Perspective
in the light of Run 1 & Run 2

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GGI, Firenze, Gearing up for LHC13, Oct 13-16 2015

UNIVERSITÉ DE GENÈVE

After 2 years of ATLAS Exotics convenership

- "So much wisdom accumulated…"
- …which I was invited to share here
- Off the job so I can finally speak my mind
- These are my personal opinions – not representing ATLAS or CMS in any way
- All blame on me!

Disclaimer

- Don’t expect any revolutionary new insights
- I’ll try to offer some *perspective*
  - And might make some *strong* statements to provoke discussion

Remember the goal

- If there is a trace of new physics in our detector

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Find it !

Remember the goal

- If there is a trace of new physics in our detector

Find it !

- Do this in a finite amount of time, making best use of the tools and person-power we have
- In addition: train the new generation of particle physicists to cultivate the expertise
  - FCC + grandchildren – I might be still around ☺


SUPERSTRING
M-theory heterotic
G_2 holonomy $E_8 \times E_8$
Type-IIA Type-I
SO(32)
Type IIB
E_6
Grand Unification
SU(5)
SO(10)
supergravity
Matter Anti-matter Asymmetry
CP
NOT YET THOUGHT OF
Little Higgs
QUANTUM DIMENSIONS
(Supersymmetry)
BLACK HOLE
Dark Energy
Composite Higgs
Flavor
Gaugino Mediation
Gauge Mediation
$\delta=7$
$\delta=6$
$\delta=5$
HIDDEN DIMENSIONS
Anomaly Mediation
$\delta=2$
$\delta=3$
RS I
AdS
Scherk-Schwarz
orbifold
$\delta=1$
RS II
DARK MATTER
NOT YET THOUGHT OF
NOT YET THOUGHT OF

Run 1 – out to catch Big Fish

- Search wide, deep & fast
- Best fishing grounds?
  - The “theory guide”: SUSY, CH, ED,…
  - Classic signatures: resonances, MET+X,…
  - Non-standard reconstruction e.g. highly displaced vertices, kinked tracks, lepton-jets,…
- Interpretation of results using a benchmark to close the loop with our theory friends
  - what fish did we (not) catch

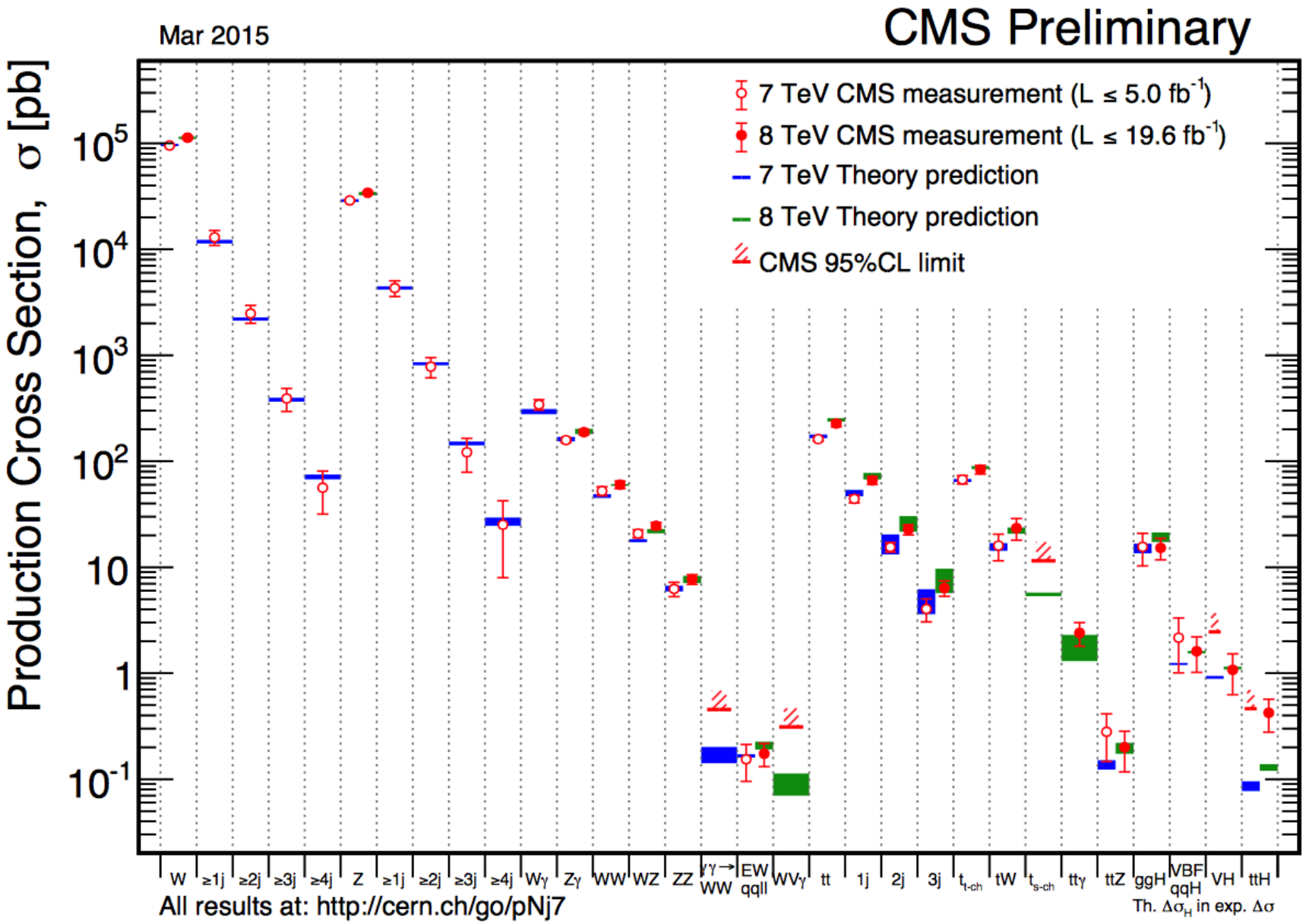
Overall Assessment In Retrospect

Overall Assessment In Retrospect

- We did well
- We covered a lot of ground
- High and low mass
- All major classic signatures, including non-standard searches
- Continuously pushing boundaries of what is possible
  - Boosted objects, c-tagging, high-pT b-tagging, non-standard objects,…
- Right mix of model- and signature-driven searches (?)
  - i.e. right mix of inclusive and exclusive searches: breadth vs. optimal sensitivity
- Speed: essentially all Run 1 searches are out and we even have the first Run 2 searches already
- Can we do even better?

Run 1 summary in 2 slides

SM works 😀


CMS Preliminary
Mar 2015
7 TeV CMS measurement (L ≤ 5.0 fb-1)
8 TeV CMS measurement (L ≤ 19.6 fb-1)
7 TeV Theory prediction
8 TeV Theory prediction
CMS 95%CL limit
Production Cross Section, σ [pb]
10^5
10^4
10^3
10^2
10
1
10^-1
W
≥1j
≥2j
≥3j
≥4j
Z
≥1j
≥2j
≥3j
≥4j
Wγ
Zγ
WW
WZ
ZZ
γγ → WW
EW qqll
WVγ
tt
1j
2j
3j
t t-ch
tW
t s-ch
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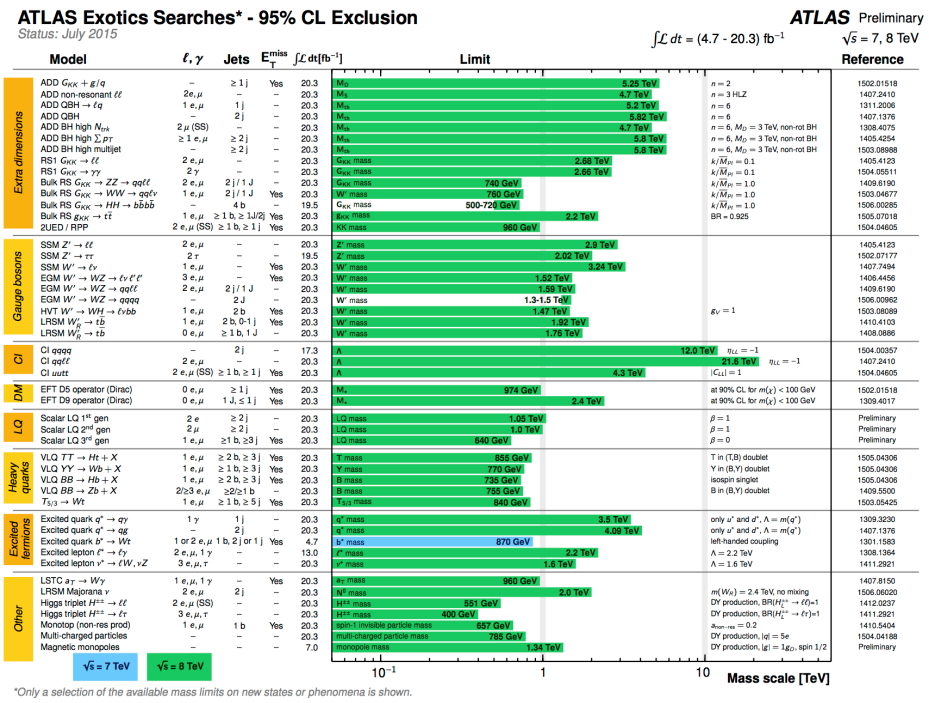
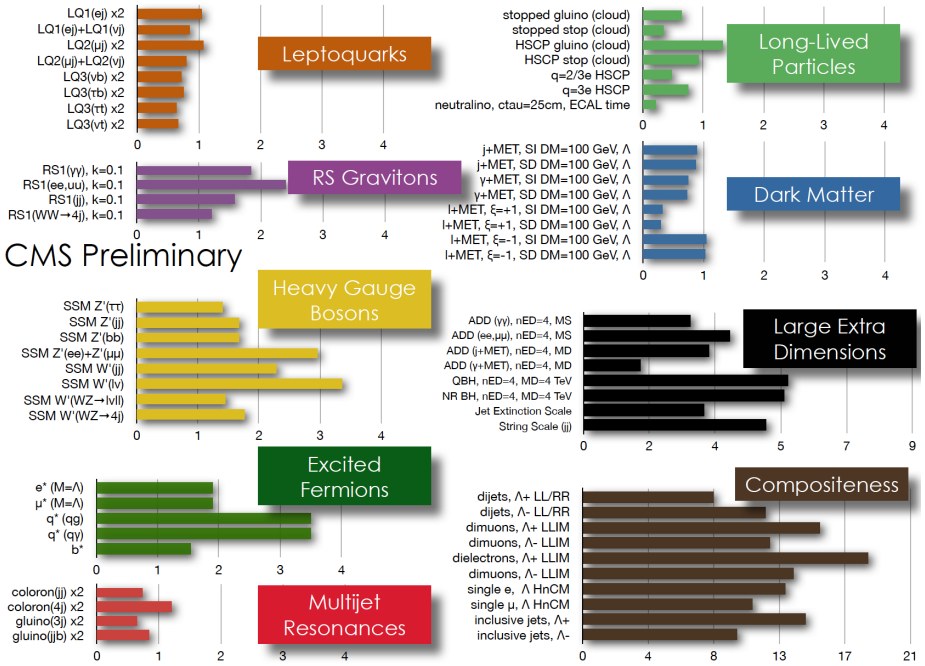
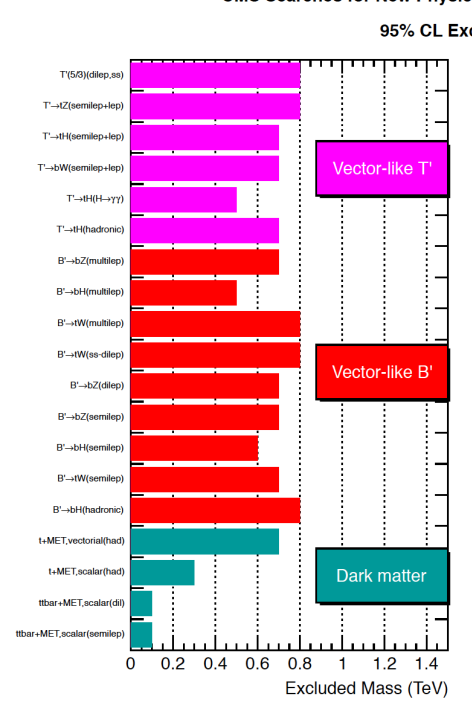
ttZ
ggH
VBF qqH
VH
ttH
All results at: http://cern.ch/go/pNj7
Th. Δσ_H in exp. Δσ

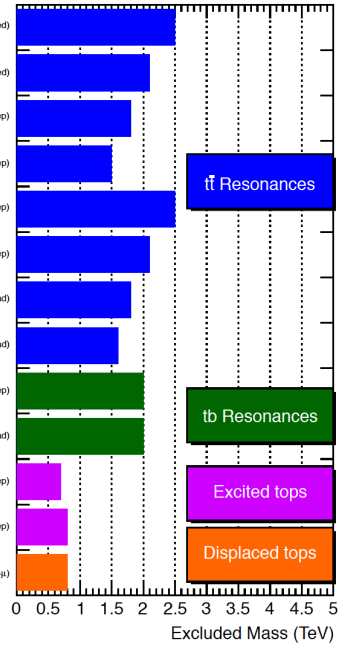




SM works 😢

Not our fault !?





https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults

Anything missing?

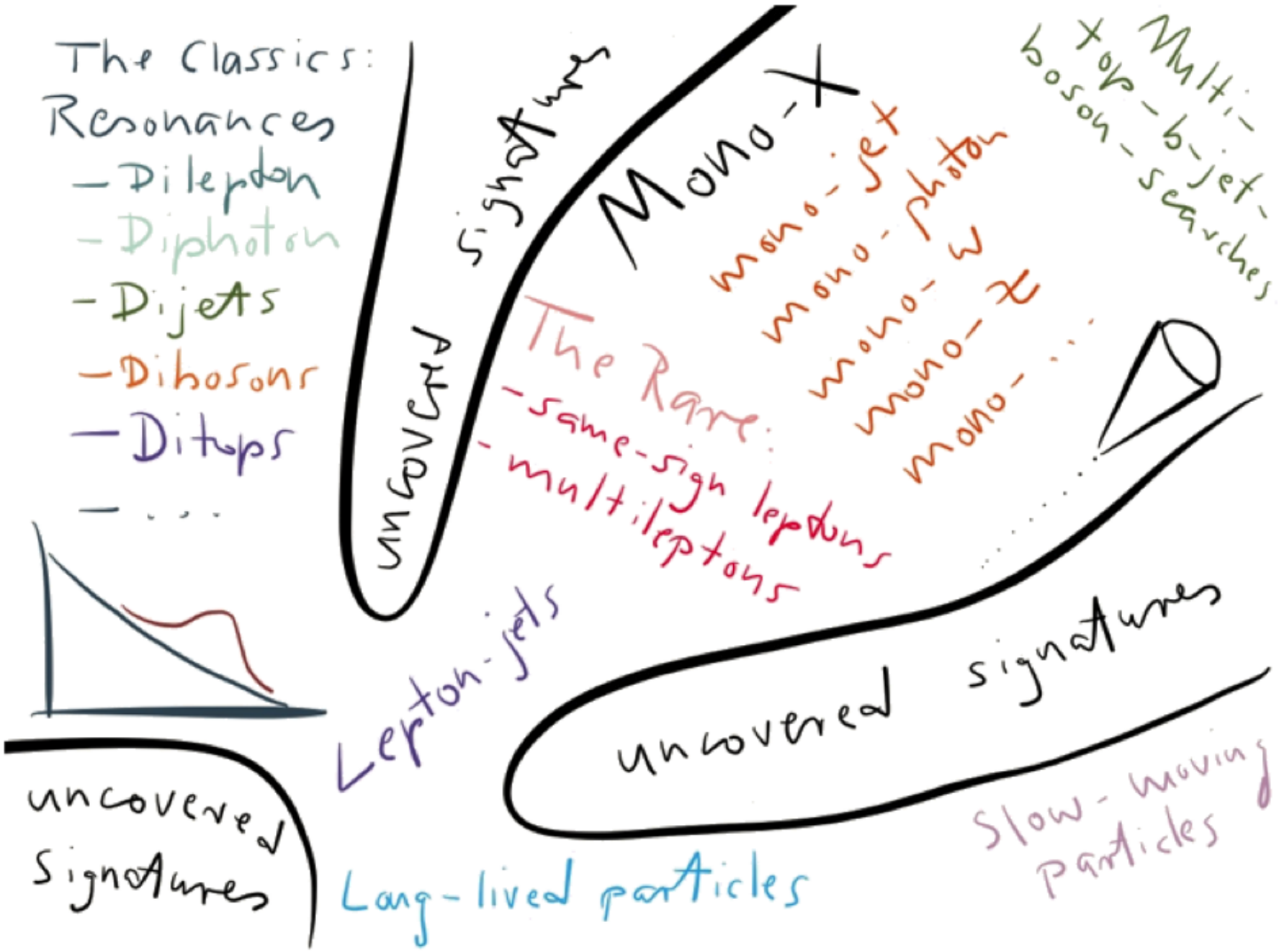
“Not yet thought of” – your turf!

