Discovery Center
Niels Bohr Institute
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New Physics Searches at the LHC

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On behalf of the
ATLAS and CMS Collaborations

15th August 2016

Outline

- Setting the landscape
  - Why New Physics? Why at the LHC? How at the LHC?
- Resonance Searches
- Mono-objects + Missing Energy; Dark Matter
- Super-symmetry Searches
- Rounding off

Disclaimer

- Enormous subject
  - more than 80 "*Search for…*" papers submitted by LHC experiments to the recent ICHEP conference
- Can really only just scratch the surface even in a 45 min talk

Setting the Landscape

Why look for "New Physics" ?

With the the discovery of the Higgs Boson, the Standard Model is now a

- ✓ complete
- ✓ coherent
- ✓ predictive

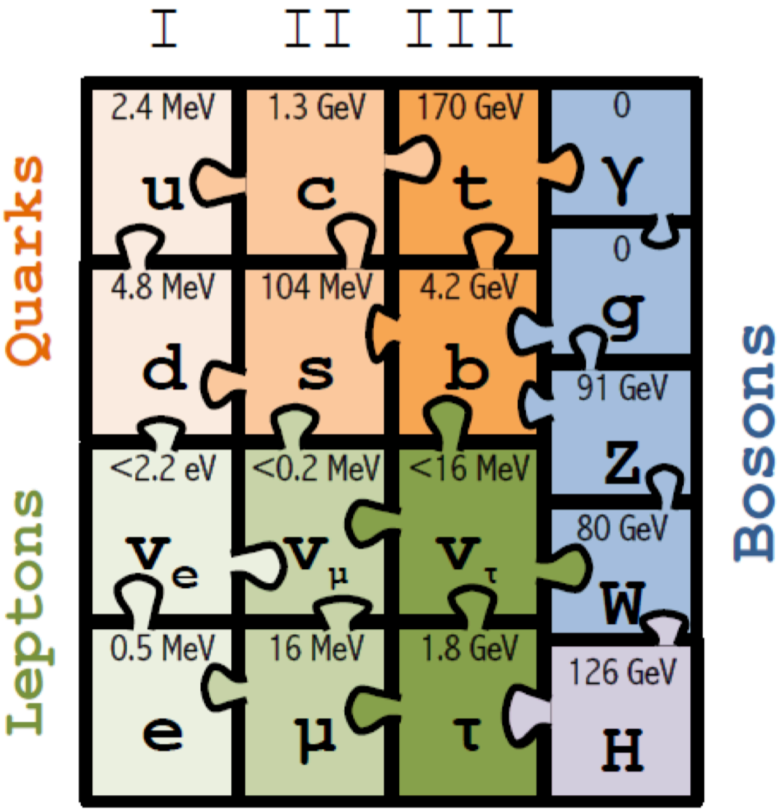
theory of particles and their interactions.

Are we done?

We are certain there exist other particles and/or phenomena.

The Standard Model does **not** explain:

- Dark Matter
- Matter/anti-matter asymmetry
- Neutrino masses
- ...and it may have problems explaining the light Higgs mass (hierarchy problem)

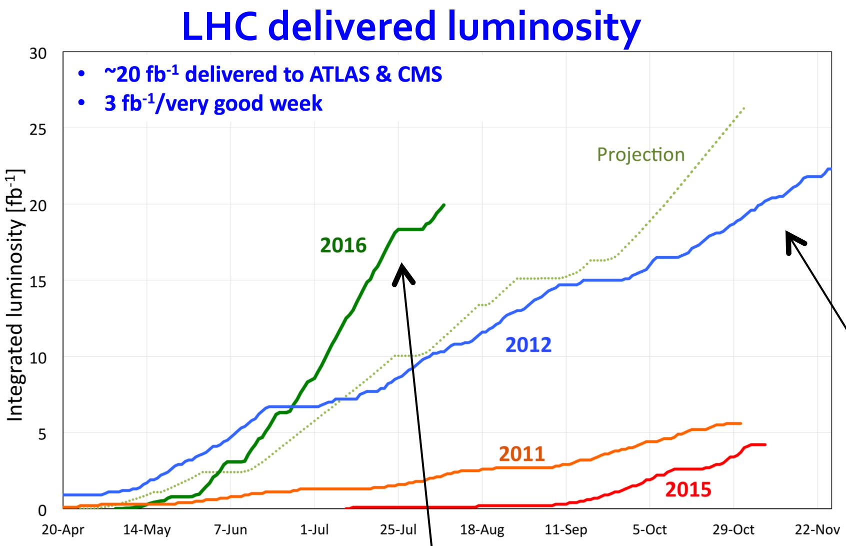


(c) Sfyrla

Only one way to find out: Go and look!

Large Hadron Collider

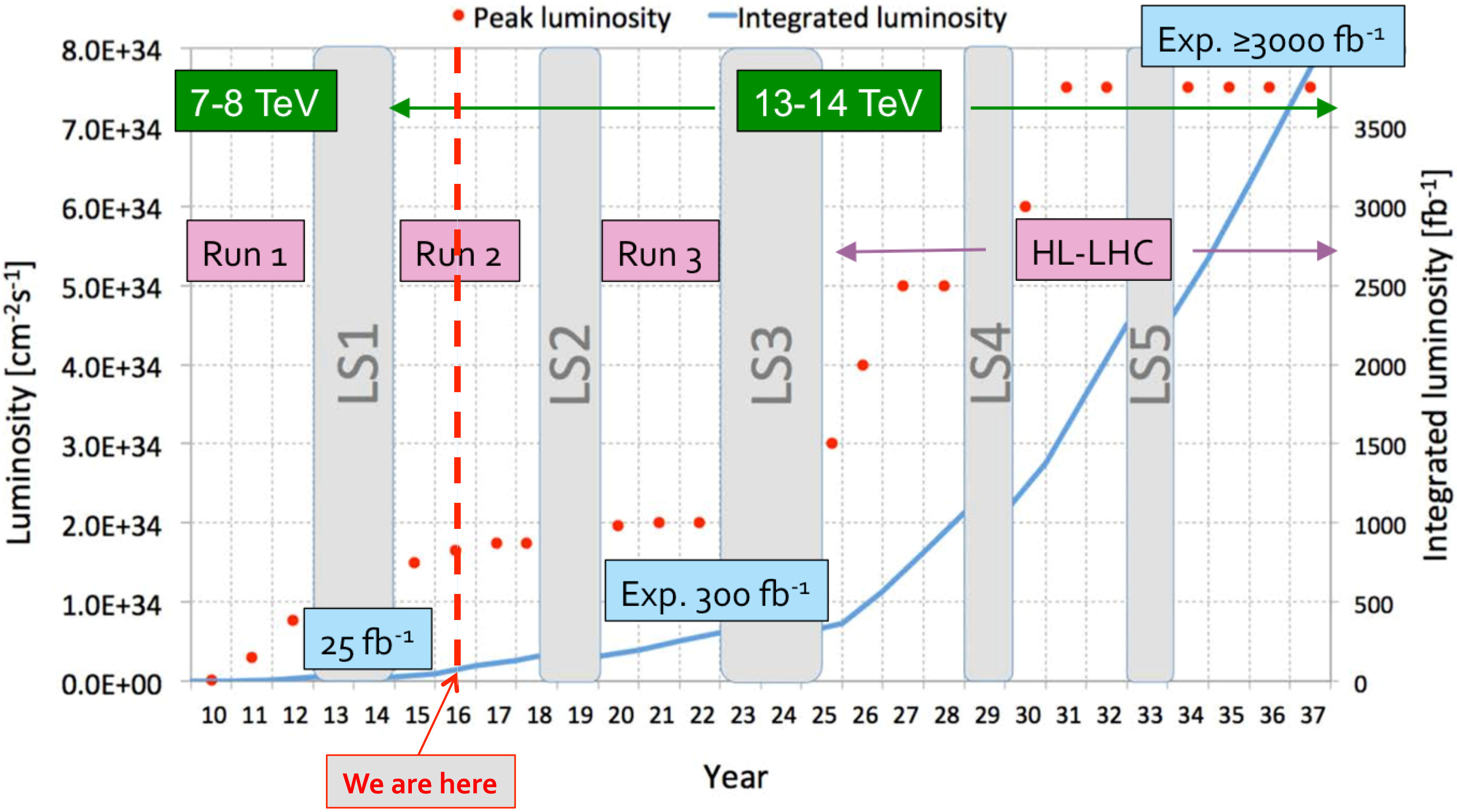
- Proton-proton collisions @ 13 TeV
  - Instantaneous luminosity of ~ 10^{34} cm^{-2} s^{-1}
  - About 30 proton-proton interactions every 25 ns
    - More then 1 GHz of proton-proton collisions !



2016: fantastic LHC performance @ 13 GeV: 20 fb^{-1} per experiment so far

2012: 20 fb^{-1} per exp. @ 8 TeV

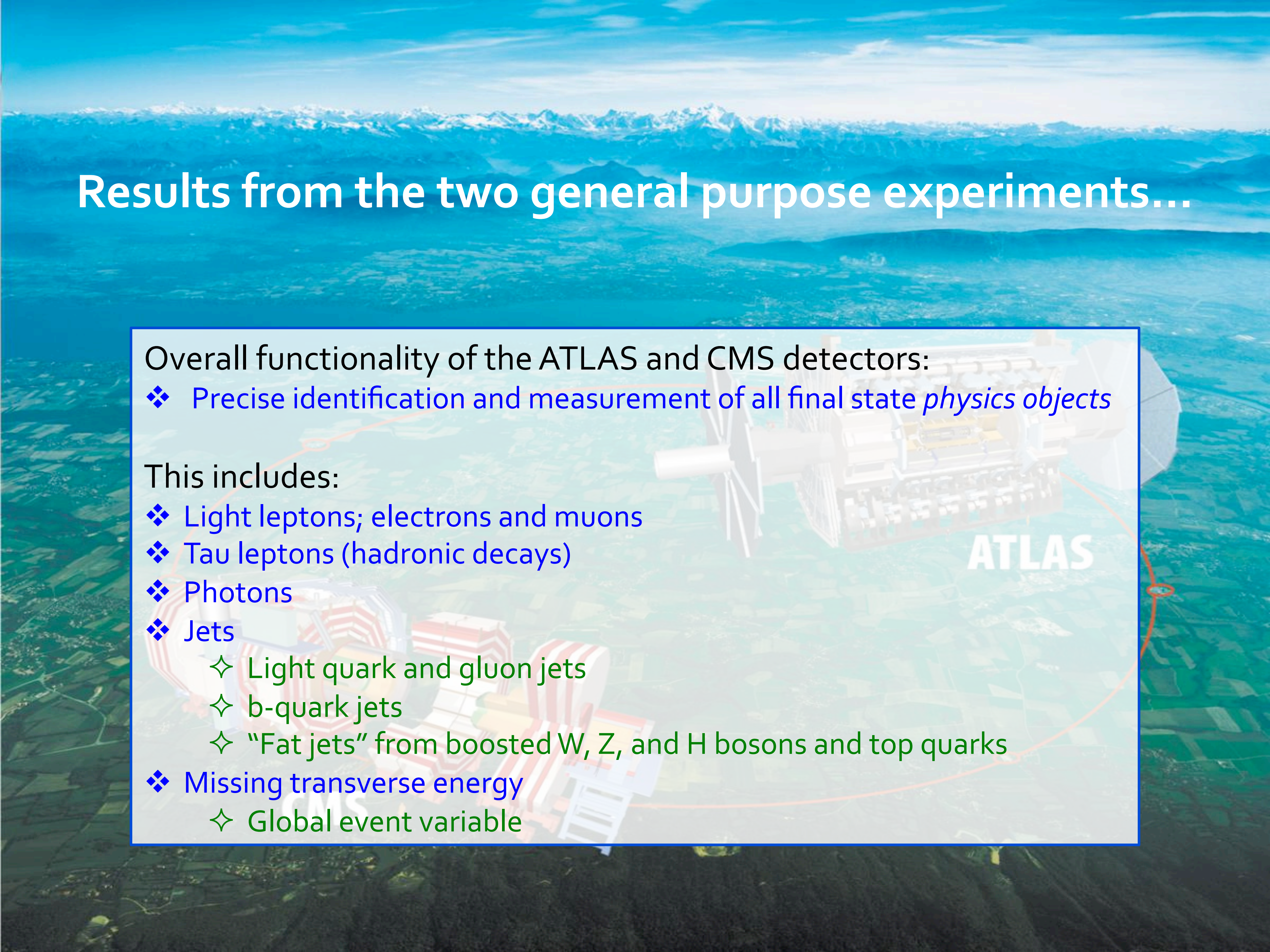
LHC Schedule



Still at the beginning of a long journey…

Results from the two general purpose experiments…

Results from the two general purpose experiments…



Overall functionality of the ATLAS and CMS detectors:

- Precise identification and measurement of all final state *physics objects*

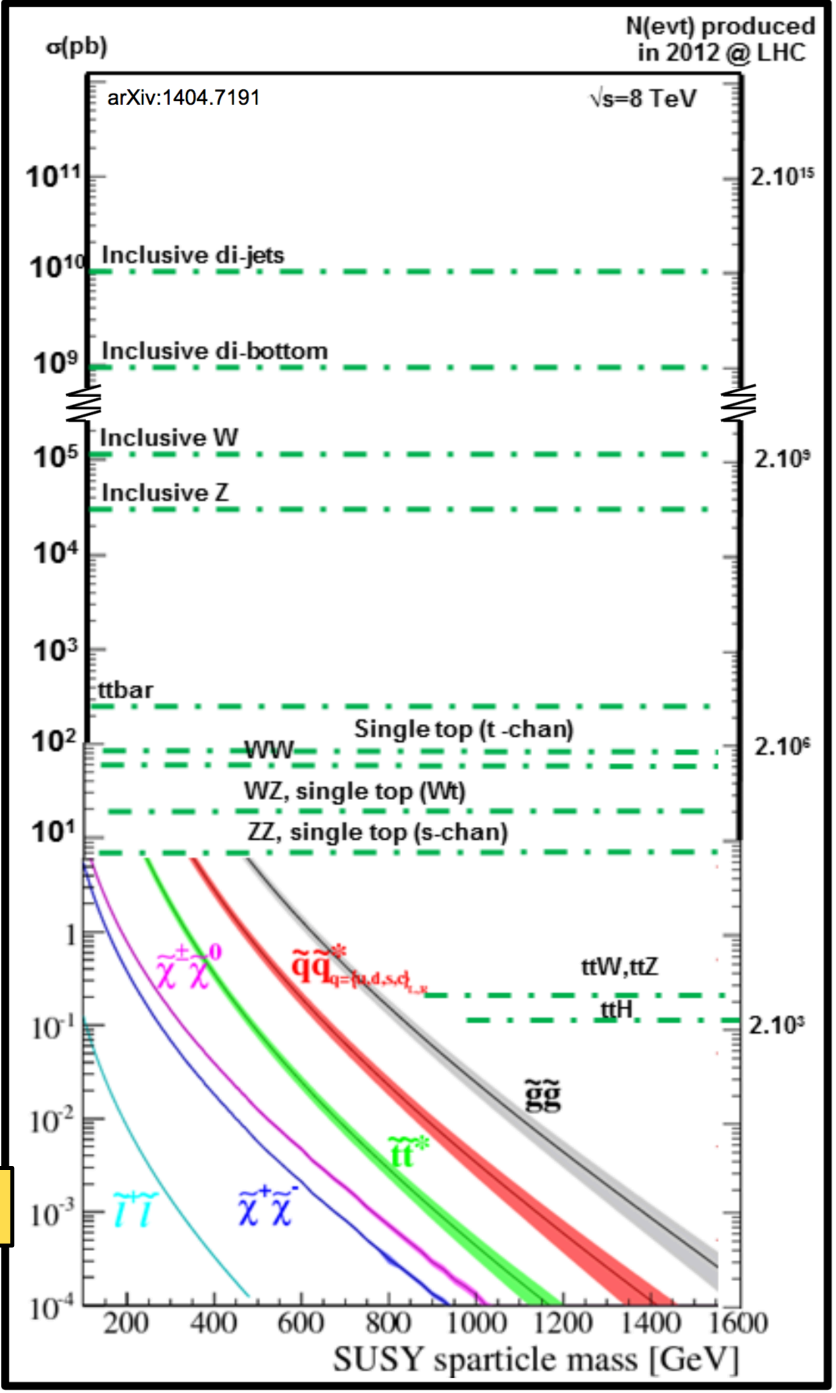
This includes:

- Light leptons; electrons and muons
- Tau leptons (hadronic decays)
- Photons
- Jets
    - Light quark and gluon jets
    - b-quark jets
    - "Fat jets" from boosted W, Z, and H bosons and top quarks
- Missing transverse energy
    - Global event variable

Challenges in Finding New Physics at the LHC

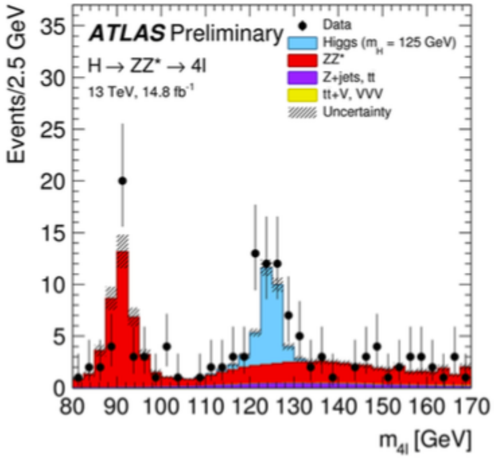
- Don’t know where to look
  - Have good guesses
    - Example models, e.g. Supersymmetry
  - Cast as wide a net as possible
- Have to cover broad phase space
  - Many different detector signatures
  - Large range of masses
  - Large span in production rates
- Production rates tiny compared to Standard Model processes

