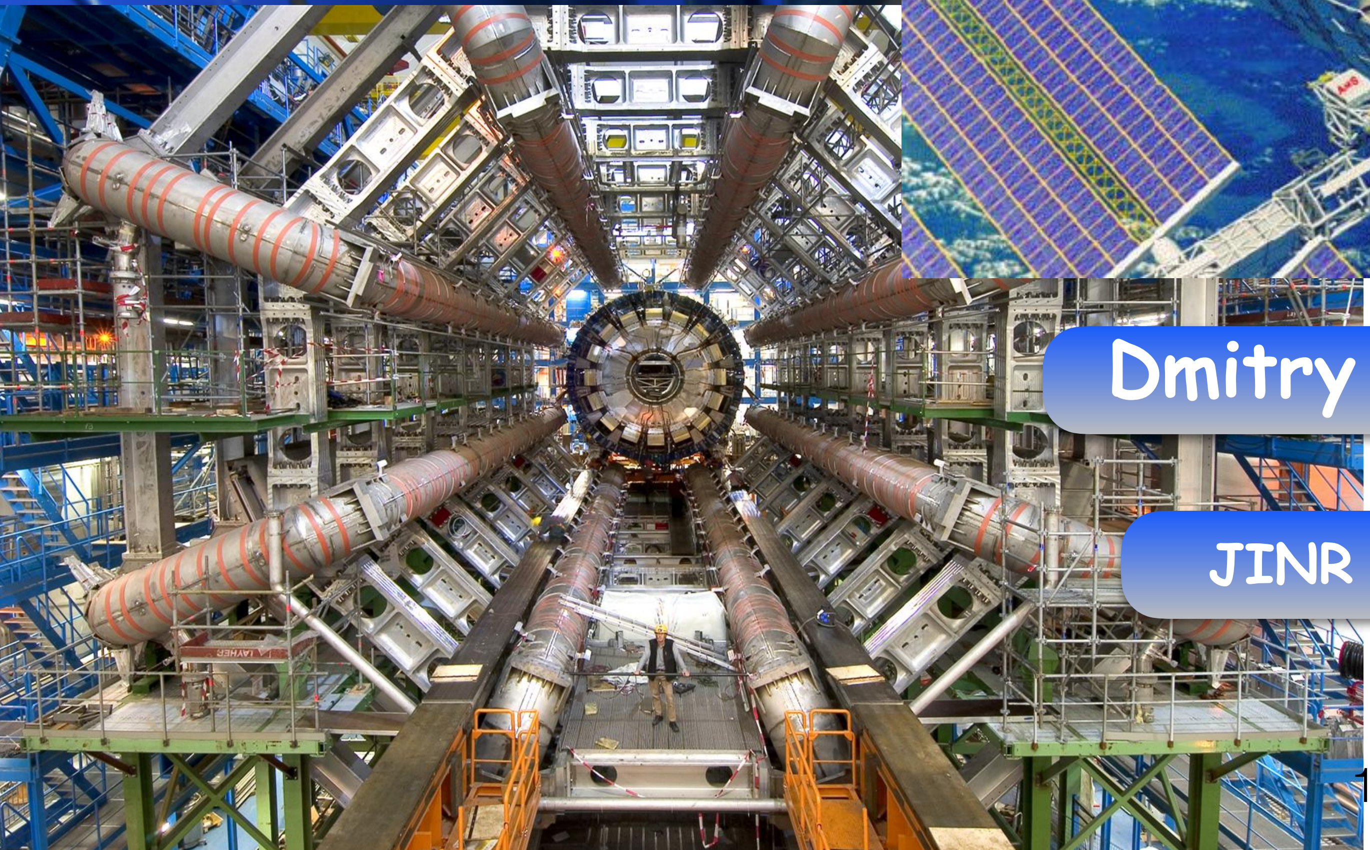
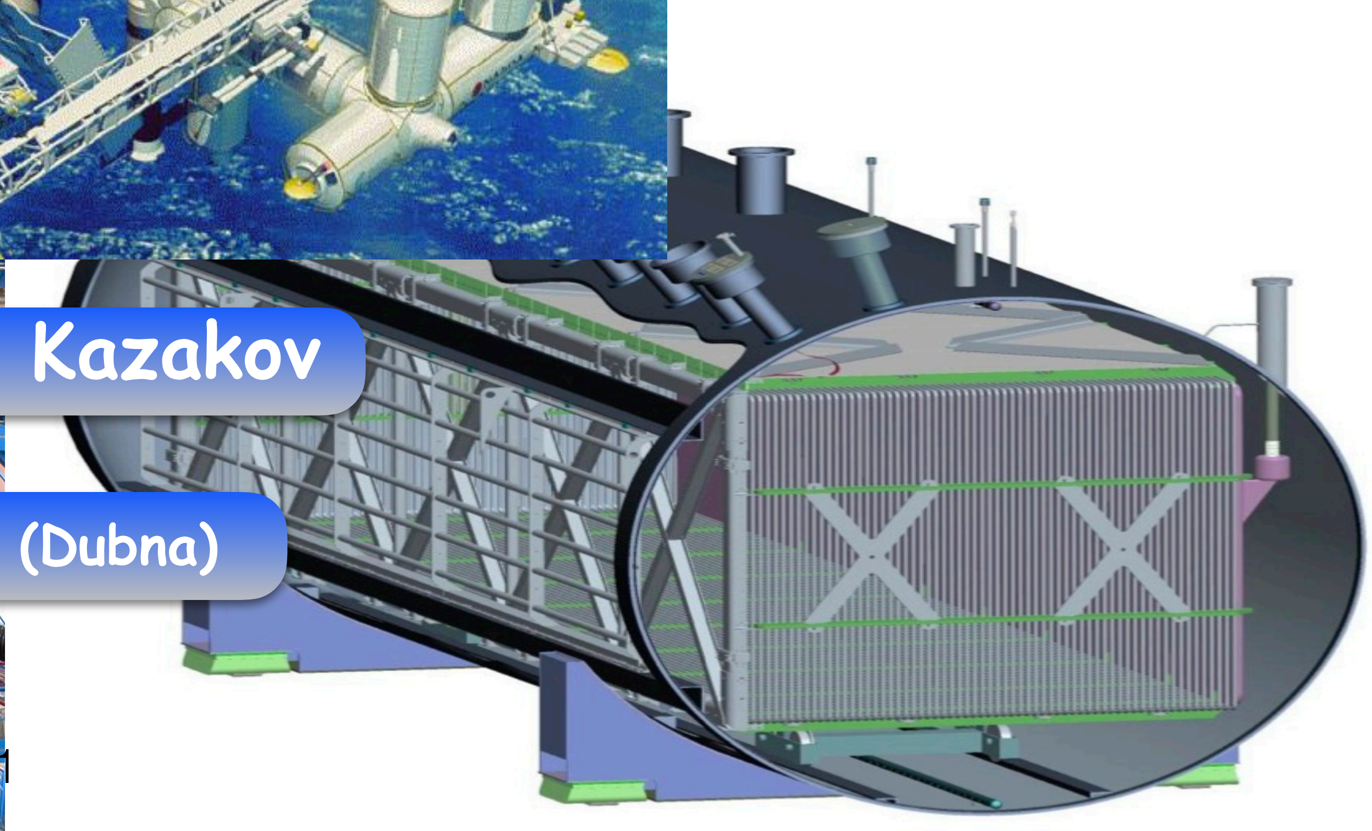
Beyond the SM Physics Perspectives in view of the LHC Run 2, Underground and Cosmic Experiments



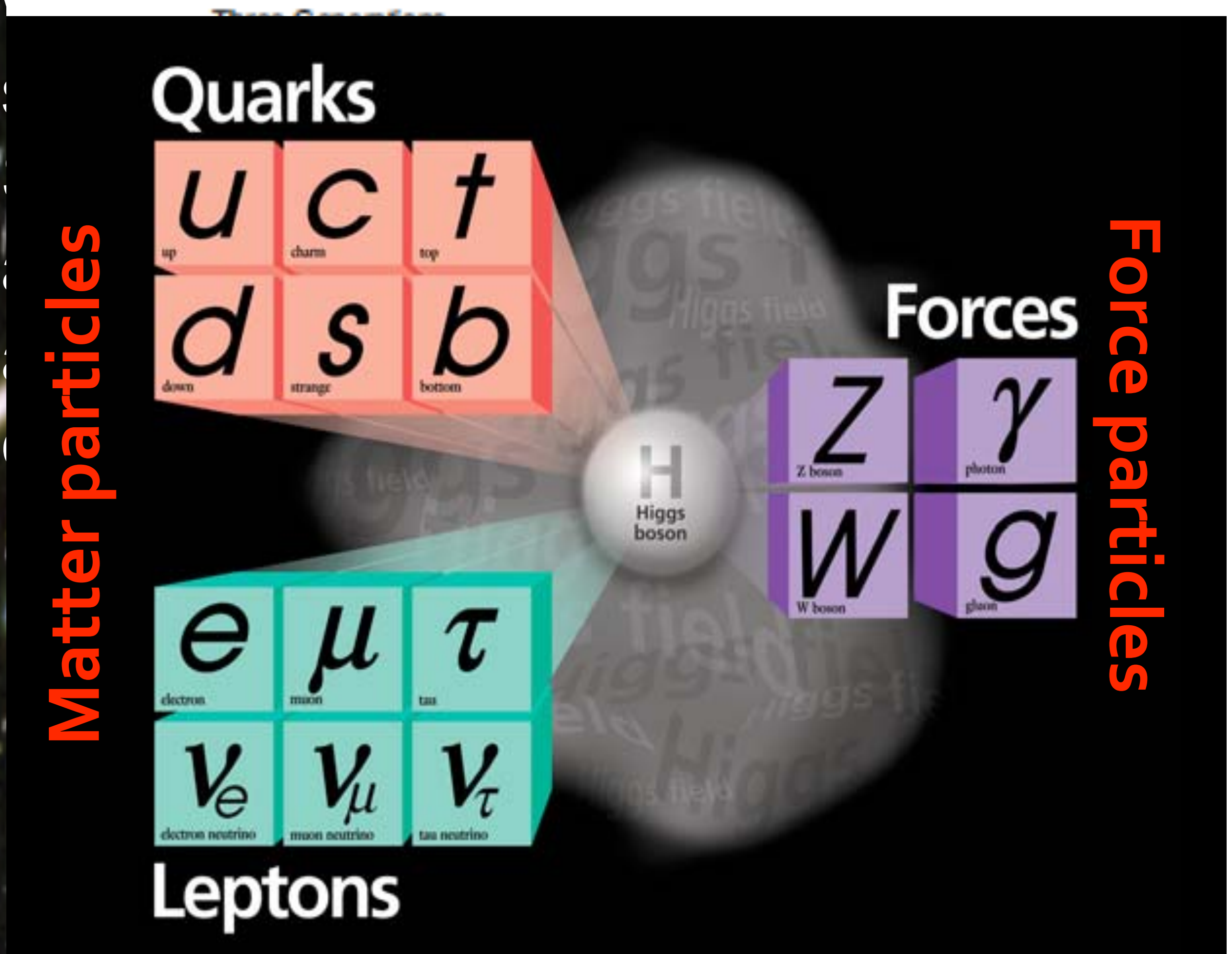


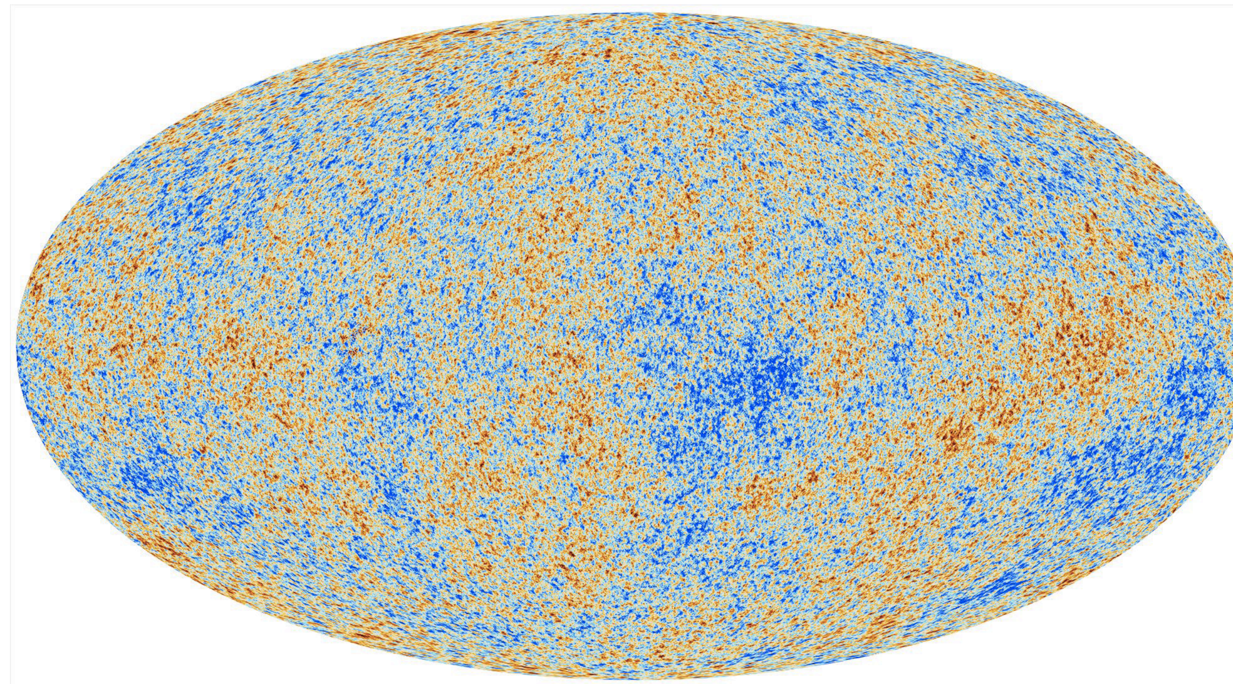
Dmitry Kazakov

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

[redacted]

[redacted]

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?

