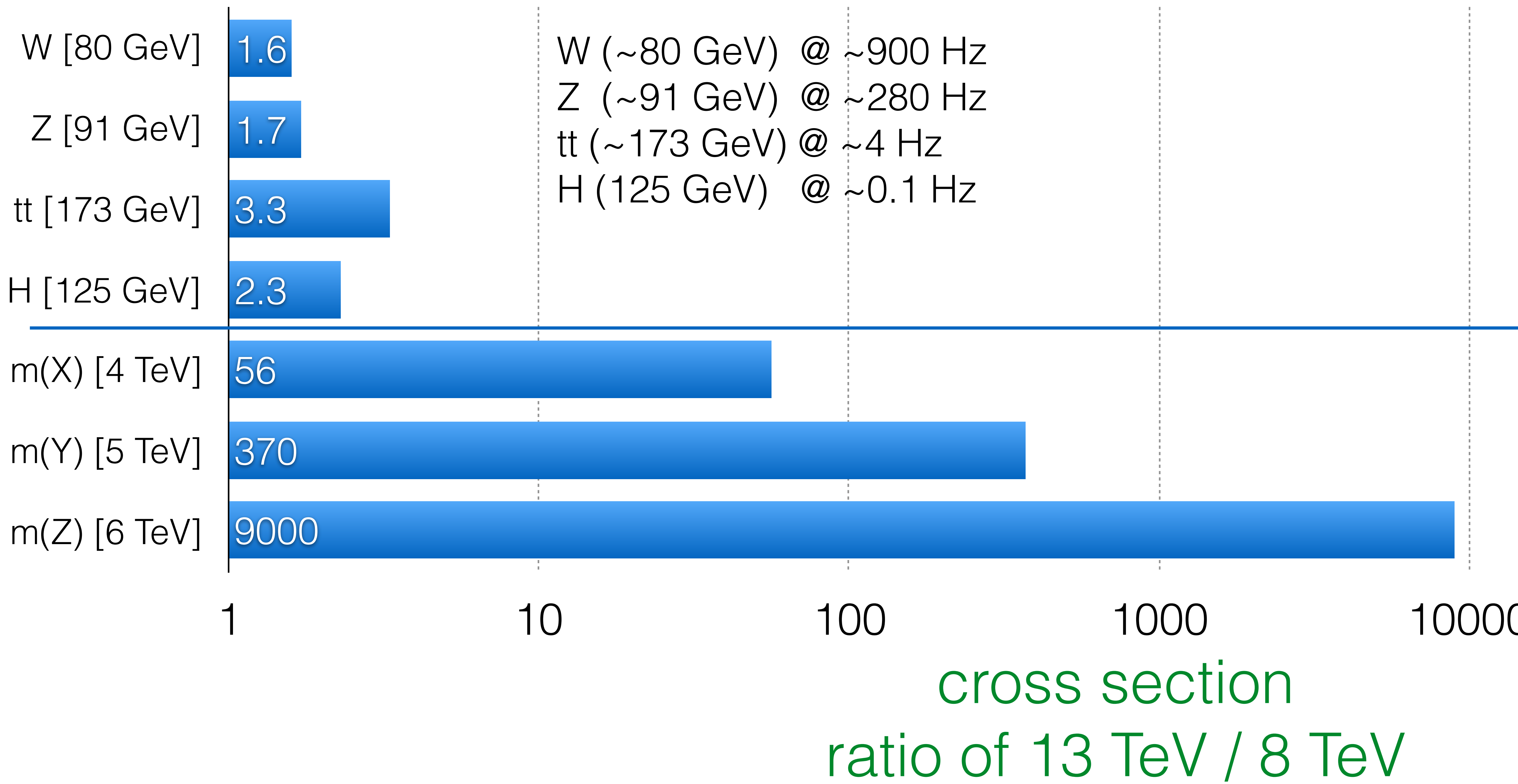
Can also search for new physics indirectly

Run 2: Pure Exploration

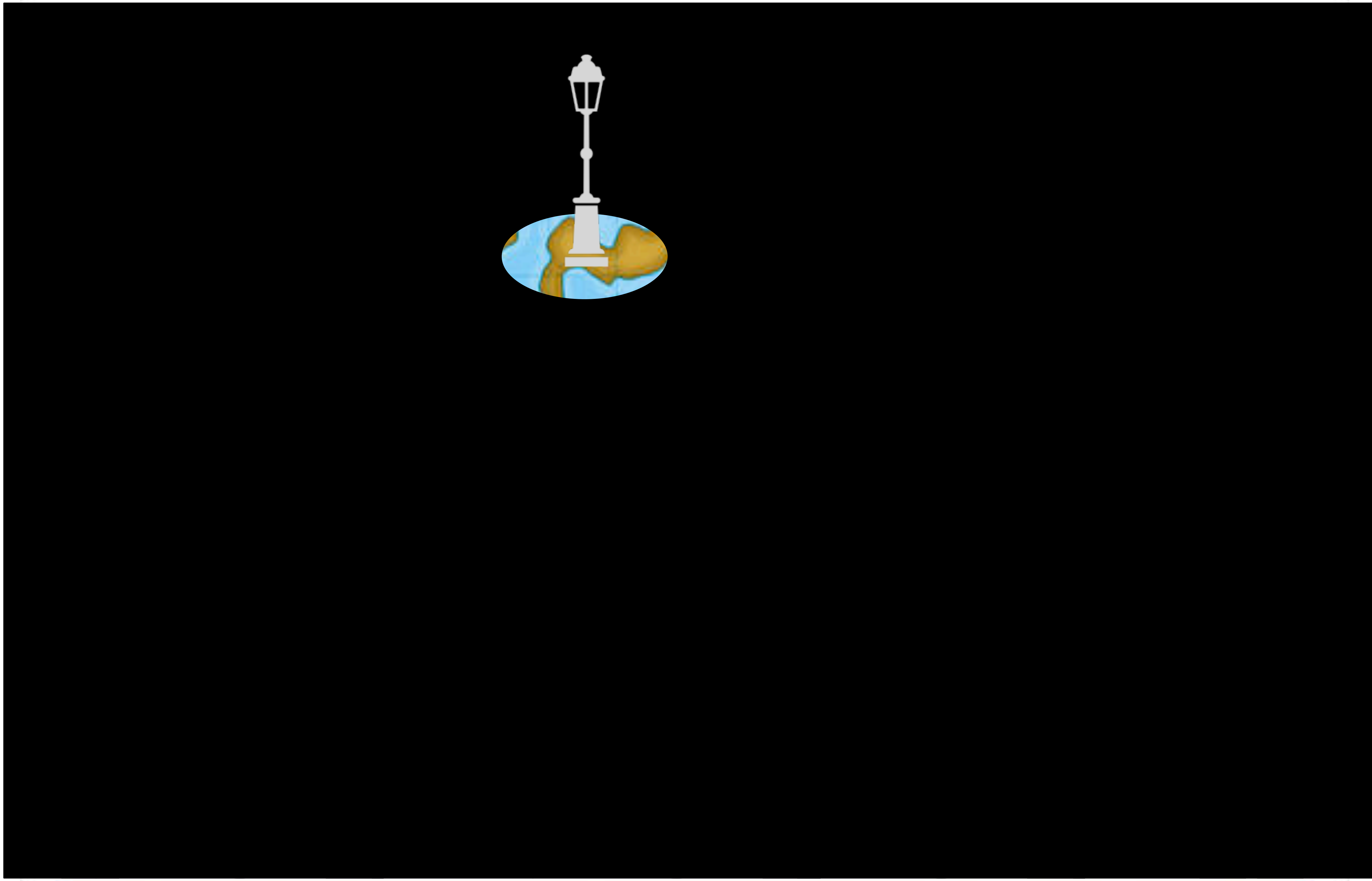
For 2015, LHC $\sqrt{s}$ ***increased*** from **8 TeV** to **13 TeV**

Results in cross section increase:

larger for heavier objects! (and production mode dependence)



Explore the Landscape



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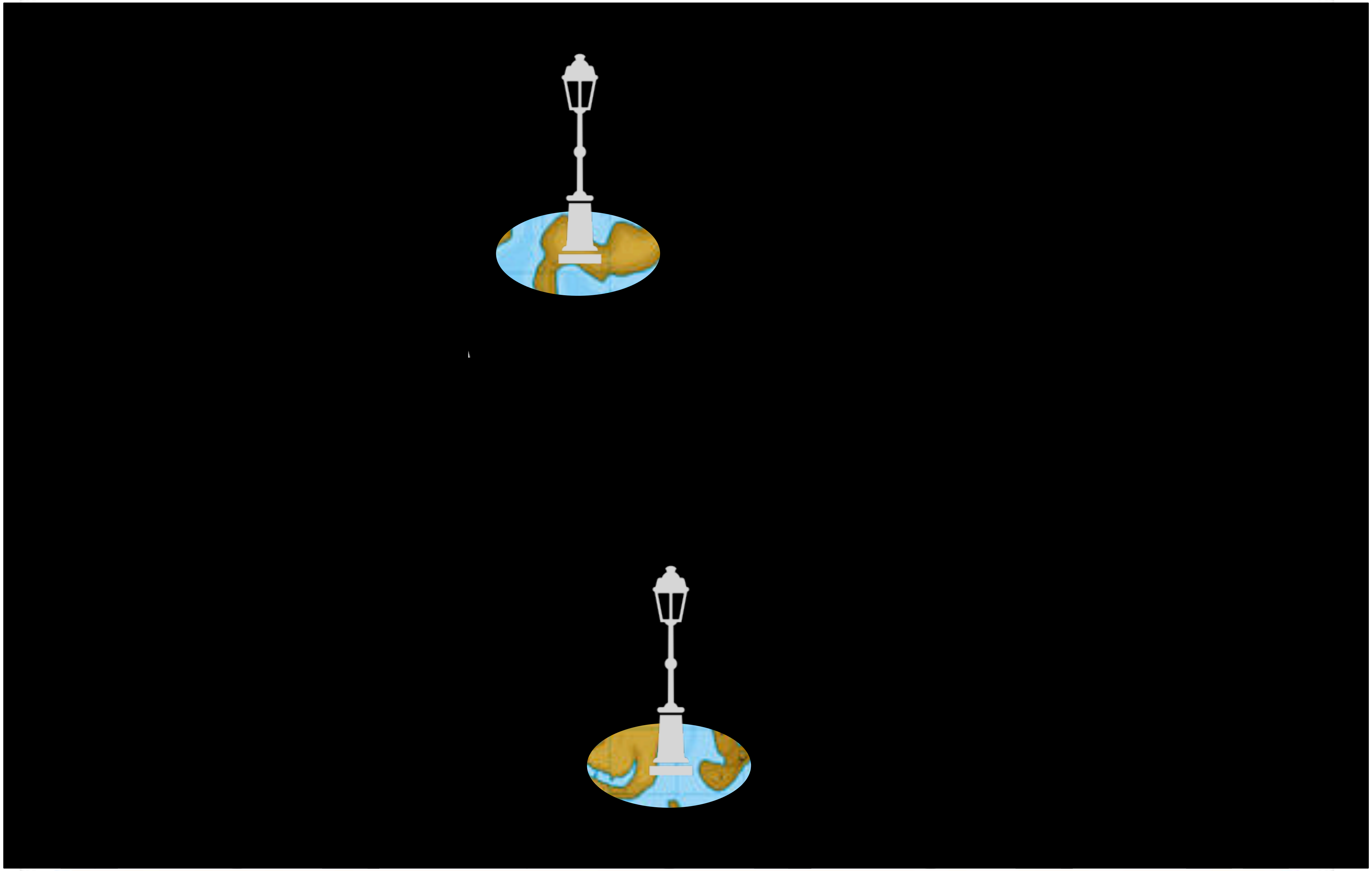

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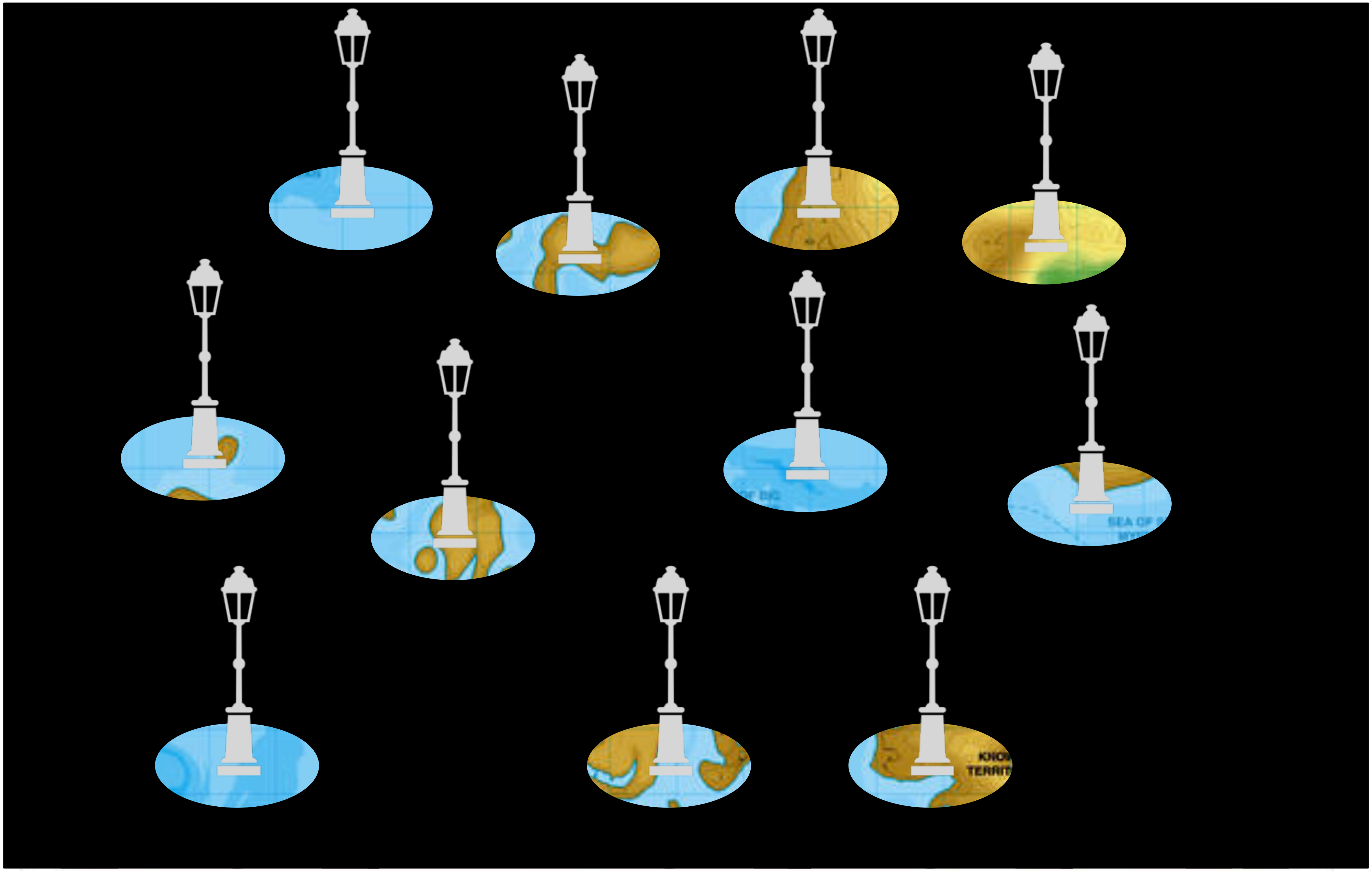

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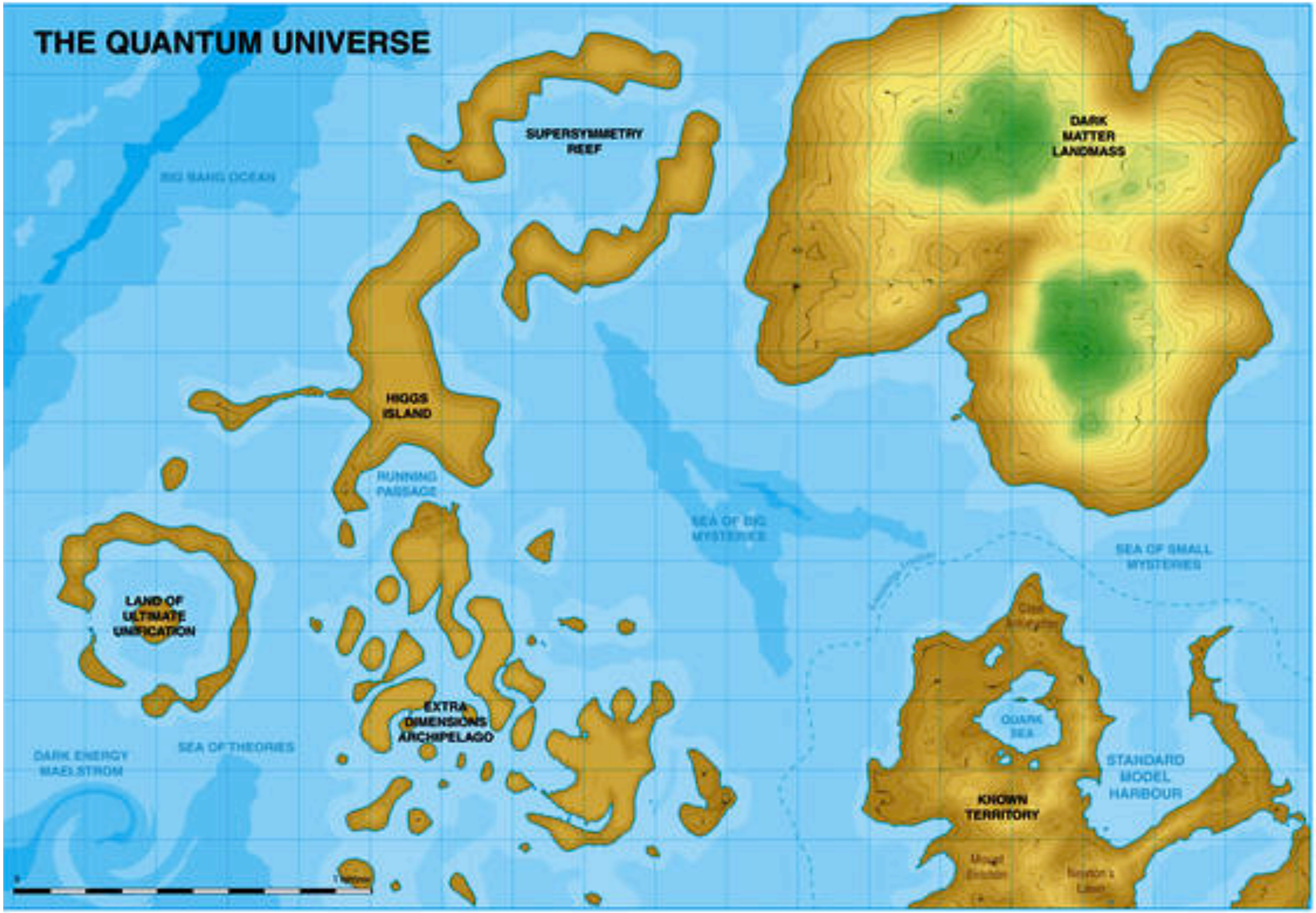
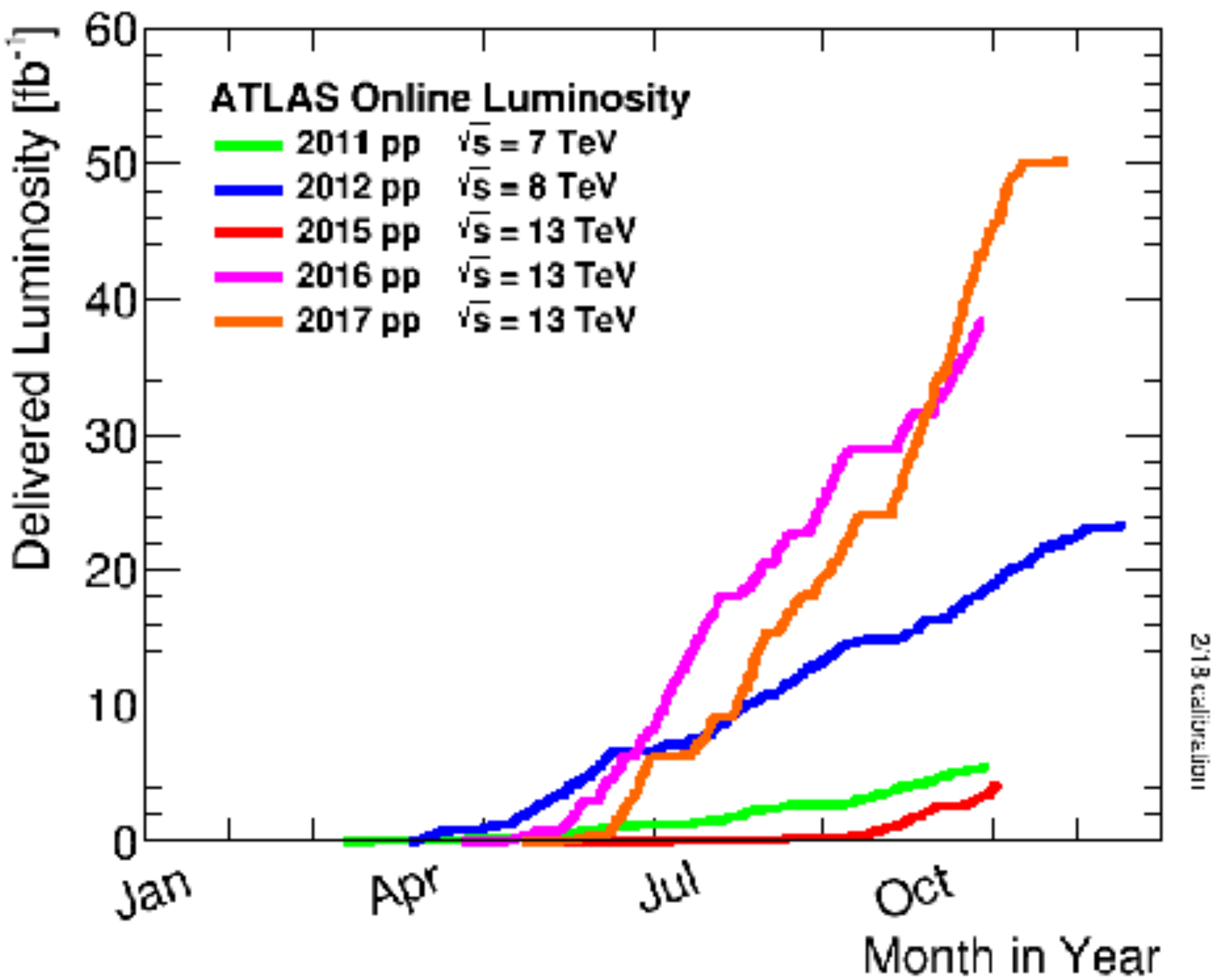
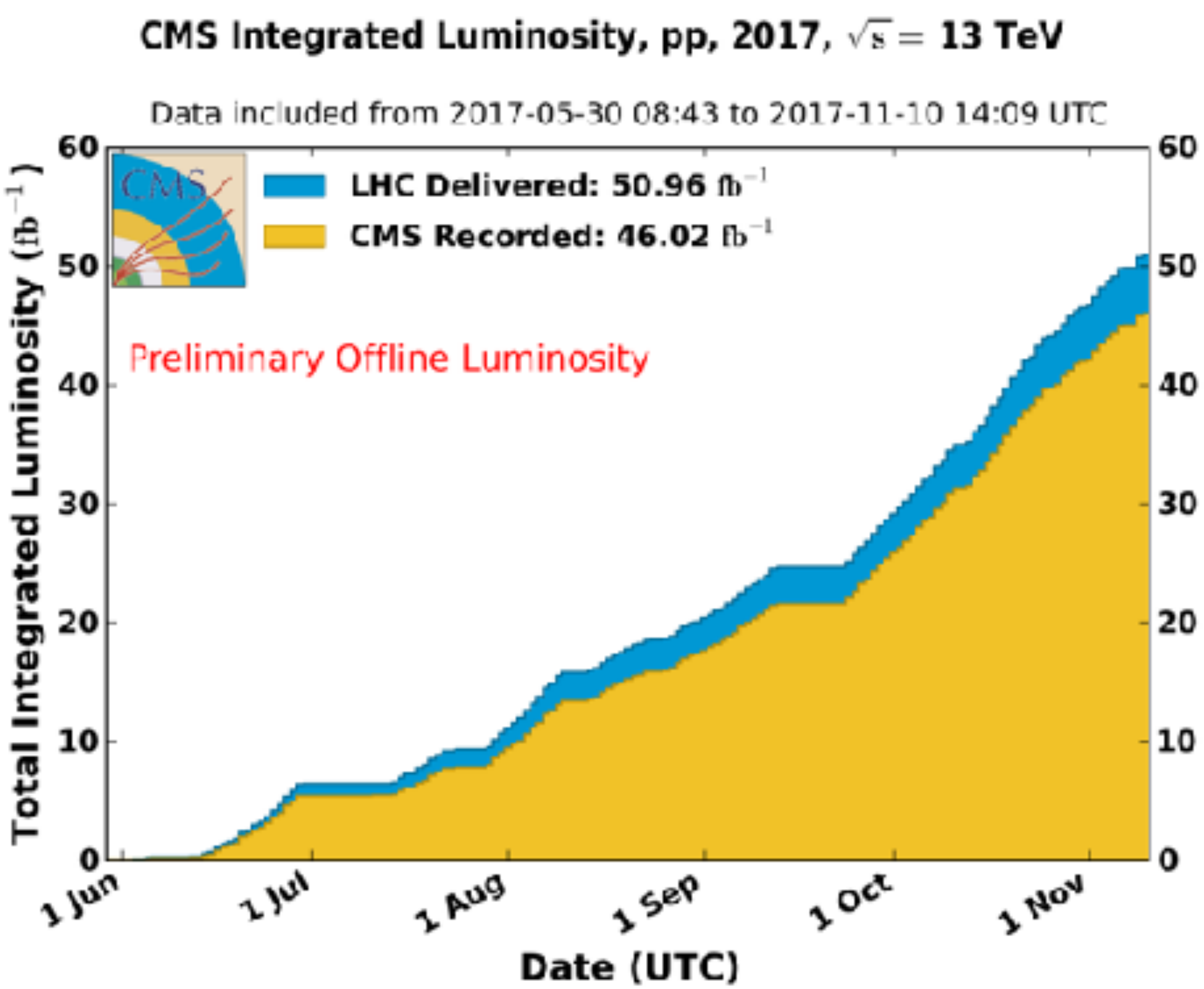


Datasets

Excellent **performance by the LHC** and high **data taking efficiency** by detectors in the **13 TeV pp** collisions period (2015, 2016).



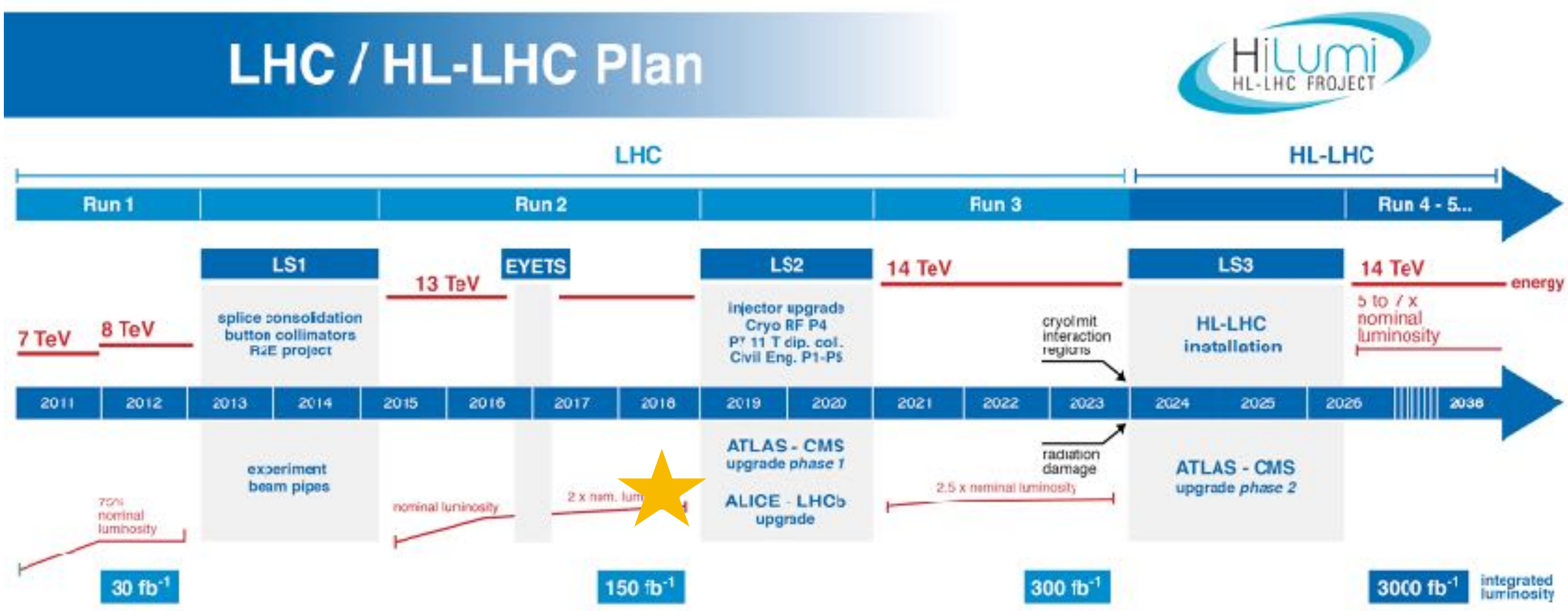


Data quality efficiency > 90%

Results shown here include data collected in 2015 & 2016 = ~36/fb
~80/fb are available for analysis - results starting this summer

HL-LHC

- ~150/fb collected by end of 2018. To cut stat error in 1/2 would take ~10 years.
- Make HL-LHC instead of simply waiting



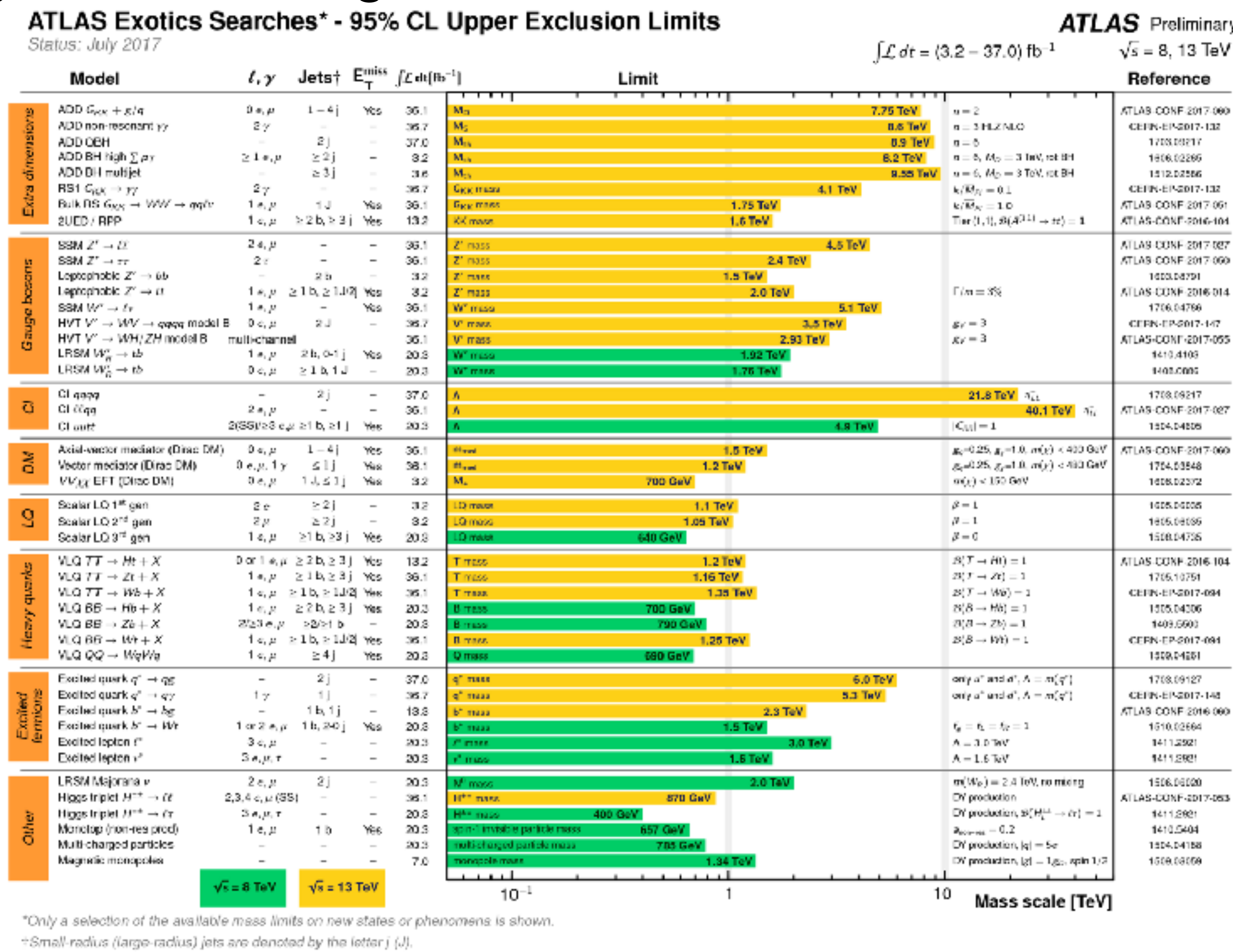
Exotics Searches

A tremendous program consisting of:

~70 searches

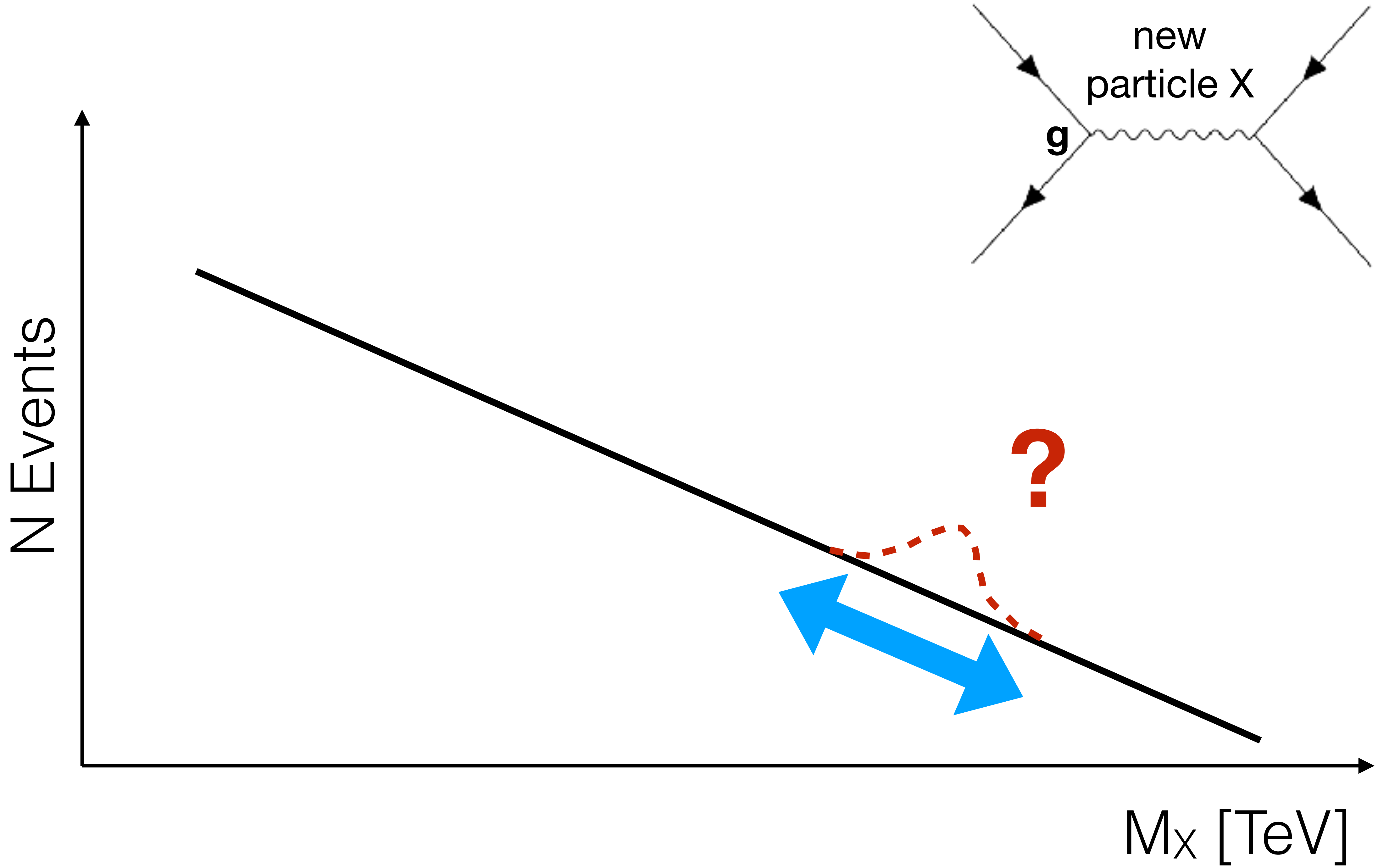
~600 scientists

I cannot cover the entire program or related programs like supersymmetry in one seminar.