Fill in the blanks

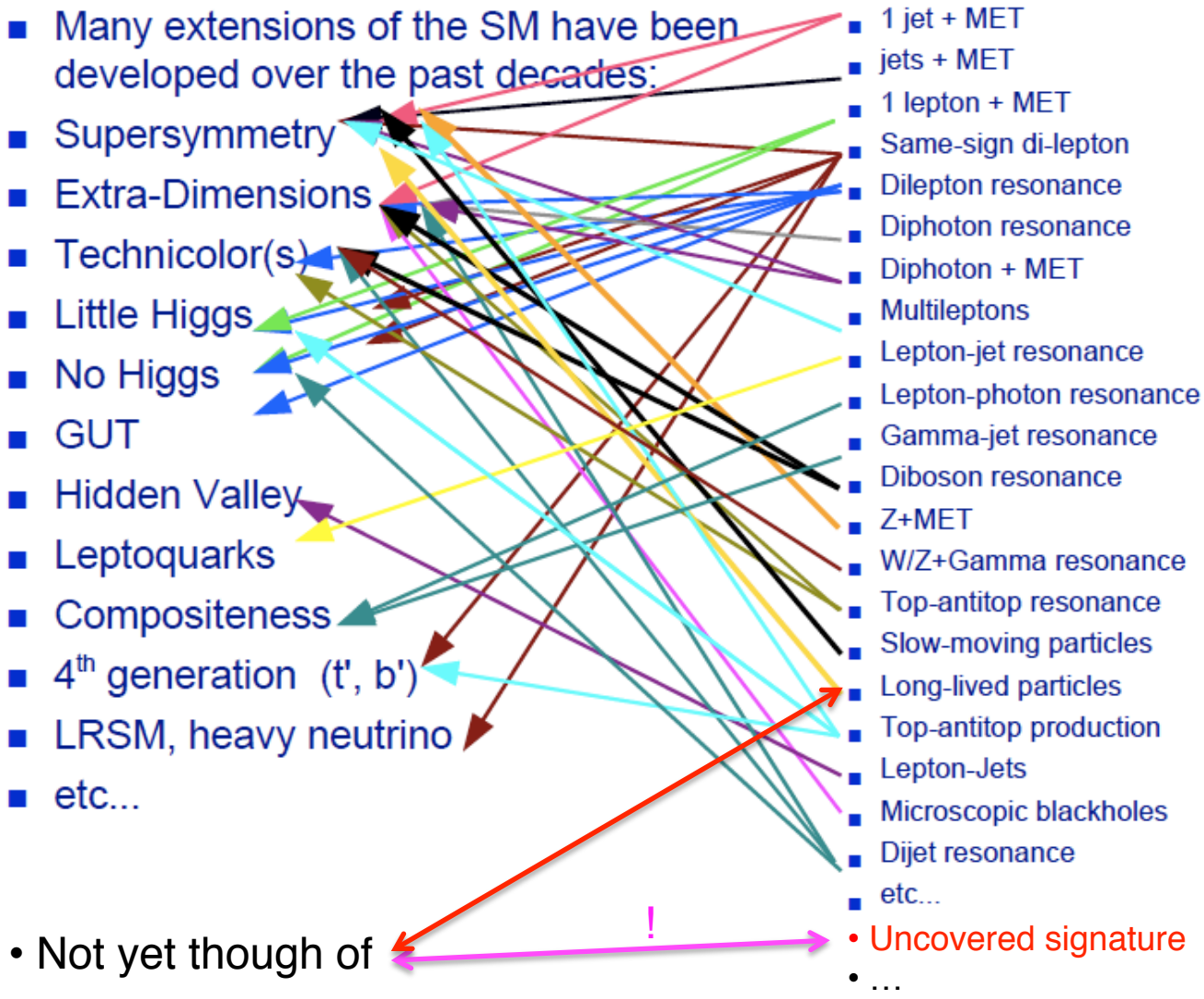
Simplified models – fill in the blanks!

- (UV-)complete top-down models *goes* simplified models = signature-based searches (traditional Exotics approach)
- New idea/model etc. ⇒ tell us what the pheno is
- We will need MC and we need to know:
  - What are the key features
  - What are features we should not count on in our analysis
  - This typically needs interaction between theory and experiment
- Is a new trigger required?
  - Communication with theory community: what triggers are available / possible – room for improvement?
- There are limitations to the reconstruction & BG rejection but we do have awesome detectors – let's try!
  - Quirks, emerging jets, displaced vertices,…

Uncovered Signatures – our job!

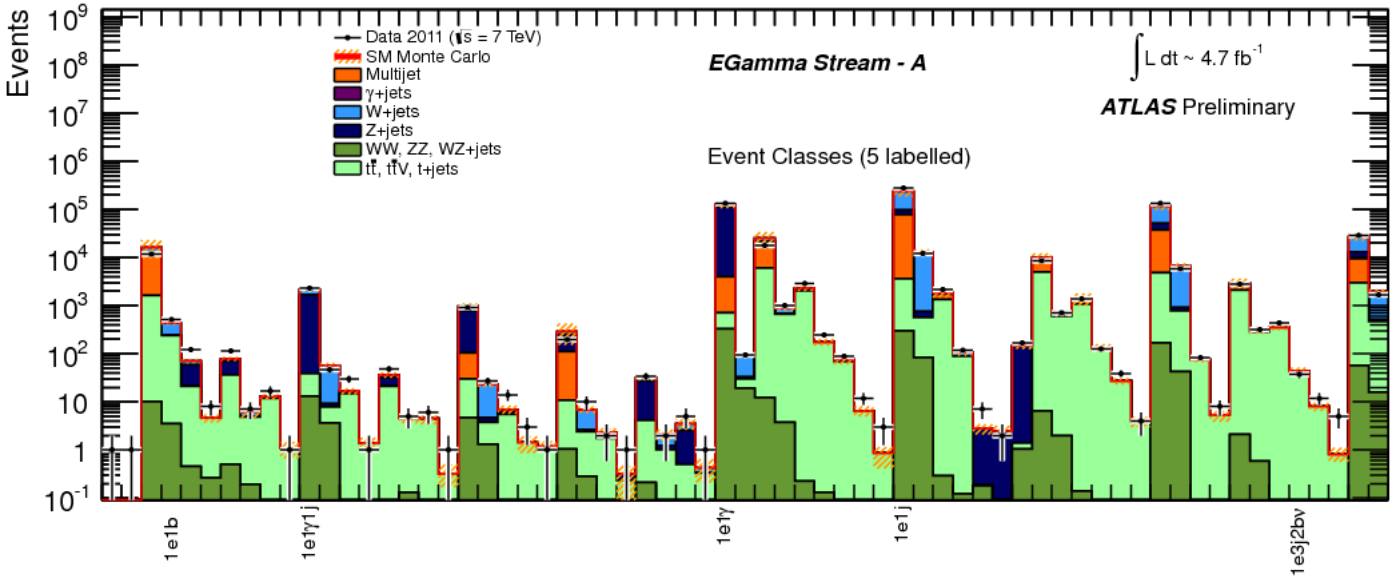


Signature-Driven Searches



Signatures – fill in the blanks

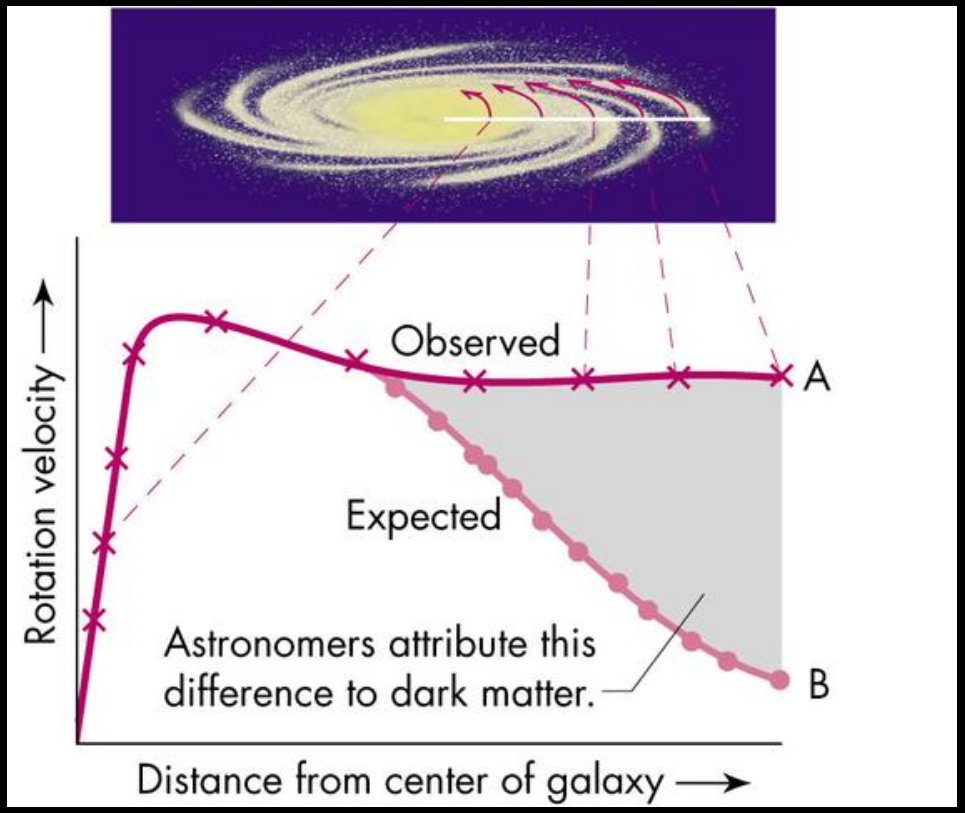
- General search for NP, assumption: "NP at high p_T"
- Hundreds of exclusive analysis channels
  - High-p_T e's, mu's, photons, neutrinos, jets, b-jets
  - SM BG from MC-only
  - Algorithm searches for largest data-MC deviations
    - Sensitive to MC mis-modelling
  - Dedicated analysis needed in case of discrepancy observed
- Generic enough?



[ATLAS-CONF-2012-107]

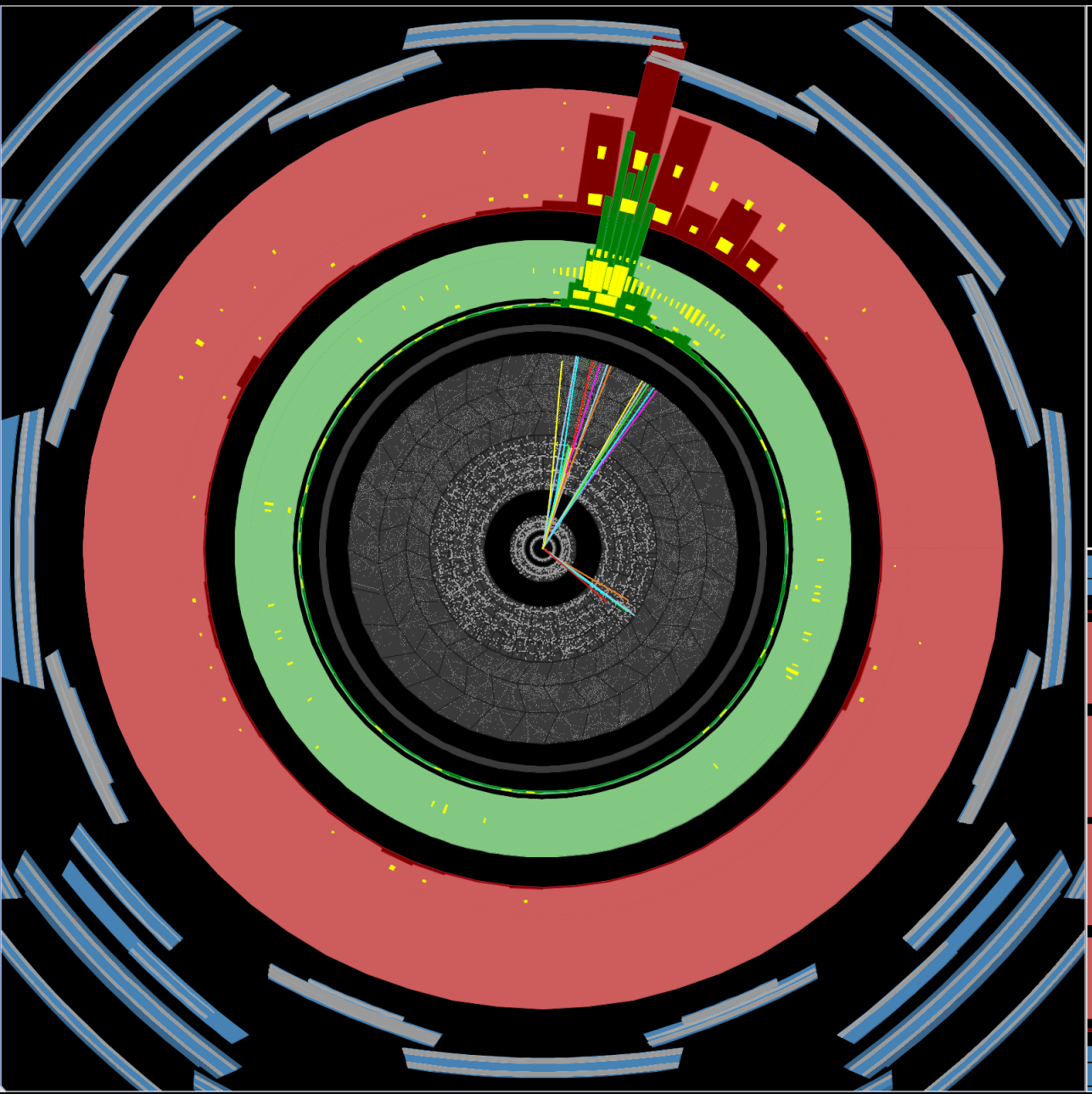
What we know

There is Dark Matter



"Should be able" to produce & see it in our pp collisions

MET+X Searches



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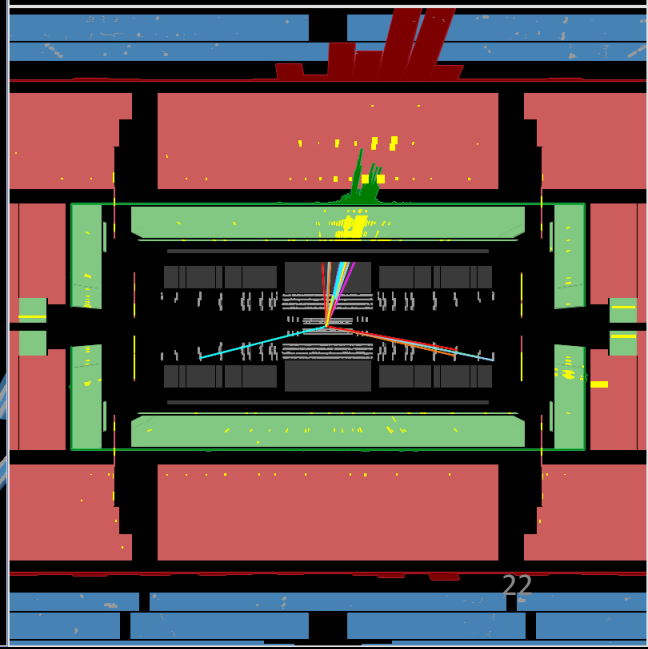
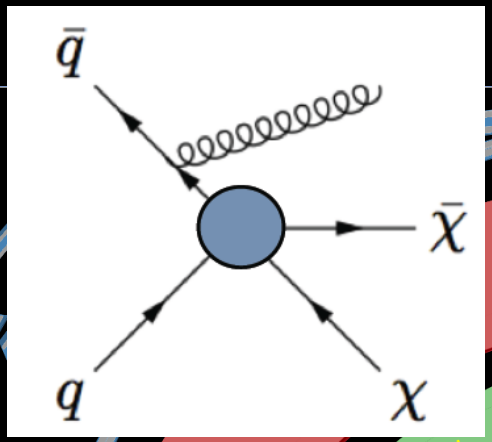
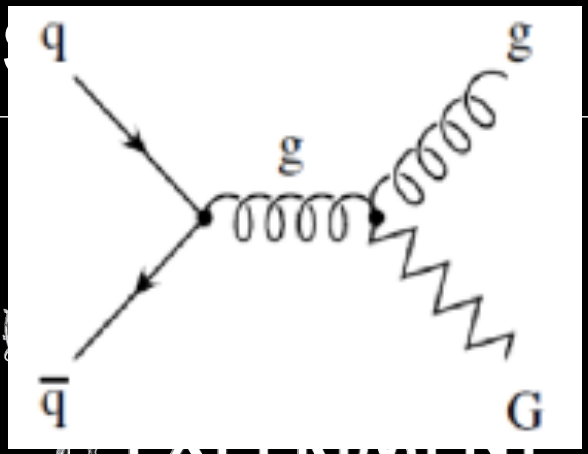
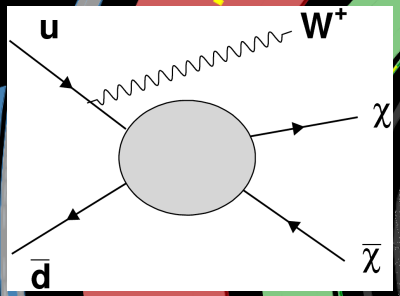
Date: 2012-07-14 10:42:26 CEST