[redacted]

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

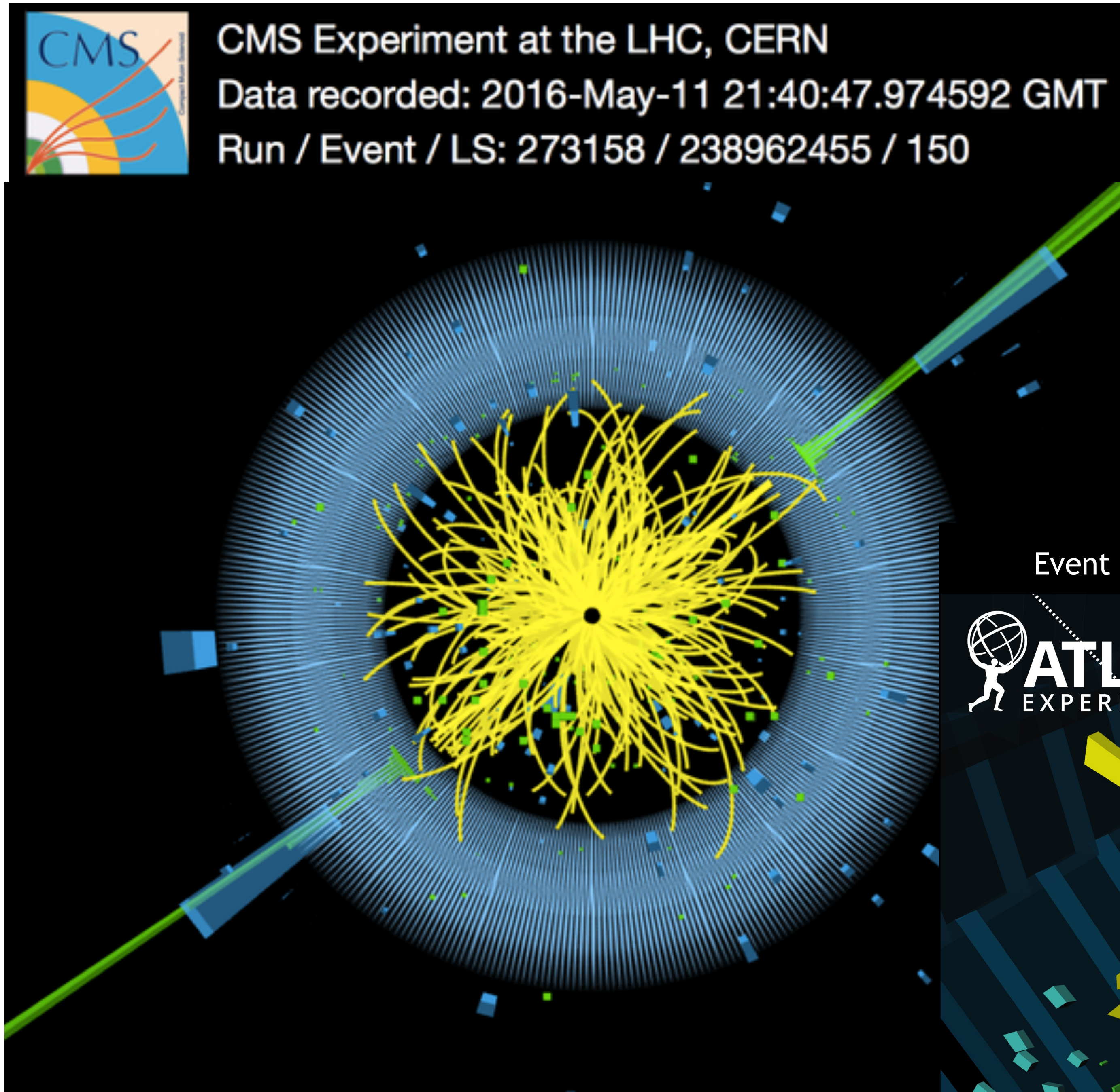
- Higgs sector: one or more?
- Neutrino sector: Dirac or Majorana?
- Neutrino sector: Masses?
- What is the DM particle?
- Are there new particles?
- Are there new interactions?

To be understood

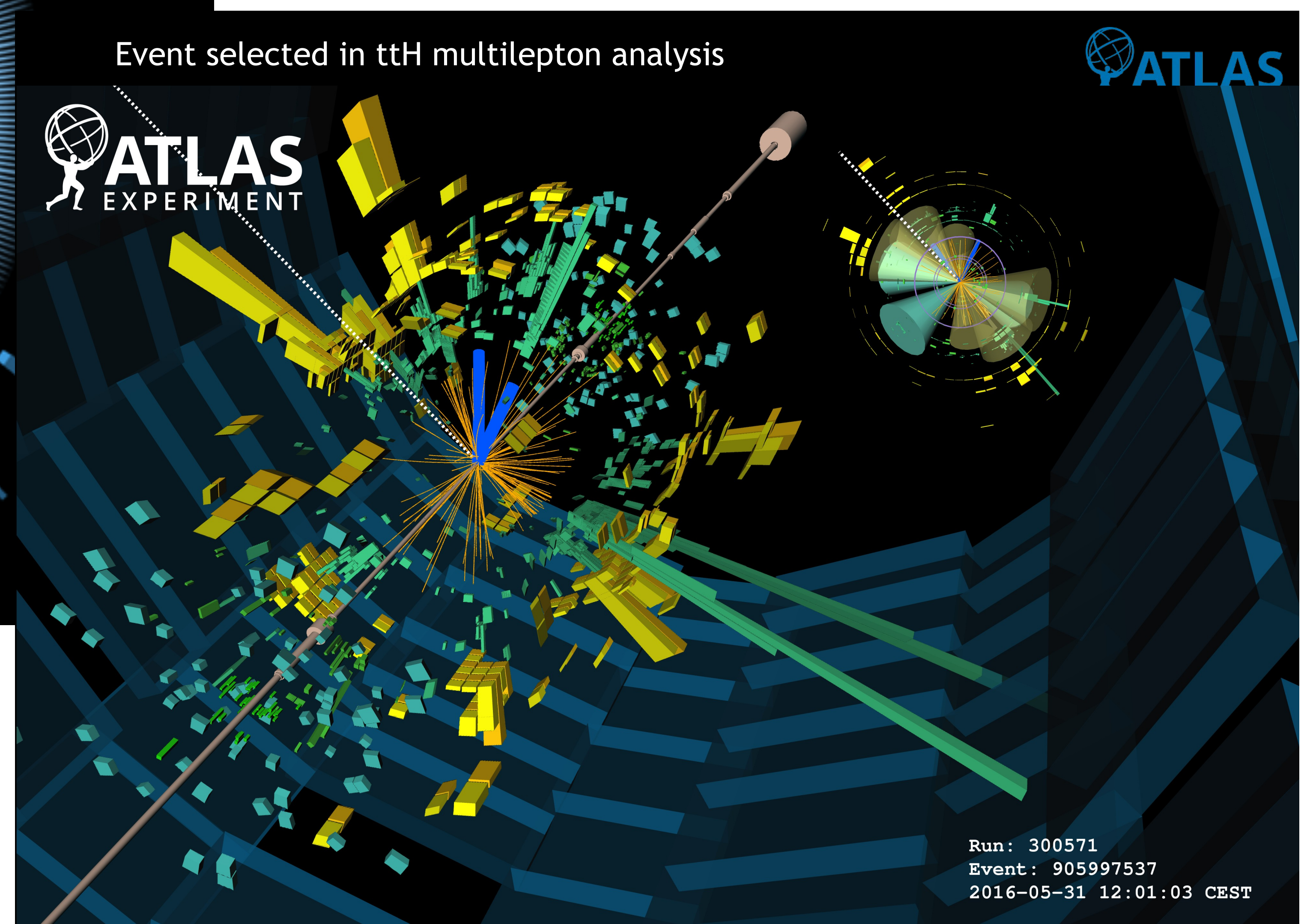
- how confinement actually works ?
- how the quark-hadron phase transition happens?
- how CP violation occurs in the Universe?
- how to protect the SM from would be heavy scale physics?

[redacted]

LHC Run2



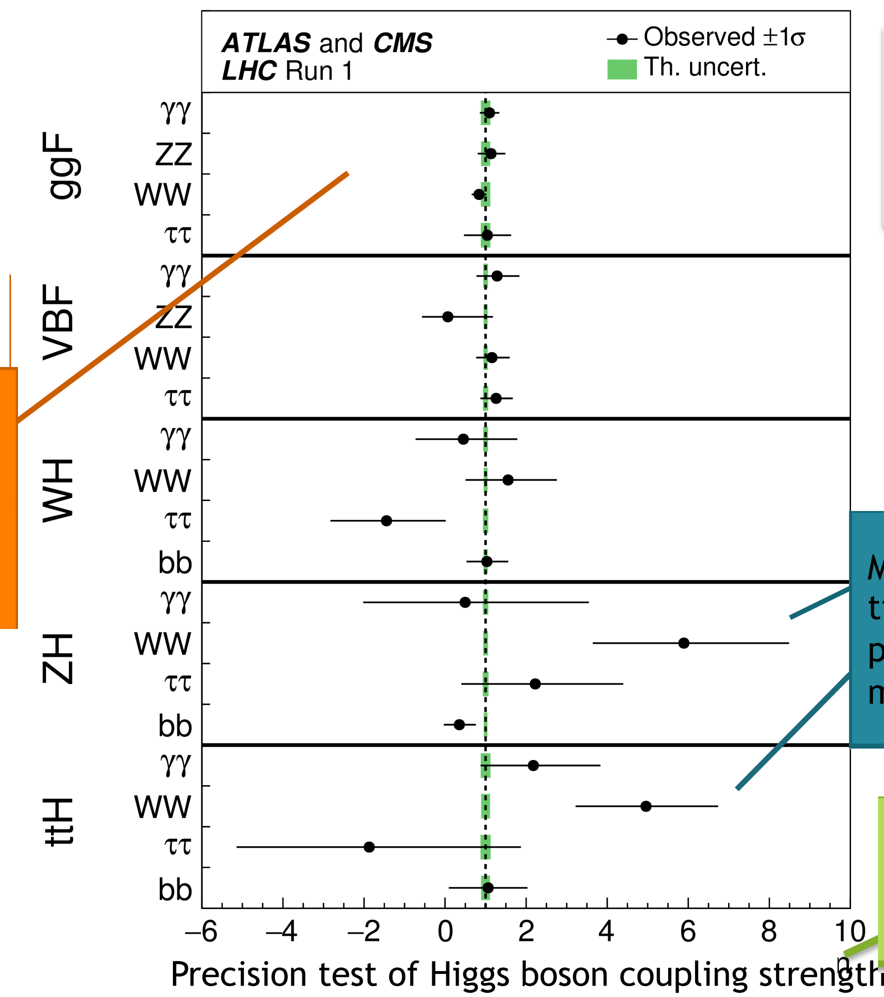
We are in a data driven era



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

Galileo Galiliei
1564-1642

Higgs Boson (125)



