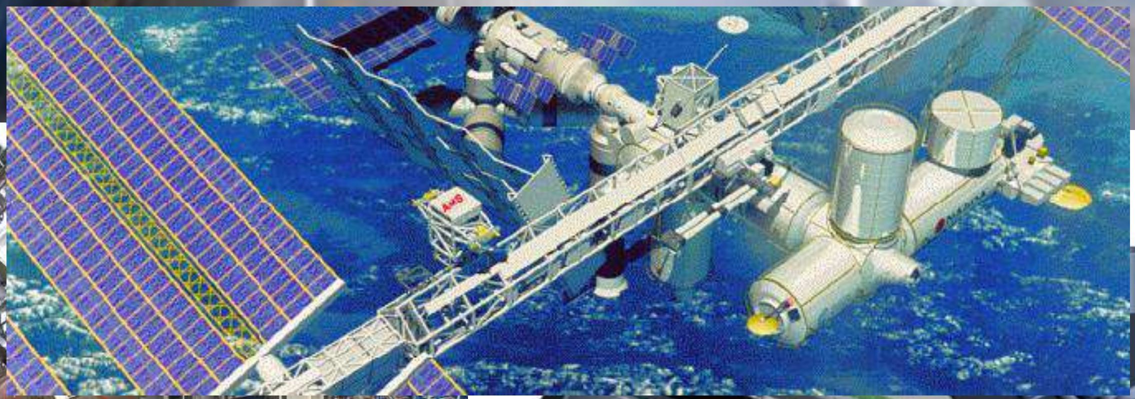
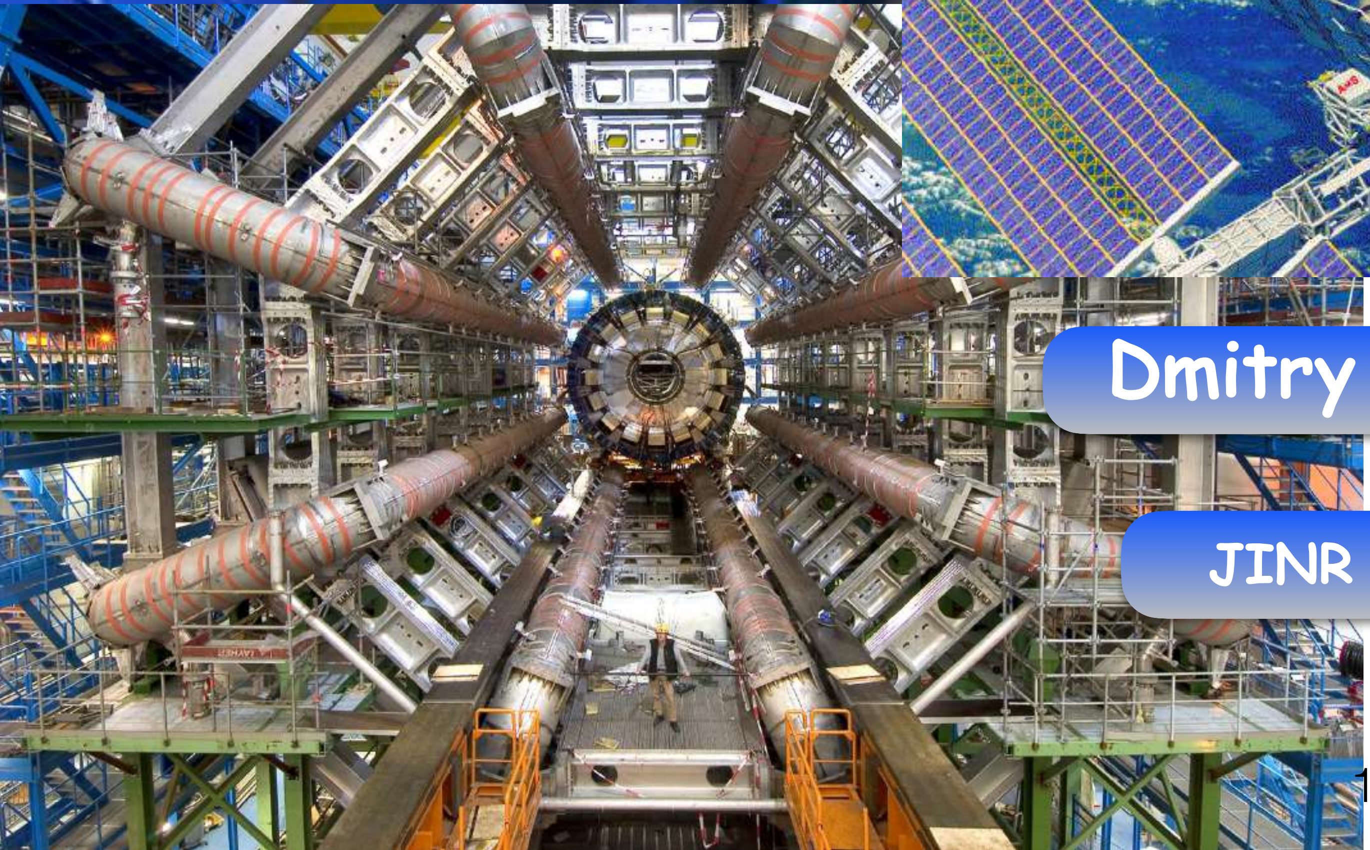
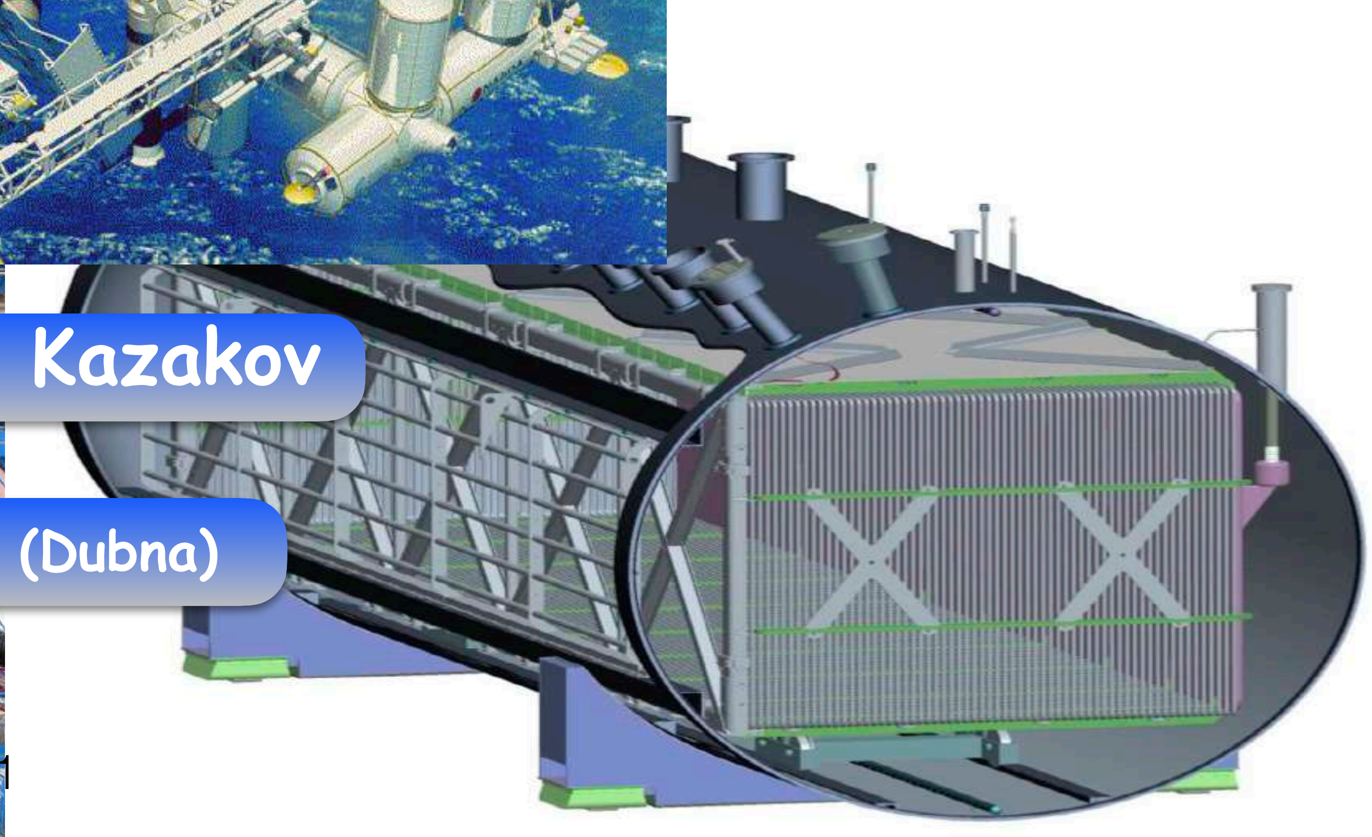
Beyond the SM Physics Perspectives in view of the LHC Run 2, Underground and Cosmic Experiments



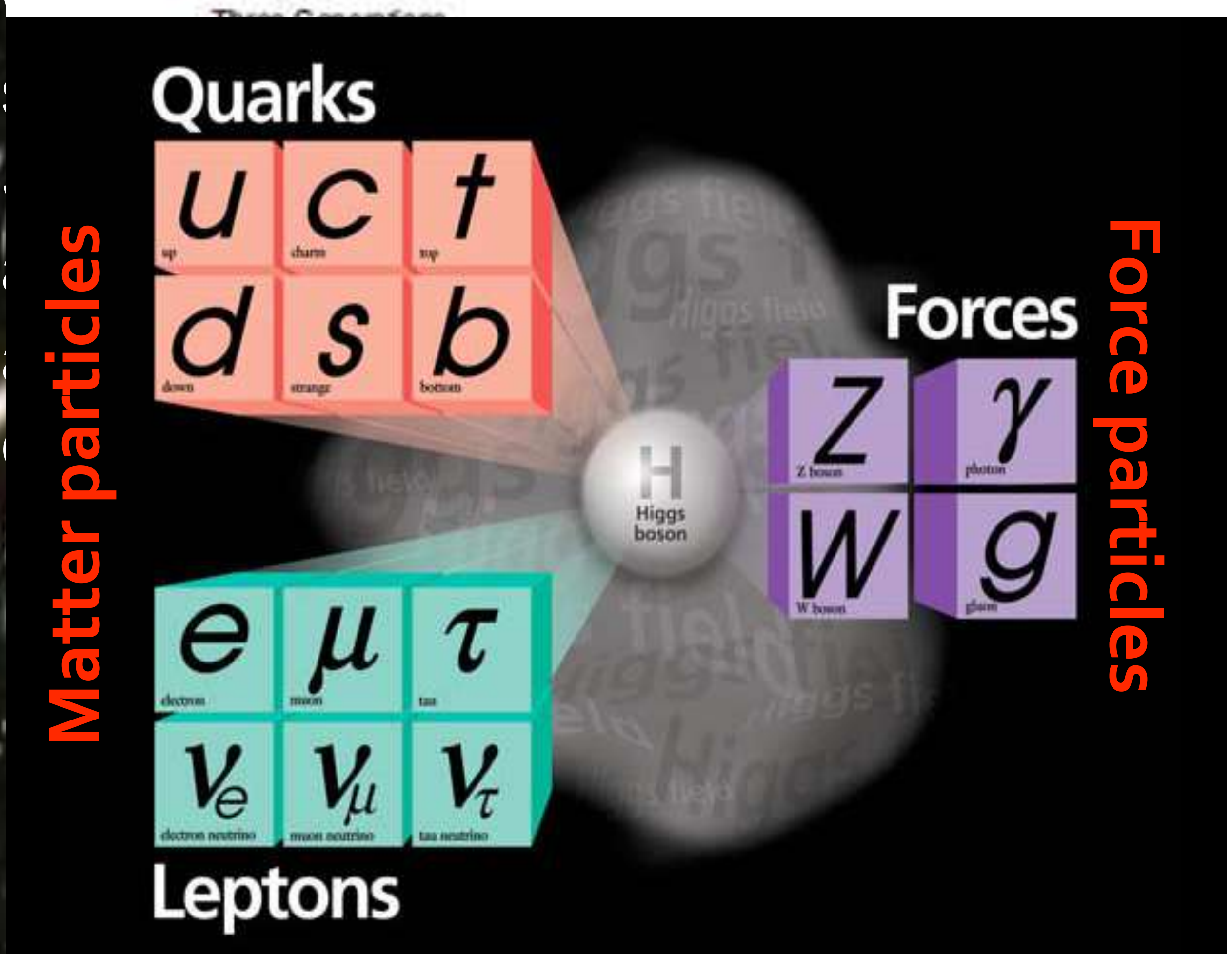




Dmitry Kazakov

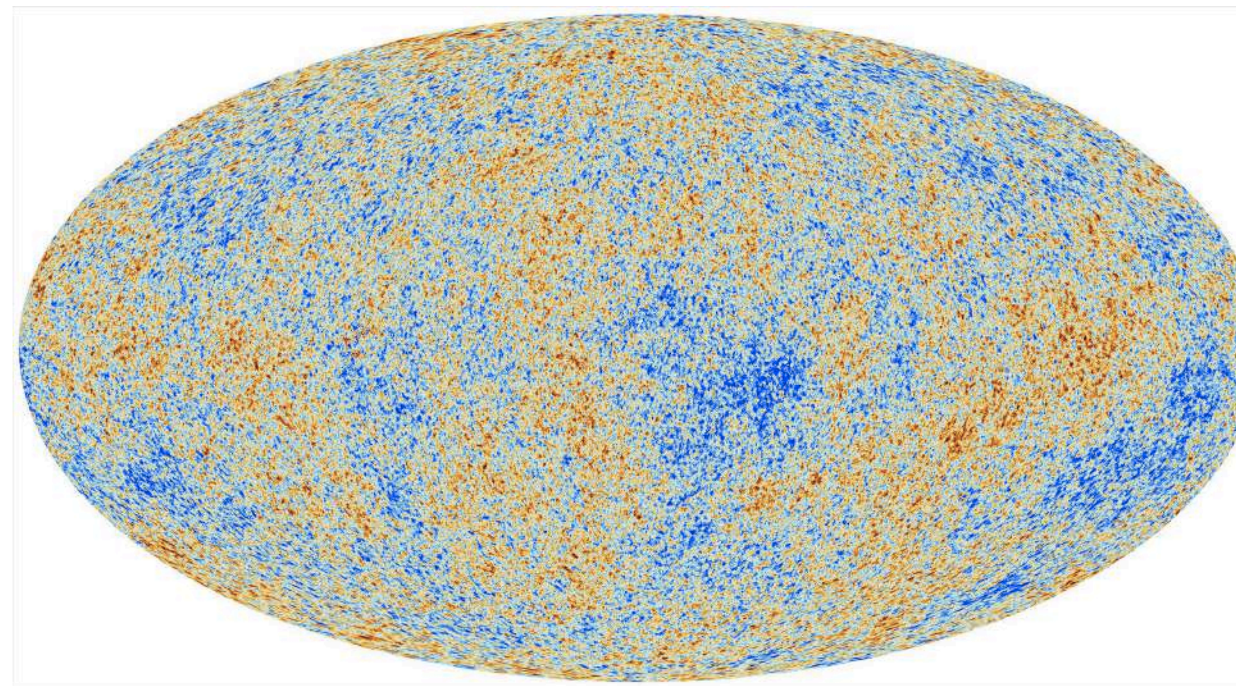
JINR (Dubna)

BUILDING AN UNDERSTANDING OF THE UNIVERSE: A WORK A CENTURY IN THE MAKING

- **PARTICLE STANDARD MODEL**



- **COSMOLOGY STANDARD MODEL**



ΛCDM + "SIMPLE" INFLATION

No more particle physics and cosmology : infinities merged into a unified picture of the Universe

The Standard Model of Particle Physics

- Three gauged symmetries SU(3)xSU(2)xU(1)
- Three families of quarks and leptons (3x2, 3x1, 1x2, 1x1)
- Brout-Englert-Higgs mechanism of spontaneous EW symmetry breaking -> Higgs boson
- CKM and PMNS mixing of flavours
- CP violation via phase factors
- Confinement of quarks and gluons inside hadrons
- Baryon and lepton number conservation
- CPT invariance -> existence of antimatter

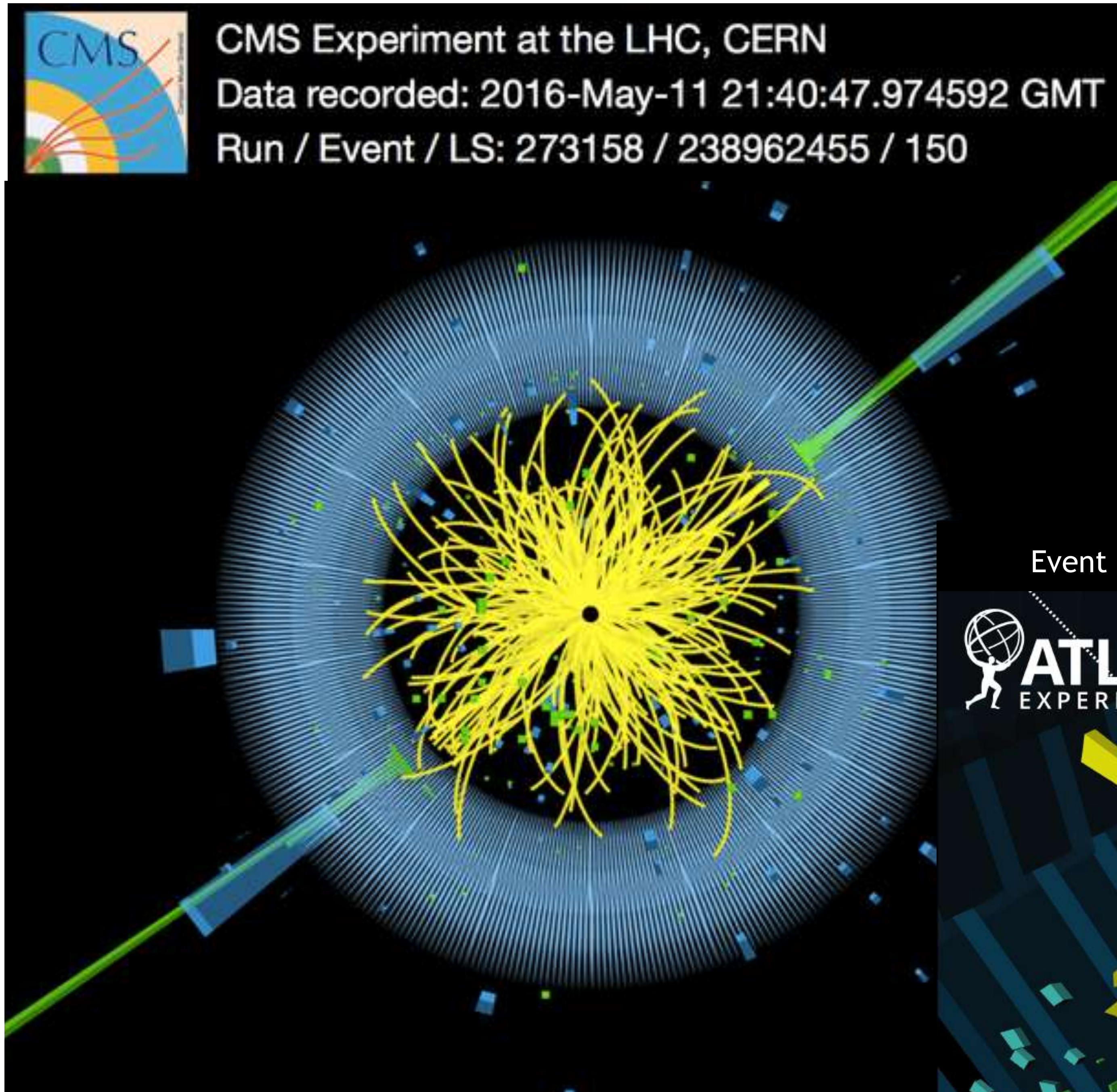
To be cleared up

- Higgs sector: one or more?
- Neutrino sector: Dirac or Majorana?
- Neutrino sector: Masses?
- What is the DM particle?
- Are there new particles?
- Are there new interactions?

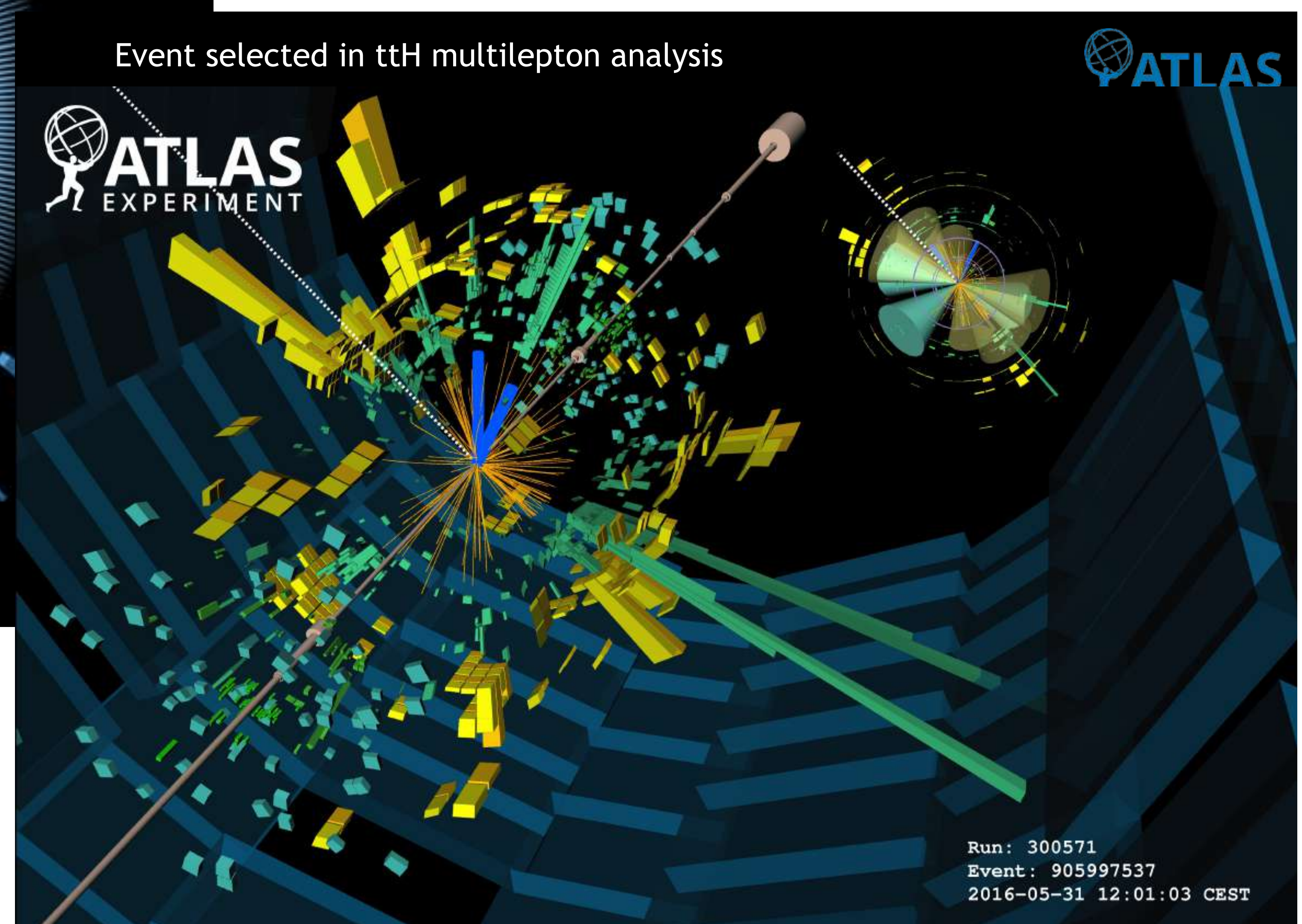
To be understood

- how confinement actually works ?
- how the quark-hadron phase transition happens?
- how CP violation occurs in the Universe?
- how to protect the SM from would be heavy scale physics?

LHC Run2



We are in a data driven era

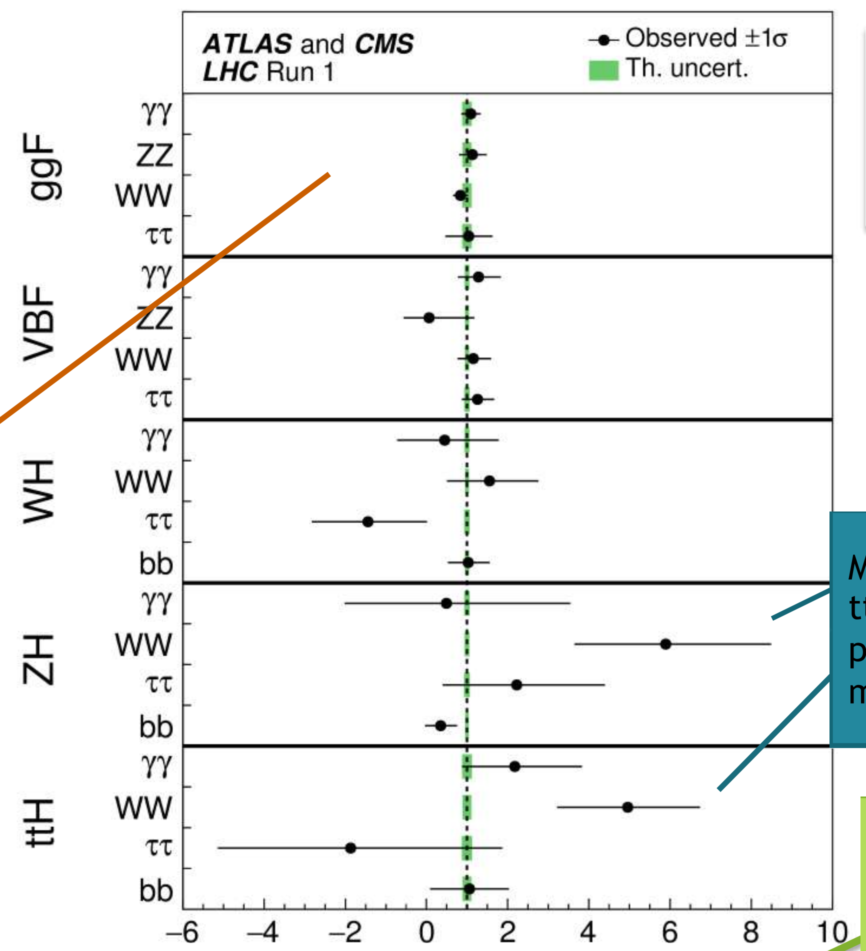


"Measure what is measureable and make measureable what is not so."

