EXOTIC SEARCHES WITH ATLAS AND CMS

Shahram Rahatlou

on behalf of ***ATLAS*** and ***CMS*** collaborations

SUSY 2016, Melbourne, 8 July 2016

DIPARTIMENTO DI FISICA

SAPIENZA
UNIVERSITÀ DI ROMA

INFN
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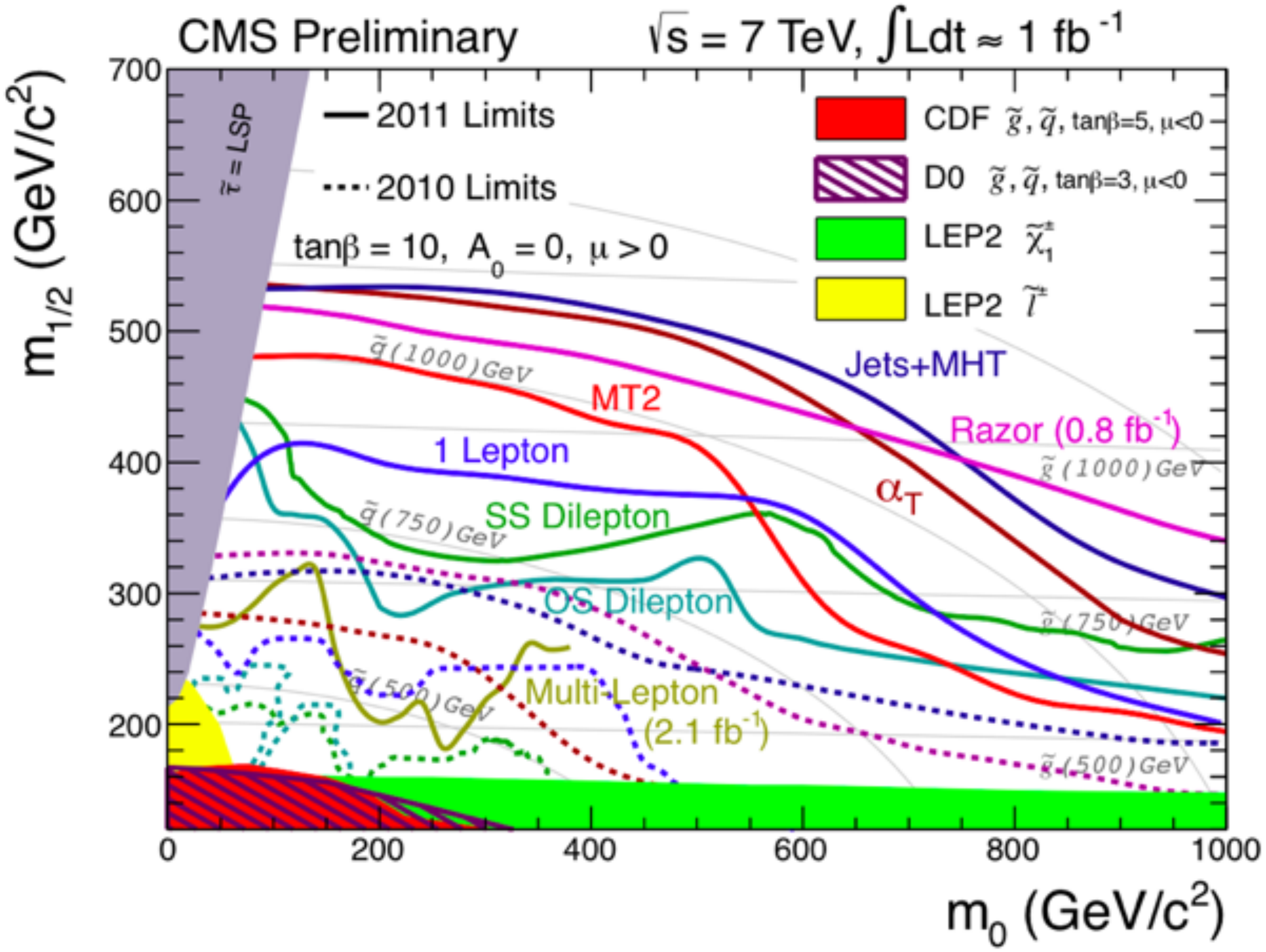
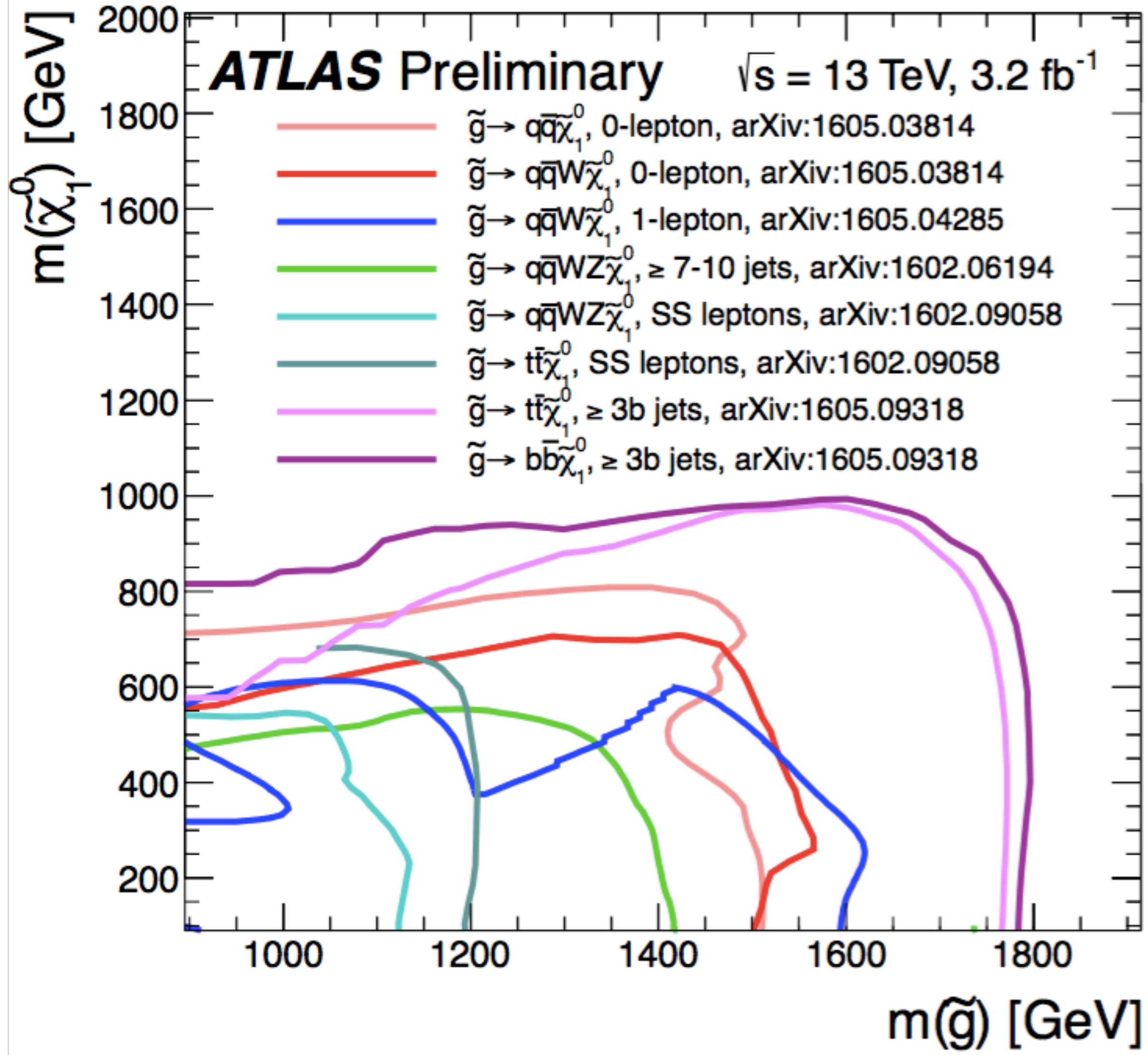
SUSY VS EXOTICA

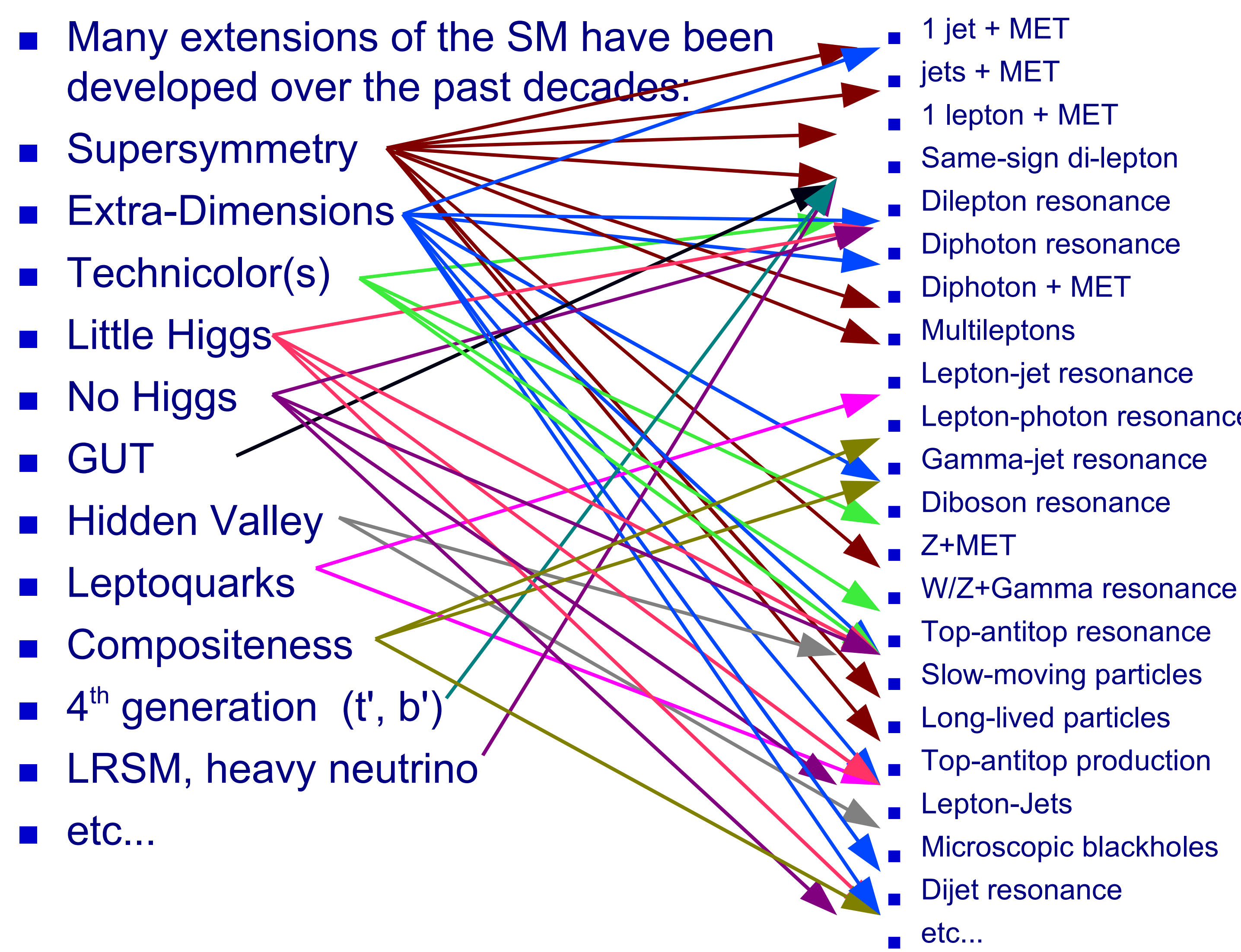




- SUSY results often reported in $(m_0, m_{1/2})$ or (m_X, m_{LSP}) plane
- Large missing transverse energy usually primary signature
- In exotica, search for particles and resonances not necessarily needed or predicted in supersymmetry

SIGNATURE- VS TOPIC-BASED

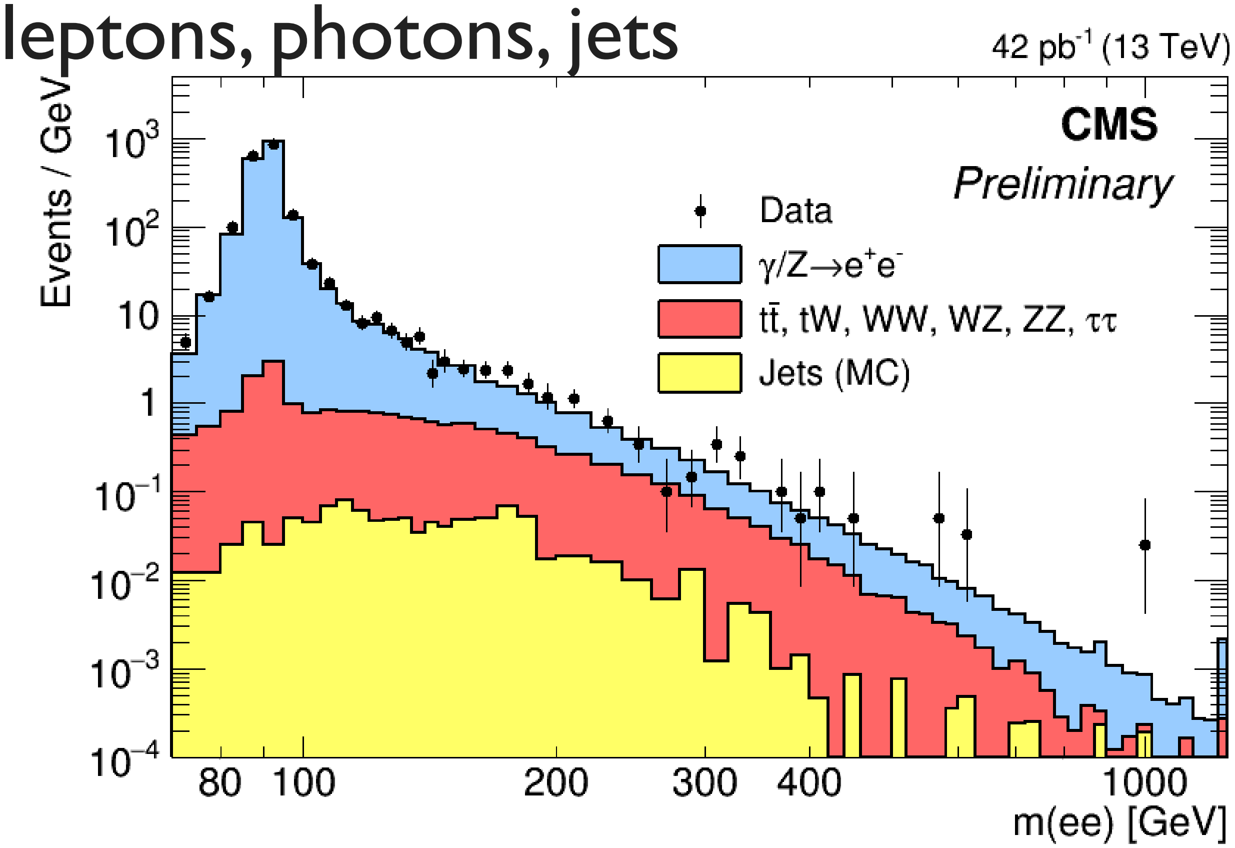
- Same final state often probing very different models or topics
  - 2 leptons, 2jets + MET, lepton+jet+MET
- Topological presentation requires jumping between very different models
- Mostly a topic-based approach in this talk
  - easier to combine constraints on model from different topologies
  - Same final state is not simple re-interpretation
    - often optimization redone to deal with acceptance for very different models
    - different analysis strategy and signal extraction methods

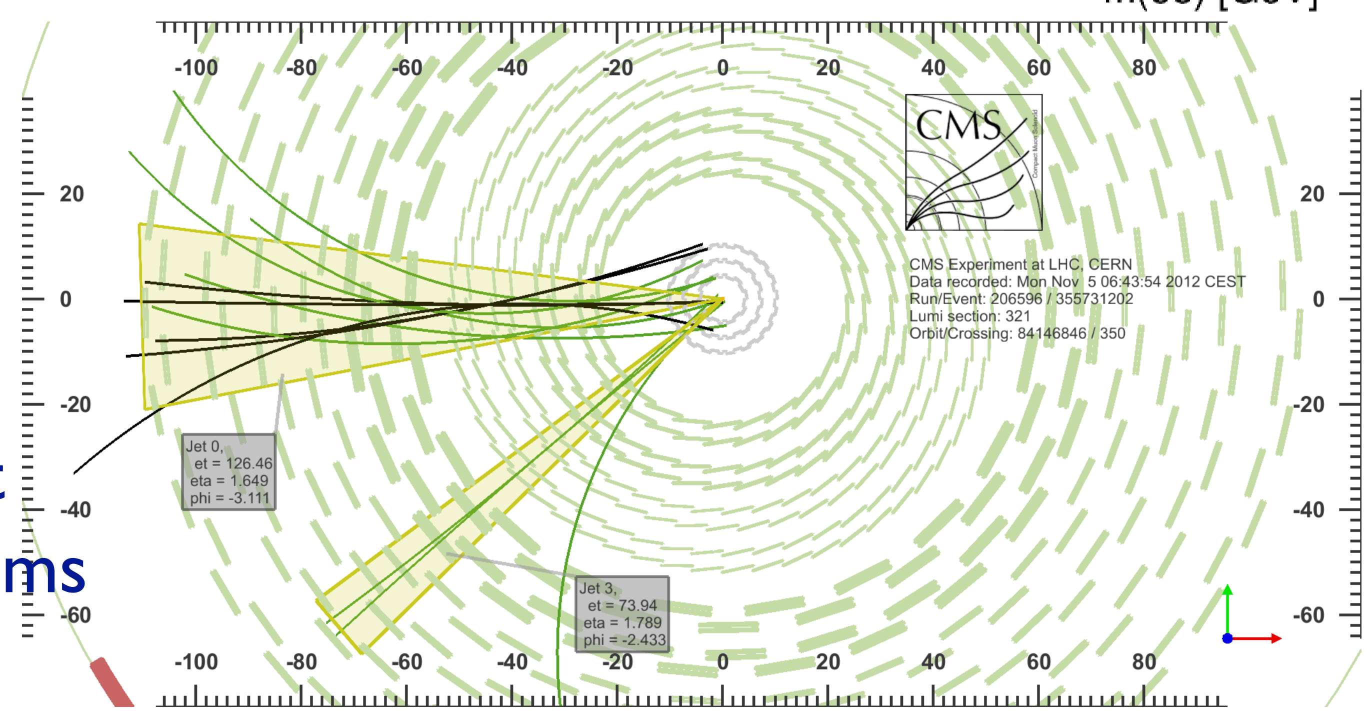


Exotica Timeline

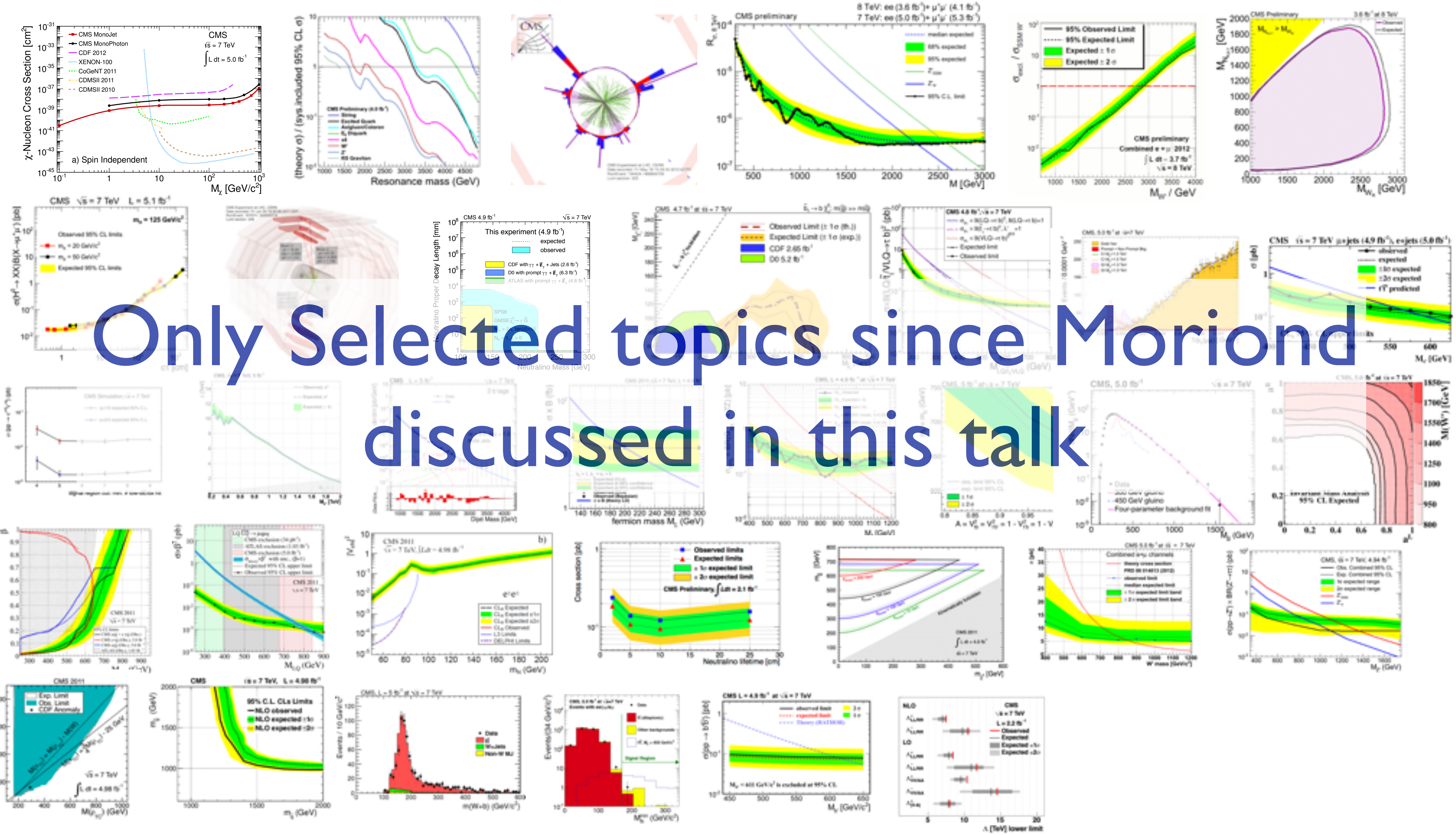
Detector Understanding (time)

- Rich variety of theoretical models and new particles
- Two-body resonances from day one: leptons, photons, jets
  - detector effects usually not critical
  - sensitive to bumps right away
- increase complexity and multiplicity of final state
  - better understanding and calibration of detector
- Final states with MET + X
- Really exotic signatures such as long-lived particles
  - control of detector conditions over longer period
  - ultimate calibration and alignment
  - optimisation of dedicated algorithms



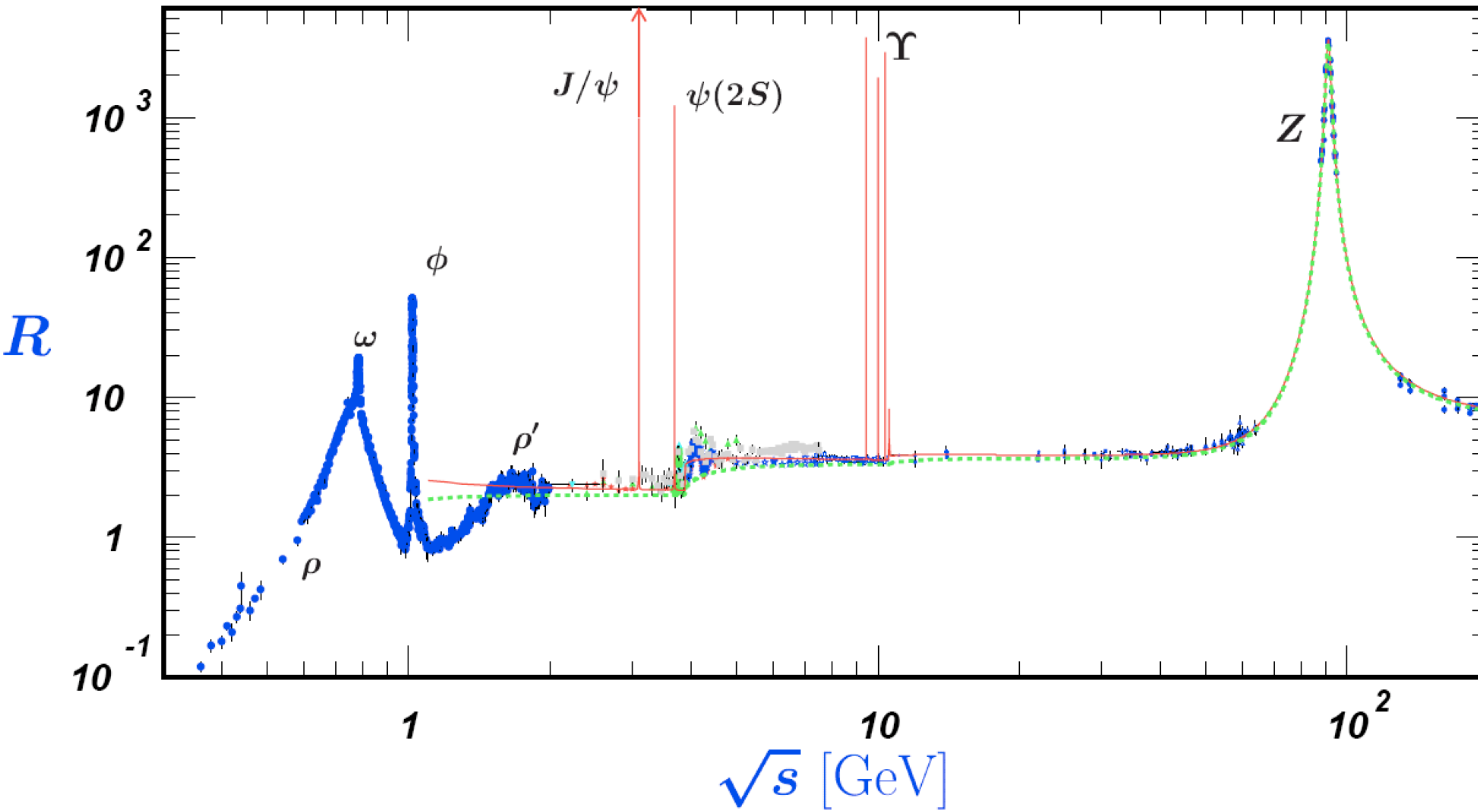


Exotica in One Page

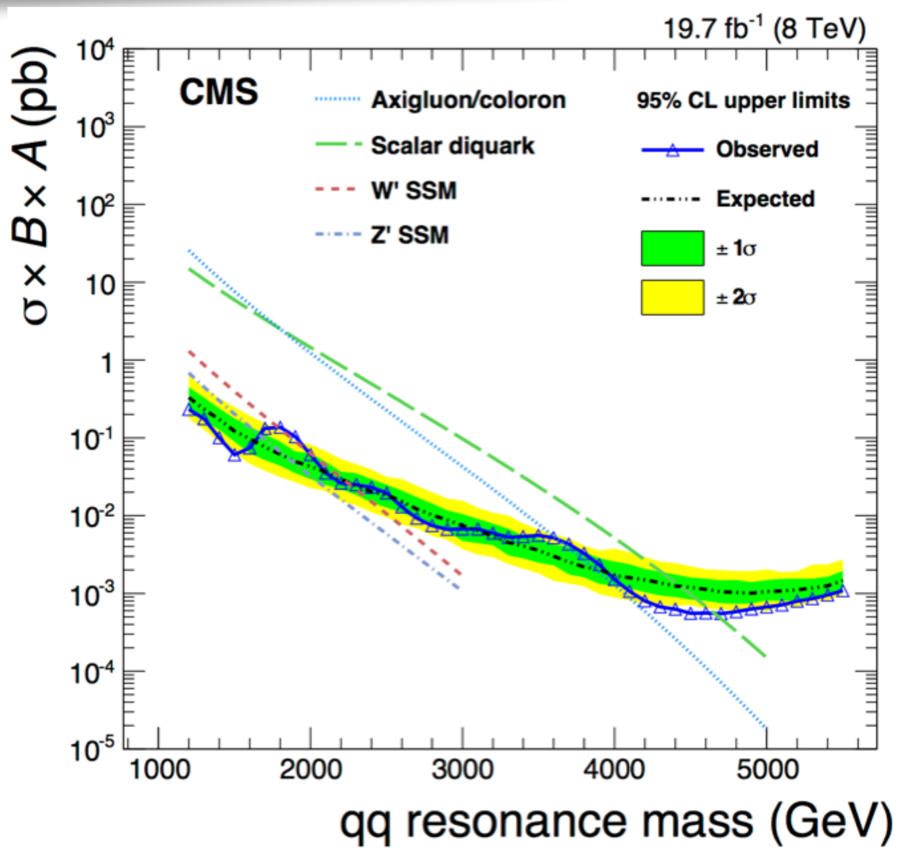


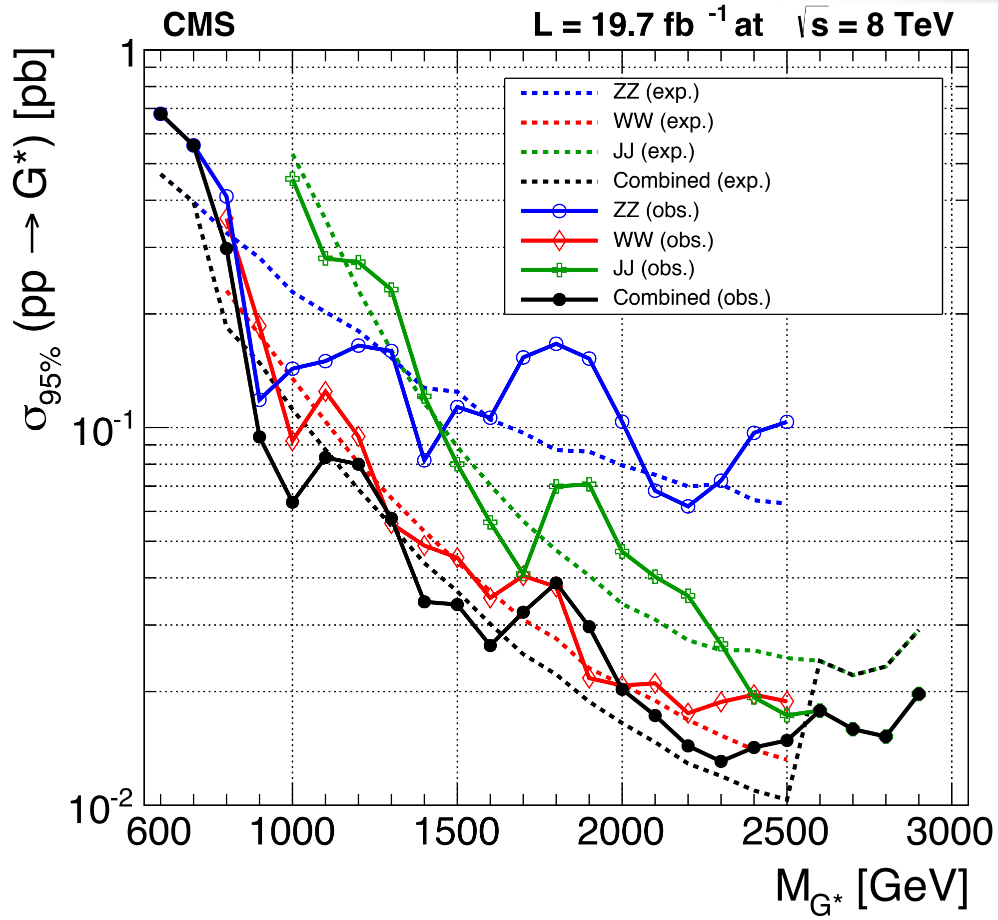
Only Selected topics since Moriond discussed in this talk