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

Mild excess in ttH and ZH production modes

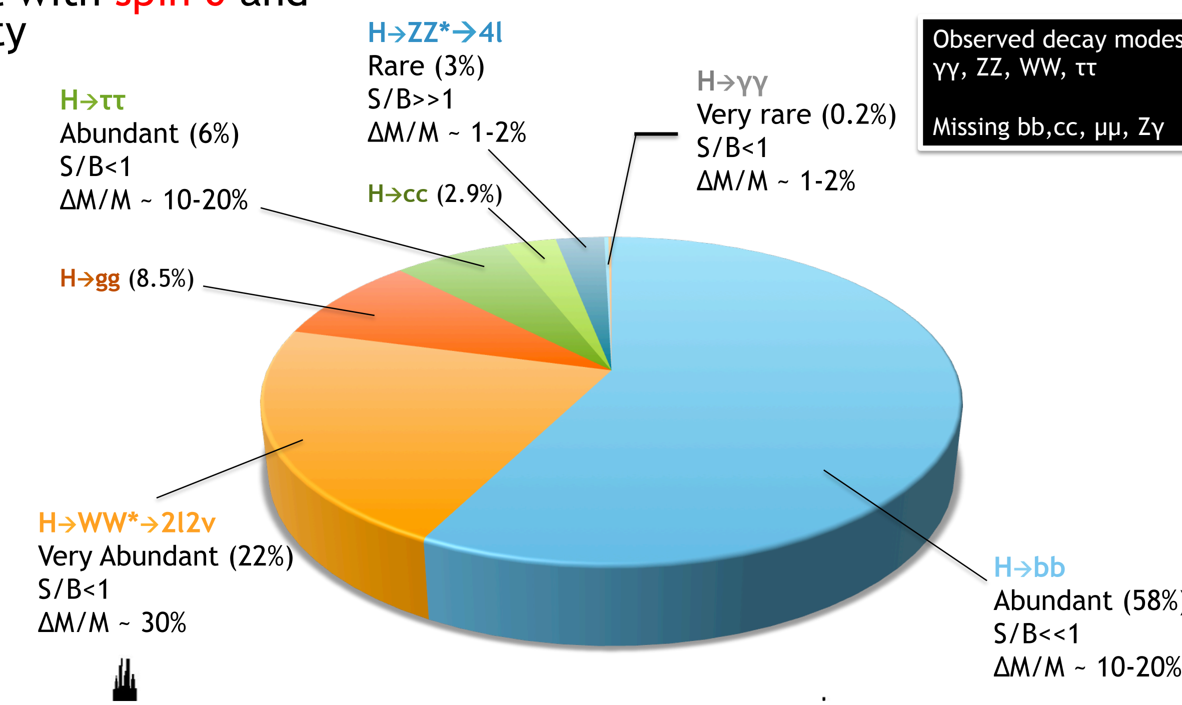
Coupling strengths

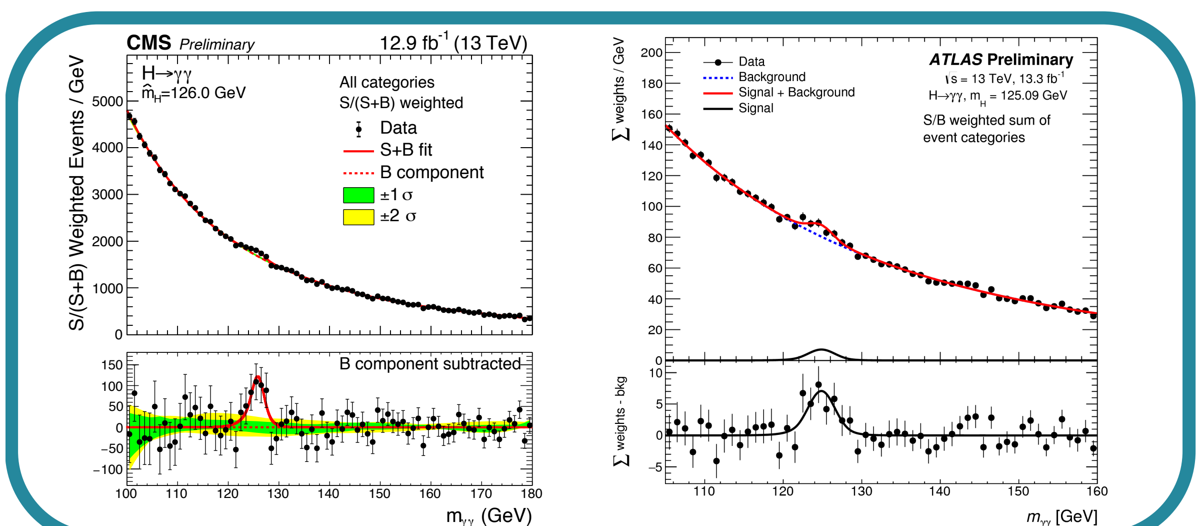
$$\mu = \frac{\sigma}{\sigma_{SM}}$$

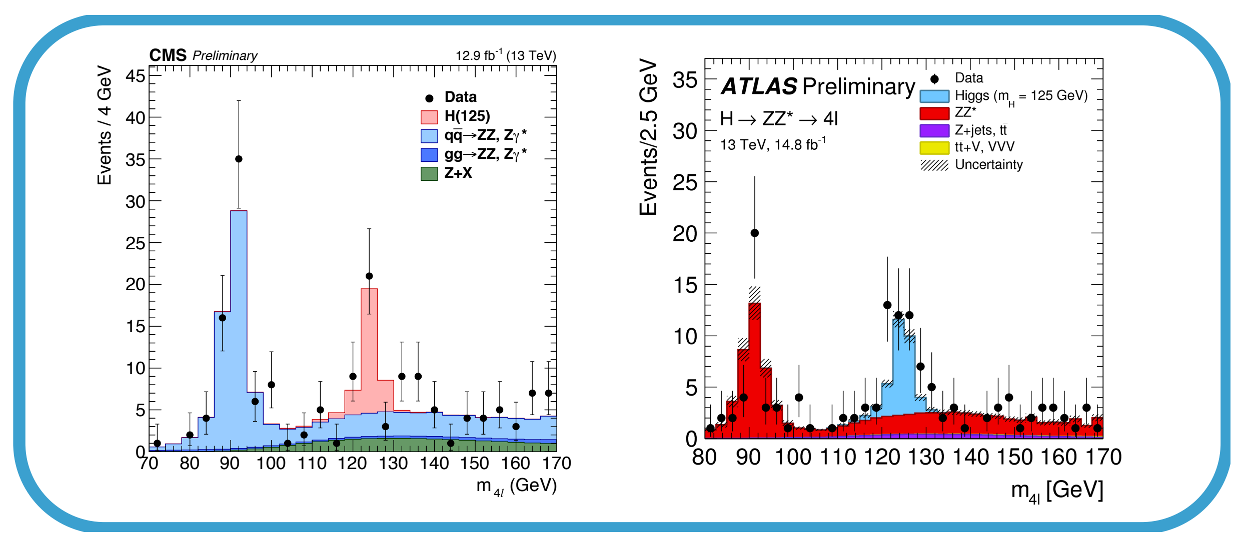
- Mass has been measured to 0.2% precision
  m_H=125.09±0.24 GeV
- Angular distributions consistent with spin 0 and even parity
- All couplings are consistent with SM within 2.5σ

Observed decay modes: γγ, ZZ, WW, ττ

Missing bb, cc, μμ, Zγ





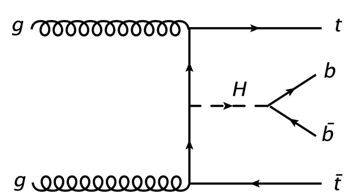


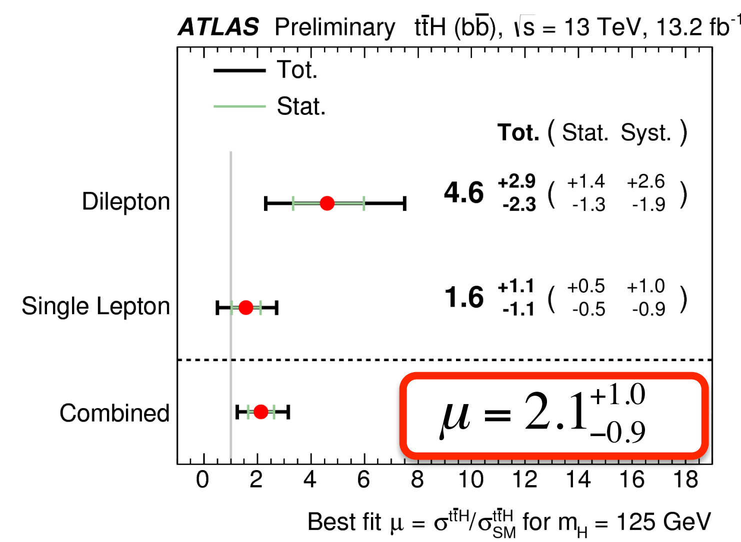
Higgs→γγ

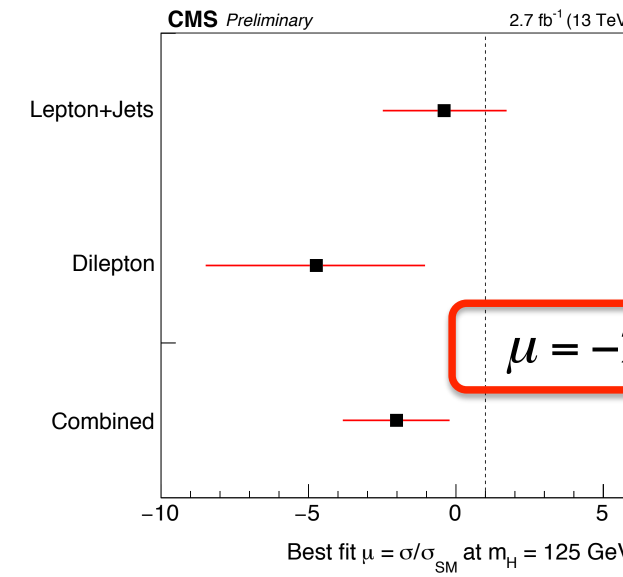
Higgs→ZZ*

Higgs Boson (125)

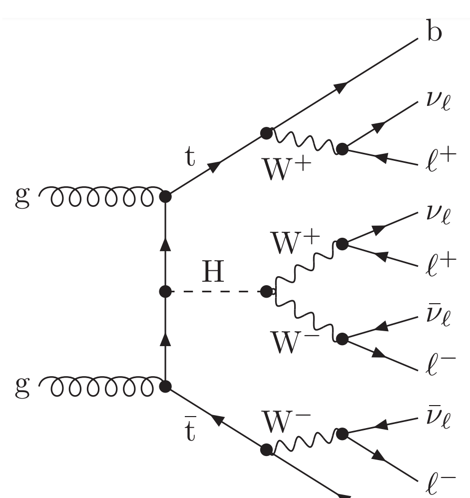
ttH(→bb)



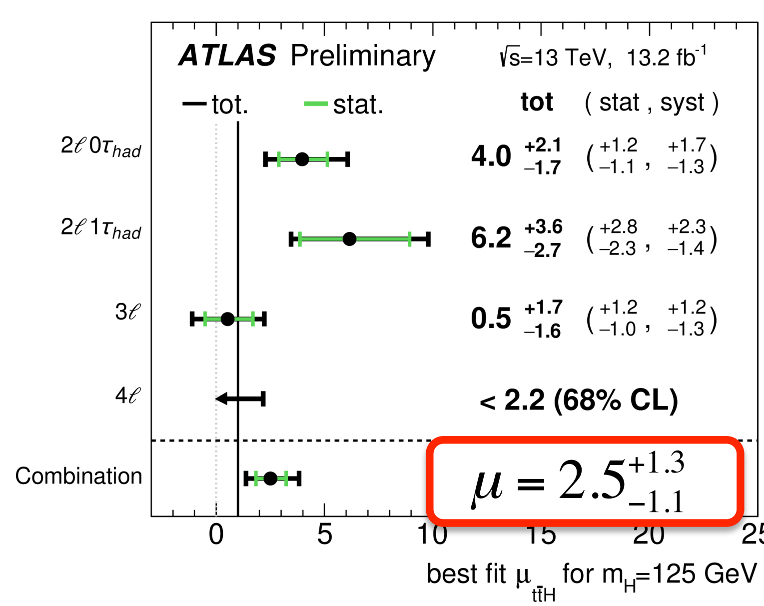


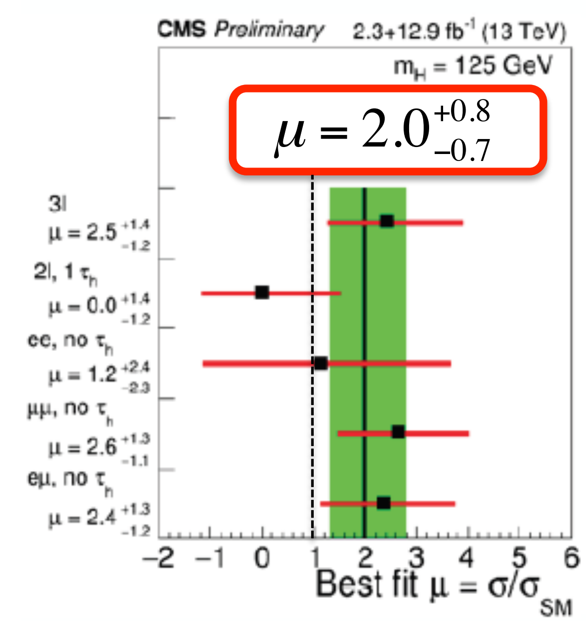


ttH(multileptons)



And also H→ZZ, H→ττ





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

Snowmass 2013 projections:

Luminosity	$300\ \text{fb}^{-1}$	$3000\ \text{fb}^{-1}$
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	$10-13\%$	$4-7\%$
κ_ℓ	$6-8\%$	$2-5\%$
Γ_H	$12-15\%$	$5-8\%$
	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 $\times 1/\sqrt{\mathcal{L}}$.