Galileo Galiliei
1564-1642

Higgs Boson (125)

- 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

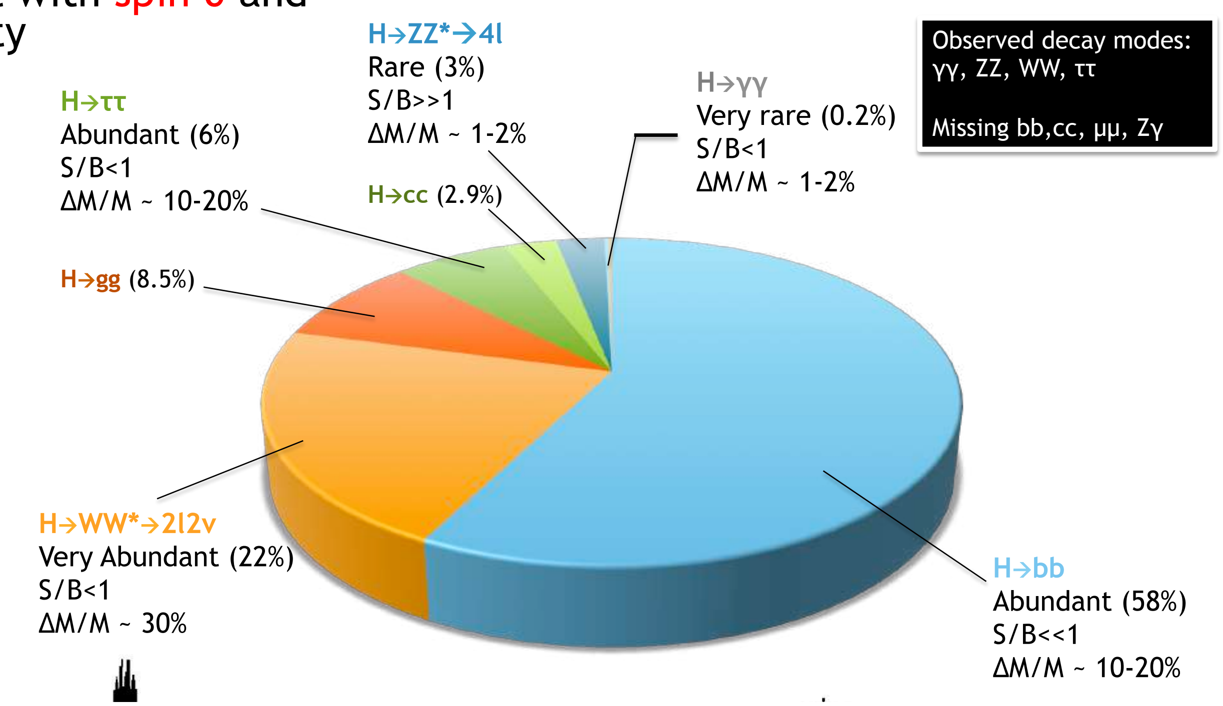


Precision test of Higgs boson coupling strength

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

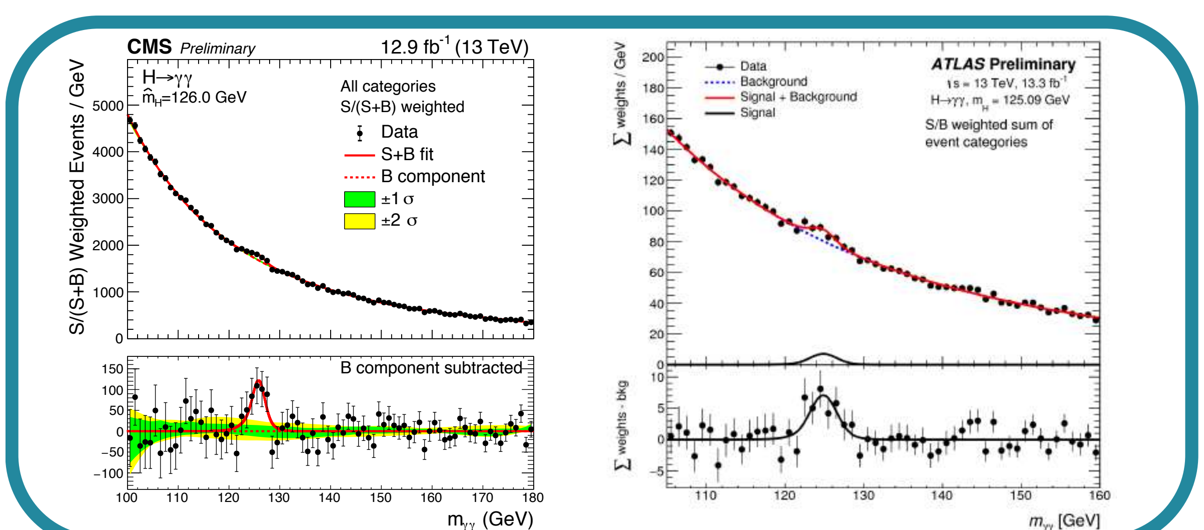
Mild excess in ttH and ZH production modes

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

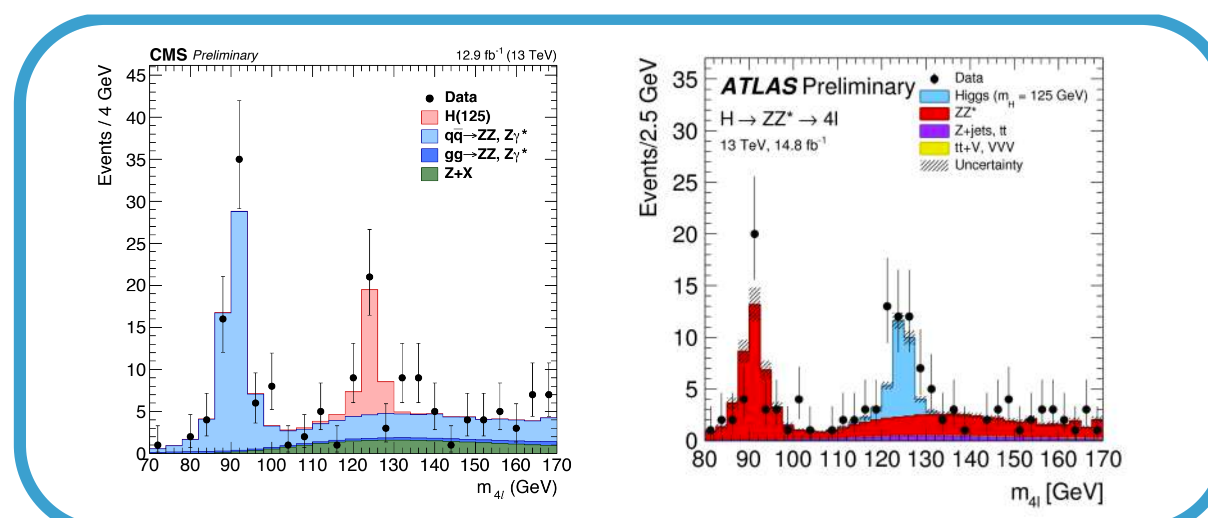


Observed decay modes: γγ, ZZ, WW, ττ

Missing bb,cc, μμ, Zγ



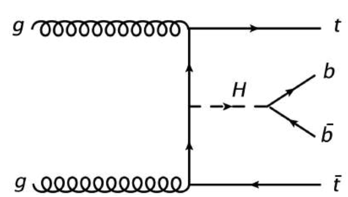
Higgs→γγ

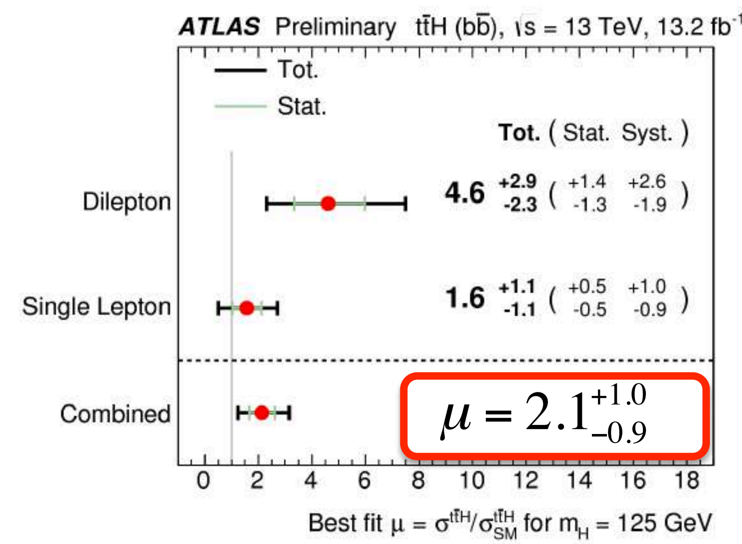


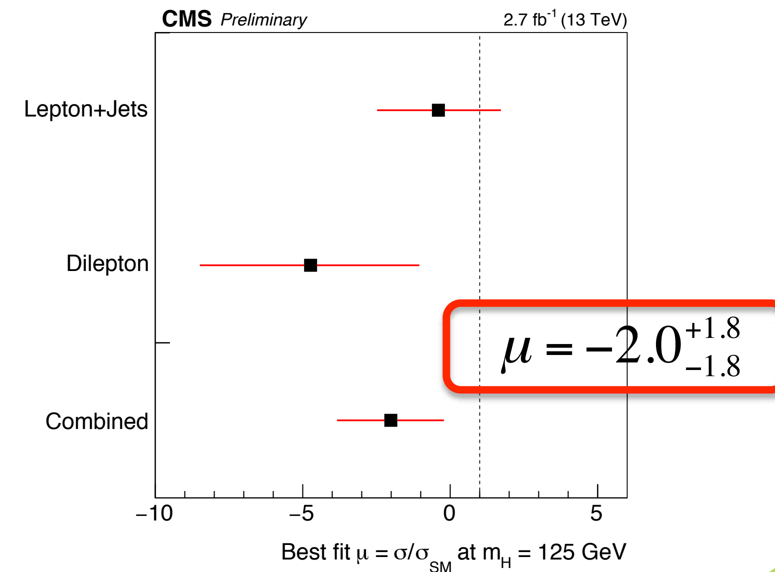
Higgs→ZZ*

Higgs Boson (125)

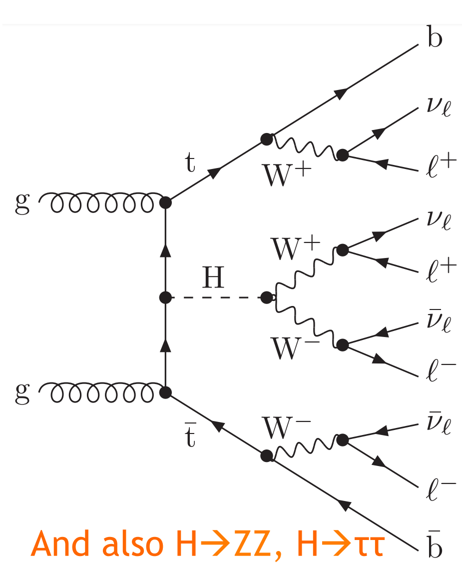
ttH(→bb)



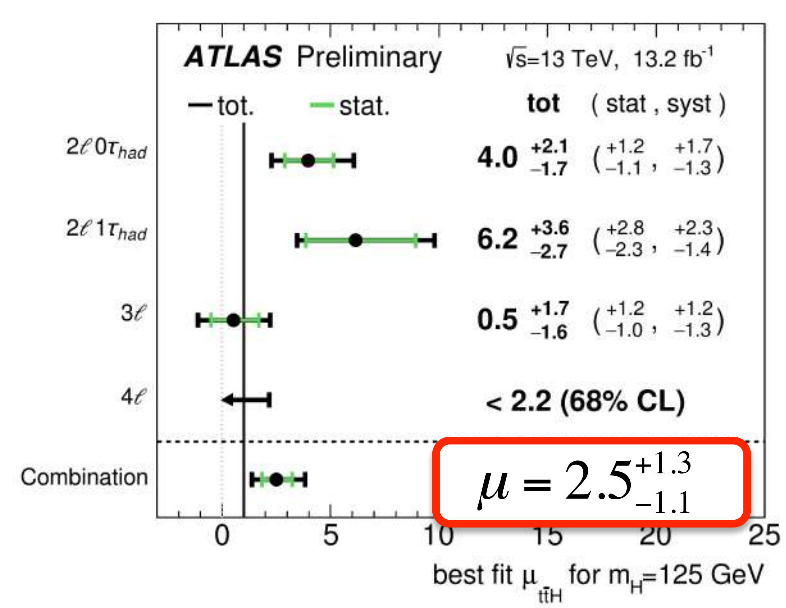


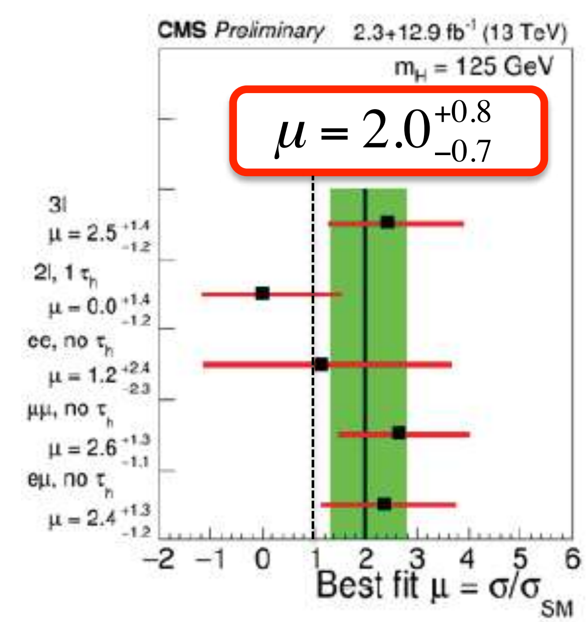


ttH(multileptons)



And also H→ZZ, H→ττ





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

Snowmass 2013 projections:

Luminosity	300 fb^{-1}	3000 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]	[illegible]-8%
	additional parameters (see text)	
$\kappa_{Z\gamma}$	$41-41\%$	$10-12\%$
κ_μ	$23-23\%$	$8-8\%$
$\mathrm{BR_{BSM}}$	$<14-18\%$	$<7-11\%$

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]MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
[illegible]omposite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

Snowmass 2013, 1310.8361

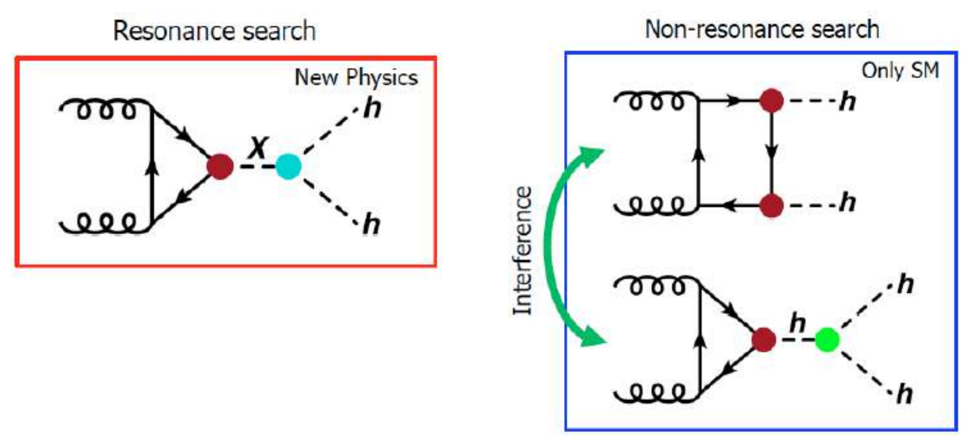
- Decoupling MSSM: κ_γ assumes 1 TeV stop with $\tan\beta = 3.2$, $X_t = 0$.

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

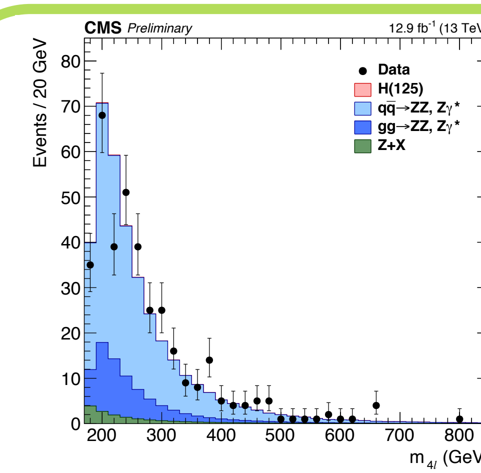
Thy uncert reductions ≈already achieved! Franz Herzog's talk

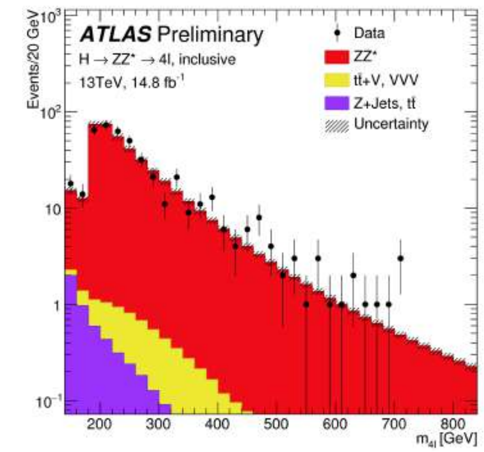
Extra Higgs Bosons

Higgs→hh→bbττ

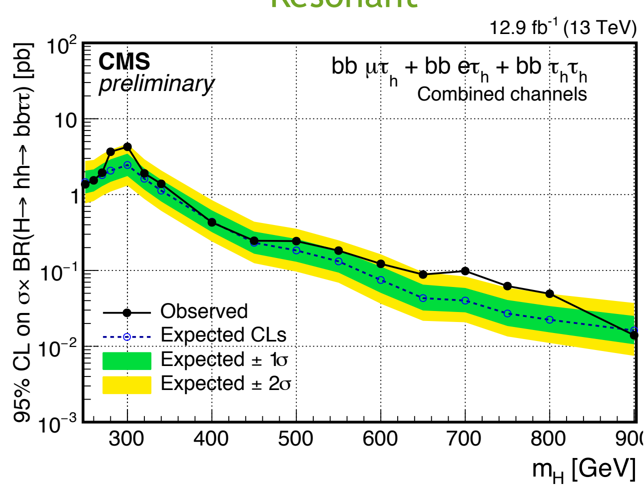


Heavy Higgs→ZZ→4l

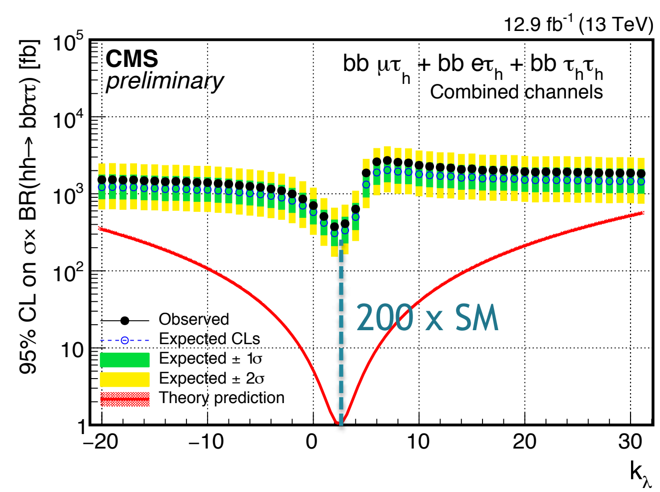




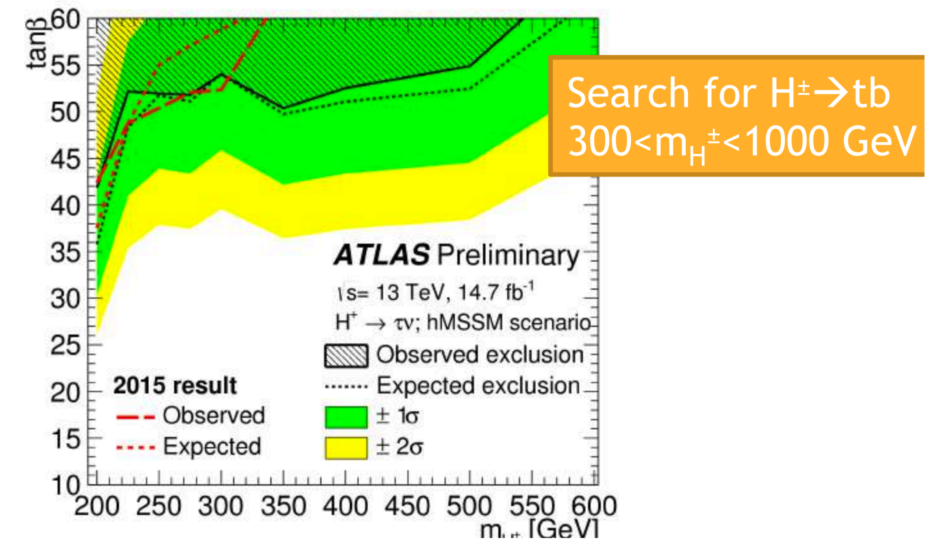
Resonant



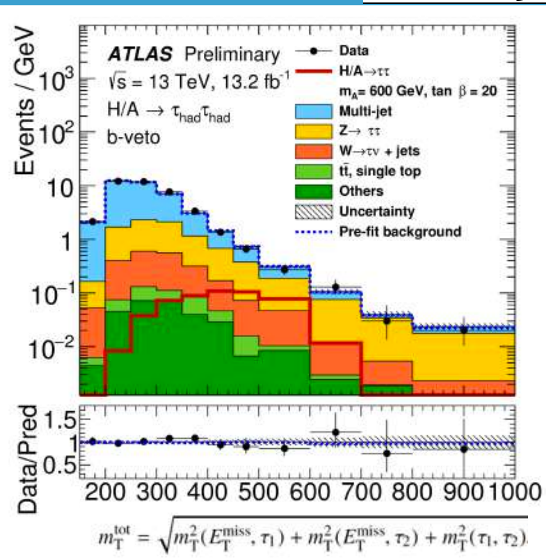
Non-Resonant



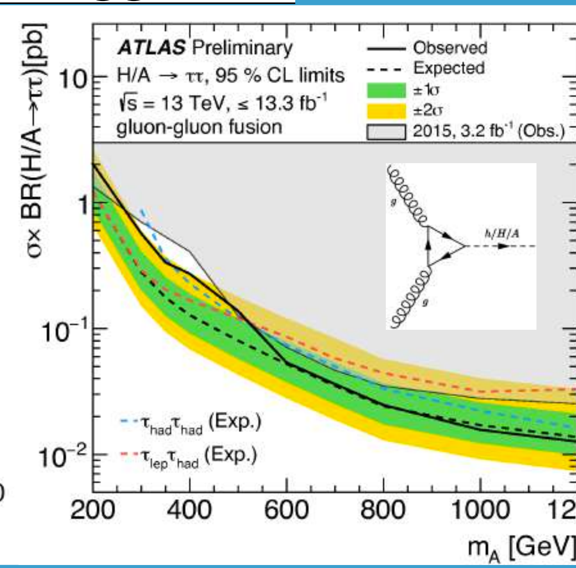
Charged Higgs



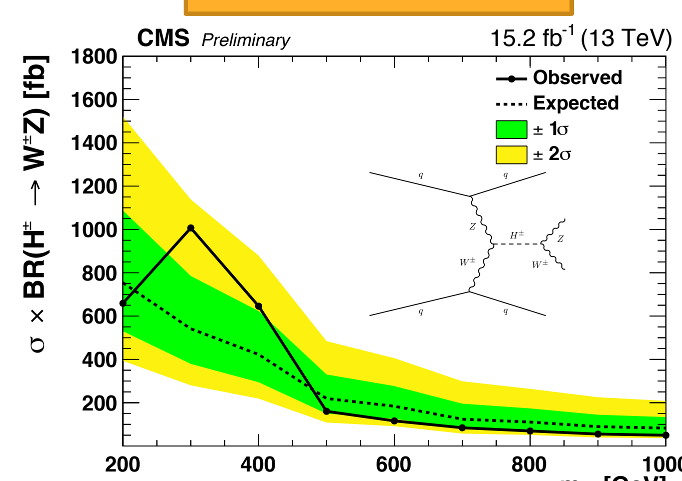
Heavy Higgs→ττ



$m_T^{tot} = \sqrt{m_T^2(E_T^{miss}, \tau_1) + m_T^2(E_T^{miss}, \tau_2) + m_T^2(\tau_1, \tau_2)}$



