Searches for New Physics at the LHC and the role of QCD and PDFs

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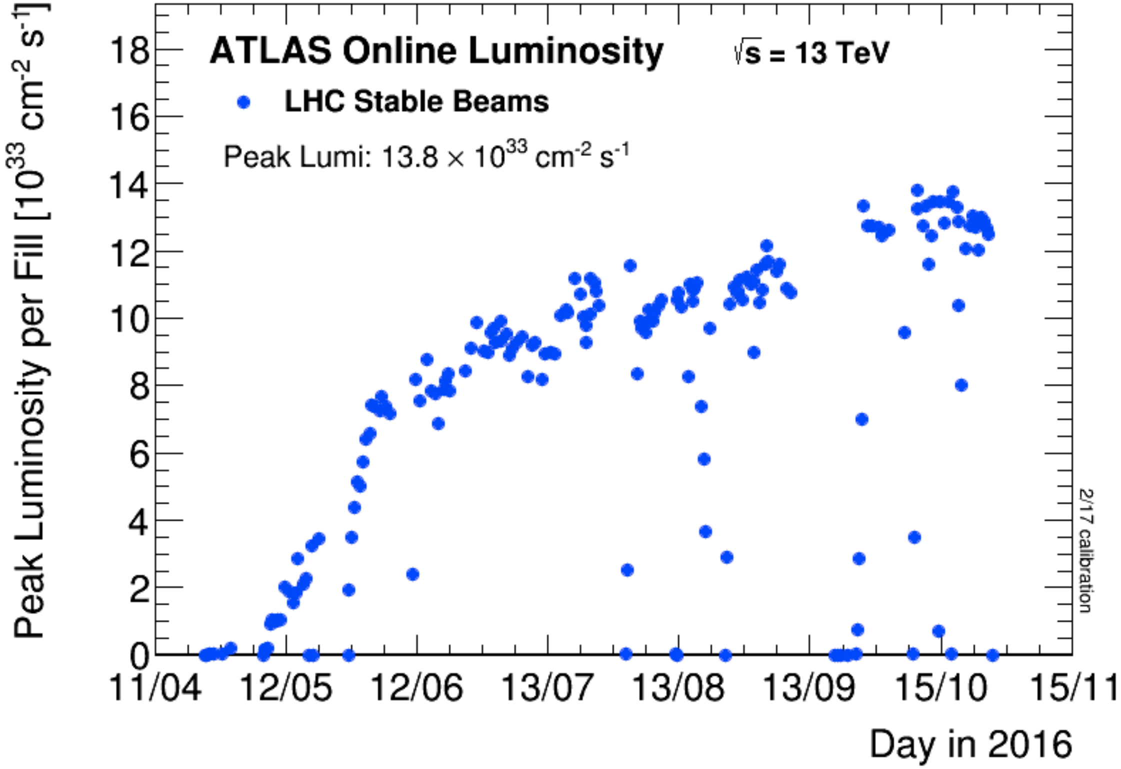
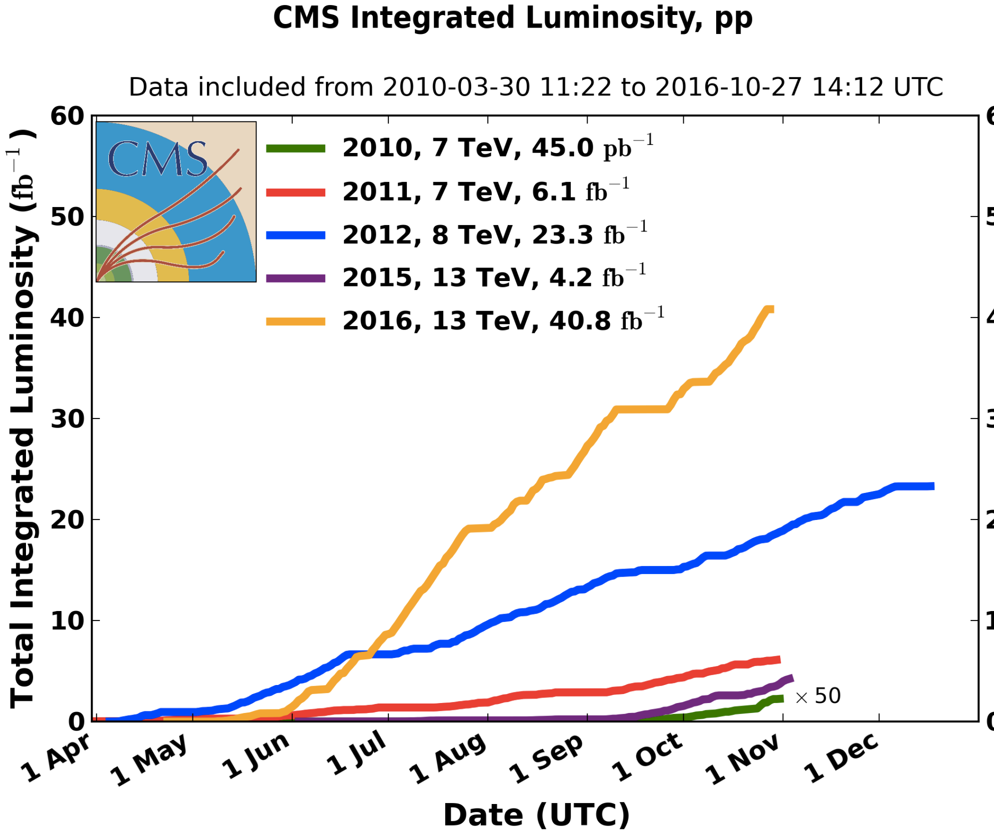
LHC Run 2 Integrated Luminosity

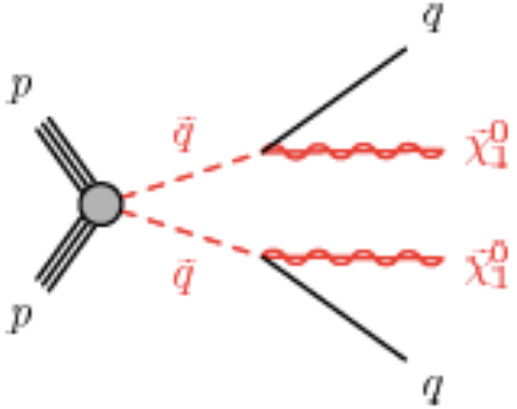


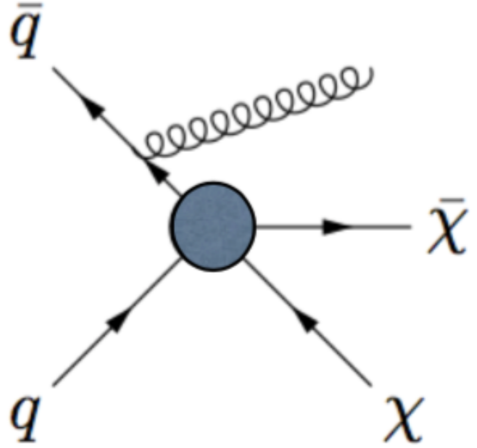


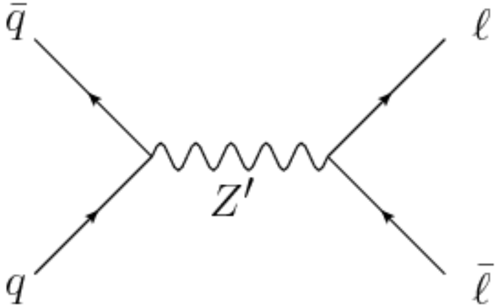
- **2016 pp run went very well**
  - *Peak L*= 1.4×10^{34} cm^{-2}s^{-1} achieved (design: 1.0×10^{34} cm^{-2}s^{-1})
  - 13 TeV data luminosity for analysis (2015+2016): ~36 fb^{-1}

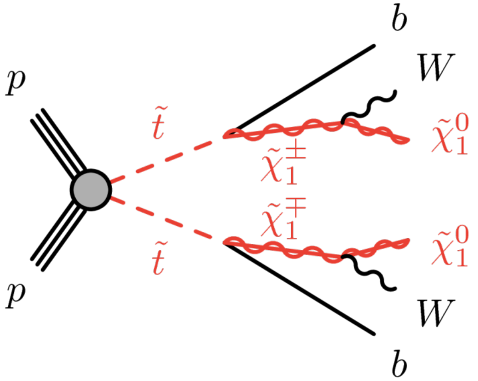
Outline

- **Background estimation methods**
  - Highlighting role of QCD
- **Searches for**
  - Supersymmetry
  - Dark Matter
  - High mass resonances
- **Conclusions**







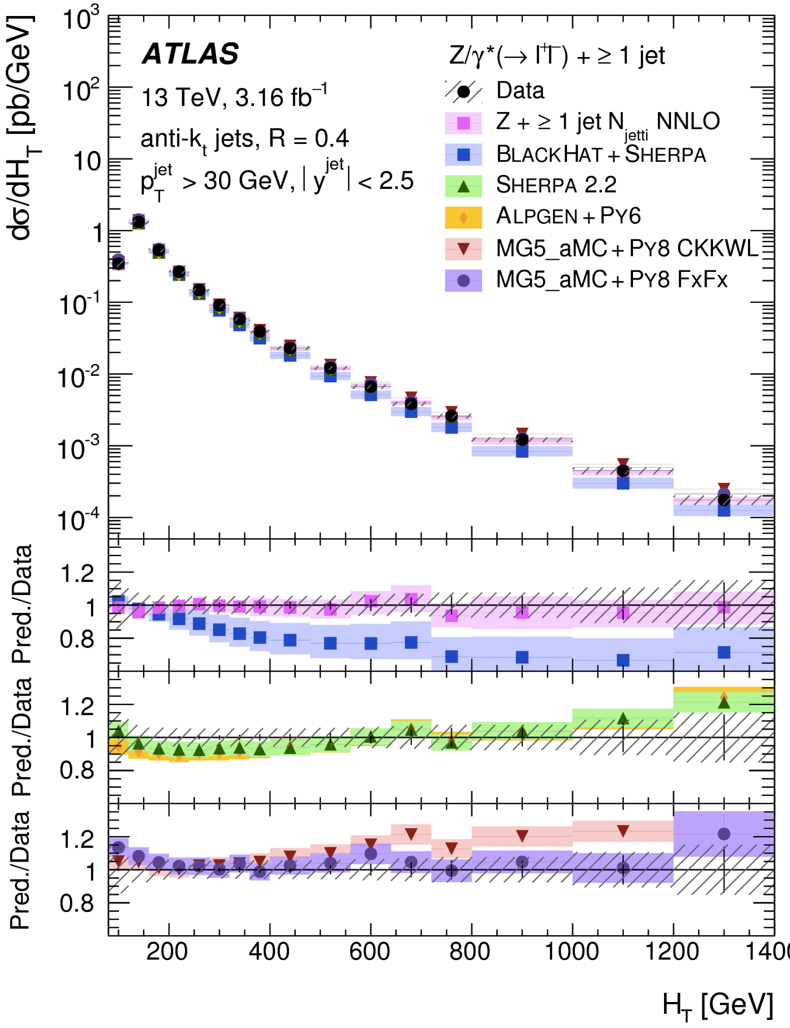


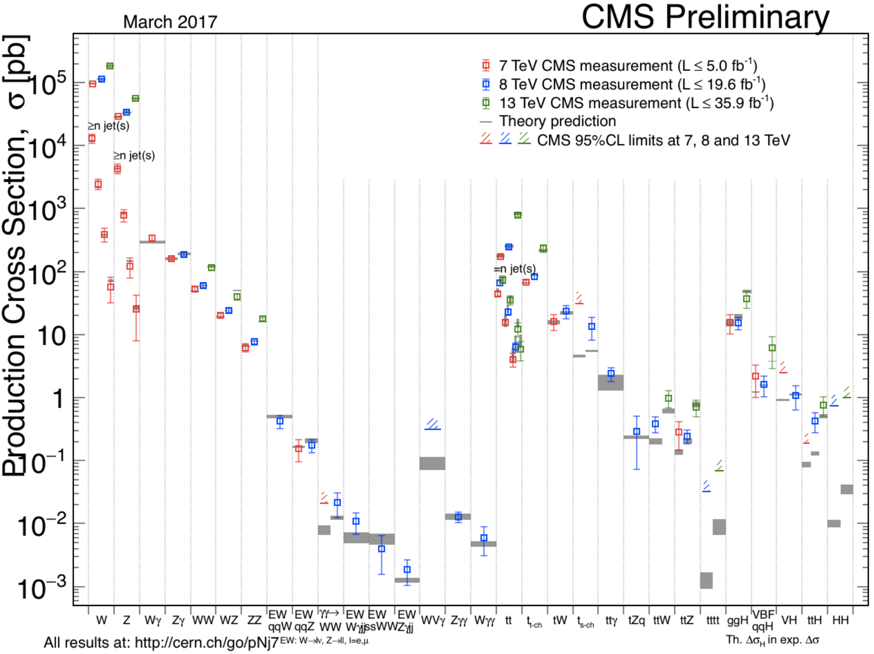
Background Estimation Methods

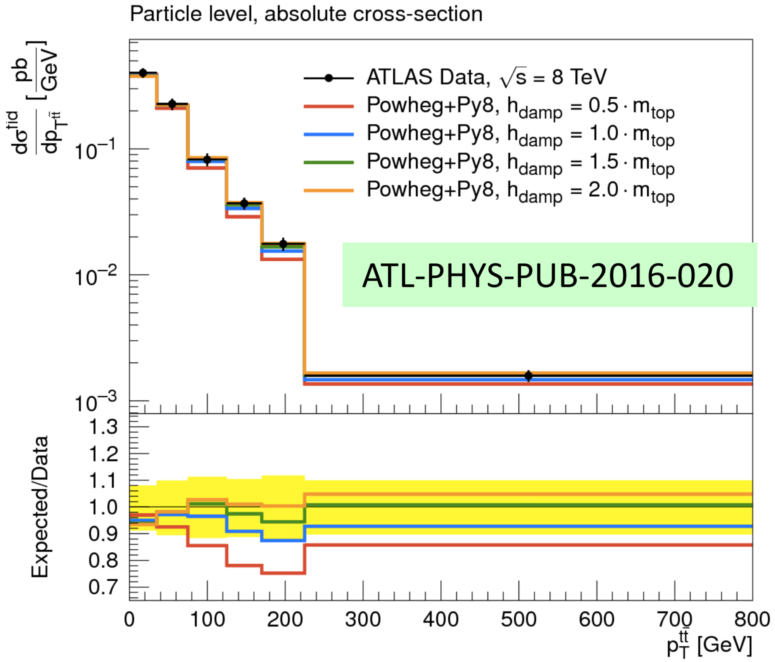
Cross-section measurements of SM processes

- **Extensive effort to measure SM processes by ATLAS & CMS but**
  - Measurements are mostly inclusive
    - Searches select "weird" regions of phase space
  - Measurements usually take longer than searches
- **Constrain background within each search**

arXiv:1702.05725





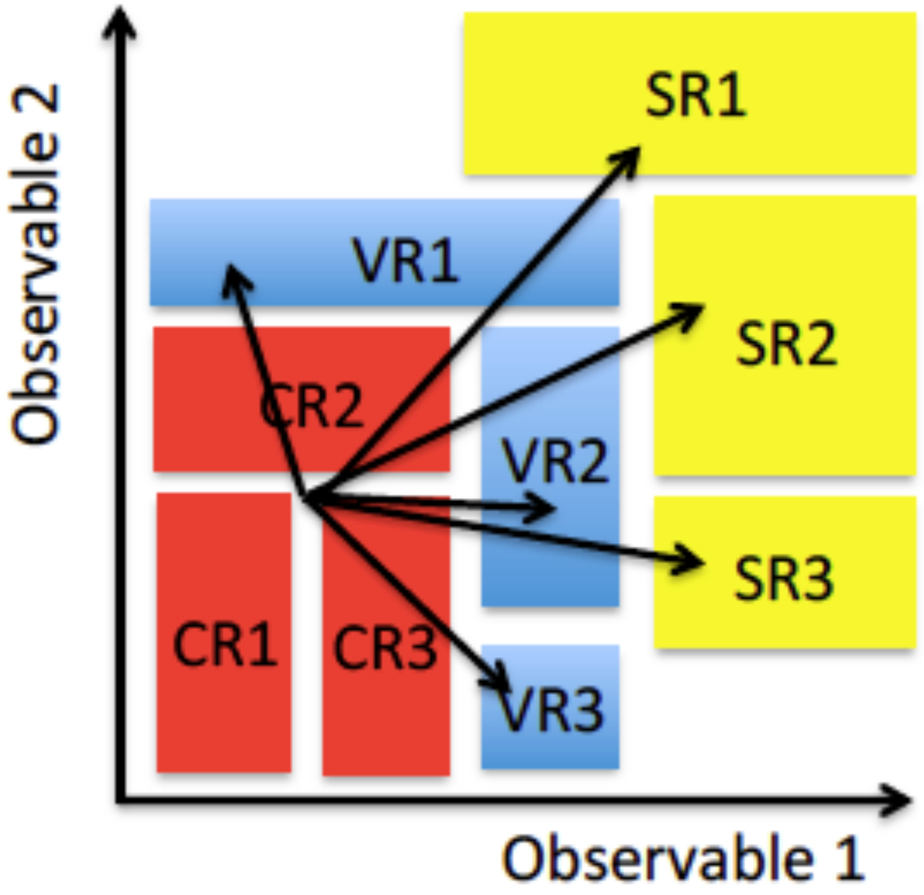


See plenary talks by J. Gumiaraes da Costa & C. Moretti + many WG talks

Background Estimation method I: data-driven

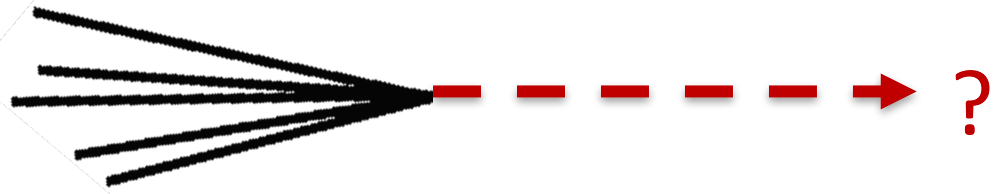
- **Define control regions (CR) where given background dominates**
  - Ideally at least one per background source
  - Normally defined by inverting one cut
- **Normalize MC in these CRs**
  - Usually via simultaneous fit of n regions for m background normalisations (ideally n≥m)
  - Uncertainty arises from data statistics in CR
- **Evaluate systematic uncertainties for extrapolation of CR to SR**
  - Use MC generators or calculations
- **Sometimes "validation regions" are used to check background estimate in intermediate region**

Sketch from Emma Kuwertz



Example for Background estimate: mono-jet

- **Analysis selection:**
  - E_t^{miss} >200 GeV
  - N_{jet} (p_T>50 GeV)=1, N_{lepton}(p_T>10 GeV)=0



SR background	CR process	Selection	Comments and concerns
Z(⟶νν)+jets	γ+jets	γ+jets with p_T(γ)>200 GeV	High statistics but m(γ)<<m(Z)
Z(⟶νν)+jets	Z(→ll)+jets	Z+jets with p_T(Z)>200 GeV	Low statistics & η-distribution biased by lepton selection
W(⟶lν)+jets	W(⟶lν)+jets	30<m_T<100 GeV, no b-jet	η-distribution biased by lepton selection
Top	tt⟶lνbbjj	30<m_T<100 GeV, ≥1 b-jet	OK but η-distribution biased by b-tag

- **In all cases extrapolation needed depending on QCD, EWK & PDFs**
  - Ratio of γ+jet to Z+jet cross section, kinematic distributions, …