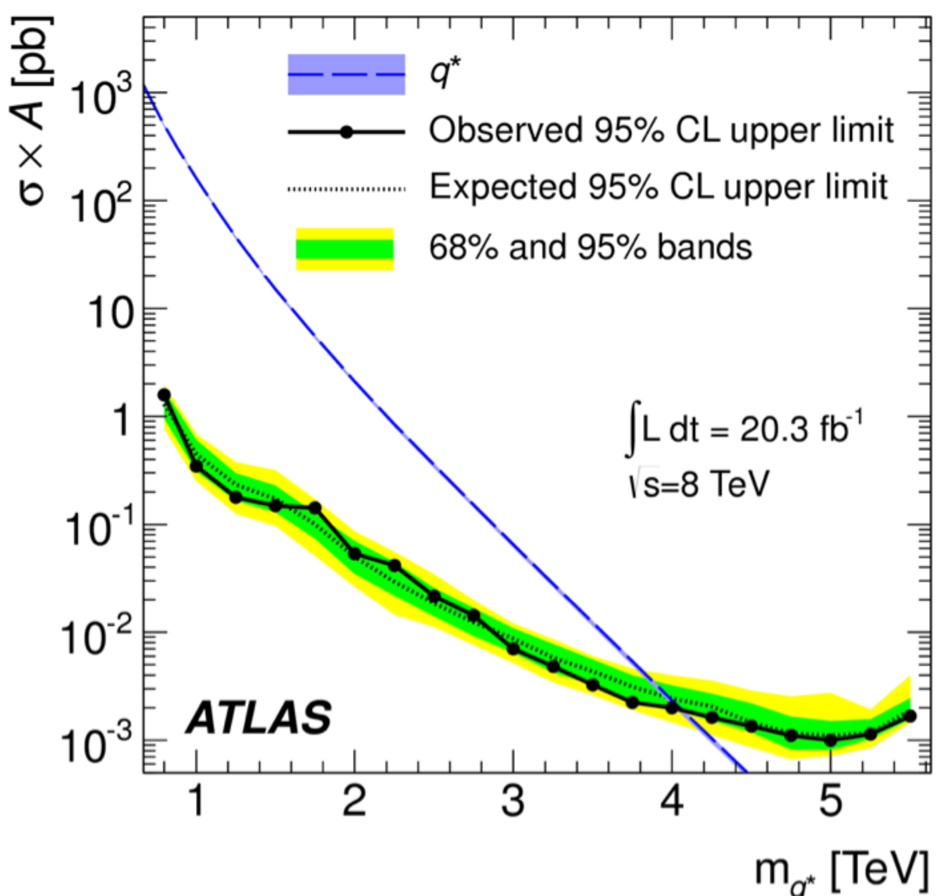
RESONANCES

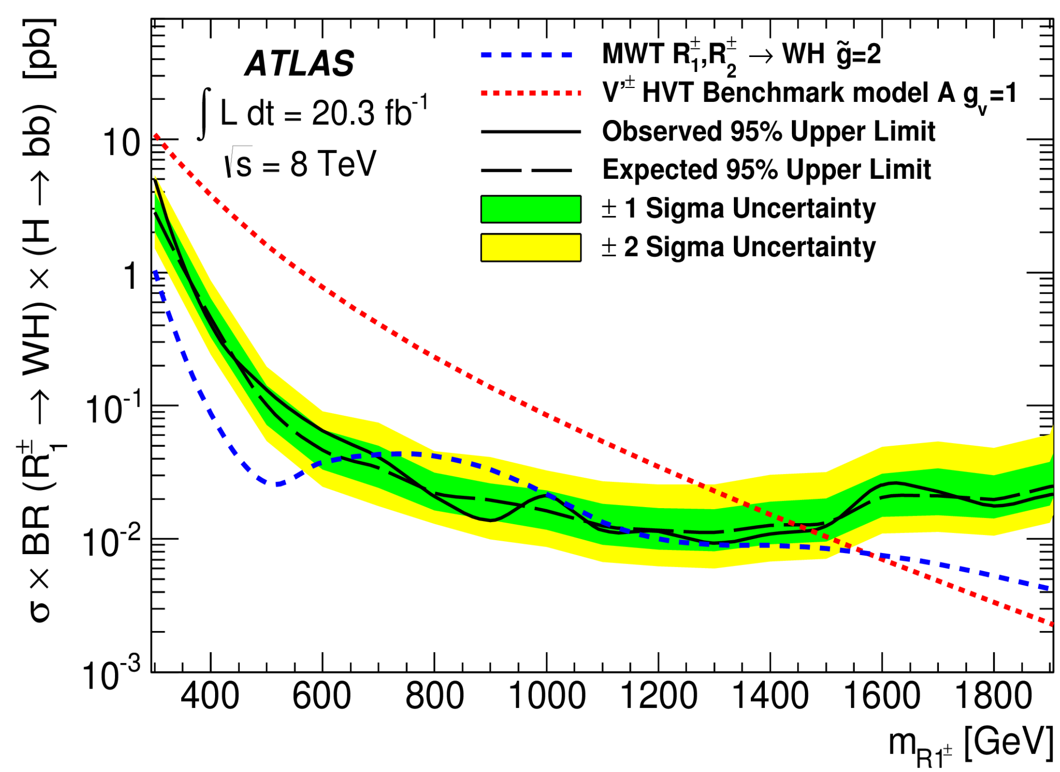


Resonances at 8 TeV

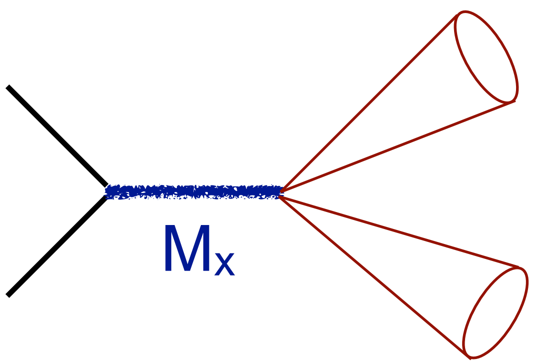


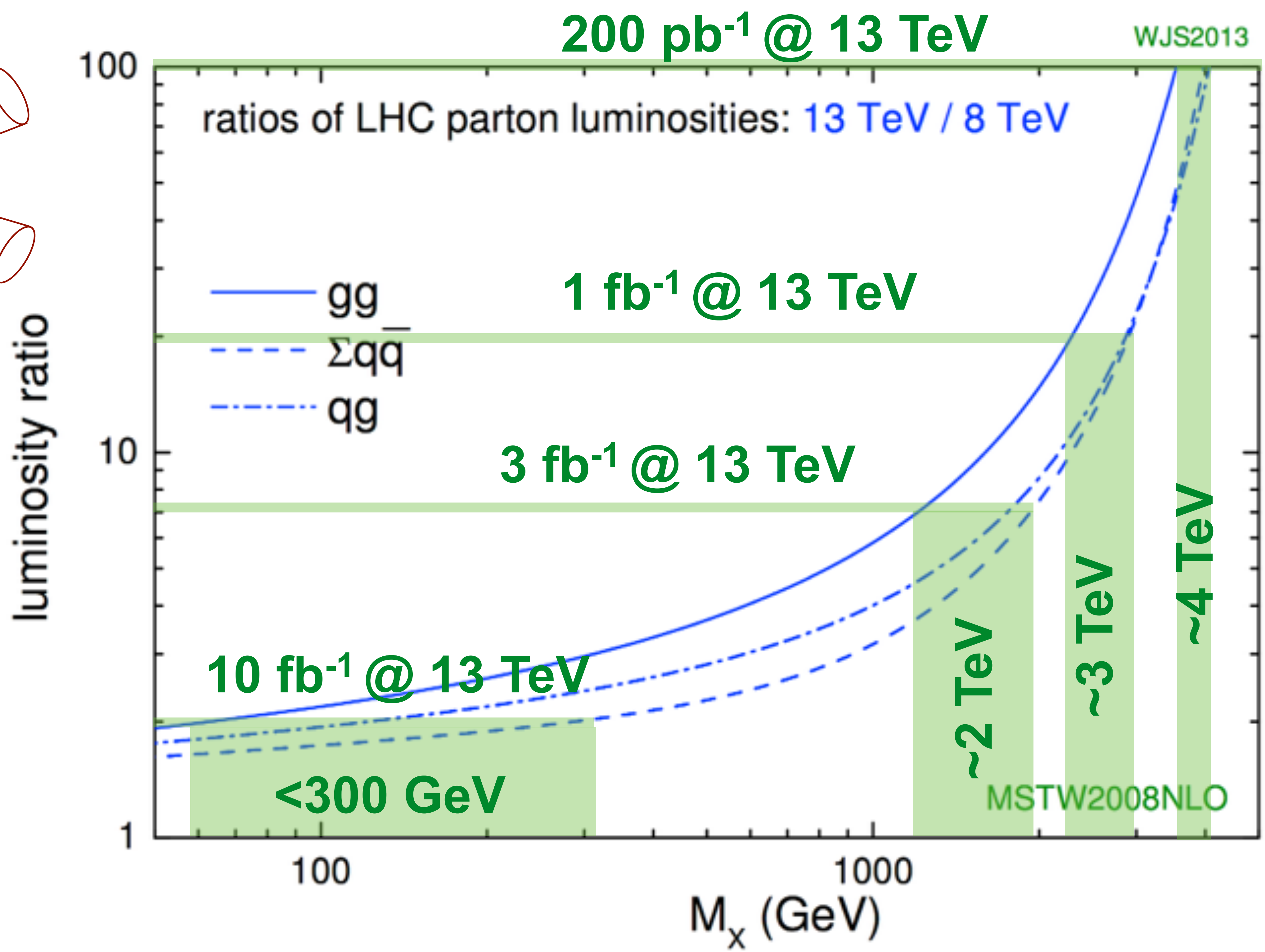






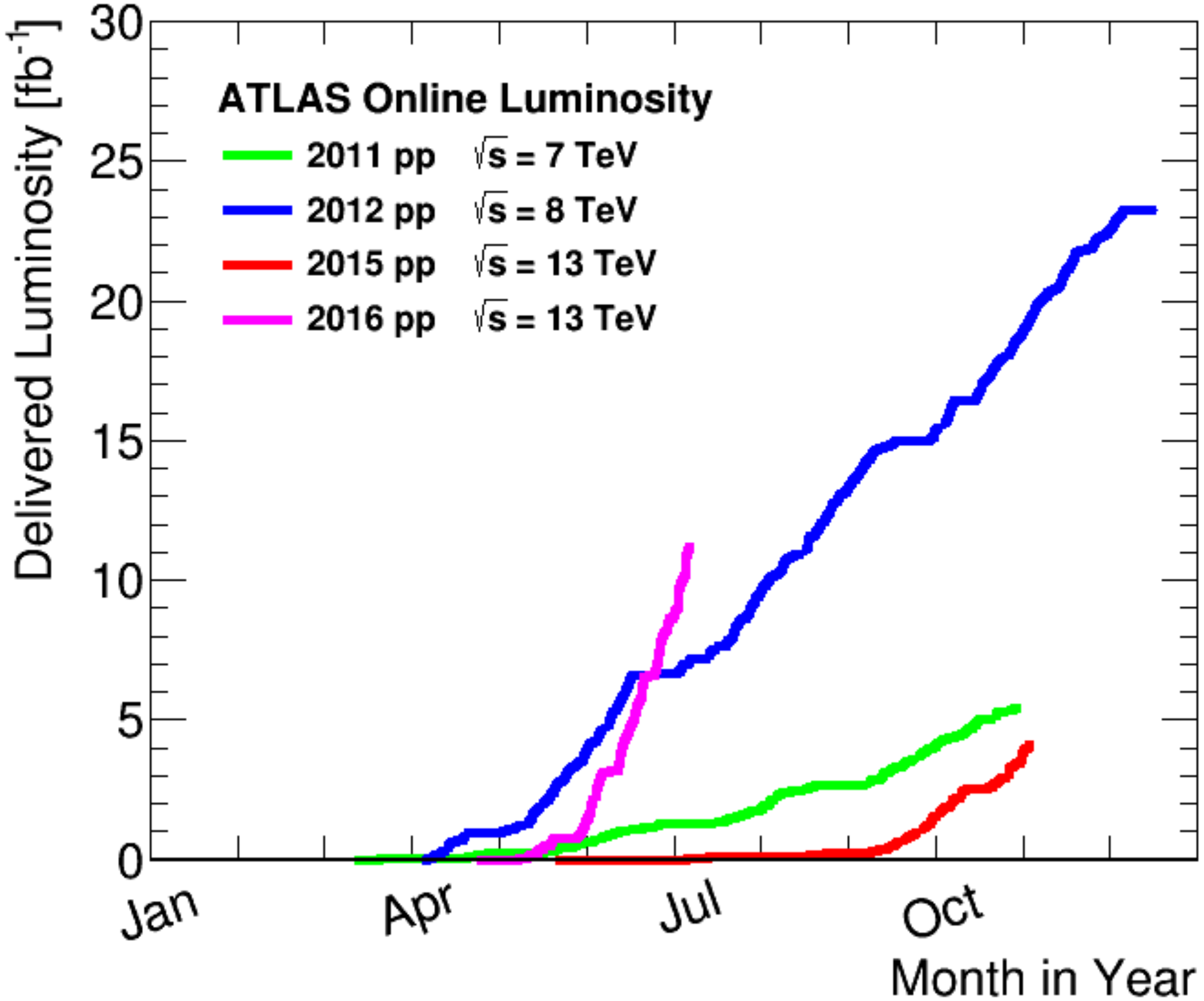
IMPORTANCE OF ENERGY INCREASE





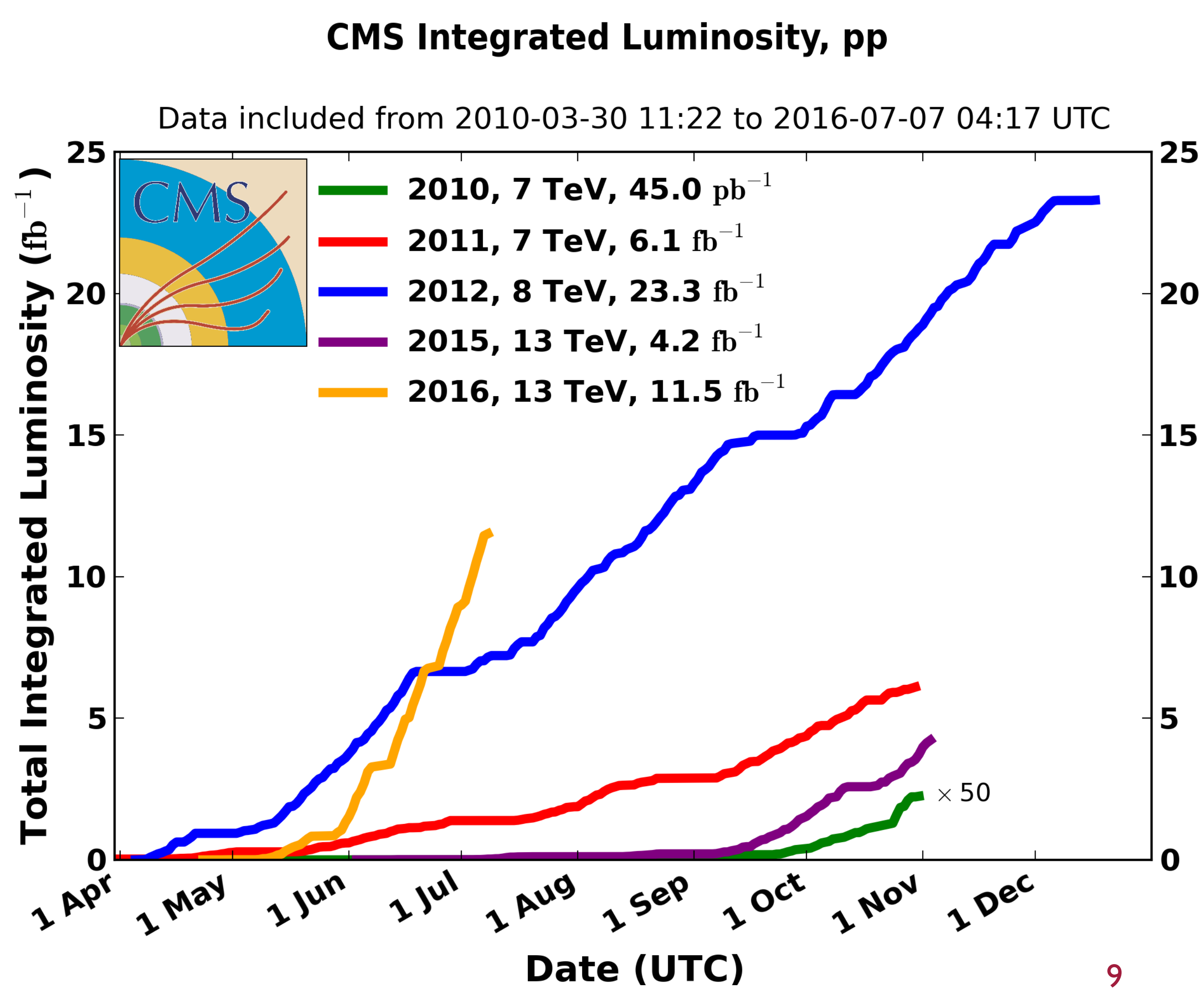
- 2015 data collected equivalent to 2012 dataset for Mx ~ 2-3 TeV

Spectacular Performance of LHC in 2016



ATLAS online luminosity

CMS online luminosity

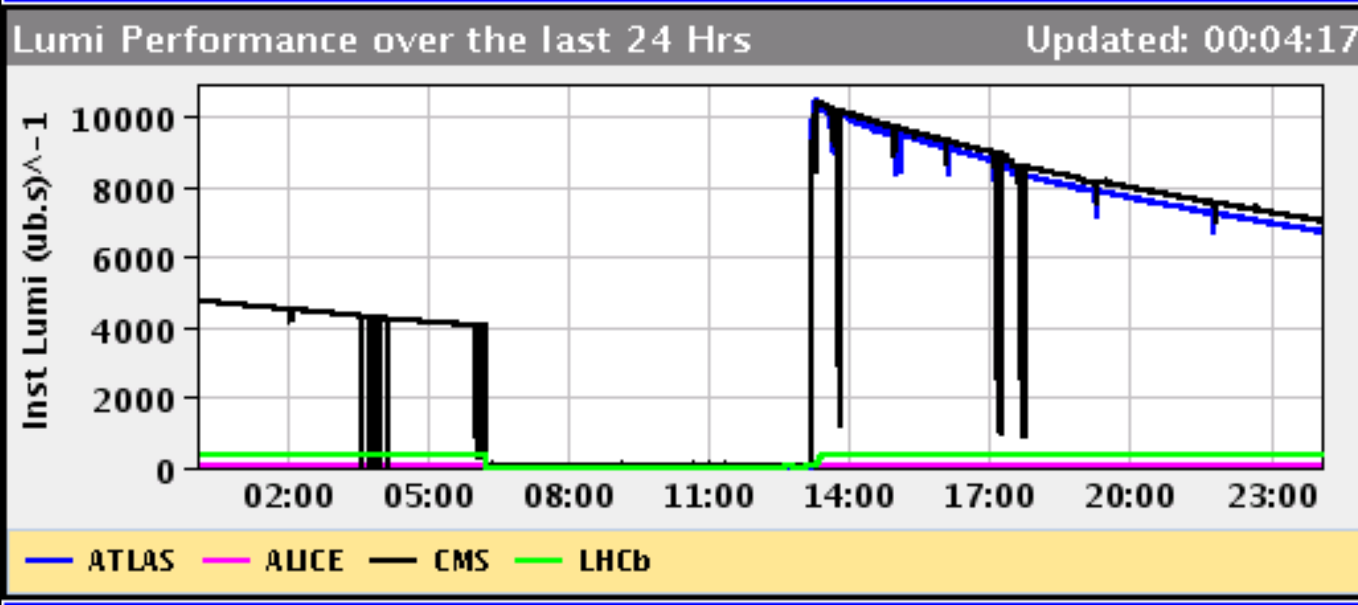


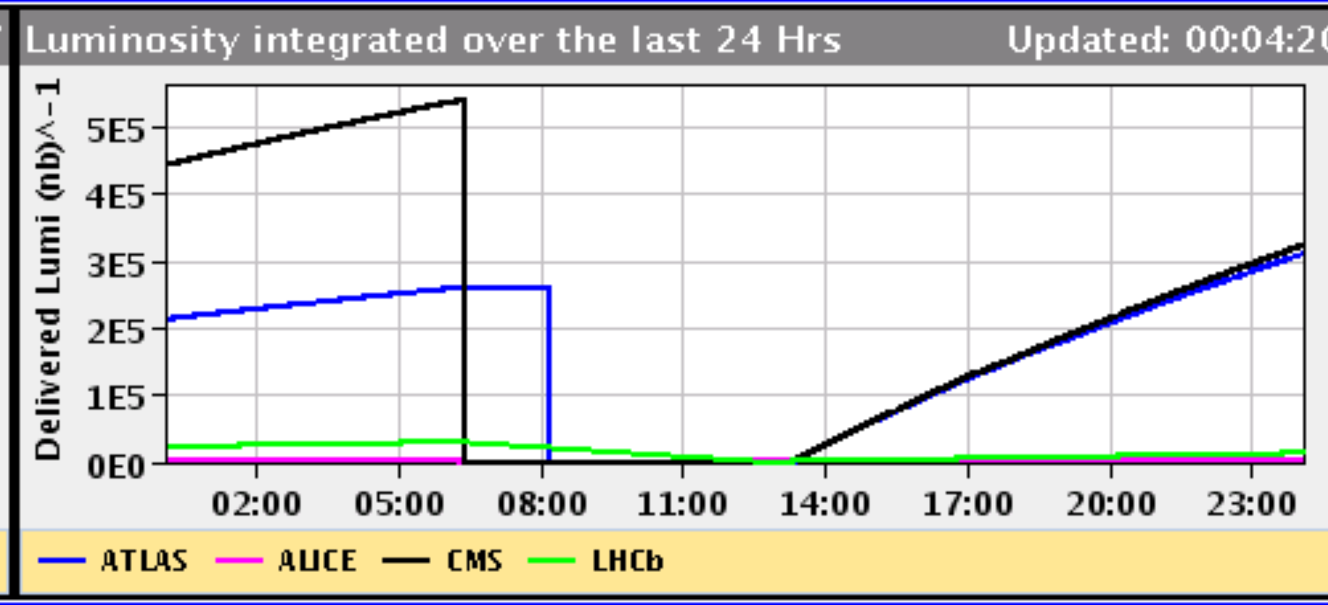
- Kudos to
  - LHC for outstanding delivery
  - ATLAS and CMS detector teams for extremely quick availability for analysis

LHC Last Night

https://op-webtools.web.cern.ch/vistar/vistars.php?usr=LHCLUMINOSITY

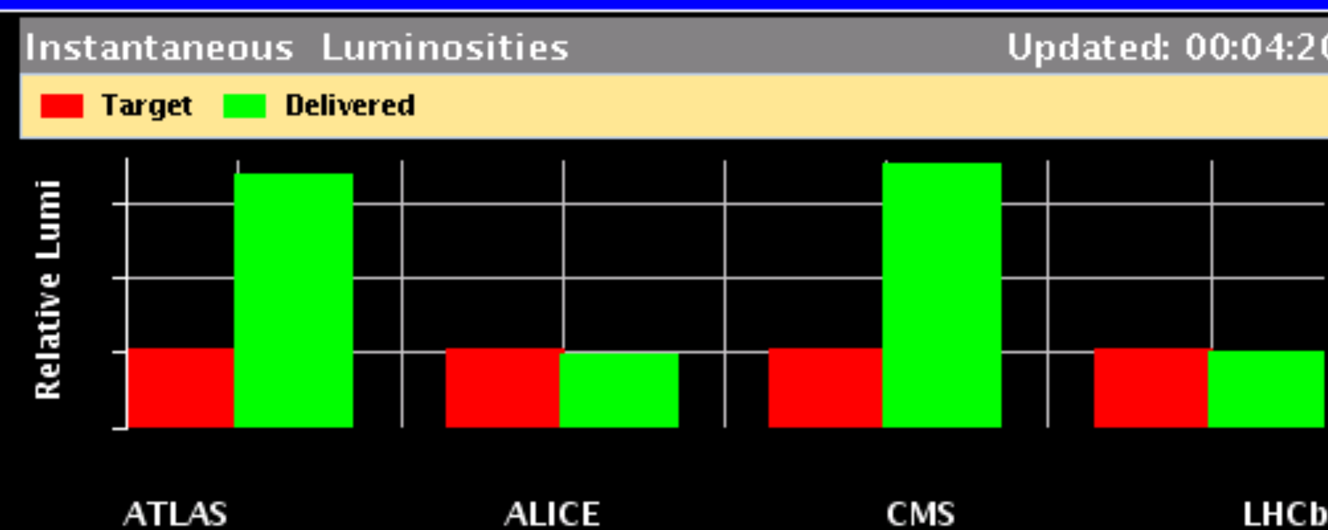
08–Jul–2016 00:04:20 Fill #: 5078 Energy: 6499 GeV I(B1): 1.95e+14 I(B2): 2.01e+14