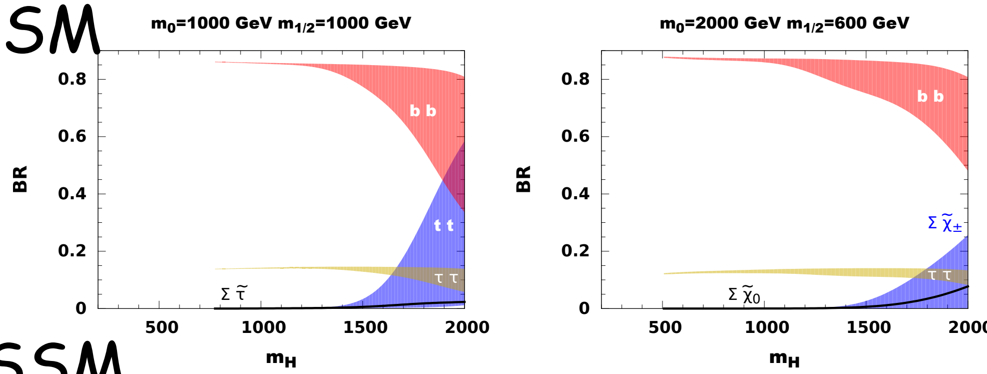
Search for H±WZ



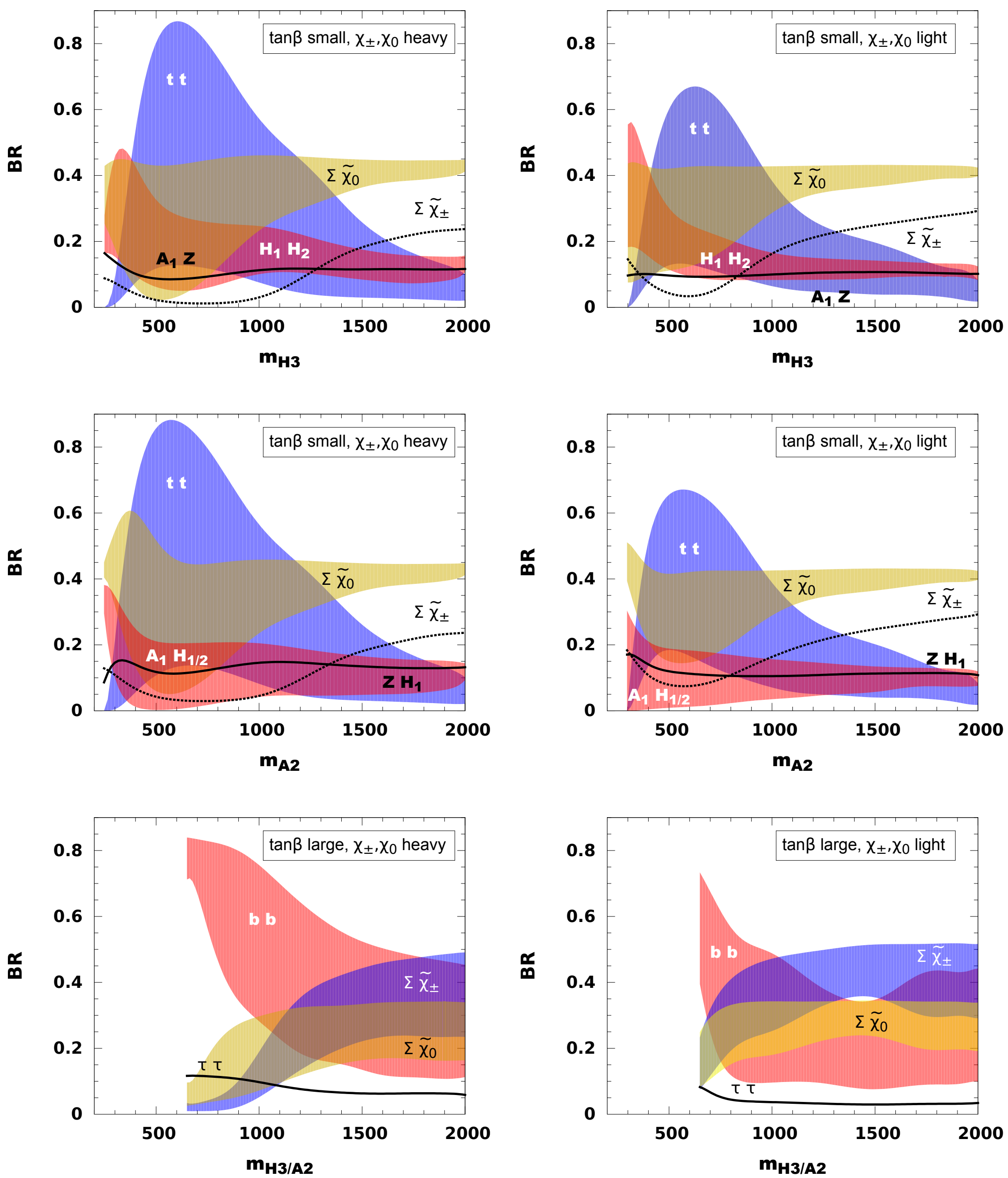
Heavy Higgs Decays

Branchings

MSSM

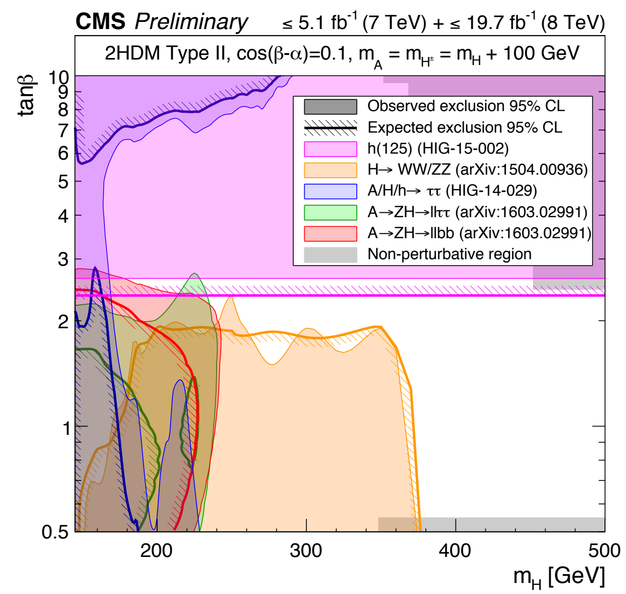


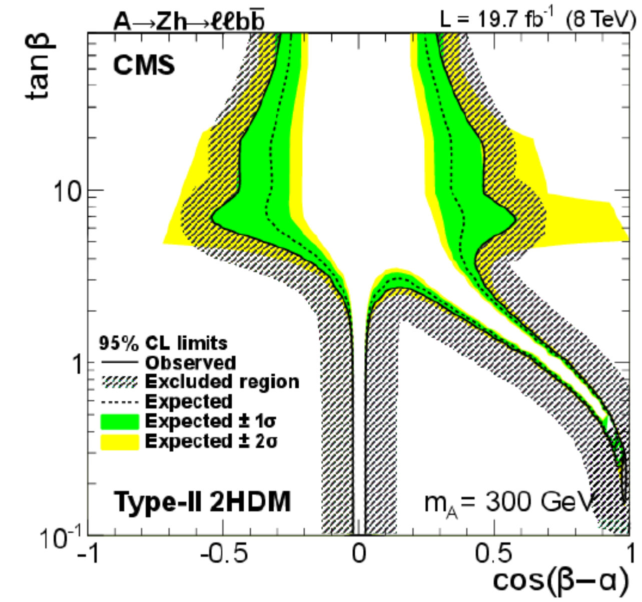
NMSSM

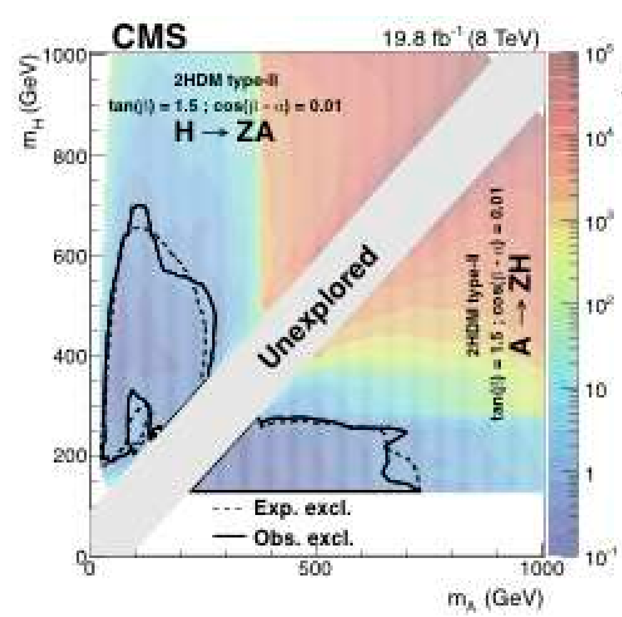


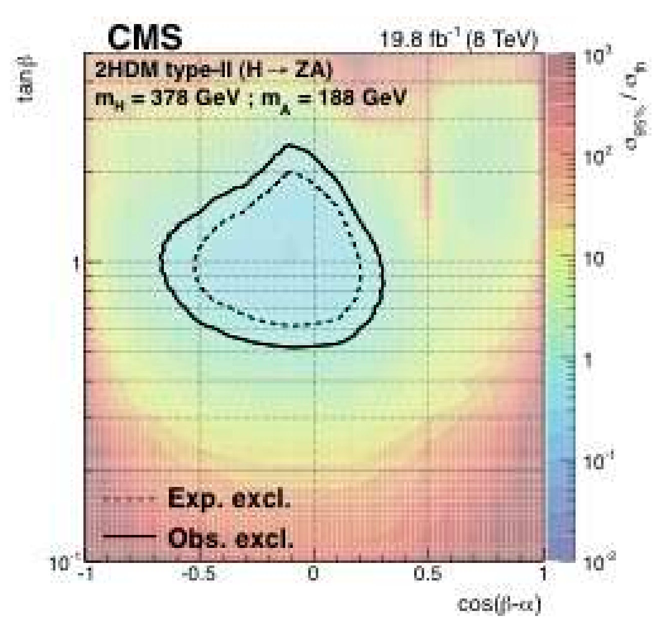
1) "Higgs to Higgs" decays

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





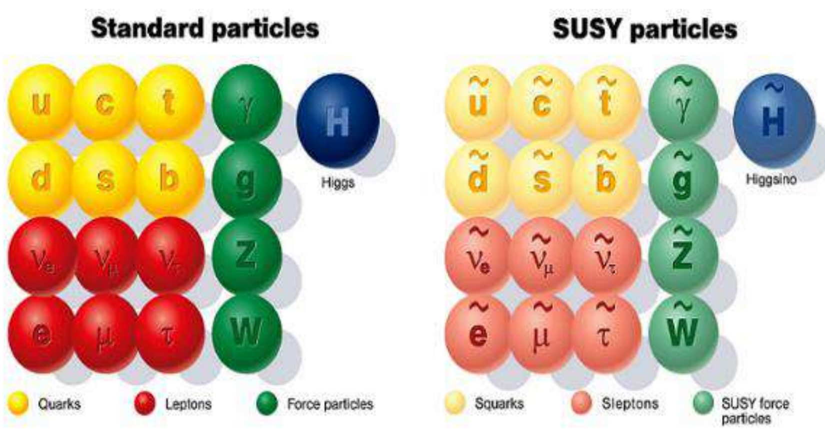




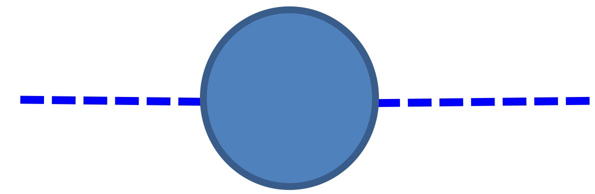
SUSY

Kiwoon Choi
(ICHEP 2016, Chicago)

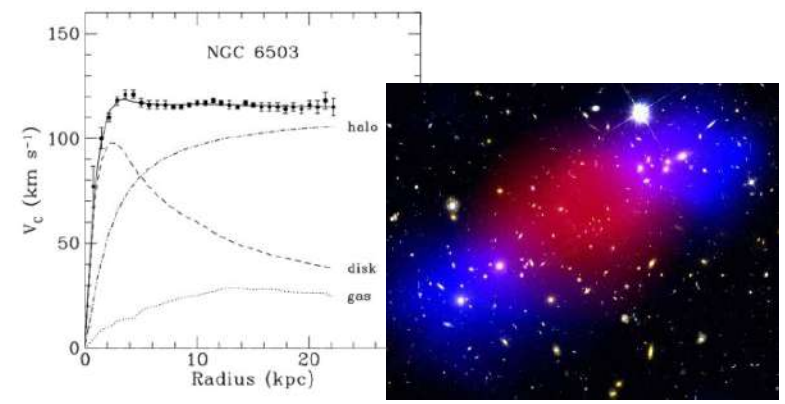
SUSY has been the prime candidate for BSM physics near the TeV scale.



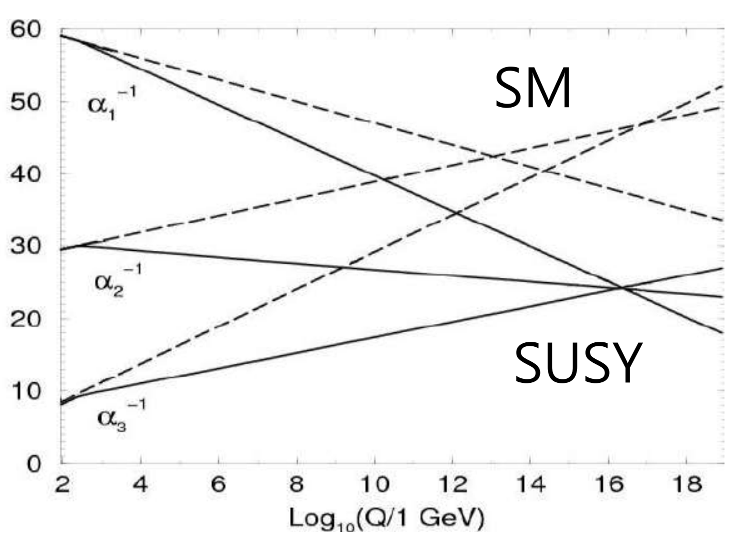
Hierarchy problem



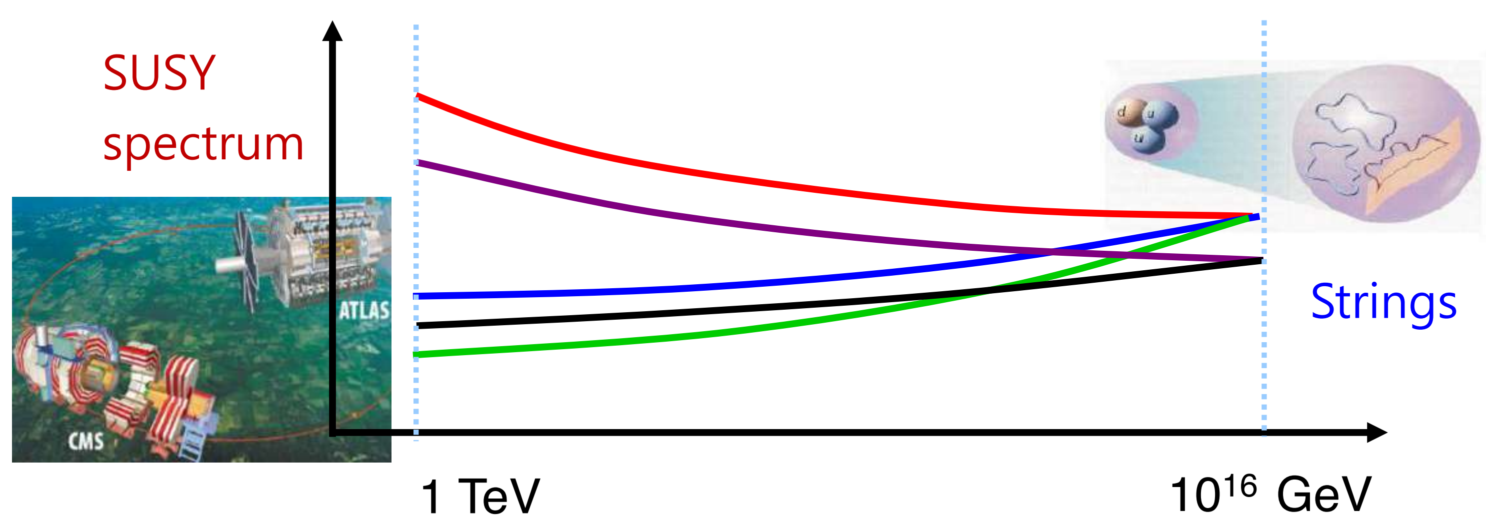
$$\delta m_H^2 \sim M_{\rm Planck}^2 \;\Rightarrow\; m_{\rm SUSY}^2$$



Dark matter



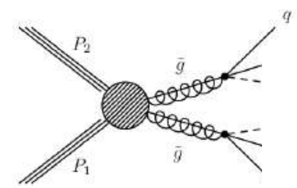
Gauge coupling unification



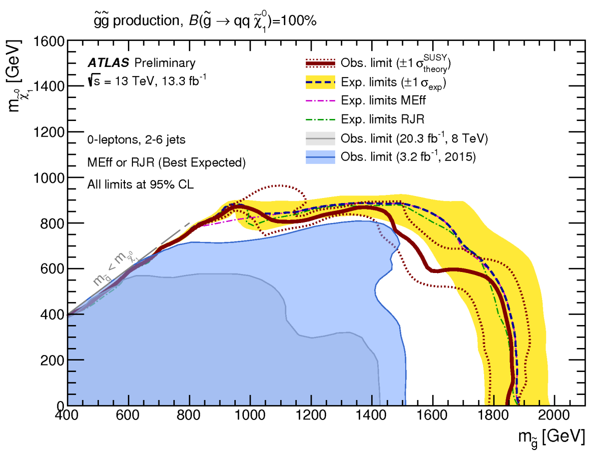
Supersymmetry remains, to this date, a well-motivated, much anticipated extension to the Standard Model of particle physics

Supersymmetry/ LHC 13

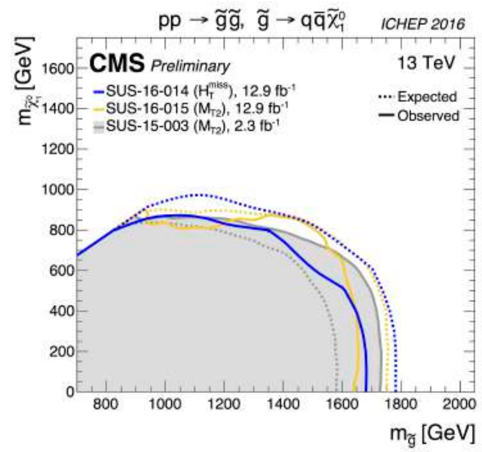
Gluino decays to qq+LSP



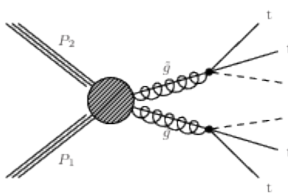
Summary of decays to light quarks + LSP



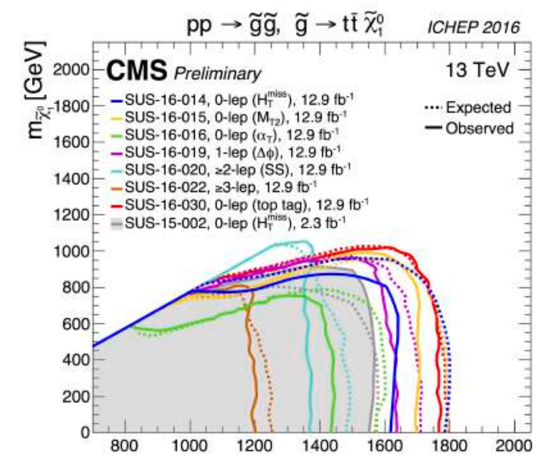
ATLAS-CONF-2016-078



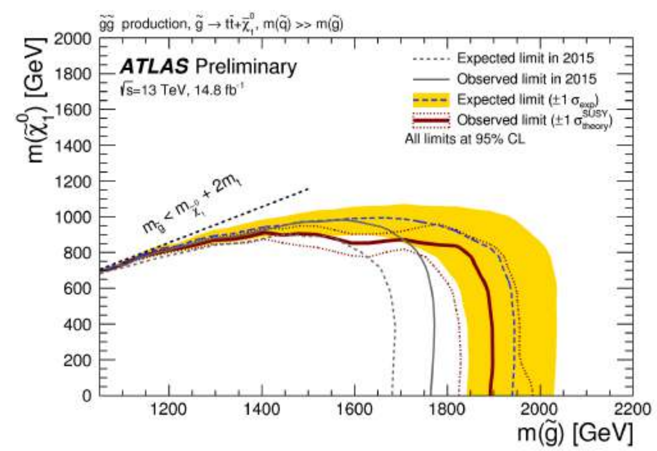
Gluino decays to tt+LSP



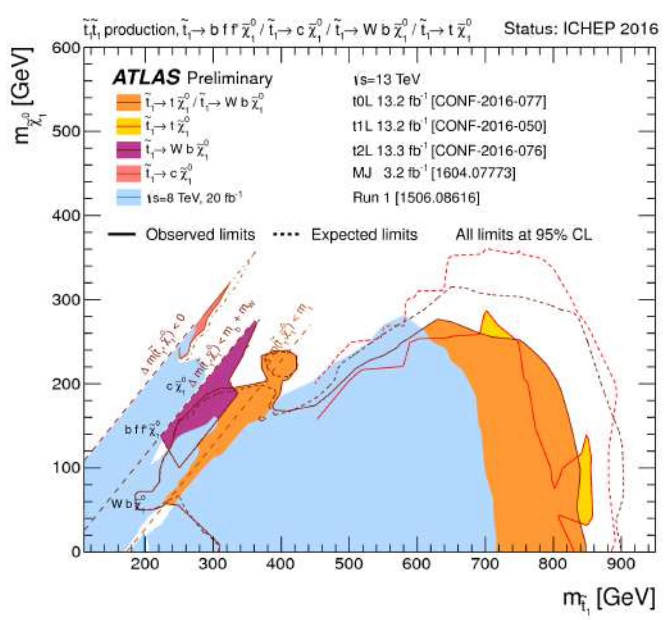
CMS summary



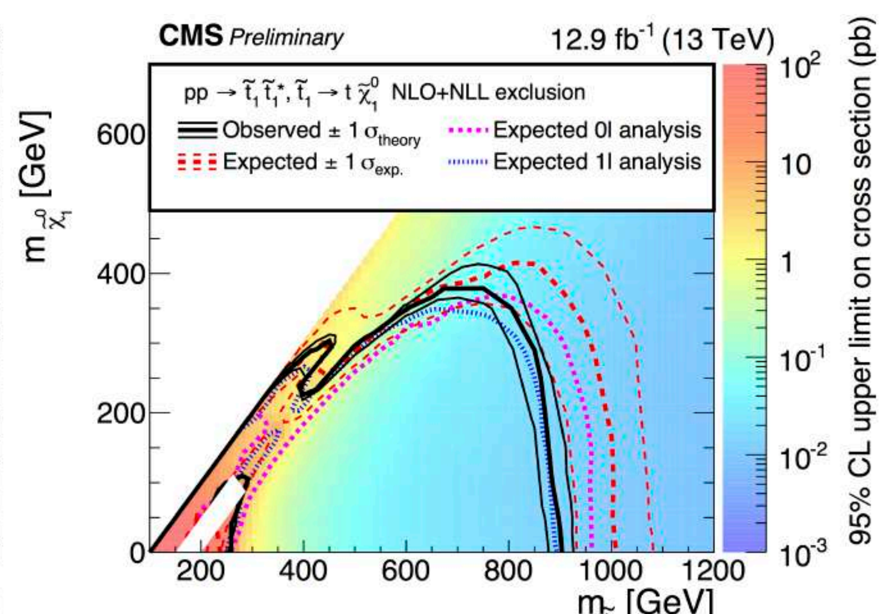
ATLAS multi-b ATLAS-CONF-2016-052



Top squarks - summaries



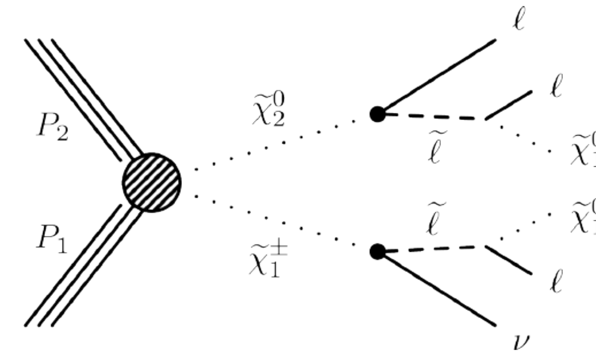
ATLAS summary



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

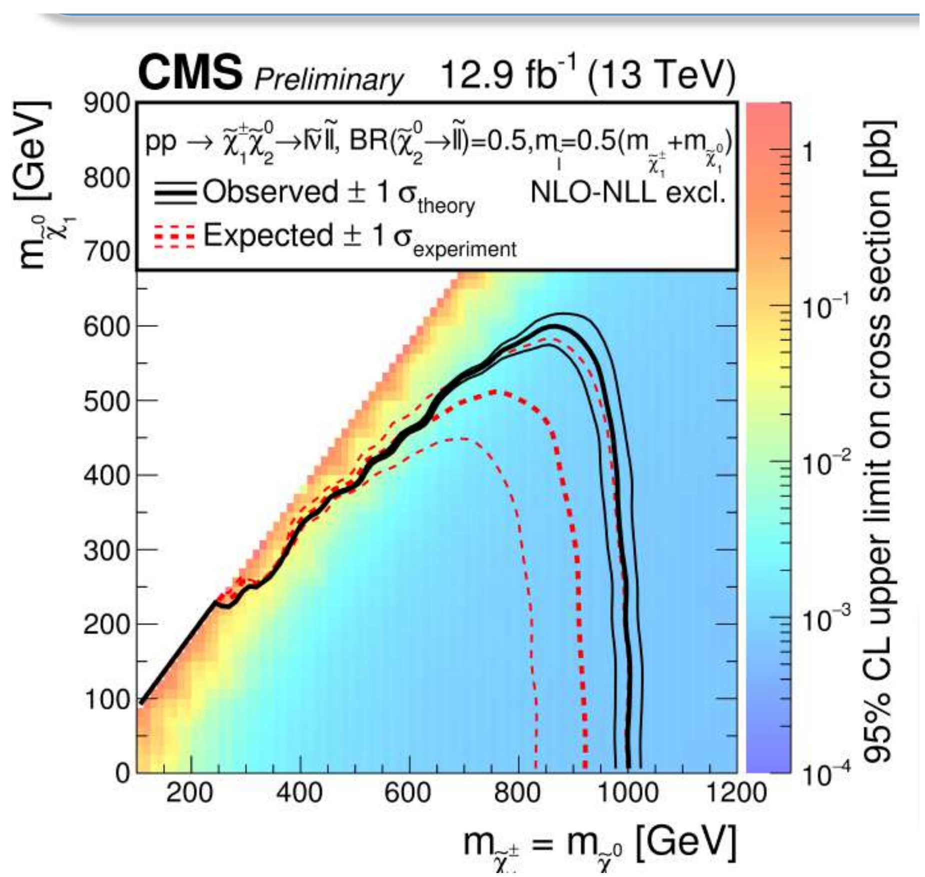
Supersymmetry/LHC 13

Chargino / neutralino production



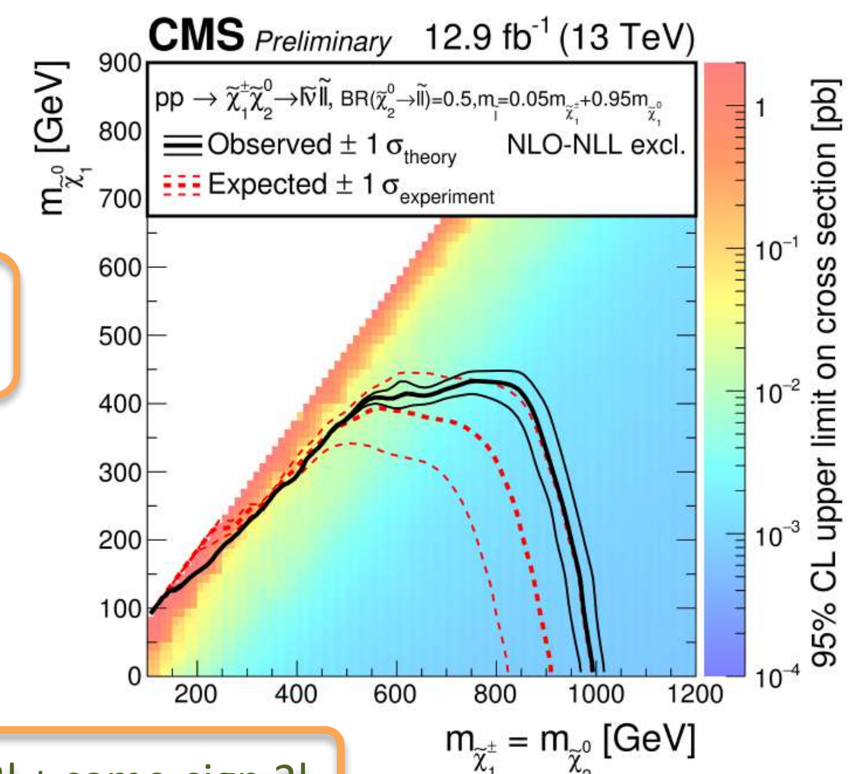
Direct production of "electroweakino" pairs