Sources of Extrapolation Uncertainty

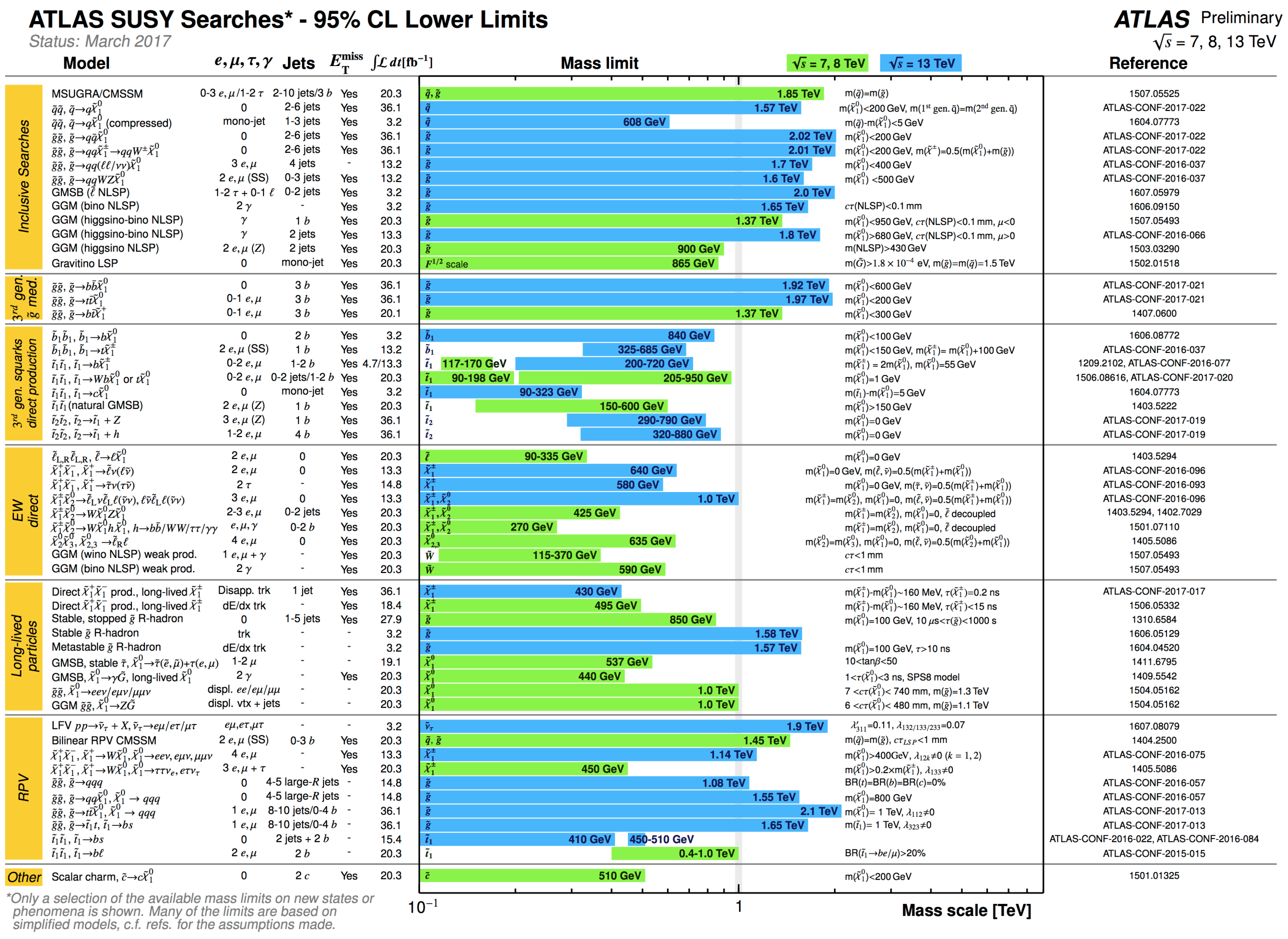
- **Trying to use highest order MC available => smallest uncertainties**
  - E.g. Sherpa MEPS@NLO or MG5_aMC+Py8 FxFx
  - Renormalize to higher order calculation if available

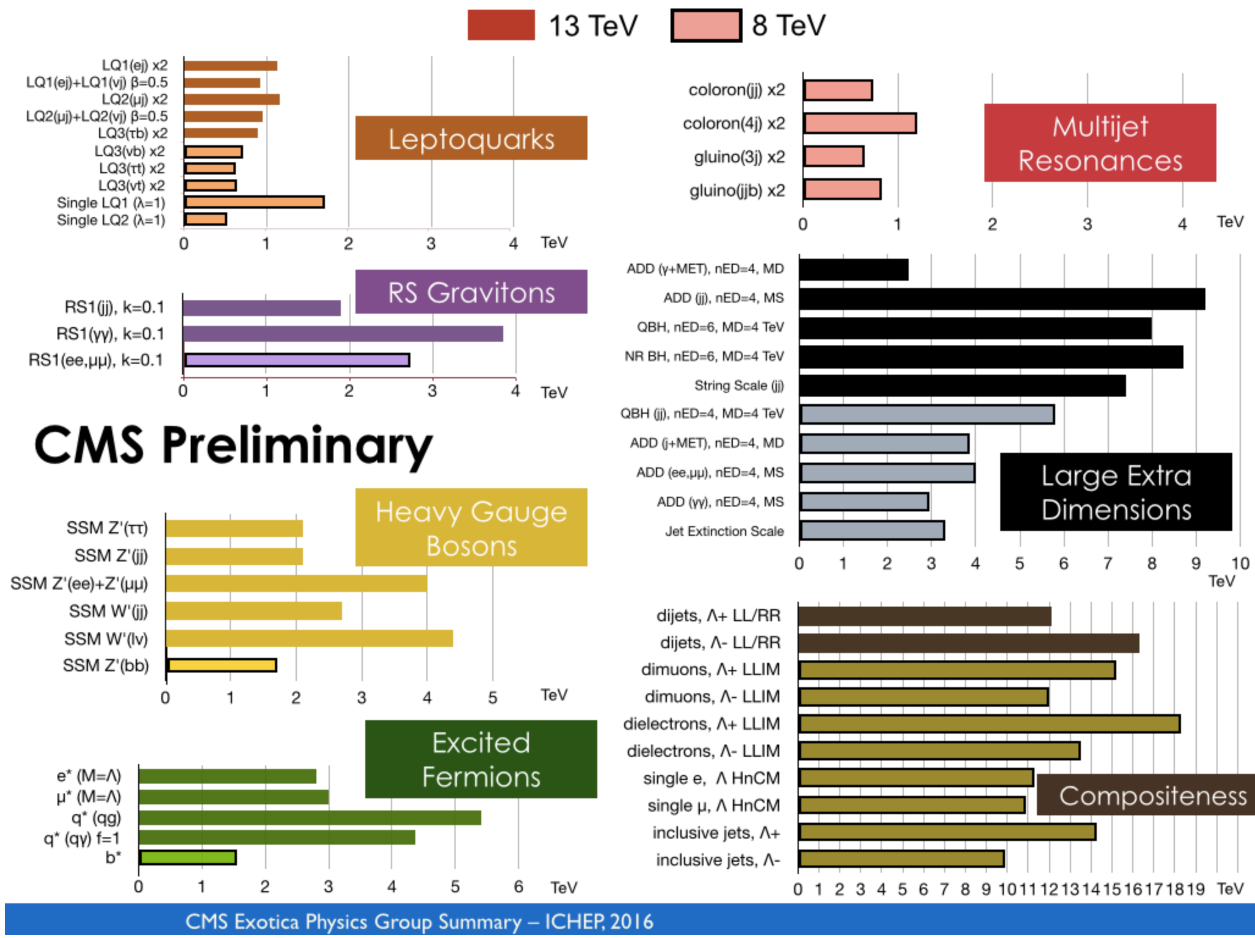
Source	How estimated
Higher order QCD	Vary renormalisation, factorisation and resummation scales by factors 0.5-2.0
Parton Distr. Functions (PDFs)	PDF4LHC recommendations (arXiv:1101.0538 or 1510.03865) • Systematic variations within PDF group • Use different PDF group • Vary α_s
Parton Shower, ISR, FSR	• Vary p_T cuts for matching in MLM/CKKW schemes • Vary underlying event tune
Electroweak corrections	$(1+\delta_{EWK}+\delta_{QCD})$ vs $(1+\delta_{EWK})x(1+\delta_{QCD})$
Heavy flavour content	No good recipe available => more measurements needed

*When data statistics on control regions poor => MC-based estimate taken using similar uncertainties

Searches for New Physics

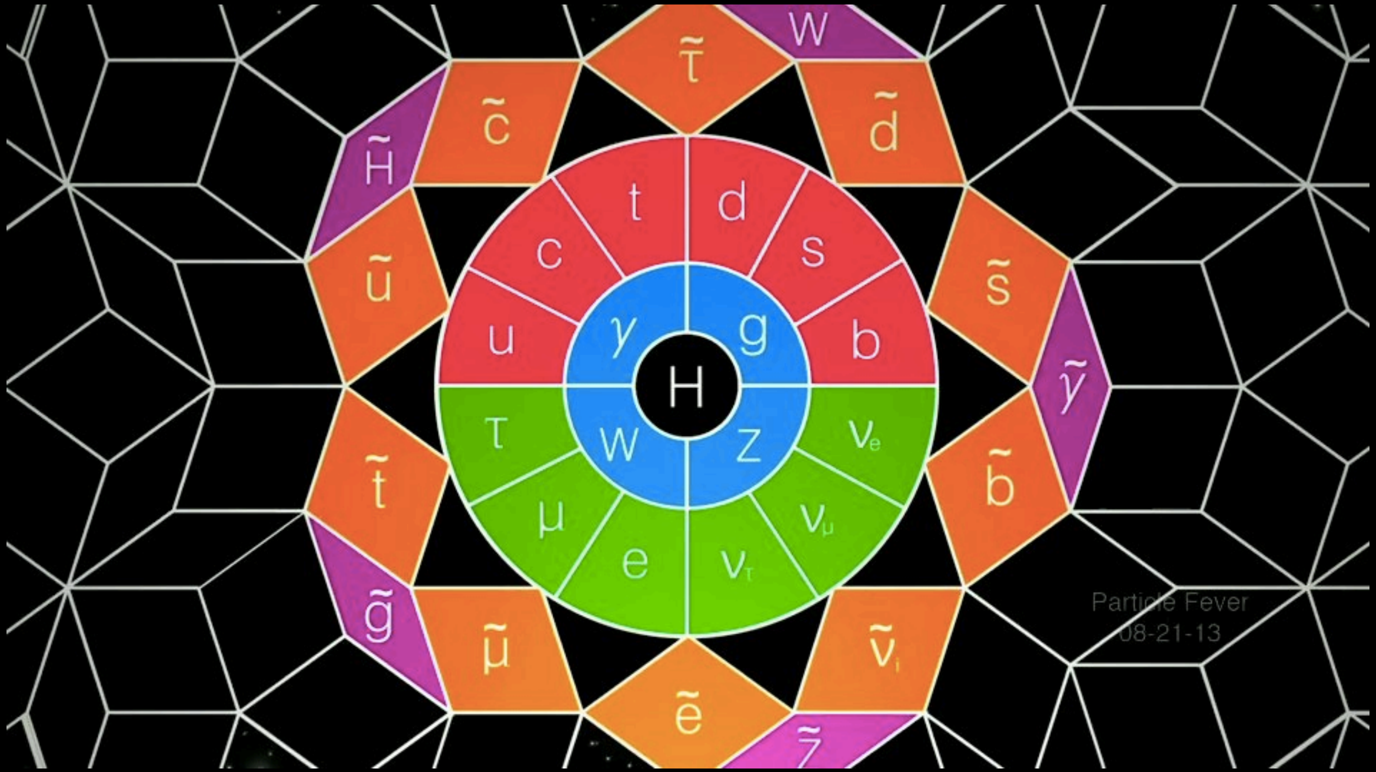
Summary of (selected) search results

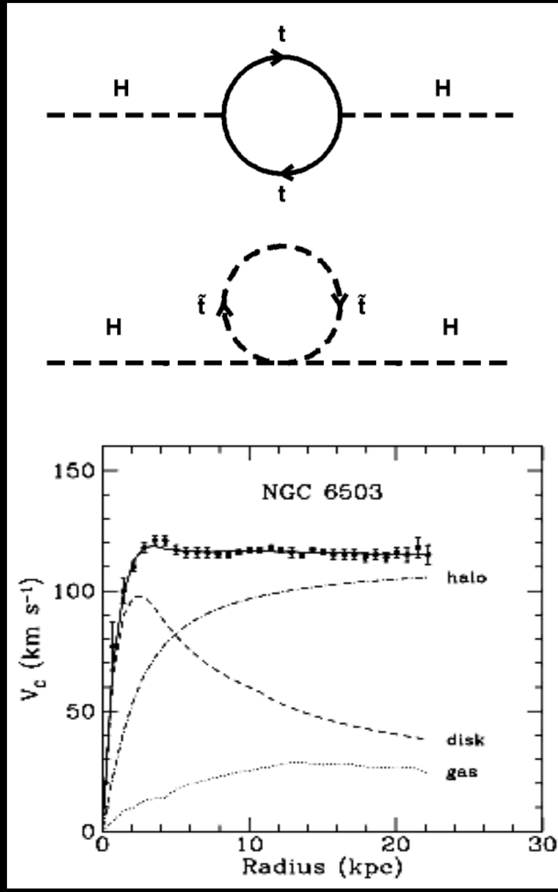




- **Very large number of searches conducted by both experiments**
  - Most (but not all) searches available now with Run-2 data
  - Will only be able to show a small selection

Supersymmetry



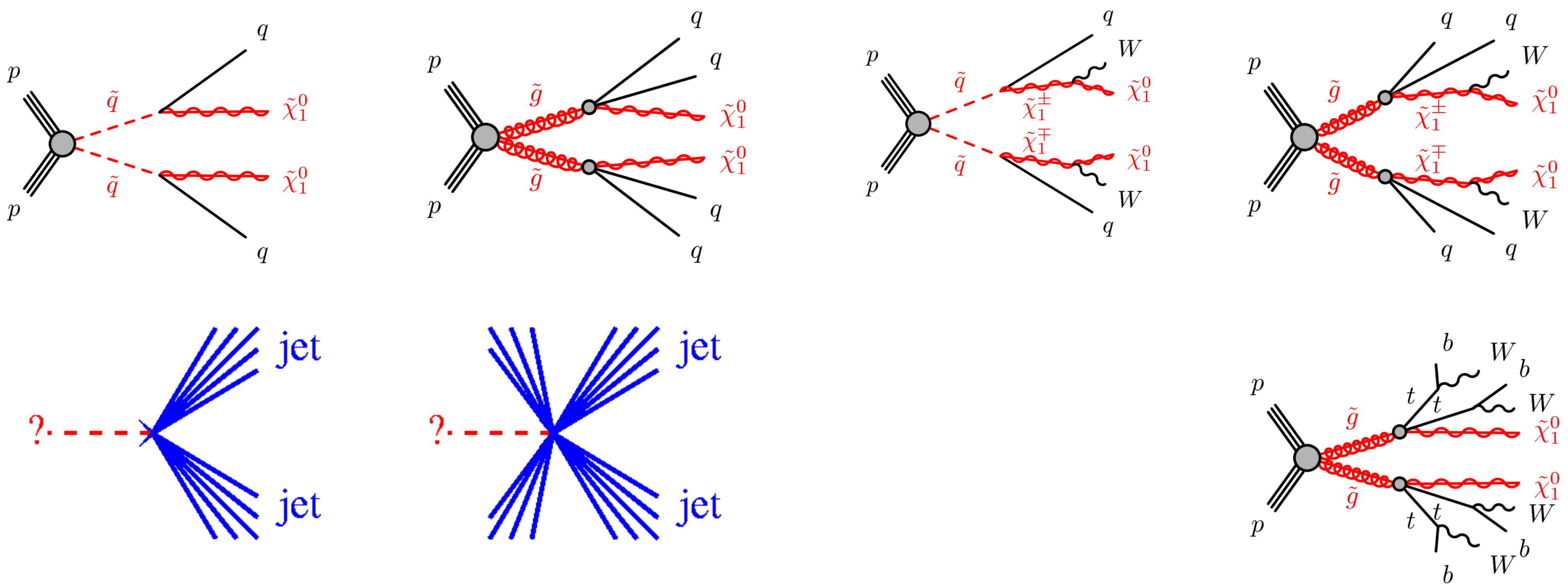


- **Supersymmetry well motivated:**
  - Can solve/reduce finetuning problem
  - Has good dark matter candidate
  - Can achieve gauge force unification

See WG3 talks by E. Asilar, I.Santoyo Castillo on Tuesday , and J. K. Anders, M. Jansova, N. Rogers Bernard, M. Bogavac, N. Suarez Andres on Wednesday

Signature depends many parameters

2 jets + E_T^{miss} 4 jets + E_T^{miss} 6 jets + E_T^{miss} 8 jets + E_T^{miss}



- **In any *real* model many signatures may appear at the same time**
  - But which exactly and with what strength very unclear
- **Strategy is to look for many signatures and to interpret both in simplified models and more complete models (e.g. pMSSM)**

ATLAS 0 leptons + 2-6 jets

- **Event selection:**
  - N_{jet}>2, 3, 4, 5 or 6
  - E_T^{miss}>250 GeV, $\Delta\Phi(\text{jet}, E_T^{miss})>0.8$
  - Other kinematic cuts
  - $m_{eff}=\sum E_t^{jets}+E_T^{miss}$
- **Main backgrounds:**
  - Top (modelled with Powheg-Box+Pythia)
  - W+jets, Z+jets (modelled with Sherpa)

N_{jet}=4-5 signal regions

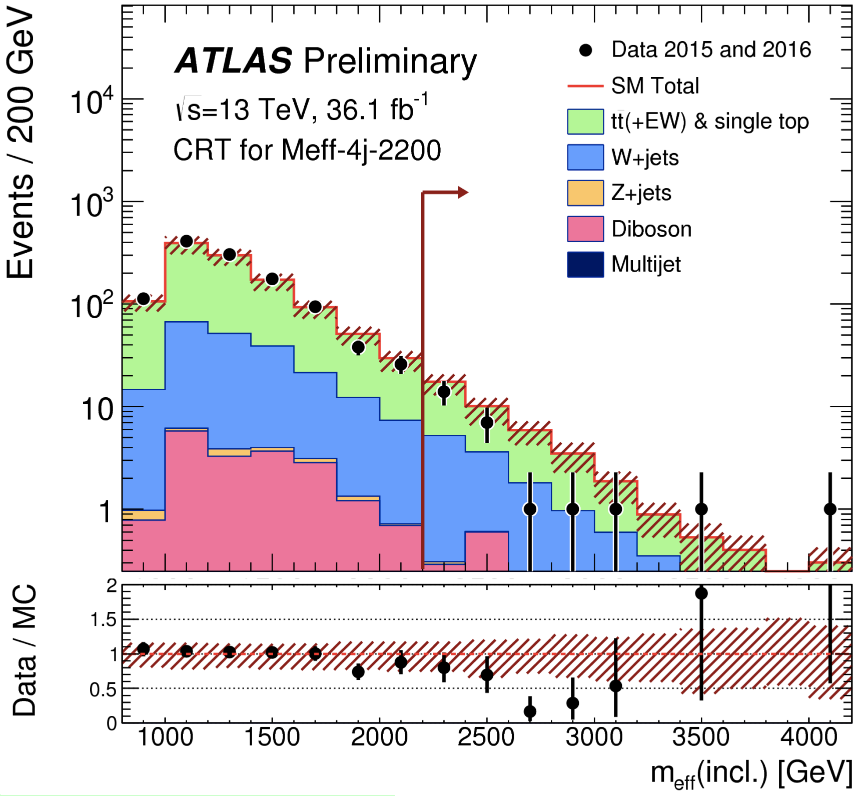
Targeted signal	$\tilde{g}\tilde{g}$, $\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$						
Requirement	Signal Region [Meff-]						
	4j-1000	4j-1400	4j-1800	4j-2200	4j-2600	4j-3000	5j-1700
E_T^{miss} [GeV] >	250						
$p_T(j_1)$ [GeV] >	200						700
$p_T(j_4)$ [GeV] >	100				150		50
$p_T(j_5)$ [GeV] >	–						50
$\lvert\eta(j_{1,2,3,4})\rvert$ <	1.2	2.0					–
$\Delta\phi(\text{jet}_{1,2,(3)}, E_T^{miss})_{min}$ >	0.4						
$\Delta\phi(\text{jet}_{i>3}, E_T^{miss})_{min}$ >	0.4						0.2
$E_T^{miss}/m_{eff}(N_j)$ >	0.3	0.25			0.2		0.3
Aplanarity >	0.04						–
m_{eff}(incl.) [GeV] >	1000	1400	1800	2200	2600	3000	1700

