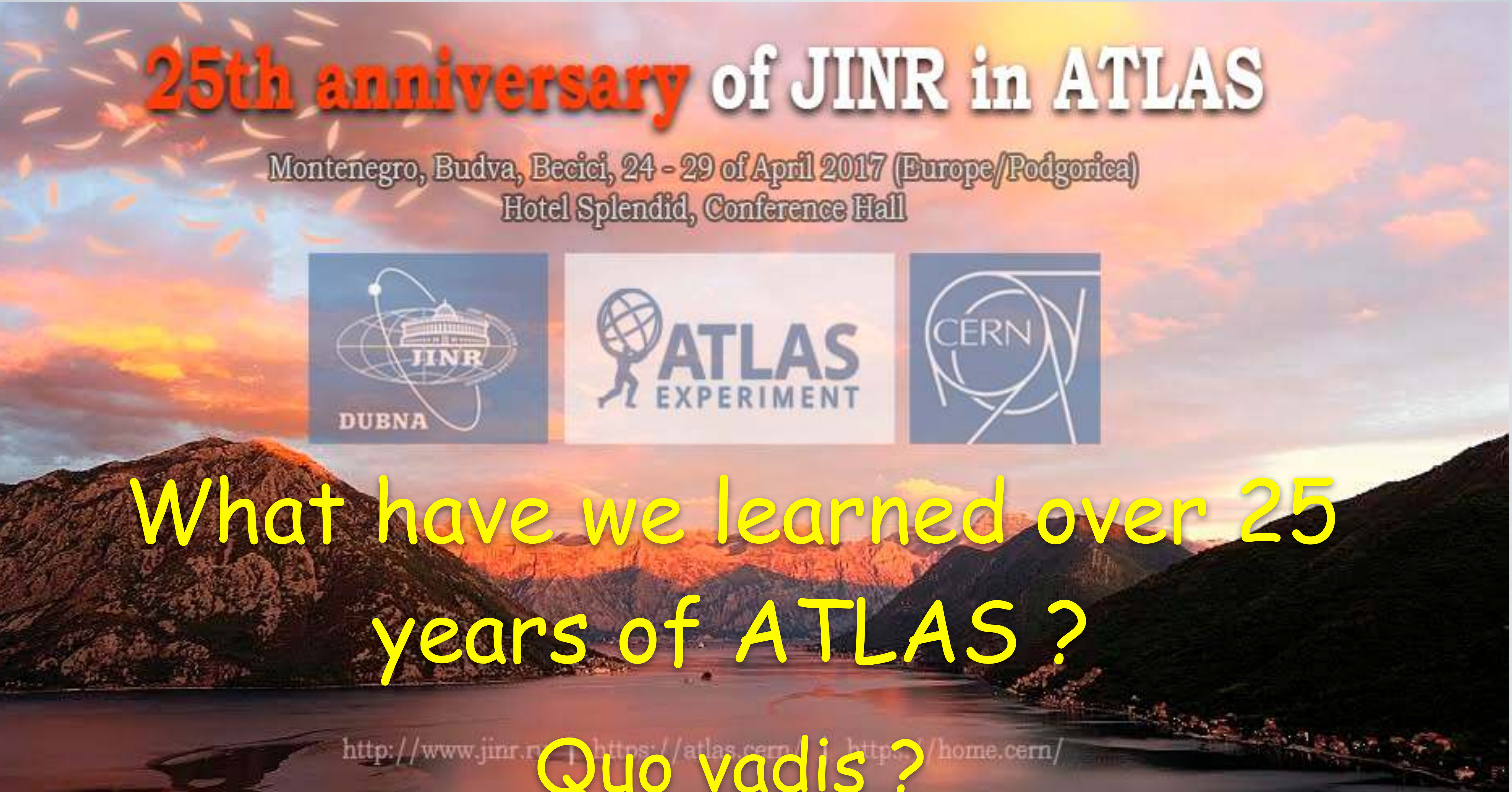


What have we learned over 25 years of ATLAS ?

Quo vadis ?

Dmitry Kazakov

Bogoliubov Laboratory of Theoretical Physics

Joint Institute for Nuclear Research

Where in HEP have we been 25 years ago?

NB: LEP was running till 2000

	1992:
• No Higgs boson	Only limits. Doubts of its existence
• No top quark	1995
• No tau neutrino	2000
• No fourth generation	Was still possible. Why not?
• No neutrino oscillations	1998 atmospheric neutrinos
• No pentaquark	Contraversal experiments
• No SUSY	Big hopes for light charginos at LEP
• No Z',W' etc	String inspired symmetries
• No Extra Dimensions	Not even in agenda
• No Dark Matter	Not even in agenda

Which questions in particle physics did we expect to answer with the LHC?

- The origin of spontaneous symmetry breaking
- The origin of flavour mixing (CKM?)
- The origin of CP violation
- The number of generations (3 or more)
- The gauge group except for SU(3)xSU(2)xU(1)
- The number of space dimensions
- The existence of exotic hadrons
- The existence of new particles (forces)
- The origin of Dark Matter

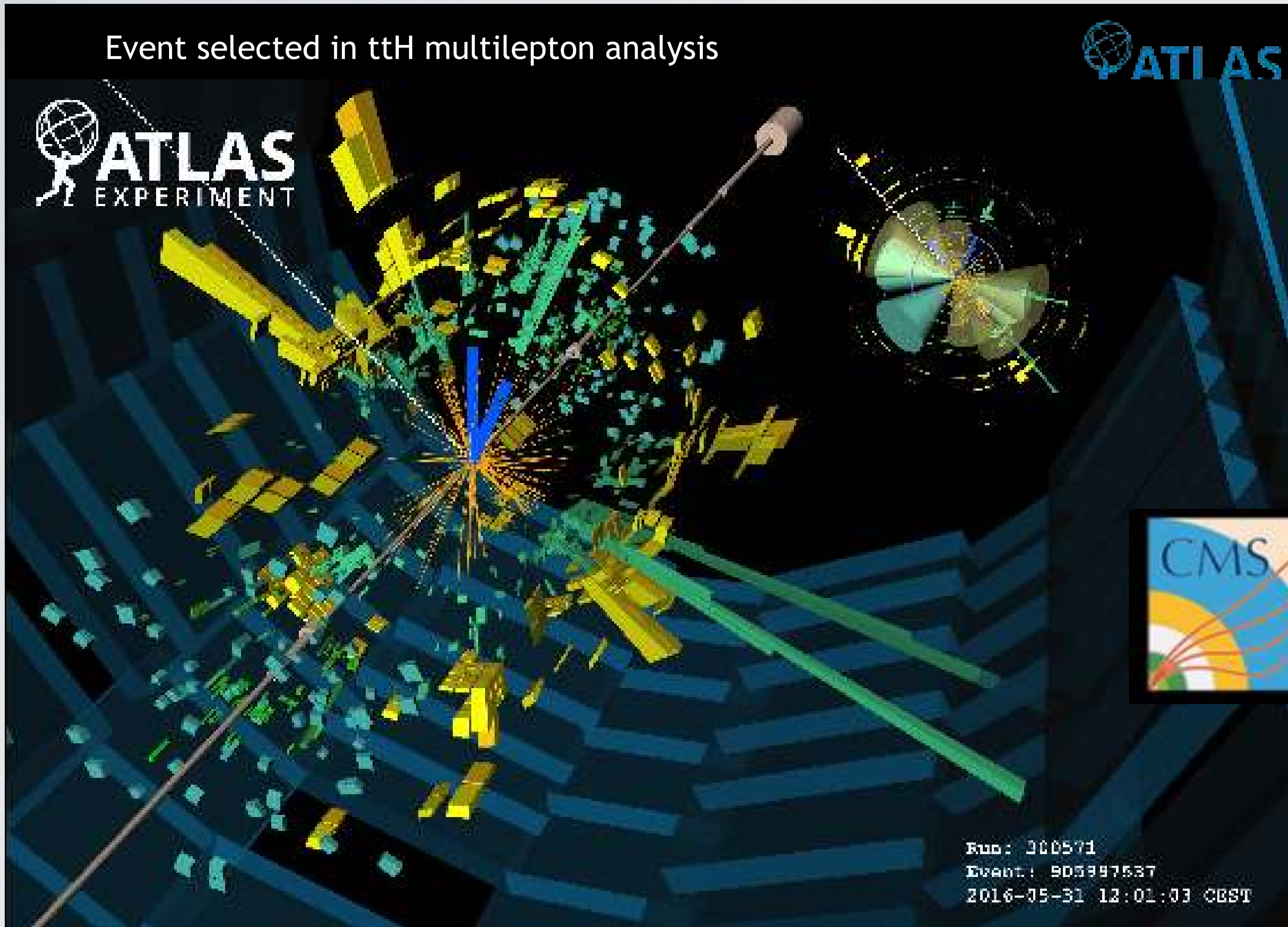
Which questions in particle physics did we answer with the LHC?

- The origin of spontaneous symmetry breaking ☑
- The origin of flavour mixing (CKM?) Measured ?
- The origin of CP violation
- The number of generations (3 or more) ☑
- The gauge group except for SU(3)xSU(2)xU(1) ? No
- The number of space dimensions Limits ?
- The existence of exotic hadrons ☑
- The existence of new particles (forces) Limits ?
- The origin of Dark Matter No ?

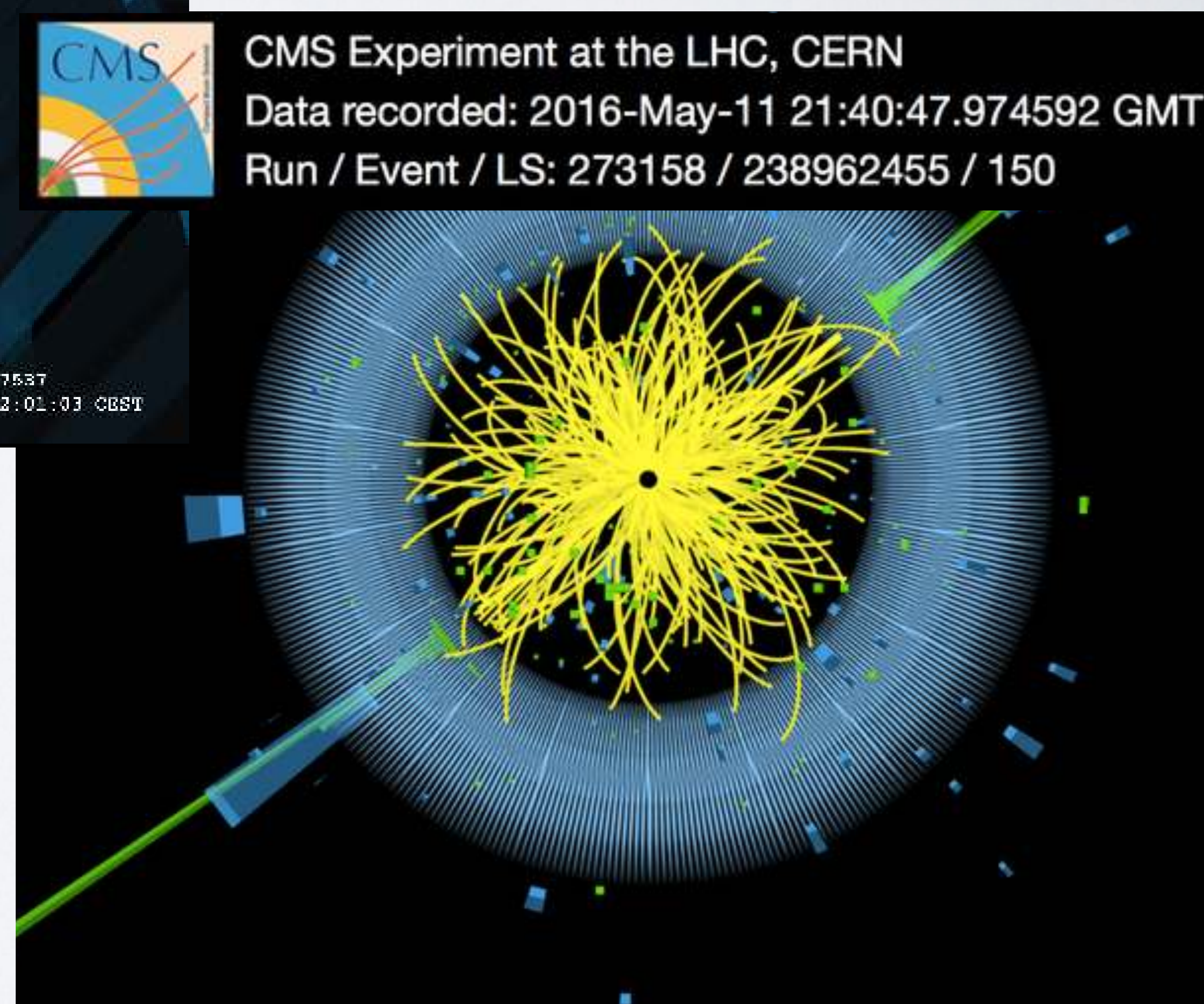
What do we expect from future runs of the LHC?

- The structure of the Higgs sector
- The search for new particles (forces)
- The search for the Dark Matter particle
- The precision tests of the CKM mixing in B-decays
- The determination of CP phases in B-decays
- The spectroscopy of exotic hadrons
- The search for new gauge bosons
- The search for extra dimensions
- Exotics (?)

What do expect from the LHC RunII?



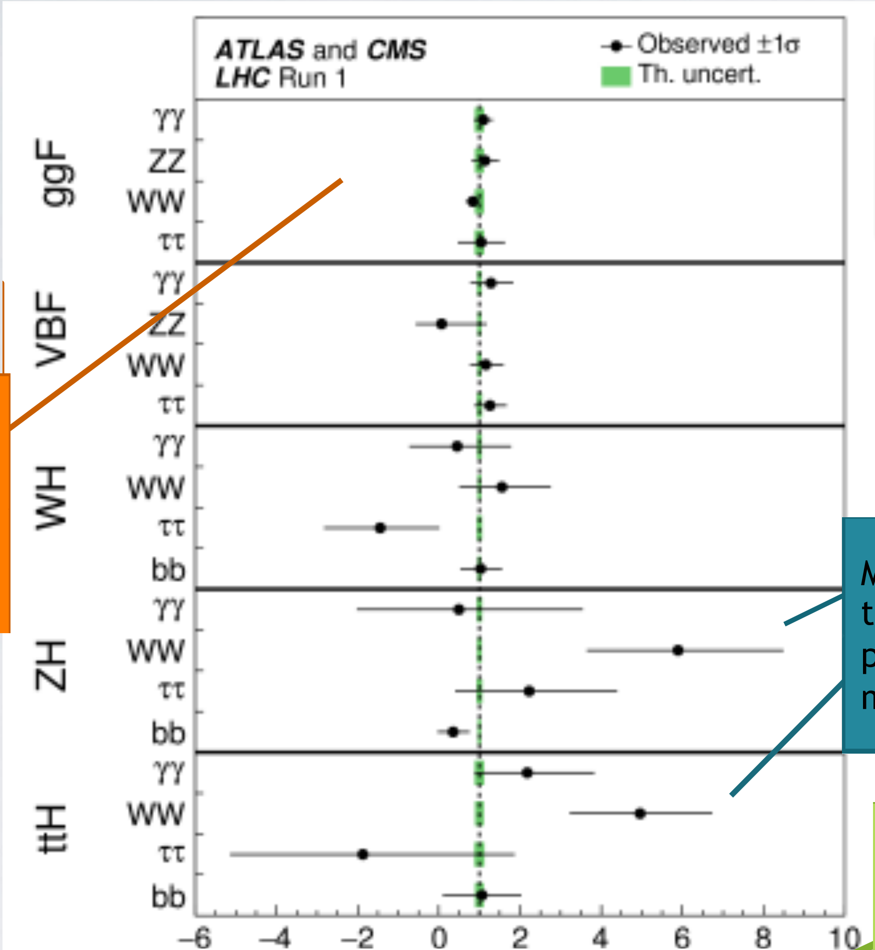
We are in a data driven era



“Measure what is measureable and make measureable what is not so.”