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



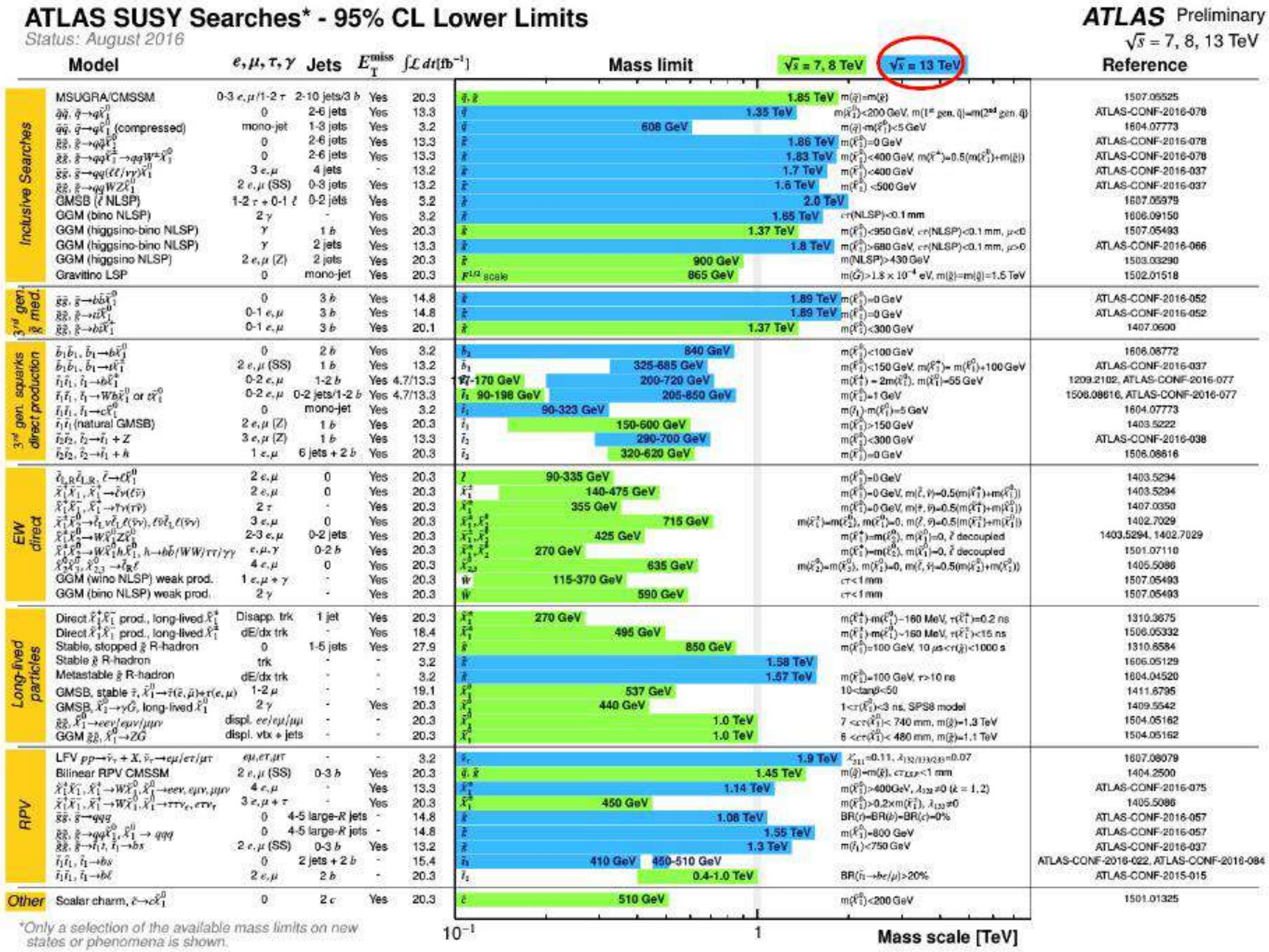
Effect of change in intermediate slepton mass

↔



3l + same-sign 2l

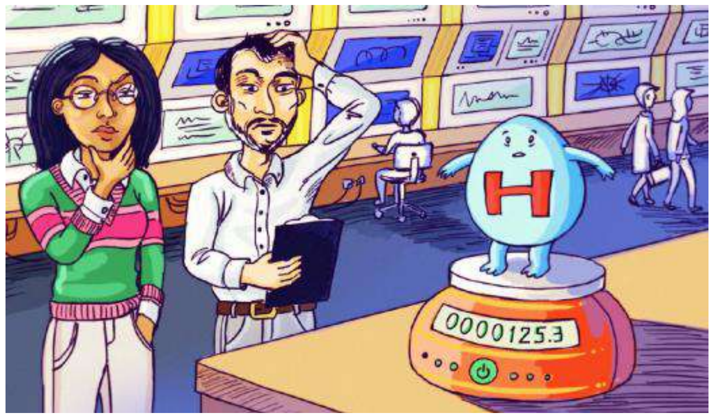
LHC Run2



ATLAS SUSY Searches* - 95% CL Lower Limits
Status: August 2016
ATLAS Preliminary
√s = 7, 8, 13 TeV
Model
e, μ, τ, γ
Jets
E_T^{miss}
∫L dt[fb^{-1}]
Mass limit
√s = 7, 8 TeV
√s = 13 TeV
Reference
Inclusive Searches
MSUGRA/CMSSM | 0-3 e,μ/1-2 τ | 2-10 jets/3 b | Yes | 20.3 | 1.85 TeV | m(q̃)=m(g̃) | 1507.05525
q̃q̃, q̃→qχ̃$_1^0$ | 0 | 2-6 jets | Yes | 13.3 | 1.35 TeV | ATLAS-CONF-2016-078
q̃q̃, q̃→qχ̃$_1^0$ (compressed) | mono-jet | 1-3 jets | Yes | 3.2 | 608 GeV | 1604.07773
g̃g̃, g̃→qq̄χ̃$_1^0$ | 0 | 2-6 jets | Yes | 13.3 | 1.86 TeV | m(χ̃$_1^0$)=0 GeV | ATLAS-CONF-2016-078
g̃g̃, g̃→qqχ̃$_1^\pm$→qqW$^\pm$χ̃$_1^0$ | 0 | 2-6 jets | Yes | 13.3 | 1.83 TeV | ATLAS-CONF-2016-078
g̃g̃, g̃→qq(ℓℓ/νν)χ̃$_1^0$ | 3 e,μ | 4 jets | - | 13.2 | 1.7 TeV | m(χ̃$_1^0$)<400 GeV | ATLAS-CONF-2016-037
g̃g̃, g̃→qqWZχ̃$_1^0$ | 2 e,μ (SS) | 0-3 jets | Yes | 13.2 | 1.6 TeV | m(χ̃$_1^0$) <500 GeV | ATLAS-CONF-2016-037
GMSB (ℓ̃ NLSP) | 1-2 τ + 0-1 ℓ | 0-2 jets | Yes | 3.2 | 2.0 TeV | 1607.05979
GGM (bino NLSP) | 2 γ | - | Yes | 3.2 | 1.65 TeV | cτ(NLSP)<0.1 mm | 1606.09150
GGM (higgsino-bino NLSP) | γ | 1 b | Yes | 20.3 | 1.37 TeV | 1507.05493
GGM (higgsino-bino NLSP) | γ | 2 jets | Yes | 13.3 | 1.8 TeV | ATLAS-CONF-2016-066
GGM (higgsino NLSP) | 2 e,μ (Z) | 2 jets | Yes | 20.3 | 900 GeV | m(NLSP)>430 GeV | 1503.03290
Gravitino LSP | 0 | mono-jet | Yes | 20.3 | 865 GeV | $F^{1/2}$ scale | 1502.01518
3rd gen. g̃ med.
g̃g̃, g̃→bb̄χ̃$_1^0$ | 0 | 3 b | Yes | 14.8 | 1.89 TeV | m(χ̃$_1^0$)=0 GeV | ATLAS-CONF-2016-052
g̃g̃, g̃→tt̄χ̃$_1^0$ | 0-1 e,μ | 3 b | Yes | 14.8 | 1.89 TeV | m(χ̃$_1^0$)=0 GeV | ATLAS-CONF-2016-052
g̃g̃, g̃→bt̄χ̃$_1^+$ | 0-1 e,μ | 3 b | Yes | 20.1 | 1.37 TeV | m(χ̃$_1^0$)<300 GeV | 1407.0600
3rd gen. squarks direct production
b̃$_1$b̃$_1$, b̃$_1$→bχ̃$_1^0$ | 0 | 2 b | Yes | 3.2 | 840 GeV | m(χ̃$_1^0$)<100 GeV | 1606.08772
b̃$_1$b̃$_1$, b̃$_1$→tχ̃$_1^\pm$ | 2 e,μ (SS) | 1 b | Yes | 13.2 | 325-685 GeV | ATLAS-CONF-2016-037
t̃$_1$t̃$_1$, t̃$_1$→bχ̃$_1^\pm$ | 0-2 e,μ | 1-2 b | Yes | 4.7/13.3 | 117-170 GeV | 200-720 GeV | 1209.2102, ATLAS-CONF-2016-077
t̃$_1$t̃$_1$, t̃$_1$→Wbχ̃$_1^0$ or tχ̃$_1^0$ | 0-2 e,μ | 0-2 jets/1-2 b | Yes | 4.7/13.3 | 90-198 GeV | 205-850 GeV | m(χ̃$_1^0$)=1 GeV | 1506.08616, ATLAS-CONF-2016-077
t̃$_1$t̃$_1$, t̃$_1$→cχ̃$_1^0$ | 0 | mono-jet | Yes | 3.2 | 90-323 GeV | 1604.07773
t̃$_1$t̃$_1$ (natural GMSB) | 2 e,μ (Z) | 1 b | Yes | 20.3 | 150-600 GeV | m(χ̃$_1^0$)>150 GeV | 1403.5222
t̃$_2$t̃$_2$, t̃$_2$→t̃$_1$ + Z | 3 e,μ (Z) | 1 b | Yes | 13.3 | 290-700 GeV | m(χ̃$_1^0$)<300 GeV | ATLAS-CONF-2016-038
t̃$_2$t̃$_2$, t̃$_2$→t̃$_1$ + h | 1 e,μ | 6 jets + 2 b | Yes | 20.3 | 320-620 GeV | m(χ̃$_1^0$)=0 GeV | 1506.08616
EW direct
ℓ̃$_{L,R}$ℓ̃$_{L,R}$, ℓ̃→ℓχ̃$_1^0$ | 2 e,μ | 0 | Yes | 20.3 | 90-335 GeV | m(χ̃$_1^0$)=0 GeV | 1403.5294
χ̃$_1^+$χ̃$_1^-$, χ̃$_1^+$→ℓ̃ν(ℓν̃) | 2 e,μ | 0 | Yes | 20.3 | 140-475 GeV | 1403.5294
χ̃$_1^+$χ̃$_1^-$, χ̃$_1^+$→τ̃ν(τν̃) | 2 τ | - | Yes | 20.3 | 355 GeV | 1407.0350
χ̃$_1^\pm$χ̃$_2^0$→ℓ̃$_L$νℓ̃$_L$ℓ(ν̃ν), ℓν̃ℓ̃$_L$ℓ(ν̃ν) | 3 e,μ | 0 | Yes | 20.3 | 715 GeV | 1402.7029
χ̃$_1^\pm$χ̃$_2^0$→Wχ̃$_1^0$Zχ̃$_1^0$ | 2-3 e,μ | 0-2 jets | Yes | 20.3 | 425 GeV | 1403.5294, 1402.7029
χ̃$_1^\pm$χ̃$_2^0$→Wχ̃$_1^0$hχ̃$_1^0$, h→bb̄/WW/ττ/γγ | e,μ,γ | 0-2 b | Yes | 20.3 | 270 GeV | 1501.07110
χ̃$_2^0$χ̃$_3^0$, χ̃$_{2,3}^0$→ℓ̃$_R$ℓ | 4 e,μ | 0 | Yes | 20.3 | 635 GeV | 1405.5086
GGM (wino NLSP) weak prod. | 1 e,μ + γ | - | Yes | 20.3 | 115-370 GeV | cτ<1 mm | 1507.05493
GGM (bino NLSP) weak prod. | 2 γ | - | Yes | 20.3 | 590 GeV | cτ<1 mm | 1507.05493
Long-lived particles
Direct χ̃$_1^+$χ̃$_1^-$ prod., long-lived χ̃$_1^\pm$ | Disapp. trk | 1 jet | Yes | 20.3 | 270 GeV | 1310.3675
Direct χ̃$_1^+$χ̃$_1^-$ prod., long-lived χ̃$_1^\pm$ | dE/dx trk | - | Yes | 18.4 | 495 GeV | 1506.05332
Stable, stopped g̃ R-hadron | 0 | 1-5 jets | Yes | 27.9 | 850 GeV | 1310.6584
Stable g̃ R-hadron | trk | - | - | 3.2 | 1.58 TeV | 1606.05129
Metastable g̃ R-hadron | dE/dx trk | - | - | 3.2 | 1.57 TeV | 1604.04520
GMSB, stable τ̃, χ̃$_1^0$→τ̃(ẽ, μ̃)+τ(e, μ) | 1-2 μ | - | - | 19.1 | 537 GeV | 10<tanβ<50 | 1411.6795
GMSB, χ̃$_1^0$→γG̃, long-lived χ̃$_1^0$ | 2 γ | - | Yes | 20.3 | 440 GeV | 1<τ(χ̃$_1^0$)<3 ns, SPS8 model | 1409.5542
g̃g̃, χ̃$_1^0$→eeν/eμν/μμν | displ. ee/eμ/μμ | - | - | 20.3 | 1.0 TeV | 1504.05162
GGM g̃g̃, χ̃$_1^0$→ZG̃ | displ. vtx + jets | - | - | 20.3 | 1.0 TeV | 1504.05162
RPV
LFV pp→ν̃$_\tau$ + X, ν̃$_\tau$→eμ/eτ/μτ | eμ,eτ,μτ | - | - | 3.2 | 1.9 TeV | 1607.08079
Bilinear RPV CMSSM | 2 e,μ (SS) | 0-3 b | Yes | 20.3 | 1.45 TeV | 1404.2500
χ̃$_1^+$χ̃$_1^-$, χ̃$_1^+$→Wχ̃$_1^0$, χ̃$_1^0$→eeν, eμν, μμν | 4 e,μ | - | Yes | 13.3 | 1.14 TeV | ATLAS-CONF-2016-075
χ̃$_1^+$χ̃$_1^-$, χ̃$_1^+$→Wχ̃$_1^0$, χ̃$_1^0$→ττν$_e$, eτν$_\tau$ | 3 e,μ + τ | - | Yes | 20.3 | 450 GeV | 1405.5086
g̃g̃, g̃→qqq | 0 | 4-5 large-R jets | - | 14.8 | 1.08 TeV | ATLAS-CONF-2016-057
g̃g̃, g̃→qqχ̃$_1^0$, χ̃$_1^0$→qqq | 0 | 4-5 large-R jets | - | 14.8 | 1.55 TeV | ATLAS-CONF-2016-057
g̃g̃, g̃→t̃$_1$t, t̃$_1$→bs | 2 e,μ (SS) | 0-3 b | Yes | 13.2 | 1.3 TeV | m(t̃$_1$)<750 GeV | ATLAS-CONF-2016-037
t̃$_1$t̃$_1$, t̃$_1$→bs | 0 | 2 jets + 2 b | - | 15.4 | 410 GeV | 450-510 GeV | ATLAS-CONF-2016-022, ATLAS-CONF-2016-084
t̃$_1$t̃$_1$, t̃$_1$→bℓ | 2 e,μ | 2 b | - | 20.3 | 0.4-1.0 TeV | BR(t̃$_1$→be/μ)>20% | ATLAS-CONF-2015-015
Other
Scalar charm, c̃→cχ̃$_1^0$ | 0 | 2 c | Yes | 20.3 | 510 GeV | m(χ̃$_1^0$)<200 GeV | 1501.01325
*Only a selection of the available mass limits on new states or phenomena is shown.
10^{-1}
1
Mass scale [TeV]

Even when we abandon the naturalness, still there are some indications that SUSY may not be too far away from the weak scale.

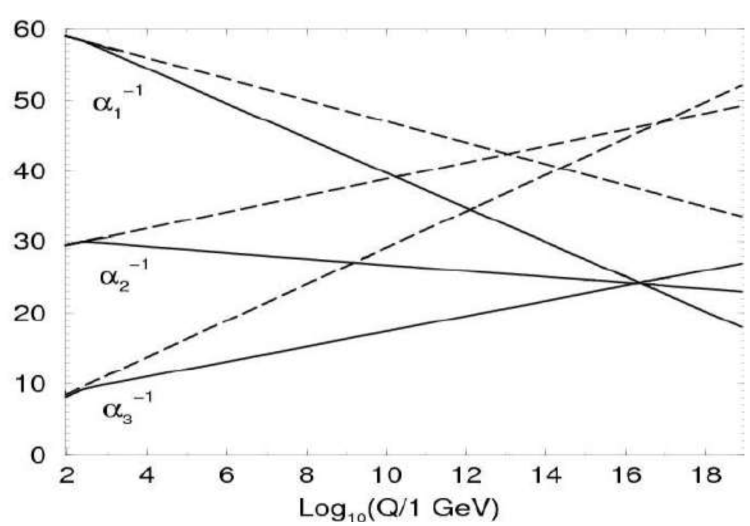
* Higgs mass = 125 GeV: $$m_h^2 = M_Z^2 \cos^2 2\beta + \frac{3 y_t^2 m_t^2}{4\pi^2} \ln\left(\frac{m_{\rm stop}}{m_t}\right) + \ldots$$

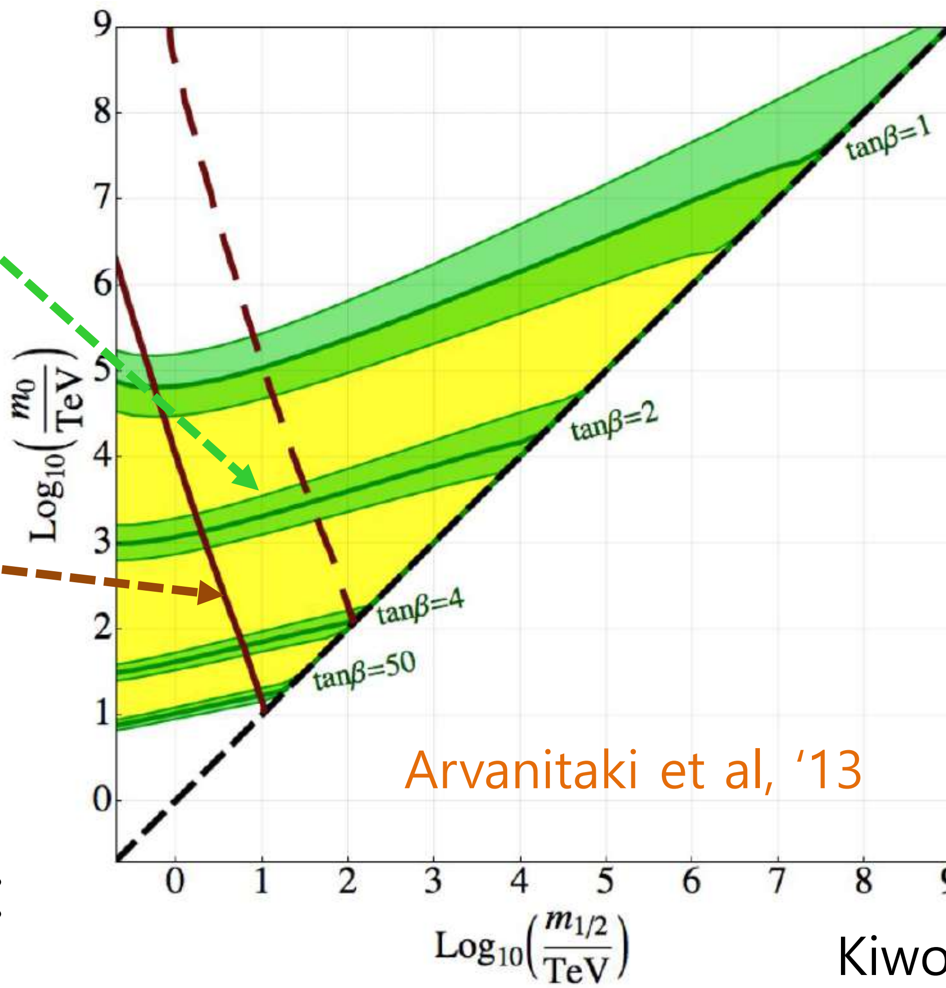


➔ squark and slepton masses:

m_0 < 1000 TeV for $\tan\beta$ > 2

* Gauge coupling unification:





➔ Higgsino and gaugino masses:

$m_{1/2}$ < 10 TeV

Kiwoon Choi

(ICHEP 2016, Chicago)

Future SUSY Searches

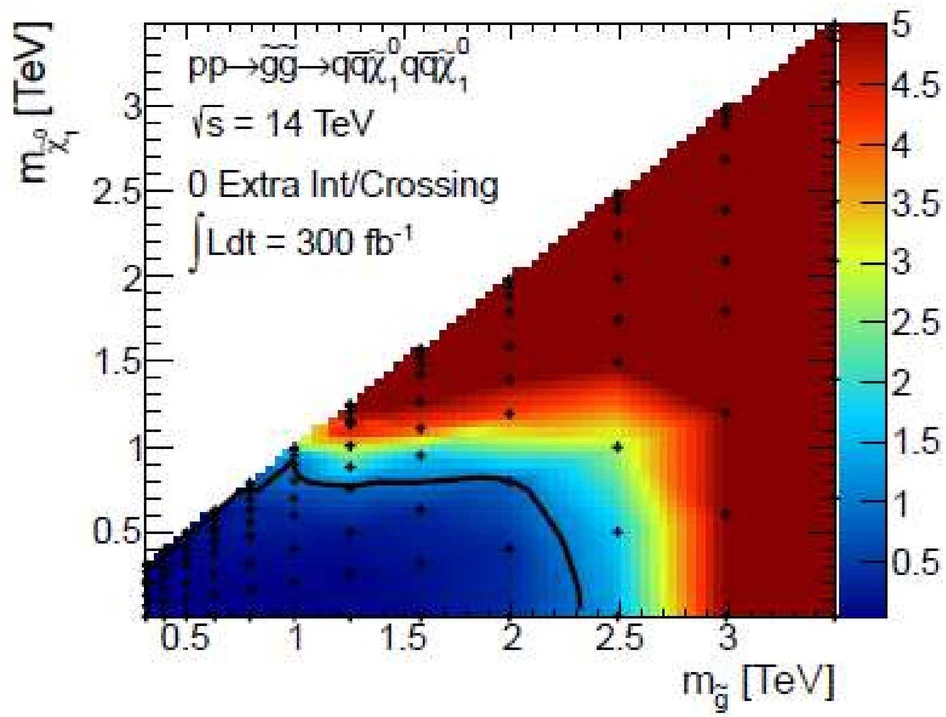
SUSY is certainly a compelling candidates of BSM physics, so we should keep searching for her without leaving any stone unturned.