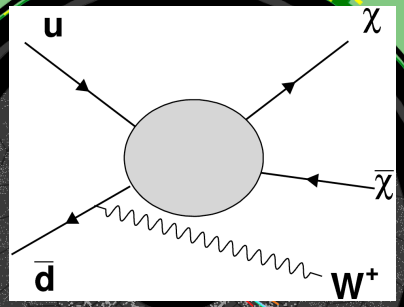


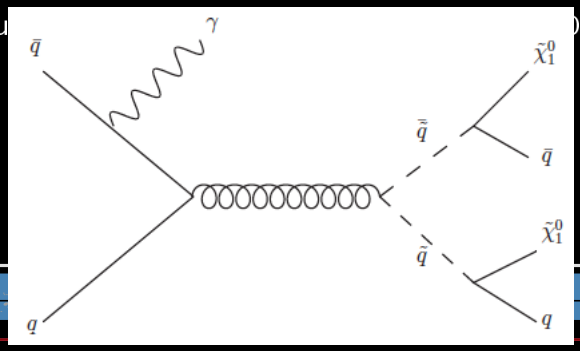
MET+X Searches

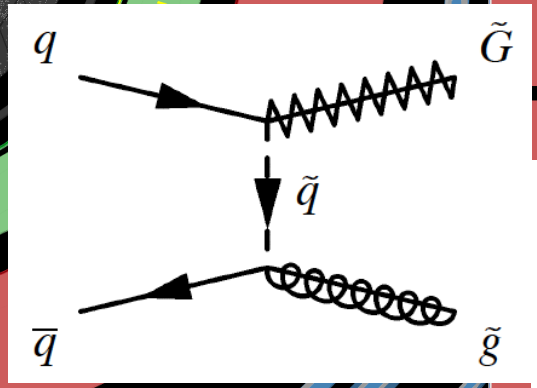


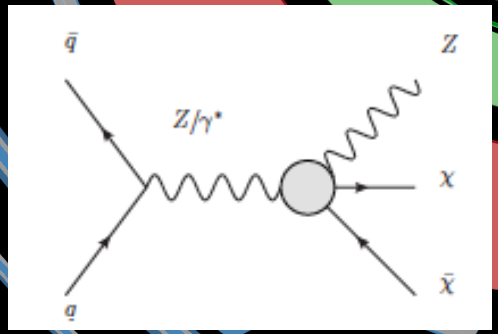


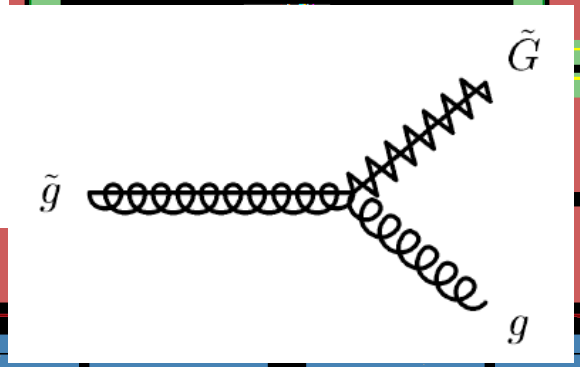










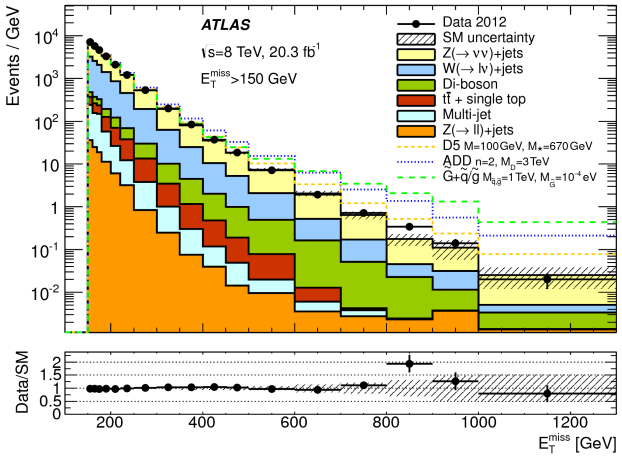


MET+X

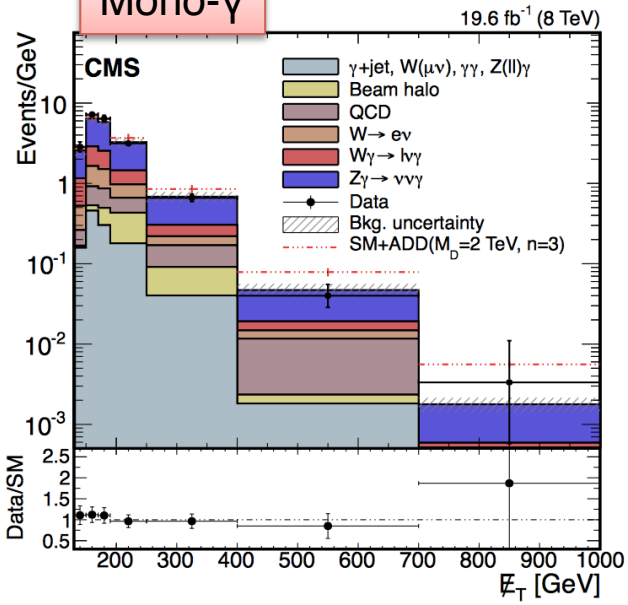
cannot do justice here

Mono-jet: 1408.3583, 1502.01518
Mono-γ: 1410.8812, PRD 91, 012008 (2015)
Mono-top / tt̄: 1410.1149, 1410.5404, 1504.03198
Mono-HF: 1410.4031, CMS-PAS-B2G-14-004, CMS-PAS-B2G-13-044)
Mono-W/Z (had): PRL 112 041802 (2014)
Mono-Z (ll): PRD 90, 012004 (2014)

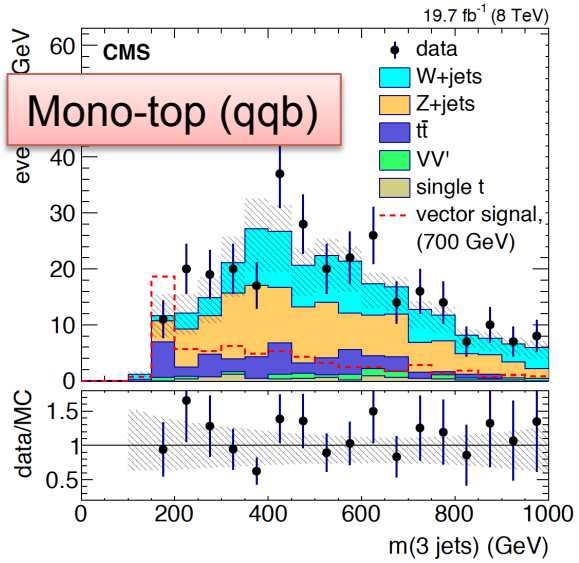
Mono-jet



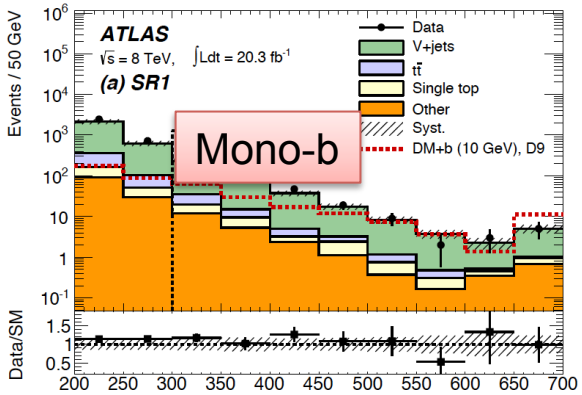
Mono-γ



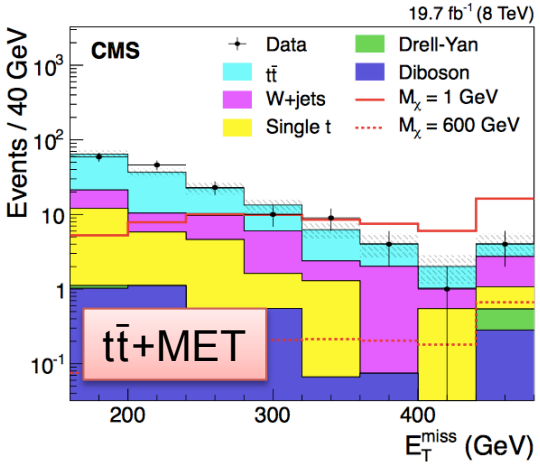
Mono-top (qqb)



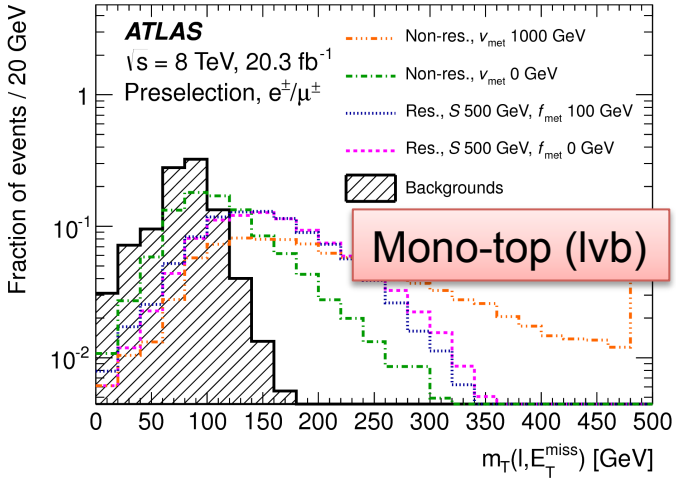
Mono-b



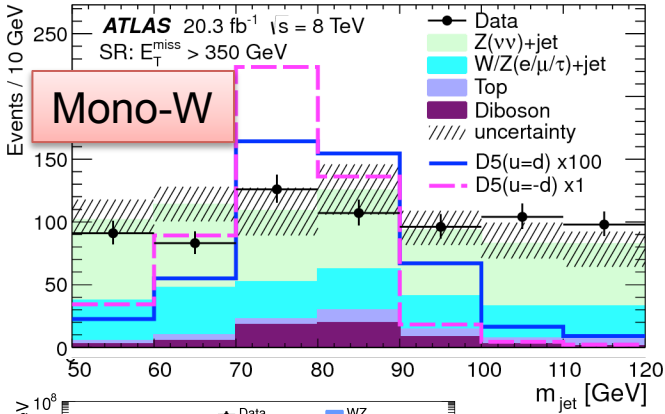
tt̄+MET



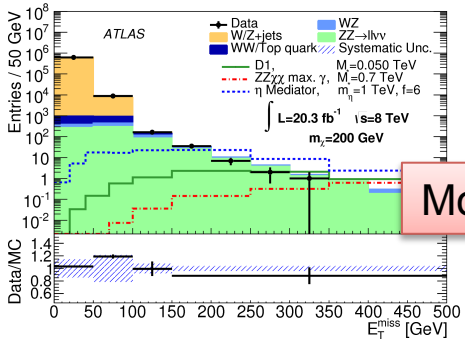
Mono-top (lvb)



Mono-W

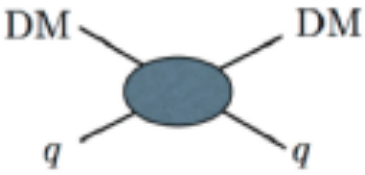


Mono-Z (ll)

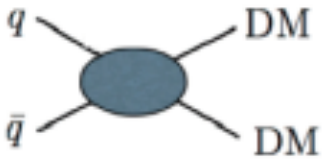


CMS arXiv:1408.3583, arXiv:1410.8812

WIMP – Direct Detection vs Collider Searches

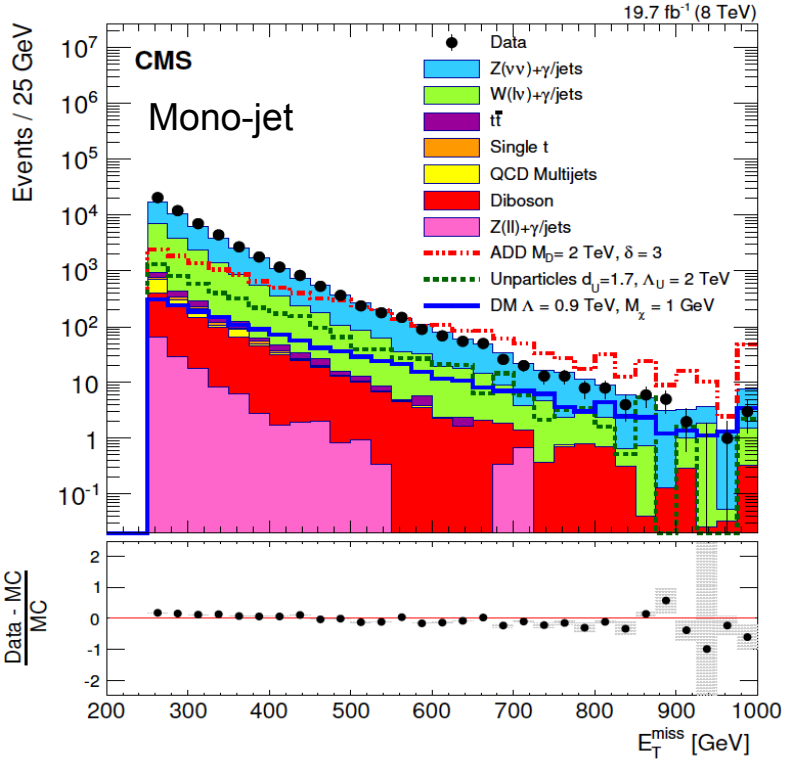


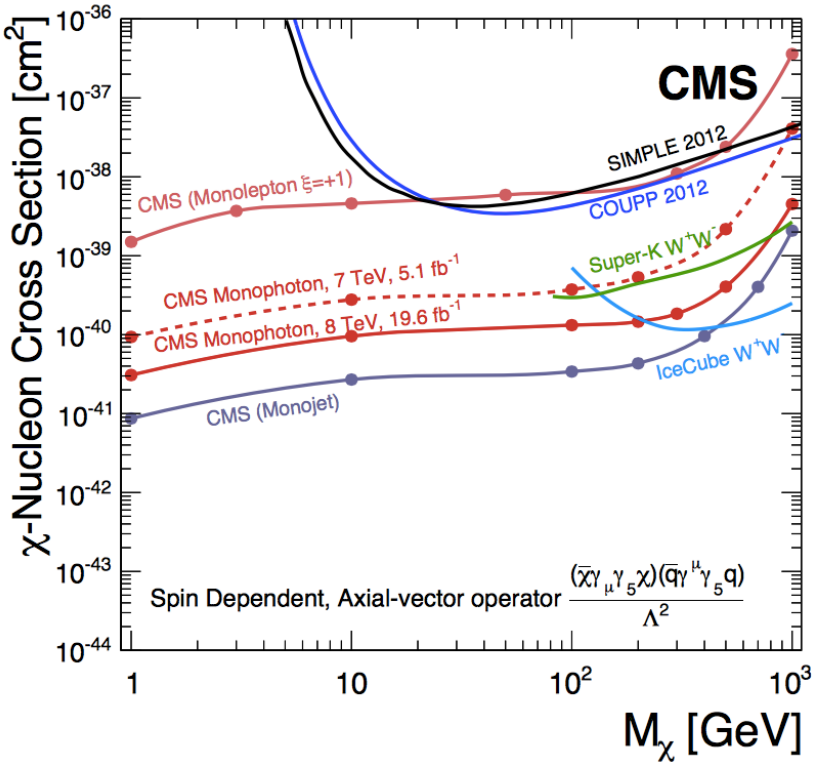
Direct Detection (t-channel)



Collider Searches (s-channel)

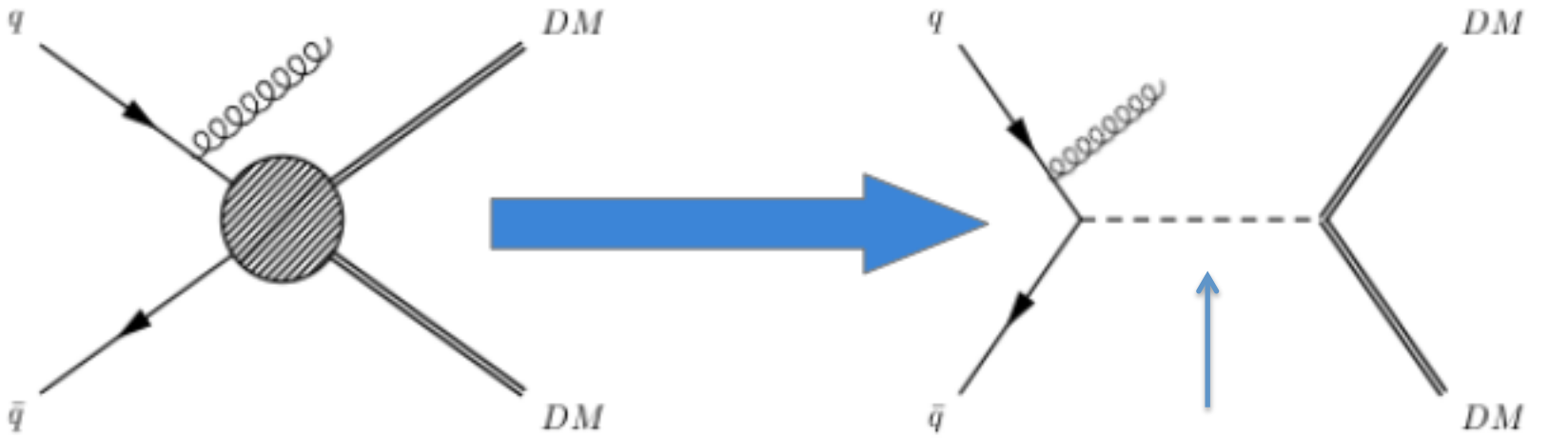
[under certain assumptions]