All results for: ATLAS and CMS

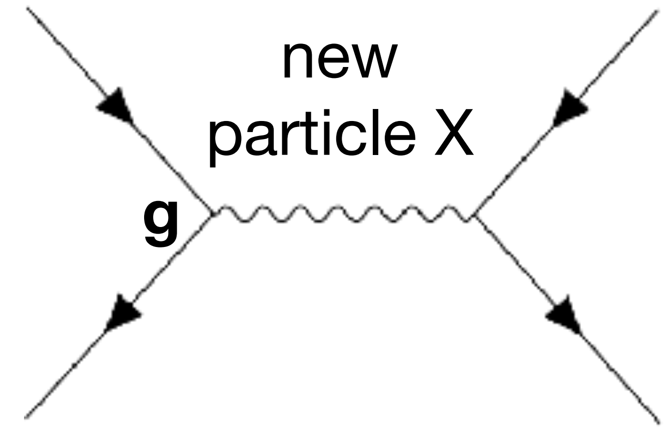
Generic Resonance Search

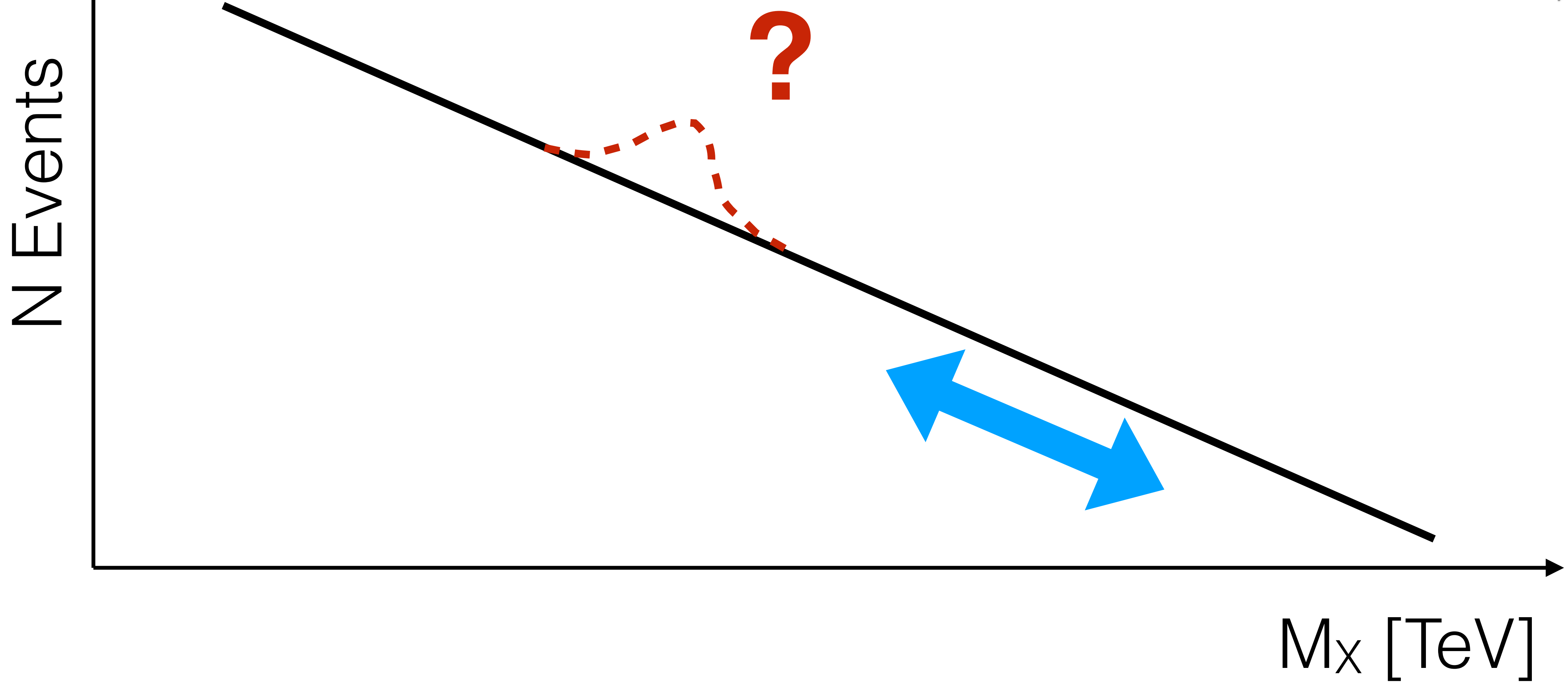


Look for a bump along an entire mass range

…as mass of new particle is never predicted by model

Generic Resonance Search





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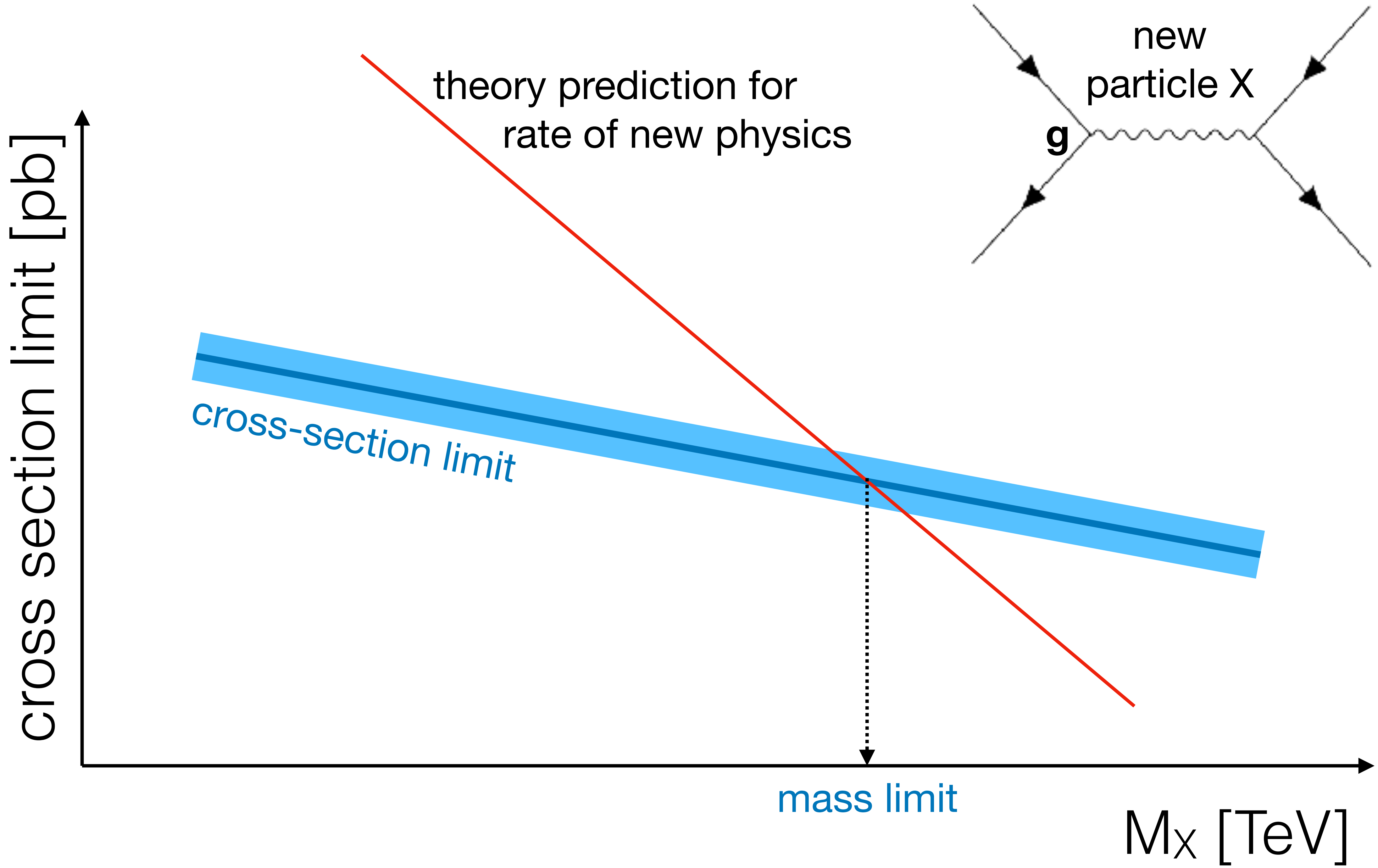
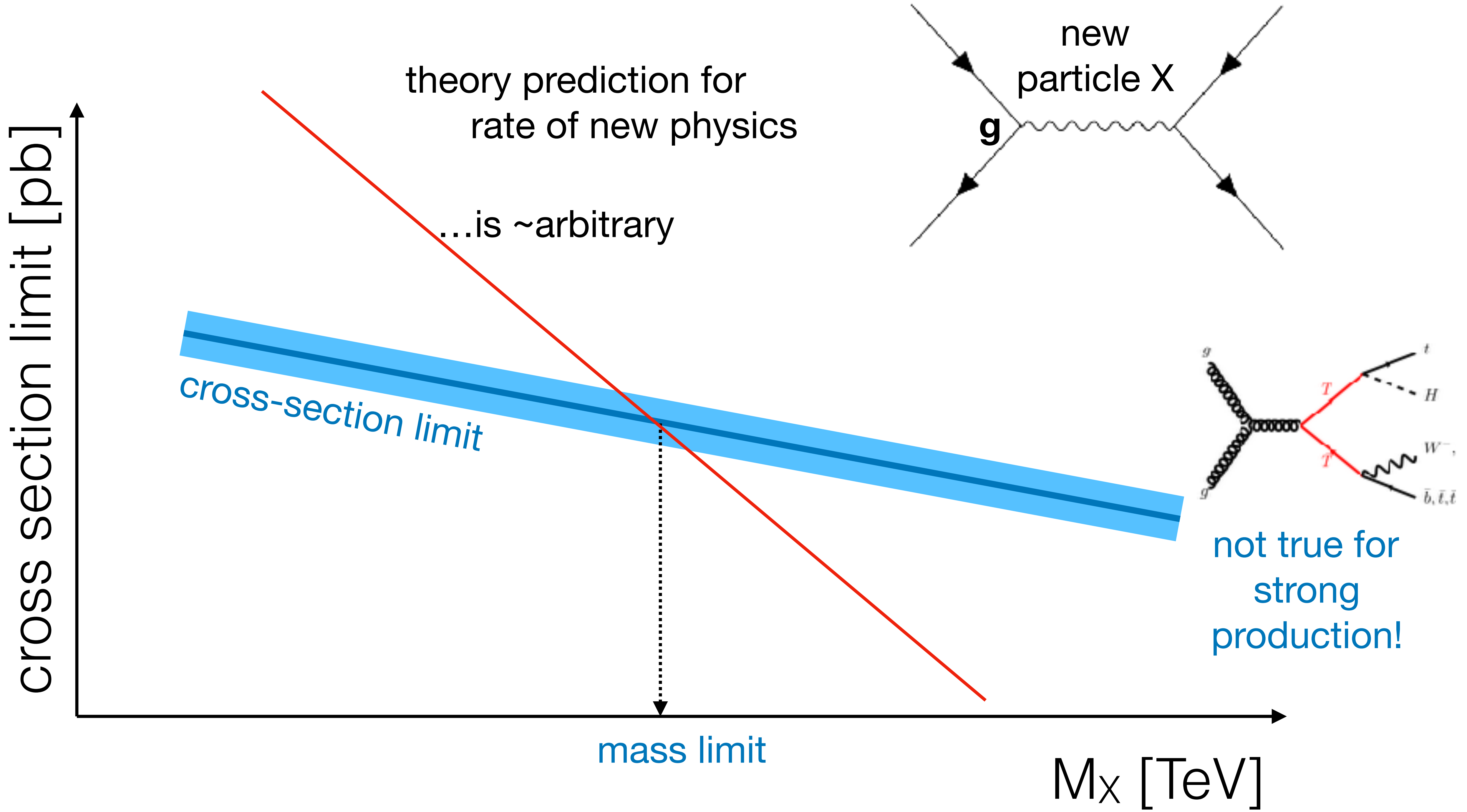
Limits on Model



Don’t see bump, so put upper bound on new particle production rate
(same procedure for searches for non-resonant physics)

Limits on Model



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Questions to Ask:

How far do we need to go?

- What mass range do we need to cover?
  - Lower bound: Previous experiments
  - Upper bound: ??
- How low in cross-section do we need to reach?
  - Strong production: Given by QCD
  - EW coupling: ??

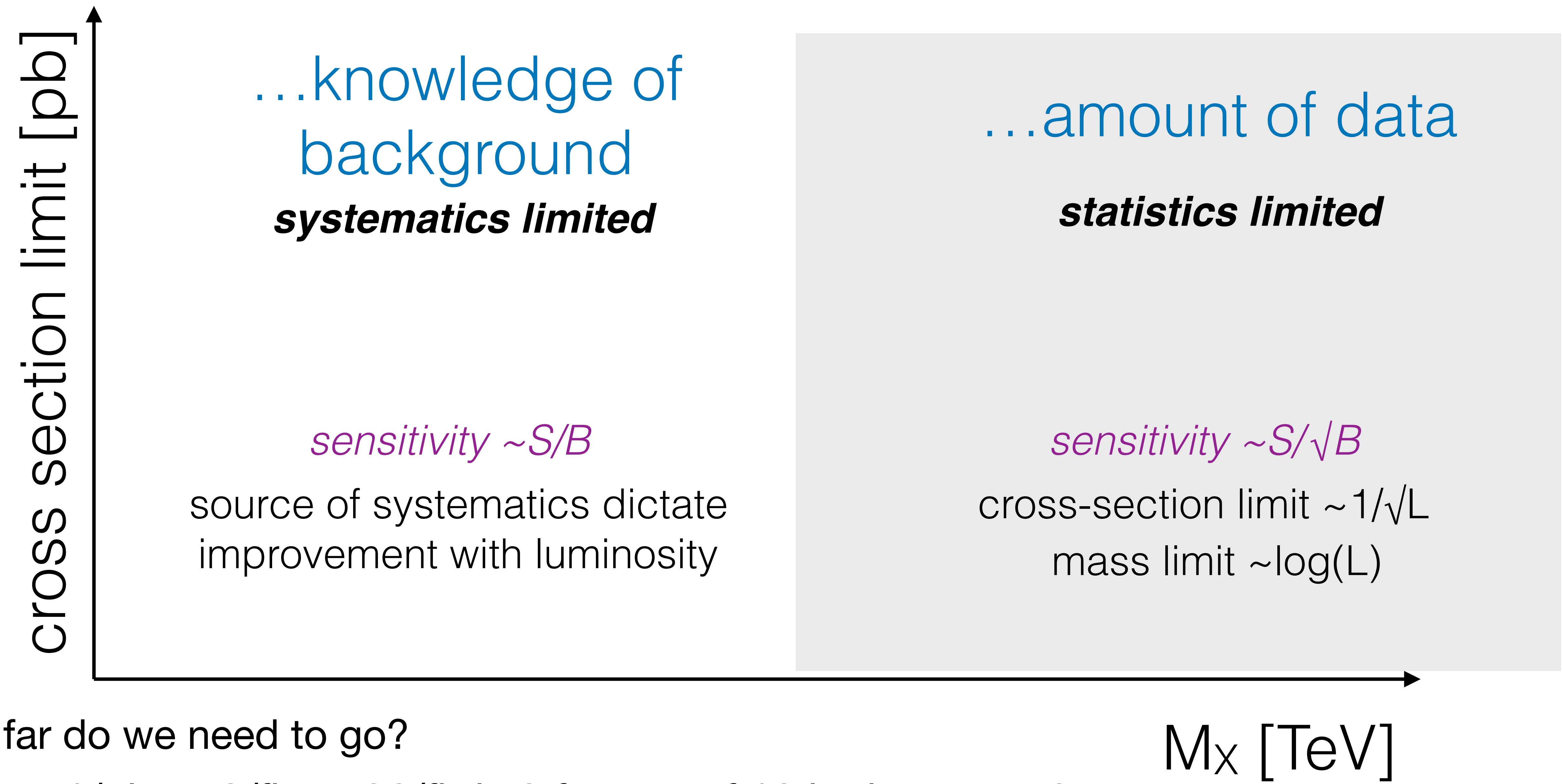
Did we cover all possible signatures/models?

- Has the correct model for nature beyond the SM been written down?

"there is no experiment nor facility, proposed or conceivable, in the lab or in space, accelerator or non-accelerator driven, which can guarantee discoveries beyond the SM, and answers to the big questions of the field" (M.Mangano, 98th ECFA, November 2015)

Reach of Experiment

New physics search sensitivity is limited by…



How far do we need to go?

- ~1/pb -> 3/fb -> 36/fb is 3 factors of 10 in the past ~2 years
- 36/fb -> 140/fb is ~x4 = factor of 2 in sensitivity (1 year)
- 36/fb -> 300/fb is ~x10 = factor of 3 in sensitivity (6 years)

Aside: Planning

- Nice for search to become a SM measurement if no discovery
  - “Discover” SM process so at least “discover” something ;)
  - Add to SM knowledge: *indirectly restricts NP models*
  - Add precision: *Kinematics of process can be altered by NP!*

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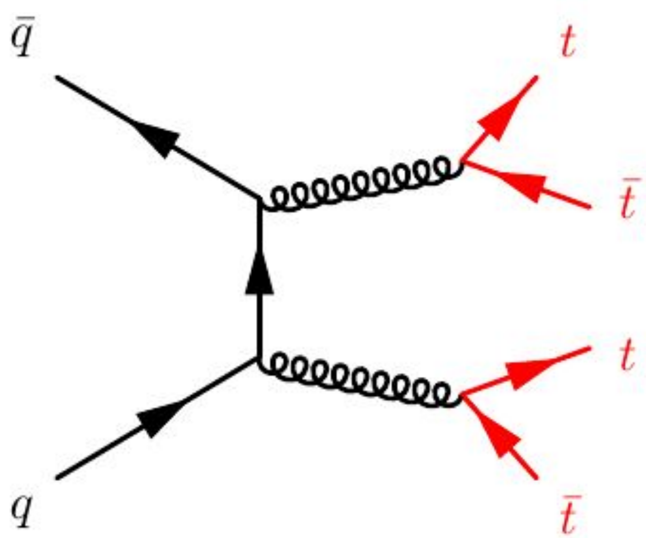

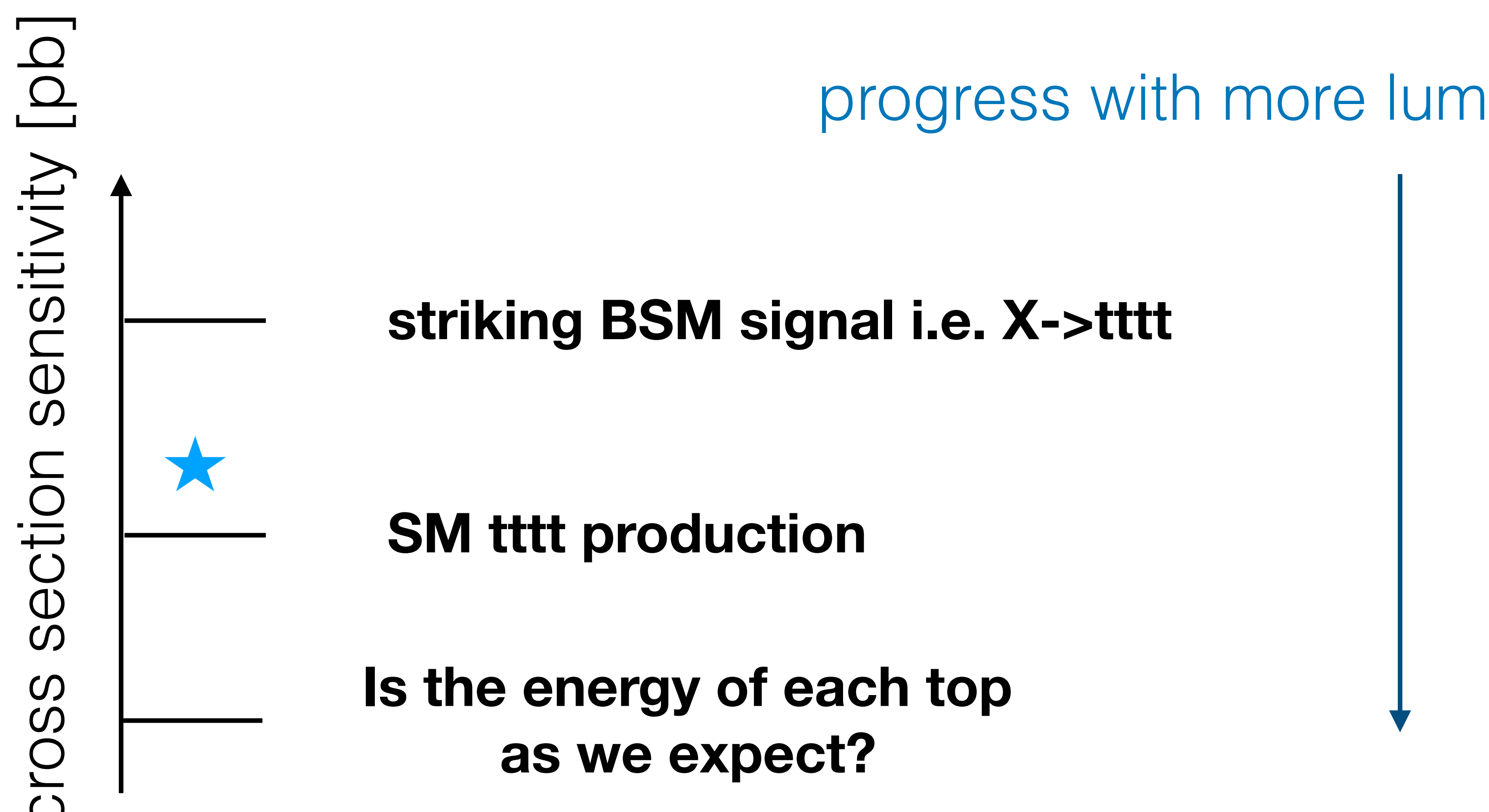

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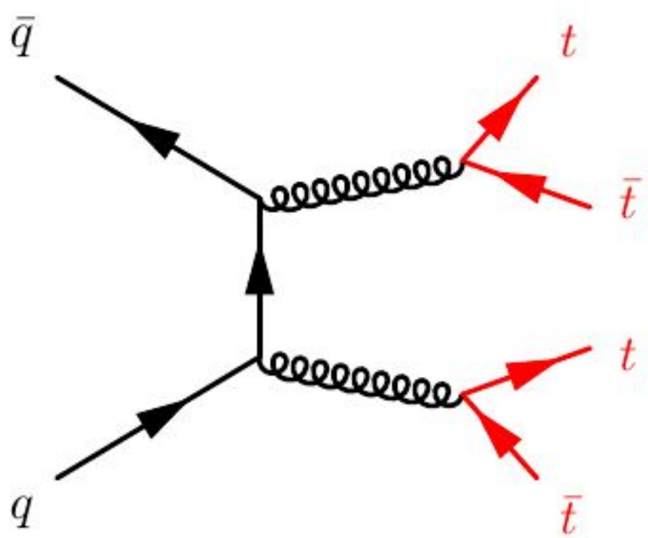
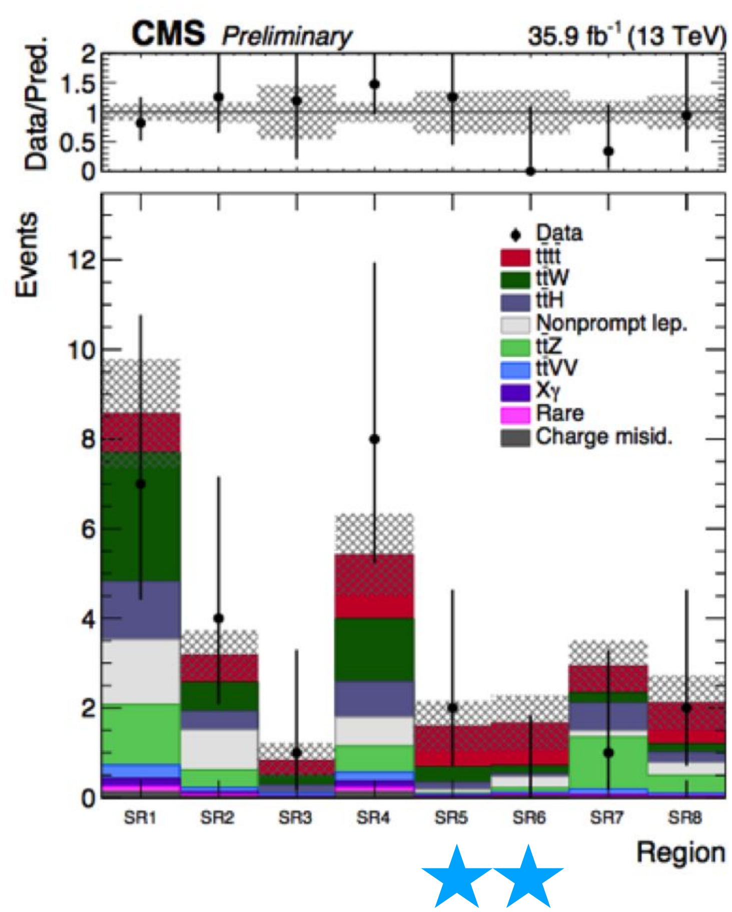




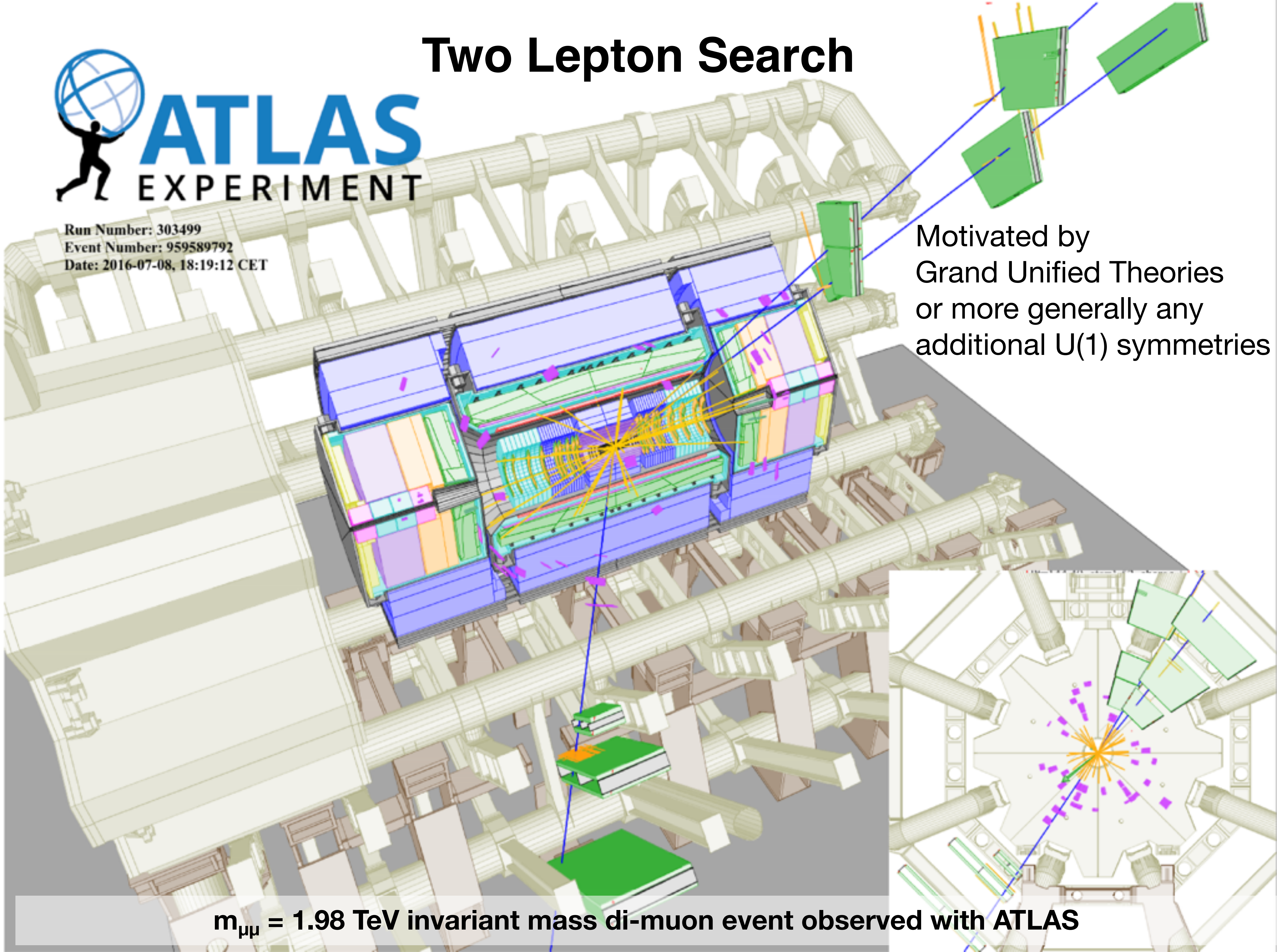
SM = 9.2 fb
CMS = 16.9 +13.8−11.4 fb

Status: Classics

- A few searches for generic signatures cover many models and have been a standard of the hadron collider search program*
- I will go through a few touching on what has happened and where we can go next.

*not considering SUSY models

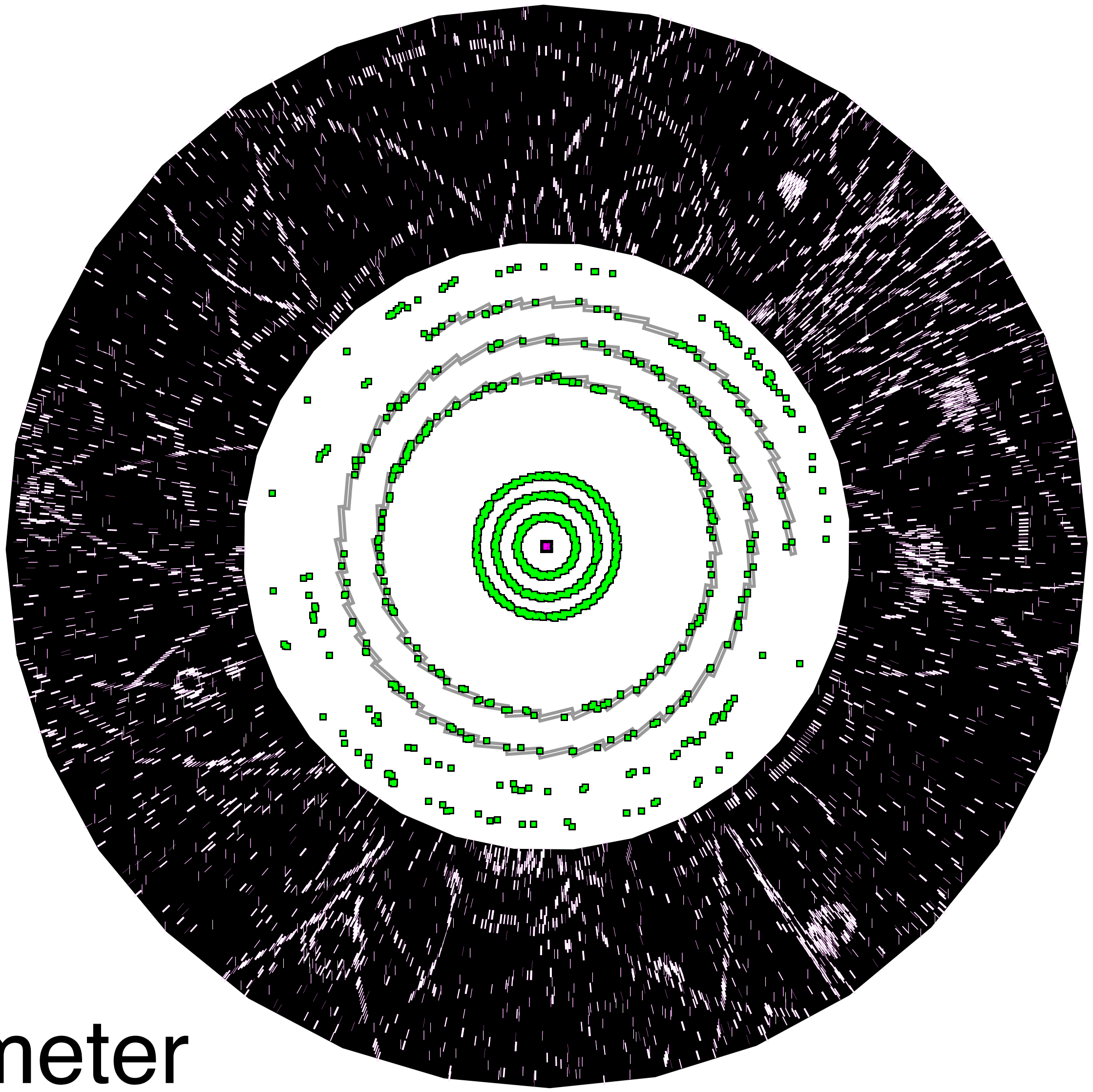
Two Lepton Search



Motivated by
Grand Unified Theories
or more generally any
additional U(1) symmetries