Expectations in various models:

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

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
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 ≈already achieved! Franz Herzog's talk

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	$10-13\%$	$4-$[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	$23-23\%$	$8-8\%$
$\mathrm{BR}_{\mathrm{BSM}}$	$< 14-18\%$	$< 7-11\%$

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

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

The name of the game is precision

Snowmass 2013, 1310.8361

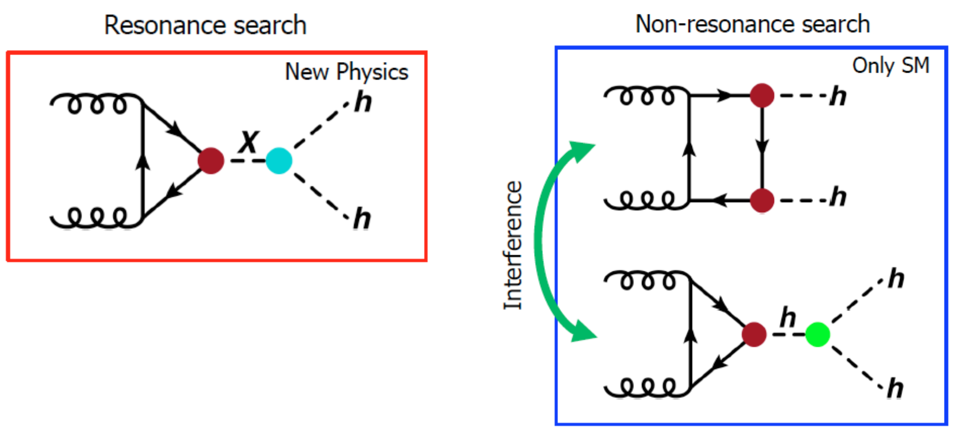
- Decoupling MSSM: κ_γ assumes 1 TeV stop with $\tan\beta = 3.2$, $X_t = 0$.

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

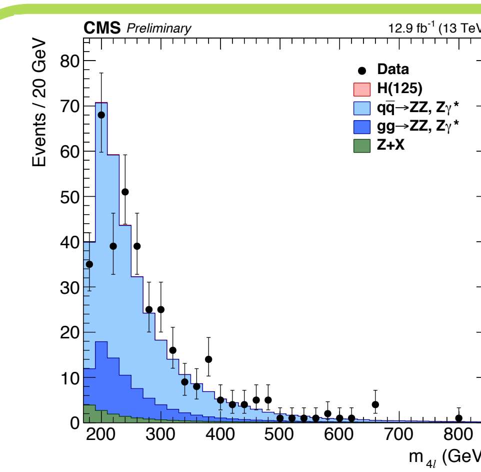
Thy uncert reductions ≈already achieved! Franz Herzog's talk

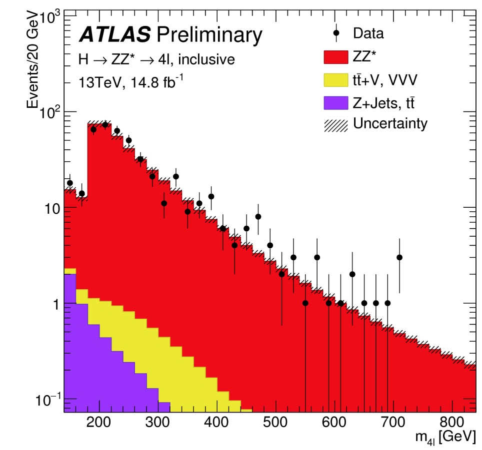
Extra Higgs Bosons

Higgs→hh→bbττ

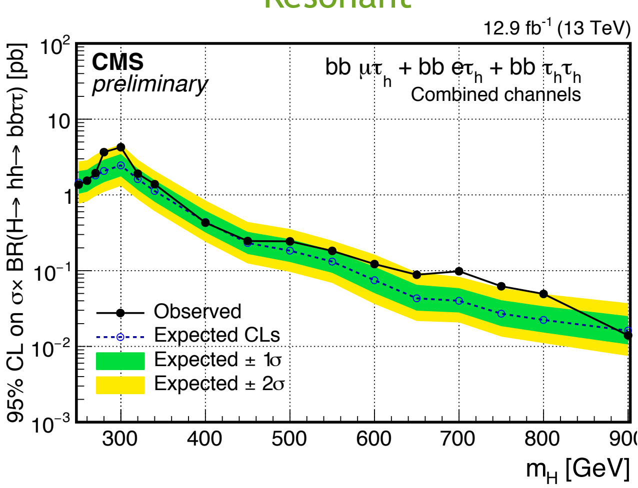


Heavy Higgs→ZZ→4l

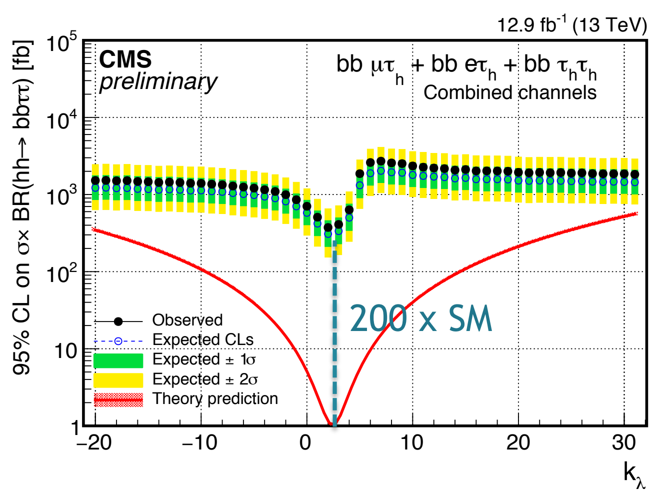




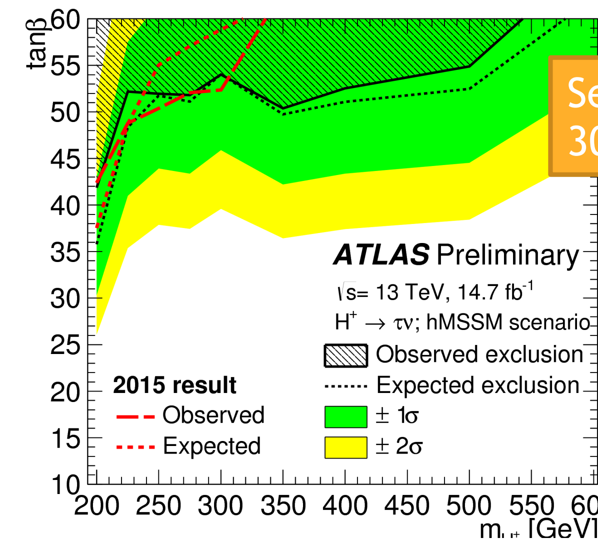
Resonant



Non-Resonant

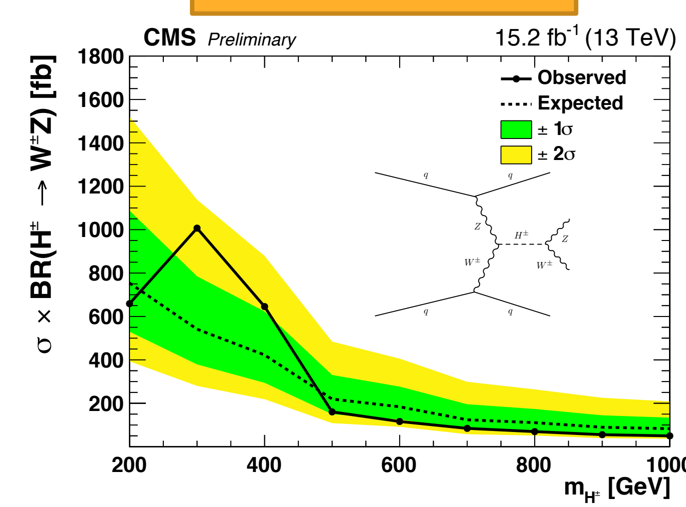


Charged Higgs

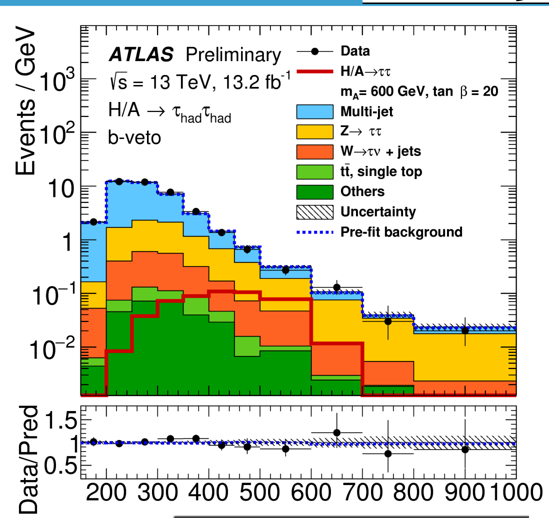


Search for H±→tb
$300<m_{H^\pm}<1000$ GeV

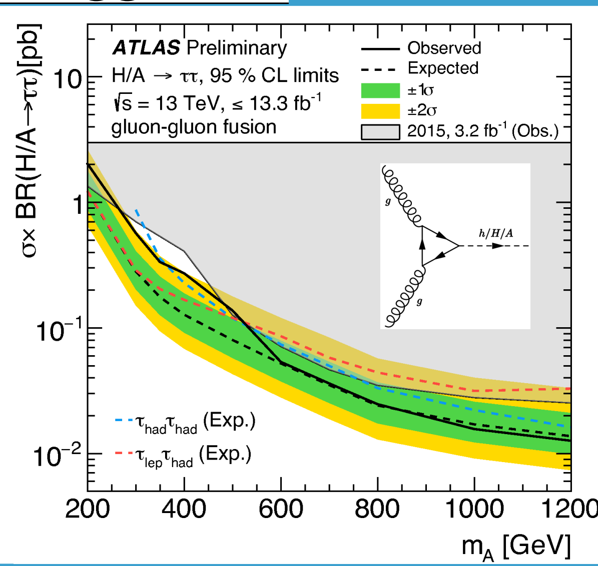
Search for H±WZ



Heavy Higgs→ττ



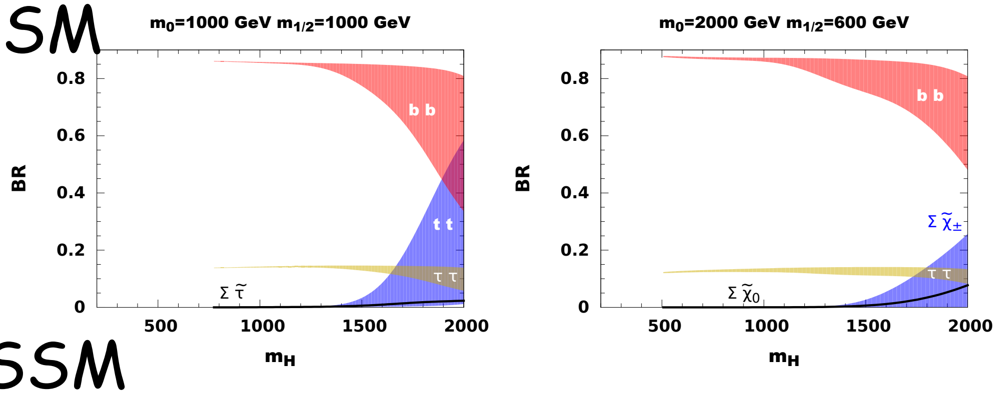
$$m_T^{tot} = \sqrt{m_T^2(E_T^{miss}, \tau_1) + m_T^2(E_T^{miss}, \tau_2) + m_T^2(\tau_1, \tau_2)}$$