Galileo Galiliei
1564-1642

HIGGS BOSON (125)



Precision test of Higgs boson coupling strength

Gluon fusion measurements, starting to approach SM theory uncertainties: **15%**

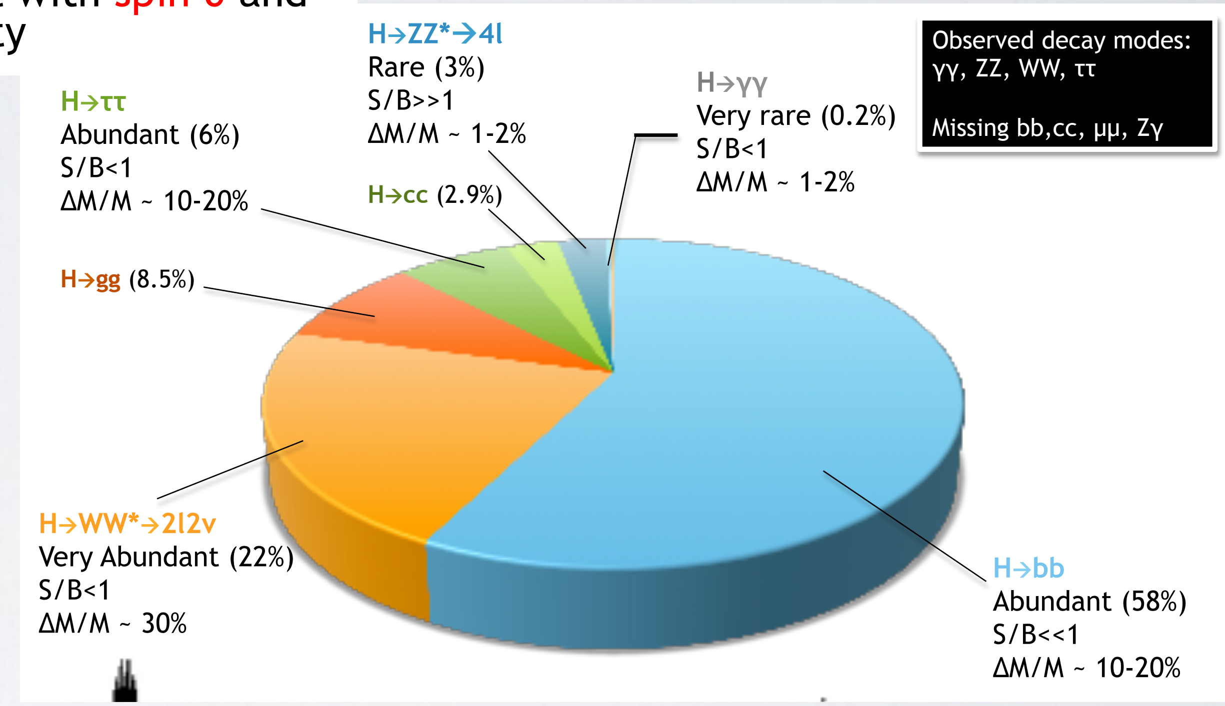
Mild excess in ttH and ZH production modes

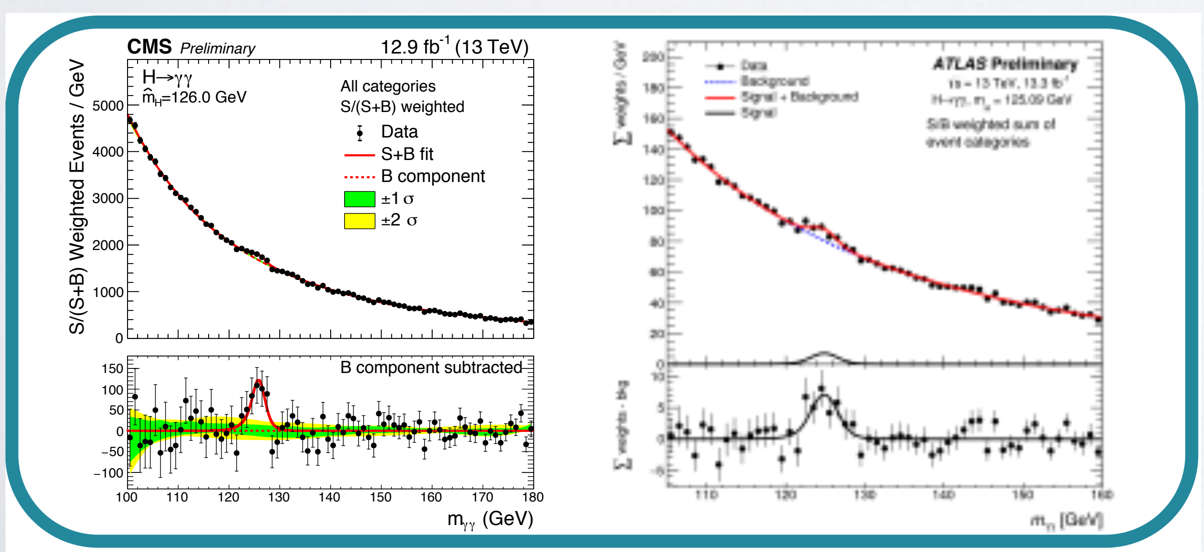
Coupling strengths

$$\mu = \frac{\sigma}{\sigma_{SM}}$$

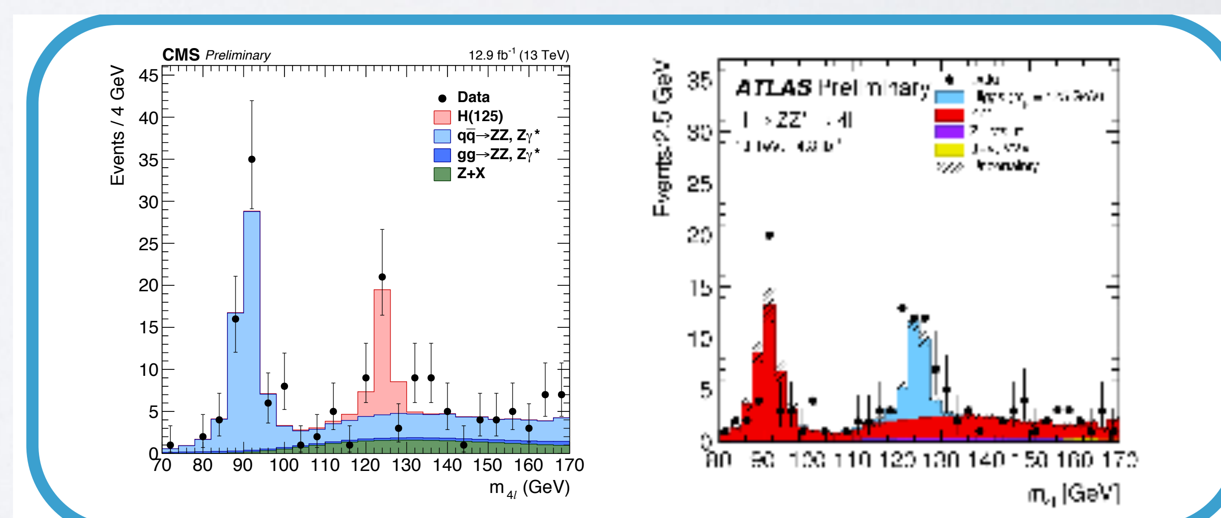
- Mass has been measured to 0.2% precision
  m_H=125.09±0.24 GeV
- Angular distributions consistent with spin 0 and even parity

- All couplings are consistent with SM within 2.5σ





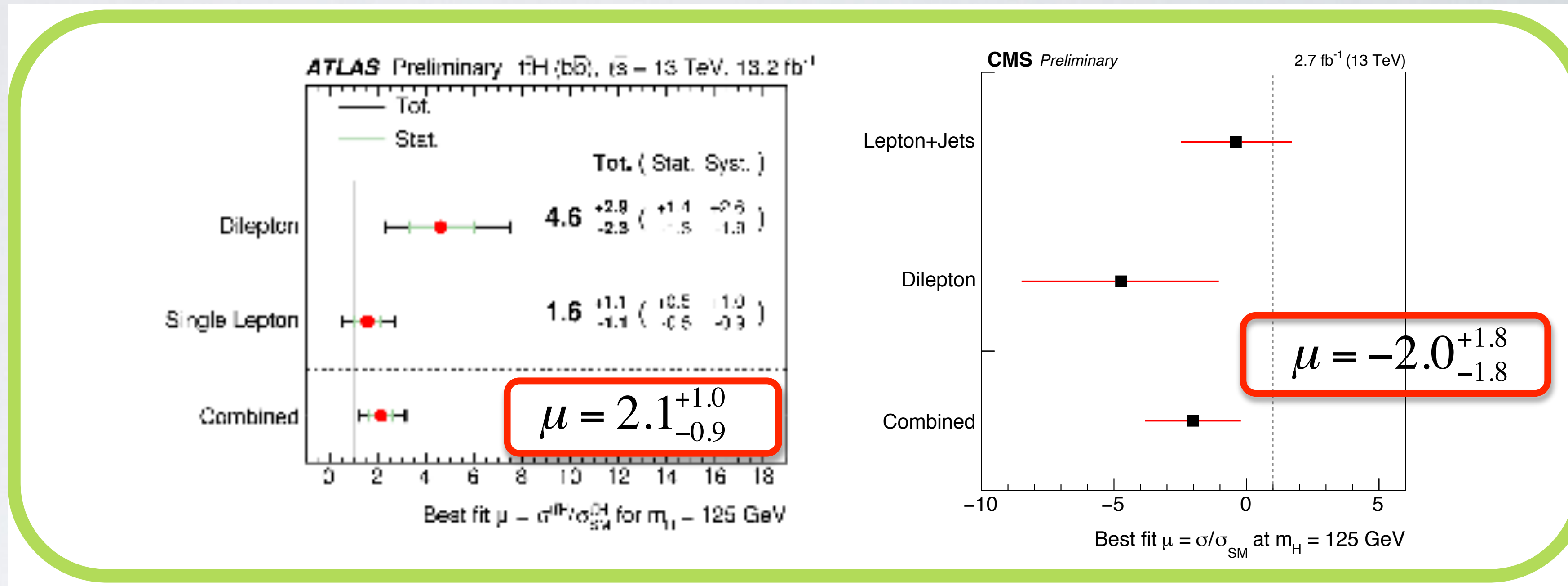
Higgs→γγ



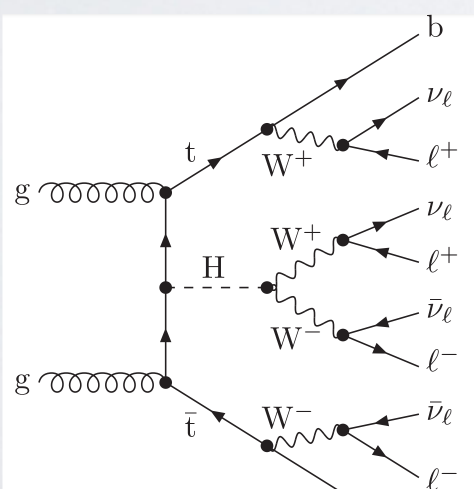
Higgs→ZZ*

HIGGS BOSON (125)

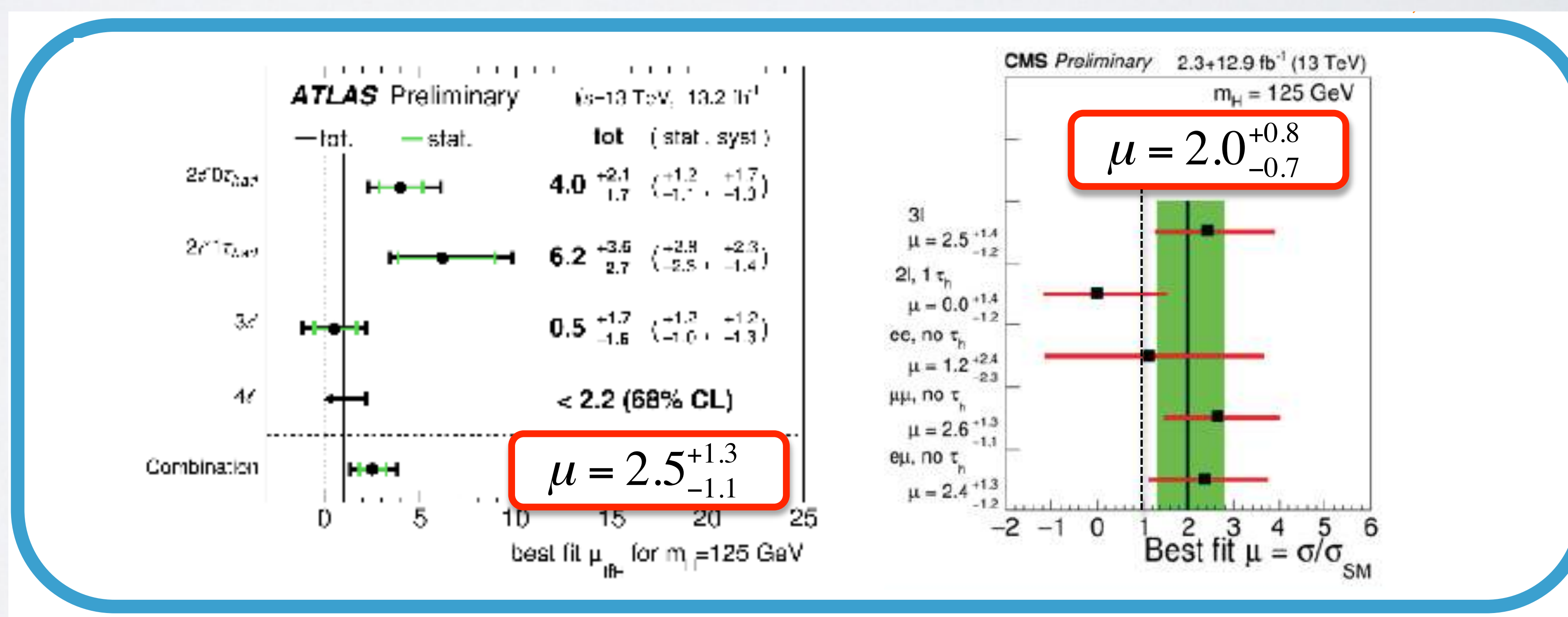
ttH(→bb)



ttH(multileptons)



And also H→ZZ, H→ττ



Higgs is now part of the Intensity Frontier. - A. Petrov

Snowmass 2013 projections:

Luminosity	$300\ \text{fb}^{-1}$	$3000\ \text{fb}^{-1}$
Coupling parameter	7-parameter fit	
κ_γ	$5-7\%$	$2-5\%$
κ_g	$6-8\%$	$3-5\%$
κ_W	$4-6\%$	$2-5\%$
κ_Z	$4-6\%$	$2-4\%$
κ_u	$14-15\%$	$7-10\%$
κ_d	$10-13\%$	$4-7$[illegible]
κ_ℓ	$6-8\%$	[illegible]
Γ_H	$12-15\%$	[illegible]-8%
	additional parameters (see text)	
$\kappa_{Z\gamma}$	$41-41\%$	$10-12\%$
κ_μ	$23-23\%$	$8-8\%$
BR_{BSM}	$<14-18\%$	$<7-11\%$

Ranges represent assumptions on systematics: low end is theory uncerts $\times 1/2$, expt systematics $\times 1/\sqrt{\mathcal{L}}$.

