Searches for NP

FERMILAB-CERN
HADRON COLLIDER PHYSICS
Summer School

Local Organizing Committee
Estia Eichten, co-chair (Fermilab)
Jim Hirschauer, co-chair (Fermilab)
David Miller (U. of Chicago)
Corrinne Mills (U. of Illinois, Chicago/Fermilab)
Stefan Prestel (Fermilab)
Jimmy Proudfoot (Argonne)
Mayda Velasco (Northwestern U.)

Claudio Campagnari
University of California
Santa Barbara

Disclaimer

- Not a comprehensive review of results.
- Selected results (mostly) shown to make some (pedagogical? interesting?) point
- Only CMS and Atlas
- Skewed towards CMS
- Not representing CMS (or Atlas)

New Physics?


OAK STREET BEACH

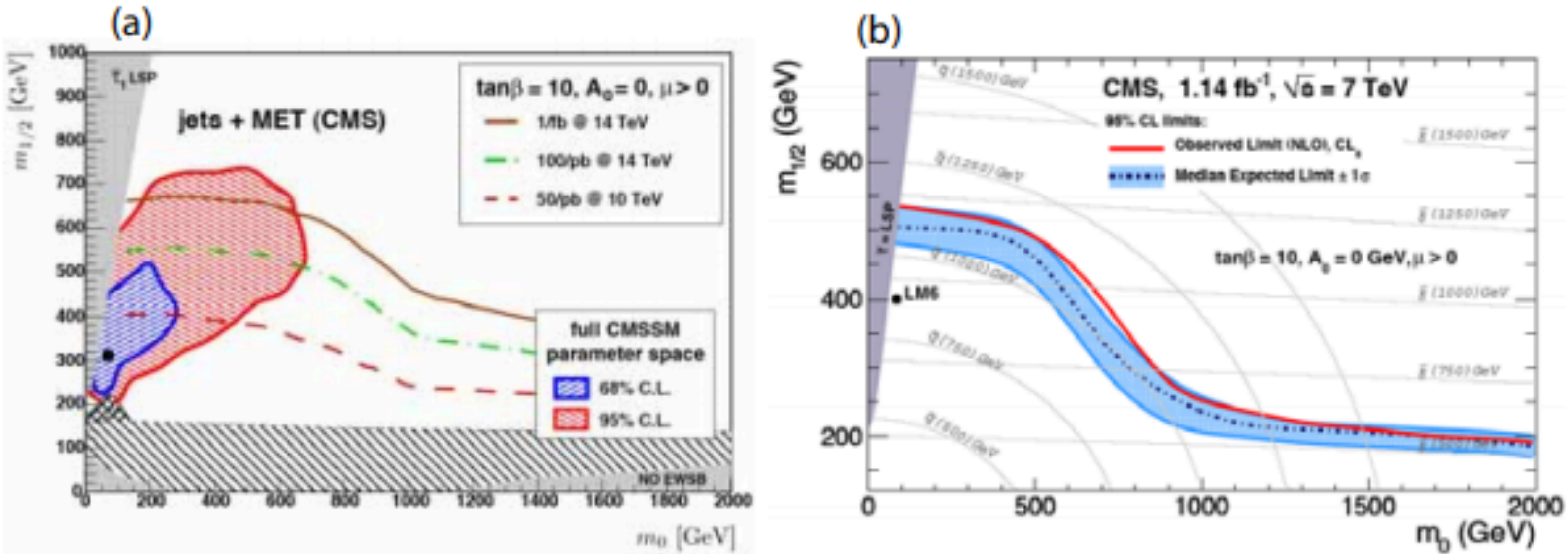

OAK STREET BEACH

2018 LHC extreme views

1. There is no new physics, we are doomed.

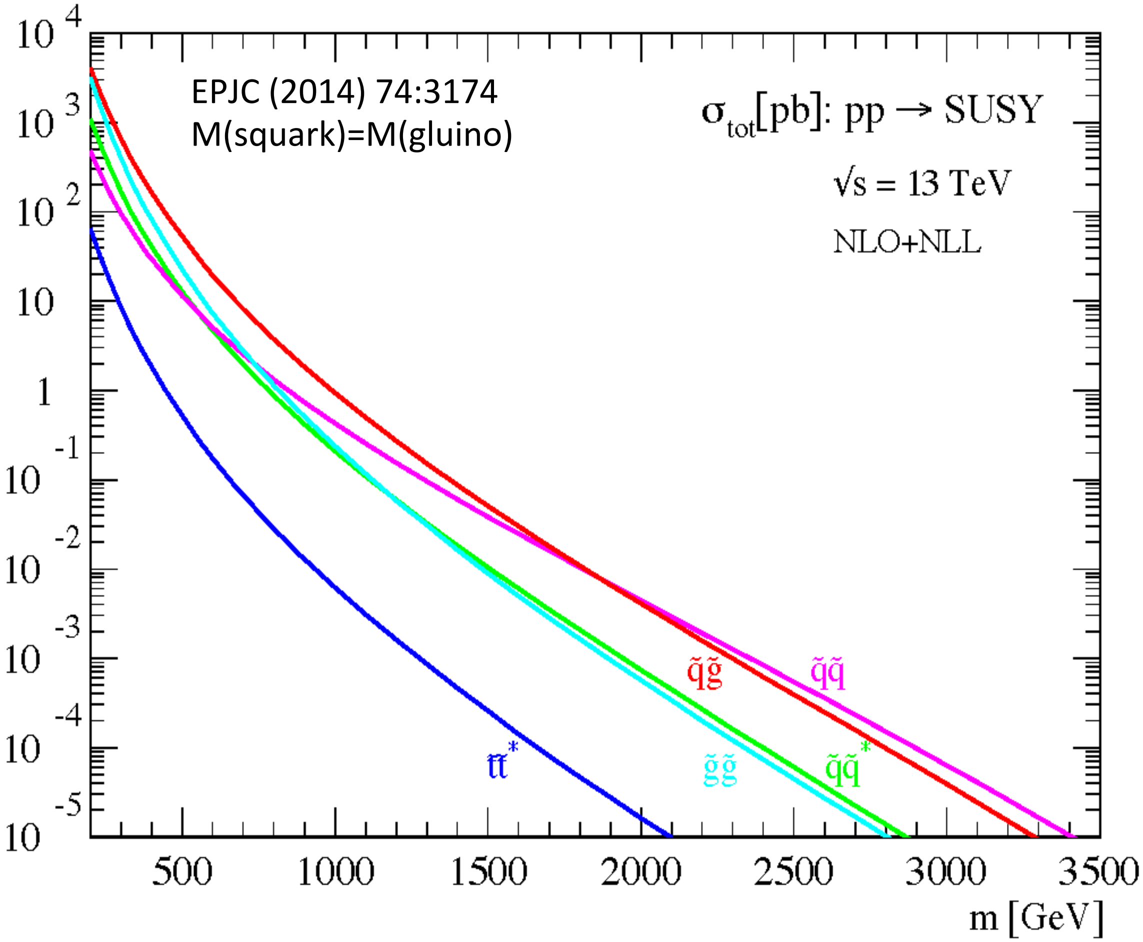
2. LHC has only taken a few % of full dataset, we have only scratched the surface! Exciting!!!

Pre-LHC NP expectations quickly met reality



arXiv:1110.3805

Figure 33: (a) Prediction of [126] at 68% and 95% confidence of the unified supersymmetry-breaking parameters $(m_0, m_{1/2})$ of the constrained Minimal Supersymmetric Standard Model. (b) 95% confidence exclusion region in the parameters $(m_0, m_{1/2})$ in the α_T search for supersymmetry presented by CMS at LP11 [127].



The steep fall of the production cross-sections of new particles with mass drives the pessimism
Hard to make progress with luminosity alone.
Worth reviewing for a few minutes why that is and some consequences

- Parton-parton x-section, i+j → X:

$$\widehat{\sigma}_{ij}(\widehat{s}) \text{ at } E_{CM} = \sqrt{\widehat{s}}$$

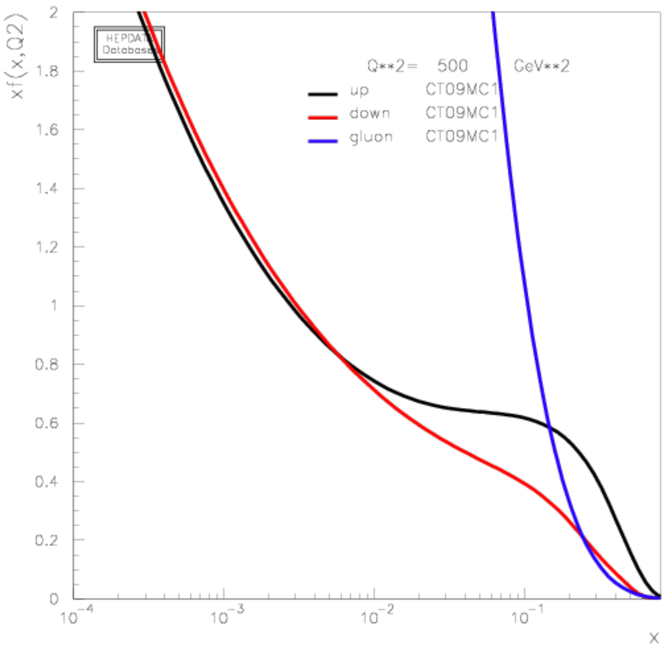
- σ for pp→X:

$$\sigma = \sum \int dx_i dx_j f_i(x_i) f_j(x_j) \widehat{\sigma}_{ij}$$

$$\hat{s} = x_i x_j s \quad \text{and} \quad \tau \equiv \frac{\hat{s}}{s}$$

- Rewrite it as:

$$\sigma(s) = \sum \int_{\tau_0}^{1} \frac{d\tau}{\tau} \cdot \frac{\tau}{\hat{s}} \frac{dL_{ij}}{d\tau} \cdot [\hat{s}\hat{\sigma}_{ij}(\hat{s})]$$

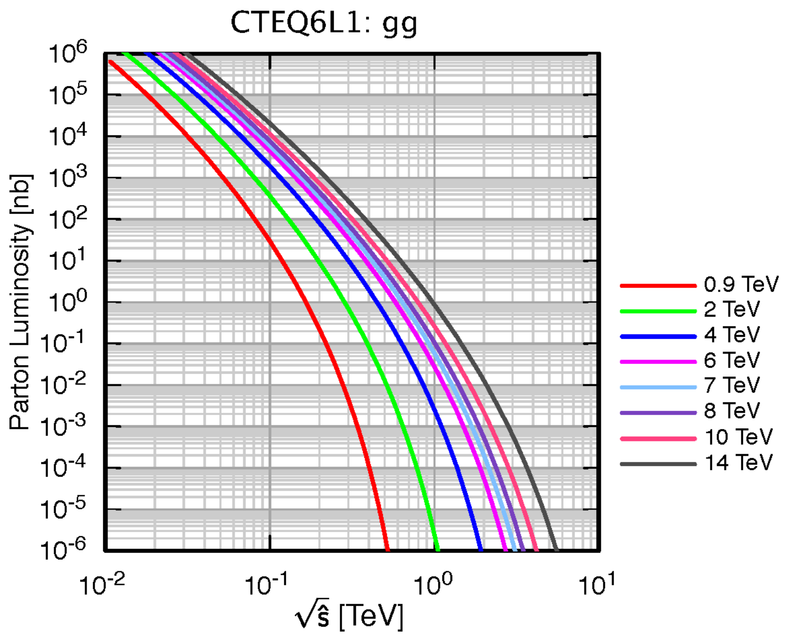


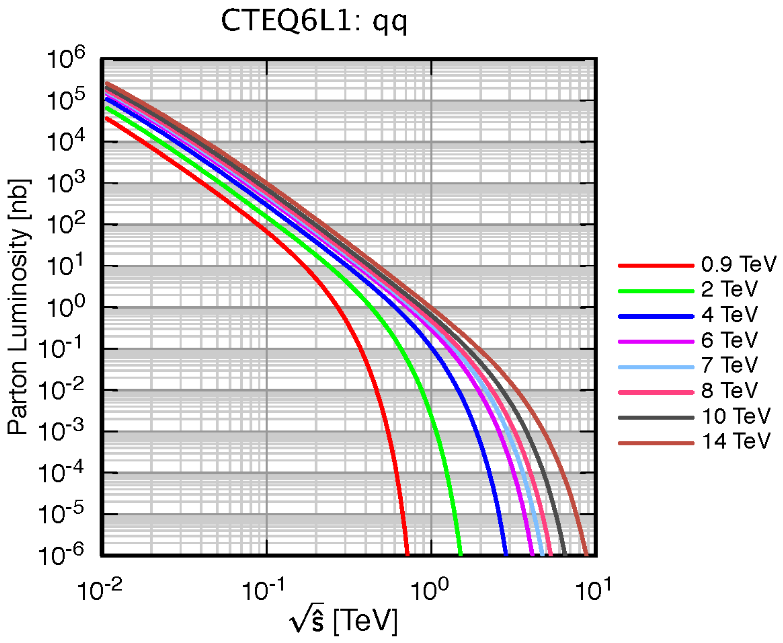
$$\frac{dL_{ij}}{d\tau} \equiv \frac{1}{1+\delta_{ij}} \int_{\tau}^{1} \frac{dx}{x} [f_i(x) f_j(\frac{\tau}{x}) + f_j(x) f_i(\frac{\tau}{x})]$$

Luminosity for parton-parton collisions.
Dimensionless, function of parton-parton shat
Multiply by (tau/shat)=(1/s) to get in units of 1/E^2, ie area, ie, nb, pb, fb…

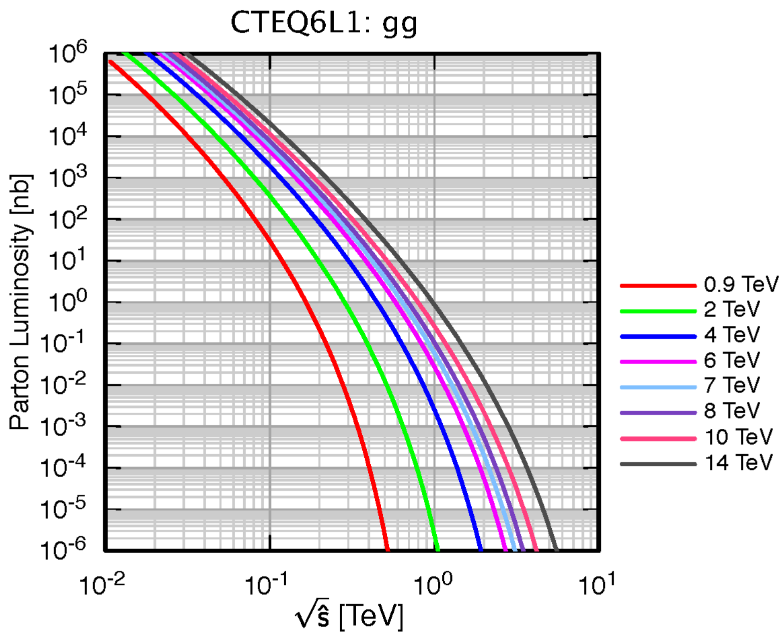
EHLQ
RMP 56 579 (1984)

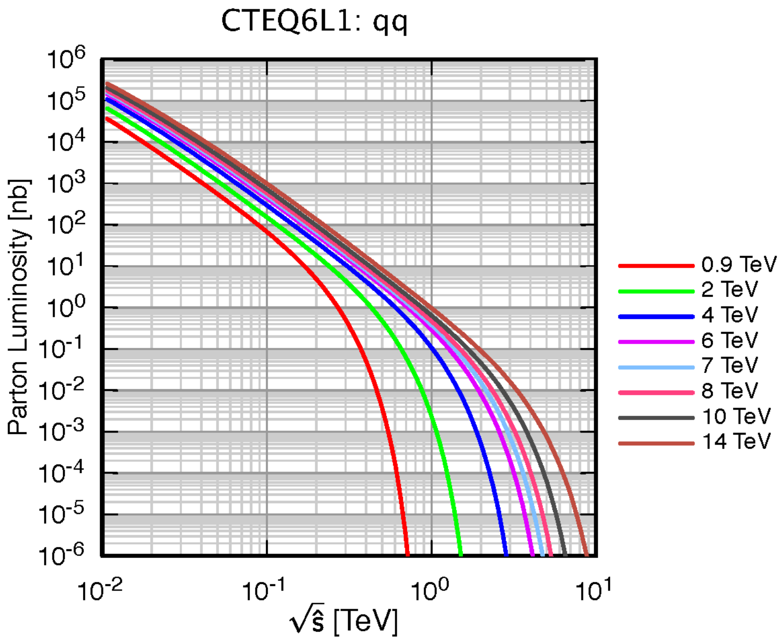
arXiv:1101.3201


CTEQ6L1: gg

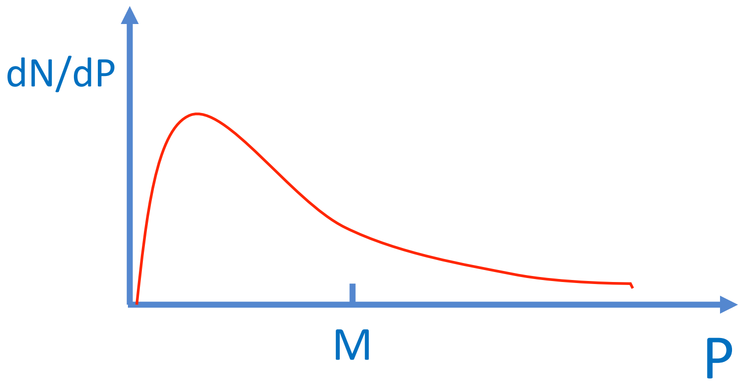

CTEQ6L1: qq

arXiv:1101.3201





As a consequence, most of the production is near threshold. Keep it in mind when you think about your own search!



New Physics Searches

3 + 1 ingredients

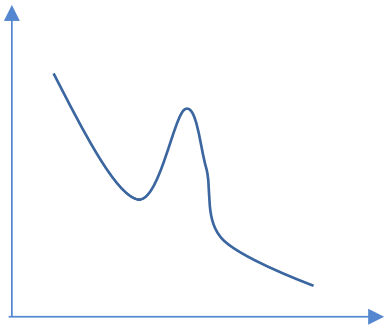
0. **Detector and machine**
1. **Trigger:** *If you didn't trigger on it, it never happened*
   - Will mostly not talk about it
2. **Backgrounds:** *It's the background, stupid*
   - Need to understand SM and instrumental backgrounds
3. **Ideas (or luck):** *If you look for something, you may not find it. But if you don't look, you will never find it*
   - Model independent vs model dependent searches

Roadmap for a search

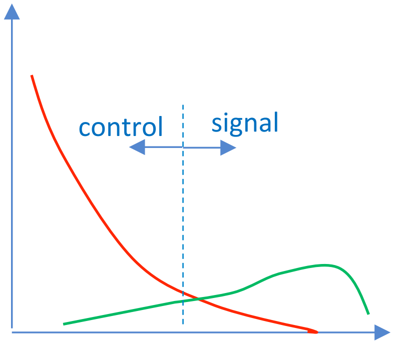
- A search is most often an analysis of BG
- Decide what to look for (!)
  - Pay attention to theory guidance, but don't go overboard
- Define trigger/event selection
  - Most often with MC of signal and BG
  - May need to develop new tools (fun)
- Do not overtune on particular signal model
  - Unless you are looking for very specific signal
- Keep it simple
  - Esp. if the 1st time and/or "next year" you get more data
- Think carefully about BG estimate at every step
  - Avoid blind use of MC.

Roadmap for a search (cont.)

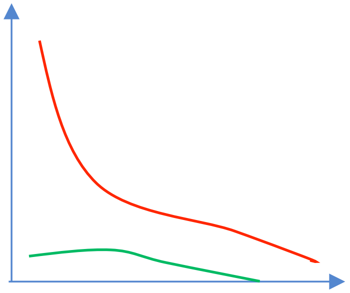
- Don’t forget very rare (maybe never seen?) SM processes. They can add up.
  - UA1 “found” SUSY in 1984 because of this (!)
  - Here sometimes all you have is MC



- If it is a mass peak it sounds easy (!)

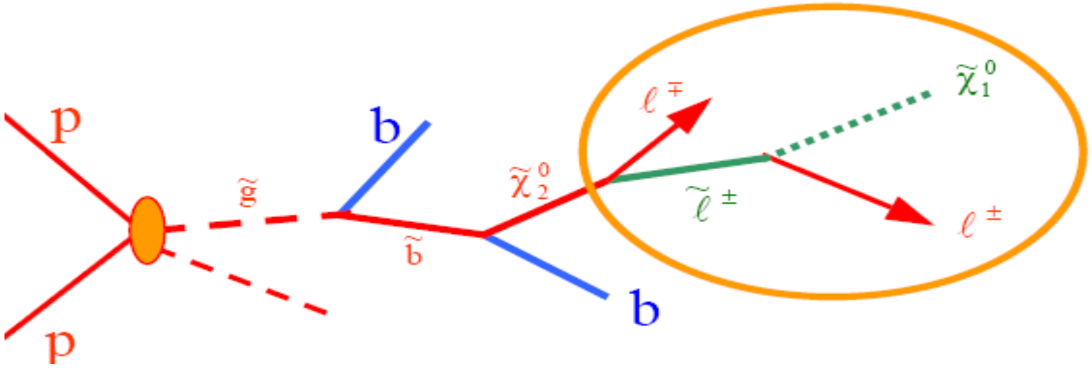


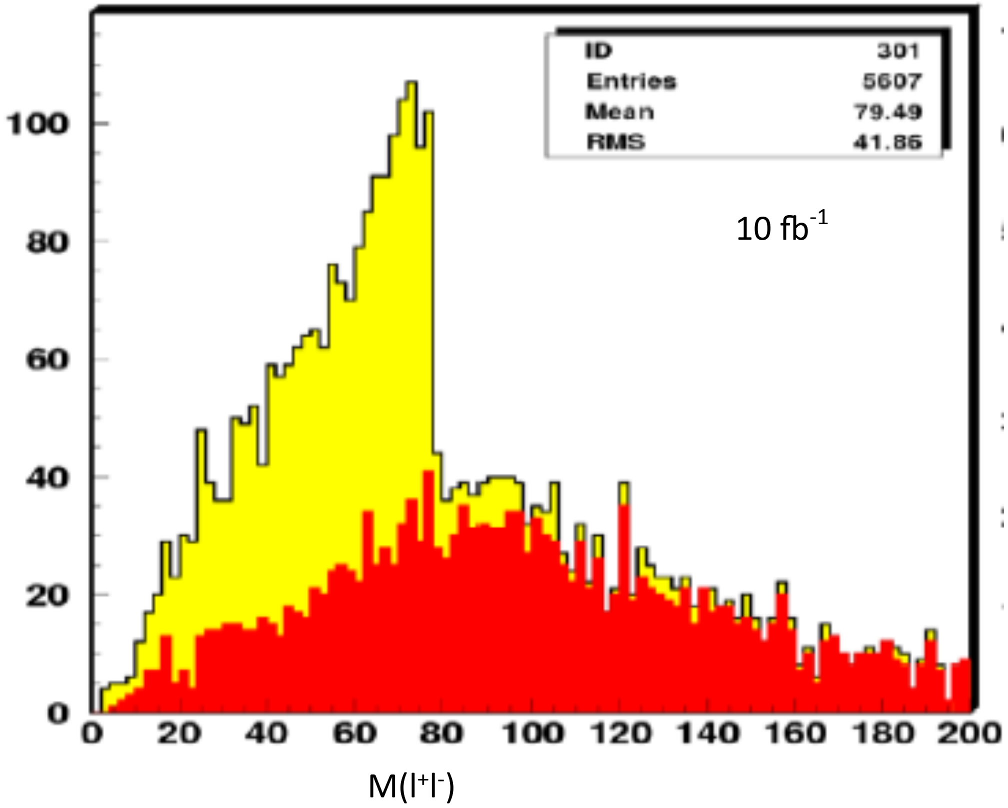
- If you can separate, use control region plus MC or other tricks to extrapolate
  - If counting instead of fitting, careful about sig. contamination
- If on top of each other, difficult
  - Need good control of shape and/or normalization of SM