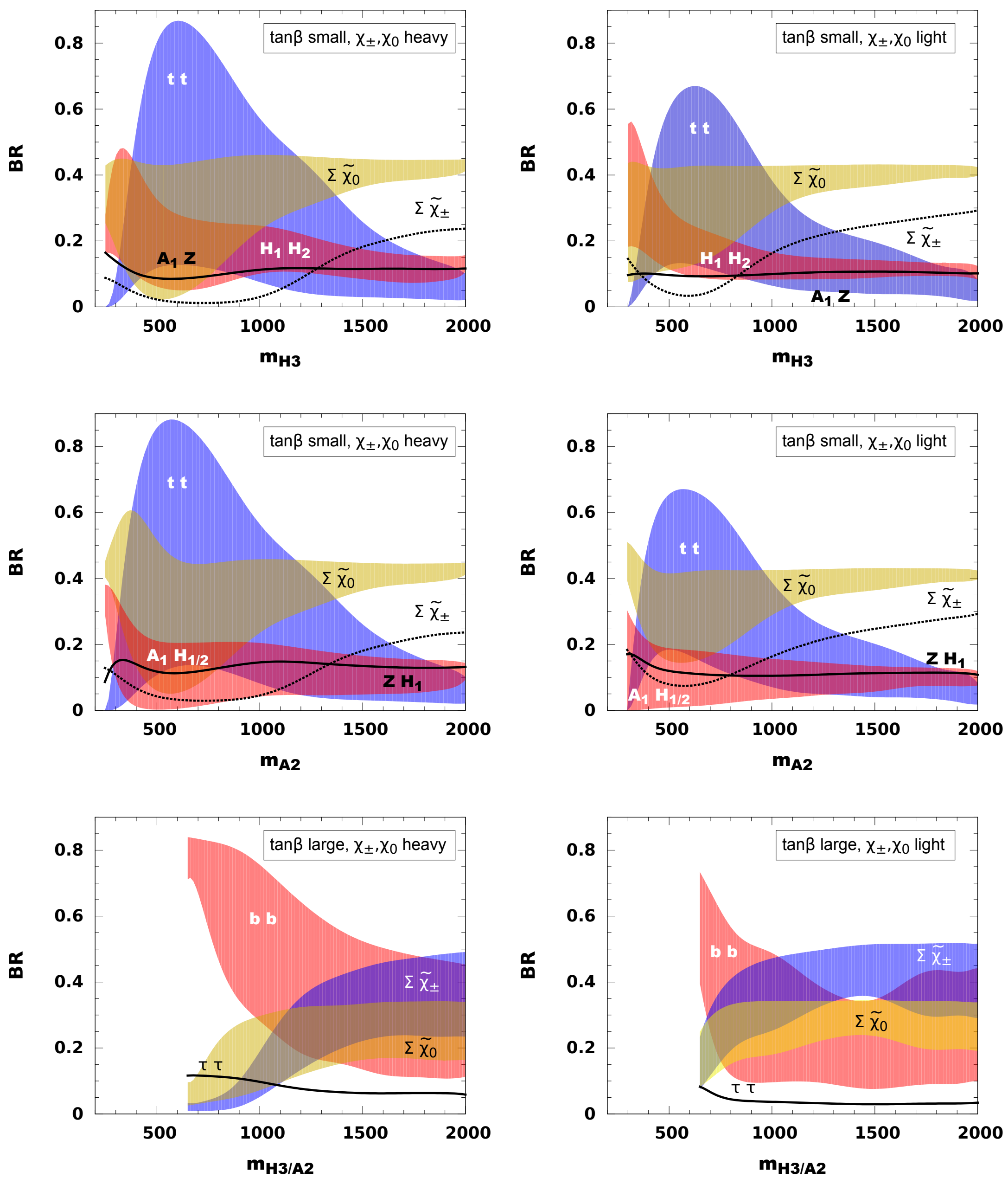
Heavy Higgs Decays

Branchings

MSSM



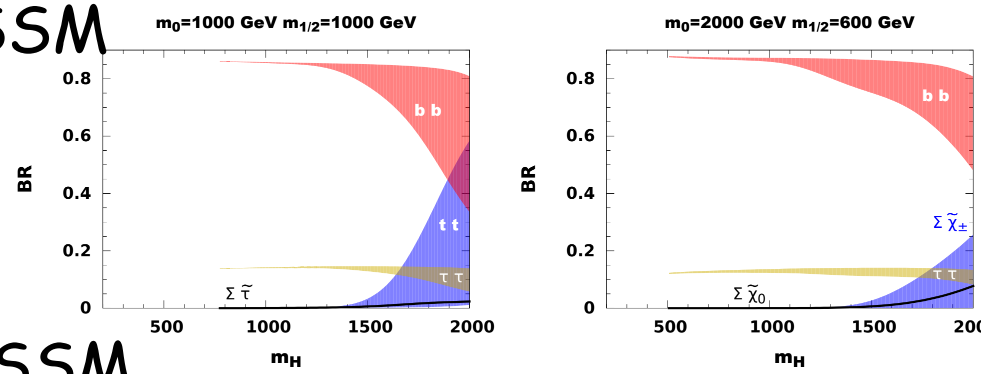
NMSSM



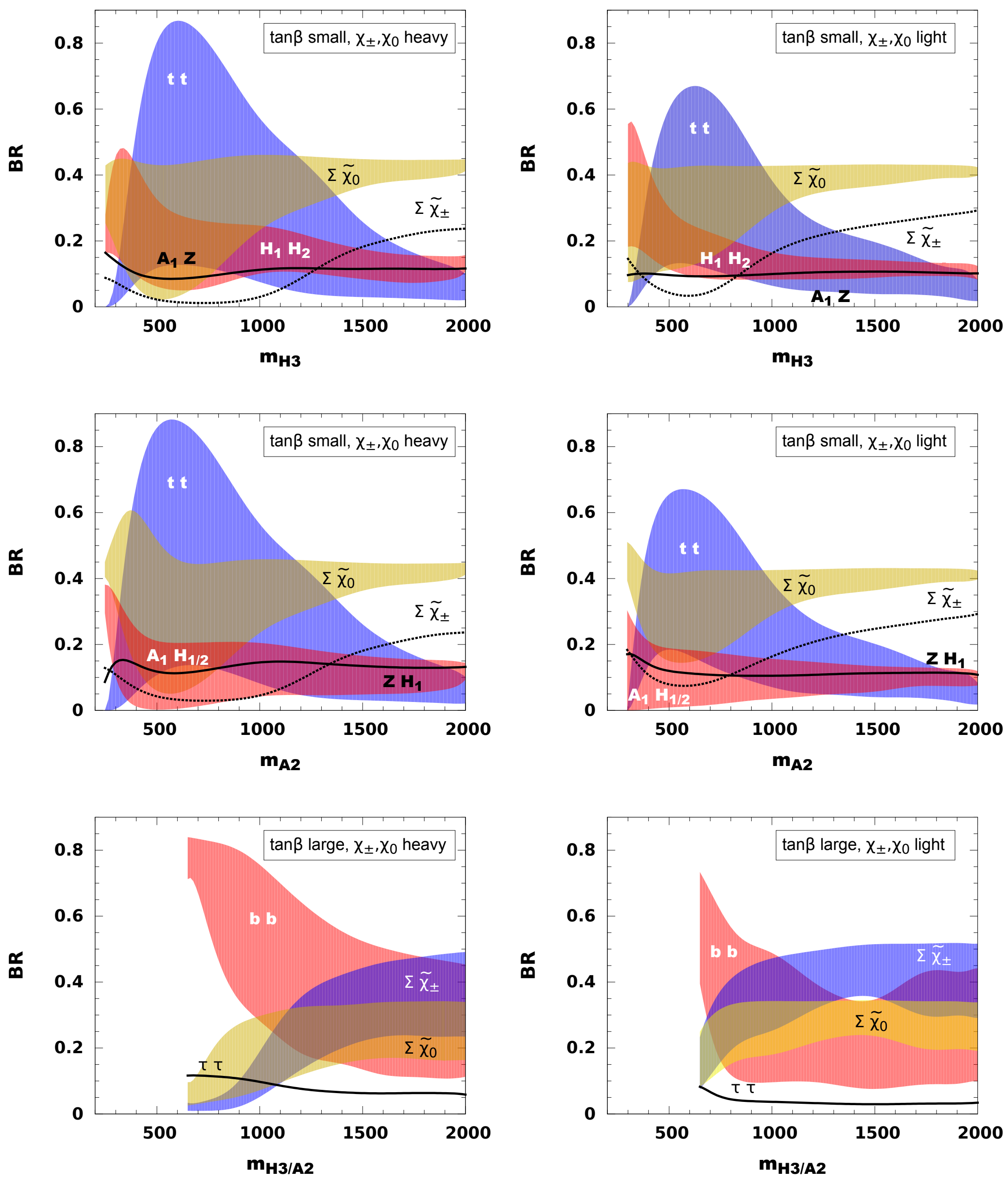
Heavy Higgs Decays

Branchings

MSSM

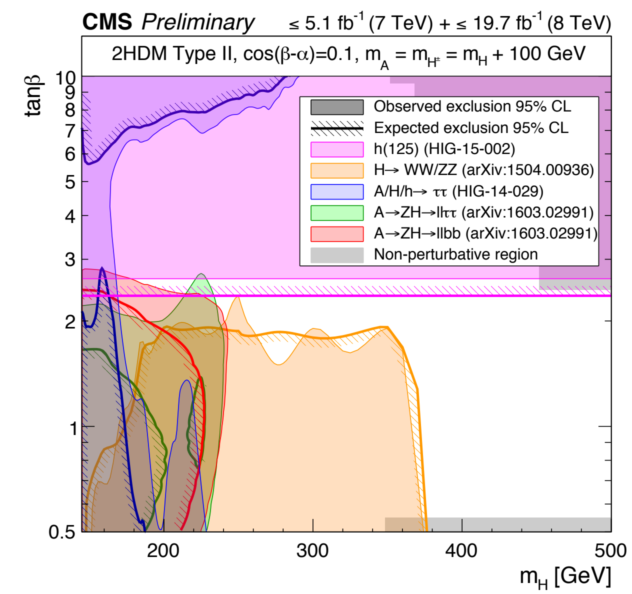


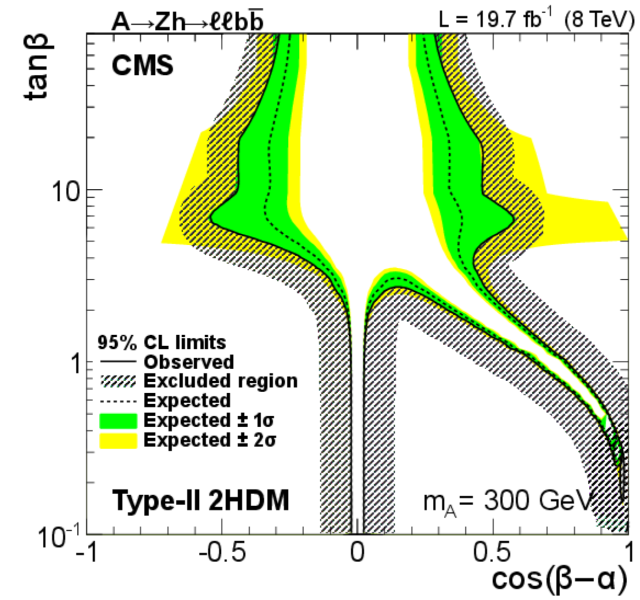
NMSSM

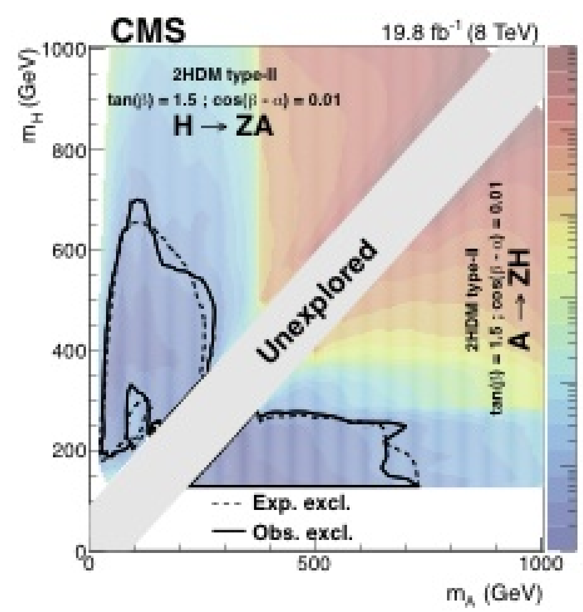


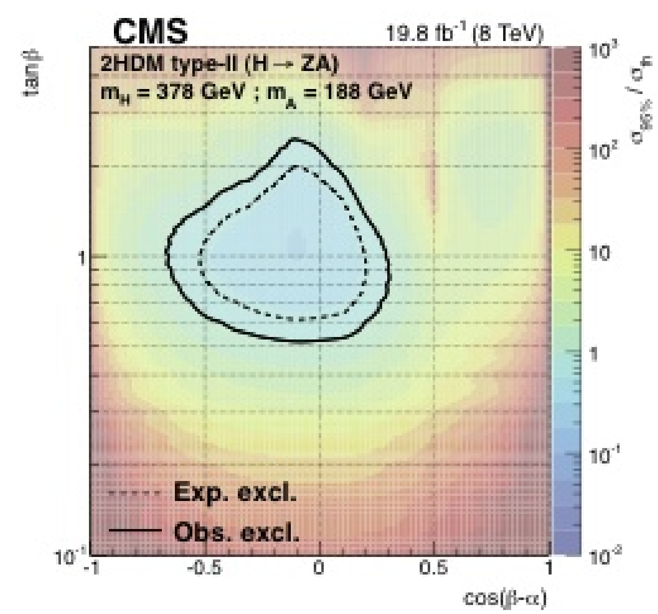
1) “Higgs to Higgs” decays

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





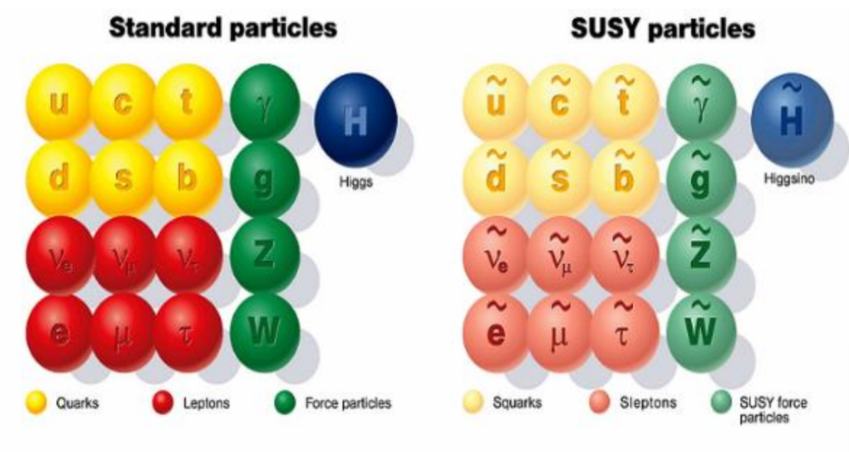




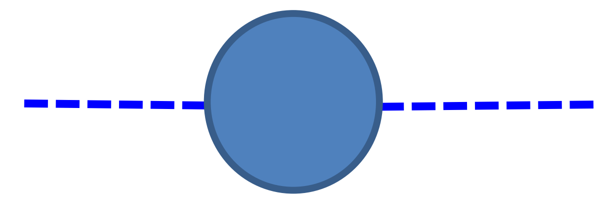
SUSY

Kiwoon Choi
(ICHEP 2016, Chicago)