Complementary sensitivity to direct detection experiments, but model dependent…

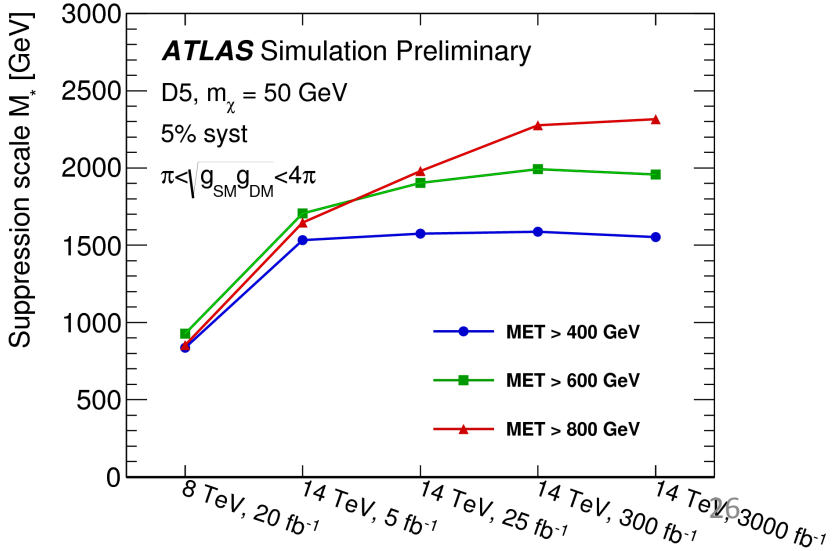
DM – don't forget to search for mediator



Complementary approach:
Direct searches for mediators

Sensitivity beyond Run 1 with first few fb^{-1}: ATL-PHYS-PUB-2014-007

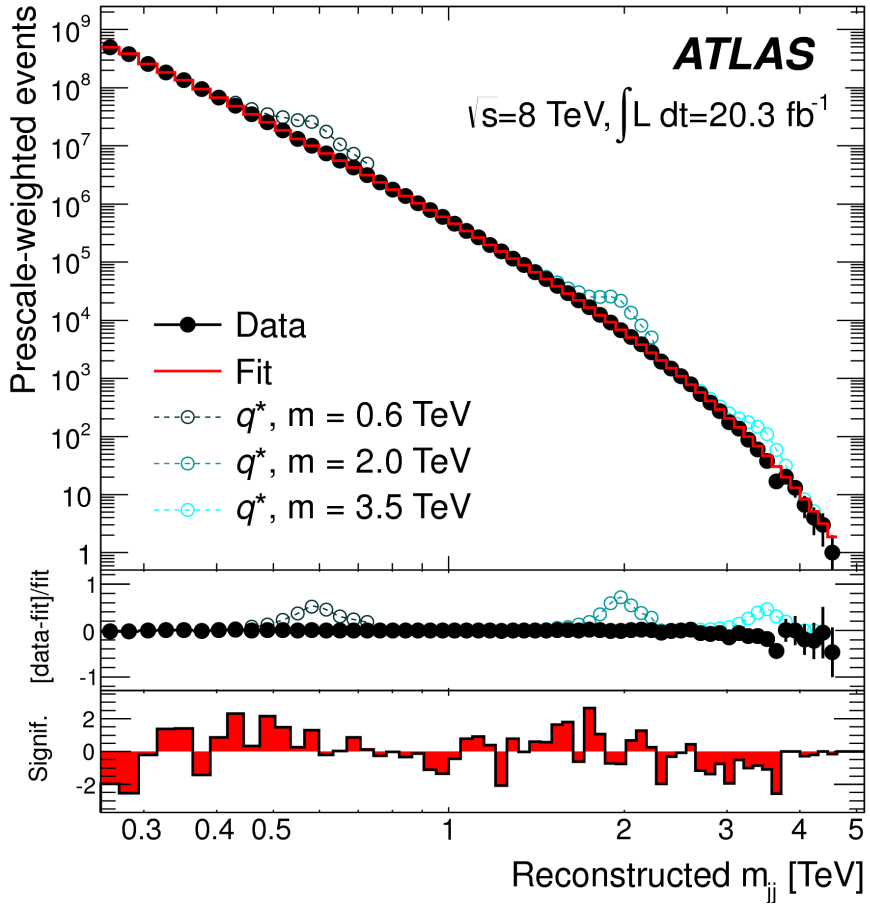
- EFT validity assessment procedure ⇒ simplified models
- ATLAS/CMS Dark Matter forum: https://twiki.cern.ch/twiki/bin/view/LHCDMF/WebHome
  - http://arxiv.org/abs/1506.03116

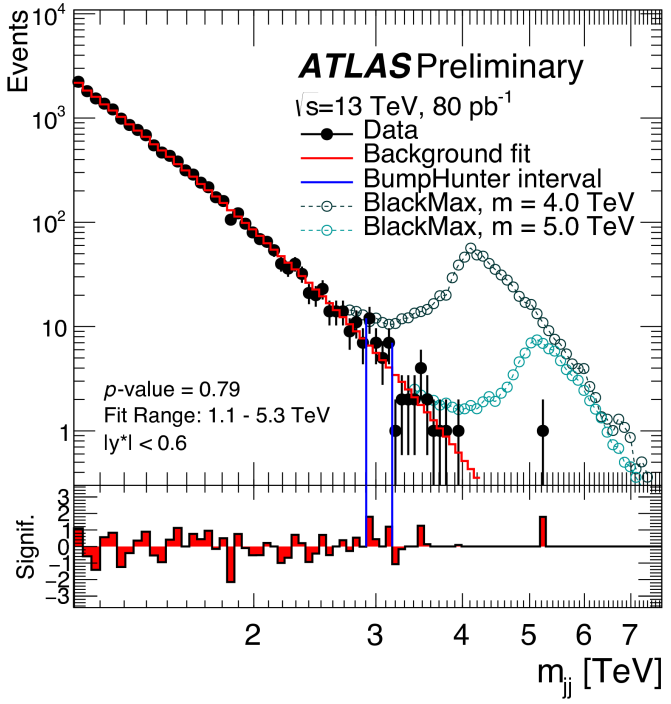


Dijets

ATLAS-CONF-2015-042
CMS-PAS-EXO-15-001

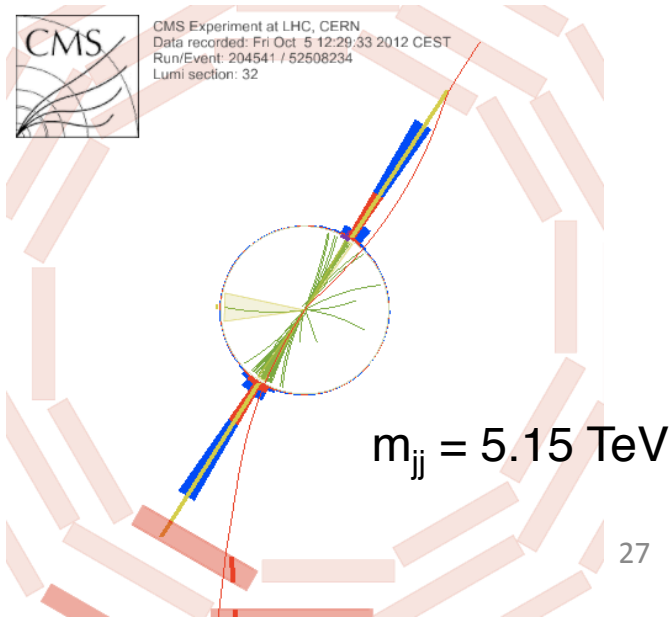
PRD 91, 052007 (2015)
PRD 91, 052009 (2015)





Large number of other reasons to look for dijets!

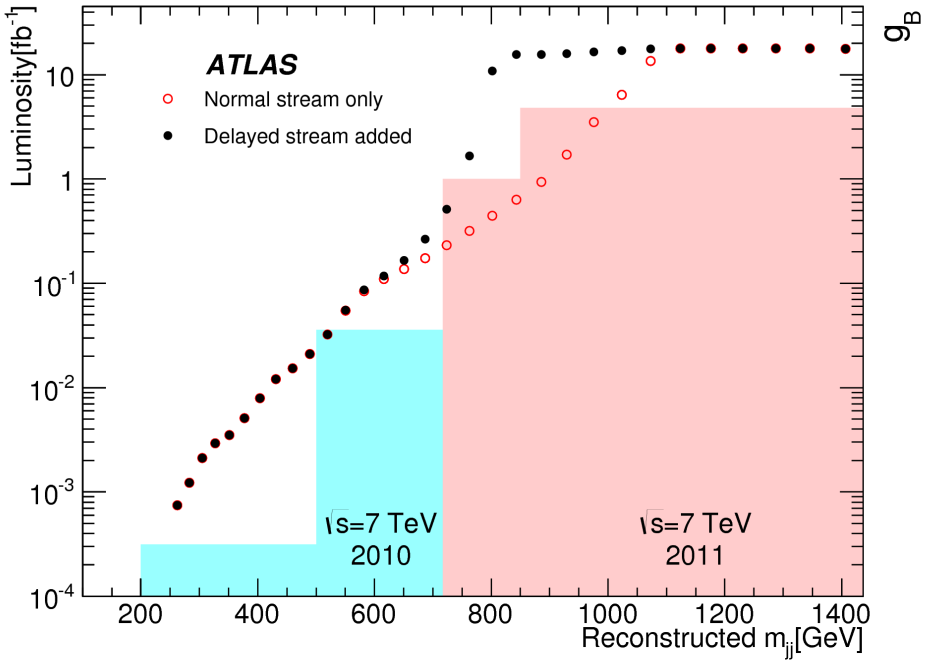
Model and Final State	95% CL Limits [TeV] Expected	Observed
$q^* \to qg$	3.99	4.09
$s8 \to gg$	2.83	2.72
$W' \to q\bar{q}'$	2.51	2.45
Leptophobic $W^* \to q\bar{q}'$	1.93	1.75
Leptophilic $W^* \to q\bar{q}'$	1.67	1.66
QBH black holes (q and g decays only)	5.82	5.82
BLACKMAX black holes (all decays)	5.75	5.75

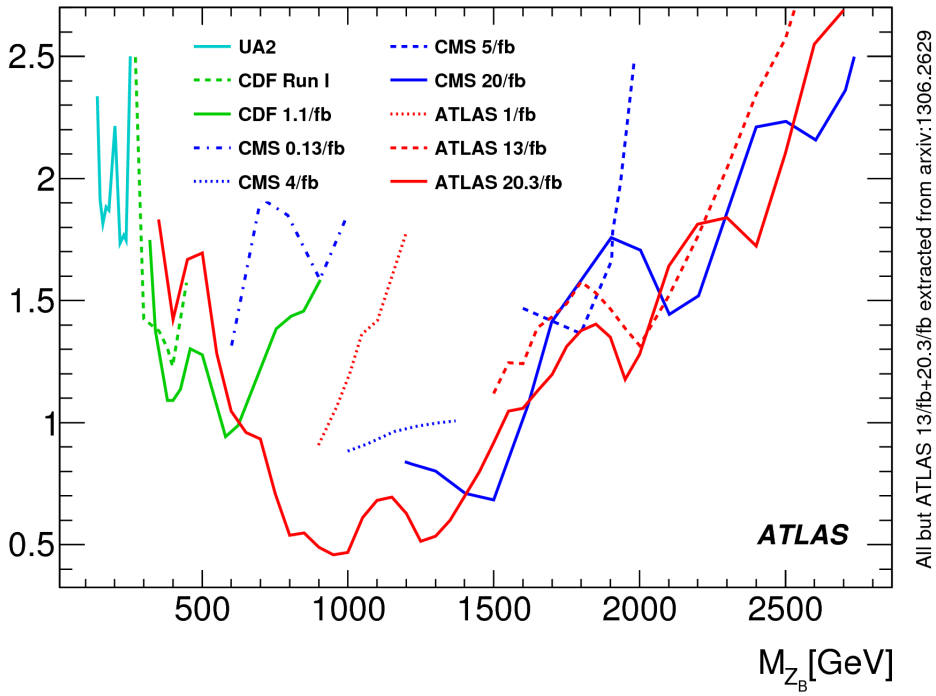


Don’t forget low mass

Don’t forget low mass

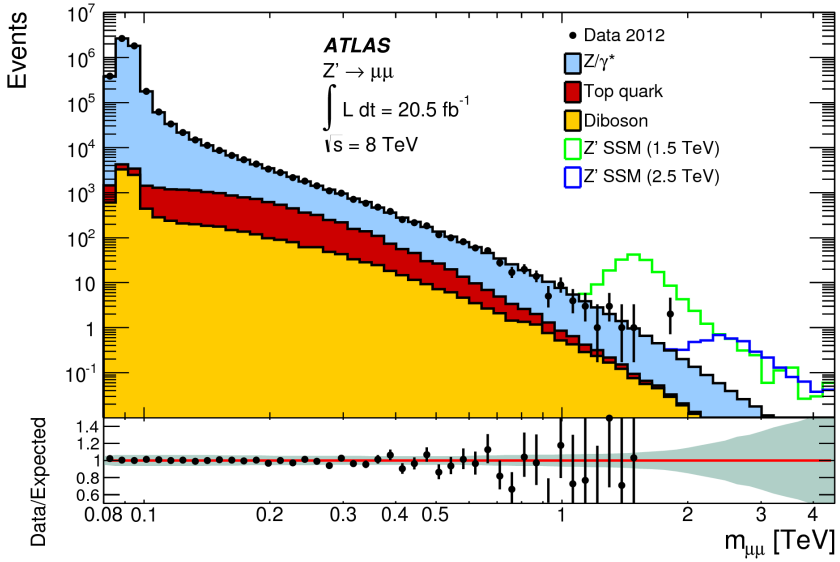
PRD 91, 052007 (2015)
PRD 91, 052009 (2015)

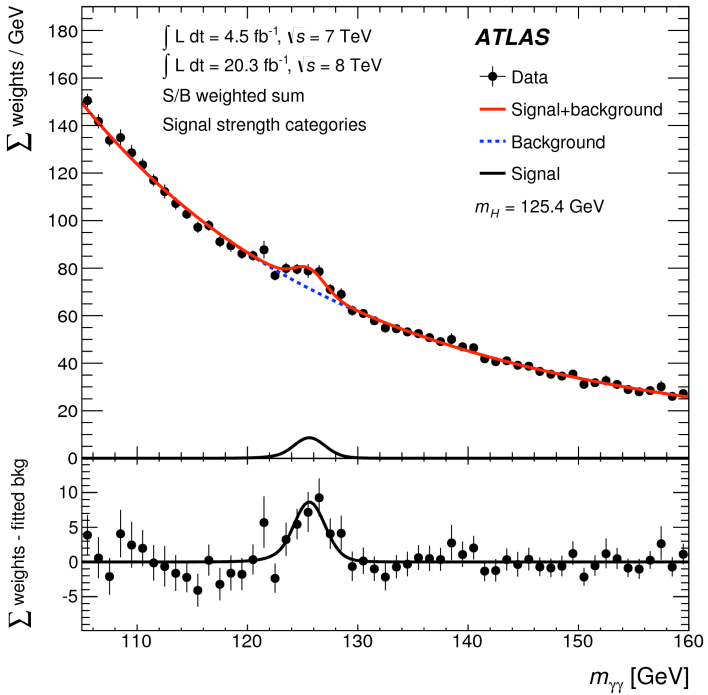


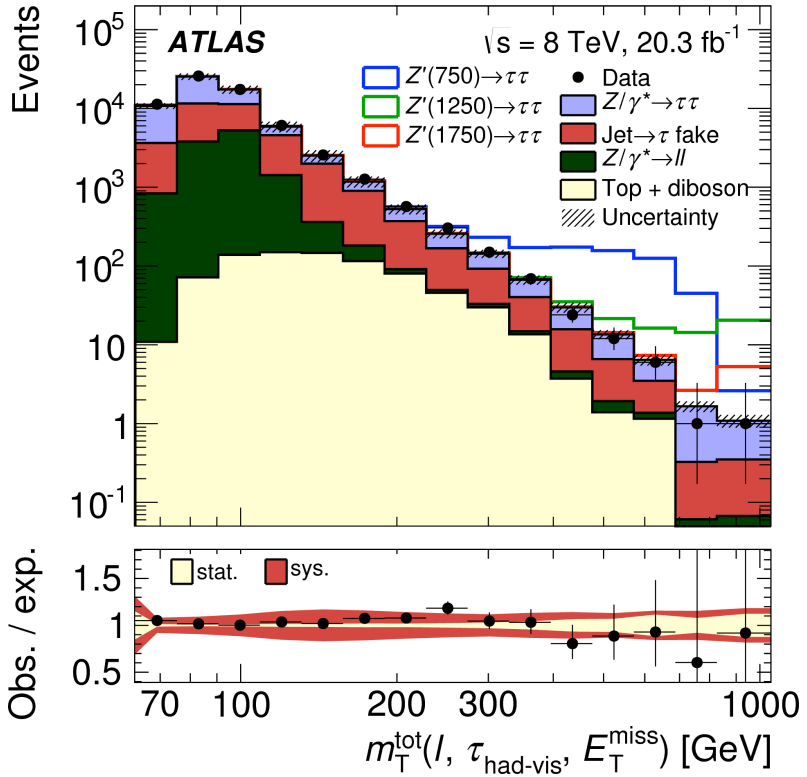


- Delayed stream
- Trigger-level analysis

Also other final states: low mass & rate







E.g. dilepton or diphoton resonance searches below Z mass (e.g. THDM or (N)MSSM)