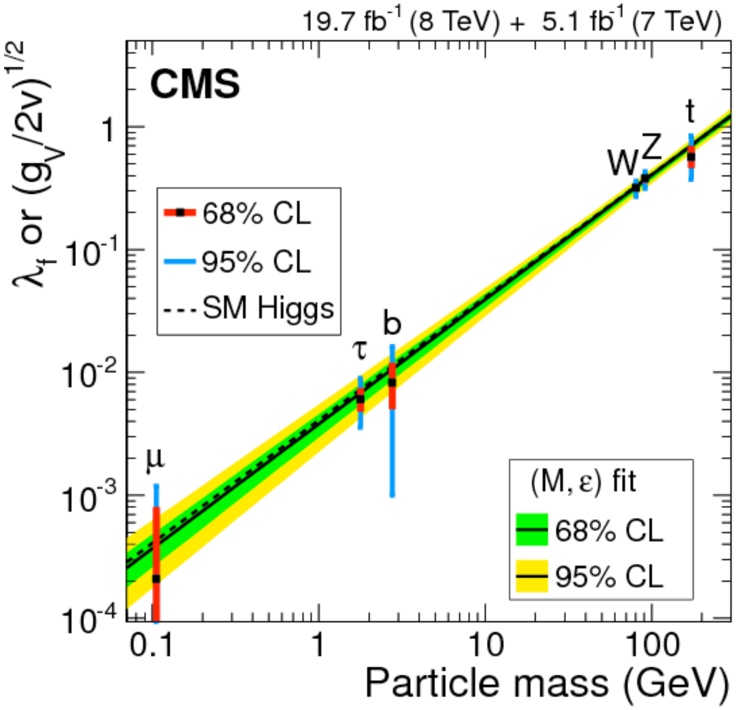
Example: SUSY



Lessons from Run-1 @ 8 TeV

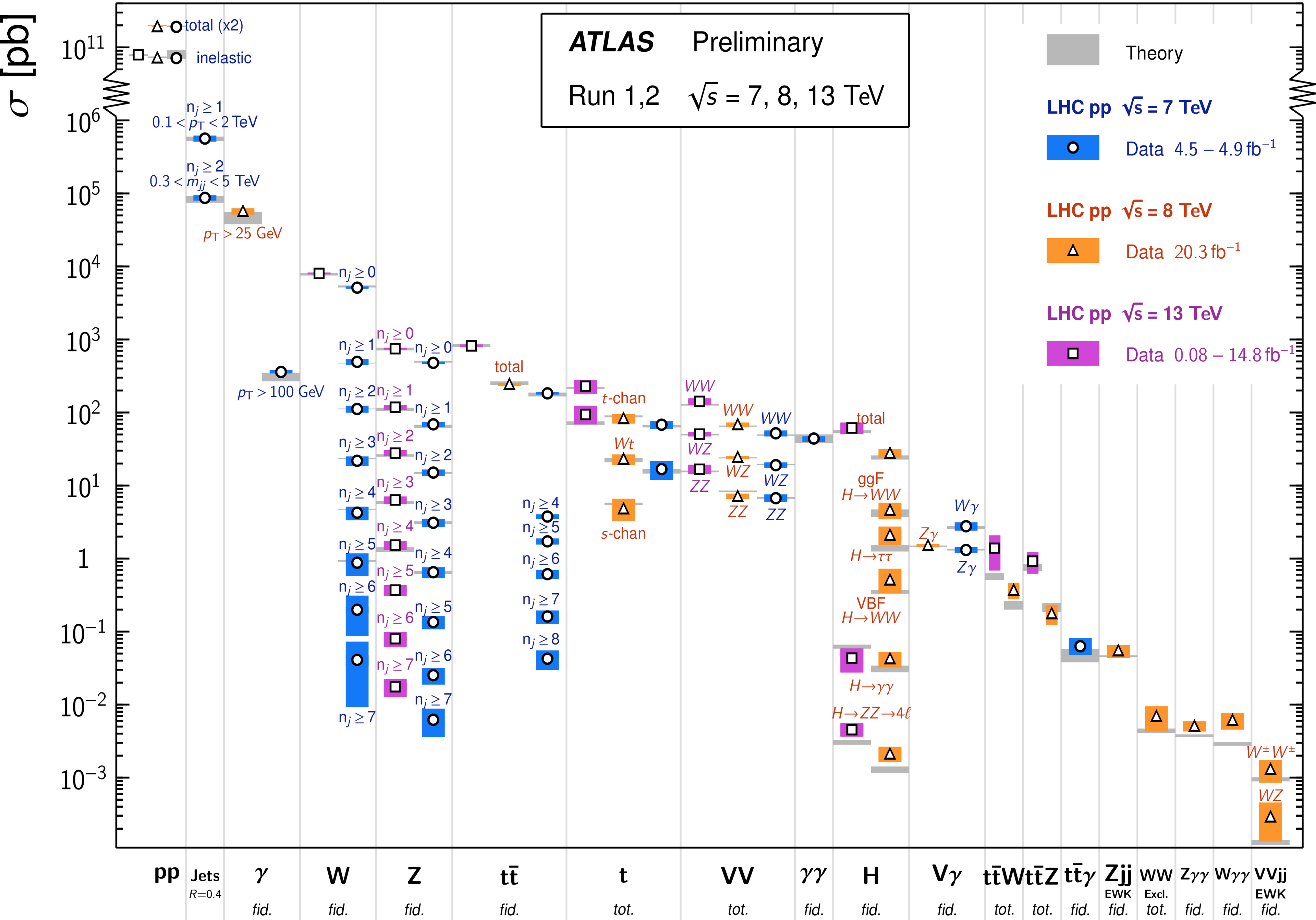
- There is a Higgs boson at 125 GeV
  - Its mass is compatible with indirect constraints from precision EW measurements
  - It is approximately Standard-Model-like (couplings, spin,…)
    - There could have been clear signs of new physics here
    - Now, it is an obvious lamppost to look under
- No clear indications of new physics
- Excellent understanding of
  - Detectors / Reconstruction / Calibration
  - Standard Model Physics



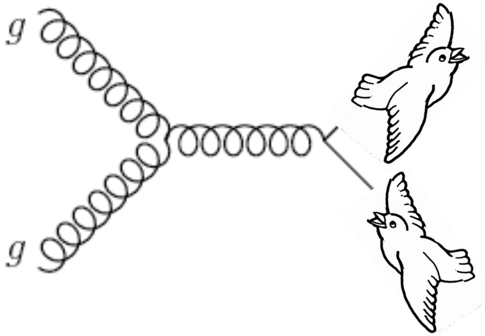


Standard Model Production Cross Section Measurements

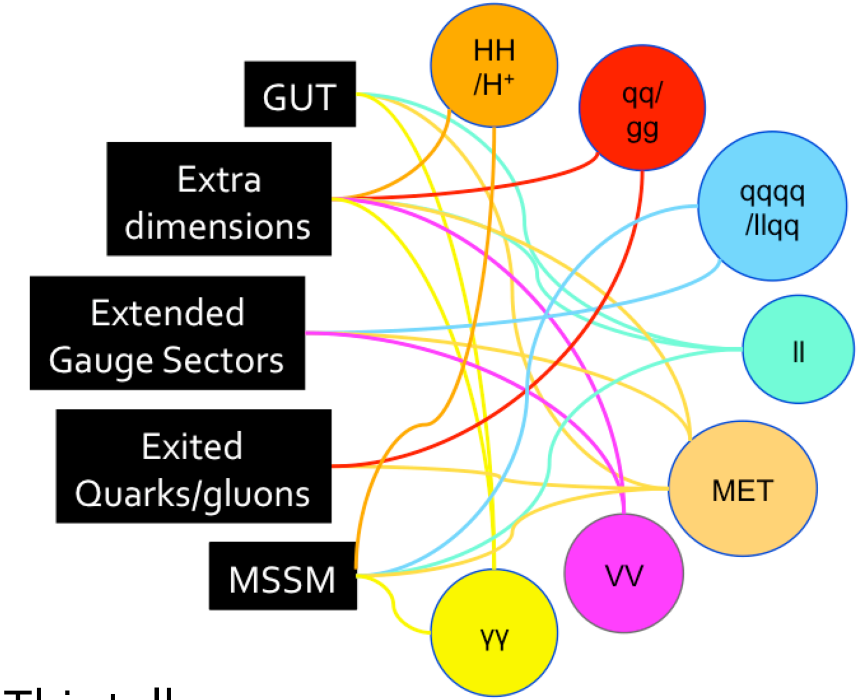
Status: August 2016



Direct New Physics Searches Overview



- Search for **new signatures** that are not produced in the SM
- Many possibilities to search for new physics at the LHC and interpret results



SUPERSYMMETRY

- High jet, lepton, photon multiplicity due to long decay chains
- Missing transverse energy due to undetected LSP

EXOTICS

- Everything which appears to have not SUSY signatures

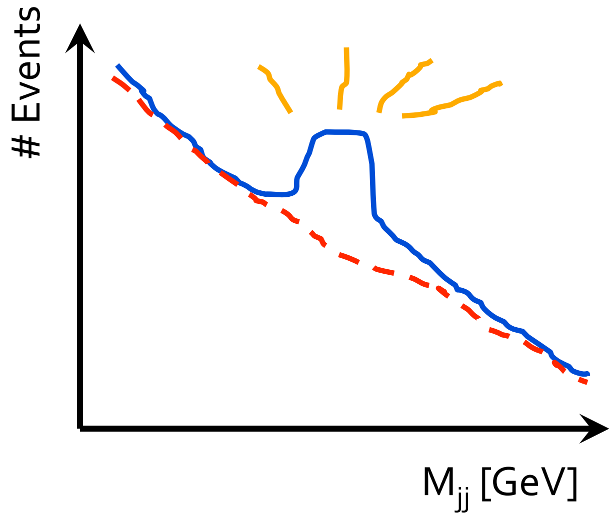
EXTENDED HIGGS SECTOR

- Rare decays of the Higgs and additional neutral/charged bosons

- This talk:
  - ❑ Most important principles and methods
  - ❑ Highlights and recent results from the 13 TeV data
  - ❑ Higgs boson topics covered by Ezio Torassa

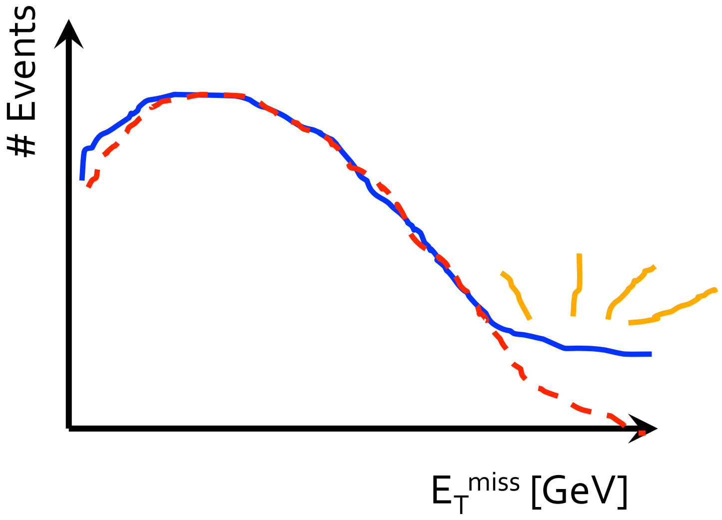
How New Physics could show up

Bump over a continuum background



- One of the most promising signatures
- Fully reconstructed signal over a smooth and well-understood background

Excess of some kinematic distribution (typically at high end)



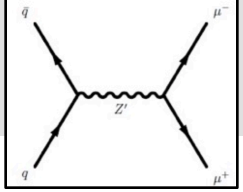
- Sensitive to high energetic objects
- Need to model precisely the tails of the kinematic distributions

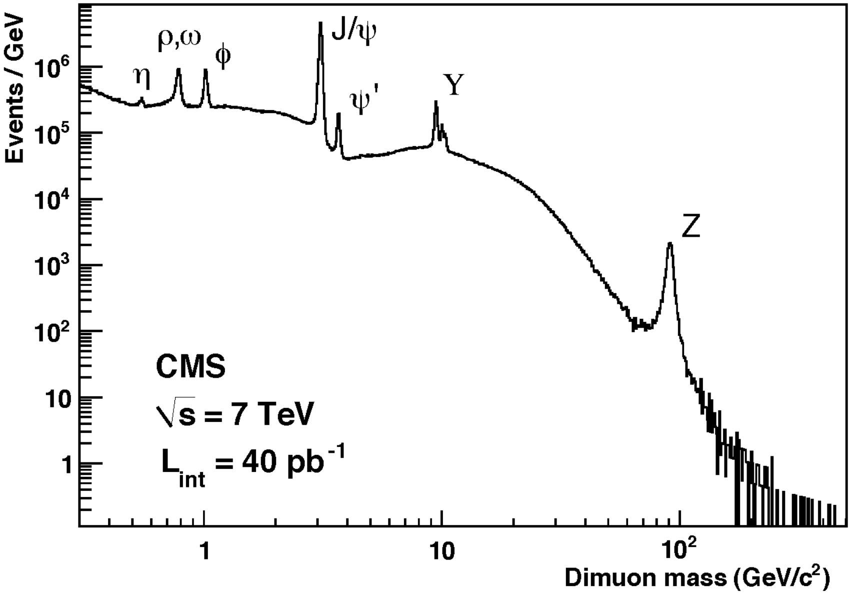
How to estimate the background?

Simulation will never get the answer completely correct → Estimate it from the only source that speaks the absolute truth: **the data!**

Resonance Searches

Di-lepton Signatures



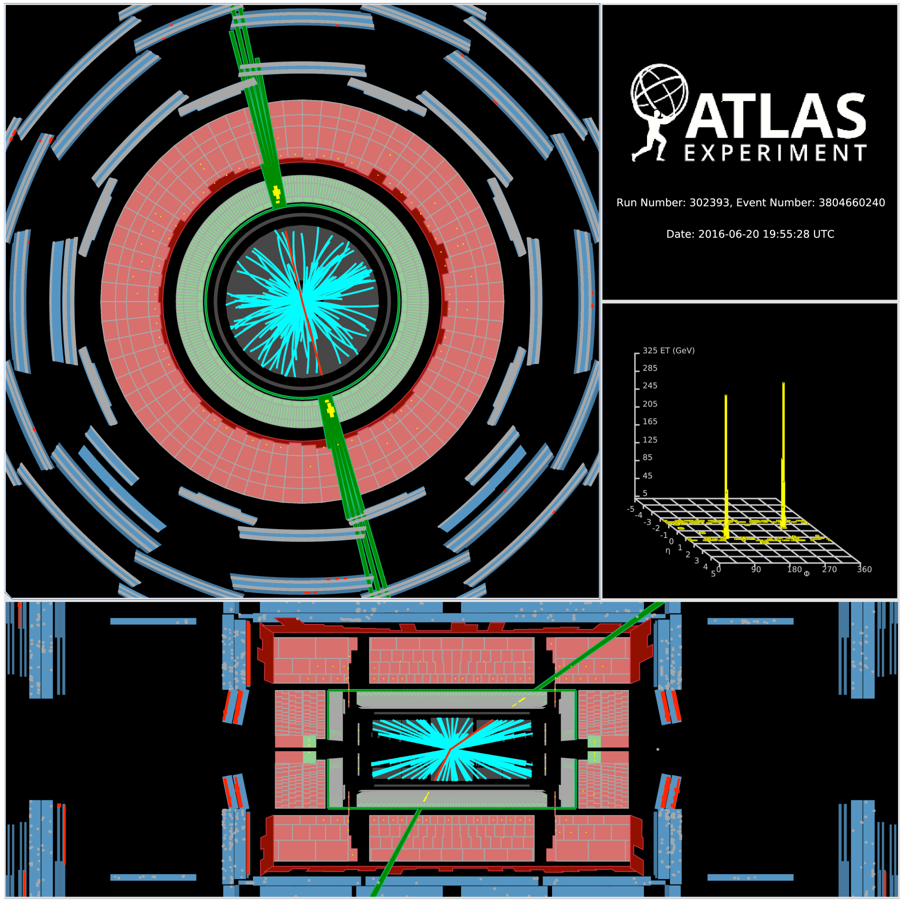


Traditional tool to probe narrow resonances

- ✧ Leptons: mainly e and μ, but also τ

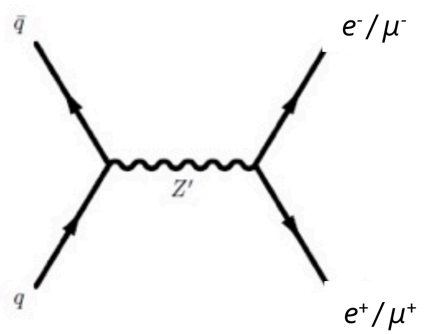
Two isolated leptons

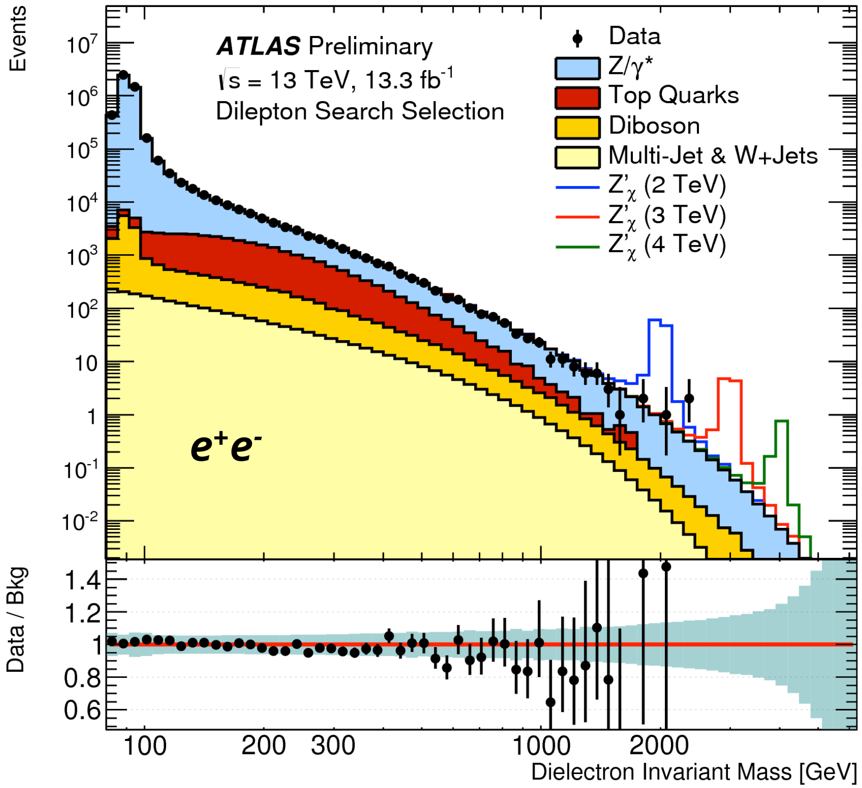
- ✧ Look for new "bump" at high mass
- ✧ Clean signature / low background
- ✧ Good mass resolution