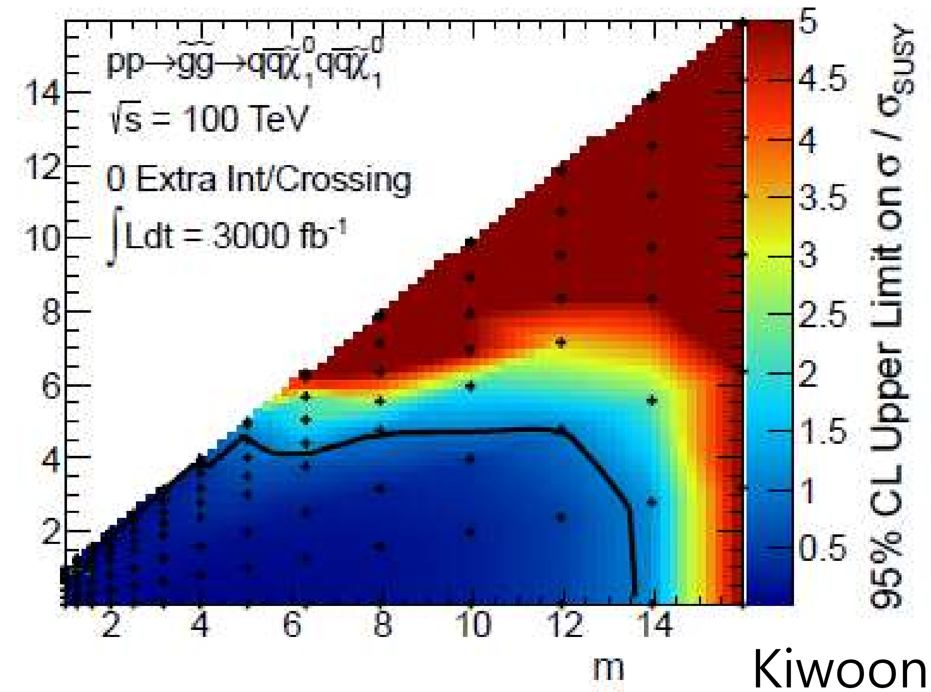
* Taking the gauge coupling unification seriously, SUSY may have some chance to be seen at LHC, and a good chance at the FCC:

High luminosity LHC

Cohen et al, '13

100 TeV collider





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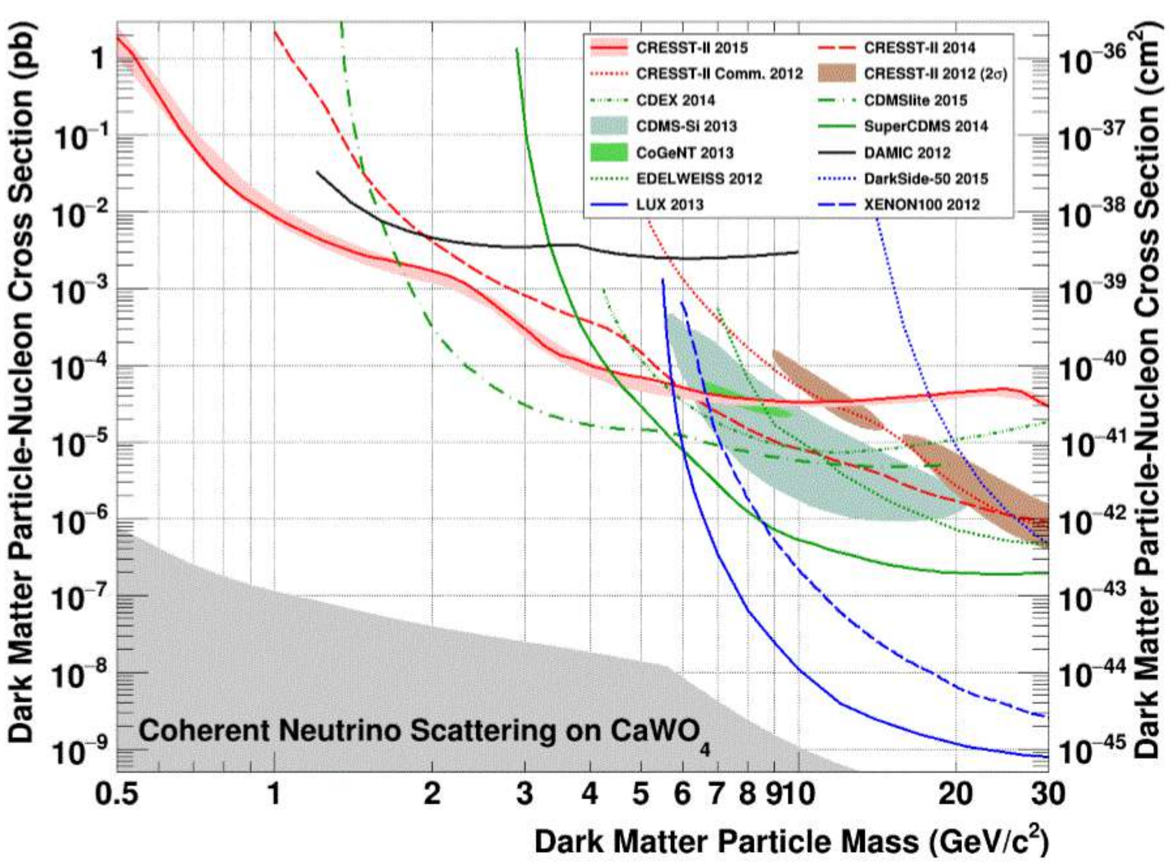
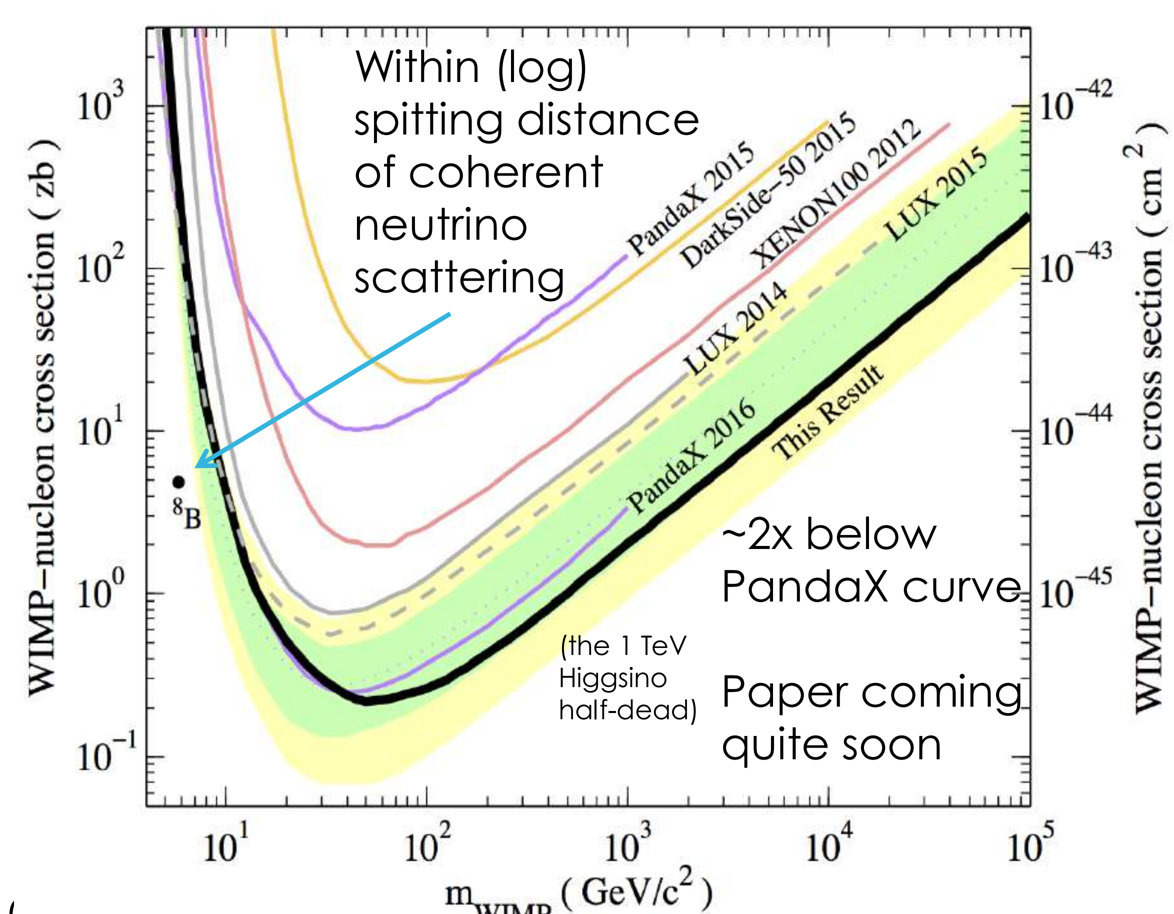
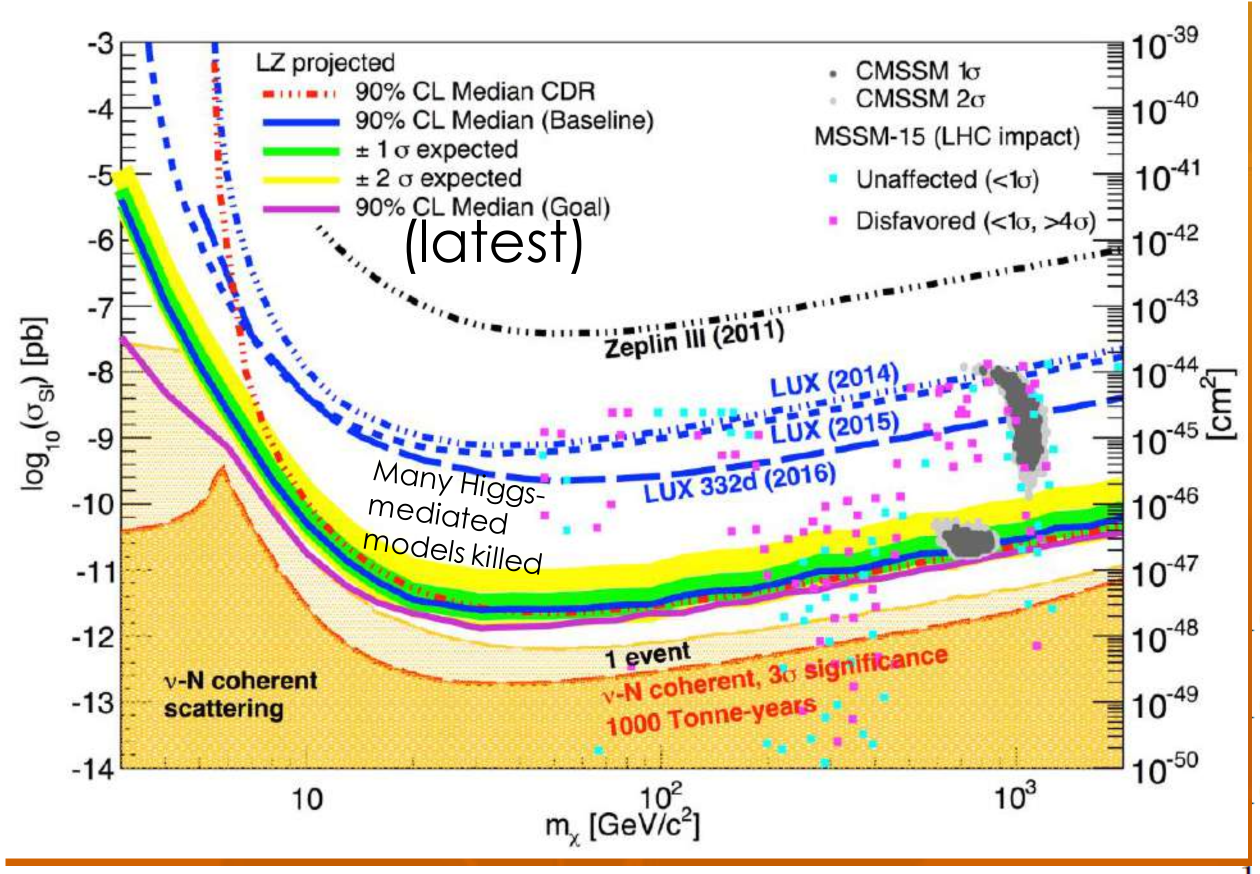
Dark Matter Searches



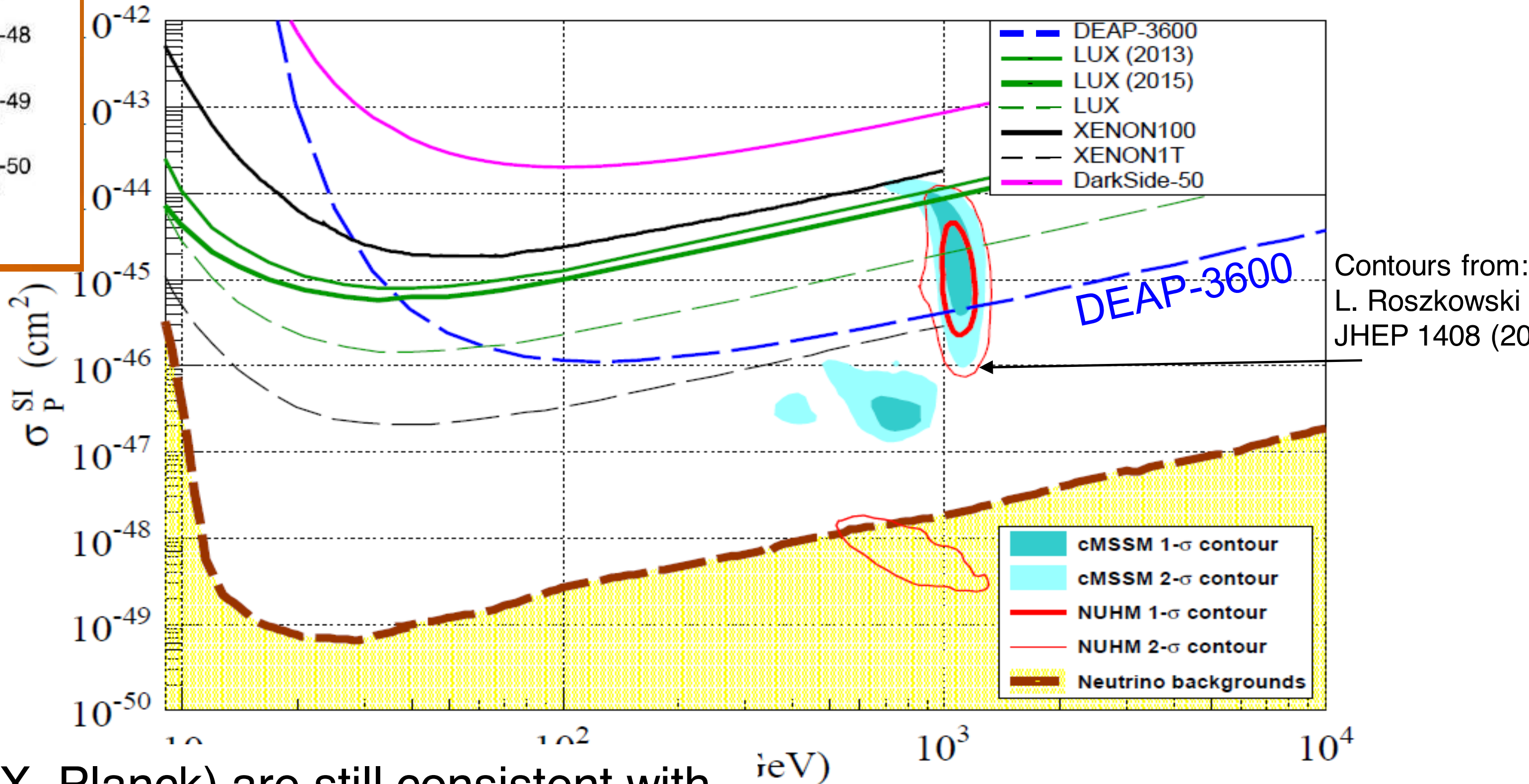
CRESST-II



Future DM Searches



Physics reach

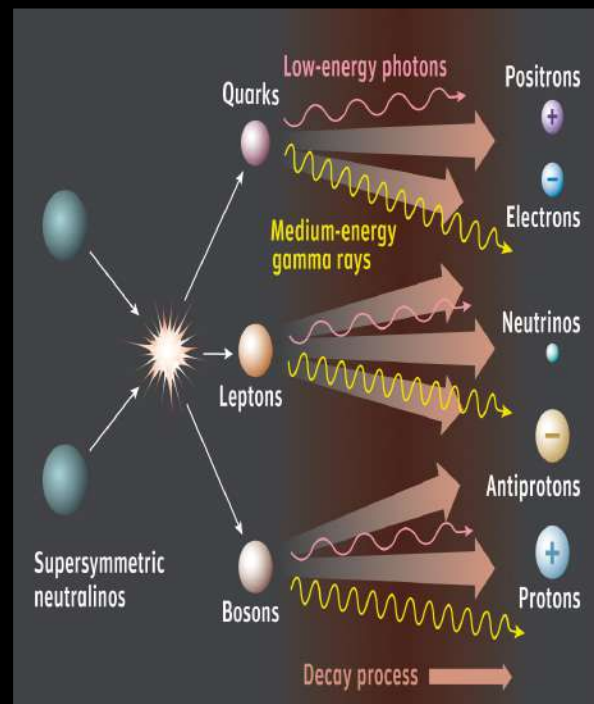


- All available experimental data combined (LHC, LUX, Planck) are still consistent with even the simplest versions of SUSY (cMSSM, NUHM)
- Remaining parameter space is directly probed by direct WIMP searches with tonne scale detectors: DEAP-3600, XENON1T, LUX/LZ
- Complementarity with LHC (cMSSM/NUHM are mostly out of reach of the 14 TeV run!)

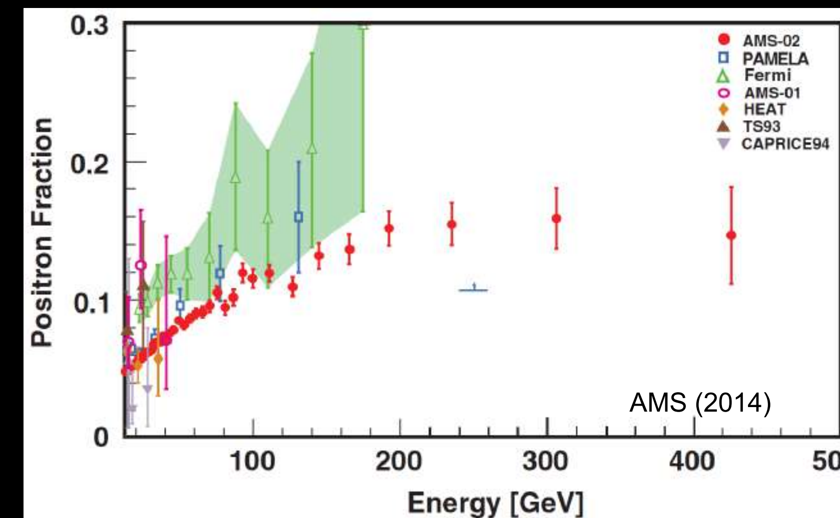
Indirect Detection of DM

INDIRECT DETECTION

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

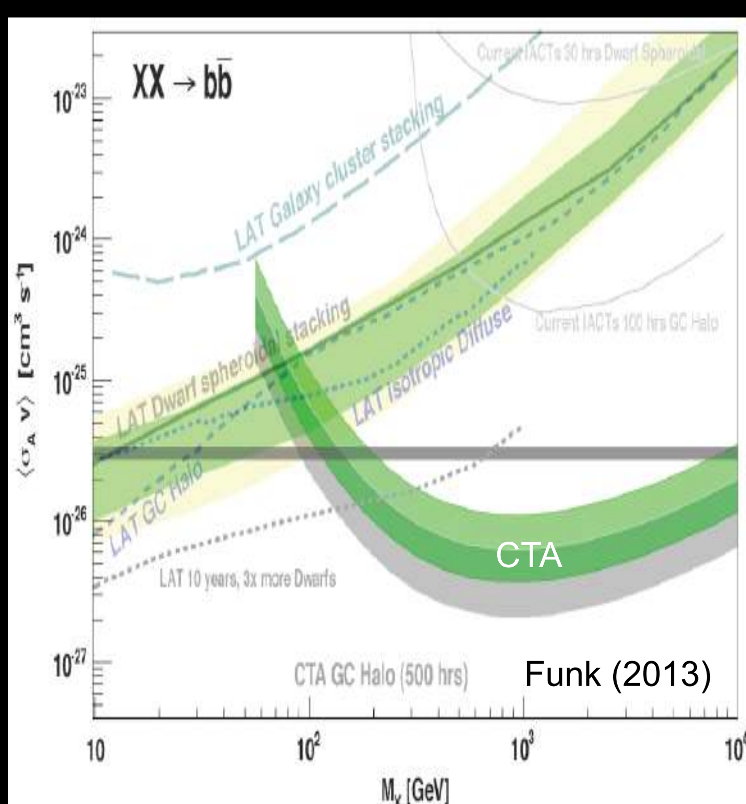


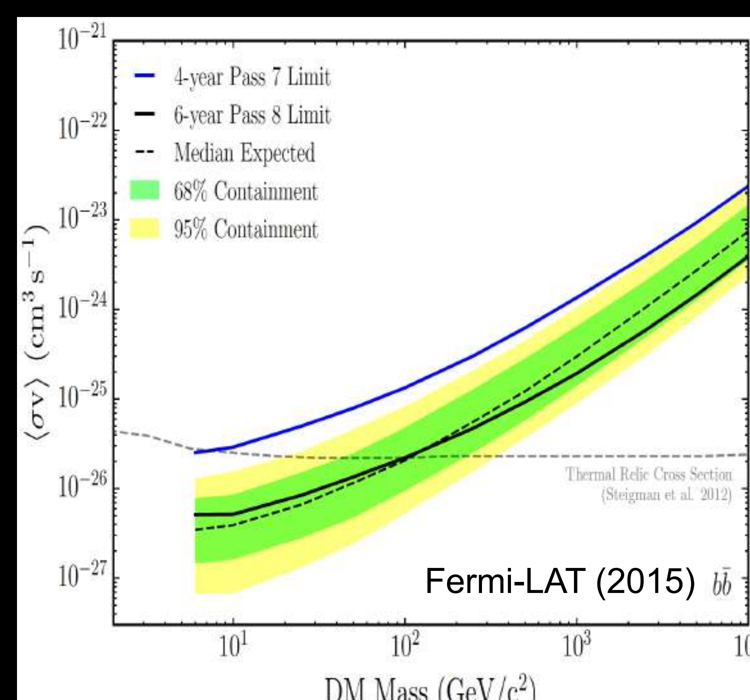
INDIRECT DM: POSITRON RESULTS



- 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

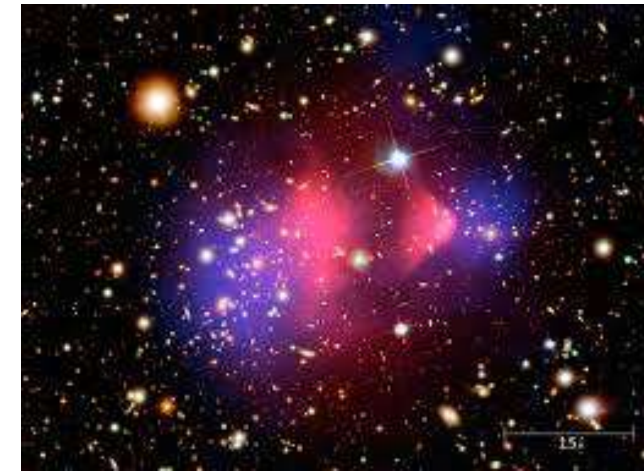




- Rapid improvements in recent years, Fermi-LAT now excludes WIMP makes up to ~100 GeV for certain annihilation channels
  - The future is the Cherenkov Telescope Array, which will extend the reach by two orders in mass up to masses

    ~ 10 TeV

Dark Matter/New Physics



The Dark Matter is made of:

- Macro objects – Not seen
- New particles – right heavy neutrino
  - axion (axino) — not favorable but possible
  - neutralino — might be invisible (?)
  - sneutrino — detectable in 3 spheres
  - gravitino — less theory favorable
  - heavy photon — might be undetectable (?)
  - heavy pseudo-goldstone — possible, but not related to the other models
  - light sterile higgs

Not from the SM: neutralino, sneutrino, gravitino, heavy photon, heavy pseudo-goldstone, light sterile higgs

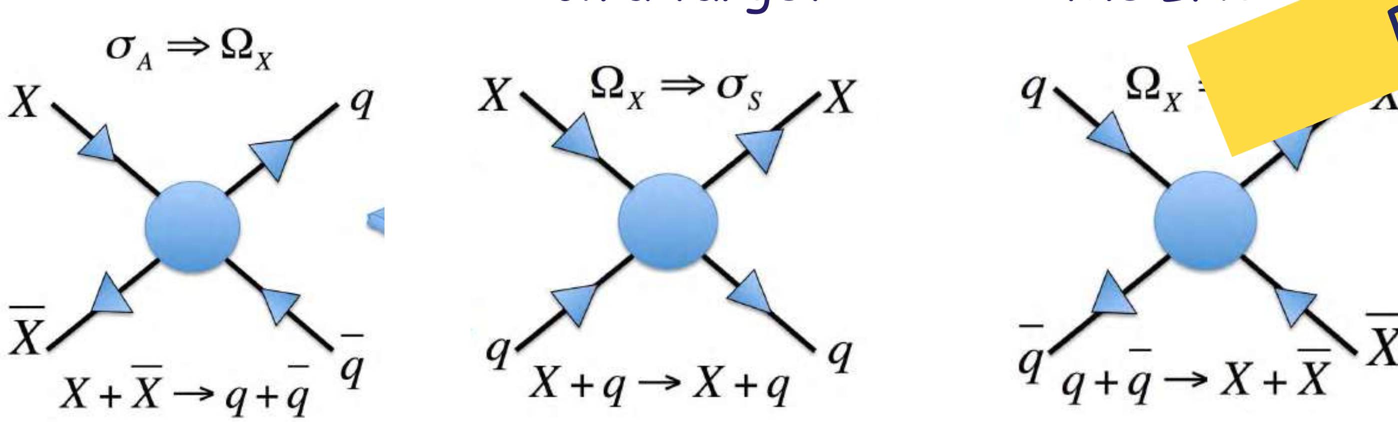
mSUGRA

WIMP is our chance !