$m_{\mu\mu}$ = 1.98 TeV invariant mass di-muon event observed with ATLAS

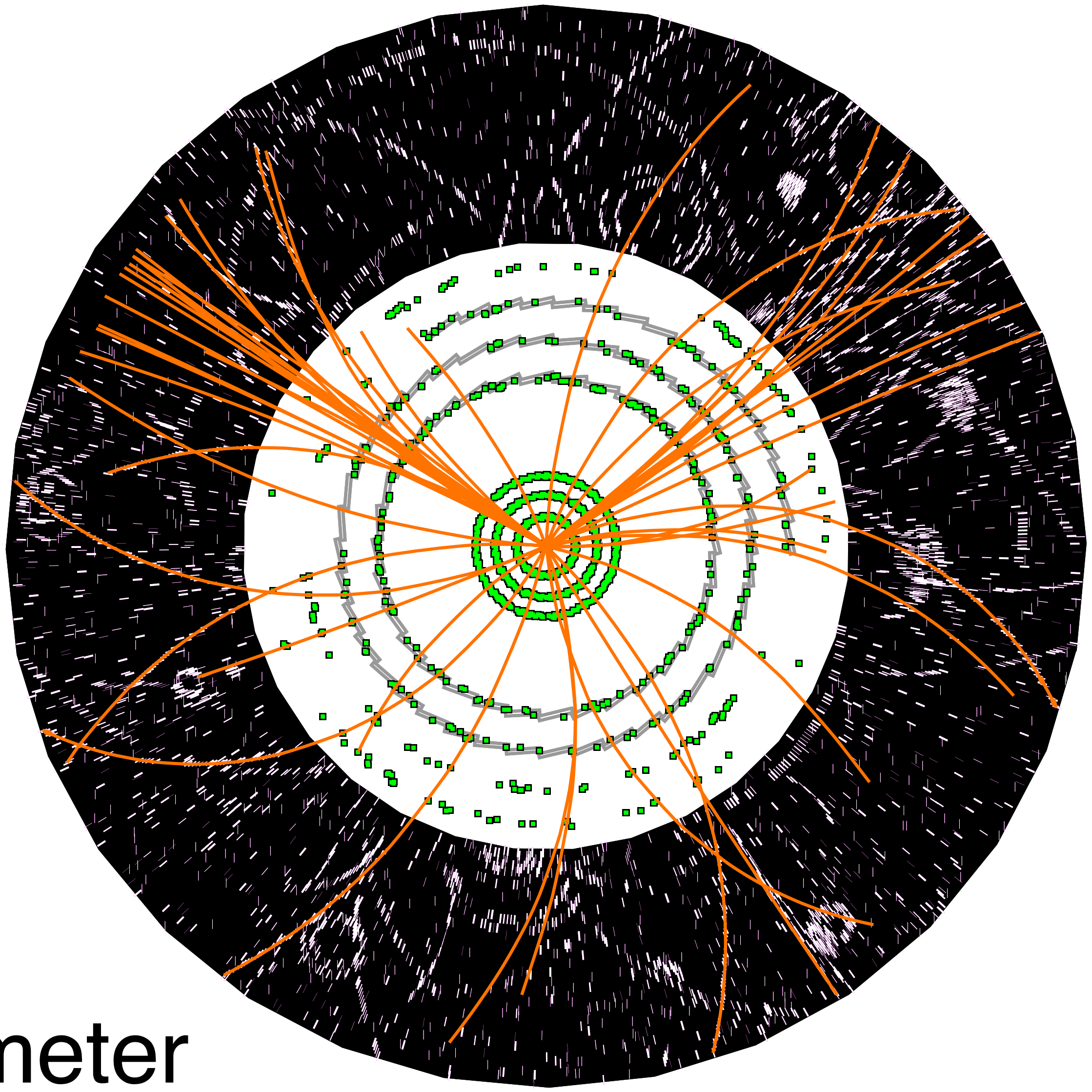
Aside: Tracking



- magnetic spectrometer
  - ➡ charged particle describes a circle of radius **R** in a magnetic field

$$p_T[\mathrm{GeV/c}] = 0.3 \cdot B[\mathrm{T}] \cdot R[\mathrm{m}]$$

Aside: Tracking



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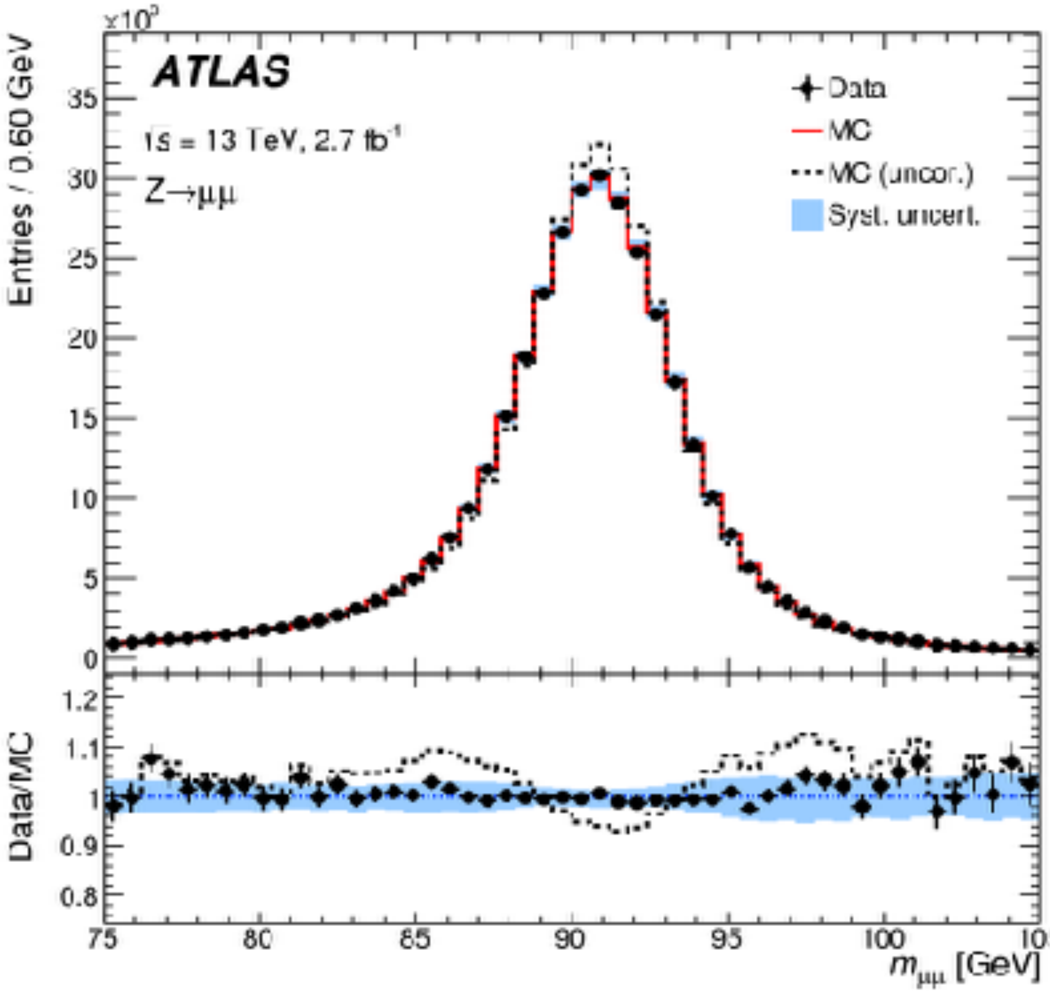
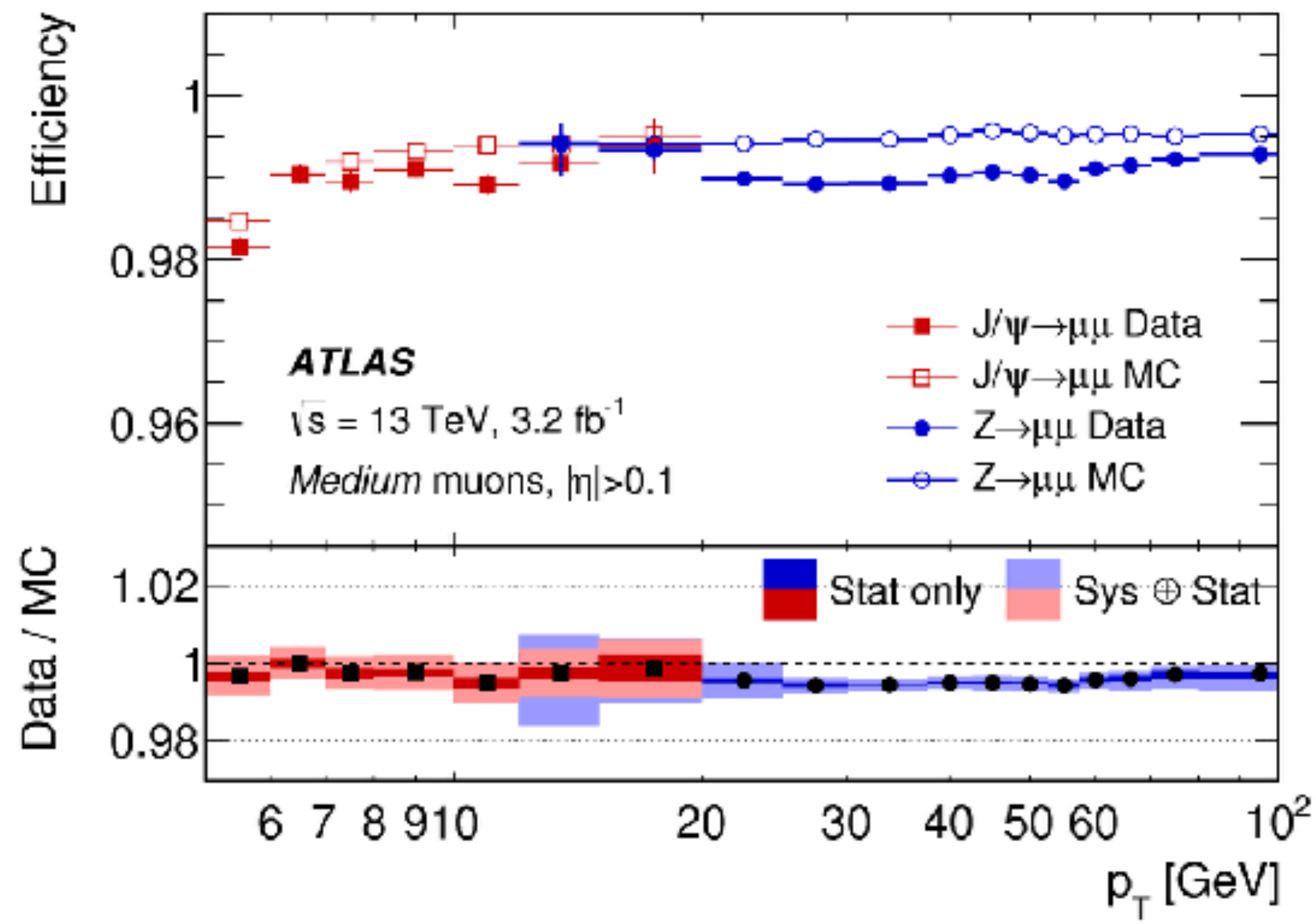
$$p_T[\mathrm{GeV/c}] = 0.3 \cdot B[\mathrm{T}] \cdot R[\mathrm{m}]$$

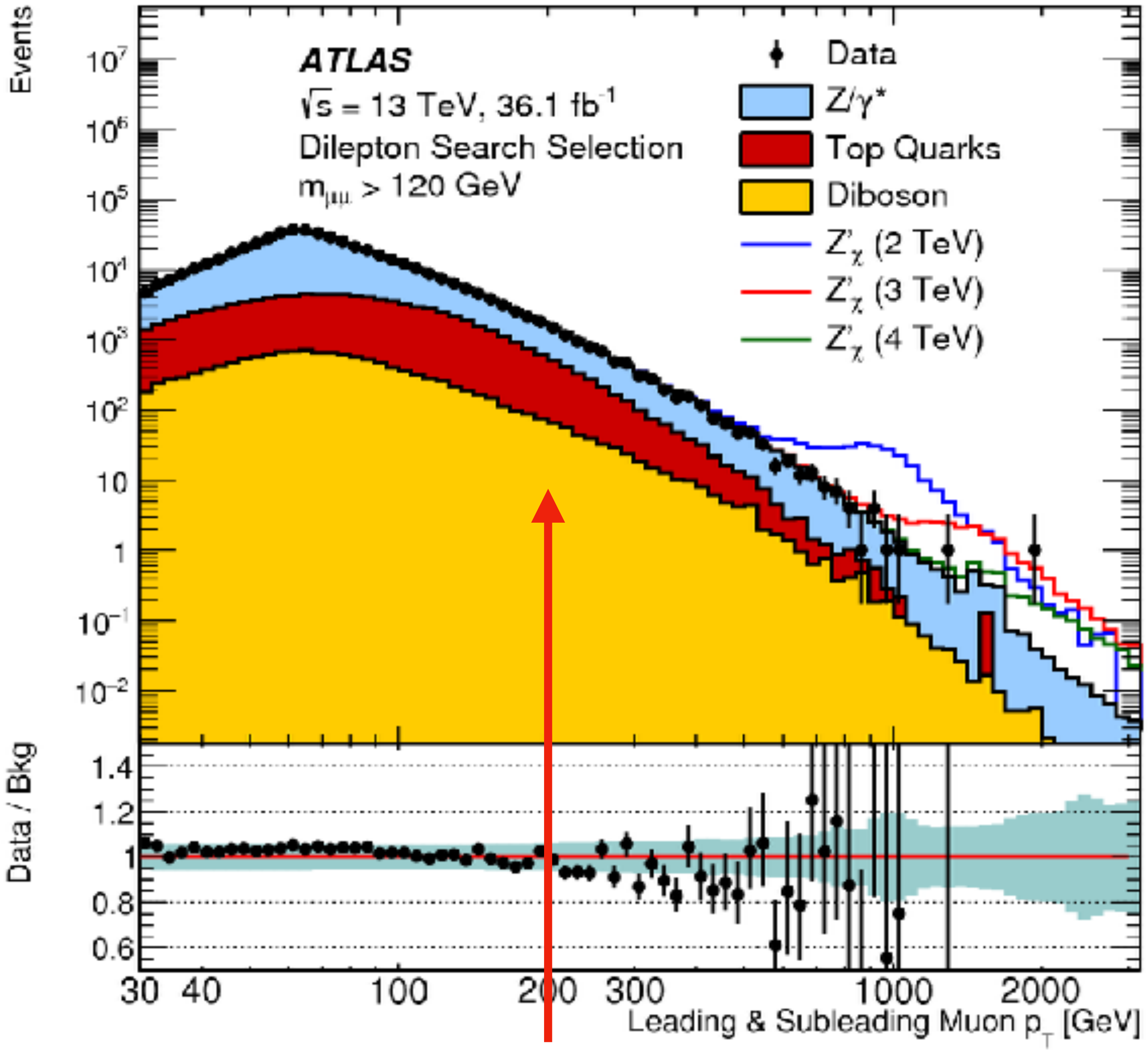
Performance: Muons

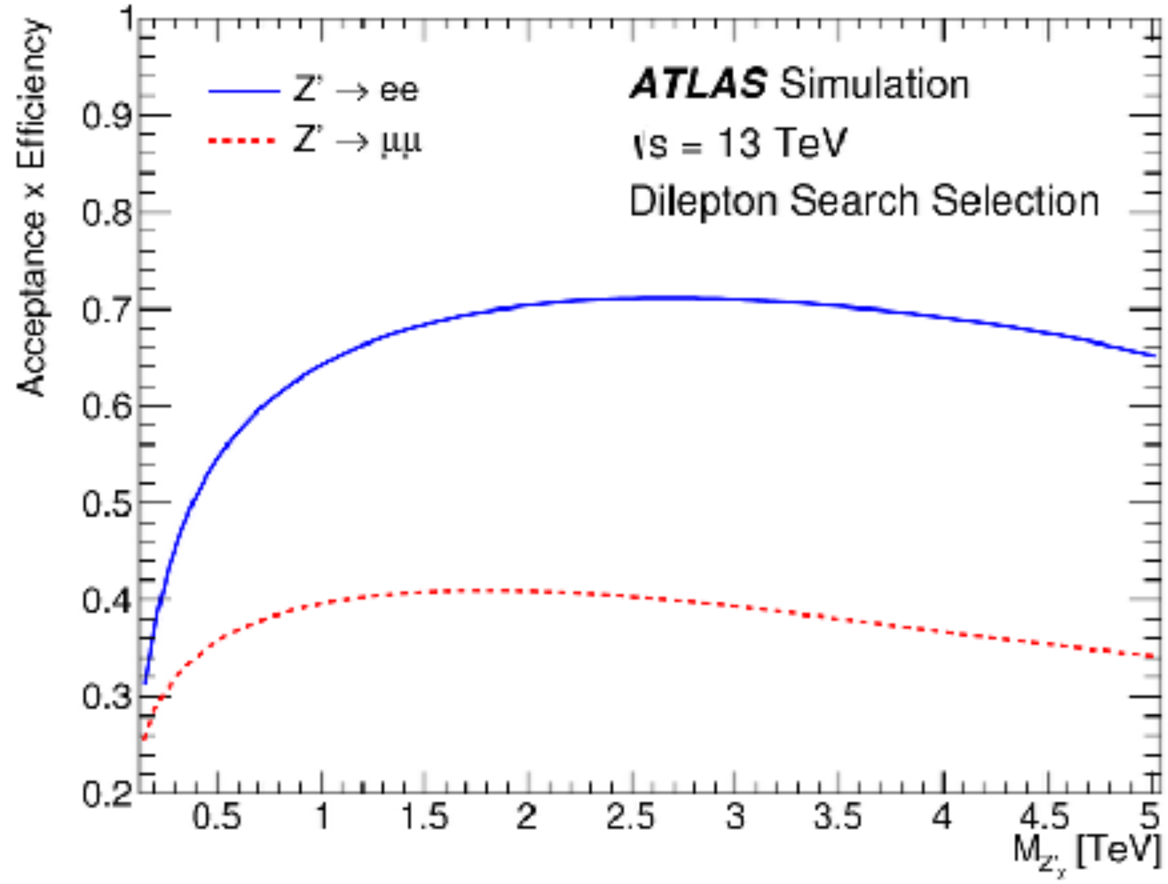




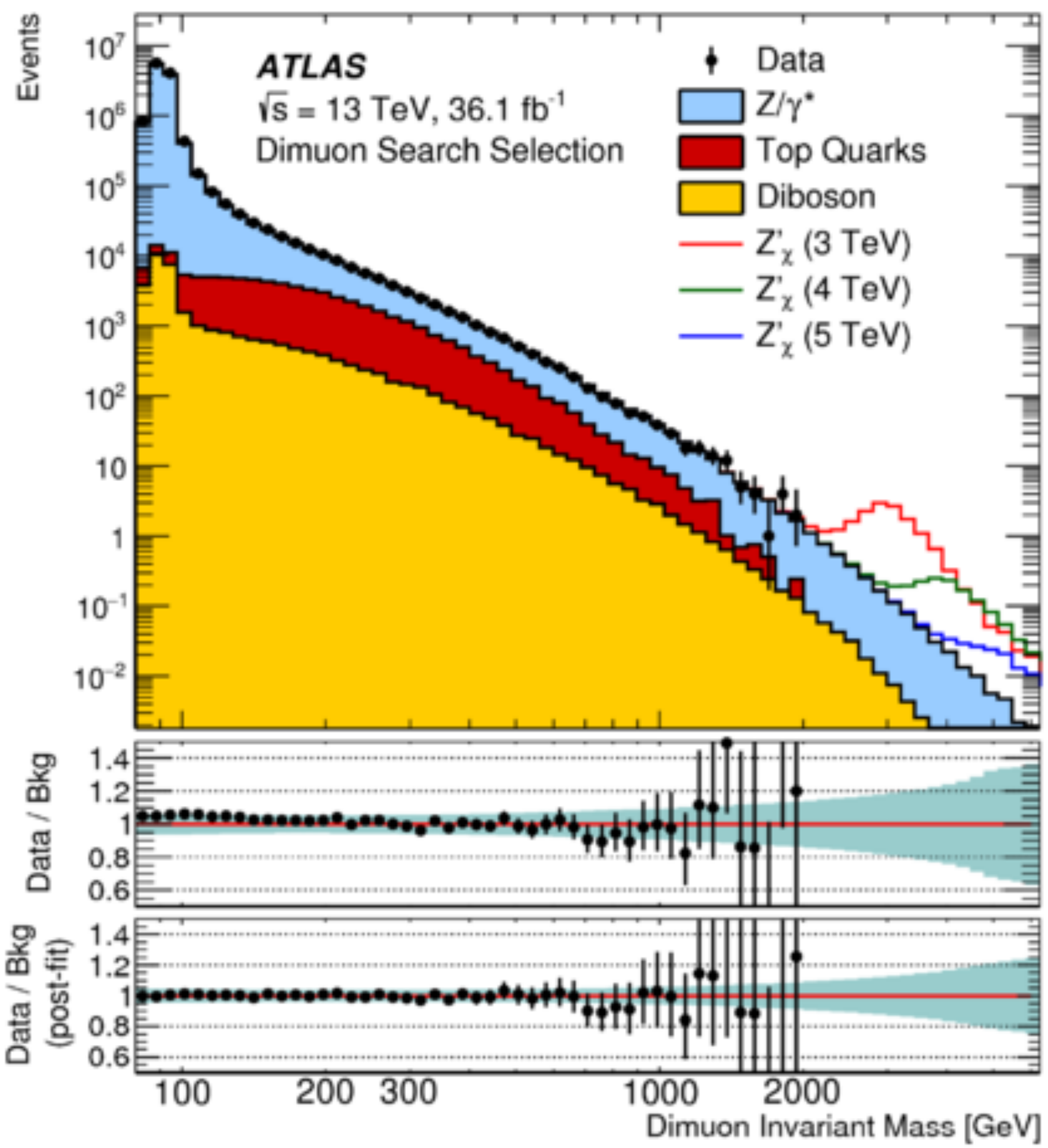
Data/MC comparisons for E_T<200 GeV
Extrapolations of knowledge above

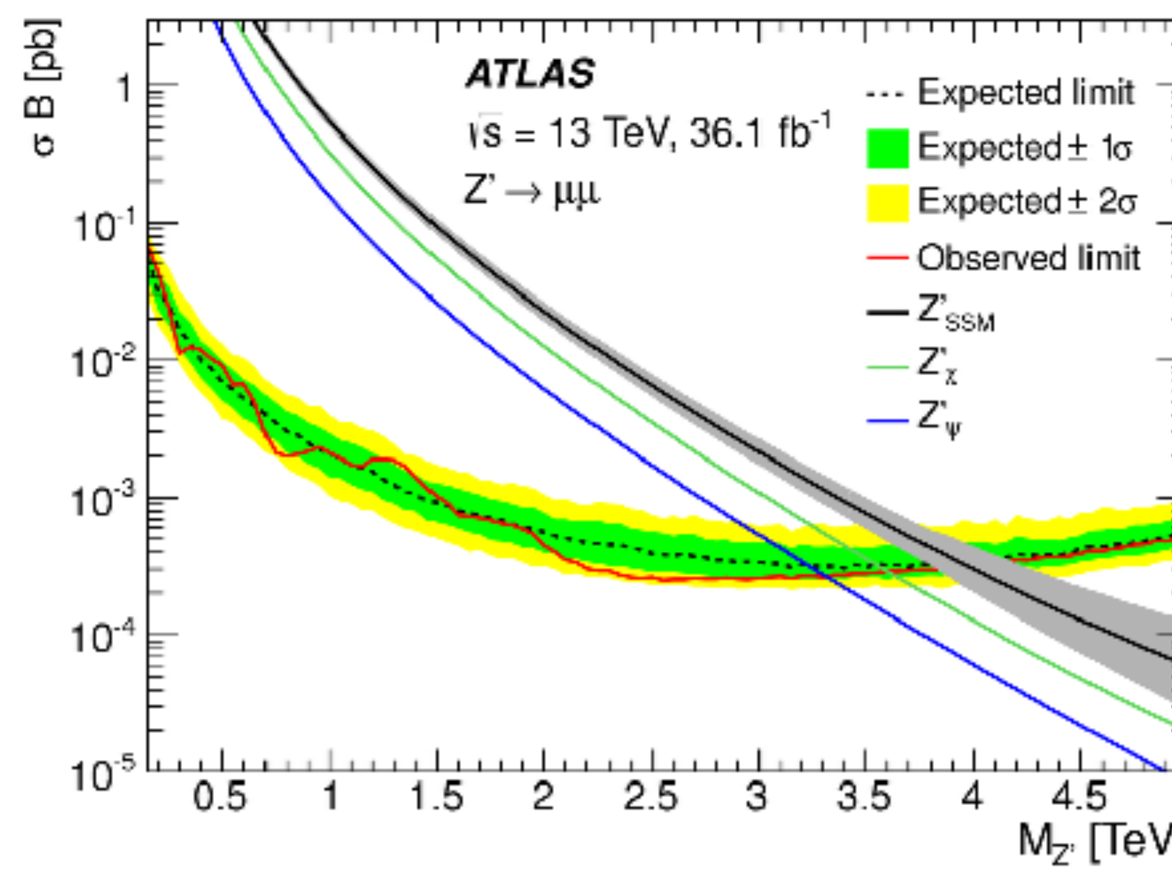
Muons in Search





Dilepton Search

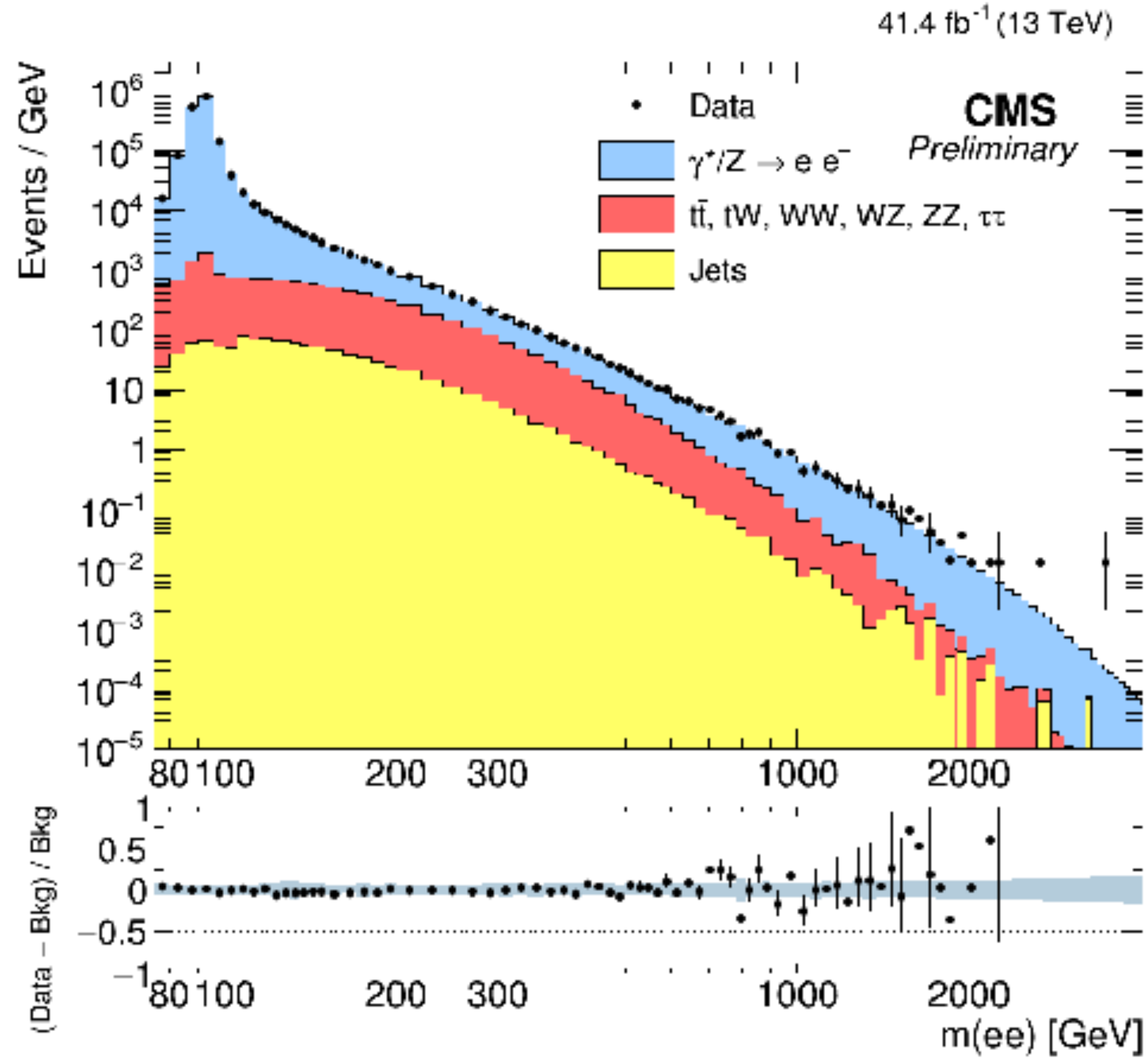




JHEP 10 (2017) 182

Latest Greatest

CMS proves the point of the demonstration of a working detector by releasing 2017 data analysis



Channel	Model	Obs. limit [TeV]	Exp. limit [TeV]
ee (2017)	Z'_{SSM}	4.10	4.15
	Z'_{ψ}	3.35	3.55
ee (2016 and 2017) + $\mu\mu$ (2016)	Z'_{SSM}	4.7	4.7
	Z'_{ψ}	4.1	4.1

Systematics

Source	Dielectron channel		Dimuon channel	
	Signal	Background	Signal	Background
Luminosity	3.2% (3.2%)	3.2% (3.2%)	3.2% (3.2%)	3.2% (3.2%)
MC statistical	<1.0% (<1.0%)	<1.0% (<1.0%)	<1.0% (<1.0%)	<1.0% (<1.0%)
Beam energy	2.0% (4.1%)	2.0% (4.1%)	1.9% (3.1%)	1.9% (3.1%)
Pile-Up effects	<1.0% (<1.0%)	<1.0% (<1.0%)	<1.0% (<1.0%)	<1.0% (<1.0%)
DY PDF choice	N/A	<1.0% (8.4%)	N/A	<1.0% (1.9%)
DY PDF variation	N/A	8.7% (19%)	N/A	7.7% (13%)
DY PDF scale	N/A	1.0% (2.0%)	N/A	<1.0% (1.5%)
DY α_S	N/A	1.6% (2.7%)	N/A	1.4% (2.2%)
DY EW corrections	N/A	2.4% (5.5%)	N/A	2.1% (3.9%)
DY γ-induced corrections	N/A	3.4% (7.6%)	N/A	3.0% (5.4%)
Top Quarks theoretical	N/A	<1.0% (<1.0%)	N/A	<1.0% (<1.0%)
Dibosons theoretical	N/A	<1.0% (<1.0%)	N/A	<1.0% (<1.0%)
Reconstruction efficiency	<1.0% (<1.0%)	<1.0% (<1.0%)	10% (17%)	10% (17%)
Isolation efficiency	9.1% (9.7%)	9.1% (9.7%)	1.8% (2.0%)	1.8% (2.0%)
Trigger efficiency	<1.0% (<1.0%)	<1.0% (<1.0%)	<1.0% (<1.0%)	<1.0% (<1.0%)
Identification efficiency	2.6% (2.4%)	2.6% (2.4%)	N/A	N/A
Lepton energy scale	<1.0% (<1.0%)	4.1% (6.1%)	<1.0% (<1.0%)	<1.0% (<1.0%)
Lepton energy resolution	<1.0% (<1.0%)	<1.0% (<1.0%)	2.7% (2.7%)	<1.0% (6.7%)
Multi-jet & W+jets	N/A	10% (129%)	N/A	N/A
Total	10% (11%)	18% (132%)	11% (18%)	14% (24%)

Largest theory uncertainty.

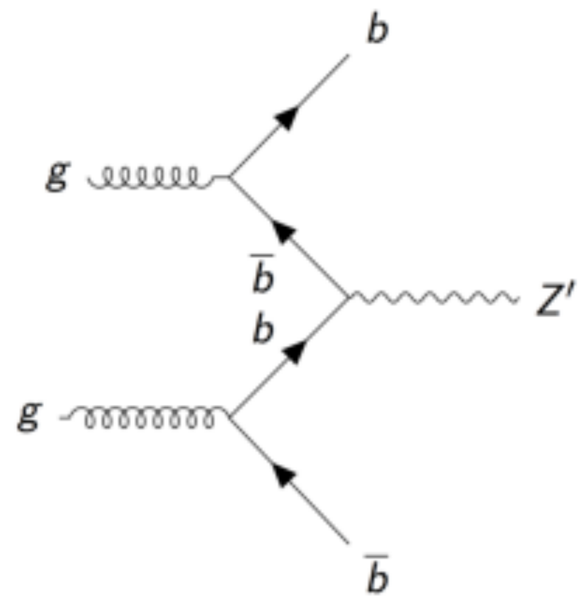
Largest exp uncertainty.

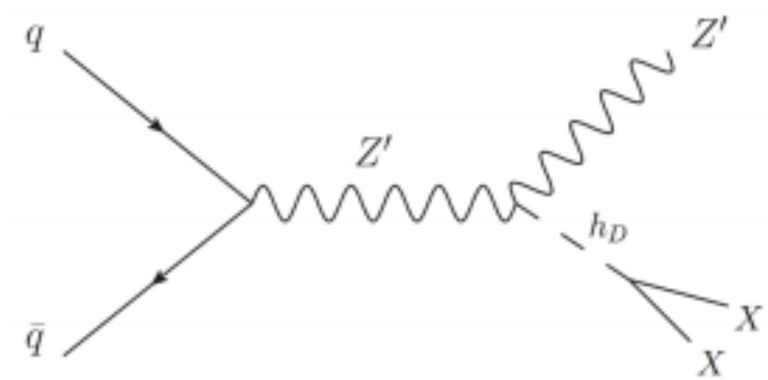
Large uncertainty at high masses due to extrapolation.

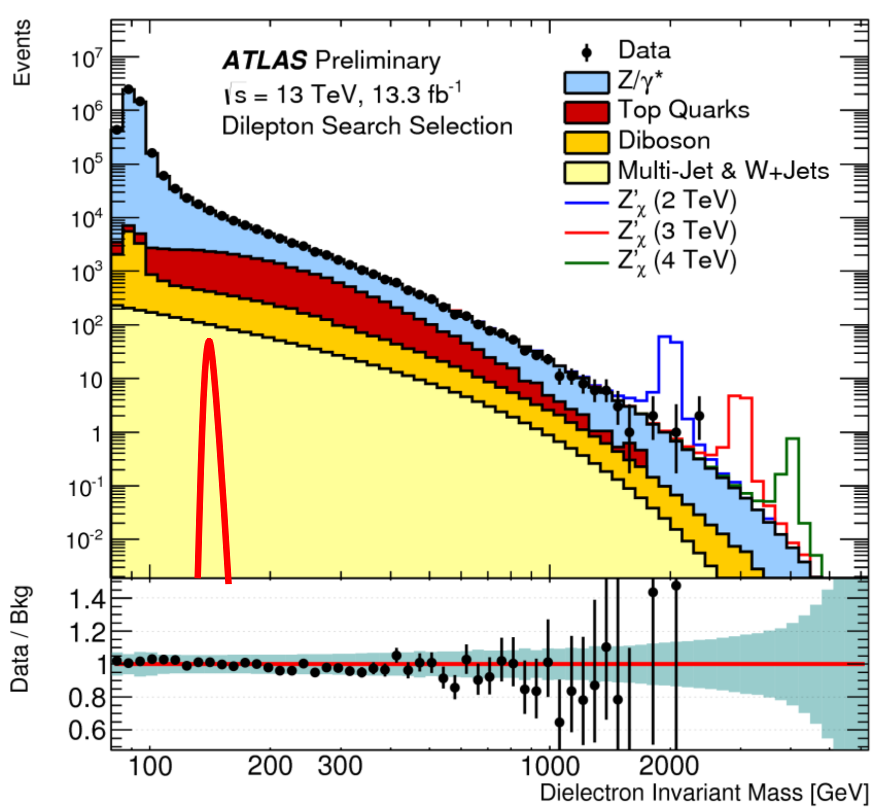
Background and signal systematic uncertainties at dilepton masses of 2 TeV (4 TeV).

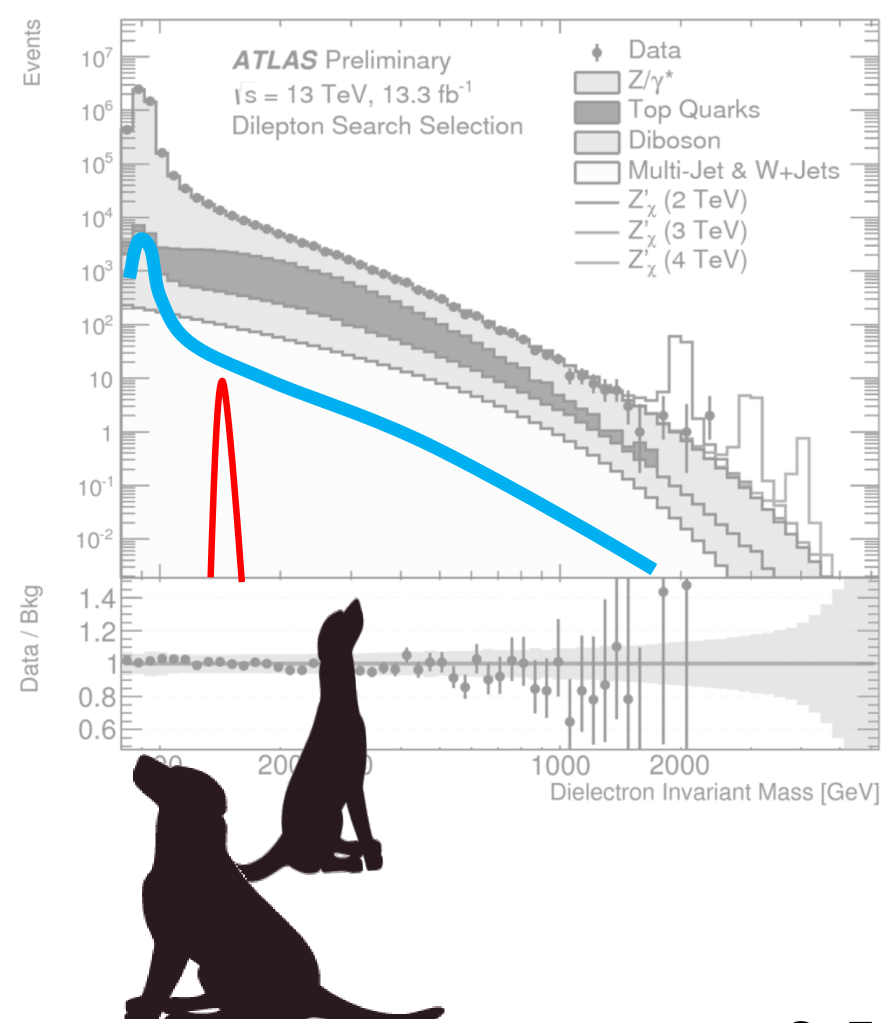
Dileptons: What's Next?