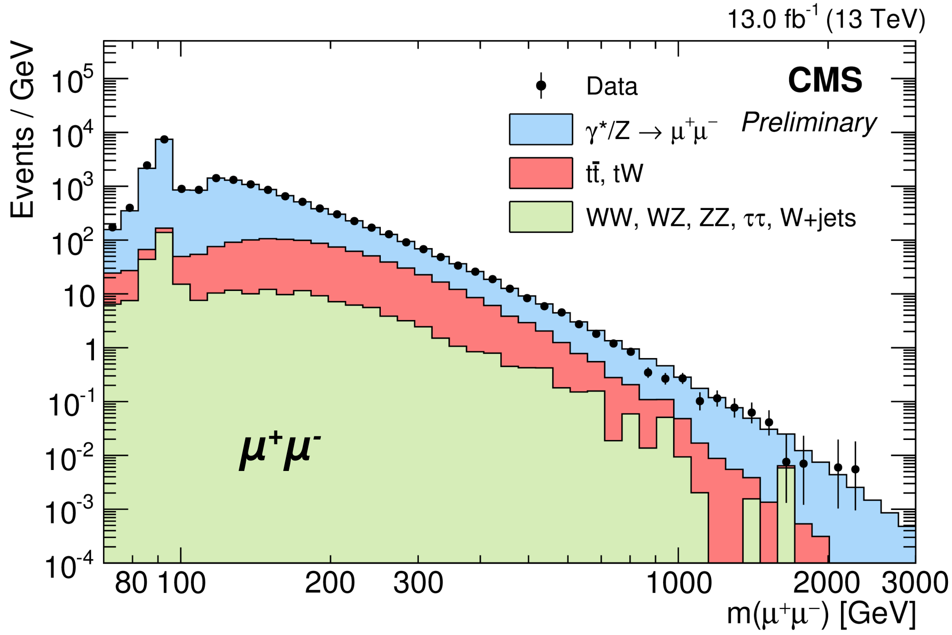
Highest di-lepton invariant mass observed in ATLAS: e^+e^- pair of 2.38 TeV

Di-leptons: Z′ → $\ell^+\ell^-$





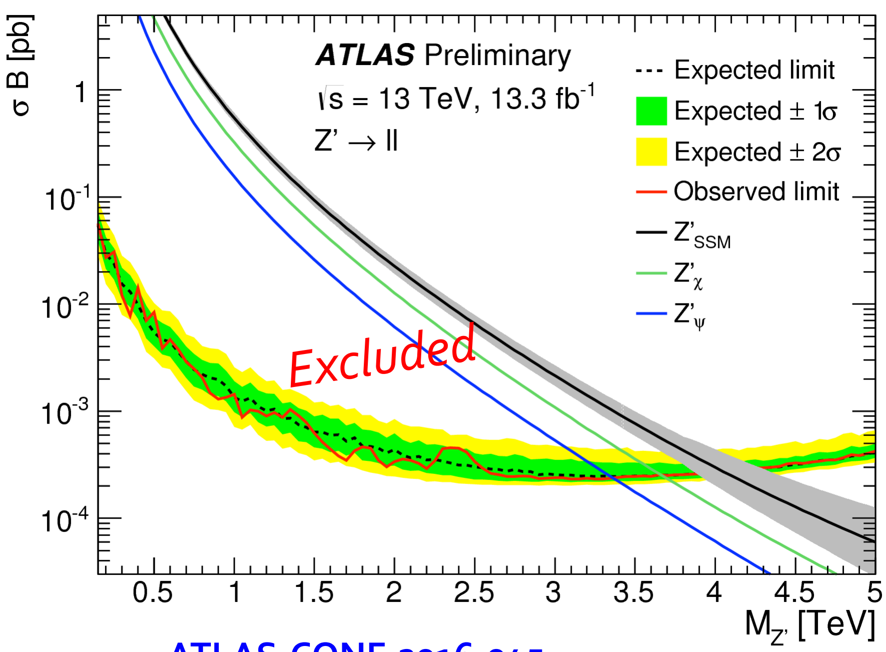
ATLAS-CONF-2016-045



CMS-PAS-EXO-16-031

Good agreement of data with expectation ➽ Set limits

Di-leptons: Z′ Limits



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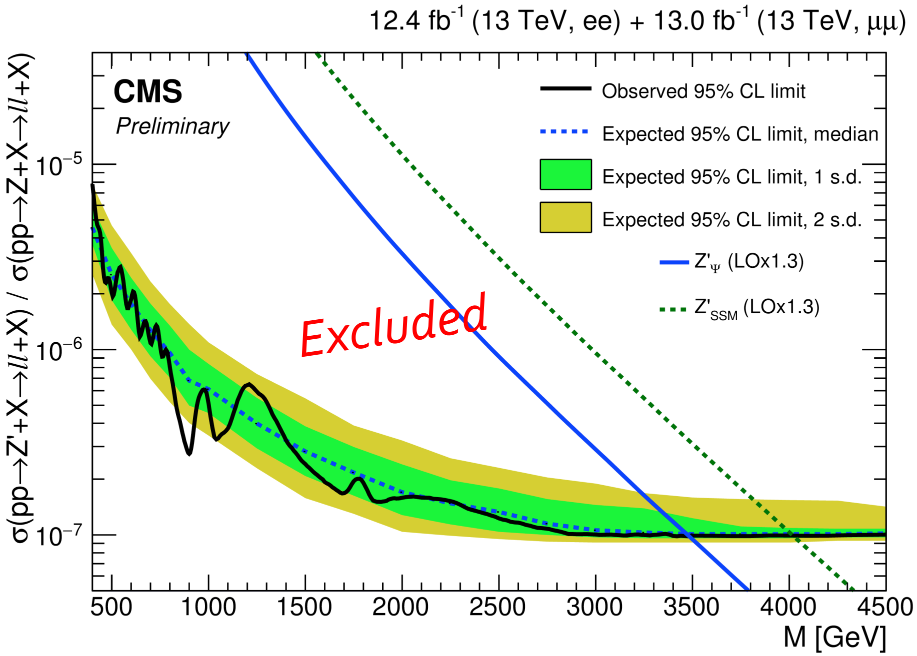


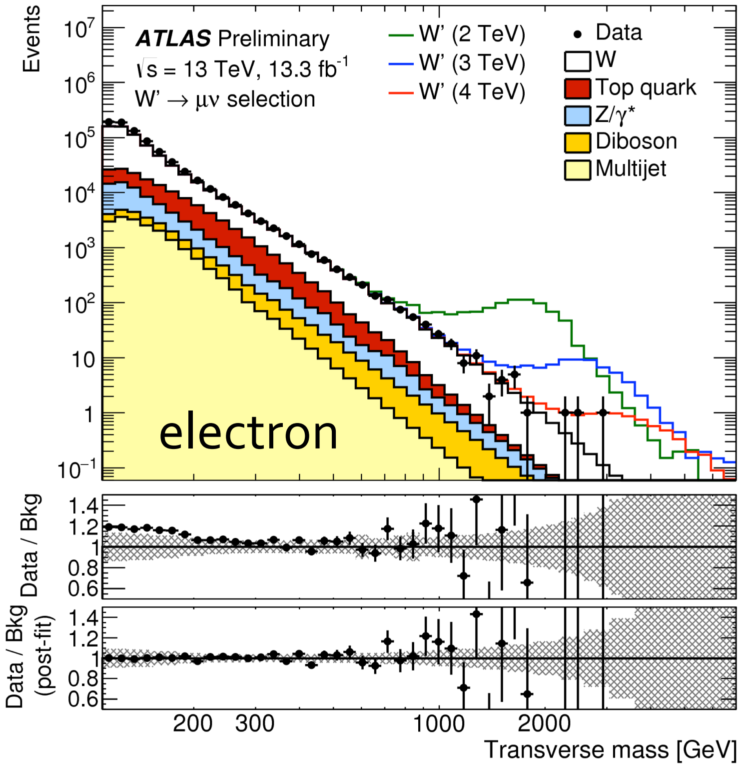
CMS-PAS-EXO-16-031

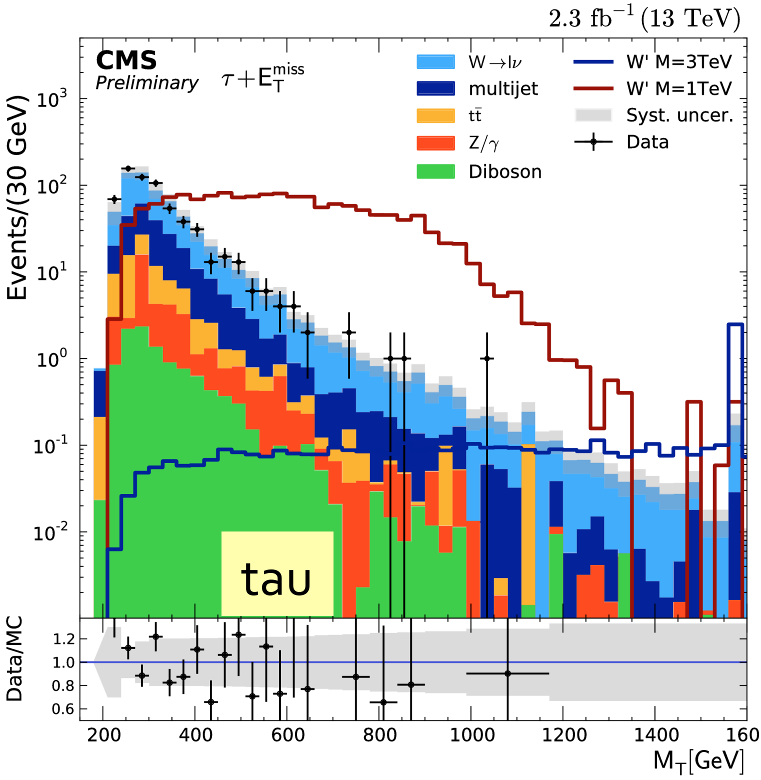
- Establish upper limit (95% CL) on σ × B.
- Compare to σ × B for models for Z′ production
  - Define lower mass limit on Z′ within models
- Typical mass limits 3.5 – 4.0 TeV

Di-leptons: $W' \rightarrow \ell\nu$

Signature: Isolated lepton + E_T^{miss}

ATLAS-CONF-2016-061





CMS-PAS-EXO-16-006

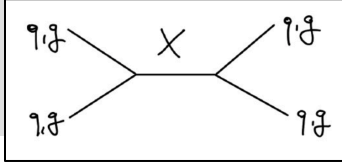
Light leptons e/μ:
Exclude W'_{SSM} below ~4.5 TeV
Sensitive also to non-resonant processes:

- ADD model of extra dimensions: dense KK states
- Contact interactions: low energy manifestation of high energy effects

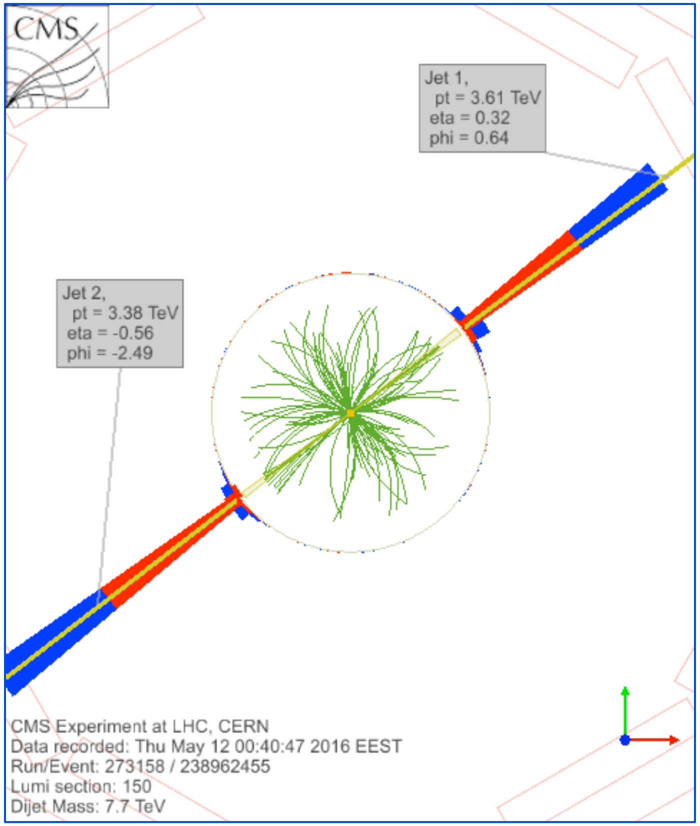
Tau leptons experimentally more difficult
Exclude W'_{SSM} below 3.3 GeV

Transverse mass: $m_T = \sqrt{2 p_T E_T^{miss}(1 - \cos\varphi_{\ell\nu})}$

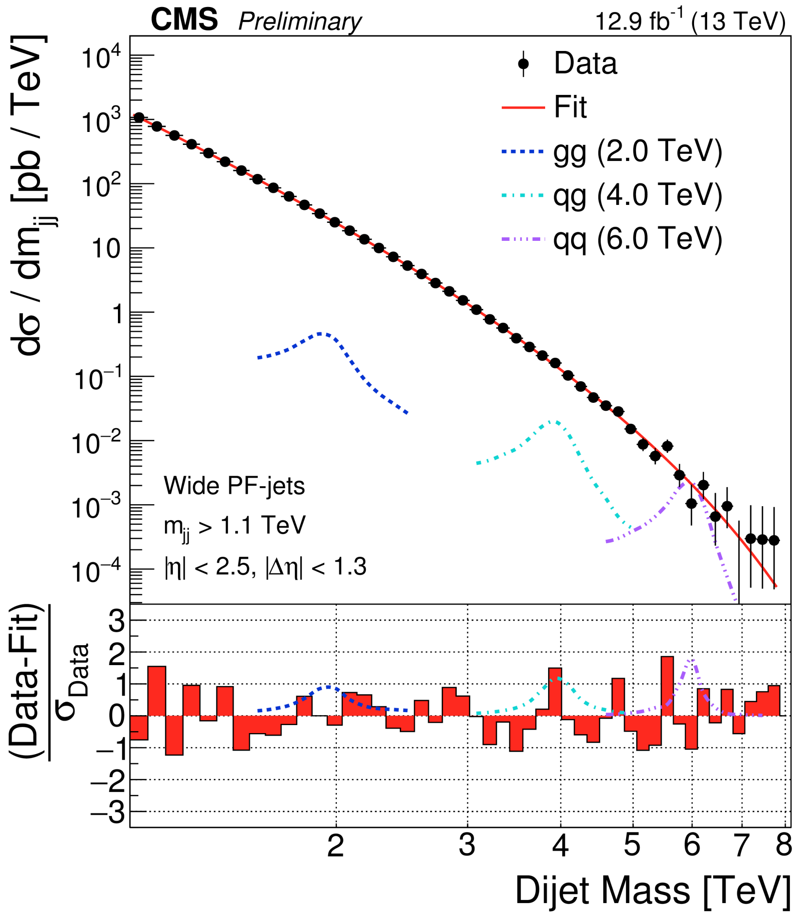
Di-jet Signatures



- **Classical bump search:** narrow resonance; up to widths 20-30% of the mass
- **Simple:** Data-driven, background parameterized by smooth function
- **Powerful**: strong production, high mass reach, generic search, many interpretations



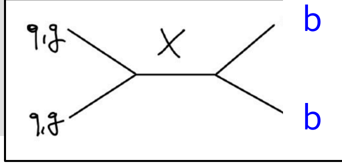
CMS: Highest di-jet invariant mass event: 7.7 TeV