What we believe in

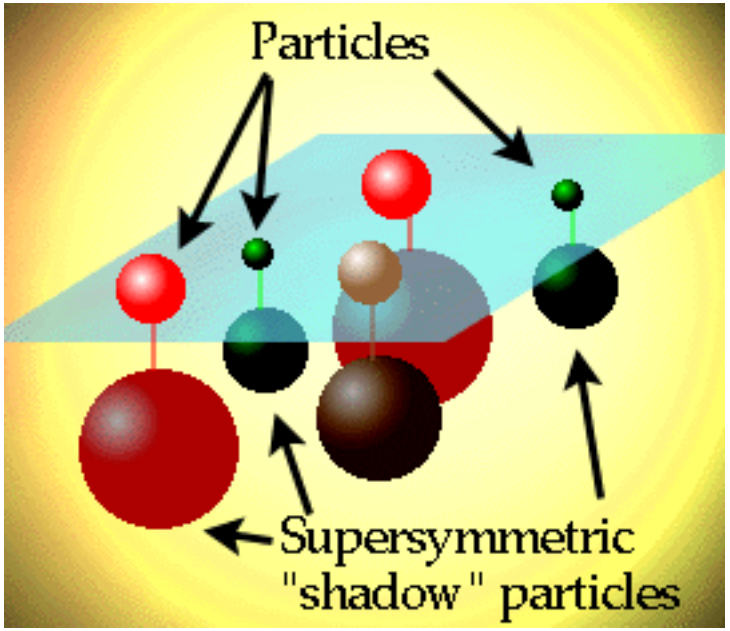
As natural as it gets

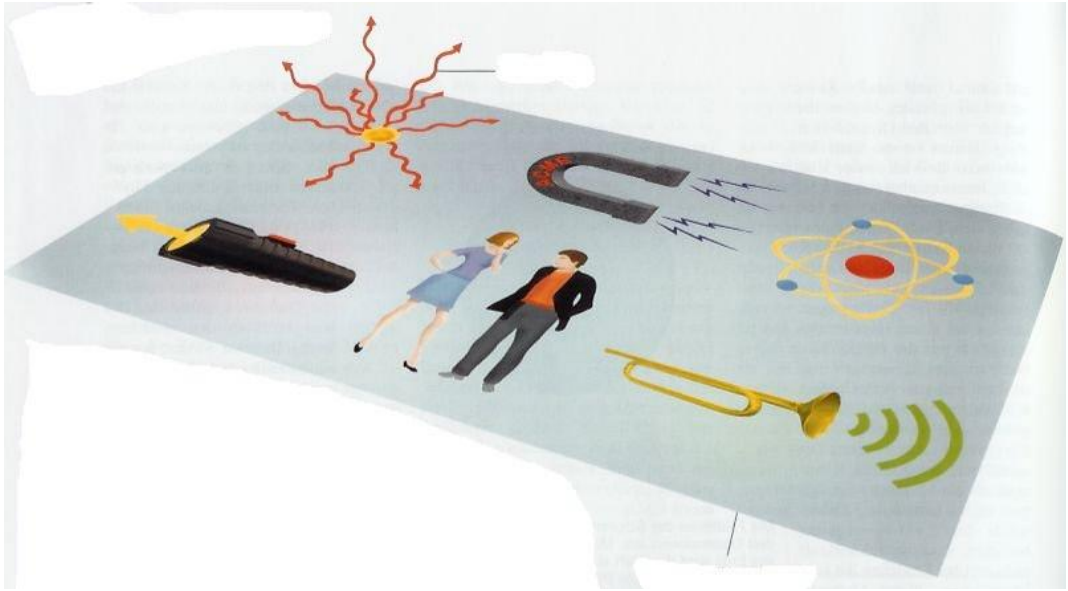
- In principle nothing wrong with SM all the way to the Planck scale
- But does not feel right
- Ugly to have cancellation up to 1 in 10^{32}
- We believe in NP to cure this (religion)
- Wishful thinking? Are we missing something?
- If we're right then Run 2 will be a blast!

Naturalness-motivated search

Supersymmetry

Extra Dimensions / Composite Higgs





Highest priority to cover all possible scenarios:
stops, VLQ's, resonances,… ⇒ approaching "no-lose" (?)

Shots in the dark

Even a blind hen sometimes finds a grain of corn

(Ein blindes Huhn findet auch einmal ein Korn)

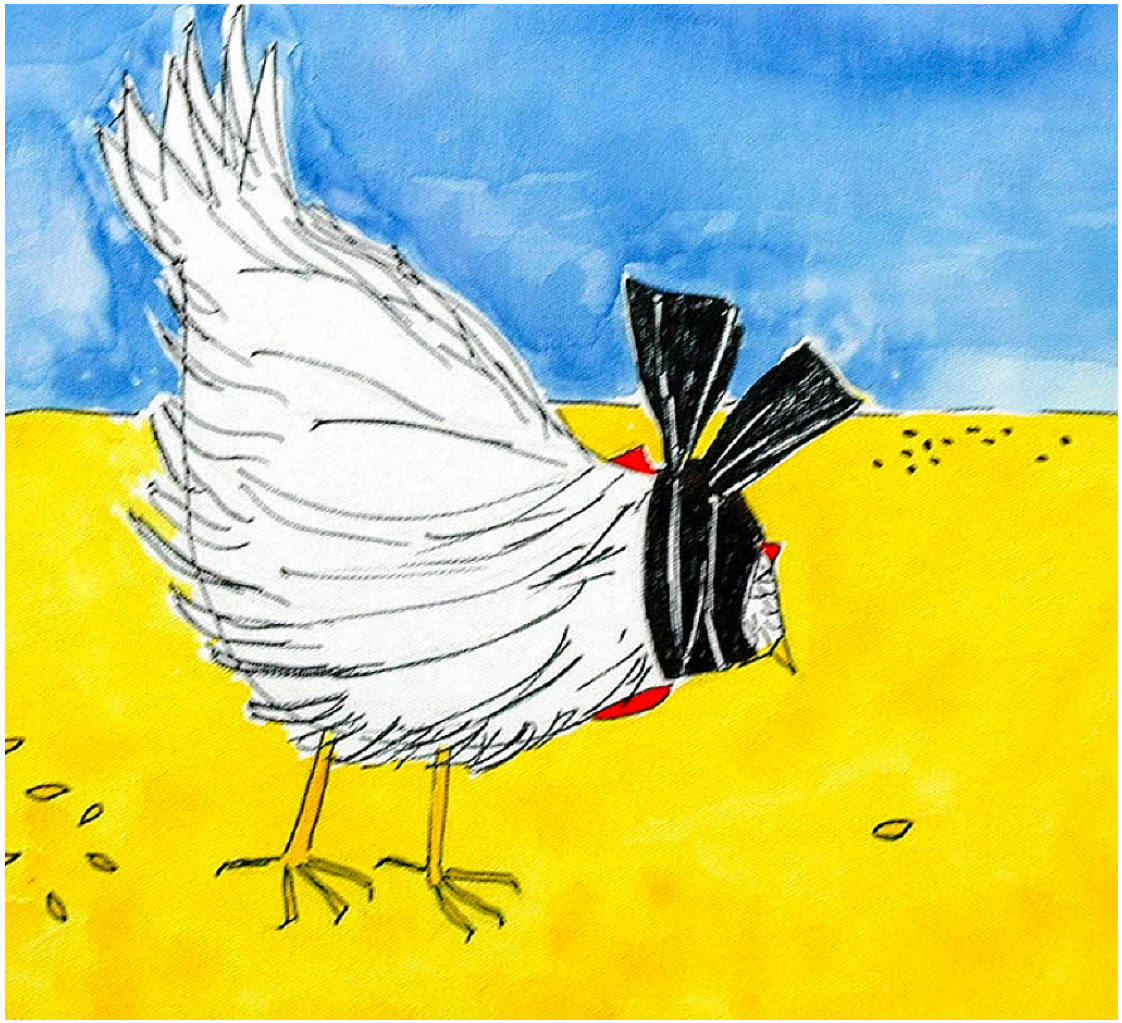
What I mean: no matter how far fetched, it might be worth a shot!

Boundary conditions:

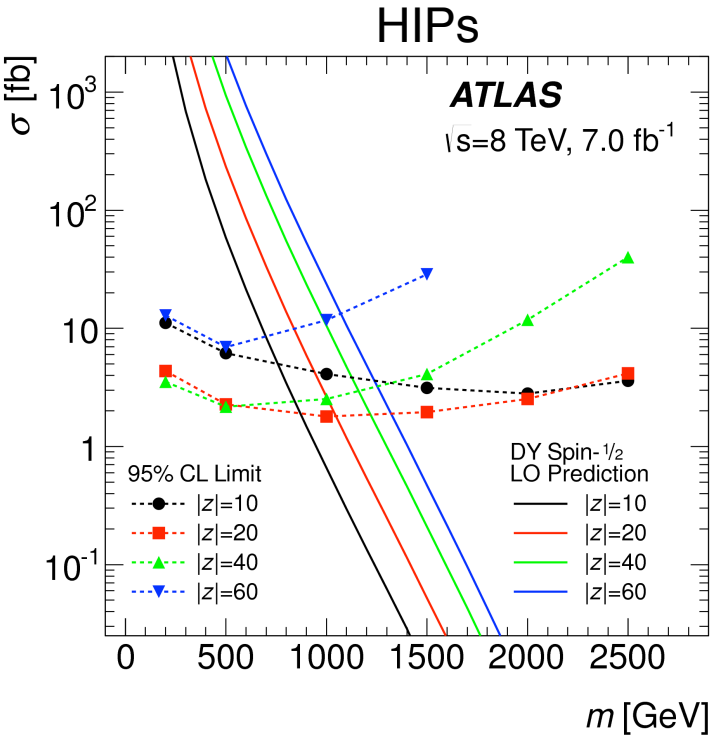
- Trigger limitations
- Reconstruction / BG
- limited person-power

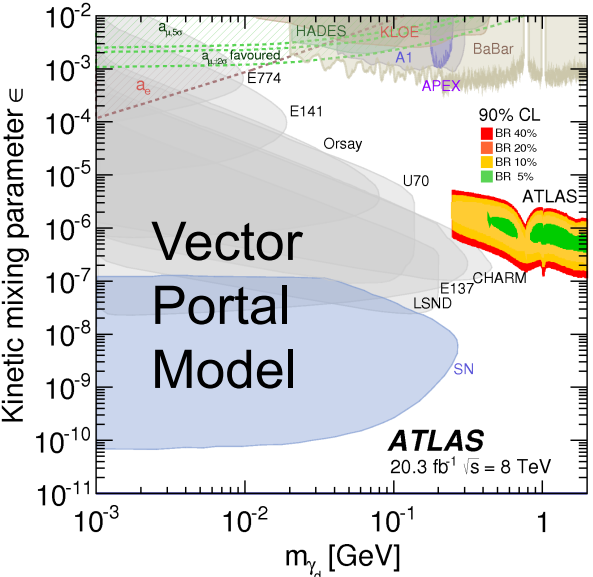
Obligation to fully exploit our data

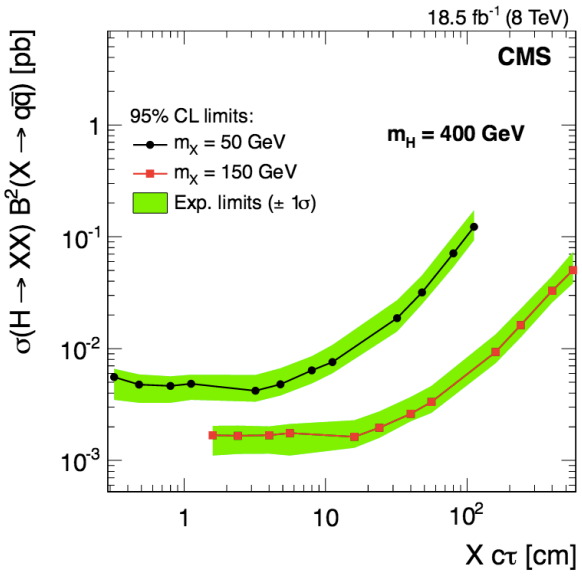
Theorists lobby / “random” encounters ⇒ analysis carried out
Attempt to prioritize?