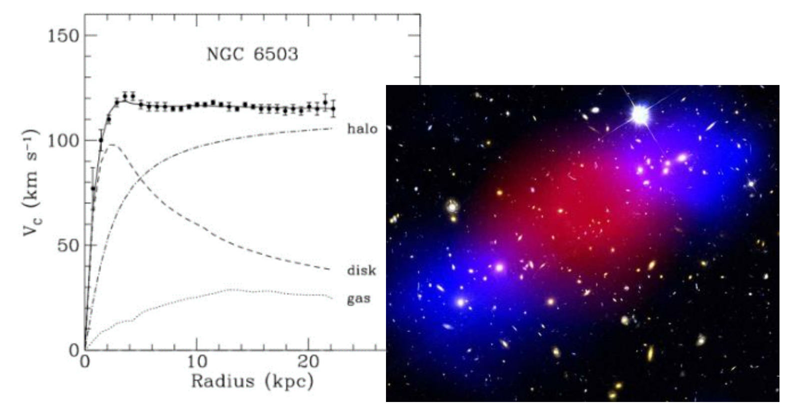
SUSY has been the prime candidate for BSM physics near the TeV scale.



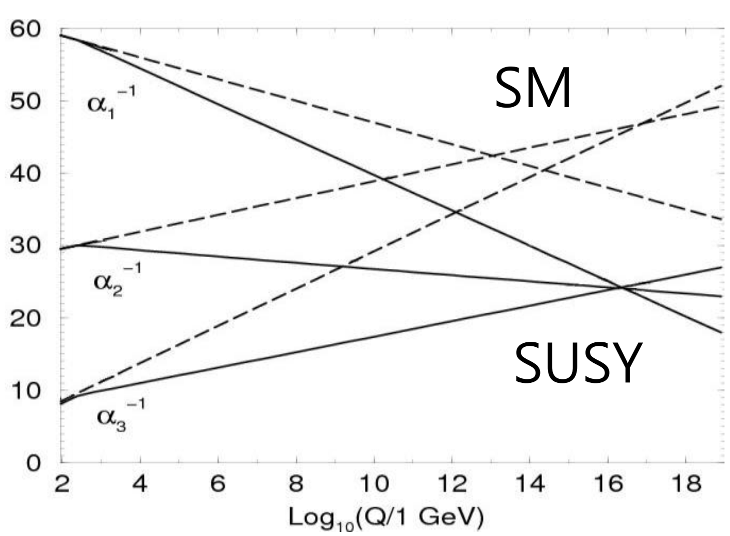
Hierarchy problem



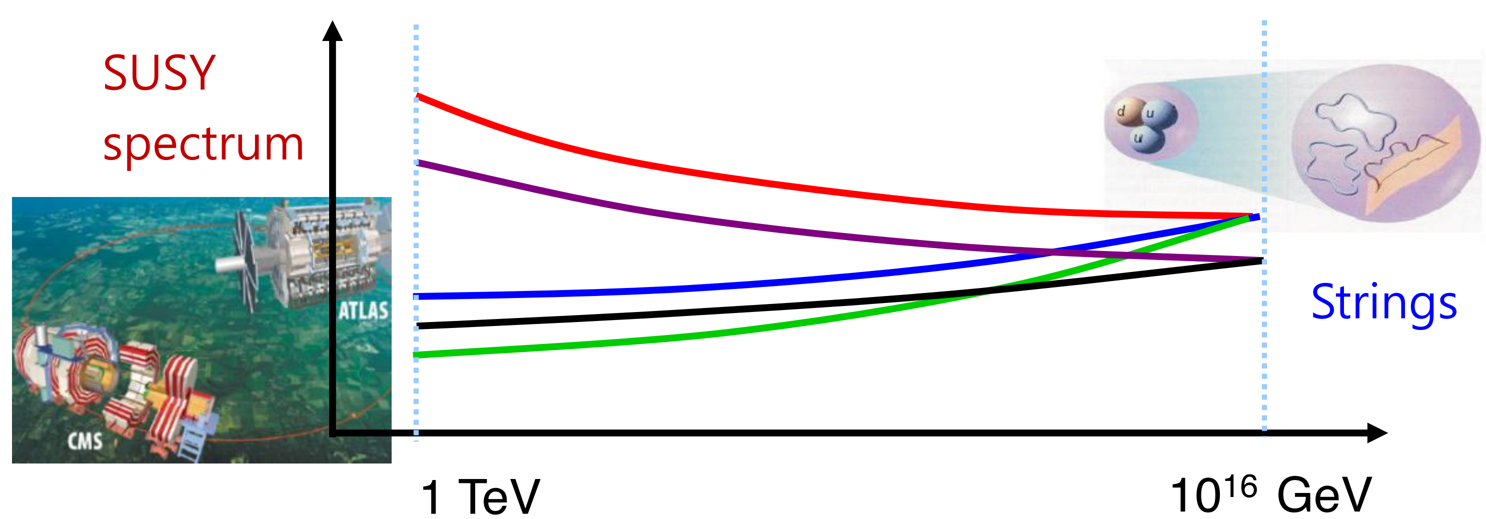
$$\delta m_H^2 \sim M_{\rm Planck}^2 \Rightarrow m_{\rm SUSY}^2$$



Dark matter



Gauge coupling unification

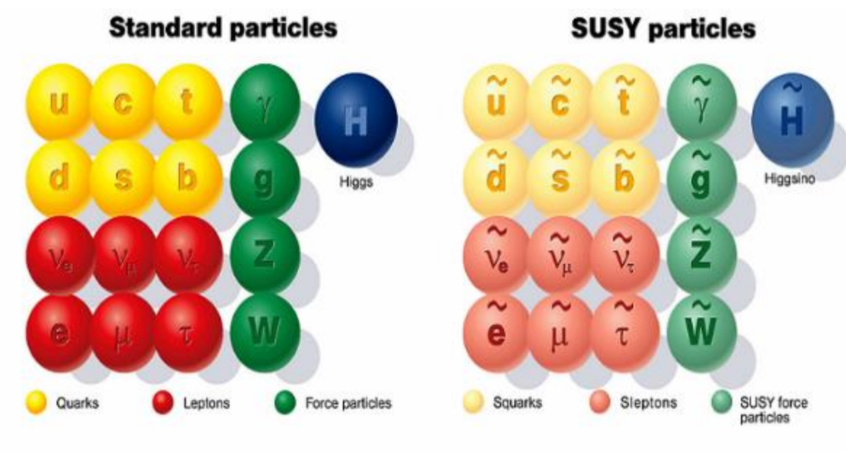


SUSY

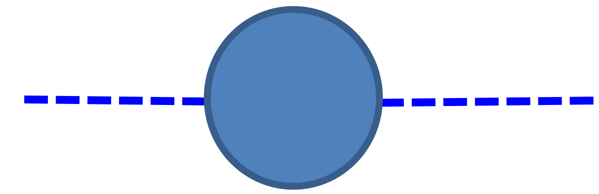
Kiwoon Choi

(ICHEP 2016, Chicago)

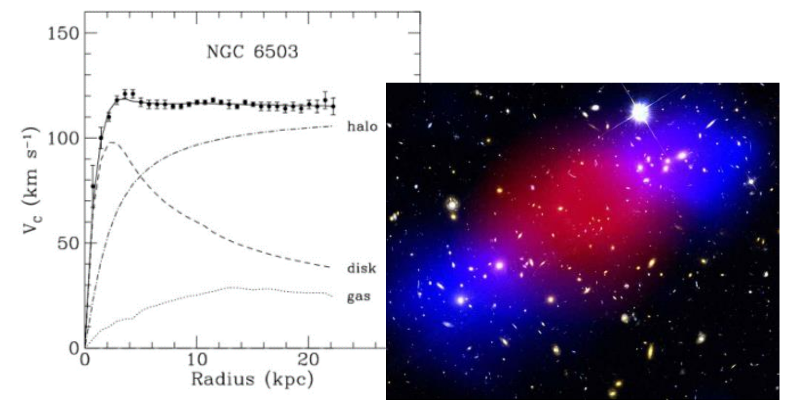
SUSY has been the prime candidate for BSM physics near the TeV scale.



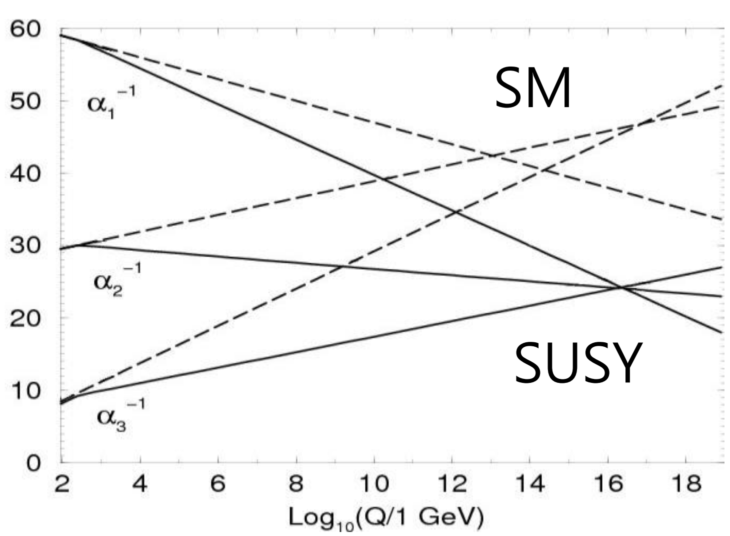
Hierarchy problem



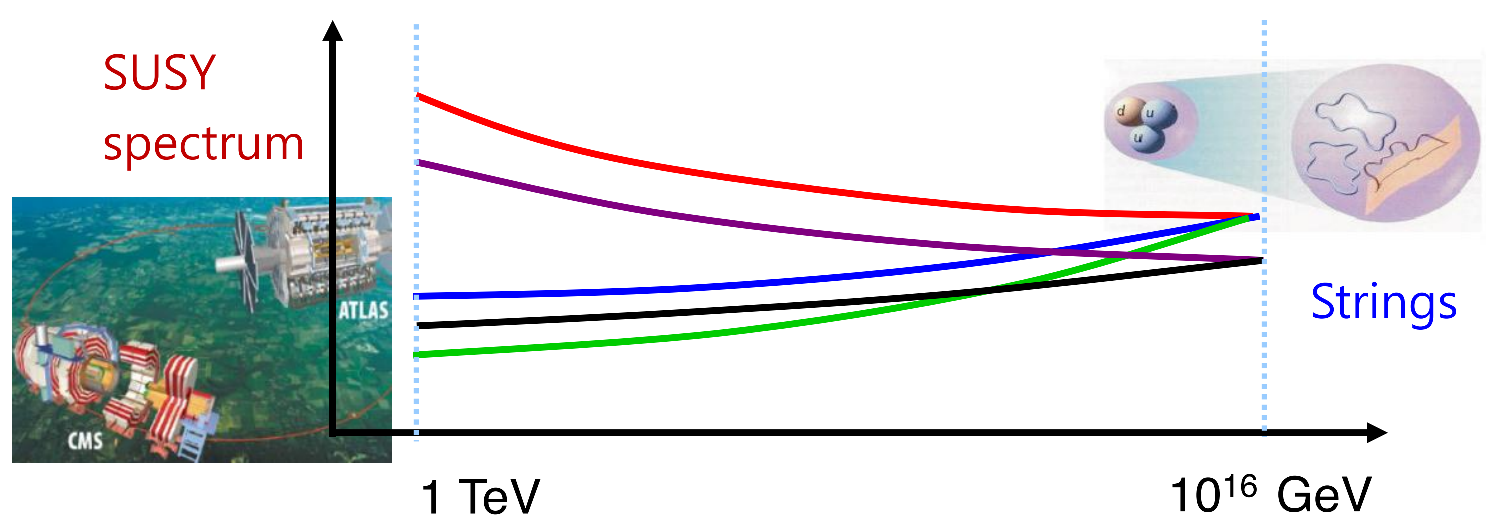
$$\delta m_H^2 \sim M_{\rm Planck}^2 \Rightarrow m_{\rm SUSY}^2$$