STABLE BEAMS

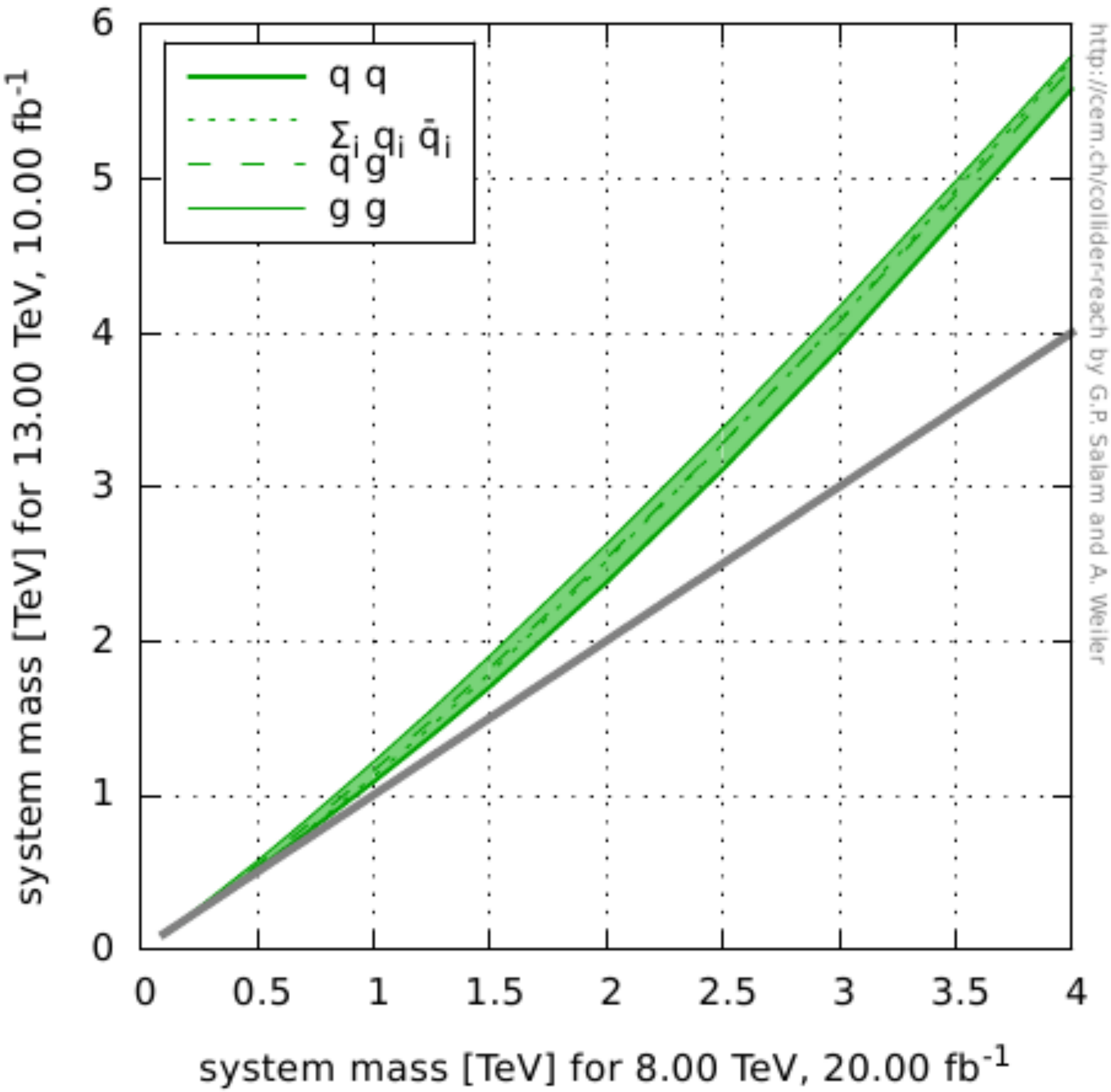
	Luminosity [(ub.s)^–1]	Fill Lumi (nb)^–1
ATLAS	6711.02	309628.0
ALICE	1.61	64.1
CMS	7023.32	322497.3
LHCb	319.36	12367.7



ALICE Target Instantaneous Lumi = 1.7 Hz/ub

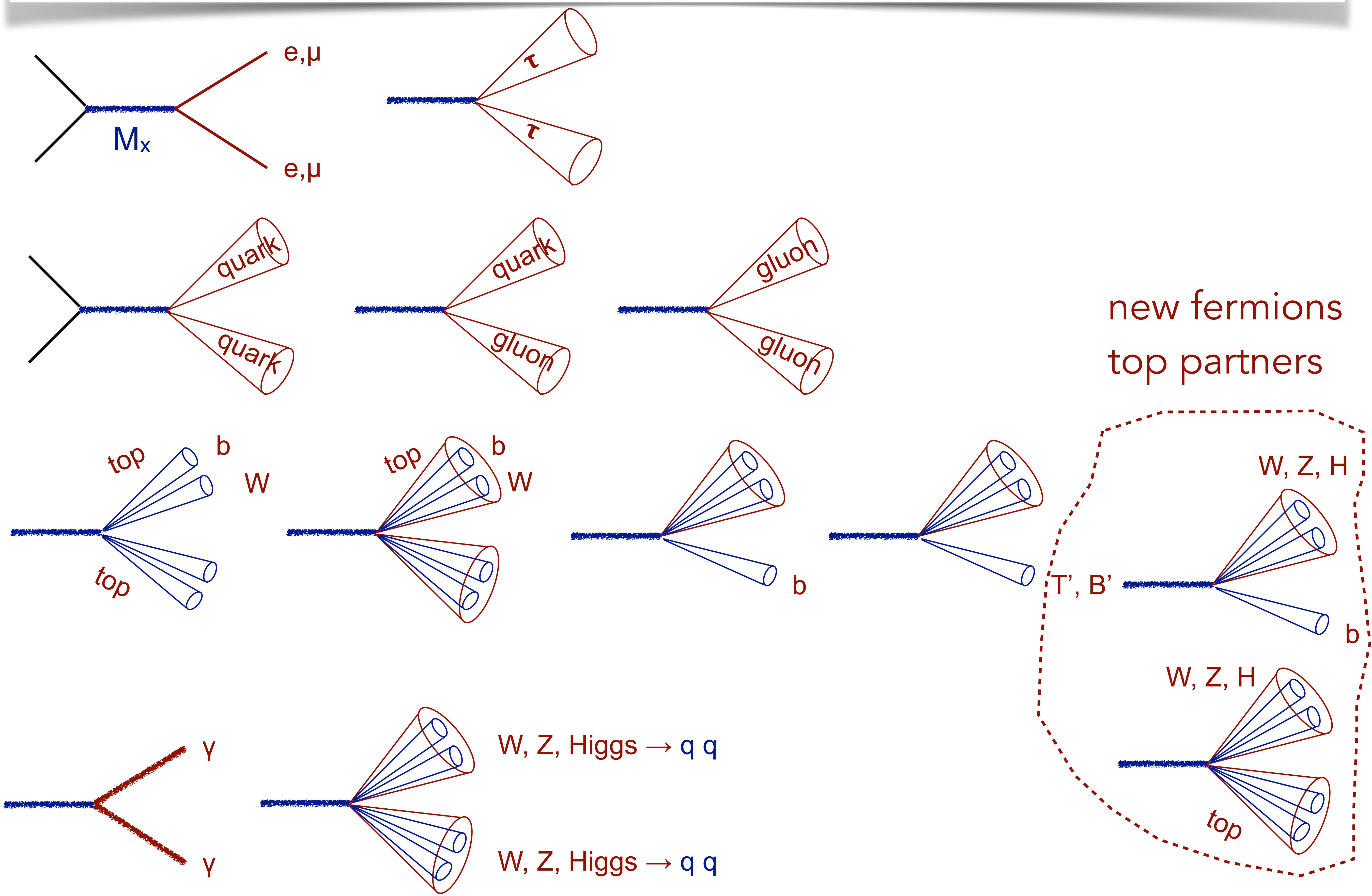
LHCb Target Instantaneous Lumi = 322.67587 Hz/ub