- Blind analysis

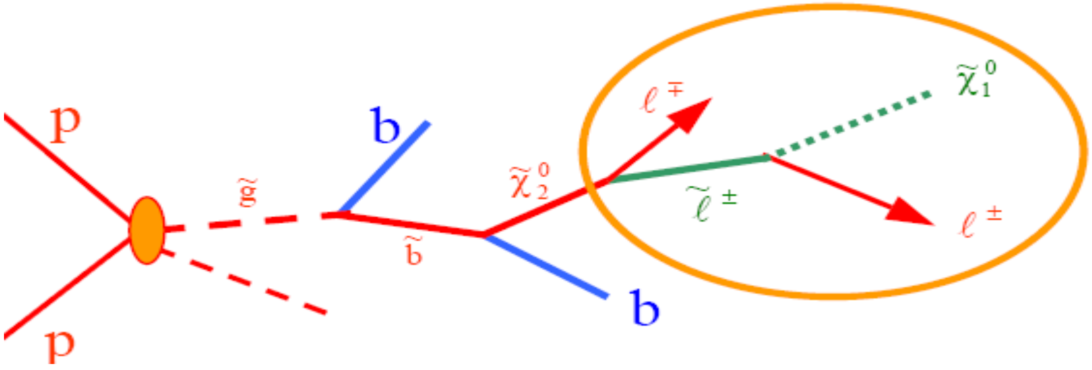
Some of these looked really easy

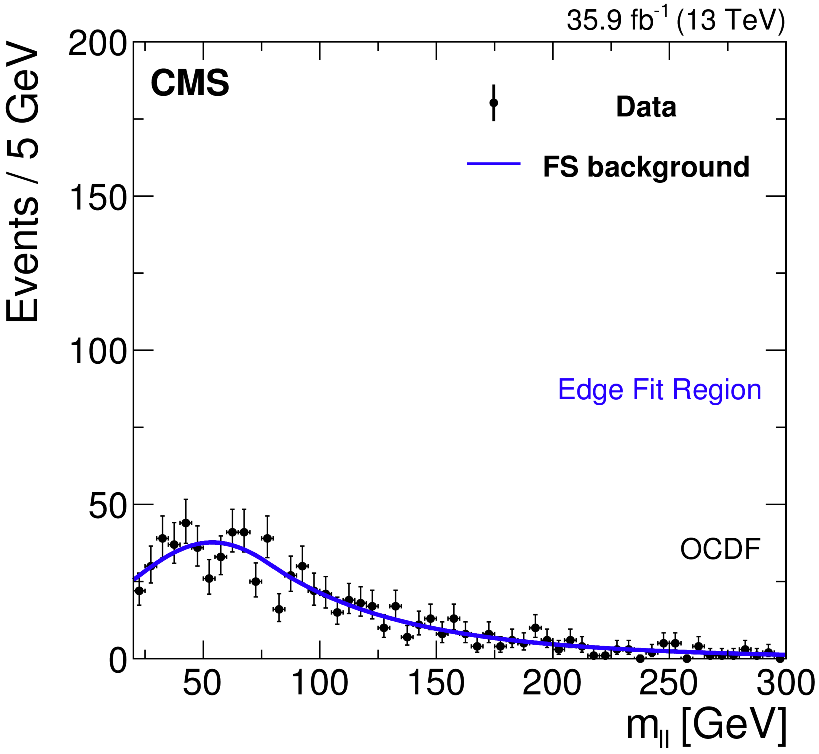




From some pre-LHC MC studies

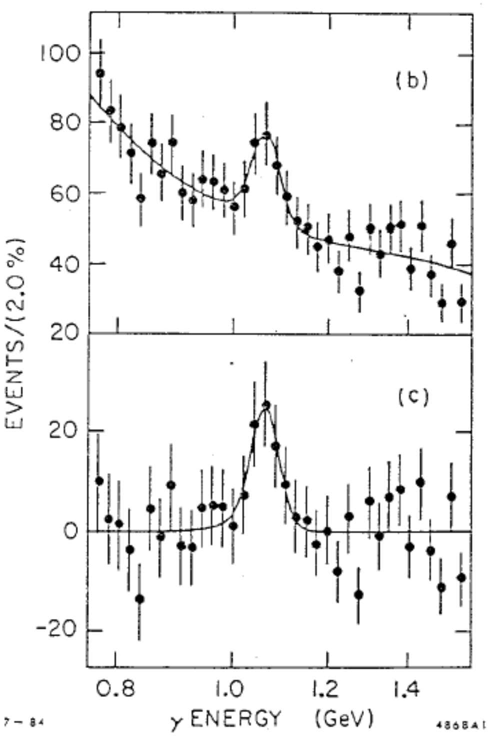
Did not quite work out that way



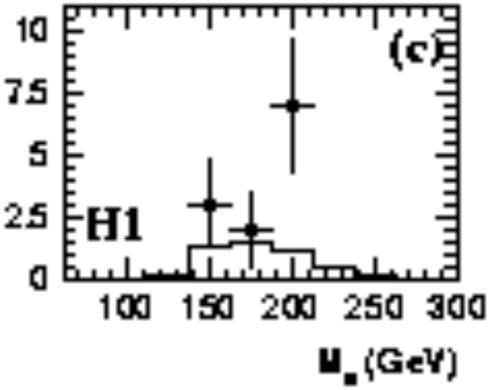


JHEP 03 (2018) 076

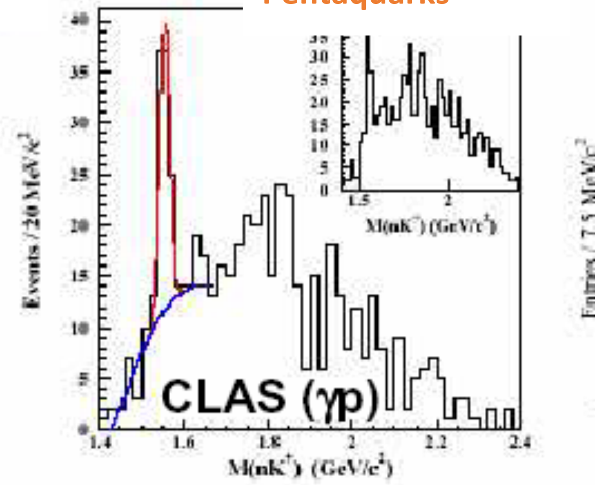
Not all that glitters is gold



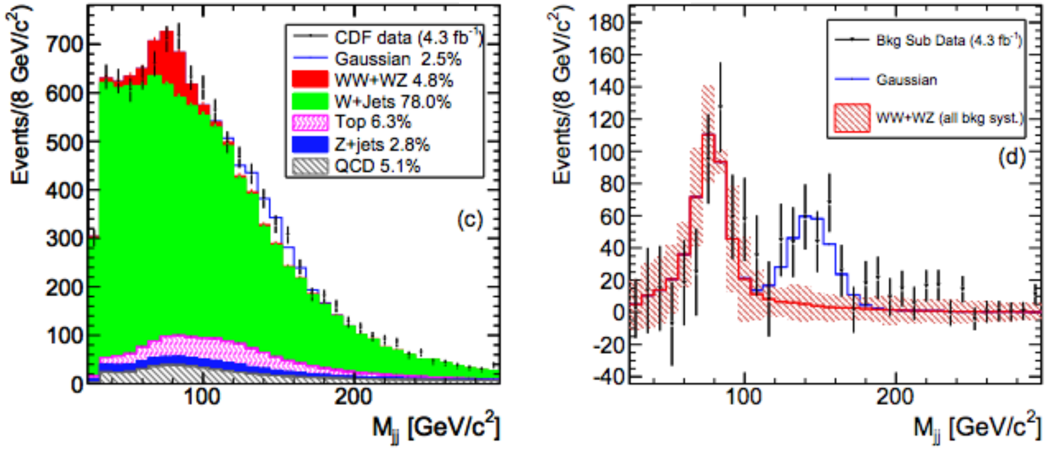
Leptoquarks



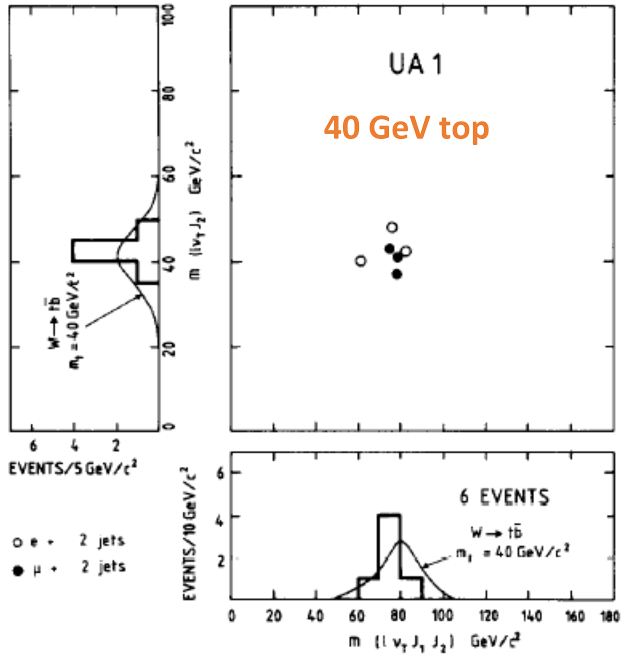
Pentaquarks



W+X, X→jj

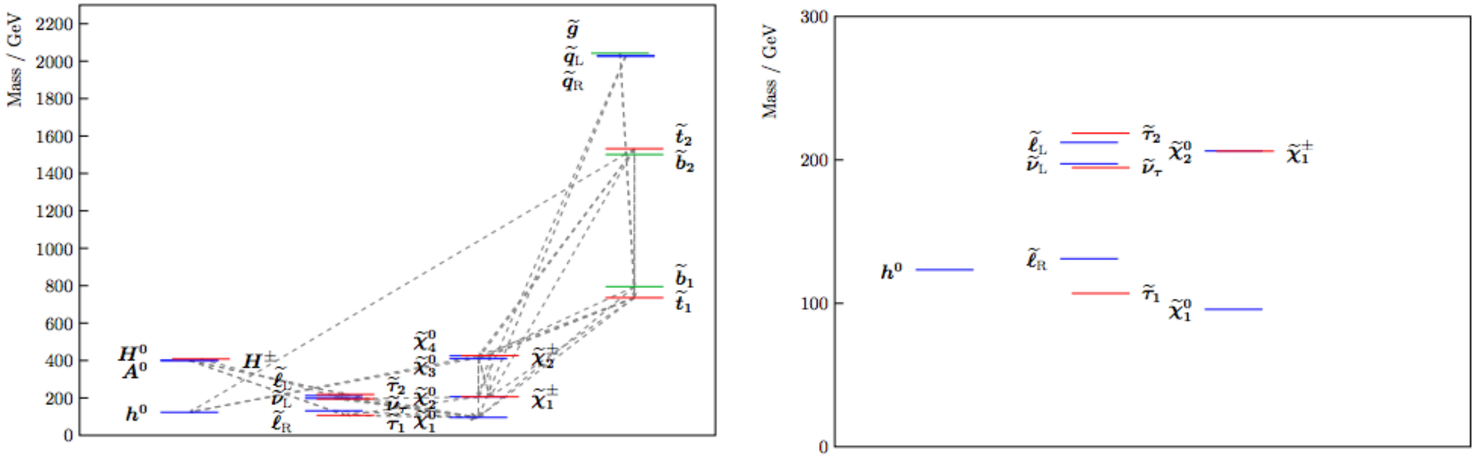


40 GeV top



SUSY

- The most popular BSM model at LHC turn-on
  - Maybe still is?
- It is not a model. It is a family of models

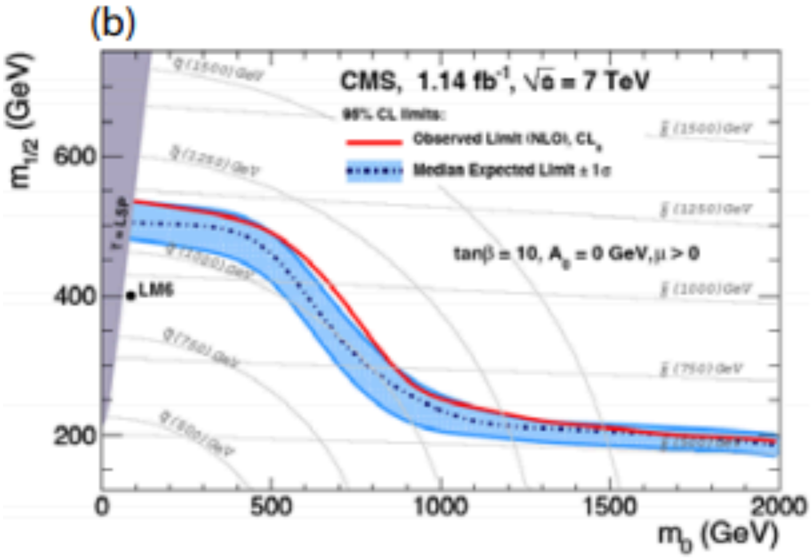


(a) (b)

EPJC (2016) 76:183

Figure 1: Full spectrum of STC8 and decay modes with a branching fraction of at least 10 % (a). The lower part of the spectrum of the STC scenarios, which features $M_{\tilde{\tau}_1} - M_{\tilde{\chi}_1^0} \approx 10\,\mathrm{GeV}$ (b).

This way of presenting the results was soon abandoned in favor of “Simplified Models”.

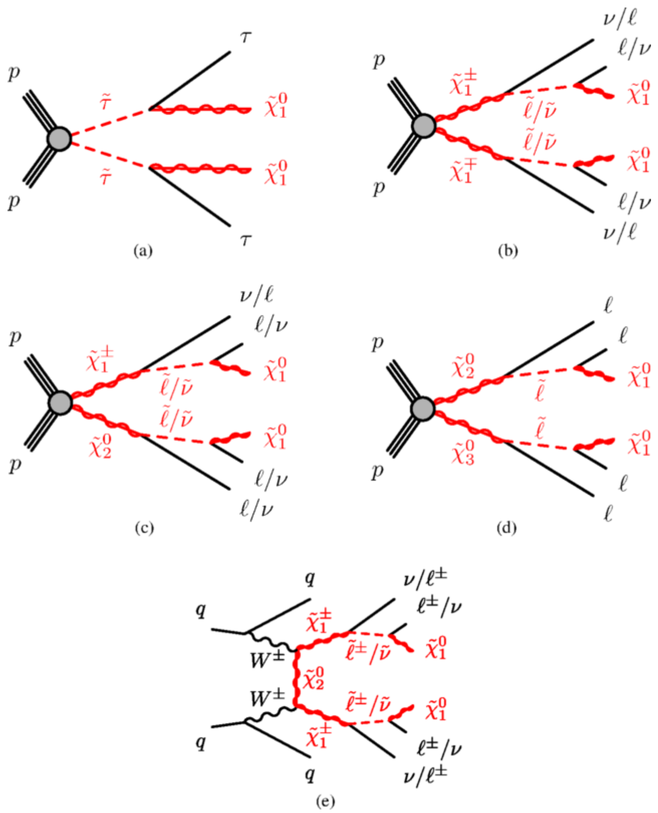


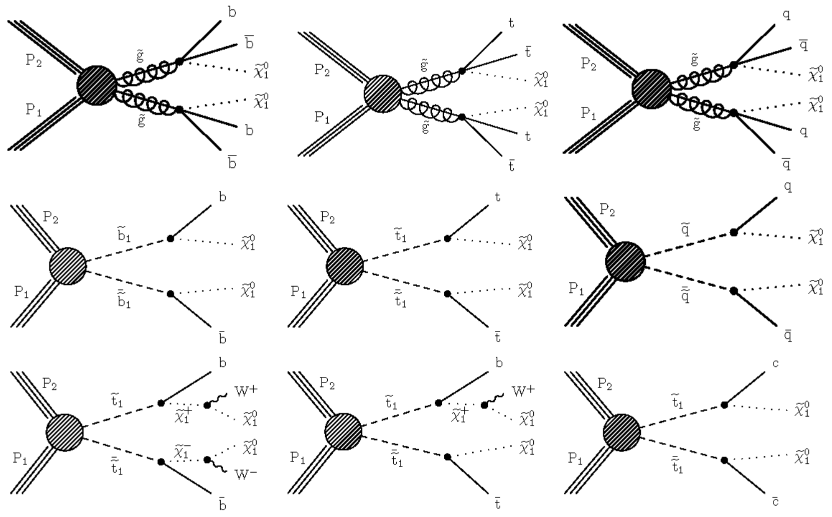
It is not just a matter of presenting results in a different, more “down to earth” way.

It also enabled a wider variety of searches with less prejudice

Simplified Models

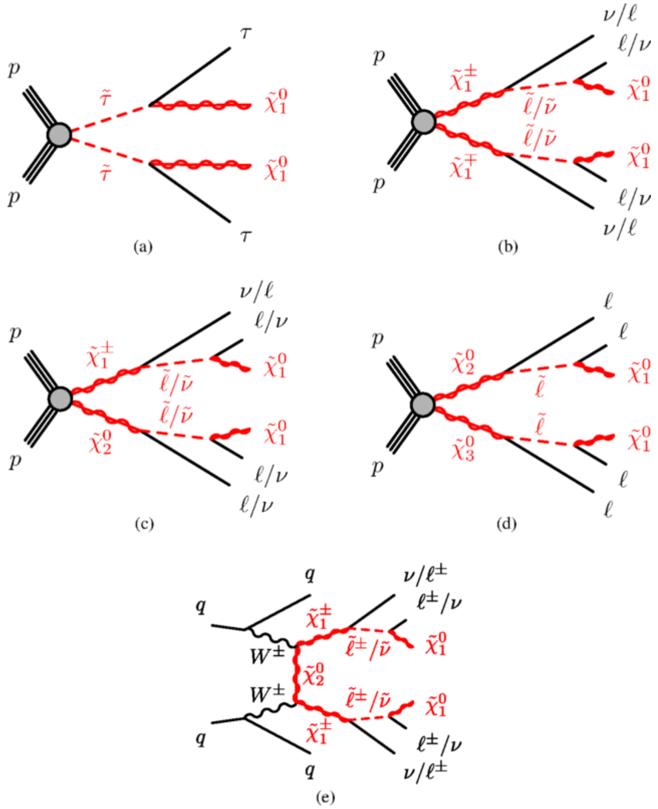
- Production of SUSY particles with well defined x-sections
- Almost always 100% BR
- Almost always neglecting spin factors, matrix element dynamics in decay

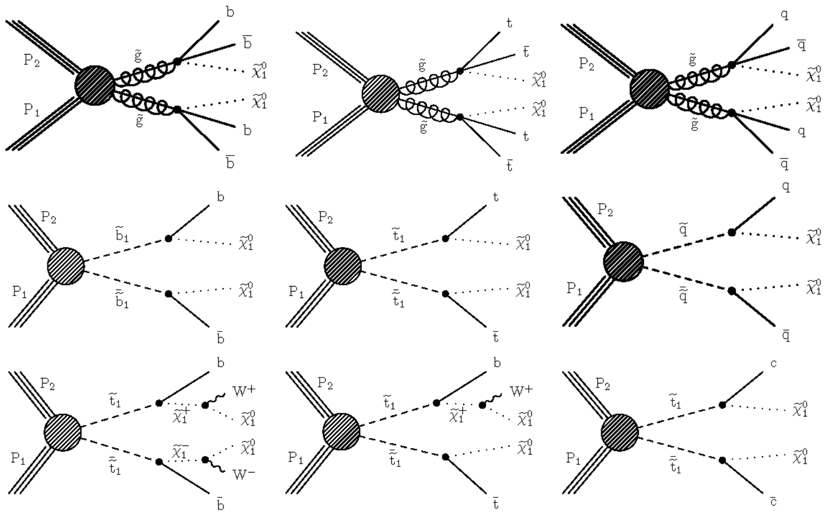




Simplified Models

- Production of SUSY particles with well defined x-sections
- Almost always 100% BR
- Almost always neglecting spin factors, matrix element dynamic in decay





- Unrealistic
- But helps to zero-in on the mass-shell physics
- Better motivation of searches
- Colorful plots

SUSY searches

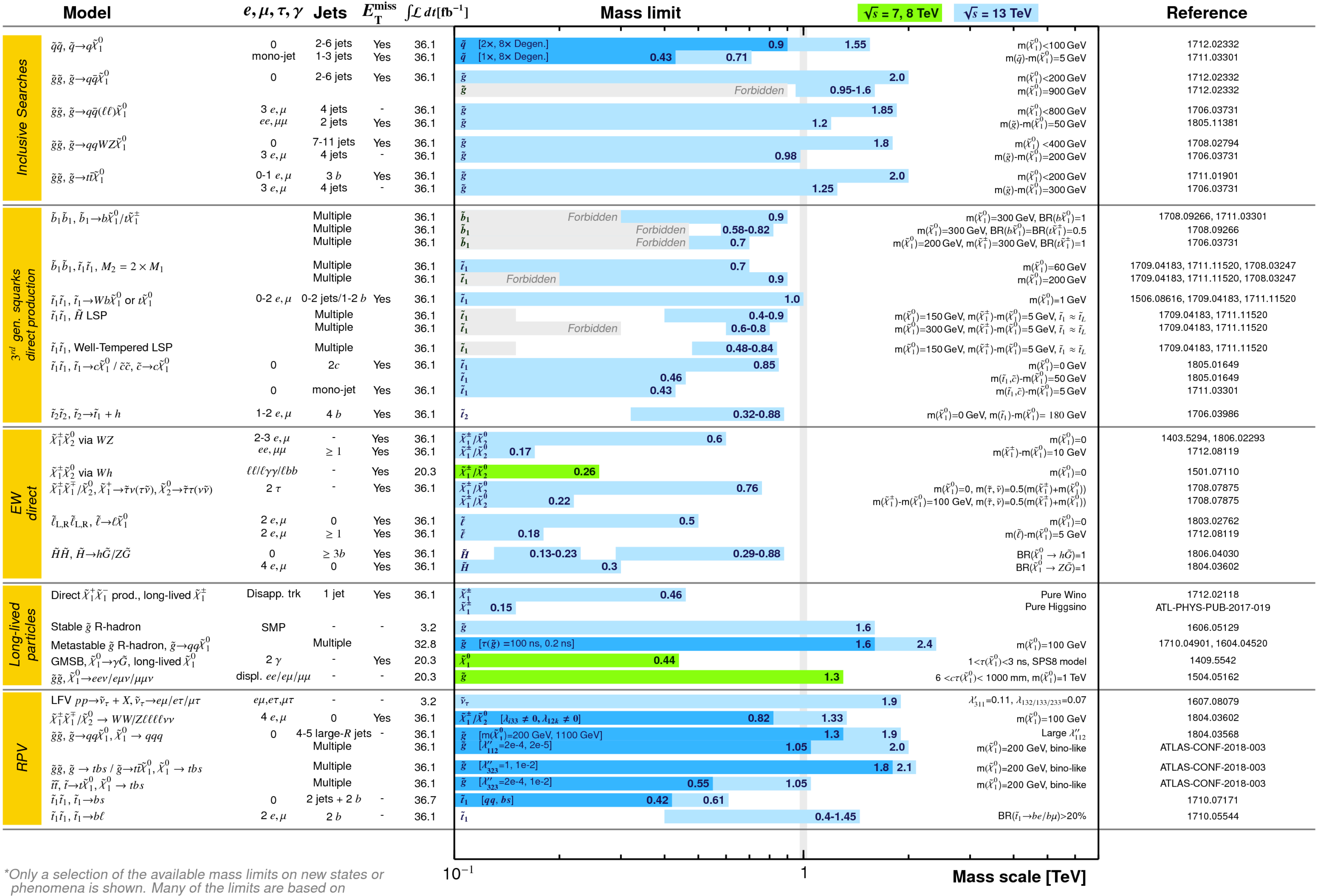
- Many different final states
  - 0L, 1L, 2LSS, 2LOS, Multilepton
  - Different N_{jets} N_b MET H_T M_{eff} …..
  - Many bins
- Most searches are "generic" enough that they are sensitive to broad range of NP possibilities
- Started with strong production, moving to EWK production