The name of the game is precision

Expectations in various models:

- All new particles at $M \sim 1$ TeV
- Electroweak precision fits satisfied

Model	κ_V	κ_b	κ_γ
Singlet Mixi[illegible]	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
[illegible]	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
[illegible]SSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

Snowmass 2013, 1310.8361

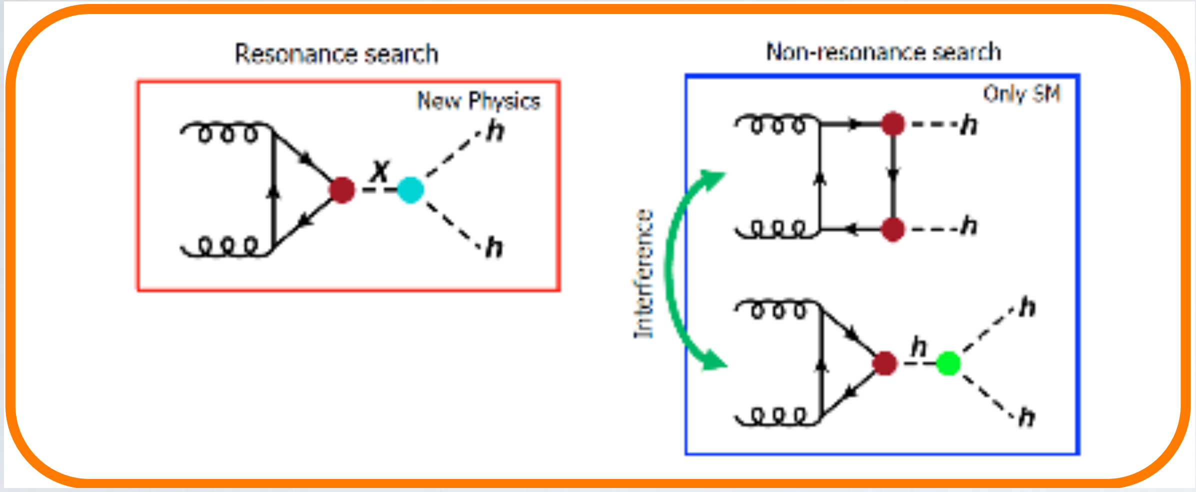
- Decoupling MSSM: κ_γ assumes 1 TeV stop with $\tan\beta = 3.2$, $X_t = 0$.

Projections based on scaling 2012–13 expt analyses to higher lumi: probably better already.

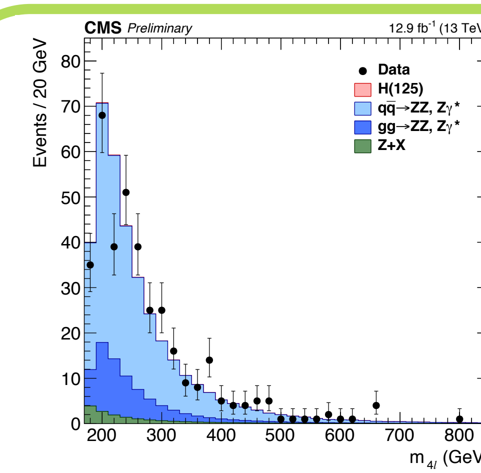
Thy uncert reductions $\approx$already achieved! Franz Herzog's talk