SENSITIVITY WITH 2016 DATA SO FAR



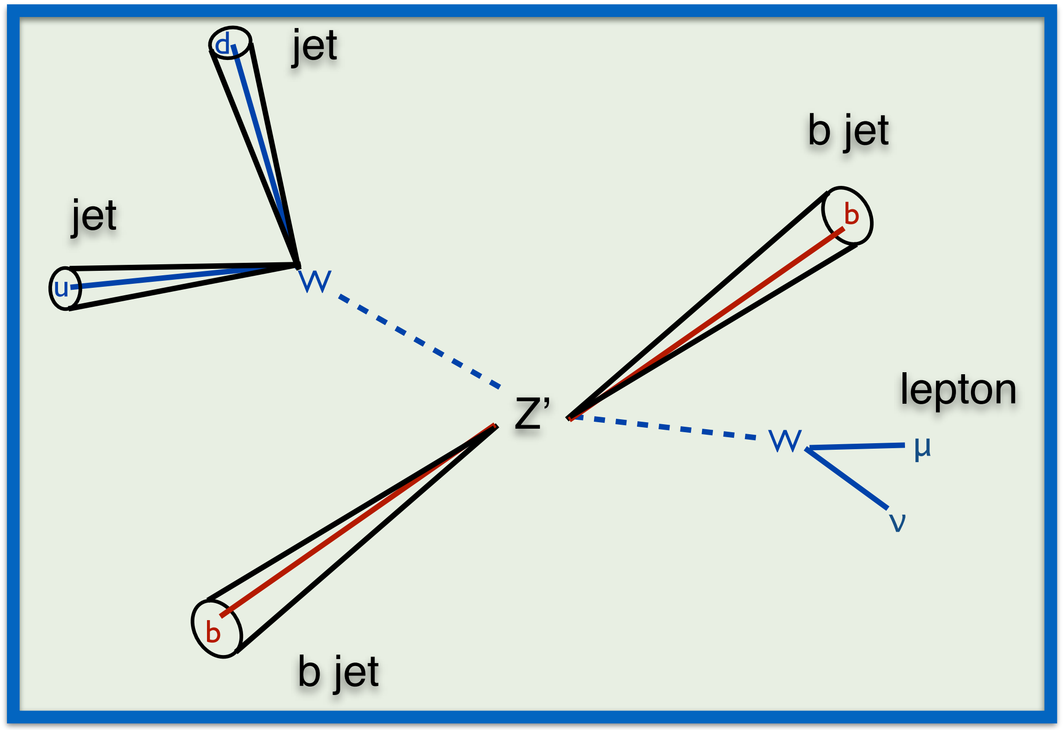
http://cern.ch/collider-reach

HEAVY RESONANCES



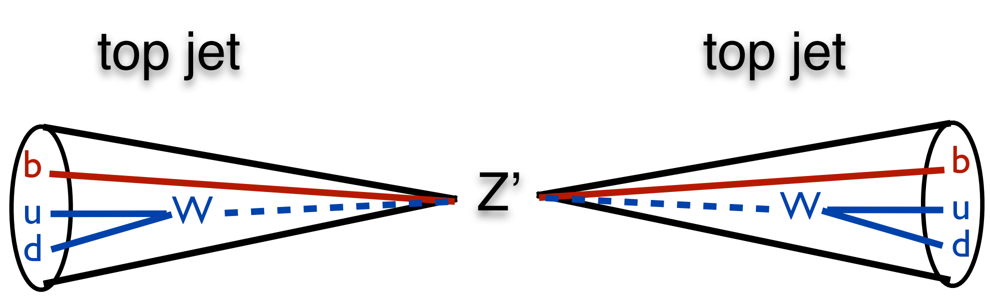
Boosted Topology

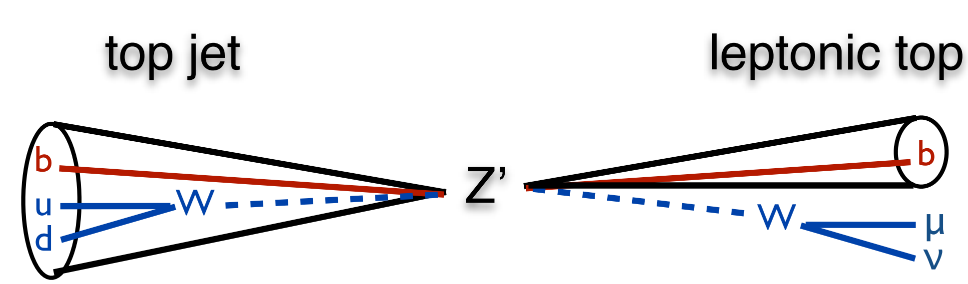
$M_x < 1$ TeV



see talks Monday afternoon covering these topologies in detail

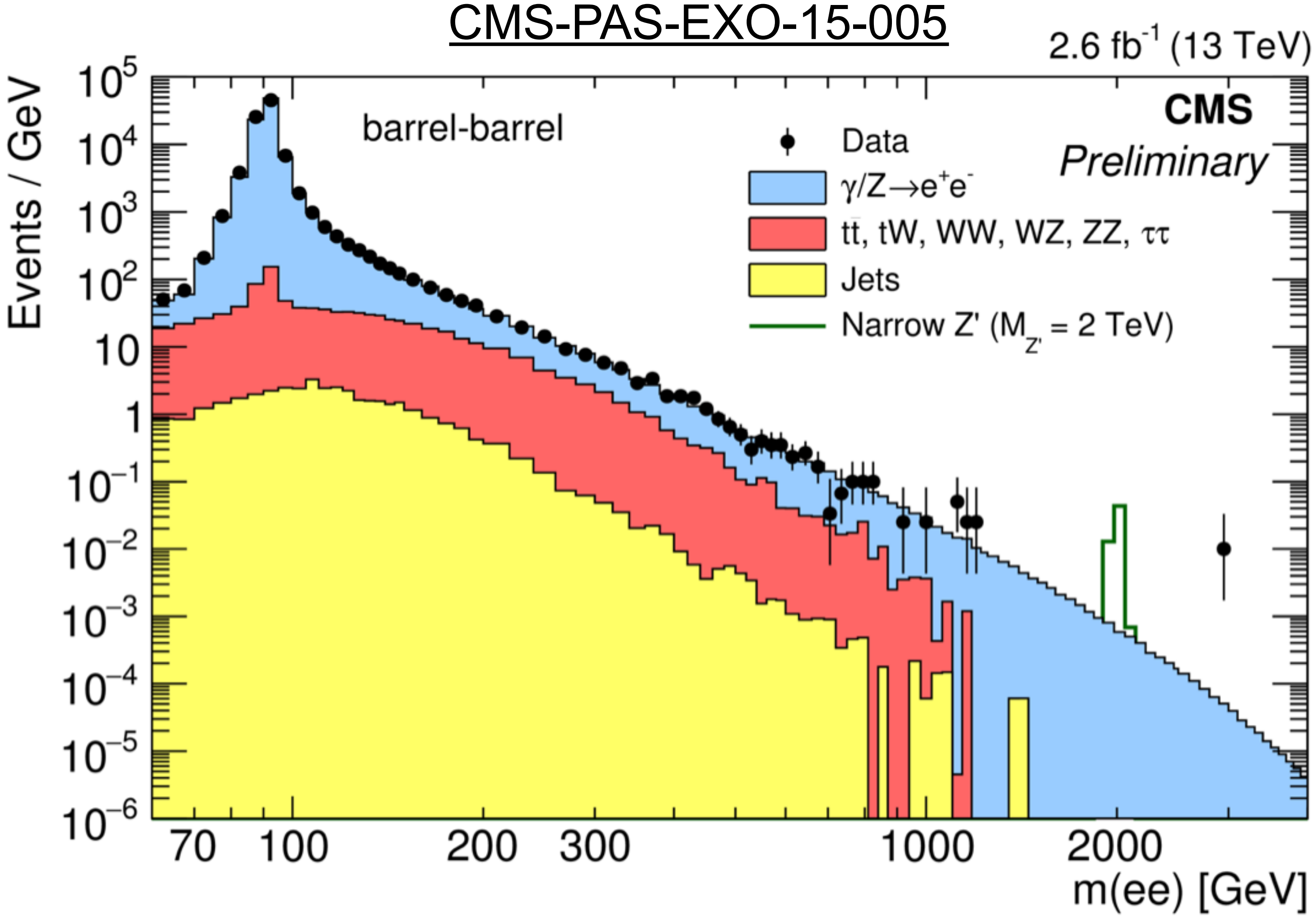
$M_x \sim 2$ TeV



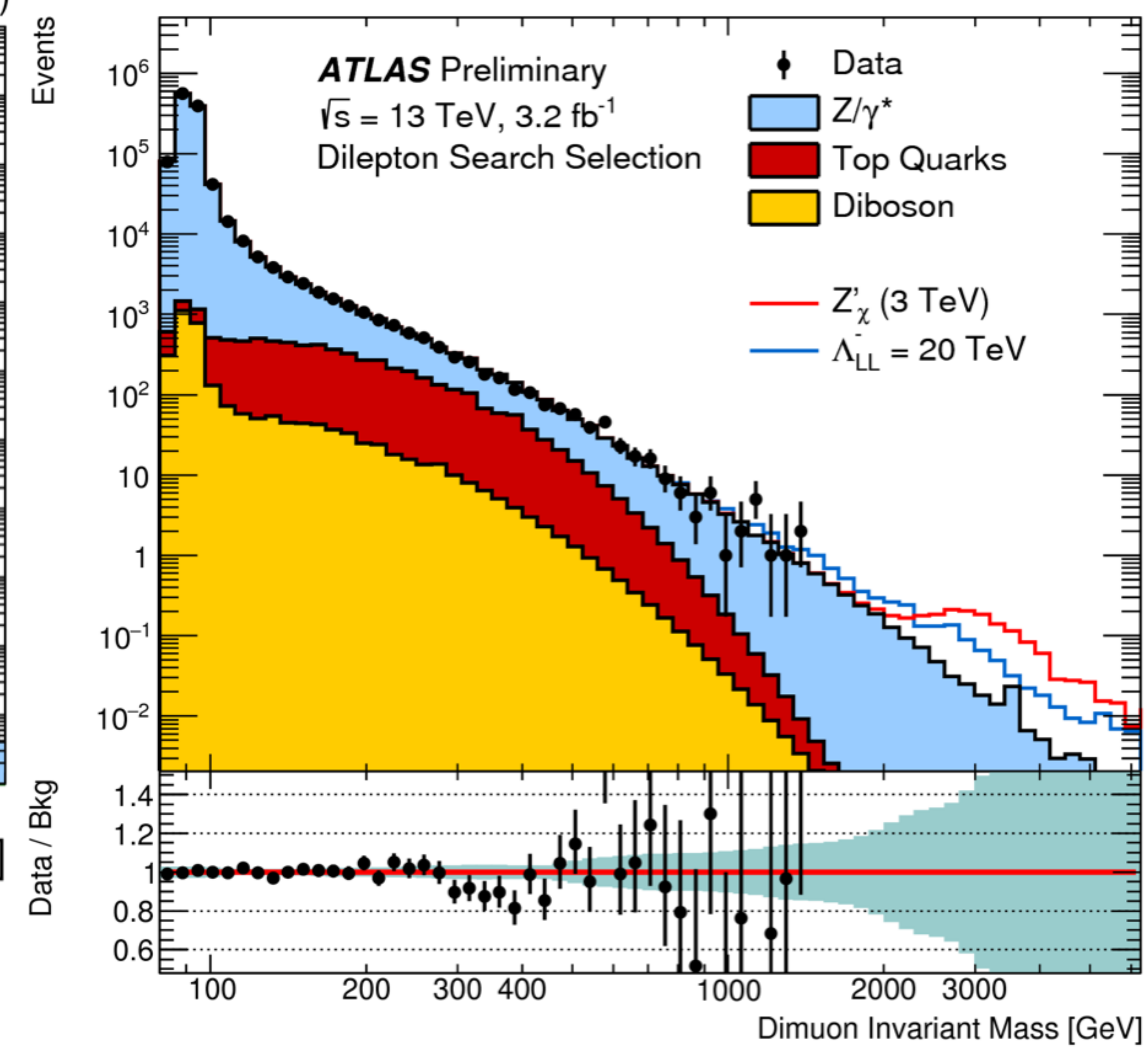


DI-LEPTONS

CMS-PAS-EXO-15-005

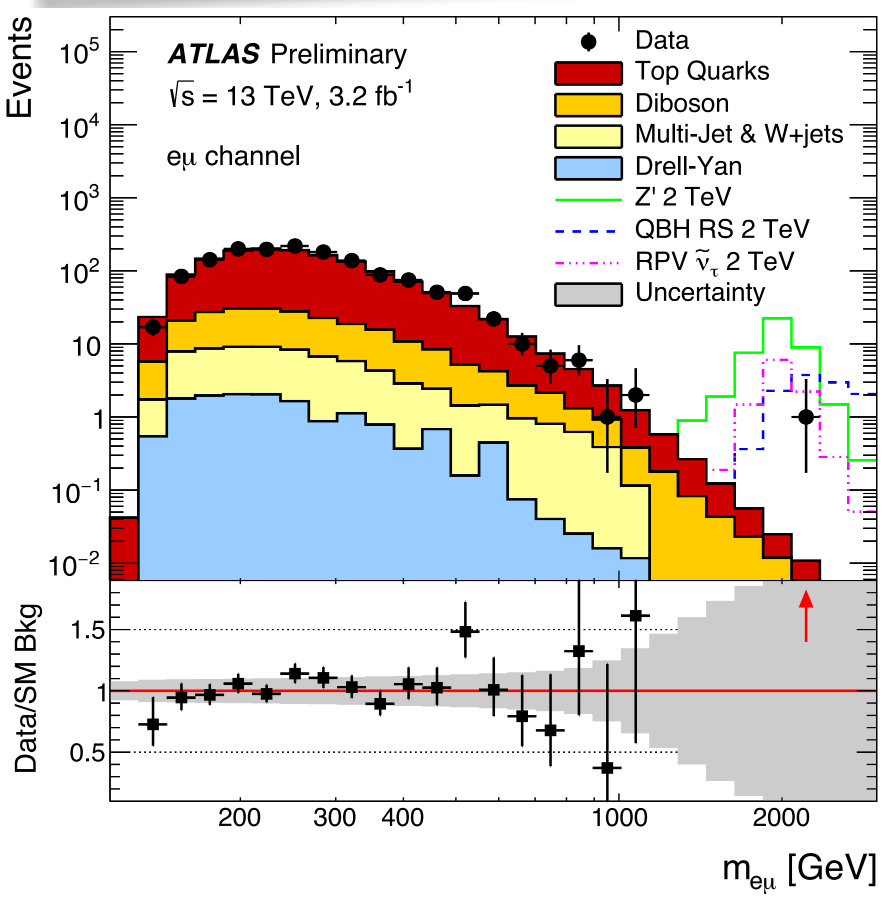


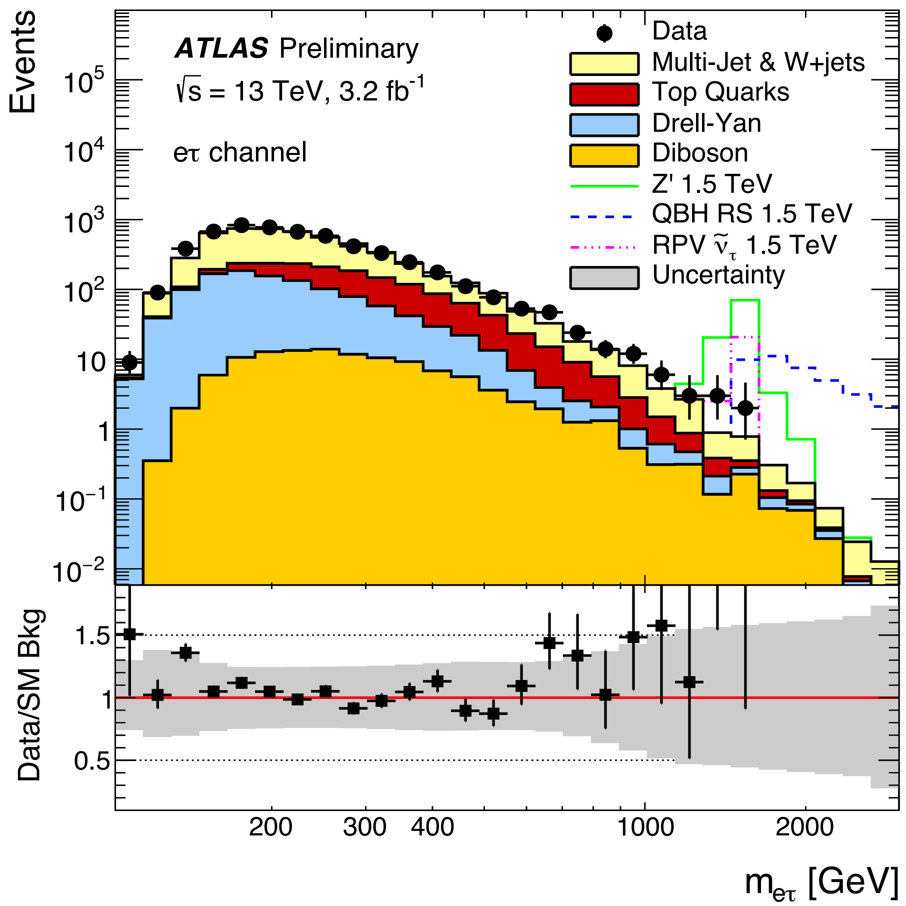
ATLAS-CONF-2015-070

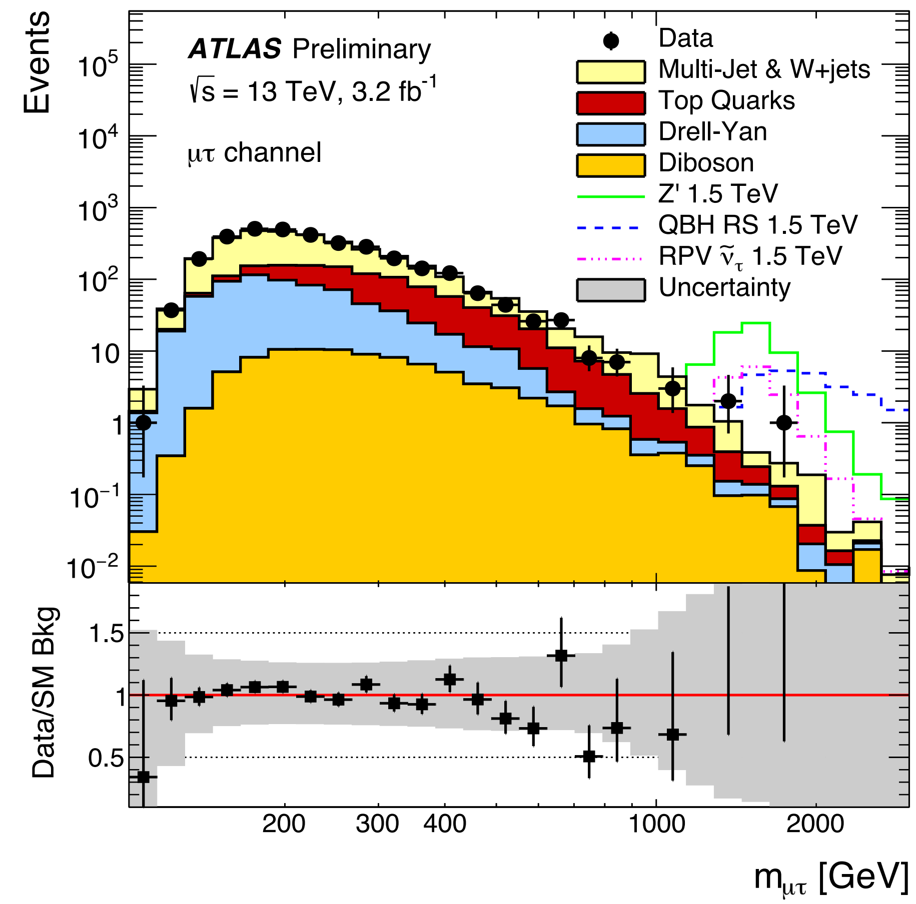


- 0.08 events expected above 2.5 TeV

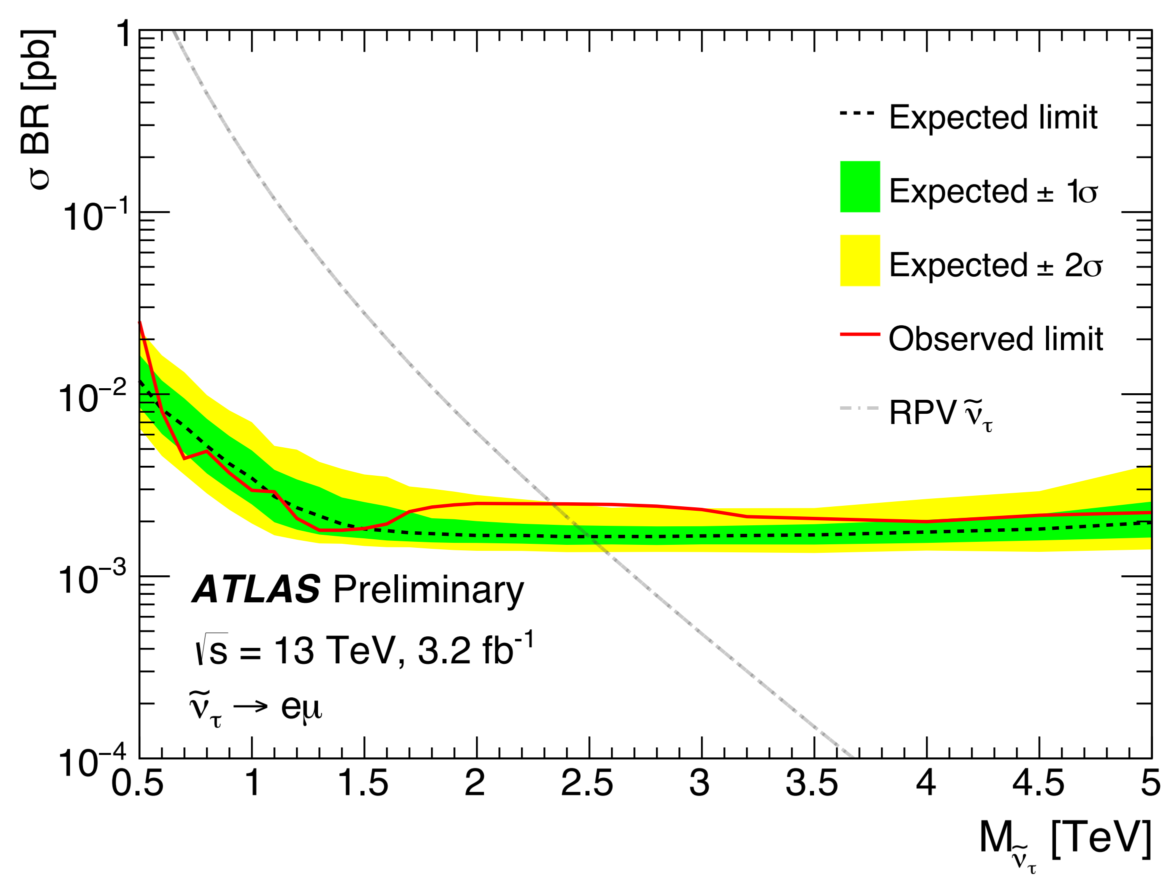
Lepton Flavor Violation





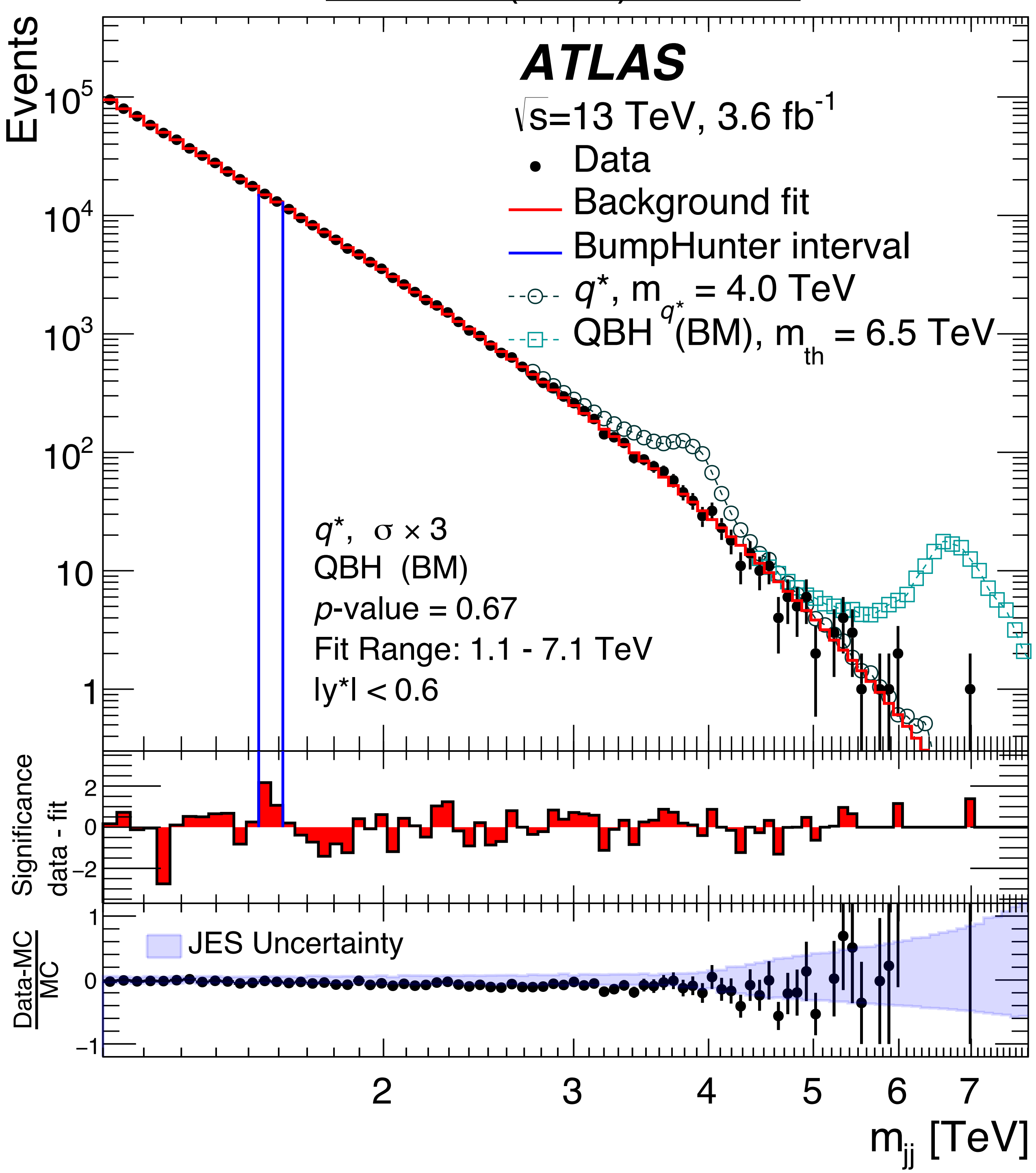


ATLAS Preliminary

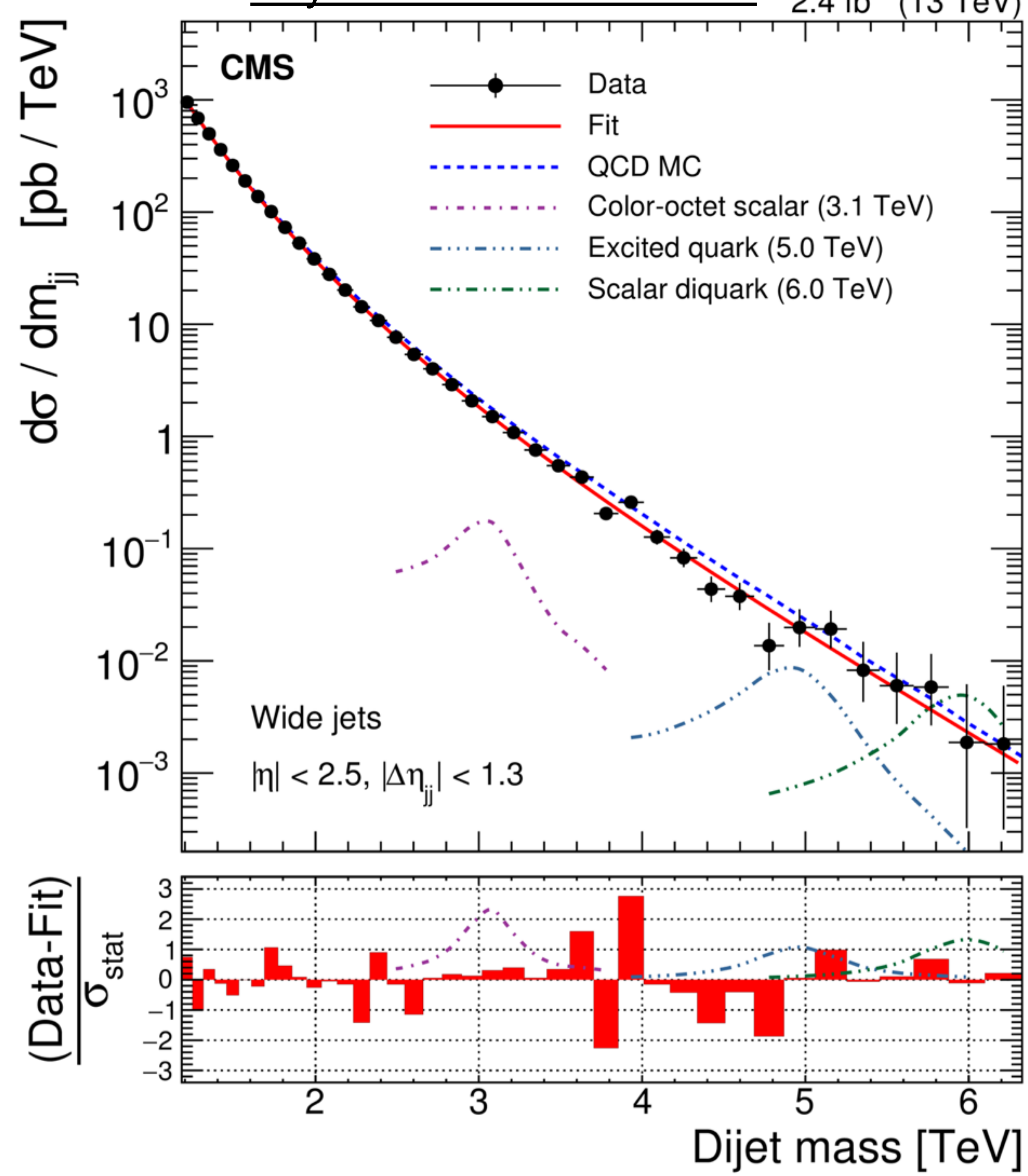


DI-JET AT 13 TEV

PLB 754 (2016) 302-322

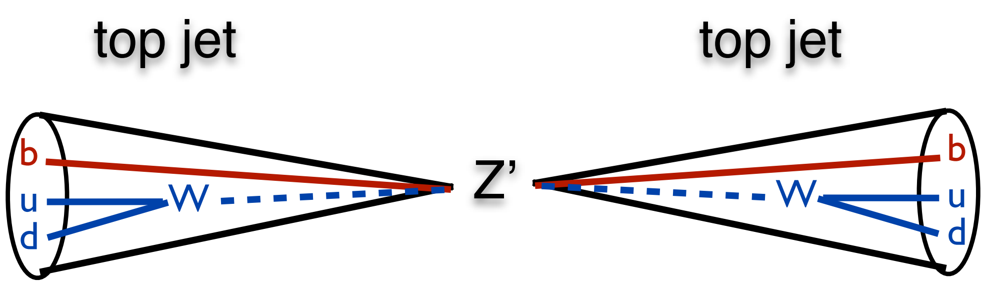


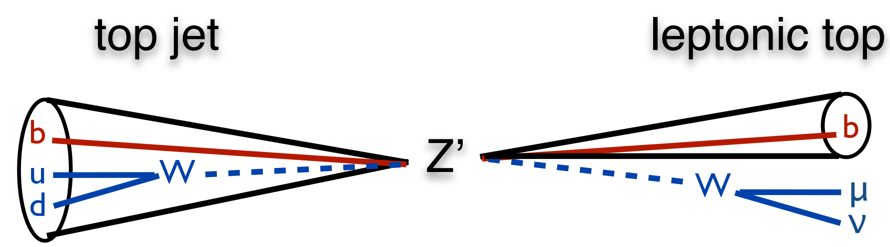
Phys Rev Lett 116 071801



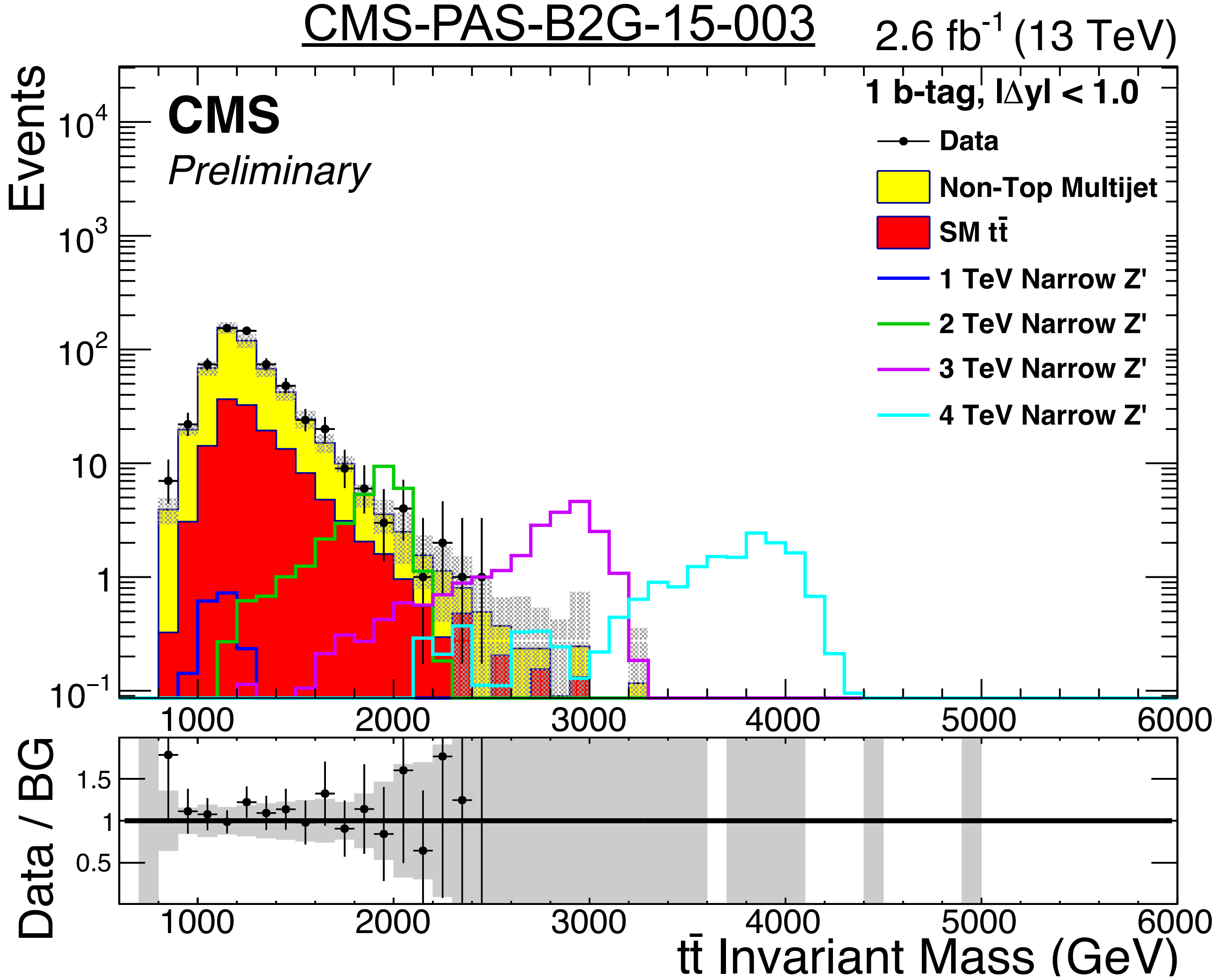
- High p_T trigger thresholds to cope with enormous cross section

T-TBAR

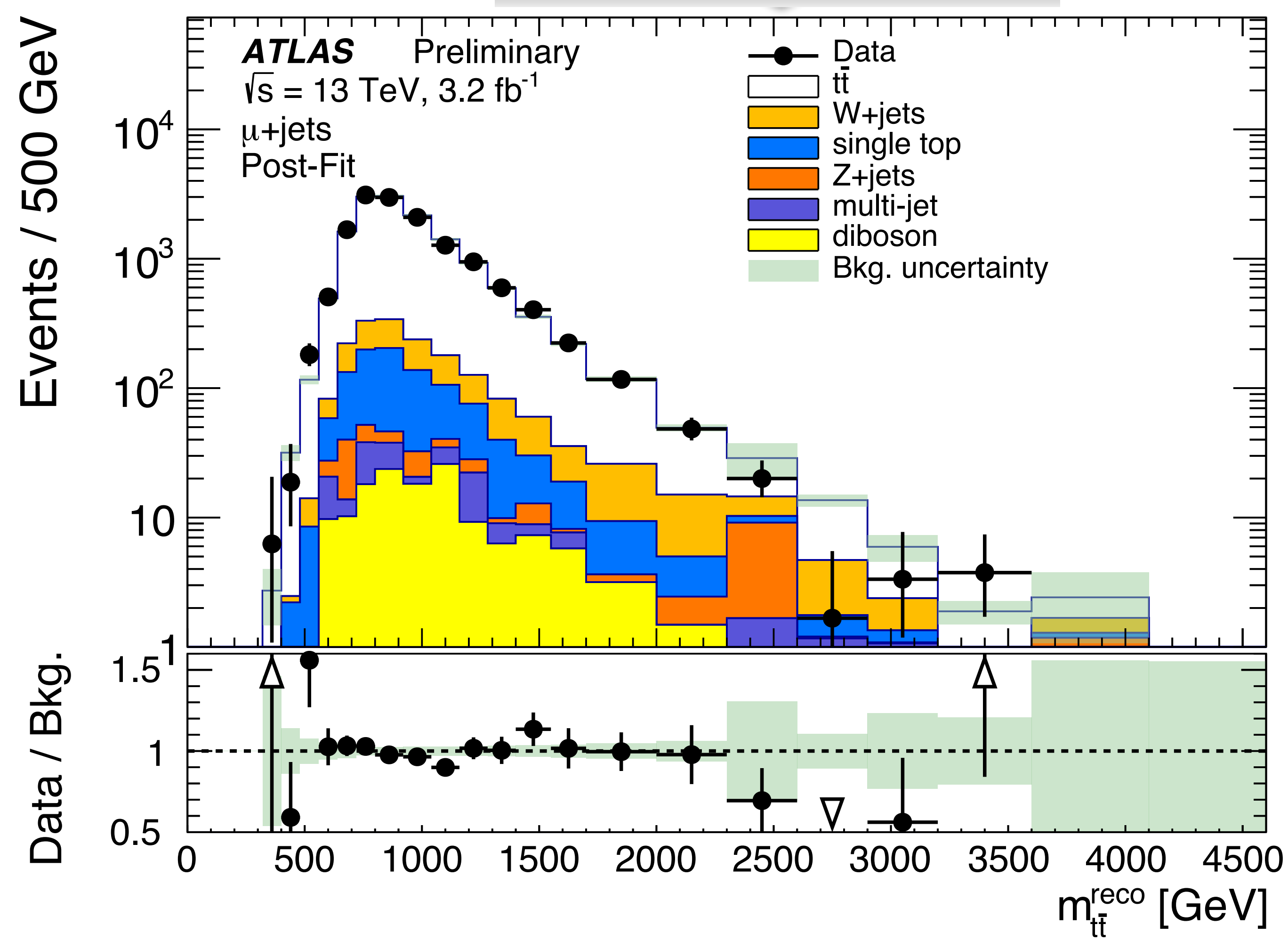




CMS-PAS-B2G-15-003

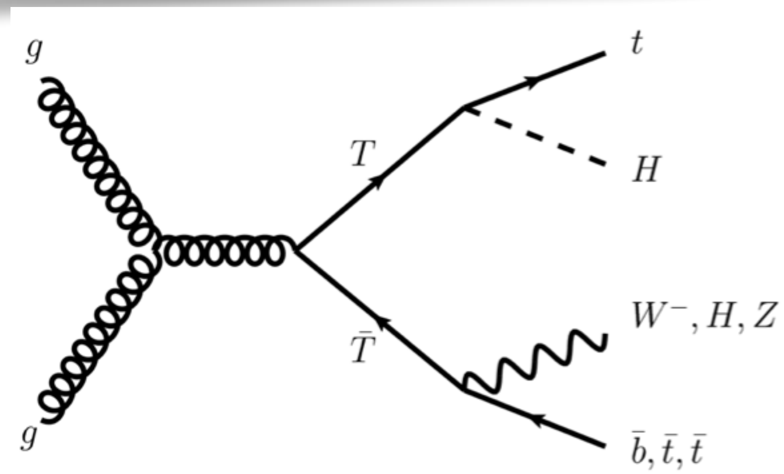


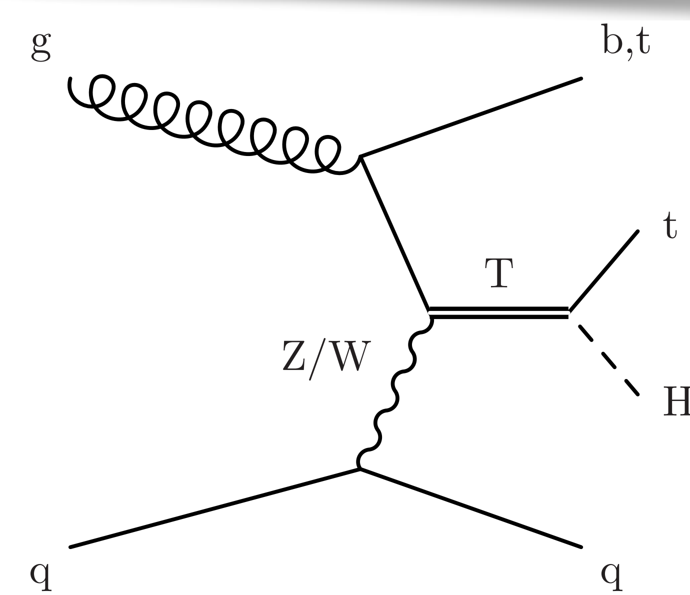
[ATLAS-CONF-2016-014]



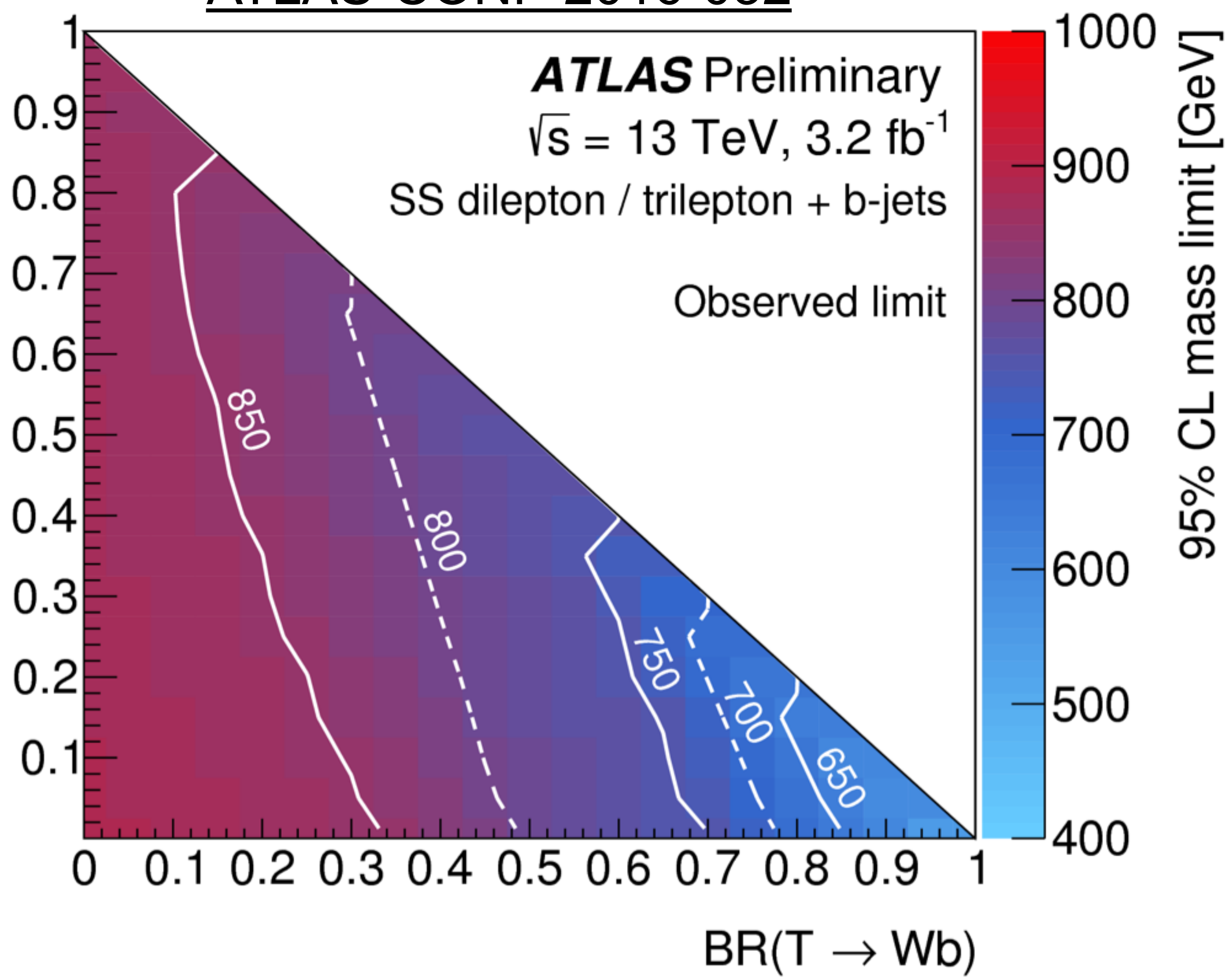
- see talks on Monday afternoon for details