Dark matter



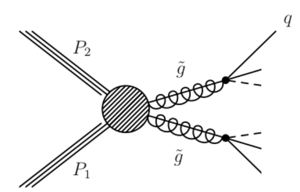
Gauge coupling unification



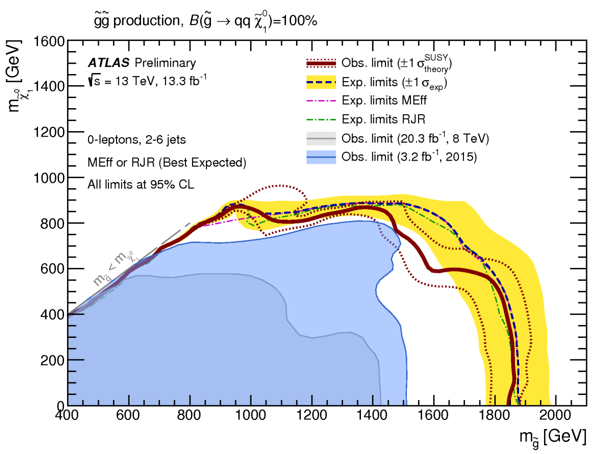
Supersymmetry remains, to this date, a well-motivated, much anticipated extension to the Standard Model of particle physics

Supersymmetry/ LHC 13

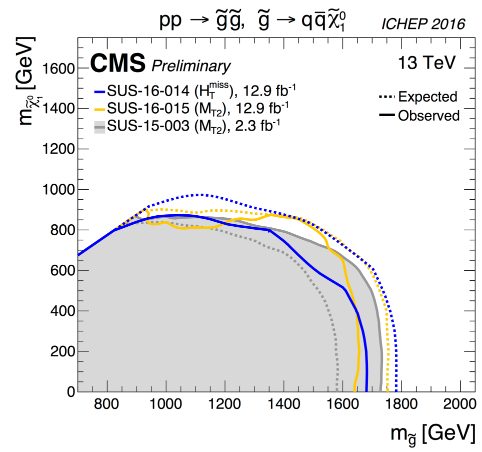
Gluino decays to qq+LSP



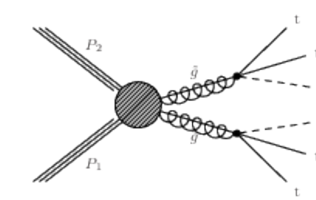
Summary of decays to light quarks + LSP



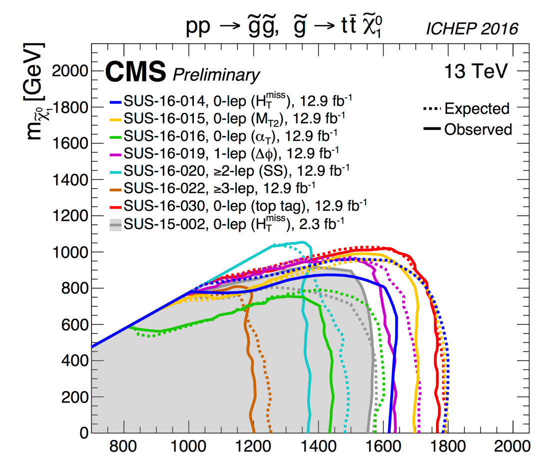
ATLAS-CONF-2016-078



Gluino decays to tt+LSP

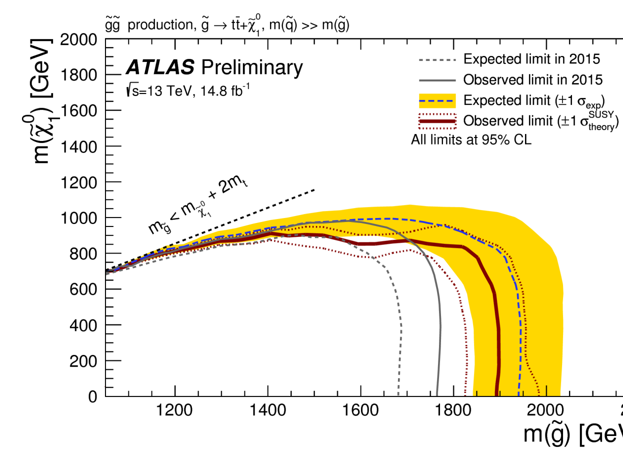


CMS summary

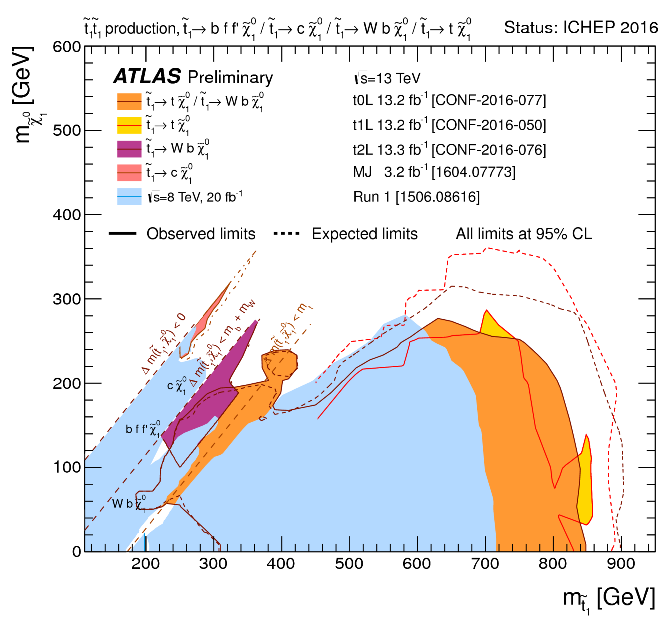


ATLAS multi-b

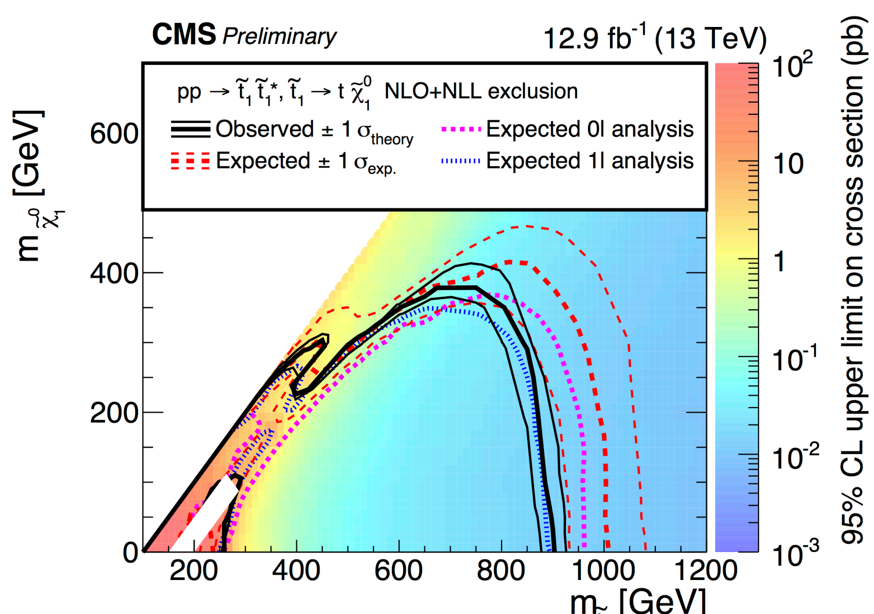
ATLAS-CONF-2016-052



Top squarks - summaries



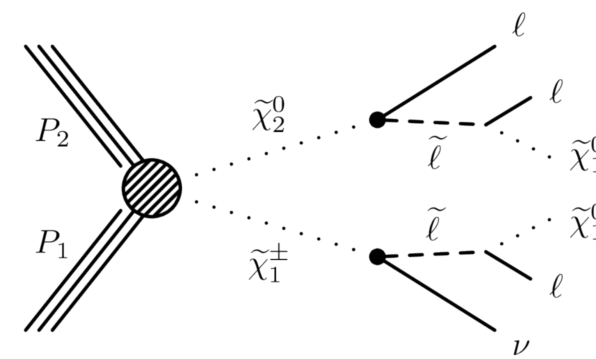
ATLAS summary



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

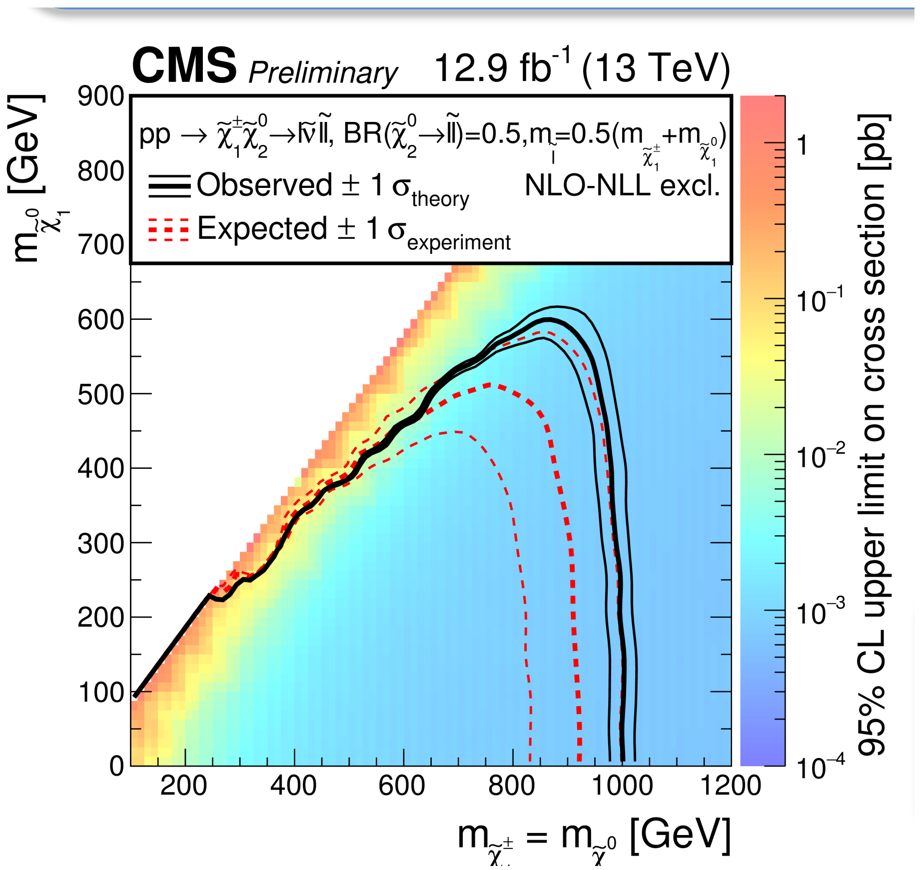
Supersymmetry/LHC 13

Chargino / neutralino production



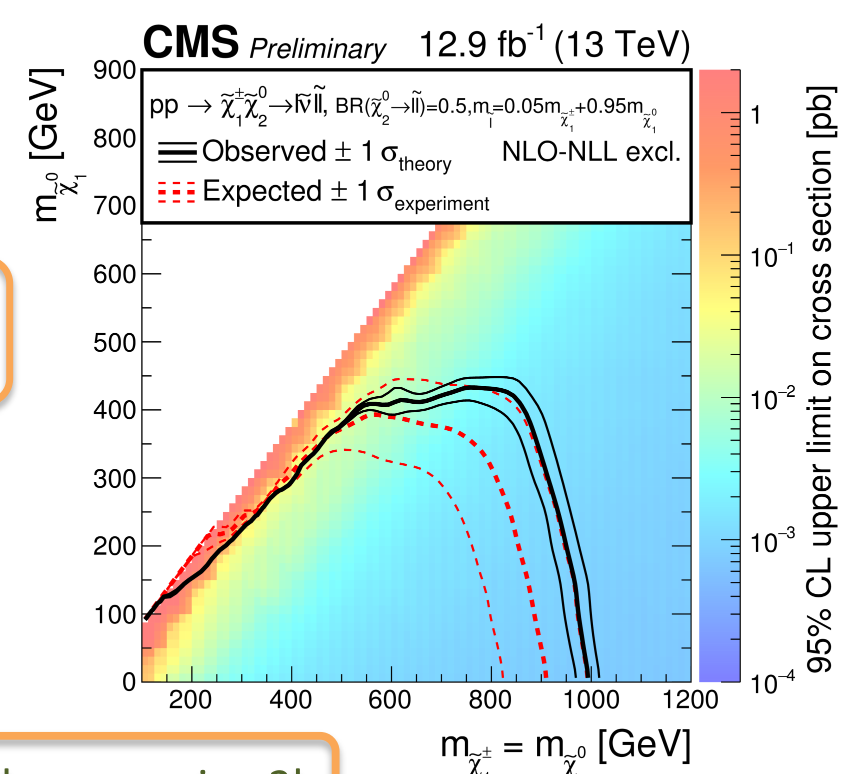
Direct production of "electroweakino" pairs