We do not know what new physics will look like!







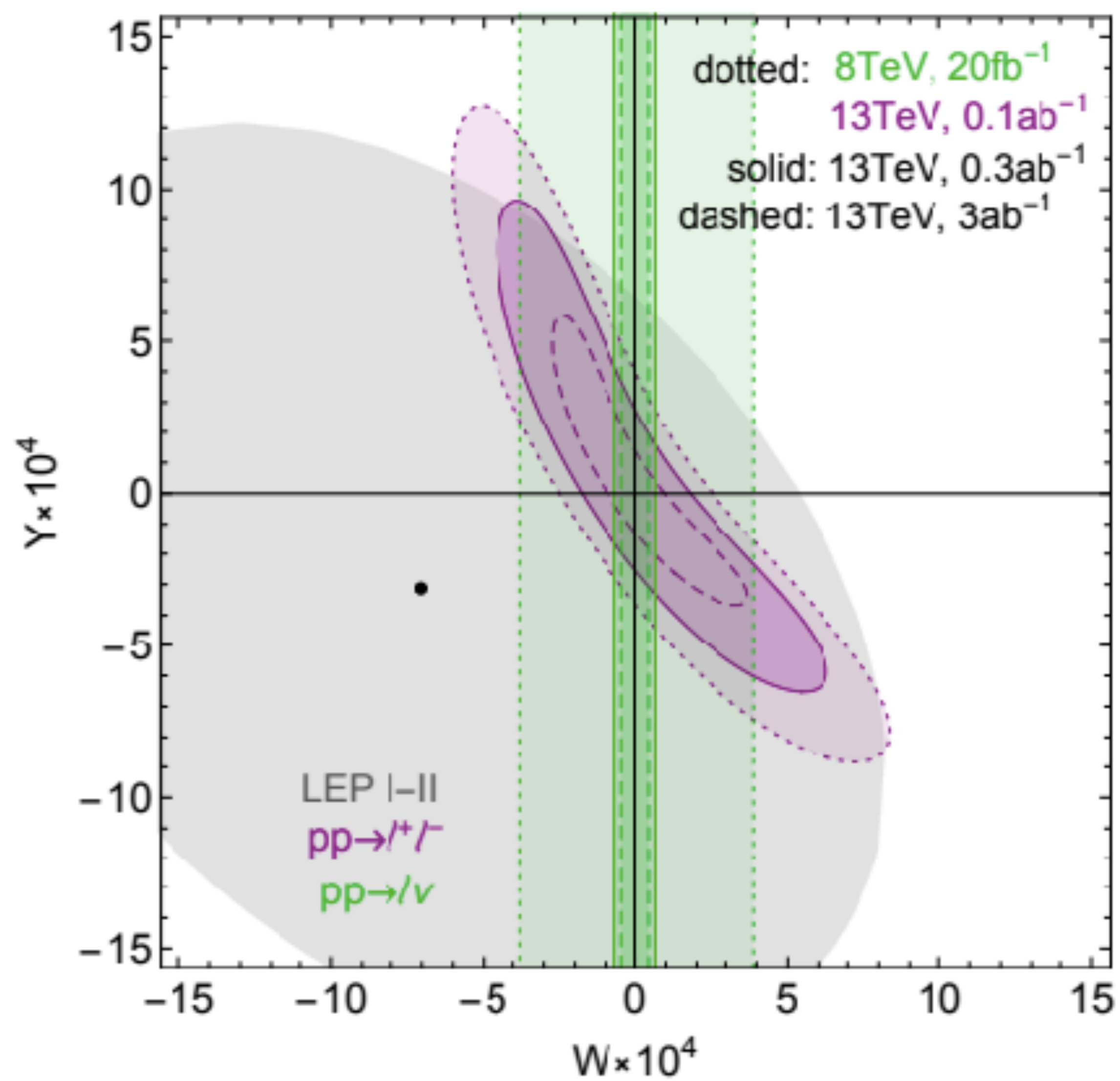


[Matt Strassler's Motivation]

Dileptons: What's Next?

Measurements

- The new physics we are looking for could be out of reach of the LHC
- Employ Effective Field Theories (EFTs) to parameterize the new physics effects when E << M
- In some variables, the BSM effects scale like $(E/M)^n$. For n>0 we can profit from the large center of mass energy

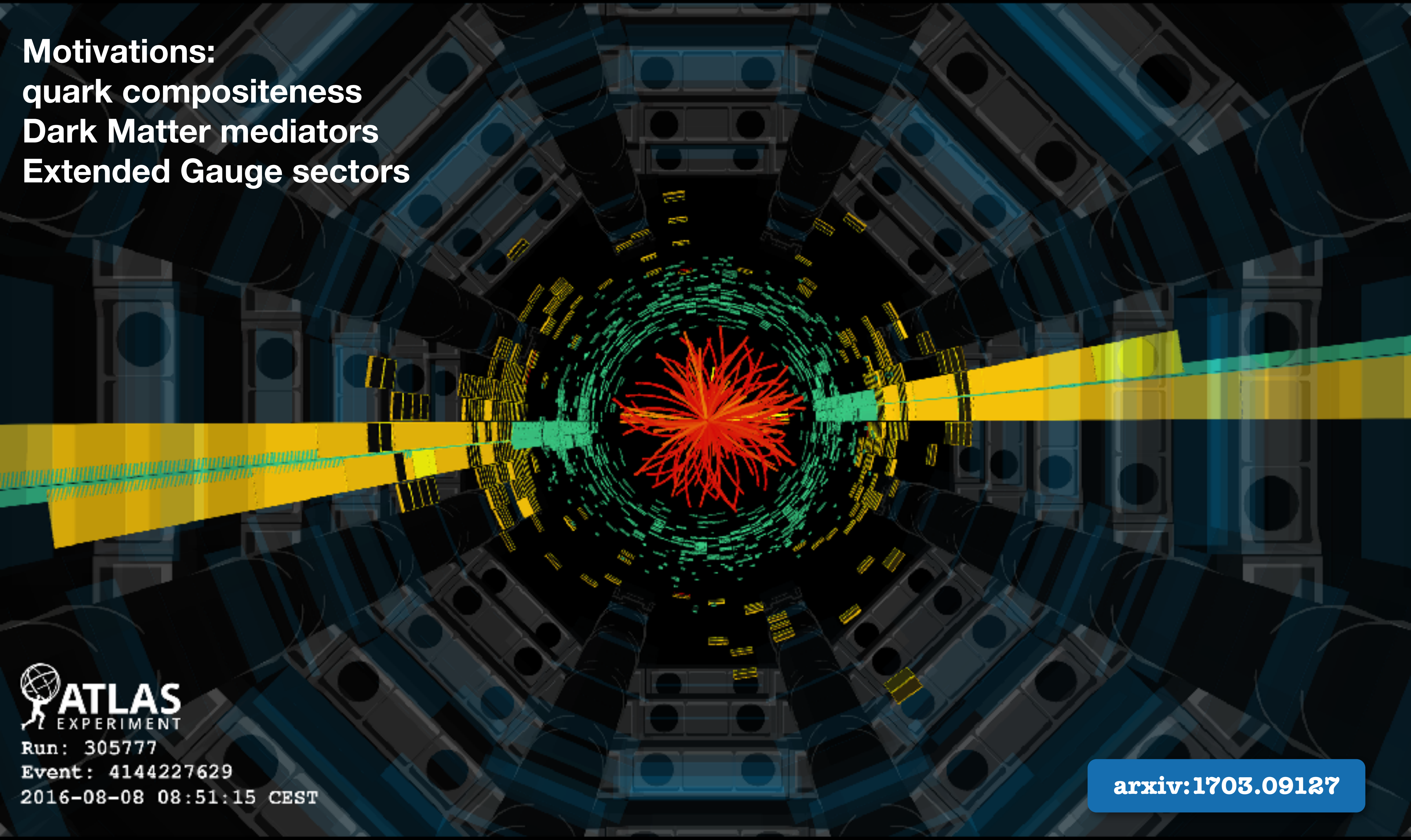


arXiv:1609.08157

$\hat{S}$, $\hat{T}$, W, and Y modify the γ, Z, and W propagators. The effects of $\hat{S}$ and $\hat{T}$ on DY processes do not grow with energy, W and Y do!

High Mass Di-Jet Search

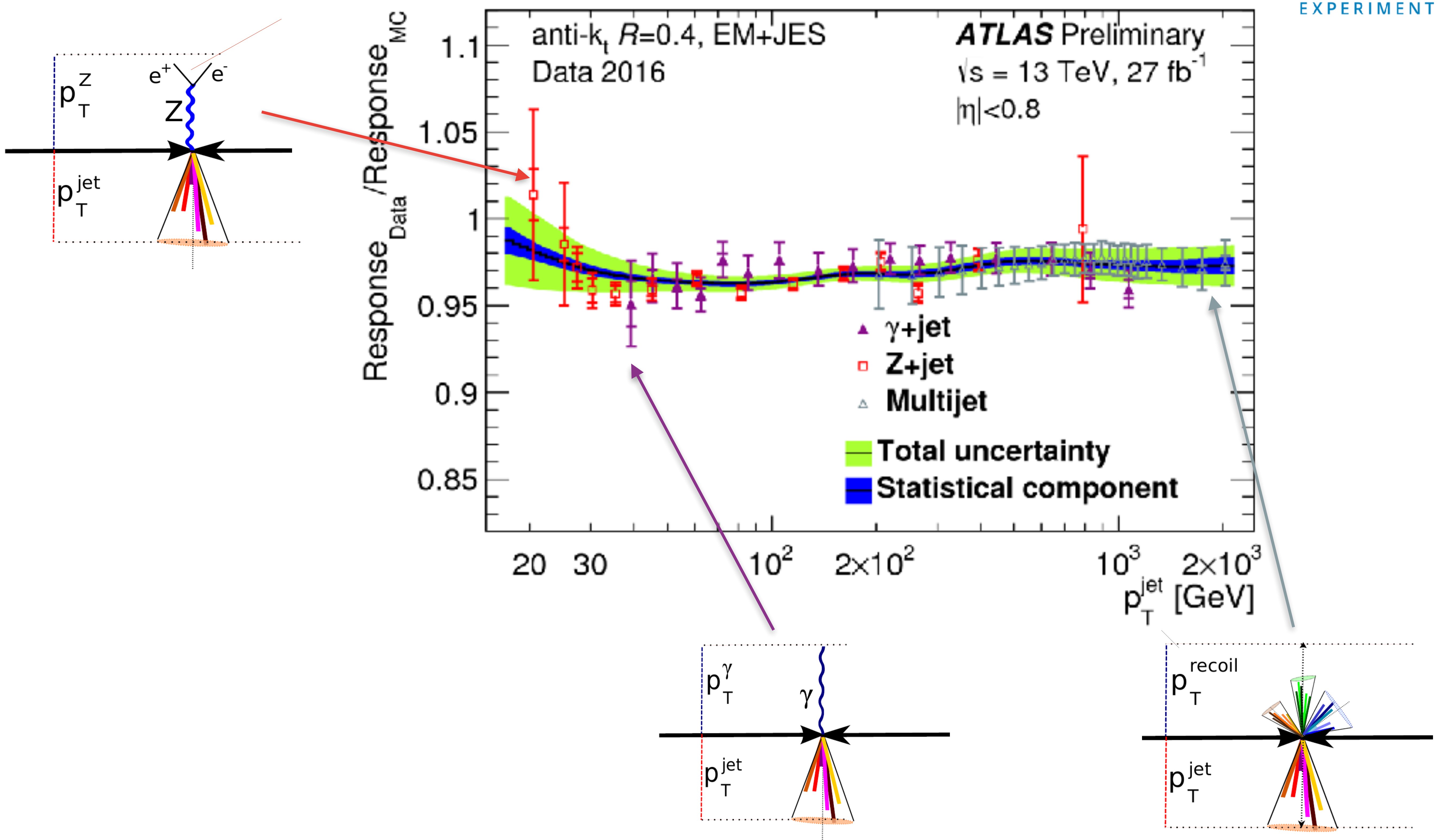
Motivations:
quark compositeness
Dark Matter mediators
Extended Gauge sectors



arxiv:1703.09127

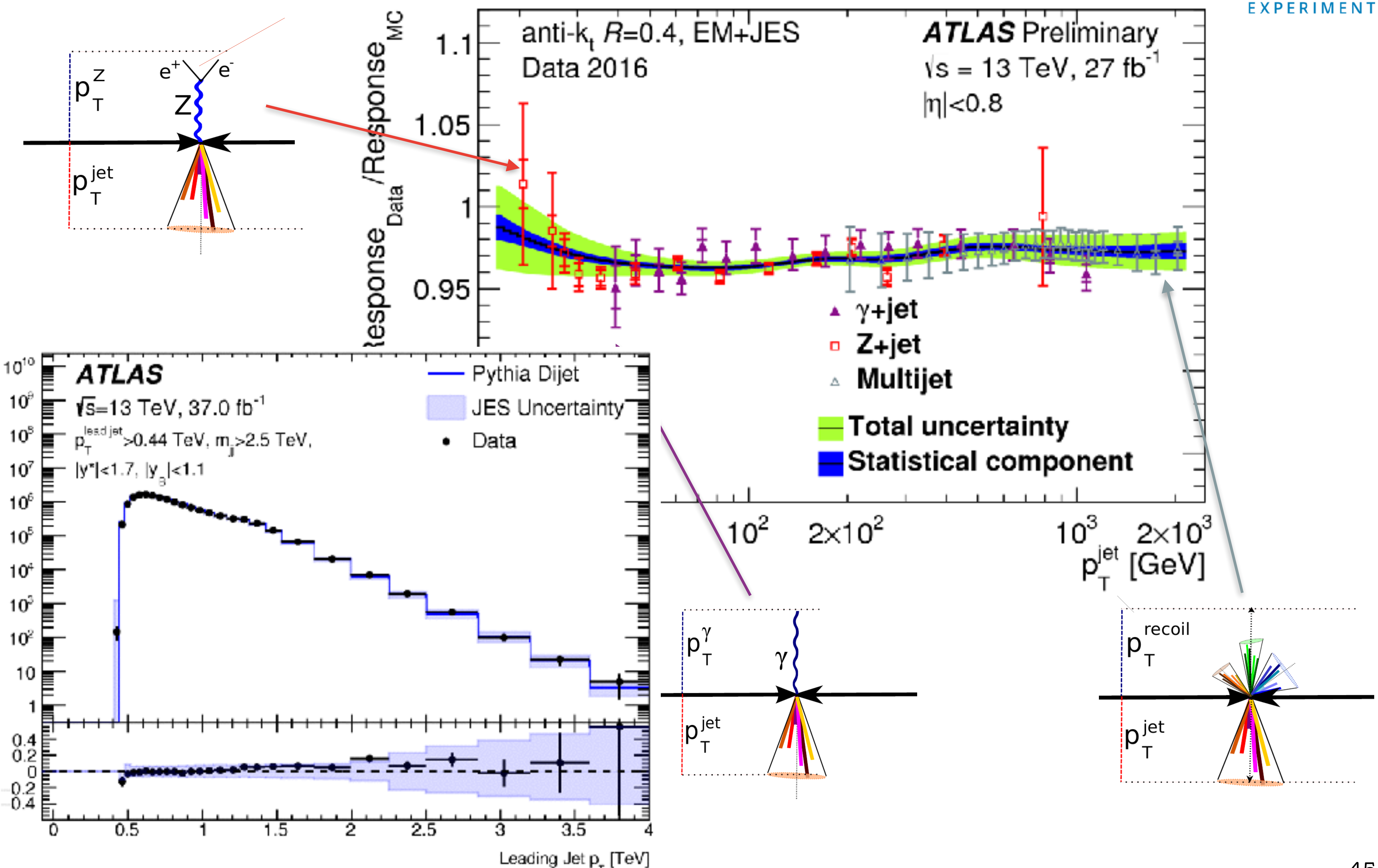
Highest-mass dijet event: m_{jj} = 8.12 TeV, $|y^*|$=0.38

Performance: Jets



cartoons from C. Doglioni

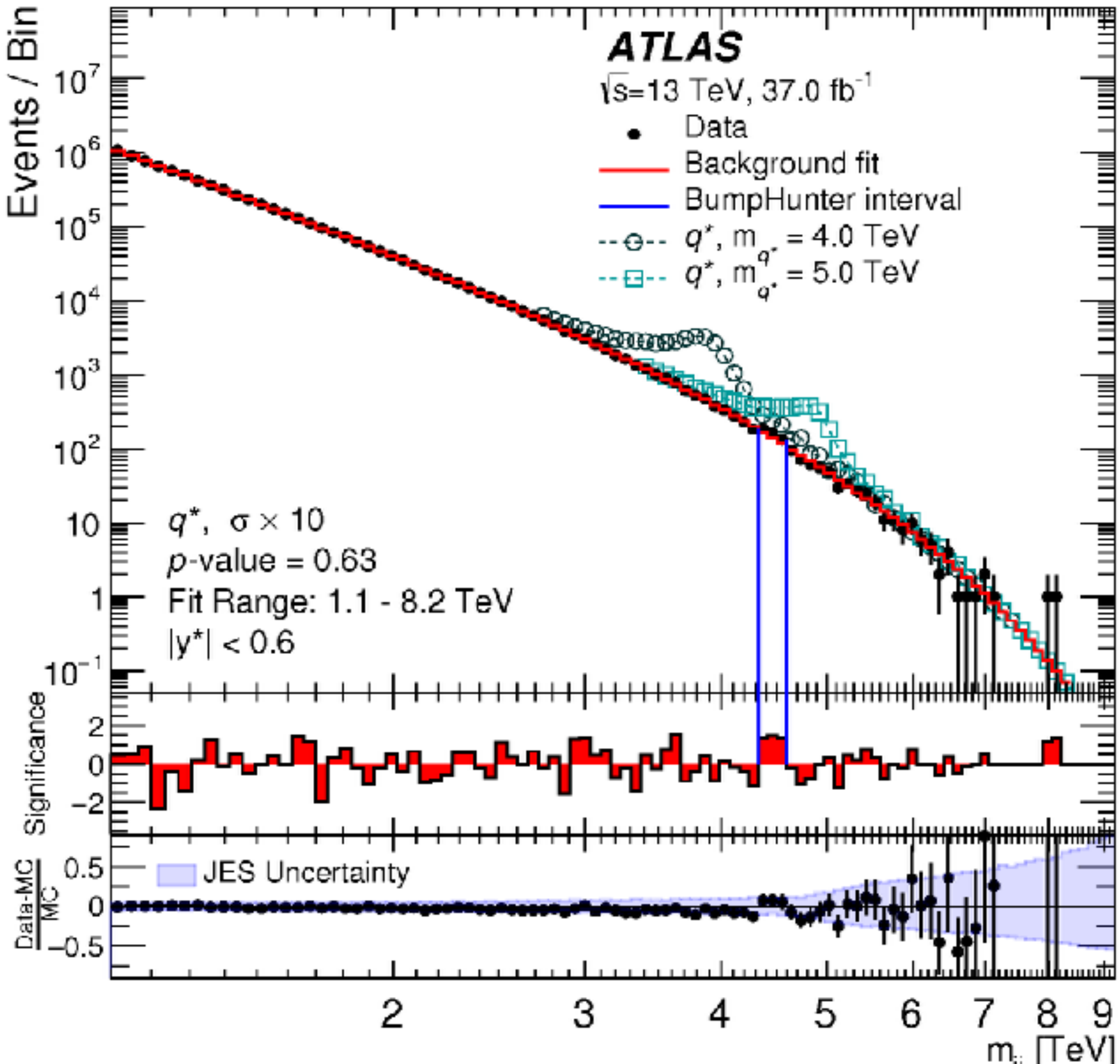
Performance: Jets



G. Facini, DESY Seminar

arxiv:1703.09127

High Mass Dijets



Leading jet pT > 0.44 TeV
2nd jet pT > 0.06 TeV
$|y^*|<0.6$

$|y^*| = |y_1-y_2|/2$

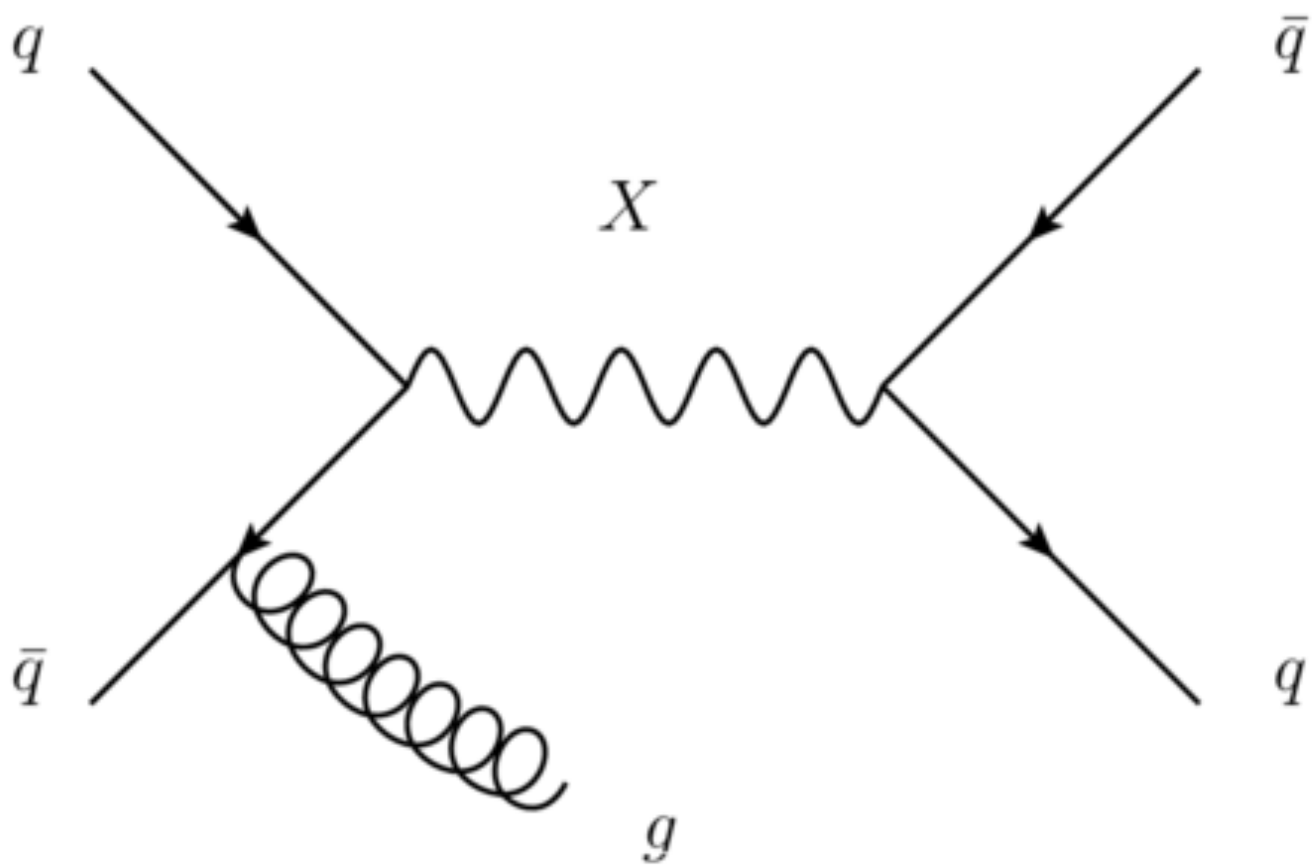
Rejects forward peaking t-channel QCD processes.

$$f(z) = p_1(1-z)^{p_2} z^{p_3} z^{p_4 \log z}$$

What next??

Low Mass Dijets

- Cannot save all LHC collisions so dijet searches were limited to have one jet with pT > 440 GeV —> m(X) > 1 TeV
- Employ the initial state radiation to go below 1 TeV

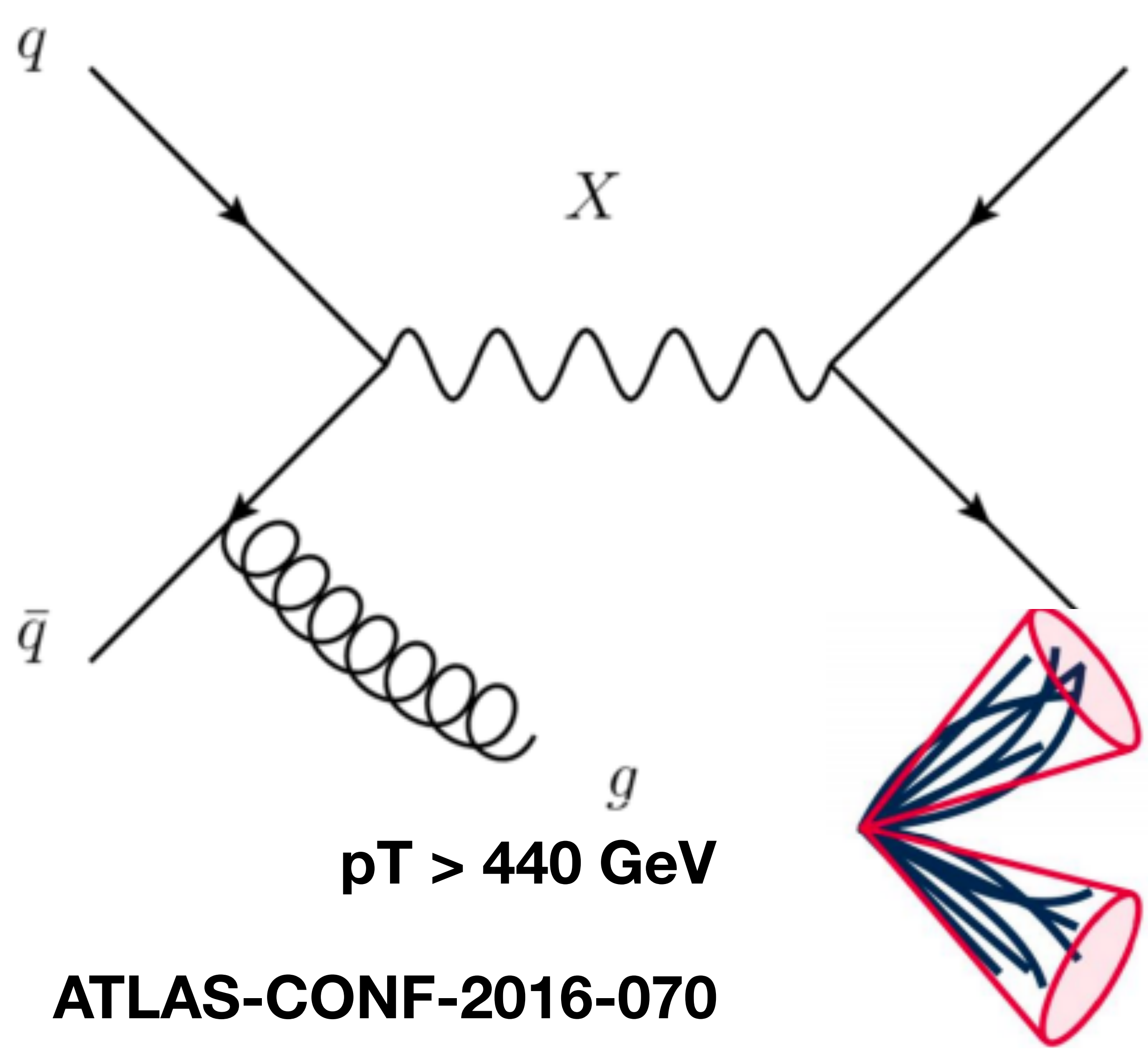


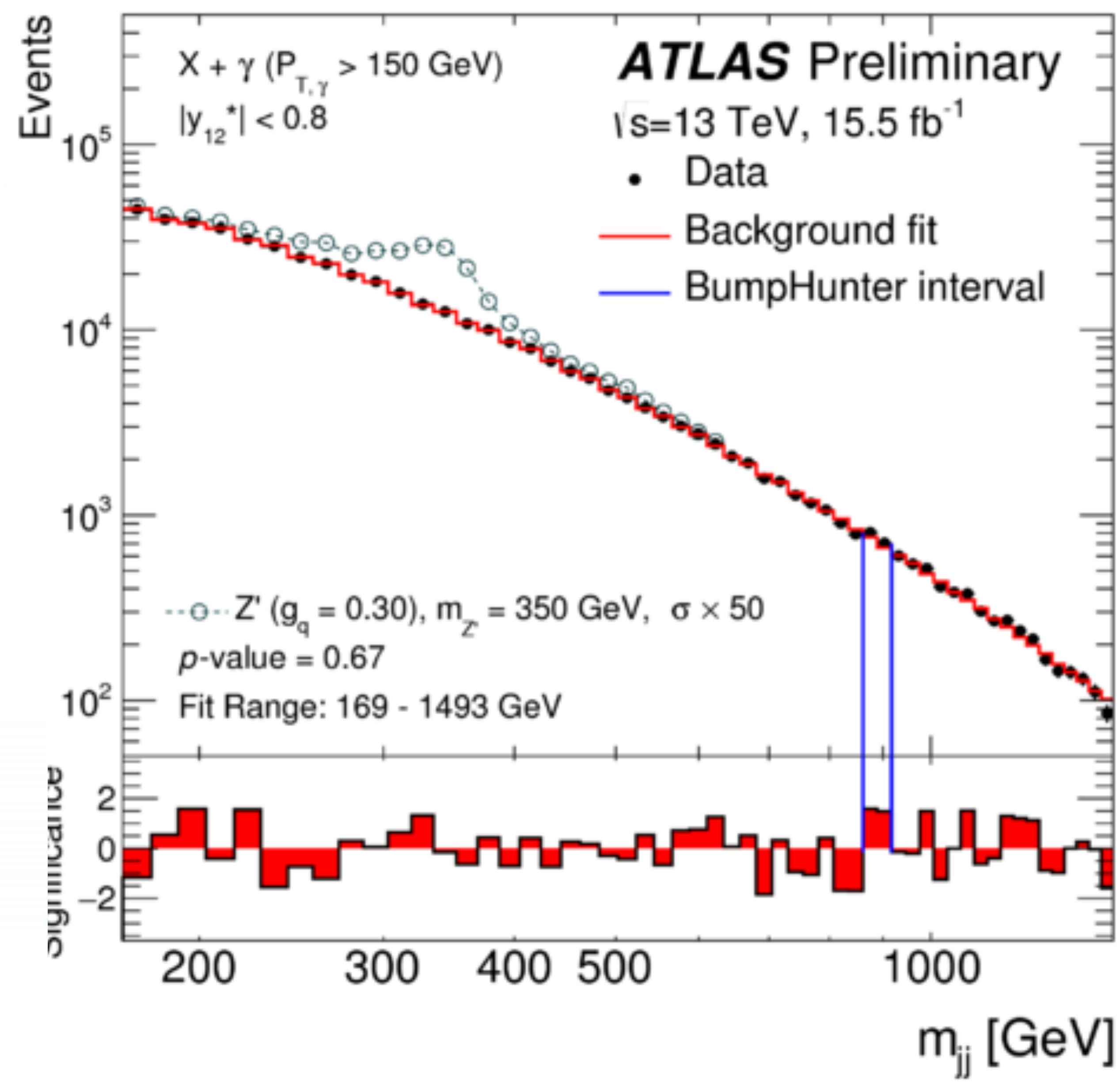
if pT > 440 GeV

opens 200 GeV < m(X) < 1 TeV

Low Mass Dijets

- Cannot save all LHC collisions so dijet searches were limited to have one jet with pT > 440 GeV —> m(X) > 1 TeV
- Employ the initial state radiation to go below 1 TeV

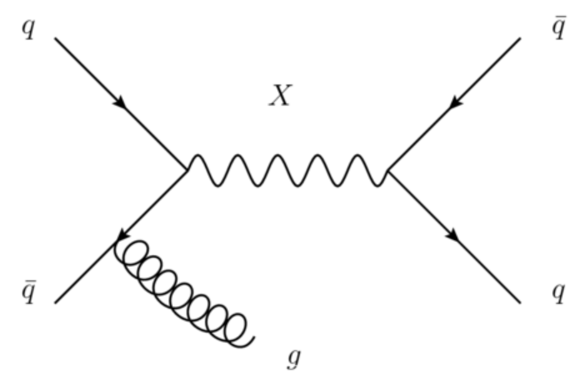


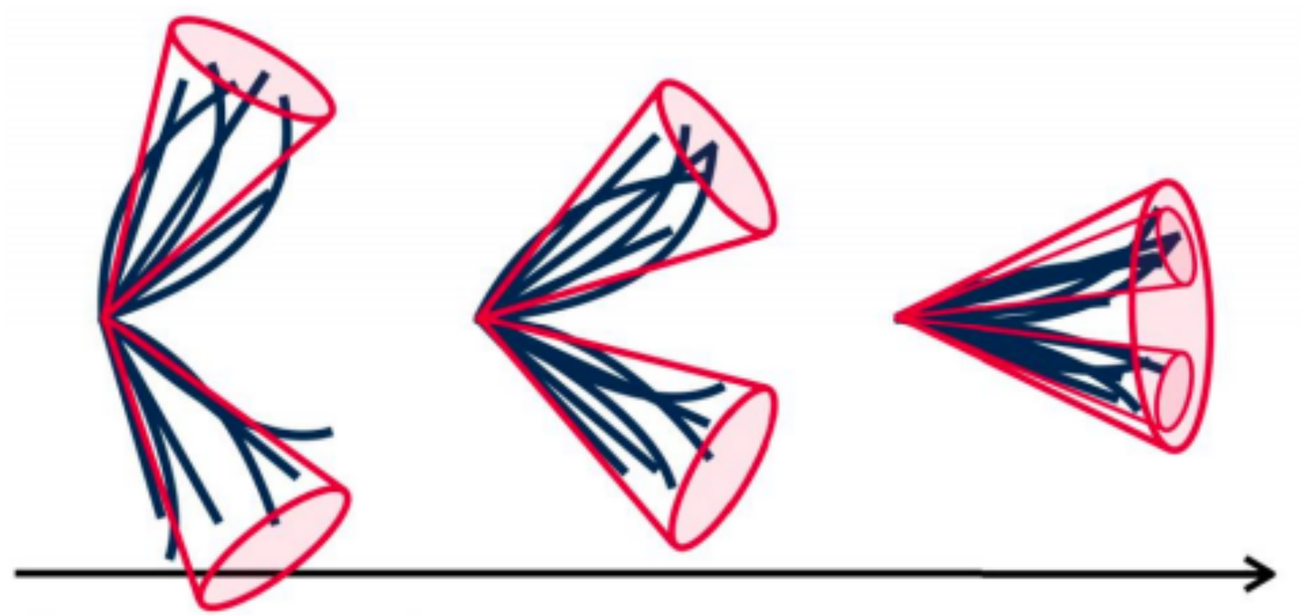


ATLAS-CONF-2016-070

Low Mass Dijets

- Employ the initial state radiation to go below 1 TeV
- With the same selection, looking at a lower mass necessitates a difference reconstruction technique