Top Partners

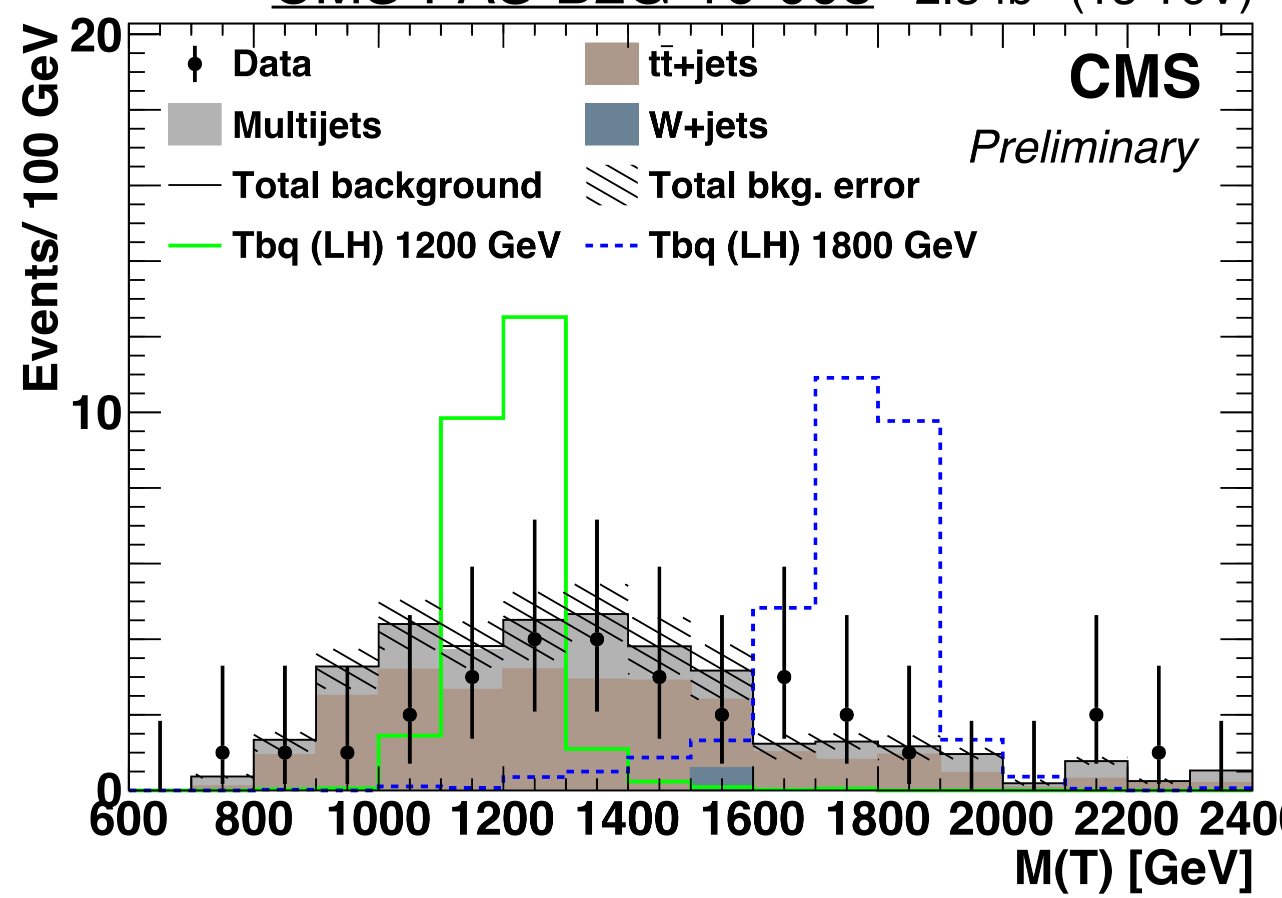




ATLAS-CONF-2016-032



CMS-PAS-B2G-16-005



- Constraints in Run2 already competitive or better than Run1

DI-BOSON FINAL STATES

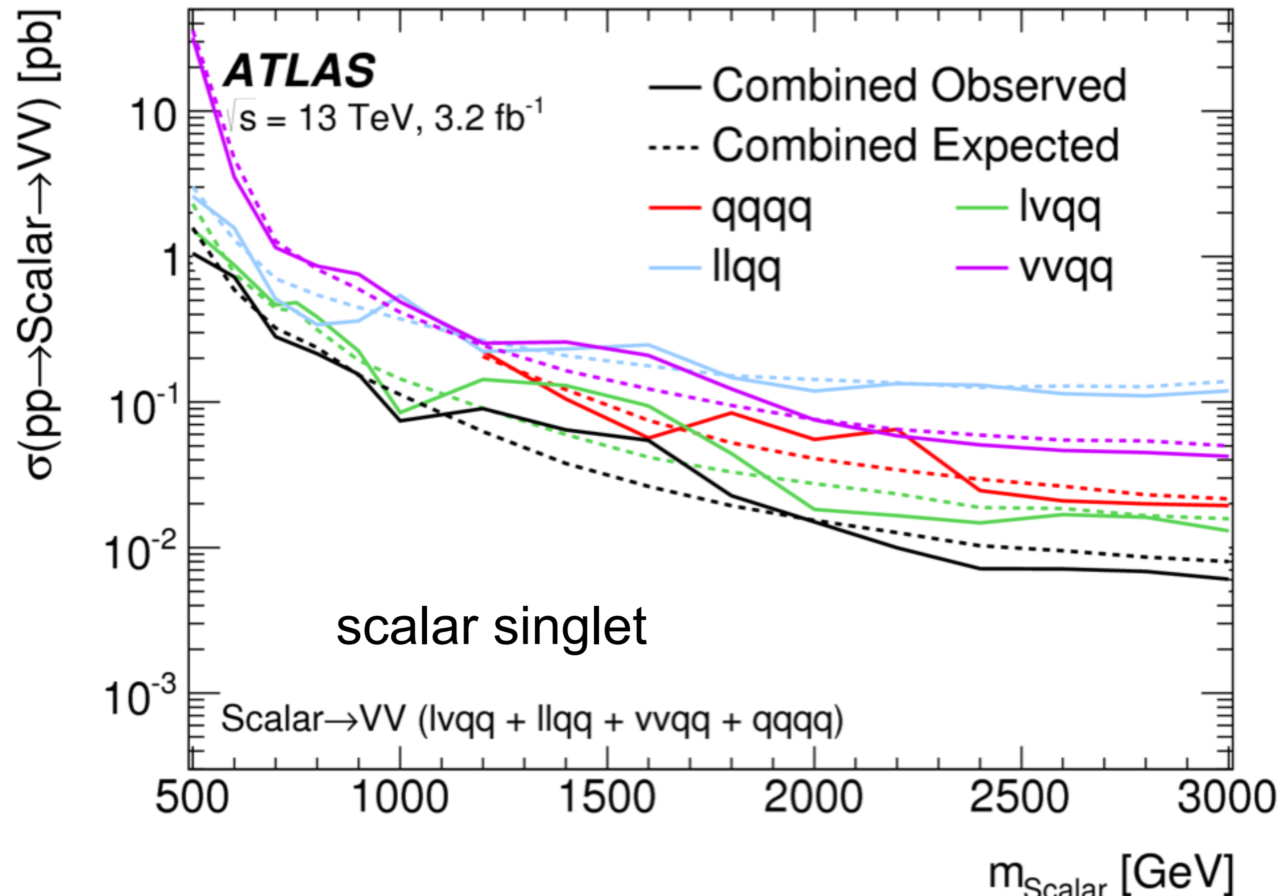
- Rich search program for both vector and scalar bosons

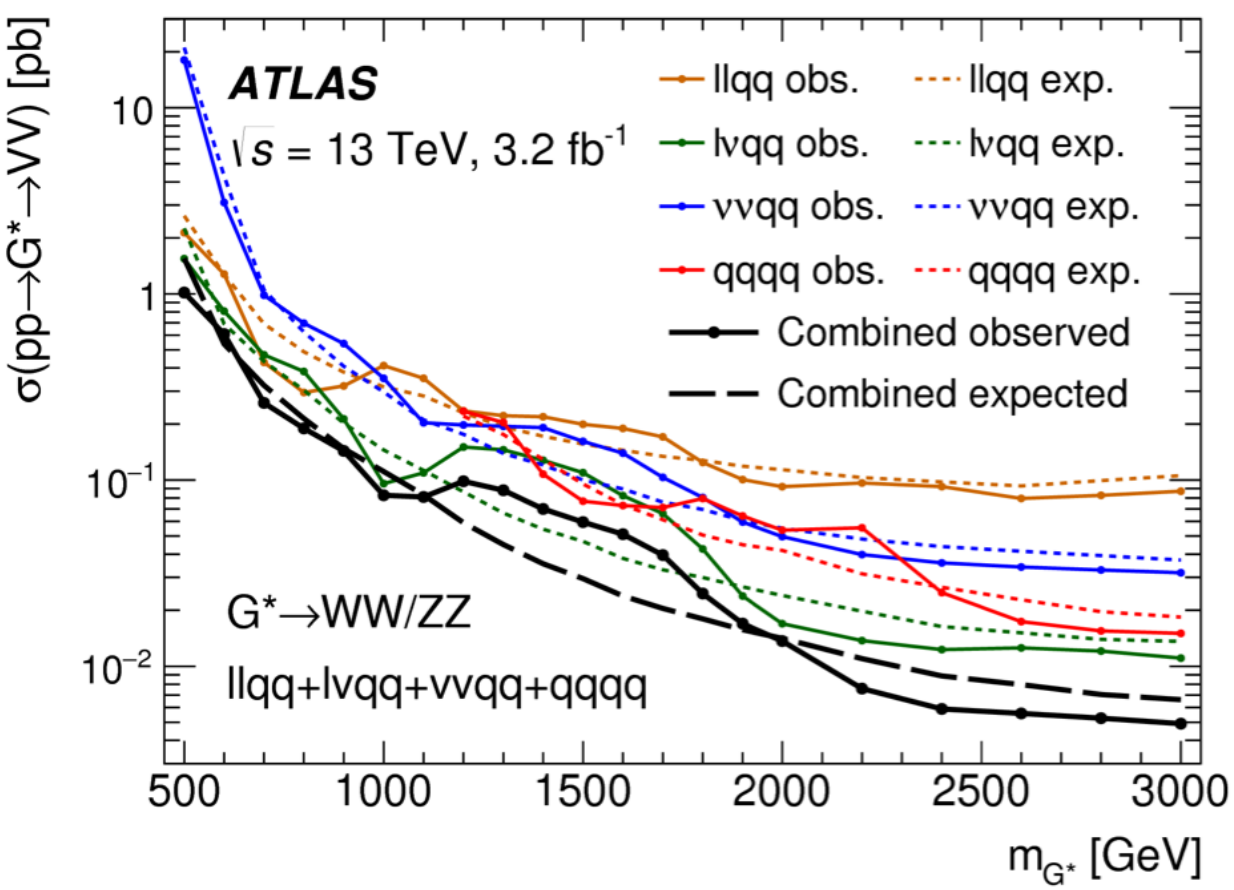
Signature	Final state	ATLAS	CMS
γγ	γγ	ATLAS-CONF-2015-081 *10.1103/PhysRevLett.113.171801* *10.1103/PhysRevD.92.032004*	CMS-PAS-EXO-15-004 *CMS-PAS-EXO-12-045* *10.1016/j.physletb.2015.09.062*
	combination	**arXiv:1606.03833**	**arXiv:1606.04093**
γZ	γll	ATLAS-CONF-2016-010 *10.1016/j.physletb.2014.10.002*	CMS-PAS-EXO-16-019 *CMS-PAS-HIG-16-014*
	γqq	ATLAS-CONF-2016-010	**CMS-PAS-EXO-16-020**
	combination		**CMS-PAS-EXO-16-021**
WW/WZ/ZZ	qqqq	**arXiv:1606.04833**	CMS-PAS-EXO-15-002 *10.1007/JHEP08(2014)174*
	qqll	**arXiv:1606.04833**	
	qqlv	**arXiv:1606.04833**	CMS-PAS-EXO-15-002 CMS-PAS-B2G-16-004
	qqvv	**arXiv:1606.04833**	
	combination	**arXiv:1606.04833**	CMS-PAS-EXO-15-002
WH/ZH	bbll	**ATLAS-CONF-2015-074**	CMS-PAS-B2G-16-003
	bblv	**ATLAS-CONF-2015-074**	CMS-PAS-B2G-16-003
	bbvv	**ATLAS-CONF-2015-074**	CMS-PAS-B2G-16-003
	combination	**ATLAS-CONF-2015-074**	CMS-PAS-B2G-16-003
Combination of VV/VH			**CMS-PAS-B2G-16-007**
HH	bbbb	**arXiv:1606.04782**	*CMS-PAS-EXO-12-053*

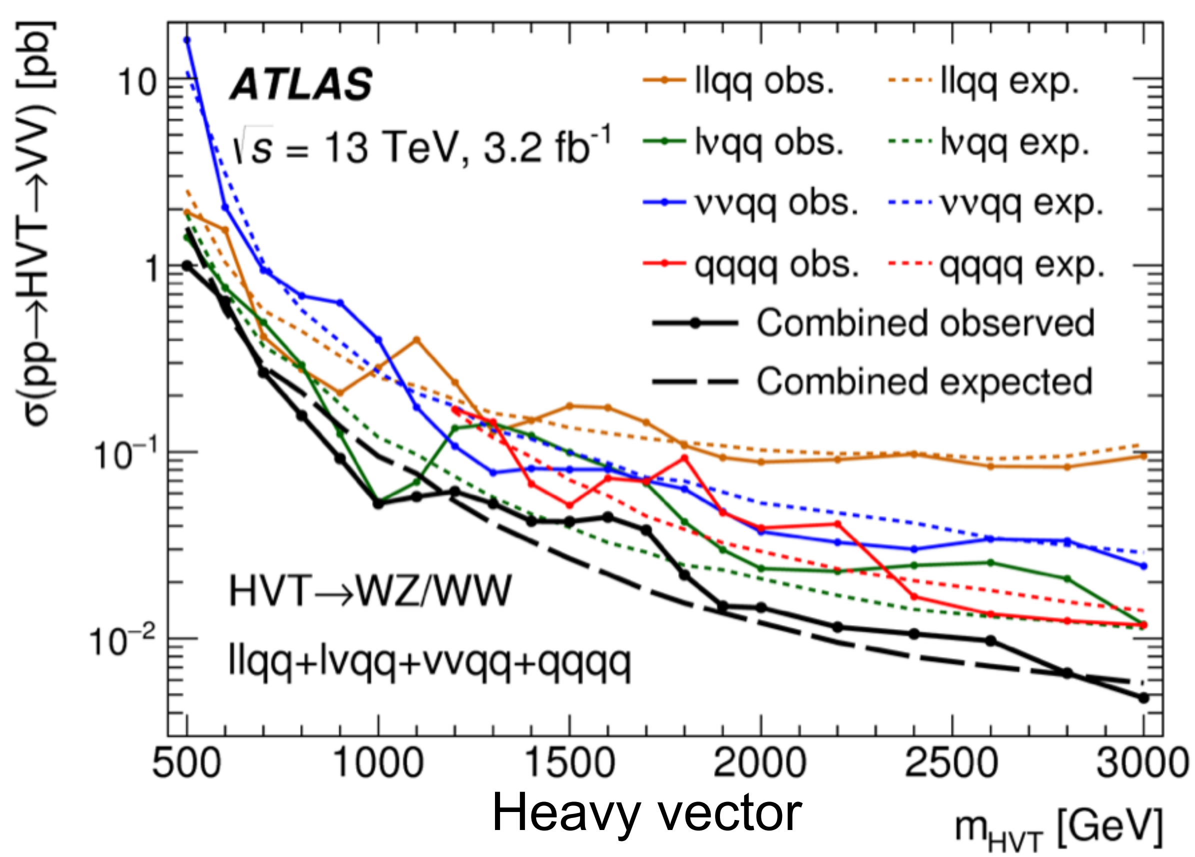
Courtesy of
Andreas Hinzmann
(U Zurich)

VV and VH Picture

arXiv:1606.04833

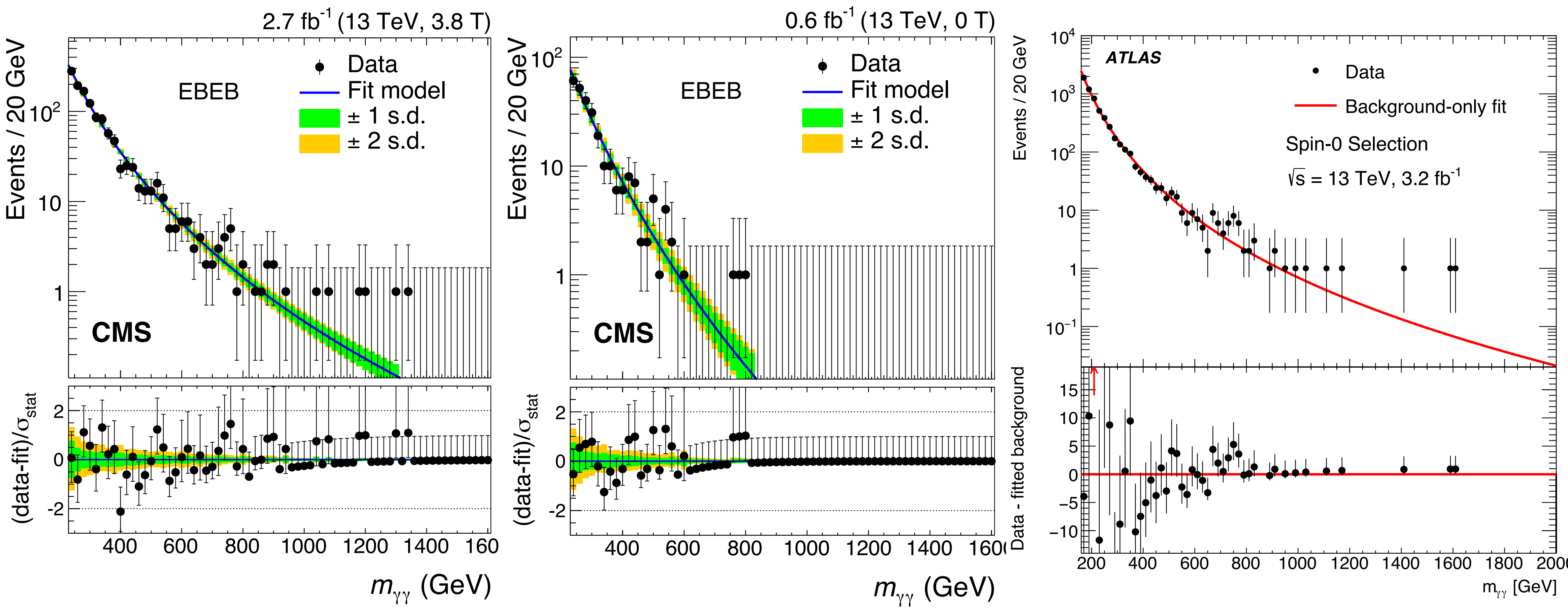






γγ SPECTRUM

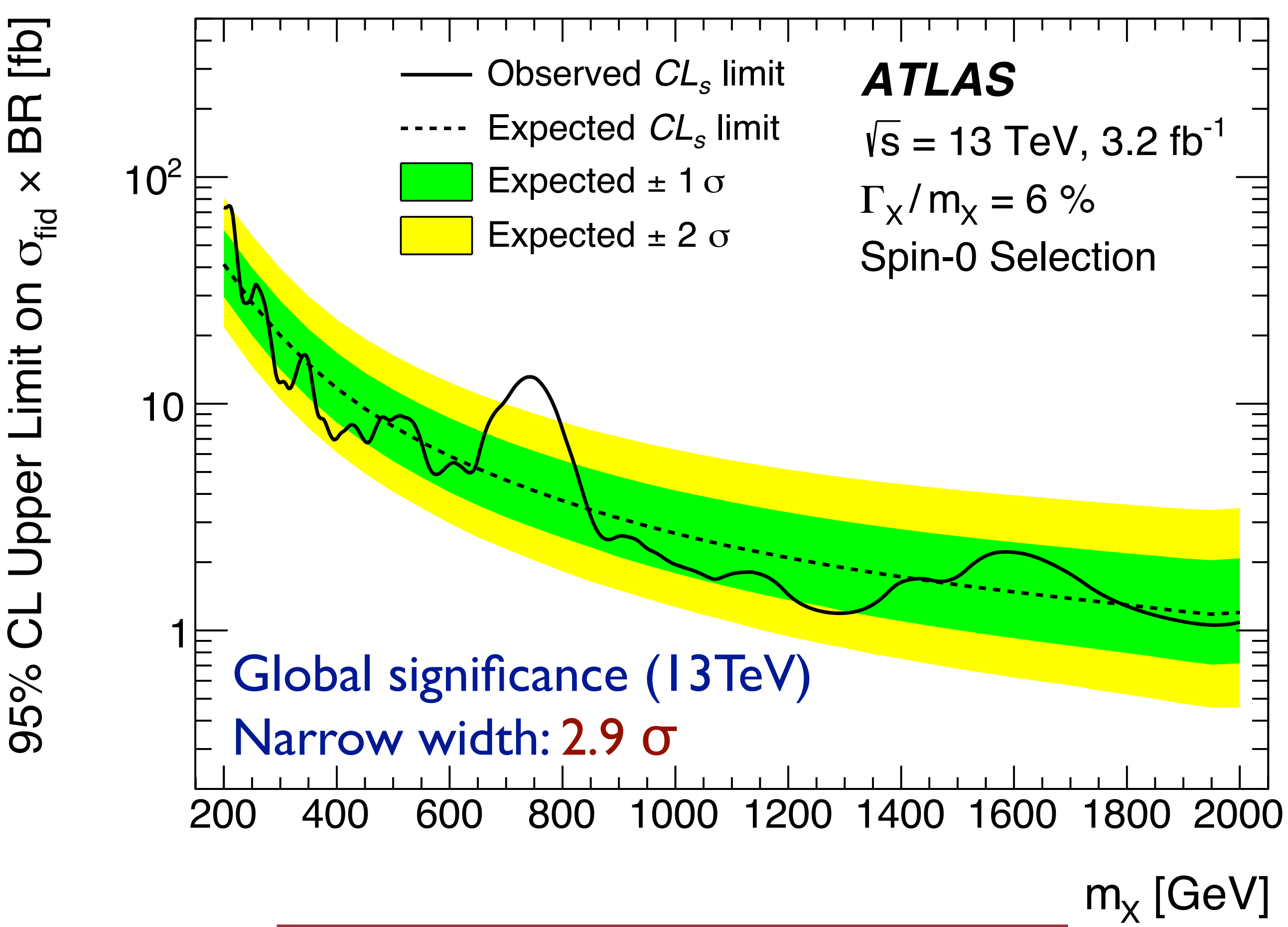
Details in parallel talks on Tuesday afternoon



- Use of data without magnetic field in CMS added 10% sensitivity
  - outstanding detector and calibration work by ECAL team
- Spin-0 and Spin-2 hypotheses, with narrow and wide width as benchmark

THE 400-SOMETHING-THEORY-PAPER BUMP

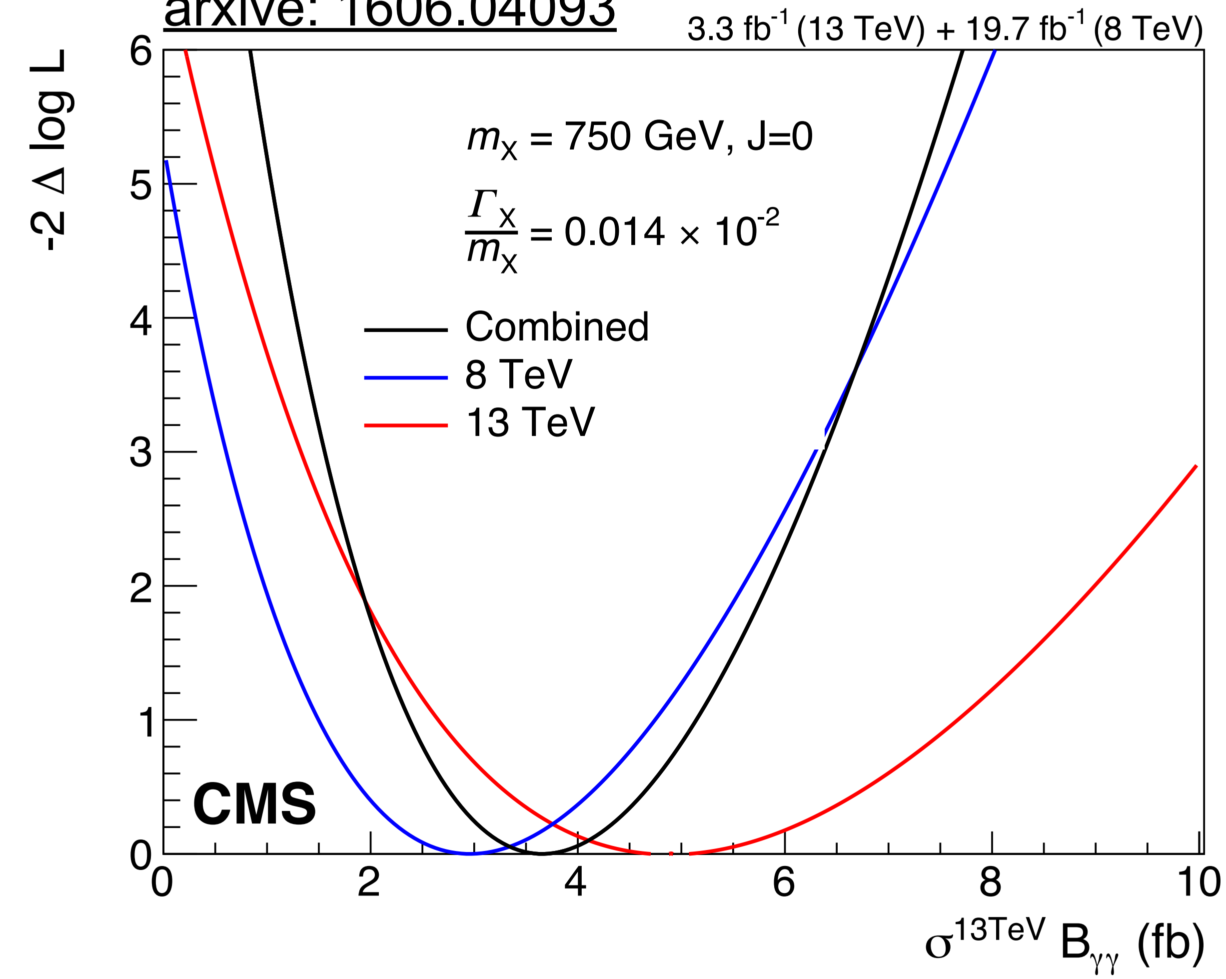
arxive: 1606.03833



	Γ = 4 MeV	Γ/m = 6%
glu-glu	1.5 σ	1.2 σ
q - q	2.0 σ	2.1 σ

ATLAS compatibility with 8 TeV

arxive: 1606.04093

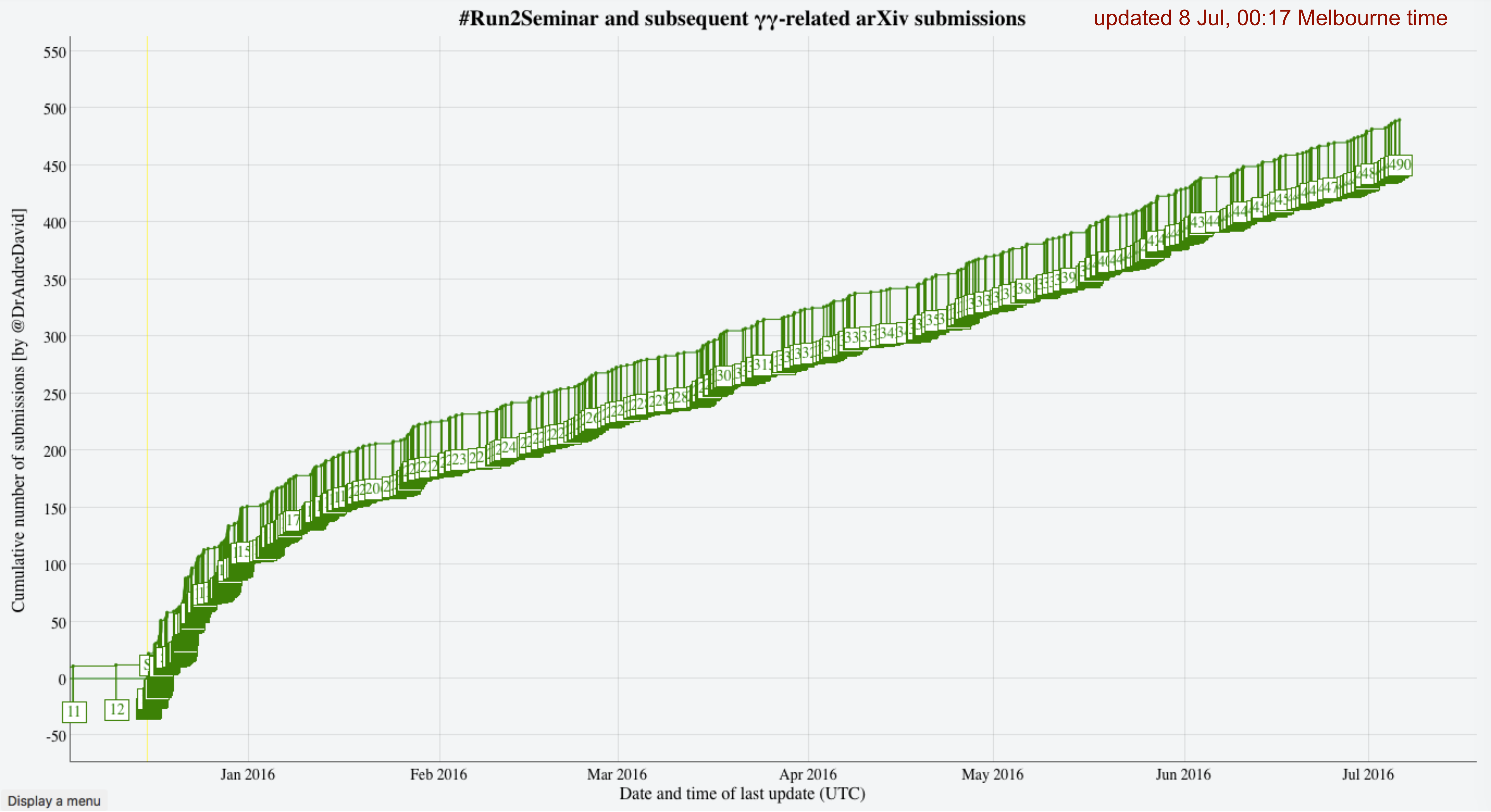


Global significance (13TeV+8TeV)
Narrow width: 1.6 σ

- Outstanding performance of LHC makes the next update interesting
  - both experiments shooting for updates with at least same luminosity
  - each experiment with almost *x3 luminosity recorded so far*

SIGNAL?