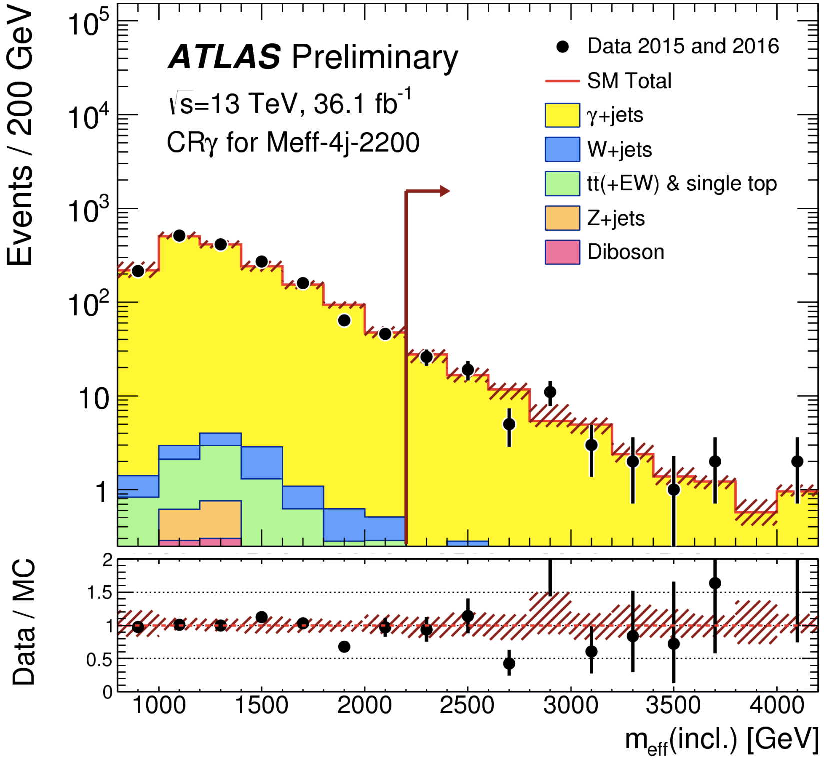
Physics process	Generator	Cross-section normalization	PDF set	Parton shower	Tune
SUSY processes	MG5_aMC@NLO 2.2.2–2.3.3	NLO+NLL	NNPDF2.3LO	Pythia 8.186	A14
$W(\to \ell\nu)$ + jets	Sherpa 2.2.1	NNLO	NNPDF3.0NNLO	Sherpa	Sherpa default
$Z/\gamma^*(\to \ell\bar{\ell})$ + jets	Sherpa 2.2.1	NNLO	NNPDF3.0NNLO	Sherpa	Sherpa default
γ + jets	Sherpa 2.1.1	LO	CT10	Sherpa	Sherpa default
$t\bar{t}$	Powheg-Box v2	NNLO+NNLL	CT10	Pythia 6.428	Perugia2012
Single top (Wt-channel)	Powheg-Box v2	NNLO+NNLL	CT10	Pythia 6.428	Perugia2012

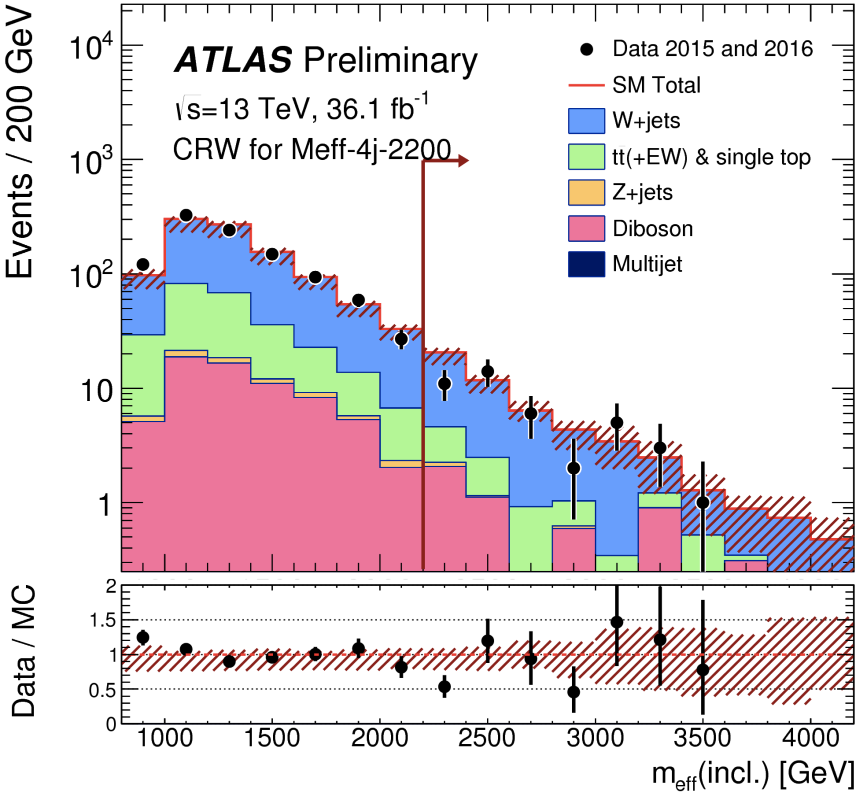
ATLAS 0 lepton 2-6 jets Control Regions

- **Each SR has 3 separate CRs**
  - One for each background source
  - Important as normalisation depends on kinematic properties

SR background	CR process	Selection
Top	$t\bar{t} \longrightarrow l\nu bbjj$	Lepton, $30<m_T<100$ GeV, ≥1 b-jet
$Z(\longrightarrow \nu\nu)$+jets	γ+jets	γ+jets with $p_T(\gamma)>150$ GeV
$W(\longrightarrow l\nu)$+jets	$W(\longrightarrow l\nu)$+jets	Lepton, $30<m_T<100$ GeV, no b-jet





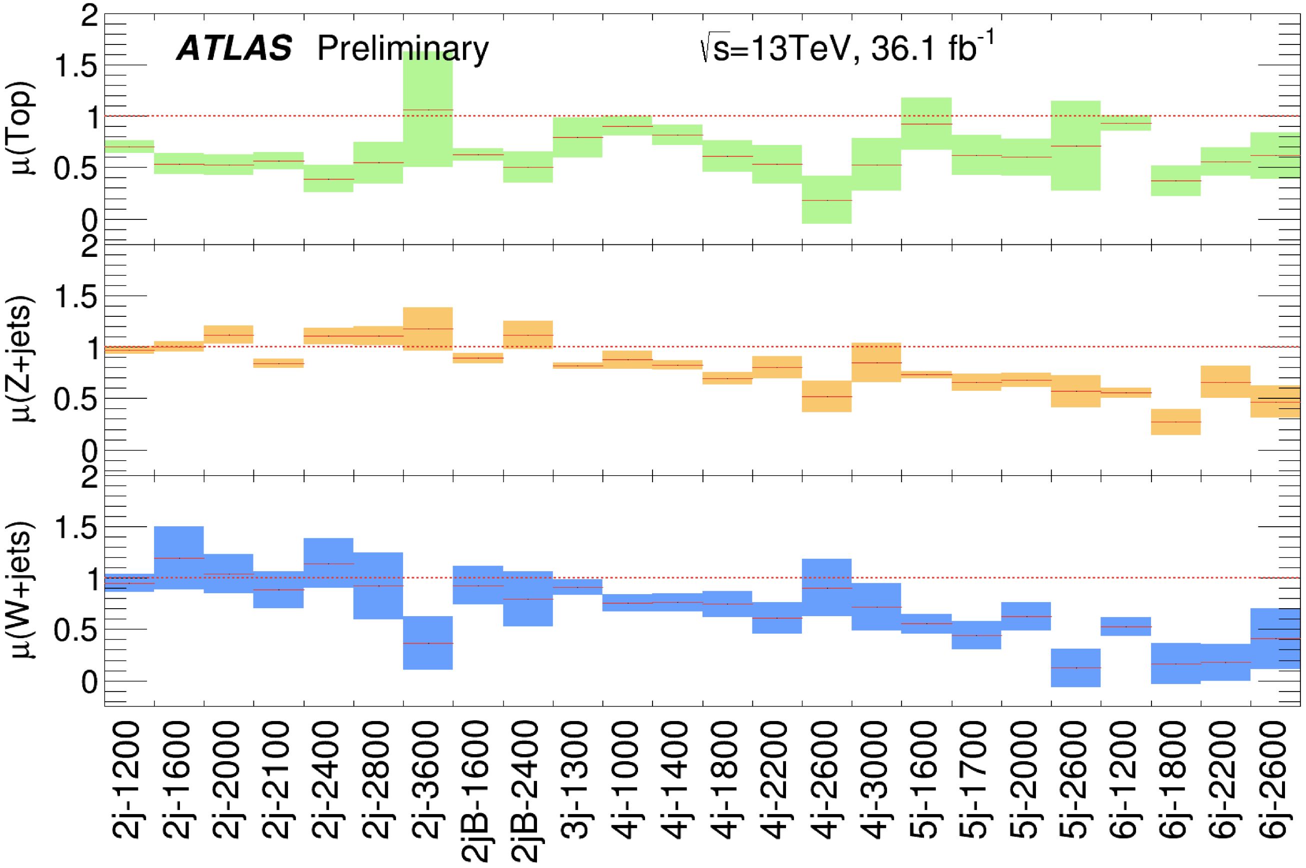


ATLAS-CONF-2017-022

ATLAS 0 lepton 2-6 jets Control Regions

- **Each SR has 3 separate CRs**
  - One for each background source
  - Important as normalisation depends on kinematic properties
- **CR fit result:**
  - Top scaled down by μ~0.5
  - Z+jets and W+jets background
    - μ~1 for $N_{jet}<4$
    - μ~0.5 for $N_{jet}>5$

SR background	CR process	Selection
Top	tt⟶lνbbjj	$30<m_T<100$ GeV, ≥1 b-jet
Z(⟶νν)+jets	γ+jets	γ+jets with $p_T(\gamma)>150$ GeV
W(⟶lν)+jets	W(⟶lν)+jets	$30<m_T<100$ GeV, no b-jet



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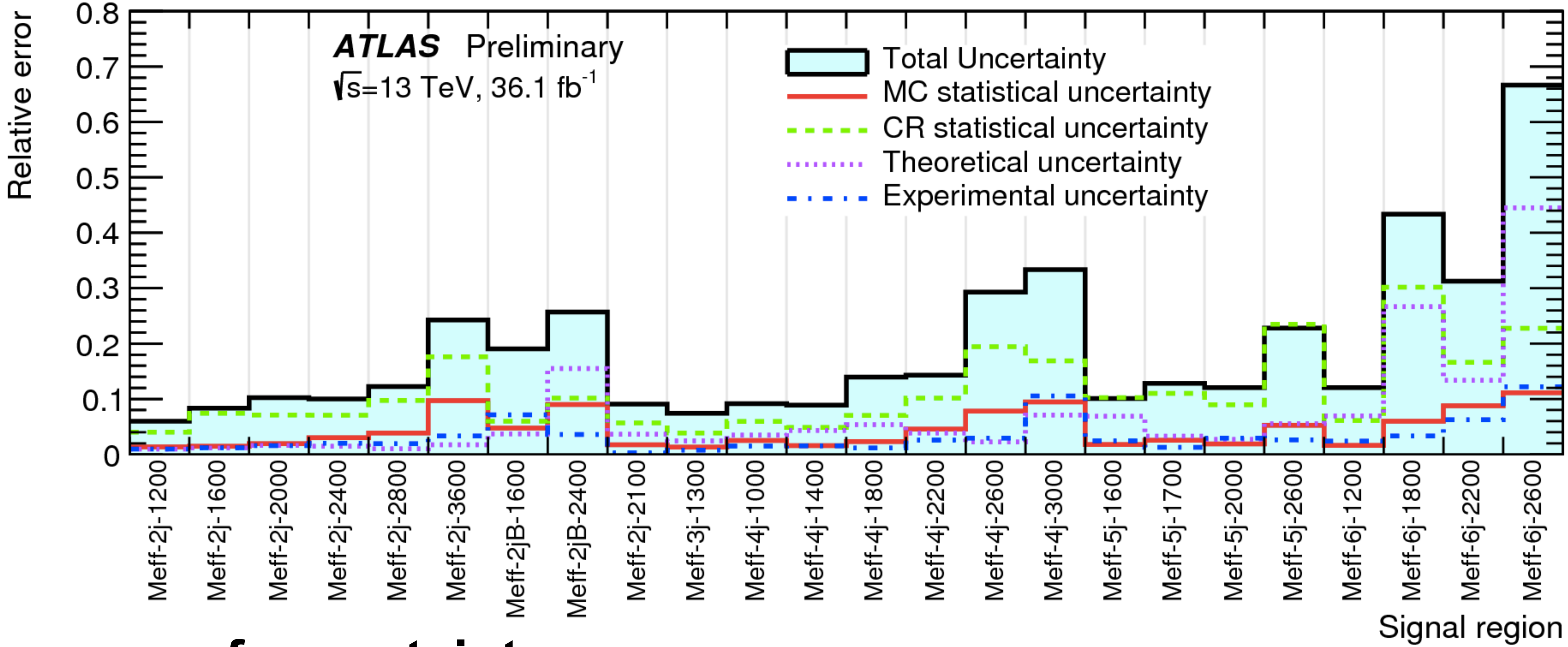
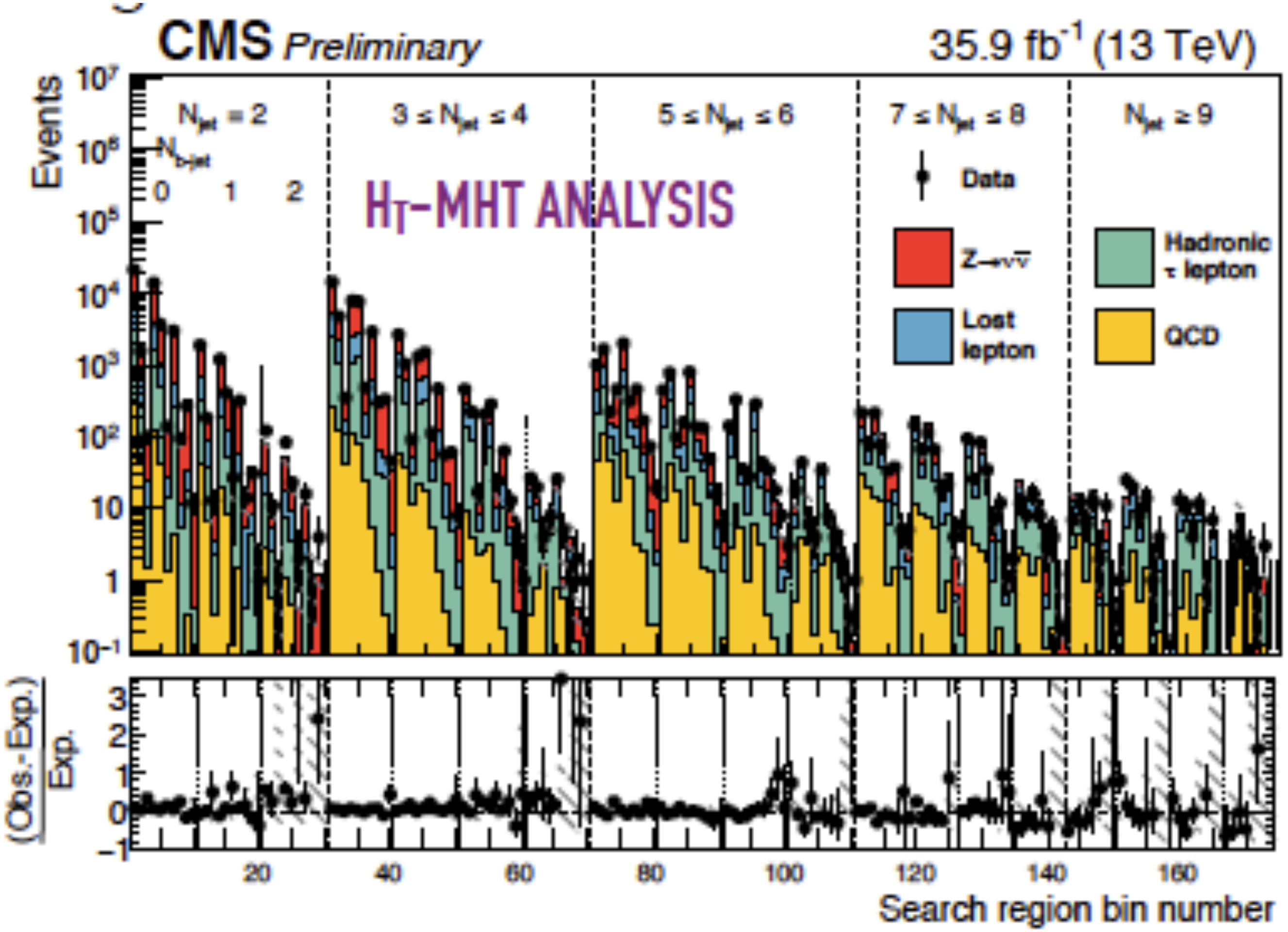
Uncertainty on Backgrounds

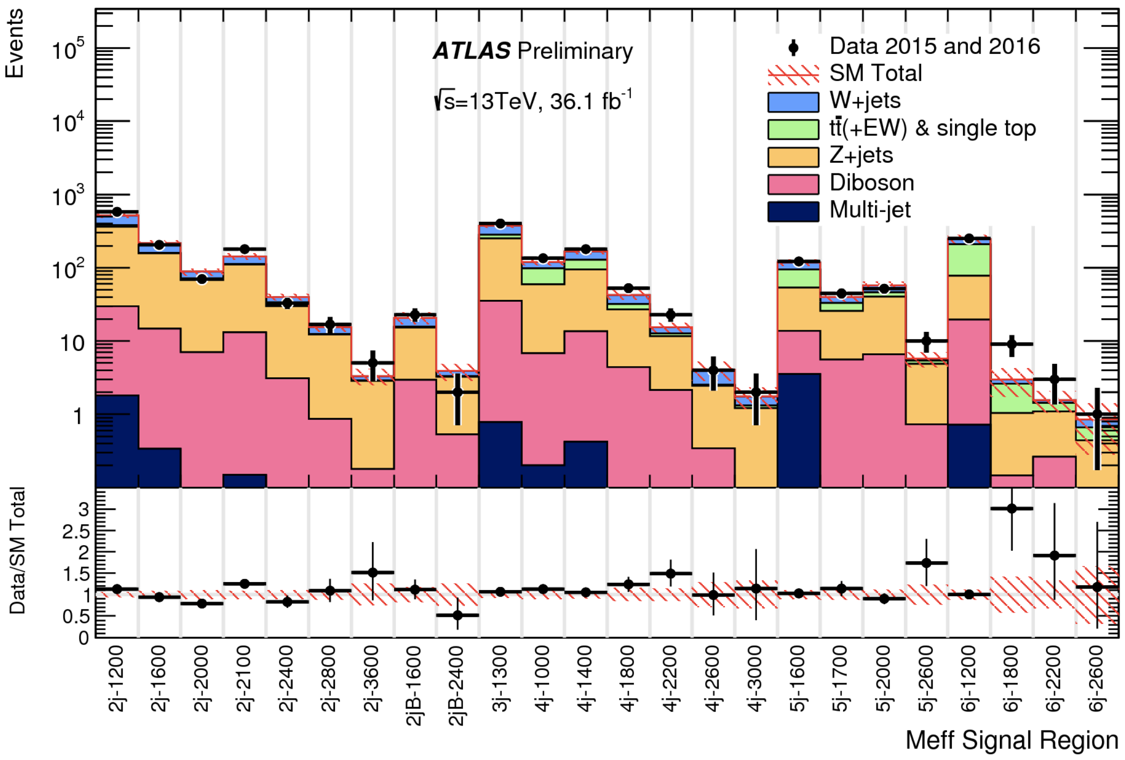


- **Sources of uncertainty:**
  - **Control region statistics**: typically 5-20%
  - **Theoretical uncertainties**: up to 50% at highest M_{eff} values and jet multiplicities
  - Experimental uncertainties small in comparison

ATLAS-CONF-2017-022

Inclusive Searches: Jets+E_t^{miss} (0 and 1 leptons)