ATLAS SUSY Searches* - 95% CL Lower Limits

July 2018

ATLAS Preliminary

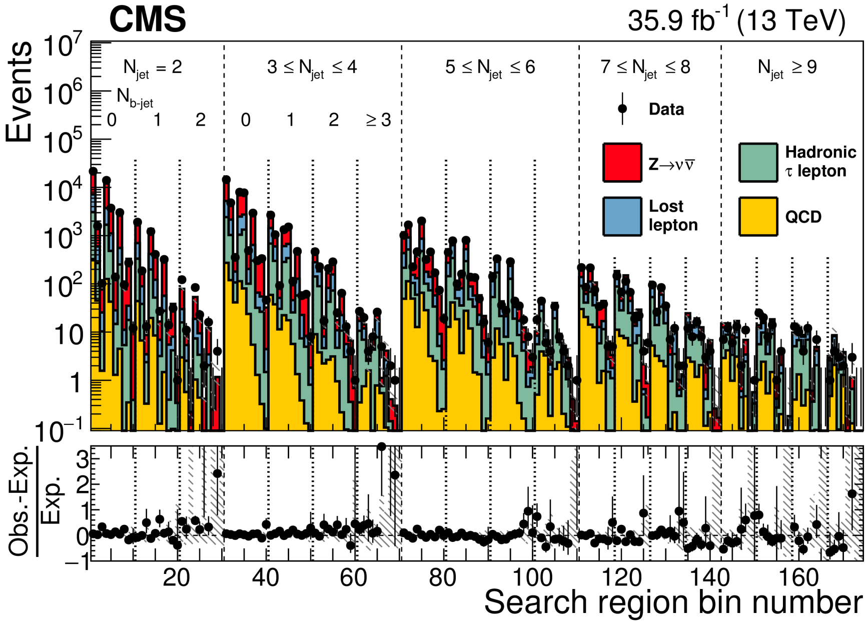
$\sqrt{s}$ = 7, 8, 13 TeV



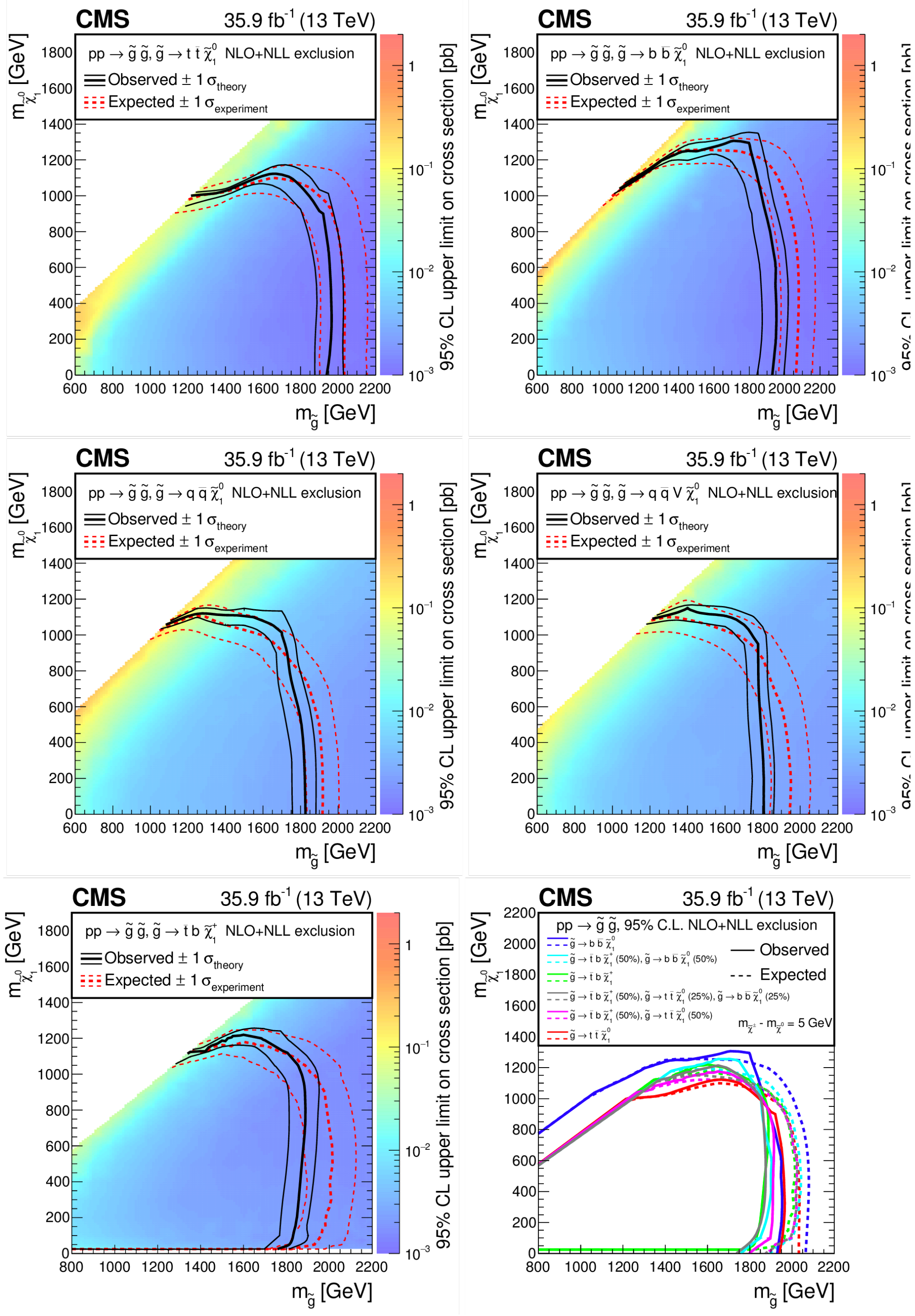
	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	$\tilde{q}\tilde{q}$, $\tilde{q}\rightarrow q\tilde{\chi}^0_1$	0	2-6 jets	Yes	36.1	$\tilde{q}$ [2×, 8× Degen.] 0.9 1.55	m($\tilde{\chi}^0_1$)<100 GeV	1712.02332
		mono-jet	1-3 jets	Yes	36.1	$\tilde{q}$ [1×, 8× Degen.] 0.43 0.71	m($\tilde{q}$)-m($\tilde{\chi}^0_1$)=5 GeV	1711.03301
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow q\bar{q}\tilde{\chi}^0_1$	0	2-6 jets	Yes	36.1	$\tilde{g}$ 2.0	m($\tilde{\chi}^0_1$)<200 GeV	1712.02332
						$\tilde{g}$ Forbidden 0.95-1.6	m($\tilde{\chi}^0_1$)=900 GeV	1712.02332
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow q\bar{q}(\ell\ell)\tilde{\chi}^0_1$	3 e, μ	4 jets	-	36.1	$\tilde{g}$ 1.85	m($\tilde{\chi}^0_1$)<800 GeV	1706.03731
		$ee, \mu\mu$	2 jets	Yes	36.1	$\tilde{g}$ 1.2	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=50 GeV	1805.11381
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow qqWZ\tilde{\chi}^0_1$	0	7-11 jets	Yes	36.1	$\tilde{g}$ 1.8	m($\tilde{\chi}^0_1$) <400 GeV	1708.02794
		3 e, μ	4 jets	-	36.1	$\tilde{g}$ 0.98	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=200 GeV	1706.03731
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow t\bar{t}\tilde{\chi}^0_1$	0-1 e, μ	3 b	Yes	36.1	$\tilde{g}$ 2.0	m($\tilde{\chi}^0_1$)<200 GeV	1711.01901
		3 e, μ	4 jets	-	36.1	$\tilde{g}$ 1.25	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=300 GeV	1706.03731
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\rightarrow b\tilde{\chi}^0_1/t\tilde{\chi}^\pm_1$		Multiple		36.1	$\tilde{b}_1$ Forbidden 0.9	m($\tilde{\chi}^0_1$)=300 GeV, BR($b\tilde{\chi}^0_1$)=1	1708.09266, 1711.03301
			Multiple		36.1	$\tilde{b}_1$ Forbidden 0.58-0.82	m($\tilde{\chi}^0_1$)=300 GeV, BR($b\tilde{\chi}^0_1$)=BR($t\tilde{\chi}^\pm_1$)=0.5	1708.09266
			Multiple		36.1	$\tilde{b}_1$ Forbidden 0.7	m($\tilde{\chi}^0_1$)=200 GeV, m($\tilde{\chi}^\pm_1$)=300 GeV, BR($t\tilde{\chi}^\pm_1$)=1	1706.03731
	$\tilde{b}_1\tilde{b}_1, \tilde{t}_1\tilde{t}_1$, $M_2 = 2 \times M_1$		Multiple		36.1	$\tilde{t}_1$ 0.7	m($\tilde{\chi}^0_1$)=60 GeV	1709.04183, 1711.11520, 1708.03247
			Multiple		36.1	$\tilde{t}_1$ Forbidden 0.9	m($\tilde{\chi}^0_1$)=200 GeV	1709.04183, 1711.11520, 1708.03247
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow Wb\tilde{\chi}^0_1$ or $t\tilde{\chi}^0_1$	0-2 e, μ	0-2 jets/1-2 b	Yes	36.1	$\tilde{t}_1$ 1.0	m($\tilde{\chi}^0_1$)=1 GeV	1506.08616, 1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, $\tilde{H}$ LSP		Multiple		36.1	$\tilde{t}_1$ 0.4-0.9	m($\tilde{\chi}^0_1$)=150 GeV, m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=5 GeV, $\tilde{t}_1 \approx \tilde{t}_L$	1709.04183, 1711.11520
			Multiple		36.1	$\tilde{t}_1$ Forbidden 0.6-0.8	m($\tilde{\chi}^0_1$)=300 GeV, m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=5 GeV, $\tilde{t}_1 \approx \tilde{t}_L$	1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, Well-Tempered LSP		Multiple		36.1	$\tilde{t}_1$ 0.48-0.84	m($\tilde{\chi}^0_1$)=150 GeV, m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=5 GeV, $\tilde{t}_1 \approx \tilde{t}_L$	1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow c\tilde{\chi}^0_1$ / $\tilde{c}\tilde{c}$, $\tilde{c}\rightarrow c\tilde{\chi}^0_1$	0	2c	Yes	36.1	$\tilde{t}_1$ 0.85	m($\tilde{\chi}^0_1$)=0 GeV	1805.01649
						$\tilde{t}_1$ 0.46	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}^0_1$)=50 GeV	1805.01649
		0	mono-jet	Yes	36.1	$\tilde{t}_1$ 0.43	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}^0_1$)=5 GeV	1711.03301
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\rightarrow\tilde{t}_1 + h$	1-2 e, μ	4 b	Yes	36.1	$\tilde{t}_2$ 0.32-0.88	m($\tilde{\chi}^0_1$)=0 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}^0_1$)= 180 GeV	1706.03986
EW direct	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via WZ	2-3 e, μ	-	Yes	36.1	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ 0.6	m($\tilde{\chi}^0_1$)=0	1403.5294, 1806.02293
		$ee, \mu\mu$	≥ 1	Yes	36.1	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ 0.17	m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=10 GeV	1712.08119
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via Wh	$\ell\ell/\ell\gamma\gamma/\ell bb$	-	Yes	20.3	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ 0.26	m($\tilde{\chi}^0_1$)=0	1501.07110
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_2$, $\tilde{\chi}^+_1\rightarrow\tilde{\tau}\nu(\tau\tilde{\nu})$, $\tilde{\chi}^0_2\rightarrow\tilde{\tau}\tau(\nu\tilde{\nu})$	2 τ	-	Yes	36.1	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ 0.76	m($\tilde{\chi}^0_1$)=0, m($\tilde{\tau}, \tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	1708.07875
						$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ 0.22	m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=100 GeV, m($\tilde{\tau}, \tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	1708.07875
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\rightarrow\ell\tilde{\chi}^0_1$	2 e, μ	0	Yes	36.1	$\tilde{\ell}$ 0.5	m($\tilde{\chi}^0_1$)=0	1803.02762
		2 e, μ	≥ 1	Yes	36.1	$\tilde{\ell}$ 0.18	m($\tilde{\ell}$)-m($\tilde{\chi}^0_1$)=5 GeV	1712.08119
	$\tilde{H}\tilde{H}$, $\tilde{H}\rightarrow h\tilde{G}/Z\tilde{G}$	0	$\geq 3b$	Yes	36.1	$\tilde{H}$ 0.13-0.23 0.29-0.88	BR($\tilde{\chi}^0_1 \rightarrow h\tilde{G}$)=1	1806.04030
		4 e, μ	0	Yes	36.1	$\tilde{H}$ 0.3	BR($\tilde{\chi}^0_1 \rightarrow Z\tilde{G}$)=1	1804.03602
Long-lived particles	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}^\pm_1$ 0.46	Pure Wino	1712.02118
						$\tilde{\chi}^\pm_1$ 0.15	Pure Higgsino	ATL-PHYS-PUB-2017-019
	Stable $\tilde{g}$ R-hadron	SMP	-	-	3.2	$\tilde{g}$ 1.6		1606.05129
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\rightarrow qq\tilde{\chi}^0_1$		Multiple		32.8	$\tilde{g}$ [$\tau(\tilde{g})$ =100 ns, 0.2 ns] 1.6 2.4	m($\tilde{\chi}^0_1$)=100 GeV	1710.04901, 1604.04520
	GMSB, $\tilde{\chi}^0_1\rightarrow\gamma\tilde{G}$, long-lived $\tilde{\chi}^0_1$	2 γ	-	Yes	20.3	$\tilde{\chi}^0_1$ 0.44	1<$\tau(\tilde{\chi}^0_1)$<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}$, $\tilde{\chi}^0_1\rightarrow ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{g}$ 1.3	6 <$c\tau(\tilde{\chi}^0_1)$< 1000 mm, m($\tilde{\chi}^0_1$)=1 TeV	1504.05162
RPV	LFV $pp\rightarrow\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\rightarrow e\mu/e\tau/\mu\tau$	$e\mu$,$e\tau$,$\mu\tau$	-	-	3.2	$\tilde{\nu}_\tau$ 1.9	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_2 \rightarrow WW/Z\ell\ell\ell\ell\nu\nu$	4 e, μ	0	Yes	36.1	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ [$\lambda_{i33} \neq 0, \lambda_{12k} \neq 0$] 0.82 1.33	m($\tilde{\chi}^0_1$)=100 GeV	1804.03602
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow qq\tilde{\chi}^0_1$, $\tilde{\chi}^0_1 \rightarrow qqq$	0	4-5 large-R jets	-	36.1	$\tilde{g}$ [m($\tilde{\chi}^0_1$)=200 GeV, 1100 GeV] 1.3 1.9	Large λ''_{112}	1804.03568
			Multiple		36.1	$\tilde{g}$ [λ''_{112}=2e-4, 2e-5] 1.05 2.0	m($\tilde{\chi}^0_1$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{g}\tilde{g}$, $\tilde{g} \rightarrow tbs$ / $\tilde{g}\rightarrow t\bar{t}\tilde{\chi}^0_1$, $\tilde{\chi}^0_1 \rightarrow tbs$		Multiple		36.1	$\tilde{g}$ [λ''_{323}=1, 1e-2] 1.8 2.1	m($\tilde{\chi}^0_1$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}$, $\tilde{t}\rightarrow t\tilde{\chi}^0_1$, $\tilde{\chi}^0_1 \rightarrow tbs$		Multiple		36.1	$\tilde{g}$ [λ''_{323}=2e-4, 1e-2] 0.55 1.05	m($\tilde{\chi}^0_1$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow bs$	0	2 jets + 2 b	-	36.7	$\tilde{t}_1$ [qq, bs] 0.42 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow b\ell$	2 e, μ	2 b	-	36.1	$\tilde{t}_1$ 0.4-1.45	BR($\tilde{t}_1\rightarrow be/b\mu$)>20%	1710.05544

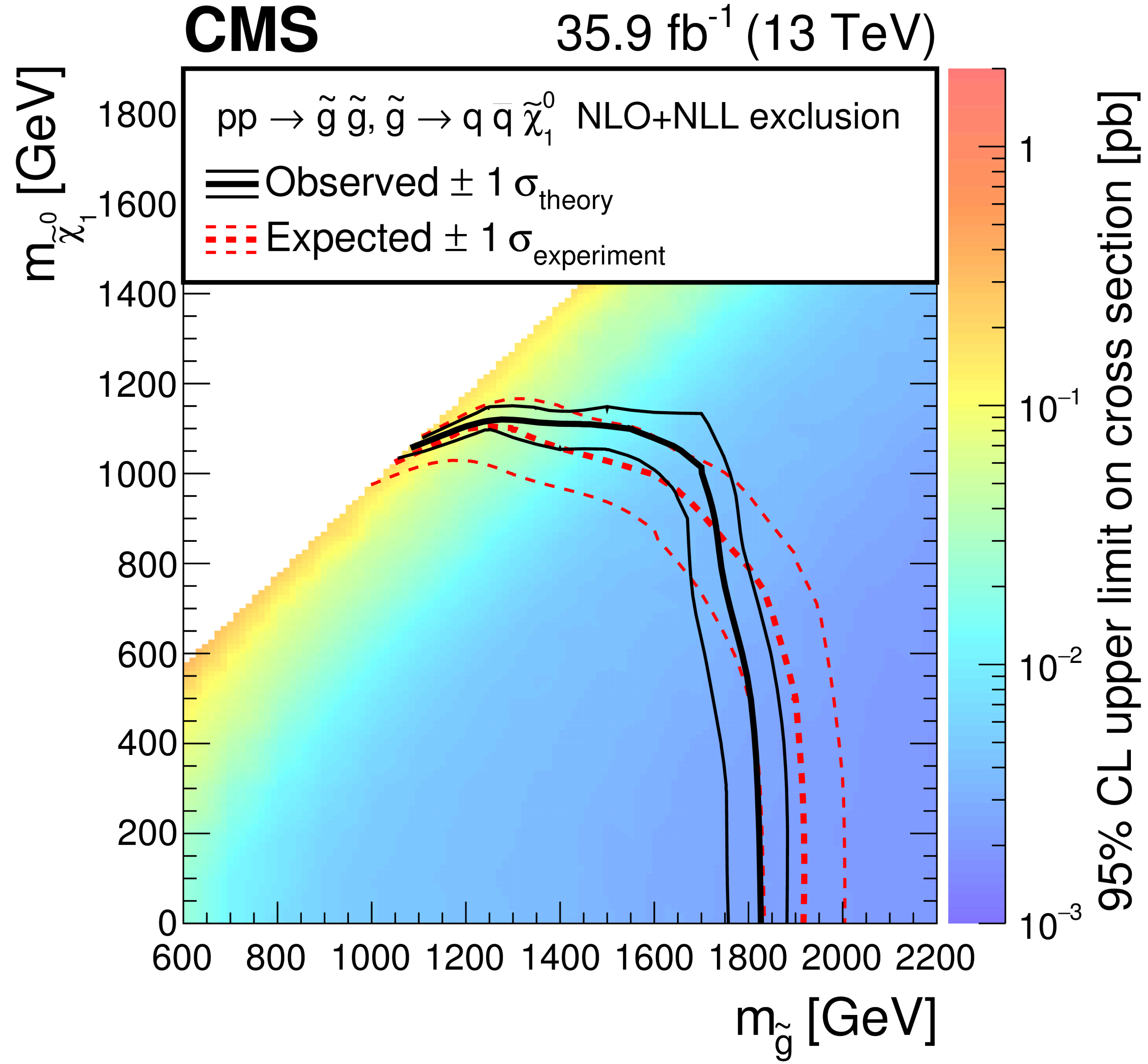
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

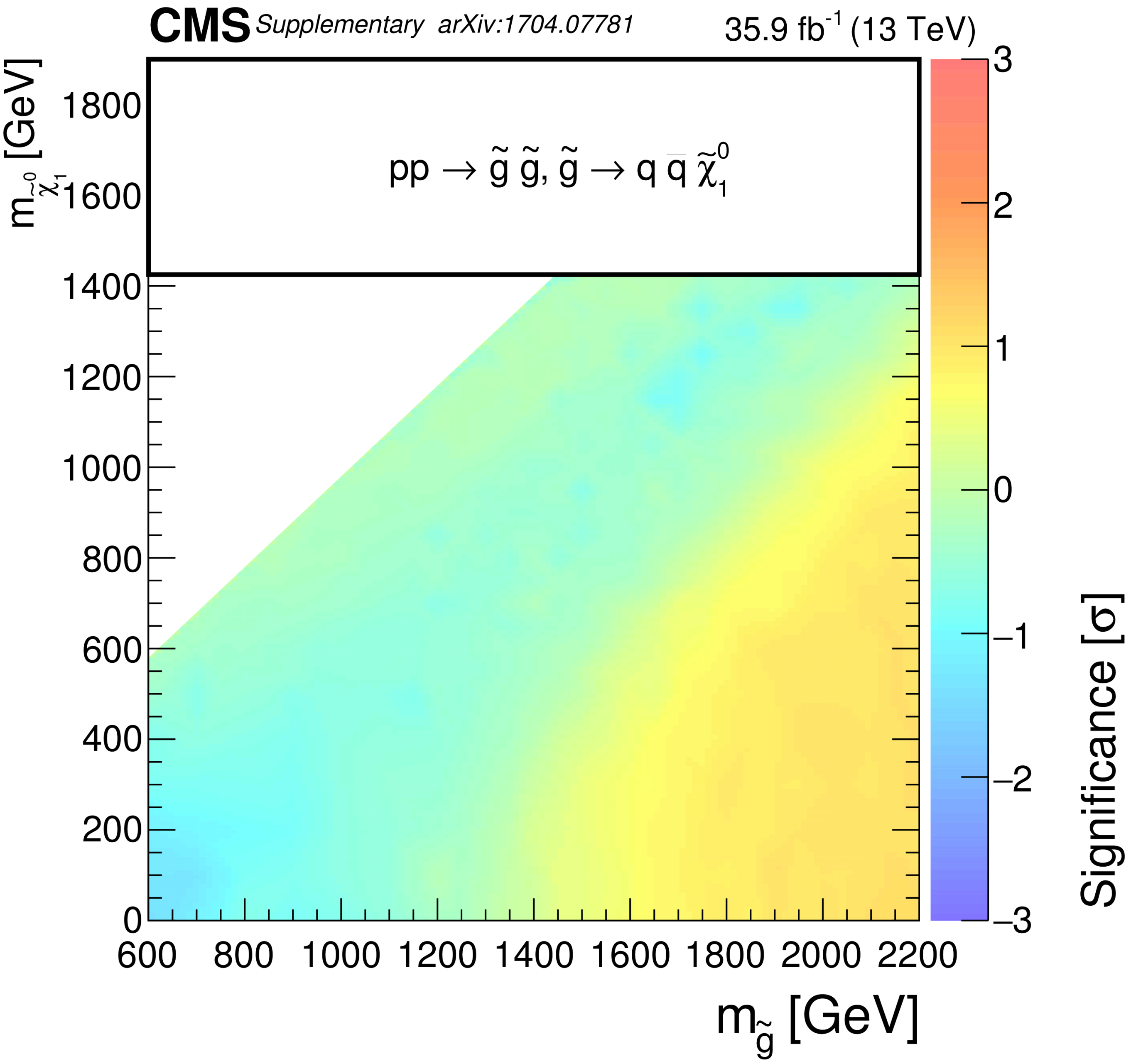
Example of results of a SUSY search



PRD 96 (2017) 032003

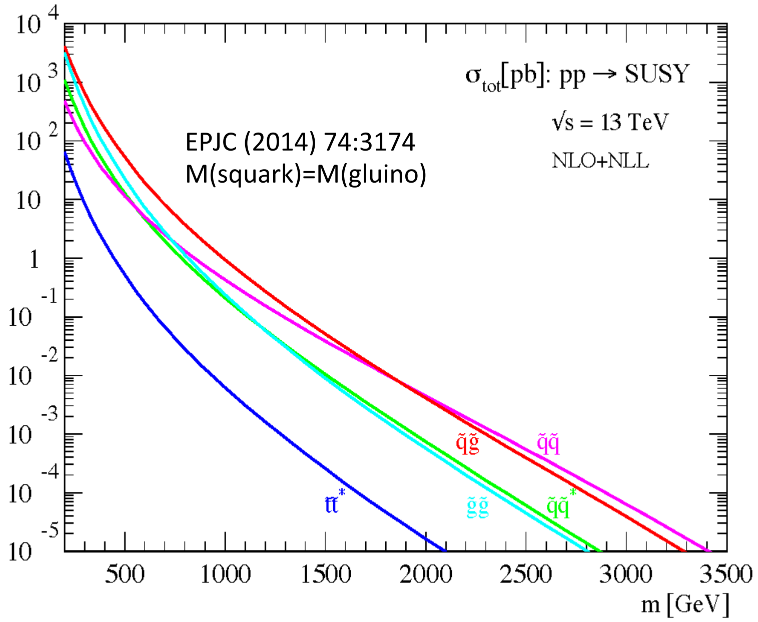


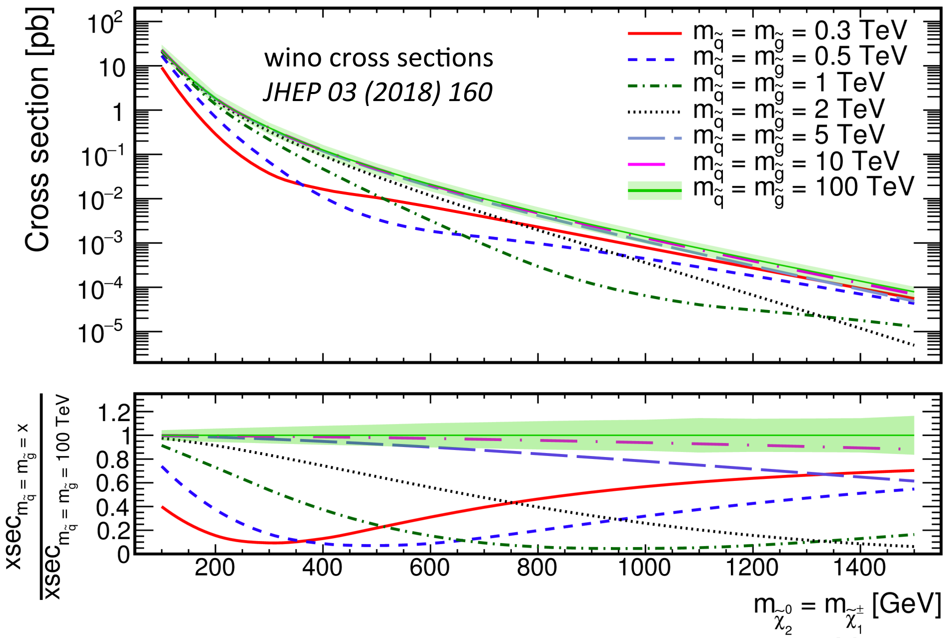

CMS
35.9 fb^{-1} (13 TeV)
pp → $\tilde{g}\,\tilde{g}$, $\tilde{g} \to q\,\bar{q}\,\tilde{\chi}^0_1$ NLO+NLL exclusion
Observed ± 1 σ_{theory}
Expected ± 1 $\sigma_{experiment}$
$m_{\tilde{\chi}^0_1}$ [GeV]
0
200
400
600
800
1000
1200
1400
1600
1800
600
800
1000
1200
1400
1600
1800
2000
2200
$m_{\tilde{g}}$ [GeV]
95% CL upper limit on cross section [pb]
1
10^{-1}
10^{-2}
10^{-3}


CMS Supplementary arXiv:1704.07781
35.9 fb^{-1} (13 TeV)
$pp \to \tilde{g}\,\tilde{g},\ \tilde{g} \to q\,\bar{q}\,\tilde{\chi}_1^0$
$m_{\tilde{\chi}_1^0}$ [GeV]
0
200
400
600
800
1000
1200
1400
1600
1800
600
800
1000
1200
1400
1600
1800
2000
2200
$m_{\tilde{g}}$ [GeV]
Significance [σ]
3
2
1
0
−1
−2
−3

More Shortcomings of Simplified Models

- No di-squark, squark-gluon production
- Cross-sections calculated in decoupling limit
- How good are the mass limits then?

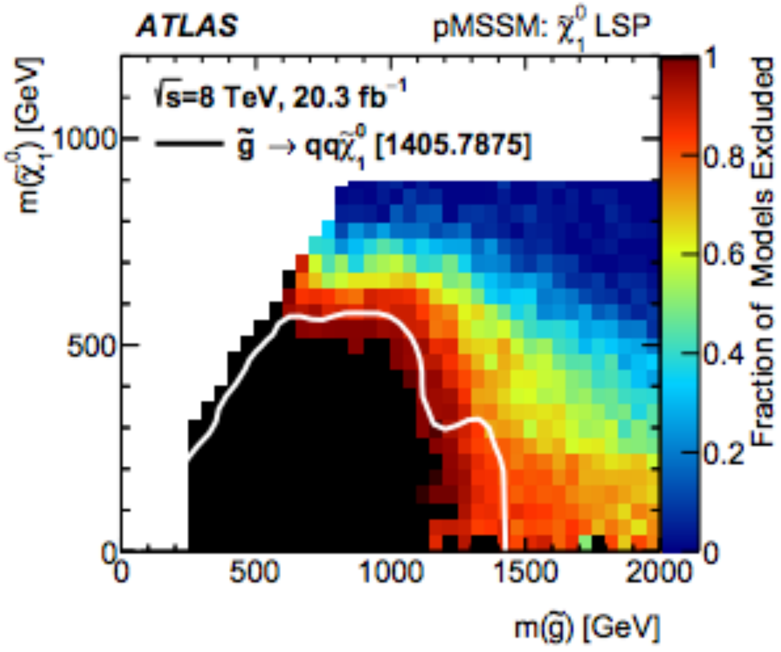


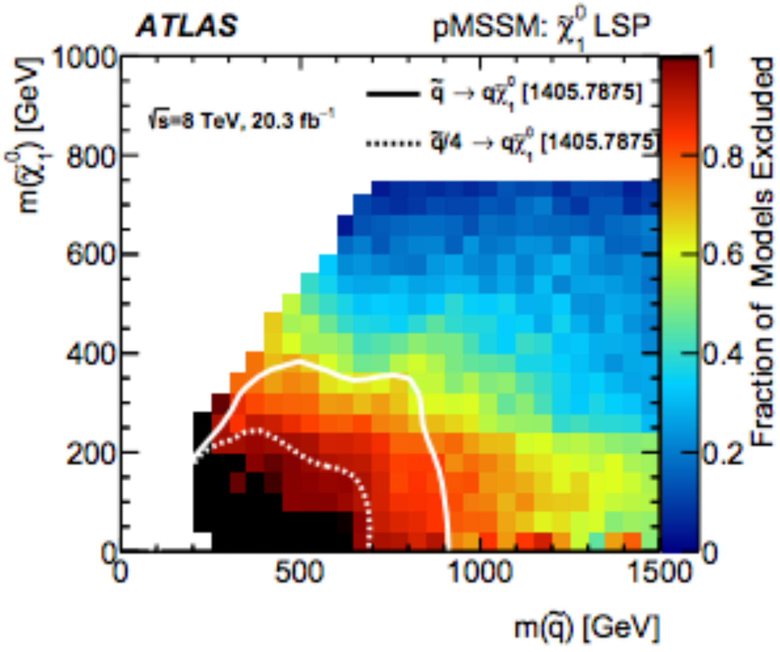


JHEP 10 (2015) 134

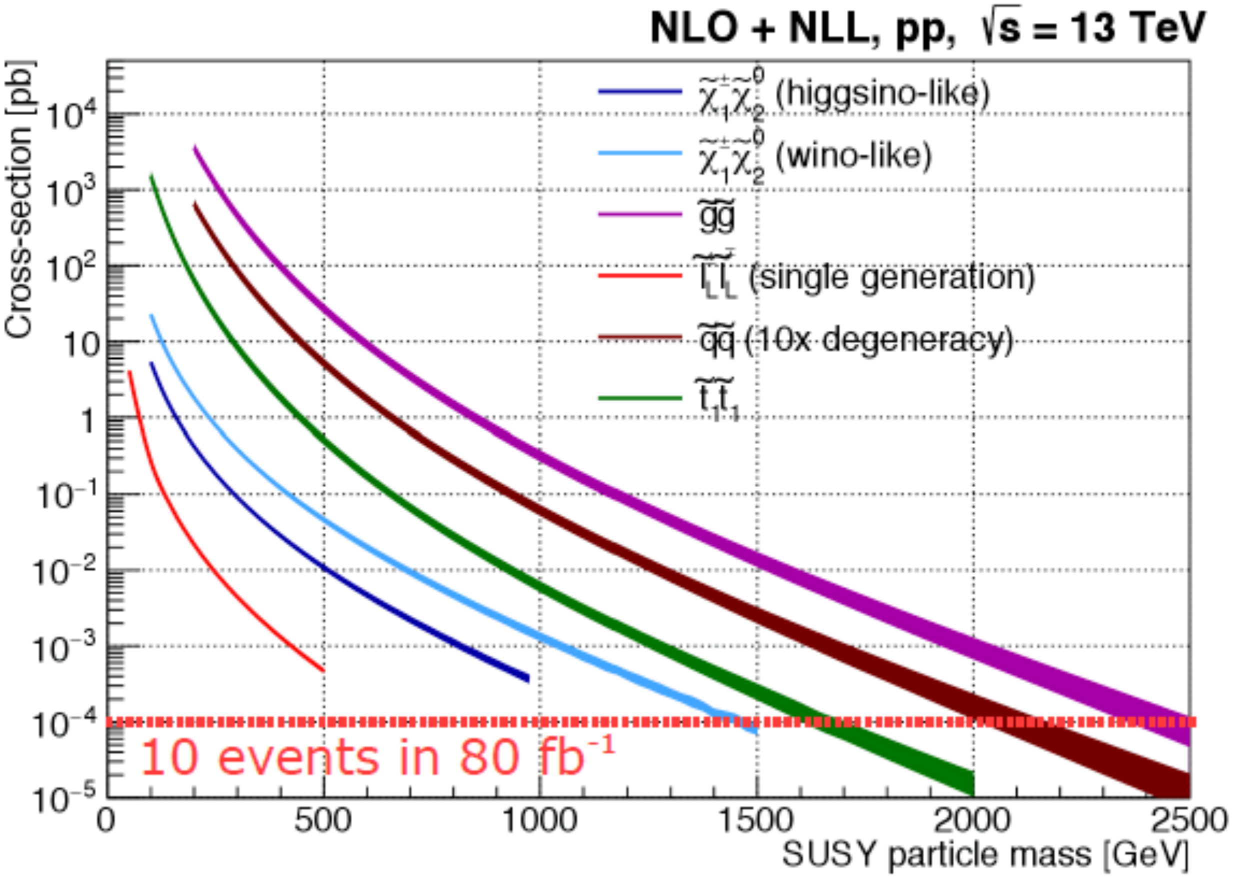
pMSSM study (8 TeV, Atlas)

- Generate MC for many “full” R-parity conserving models consistent with Dark matter and other constraints
- Feed them through 22 Atlas searches
- Look at SUSY masses of excluded vs. allowed models