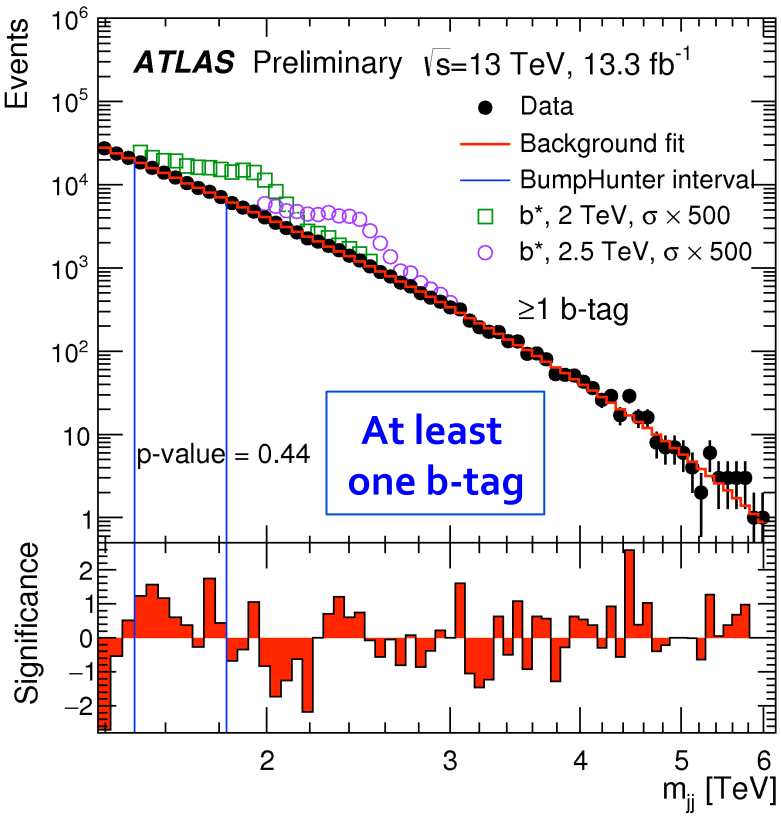
CMS-PAS-EXO-16-032

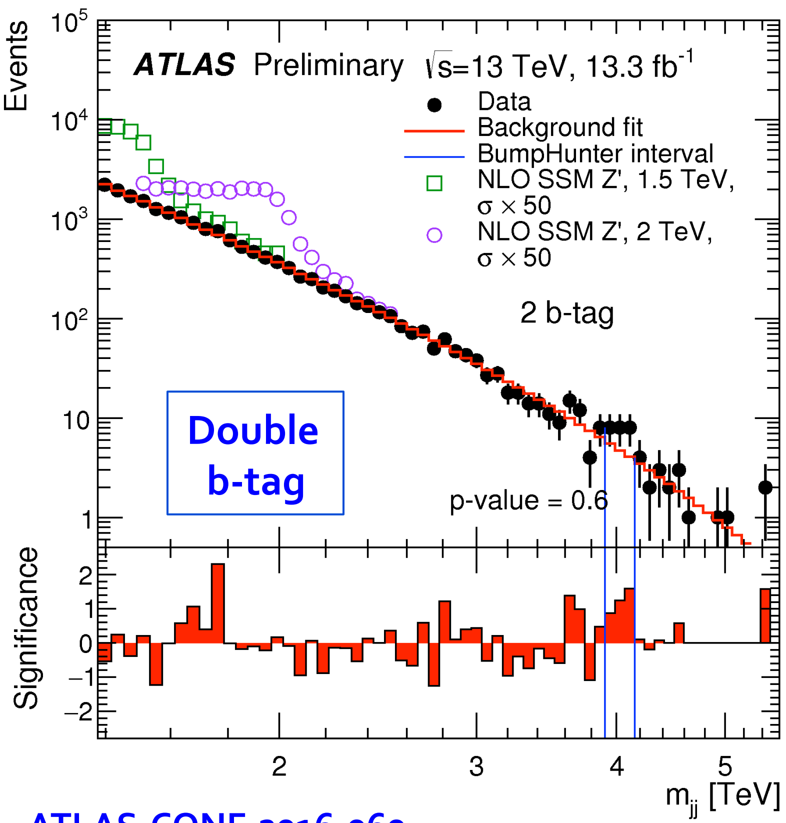
Exclude resonances with masses up to ~7 TeV depending on model

Di-jet Signatures – b-jets



- **Resonance search also for b-jets** – similar approach to di-jet resonance
- Separate search for ≥ 1 and ≥ 2 b-tagged jets
  - Benchmark models: b* → bg and Z′ → bb



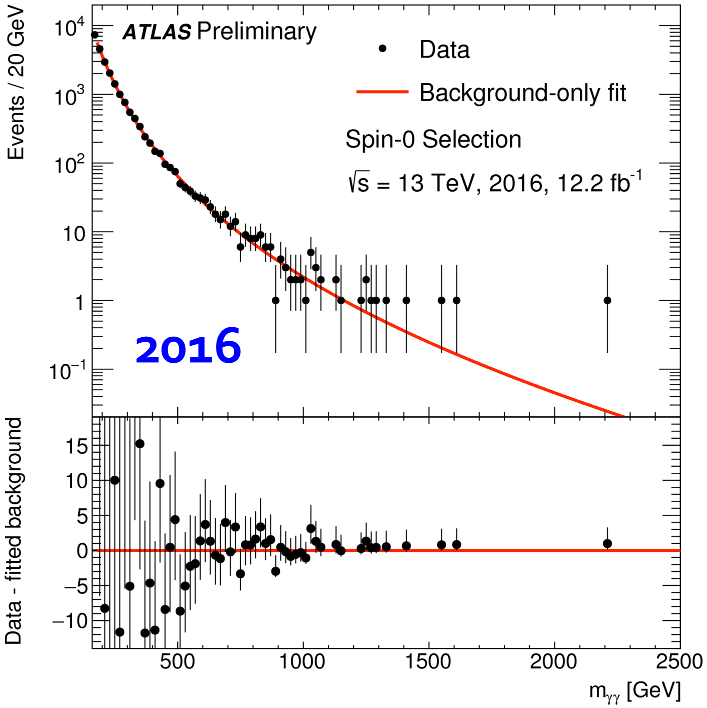


ATLAS-CONF-2016-060

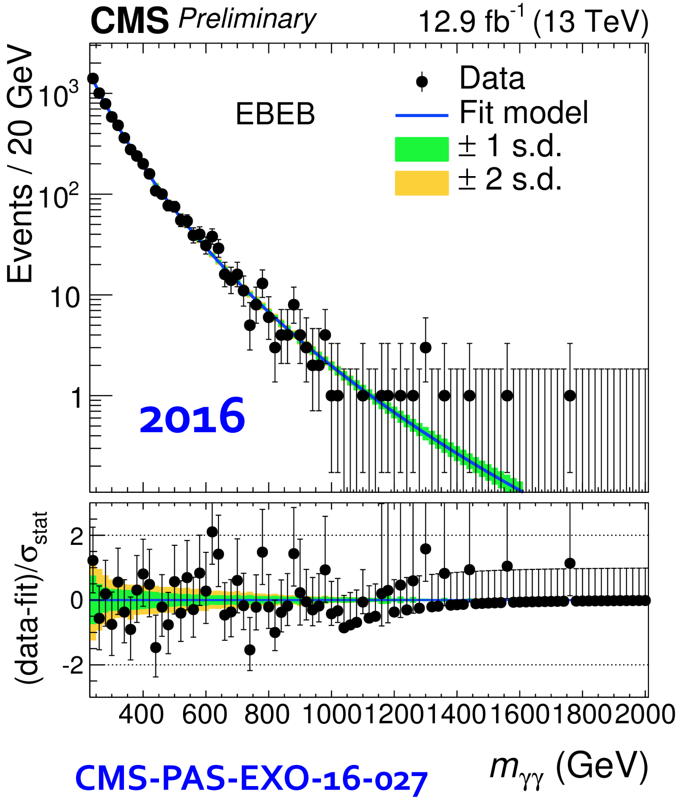
- Exclude excited b* in 1.4-2.3 TeV range
- Exclude Gaussian signal shape with 0.2–0.001 pb cross section in range 1.4–5.5 TeV

Di-photons

- Sensitive to spin-0 (heavy Higgs) and spin-2 (RS graviton) resonances
- Clean topology with well understood SM γγ background (Higgs searches)
- Challenge is photon reconstruction and ID at high energies



ATLAS-CONF-2016-059



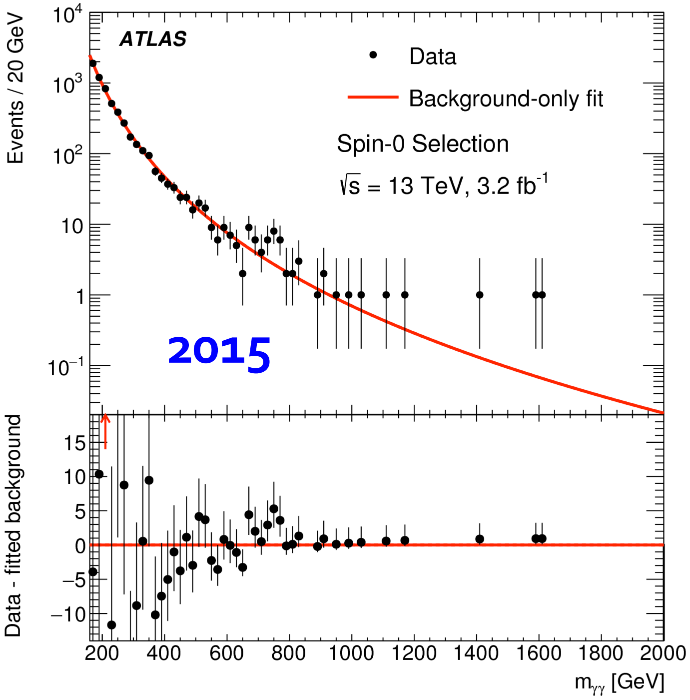
CMS-PAS-EXO-16-027

- Data consistent with background-only hypothesis over the full mass range

Di-photons flashback

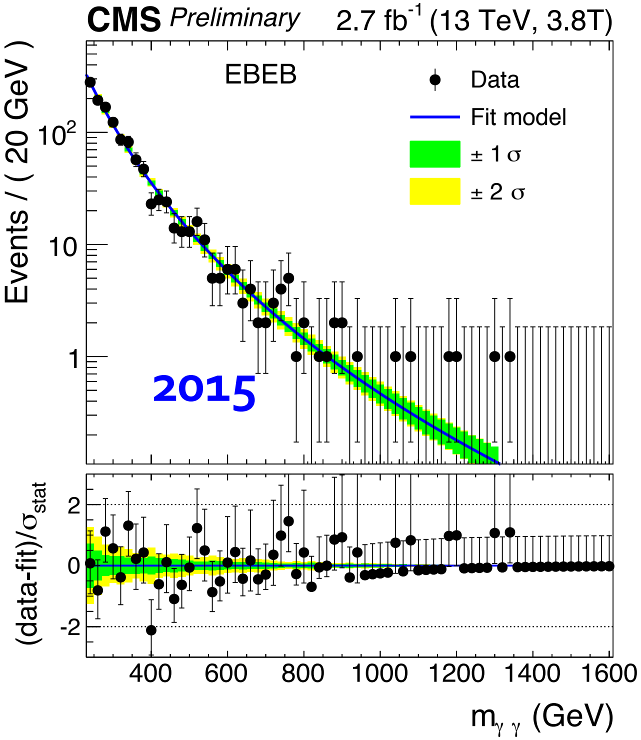
- In 2015 there were indeed tantalizing hints of an excess around 750 GeV

arXiv:1606.03833



ATLAS (2015):

- 3.9 σ local, 2.0 σ global significance for a broad excess at $m_{\gamma\gamma}$ = 750 GeV



Phys.Rev.Let. 117(2016), no. 5, 051802

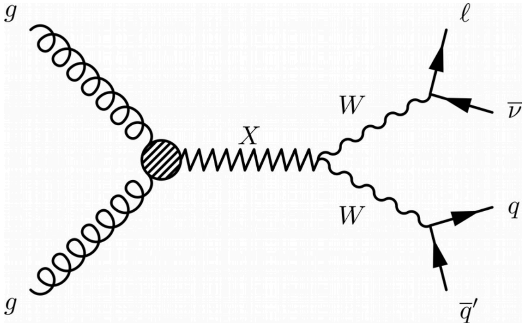
ATLAS (2015):

- 2.9 σ local significance for $m_{\gamma\gamma}$ = 760 GeV

- As demonstrated, this is not confirmed by the larger dataset of 2016

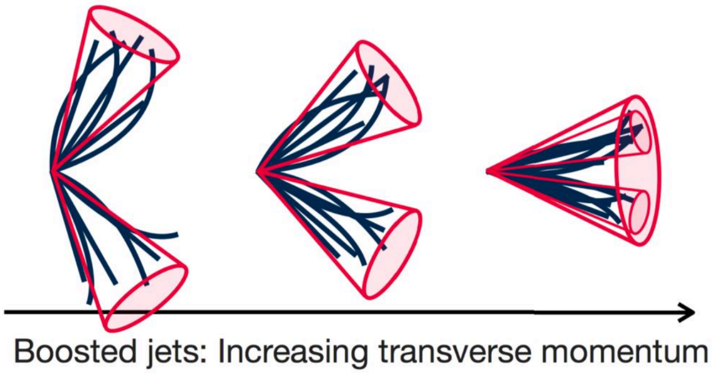
Di-bosons – W/Z

- Search for high-mass objects decaying to pairs of vector bosons V = W, Z

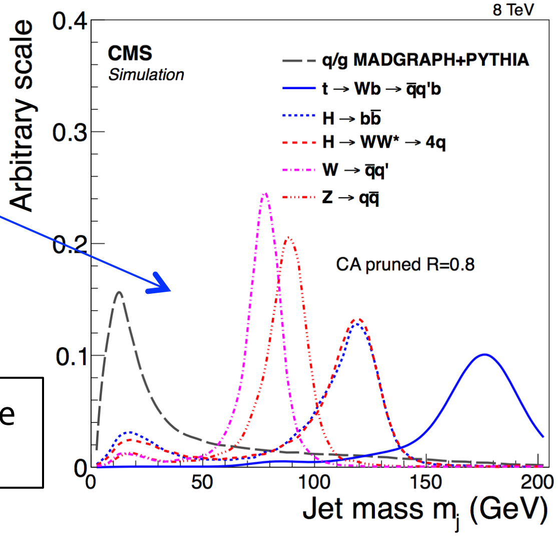


BR of V	W	Z
Leptons (e/μ)	22%	7%
Hadrons (and τ)	78%	73%
Neutrinos	-	20%

- At high masses
  - Backgrounds fall steeply
  - Hadronic decays (dominant) become increasingly more sensitive
- Hadronic decay products become collimated at high W/Z boosts
  - Detected as a single ***fat jet***
    - Boson tagging: Analyse ***fat jet*** substructure, derive jet mass



Difficult to separate between W and Z



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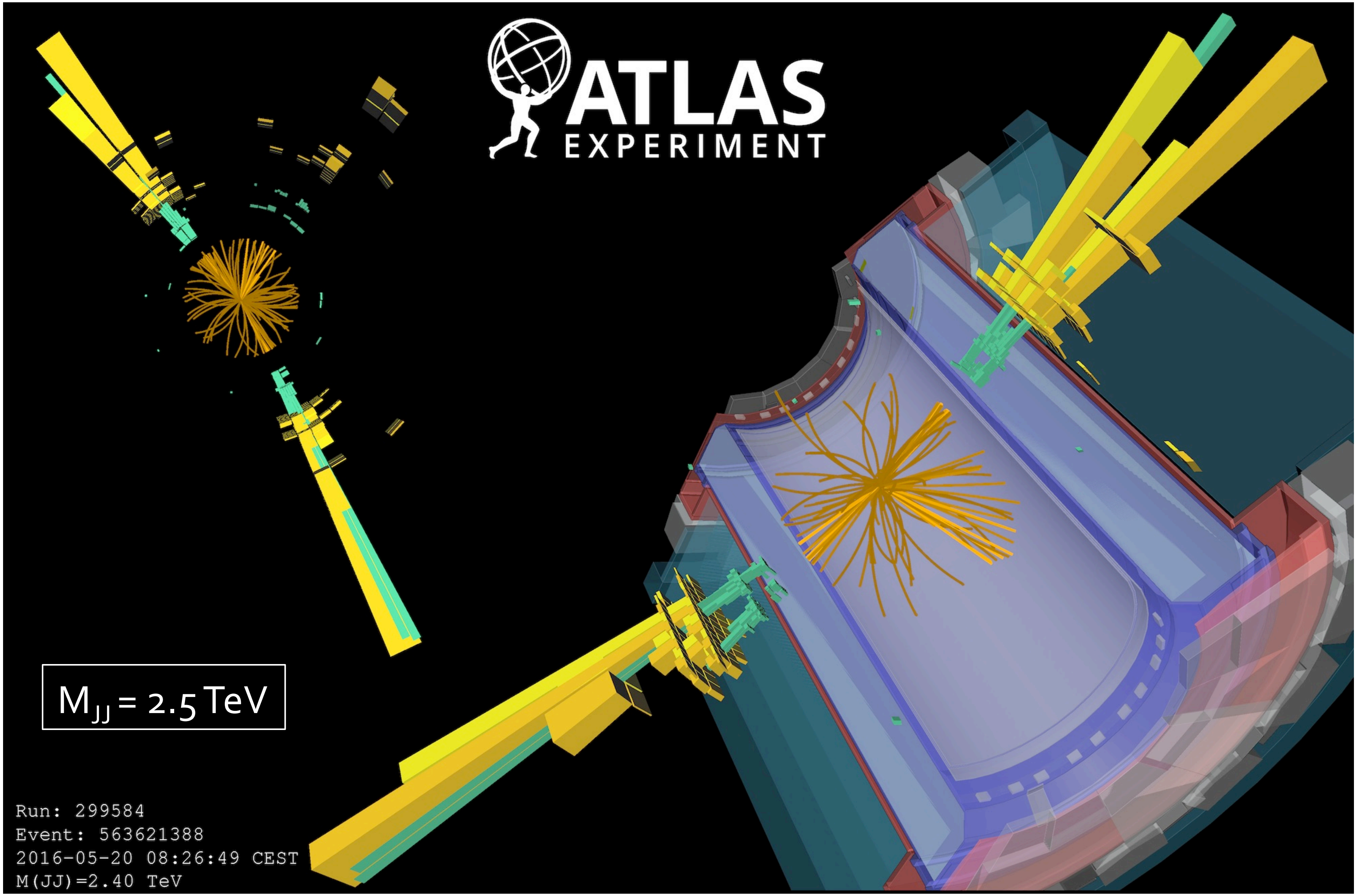
High mass di-boson candidate