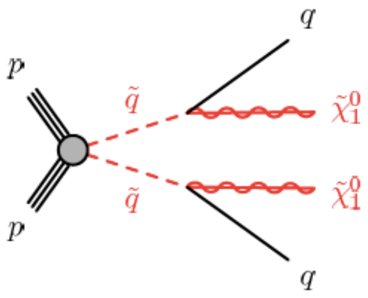


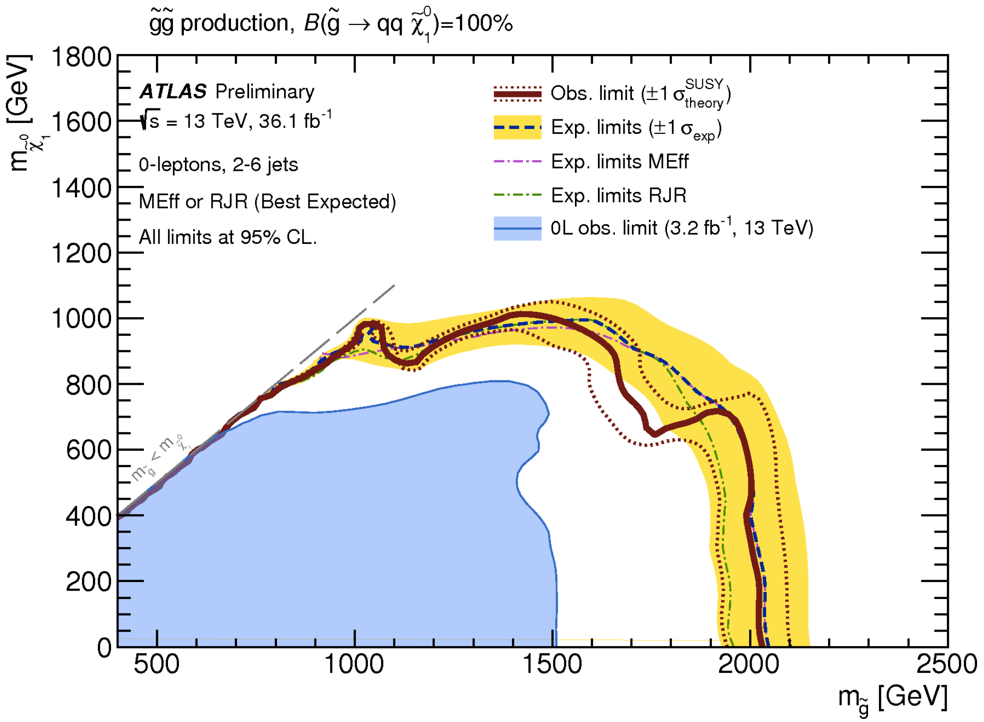


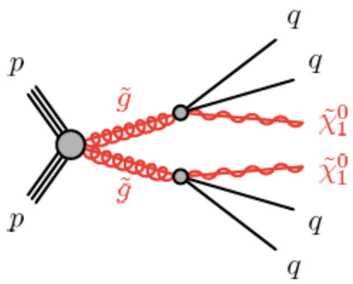
Data consistent with background estimates

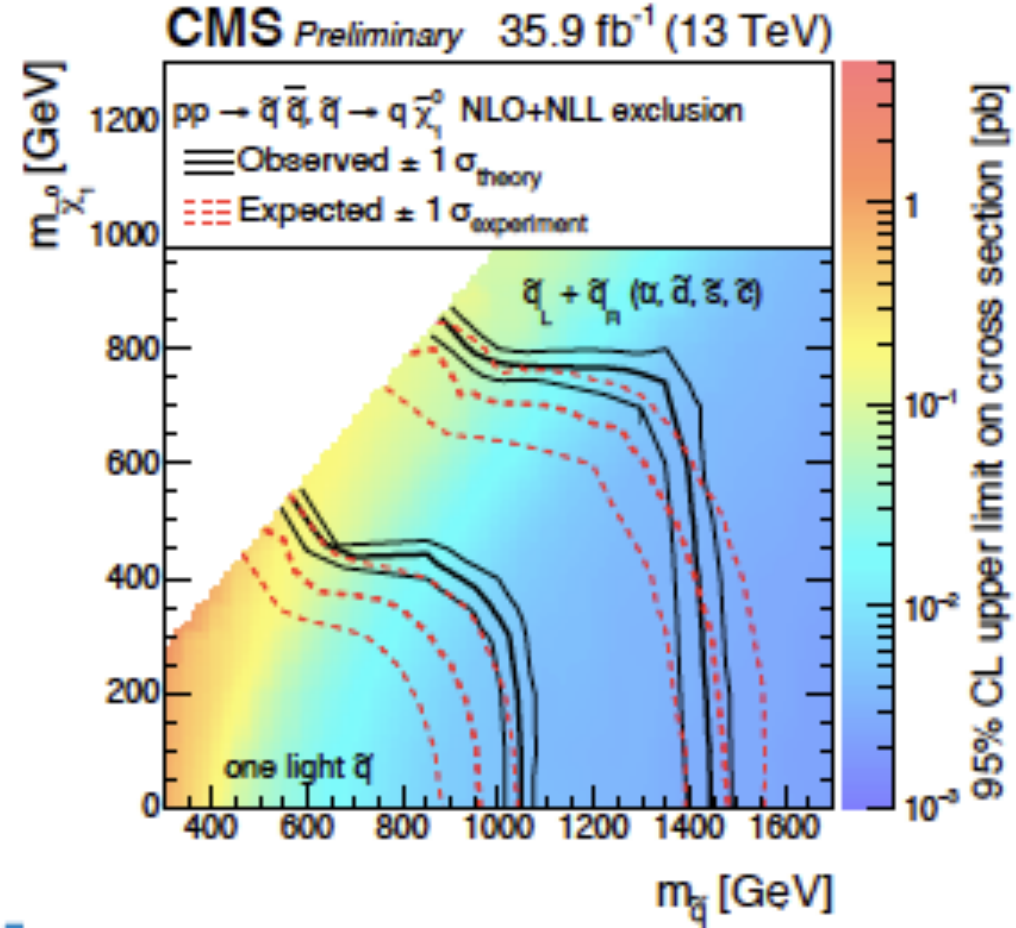
ATLAS-CONF-2017-022
CMS-PAS-SUS-16-033

SUSY constraints from 0L/1L+jets searches







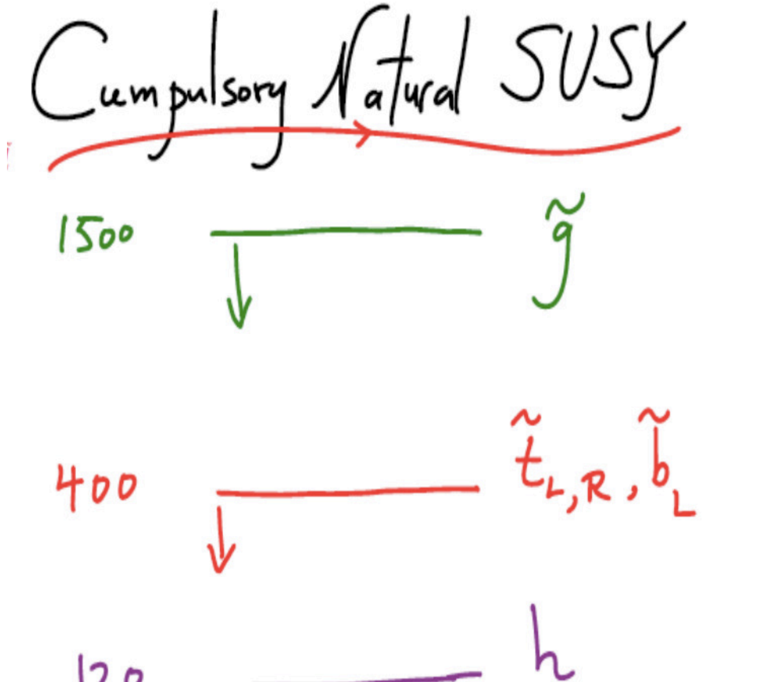


- **Limits depend on exact scenarios**
  - M(gluino) limits up to 2 TeV
  - M(squark) limits up to 1.6 TeV
  - M(χ_1^0) limits up to 1 TeV

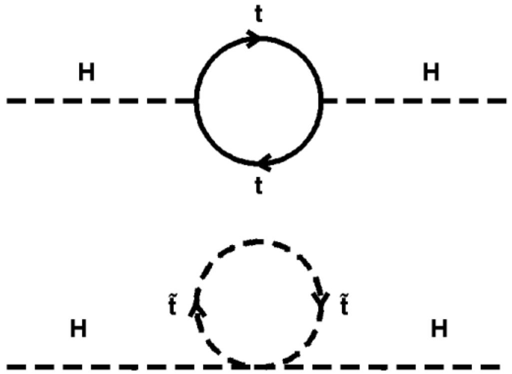
ATLAS-CONF-2017-022
CMS-PAS-SUS-16-033
CMS-PAS-SUS-16-036

Naturalness

- **Stops, sbottom and gluinos should not be “too heavy”**
  - Reduce fine-tuning at the weak scale
  - Cancellation of large top loop works better the lower m(stop) is
    - m(gluino) cannot be too high either
- **Large effort targeting 3rd generation**



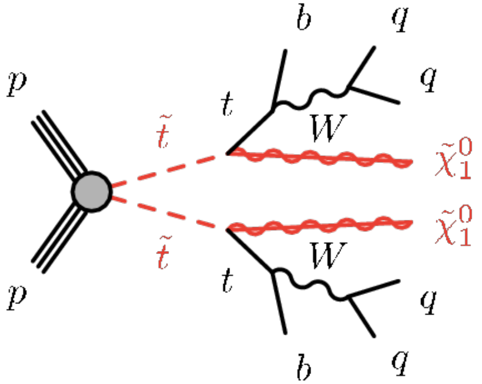
N. Arkani-Hamed



Direct stop production: 0-lepton channel

See WG3 talks by J. K. Anders & M. Jansova, Wednesday

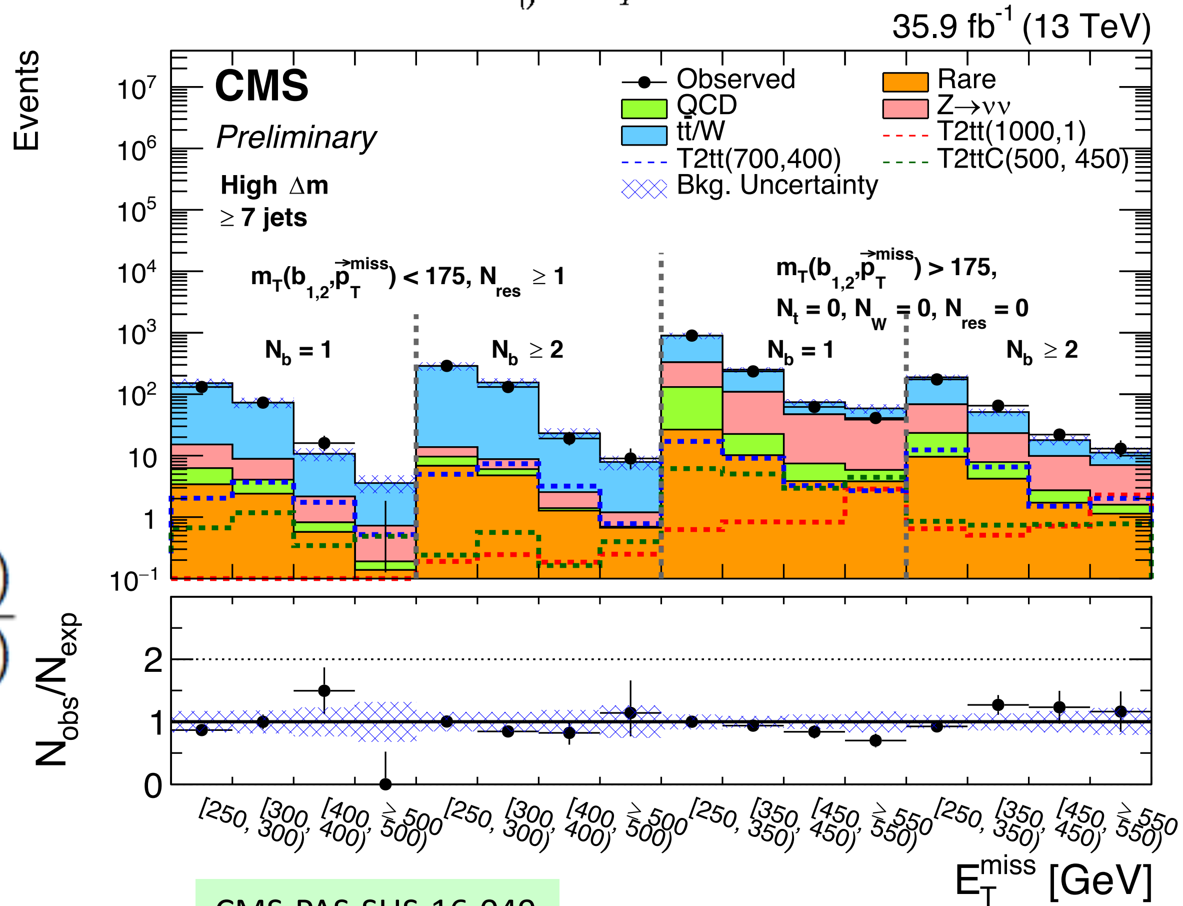
- **Many signal regions defined to optimally reduce enhance sensitivity to signal**
  - # of jets
  - # of tagged b-jets
  - # of tagged top or W candidates
    - Boosted or resolved
  - Use ISR jet tagging



- **Background estimates**
  - Top/W+jets with lepton lost
    - Invert lepton veto
    - Use MC to extrapolate $TF_{\mathrm{LL}} = \frac{N_{\mathrm{MC}}(0\ell)}{N_{\mathrm{MC}}(1\ell)}$

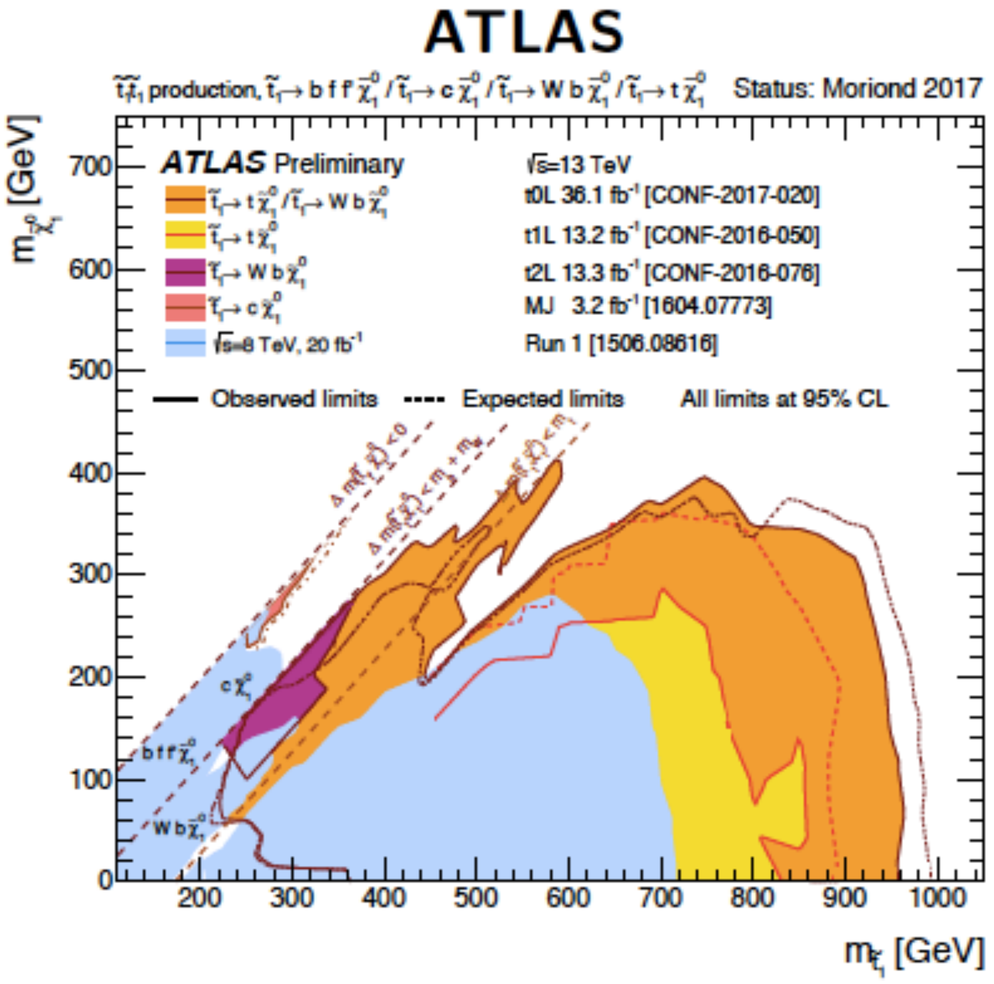
$$\boxed{N_{\mathrm{pred}}^{\mathrm{LL}} = TF_{\mathrm{LL}} \cdot N_{\mathrm{data}}(1\ell)}$$

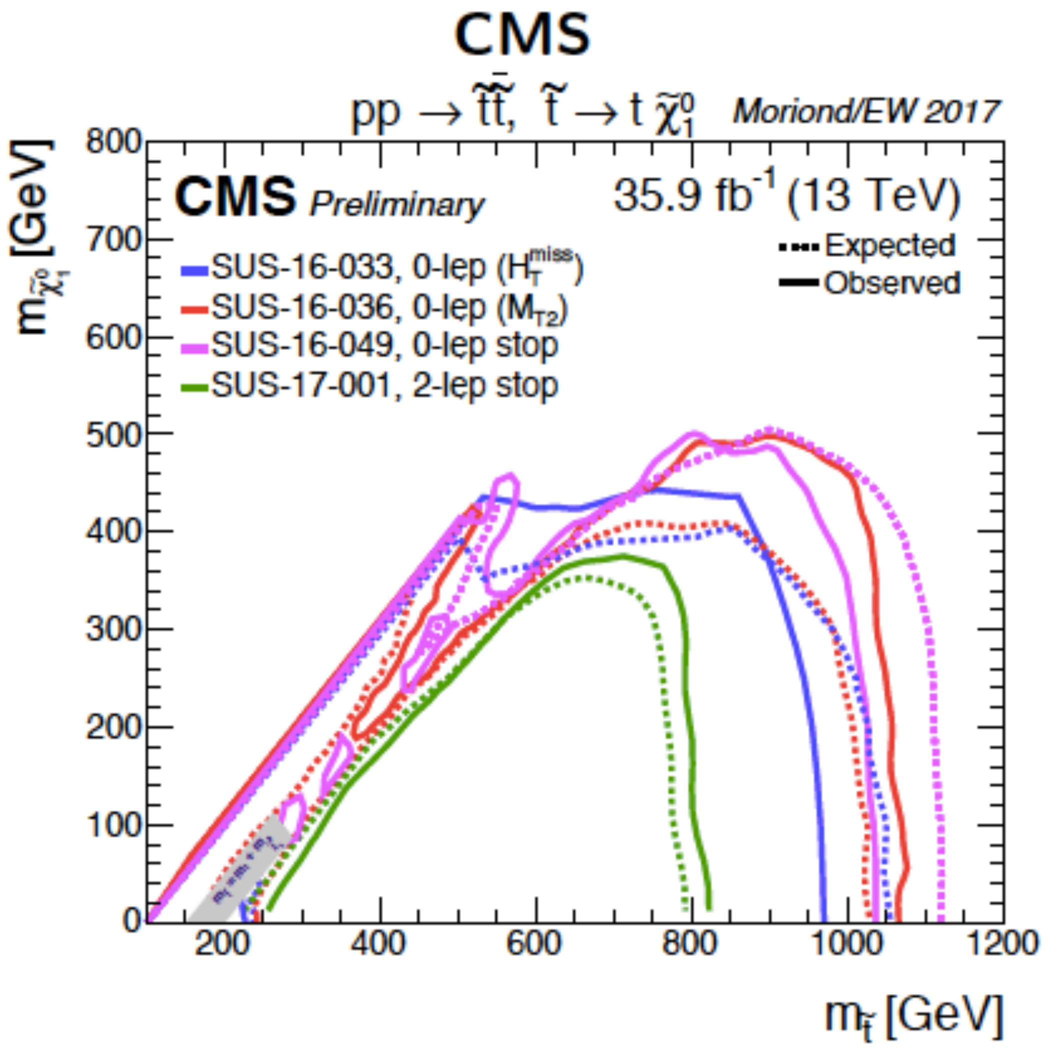
  - Z->vv + jets => use Z->ll and gamma



CMS-PAS-SUS-16-049

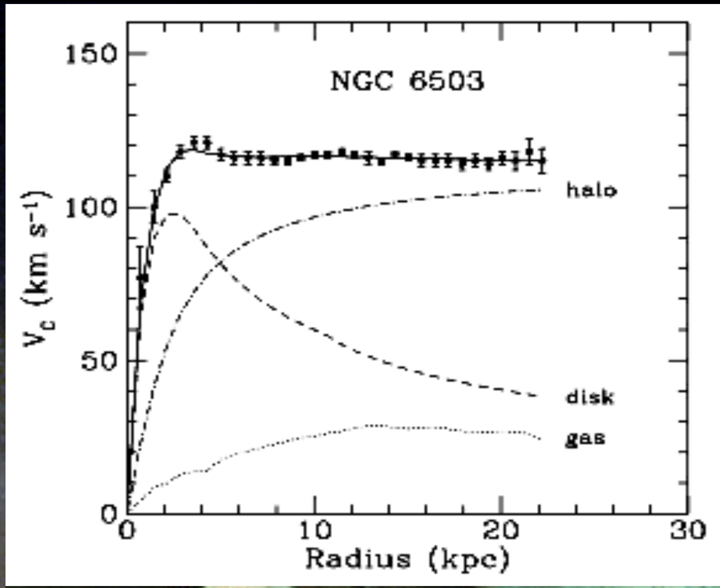
Stop Exclusion limits





- **Stop masses <1 TeV excluded for neutralino masses below 400 GeV**
  - Assuming the stop decay via top has 100% branching ratio