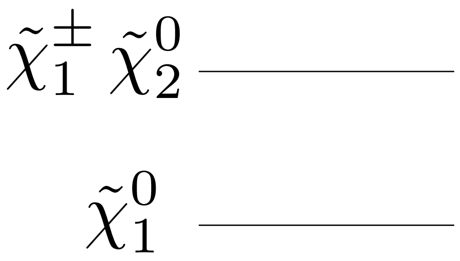


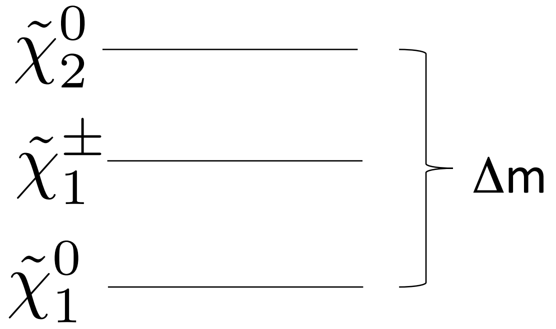
EWK SUSY



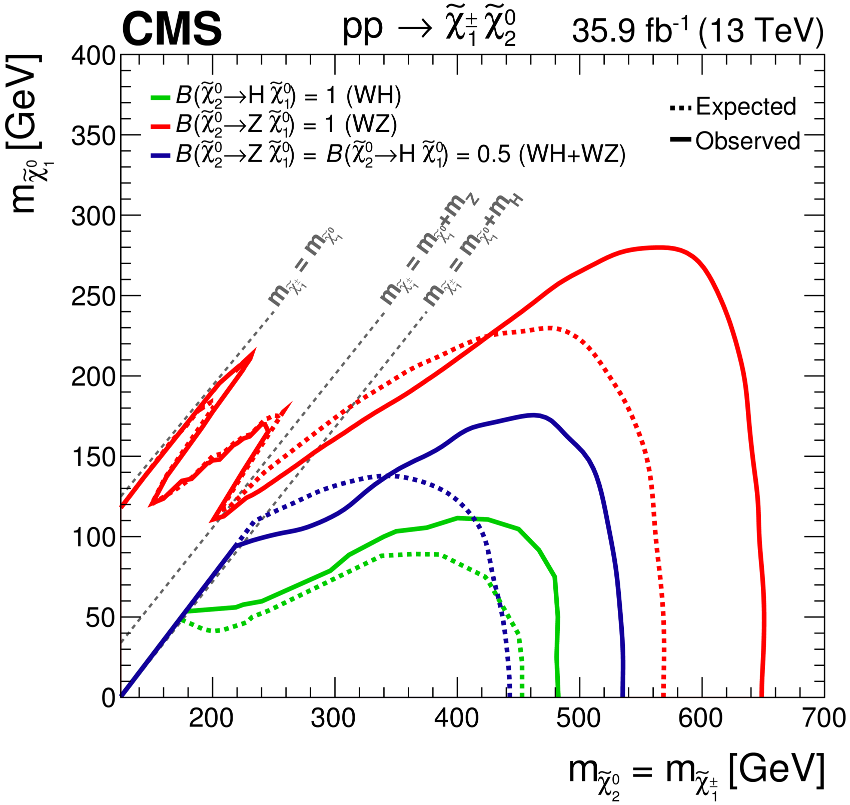
S. Strandberg
ICHEP 2018

Low cross-section



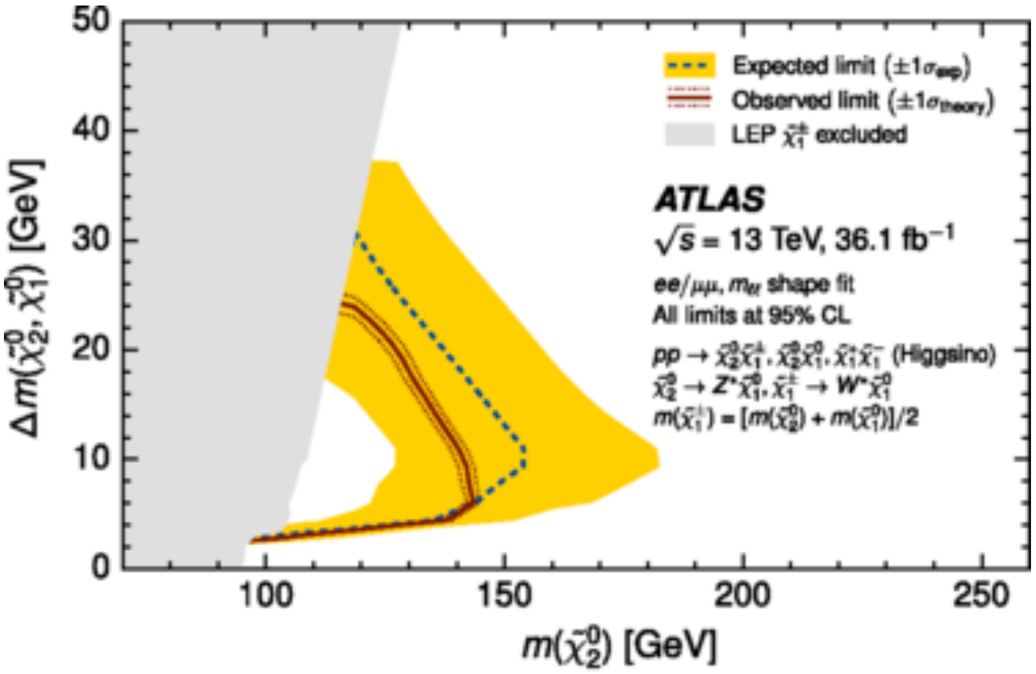


JHEP 03 (2018) 160



Wino-like cross-sections

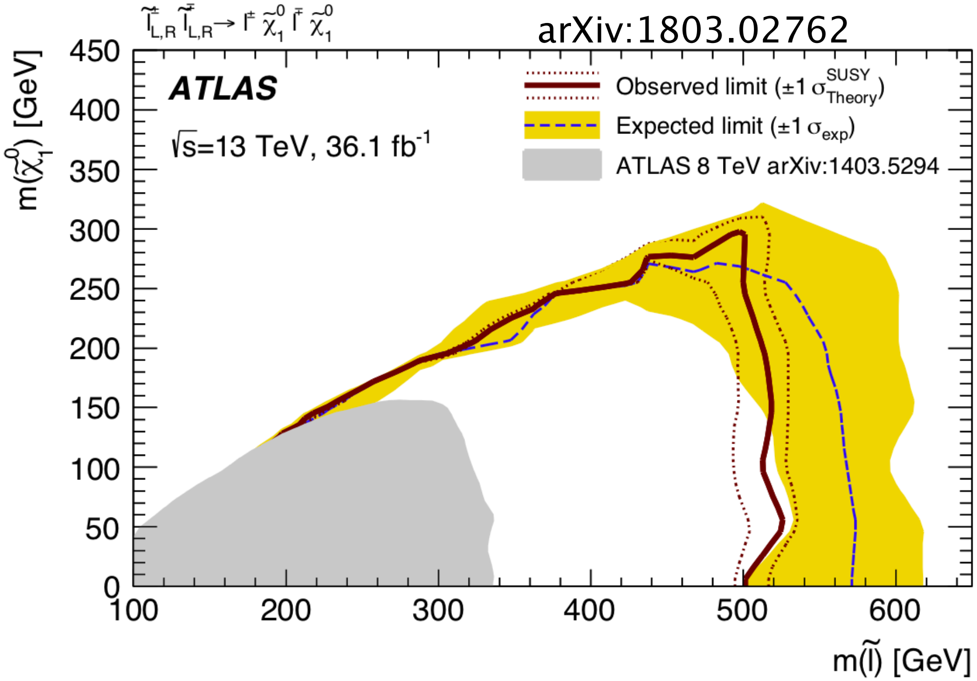
PRD 97 (2018) 052010



Higgsino-like cross-sections

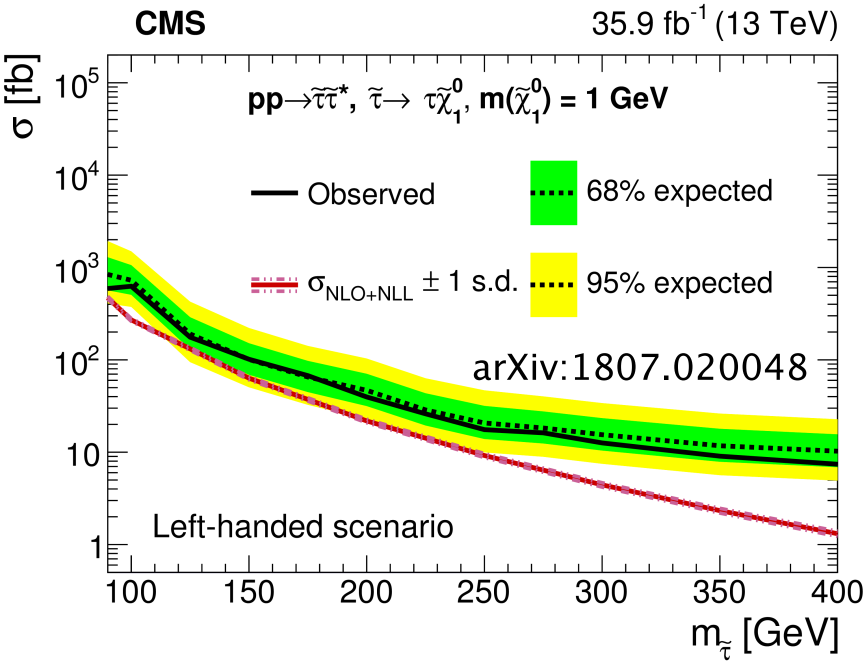
Sleptons

$\tilde{e}, \tilde{\mu}$



arXiv:1803.02762

$\tilde{\tau}$



arXiv:1807.020048

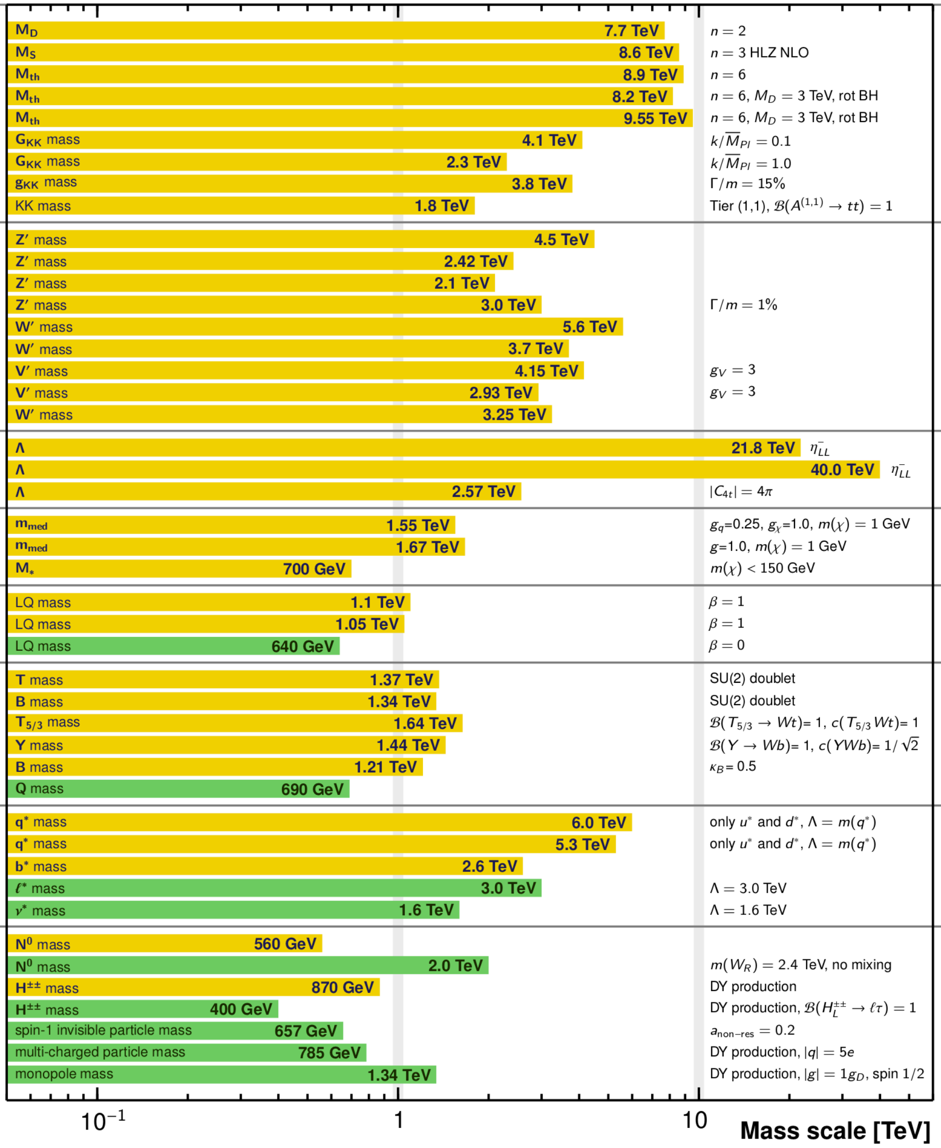
End of Lecture 1

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2018

ATLAS Preliminary

$\int\mathcal{L}\,dt = (3.2 - 79.8)\ \text{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV



	Model	ℓ, γ	Jets†	E_T^{miss}	$\int\mathcal{L}\,dt[\text{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	$0\ e, \mu$	$1-4$ j	Yes	36.1	🟨 M_D 7.7 TeV	$n = 2$	1711.03301
	ADD non-resonant $\gamma\gamma$	$2\ \gamma$	–	–	36.7	🟨 M_S 8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	🟨 M_{th} 8.9 TeV	$n = 6$	1703.09127
	ADD BH high $\sum p_T$	$\geq 1\ e, \mu$	≥ 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 $G_{KK} \to \gamma\gamma$	$2\ \gamma$	–	–	36.7	🟨 G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	1707.04147
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	🟨 G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	CERN-EP-2018-179
	Bulk RS $g_{KK} \to tt$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	36.1	🟨 g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	$1\ e, \mu$	≥ 2 b, ≥ 3 j	Yes	36.1	🟨 KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	$2\ e, \mu$	–	–	36.1	🟨 Z' mass 4.5 TeV		1707.02424
	SSM $Z' \to \tau\tau$	$2\ \tau$	–	–	36.1	🟨 Z' mass 2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	🟨 Z' mass 2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	36.1	🟨 Z' mass 3.0 TeV	$\Gamma/m = 1\%$	1804.10823
	SSM $W' \to \ell\nu$	$1\ e, \mu$	–	Yes	79.8	🟨 W' mass 5.6 TeV		ATLAS-CONF-2018-017
	SSM $W' \to \tau\nu$	$1\ \tau$	–	Yes	36.1	🟨 W' mass 3.7 TeV		1801.06992
	HVT $V' \to WV \to qqqq$ model B	$0\ e, \mu$	2 J	–	79.8	🟨 V' mass 4.15 TeV	$g_V = 3$	ATLAS-CONF-2018-016
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	🟨 V' mass 2.93 TeV	$g_V = 3$	1712.06518
	LRSM $W'_R \to tb$	multi-channel			36.1	🟨 W' mass 3.25 TeV		CERN-EP-2018-142
CI	CI $qqqq$	–	2 j	–	37.0	🟨 Λ 21.8 TeV η_{LL}^{-}		1703.09127
	CI $\ell\ell qq$	$2\ e, \mu$	–	–	36.1	🟨 Λ 40.0 TeV η_{LL}^{-}		1707.02424
	CI $tttt$	$\geq 1\ e,\mu$	≥ 1 b, ≥ 1 j	Yes	36.1	🟨 Λ 2.57 TeV	$\lvert C_{4t}\rvert = 4\pi$	CERN-EP-2018-174
DM	Axial-vector mediator (Dirac DM)	$0\ e, \mu$	$1-4$ j	Yes	36.1	🟨 m_{med} 1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi) = 1$ GeV	1711.03301
	Colored scalar mediator (Dirac DM)	$0\ e, \mu$	$1-4$ j	Yes	36.1	🟨 m_{med} 1.67 TeV	g=1.0, $m(\chi) = 1$ GeV	1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	$0\ e, \mu$	1 J, ≤ 1 j	Yes	3.2	🟨 M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
LQ	Scalar LQ 1st gen	$2\ e$	≥ 2 j	–	3.2	🟨 LQ mass 1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	$2\ \mu$	≥ 2 j	–	3.2	🟨 LQ mass 1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	$1\ e, \mu$	≥ 1 b, ≥ 3 j	Yes	20.3	🟩 LQ mass 640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \to Ht/Zt/Wb + X$	multi-channel			36.1	🟨 T mass 1.37 TeV	SU(2) doublet	ATLAS-CONF-2018-032
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	🟨 B mass 1.34 TeV	SU(2) doublet	ATLAS-CONF-2018-032
	VLQ $T_{5/3} T_{5/3} \vert T_{5/3} \to Wt + X$	2(SS)/$\geq 3\ e,\mu$	≥ 1 b, ≥ 1 j	Yes	36.1	🟨 $T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3} Wt)$= 1	CERN-EP-2018-171
	VLQ $Y \to Wb + X$	$1\ e, \mu$	≥ 1 b, ≥ 1j	Yes	3.2	🟨 Y mass 1.44 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c(YWb)$= $1/\sqrt{2}$	ATLAS-CONF-2016-072
	VLQ $B \to Hb + X$	$0\ e,\mu$, $2\ \gamma$	≥ 1 b, ≥ 1j	Yes	79.8	🟨 B mass 1.21 TeV	κ_B= 0.5	ATLAS-CONF-2018-024
	VLQ $QQ \to WqWq$	$1\ e, \mu$	≥ 4 j	Yes	20.3	🟩 Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	37.0	🟨 q^* mass 6.0 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1703.09127
	Excited quark $q^* \to q\gamma$	$1\ \gamma$	1 j	–	36.7	🟨 q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	36.1	🟨 b^* mass 2.6 TeV		1805.09299
	Excited lepton ℓ^*	$3\ e, \mu$	–	–	20.3	🟩 ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	$3\ e, \mu, \tau$	–	–	20.3	🟩 ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	$1\ e, \mu$	≥ 2 j	Yes	79.8	🟨 N^0 mass 560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	$2\ e, \mu$	2 j	–	20.3	🟩 N^0 mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	🟨 $H^{\pm\pm}$ mass 870 GeV	DY production	1710.09748
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	$3\ e, \mu, \tau$	–	–	20.3	🟩 $H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Monotop (non-res prod)	$1\ e, \mu$	1 b	Yes	20.3	🟩 spin-1 invisible particle mass 657 GeV	$a_{\text{non-res}} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	🟩 multi-charged particle mass 785 GeV	DY production, $\lvert q\rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	🟩 monopole mass 1.34 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1509.08059

🟩 $\sqrt{s}$ = 8 TeV

🟨 $\sqrt{s}$ = 13 TeV

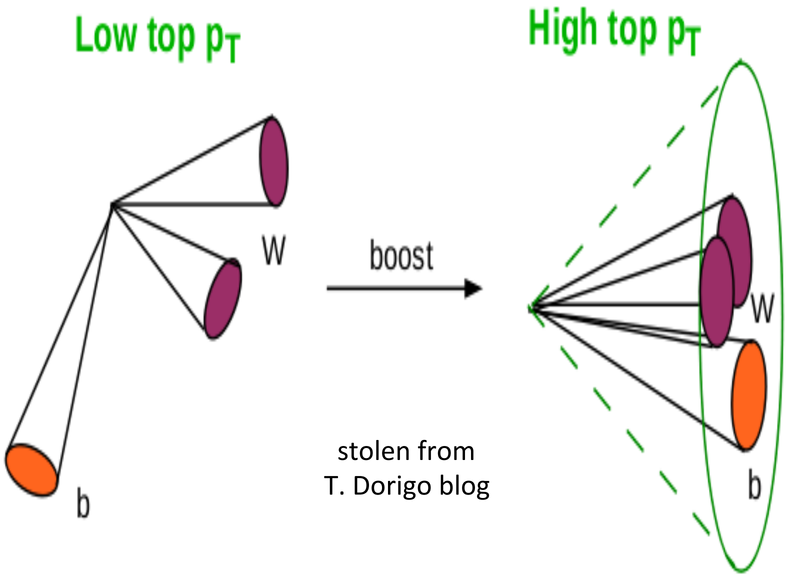
**Only a selection of the available mass limits on new states or phenomena is shown.*

†Small-radius (large-radius) jets are denoted by the letter j (J).

New technique: boosted objects

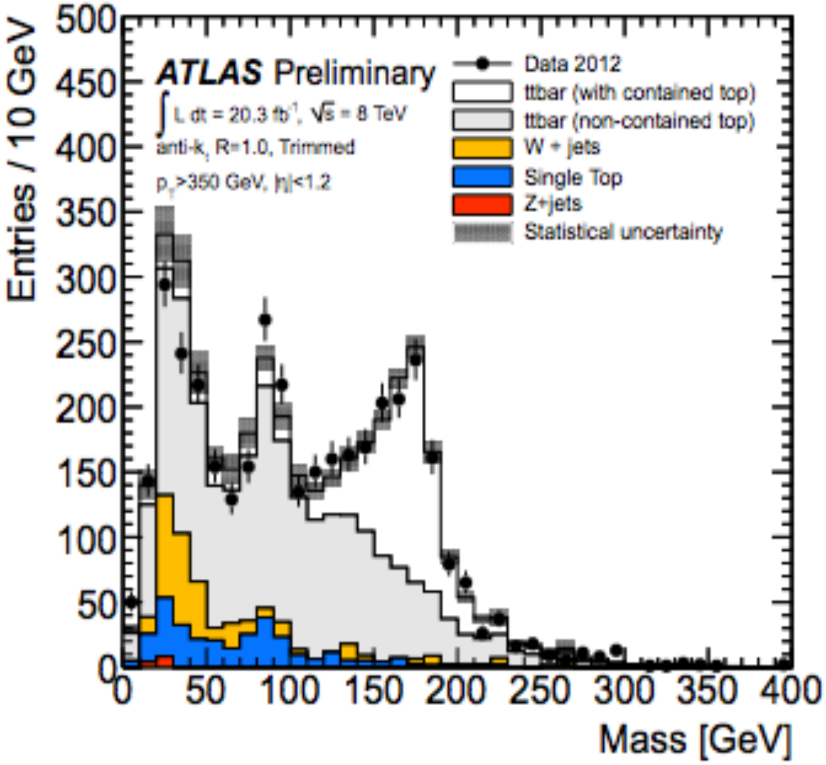
(OK, maybe not so new anymore)

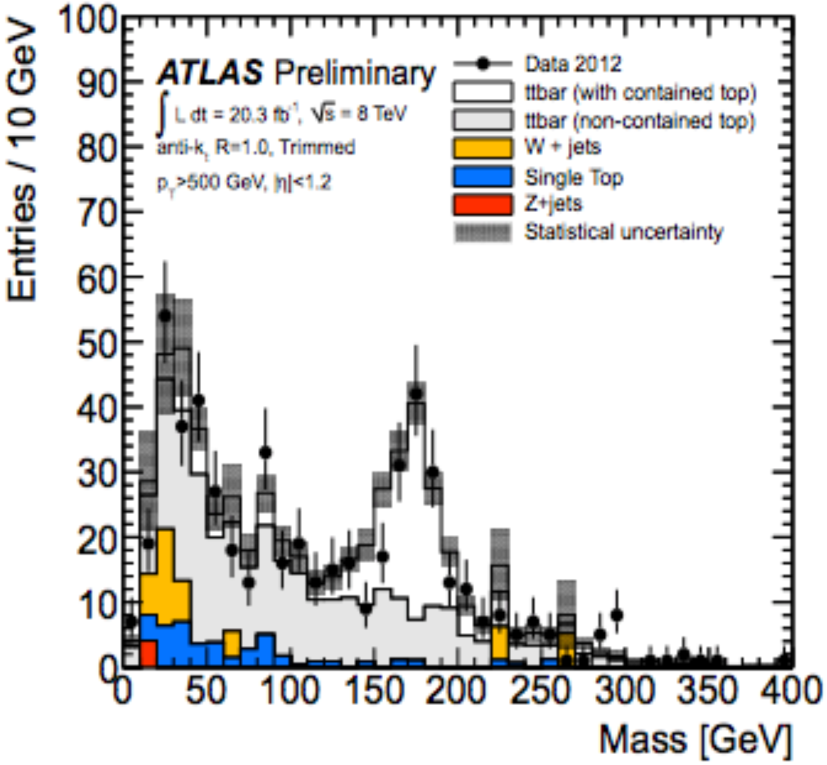
- All sorts of neat tricks
- Enables new type of searches
  - X → VV, VH(bb), qq (with ISR)
  - H(bb) in SUSY cascades
  - X→tt
  - High P_T tops in SUSY
  - …..