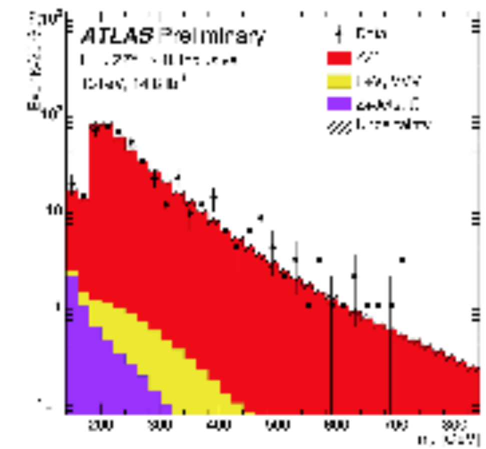
EXTRA HIGGS BOSONS

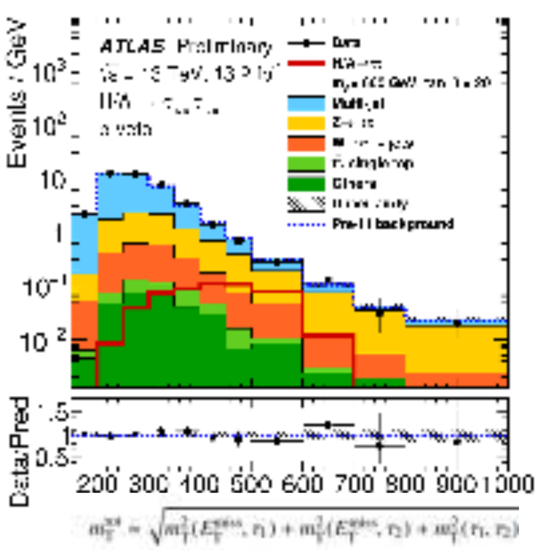
Higgs→hh→bbττ

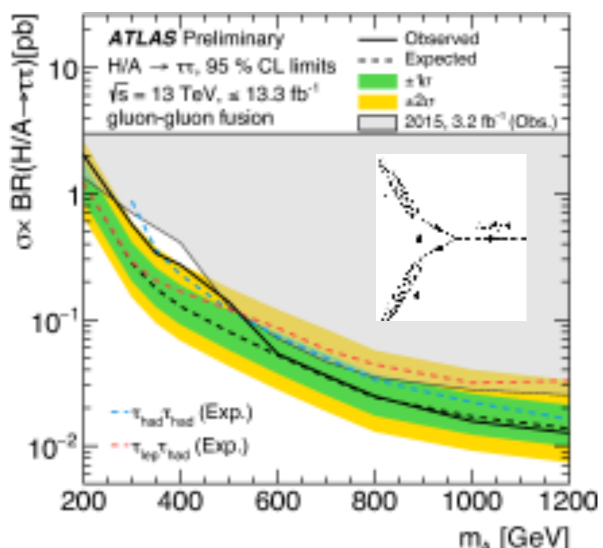


Heavy Higgs→ZZ→4l



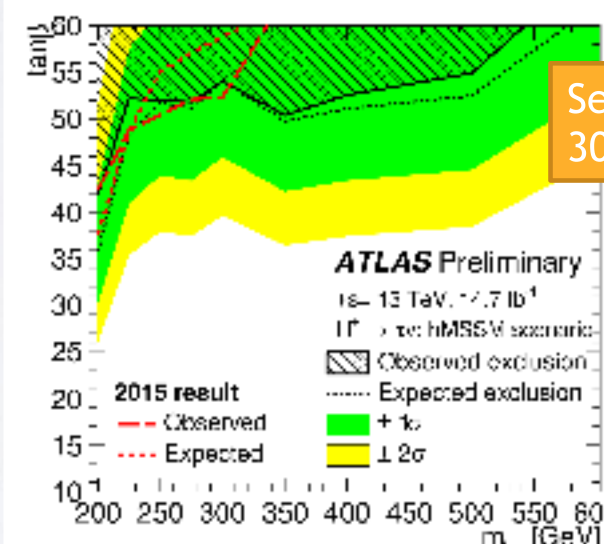






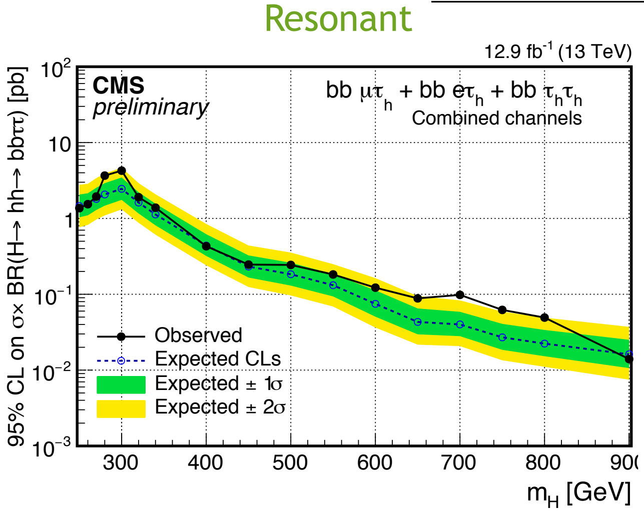
Charged Higgs

Search for H±→tb 300<$m_{H^\pm}$<1000 GeV

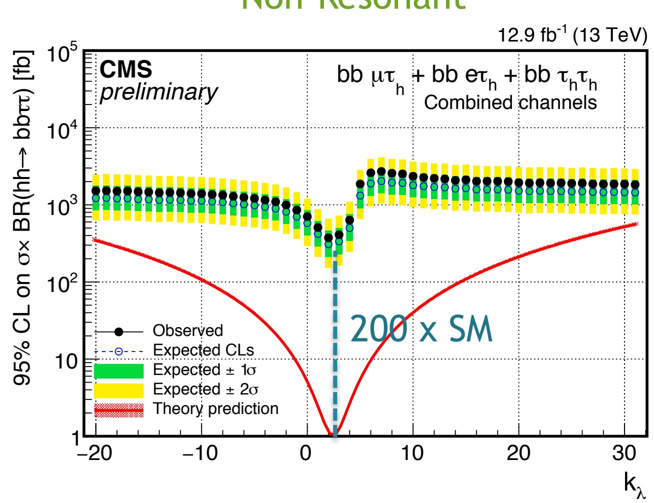


Heavy Higgs→ττ

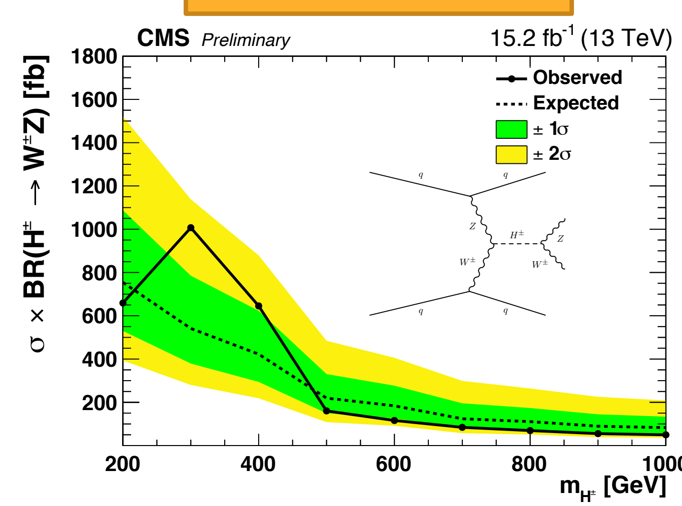
Resonant



Non-Resonant



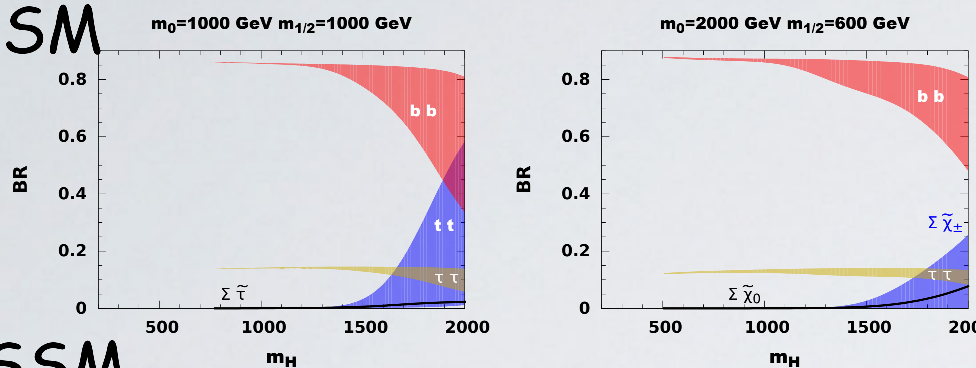
Search for H±WZ



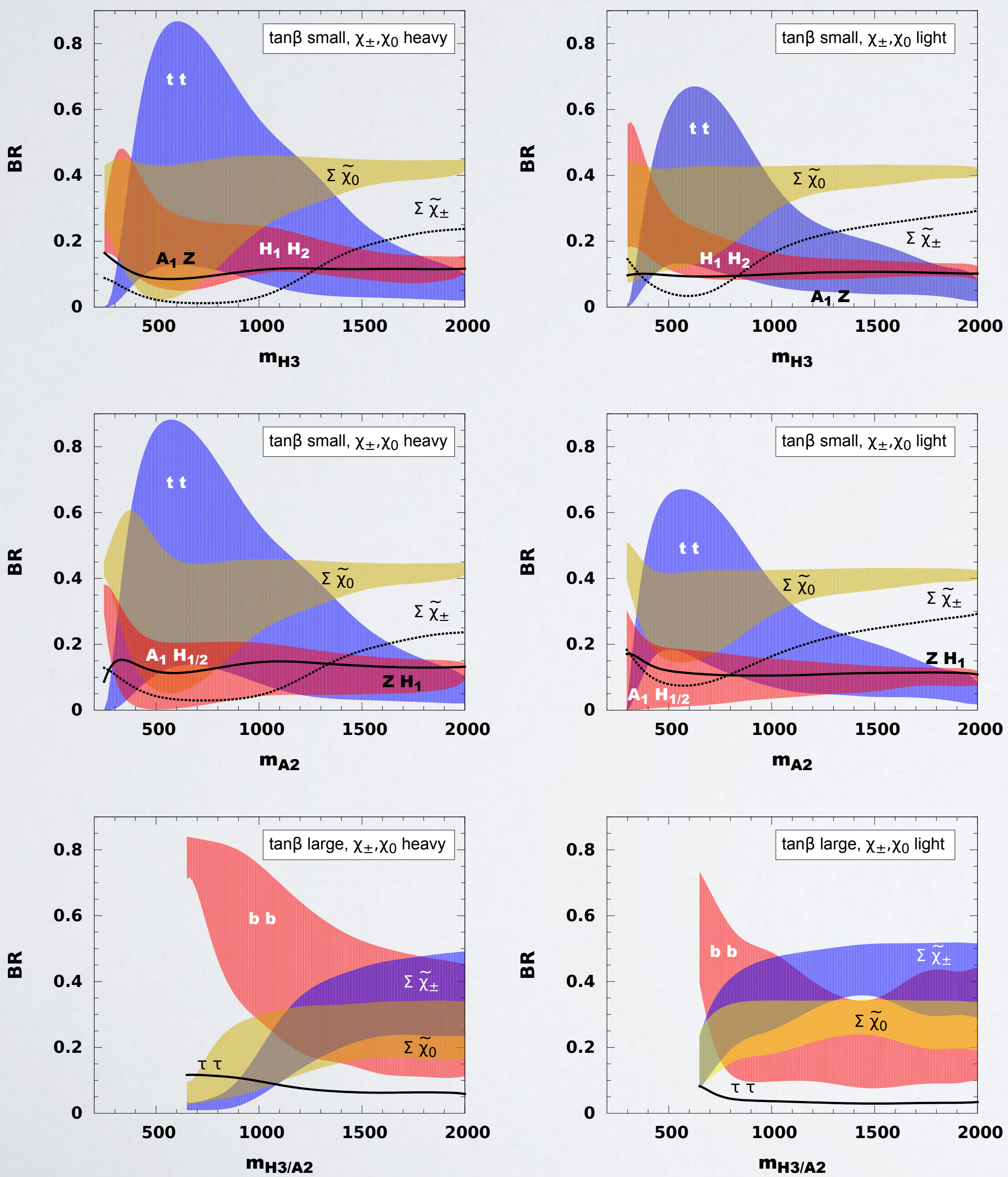
HEAVY HIGGS DECAYS

Branchings

MSSM

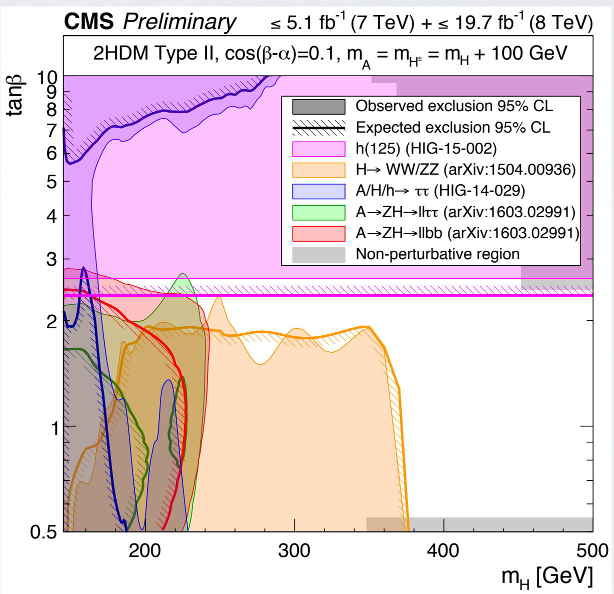


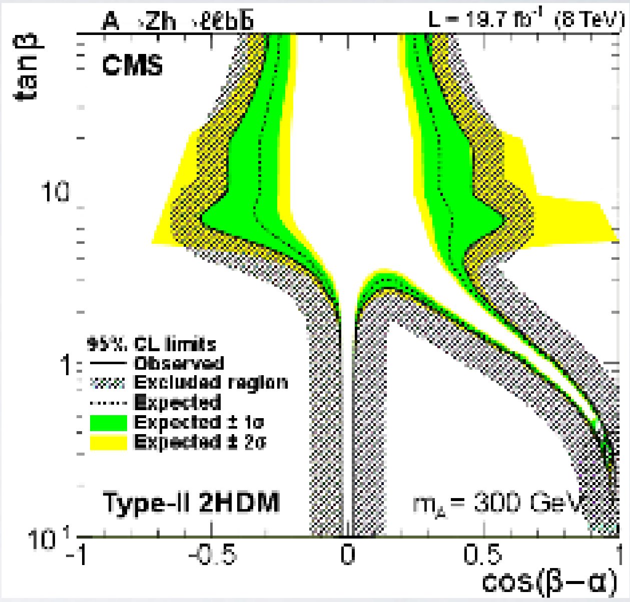
NMSSM

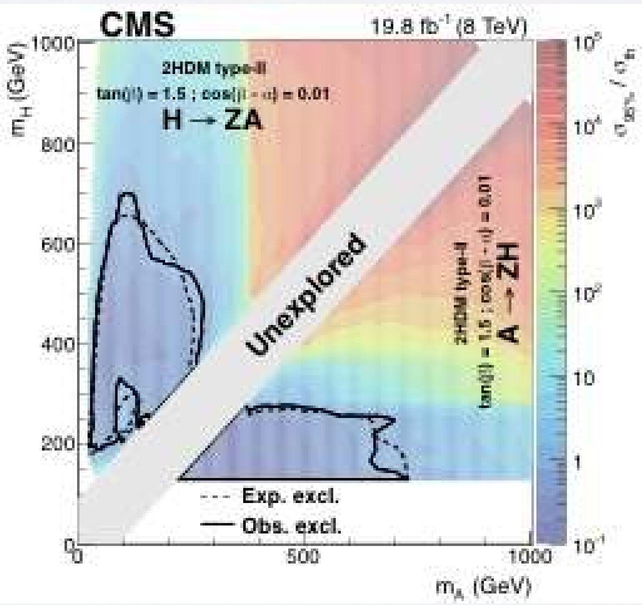


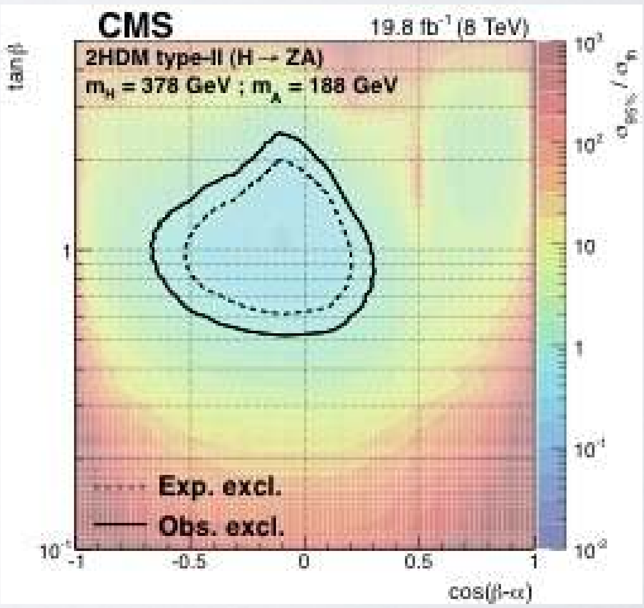
1) "Higgs to Higgs" decays

$A \to Zh$ and $A \to ZH$, $H \to ZA$









The Higgs Sector

Precision tests

- This is existing physics to be tested with high precision
- The case for future machines
- Can distinguish between different models but cannot prove the one

New Higgs bosons

- Exist in all extensions of the SM
- The spectrum is not predicted but can be foreseen in some models
- No doubt is the new physics case

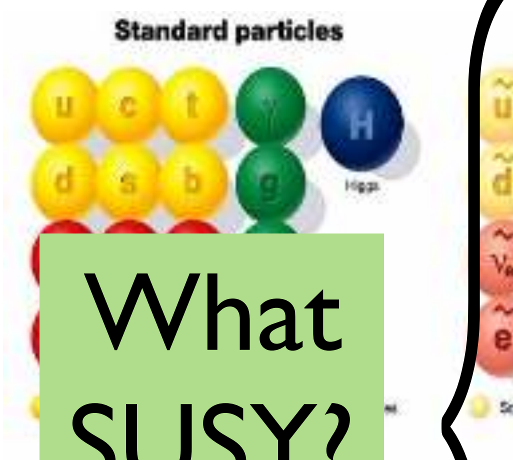
SUSY

Kiwoon Choi
(ICHEP 2016, Chicago)

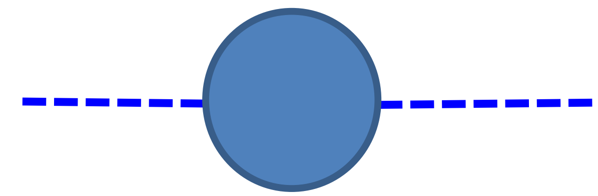
SUSY has been didate for BSM physics near the TeV scale.

What SUSY?

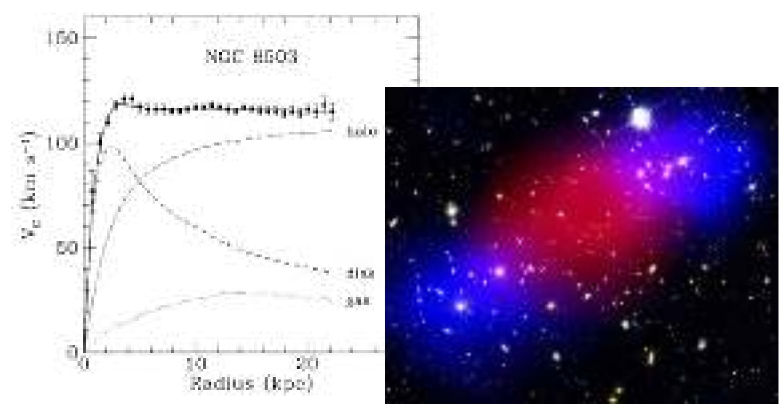
MSSM
CMSSM
mSUGRA
mGMSB
mAMSB
NUHM
NMSSM
pMSSM
Split SUSY
No Scale
...



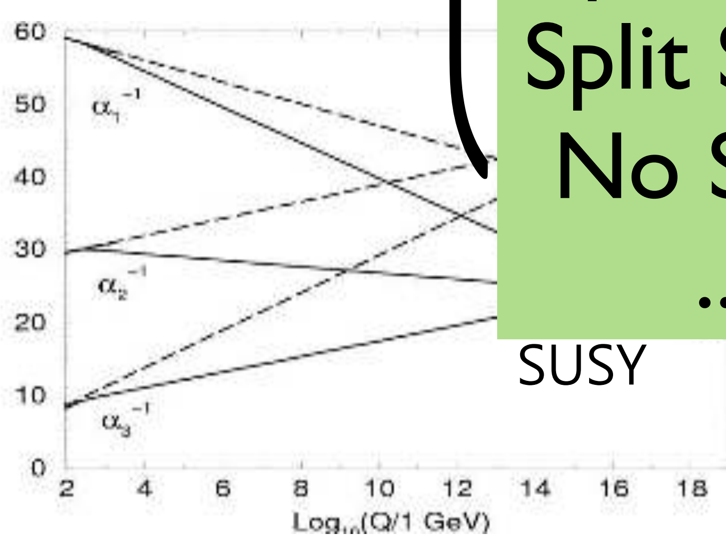
Hierarchy problem



$$\delta m_H^2 \sim M_{\text{Planck}}^2 \Rightarrow m_{\text{SUSY}}^2$$



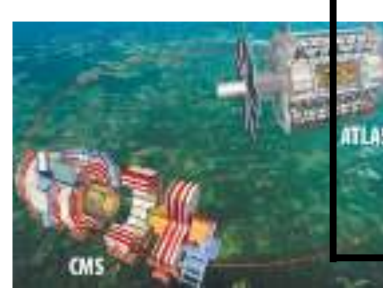
Dark matter

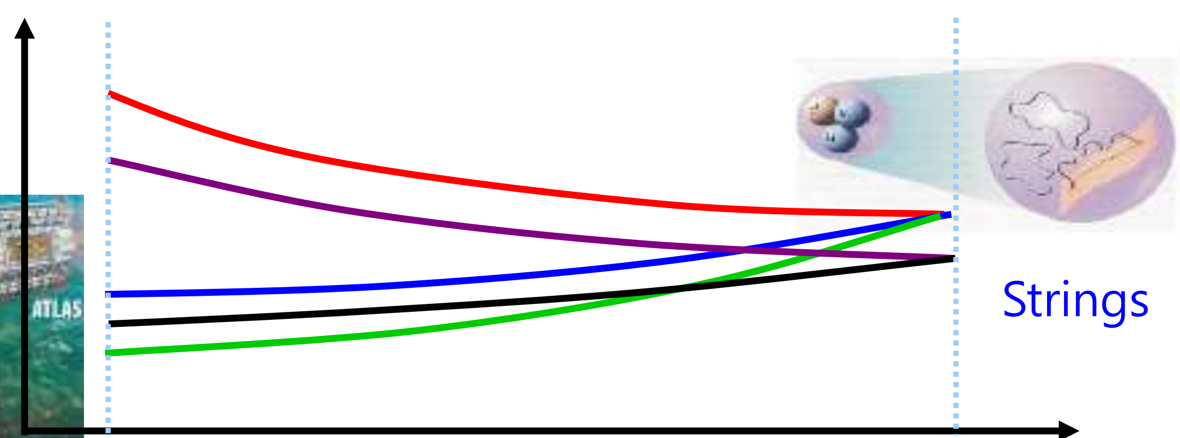


SUSY

Gauge coupling unification

SUSY spectrum





Strings

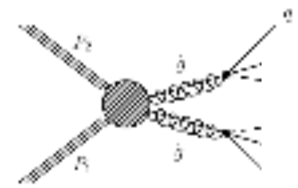
1 TeV

10^{16} GeV

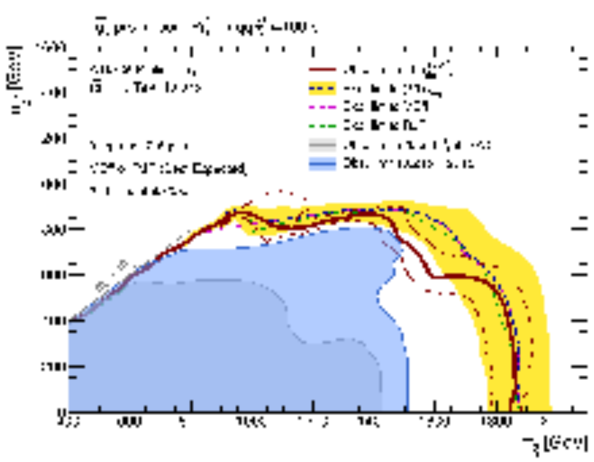
Supersymmetry remains, to this date, a well-motivated, much anticipated extension to the Standard Model of particle physics