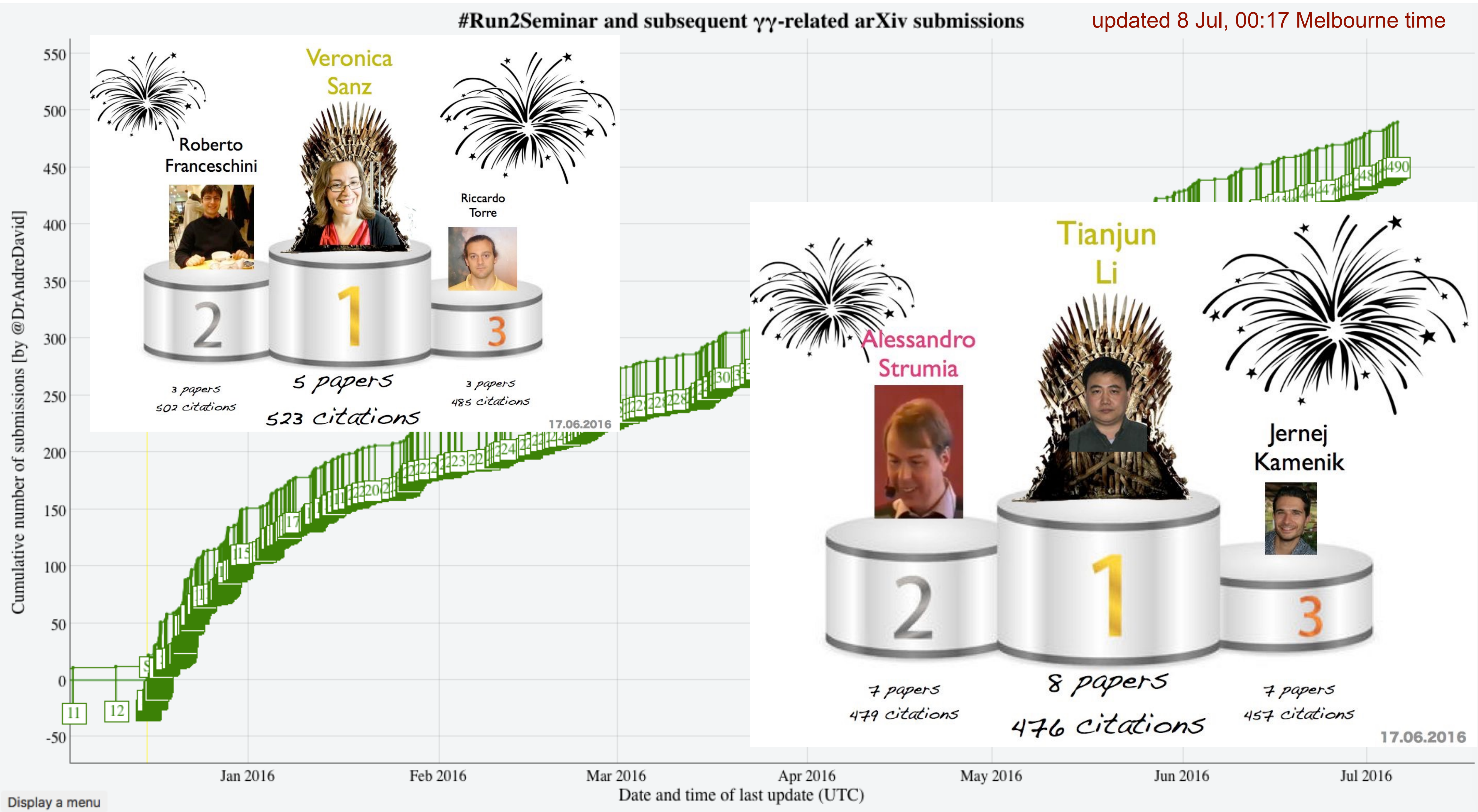
Daily diphoton theory report



SIGNAL?

Daily diphoton theory report

Game of Thrones: 750 GeV Edition



WHAT ELSE?

Warped Geometries Example: 750 GeV Graviton KK-state

SLAC

Hewett, Rizzo 1603.08250

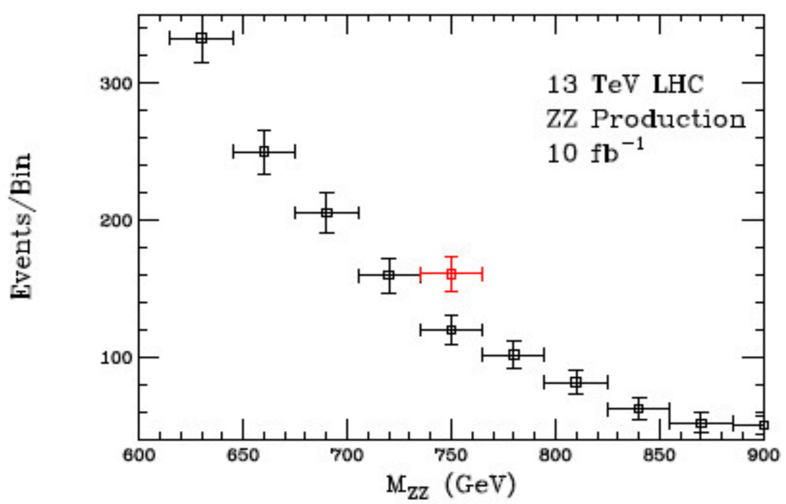
- 750 GeV G_1 diphoton rate

$$\sigma_{\gamma\gamma} = 4.86 \text{ fb } (1 + 2\gamma_0)/25 \ (5 \text{ TeV}/\Lambda_\pi)^2$$

- Naturally fits excess w/ IR-physics at few TeV
- 1st KK should be visible in other channels

Channel	σ^{13} (fb)	σ^{8} (fb)
$\sigma_{\gamma\gamma}$	5.0	1.18
σ_{gg}	40.0	9.44
σ_{ZZ}	7.48	1.77
σ_{WW}	14.6	3.45
σ_{hh}	2.48	0.59
$\sigma_{b\bar{b}}$	29.9	7.06
$\sigma_{t\bar{t}}$	23.9	5.64

ZZ Production



- Gauge 1st KK ~ 566 GeV very weakly coupled
- `Light' RS KK states accessible @LHC w/ natural hierarchy solution!

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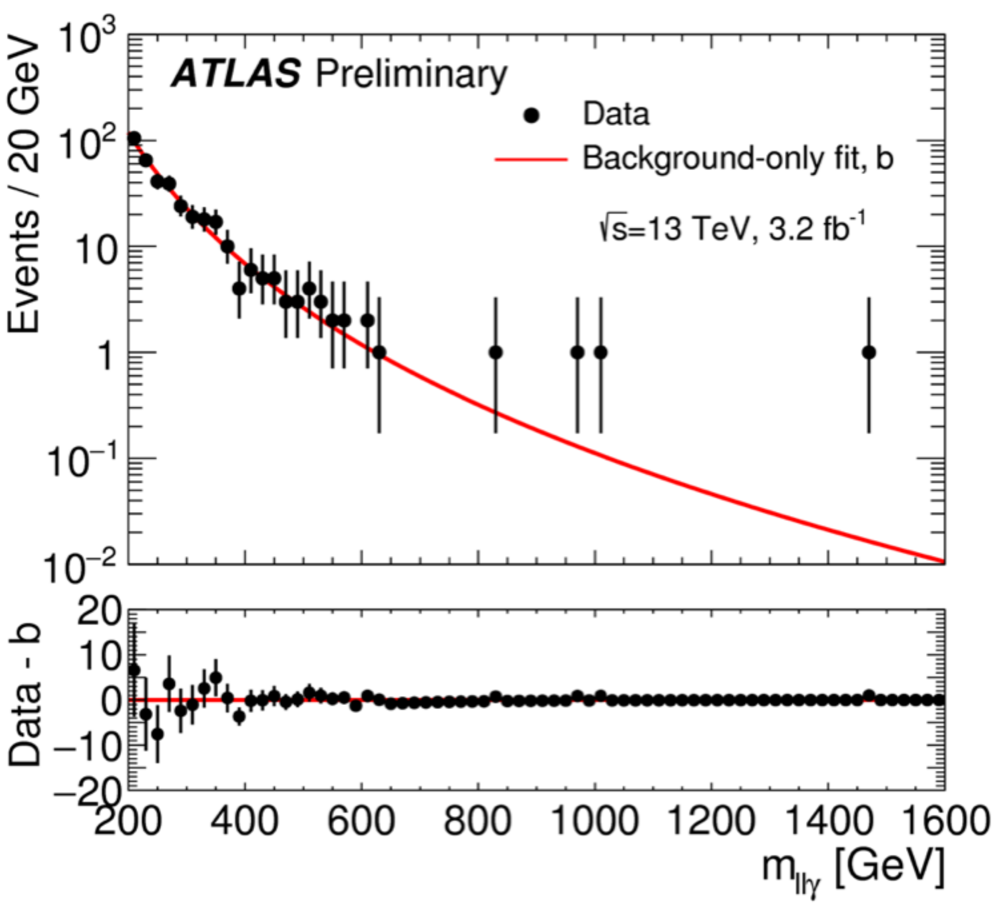
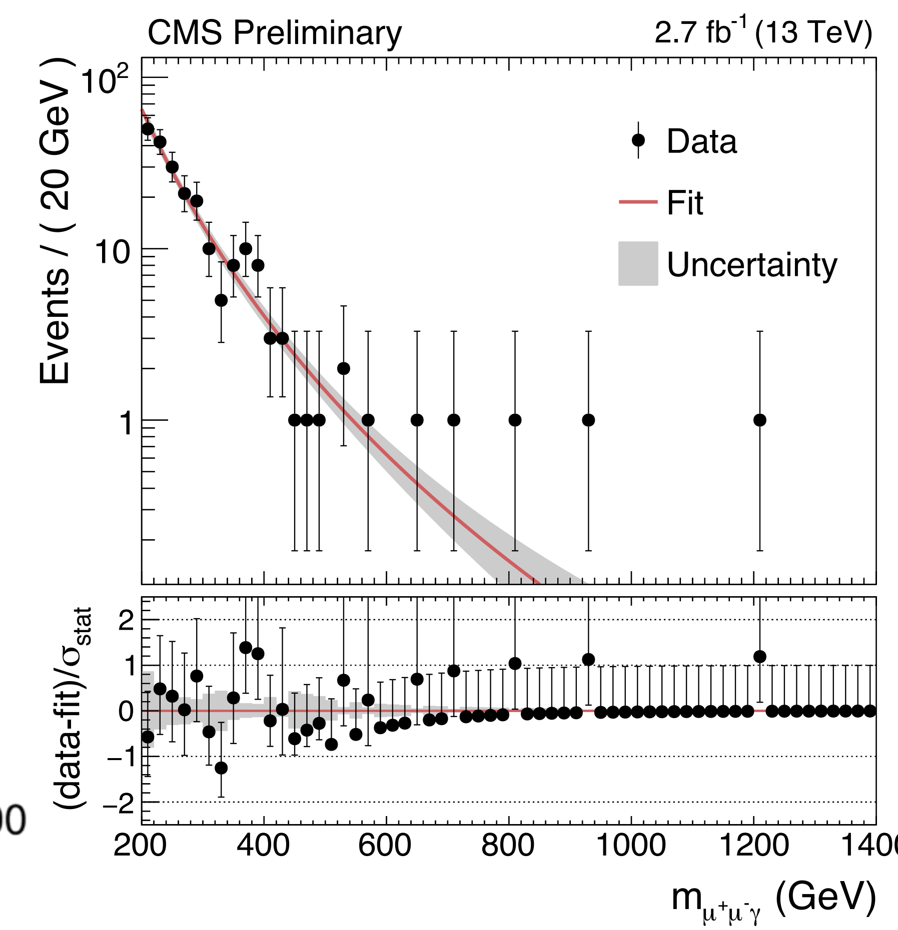
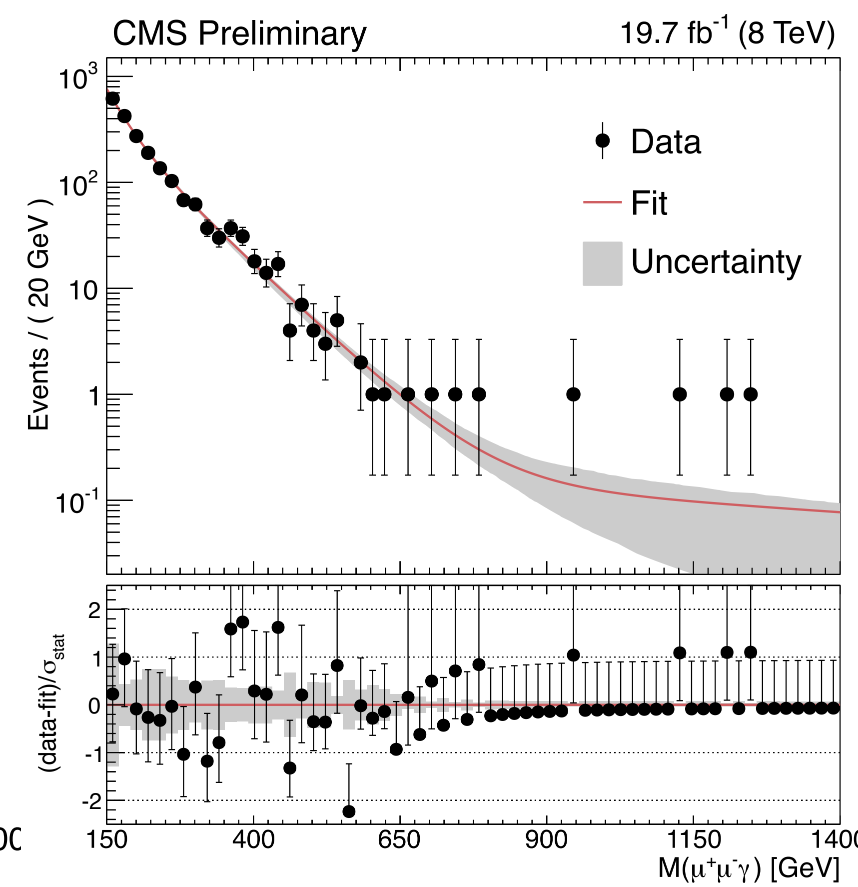
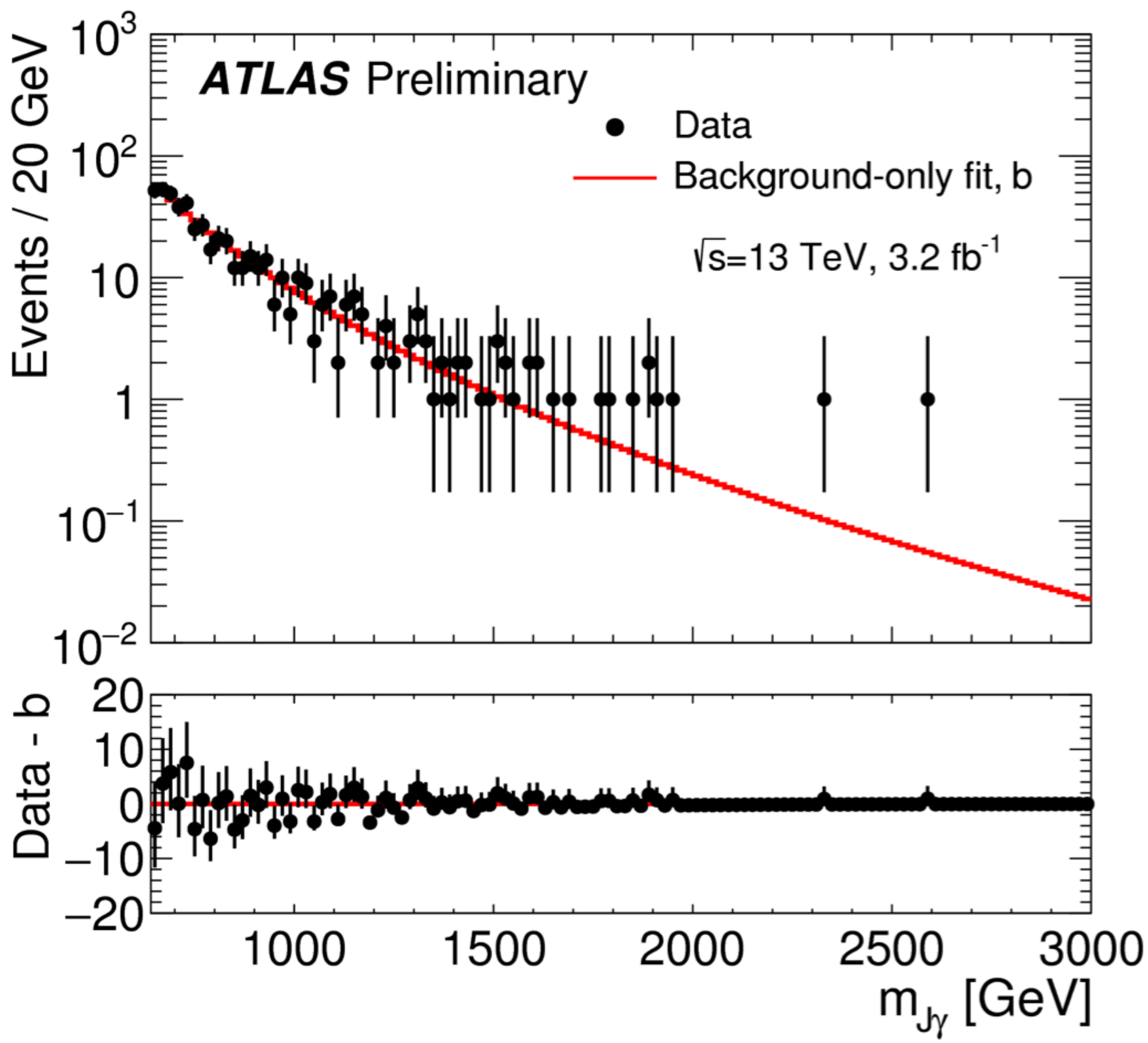
Z(ll)+γ SPECTRUM

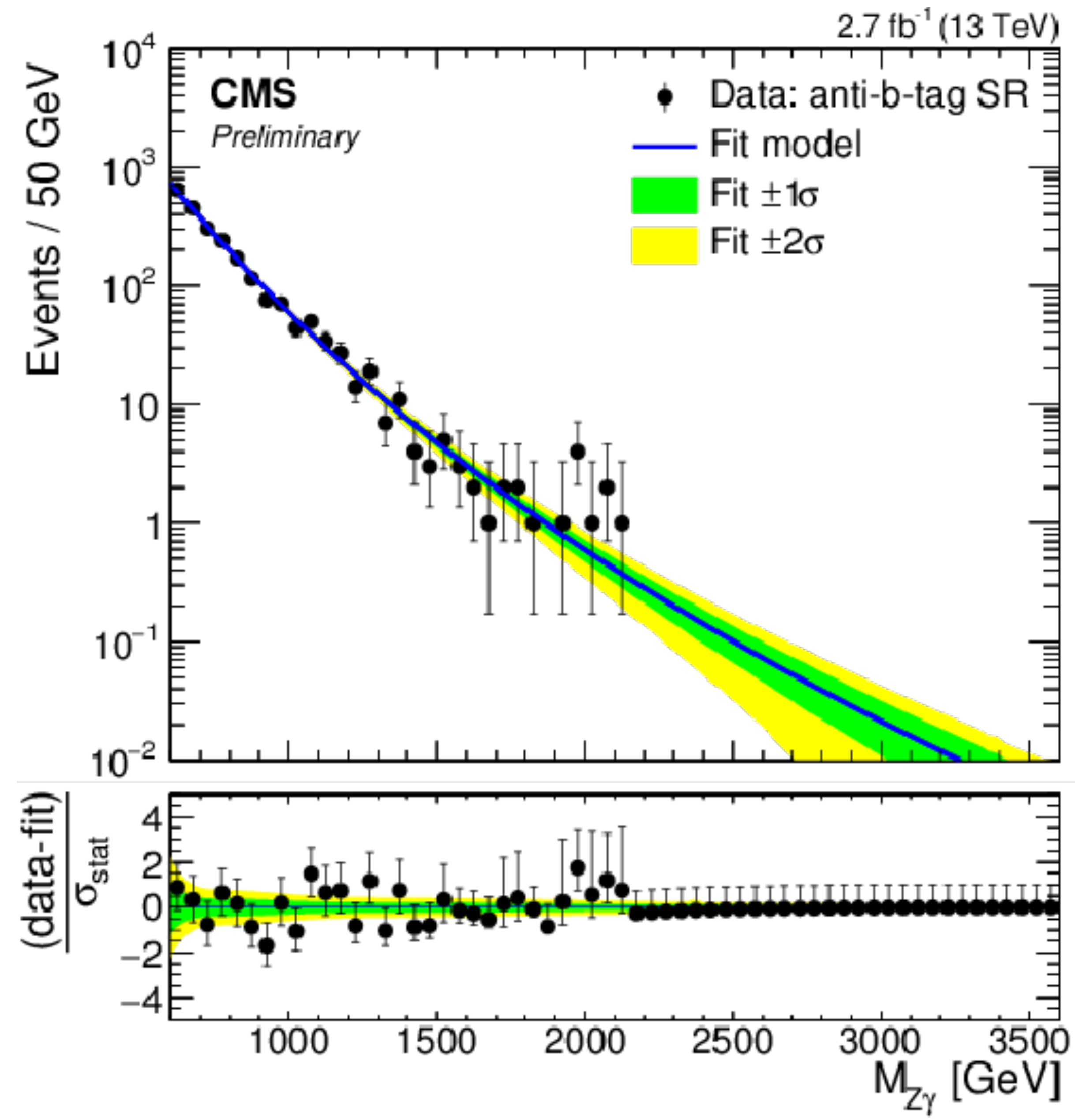






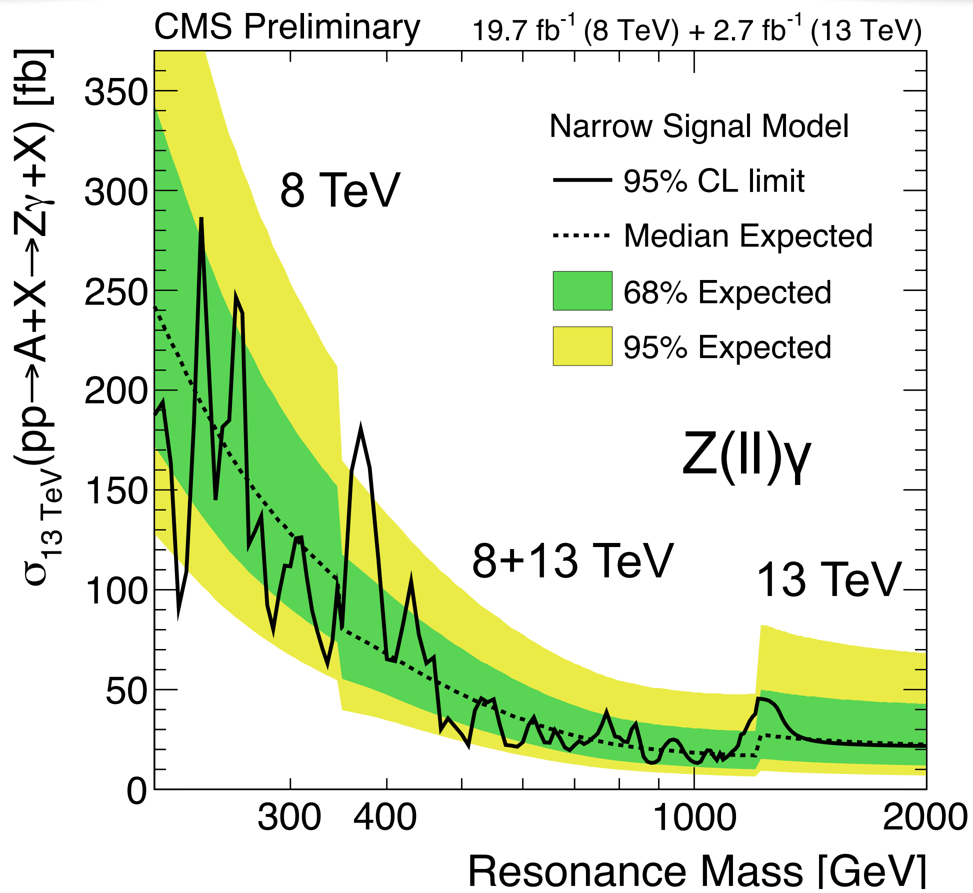
Z(qq)+γ SPECTRUM



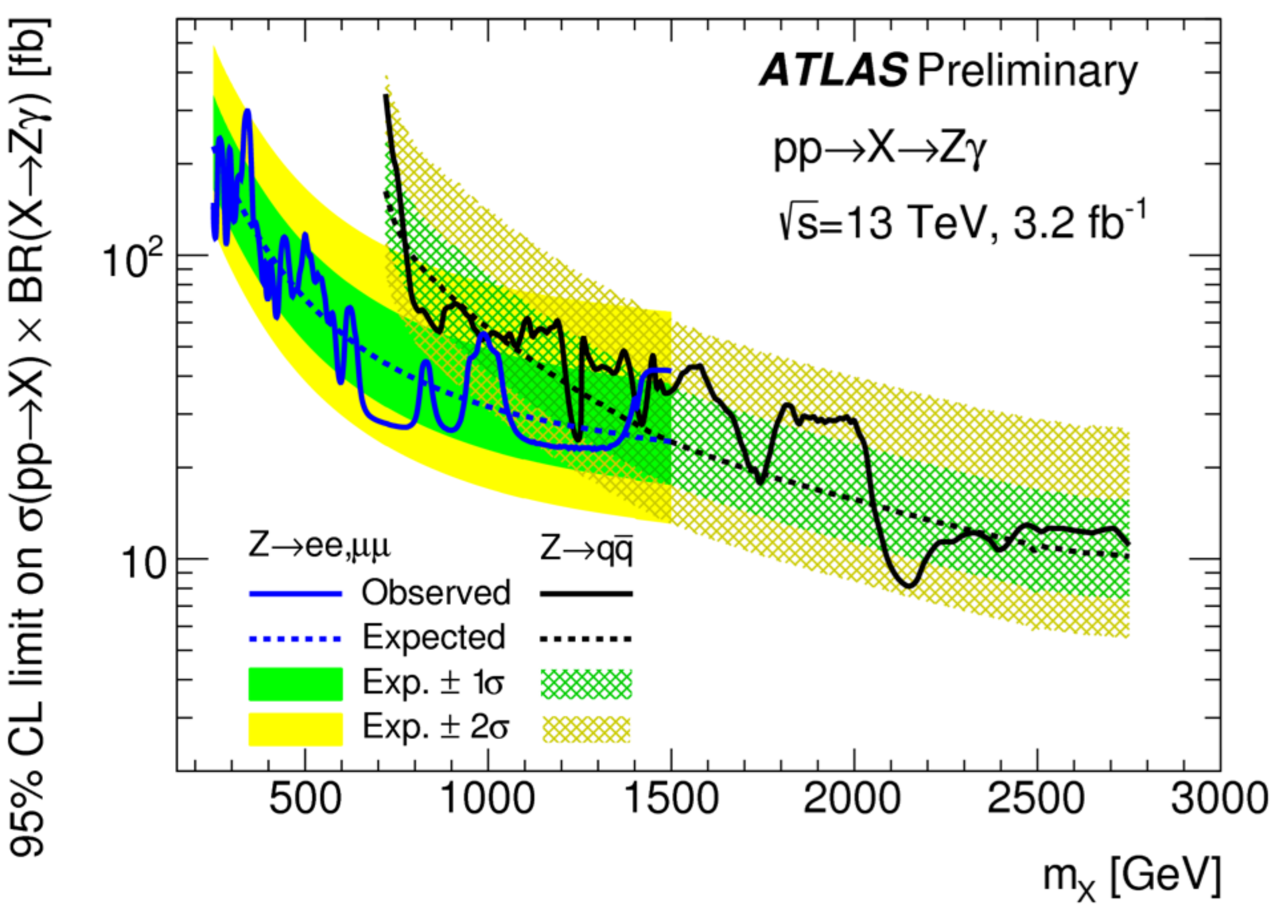


- Merged jets and substructure analysis to reconstruct Z

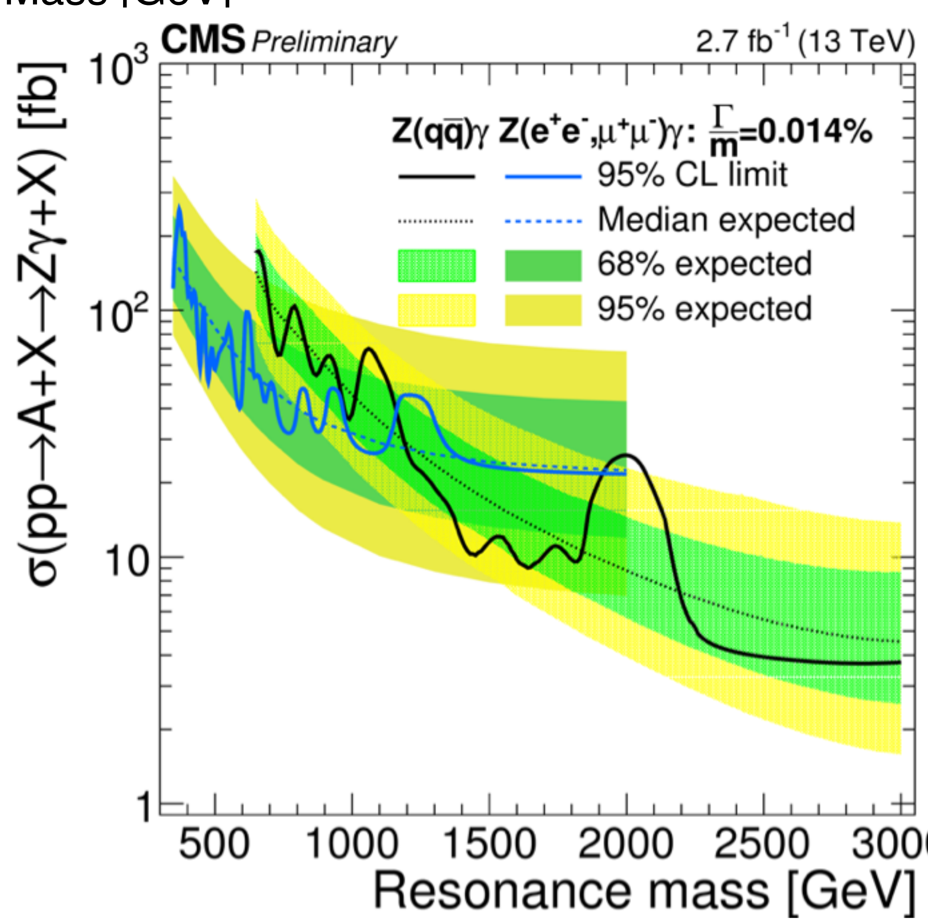
Z+γ Picture



CMS Preliminary
19.7 fb-1 (8 TeV) + 2.7 fb-1 (13 TeV)
Narrow Signal Model
95% CL limit
Median Expected
68% Expected
95% Expected
8 TeV
8+13 TeV
13 TeV
Z(ll)γ
σ13 TeV(pp→A+X→Zγ+X) [fb]
Resonance Mass [GeV]