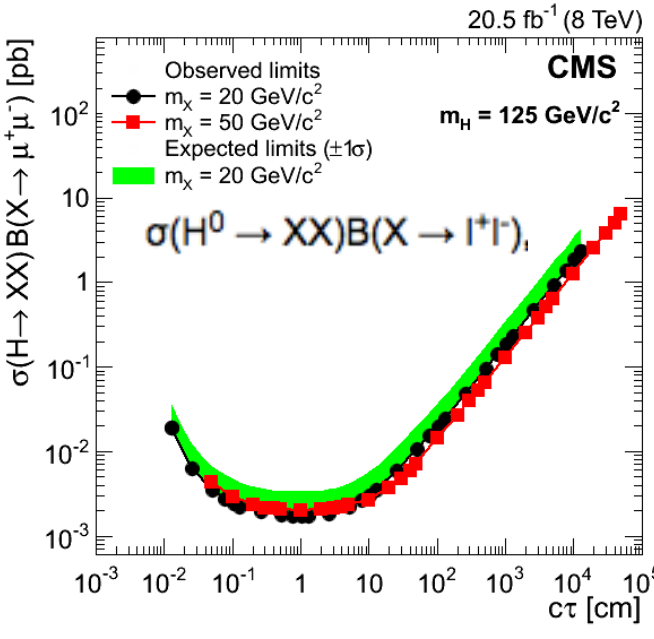


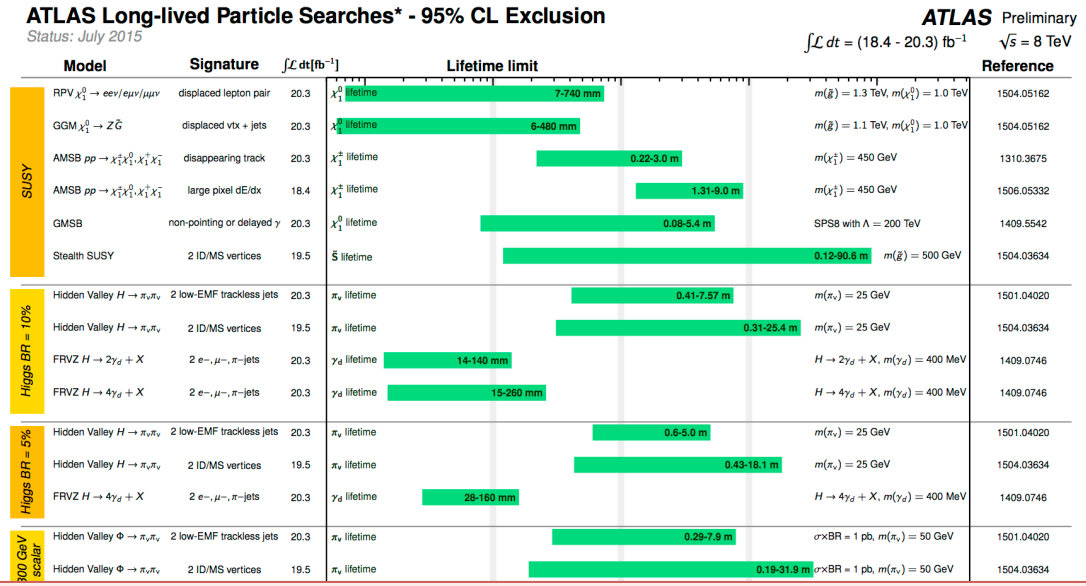

ATLAS Long-lived Particle Searches* - 95% CL Exclusion
Status: July 2015
ATLAS Preliminary
∫L dt = (18.4 - 20.3) fb⁻¹
√s = 8 TeV
Model
Signature
∫L dt[fb⁻¹]
Lifetime limit
Reference
SUSY
RPV $\chi_1^0 \to eev/e\mu\nu/\mu\mu\nu$ displaced lepton pair 20.3 χ_1^0 lifetime 7-740 mm $m(\tilde{g}) = 1.3$ TeV, $m(\chi_1^0) = 1.0$ TeV 1504.05162
GGM $\chi_1^0 \to Z\tilde{G}$ displaced vtx + jets 20.3 χ_1^0 lifetime 6-480 mm $m(\tilde{g}) = 1.1$ TeV, $m(\chi_1^0) = 1.0$ TeV 1504.05162
AMSB $pp \to \chi_1^\pm\chi_1^0, \chi_1^+\chi_1^-$ disappearing track 20.3 $\chi_1^\pm$ lifetime 0.22-3.0 m $m(\chi_1^\pm) = 450$ GeV 1310.3675
AMSB $pp \to \chi_1^\pm\chi_1^0, \chi_1^+\chi_1^-$ large pixel dE/dx 18.4 $\chi_1^\pm$ lifetime 1.31-9.0 m $m(\chi_1^\pm) = 450$ GeV 1506.05332
GMSB non-pointing or delayed γ 20.3 χ_1^0 lifetime 0.08-5.4 m SPS8 with Λ = 200 TeV 1409.5542
Stealth SUSY 2 ID/MS vertices 19.5 $\tilde{S}$ lifetime 0.12-90.6 m $m(\tilde{g}) = 500$ GeV 1504.03634
Higgs BR = 10%
Hidden Valley $H \to \pi_v\pi_v$ 2 low-EMF trackless jets 20.3 π_v lifetime 0.41-7.57 m $m(\pi_v) = 25$ GeV 1501.04020
Hidden Valley $H \to \pi_v\pi_v$ 2 ID/MS vertices 19.5 π_v lifetime 0.31-25.4 m $m(\pi_v) = 25$ GeV 1504.03634
FRVZ $H \to 2\gamma_d + X$ 2 e−,μ−,π−jets 20.3 γ_d lifetime 14-140 mm $H \to 2\gamma_d + X$, $m(\gamma_d) = 400$ MeV 1409.0746
FRVZ $H \to 4\gamma_d + X$ 2 e−,μ−,π−jets 20.3 γ_d lifetime 15-260 mm $H \to 4\gamma_d + X$, $m(\gamma_d) = 400$ MeV 1409.0746
Higgs BR = 5%
Hidden Valley $H \to \pi_v\pi_v$ 2 low-EMF trackless jets 20.3 π_v lifetime 0.6-5.0 m $m(\pi_v) = 25$ GeV 1501.04020
Hidden Valley $H \to \pi_v\pi_v$ 2 ID/MS vertices 19.5 π_v lifetime 0.43-18.1 m $m(\pi_v) = 25$ GeV 1504.03634
FRVZ $H \to 4\gamma_d + X$ 2 e−,μ−,π−jets 20.3 γ_d lifetime 28-160 mm $H \to 4\gamma_d + X$, $m(\gamma_d) = 400$ MeV 1409.0746
300 GeV scalar
Hidden Valley $\Phi \to \pi_v\pi_v$ 2 low-EMF trackless jets 20.3 π_v lifetime 0.29-7.9 m σ×BR = 1 pb, $m(\pi_v) = 50$ GeV 1501.04020
Hidden Valley $\Phi \to \pi_v\pi_v$ 2 ID/MS vertices 19.5 π_v lifetime 0.19-31.9 m σ×BR = 1 pb, $m(\pi_v) = 50$ GeV 1504.03634
900 GeV scalar
Hidden Valley $\Phi \to \pi_v\pi_v$ 2 low-EMF trackless jets 20.3 π_v lifetime 0.15-4.1 m σ×BR = 1 pb, $m(\pi_v) = 50$ GeV 1501.04020
Hidden Valley $\Phi \to \pi_v\pi_v$ 2 ID/MS vertices 19.5 π_v lifetime 0.11-18.3 m σ×BR = 1 pb, $m(\pi_v) = 50$ GeV 1504.03634
Other
HV Z'(1 TeV) $\to q_v q_v$ 2 ID/MS vertices 20.3 π_v lifetime 0.1-4.9 m σ×BR = 1 pb, $m(\pi_v) = 50$ GeV 1504.03634
HV Z'(2 TeV) $\to q_v q_v$ 2 ID/MS vertices 20.3 π_v lifetime 0.1-10.1 m σ×BR = 1 pb, $m(\pi_v) = 50$ GeV 1504.03634
0.01
0.1
1
10
100
cτ [m]
√s = 8 TeV
*Only a selection of the available lifetime limits on new states is shown.

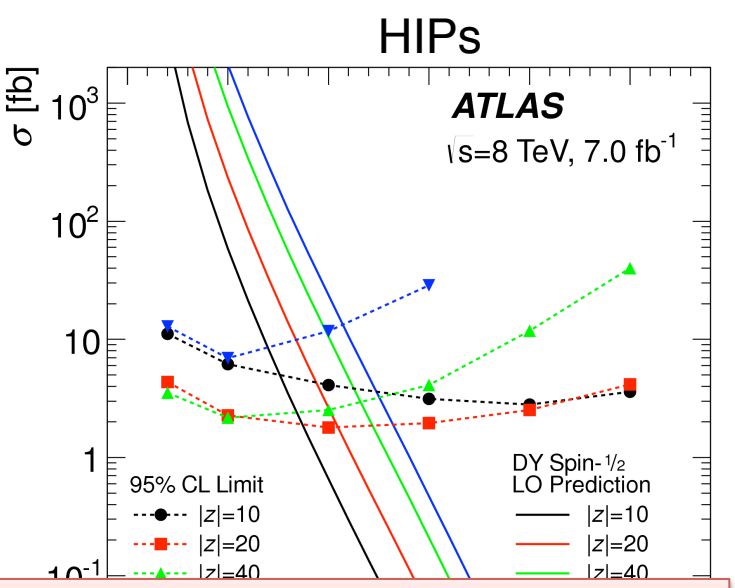

HIPs
ATLAS
√s=8 TeV, 7.0 fb⁻¹
σ [fb]
95% CL Limit
|z|=10
|z|=20
|z|=40
|z|=60
DY Spin-½
LO Prediction
|z|=10
|z|=20
|z|=40
|z|=60
m [GeV]


Vector
Portal
Model
HADES
KLOE
BaBar
A1
APEX
E774
E141
Orsay
U70
favoured
90% CL
BR 40%
BR 20%
BR 10%
BR 5%
ATLAS
CHARM
E137
LSND
SN
ATLAS
20.3 fb⁻¹ √s = 8 TeV
Kinetic mixing parameter ∈
m_γd [GeV]

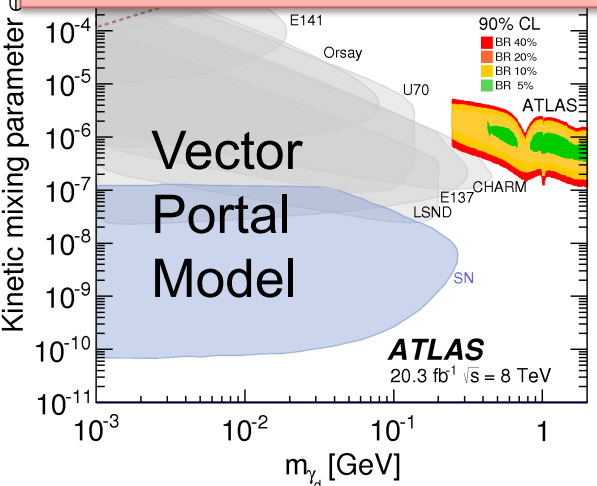

18.5 fb⁻¹ (8 TeV)
CMS
95% CL limits:
m_X = 50 GeV
m_X = 150 GeV
Exp. limits (± 1σ)
m_H = 400 GeV
σ(H → XX) B²(X → qq̄) [pb]
X cτ [cm]

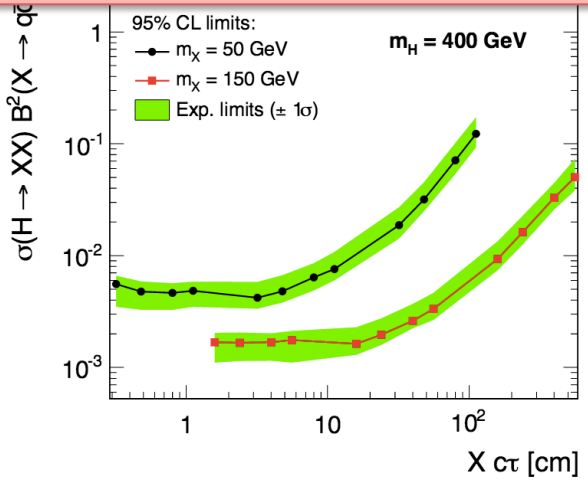

20.5 fb⁻¹ (8 TeV)
CMS
Observed limits
m_X = 20 GeV/c²
m_X = 50 GeV/c²
Expected limits (±1σ)
m_X = 20 GeV/c²
m_H = 125 GeV/c²
σ(H⁰ → XX)B(X → l⁺l⁻),
σ(H→ XX)B(X→ μ⁺μ⁻) [pb]
cτ [cm]

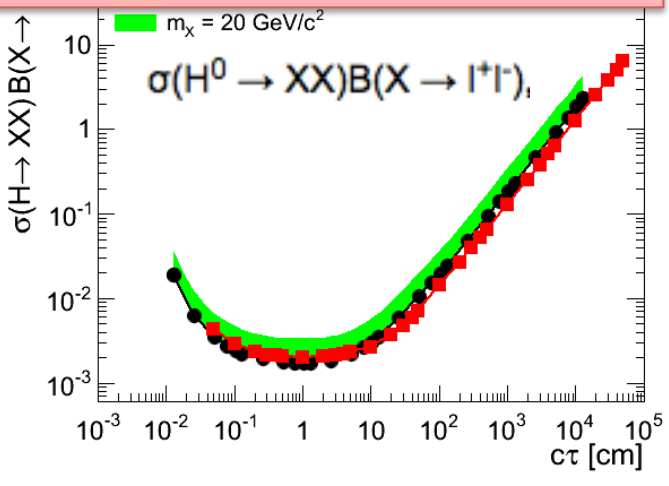




Trigger+background rejection vs generality





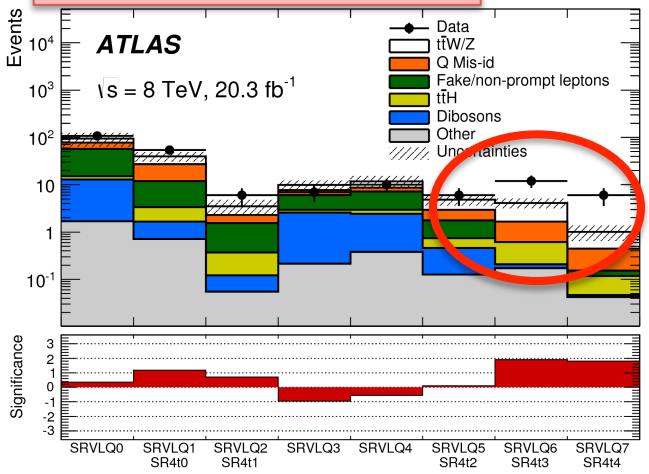


First signs of NP?

First signs of New Physics?