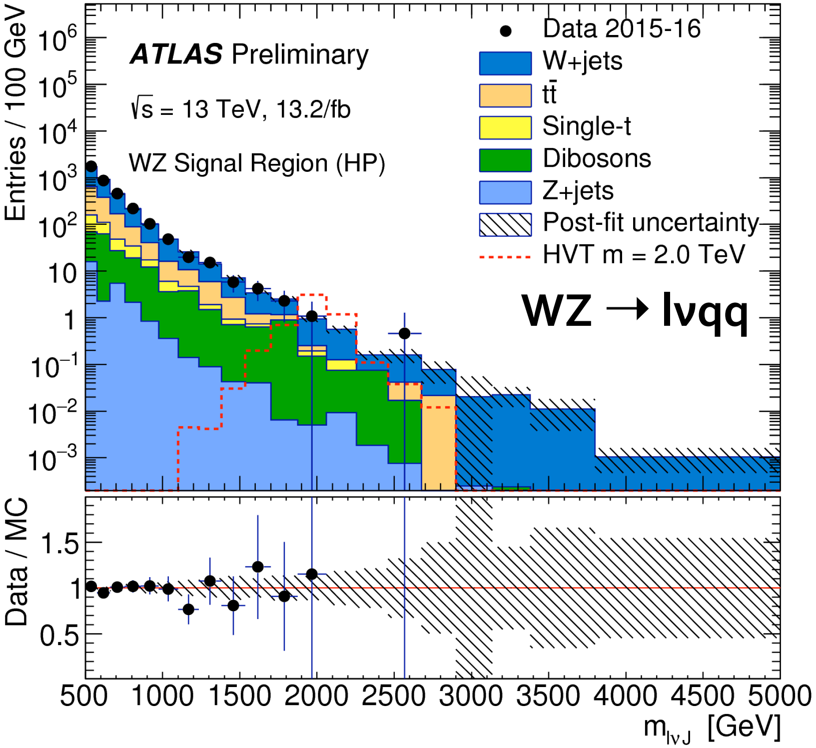


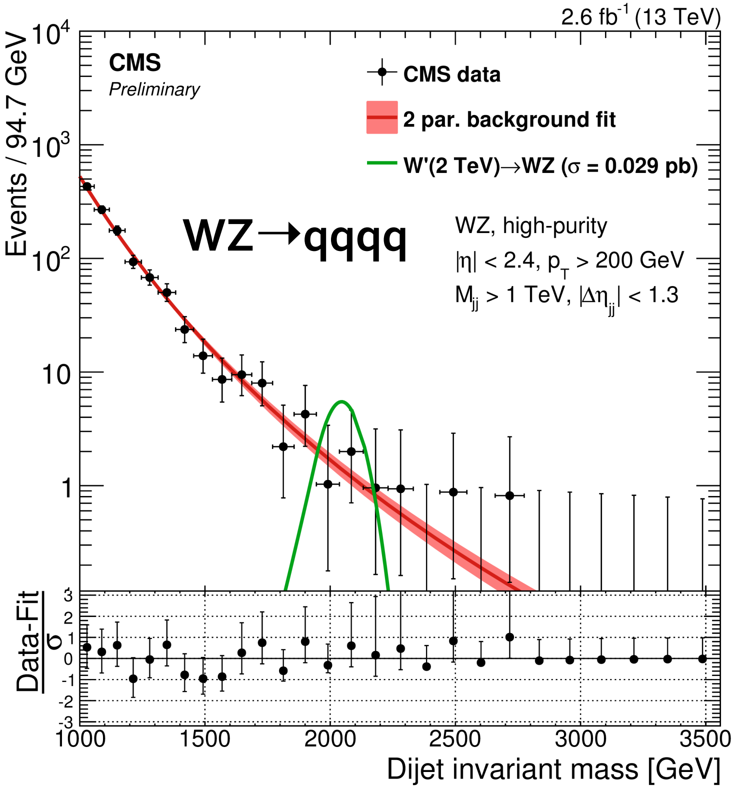
M_{JJ} = 2.5 TeV

Di-bosons – W/Z

- Sensitivity to many models, e.g. spin-1 (Z′, W′), spin-2 (RS graviton), and spin-0
- Large variety of final states: leptonic, semi-leptonic, all hadronic

ATLAS-CONF-2016-062



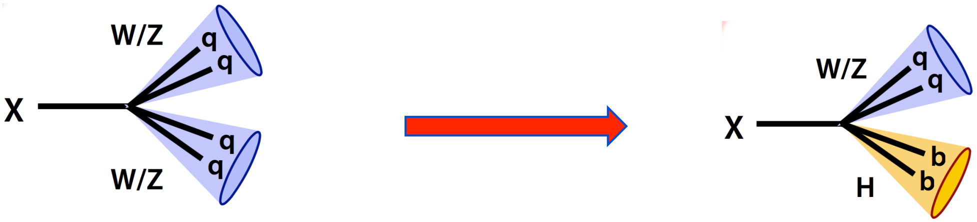


CMS-PAS-EXO-15-002

- Data consistent with SM expectation
    - ❑ Exclude mass range below about 2.5 – 3 TeV for Z′ or W′ decaying to VV

Di-bosons – Targeting also Higgs

- Now, also targeting VH final state
  - Using Higgs boson as discovery tool
- Exploiting that Higgs is predominantly decaying to bb



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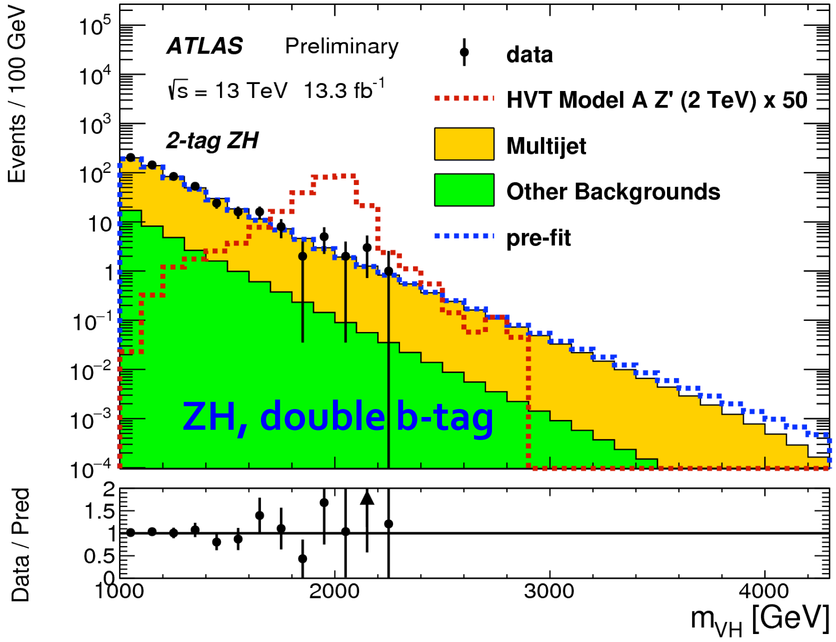
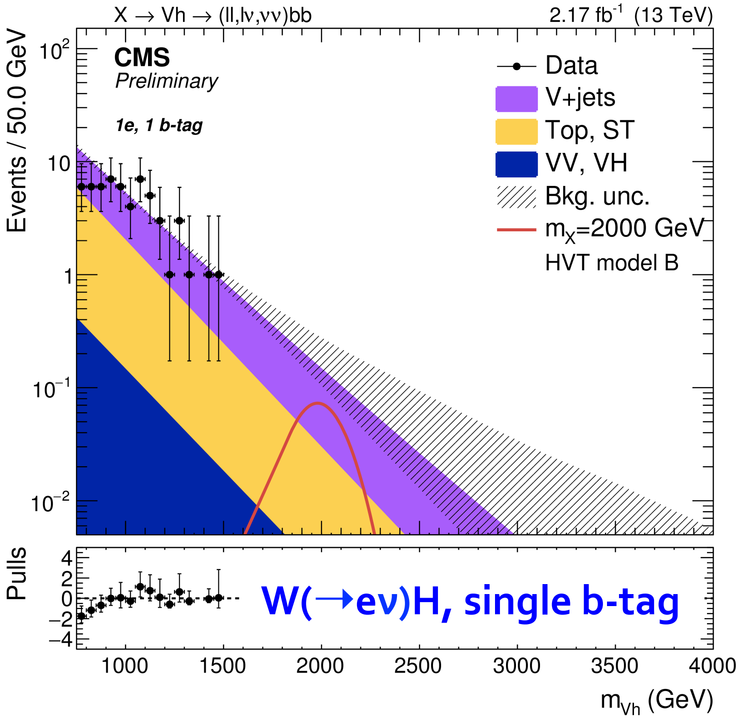




CMS-PAS-B2G-16-003

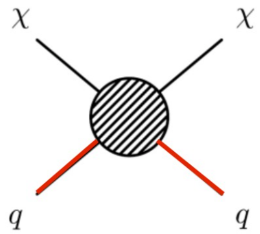
Mono-objects + Missing Energy

Dark Matter

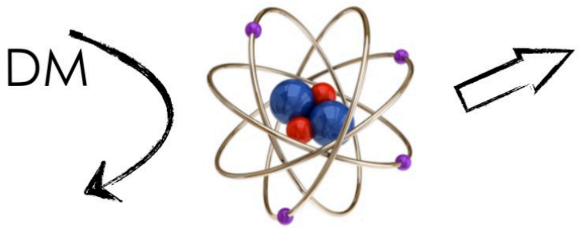
Dark Matter Searches

Complementary strategies to look for DM interaction:

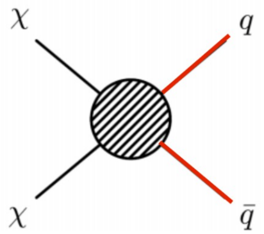
Direct



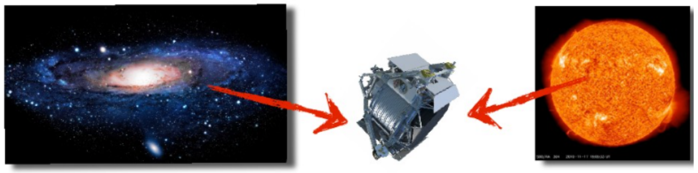
Probe DM-nucleon elastic scattering



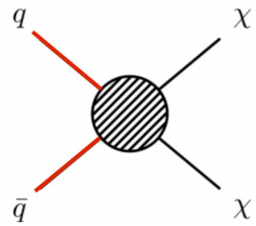
Indirect



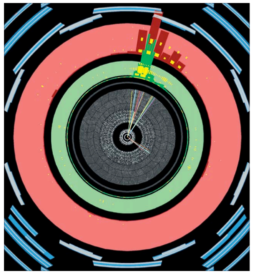
Astro. observation of DM annihilation or decay



@ colliders



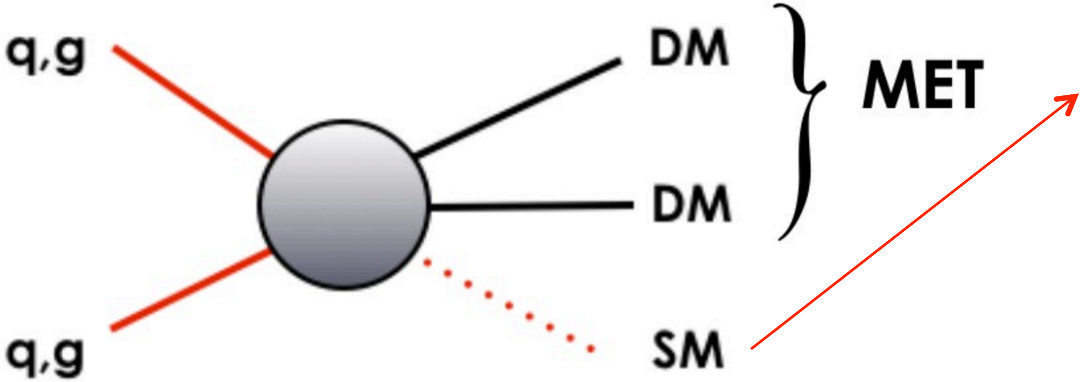
Look for WIMP*) pair-production



*) WIMP = Weakly Interacting Massive Particle

Dark Matter @ LHC

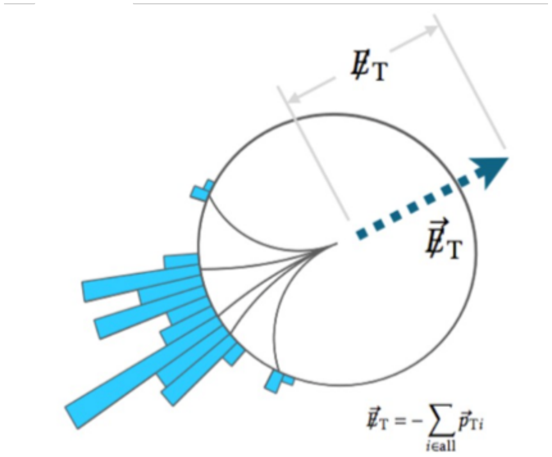
- Producing Dark Matter in the laboratory:
  - DM particles escape detector without interacting
  - Identify DM production by looking for **other particles recoiling against DM**
  - Infer DM production by measuring the **energy imbalance in the detector**
  - Search for DM in the **tails of the MET distributions**
- Signature of Mono-X: **MET + SM**
  - Invisible WIMPs balanced by associated SM particle(s)

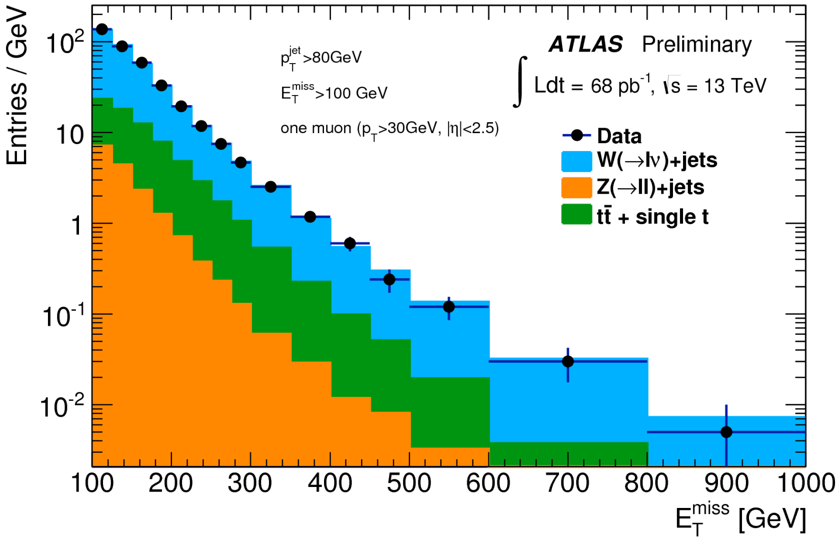


SM =
- ✓ jet
- ✓ photon
- ✓ Z/W
- ✓ b/t
- ✓ Higgs (new)

Measuring the Invisible

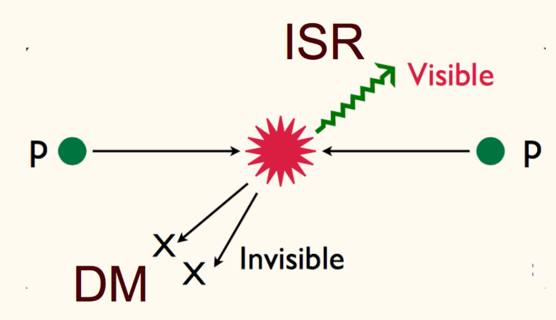
- MET: Energy imbalance in the plane transverse to the colliding beams





ATLAS, EXOT-2015-005

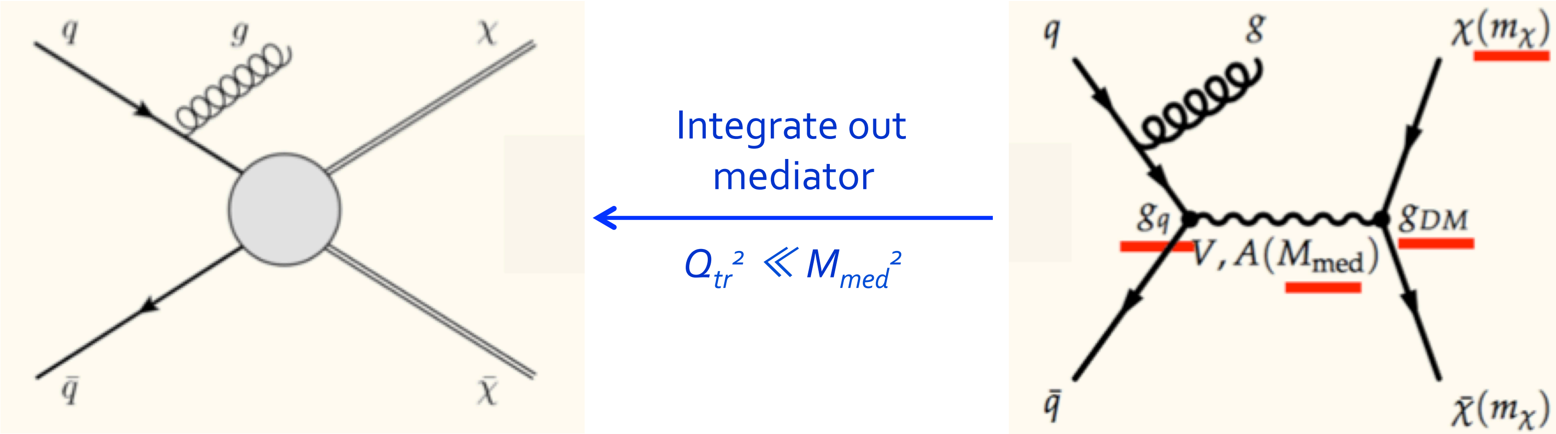
- Imbalance caused by particles escaping detection
- Need good control over entire detector: noise, dead/hot cells
- Escaping particles:
  - Neutrinos
  - Potential non-SM weakly interacting particles
  - Very forward particles (outside calorimeter acceptance)



Modelling the DM Interaction

- DM-SM interaction can be described by two alternative approaches

Effective Field Theory (contact interaction) vs. **Simplified Model**



Integrate out mediator

$Q_{tr}^2 \ll M_{med}^2$

- Validity issues for momentum transfers exceeding mediator mass
- Two parameter dependence
  - Dark Matter mass
  - Suppression scale M_*
    - related to mediator mass and couplings to SM and DM

- Retain information on the mediator
- Four parameters (narrow width assumed)
  - Mediator and DM masses (M_{med}, $m_X = m_{DM}$)
  - Mediator coupling to quarks (or gluons) and to DM particle (g_q / g_g, g_{DM})