SUPERSYMMETRY/ LHC 13

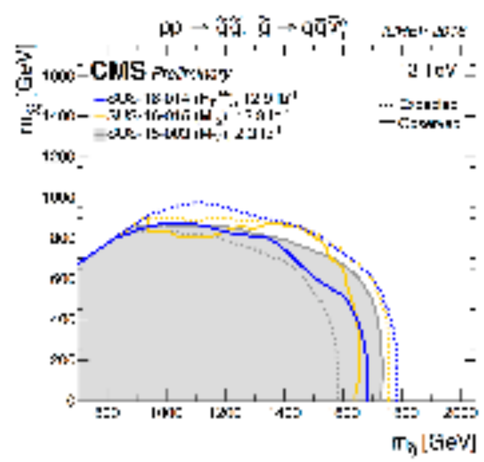
Gluino decays to qq+LSP



Summary of decays to light quarks + LSP

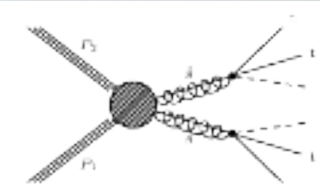


ATLAS-CONF-2016-078



CMS-SUS-16-014
CMS-SUS-16-015

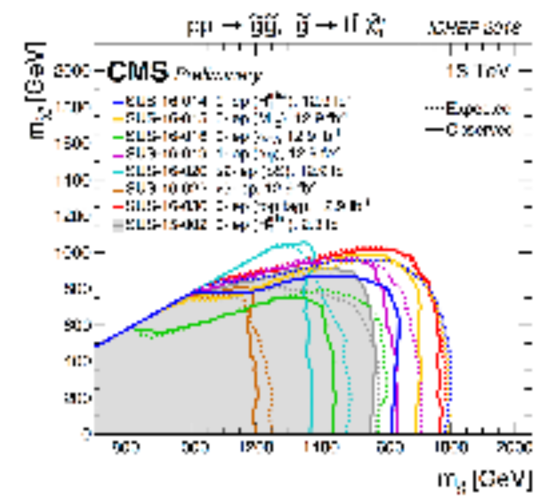
Gluino decays to tt+LSP

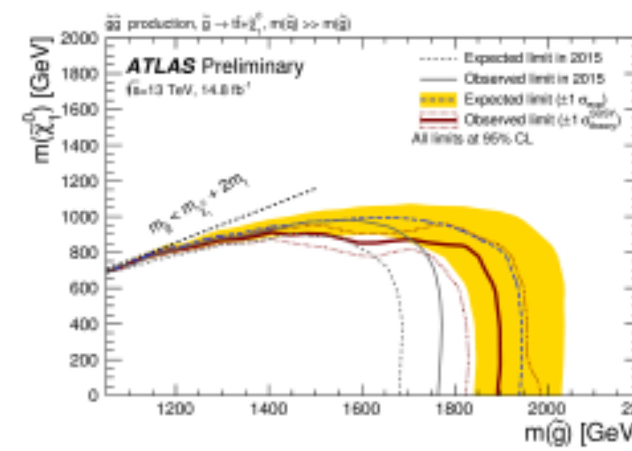


CMS summary

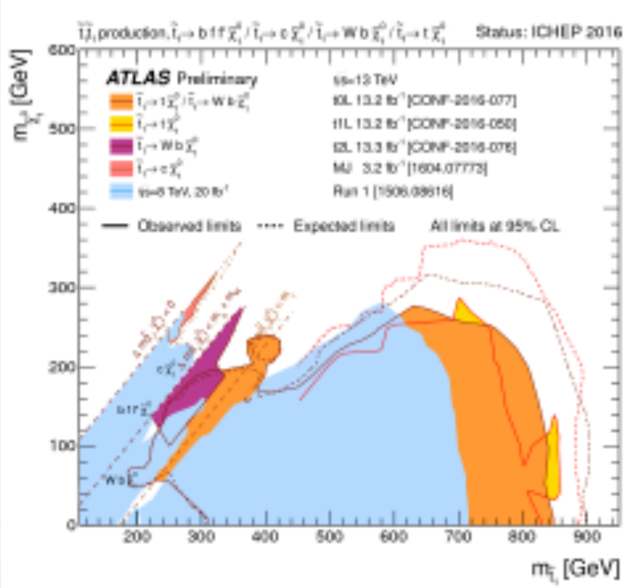
ATLAS multi-b

ATLAS-CONF-2016-052

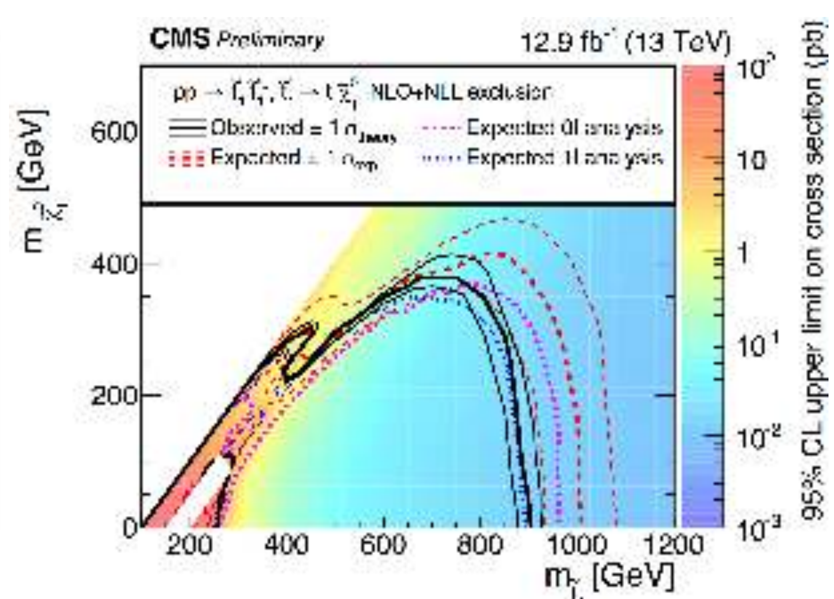




Top squarks - summaries



ATLAS summary

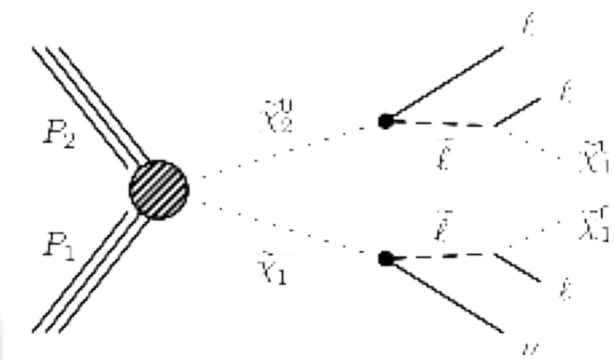


CMS 0l+1l combination
for 2-/3-body decay

- SUSY limits for strong int’s are pushed above 1 TeV
- This already requires fine tuning - little hierarchy prob
- No guiding lines

SUPERSYMMETRY/LHC 13

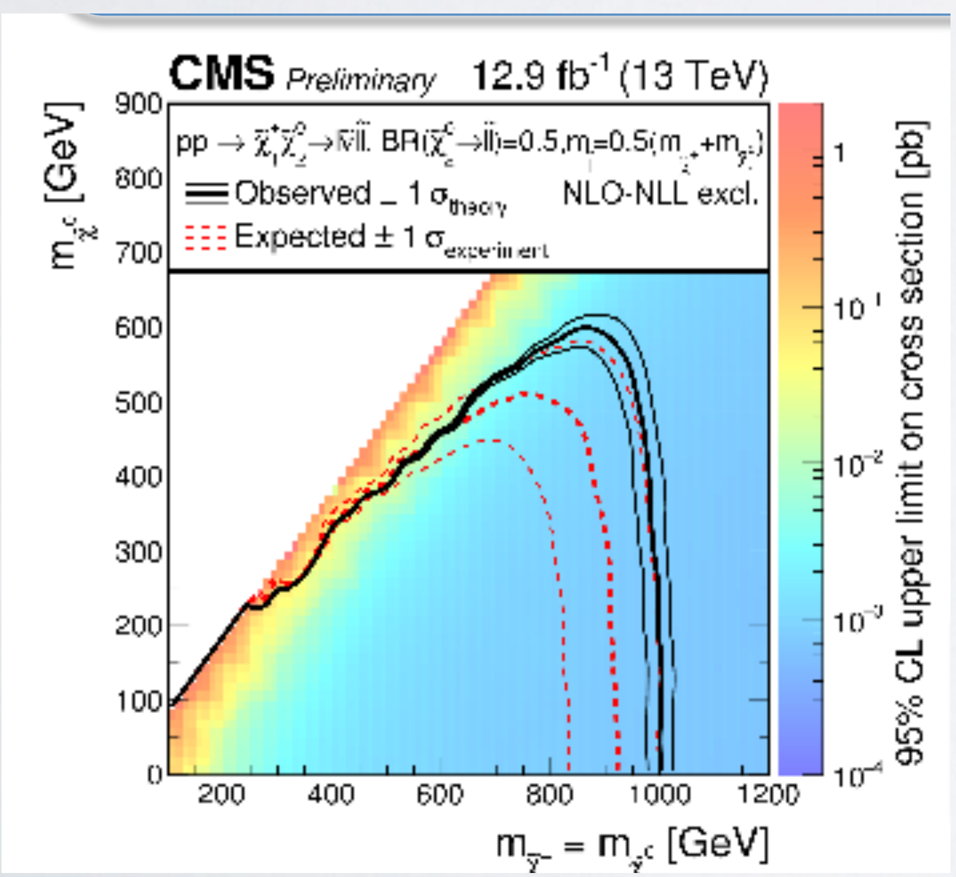
Chargino / neutralino production



Direct production of "electroweakino" pairs

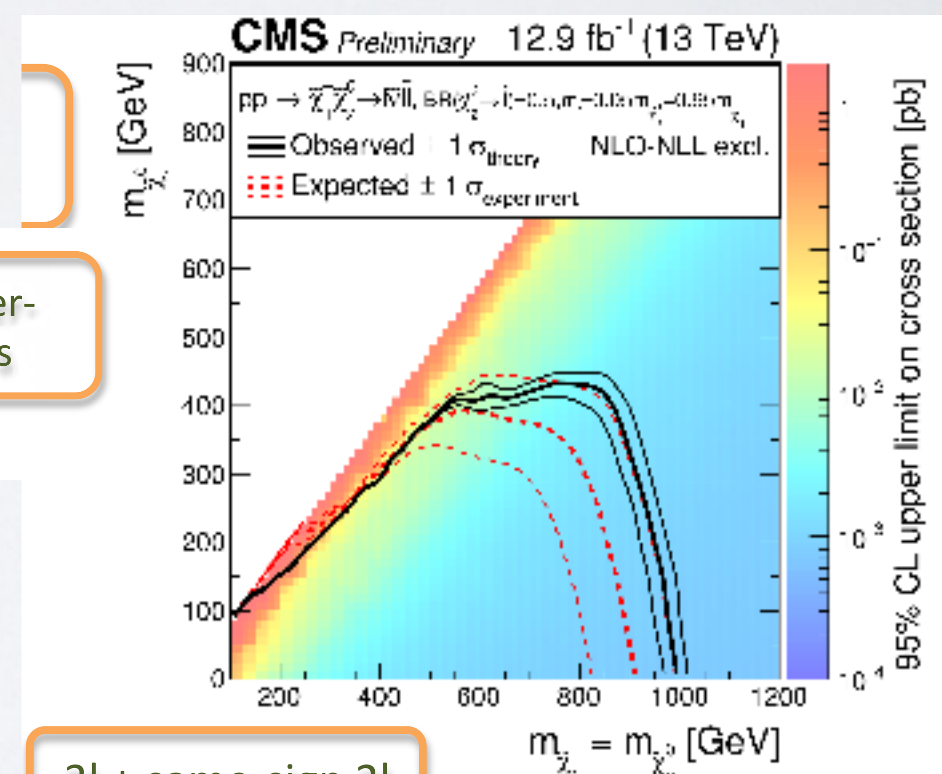
- decays via sleptons / sneutrinos
- using benchmarks to illustrate different scenarios (depend on mixings and nature of lightest slepton)

No light EWkinos



Effect of change in inter-mediate slepton mass

↔



3l + same-sign 2l

FUTURE SUSY SEARCHES

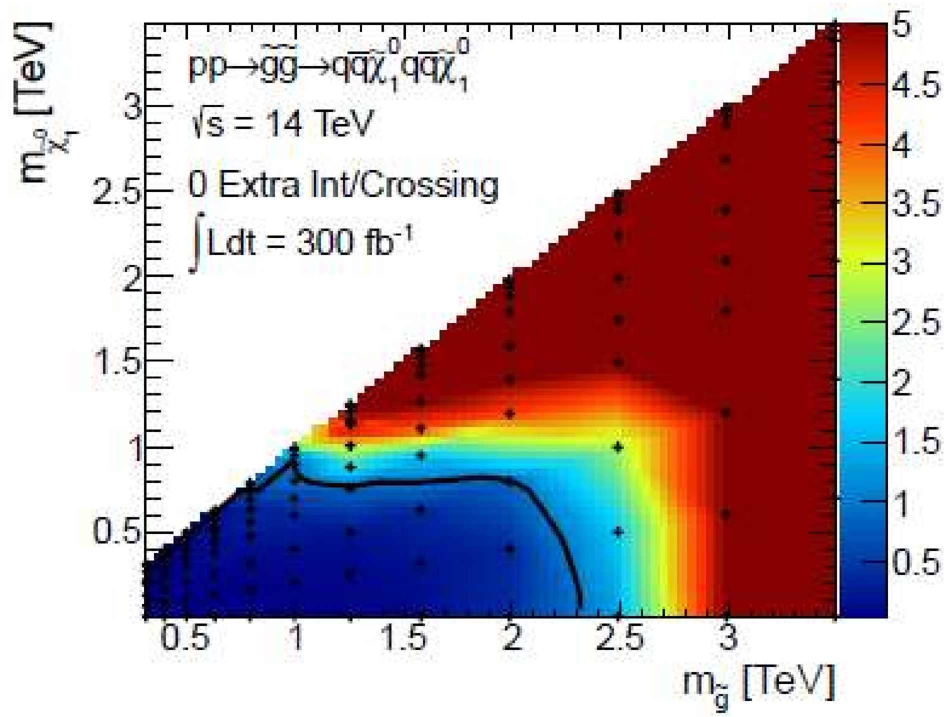
SUSY is certainly a compelling candidates of BSM physics, so we should keep searching for her without leaving any stone unturned.

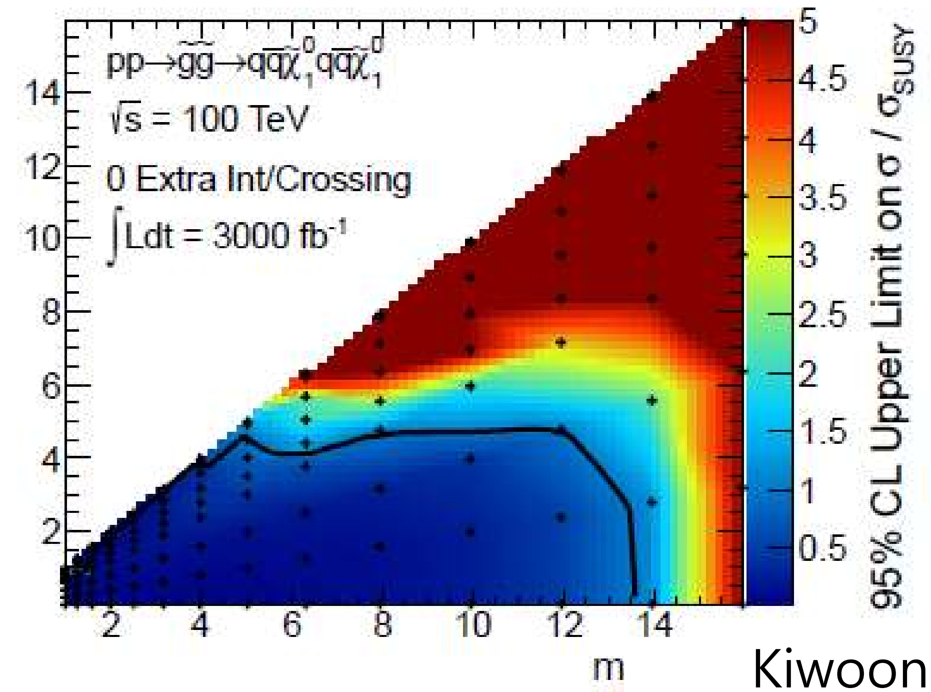
* Taking the gauge coupling unification seriously, SUSY may have some chance to be seen at LHC, and a good chance at the FCC:

High luminosity LHC

Cohen et al, '13

100 TeV collider

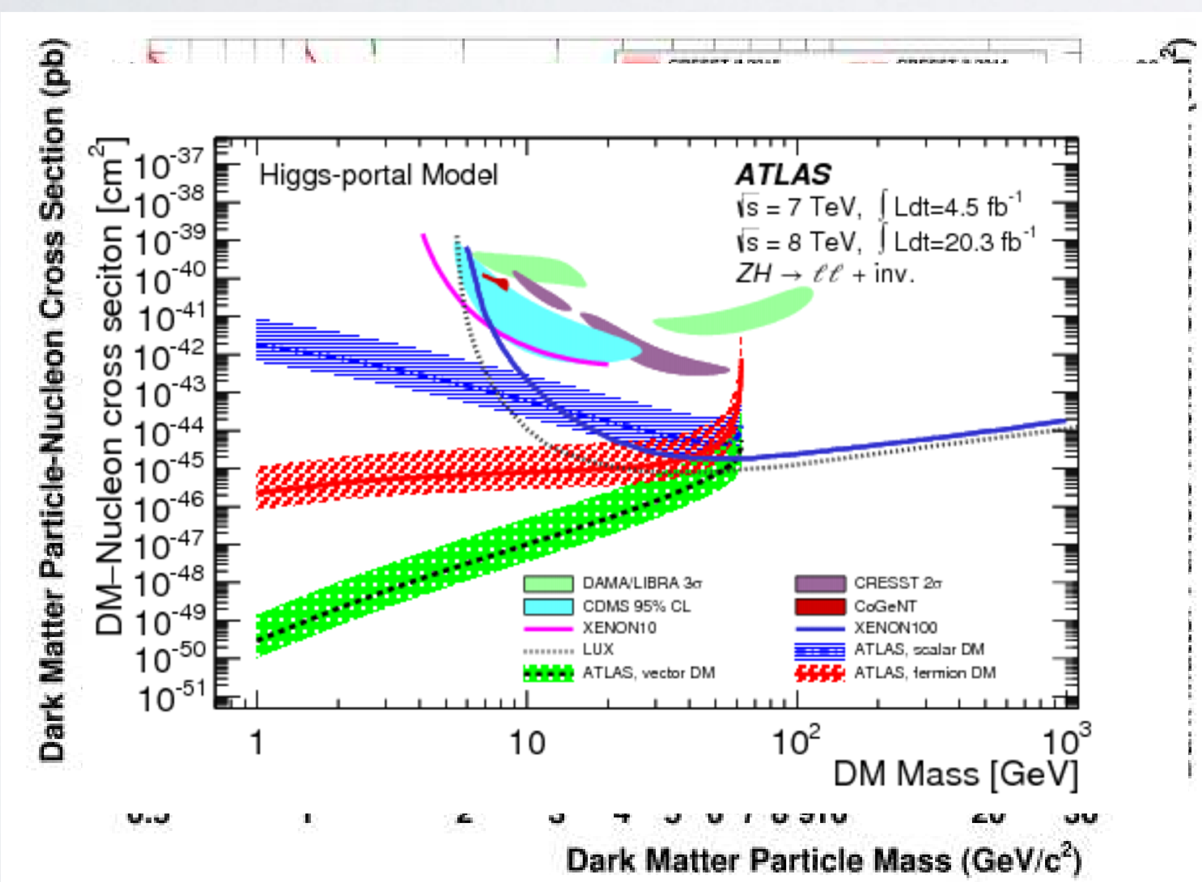




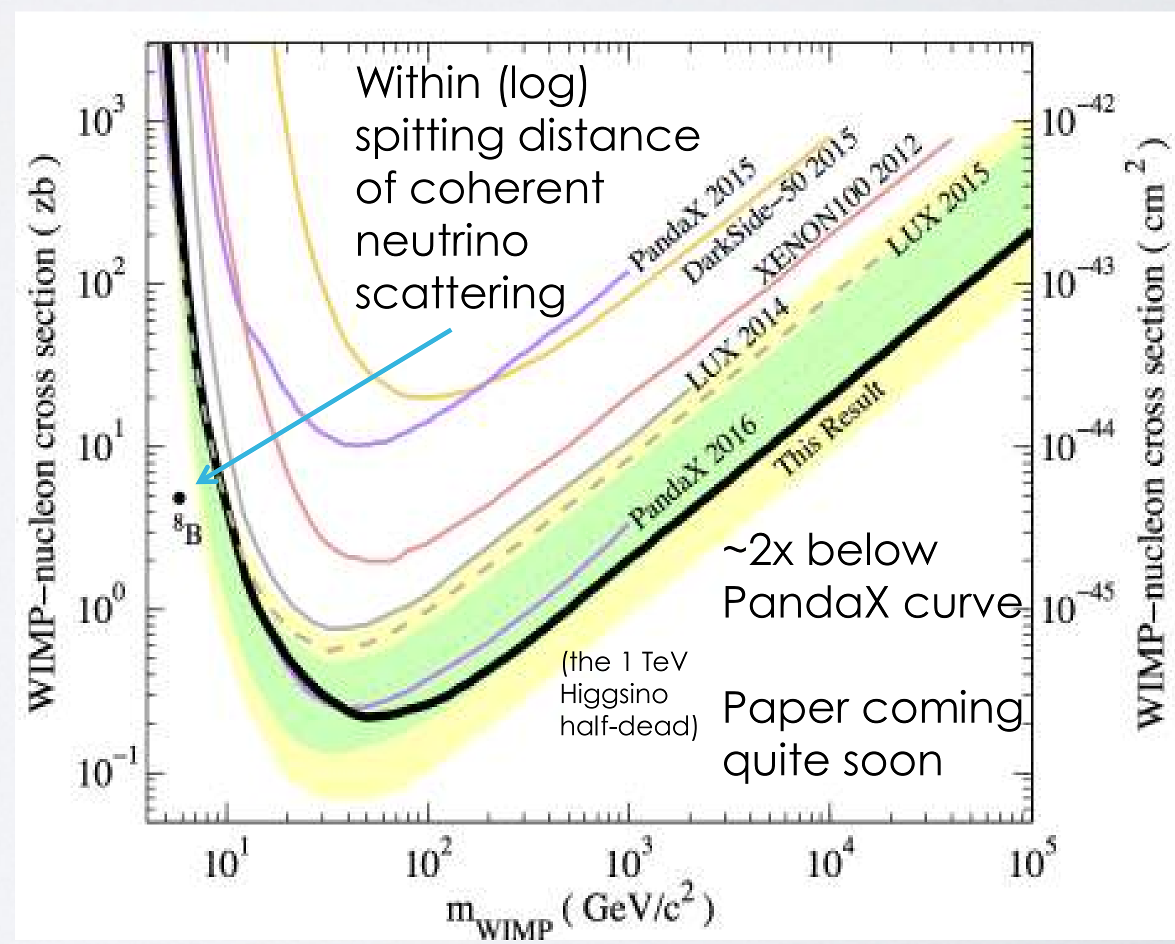
Kiwoon Choi

(ICHEP 2016, Chicago)

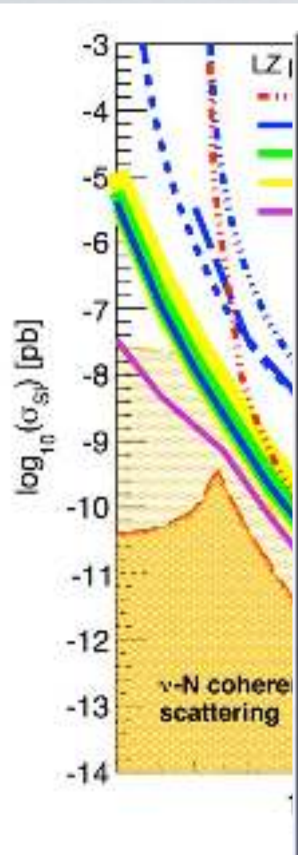
Dark Matter Searches   Direct detection

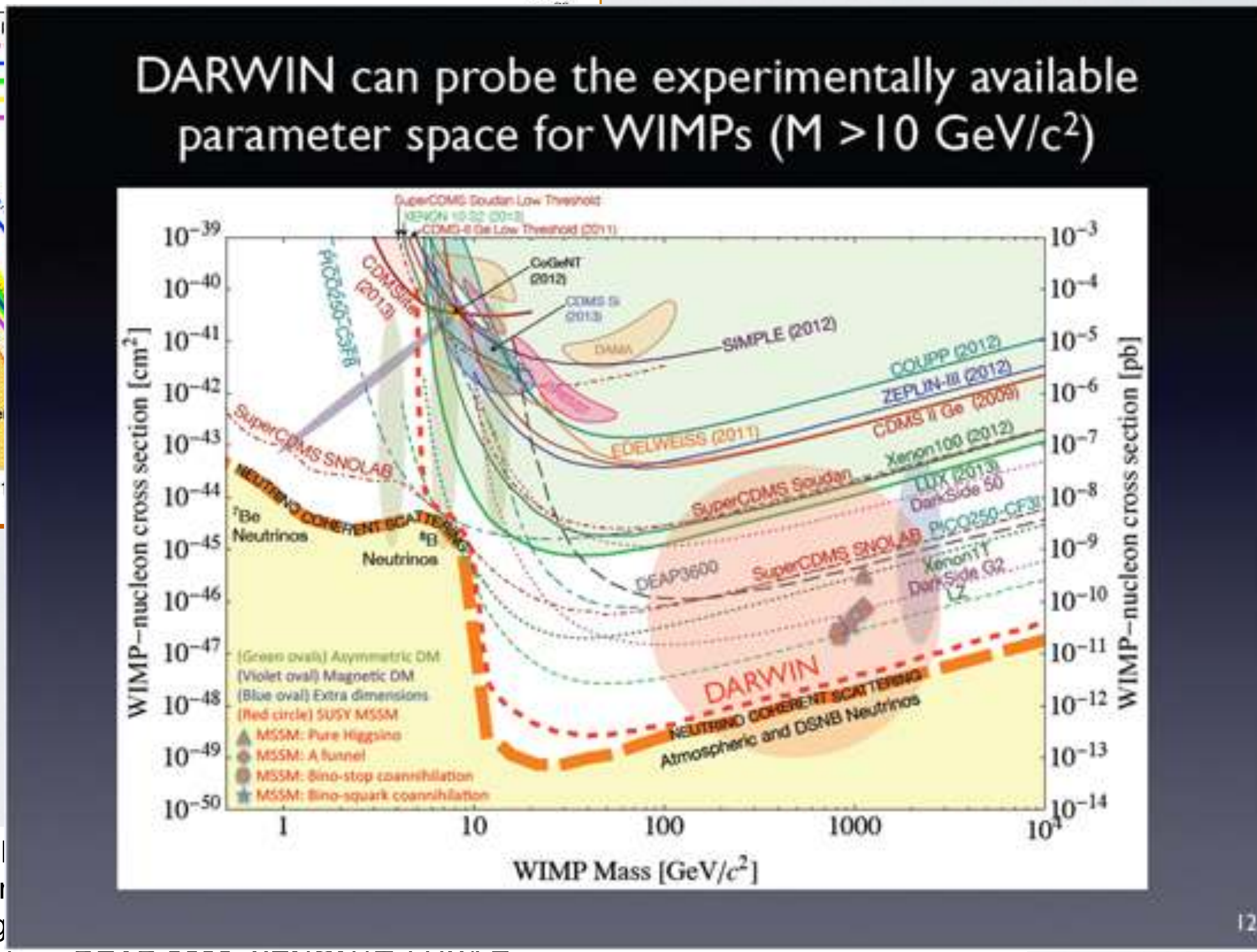


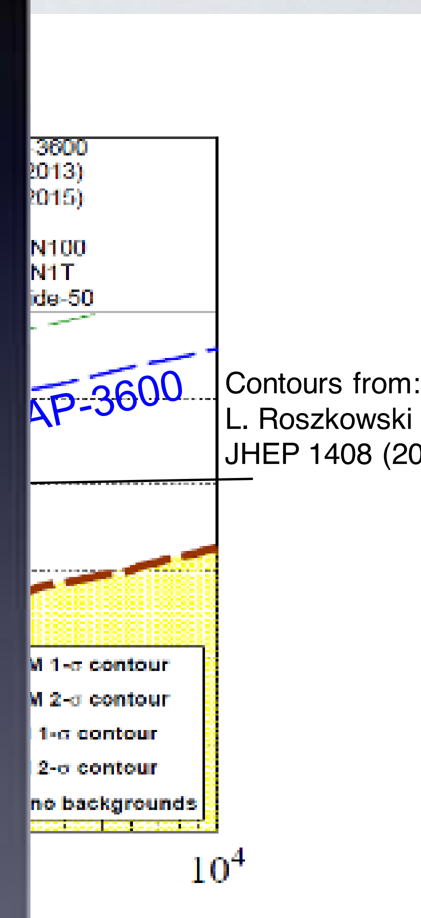
CRESST-II



FUTURE DM SEARCHES





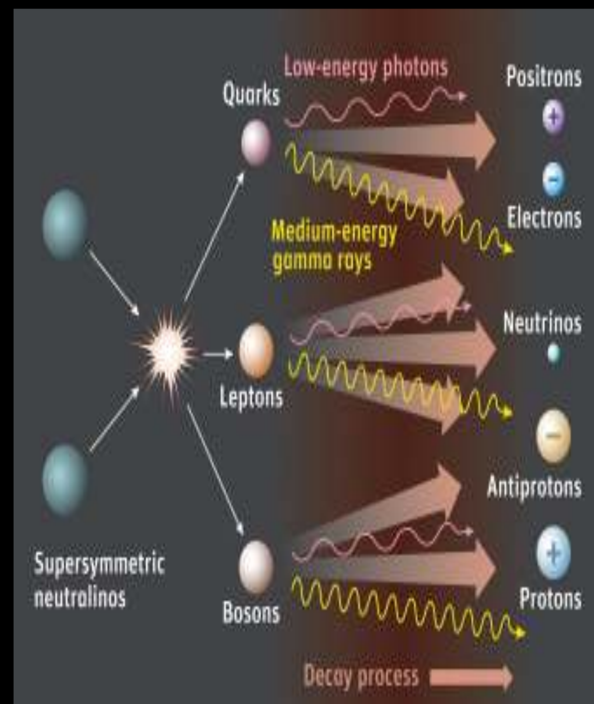


All availabl
even the si
Remaining
scale detectors: DEAP-3600, XENON1T, LUX/LZ
Complementarity with LHC (cMSSM/NUHM are mostly out of reach of the 14 TeV run!)