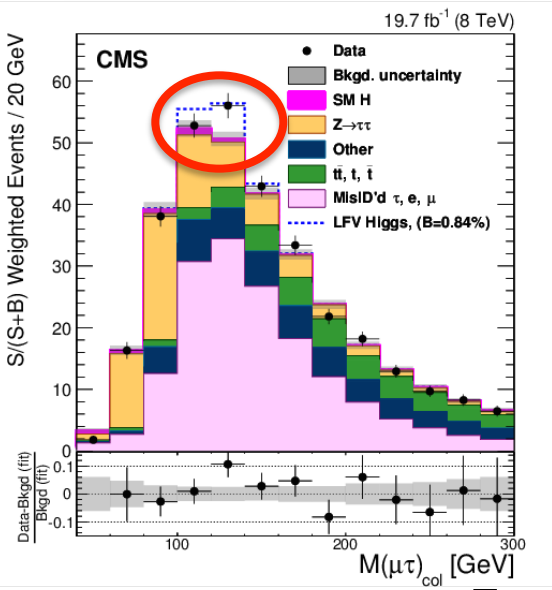
SS leptons + b-jets

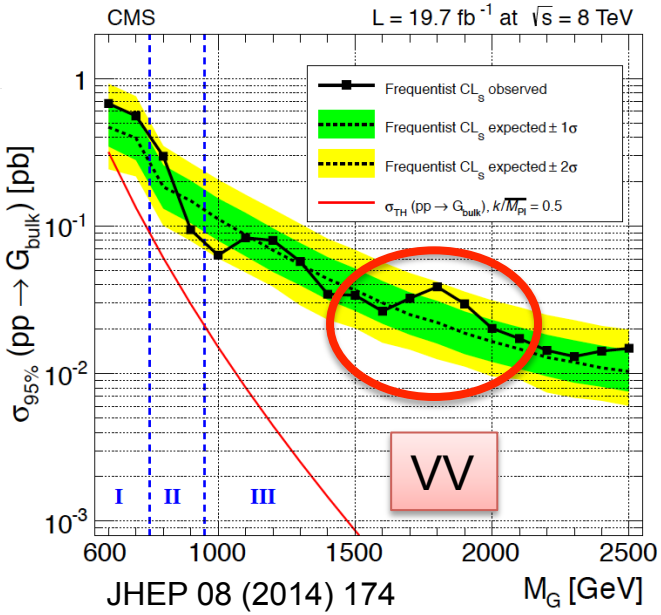
1504.04605



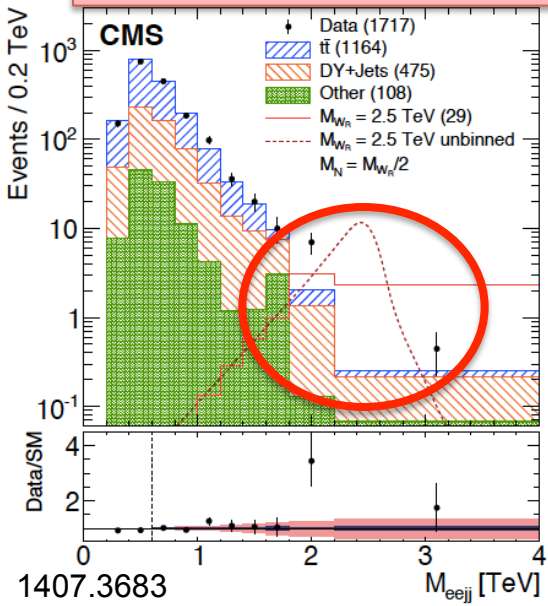
H→μτ

arxiv:1502.07400

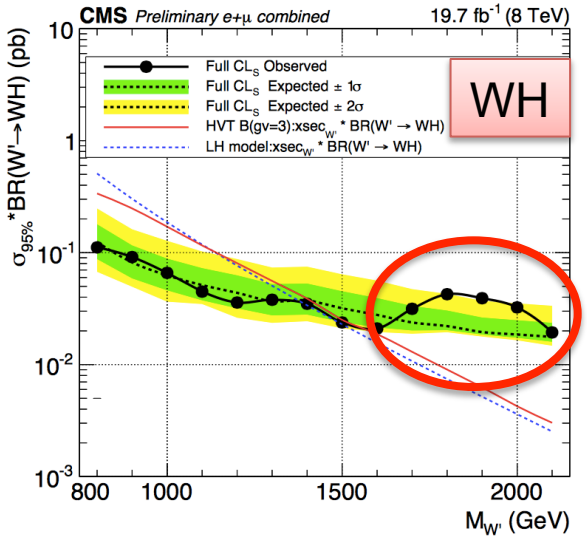


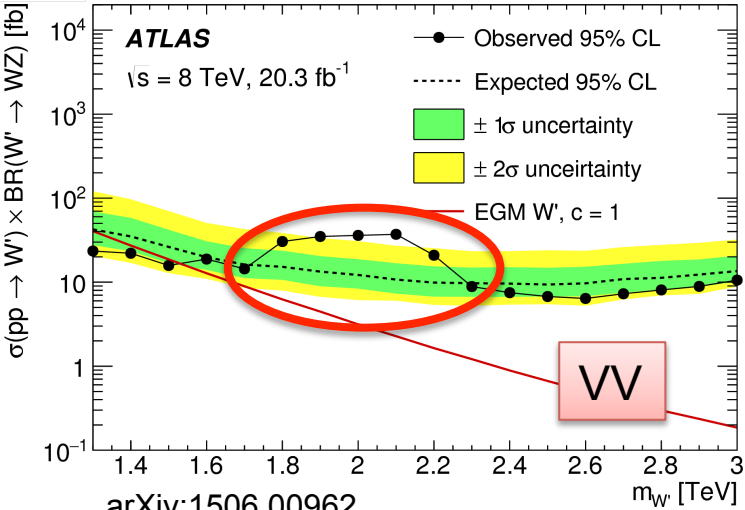


W_R and Heavy Neutrinos



CMS: PAS EXO14010



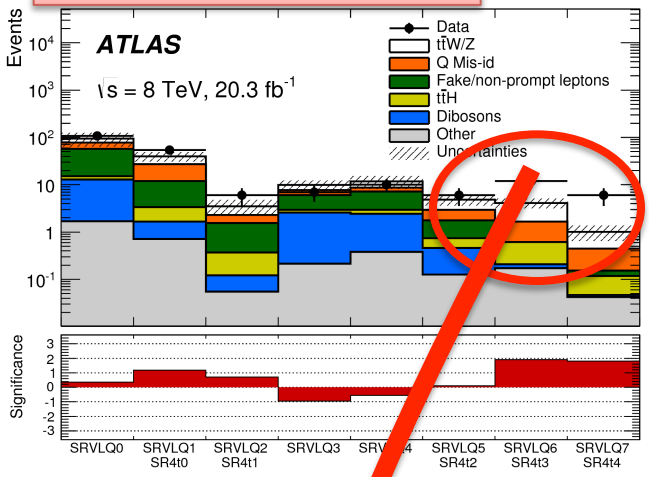


La vie en rose

With Pink Glasses

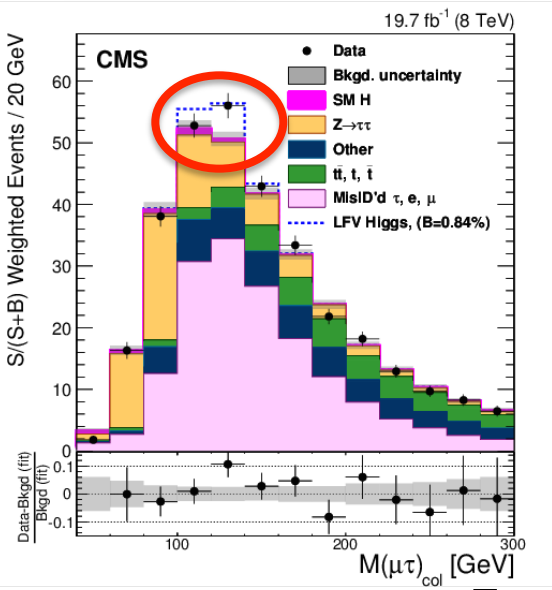
SS leptons + b-jets

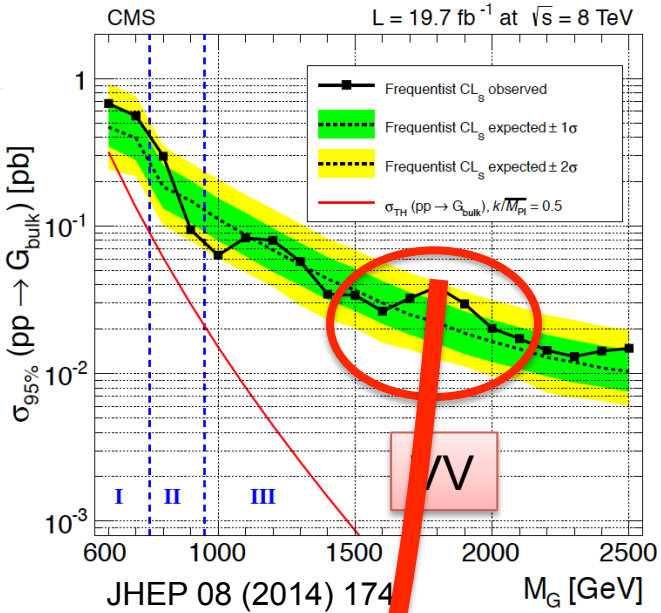
1504.04605



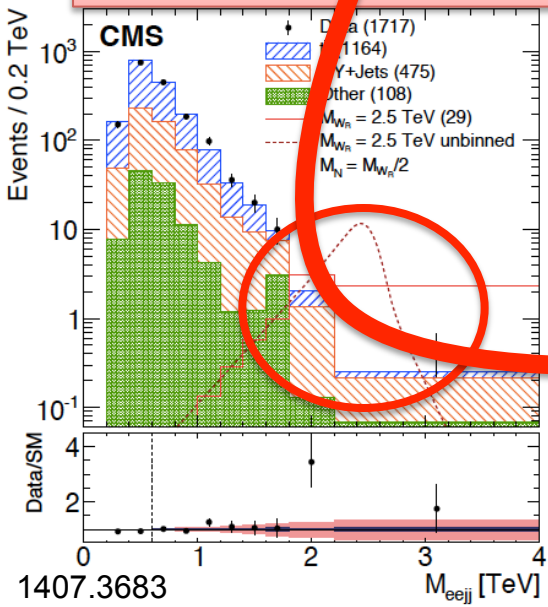
H→μτ

arxiv:1502.07400

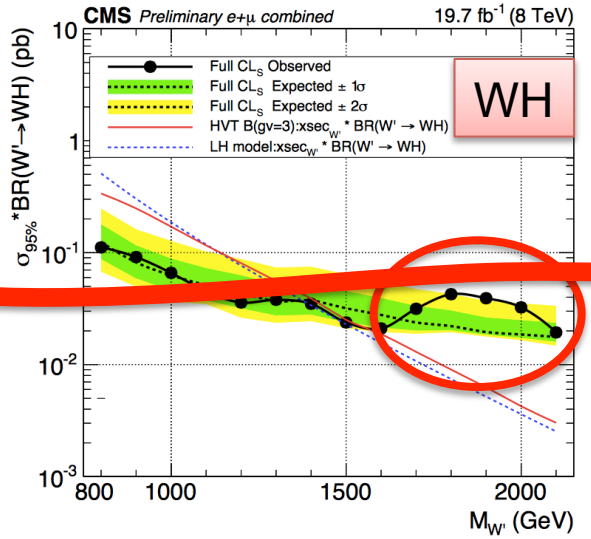


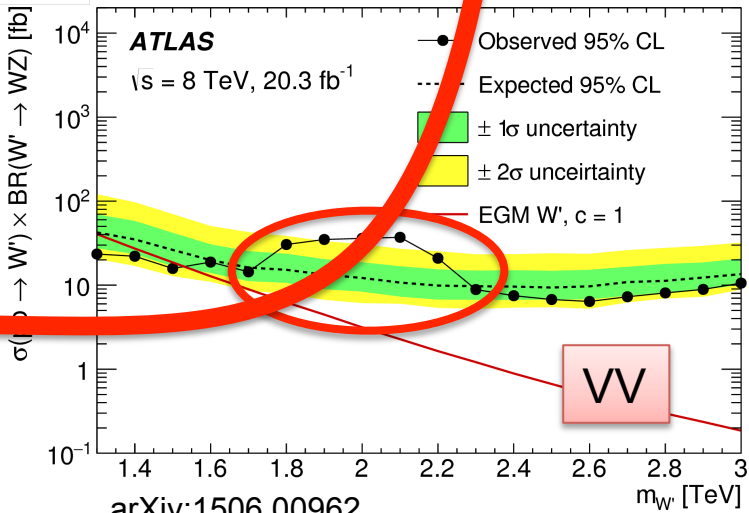


W_R and Heavy Neutrinos



CMS: PAS EXO14010





One example
(there are more)

Concrete L-R-sym model which does the trick & more!

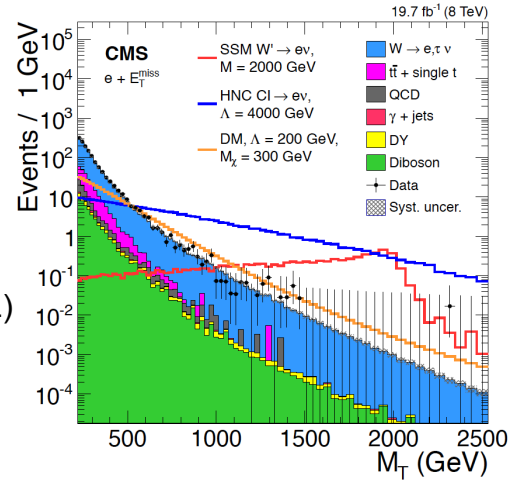
1507.01923

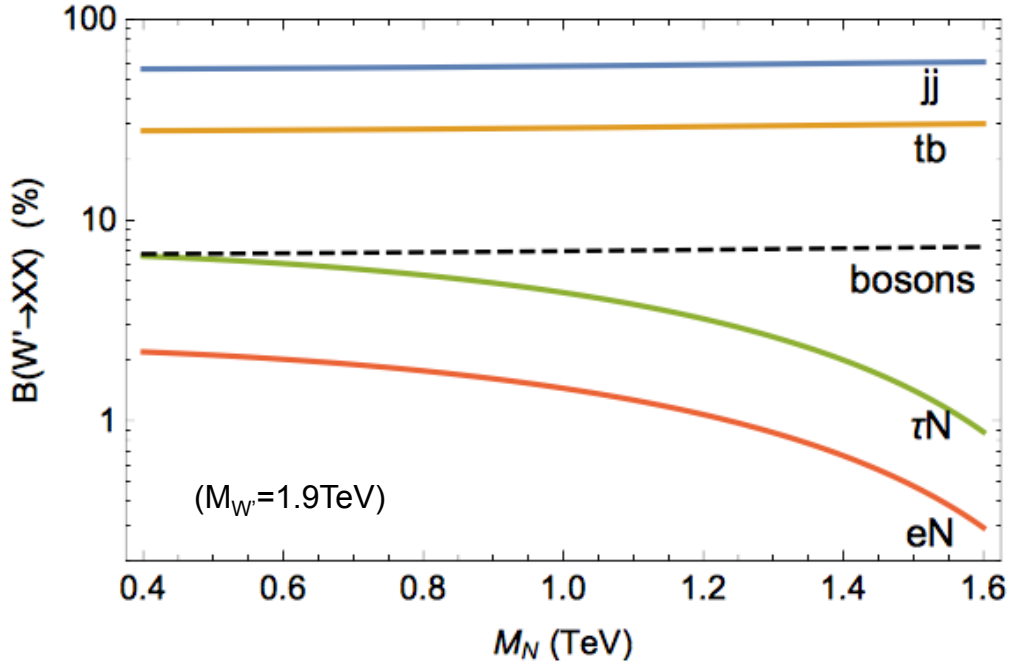
$$\Gamma(W' \to t\bar{b}) \simeq \Gamma(W' \to c\bar{s}) = \Gamma(W' \to u\bar{d}) = \frac{g_R^2}{16\pi} M_{W'}$$

$$\Gamma(W' \to e\bar{N}) \simeq \frac{s_{\theta_e}^2 g_R^2}{48\pi} M_{W'} \quad , \quad \Gamma(W' \to \tau\bar{N}) \simeq \frac{c_{\theta}^2 g_R^2}{48\pi} M_{W'}$$

$$\frac{1}{c_W^4}\Gamma(W' \to WZ) \simeq \Gamma(W' \to Wh^0) \simeq \frac{g_R^2}{192\pi} \sin^2 2\beta \, M_{W'}$$

Lower mass limit (95% CL) on W'_{SSM} is 3.3 TeV



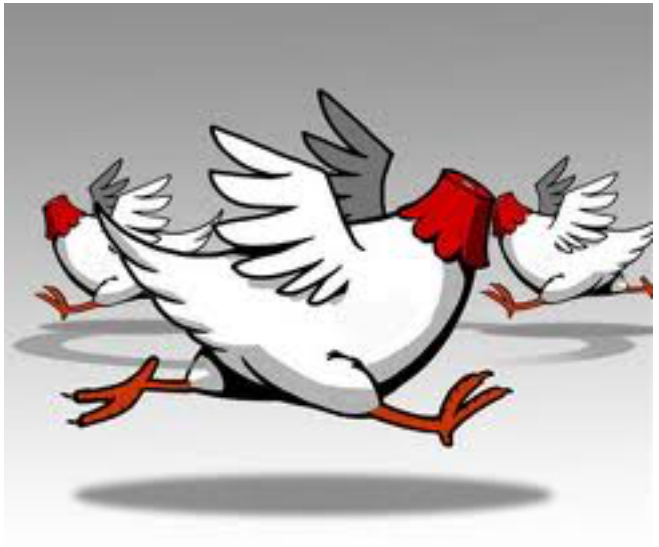


- Mainly decay to jj (2/3) and tb (1/3)
- Also decay to bosons
- No coupling to left-handed leptons
  - Evade strong W'→lν limits
- e^+e^-jj but not e^+e^+jj (Dirac mass for N, not Majorana mass)
- Evade strong Z'→ll limits

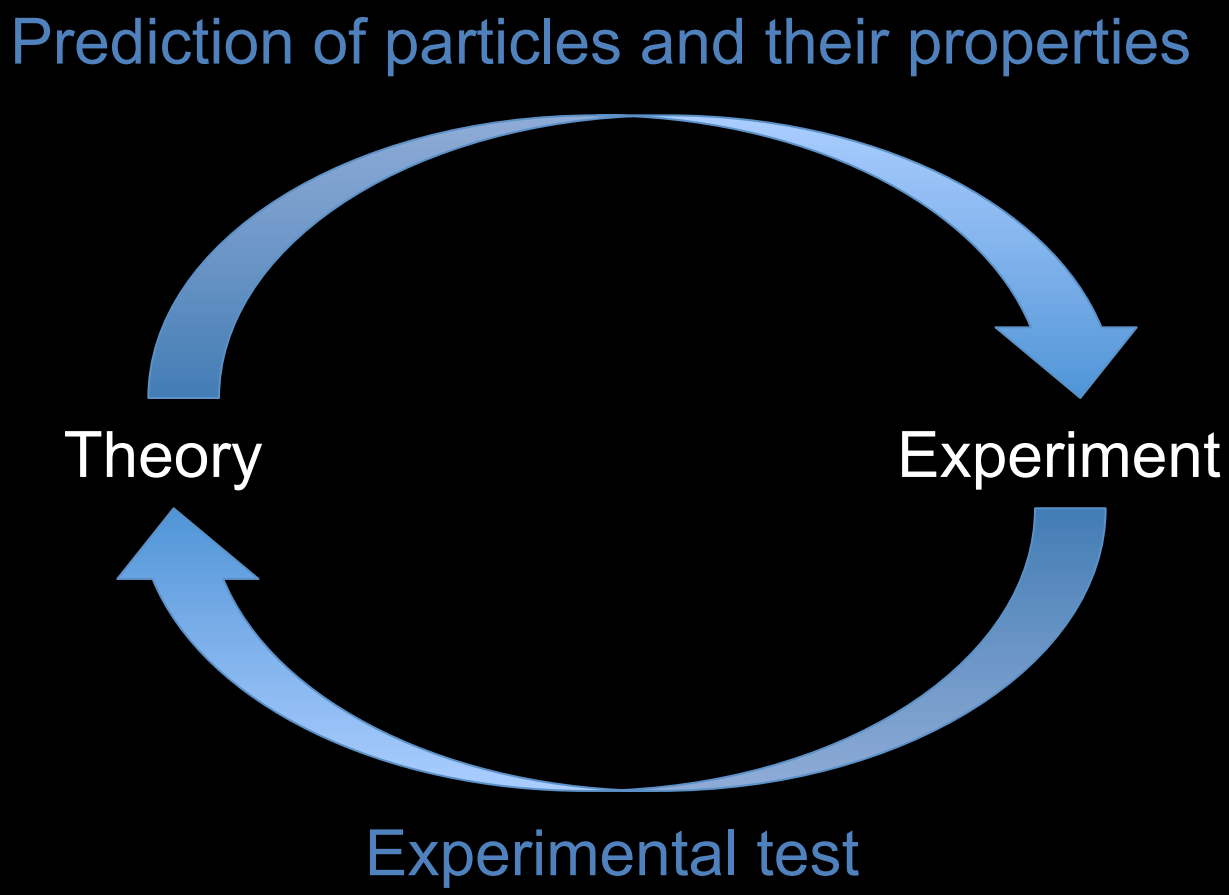
Chapeau!

(eierlegende Wollmilchsau)

Or just headless ambulance chasing?