But we have to look elsewhere !

WIMP

Annihilation in the halo	Scattering on a target	Creation at the LHC

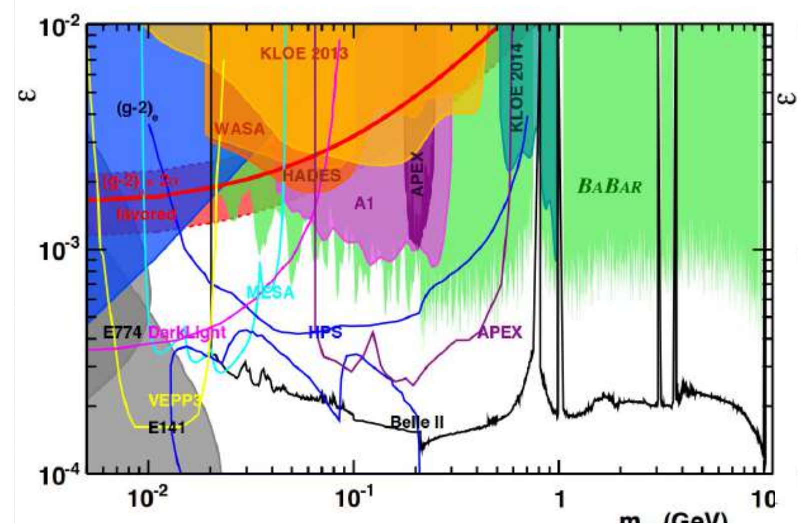


Dark Matter/New Physics

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

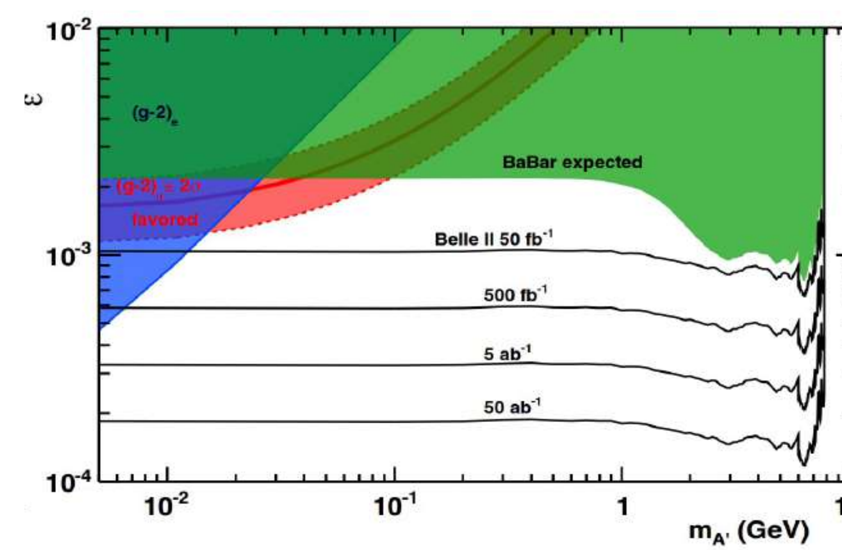
$e^+e^- \to \gamma A' \to \gamma e^+e^-, \gamma\mu^+\mu^-$, *prompt*



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.

Neutrino Physics

Long Baseline Experiments

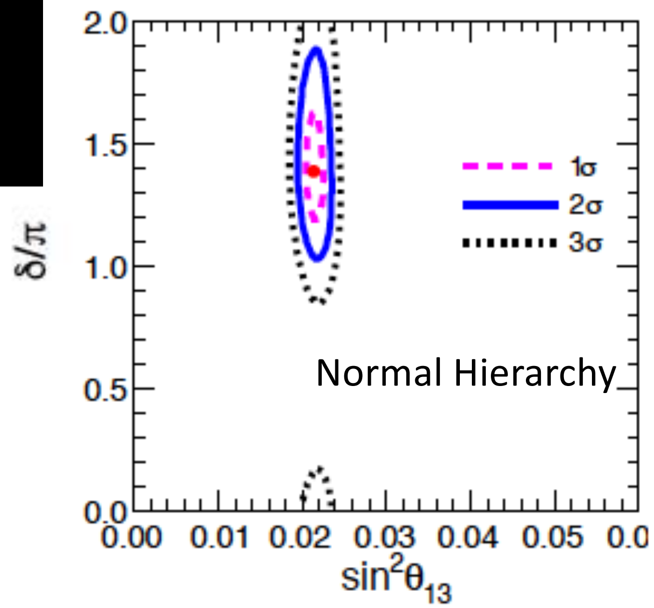
Long baseline oscillation experiments:
an international campaign to test the
3-flavor paradigm, measure CP violation and
go beyond.

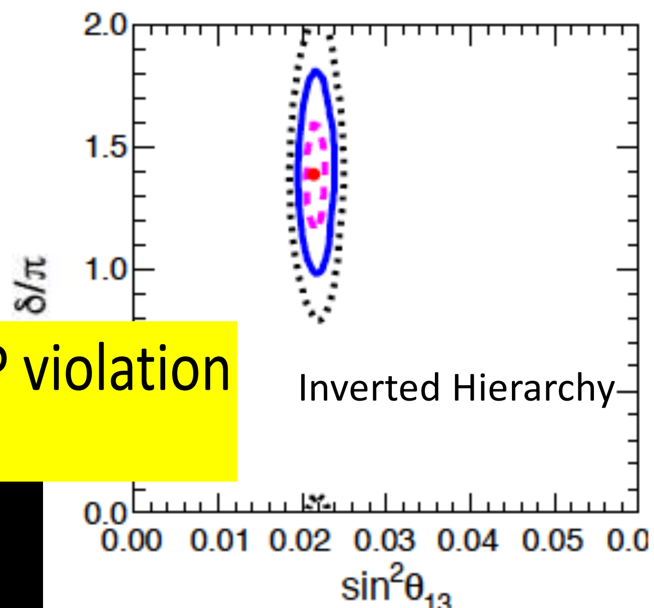
Generation 2 expts

T2K NOvA

By combining with SK in a global fit
Marrone @ Neutrino 2016

CP conservation excluded at >2 σ

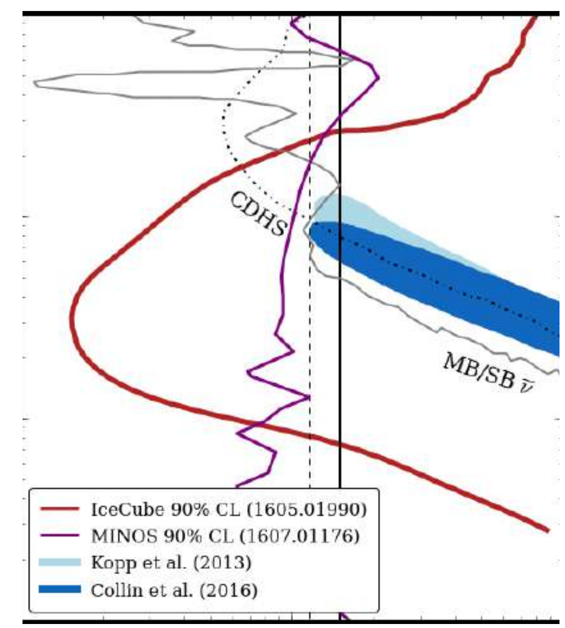


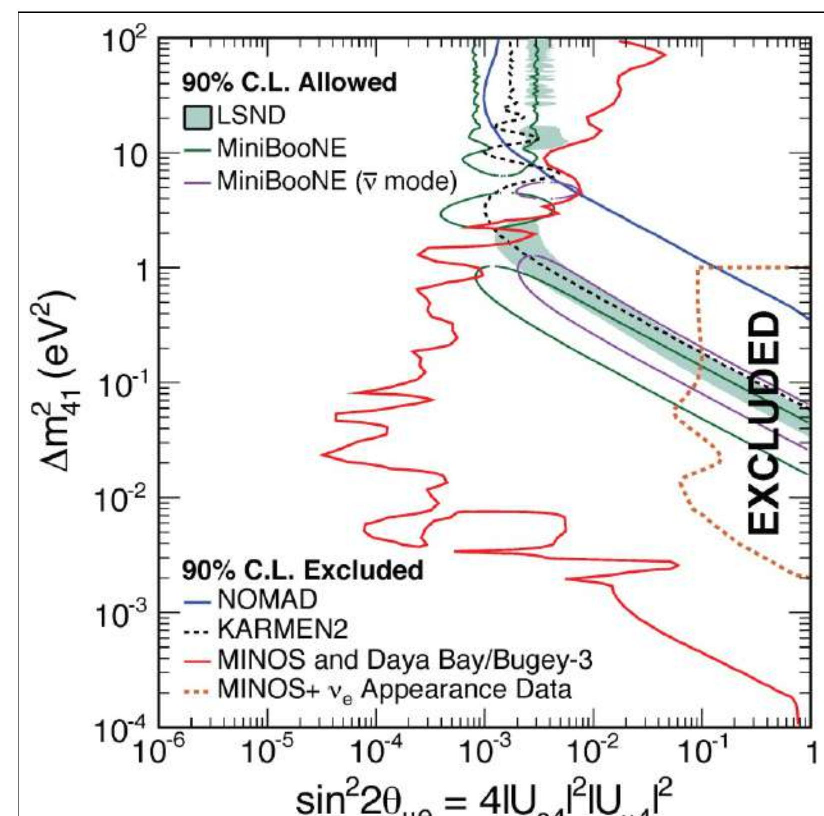


For the first time robust indication of CP violation in the leptonic sector

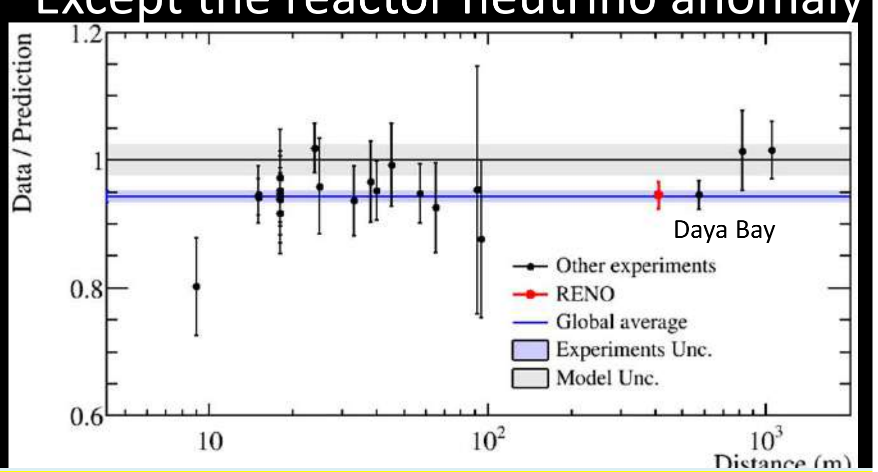
ICHEP 2016 -- I. Shipsey

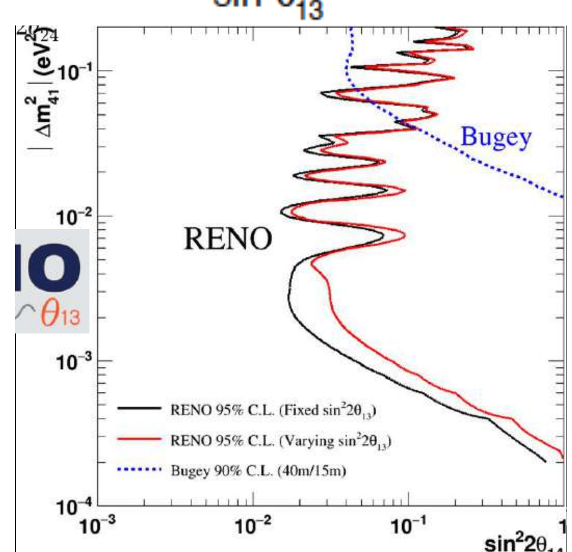
No evidence for sterile neutrinos





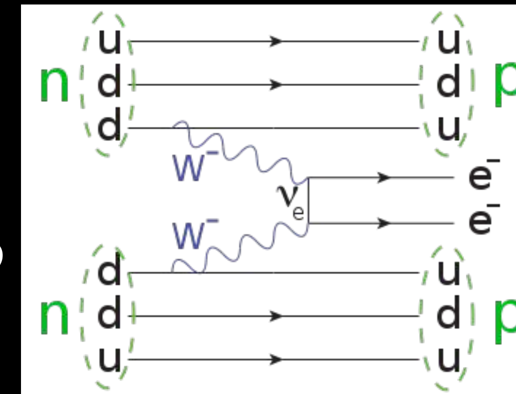
Except the reactor neutrino anomaly

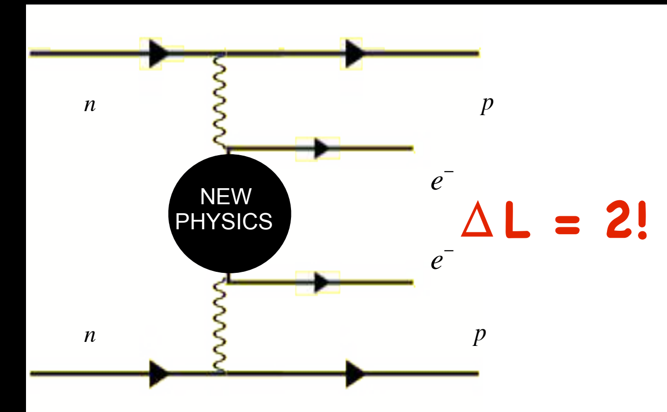




$0\beta\beta\nu$

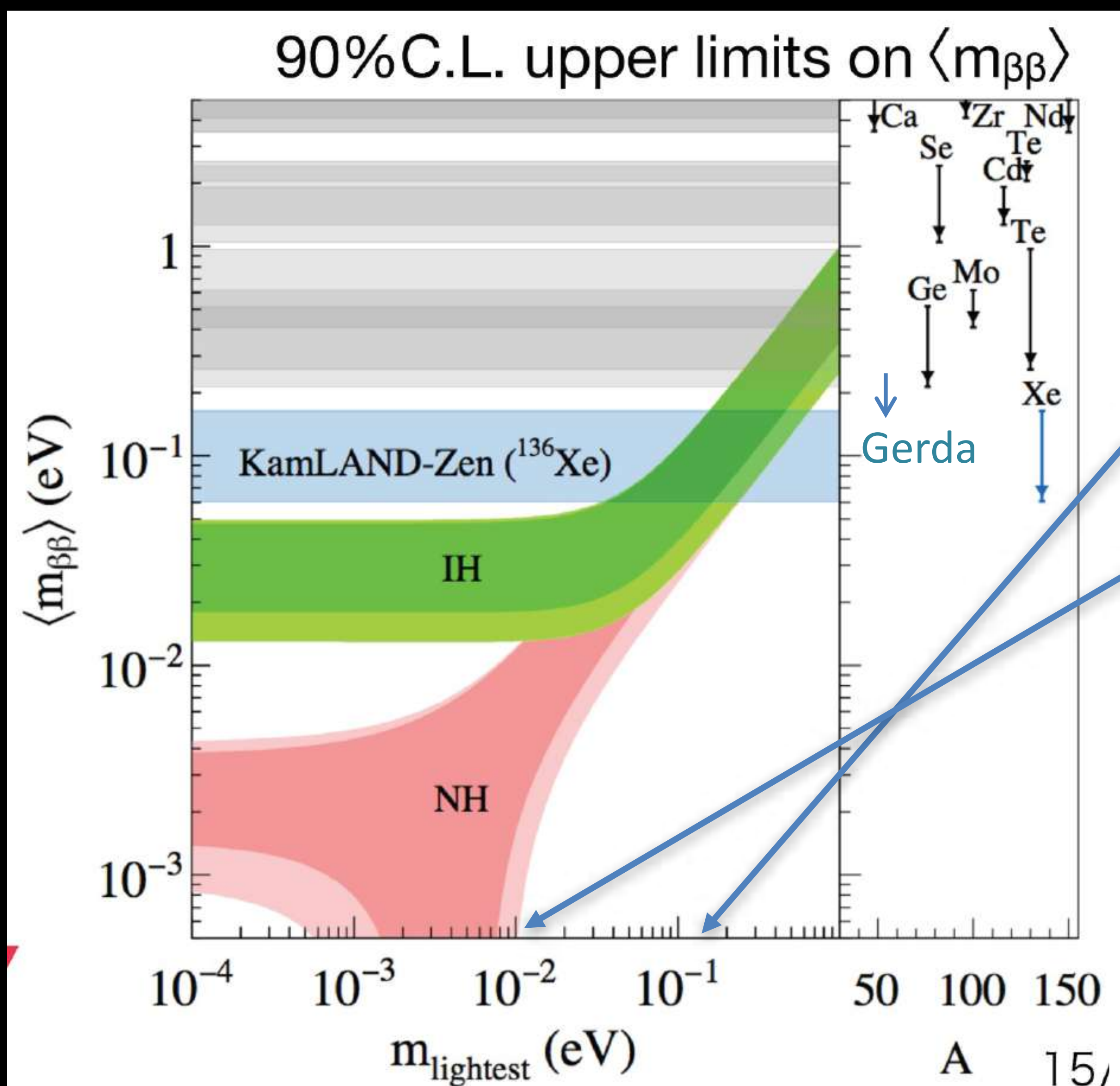
Is ν Dirac or Majorana?





$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot \langle m_{\beta\beta} \rangle^2$$

$$\langle m_{\beta\beta} \rangle^2 = |\sum_i U^2_{ei} \, m_{\nu i}|^2$$



knowledge of the neutrino mixing parameters provides a firm prediction for the range of values of the parameter $m_{\beta\beta}$ in both hierarchies (NH favored)

tritium expts m_e < 2 eV, -→ KATRIN < 0.2 eV.

From cosmology: Σ m < 0.23 eV (95% CL) In the next decade there are good prospects to reach, via multiple probes, a sensitivity at the level of Σ mi < 0.01 eV

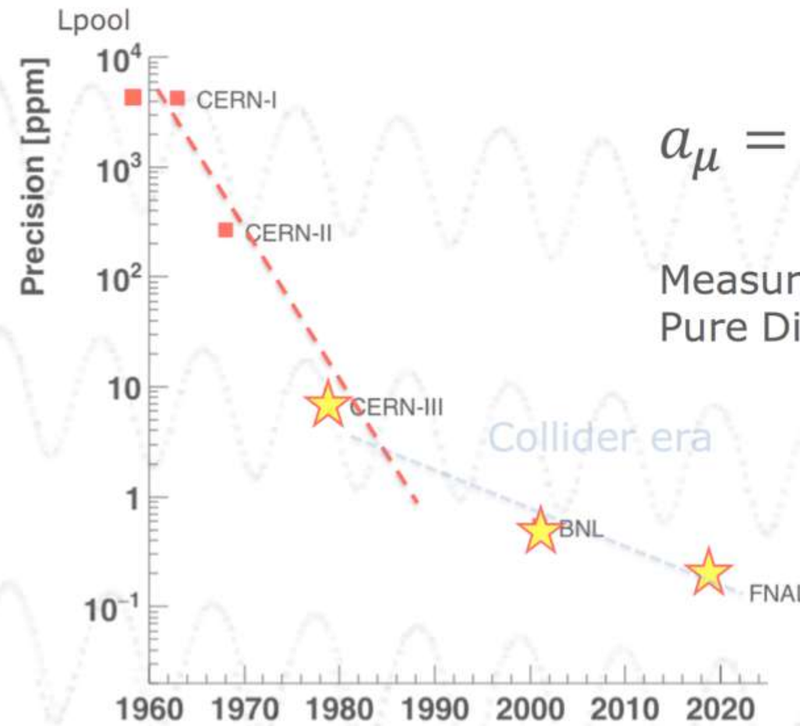
Therefore, it is timely and compelling to embark on a renewed discovery quest to observe neutrinoless double beta decay.

g-2

Theory: 12,672 Feynman Diagrams

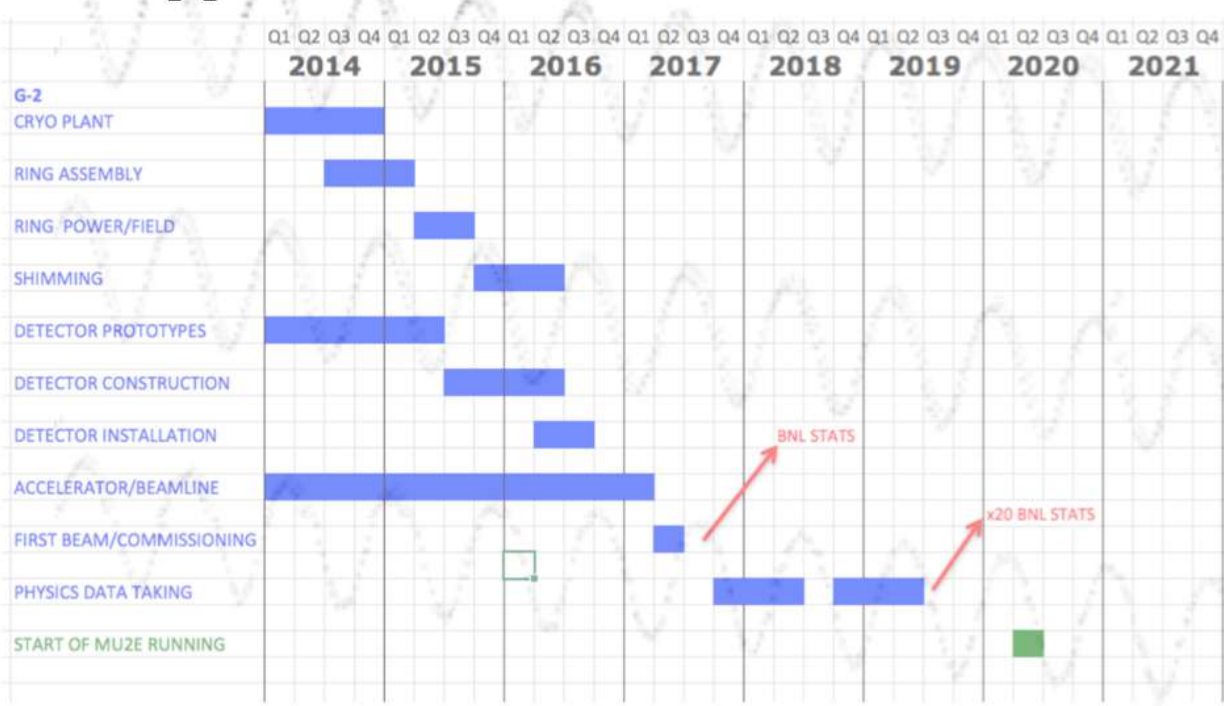
2.00231930436356 ± 0.0000000000154

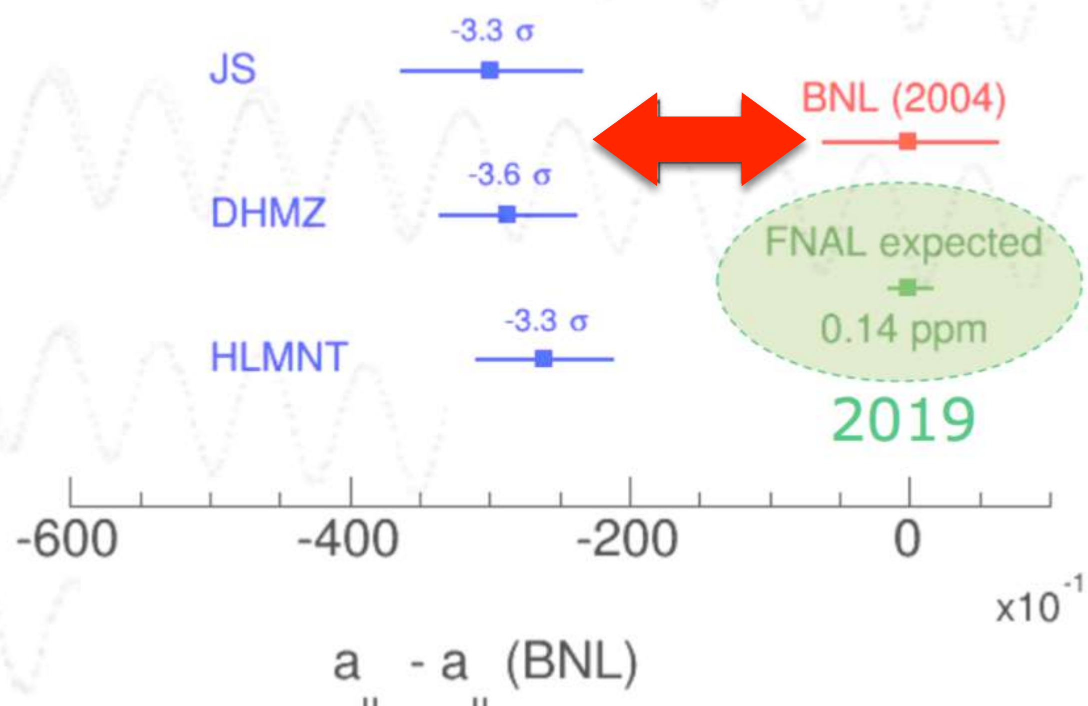
- Experiment construction on schedule and on budget.
- Improved experimental design.
- Improved simulaton.
- Aims to reduce error from 0.2ppm to 0.07ppm.