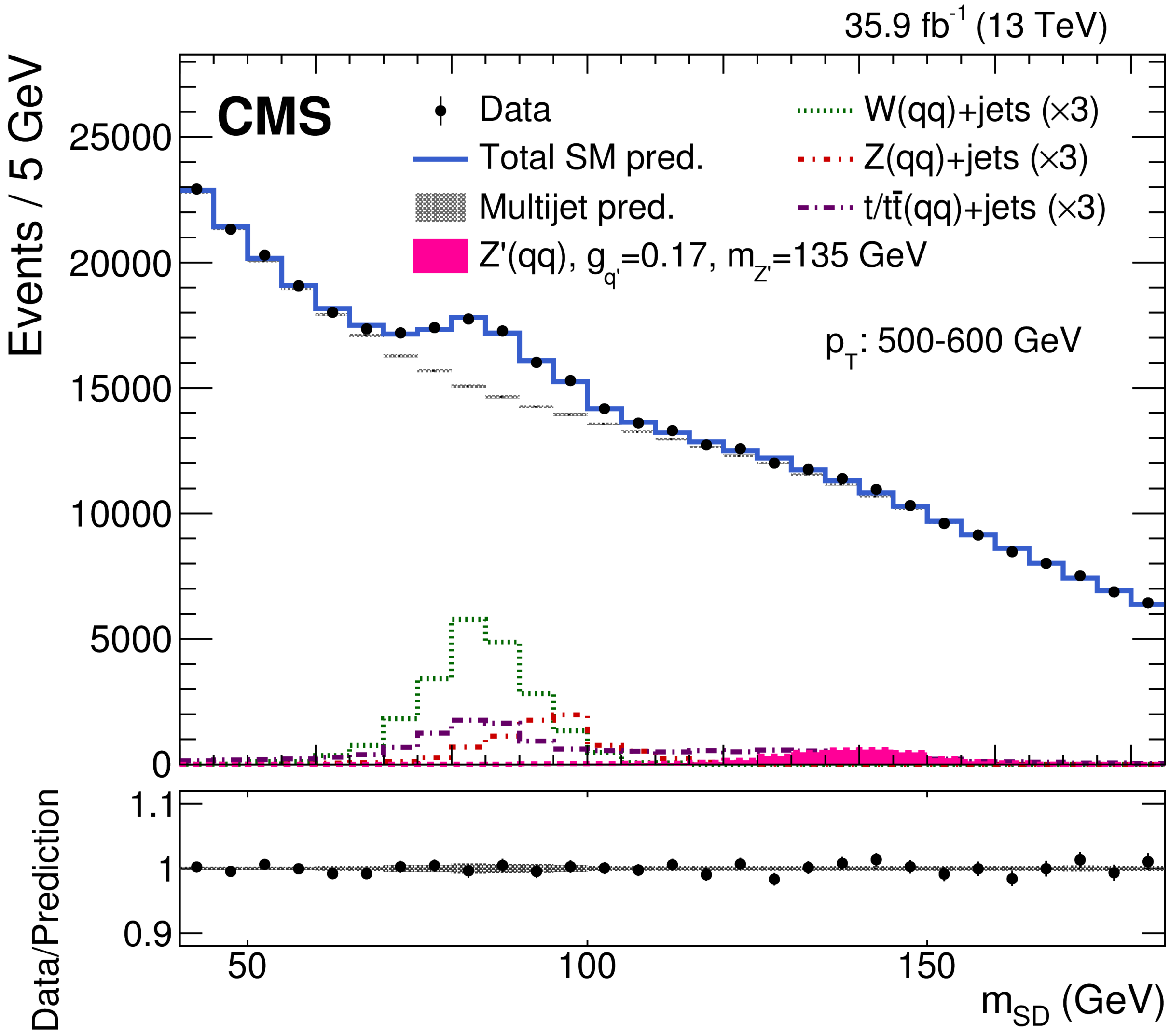


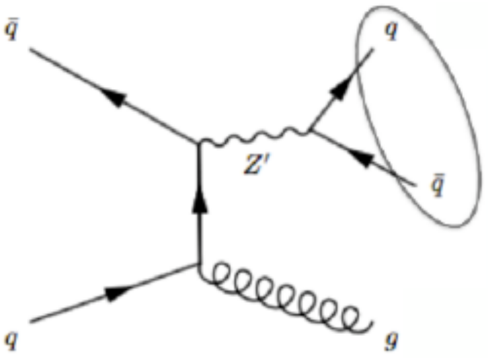
stolen from
T. Dorigo blog

Semileptonic ttbar events – ATLAS-CONF 2013-084



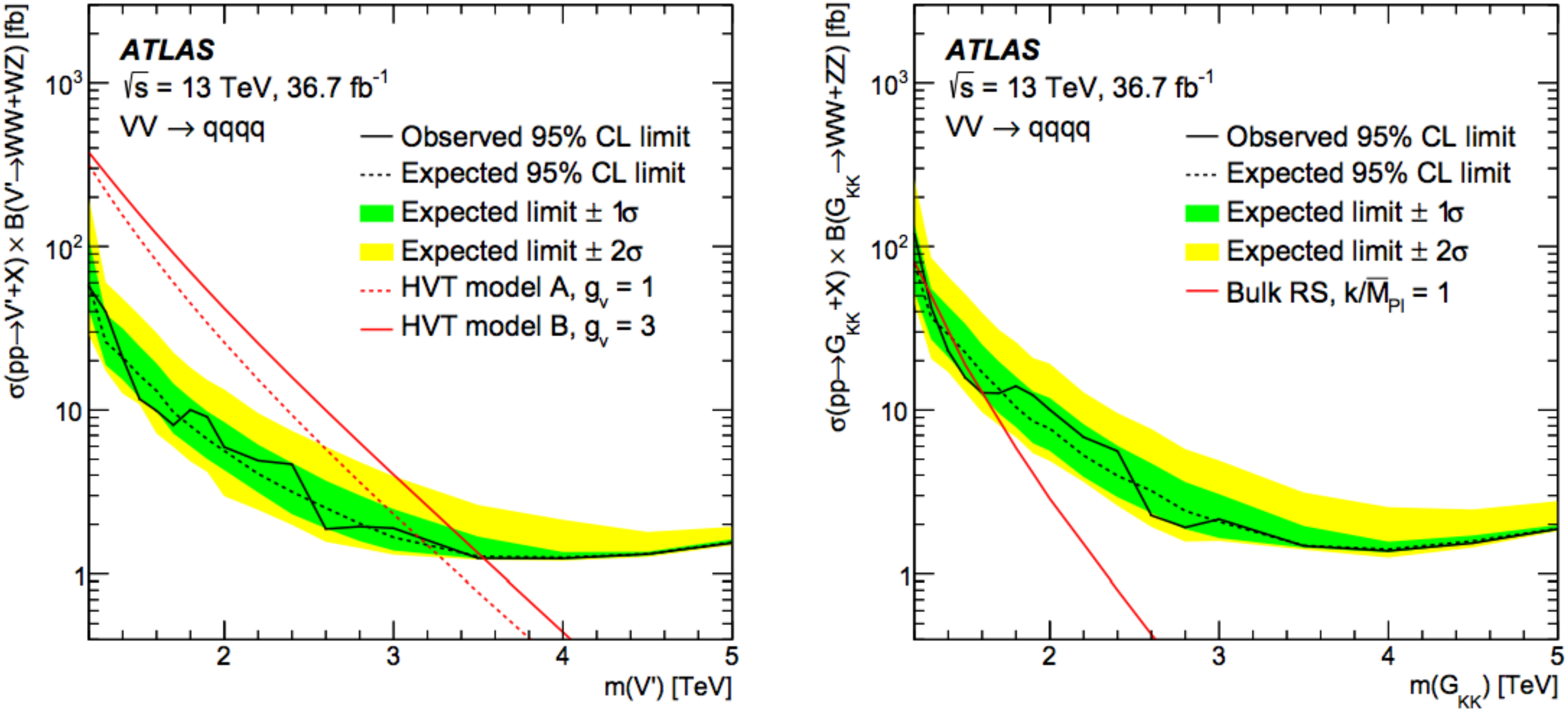






JHEP01(2018)097

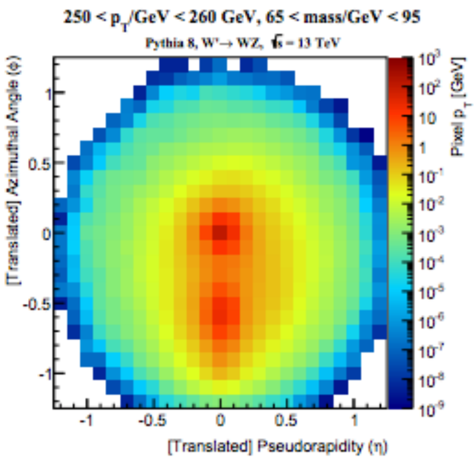
PLB 777 (2017) 91



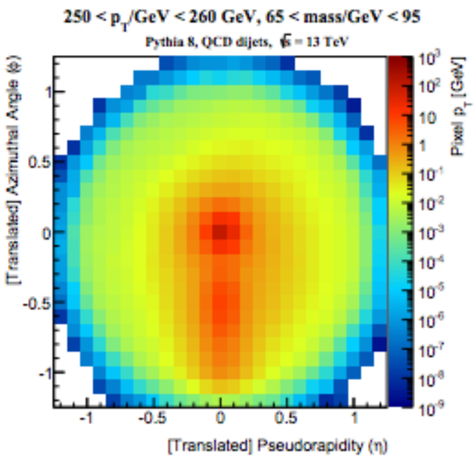
(a) *WW* + *WZ* signal region for HVT model

(b) *WW* + *ZZ* signal region for bulk RS model

A new frontier: machine learning?

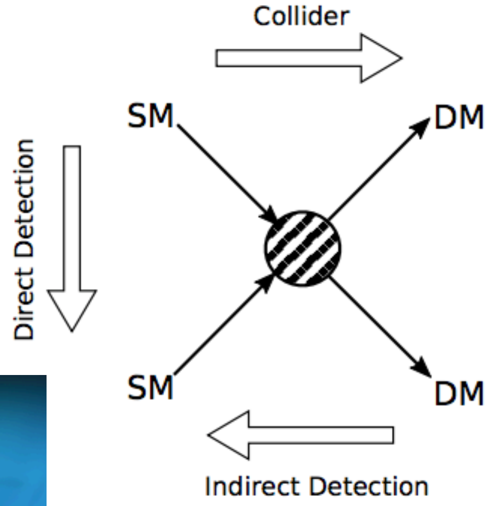


JHEP07(2016)069

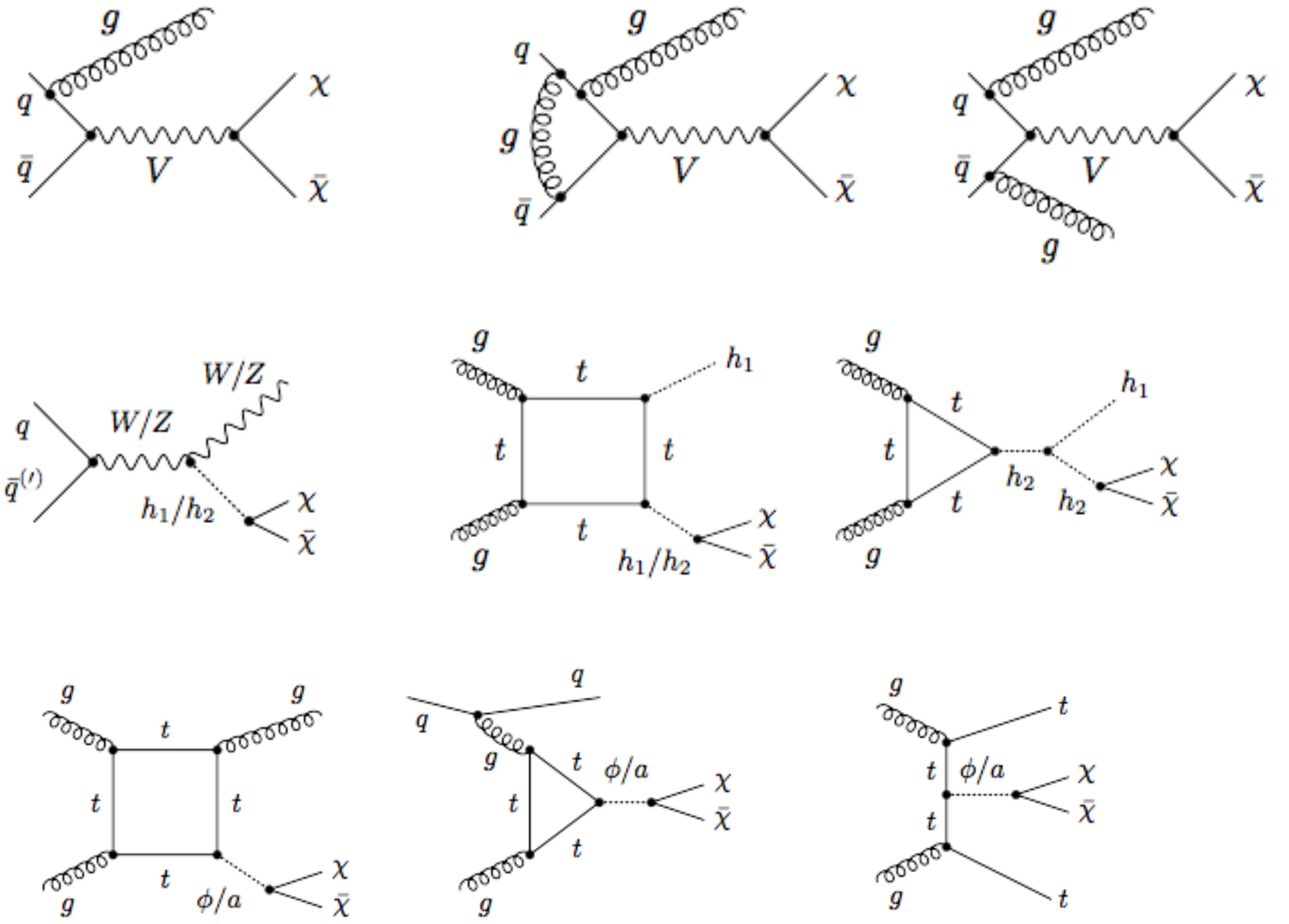


Dark Matter Searches

- These have become very popular as they potentially connect with the direct DM searches
- A new industry….



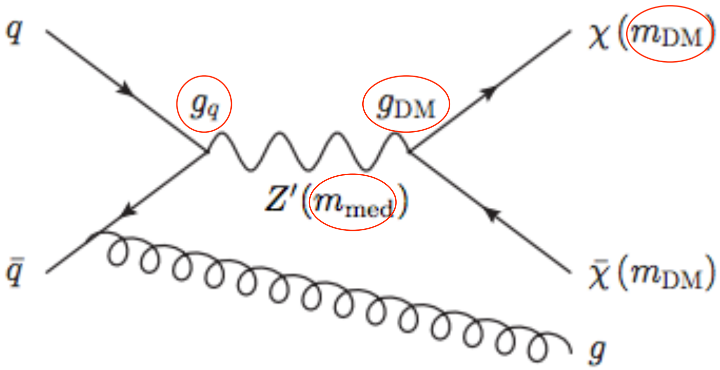
Simplified Models (again)



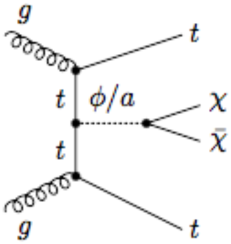
In addition to χ they introduce other new particles (V, ϕ, a….) and interactions

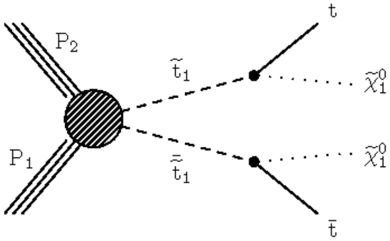
DM Simplified Models (cont.)

- More ad-hoc that SUSY simplified models as they need to introduce new particles and interactions (more parameters)

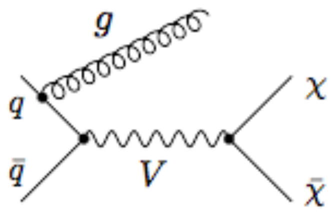


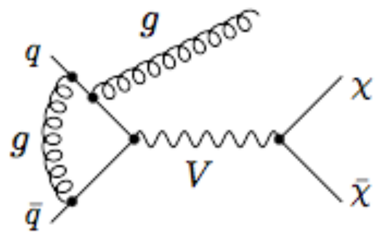
- In some cases the final states are ~ same as in SUSY models, and the analysis can be ~ same (but they aren't)

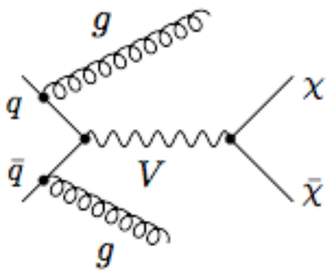




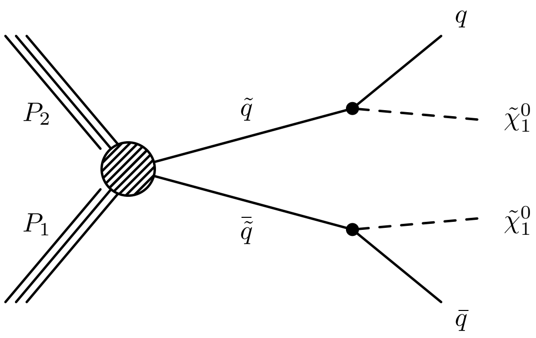
- In other cases the final states look the same but are really different.
- This is “jets + MET” a classic SUSY final state

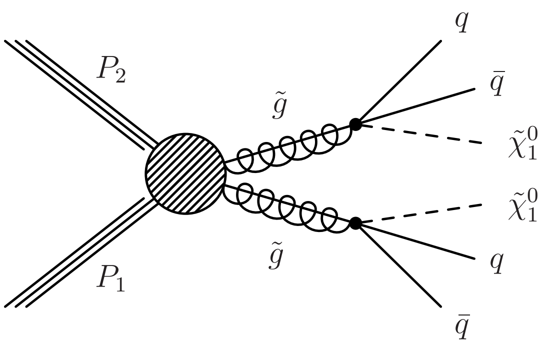


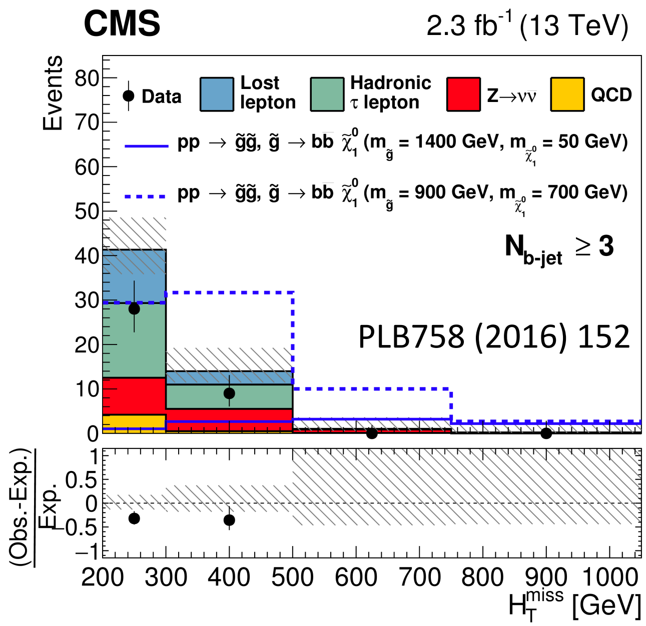




vs.



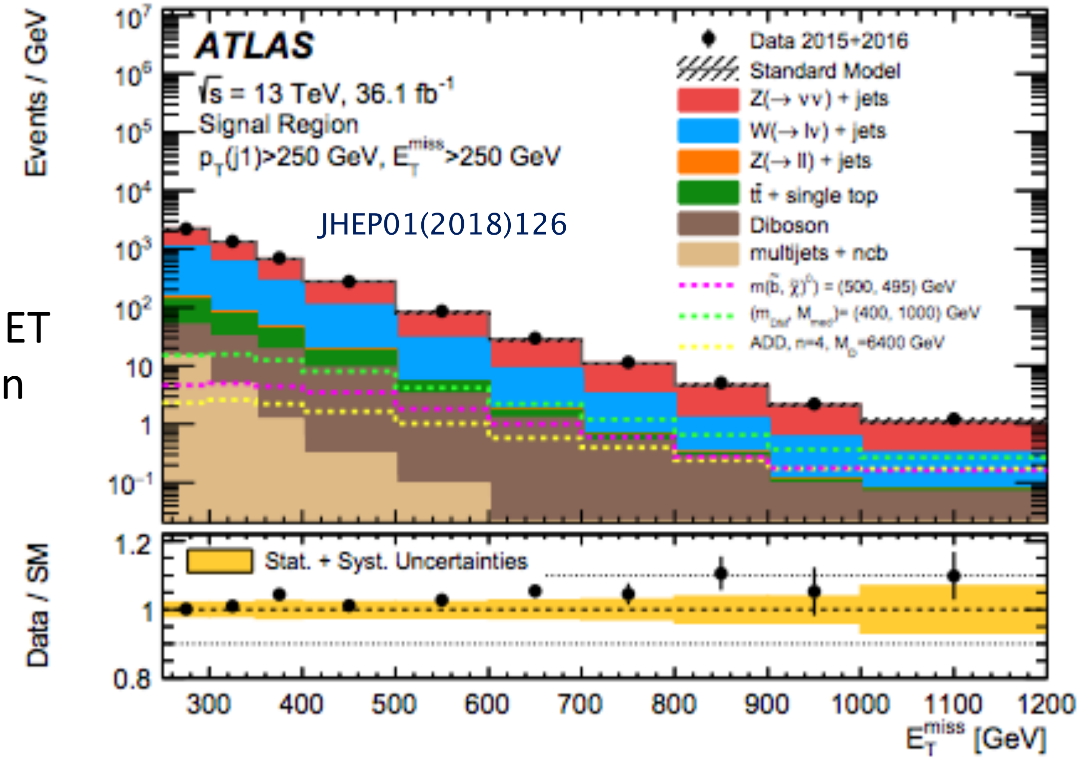




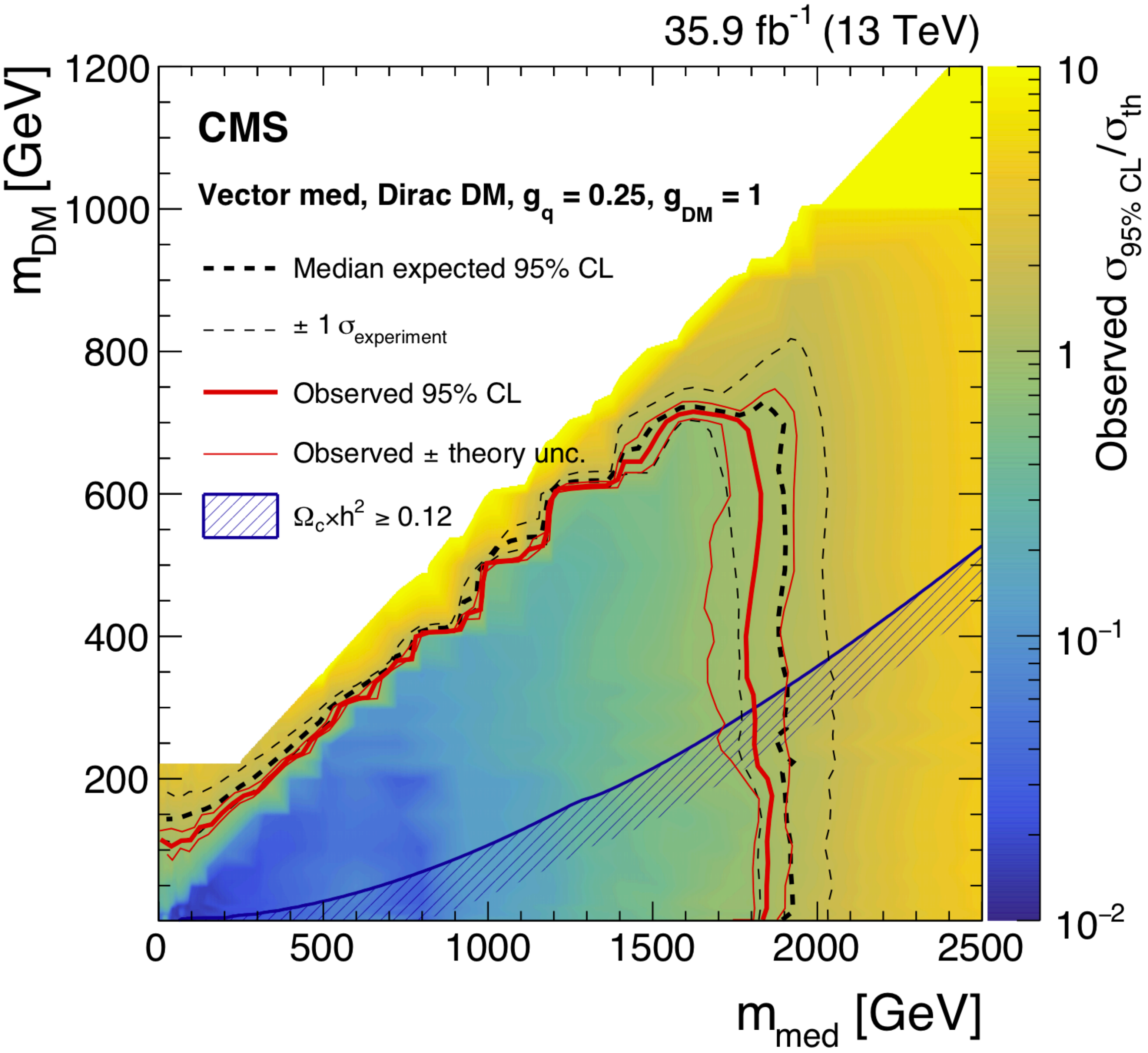
PLB758 (2016) 152

SUSY searches operate in the tails of MET

DM searches are in the bulk of SM MET
Requires fine control of SM prediction

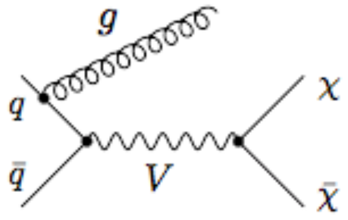


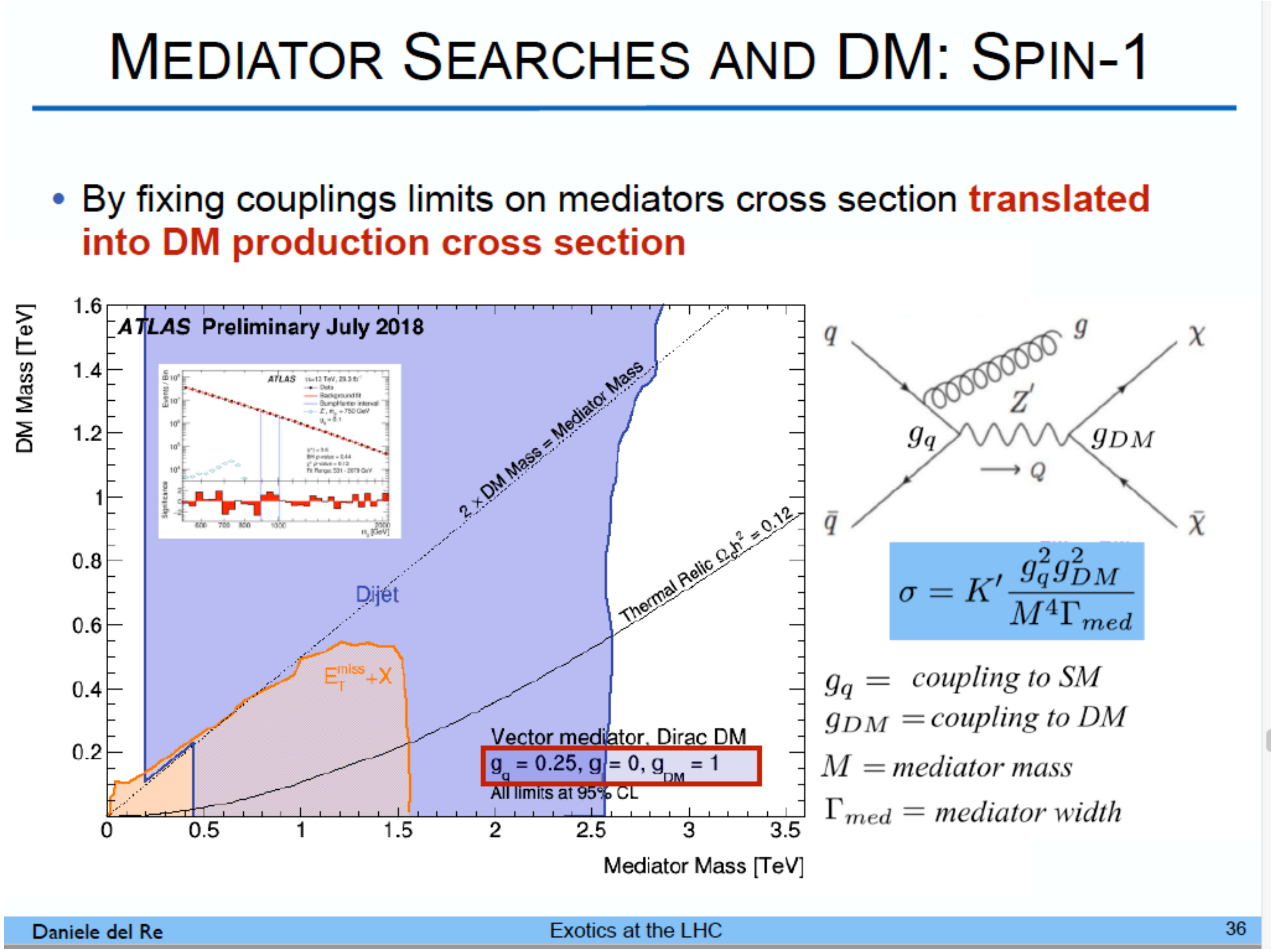
JHEP01(2018)126



35.9 fb^{-1} (13 TeV)
CMS
Vector med, Dirac DM, g_q = 0.25, g_{DM} = 1
Median expected 95% CL
± 1 $\sigma_{experiment}$
Observed 95% CL
Observed ± theory unc.
$\Omega_c \times h^2 \geq 0.12$
m_{DM} [GeV]
1200
1000
800
600
400
200
0
500
1000
1500
2000
2500
m_{med} [GeV]
10
1
10^{-1}
10^{-2}
Observed $\sigma_{95\%\ CL}/\sigma_{th}$

Some mediators are made through quark couplings.
So instead of decay to χχ they could decay to dijets.