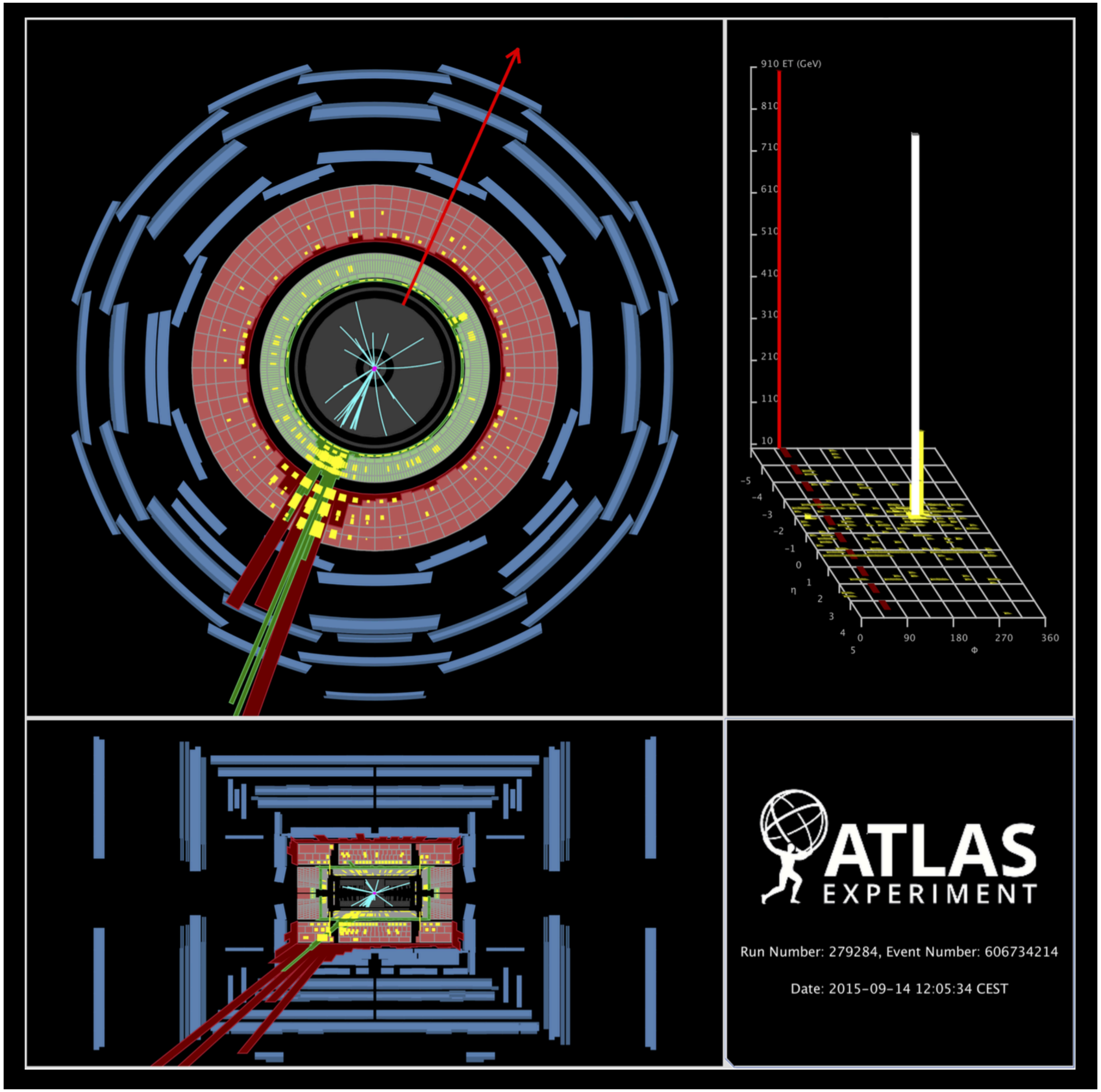
ATLAS-CMS Dark Matter Forum: arXiv: 1507.00966

Mono-object + Missing Energy

The highest E_T^{miss} monojet event in the 2015 ATLAS data

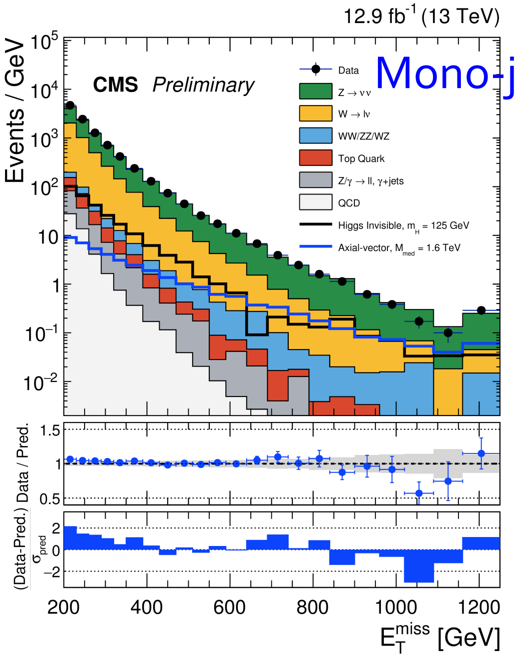
Jet p_T = 973 GeV

E_T^{miss} = 954 GeV

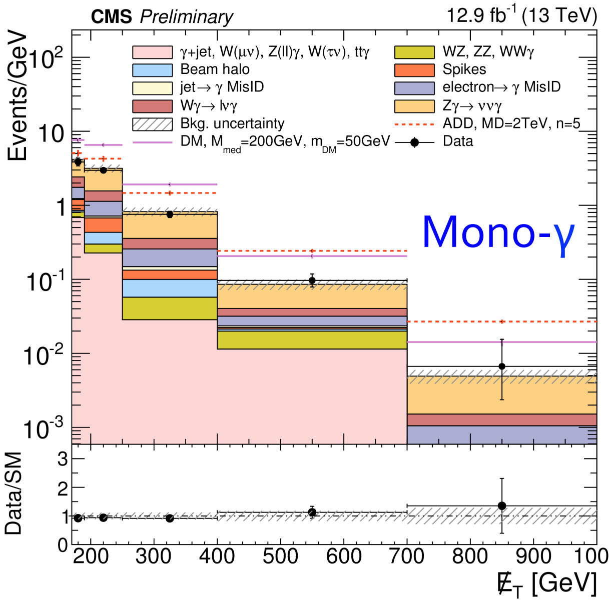


Dark Matter Searches

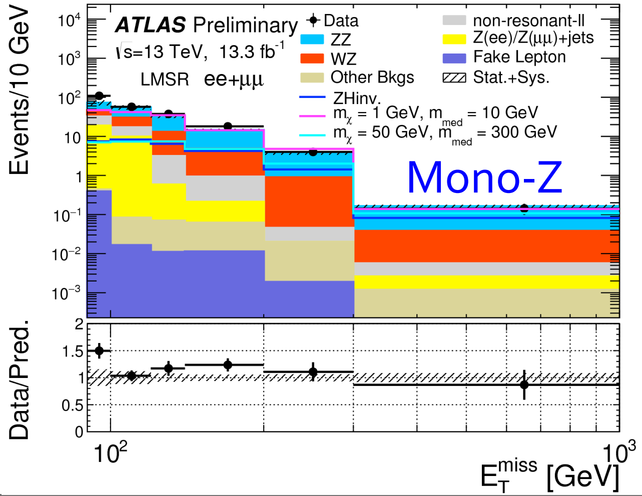
Examples of many different mono-object searches



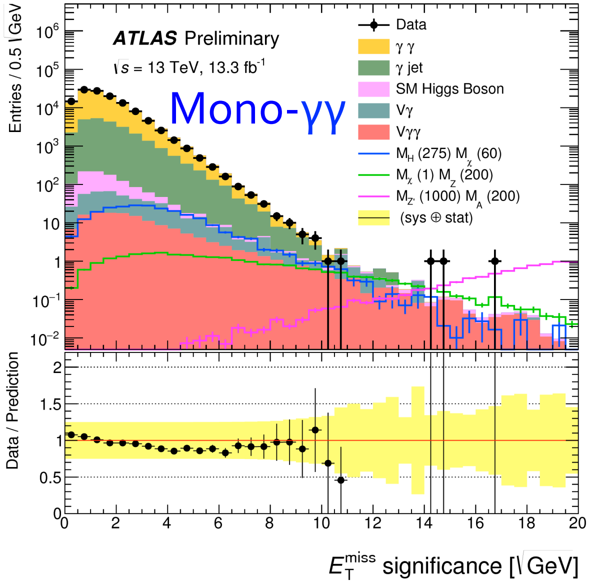
CMS-PAS-EXO-16-037



CMS-PAS-EXO-16-039



ATLAS-CONF-2016-056

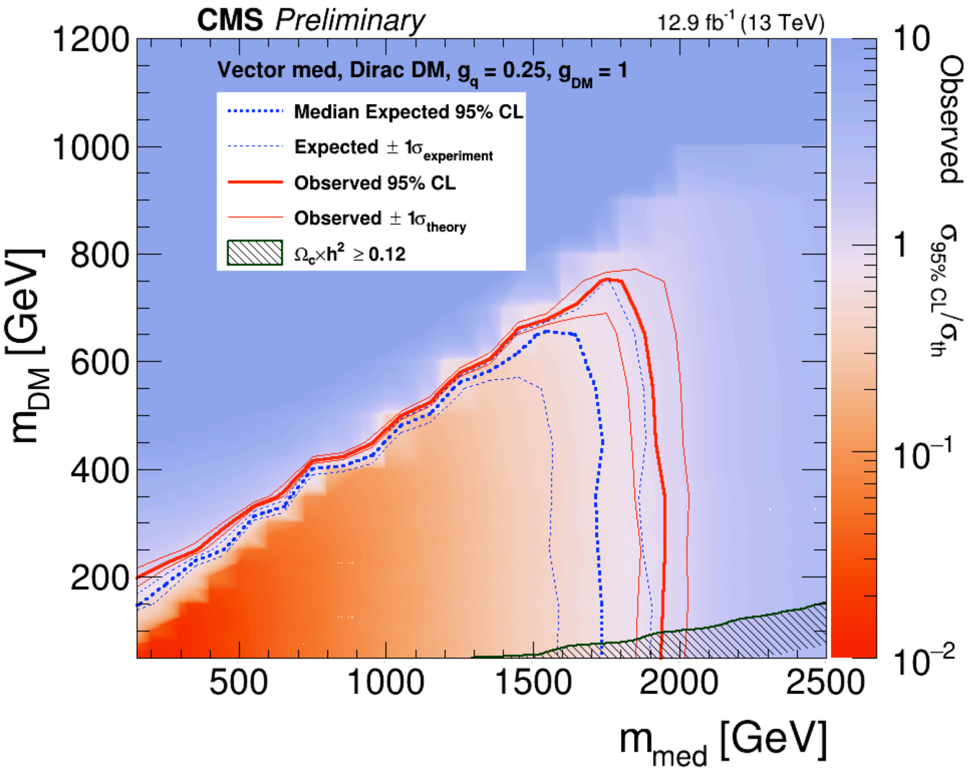


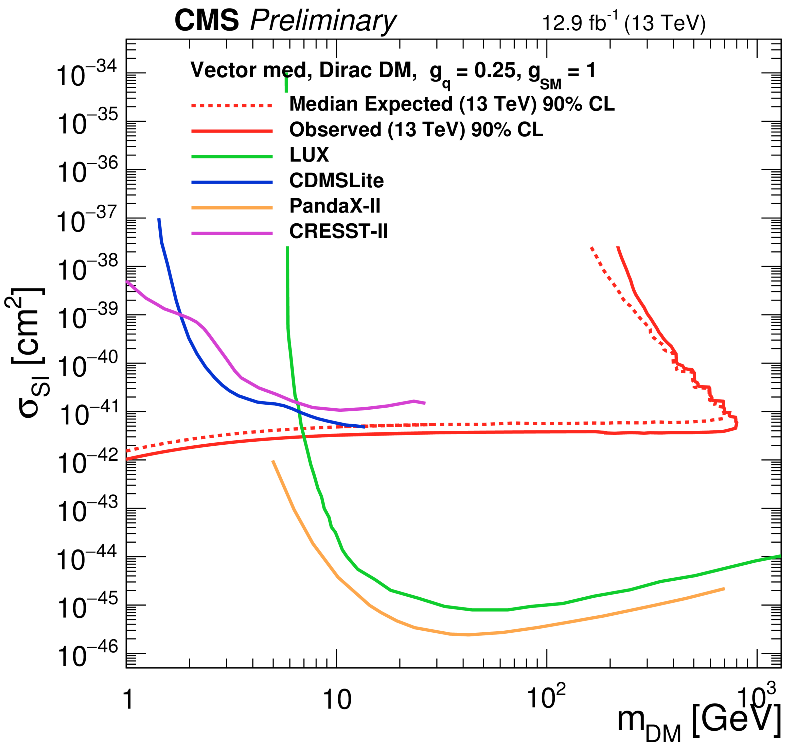
ATLAS-CONF-2016-087

Dark Matter Results

Example of exclusion from mono-jet + mono-Z

CMS-PAS-EXO-16-037

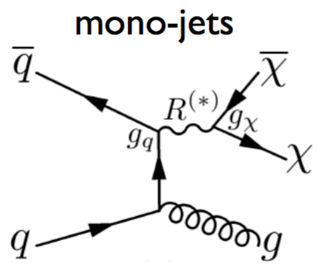


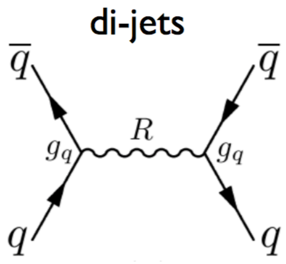


Exculsion in the plane of mediator and dark matter mass (for assumed values of couplings)

Competitive limits relative to direct and indirect searches *for small values of DM mass*

Mono-jet and Di-jet Complementarity





In Simplified Model, DM mediator will also give rise to di-jet events

- Probe DM mediator with di-jet events
- Relative yield of mono- and di-jets depends on relative strength of couplings, g_q and $g_{DM} = g_X$

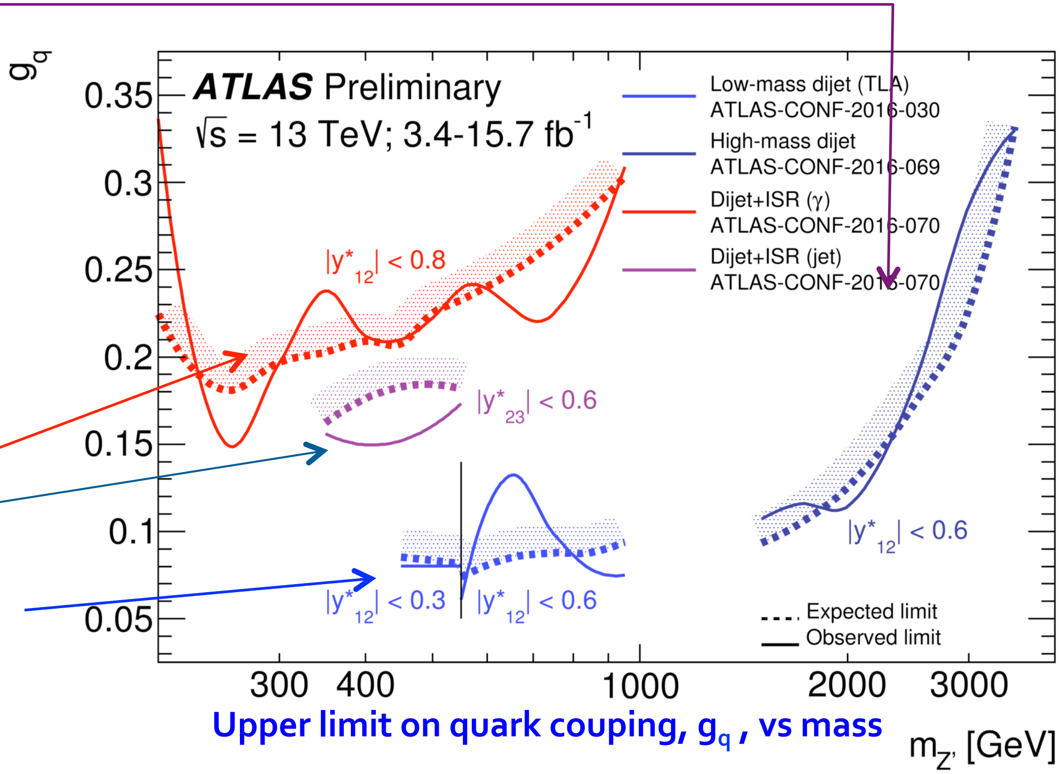
High-mass searches provide constraints for massive mediators.

Weaker constraints at lower masses, due to large prescales on triggers.