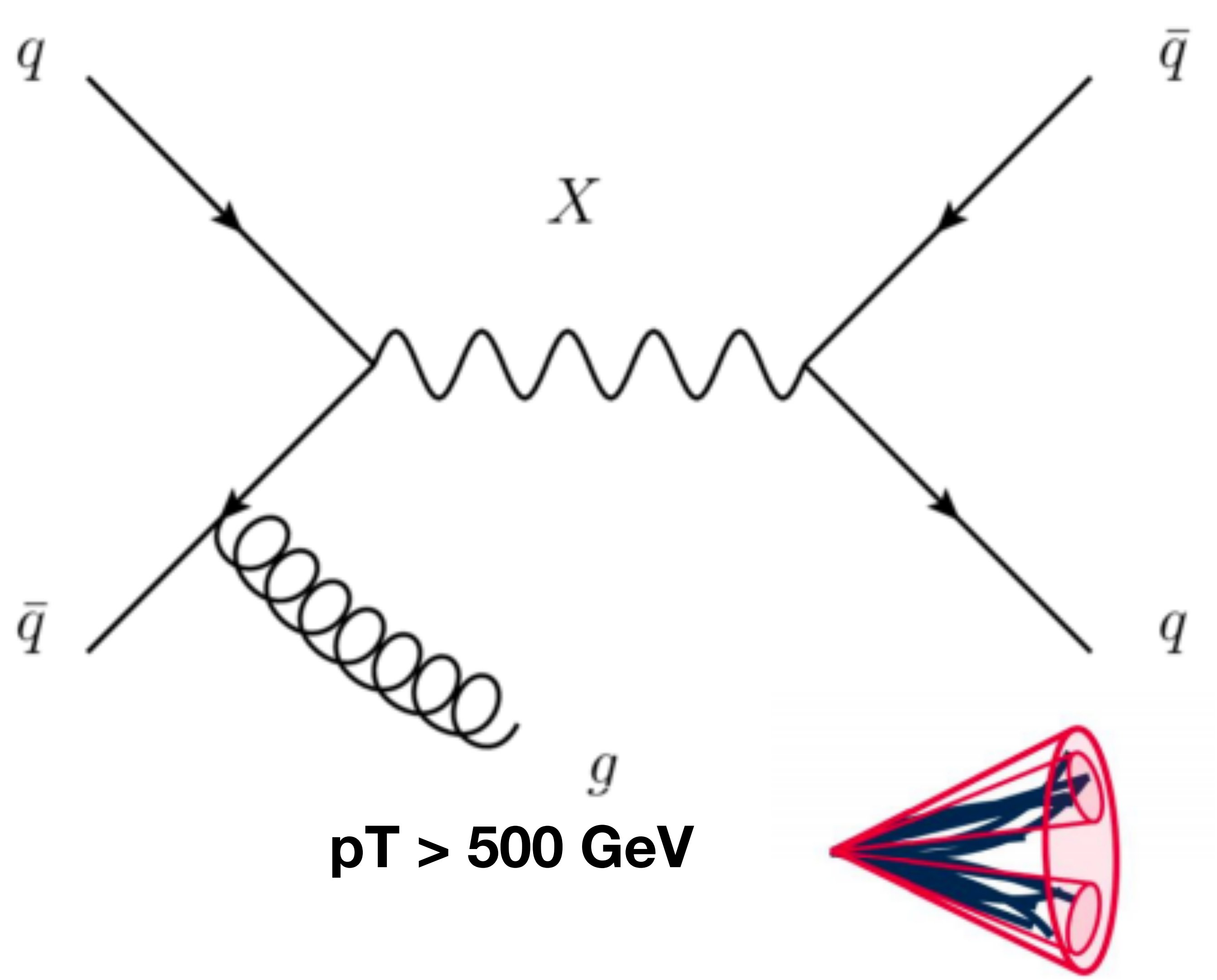
R = 2m/p_T

Boosted jet: Increasing transverse momentum

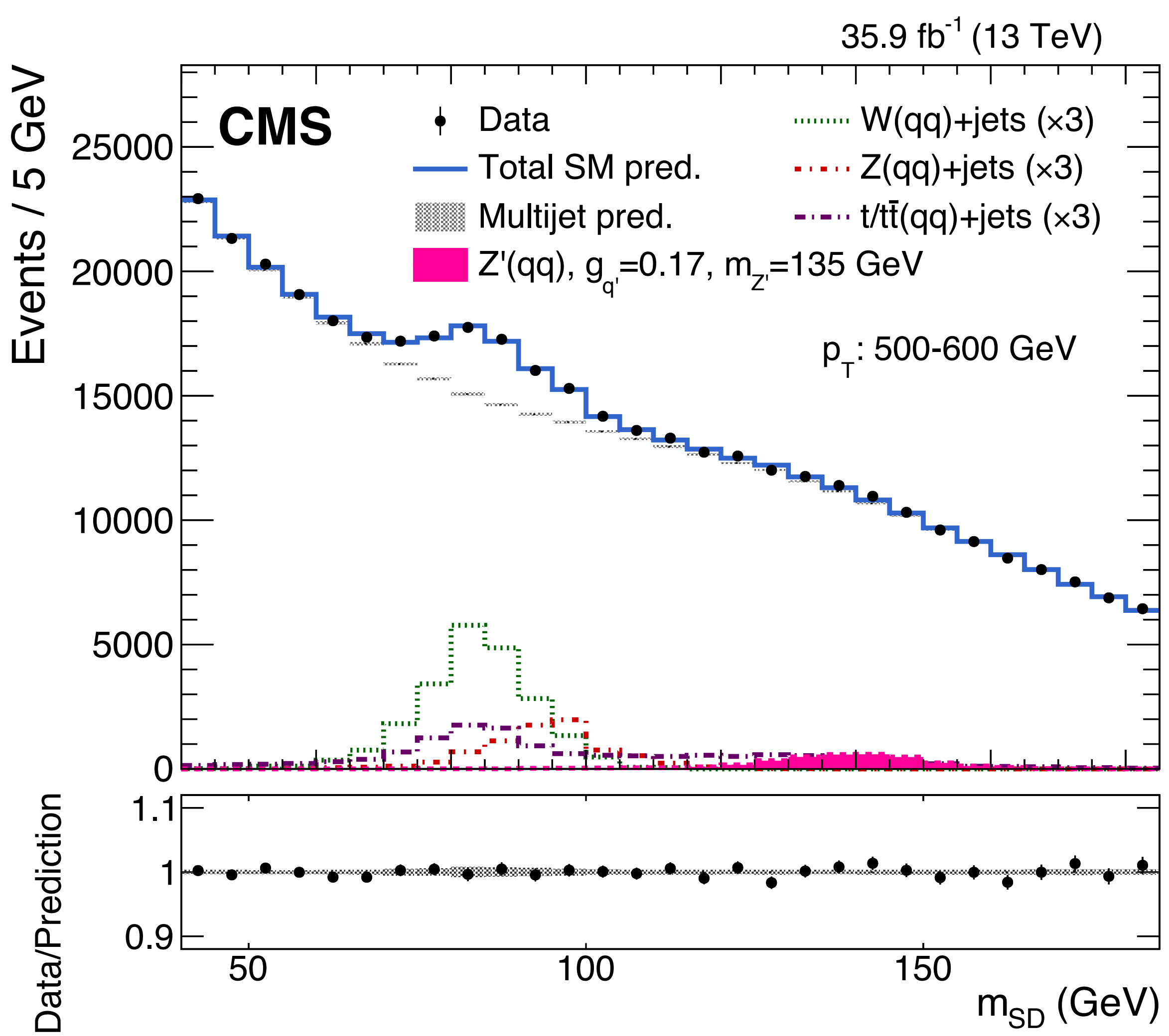
Boosted jet: Same momentum, decrease object mass!

Low Mass Dijets

- With the trick CMS introduced, we can now search from the Z-peak to the highest jet energies that the LHC can produce



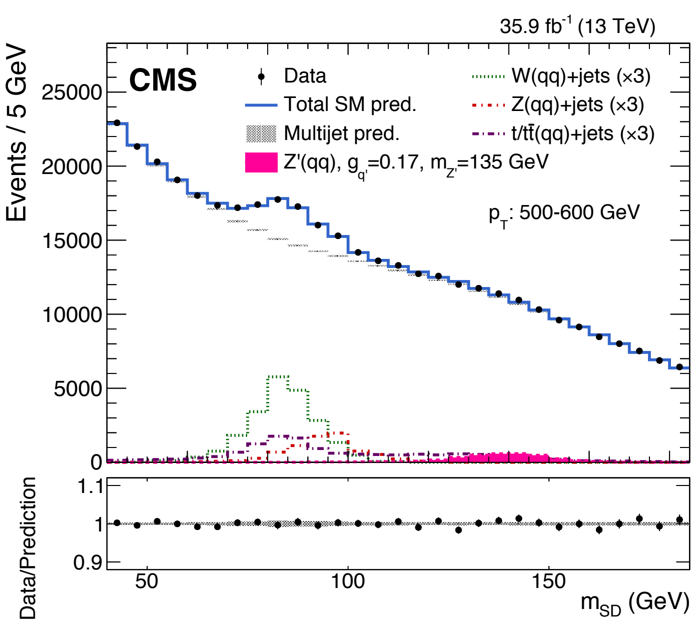
pT > 500 GeV

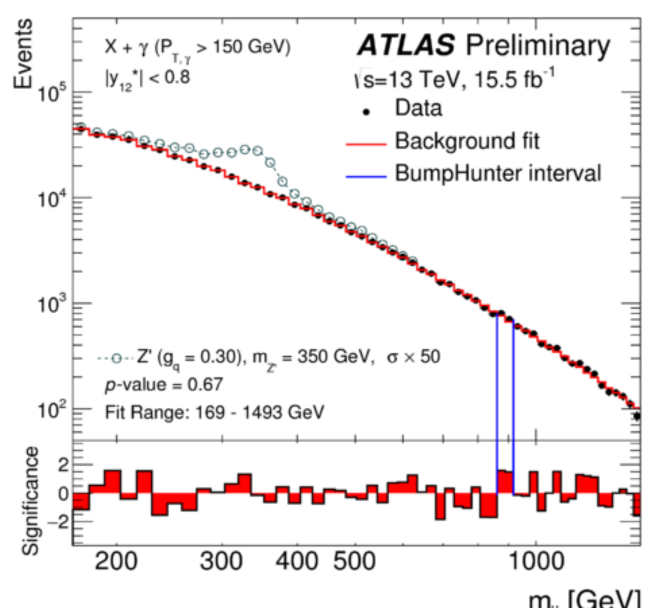


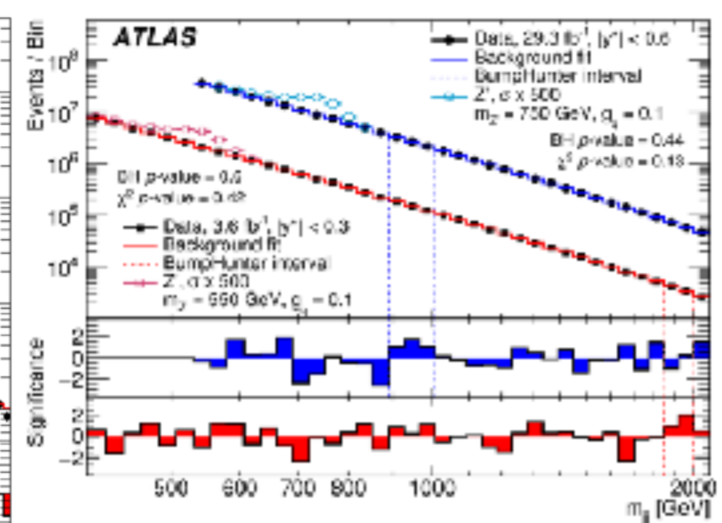
arXiv:1710.00159

The Full Range

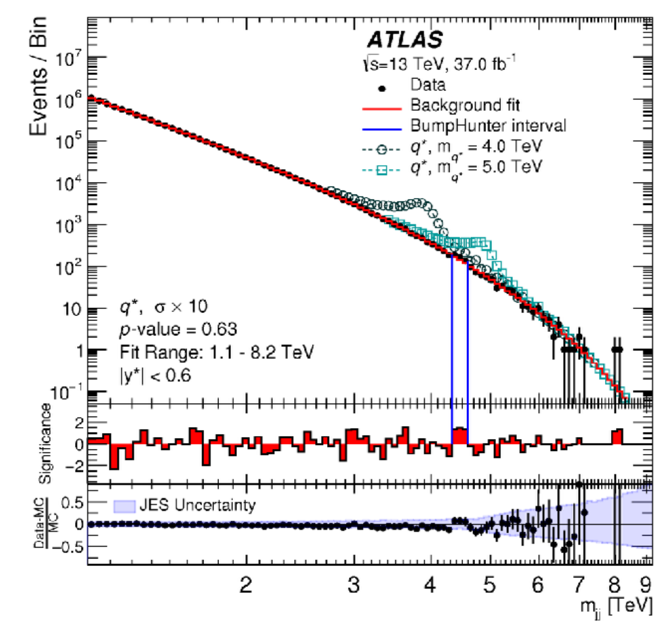
- The full dijet mass range is covered!
- What about b-quarks?

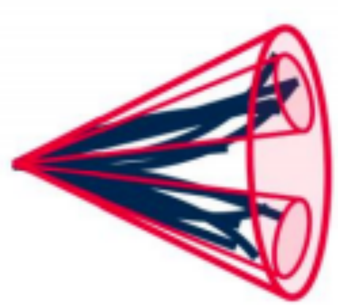


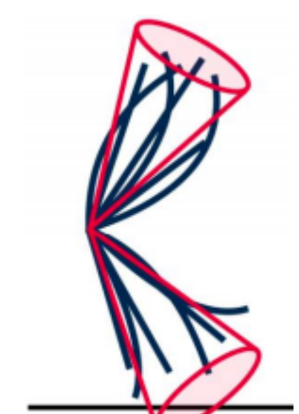




arXiv:1804.03496





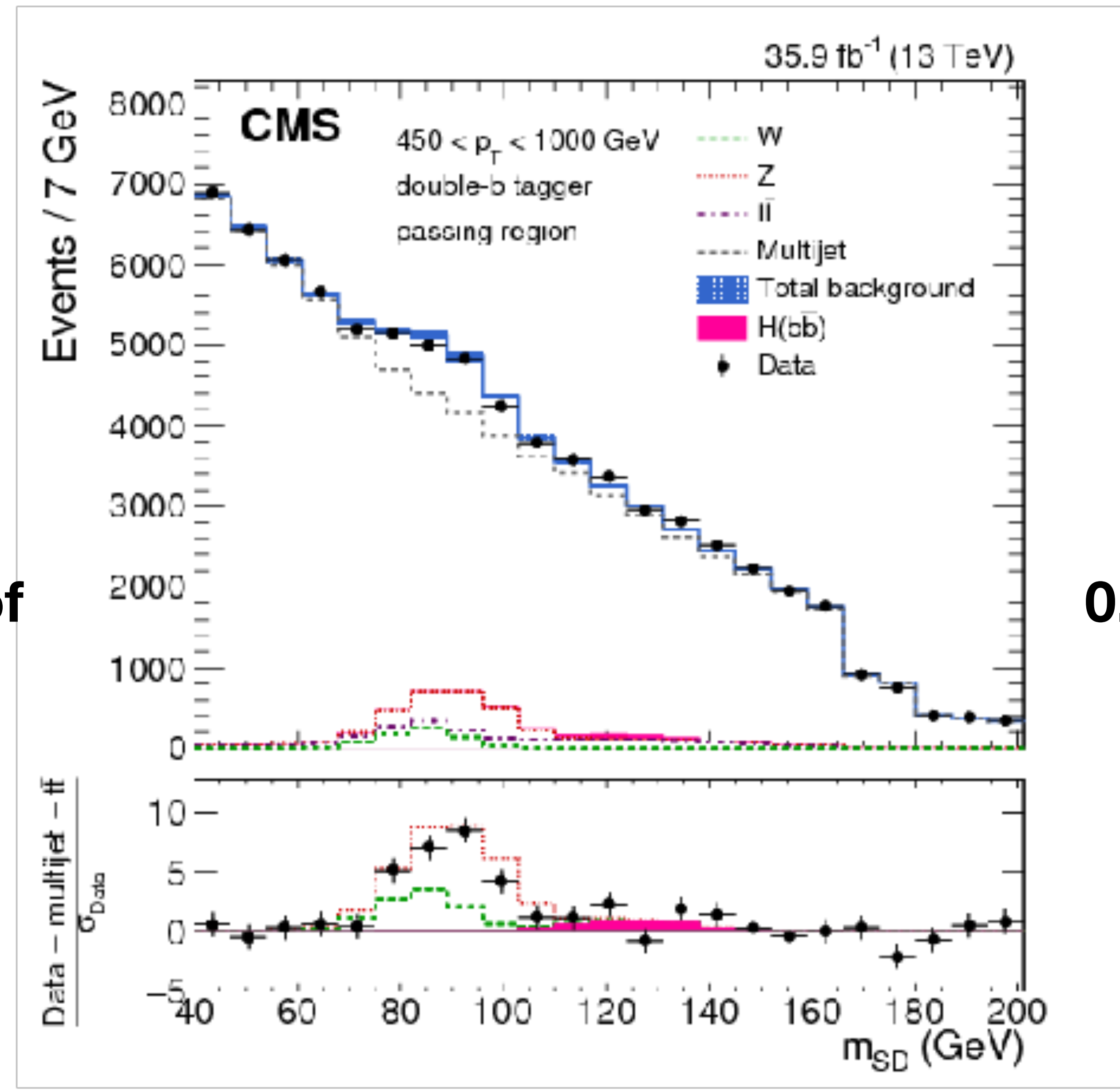


arXiv:1710.00159

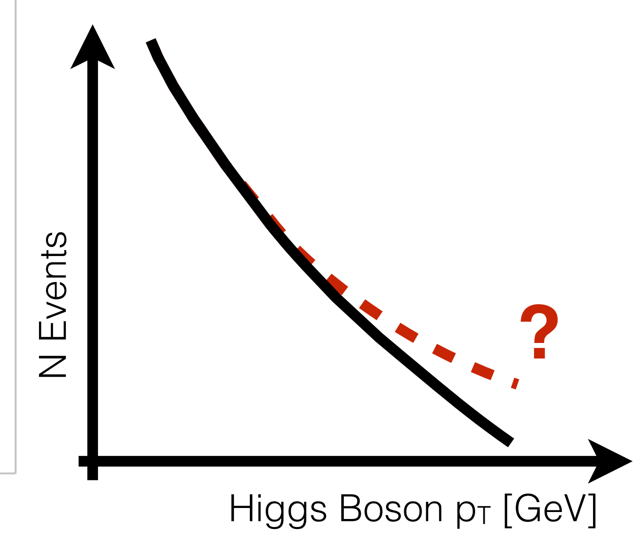
Search -> Measurement

- Thinking about EFTs, a variable that has BSM sensitivity that scales with energy is the Higgs pT

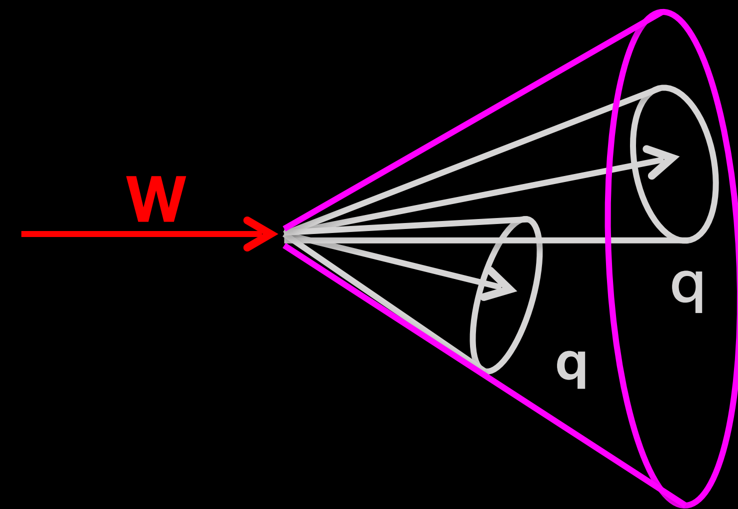
This will be a flagship legacy measurement of the LHC

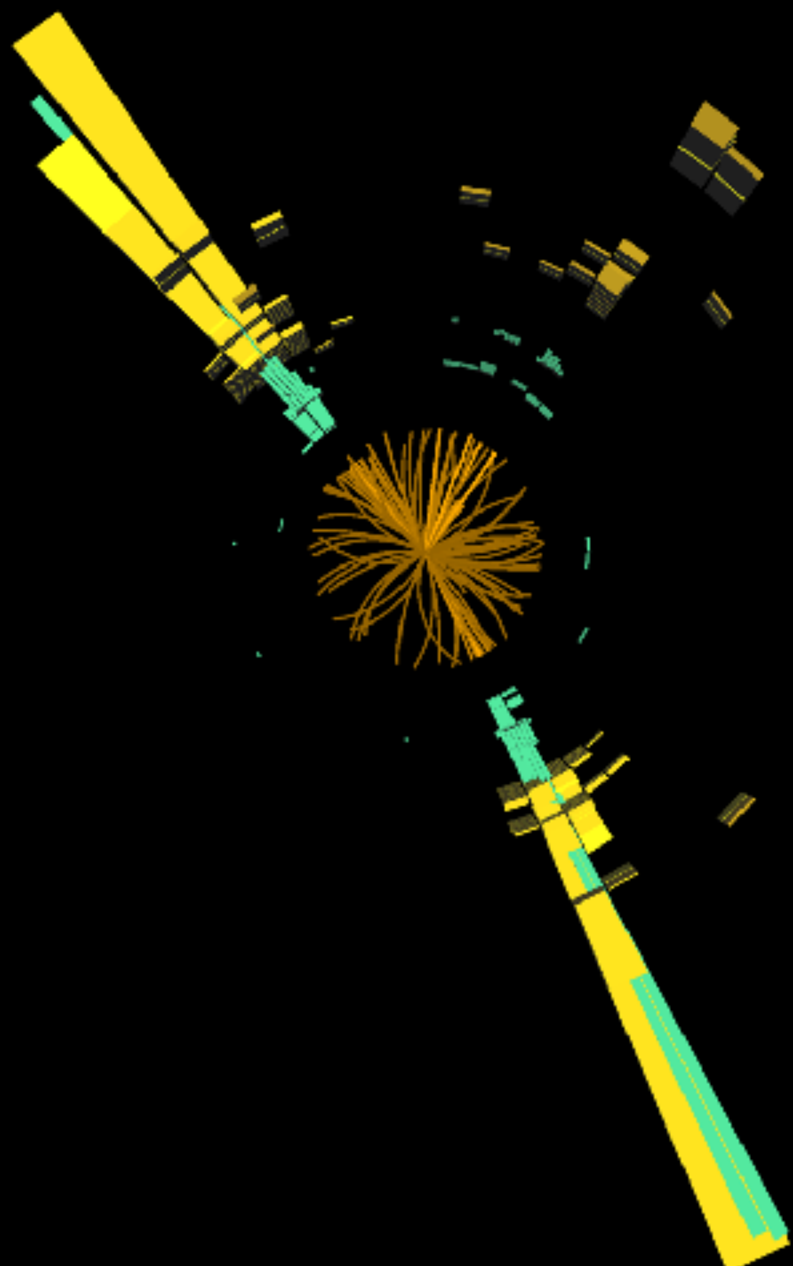


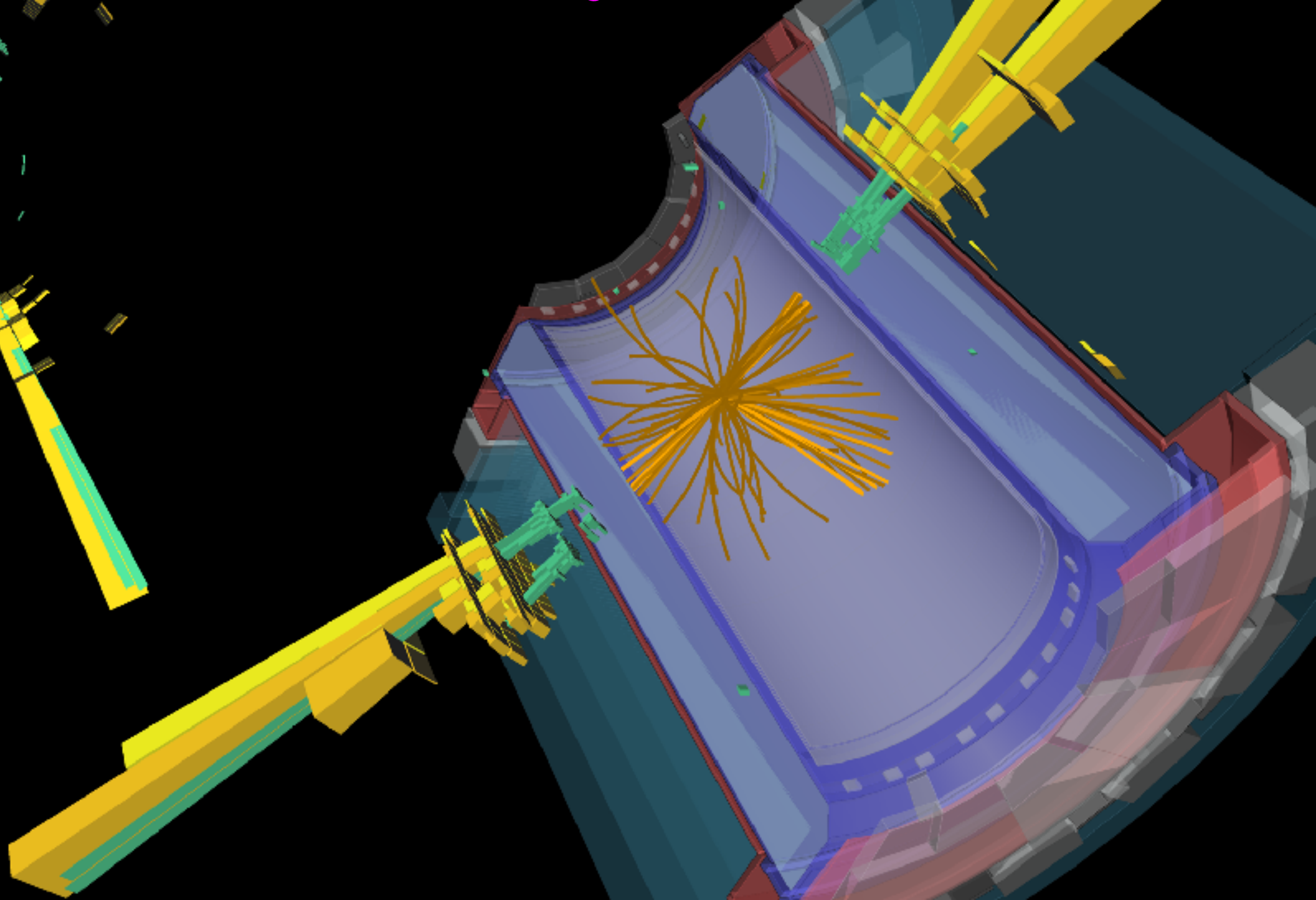
observation of Z->bb
0.7σ sensitivity to H->bb



arXiv:1709.05543

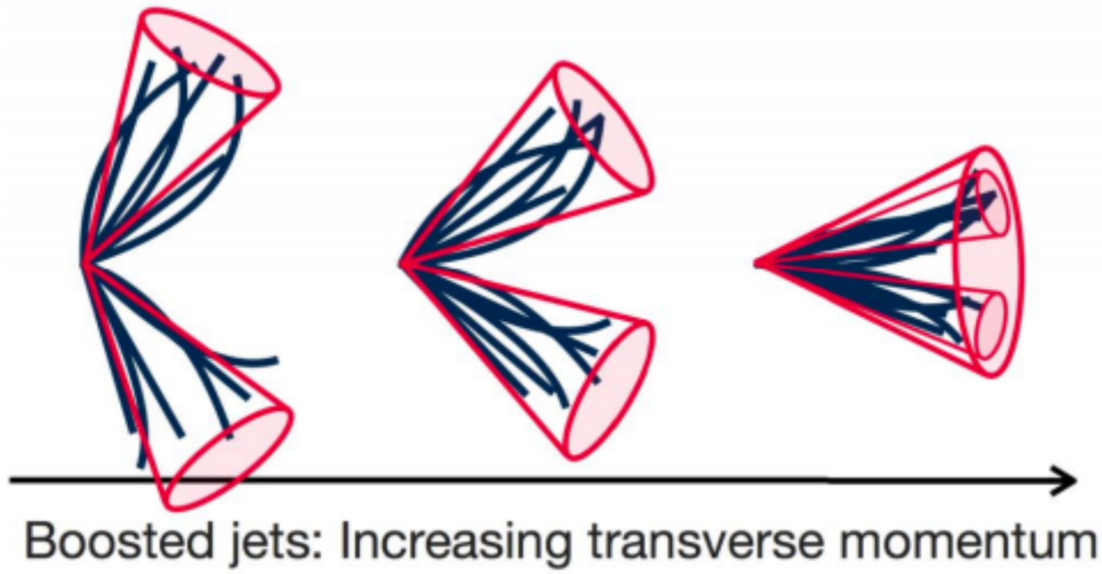

W
q
q
Large-R jet




Run: 299584
Event: 563621388
2016-05-20 08:26:49 CEST
M(JJ)=2.40 TeV

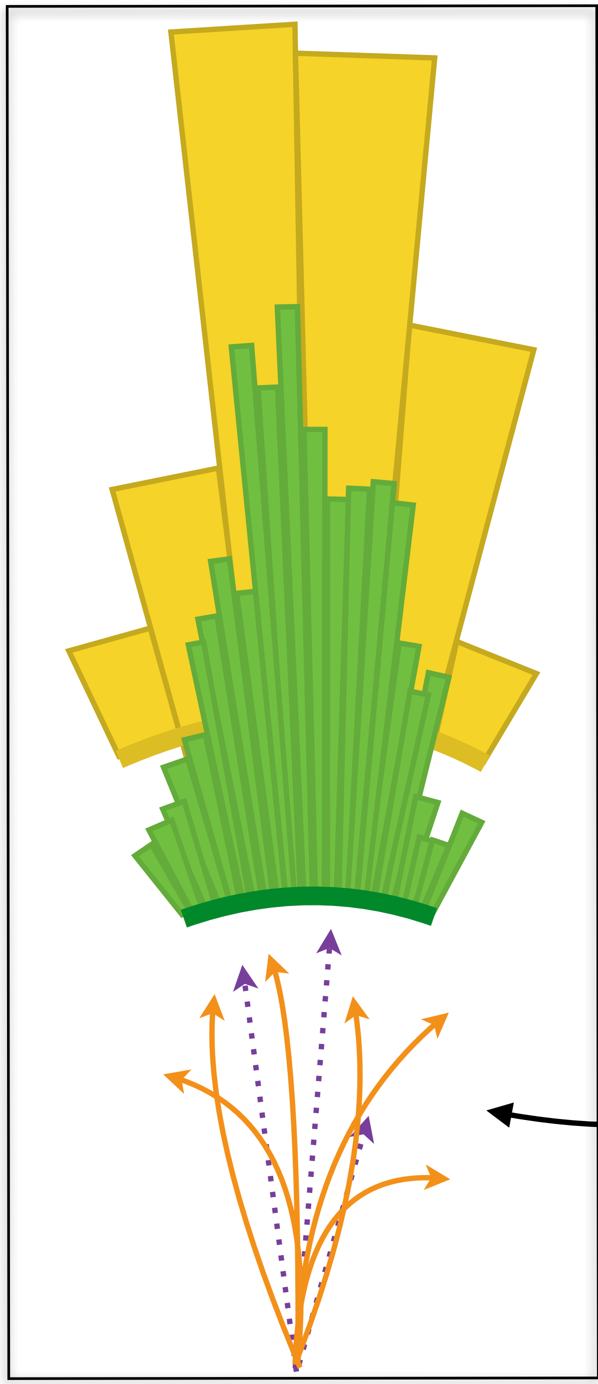
Two Bosons

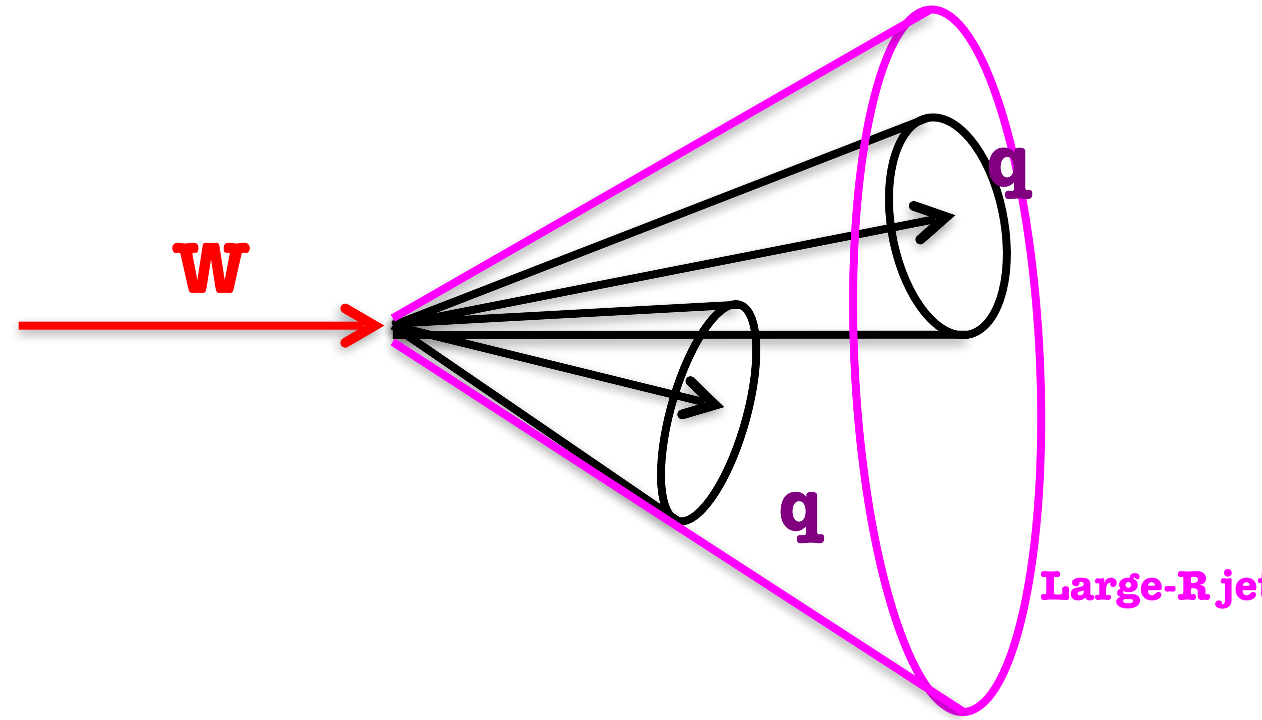
- Diboson resonances historically connected to electroweak symmetry breaking models
    - Spin 0: Heavy scalars in extended Higgs sector
      Spin 1: Extended gauge models (W', Z' in SSM/ HVT)
      Spin 2: Kaluza-Klein gravitons (bulk RS)
- Employ jet substructure (JSS) techniques, so remains a "hot topic"



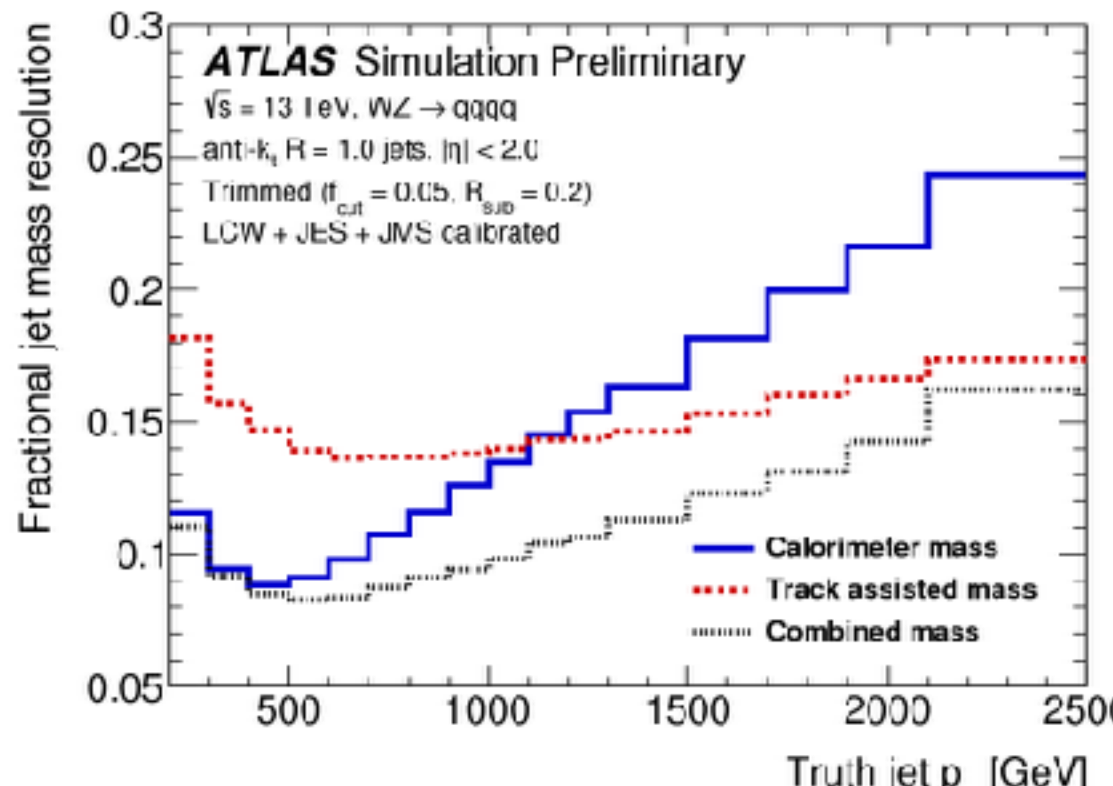
- Entire industry of variables developed to exploit 2 prong structure
- Mass of jet represents object mass (after calibration)

Performance: Boson Tagging





Use both!