MEDIATOR SEARCHES AND DM: SPIN-1

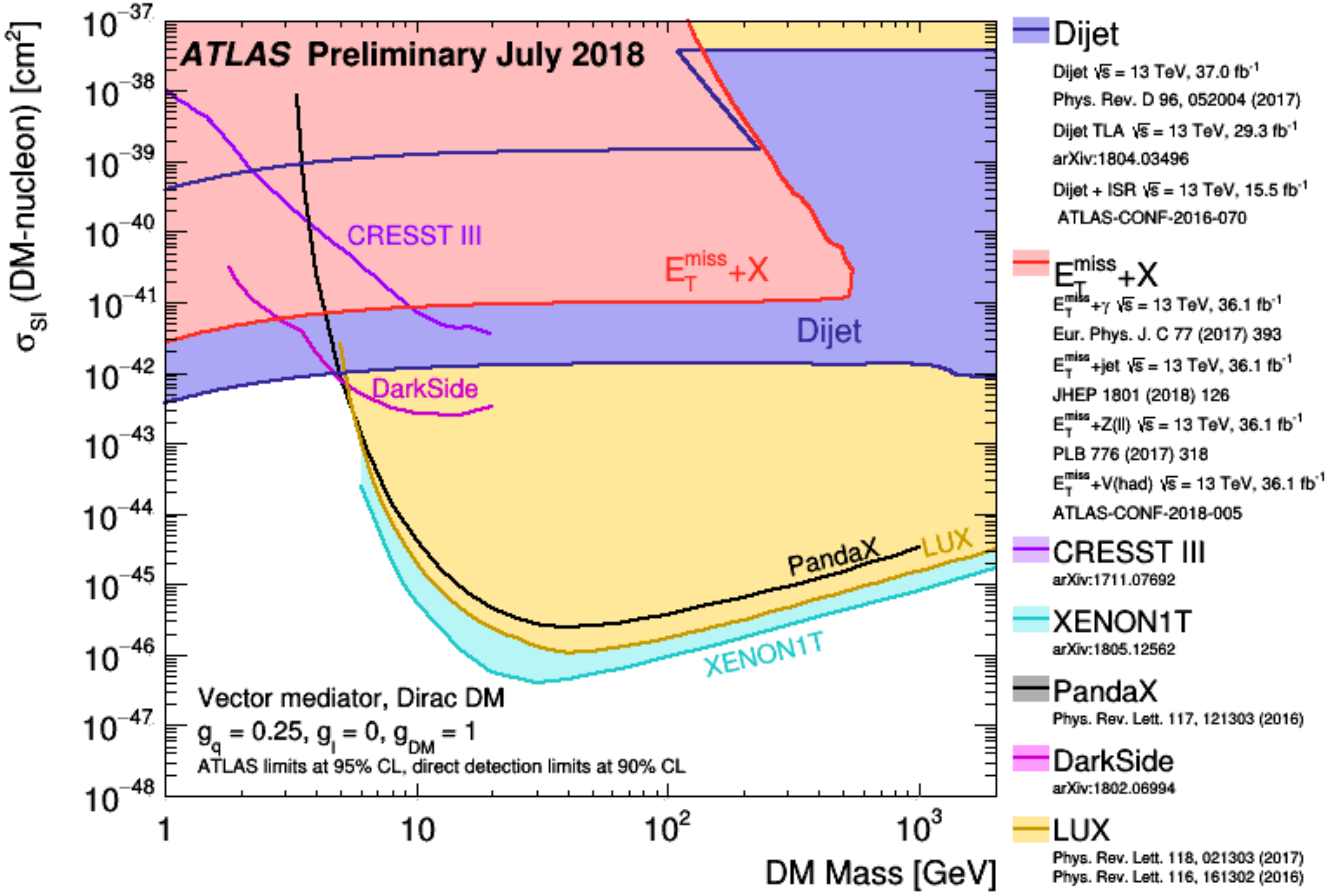
- By fixing couplings limits on mediators cross section **translated into DM production cross section**

$$\sigma = K' \frac{g_q^2 g_{DM}^2}{M^4 \Gamma_{med}}$$

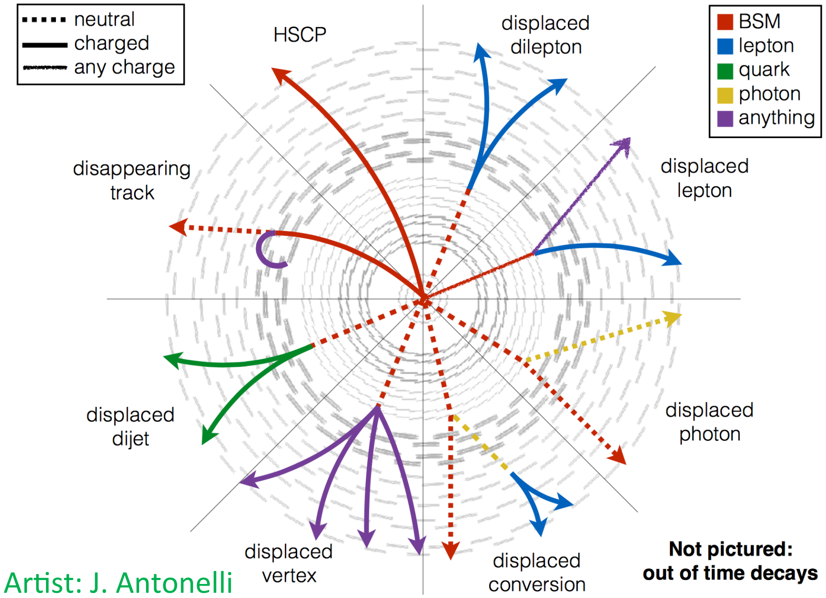
$g_q =$ coupling to SM
$g_{DM} =$ coupling to DM
$M =$ mediator mass
$\Gamma_{med} =$ mediator width

Daniele del Re Exotics at the LHC 36

ICHEP18 Conference

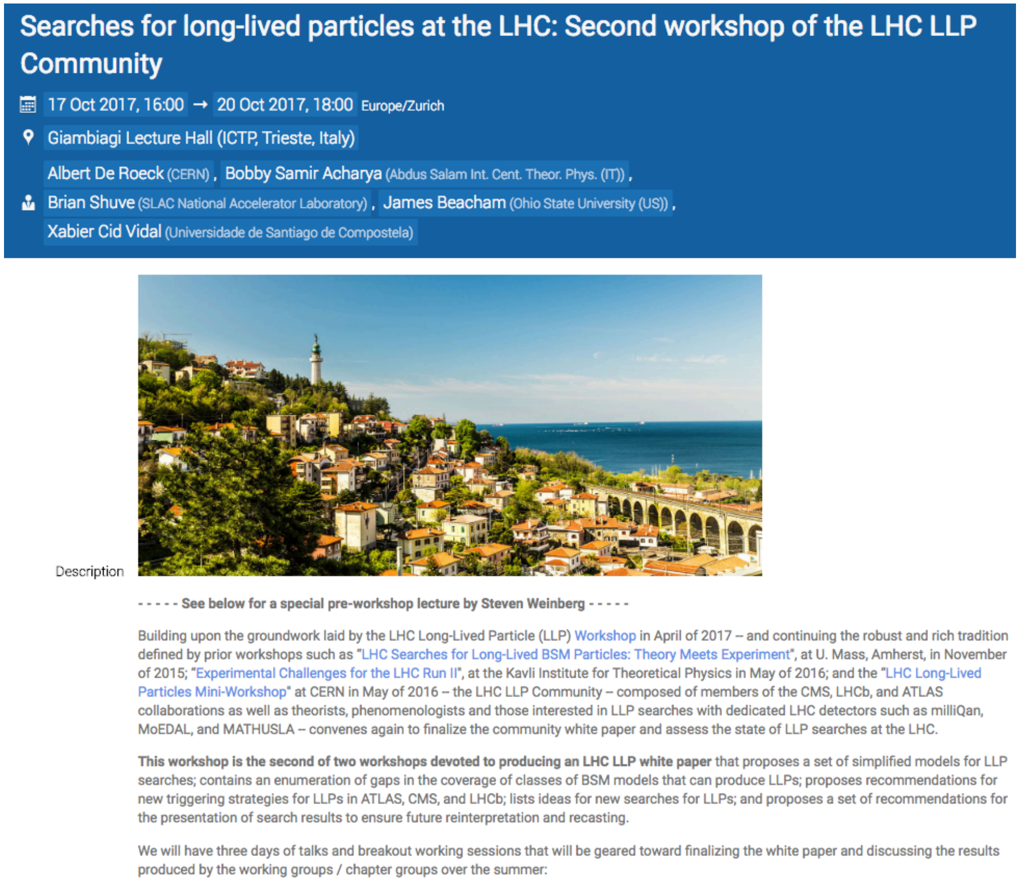

ATLAS Preliminary July 2018
σ_{SI} (DM-nucleon) [cm^2]
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
1
10
10^2
10^3
DM Mass [GeV]
CRESST III
E_T^{miss}+X
Dijet
DarkSide
PandaX
LUX
XENON1T
Vector mediator, Dirac DM
$g_q = 0.25$, $g_l = 0$, $g_{DM} = 1$
ATLAS limits at 95% CL, direct detection limits at 90% CL
Dijet
Dijet $\sqrt{s}$ = 13 TeV, 37.0 fb^{-1}
Phys. Rev. D 96, 052004 (2017)
Dijet TLA $\sqrt{s}$ = 13 TeV, 29.3 fb^{-1}
arXiv:1804.03496
Dijet + ISR $\sqrt{s}$ = 13 TeV, 15.5 fb^{-1}
ATLAS-CONF-2016-070
E_T^{miss}+X
E_T^{miss}+γ $\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
Eur. Phys. J. C 77 (2017) 393
E_T^{miss}+jet $\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
JHEP 1801 (2018) 126
E_T^{miss}+Z(ll) $\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
PLB 776 (2017) 318
E_T^{miss}+V(had) $\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
ATLAS-CONF-2018-005
CRESST III
arXiv:1711.07692
XENON1T
arXiv:1805.12562
PandaX
Phys. Rev. Lett. 117, 121303 (2016)
DarkSide
arXiv:1802.06994
LUX
Phys. Rev. Lett. 118, 021303 (2017)
Phys. Rev. Lett. 116, 161302 (2016)

Long Lived and other weirdness



Not pictured:
out of time decays

Artist: J. Antonelli



Searches for long-lived particles at the LHC: Second workshop of the LHC LLP Community

17 Oct 2017, 16:00 → 20 Oct 2017, 18:00 Europe/Zurich

Giambiagi Lecture Hall (ICTP, Trieste, Italy)

Albert De Roeck (CERN), Bobby Samir Acharya (Abdus Salam Int. Cent. Theor. Phys. (IT)), Brian Shuve (SLAC National Accelerator Laboratory), James Beacham (Ohio State University (US)), Xabier Cid Vidal (Universidade de Santiago de Compostela)

Description

- - - - - See below for a special pre-workshop lecture by Steven Weinberg - - - - -

Building upon the groundwork laid by the LHC Long-Lived Particle (LLP) Workshop in April of 2017 -- and continuing the robust and rich tradition defined by prior workshops such as "LHC Searches for Long-Lived BSM Particles: Theory Meets Experiment", at U. Mass, Amherst, in November of 2015; "Experimental Challenges for the LHC Run II", at the Kavli Institute for Theoretical Physics in May of 2016; and the "LHC Long-Lived Particles Mini-Workshop" at CERN in May of 2016 -- the LHC LLP Community -- composed of members of the CMS, LHCb, and ATLAS collaborations as well as theorists, phenomenologists and those interested in LLP searches with dedicated LHC detectors such as milliQan, MoEDAL, and MATHUSLA -- convenes again to finalize the community white paper and assess the state of LLP searches at the LHC.

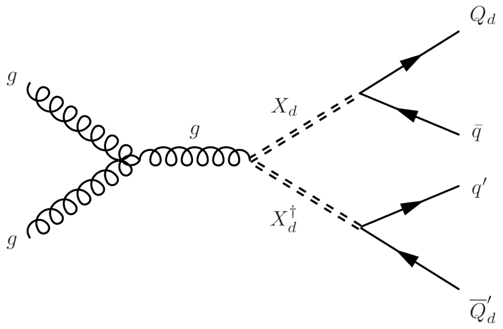
This workshop is the second of two workshops devoted to producing an LHC LLP white paper that proposes a set of simplified models for LLP searches; contains an enumeration of gaps in the coverage of classes of BSM models that can produce LLPs; proposes recommendations for new triggering strategies for LLPs in ATLAS, CMS, and LHCb; lists ideas for new searches for LLPs; and proposes a set of recommendations for the presentation of search results to ensure future reinterpretation and recasting.

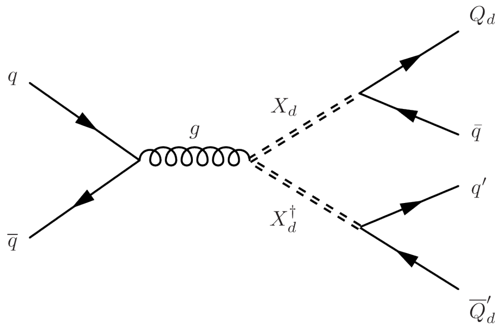
We will have three days of talks and breakout working sessions that will be geared toward finalizing the white paper and discussing the results produced by the working groups / chapter groups over the summer:

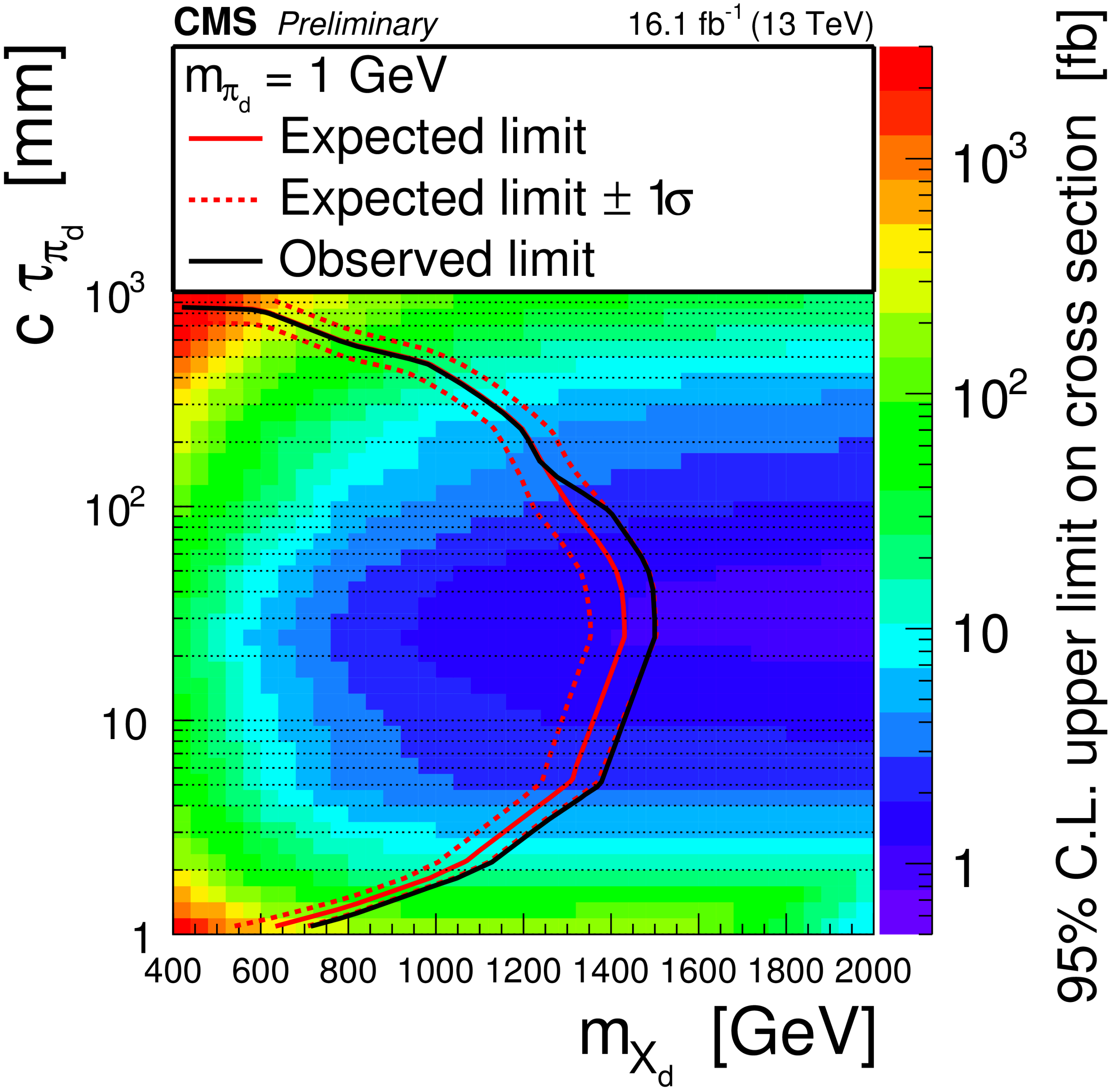
One example

CMS-EXO-18-001

- There is a “dark” QCD sector
- There is a TeV-scale mediator (X) that couples to dark quarks (Q) and ”our” quarks (q)
- The dark quarks make GeV-scale dark pions (π_d)
- The dark pions have long lifetimes (mm → m)
- Mediators are pair-produced, then X→Qq
- Get four jets
  - Two “normal” jets
  - Two emerging jets, with many displaced tracks
    - Maybe even decaying outside tracker (MET)







CMS Preliminary
16.1 fb^{-1} (13 TeV)
m_{π_d} = 1 GeV
Expected limit
Expected limit ± 1σ
Observed limit
$c\,\tau_{\pi_d}$ [mm]
1
10
10^2
10^3
400
600
800
1000
1200
1400
1600
1800
2000
m_{X_d} [GeV]
1
10
10^2
10^3
95% C.L. upper limit on cross section [fb]

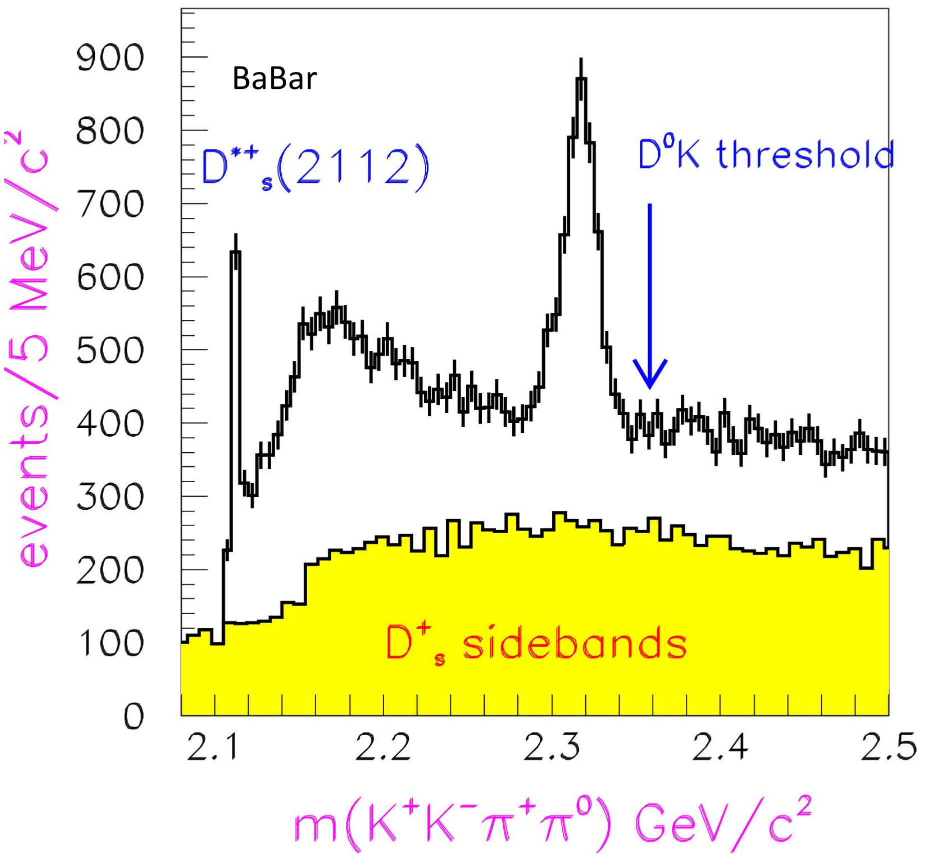
Comments

- The search is very cool
  - Two standard jets, two weird jets
- Model not very compelling
  - But it motivated a cool search
- Why do we need (crazy) models to motivate cool searches?
- Why isn't there a search for e.g. Z + two weird jets
  - Because there is no model?
- Sociological reality: without model search does not start
  - Also: how to make pretty colorful plots without a model?

What are we missing?

- What are we missing in the trigger?

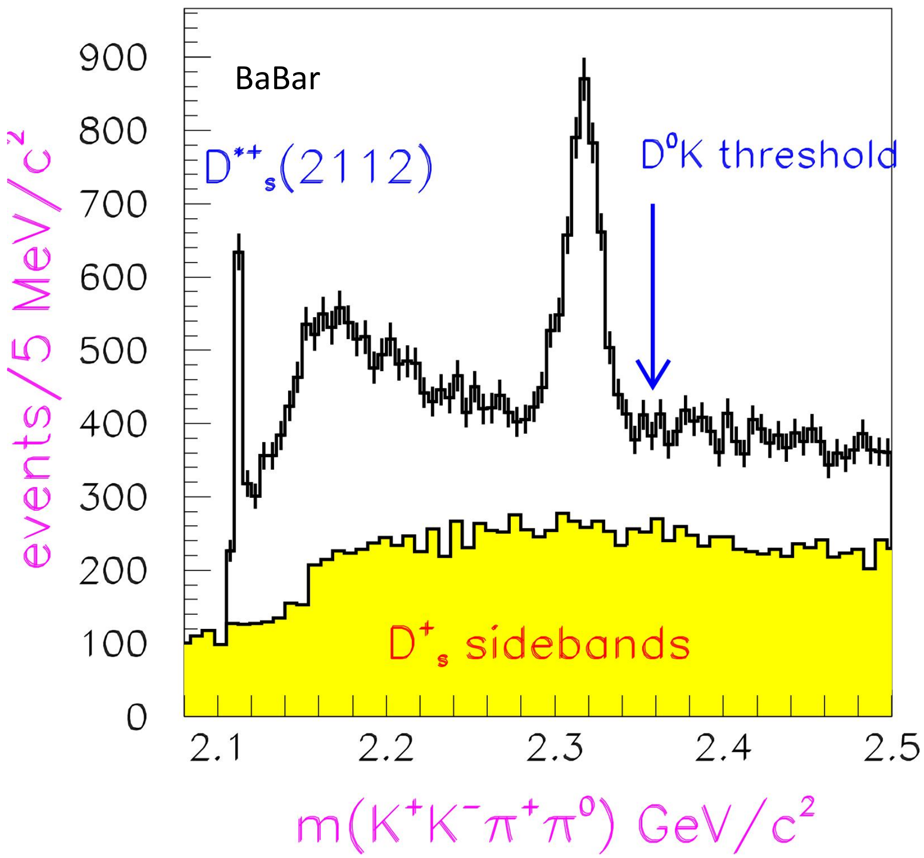
- What are we missing by not looking?



$D_{sJ}(2317) \rightarrow D_S\, \pi^0$
PRL90 242001 (2003)

This huge signal had been in various data sets for many years.

- Nobody had ever looked
- Why?



$D_{sJ}(2317) \rightarrow D_S\, \pi^0$
PRL90 242001 (2003)

This huge signal had been in various data sets for many years.

- Nobody had ever looked
- Why?

Don't believe theorists too much!

Trigger issues

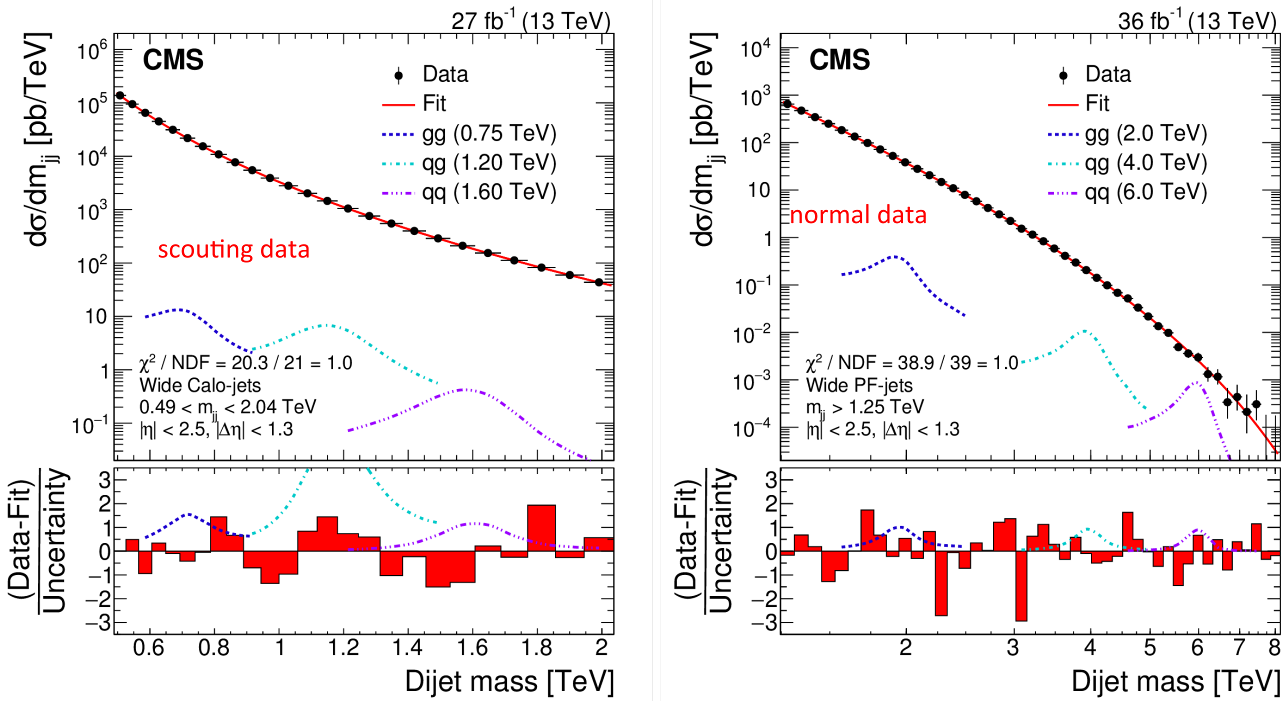
- New clever triggers are being developed all the time
  - Very important
- Even more possibilities at HL-LHC
  - Track triggers, etc
- Fundamentally we are limited by 1-2 kHz output rate
- A colleague suggested that in Run 3 we should prescale by (say) factor 2 the “standard” triggers on which the high P_T searches have been based. Give the bandwidth to other stuff
  - Just a bit crazy?