$$a_\mu = \frac{(g-2)}{2}$$

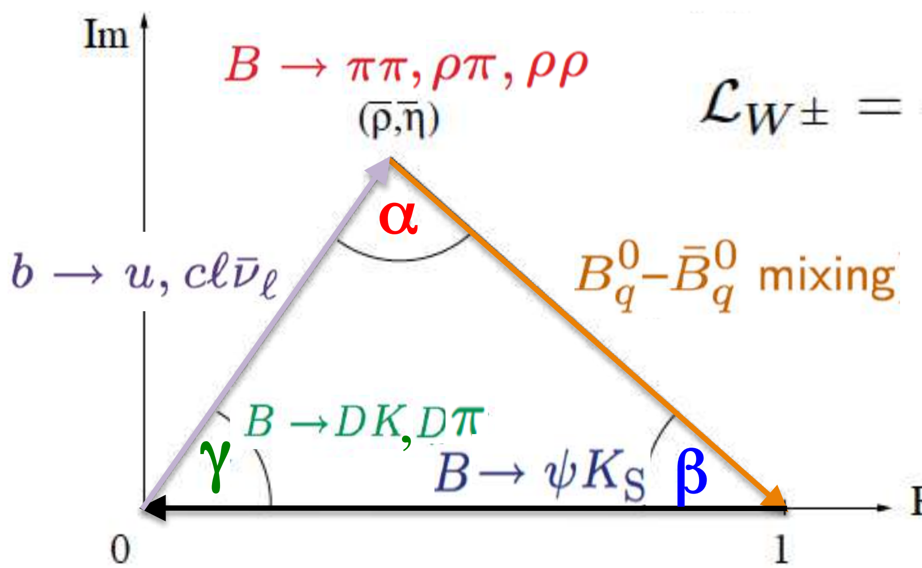
Measuring deviations from Pure Dirac prediction





The CKM Unitarity Triangle

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



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

From CKM matrix unitarity

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

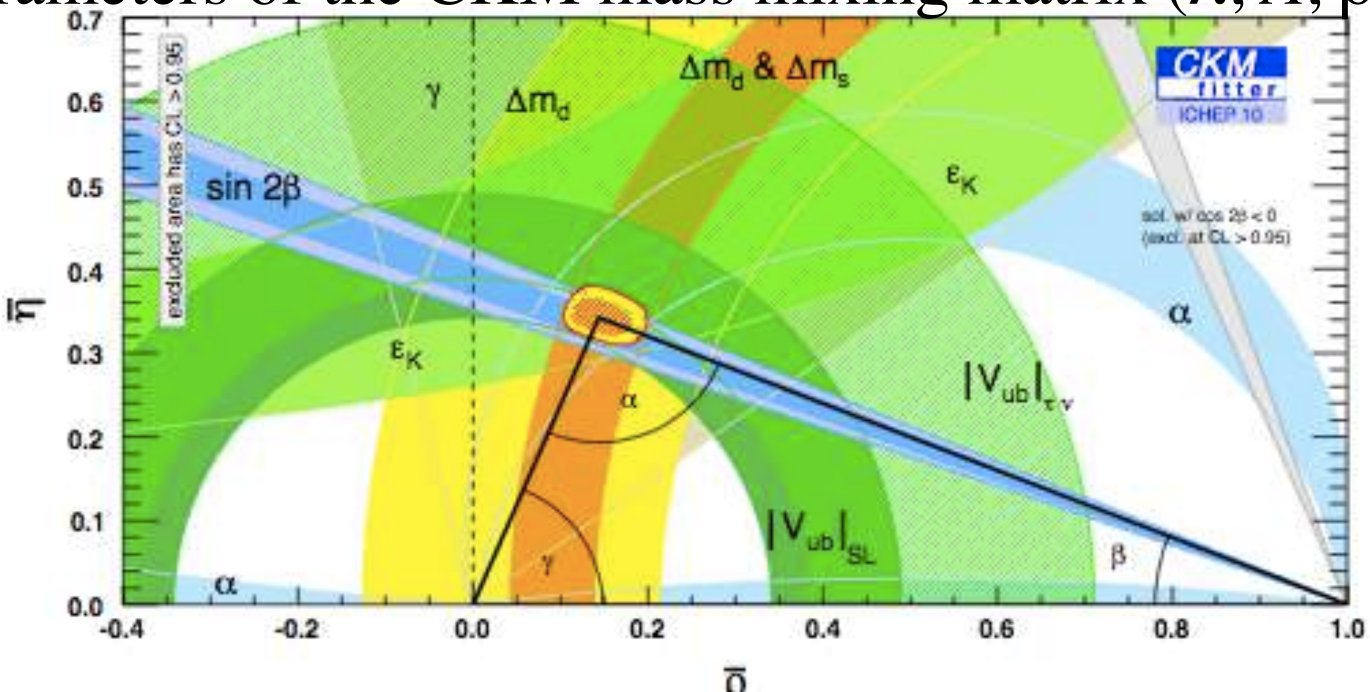
- UT defined by two parameters only → can be overconstrained
- The height (irreducible complex phase $\bar{\eta}$) controls the strength of *CP* violation in the Standard Model

2

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.

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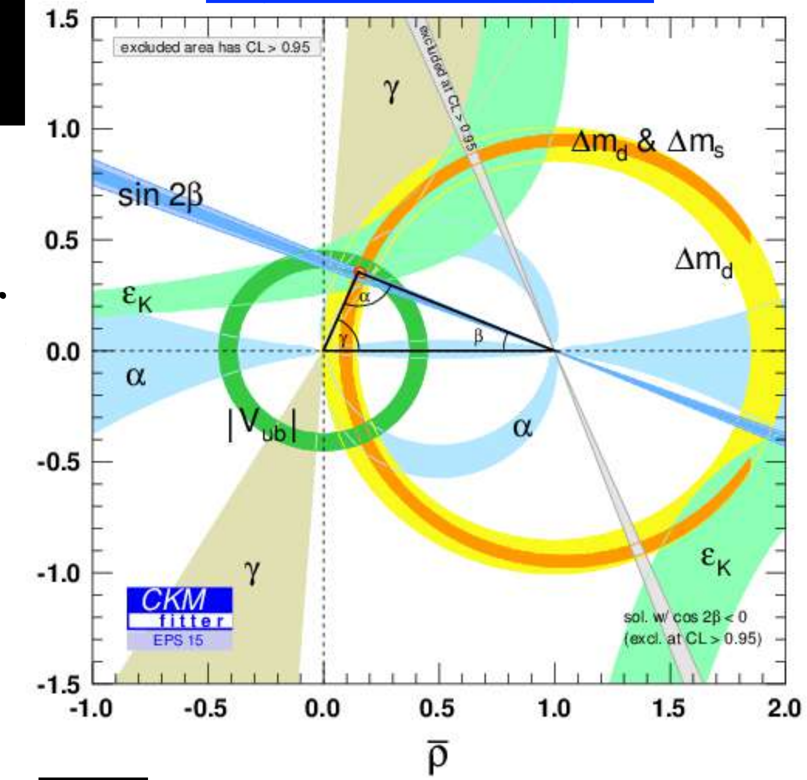
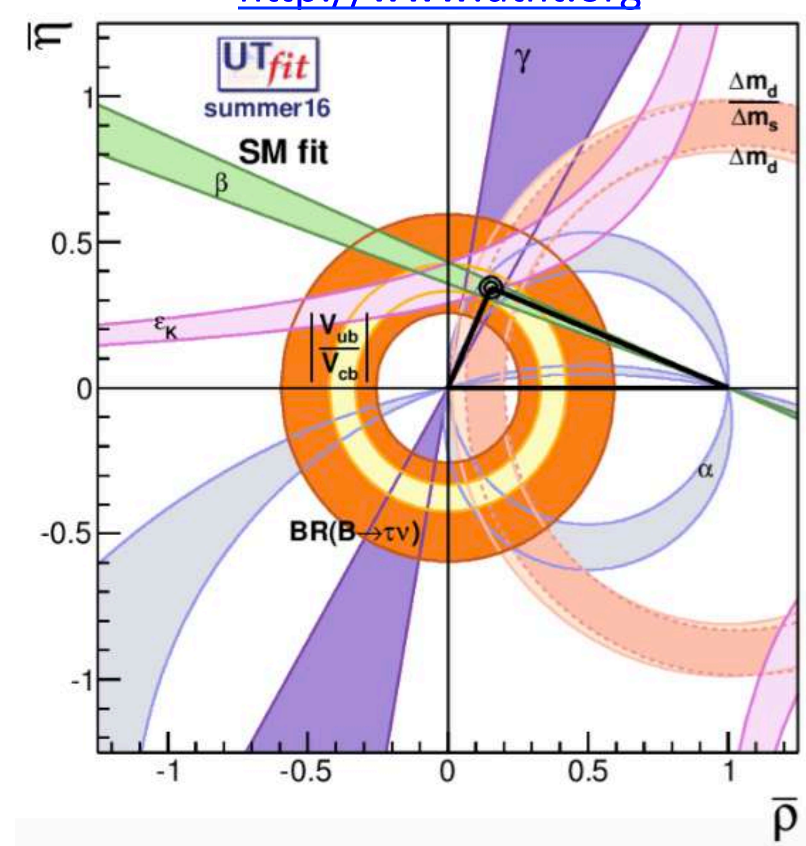
http://ckmfitter.in2p3.fr



2015->2016

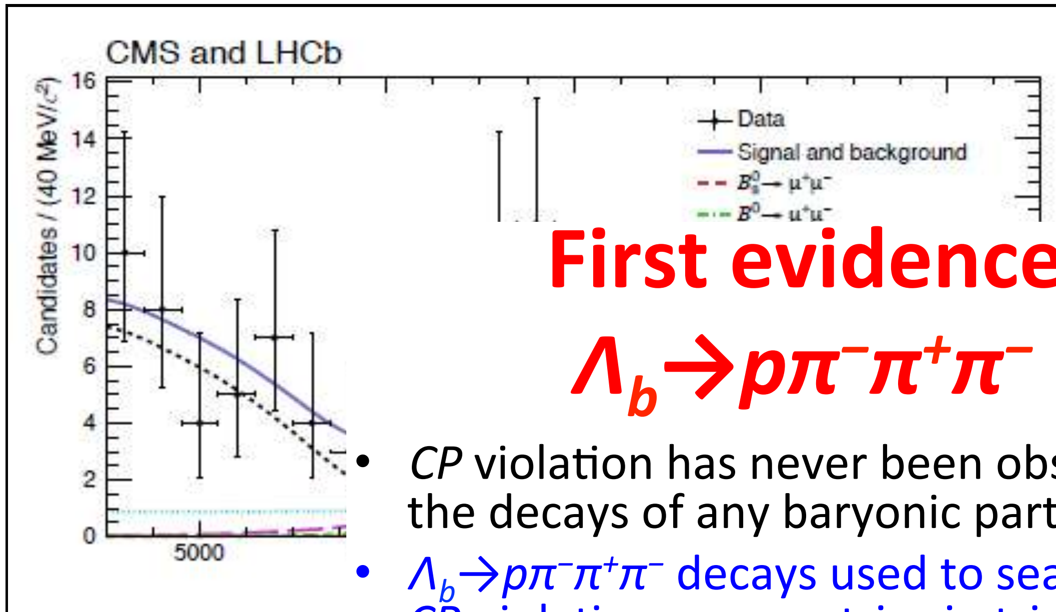
http://www.utfit.org



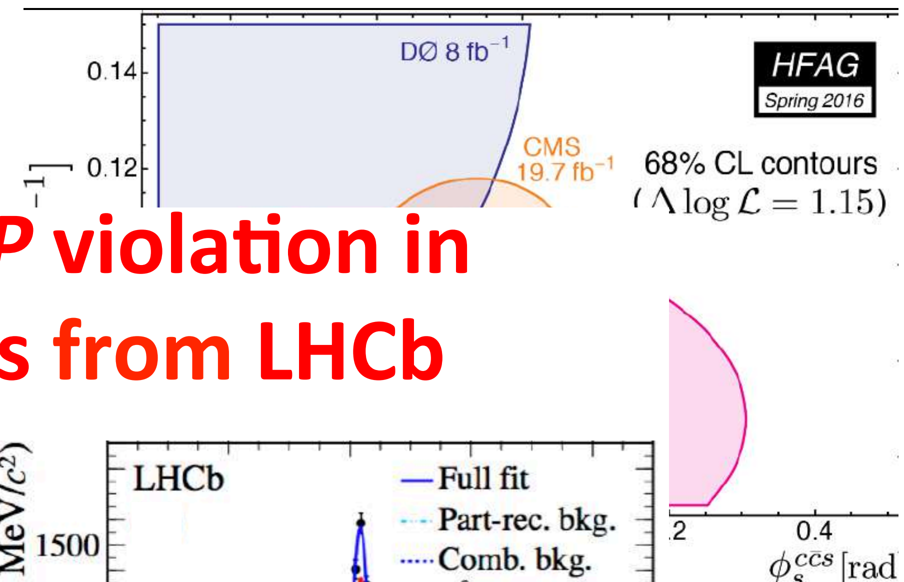
- Great success of the Standard Model CKM picture!
  - All of the measurements agree in a highly profound way
  - In the presence of relevant New Physics effects, the various contours would cross each other in a single point

Flavour physics at the LHC a great success, with run-1 delivering in all important topics

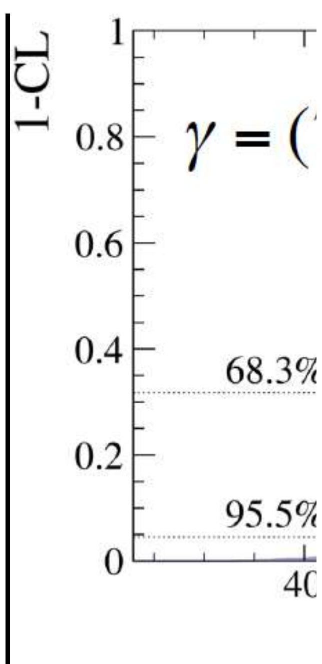
Observation of $B_s \to \mu\mu$



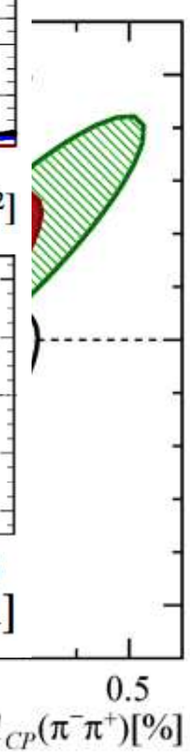
Precise studies of CPV in the B_s system



Great st... of unitar...

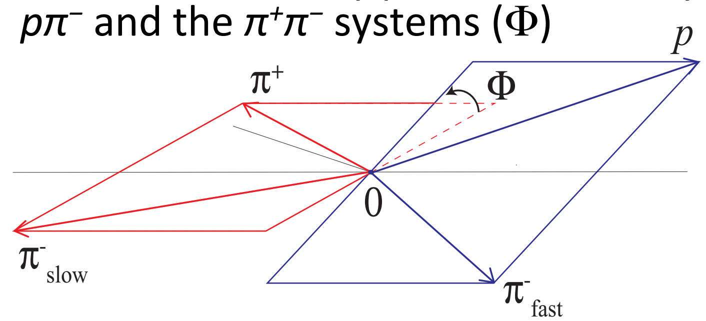


...h per mille precision

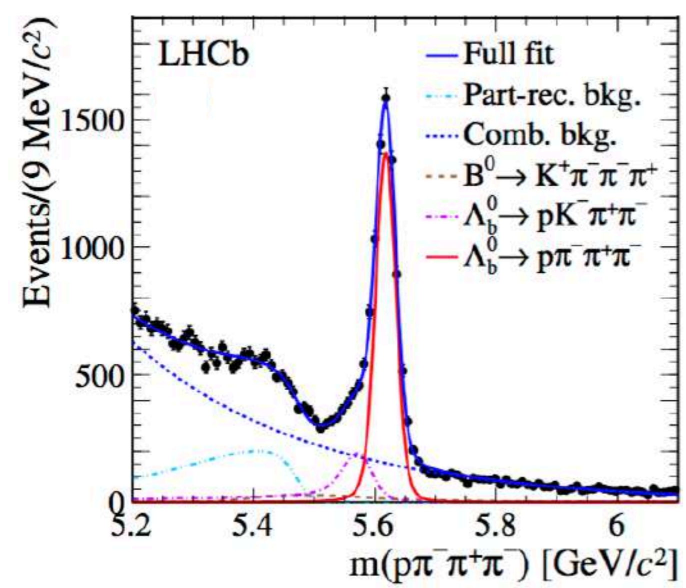


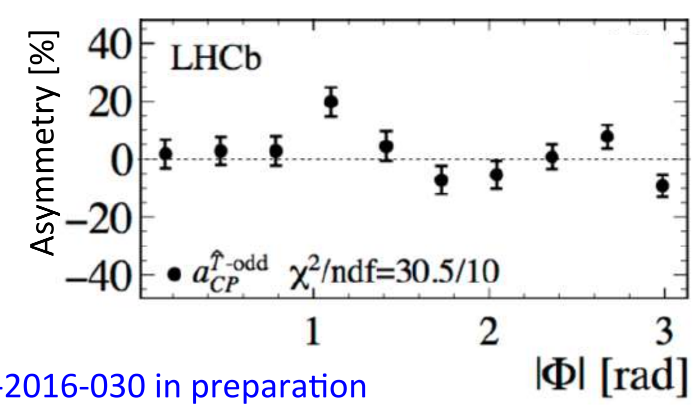
First evidence for *CP* violation in $\Lambda_b \to p\pi^-\pi^+\pi^-$ decays from LHCb

- *CP* violation has never been observed in the decays of any baryonic particle
- $\Lambda_b \to p\pi^-\pi^+\pi^-$ decays used to search for *CP*-violating asymmetries in triple products of final-state particle momenta
  - Local *CP*-violating effects studied as a function of the the relative orientation between the decay planes formed by the $p\pi^-$ and the $\pi^+\pi^-$ systems (Φ)



- An evidence for *CP* violation at the 3.3σ level is found
- This represents the first evidence of *CP* violation in the baryon sector



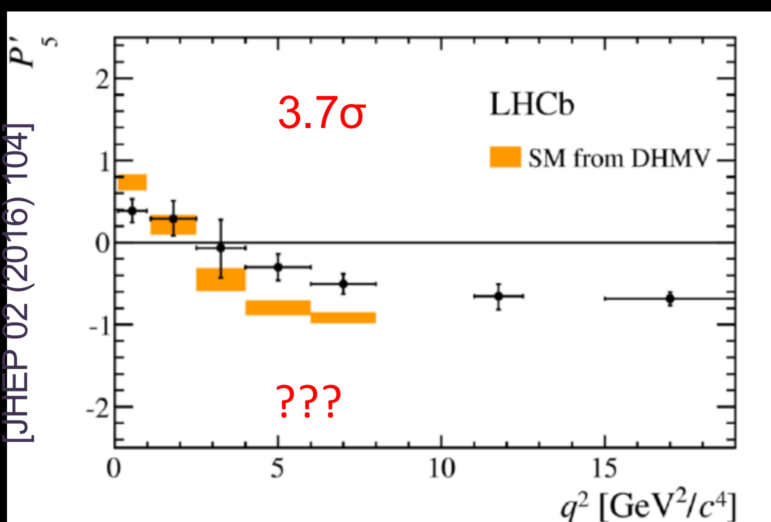


LHCb-PAPER-2016-030 in preparation

But some intriguing anomalies have emerged from LHC-b and the B-factories

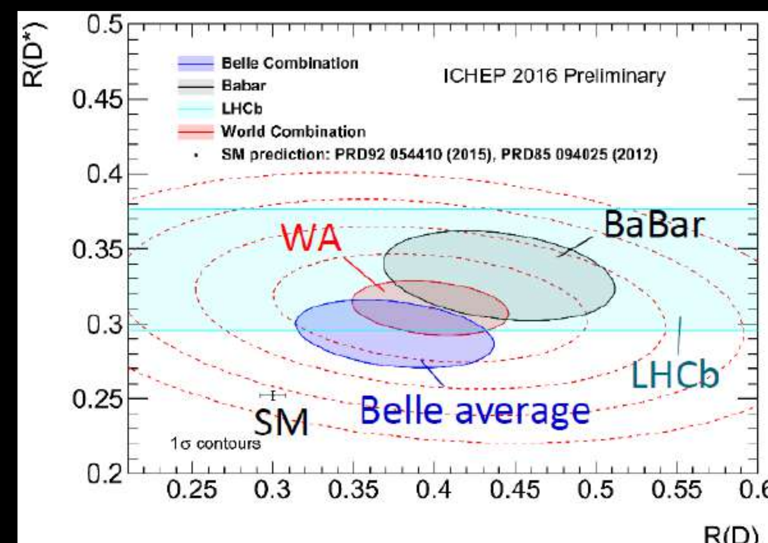
Anomalous behaviour
In b→sl+l- observables

$B^0 \to K^* \mu\mu$ P_5' vs q^2



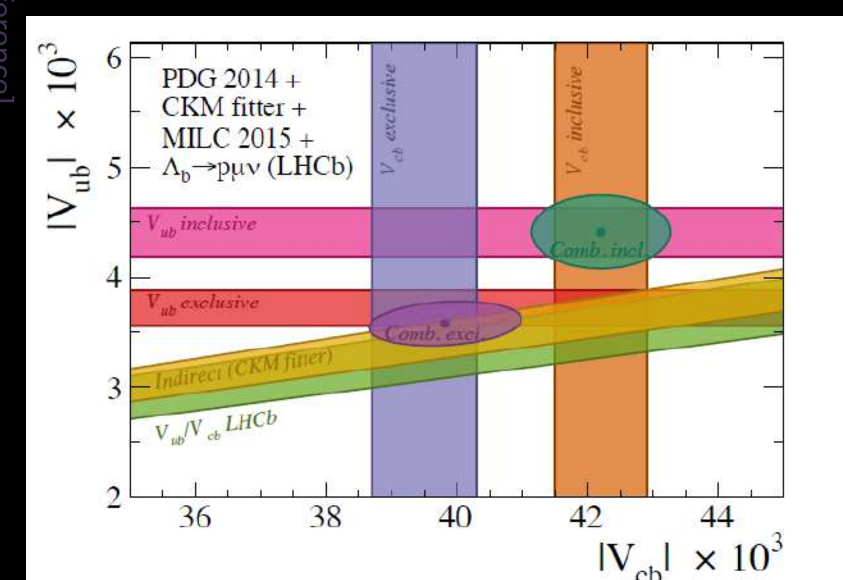
[JHEP 02 (2016) 104]

Hints of lepton universality violation in $B \to D^{(*)} l\nu$ …



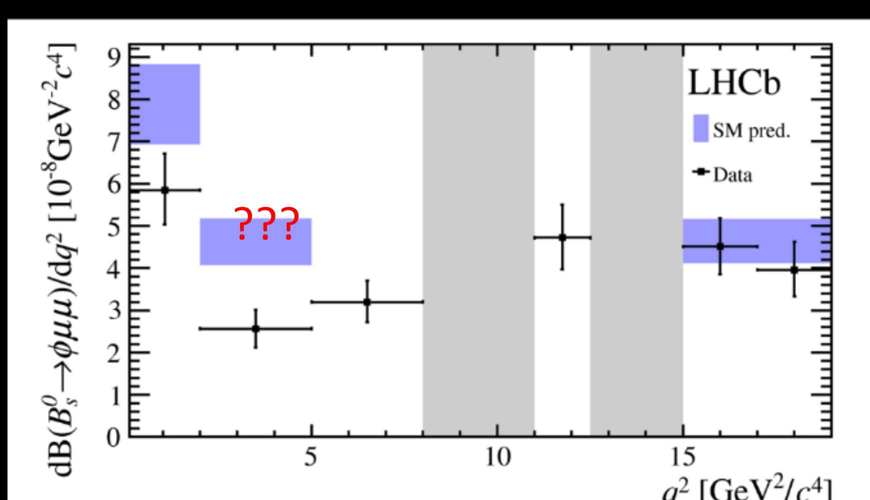
[Y. Sato, this conference]

And longstanding inconsistency In exclusive vs inclusive V_{ub} and V_{cb} determinations.