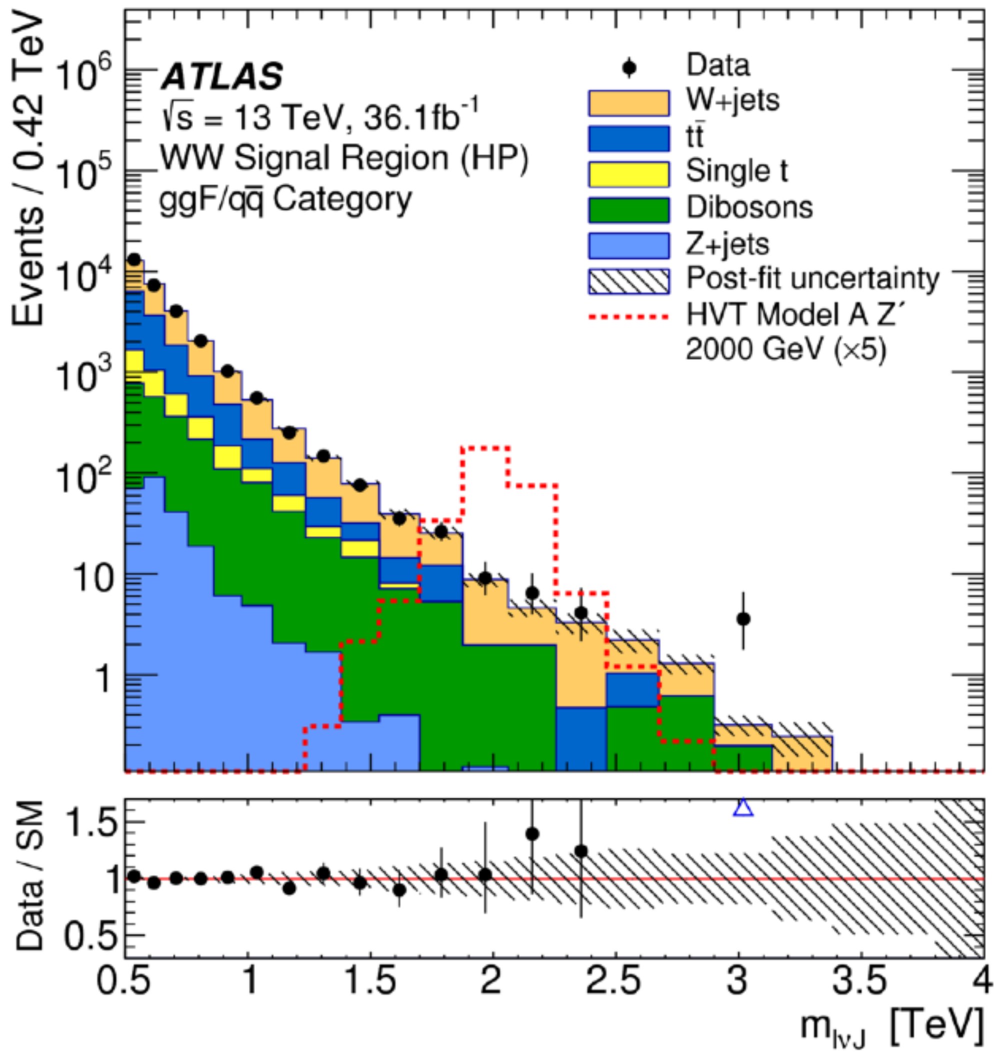


$$m_J \equiv w_{\text{calo}} \times m_{\text{J}}^{\text{calo}} + w_{\text{track}} \times \left(m_{\text{J}}^{\text{track}} \frac{p_{\text{T}}^{\text{calo}}}{p_{\text{T}}^{\text{track}}} \right)$$

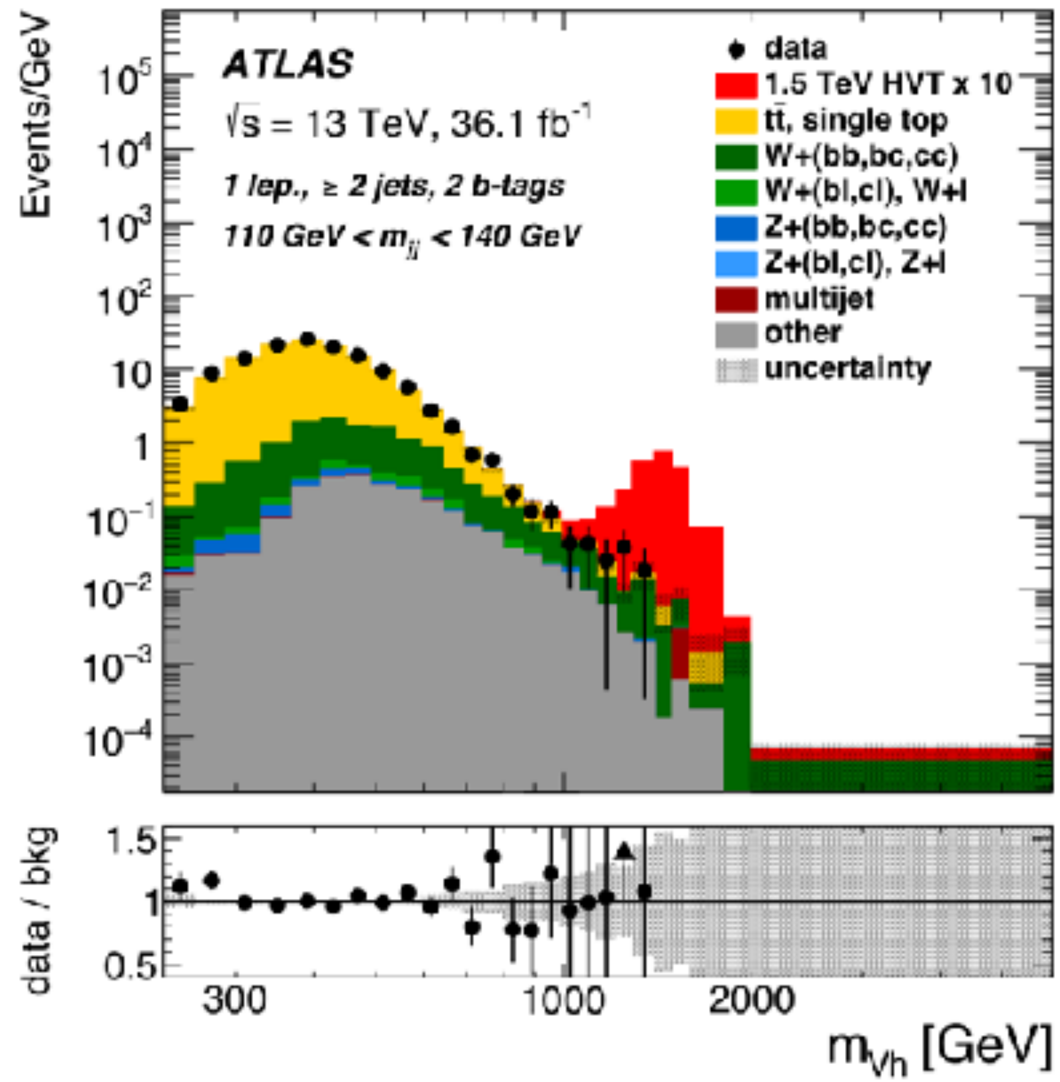
ATLAS-PHYS-PUB-2015-033

Final States

(VV, Vγ, VH, HH) x (leptonic, hadronic) = large program



WV->lvqq
arXiv:1710.07235

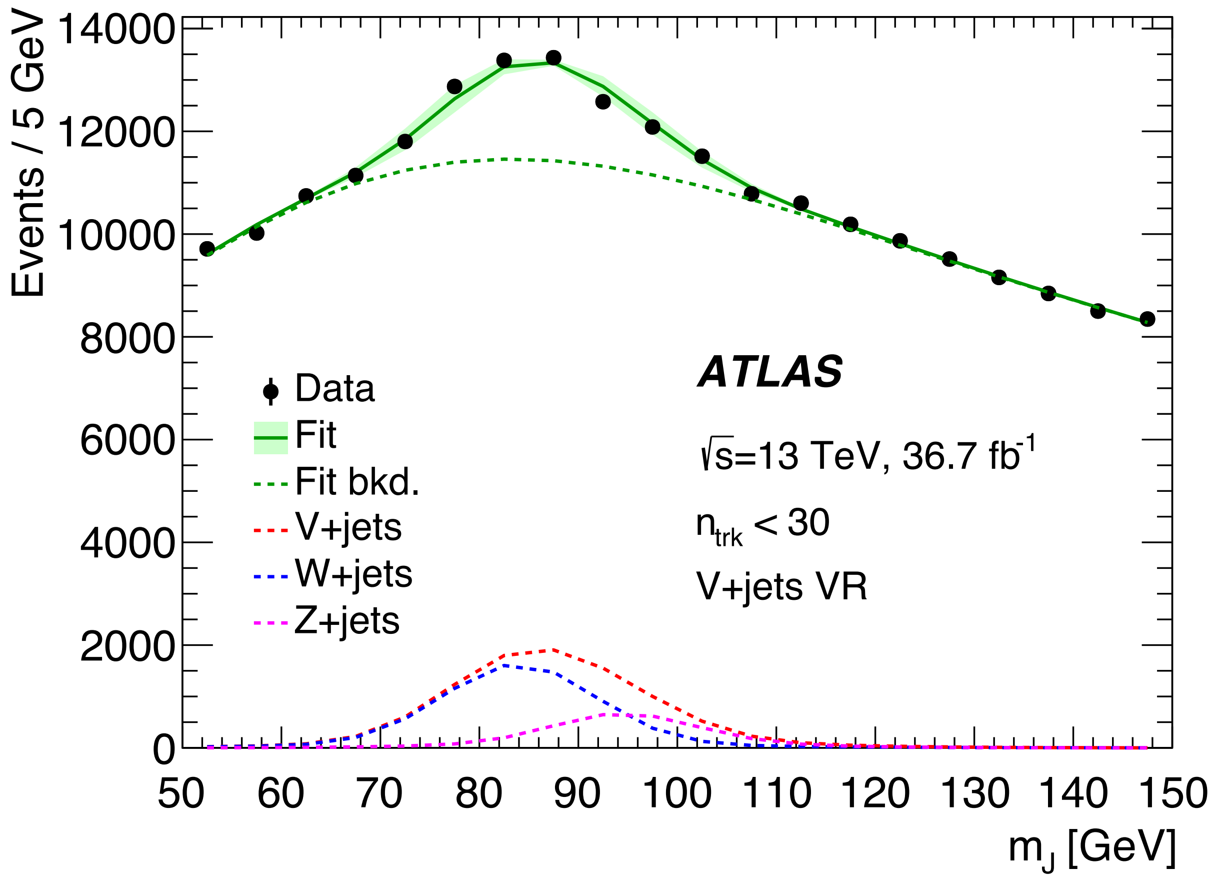


WH->lvbb
arXiv:1712.06518

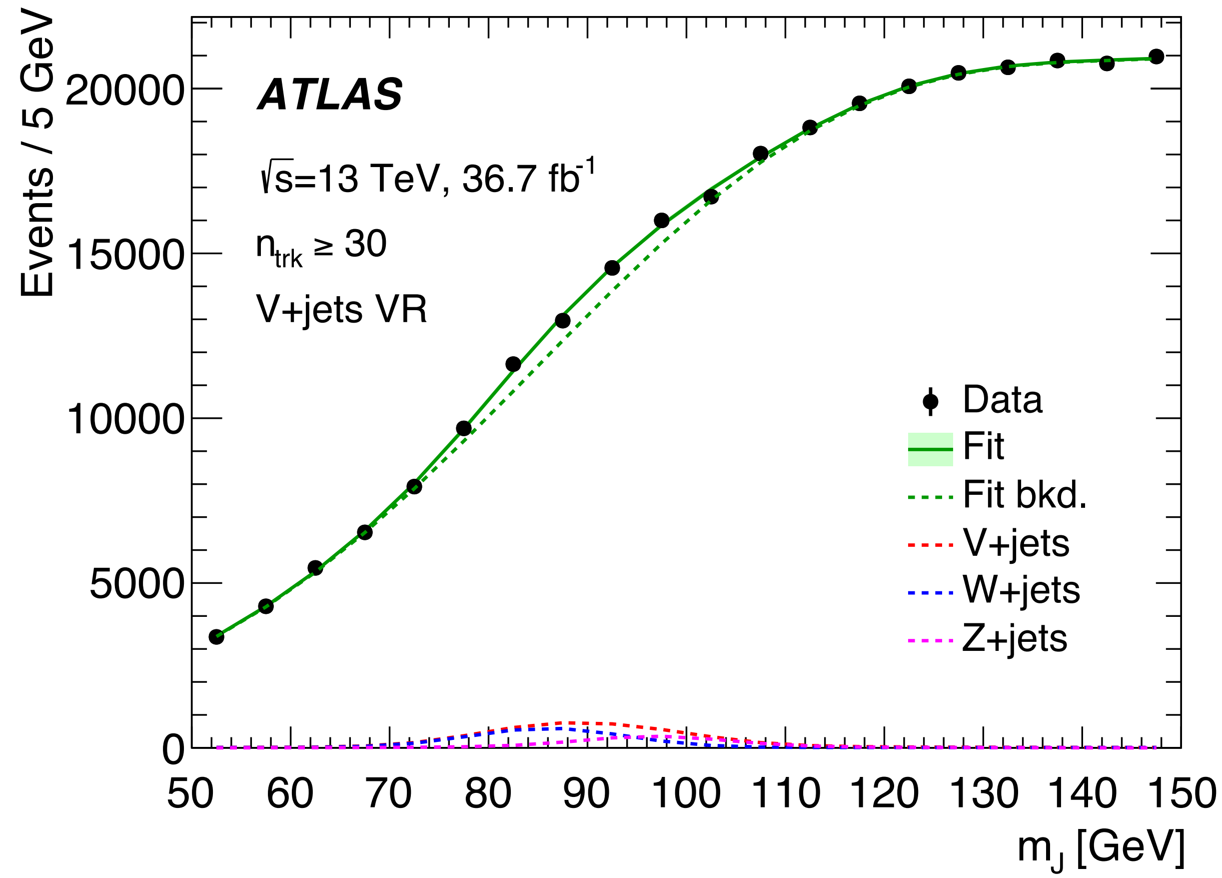
	W	Z	
Charged leptons	~33%	~10%	rare/clean
Hadrons	~67%	~70%	common/ dirty
Neutrinos	-	~20%	

VV->JJ

All hadronic analyses: Playground for new ideas



(a) Leading-jet mass for $n_{\mathrm{trk}} < 30$

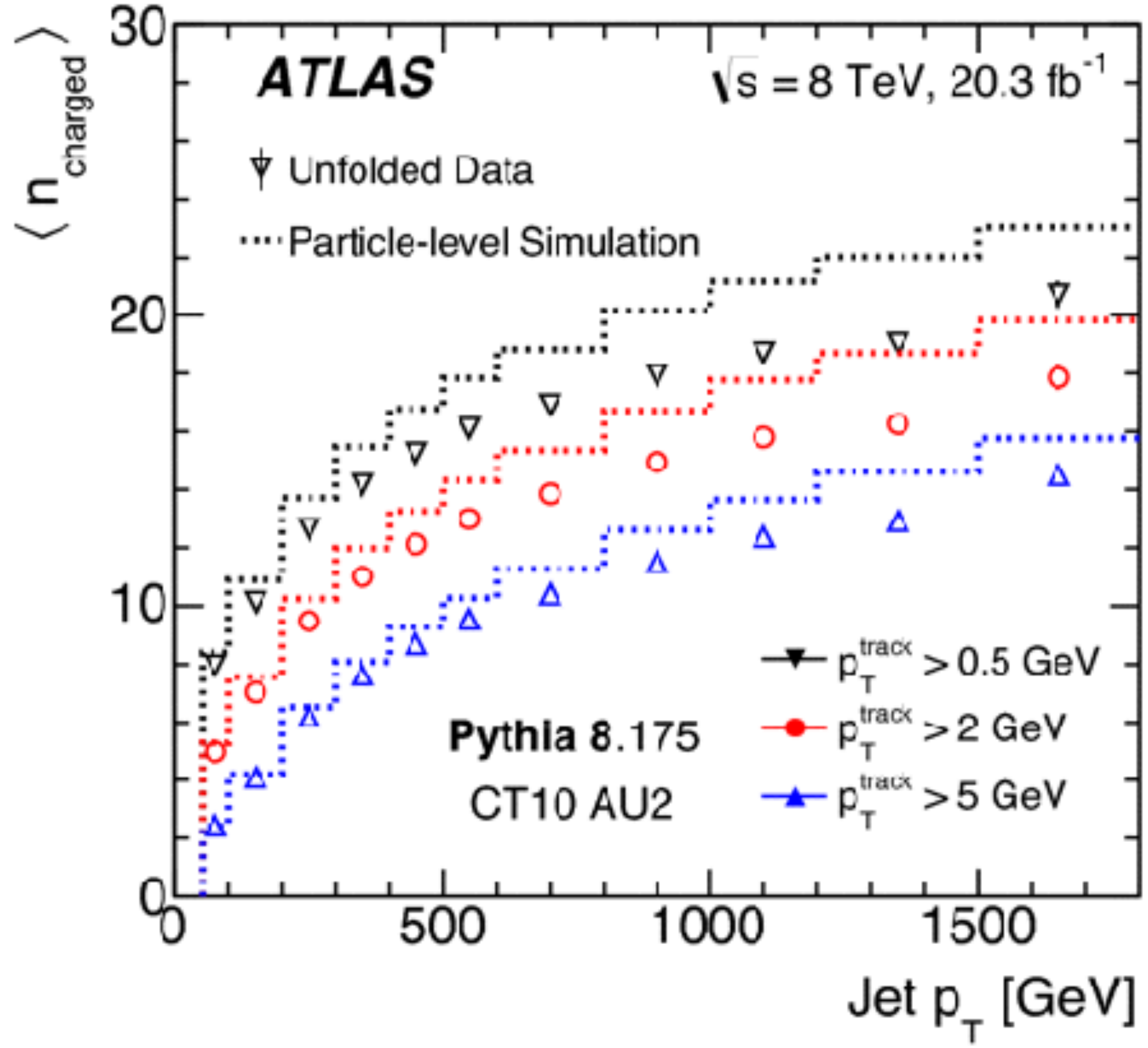


(b) Leading-jet mass for $n_{\mathrm{trk}} \geq 30$

gluon jets have more tracks than V-jets

VV->JJ

All hadronic analyses: Playground for new ideas

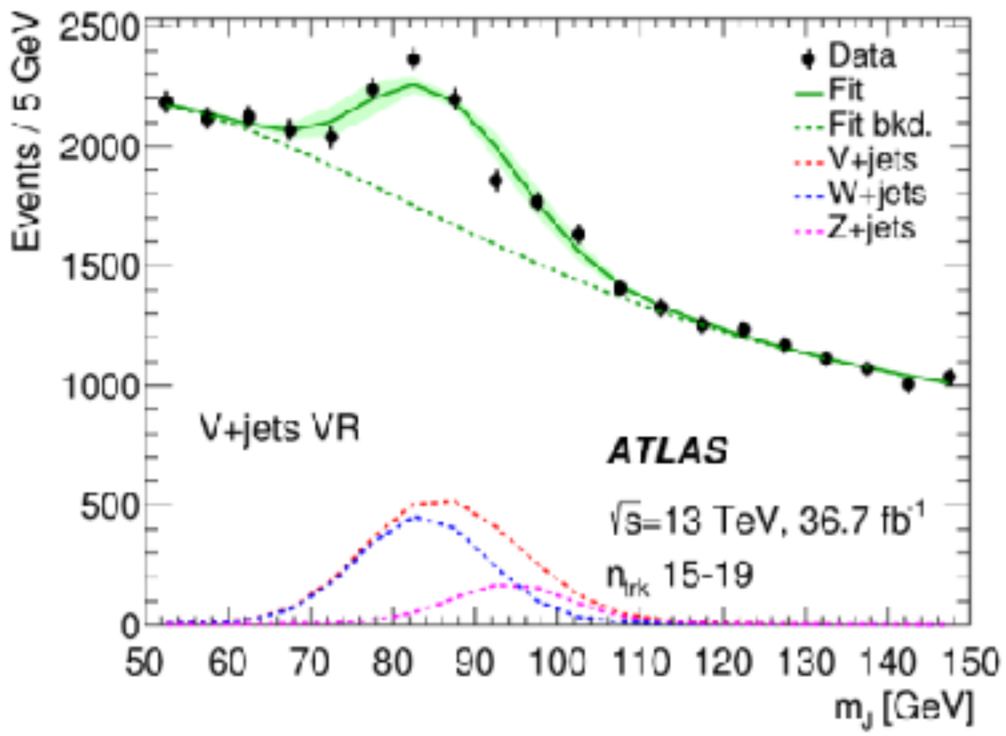


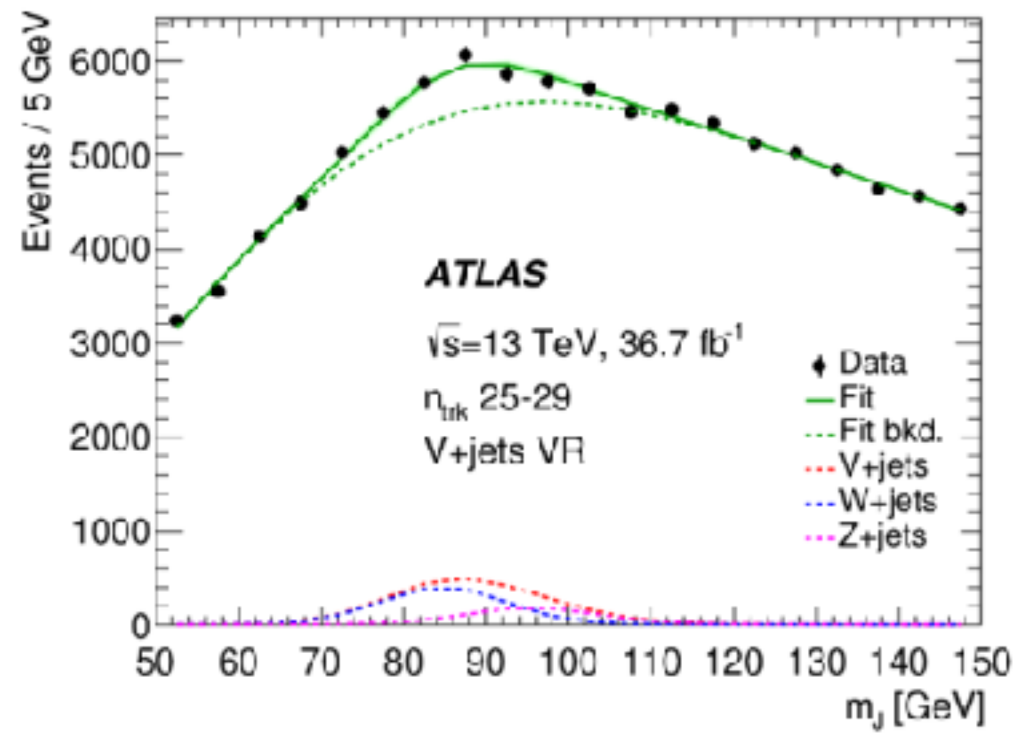
N-tracks is not well modeled

arXiv:1602.00988

VV->JJ

All hadronic analyses: Playground for new ideas



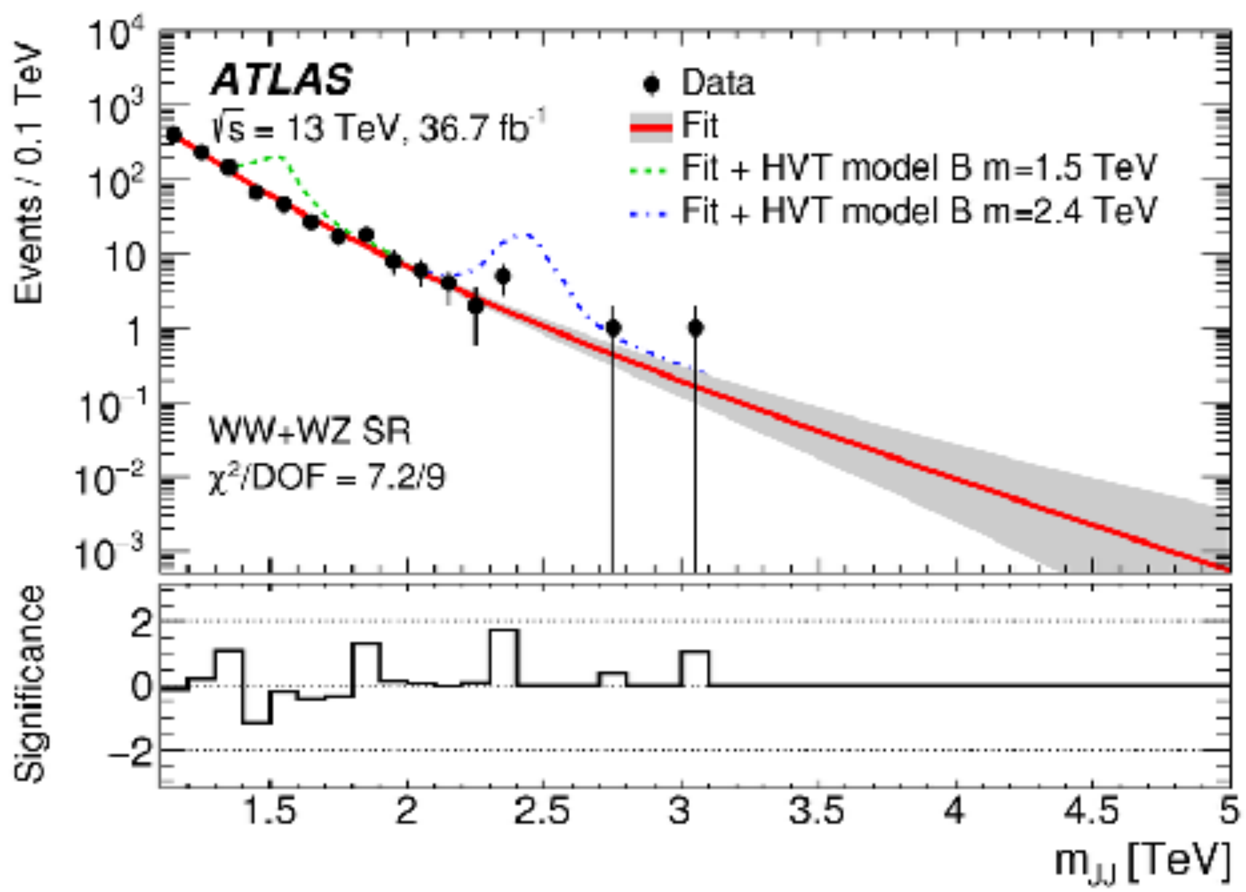


determine correction for signal using data
in an inclusive 1 V sample

arXiv:1708.04445

VV->JJ

All hadronic analyses: Playground for new ideas

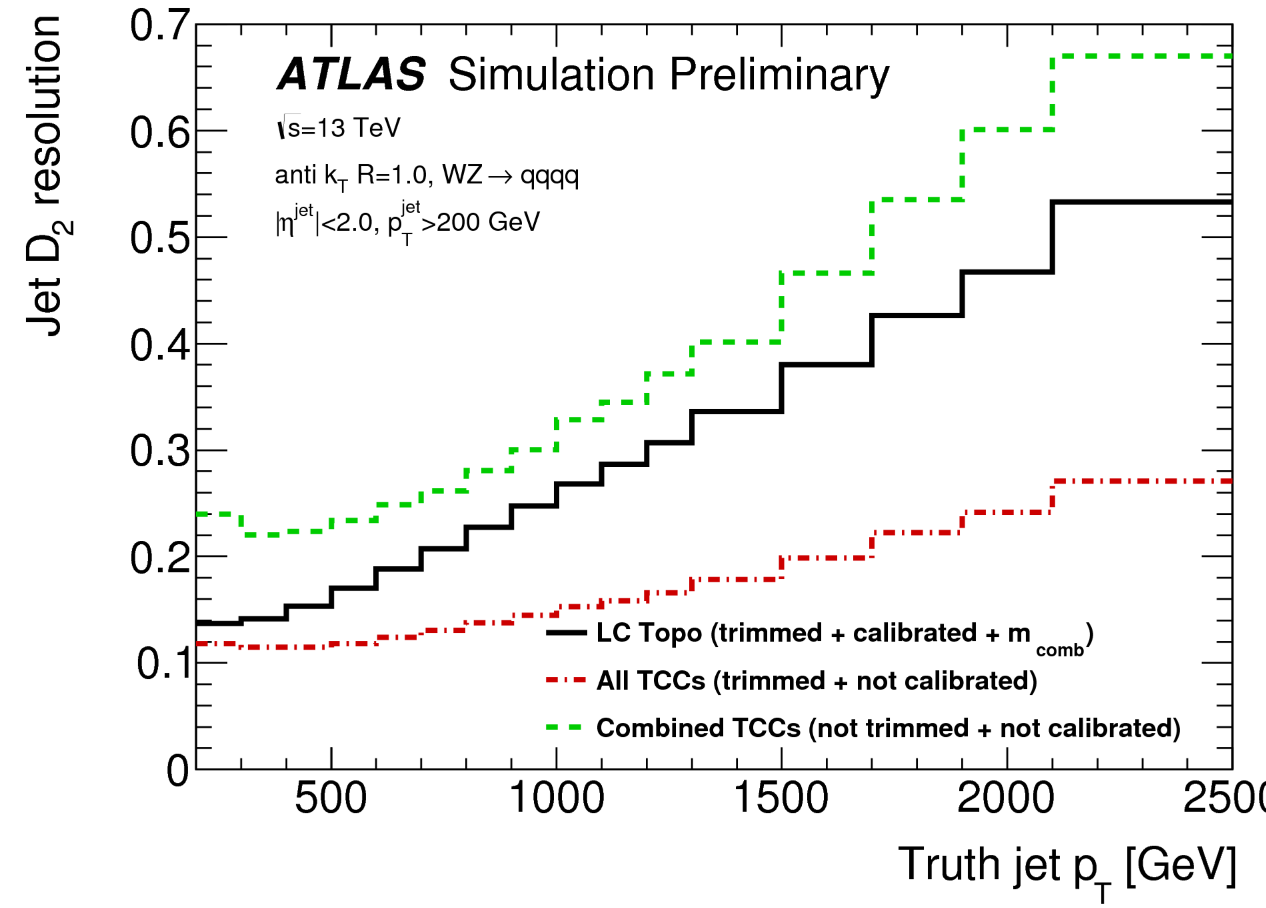


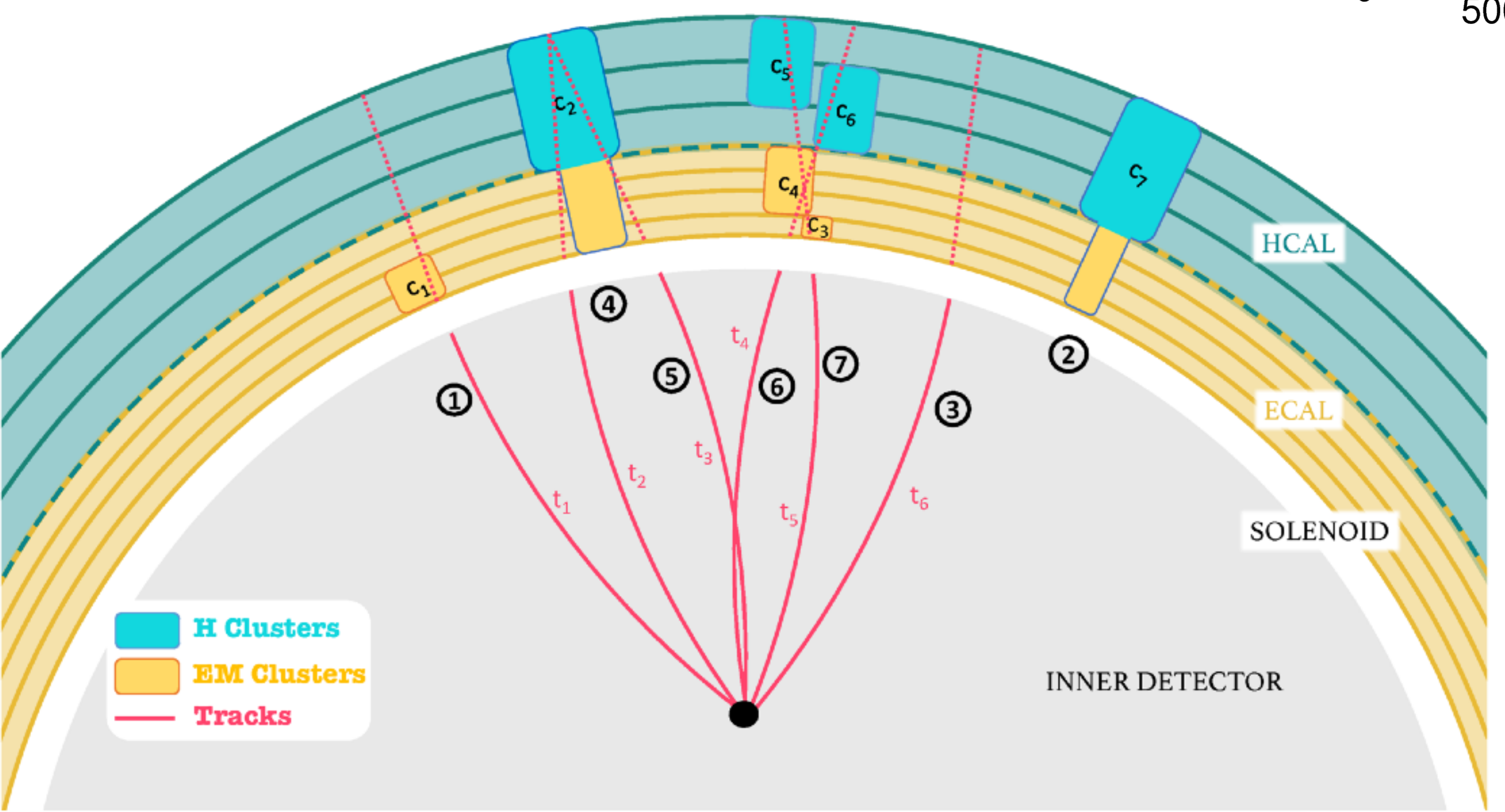
Fit the background! N(Track) modeling = non-issue

$$\frac{dn}{dx} = p_1(1-x)^{p_2-\xi p_3}x^{-p_3},$$

Whats the New Toy?