Dark Matter Searches

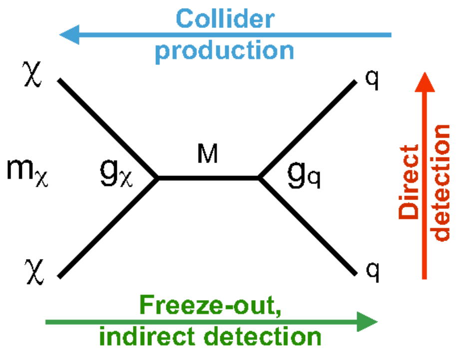


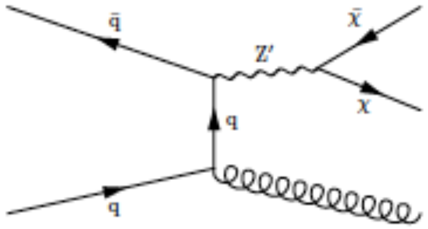
Vera Rubin (1928-2016):
“Science progresses best when observations force us to alter our preconceptions”

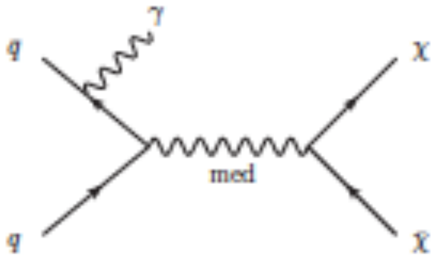
Dark Matter Searches

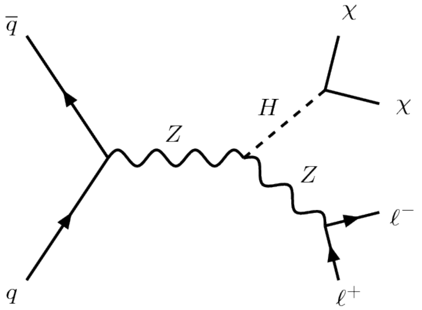
See WG3 talks by C. Fisher & C. Laner Ogilvy on Tuesday

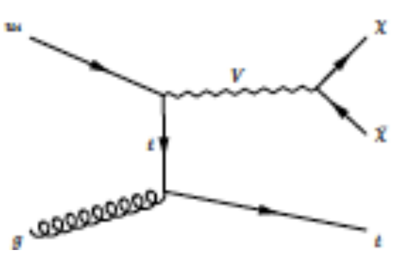
- **Many ideas for how dark matter could couple (weakly) to ordinary matter**
  - Key signature: E_T^{miss}
- **Many new analyses from ATLAS and CMS:**
  - Jet+E_T^{miss} (CMS)
  - Photon+E_T^{miss} (CMS & ATLAS)
  - W/Z+E_T^{miss} (CMS)
  - H+E_T^{miss} (ATLAS)
  - Top +E_T^{miss} (CMS)

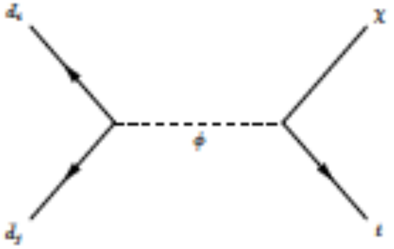








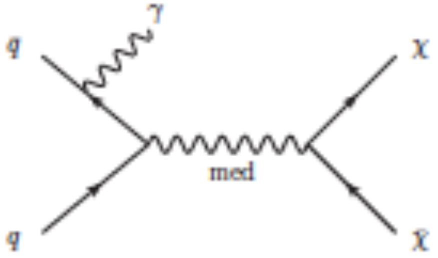




Large effort from experiments to leave no stone unturned

CMS Mono-Photon analysis

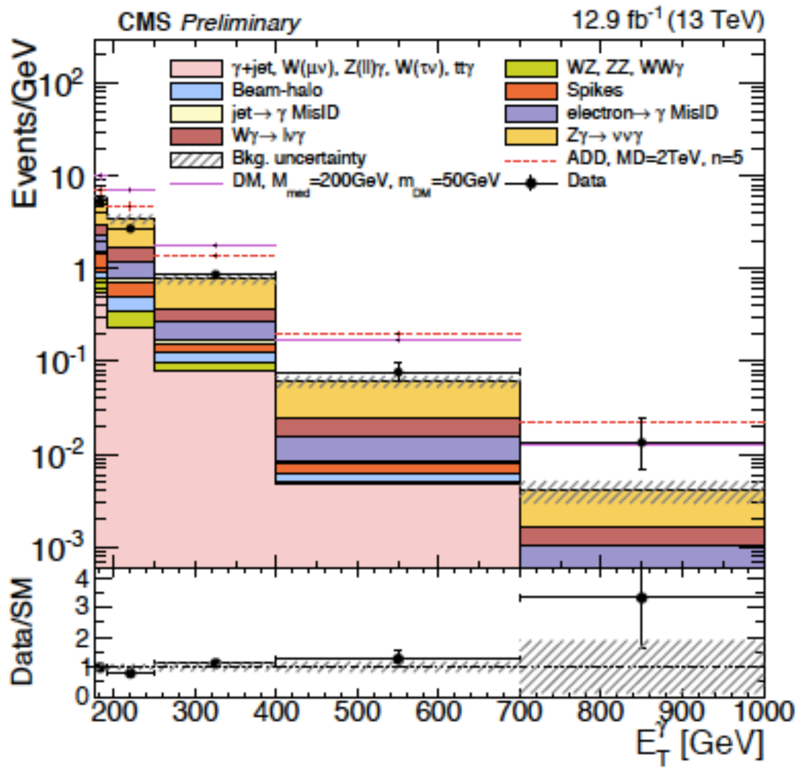
- **Event selection:**
  - Photon: p_T>175 GeV, $|\eta|$<1.44
  - E_T^{miss}>170 GeV
  - Min($\Delta\Phi$(E_T^{miss}, jet))>0.5
  - no leptons
- **Main backgrounds:**
  - Z($\rightarrow\nu\nu$)+γ and W($\rightarrow l\nu$)+γ
  - Modeling:
    - MADGRAPH5_AMC@NLO
    - Reweight $p_T(\gamma)$ to account for QCD NNLO & EWK NLO corrections
- **Cross-check using Z->ll estimate agrees and has similar errors**



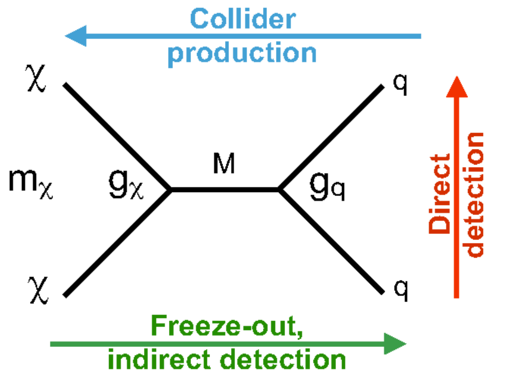
Background	MC based	Data (Z->ll)
Z+γ	215.4±32.3	242±35
W+γ	57.2±8.0	--

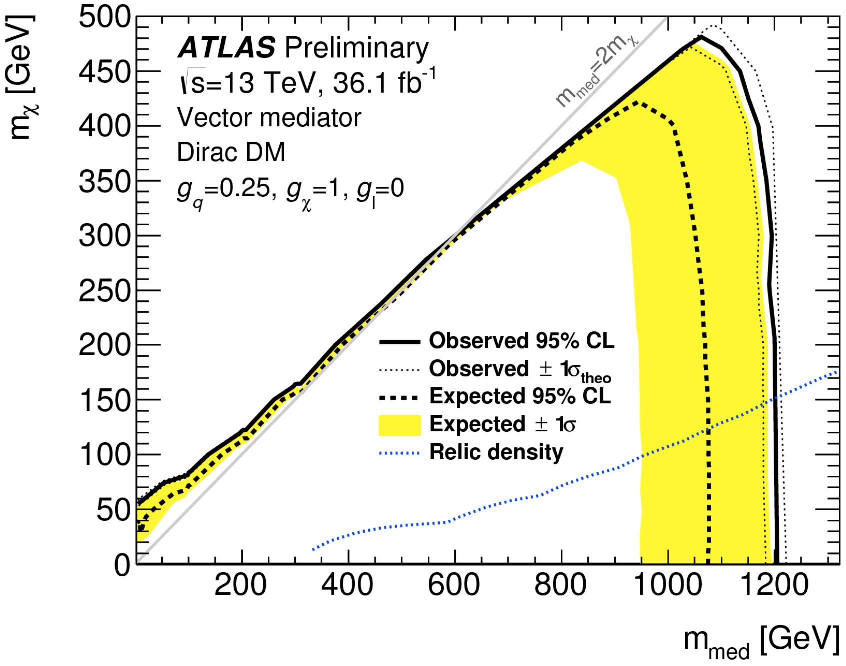
Uncertainties on MC-based estimate		
Source	**Zγ**	**Wγ**
PDF+higher order QCD	5.4%	8.9%
Higher order EWK	11%	7%
Lepton efficiencies	6%	6%
Other exp. Syst.	6.2%	6.2%

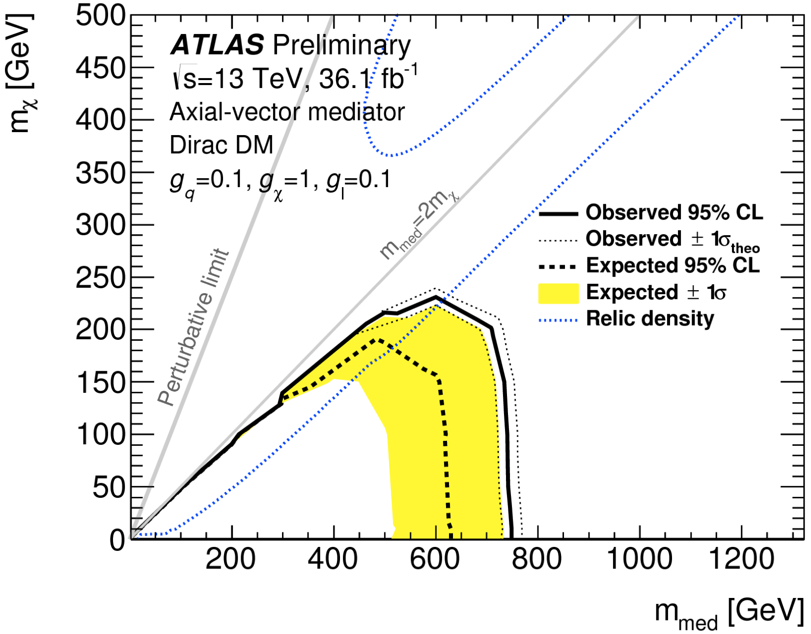
Mono-photon analysis results



- **Data agree with background estimates**
- **Limits set as function of**
  - Mediator mass m_{med}
  - Dark matter candidate mass m_χ
  - Couplings of mediator to quarks (g_q) and DM (g_χ)