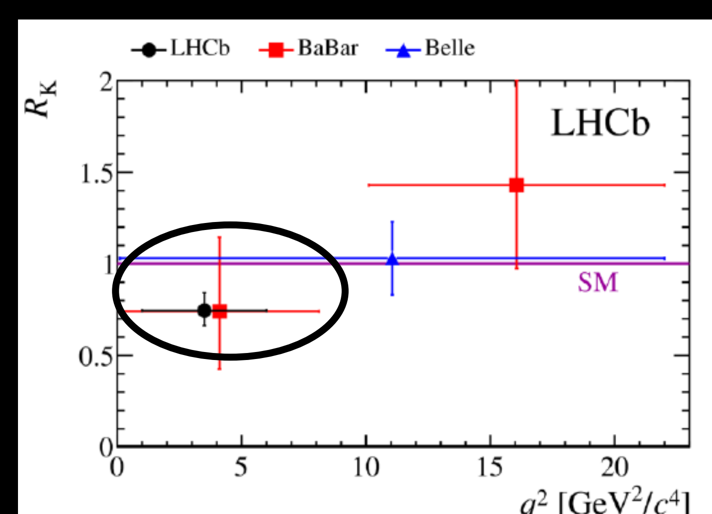


[JHEP 09 (2015) 179]

$B_s \to \phi\mu\mu$
differential BR vs q^2



…and in $B \to K l^+ l^-$

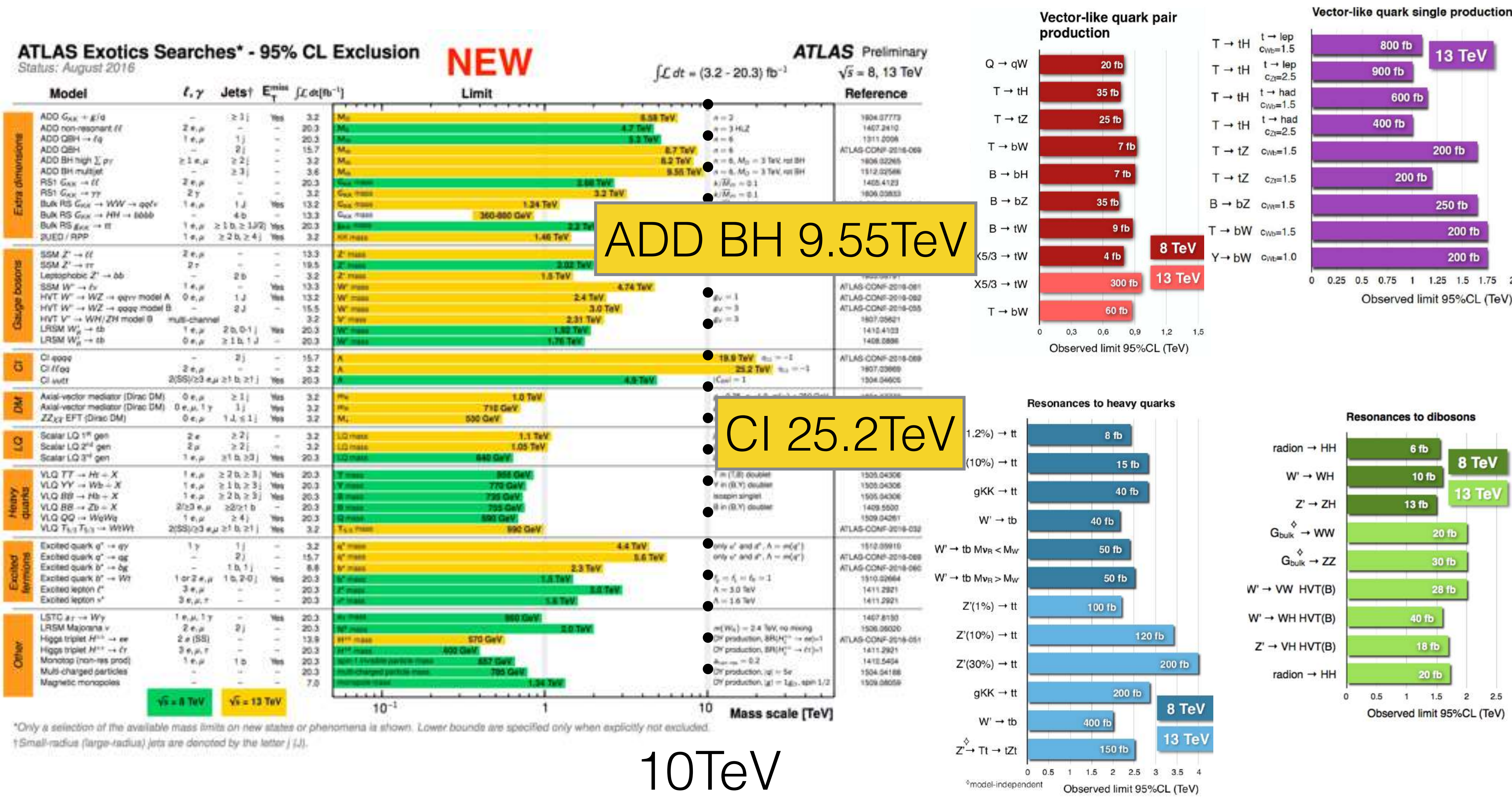


[PRL 113 (2014) 151601]

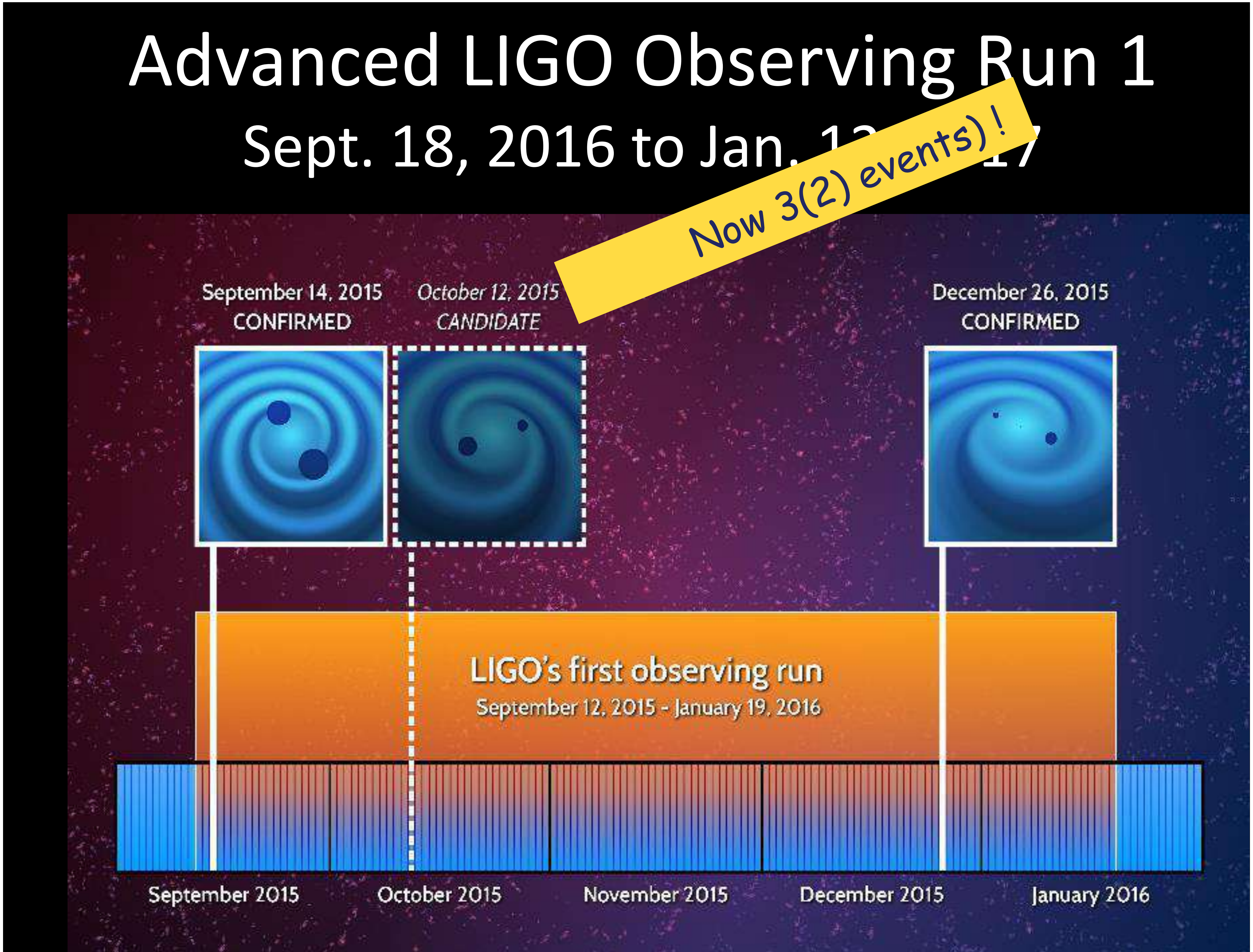
The quest for indirect discovery of new physics requires patterns of deviations to exist

Exotics … What to say?

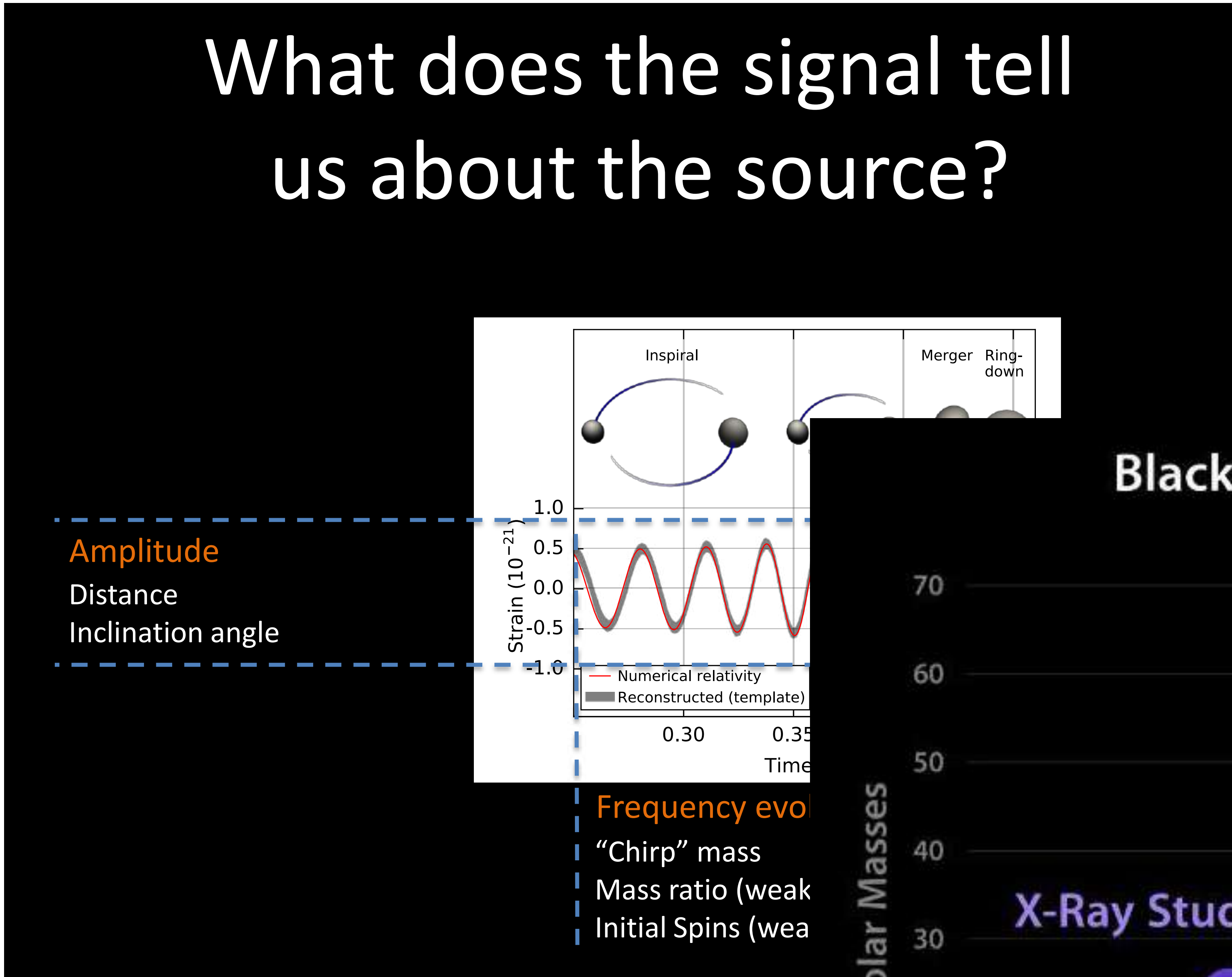
- Up to 25% mass limit increase by extending 2015 to 2016
- ~50% of the analyses updated to Run2

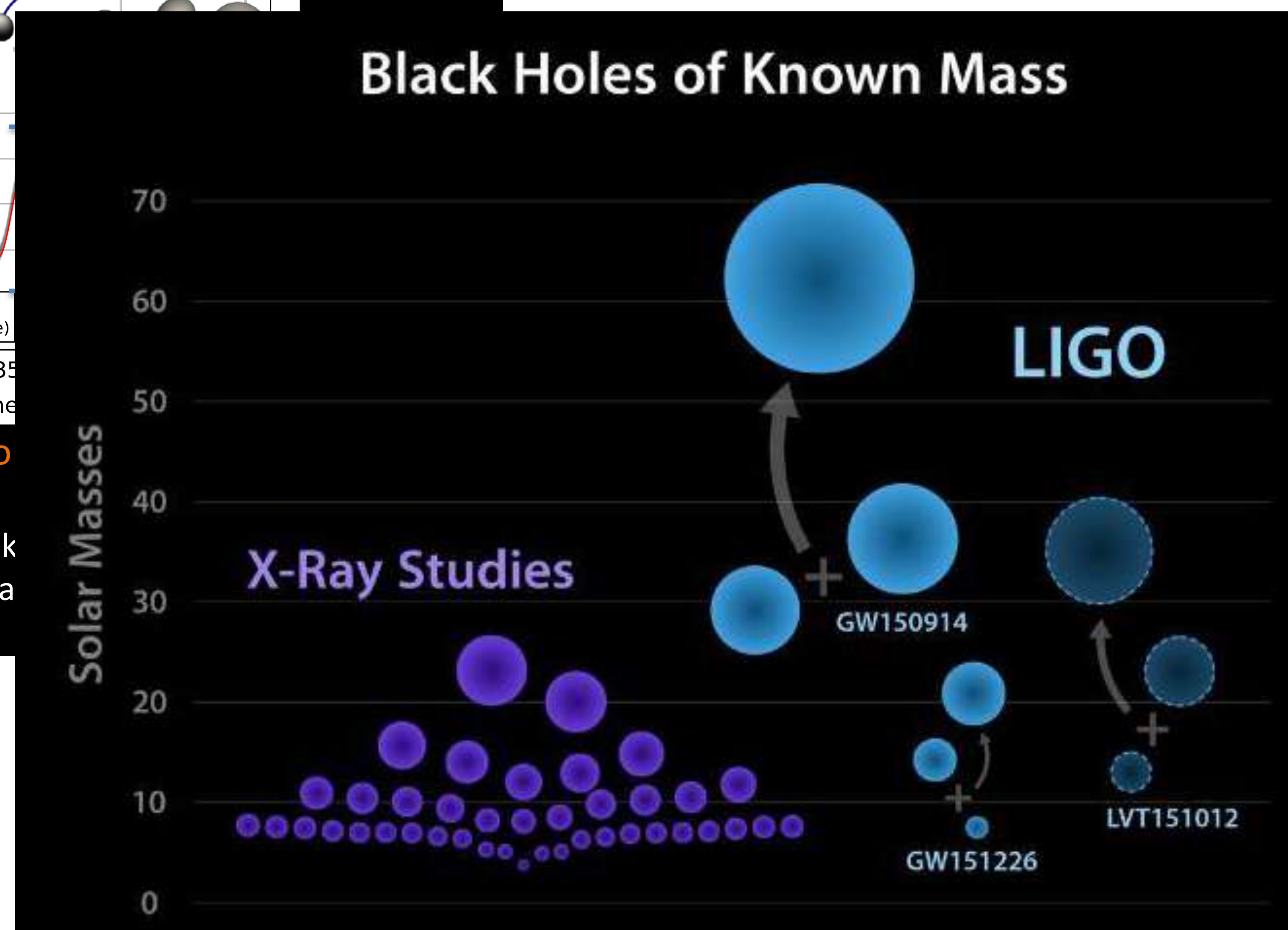


Gravitational Waves! Amazing!



Gravitational Waves





Probing Dark Energy

Equation of state

$$p = w\rho$$

pressure density

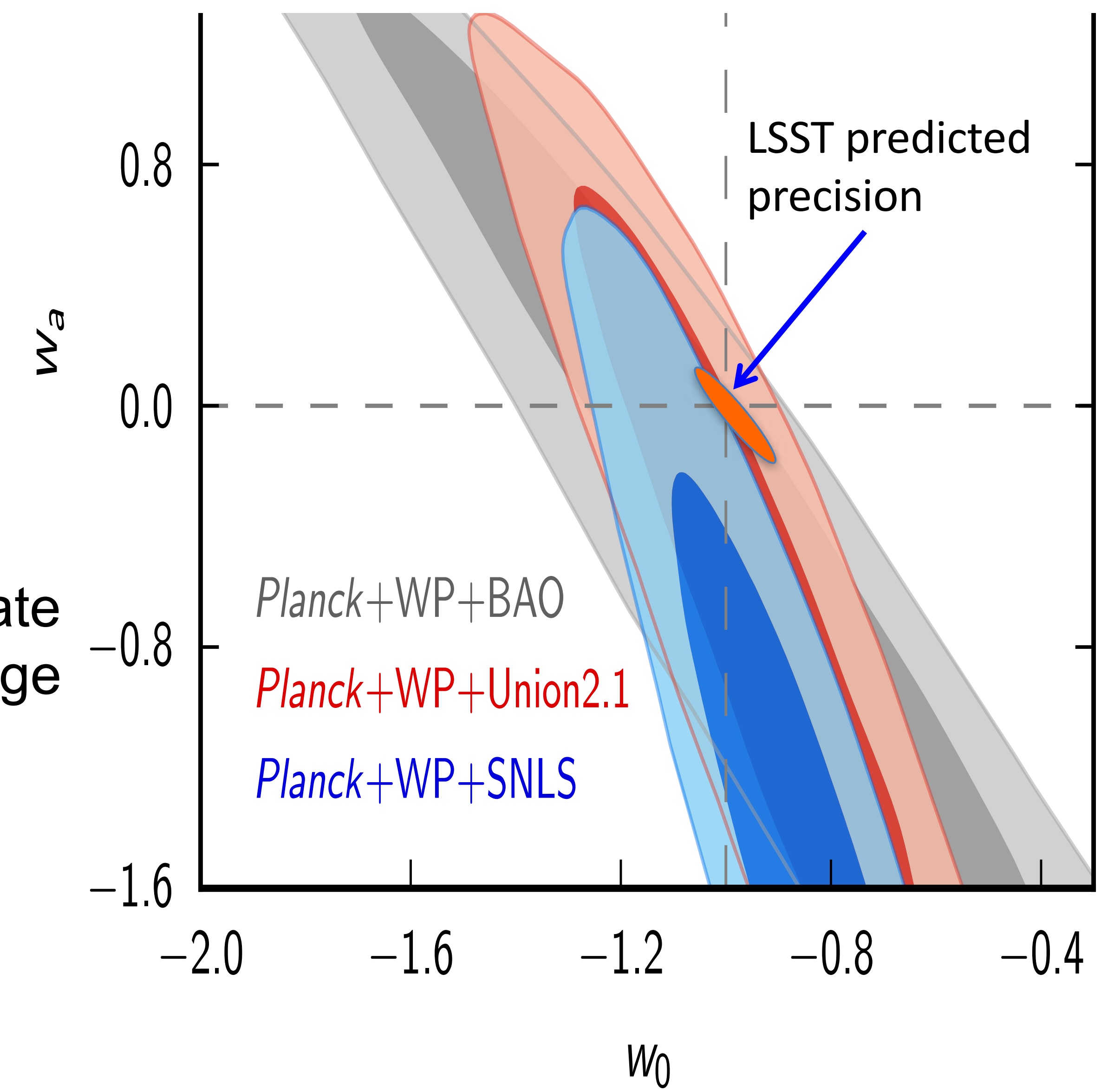
$w = 0$	Non-rel matter
$w = 1/3$	Ultra-rel matter
$w = -1$	Vacuum

$$\rho = a^{-3(1+w)}$$

$$w = w_0 + (1-a)w_1 = w_0 + \frac{z}{1+z}w_1$$

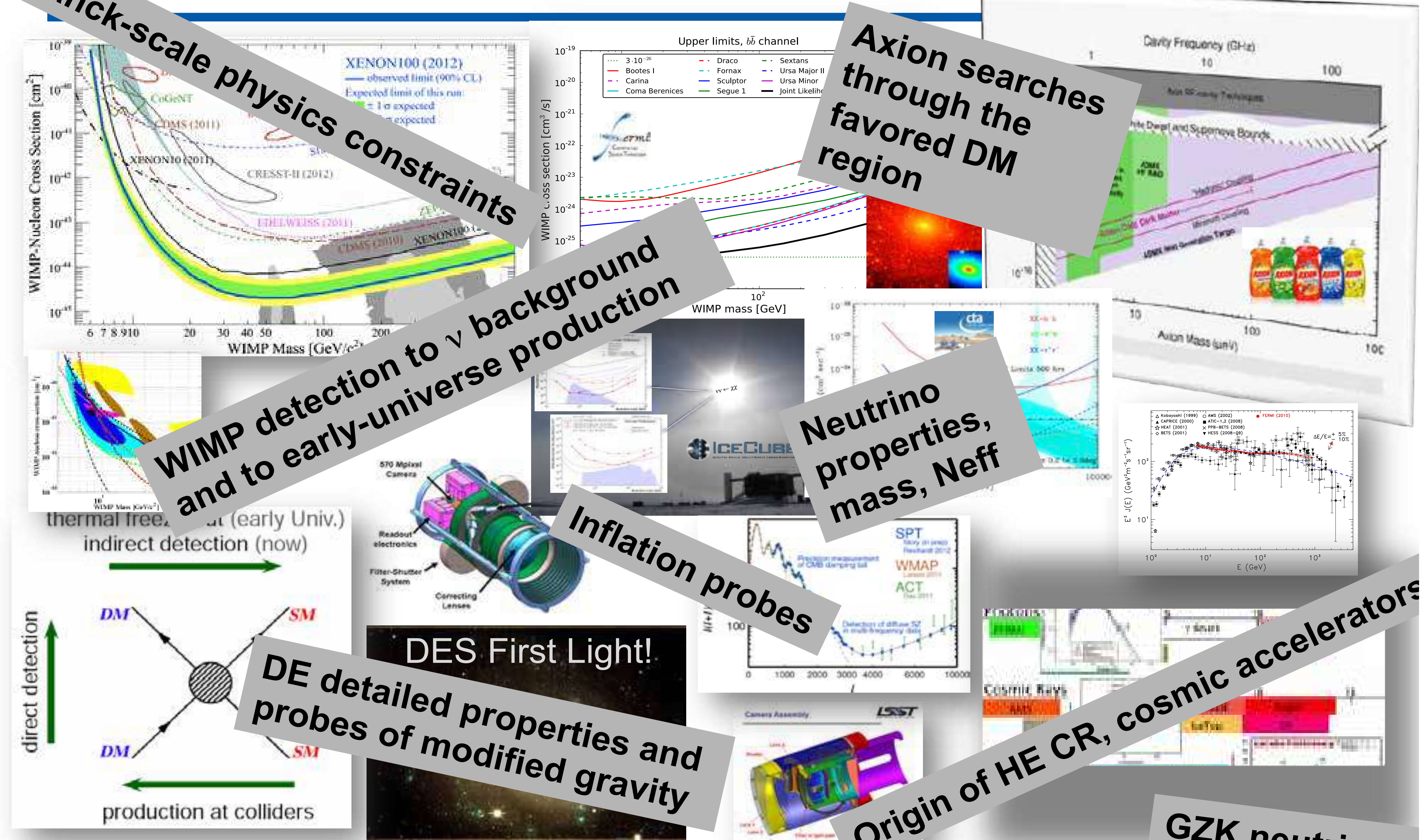
$$\rho = a^{-3(1+w_0+w_1)}e^{-\frac{3w_1 z}{1+z}}$$

Present state of knowledge



LSST Glasgow --I.Shipsey

Particle Physics Using Cosmic Frontier Techniques



Activities at the Cosmic Frontier are marked by rapid, surprising, and exciting developments

Outstanding Questions in Particle Physics *circa* 2016

… there has never been a better time to be a particle physicist!

Higgs boson and EWSB
- ❑ m_H natural or fine-tuned ?
- → if natural: what new physics/symmetry?
- ❑ does it regularize the divergent $V_L V_L$ cross-section at high $M(V_L V_L)$? Or is there a new dynamics ?
- ❑ elementary or composite Higgs ?
- ❑ is it alone or are there other Higgs bosons ?
- ❑ origin of couplings to fermions
- ❑ coupling to dark matter ?
- ❑ does it violate CP ?
- ❑ cosmological EW phase transition

Quarks and leptons:
- ❑ why 3 families ?
- ❑ masses and mixing
- ❑ *CP* violation in the lepton sector
- ❑ matter and antimatter asymmetry
- ❑ baryon and charged lepton number violation

Physics at the highest E-scales:
- ❑ how is gravity connected with the other forces ?
- ❑ do forces unify at high energy ?

Dark matter:
- ❑ composition: WIMP, sterile neutrinos, axions, other hidden sector particles, ..
- ❑ one type or more ?
- ❑ only gravitational or other interactions ?

Neutrinos:
- ❑ *ν* masses and and their origin
- ❑ what is the role of *H*(125) ?
- ❑ Majorana or Dirac ?
- ❑ *CP* violation
- ❑ additional species → sterile *ν* ?

The two epochs of Universe's accelerated expansion:
- ❑ primordial: is inflation correct ? which (scalar) fields? role of quantum gravity?
- ❑ today: dark energy (why is Λ so small?) or gravity modification ?

Conclusion

the discussion of the **future** in HEP must start from the understanding that there is no experiment/facility, proposed or conceivable, in the lab or in space, accelerator or non-accelerator driven, which can ***guarantee*** ***discoveries*** beyond the SM, and/or ***answers*** to the big questions of the field:

To understand the fundamental nature of energy, matter, space, and time, and to apply that knowledge to understand the birth, evolution and fate of the universe