Tack-Calo Cluster (TCC) exploits better spacial resolution of tracking detector at high momentum to get better view of energy density inside jets

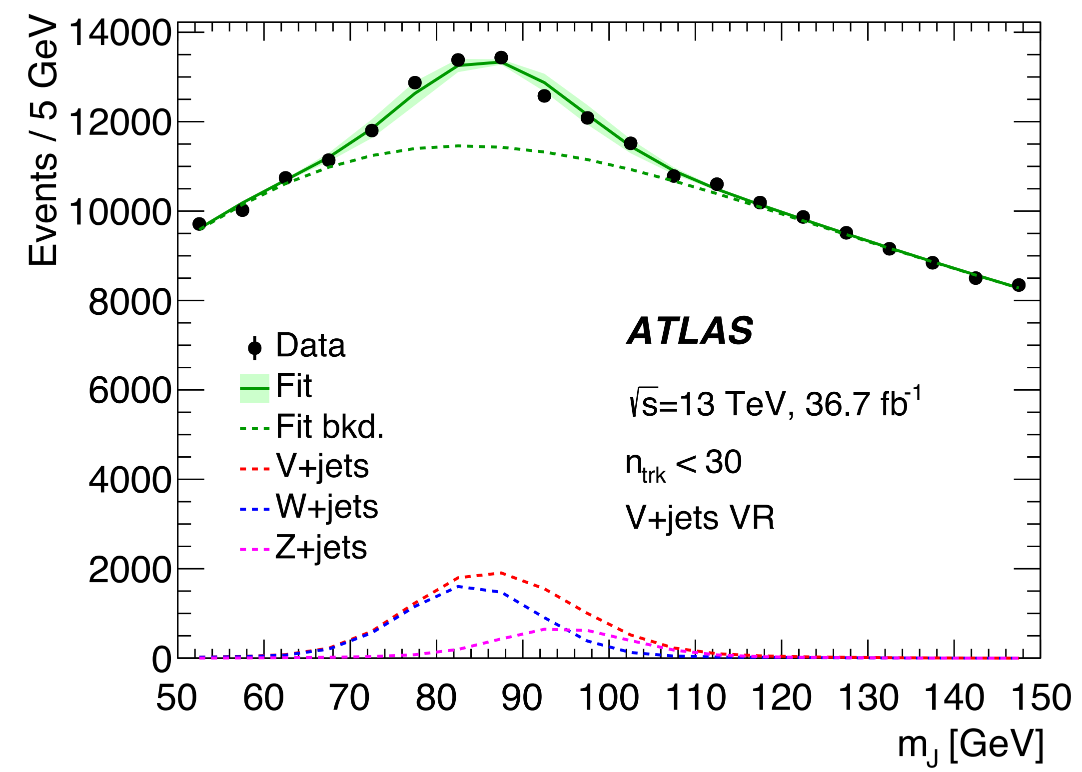


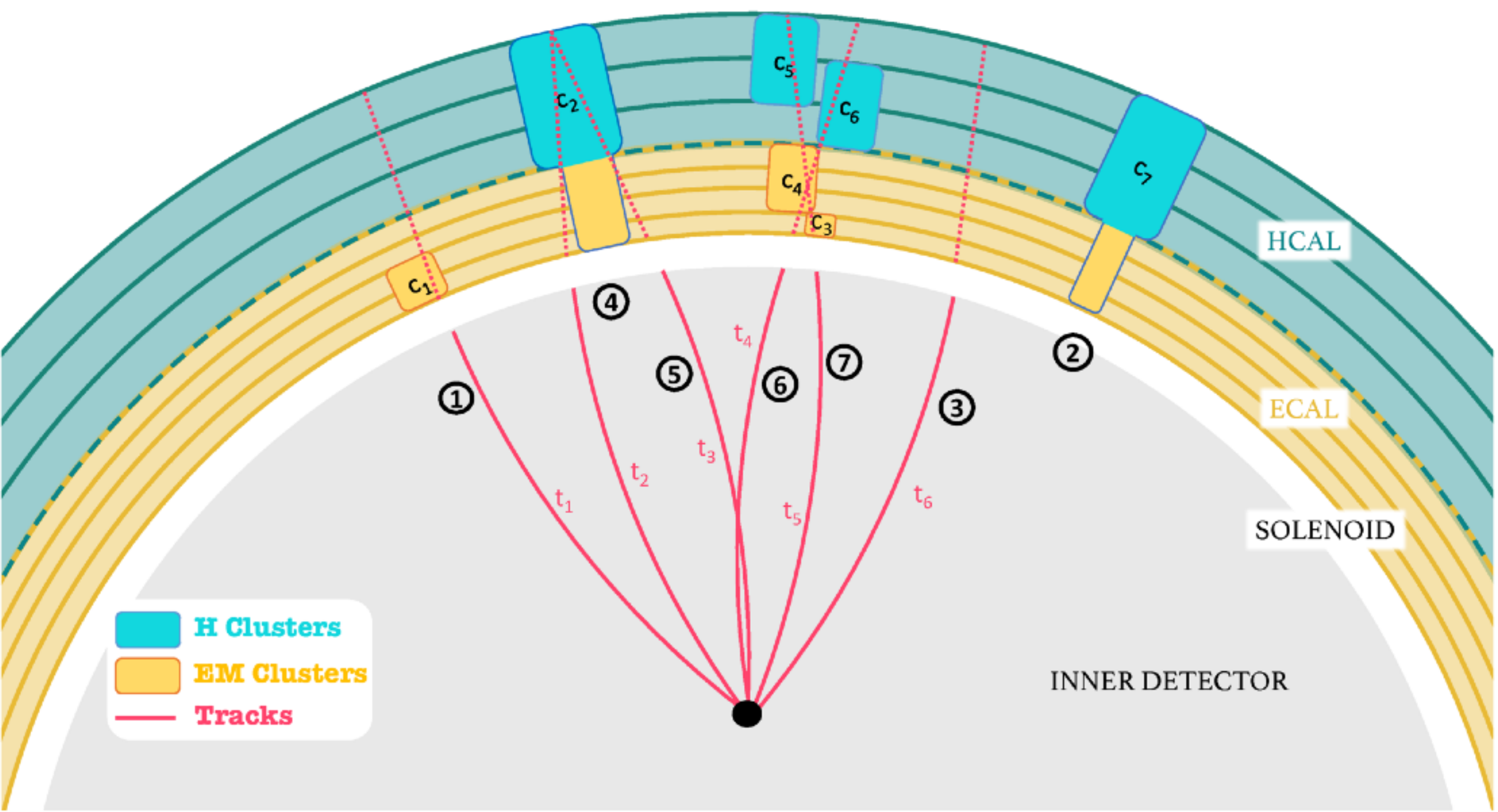


ATL-PHYS-PUB-2017-15

Whats the New Toy?

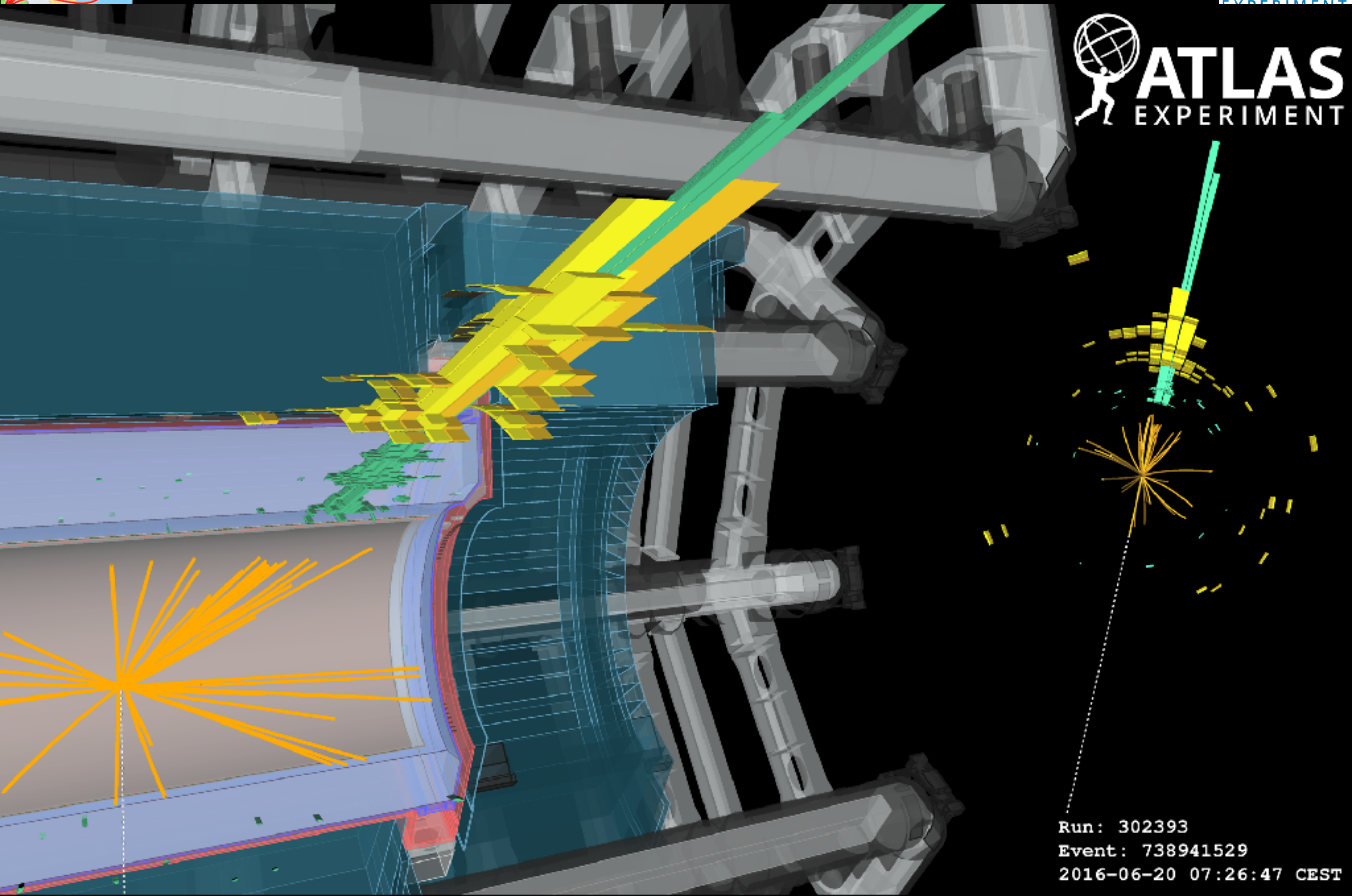
Tack-Calo Cluster (TCC) exploits better spacial resolution of tracking detector at high momentum to get better view of energy density inside jets





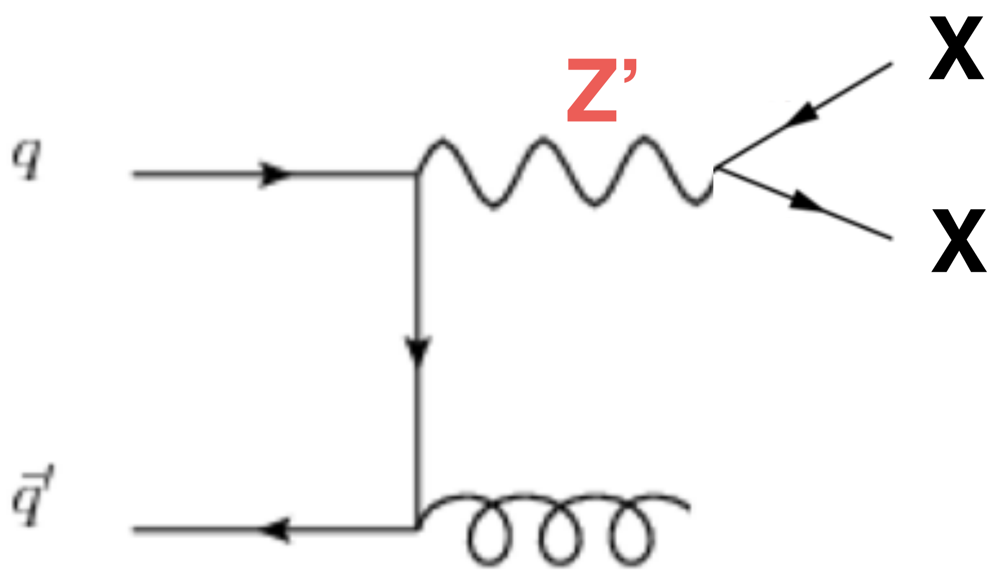
If know number of V-jets before tagging, can compare efficiency in data/MC. Done!! ;)

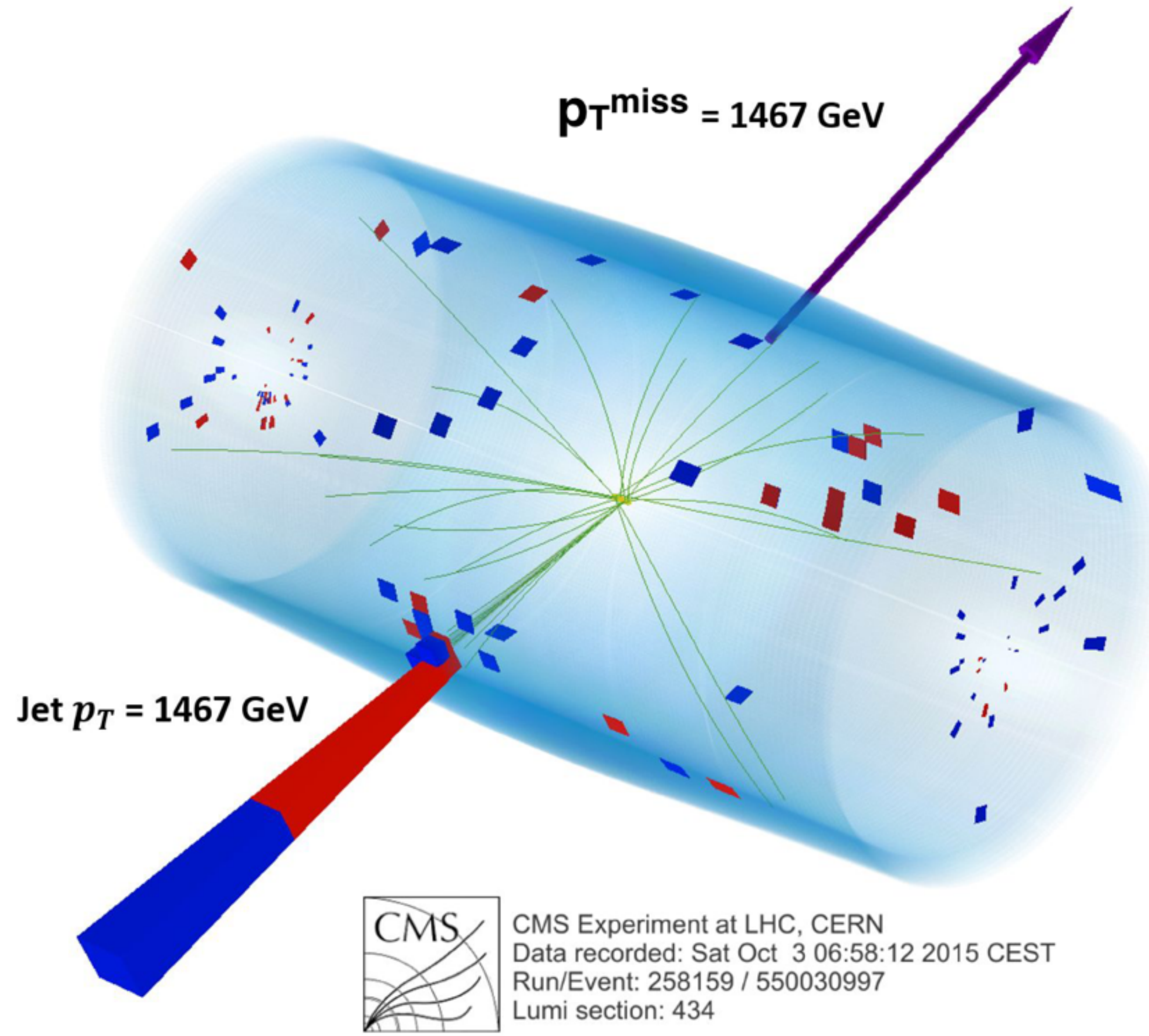
ATL-PHYS-PUB-2017-15


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

MET+Jet

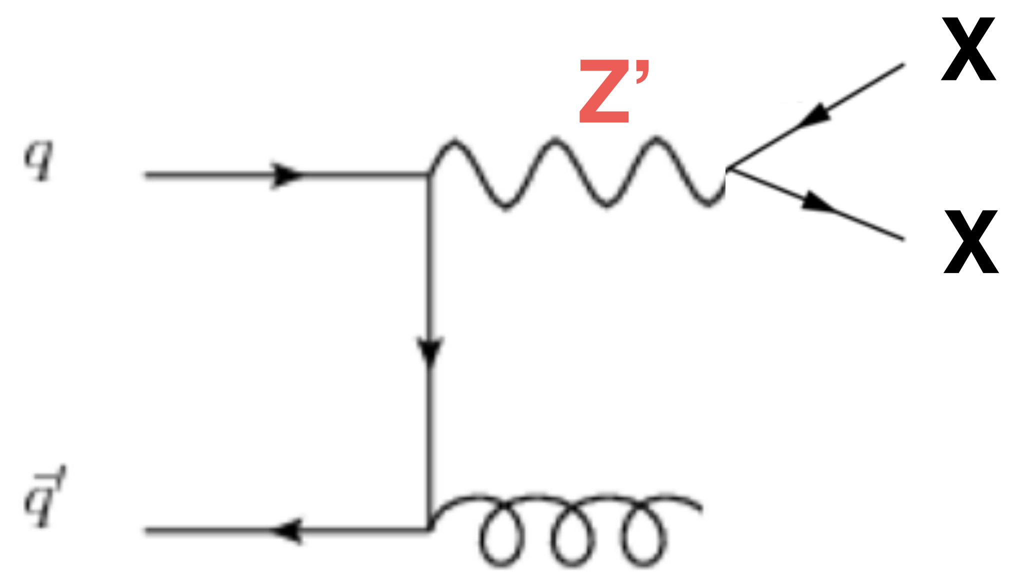
- Dark Matter! There is evidence for something we cannot explain. Is it Dark Matter?



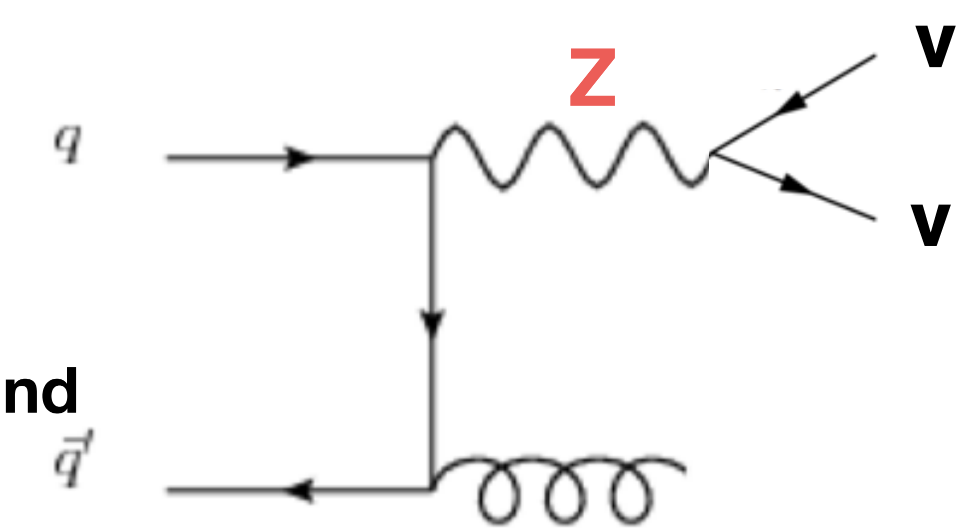


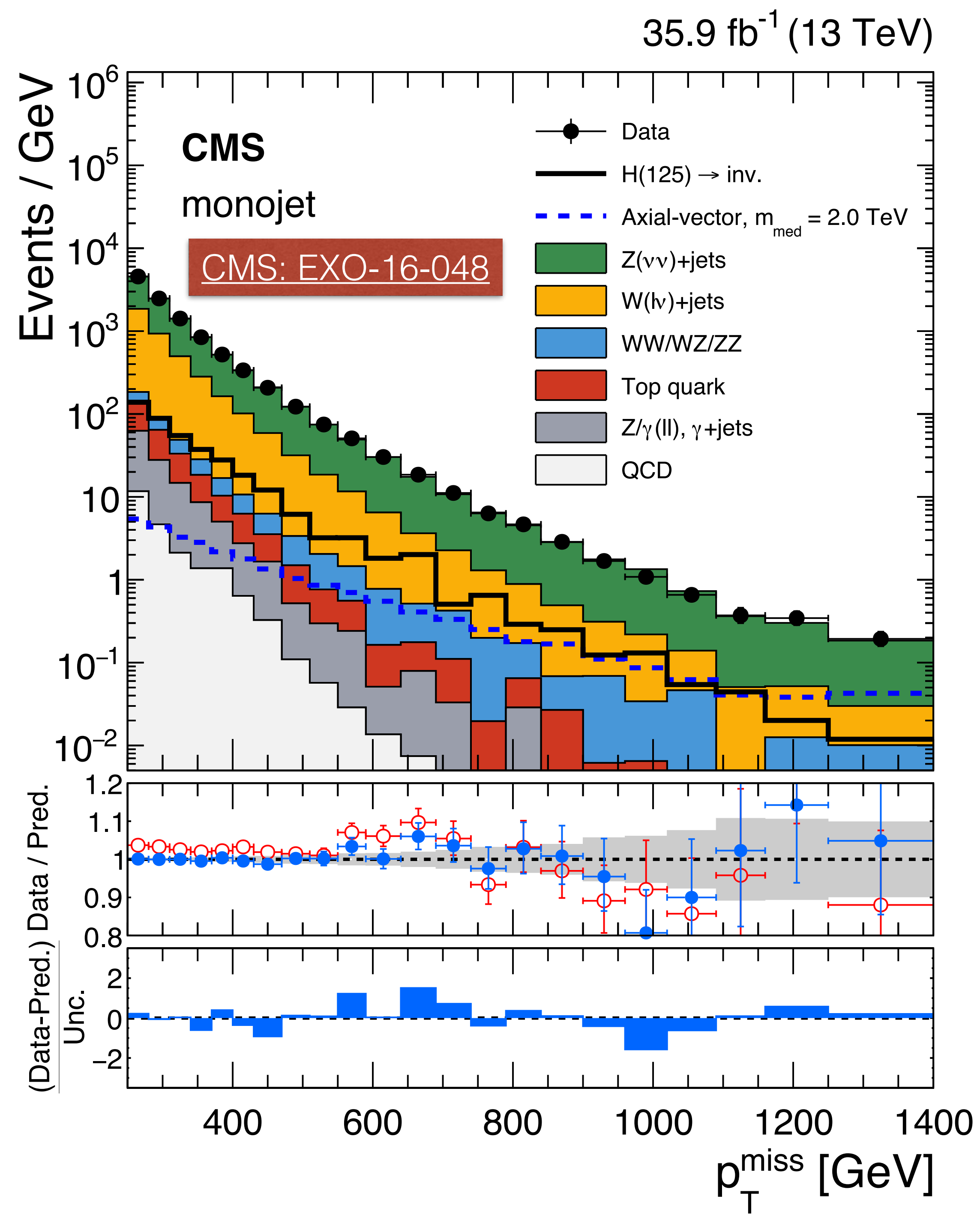
Backgrounds

signal



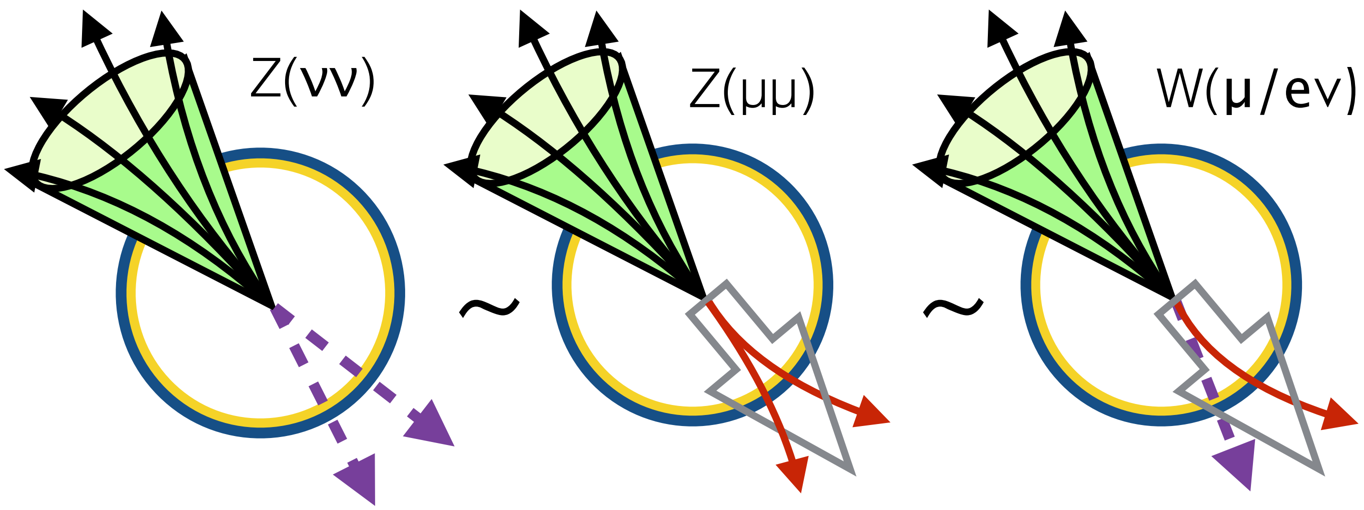
background





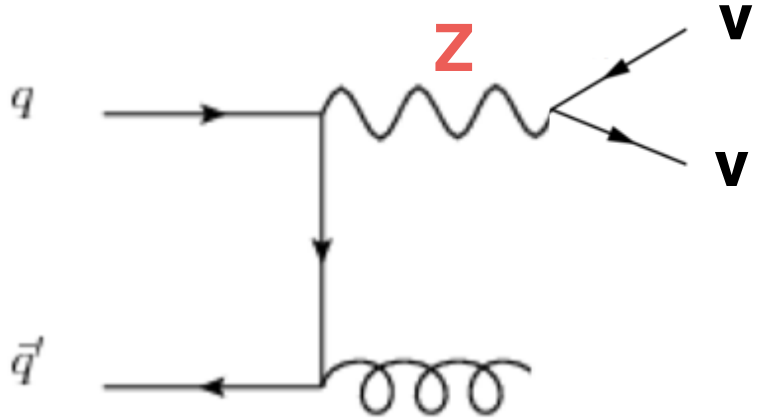
G. Facini, DESY Seminar

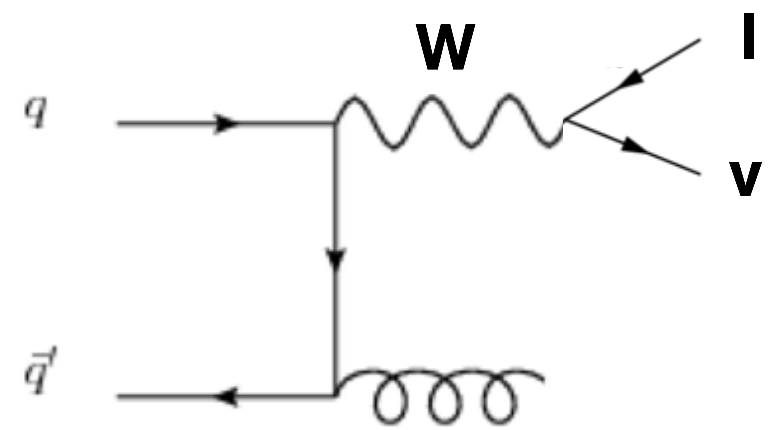
Backgrounds



Can we exploit knowledge of visible W/Z decays to control the invisible Z decays? *What about the photon?*

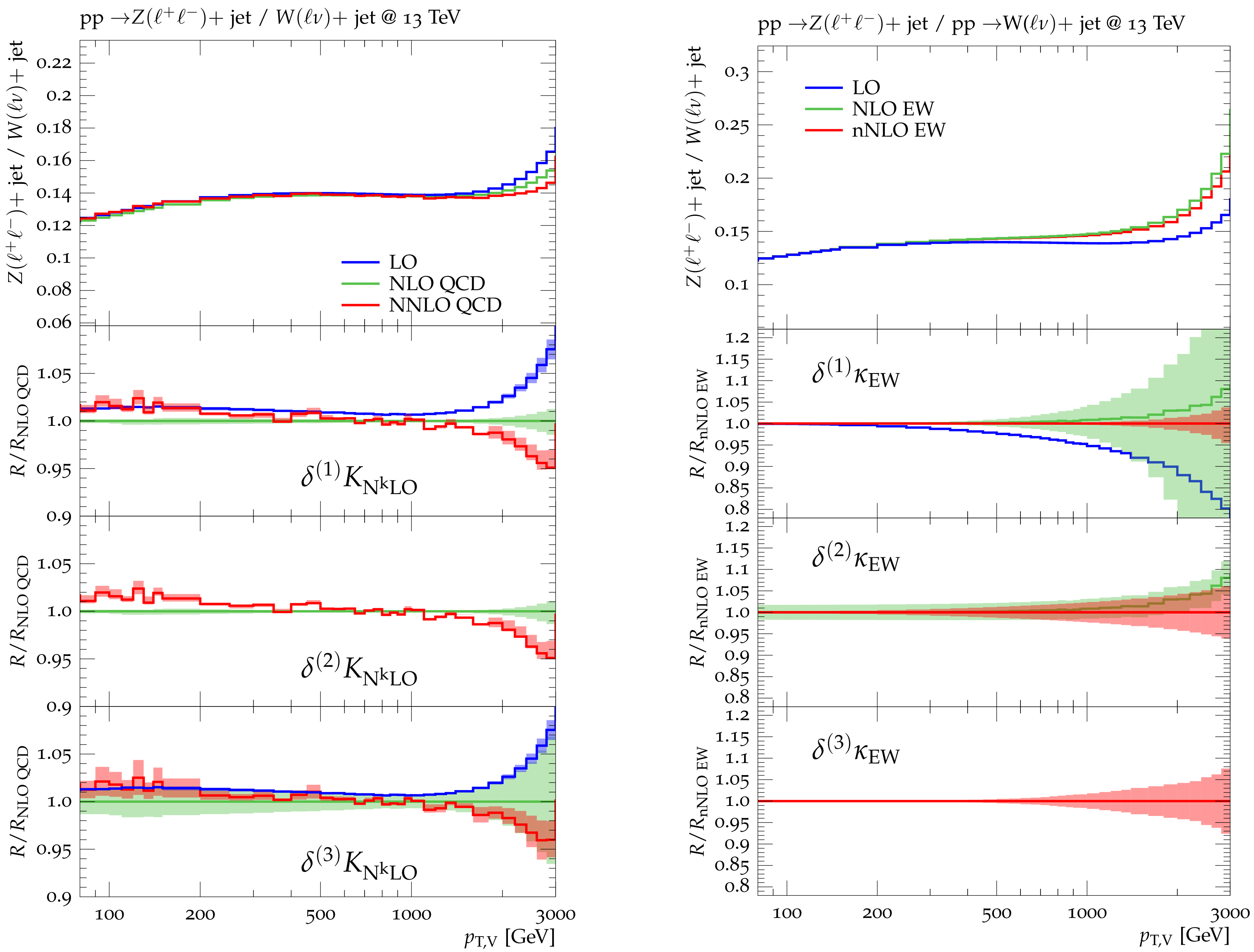
MET ~ boson p_T



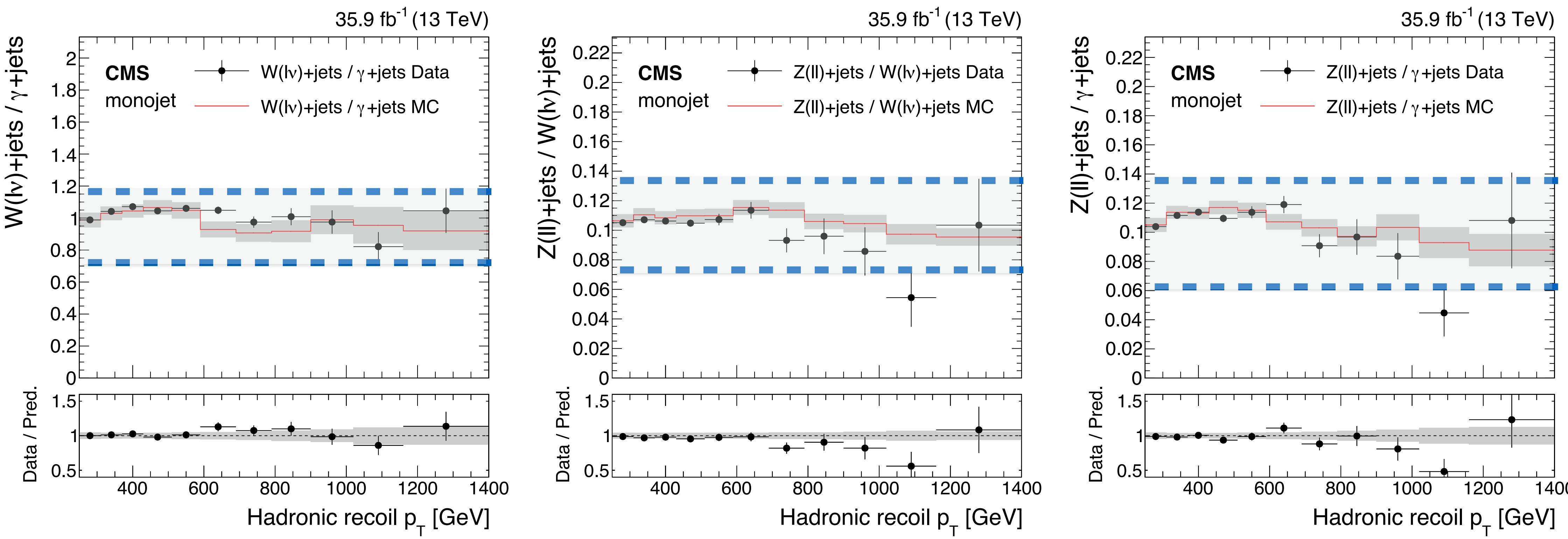


The experimental effects we can control, the theoretical ones, we need help!