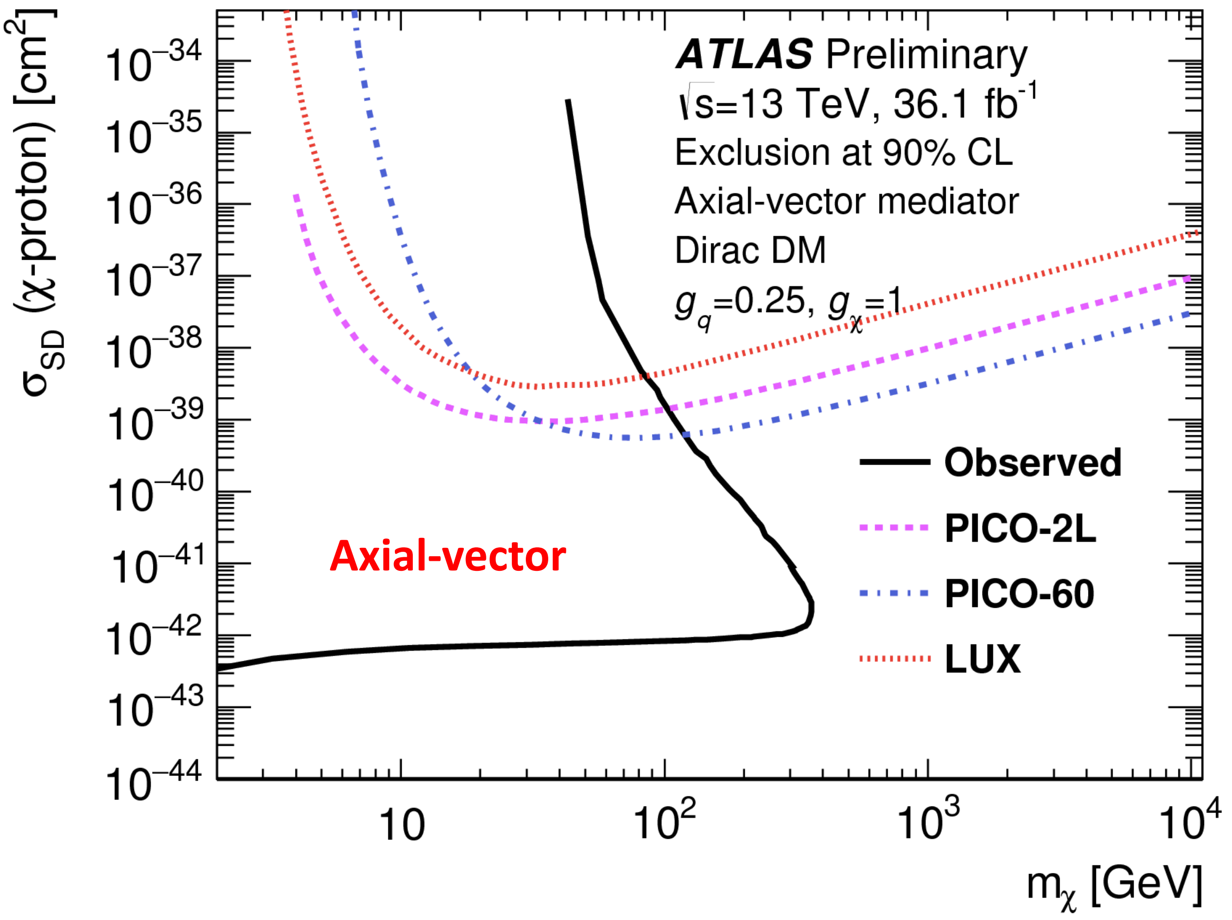


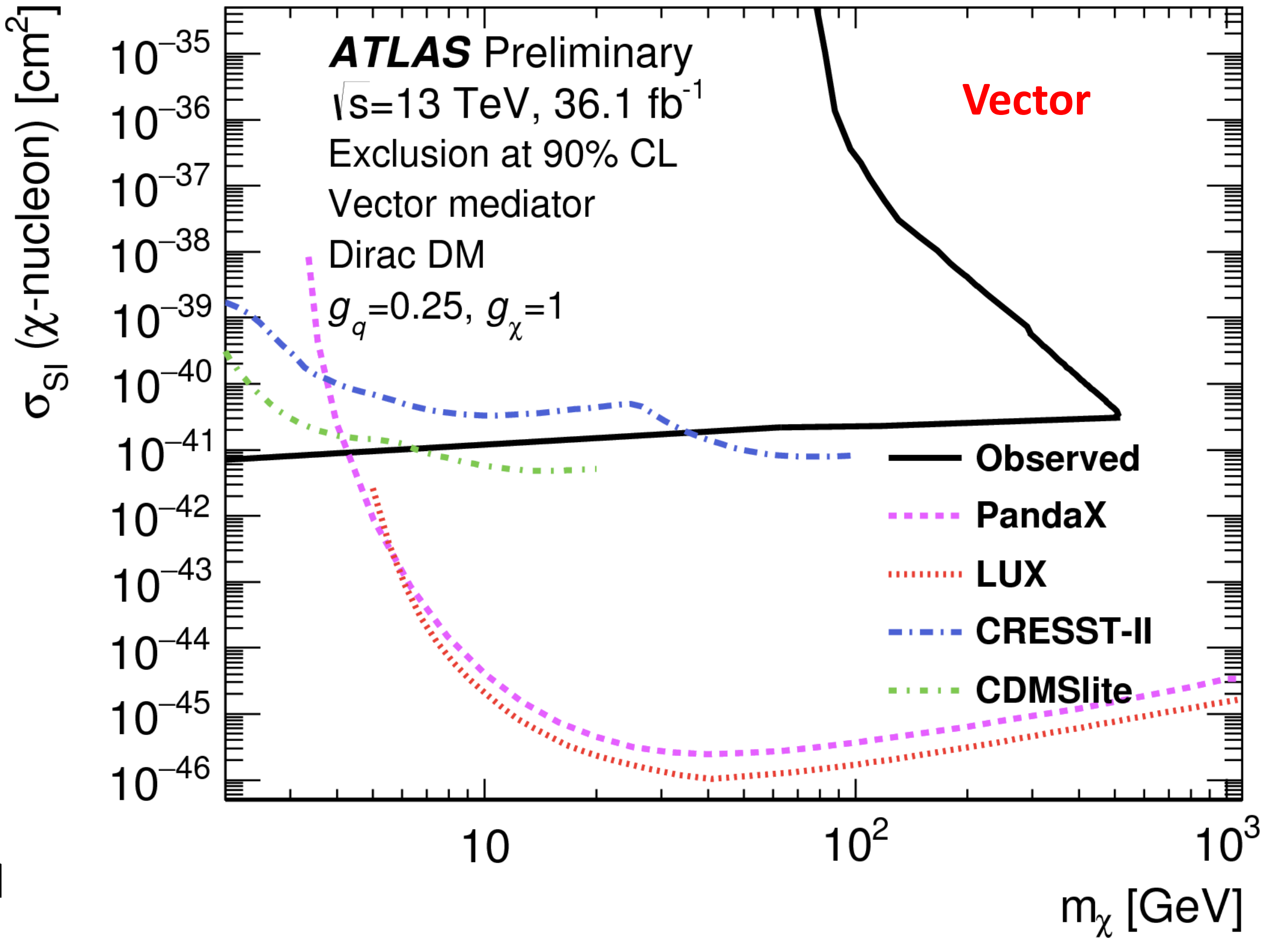




CMS-PAS-EXO-16-039
CERN-EP-2017-044

Mono-photon: constraints on χ-nucleon cross section

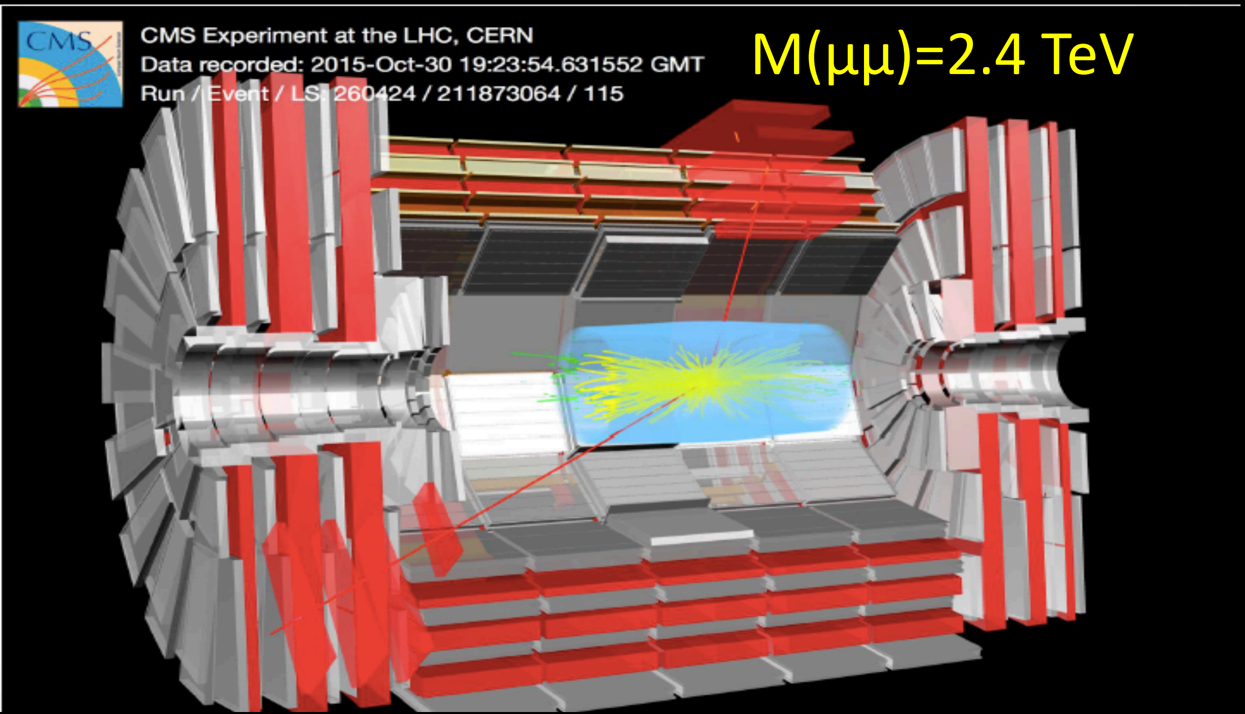


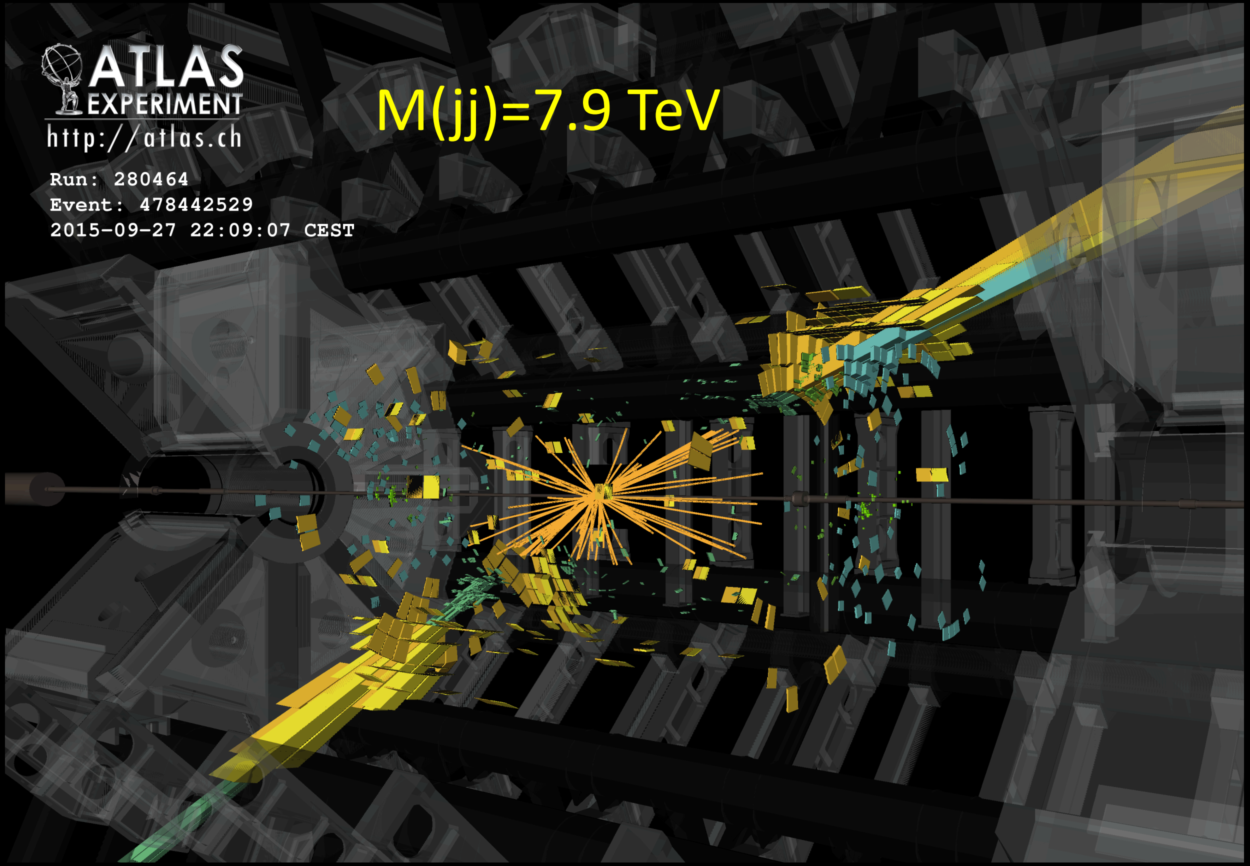


- **Complementary sensitivity compared to direct detection experiments**

CMS-PAS-EXO-16-039
CERN-EP-2017-044

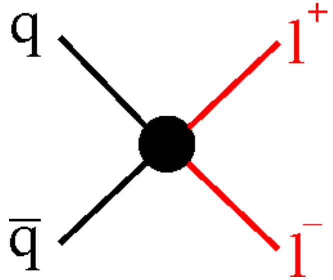
High-mass resonance searches



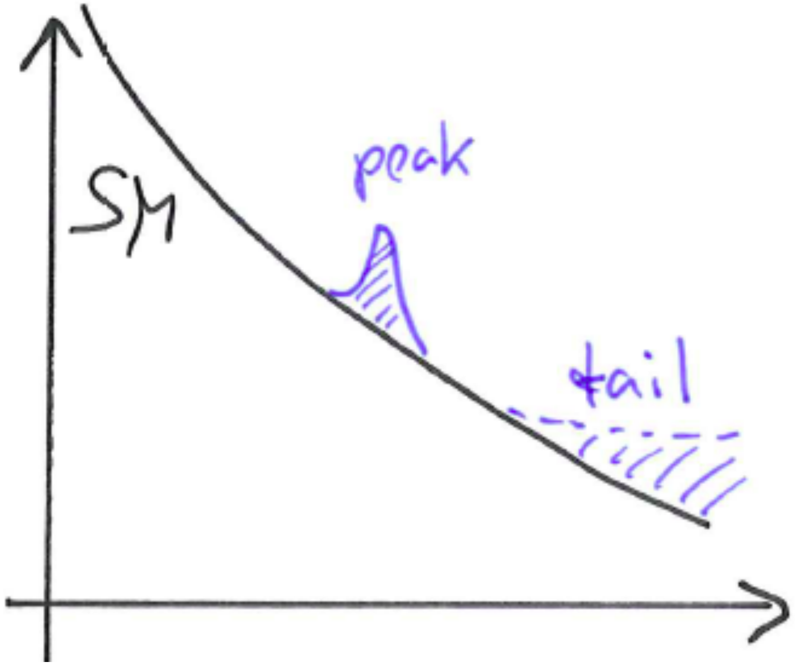


Tails and Peaks

- **High mass resonances:**
  - s-channel production => peak
  - t-channel exchange => hard tail (as e.g. in contact interaction)



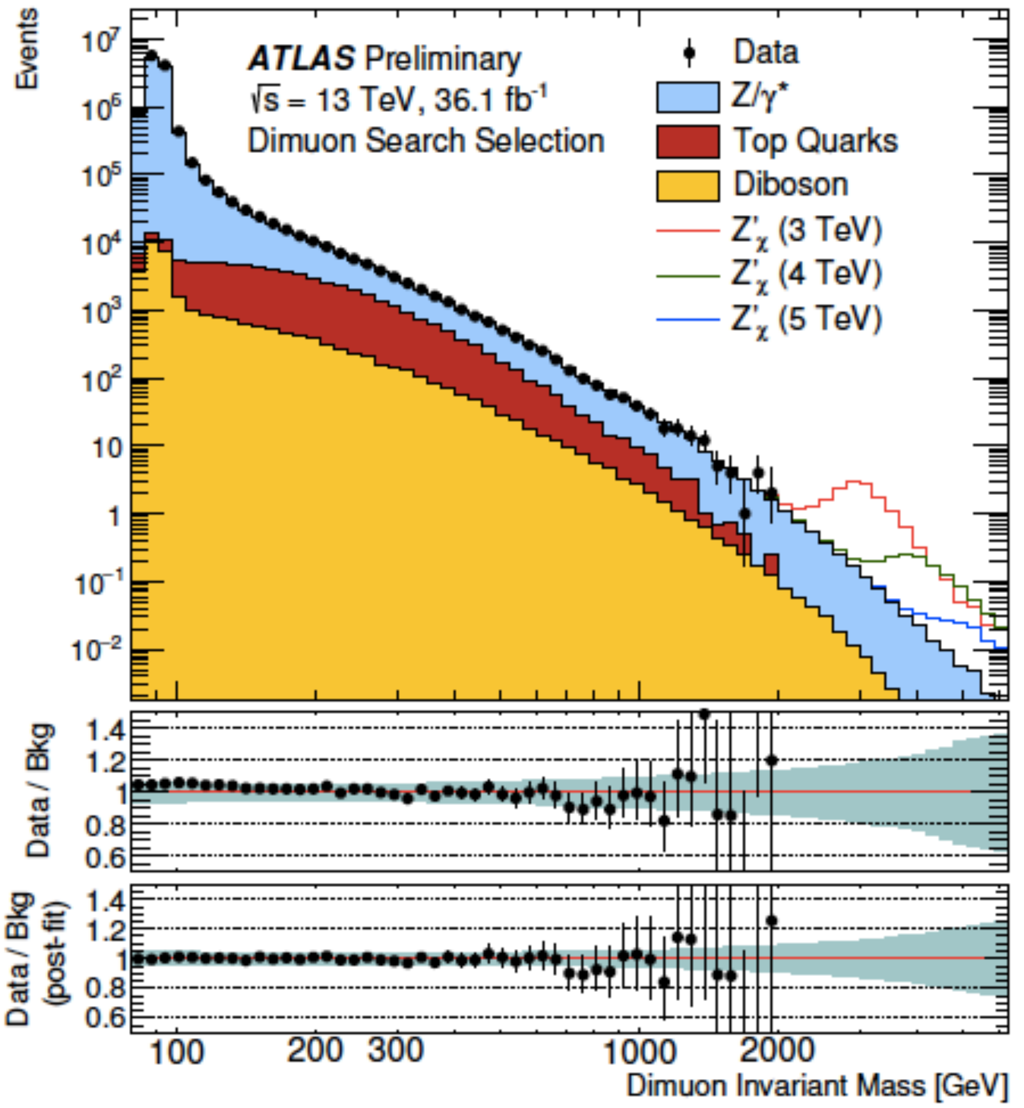
- **Requires good understanding of invariant mass spectrum of backgrounds**



See WG3 talks by H. Meyer zu Theenhausen, J. Zhang, Y. Liu and H. Saka on Wednesday

High Mass dilepton search

- **Main background is Drell-Yan**
  - POWHEG with CT10 PDFs
  - Mass-dependent corrections
    - NNLO QCD: ~0.98 at m(ll)=3 TeV
      - VRAP v0.9 and CT14NNLO PDFs
    - NLO EWK: ~0.86 at m(ll)=3 TeV
      - MCSANC v1.20
      - Includes γγ⟶ll with MRST2004QED PDFs

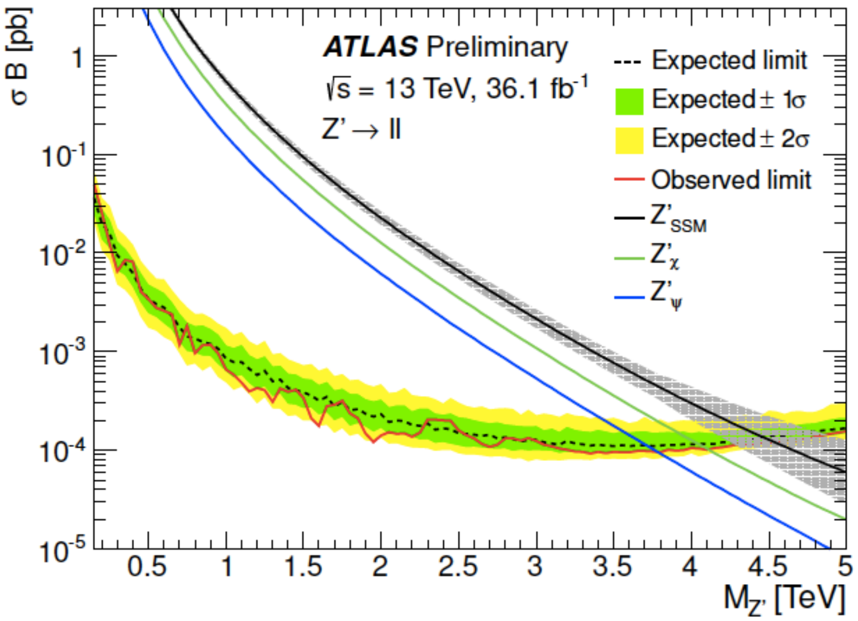


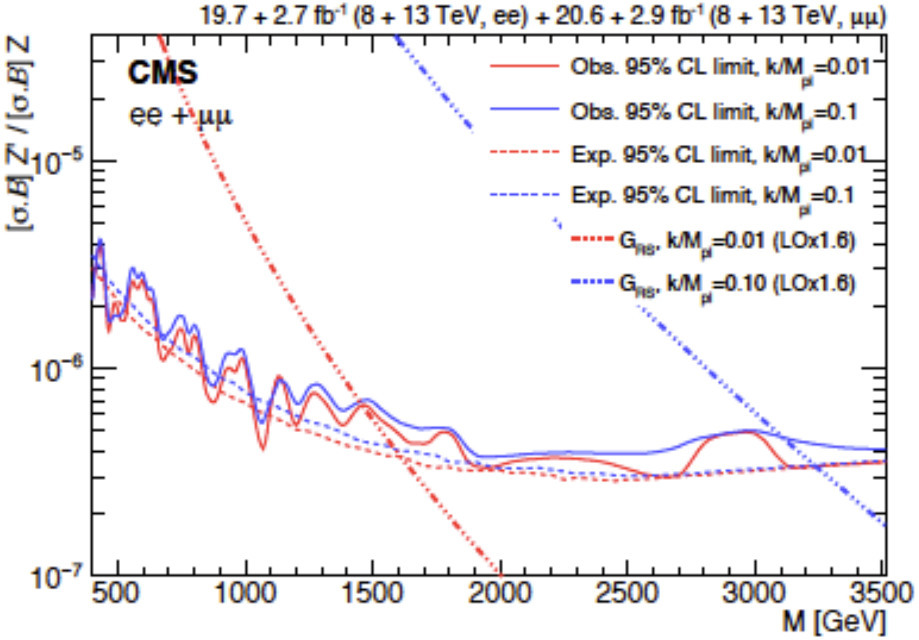
Source of error on DY background (μμ)	M(Z')=2 TeV	M(Z')=4 TeV
PDFs: CT14NNLO vs MMHT vs NNPDF3.0	<1%	1.9%
PDFs: CT14NNLO eigenvectors	7.7%	12.8%
Renorm. and fact. scales and α_s	1.4%	2.7%
EW corr.: QED & EWK: add or multiply	2.1%	3.9%
γ contributions	3.0%	5.4%
All other uncertainties:	**11.1%**	**18.6%**

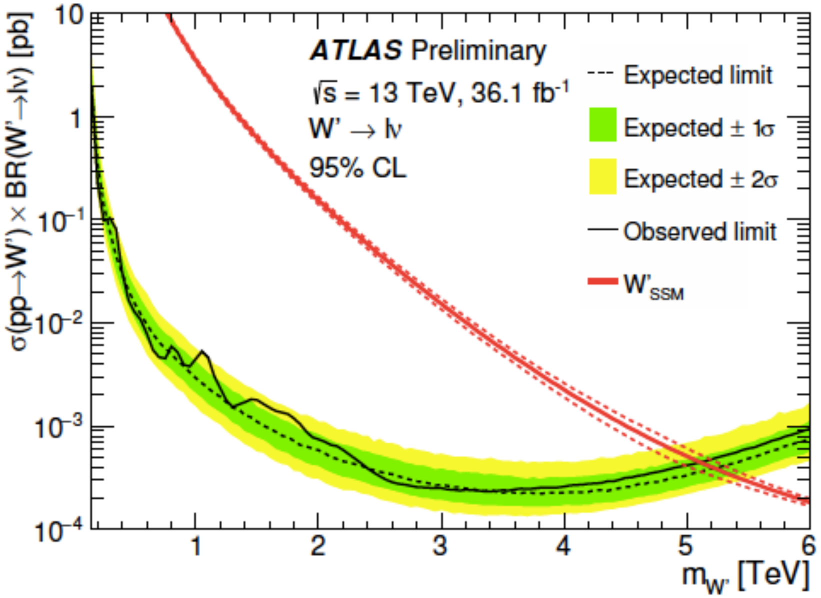
But upper limit is statistically limited

ATLAS-CONF-2017-016
ATLAS-CONF-2017-027
CMS-PAS-EXO-16-031

Constraints on dilepton resonances





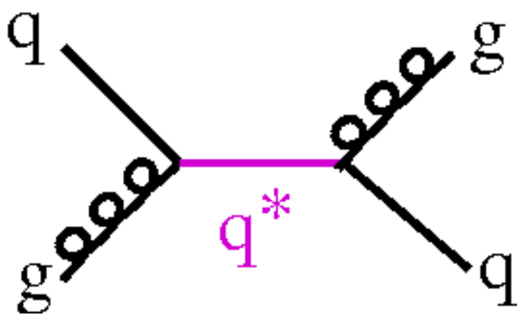


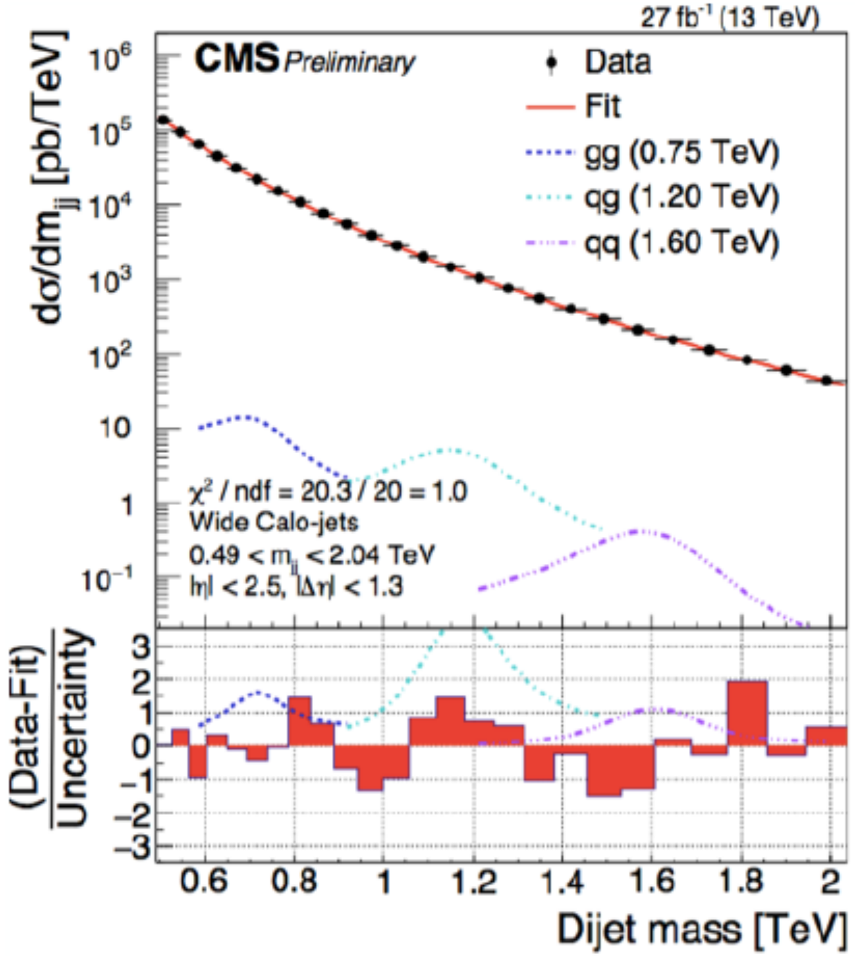
- **Strong constraints on**
  - Z' bosons
  - W' bosons
  - KK gravitons in Randall-Sundrom models