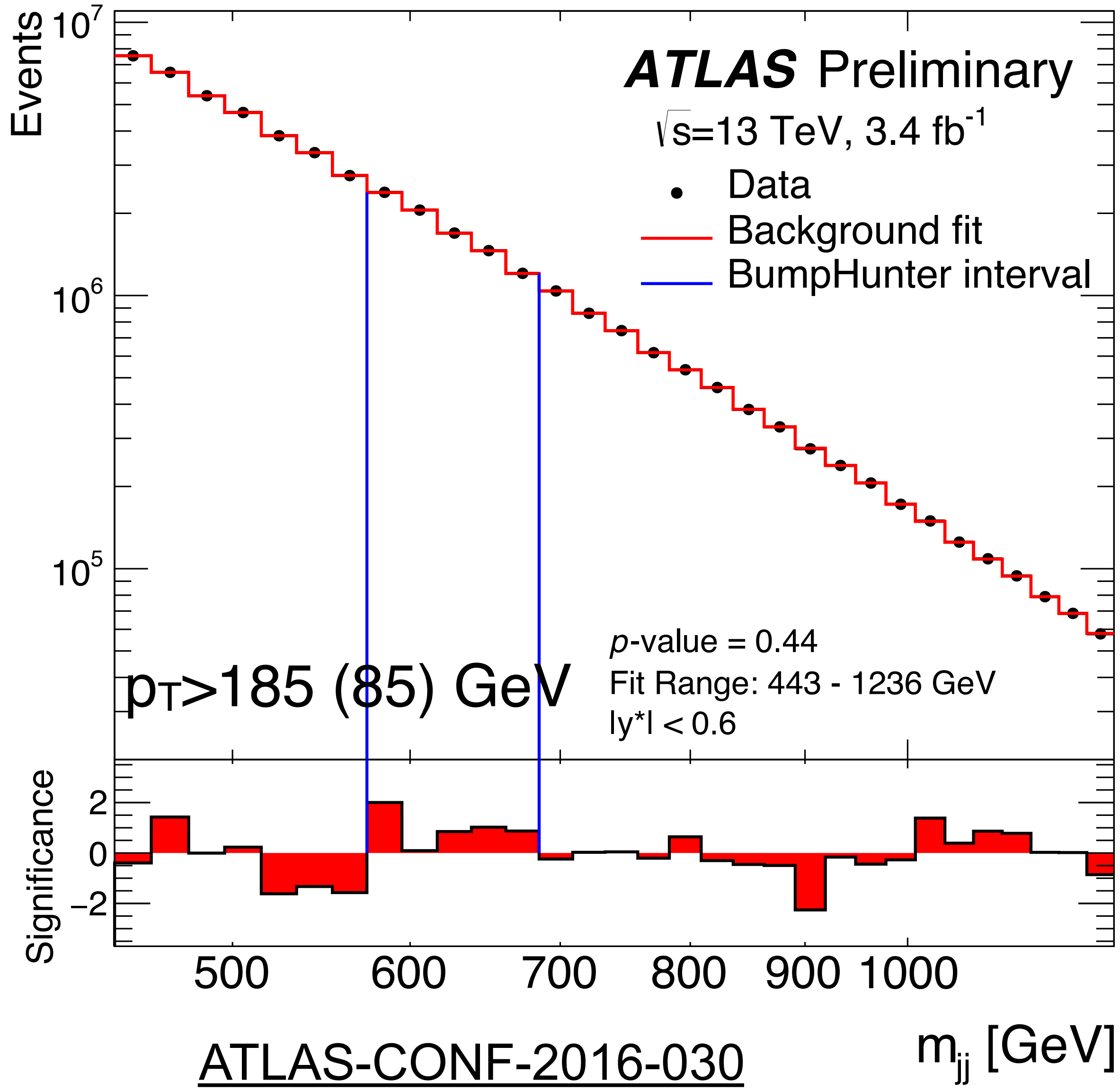


ATLAS Preliminary
pp→X→Zγ
√s=13 TeV, 3.2 fb-1
Z→ee,μμ
Z→qq̄
Observed
Expected
Exp. ± 1σ
Exp. ± 2σ
95% CL limit on σ(pp→X) × BR(X→Zγ) [fb]
mX [GeV]

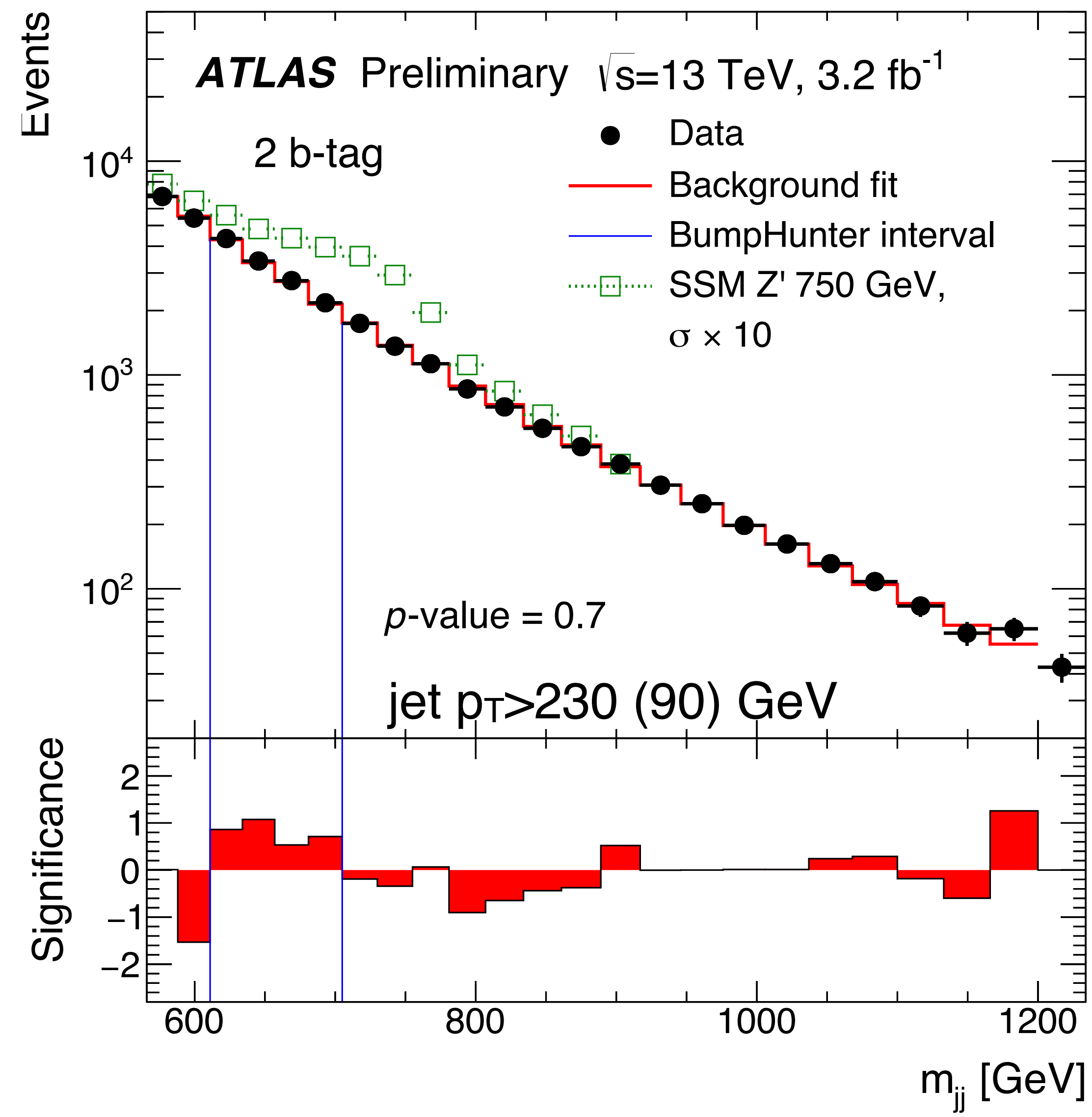


CMS Preliminary
2.7 fb-1 (13 TeV)
Z(qq̄)γ Z(e+e-,μ+μ-)γ: Γ/m=0.014%
95% CL limit
Median expected
68% expected
95% expected
σ(pp→A+X→Zγ+X) [fb]
Resonance mass [GeV]

No Stone Unturned: low-mass di-jet



ATLAS-CONF-2016-030



- Dedicated triggers and data parking techniques to explore low-mass dijet
  - use trigger-level jet objects
  - dedicated jet calibration and corrections
  - *not suffering from pre-scales due to huge hadronic trigger rates*

SUMMARY OF RESONANCES

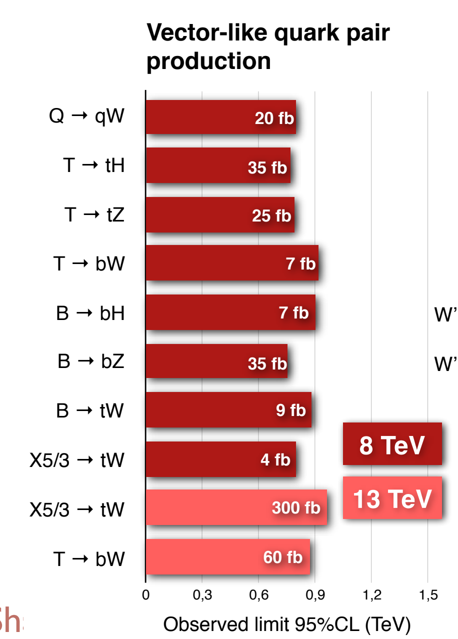
ATLAS Exotics Searches* - 95% CL Exclusion

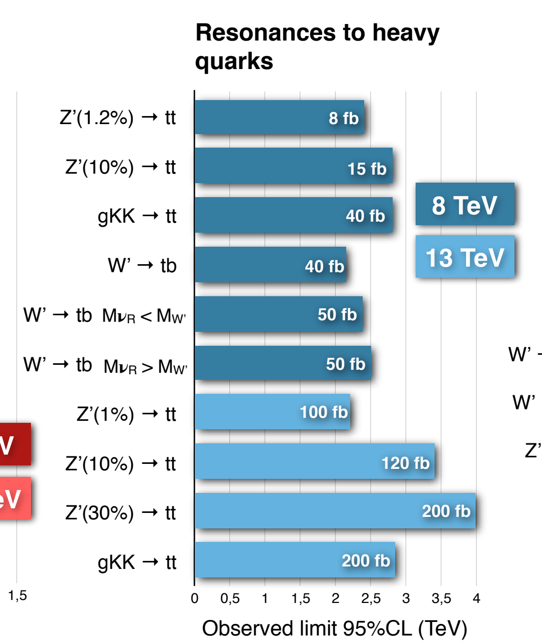
ATLAS Preliminary

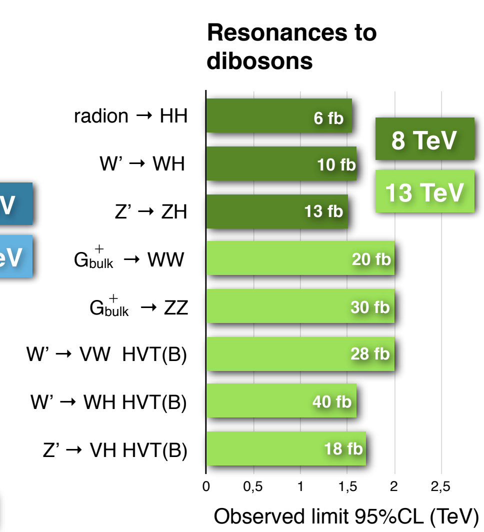
Status: March 2016

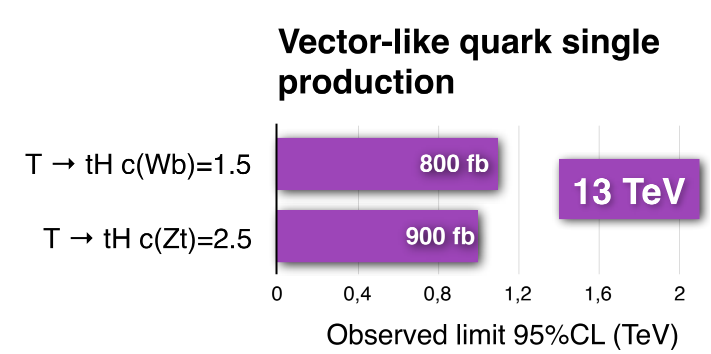
$\int \mathcal{L}\, dt = (3.2 - 20.3)\ \text{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt[\text{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	≥ 1 j	Yes	3.2	M_D 6.58 TeV	$n = 2$	1604.07773
	ADD non-resonant $\ell\ell$	2 e, μ	–	–	20.3	M_S 4.7 TeV	$n = 3$ HLZ	1407.2410
	ADD QBH $\rightarrow \ell q$	1 e, μ	1 j	–	20.3	M_{th} 5.2 TeV	$n = 6$	1311.2006
	ADD QBH	–	2 j	–	3.6	M_{th} 8.3 TeV	$n = 6$	1512.01530
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \rightarrow \ell\ell$	2 e, μ	–	–	20.3	G_{KK} mass 2.68 TeV	$k/\overline{M}_{Pl} = 0.1$	1405.4123
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2 γ	–	–	20.3	G_{KK} mass 2.66 TeV	$k/\overline{M}_{Pl} = 0.1$	1504.05511
	Bulk RS $G_{KK} \rightarrow WW \rightarrow qq\ell\nu$	1 e, μ	1 J	Yes	3.2	G_{KK} mass 1.06 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2015-075
	Bulk RS $G_{KK} \rightarrow HH \rightarrow bbbb$	–	4 b	–	3.2	G_{KK} mass 480-770 GeV	$k/\overline{M}_{Pl} = 1.0$	1606.04782
	Bulk RS $g_{KK} \rightarrow tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	20.3	g_{KK} mass 2.2 TeV	BR = 0.925	1505.07018
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 4 j	Yes	3.2	KK mass 1.46 TeV	Tier (1,1), BR($A^{(1,1)} \rightarrow tt$) = 1	ATLAS-CONF-2016-013
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	2 e, μ	–	–	3.2	Z' mass 3.4 TeV		ATLAS-CONF-2015-070
	SSM $Z' \rightarrow \tau\tau$	2 τ	–	–	19.5	Z' mass 2.02 TeV		1502.07177
	Leptophobic $Z' \rightarrow bb$	–	2 b	–	3.2	Z' mass 1.5 TeV		1603.08791
	SSM $W' \rightarrow \ell\nu$	1 e, μ	–	Yes	3.2	W' mass 4.07 TeV		1606.03977
	HVT $W' \rightarrow WZ \rightarrow qq\nu\nu$ model A	0 e, μ	1 J	Yes	3.2	W' mass 1.6 TeV	$g_V = 1$	ATLAS-CONF-2015-068
	HVT $W' \rightarrow WZ \rightarrow qqqq$ model A	–	2 J	–	3.2	W' mass 1.38-1.6 TeV	$g_V = 1$	ATLAS-CONF-2015-073
	HVT $W' \rightarrow WH \rightarrow \ell\nu bb$ model B	1 e, μ	1-2 b, 1-0 j	Yes	3.2	W' mass 1.62 TeV	$g_V = 3$	ATLAS-CONF-2015-074
	HVT $Z' \rightarrow ZH \rightarrow \nu\nu bb$ model B	0 e, μ	1-2 b, 1-0 j	Yes	3.2	Z' mass 1.76 TeV	$g_V = 3$	ATLAS-CONF-2015-074
	LRSM $W'_R \rightarrow tb$	1 e, μ	2 b, 0-1 j	Yes	20.3	W' mass 1.92 TeV		1410.4103
	LRSM $W'_R \rightarrow tb$	0 e, μ	≥ 1 b, 1 J	–	20.3	W' mass 1.76 TeV		1408.0886
Heavy quarks	VLQ $TT \rightarrow Ht + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	T mass 855 GeV	T in (T,B) doublet	1505.04306
	VLQ $YY \rightarrow Wb + X$	1 e, μ	≥ 1 b, ≥ 3 j	Yes	20.3	Y mass 770 GeV	Y in (B,Y) doublet	1505.04306
	VLQ $BB \rightarrow Hb + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	B mass 735 GeV	isospin singlet	1505.04306
	VLQ $BB \rightarrow Zb + X$	2/$\geq$3 e, μ	$\geq$2/$\geq$1 b	–	20.3	B mass 755 GeV	B in (B,Y) doublet	1409.5500
	VLQ $QQ \rightarrow WqWq$	1 e, μ	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
	$T_{5/3} \rightarrow Wt$	1 e, μ	≥ 1 b, ≥ 5 j	Yes	20.3	$T_{5/3}$ mass 840 GeV		1503.05425