Backgrounds

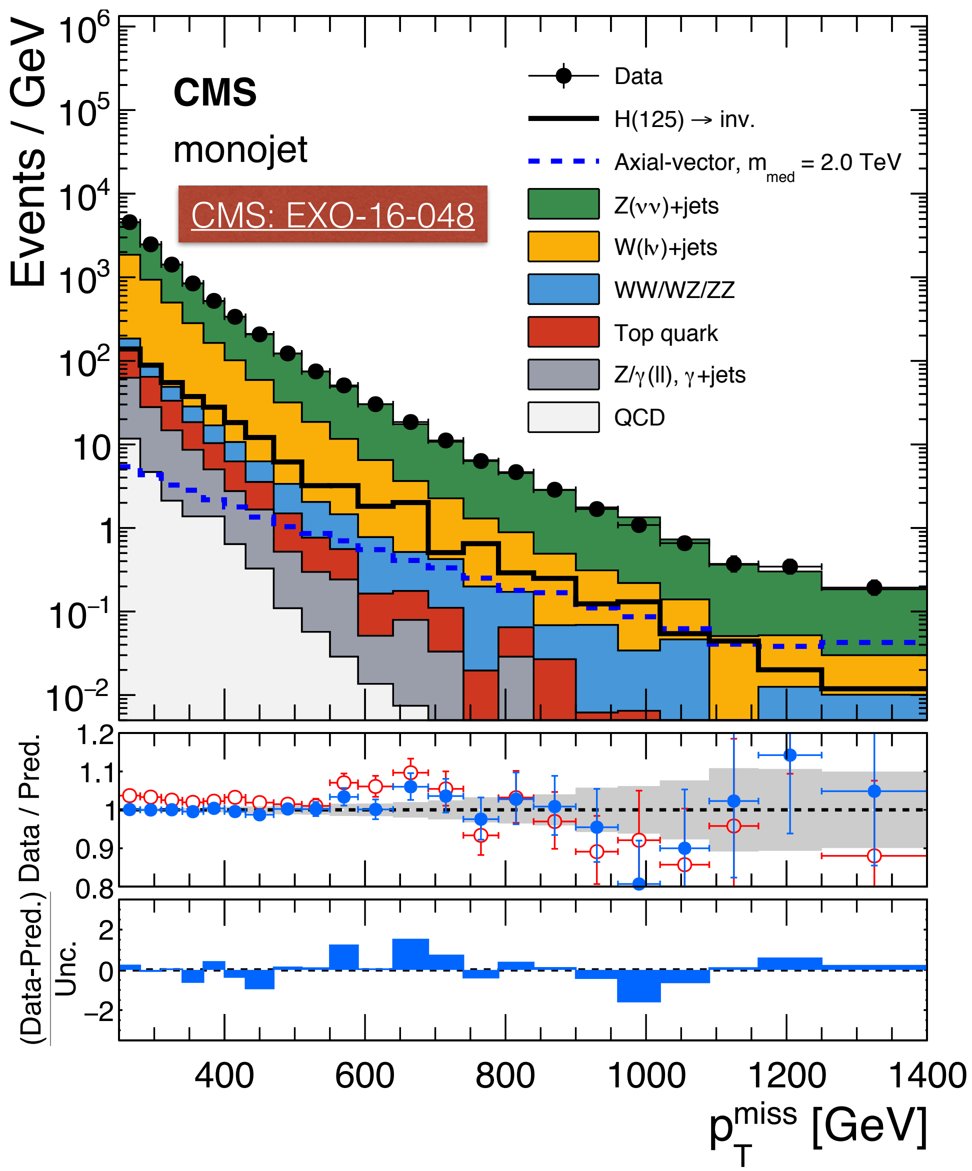


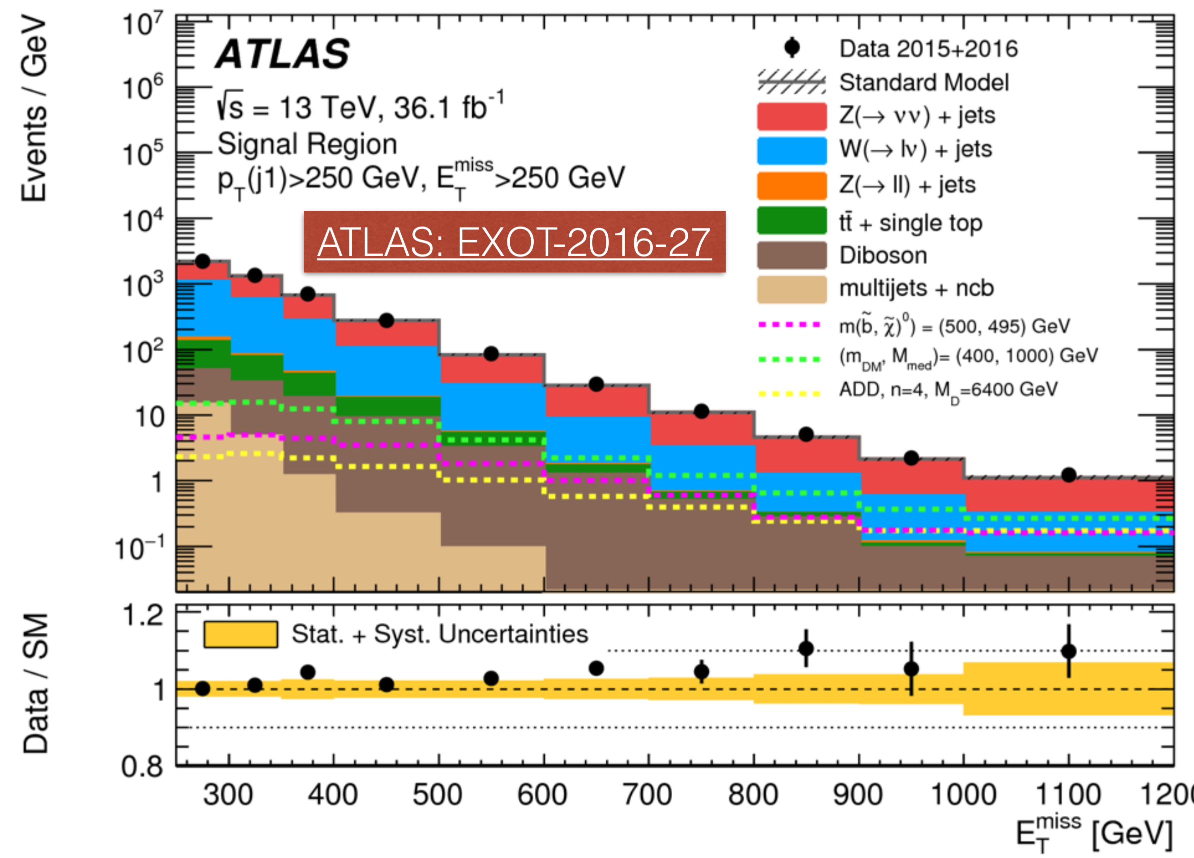
Thank you, Theorists!



Where else can we exploit such sophisticated techniques?

Precision Searching

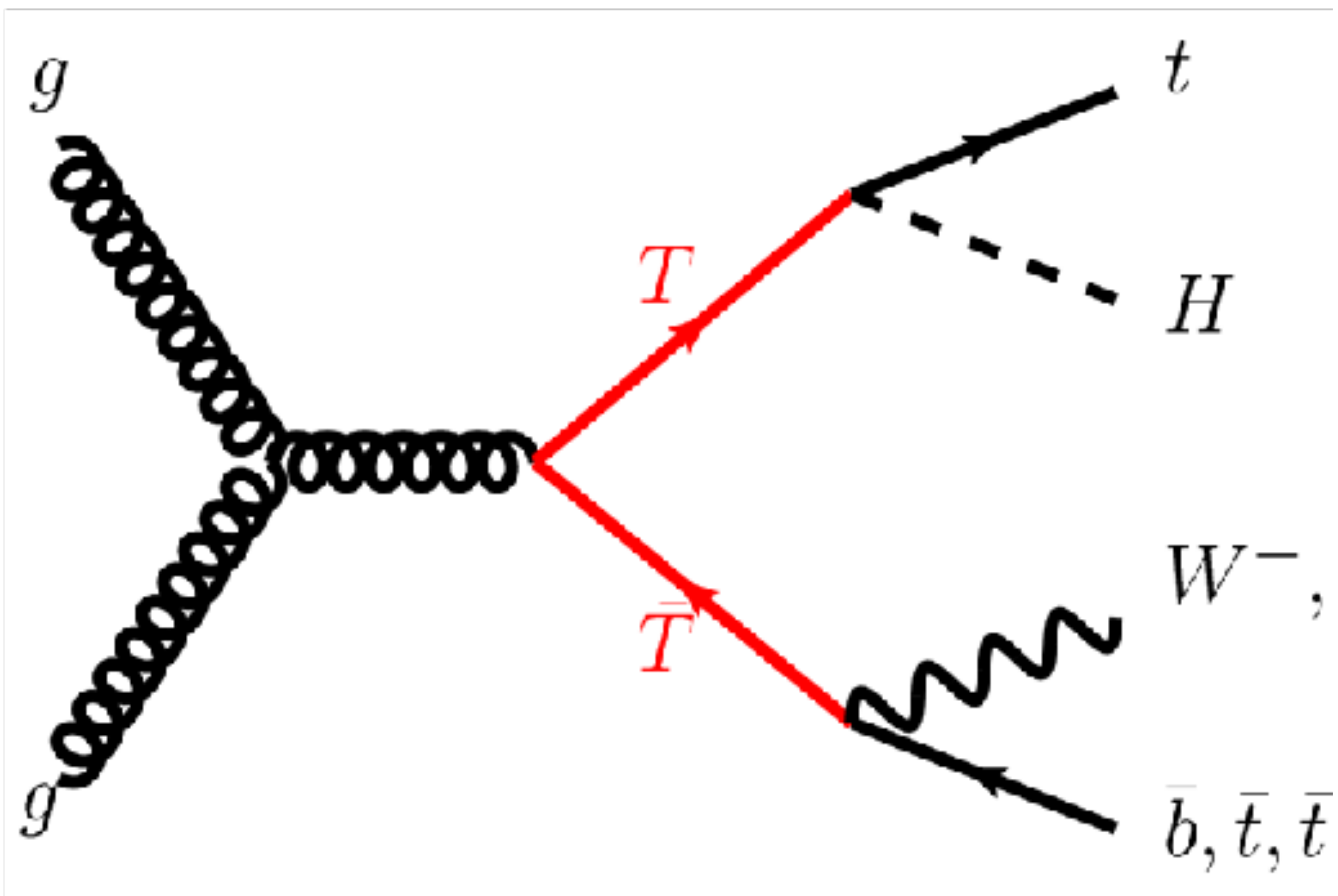




2-3% uncertainty at low MET to 10-15% uncertainty at high MET

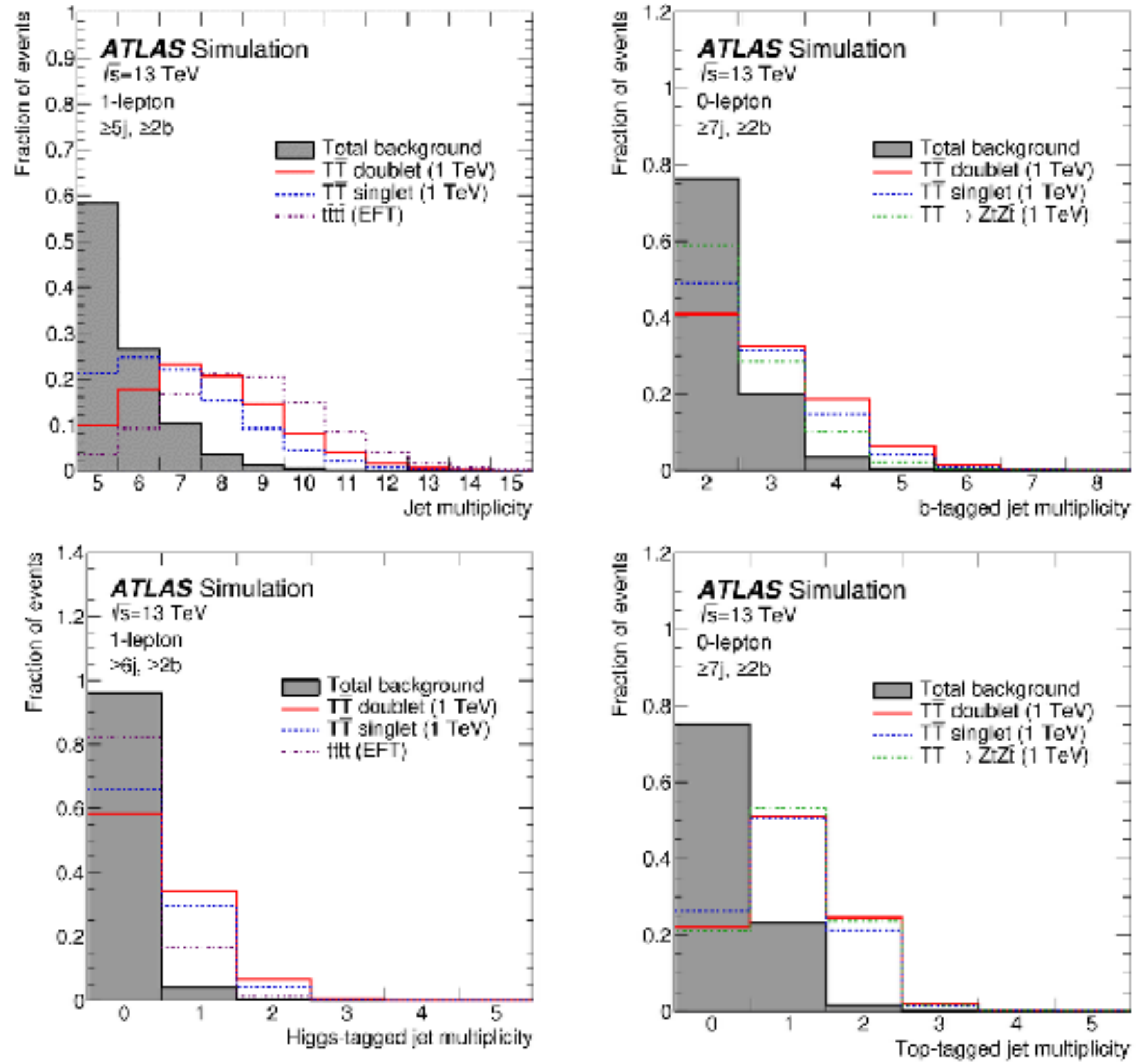
Vectorlike Quarks

- Why is Higgs mass so far from Planck scale?
- New strong sector in which in which the Higgs boson would be a pseudo–Nambu–Goldstone such as Composite Higgs Models



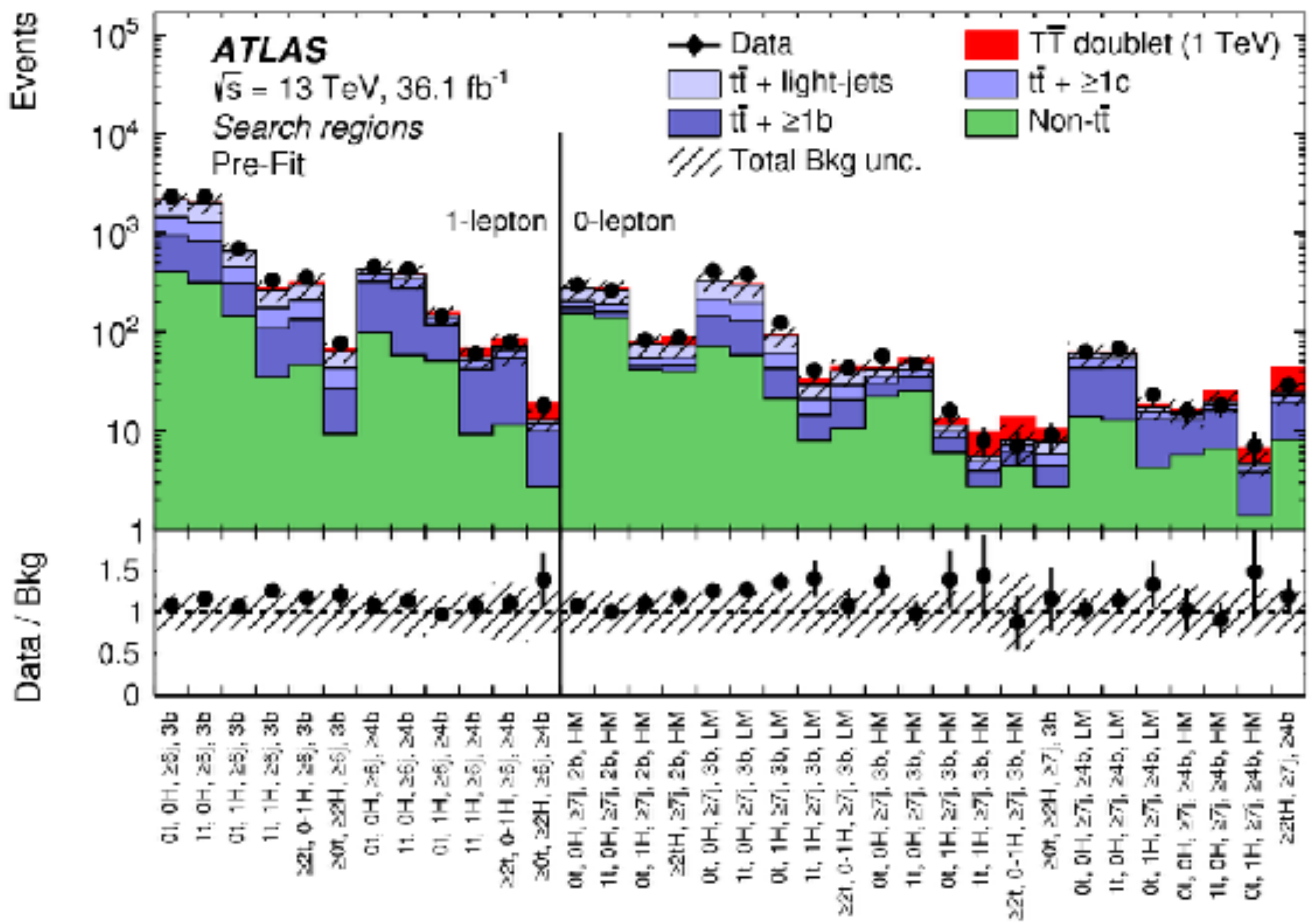
Vectorlike Quarks

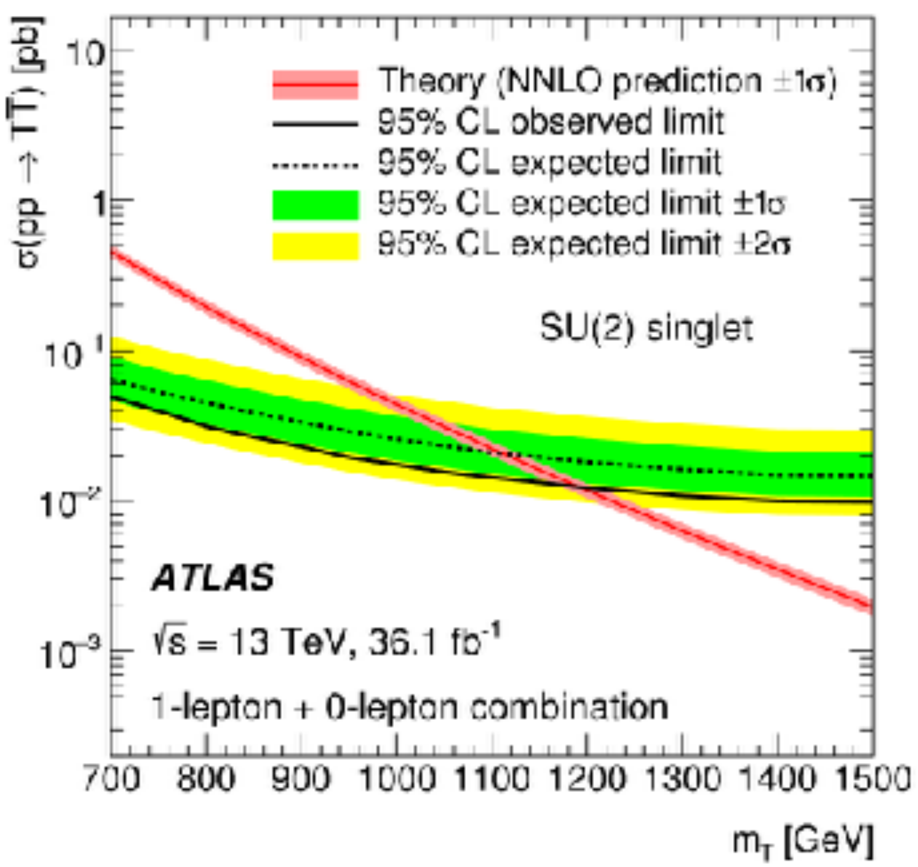
- This signature forces us to an extreme phase space not just of energy but of ***multiplicity***



Vectorlike Quarks

- …yet we manage

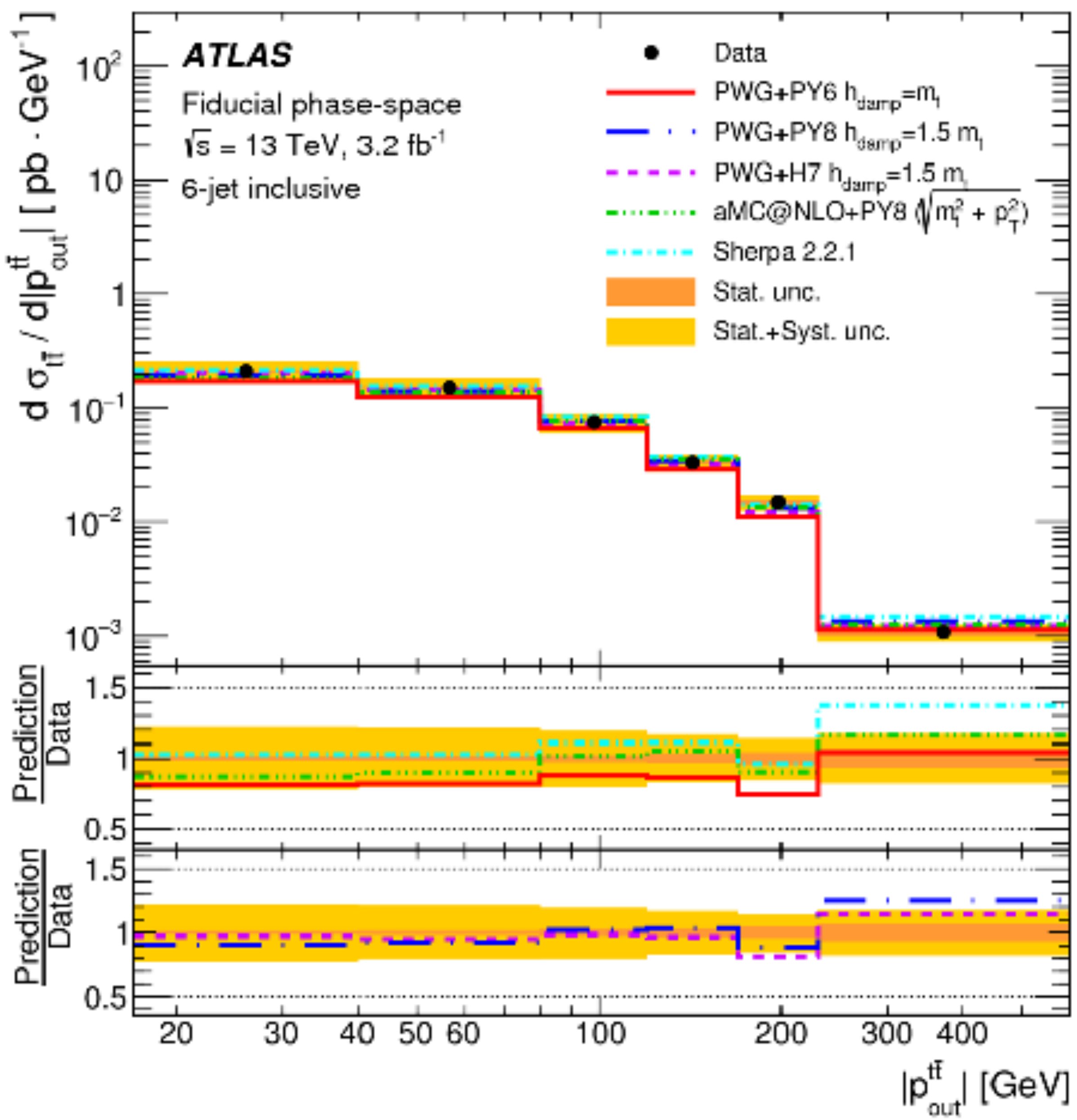




arXiv:1803.09678

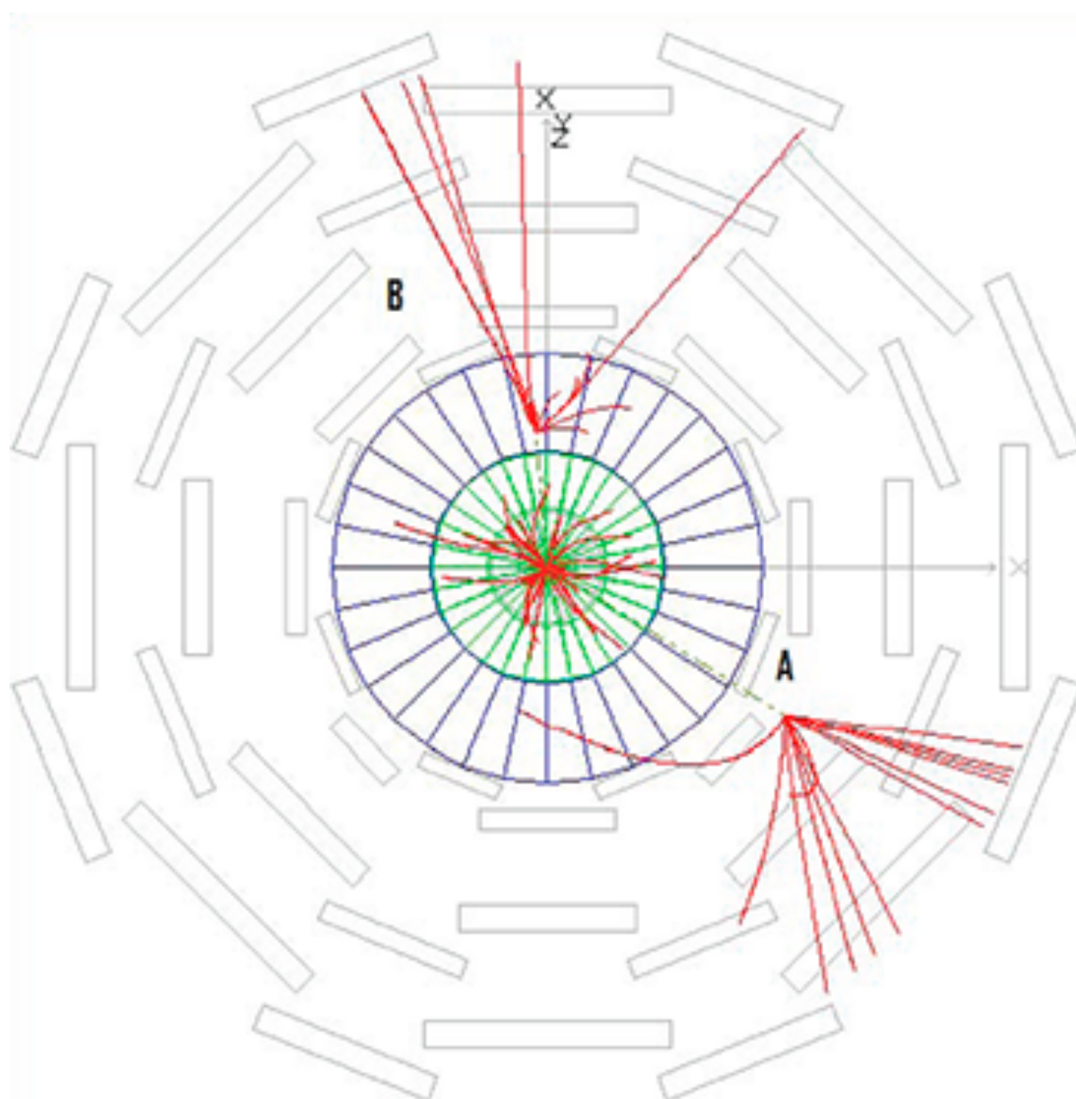
Top Measurements

- Impressive top measurements are critical to the program



Somethings left out

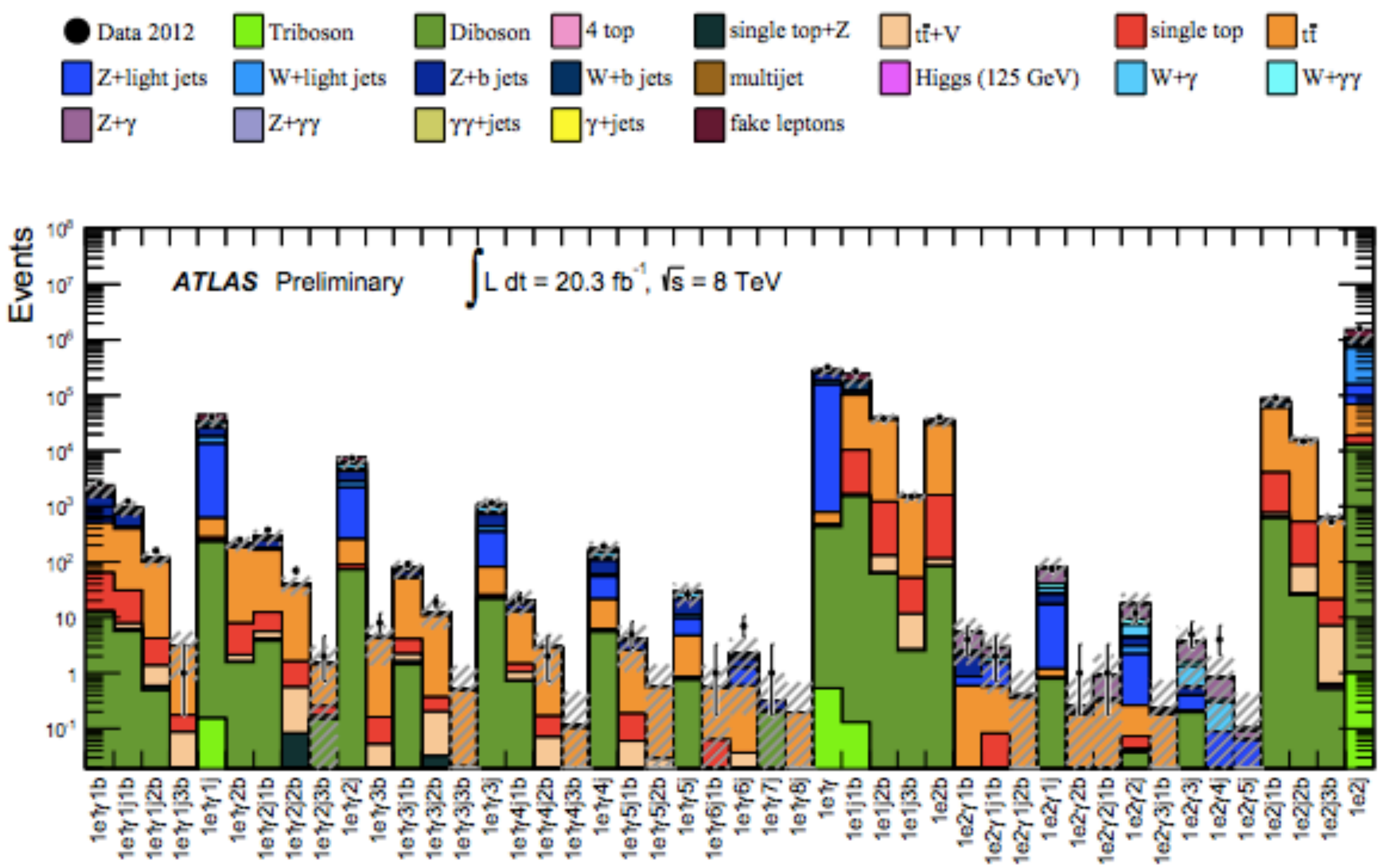
- Unusual signatures i.e. long-lived particles - see recent seminar from G. Watts (link)



Somethings left out

- General Search (ATLAS), MUSIC (CMS) - important parts of the search program that deserve more time

- *How do we ensure we looked everywhere?*



Somethings left out

- Flavor anomalies … more information needed!!
  - B-physics anomalies could be explained by LQ-like or Z'-like mediators
    - TeV-scale and 3rd generation favored
  - LQ could also explain g-2

Quark level transition b $\to c\ell\bar{\nu}$

R_D, R_{D*}: combined $\sim 4\sigma$ deviation

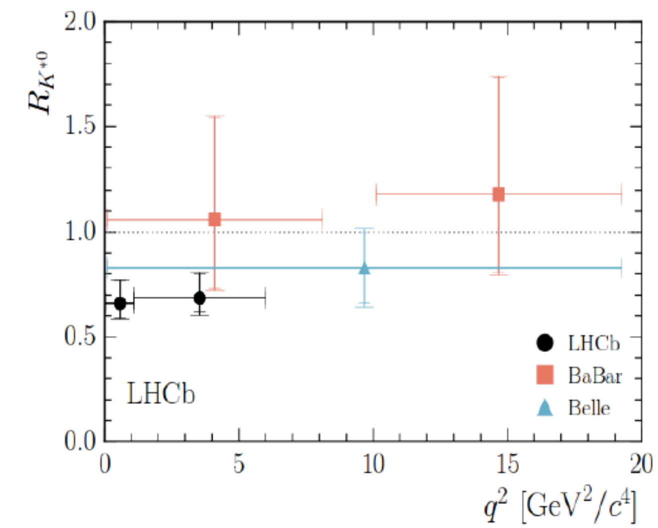
$$R^{\tau/\ell}_{D^{(*)}} = \frac{\Gamma(\bar{B} \to D^{(*)}\tau\bar{\nu})}{\Gamma(\bar{B} \to D^{(*)}\ell\bar{\nu})}$$

Quark level transition b $\to s\ell\bar{\ell}$

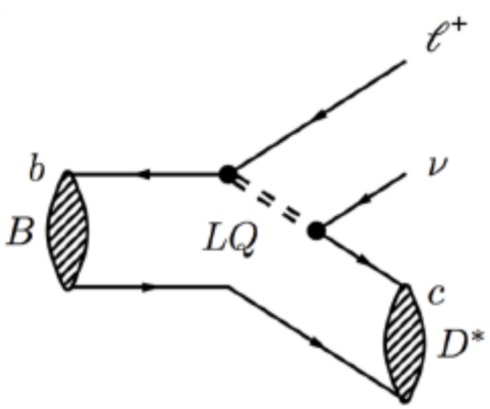
R_K, R_{K*}: $\sim 2.5\ \sigma$ deviation (LHCb)

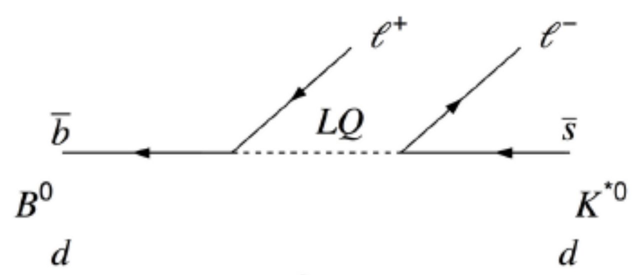
$$R_{K^{(*)}} = \frac{\Gamma(\bar{B} \to \bar{K}^{(*)}\mu^+\mu^-)}{\Gamma(\bar{B} \to \bar{K}^{(*)}e^+e^-)}$$

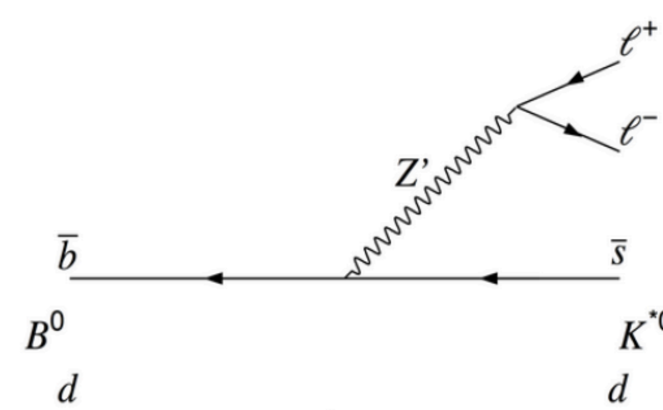
$B^0 \to K^{\star 0}\mu^+\mu-$ angular analysis:
3.4 σ deviation (LHCb) (Click Me)



Possible new contribution in the
$b \to s\ell\ell$ transition
in BSM scenarios involving Z'







Conclusion

- Collected over 80/fb of data and analyzed a lot of 36/fb dataset
  - ~140/fb expected by the end of this year
- **Null results** so far but there is still much work to be done!
- To push the frontier of knowledge we need to:
  - Be **creative** and improve our experimental tools (taggers!)
  - **Transition** from search mode to measurement mode.
  - With **theorists**, improve knowledge of SM processes by also providing measurements (backgrounds!)
  - Expand the search to all possible final states and signatures - ***we do not know where new physics is hiding!!***