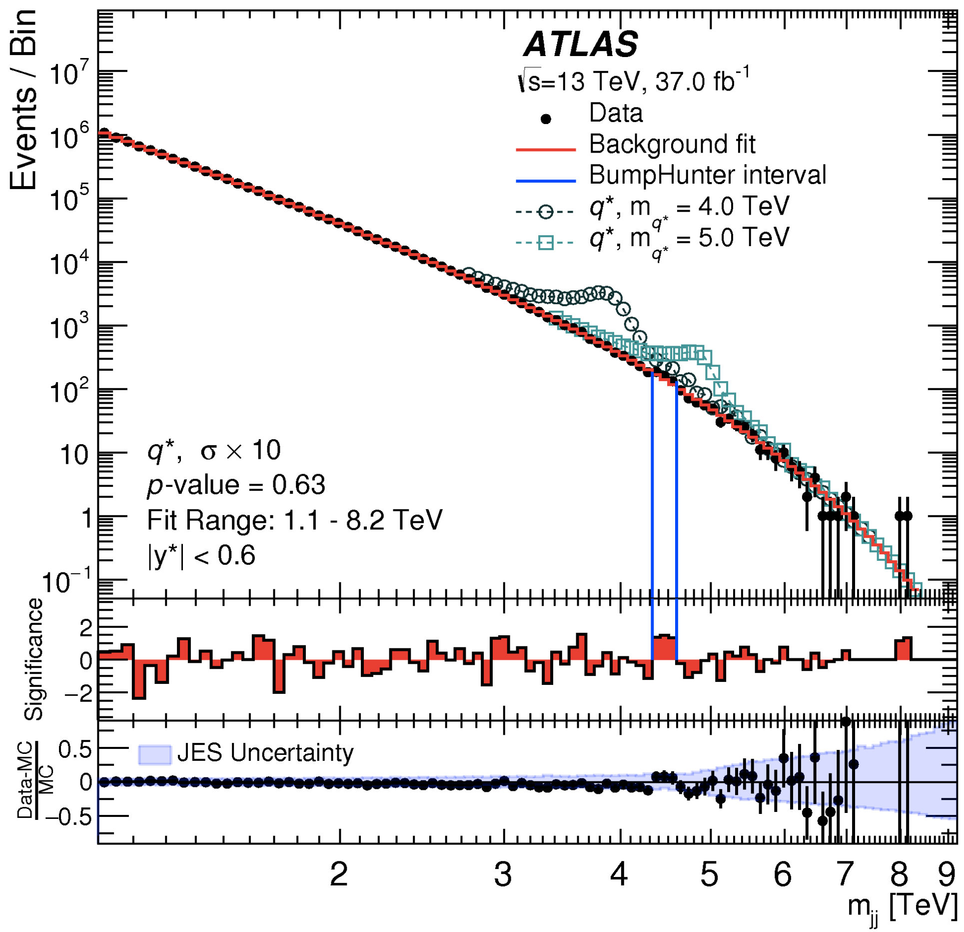
ATLAS-CONF-2017-016, ATLAS-CONF-2017-027, CMS-PAS-EXO-16-031

Dijet search

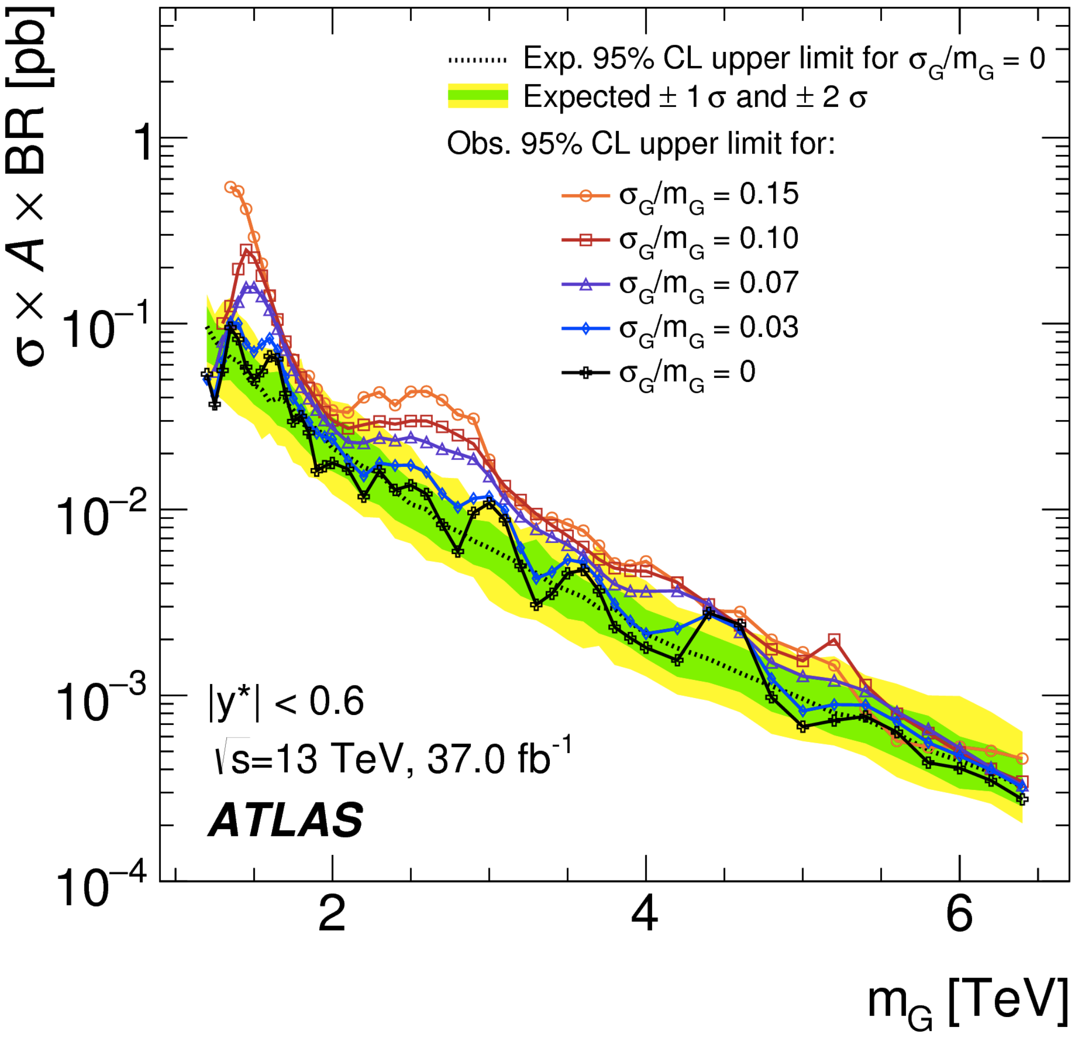
- **Search for new resonance decaying to dijets**
  - Excited quark, W' or Z', quantum black holes,…
- **Do searches at high and low masses**
  - At low mass probe weaker couplings
  - Use trigger-level analyses and/or ISR triggers

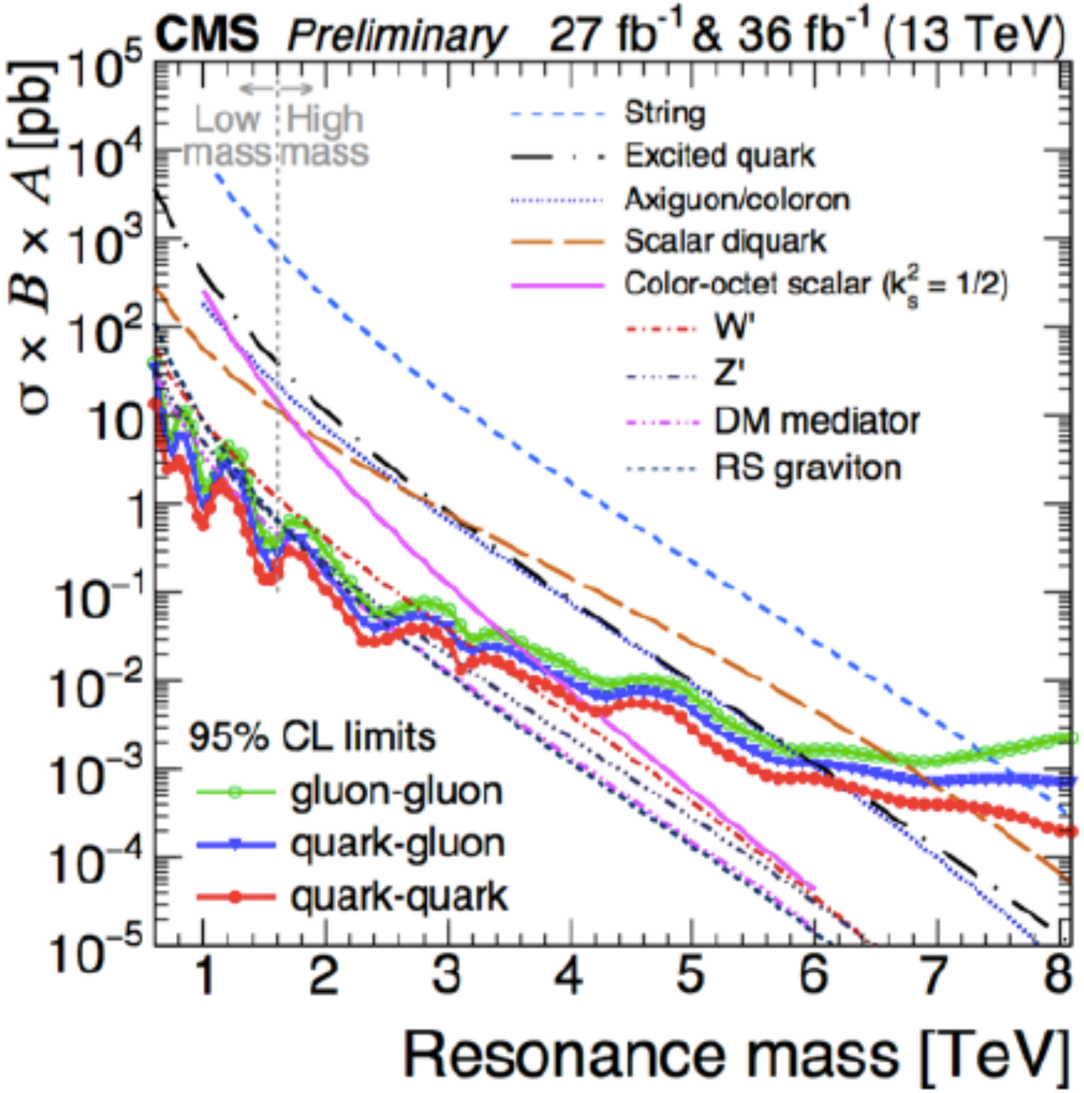






Dijet Resonance Limits

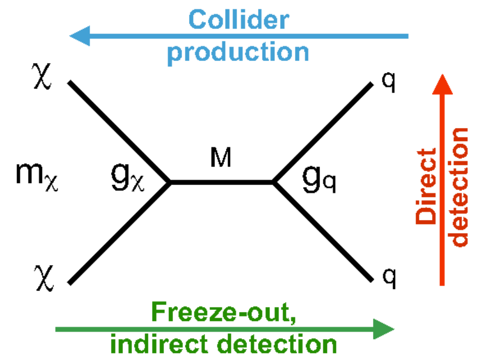




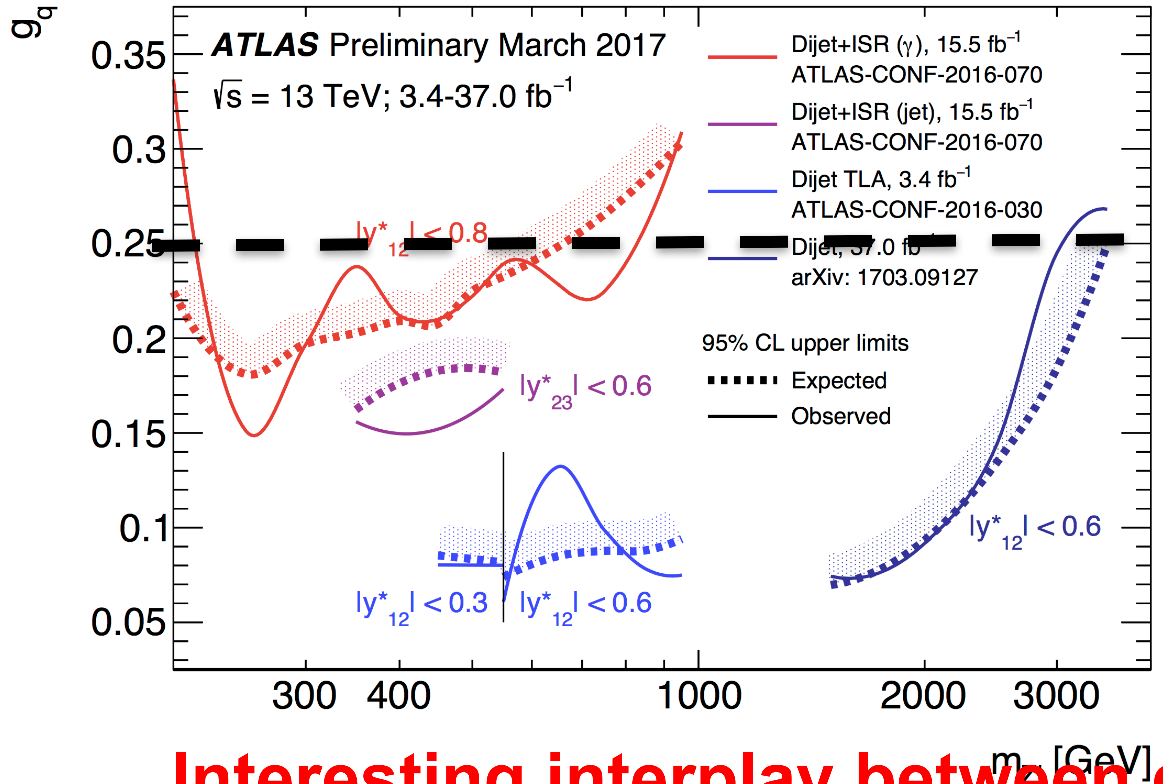
- **Limits set in model-independent way and on large variety of models**

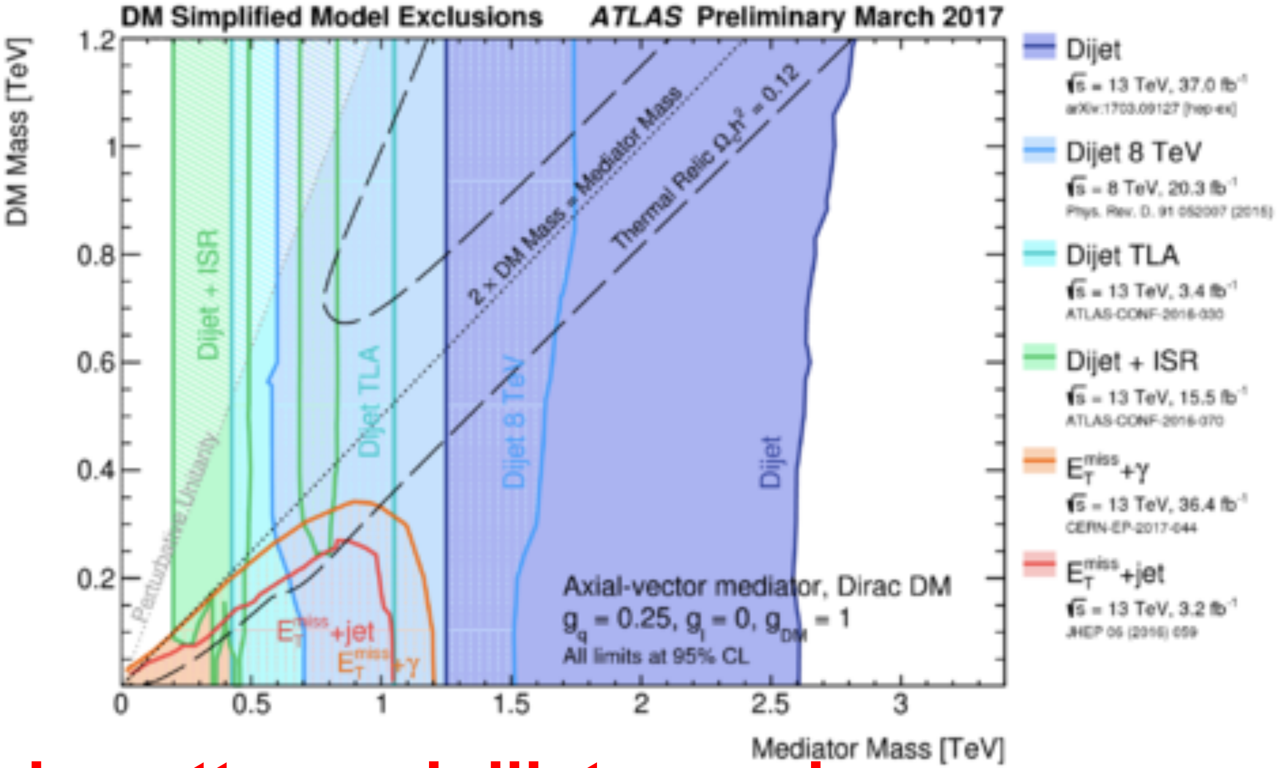
Synergy of Dijet and Dark Matter Searches

- **Classic Monojet search:**
  - qq->χχ+g (via mediator, e.g. Z')
- **Dijet search complements it:**
  - Mediator must also decay to dijets as g_q>0



g_q=0.25

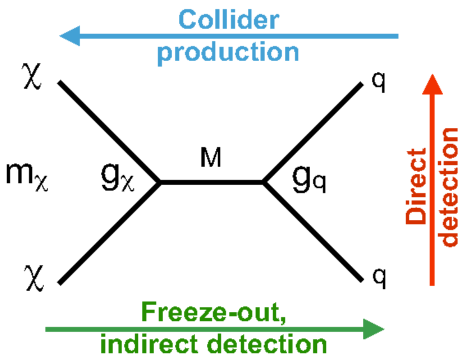




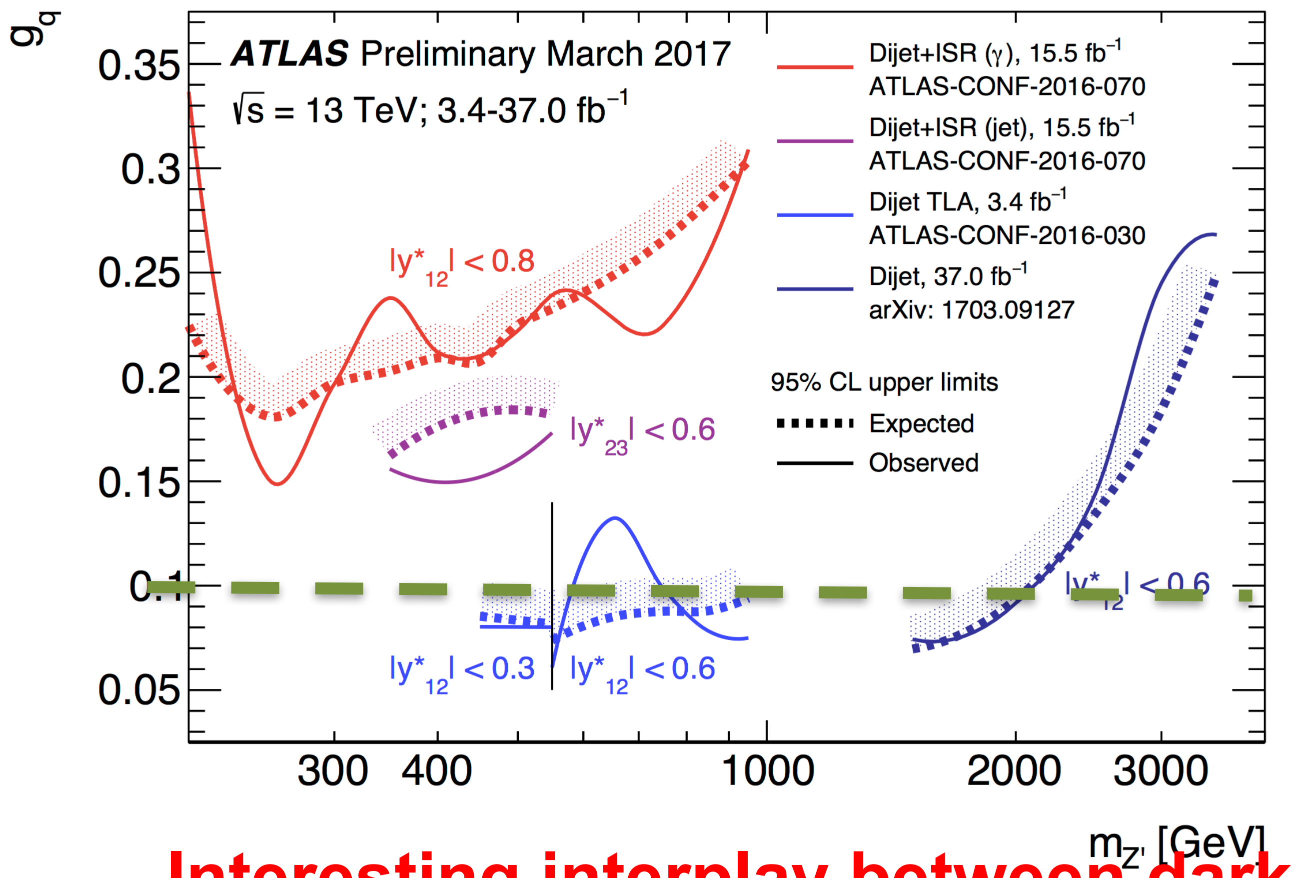
Interesting interplay between dark-matter and dijet searches