At low mass, two methods to gain sensitivity

a) Look for resonance in di-jet system recoiling against photon, or a jet

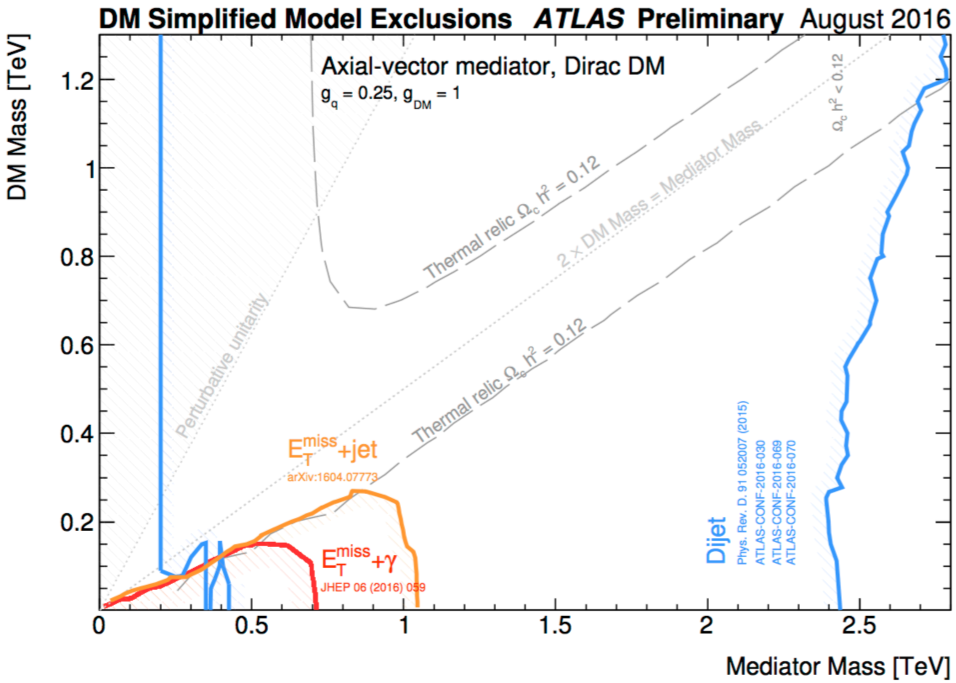
b) Trigger level analysis: gain rate, store only jet 4-momenta



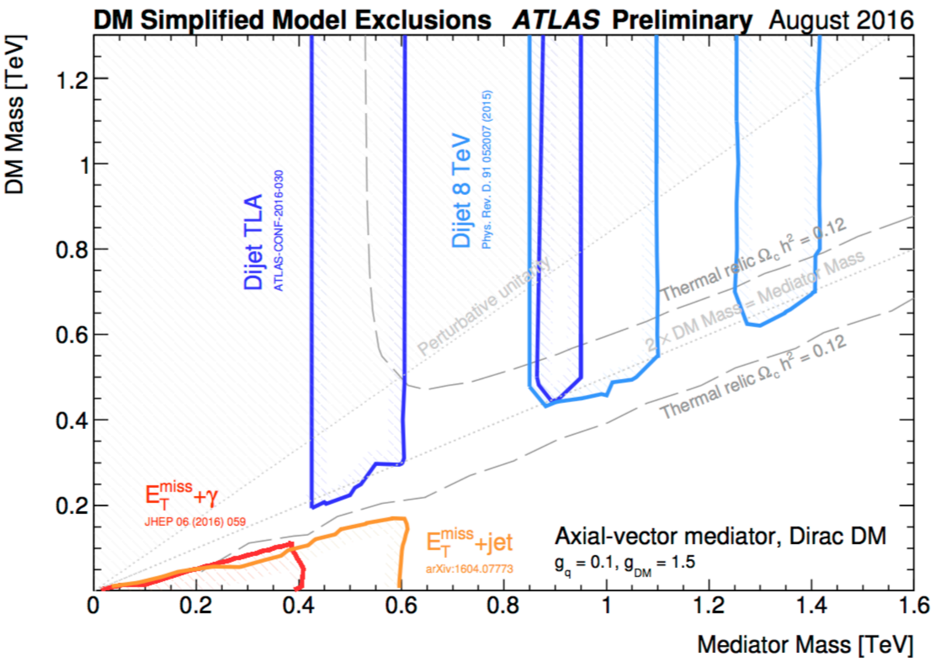
Upper limit on quark couping, g_q , vs mass

Dark Matter Exclusions

- Complementarity searches by **mono-X** and **dijet**
  - ❑ Di-jet searches cover a broad mediator mass range
  - ❑ Results highly depend on choice of coupling parameters



$g_q=0.25$ $g_{DM}=1$

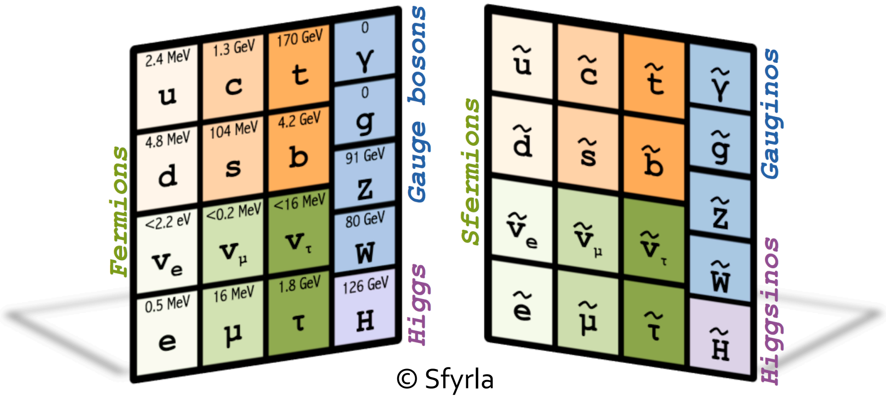


$g_q=0.1$ $g_{DM}=1.5$

SUSY Searches

Super Symmetry

Global symmetry between fermions and bosons: all SM particles have SUSY partners with spin difference of ±1/2



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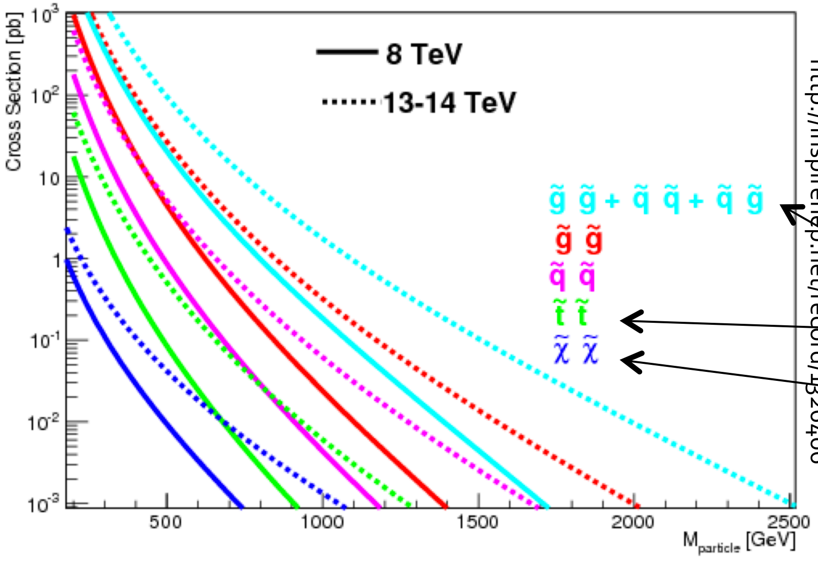


http://inspirehep.net/record/1326406

Why SUSY?

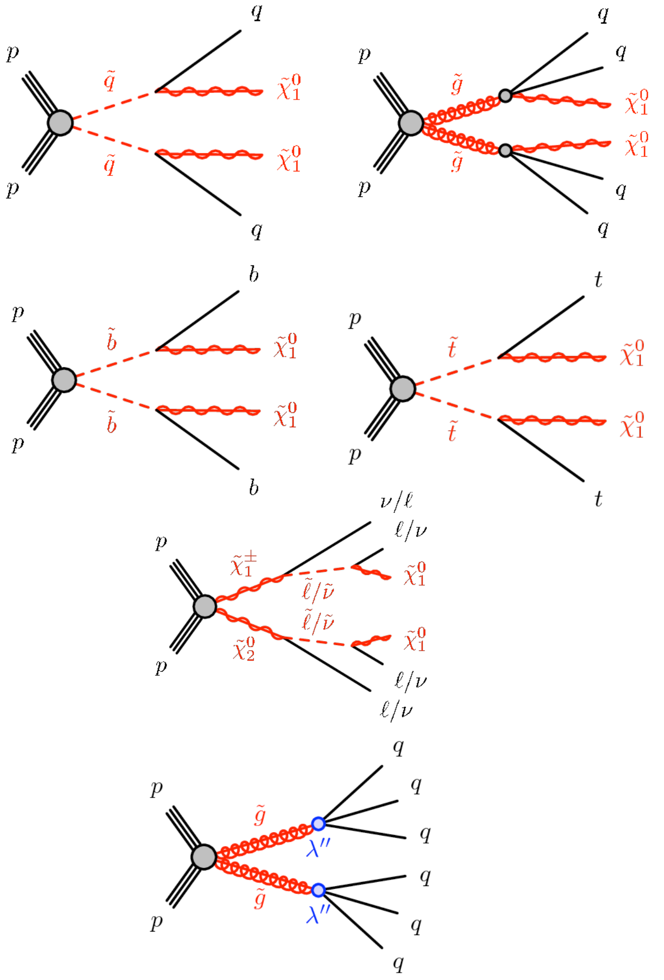
- Provides a dark matter candidate
  - if R-parity is conserved, lightest SUSY particle (LSP, neutralino) is stable
- Unification of gauge couplings
  - Presense of sparticles changes running of couplings
- Solves the hierarchy problem
  - if $m_{SUSY} \lesssim 1$ TeV, i.e. *natural SUSY*
- Extends the Poincaré group
- Required for string theory…

SUSY physics processes

- Strong production ($\tilde{g}\tilde{g}$, $\tilde{q}\tilde{q}$)
- 3rd-generation squarks ($\tilde{t}\tilde{t}$, $\tilde{b}\tilde{b}$)
- Electroweak production ($\tilde{\chi}$s, $\tilde{l}\tilde{l}$)
- R-parity violating scenarios, long-lived particles.

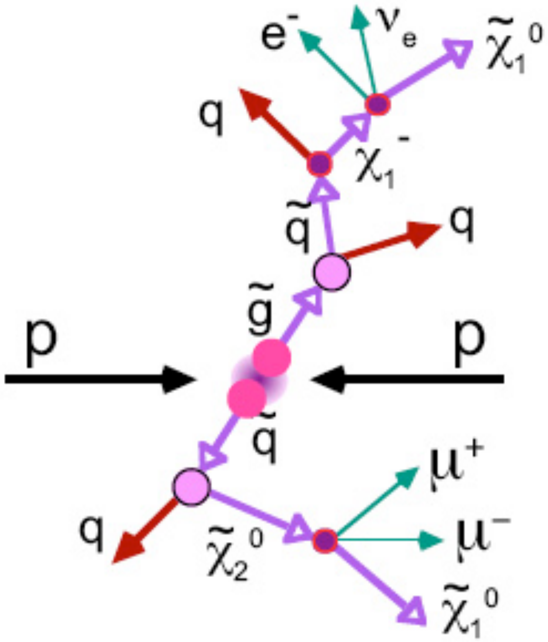
SUSY Signatures

- **R-parity conservation:** pair production with two invisible final state particles
  - ❑ **Strong production of squarks and gluinos**
    - high cross section/mass scale; jets and missing E_T
  - ❑ **Third generation squarks**
    - same as above, but lower cross section/mass scale; b-tagging
  - ❑ **Electroweak production**:
    - low cross section/mass scale; typical (but not only) signature: many leptons, missing E_T, no jets
- **R-parity violating signatures**
  - no missing E_T but high jet multiplicity (jets or leptons depending on couplings) and resonances
- **Long lived particles**
  - model independent searches for "stable" coloured/charged particles and particles decaying inside the detector



SUSY Signatures Common Themes

- Decay of heavy SUSY particles
  - Large total final state energies
    - Variables that sum the total energy of the event, e.g. **m_{eff}, H_T**
- Long SUSY decay chains
  - High multiplicity of final state objects
    - Strong production: mainly jets
    - Electroweak production: leptons and possibly jets
  - Kinematics controlled by difference between SUSY particle masses
    - Kinematic variables, e.g. **m_T, m_{T2}**
- R-parity conservation: Invisible particles in final state
  - Large missing transverse energy, **E_T^{miss}**



M_{eff} : scalar sum of E_T^{miss} and jet p_Ts

H_T : scalar sum of p_T of visible objects (sometimes just jets)

SUSY Example: Strong Production Analyses

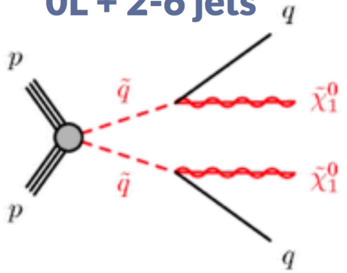
Complex analyses: many signal regions

- Example: ATLAS

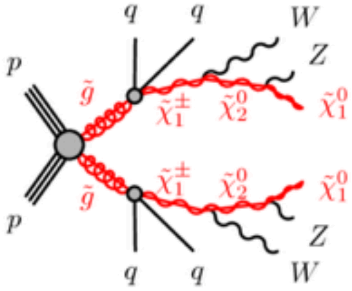
largest branching ratio ↔ **smallest SM background**

0 leptons

0L + 2-6 jets

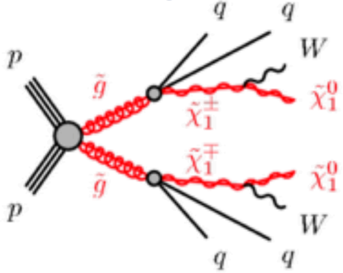


0L + 7-10 jets

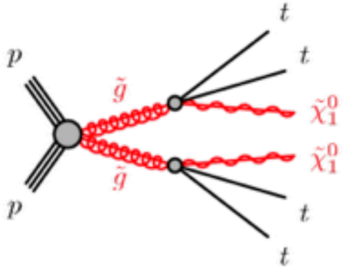


1 lepton

1L + jets

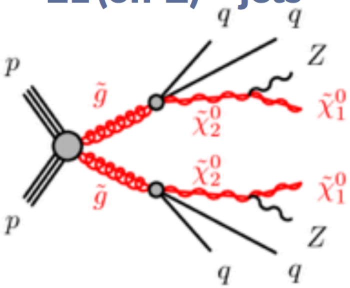


0/1L + 3 b-jets



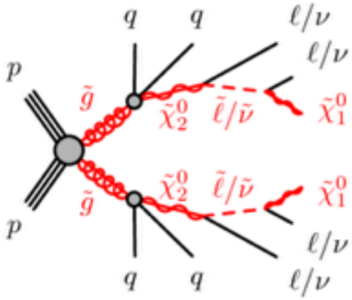
2 leptons

2L (on-Z) + jets



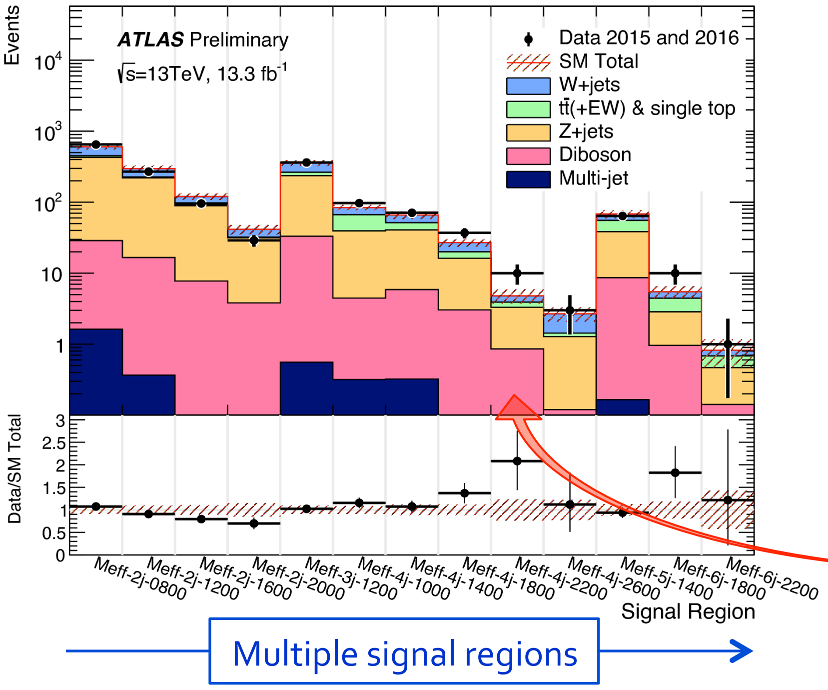
2 SS/3 leptons

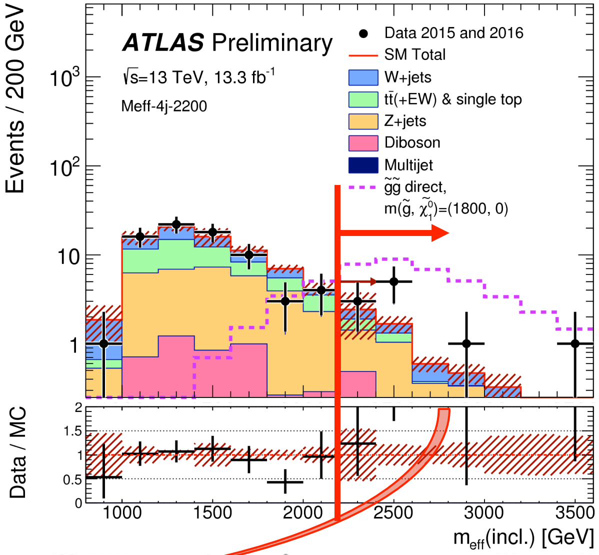
2 SS / 3L + jets



- complementary final states cover large areas of phase space and large range of models