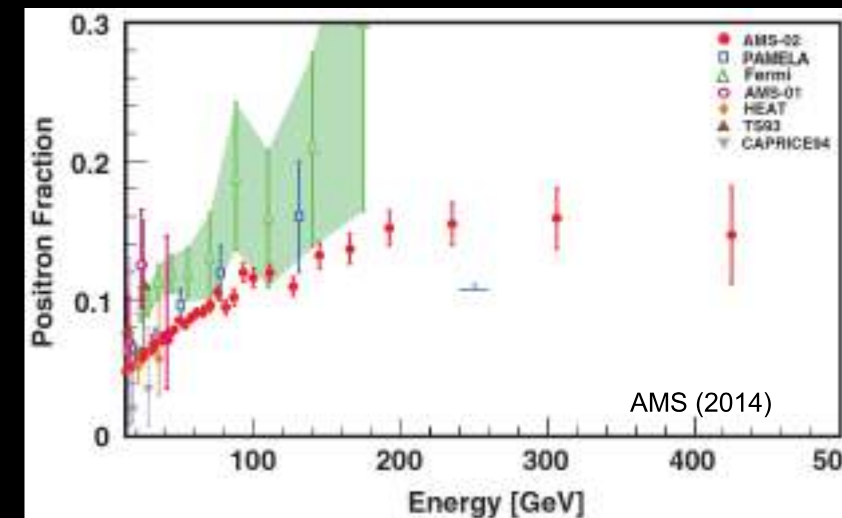
INDIRECT DETECTION OF DM

INDIRECT DETECTION

- Dark matter may pair annihilate or decay in our galactic neighborhood to
  - Positrons
  - High-Energy Photons
  - Neutrinos
  - Antiprotons
  - Antideuterons
  - …

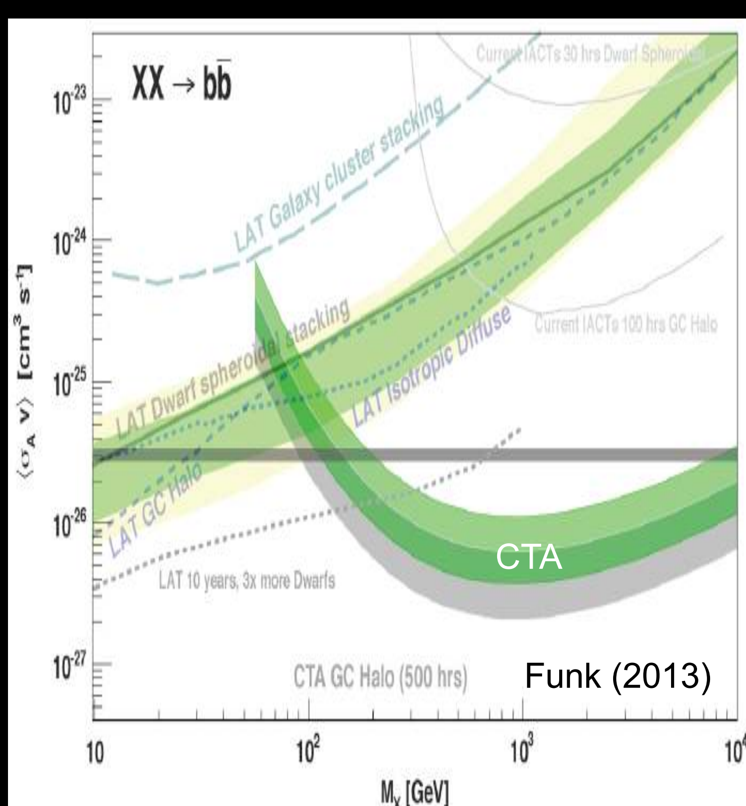


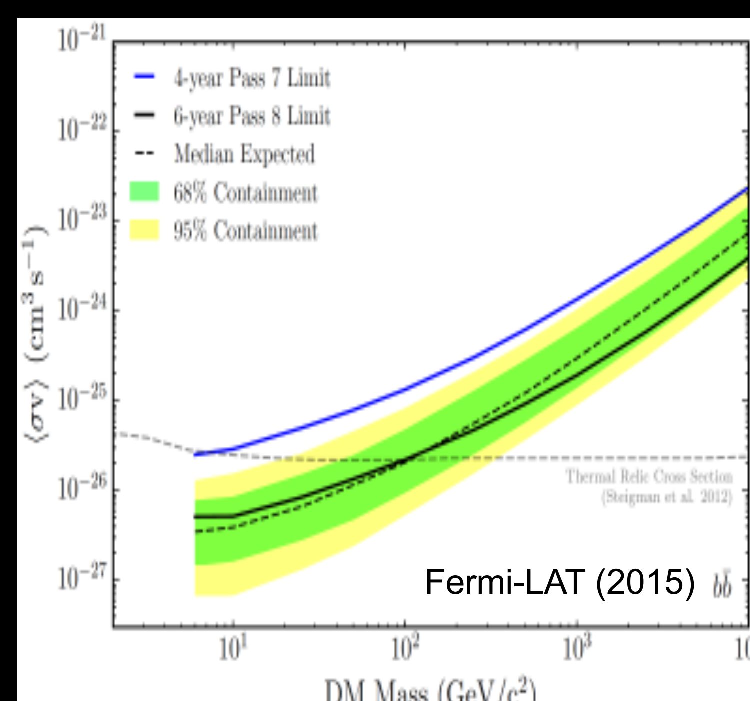
INDIRECT DM: POSITRON RESULTS



- Since 2010, electron and positron fluxes have been measured by AMS with remarkable precision, constrained up to ~400 GeV
- Dark matter implications require precise determinations of cosmic ray

INDIRECT DM: PHOTON RESULTS





- Rapid improvements in recent years, Fermi-LAT now excludes WIMP makes up to ~100 GeV for certain annihilation channels
  - The future is the Cherenkov Telescope Array, which will extend the reach by two orders in mass up to masses

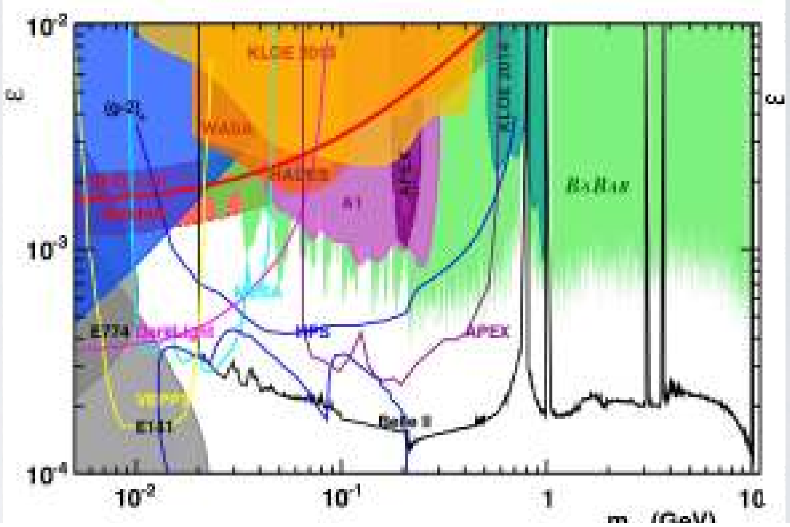
    ~ 10 TeV

DARK MATTER/NEW PHYSICS

SIMPs(strong interacting massive particle)

- dark matter is strongly interacting under the **other SU(N) gauge interactions.**
- DM may be pion/Baryon/gluball of the new strong interactions or couple to new scalar by large Yukawa coupling

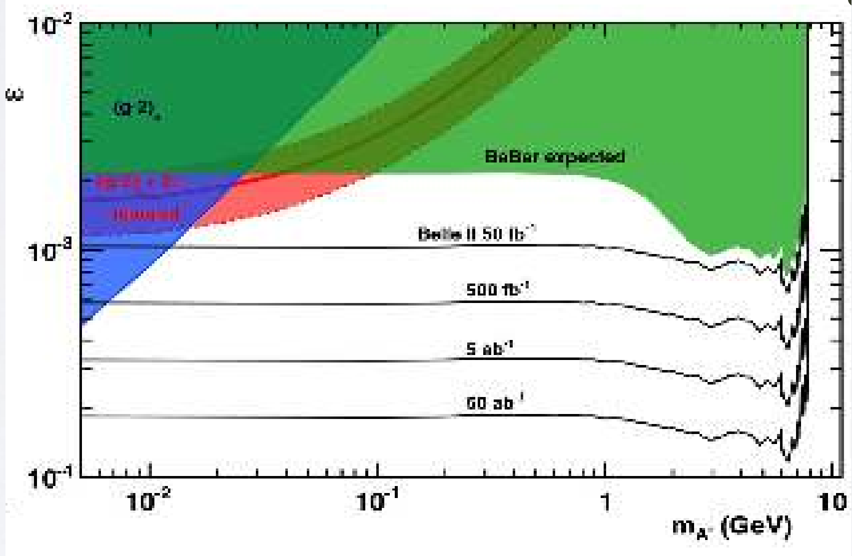
$e^+e^- \to \gamma A' \to \gamma e^+e^-, \gamma\mu^+\mu^-$, *prompt*



dark photon

- U(1) gauge boson is relatively easy going object "gauge invariant $F'_{\mu\nu}$"
- sequestering $U(1)_D$ dark sector from SM sector,
- Interaction with SM may arises from kinetic mixing $F_{\mu\nu}F'^{\mu\nu}$
- Dark matter couple to $U(1)_D$ can have very small coupling, and also Very light $U(1)_D$ $a' \to 3\gamma$ has very long lifetime. Both can be dark matter.

$e^+e^- \to \gamma A' \to \gamma\chi\bar{\chi}$



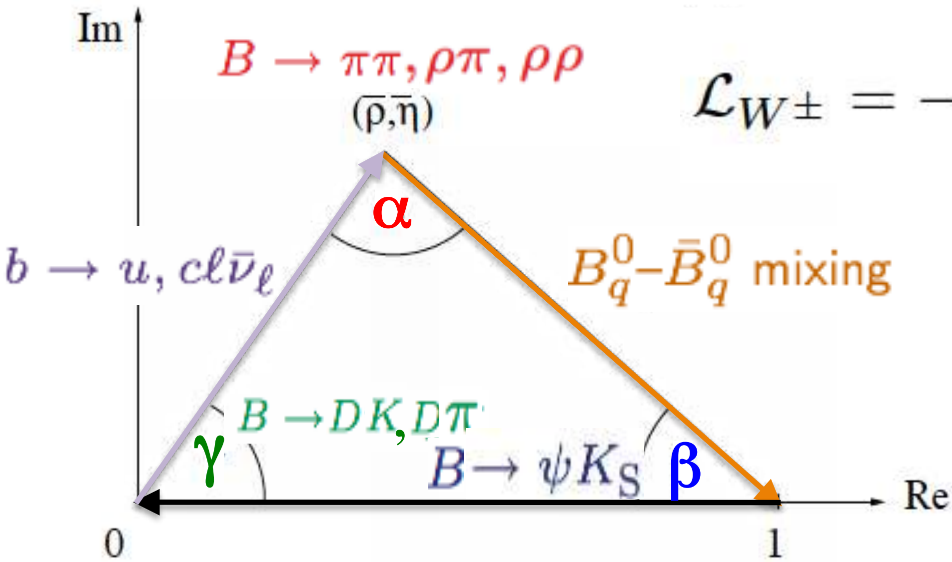
- **Nature of Dark matter** is one of the big questions that particle physics should answer.
- Success of LHC and dark matter searches and we are wondering over next steps to go.

Flavour Physics

The CKM Unitarity Triangle

$$V_{CKM} = \begin{array}{c} \\ u \\ c \\ t \end{array}\begin{array}{c} d \quad\quad s \quad\quad b \\ \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\bar\rho - i\bar\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\bar\rho-i\bar\eta) & -A\lambda^2 & 1 \end{pmatrix} \end{array} + O(\lambda^4)$$

$$\mathcal{L}_{W^\pm} = -\frac{g}{\sqrt{2}}\overline{U}_i\gamma^\mu\frac{1-\gamma^5}{2}(V_{\rm CKM})_{ij}\,D_j W_\mu^+ + h.c.$$



From CKM matrix unitarity

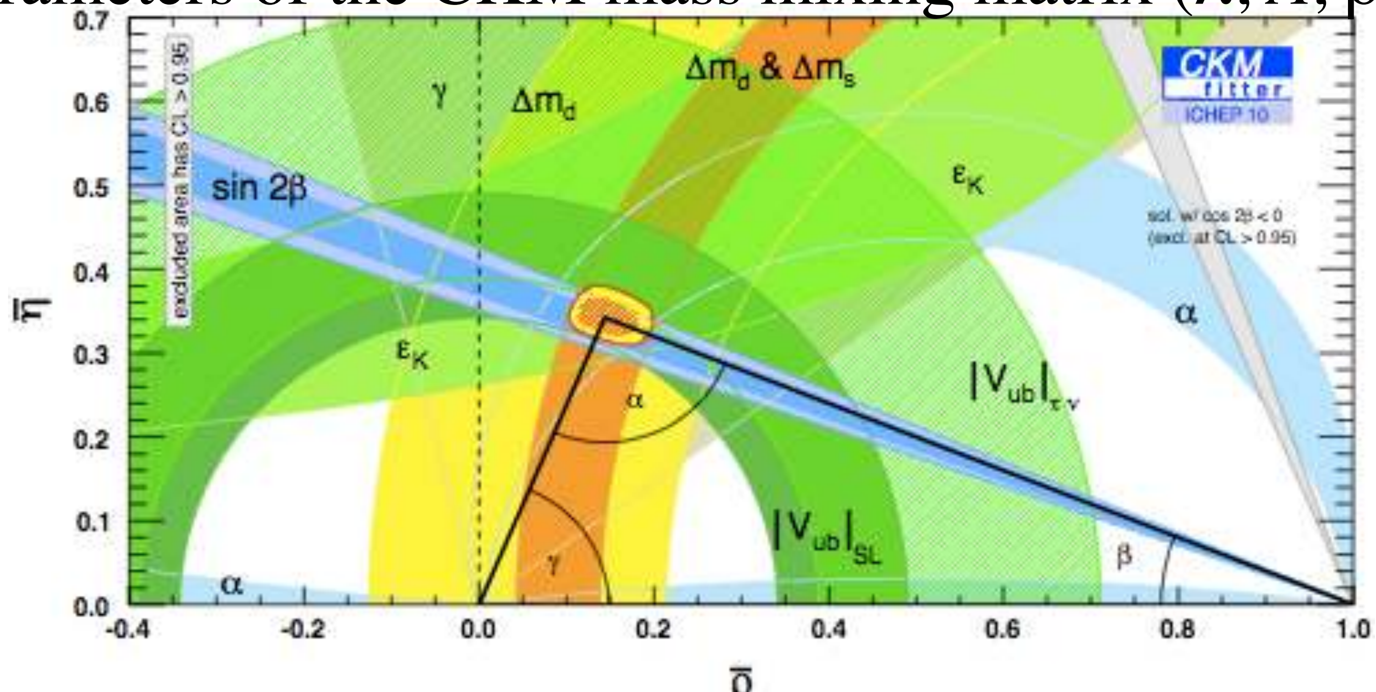
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

- UT defined by two parameters only → can be overconstrained
- The height (irreducible complex phase $\bar\eta$) controls the strength of *CP* violation in the Standard Model

Quark flavor physics

Triumph of the CKM description

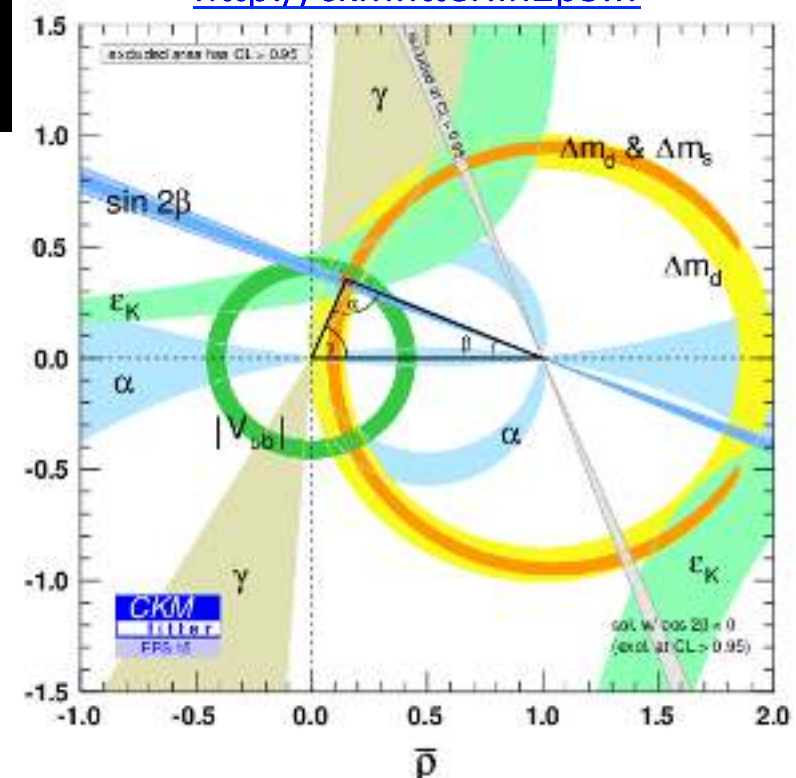
- All the flavour changing processes are described by the four parameters of the CKM mass mixing matrix (λ, A, ρ, η)



- From this plot, we know already either new physics energy scale is >> TeV (far beyond LHC) or the flavour structure o new physics is very special.