Delayed reco. & Real Time Analysis

- The ~ 1 kHz limit is not determined by DAQ hardware but by rate at which data can be reconstructed
- Read out more data that can be processed and set some of it aside for later reconstruction
  - Lower priority analyses
  - Data Parking, Delayed Stream
- Reasonably straightforward

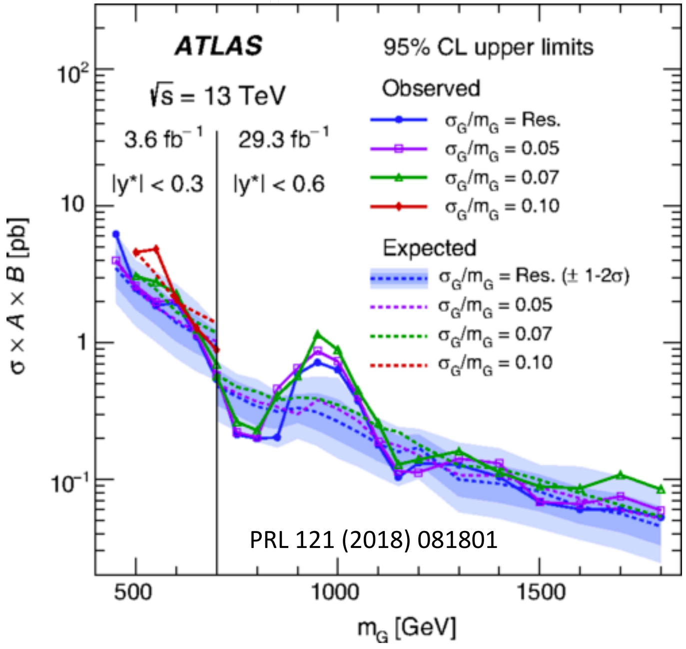
- In some cases move much of the analysis to HLT
- Write out data in reduced format (smaller events)
  - Scouting, Trigger Level Object Analysis
- Challenges with calibrations, etc.
  - Demonstrated
  - Dijet mass searches

arXiv:1806.00843



scouting data

normal data



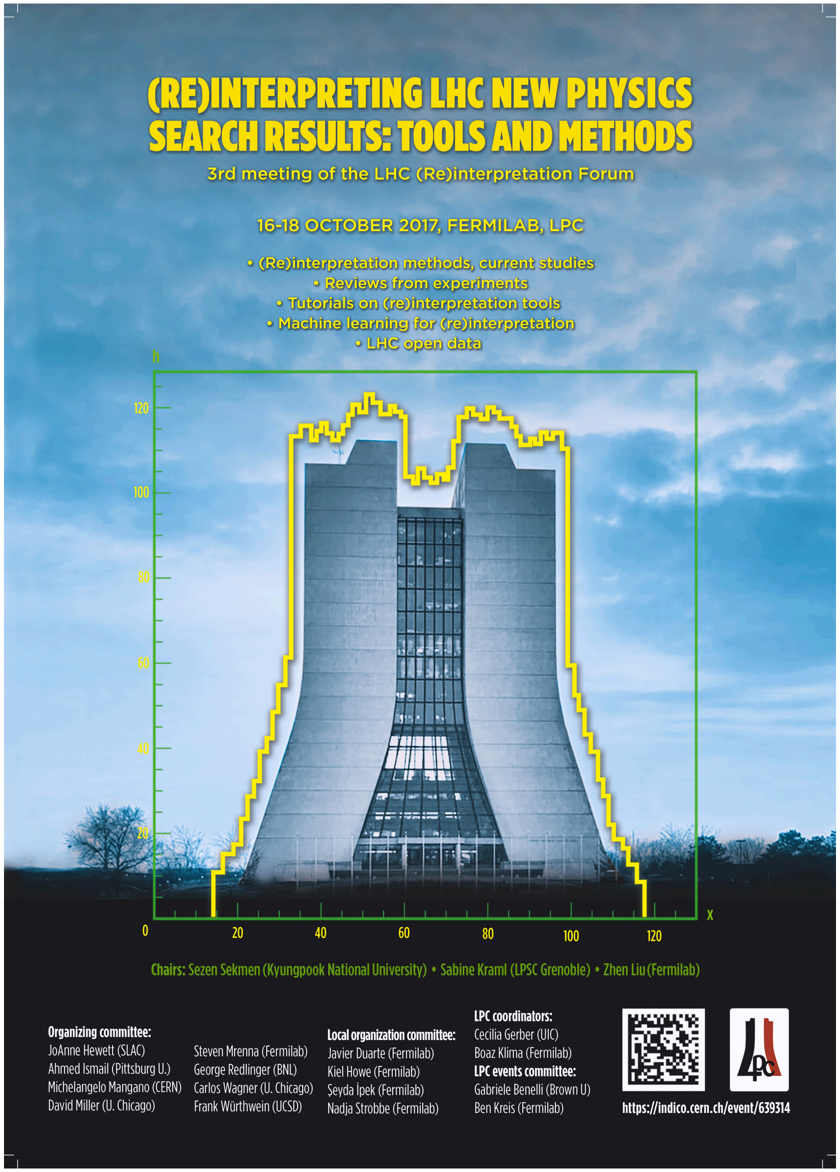
PRL 121 (2018) 081801

Communicating results

- Important to communicate results of searches so that they can be re-used to challenge new models or ideas

  → Make it possible for outsiders to reinterpret results

- Seems obvious, but
  - A bit controversial inside experiments at the beginning of LHC
  - Confusion with many tools/ approaches on the market



(RE)INTERPRETING LHC NEW PHYSICS SEARCH RESULTS: TOOLS AND METHODS

3rd meeting of the LHC (Re)interpretation Forum

16-18 OCTOBER 2017, FERMILAB, LPC

- (Re)interpretation methods, current studies
- Reviews from experiments
- Tutorials on (re)interpretation tools
- Machine learning for (re)interpretation
- LHC open data

Chairs: Sezen Sekmen (Kyungpook National University) • Sabine Kraml (LPSC Grenoble) • Zhen Liu (Fermilab)

Organizing committee:
JoAnne Hewett (SLAC)
Ahmed Ismail (Pittsburg U.)
Michelangelo Mangano (CERN)
David Miller (U. Chicago)
Steven Mrenna (Fermilab)
George Redlinger (BNL)
Carlos Wagner (U. Chicago)
Frank Würthwein (UCSD)

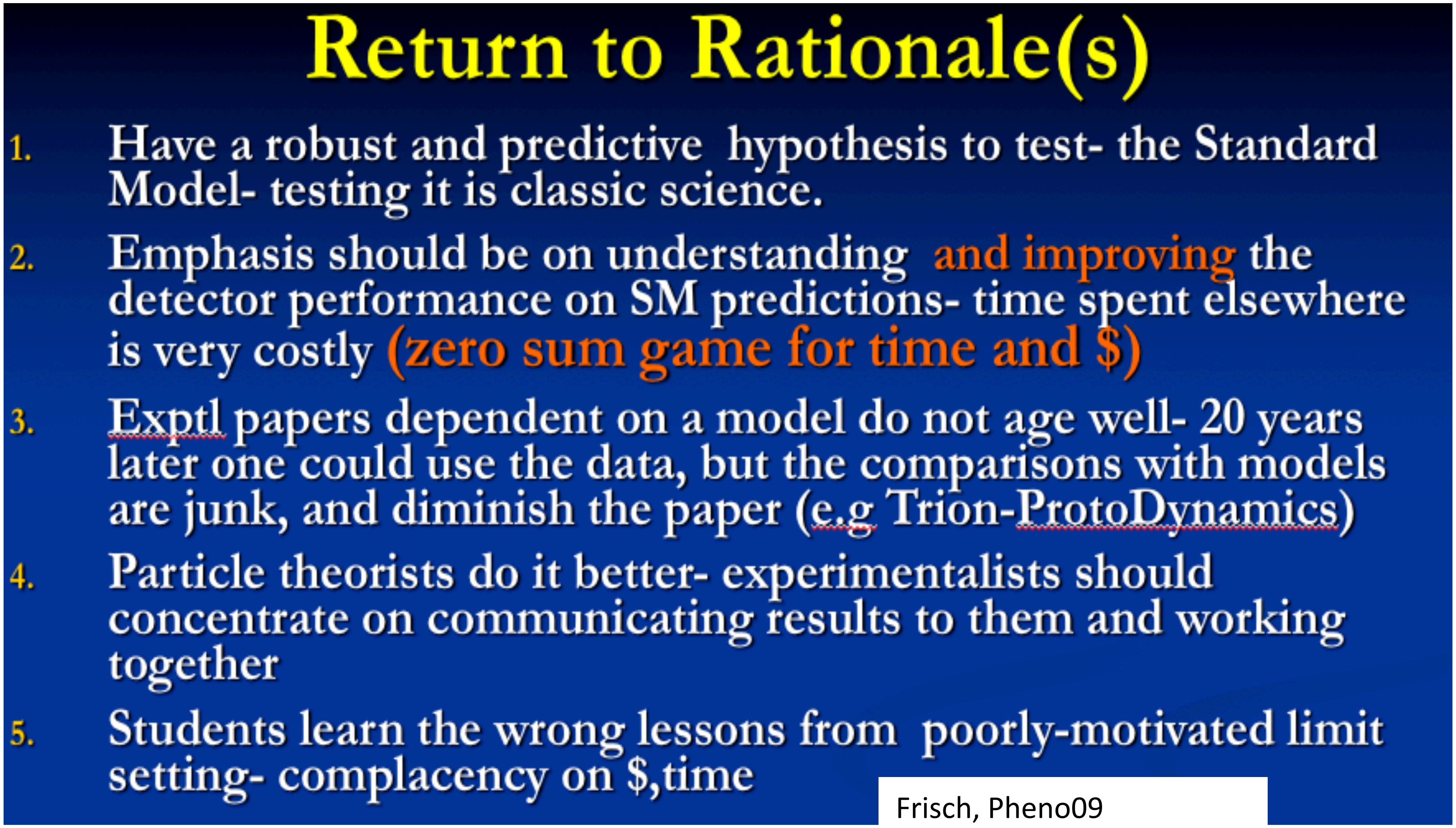
Local organization committee:
Javier Duarte (Fermilab)
Kiel Howe (Fermilab)
Şeyda İpek (Fermilab)
Nadja Strobbe (Fermilab)

LPC coordinators:
Cecilia Gerber (UIC)
Boaz Klima (Fermilab)

LPC events committee:
Gabriele Benelli (Brown U)
Ben Kreis (Fermilab)

https://indico.cern.ch/event/639314

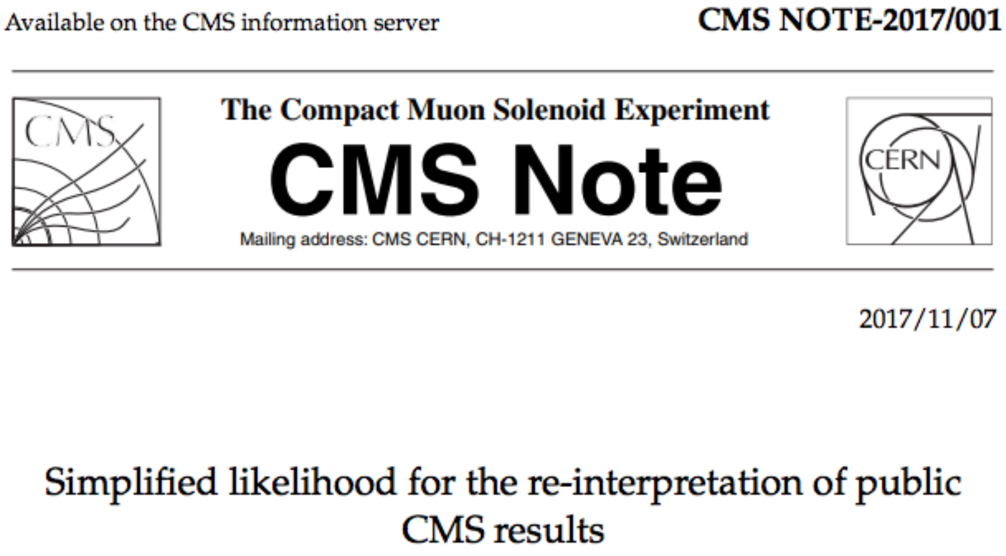
Some people never liked the emphasis on models.....



Return to Rationale(s)

1. Have a robust and predictive hypothesis to test- the Standard Model- testing it is classic science.
2. Emphasis should be on understanding and improving the detector performance on SM predictions- time spent elsewhere is very costly (zero sum game for time and $)
3. Exptl papers dependent on a model do not age well- 20 years later one could use the data, but the comparisons with models are junk, and diminish the paper (e.g Trion-ProtoDynamics)
4. Particle theorists do it better- experimentalists should concentrate on communicating results to them and working together
5. Students learn the wrong lessons from poorly-motivated limit setting- complacency on $,time

Frisch, Pheno09



Available on the CMS information server

CMS NOTE-2017/001

The Compact Muon Solenoid Experiment

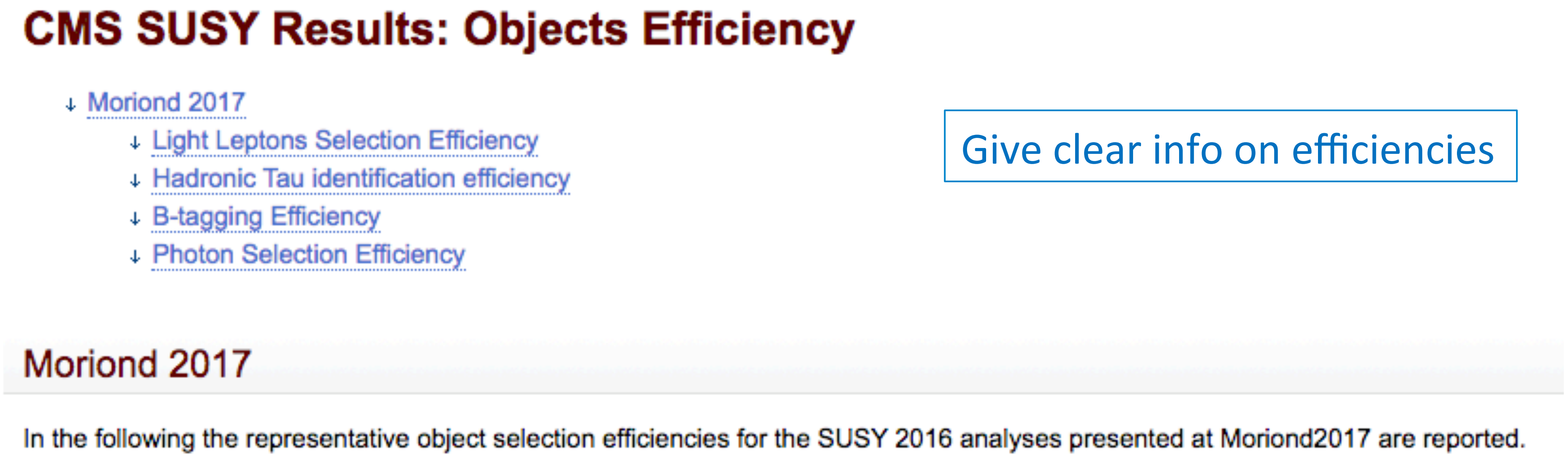
CMS Note

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

2017/11/07

Simplified likelihood for the re-interpretation of public CMS results

Make info available to re-interpret complicated searches
(many bins, results of fits, etc.)



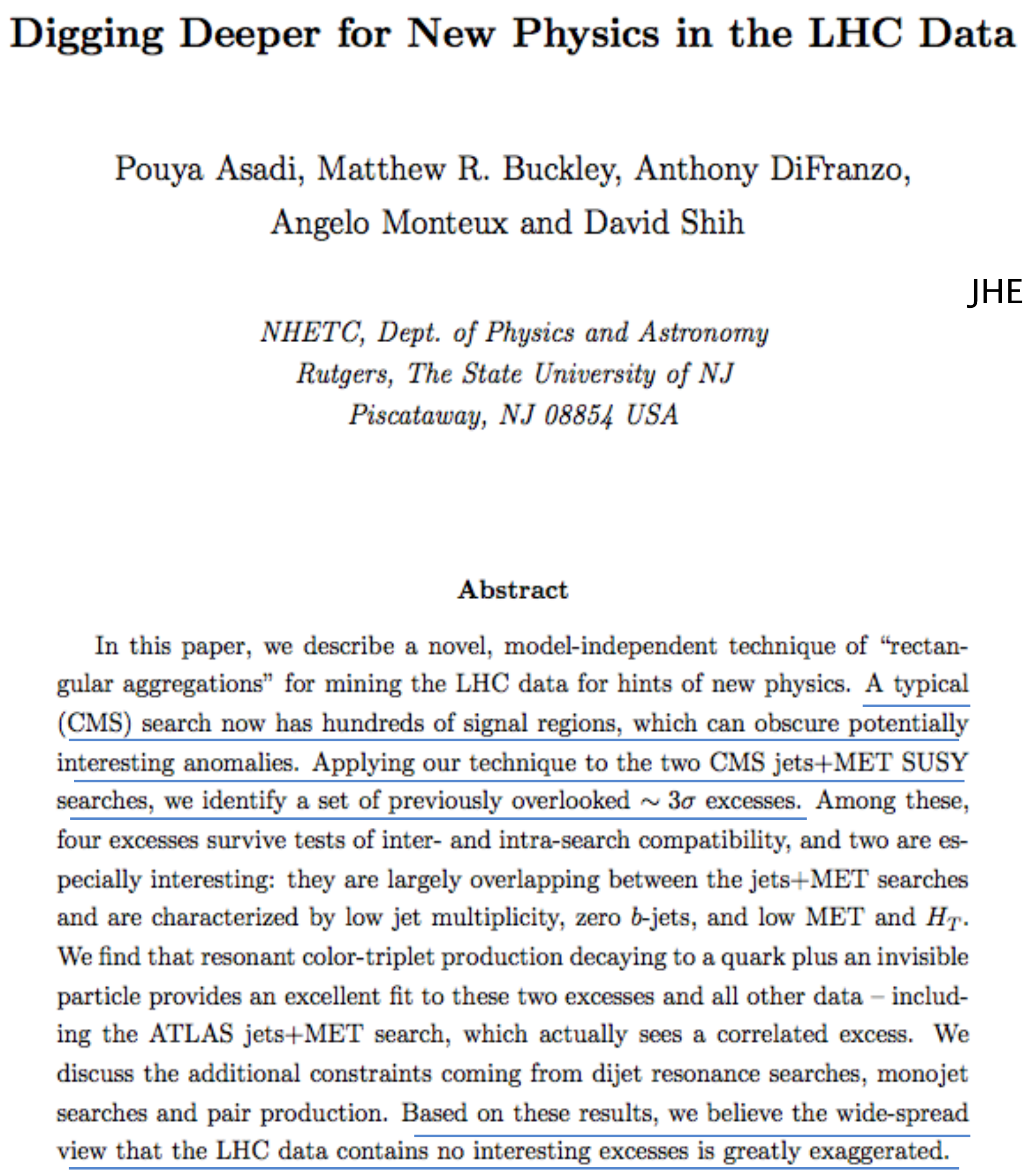
CMS SUSY Results: Objects Efficiency

- Moriond 2017
    - Light Leptons Selection Efficiency
    - Hadronic Tau identification efficiency
    - B-tagging Efficiency
    - Photon Selection Efficiency

Moriond 2017

In the following the representative object selection efficiencies for the SUSY 2016 analyses presented at Moriond2017 are reported.

Give clear info on efficiencies



Digging Deeper for New Physics in the LHC Data

Pouya Asadi, Matthew R. Buckley, Anthony DiFranzo,
Angelo Monteux and David Shih

NHETC, Dept. of Physics and Astronomy
Rutgers, The State University of NJ
Piscataway, NJ 08854 USA

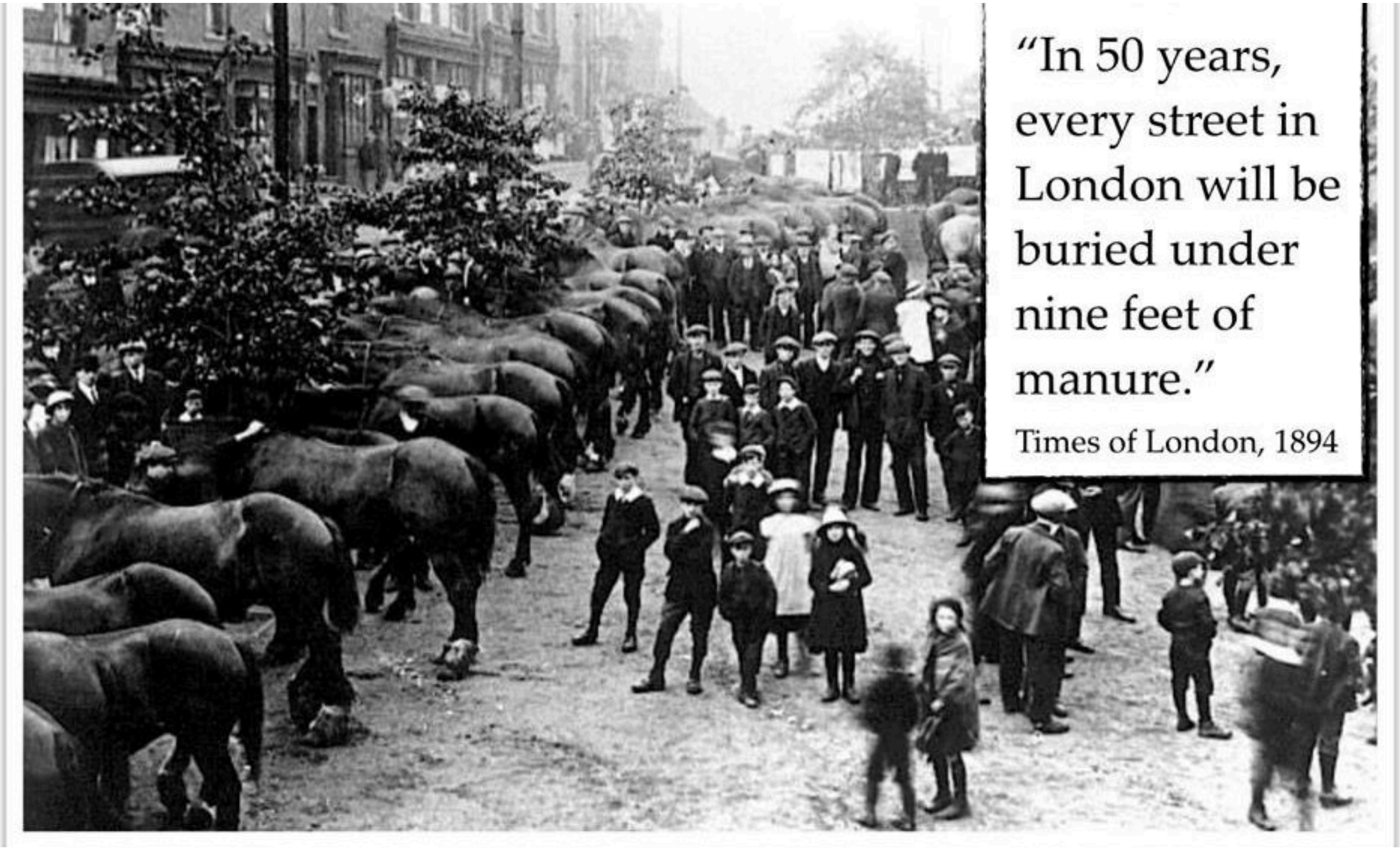
JHEP11(2017)194

Abstract

In this paper, we describe a novel, model-independent technique of "rectangular aggregations" for mining the LHC data for hints of new physics. A typical (CMS) search now has hundreds of signal regions, which can obscure potentially interesting anomalies. Applying our technique to the two CMS jets+MET SUSY searches, we identify a set of previously overlooked $\sim 3\sigma$ excesses. Among these, four excesses survive tests of inter- and intra-search compatibility, and two are especially interesting: they are largely overlapping between the jets+MET searches and are characterized by low jet multiplicity, zero b-jets, and low MET and H_T. We find that resonant color-triplet production decaying to a quark plus an invisible particle provides an excellent fit to these two excesses and all other data – including the ATLAS jets+MET search, which actually sees a correlated excess. We discuss the additional constraints coming from dijet resonance searches, monojet searches and pair production. Based on these results, we believe the wide-spread view that the LHC data contains no interesting excesses is greatly exaggerated.

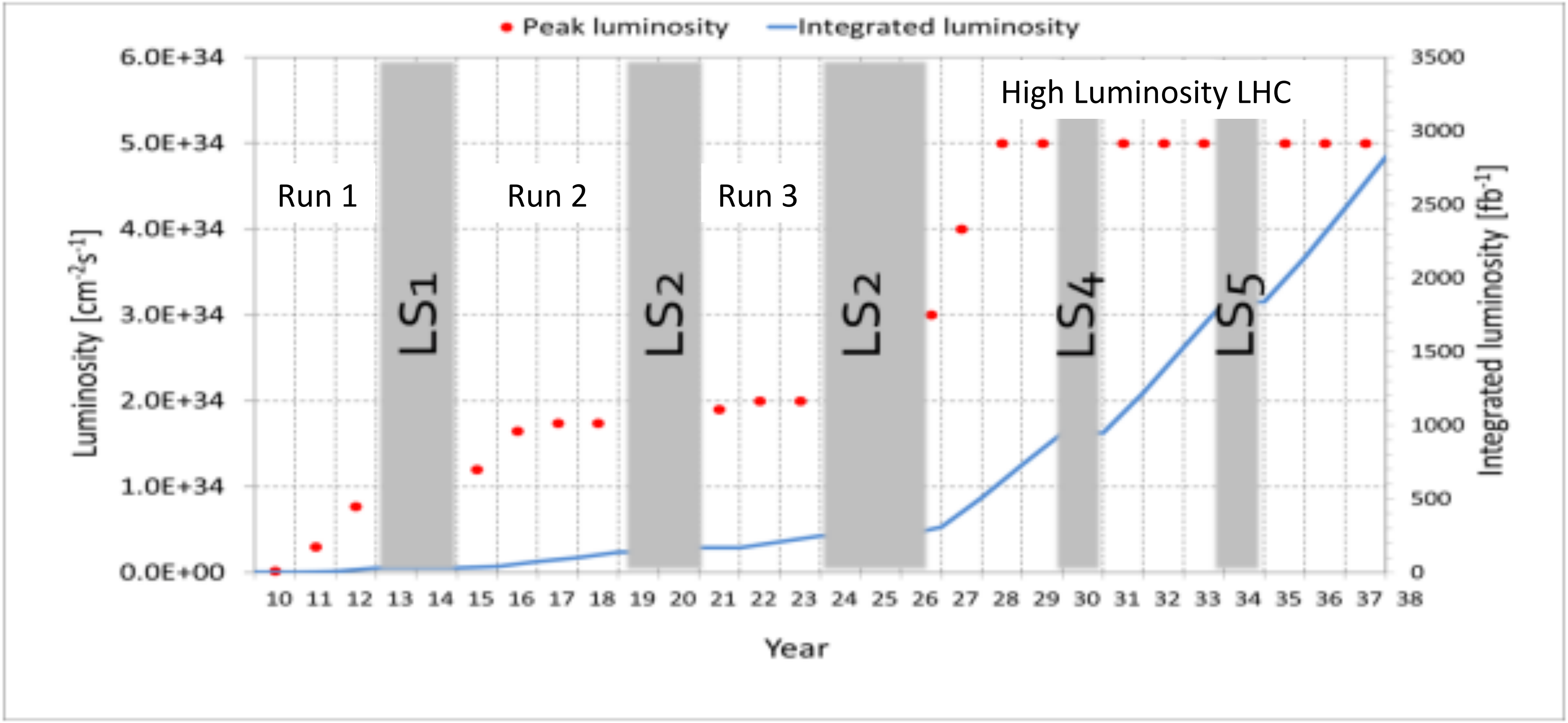
The future?