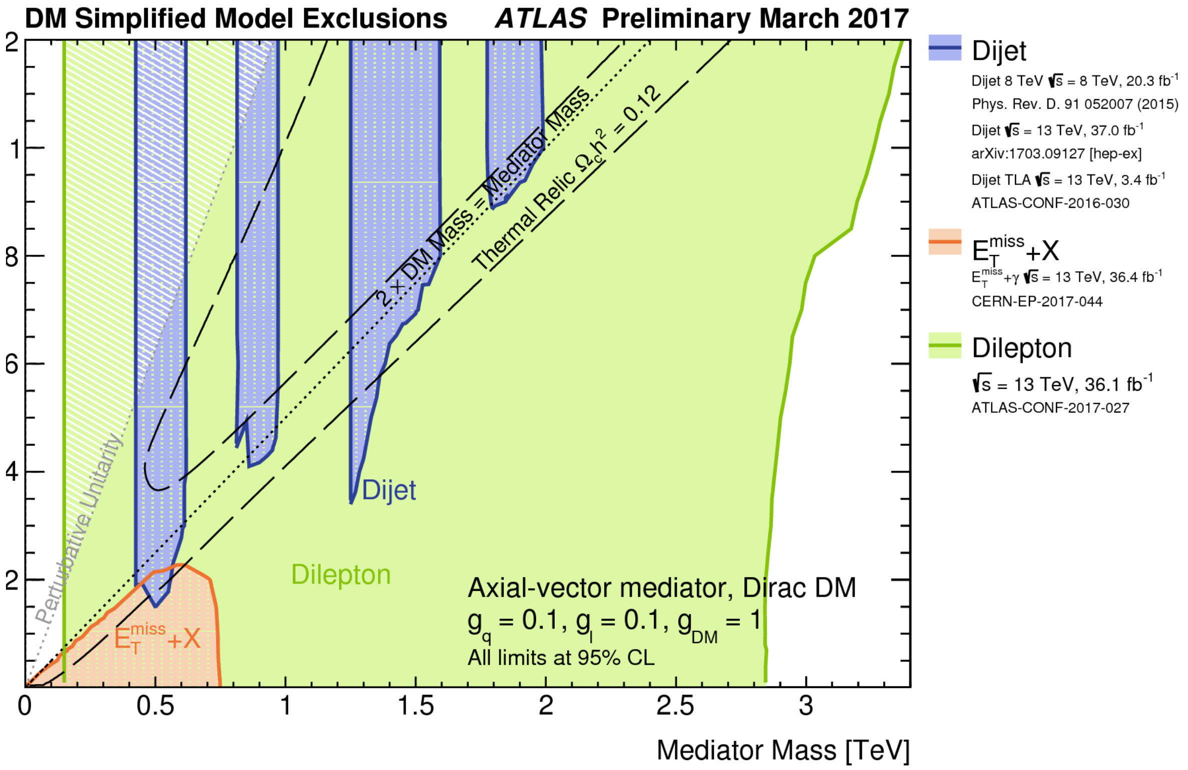
Dark Matter Searches

- **Classic Monojet search:**
  - qq->χχ+g (via mediator, e.g. Z')
- **Dijet search complements it:**
  - Mediator must also decay to dijets as $g_q>0$



g_q=0.1





Interesting interplay between dark-matter and dijet searches

Conclusions and Outlook

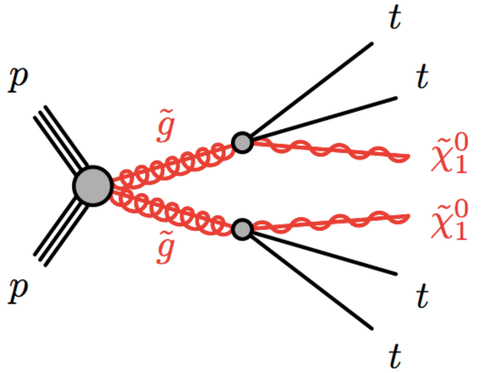
- **LHC provided about 40 fb^{-1} of data in 2016**
  - LHC, ATLAS and CMS working very well!
- **ATLAS and CMS have used dataset to vigorously search for new physics**
  - No significant excess seen in data
    - 2015 and run-1 excesses not confirmed with new data
  - Stringent limits on new physics scenarios
  - Analyses rely extensively on Monte Carlo generators for background estimates
    - Even when data-driven techniques are used, theory uncertainties often dominate
      - E.g. parton showering, higher order corrections (QCD, EWK)
      - Higher order calculations (e.g. NNLO) also needed to understand origin of observed data/MC discrepancy
    - PDFs also considerable source of uncertainty for very high mass searches: $x \approx m/\sqrt{s} \sim 0.25$
- **This dataset represents only about 1.2% of full LHC data at 13 TeV**
  - In run-2 we expect ~120-150 fb^{-1} and by 2035 expect ~3000 fb^{-1} of data
- **Big thanks to theorist colleagues for the amazing progress in MC generators, NLO and NNLO calculations and PDF fitting since LHC start**
  - Critical for fully exploiting the LHC data experimentally
  - As precision of data increases demand on QCD understanding/tools will increase further

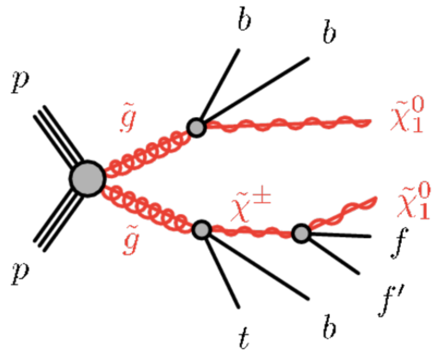
The End

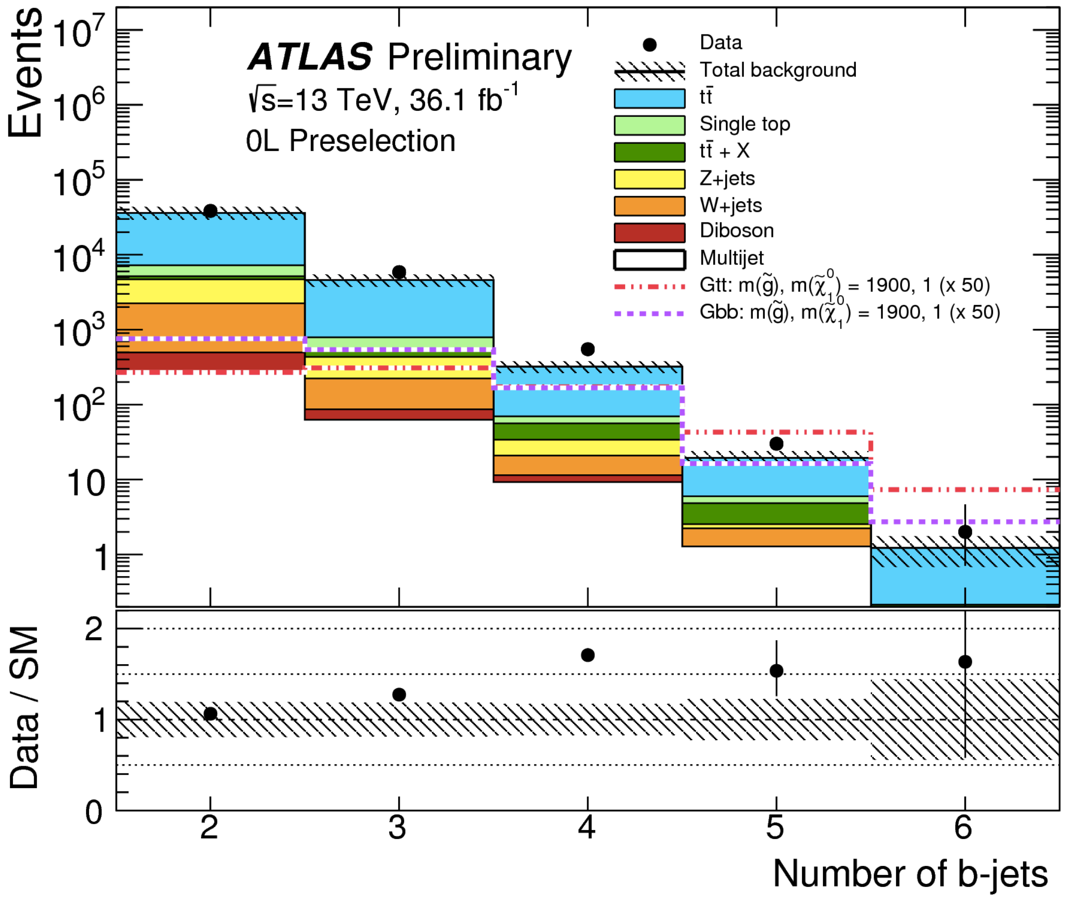
Thanks for your attention!

Top squarks in gluino decays

- **Searches for multi-jet final states with top-quark decays**
  - Using b-tagging and/or top-tagging
- **ATLAS analysis uses similar technique for background as inclusive searches**
  - Background lower => simplified method used
- **CMS analysis uses very different technique, see next slide**



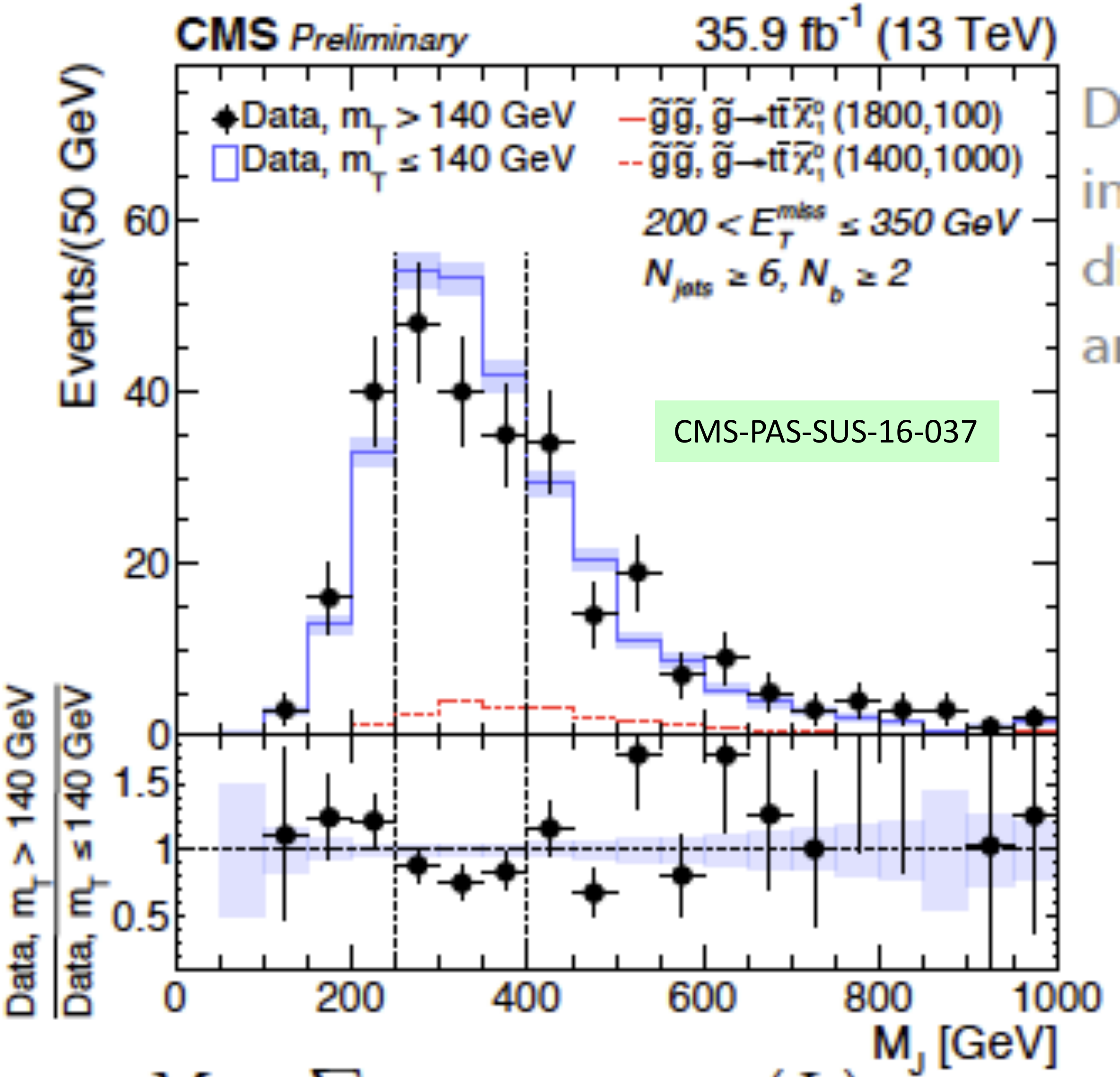




ATLAS-CONF-2017-021, CMS-PAS-SUS-16-037

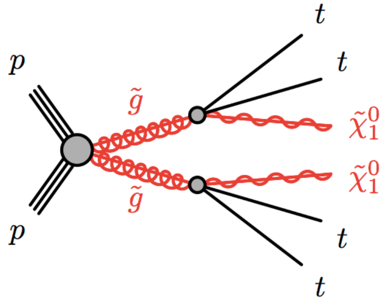
CMS 1-lepton and ≥ 6 jets

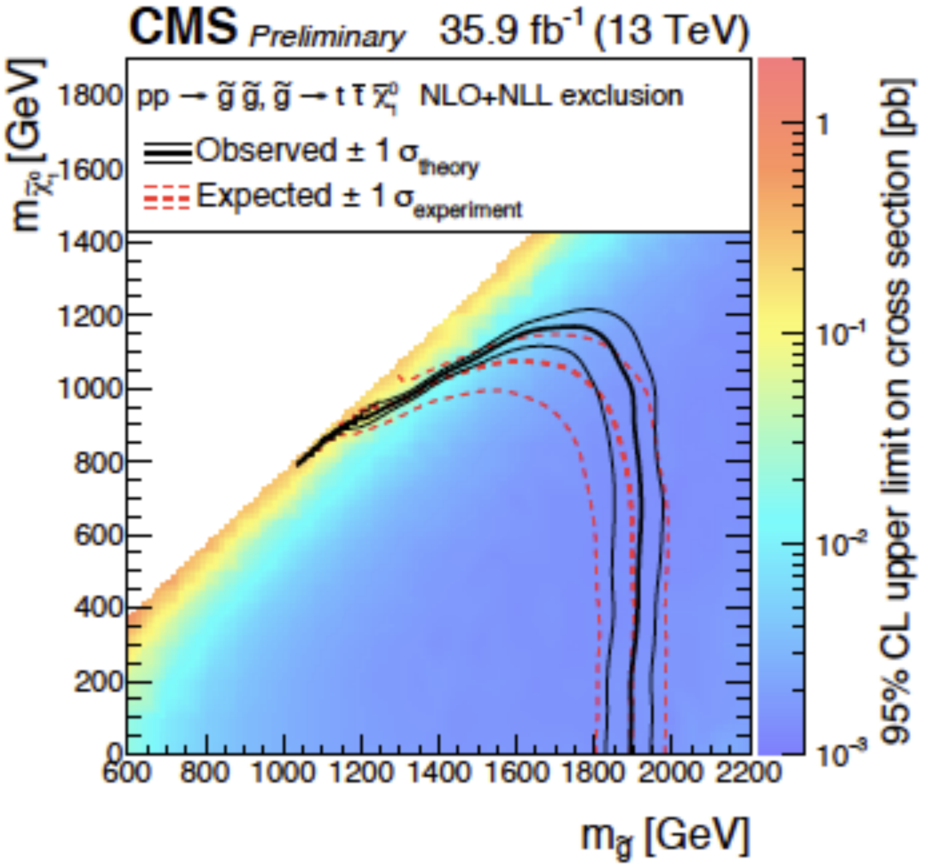
- **Selection**
  - 1 lepton
  - ≥6 jets with p_T>X, b-jets
  - m_T>140 GeV, E_T^{miss}>350 GeV
- **Backgrounds:**
  - Top background important!
  - W+jets negligible after mT cut
  - QCD multijet negligible
- **Background estimate**
  - Demonstrate that M_J distribution independent of m_T
  - $M_J=\sum m(jet_i)$
  - Use lower E_T^{miss} region for demo

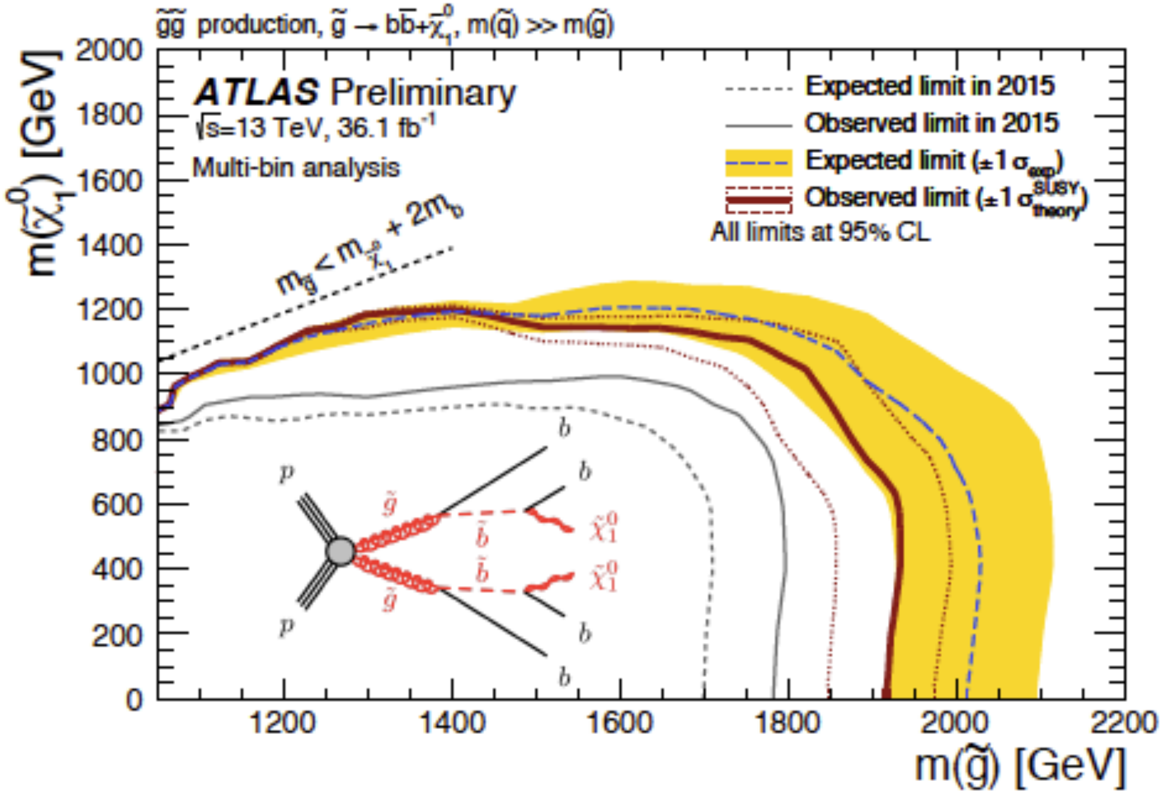


$$M_J = \sum_{J_i=\text{large-}R\text{ jets}} m(J_i)$$

Limits on gluinos decaying via stop/sbottom







- **Gluino mass excluded up to 1.9 TeV**
  - Compared to ~1.4 TeV limit in Run-1