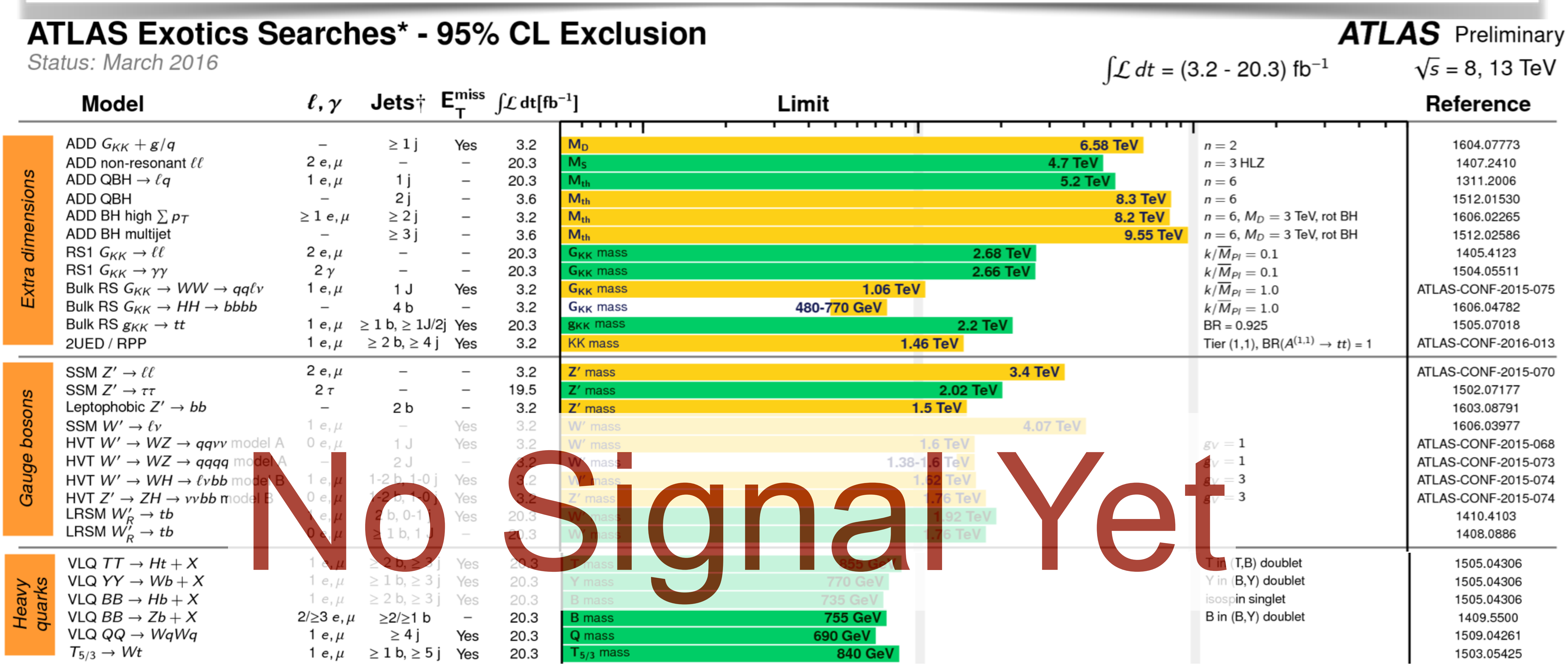


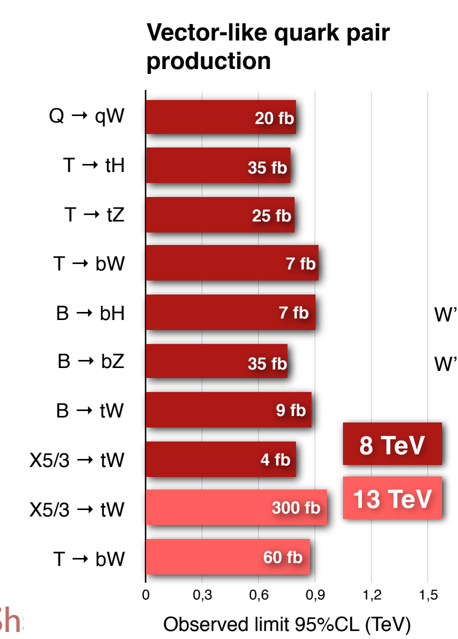


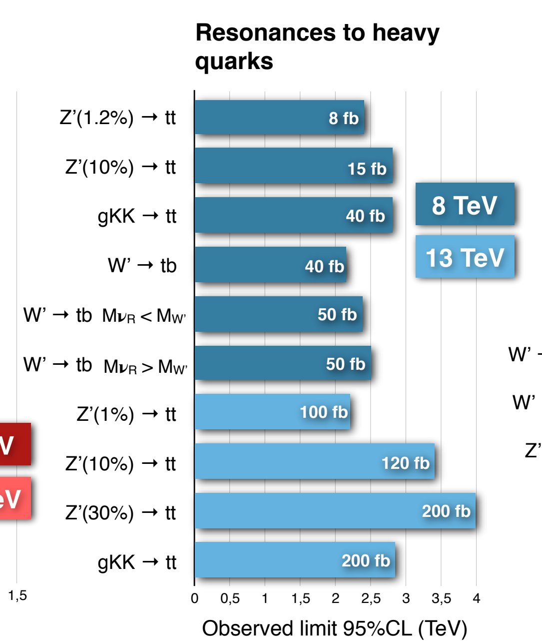


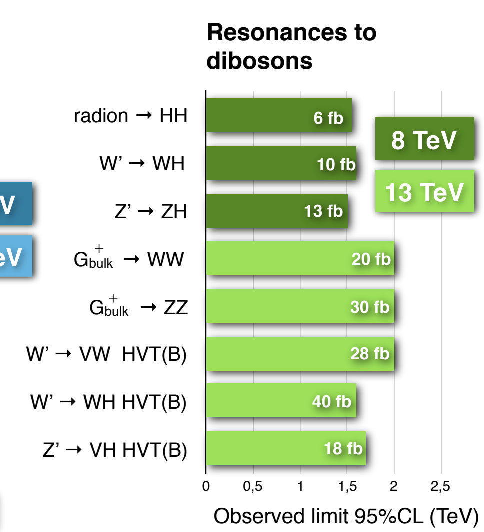


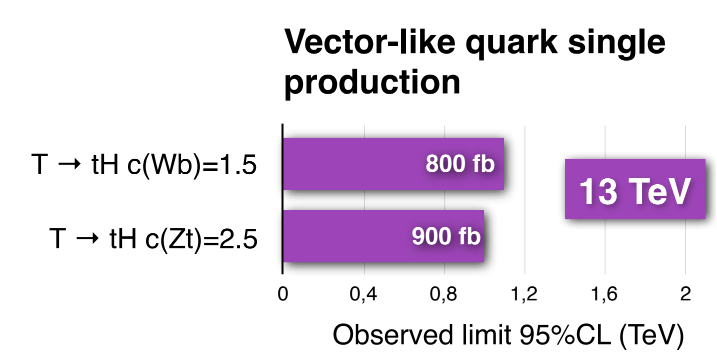
SUMMARY OF RESONANCES







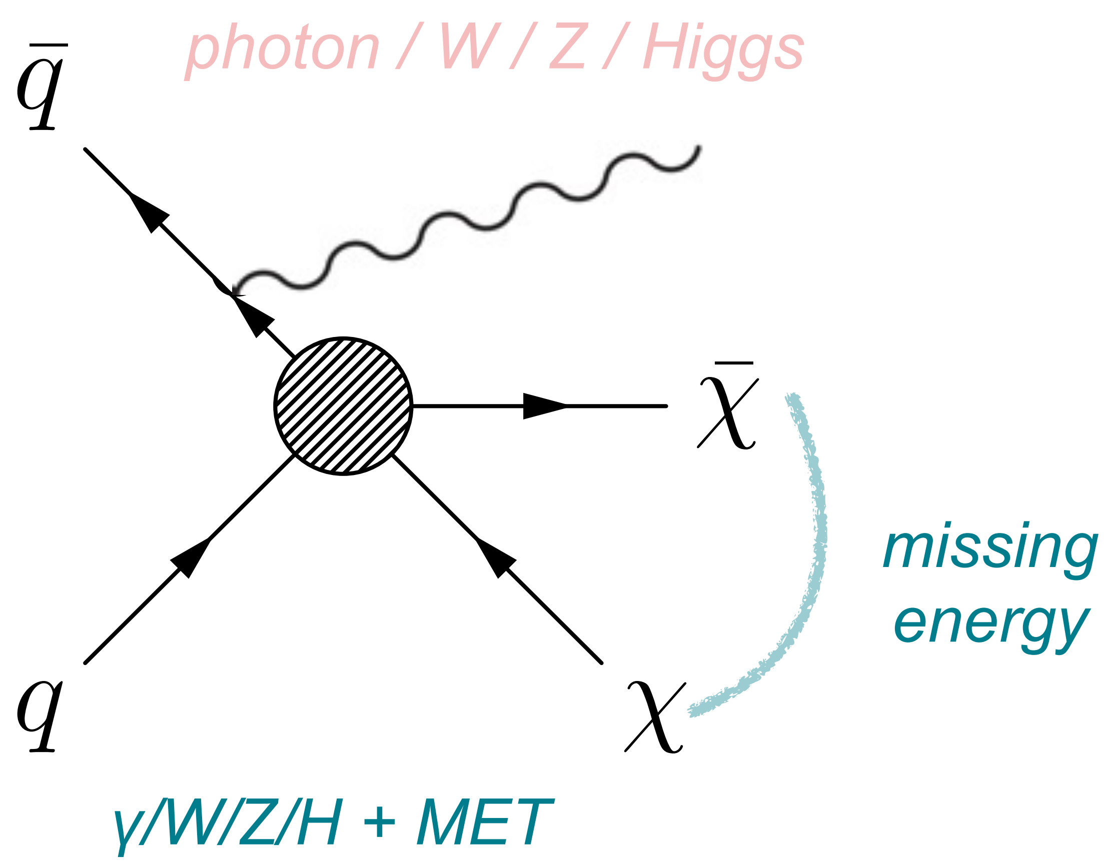


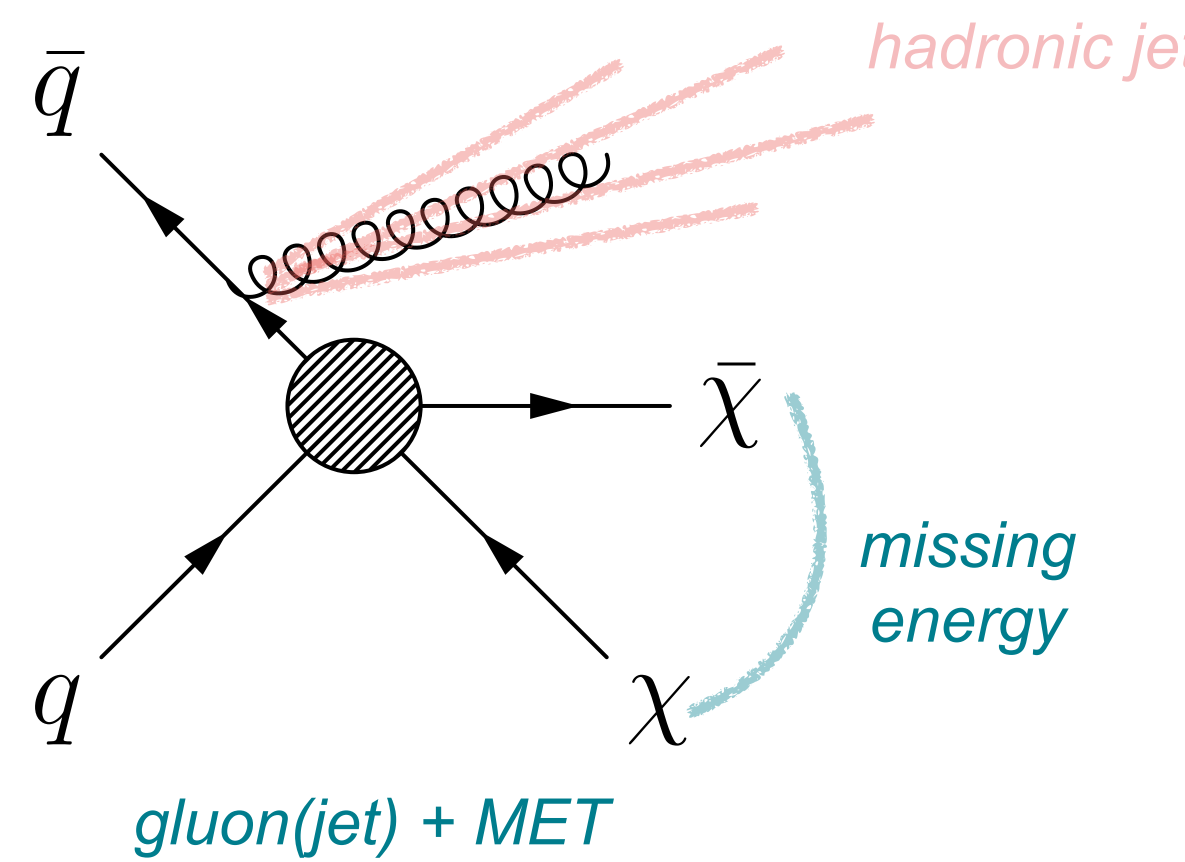


Sh

X + MET

X + MET

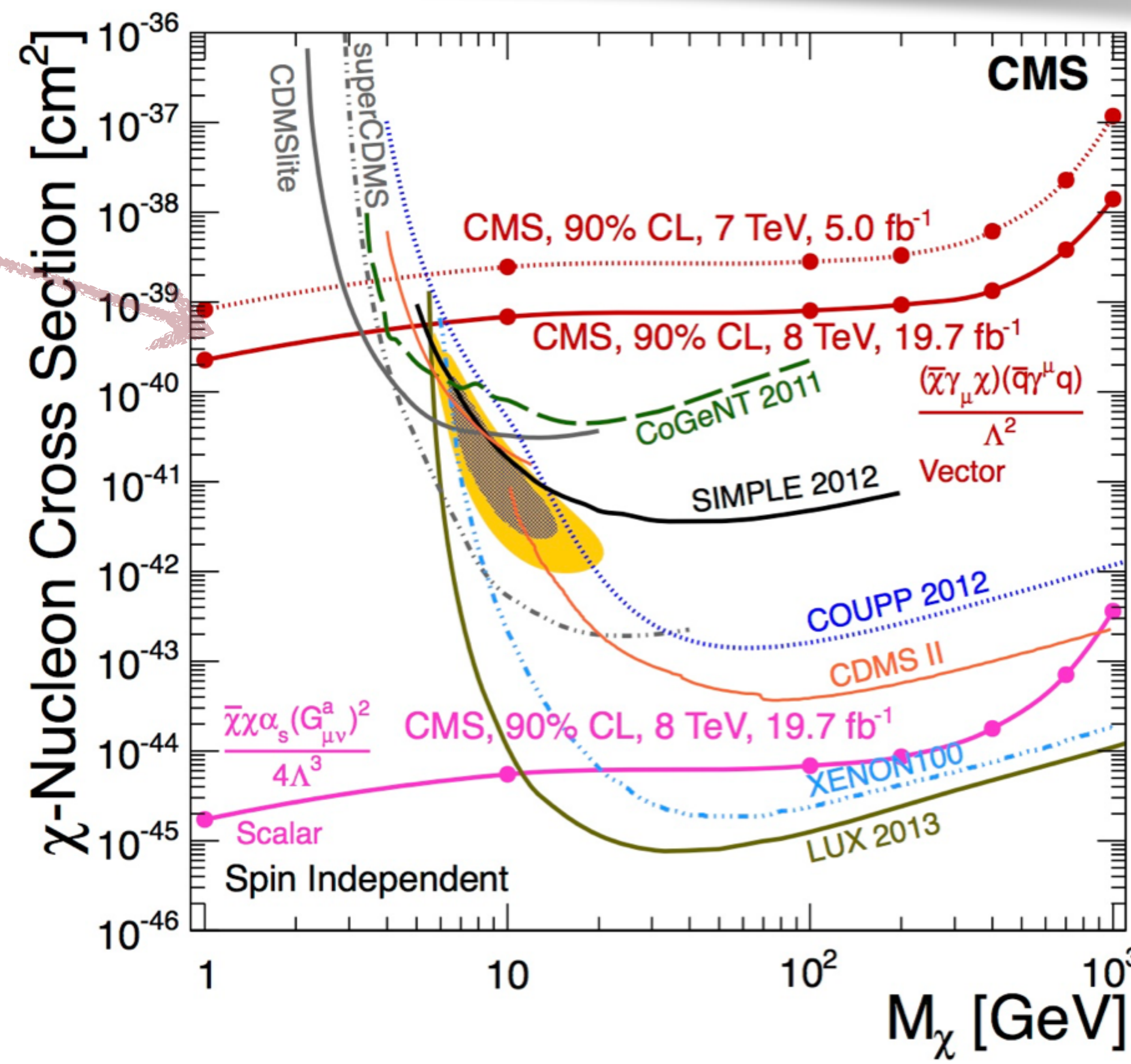


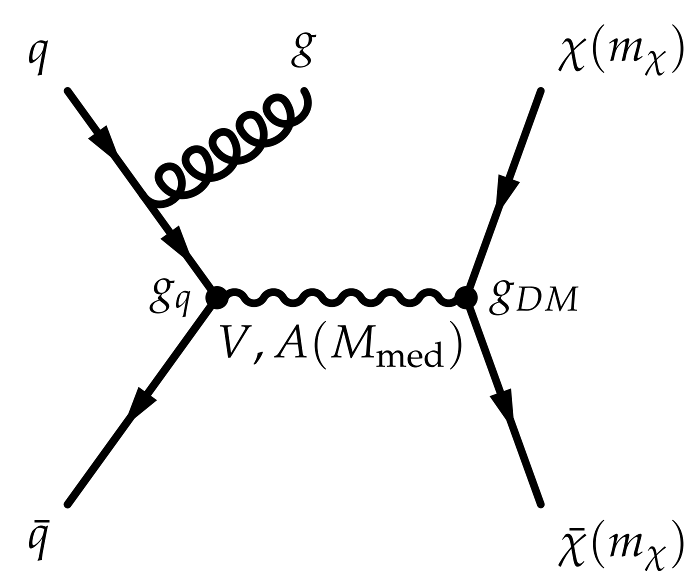


- Radiated by initial partons necessary to trigger the event
- Presence of high energy photon/W/Z/Higgs or jet(s) *in addition* to large missing transverse energy
- Results interpreted in terms of cross section on nucleons

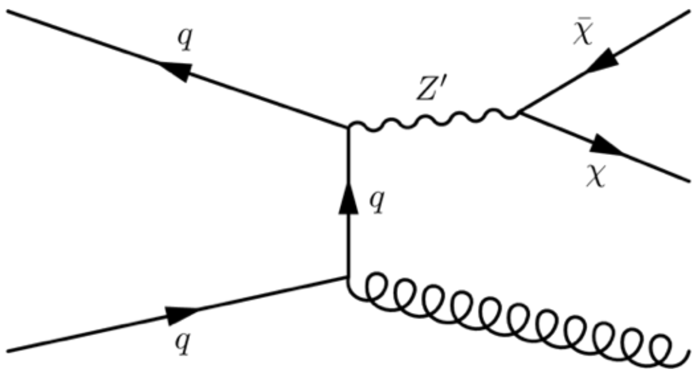
X + MET INTERPRETATION

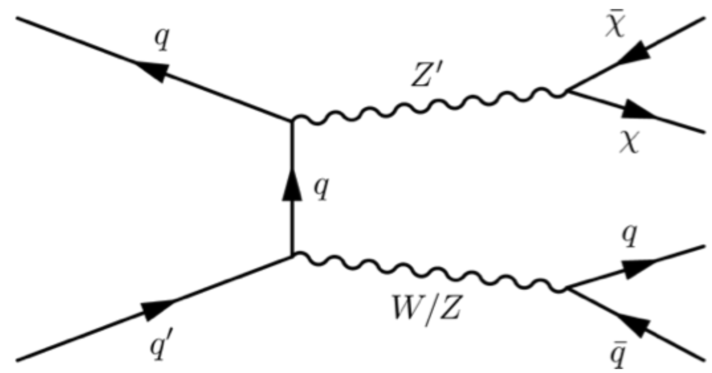
- Original intent
  - *complementary approach to direct searches at low mass*
- Criticism to use of effective theories
  - *mediator mass assumed to be negligible at LHC*
- Suggestions to use SUSY approach
  - *simplified models for final state*
  - *provide 2D constraints in (m_χ, $m_{mediator}$) plane*

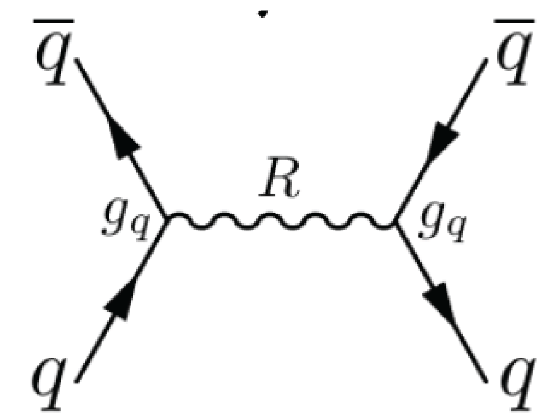


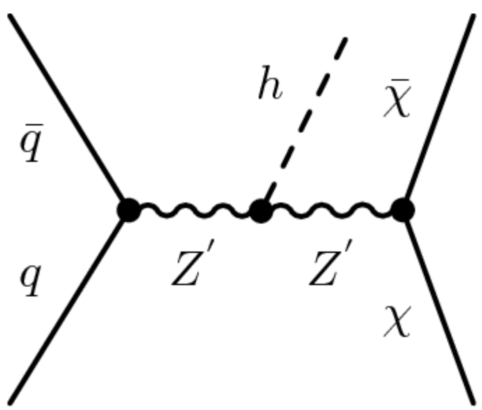


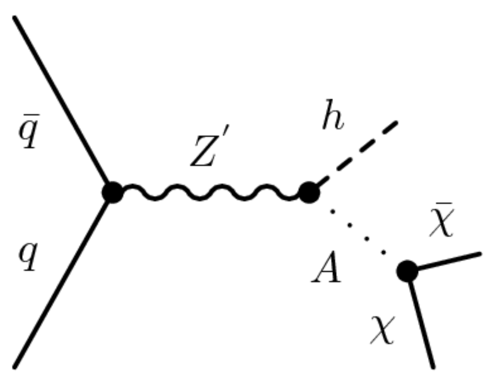
X + MET Signatures after Run1

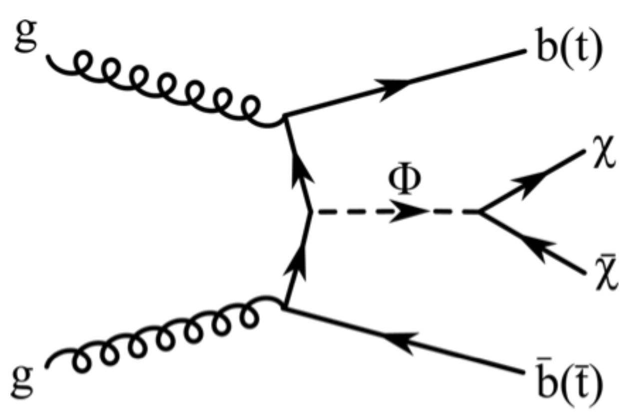


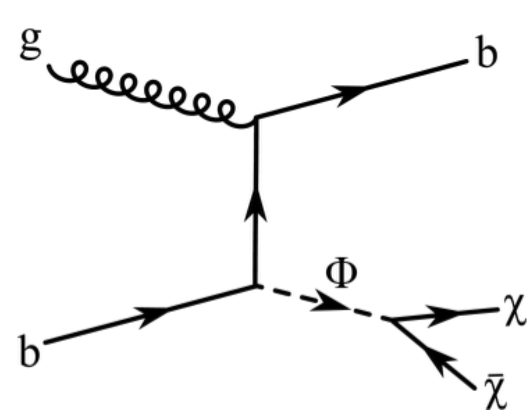




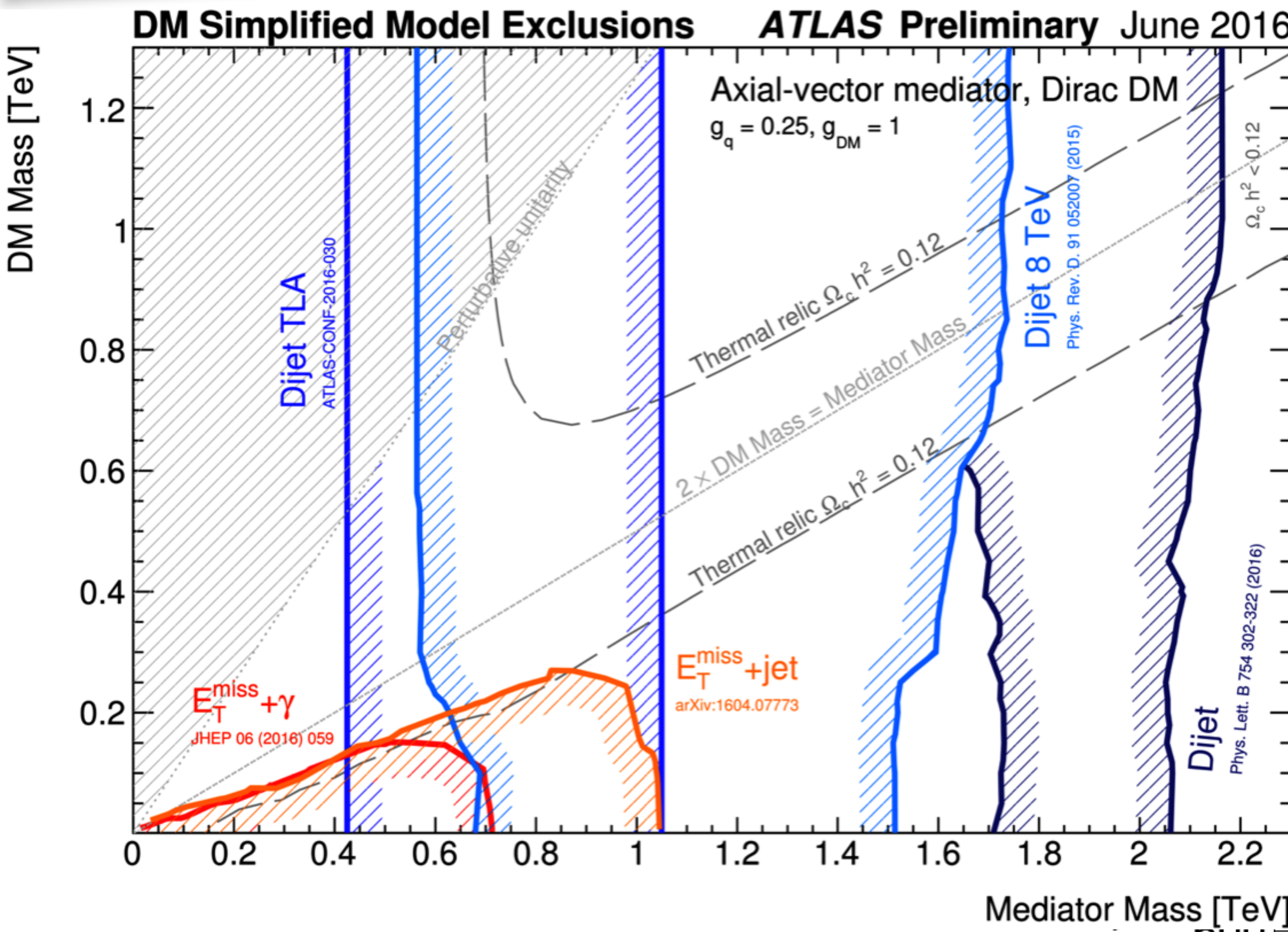




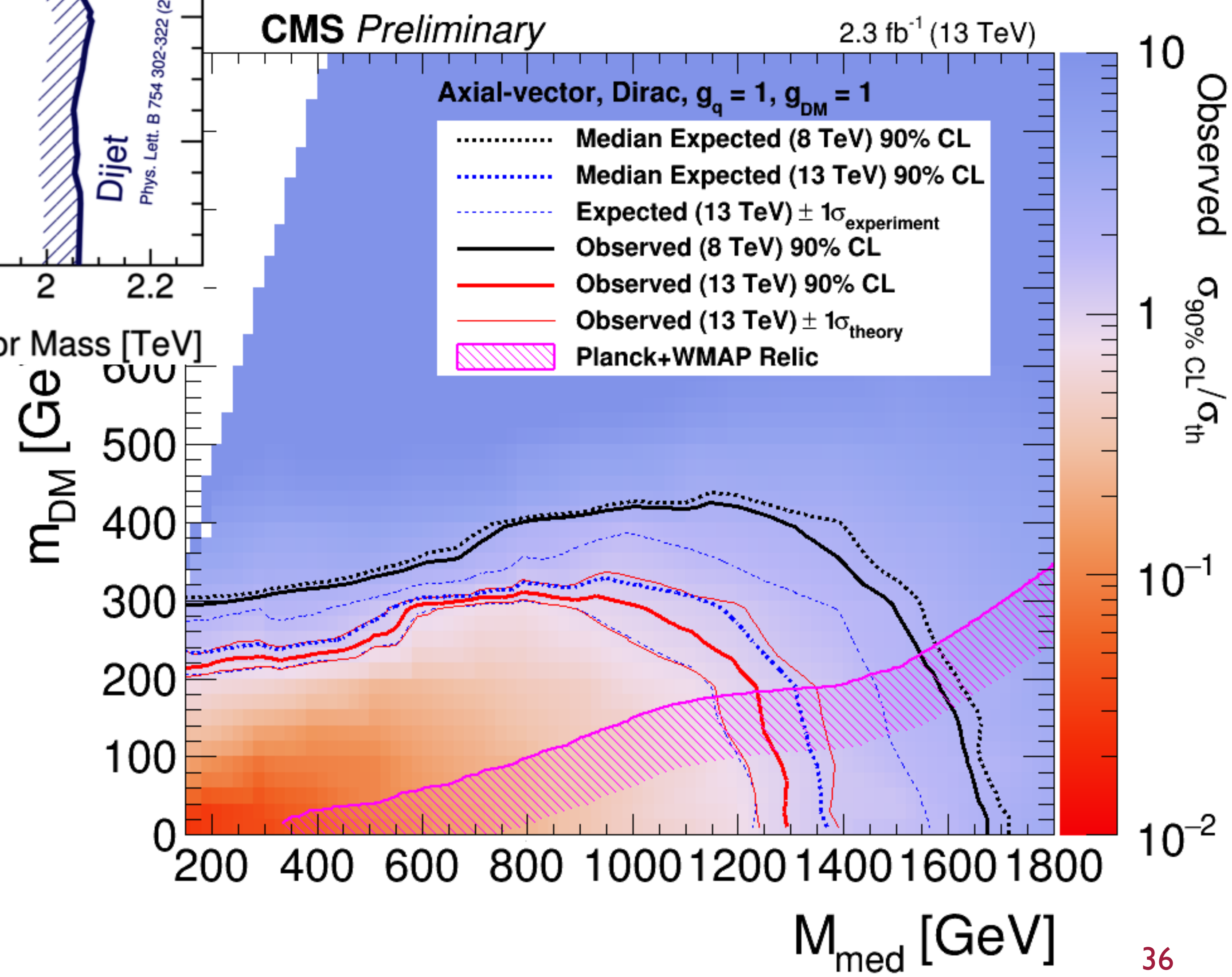




X + MET Interpretation



mono-V



Long-Lived Objects

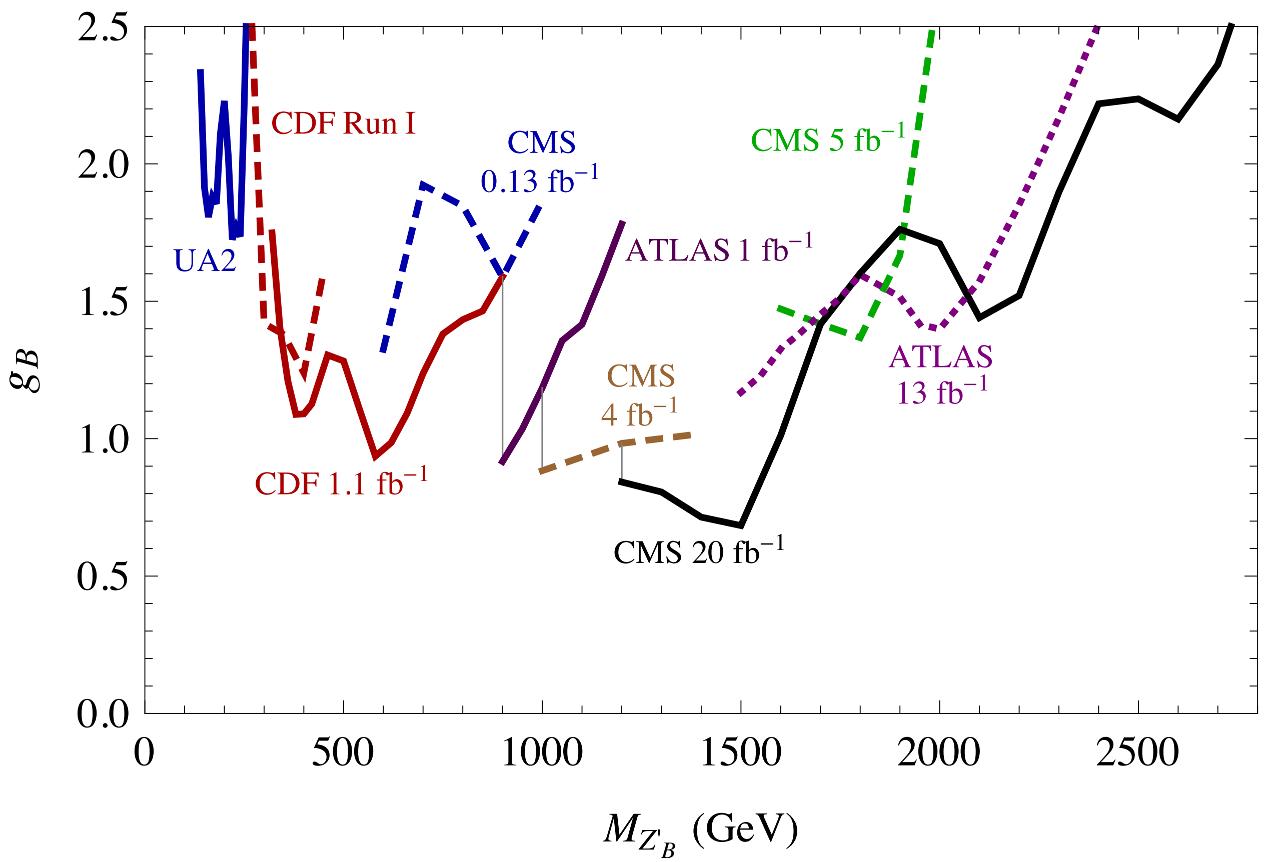
- Most exotic part of exotic program
- Search for long-lived particles relies on detector features more than other exotic searches
  - dedicated trigger
    - stopped particles
  - dedicated reconstruction algorithms
    - muon reconstruction: heavy stable charged particles
    - tracking: disappearing tracks
  - dedicated detector calibration
    - calorimeter time calibration
- Many searches in Run1 but no discrepancy or excess
- *So far only the classic heavy stable charged particle search at 13 TeV*

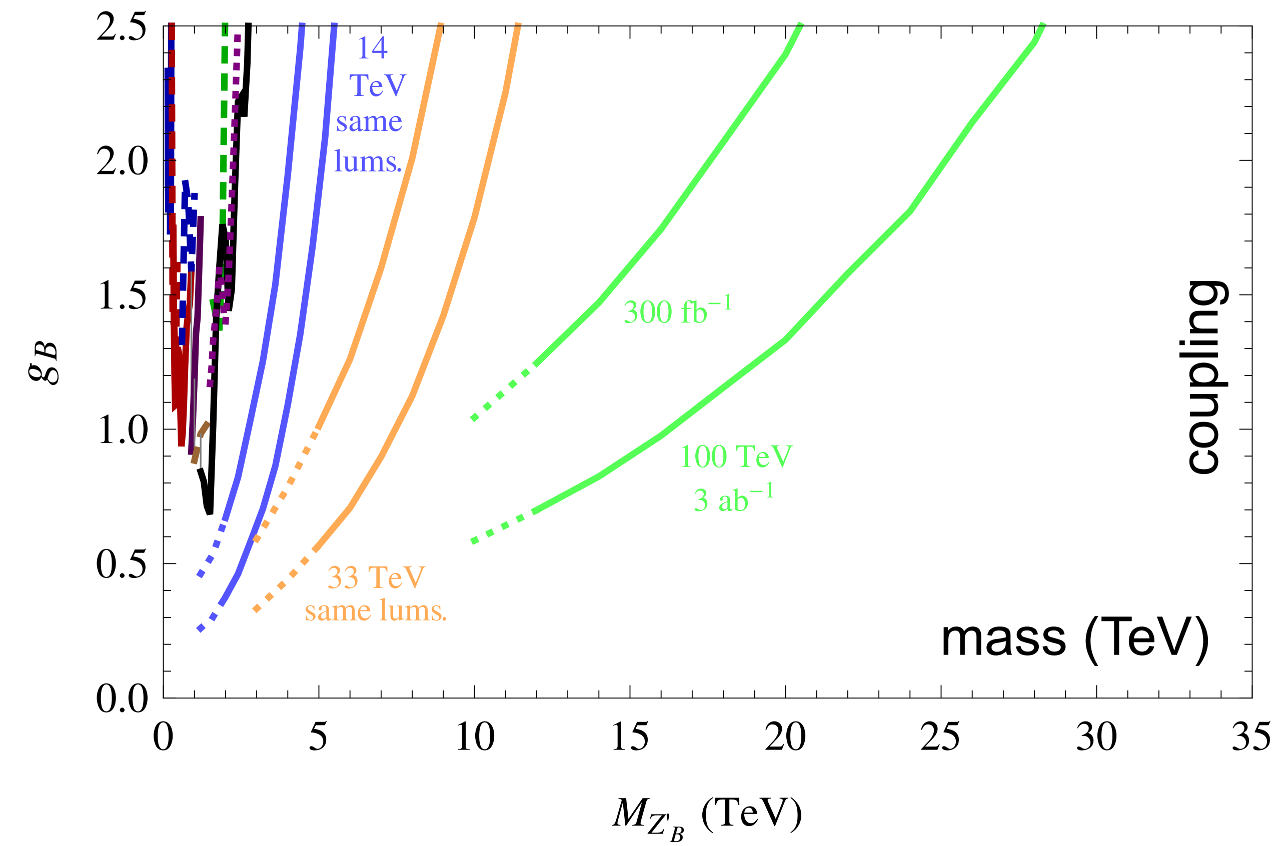
OUTLOOK

- Extensive direct search program now starting to probe new territories beyond Standard Model
  - Only most basic and simplistic theories probed at this point
  - many assume strong coupling
- Some old bumps from Run 1 are gone
- At least one interesting one has appeared
- Impressive LHC performance in 2016
  - data should address $\gamma\gamma$ bump by end of year

Prospects

- These next two years critical for future of searches
  - Happy Ending: New particles discovered
    - if mass not too large, accumulate data with high-luminosity LHC to study properties and define next step
    - if heavy, aim at upgrade of energy
  - No particles found
    - Indirect search through Higgs couplings becomes critical
    - Maybe new particles weakly coupled to known particles
    - Use high-luminosity LHC to probe weakly coupled scenario





Extra