Predicting the **future** is hard



> "In 50 years, every street in London will be buried under nine feet of manure."
>
> Times of London, 1894

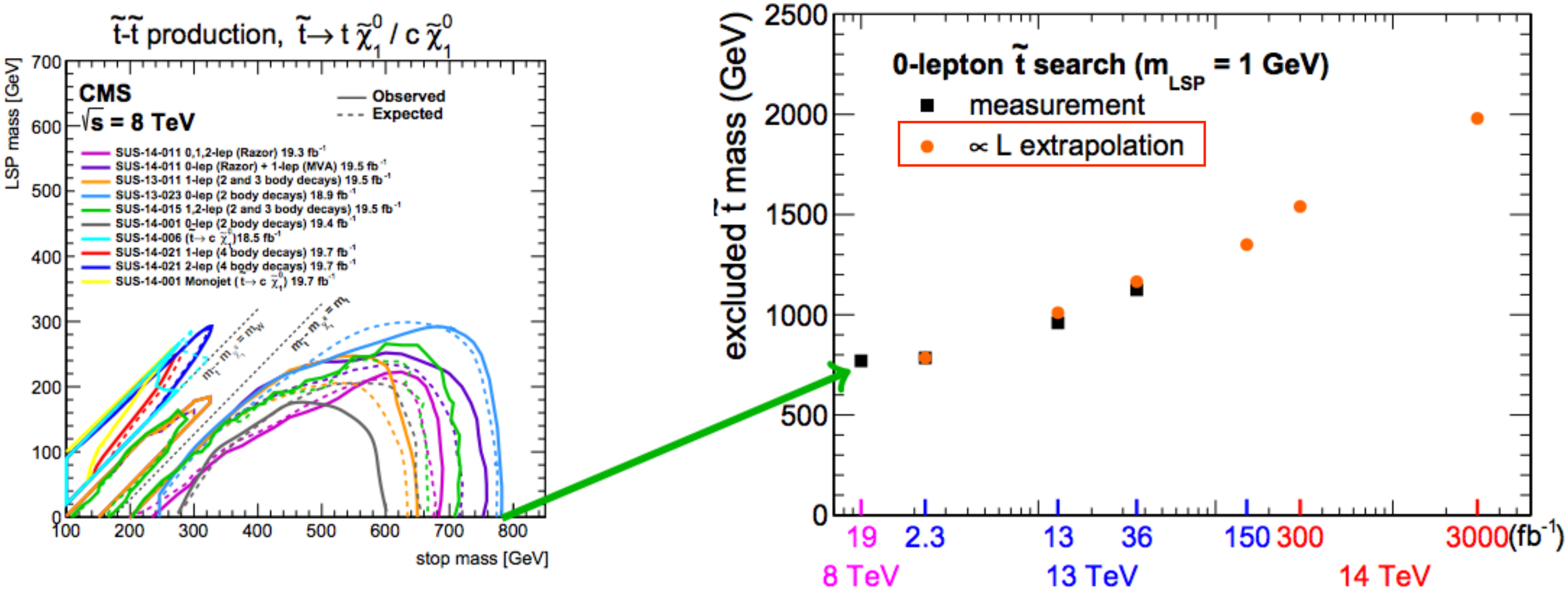
The great horse manure crisis of 1894

● Peak luminosity
Integrated luminosity
Luminosity [cm^{-2}s^{-1}]
6.0E+34
5.0E+34
4.0E+34
3.0E+34
2.0E+34
1.0E+34
0.0E+00
Integrated luminosity [fb^{-1}]
3500
3000
2500
2000
1500
1000
500
0
10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38
Year
Run 1
Run 2
Run 3
High Luminosity LHC
LS1
LS2
LS2
LS4
LS5

Future of Searches

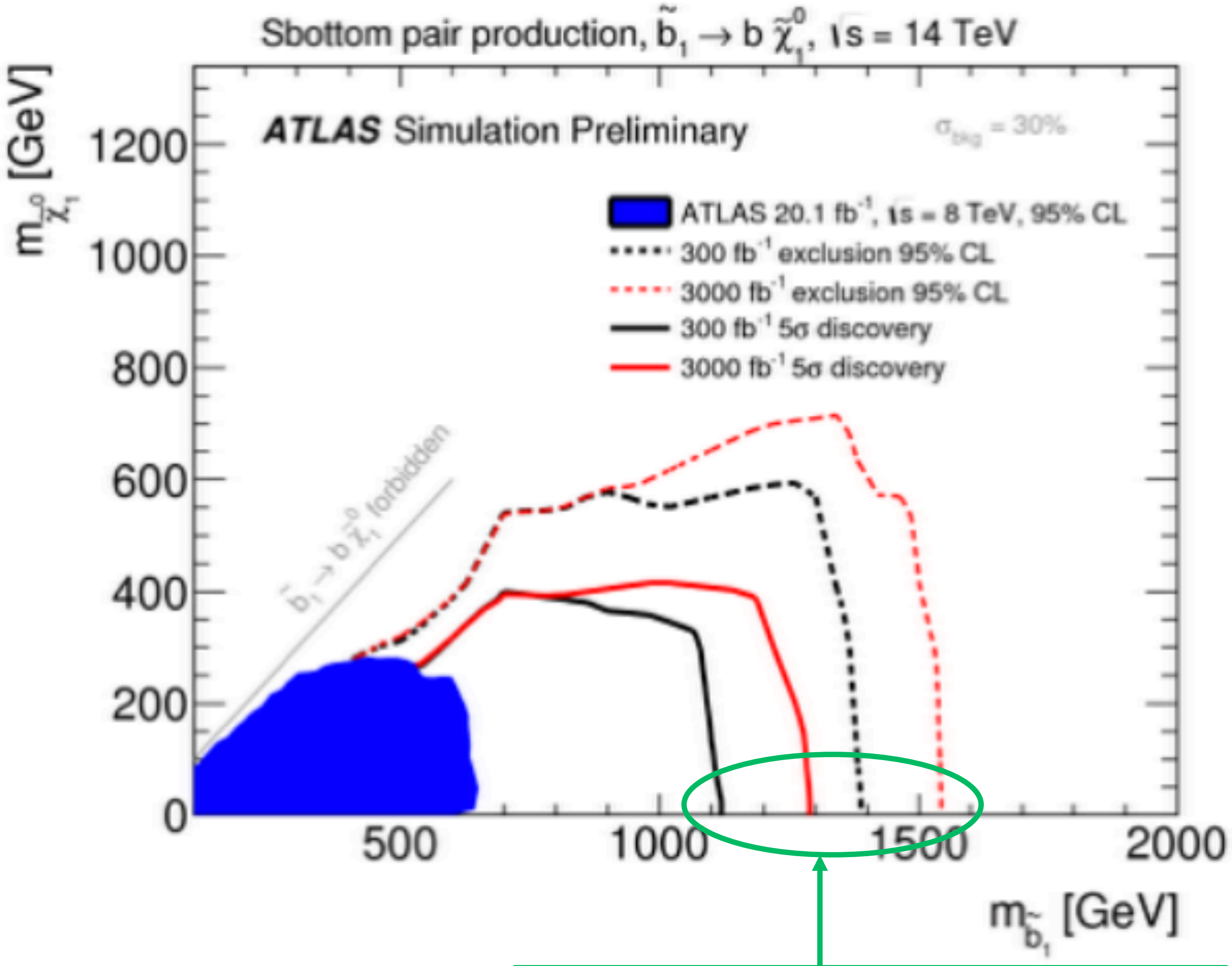
- Only ~ ¼ of the Run 2 dataset has been analyzed
- “Standard” searches will be updated with full Run 2 data and then Run 3
    - Limits will improve somewhat, discovery unlikely
- Clever ideas, new searches to be developed
    - Unexplored corners of phase space
    - New (crazy?) signatures
    - Need your creativity!
- HL-LHC will push out further
- Projections are being developed
    - Don’t take them too seriously, qualitatively ~ OK
    - Experience is that we (mostly) do better than projections
        - People get smarter when they get their hands on the data

Prediction power of the common sense: $\tilde{t}$ example

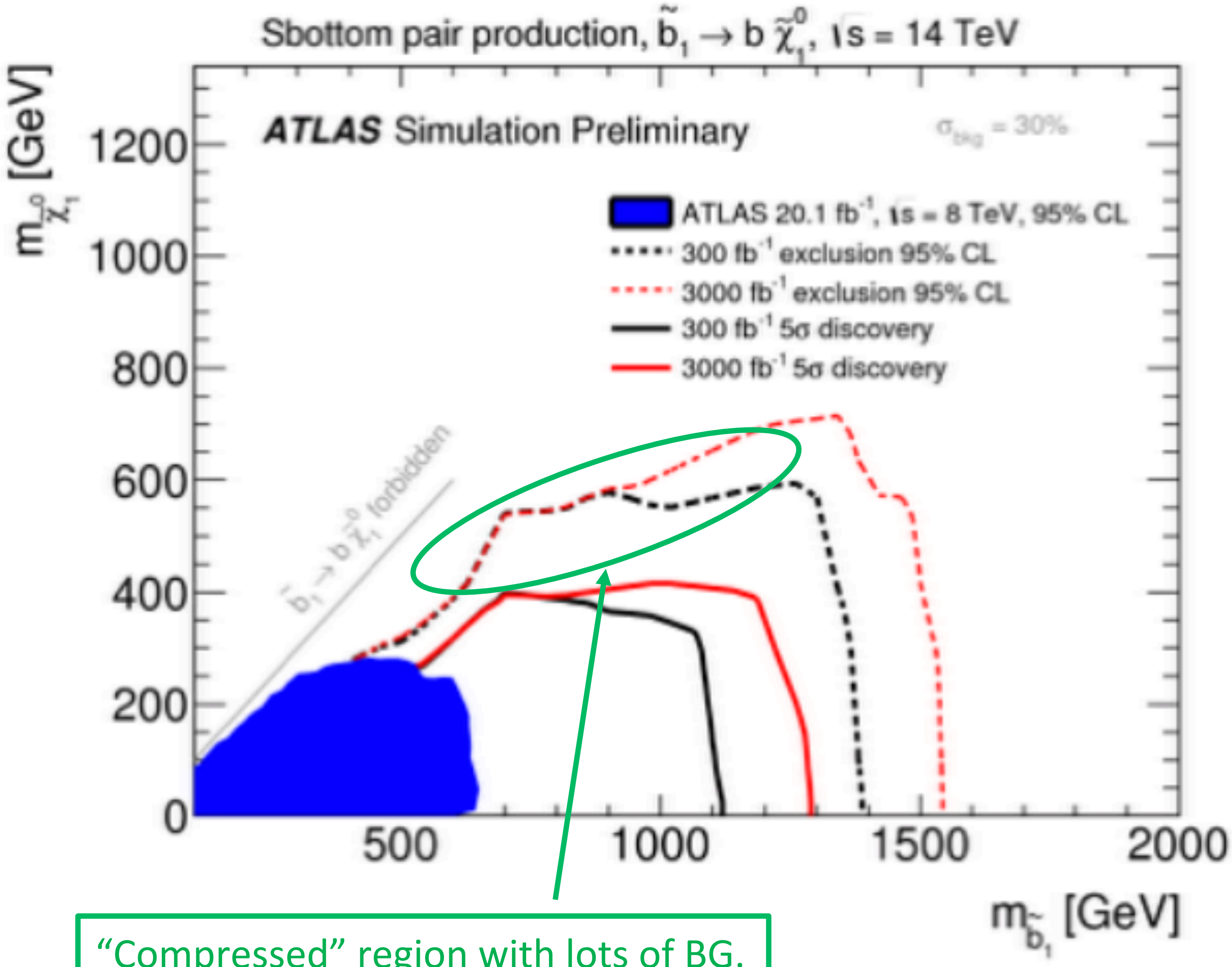


extrapolation with ≈ 0 background in the **highest mass** excluded point works very well

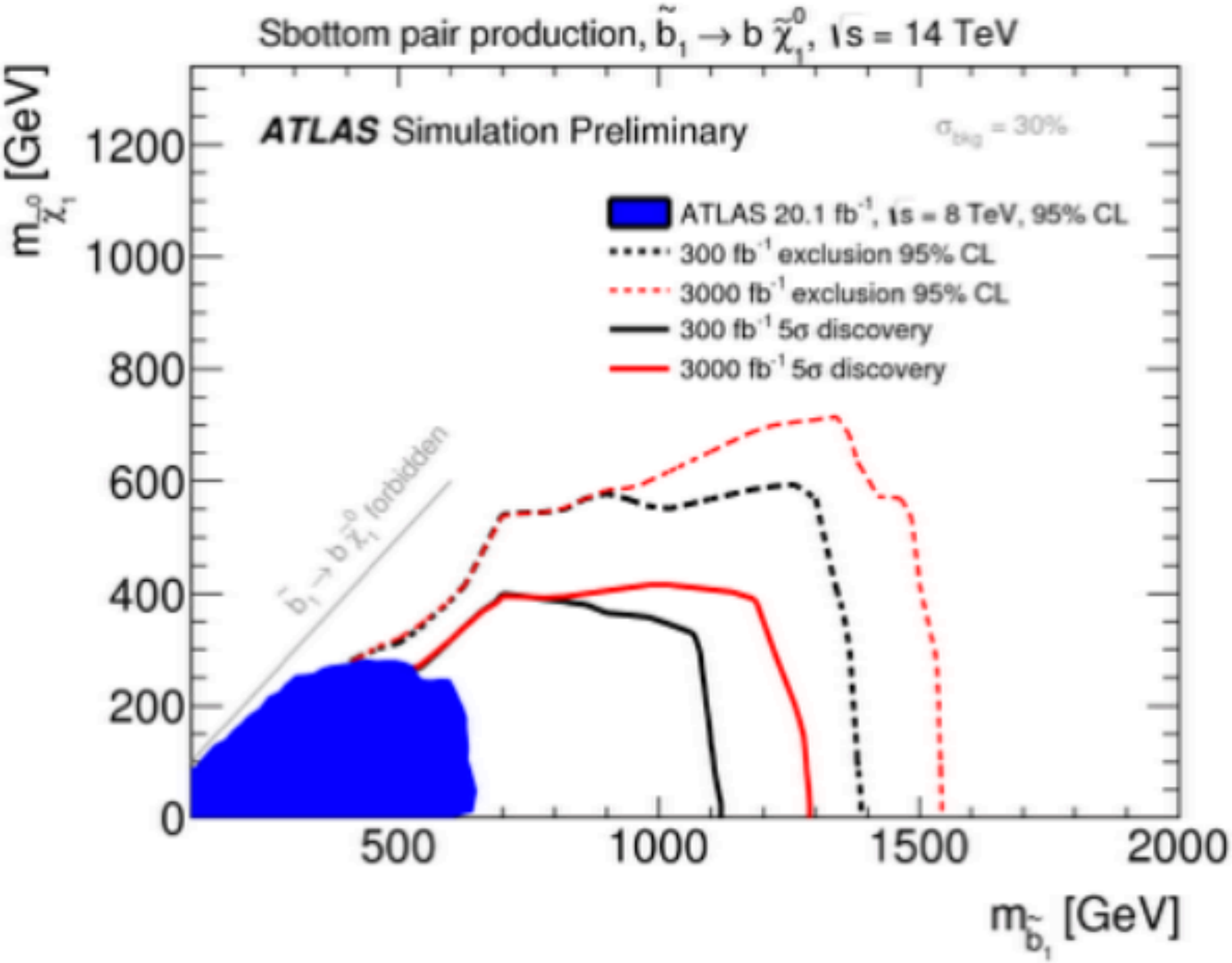
L. Shutska, Moriond 17



Region of ~ 0 BG…Here things improve



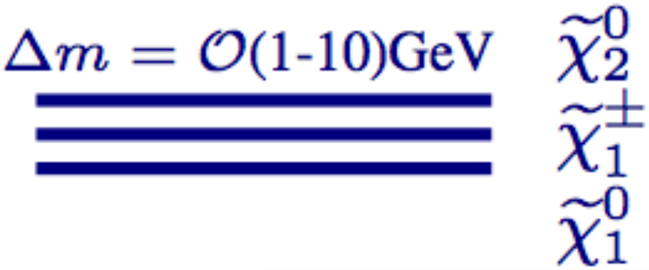
"Compressed" region with lots of BG.
Here things don't change much
Probably pessimistic

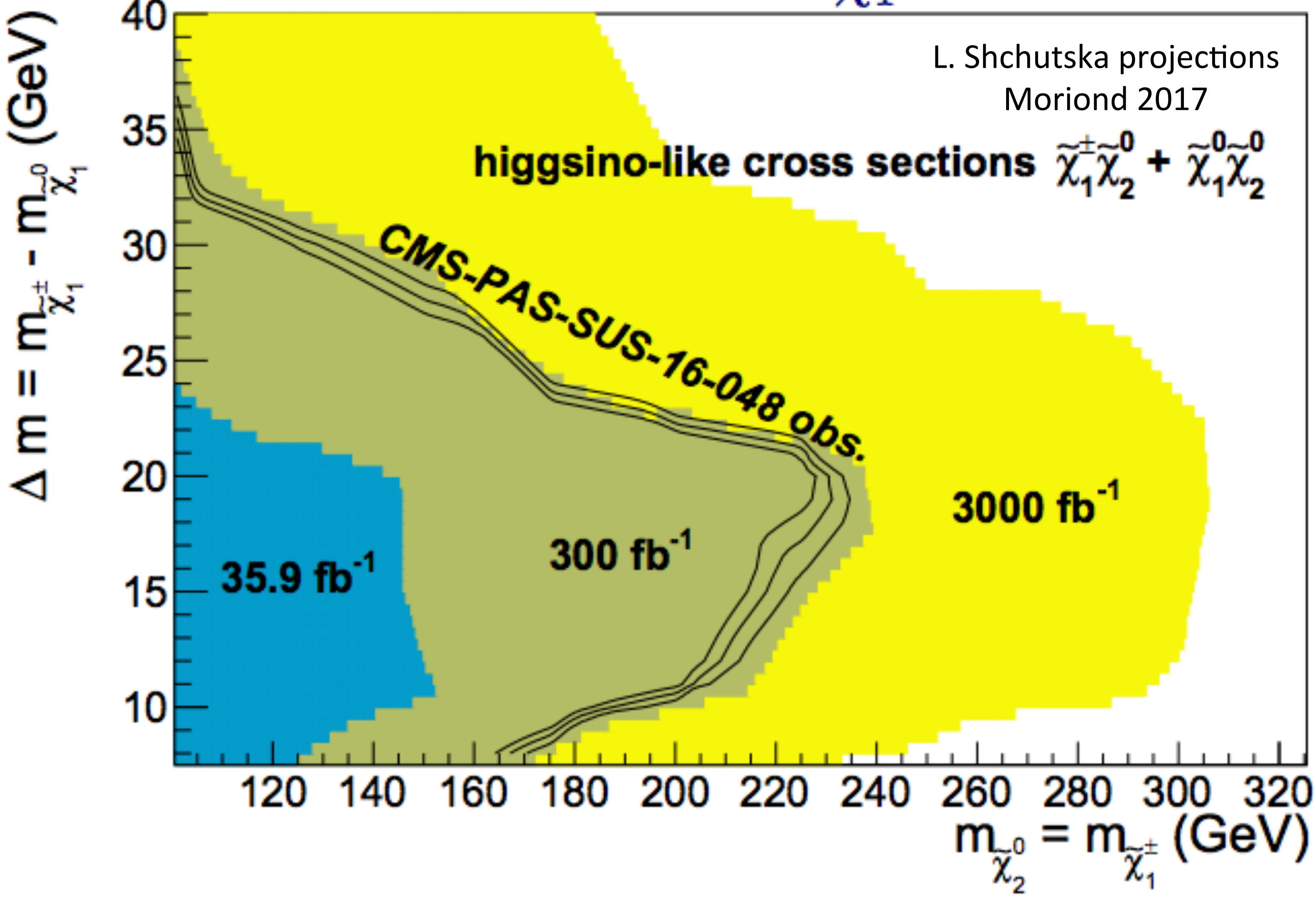


Note that the 300 fb^{-1} exclusion on paper precludes the 5σ discovery….

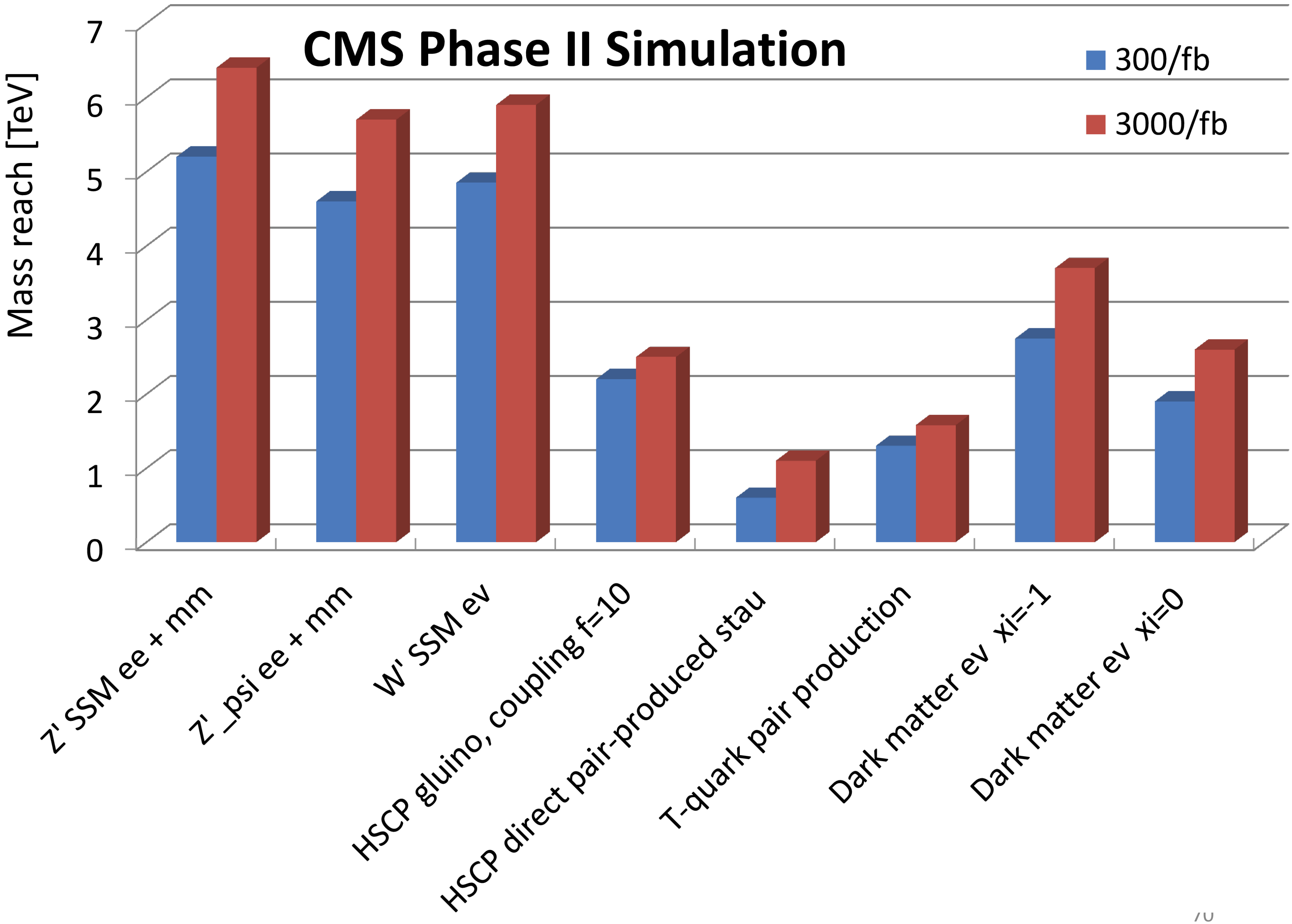
higgsino spectrum

$\Delta m = \mathcal{O}(1\text{-}10)\mathrm{GeV}$





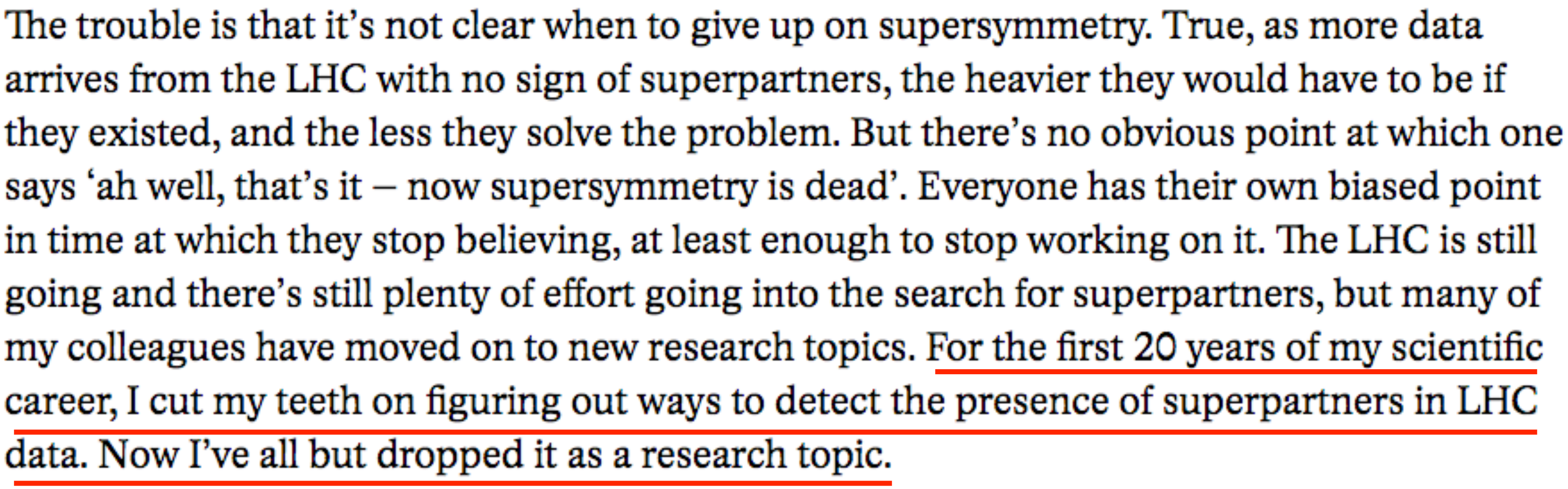
L. Shchutska projections
Moriond 2017


CMS Phase II Simulation
300/fb
3000/fb
Mass reach [TeV]
0
1
2
3
4
5
6
7
Z' SSM ee + mm
Z'_psi ee + mm
W' SSM ev
HSCP gluino, coupling f=10
HSCP direct pair-produced stau
T-quark pair production
Dark matter ev xi=-1
Dark matter ev xi=0

Conclusions

- The LHC has been working very well, and has given us a wonderful gift: the Higgs boson
- But Nature is toying with us
  - The conventional wisdom on NP at the TeV scale has failed

Theorists are confused

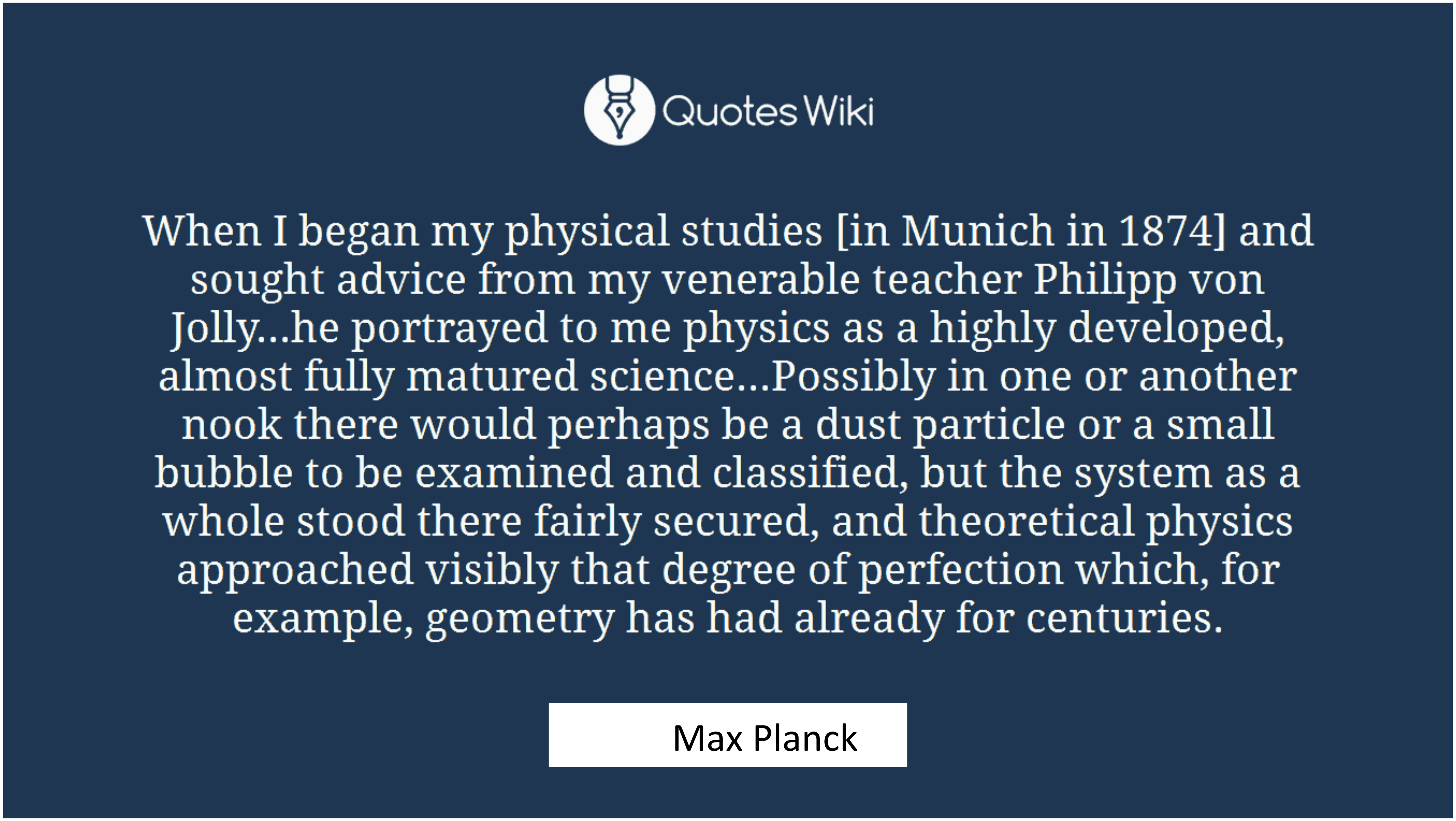


The trouble is that it's not clear when to give up on supersymmetry. True, as more data arrives from the LHC with no sign of superpartners, the heavier they would have to be if they existed, and the less they solve the problem. But there's no obvious point at which one says 'ah well, that's it – now supersymmetry is dead'. Everyone has their own biased point in time at which they stop believing, at least enough to stop working on it. The LHC is still going and there's still plenty of effort going into the search for superpartners, but many of my colleagues have moved on to new research topics. For the first 20 years of my scientific career, I cut my teeth on figuring out ways to detect the presence of superpartners in LHC data. Now I've all but dropped it as a research topic.

Ben Allanach, Cambridge

Conclusions

- The LHC has been working very well, and has given us a wonderful gift: the Higgs boson
- But Nature is toying with us
  - The conventional wisdom on NP at the TeV scale has failed
- We do not have a lot of theoretical guidance
  - But we know that the SM is not the end of the story



Quotes Wiki

When I began my physical studies [in Munich in 1874] and sought advice from my venerable teacher Philipp von Jolly...he portrayed to me physics as a highly developed, almost fully matured science...Possibly in one or another nook there would perhaps be a dust particle or a small bubble to be examined and classified, but the system as a whole stood there fairly secured, and theoretical physics approached visibly that degree of perfection which, for example, geometry has had already for centuries.

Max Planck

Conclusions

- The LHC has been working very well. It has given us a wonderful gift: the Higgs boson
- But Nature is toying with us
  - The conventional wisdom on NP at the TeV scale has failed
- We do not have a lot of theoretical guidance
  - But we know that the SM is not the end of the story
- As experimentalists we'll keep looking