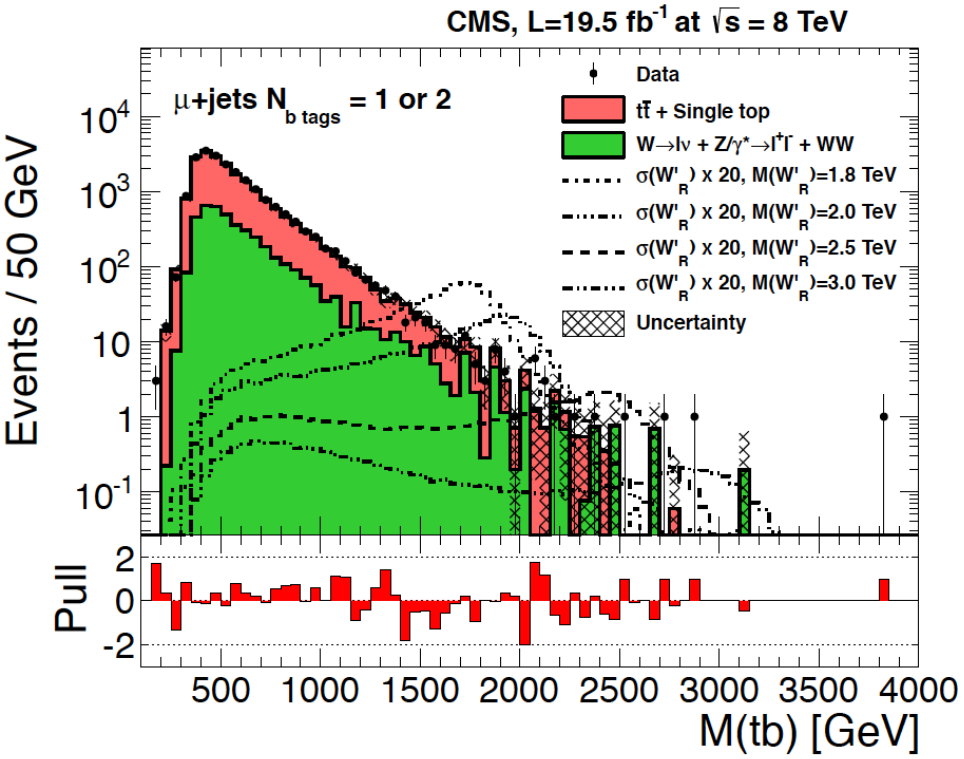
Closing the Loop

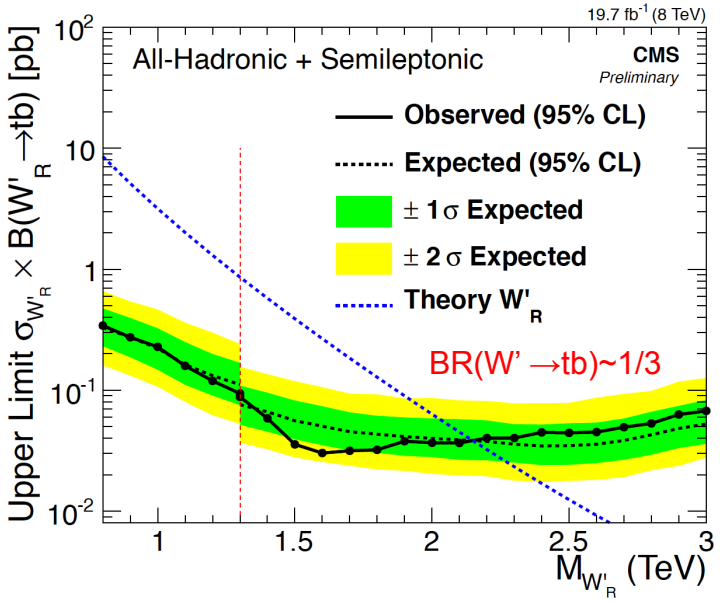


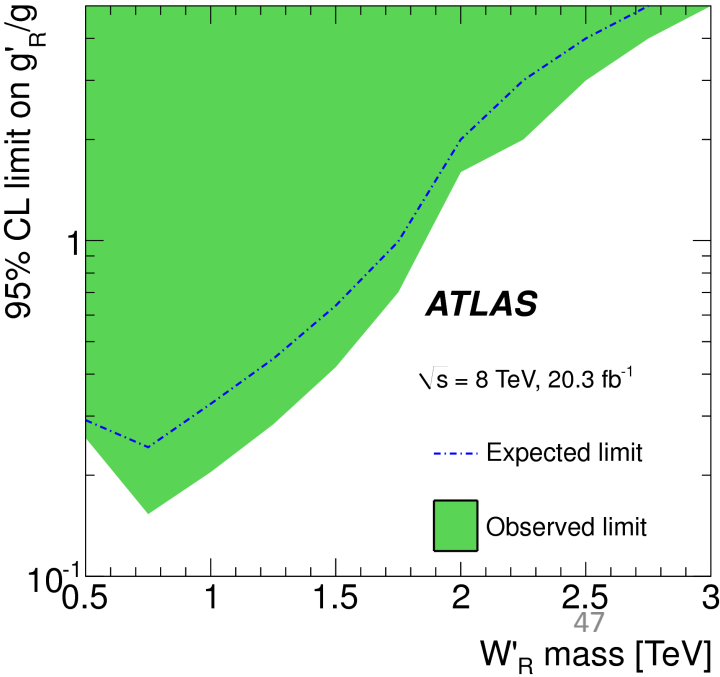
(New) signals predicted: W'→tb

ATLAS (1408.0886, 1410.4103)

CMS (1410.4103), CMS PAS B2G-12-009





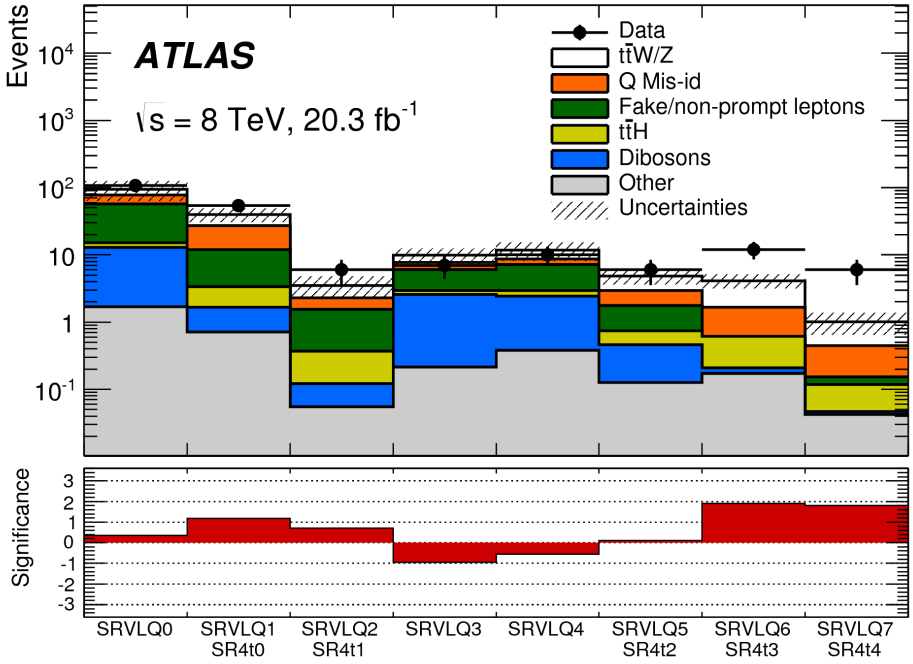


1507.01923

W′ decays into heavy Higgs bosons

- Model predicts: $W' \rightarrow H^+H^0, H^+A^0 \rightarrow (tb)(tt) \rightarrow 3W+4b$
- We happen to have a search for $BB \rightarrow (tW)(tW) \rightarrow 4W+2b$ and non-DM 4-top production $\rightarrow 4W+4b$
  - And it has an excess (SS leptons / 3 leptons + b-jets)

1504.04605

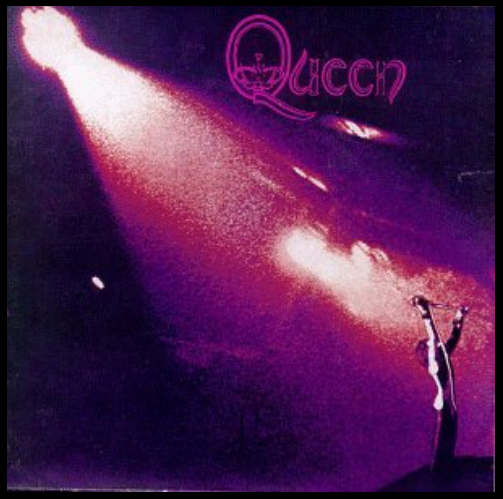


Excess explained for
$M(H^{\pm}) \approx M(H^0) \approx M(A^0) \approx 500$ GeV
($M_{W'} \approx 1.9-2$TeV)

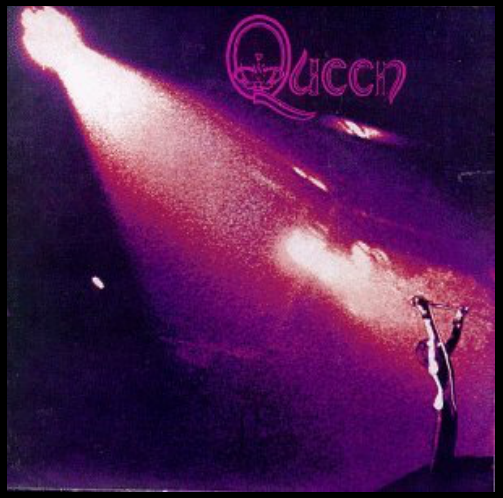
Design dedicated searches for new signals predicted by hypotheses explaining excess(es), e.g. look for resonance in this case

What’s next?


The Show Must Go On

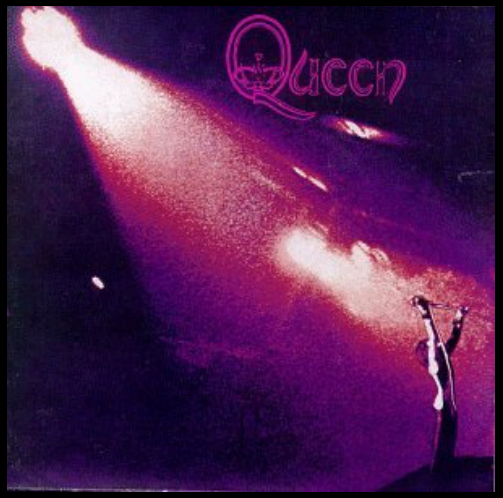


Run 1



Run 1

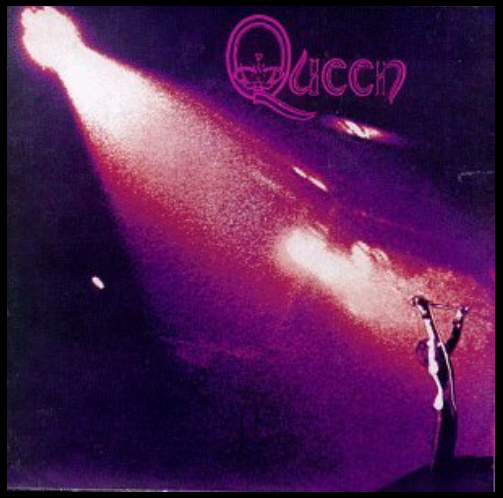
Run 2 (highly underrated album)



Run 1

Run 2 (highly underrated album)

13-14 TeV?

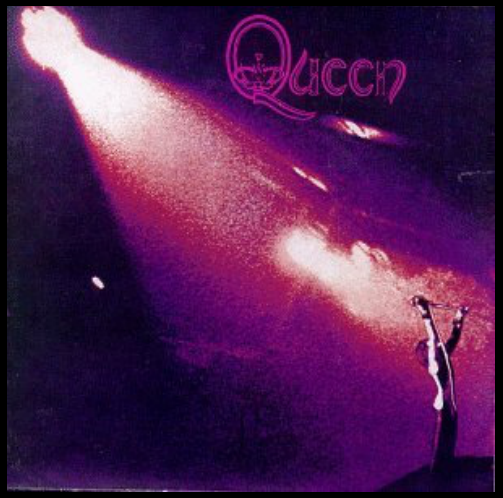


Run 1

Run 2 (highly underrated album)

13-14 TeV?

HL-LHC?



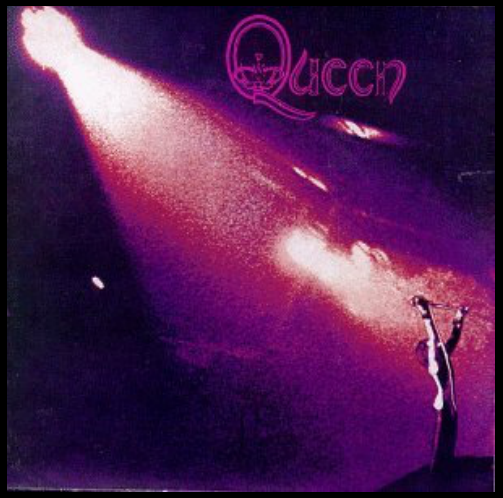
Run 1

Run 2 (highly underrated album)

13-14 TeV?

HL-LHC?

FCC?



Run 1

Run 2 (highly underrated album)

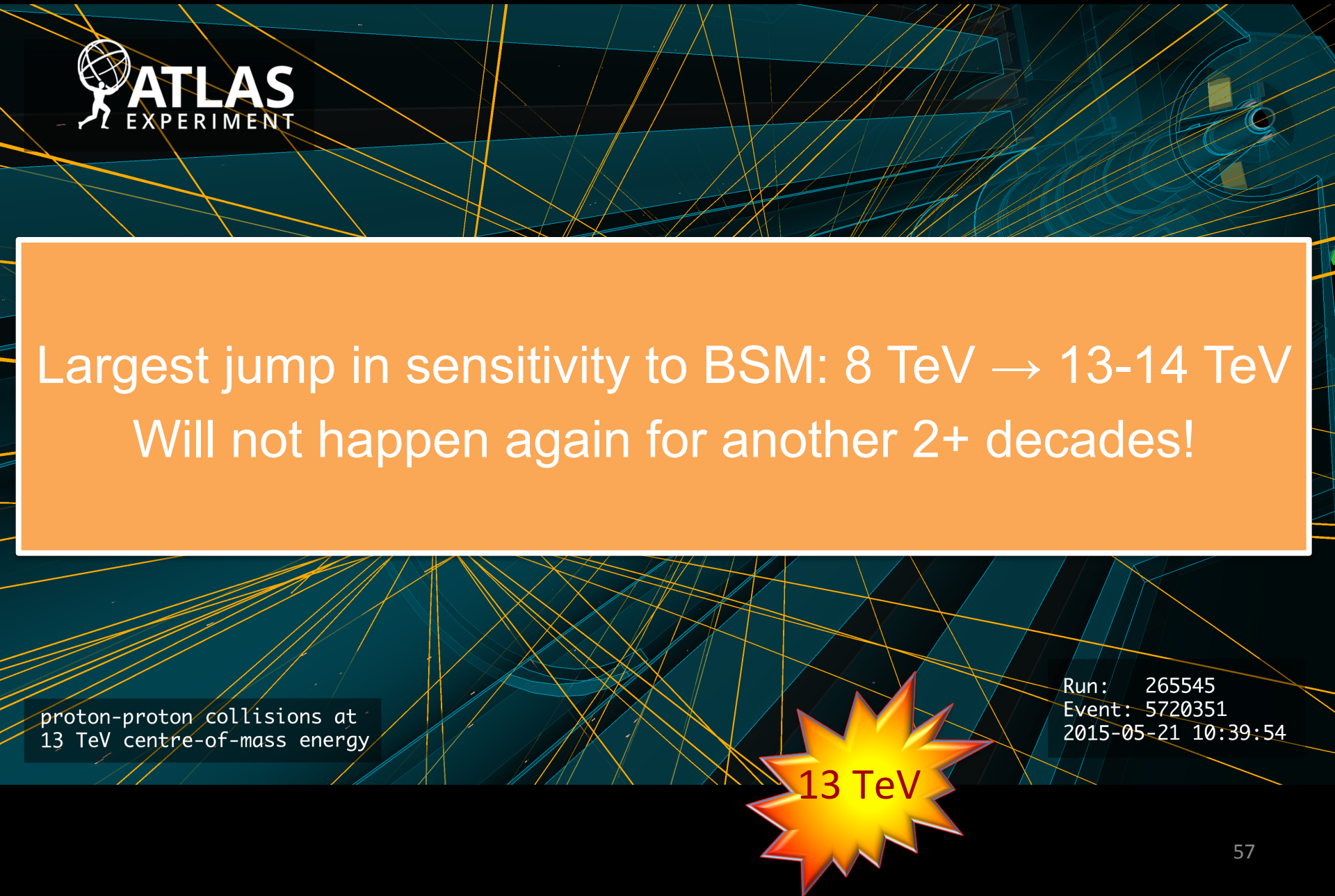
13-14 TeV?

HL-LHC?

FCC?

What's next?

Second chance for discovery: Run 2



Largest jump in sensitivity to BSM: 8 TeV → 13-14 TeV

Will not happen again for another 2+ decades!

5 excesses of ~2σ $\ll$ 2 excesses of 5σ

(Bogdan Dobrescu @ BOOST 2015)

We need only 1 to be true! $\rightarrow$ Run 2

5 excesses of ~2σ $\ll$ 2 excesses of 5σ

(Bogdan Dobrescu @ BOOST 2015)

We need only 1 to be true! $\rightarrow$ Run 2

Run 2 Plans

- First things first: high mass (& check excesses)
  - Crucial: boosted techniques for top/W/Z/H and high-p_T b-tagging
- Fast: take advantage of fast raise in L
  - High-quality (goes without saying)
- Don't "waste time" with recasting (your job)
  - experimental results + O(1) interpretation + provide all information to allow for recasting
- In addition: have some more (UV-)complete models?
  - There is SUSY – what about HVT, L-R sym, …?
  - Takes time for us, needs interaction with you guys (STA)
  - Lower priority? Do later?
- Keep closing the loop with you: add new signatures
- First do search ⇒ then precision measurement (make better use of our manpower)

Keep innovating

- Keep improving understanding / performance / calibration
  - New better detectors: ATLAS IBL, CMS pixel to be installed winter 2016-2017 (both 4-layers): improves tracking & b-tagging
  - Boosted objects, high-p_T b-tagging (more $t\bar{t}$ ⇒ calibration source)
- Trigger-level analysis
- Extend non-standard reconstruction: DV, LJ, kinks etc. (trigger!)
- Turning the crank vs. innovation: mandate to educate students – environment where young kids can blossom: novel ideas
- Modern Machine Learning (MML), see Data Science @ LHC WS: http://indico.cern.ch/event/395374/
  - Kinematic selection, object identification, tracking, jet reconstruction,…
  - Deep Neural Nets to understand language like we do ⇒ teach them to understand physics (i.e. SM) and look for anomalies

Summing it up

- Cover all bases: usual suspects (theory guide)
- Do whatever is possible: low-hanging fruit + reach for stars (exploit data in all possible ways)
- Be prepared & hope for the unexpected…

Surprise me!