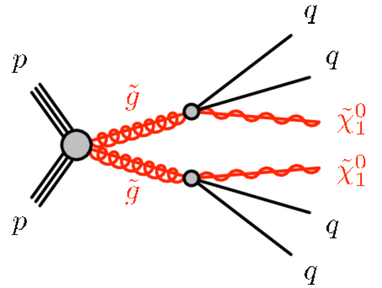
SUSY Searches – Strong Production

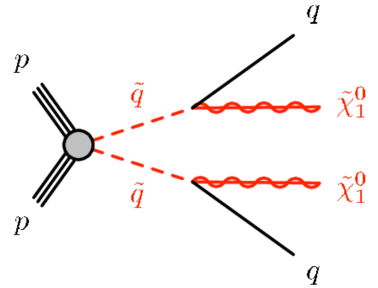


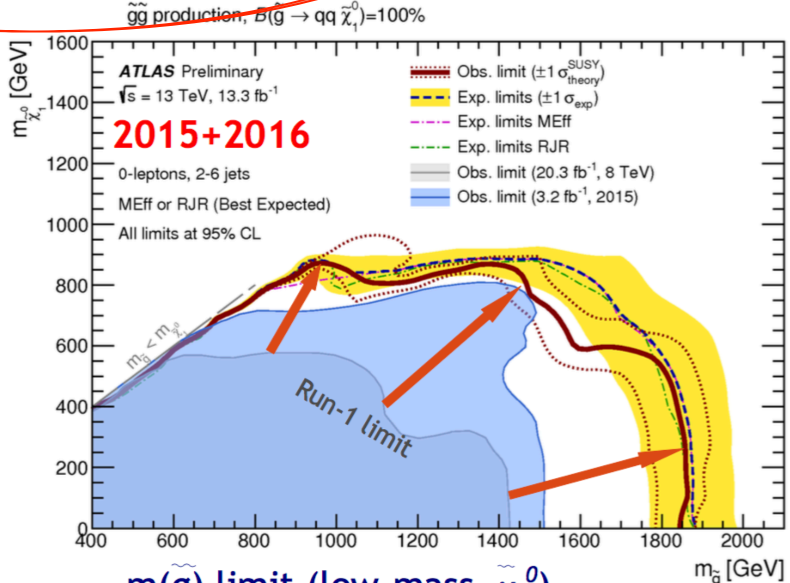


Require 2-6 jets; veto leptons

- Sensitive to gluino and squark production







m($\tilde{g}$) limit (low-mass $\tilde{\chi}_1^0$)
(Run-1) 1.4 TeV → 1.86 TeV

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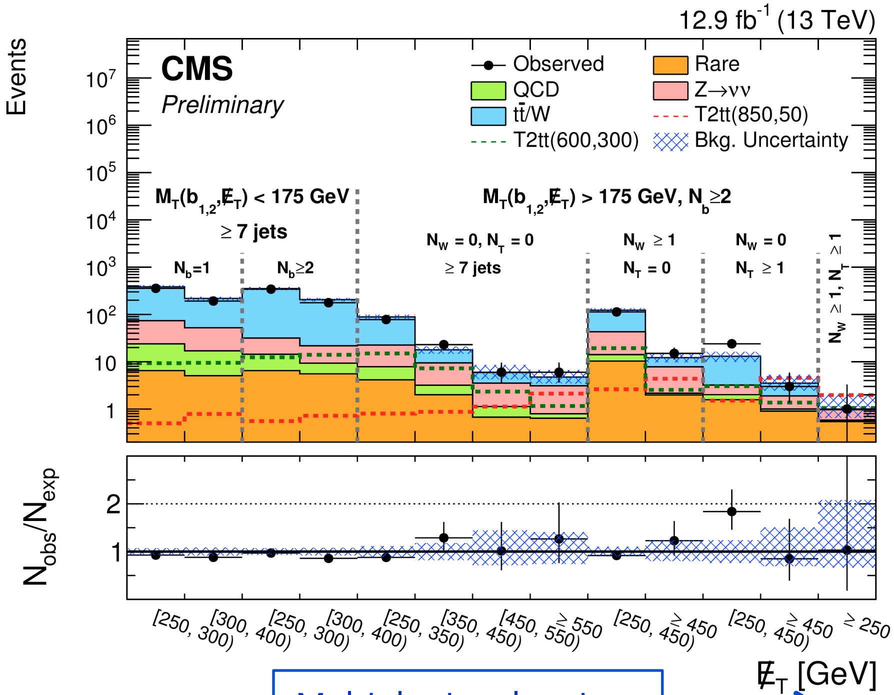
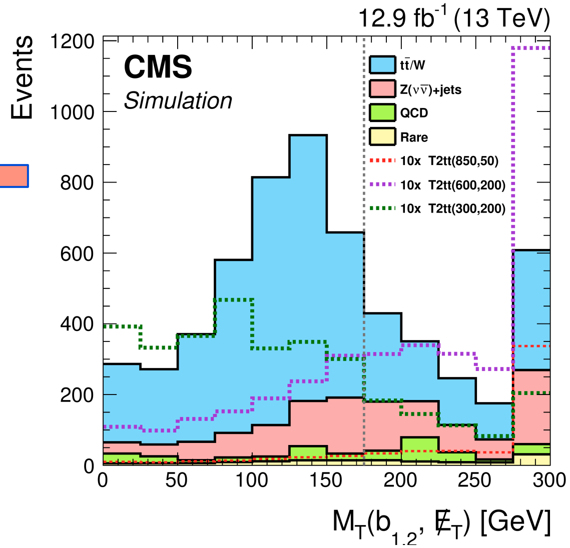
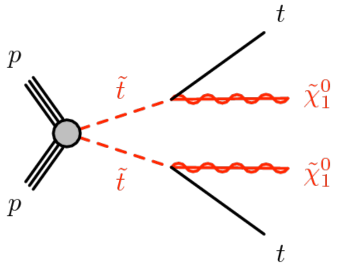
SUSY Searches – Top Squark

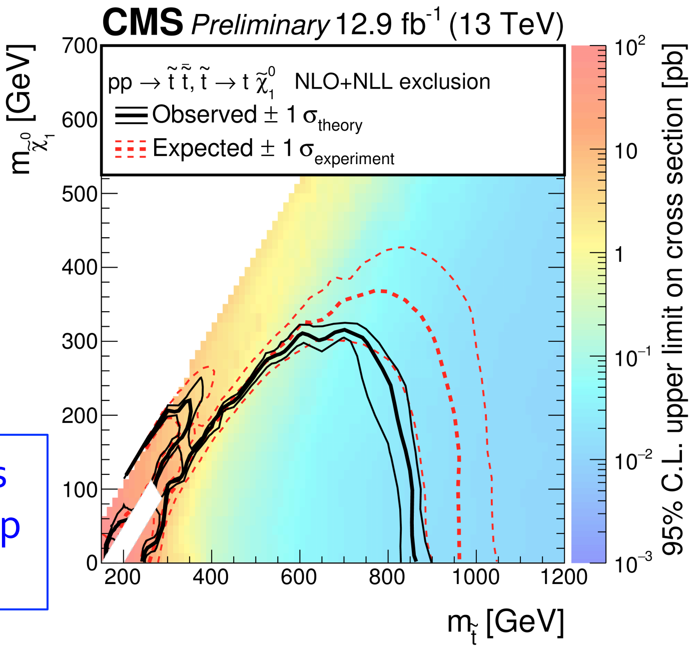


Multiple signal regions



Using #jets, #b-jets, $m_T(b)$, and E_t^{miss}

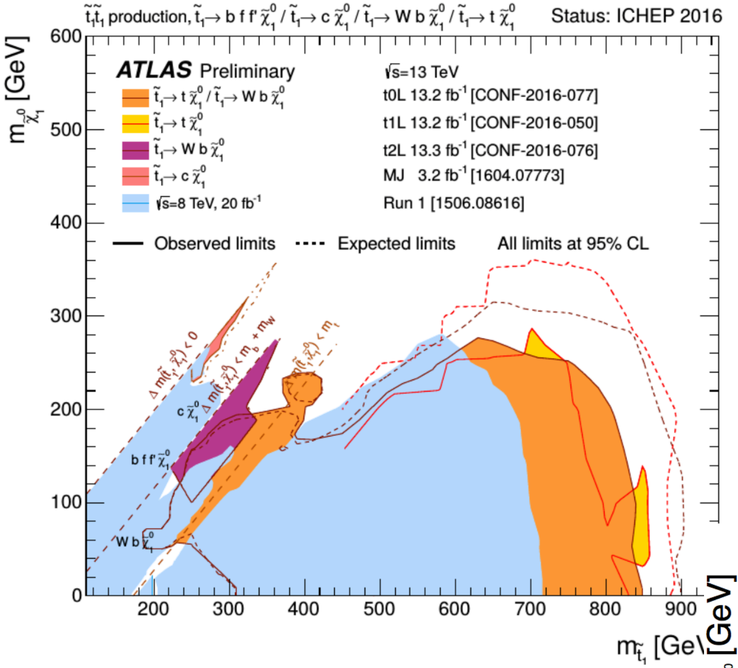




Exclusion limits for top squark up to 860 GeV

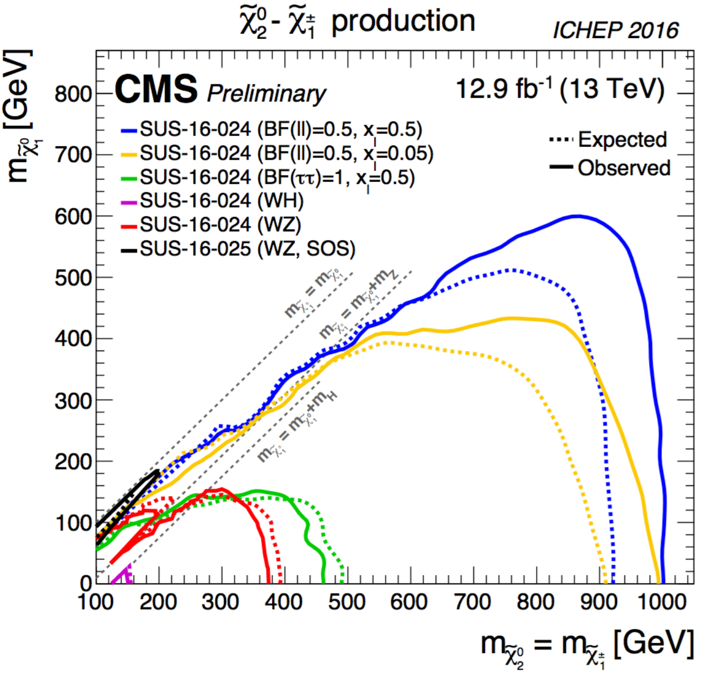
SUSY Searches – Other Models

Examples of exclusions

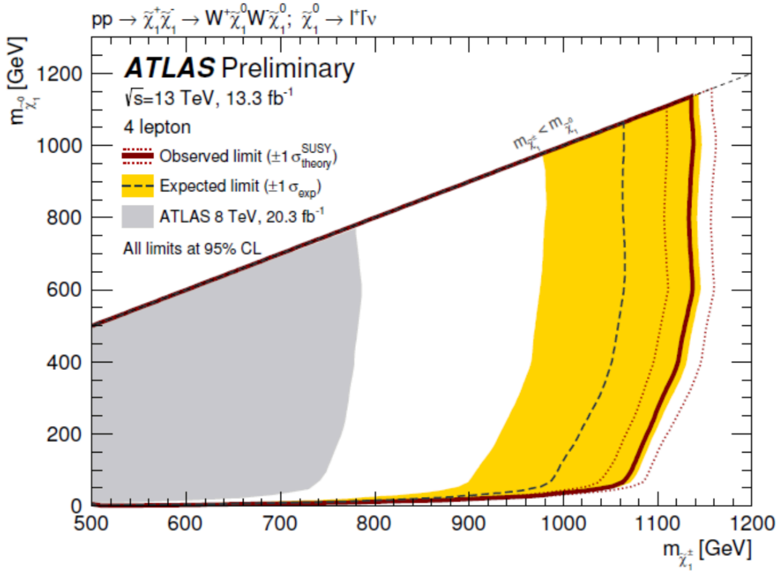


3rd generation: stop

Electroweak production

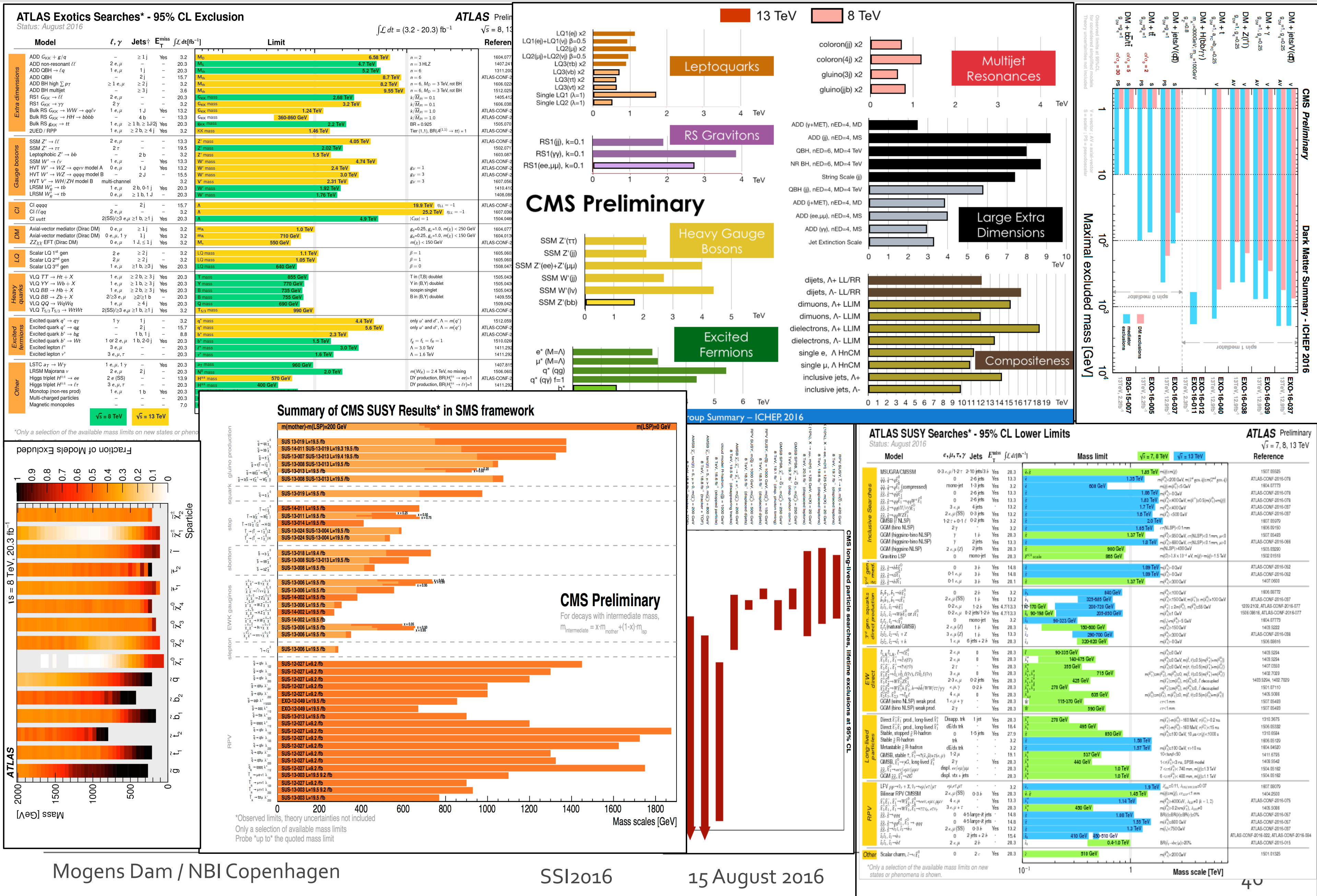


R-parity violating



Rounding off

No Evidence of New Physics Seen : Setting Limits



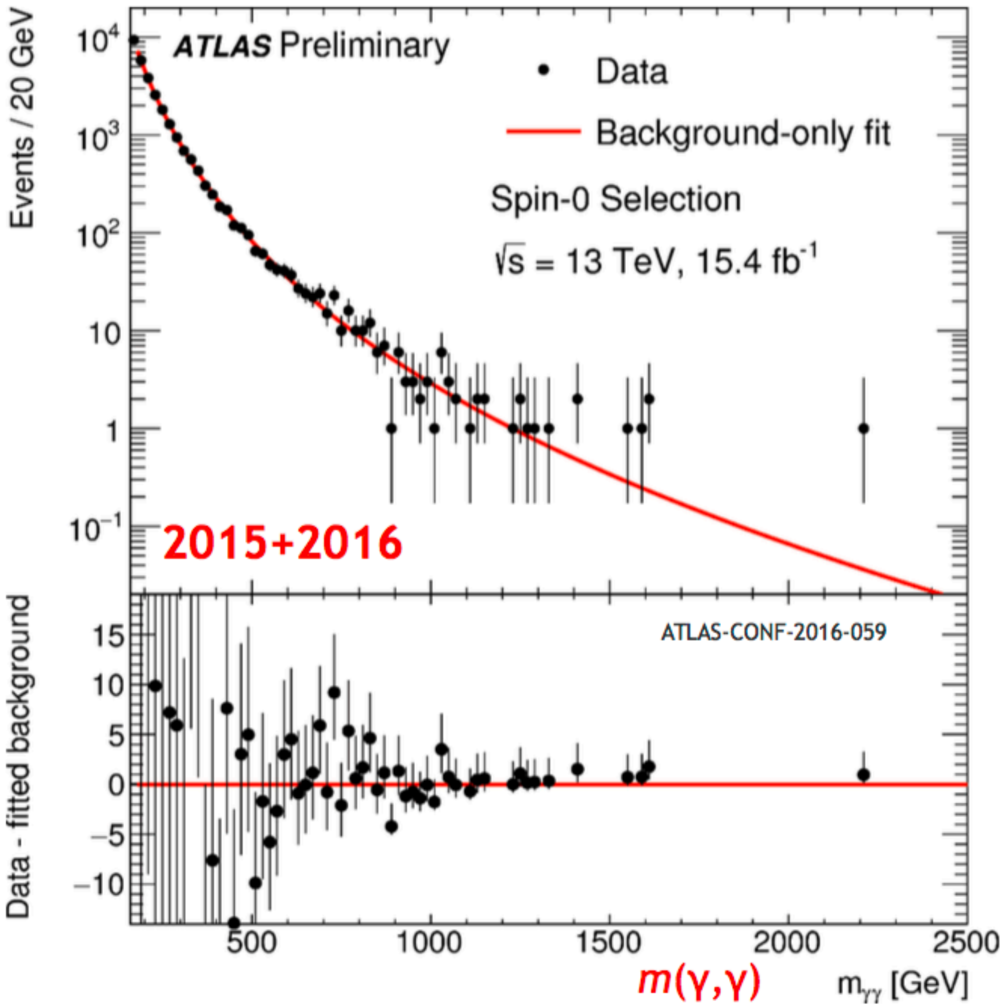
Summary and Outlook

- Good reasons to believe there exits physics beyond the SM
- The LHC machine and its experiments ATLAS and CMS are performing extremely well
- Wide range of New Physics channels being probed at a fast pace
- So far, no clear signs of New Physics have been uncovered
  - For more quantitative conclusions, see summary talks of recent ICHEP conference and links therein
    - ICHEP Beyond the Standard Model session
- We are still at the beginning of a long journey, so stay tuned.

Thank you for your attention!

Extra Material

ATLAS di-photon 2015 + 2016



With 2015+2016 data:

- Small excess at 710 GeV ($\Gamma/m \sim 10\%$)
- Local significance 1.4σ, global $<1\sigma$