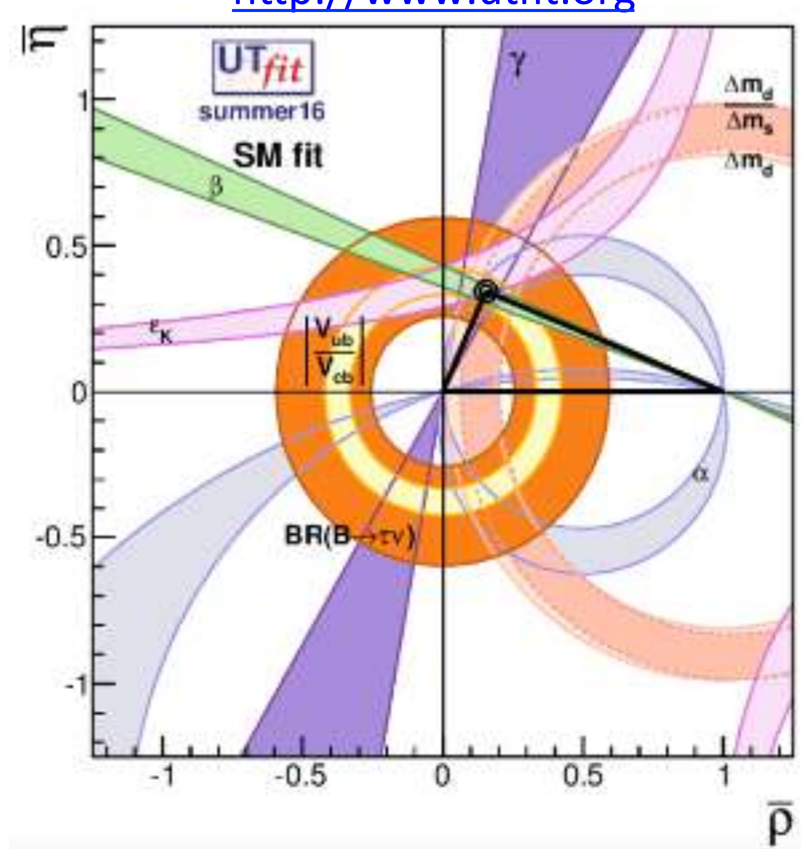
ICHEP 2016 -- I. Shipsey

http://ckmfitter.in2p3.fr



2015->2016

http://www.utfit.org



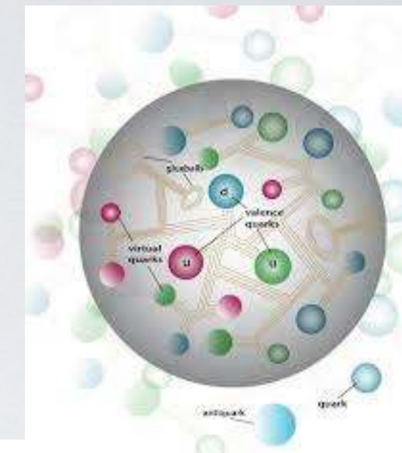
- Great success of the Standard Model CKM picture!
  - All of the measurements agree in a highly profound way
  - In the presence of relevant New Physics effects, the various contours would cross each other in a single point

Exotic hadrons

Challenging problem in particle physics well inside the SM

Time to come back?

- How confinement actually works?
- Why colourless states?
- Which bound states exist in Nature?



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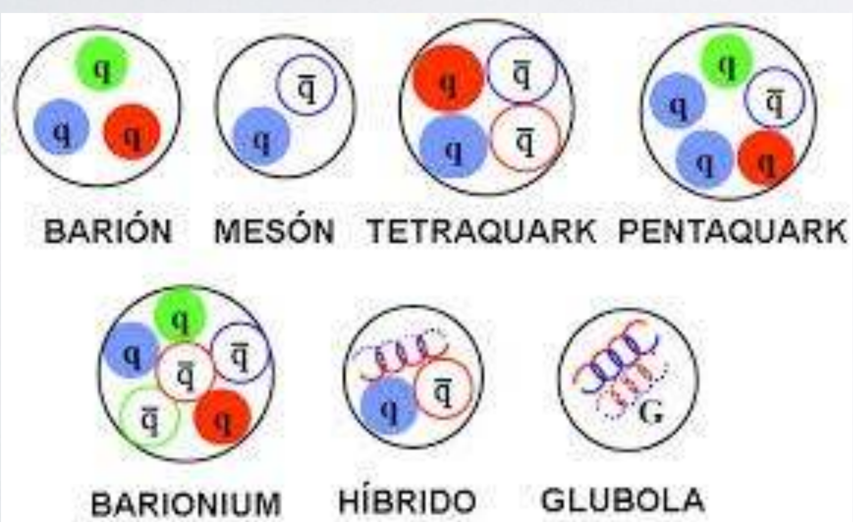

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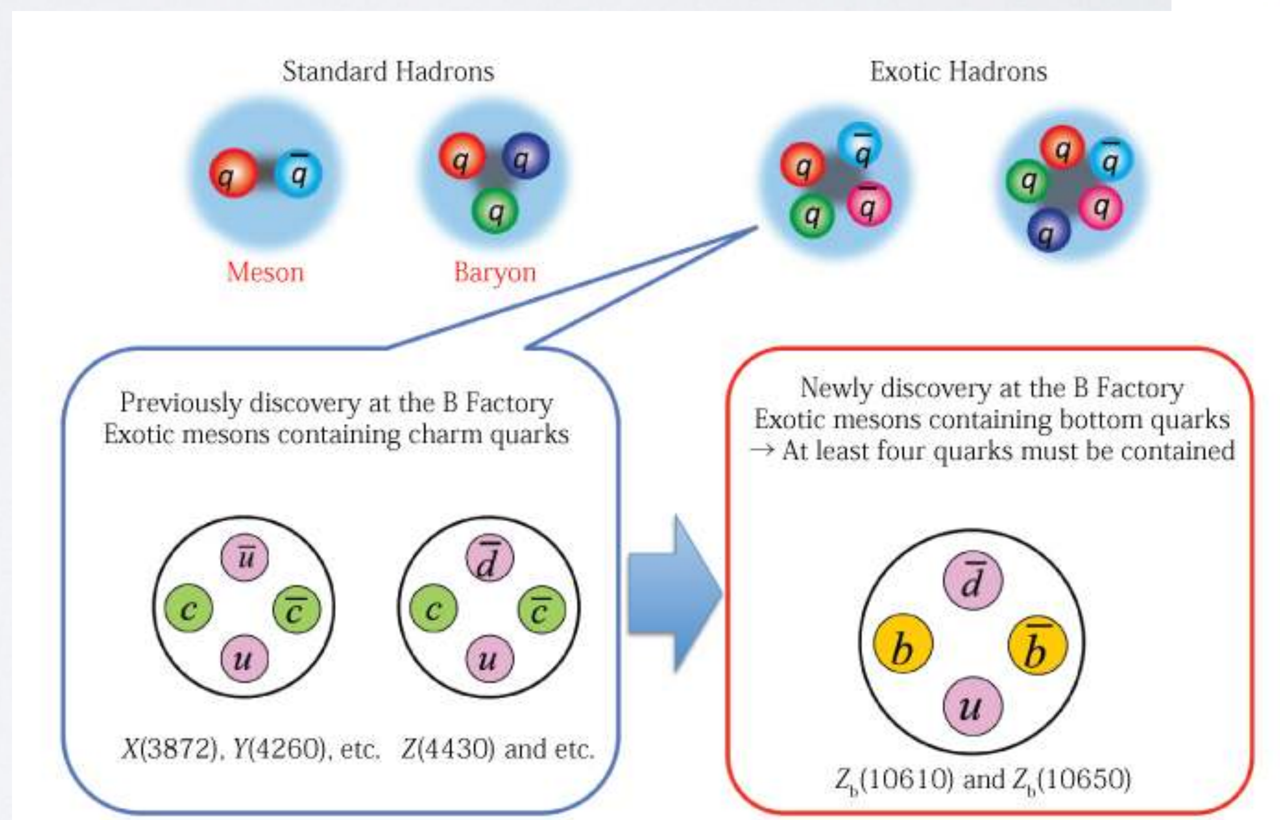


- Lattice gauge theories
- Holographic approach
- Gauge theories in dual description
- Back to analyticity & unitarity ?

Exotics/Extra Dim/Extra Sym

• LHC experiments conducting BSM searches in broad and complementary signatures

• Known excesses (Diboson in Run1 and Diphoton in 2015) **not** confirmed using 2016 data

• No new significant excesses observed. Set new frontier scale: • Contact Interaction **energy**: 25.2 TeV

• ADD BH **mass**: 9.55 TeV

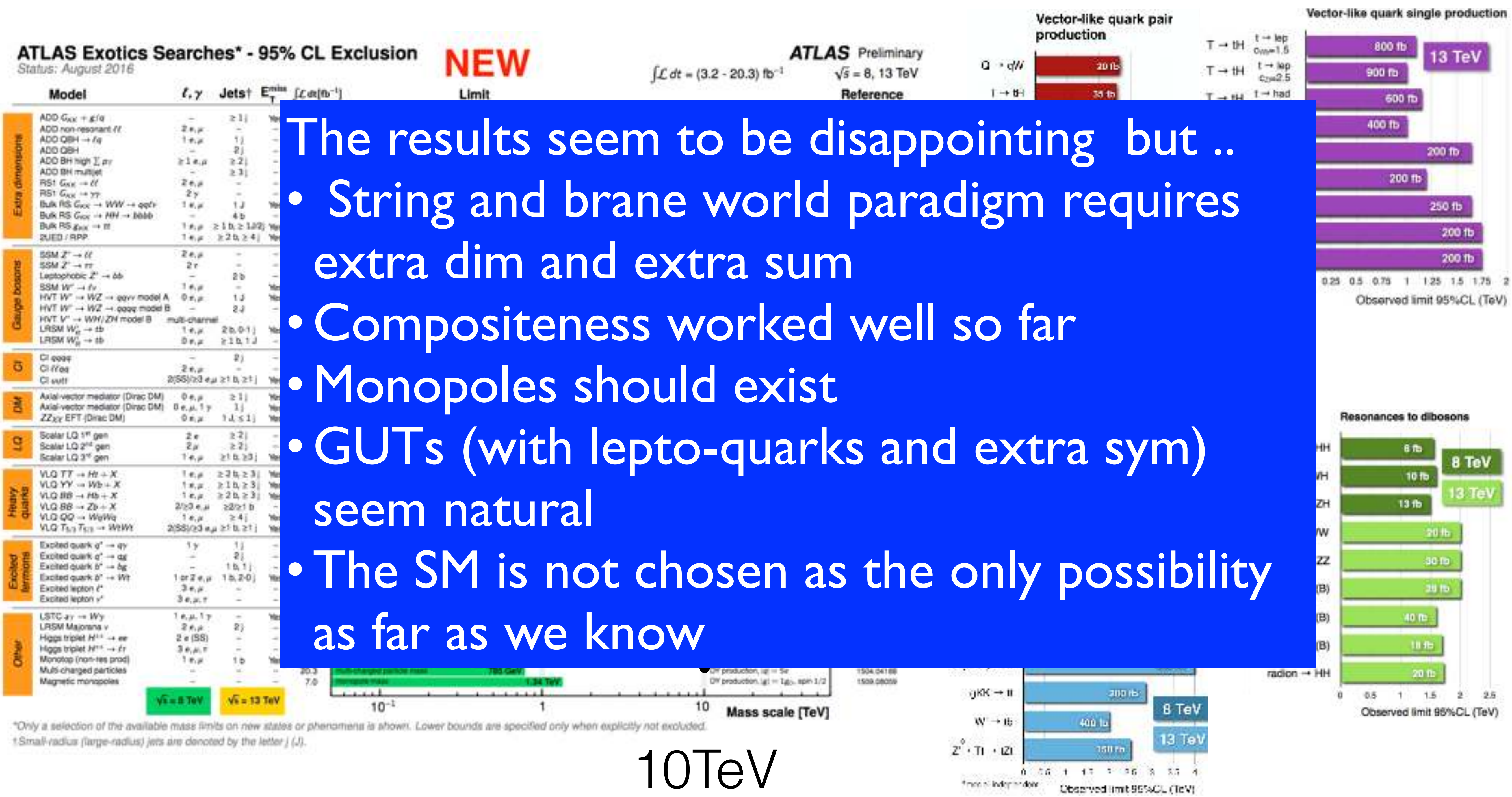
• W' **mass**: 4.74 TeV

• Dark photon **lifetime**: 2.5~100 mm (dark photon 400 MeV)

• **Magnetic charge**: |g|>1.5gD (up to 4 gD)

Resonance search summary

- Up to 25% mass limit increase by extending 2015 to 2016
- ~50% of the analyses updated to Run2



The results seem to be disappointing but ..

- String and brane world paradigm requires extra dim and extra sum
- Compositeness worked well so far
- Monopoles should exist
- GUTs (with lepto-quarks and extra sym) seem natural
- The SM is not chosen as the only possibility as far as we know

10TeV

Quo vadis?

The situation before the LHC:

- The SM was incomplete at 100 GeV scale (WW x-section increases with energy)
- There should be either Higgs boson or its substitute (elementary or composite) to make the SM consistent
- Guaranteed discovery and 100 GeV !

- If the Higgs boson, then its mass is not protected - quadratic radiative corrections of possible new physics
- New physics at TeV scale leads to little fine-tuning -> naturalness

Conclusion: look for new physics at TeV scale!

Quo vadis?

The situation with the LHC:

- The Higgs boson is discovered!
- The SM is consistent (at least up to high scale: metastability of the vacuum, ghost poles above the Plank scale)
- But the Higgs mass is not protected

- Is the naturalness the right argument?
- No guaranteed discovery at TeV scale !

Conclusion: look for new physics everywhere

Quo vadis?

What tells us that there is something beyond?

- The SM does not seem to be the ultimate consistent theory: leaves many whys and hows
- The Dark matter is made of something, presumably new particle(s)
- The string and braneworld paradigm is still appealing and gravity is still not conquered
- Complete picture should include cosmology, hence the dark energy puzzle awaits solution

The situation may change in a second when something shows up (remind the situation with DM and DE)

Procedo!