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



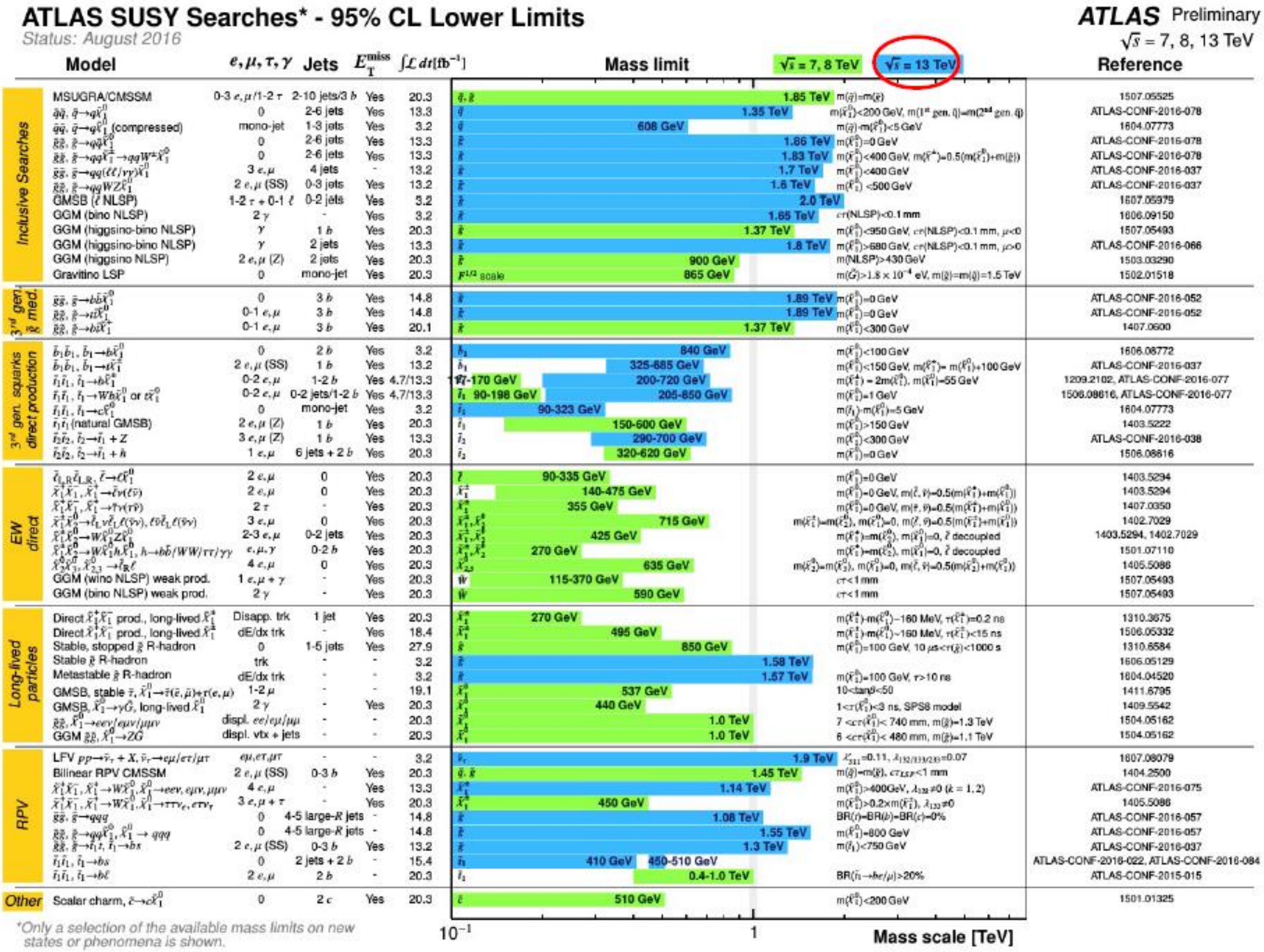
Effect of change in intermediate slepton mass

↔



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→qχ̃1^0 | 0 | 2-6 jets | Yes | 13.3 | 1.35 TeV | m(χ̃1^0)<200 GeV, m(1st gen. q̃)=m(2nd gen. q̃) | ATLAS-CONF-2016-078
q̃q̃, q̃→qχ̃1^0 (compressed) | mono-jet | 1-3 jets | Yes | 3.2 | 608 GeV | m(q̃)-m(χ̃1^0)<5 GeV | 1604.07773
g̃g̃, g̃→qq̄χ̃1^0 | 0 | 2-6 jets | Yes | 13.3 | 1.86 TeV | m(χ̃1^0)=0 GeV | ATLAS-CONF-2016-078
g̃g̃, g̃→qqχ̃1^±→qqW^±χ̃1^0 | 0 | 2-6 jets | Yes | 13.3 | 1.83 TeV | m(χ̃1^0)<400 GeV, m(χ̃^±)=0.5(m(χ̃1^0)+m(g̃)) | ATLAS-CONF-2016-078
g̃g̃, g̃→qq(ℓℓ/νν)χ̃1^0 | 3 e,μ | 4 jets | - | 13.2 | 1.7 TeV | m(χ̃1^0)<400 GeV | ATLAS-CONF-2016-037
g̃g̃, g̃→qqWZχ̃1^0 | 2 e,μ (SS) | 0-3 jets | Yes | 13.2 | 1.6 TeV | m(χ̃1^0) <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 | m(χ̃1^0)<950 GeV, cτ(NLSP)<0.1 mm, μ<0 | 1507.05493
GGM (higgsino-bino NLSP) | γ | 2 jets | Yes | 13.3 | 1.8 TeV | m(χ̃1^0)>680 GeV, cτ(NLSP)<0.1 mm, μ>0 | 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 | F^1/2 scale | 865 GeV | m(G̃)>1.8 × 10^-4 eV, m(g̃)=m(q̃)=1.5 TeV | 1502.01518
3rd gen. g̃ med.
g̃g̃, g̃→bb̄χ̃1^0 | 0 | 3 b | Yes | 14.8 | 1.89 TeV | m(χ̃1^0)=0 GeV | ATLAS-CONF-2016-052
g̃g̃, g̃→tt̄χ̃1^0 | 0-1 e,μ | 3 b | Yes | 14.8 | 1.89 TeV | m(χ̃1^0)=0 GeV | ATLAS-CONF-2016-052
g̃g̃, g̃→bt̄χ̃1^+ | 0-1 e,μ | 3 b | Yes | 20.1 | 1.37 TeV | m(χ̃1^0)<300 GeV | 1407.0600
3rd gen. squarks direct production
b̃1b̃1, b̃1→bχ̃1^0 | 0 | 2 b | Yes | 3.2 | 840 GeV | m(χ̃1^0)<100 GeV | 1606.08772
b̃1b̃1, b̃1→tχ̃1^± | 2 e,μ (SS) | 1 b | Yes | 13.2 | 325-685 GeV | m(χ̃1^0)<150 GeV, m(χ̃1^±)= m(χ̃1^0)+100 GeV | ATLAS-CONF-2016-037
t̃1t̃1, t̃1→bχ̃1^± | 0-2 e,μ | 1-2 b | Yes | 4.7/13.3 | 117-170 GeV | 200-720 GeV | m(χ̃1^±) = 2m(χ̃1^0), m(χ̃1^0)=55 GeV | 1209.2102, ATLAS-CONF-2016-077
t̃1t̃1, t̃1→Wbχ̃1^0 or tχ̃1^0 | 0-2 e,μ | 0-2 jets/1-2 b | Yes | 4.7/13.3 | 90-198 GeV | 205-850 GeV | m(χ̃1^0)=1 GeV | 1506.08616, ATLAS-CONF-2016-077
t̃1t̃1, t̃1→cχ̃1^0 | 0 | mono-jet | Yes | 3.2 | 90-323 GeV | m(t̃1)-m(χ̃1^0)=5 GeV | 1604.07773
t̃1t̃1 (natural GMSB) | 2 e,μ (Z) | 1 b | Yes | 20.3 | 150-600 GeV | m(χ̃1^0)>150 GeV | 1403.5222
t̃2t̃2, t̃2→t̃1 + Z | 3 e,μ (Z) | 1 b | Yes | 13.3 | 290-700 GeV | m(χ̃1^0)<300 GeV | ATLAS-CONF-2016-038
t̃2t̃2, t̃2→t̃1 + h | 1 e,μ | 6 jets + 2 b | Yes | 20.3 | 320-620 GeV | m(χ̃1^0)=0 GeV | 1506.08616
EW direct
ℓ̃L,Rℓ̃L,R, ℓ̃→ℓχ̃1^0 | 2 e,μ | 0 | Yes | 20.3 | 90-335 GeV | m(χ̃1^0)=0 GeV | 1403.5294
χ̃1^+χ̃1^-, χ̃1^+→ℓ̃ν(ℓν̃) | 2 e,μ | 0 | Yes | 20.3 | 140-475 GeV | m(χ̃1^0)=0 GeV, m(ℓ̃, ν̃)=0.5(m(χ̃1^±)+m(χ̃1^0)) | 1403.5294
χ̃1^±χ̃1^∓, χ̃1^+→τ̃ν(τν̃) | 2 τ | - | Yes | 20.3 | 355 GeV | m(χ̃1^0)=0 GeV, m(τ̃, ν̃)=0.5(m(χ̃1^±)+m(χ̃1^0)) | 1407.0350
χ̃1^±χ̃2^0→ℓ̃Lνℓ̃Lℓ(ν̃ν), ℓν̃ℓ̃Lℓ(ν̃ν) | 3 e,μ | 0 | Yes | 20.3 | 715 GeV | m(χ̃1^±)=m(χ̃2^0), m(χ̃1^0)=0, m(ℓ̃, ν̃)=0.5(m(χ̃1^±)+m(χ̃1^0)) | 1402.7029
χ̃1^±χ̃2^0→Wχ̃1^0Zχ̃1^0 | 2-3 e,μ | 0-2 jets | Yes | 20.3 | 425 GeV | m(χ̃1^±)=m(χ̃2^0), m(χ̃1^0)=0, ℓ̃ decoupled | 1403.5294, 1402.7029
χ̃1^±χ̃2^0→Wχ̃1^0hχ̃1^0, h→bb̄/WW/ττ/γγ | e,μ,γ | 0-2 b | Yes | 20.3 | 270 GeV | m(χ̃1^±)=m(χ̃2^0), m(χ̃1^0)=0, ℓ̃ decoupled | 1501.07110
χ̃2^0χ̃3^0, χ̃2,3^0→ℓ̃Rℓ | 4 e,μ | 0 | Yes | 20.3 | 635 GeV | m(χ̃2^0)=m(χ̃3^0), m(χ̃1^0)=0, m(ℓ̃, ν̃)=0.5(m(χ̃2^0)+m(χ̃1^0)) | 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 χ̃1^+χ̃1^- prod., long-lived χ̃1^± | Disapp. trk | 1 jet | Yes | 20.3 | 270 GeV | m(χ̃1^±)-m(χ̃1^0)~160 MeV, τ(χ̃1^±)=0.2 ns | 1310.3675
Direct χ̃1^+χ̃1^- prod., long-lived χ̃1^± | dE/dx trk | - | Yes | 18.4 | 495 GeV | m(χ̃1^±)-m(χ̃1^0)~160 MeV, τ(χ̃1^±)<15 ns | 1506.05332
Stable, stopped g̃ R-hadron | 0 | 1-5 jets | Yes | 27.9 | 850 GeV | m(χ̃1^0)=100 GeV, 10 μs<τ(g̃)<1000 s | 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 | m(χ̃1^0)=100 GeV, τ>10 ns | 1604.04520
GMSB, stable τ̃, χ̃1^0→τ̃(ẽ, μ̃)+τ(e, μ) | 1-2 μ | - | - | 19.1 | 537 GeV | 10<tanβ<50 | 1411.6795
GMSB, χ̃1^0→γG̃, long-lived χ̃1^0 | 2 γ | - | Yes | 20.3 | 440 GeV | 1<τ(χ̃1^0)<3 ns, SPS8 model | 1409.5542
g̃g̃, χ̃1^0→eeν/eμν/μμν | displ. ee/eμ/μμ | - | - | 20.3 | 1.0 TeV | 7 <cτ(χ̃1^0)< 740 mm, m(g̃)=1.3 TeV | 1504.05162
GGM g̃g̃, χ̃1^0→ZG̃ | displ. vtx + jets | - | - | 20.3 | 1.0 TeV | 6 <cτ(χ̃1^0)< 480 mm, m(g̃)=1.1 TeV | 1504.05162
RPV
LFV pp→ν̃τ + X, ν̃τ→eμ/eτ/μτ | eμ,eτ,μτ | - | - | 3.2 | 1.9 TeV | λ'311=0.11, λ132/133/233=0.07 | 1607.08079
Bilinear RPV CMSSM | 2 e,μ (SS) | 0-3 b | Yes | 20.3 | 1.45 TeV | m(q̃)=m(g̃), cτLSP<1 mm | 1404.2500
χ̃1^+χ̃1^-, χ̃1^+→Wχ̃1^0, χ̃1^0→eeν, eμν, μμν | 4 e,μ | - | Yes | 13.3 | 1.14 TeV | m(χ̃1^0)>400GeV, λ12k≠0 (k = 1, 2) | ATLAS-CONF-2016-075
χ̃1^+χ̃1^-, χ̃1^+→Wχ̃1^0, χ̃1^0→ττνe, eτντ | 3 e,μ + τ | - | Yes | 20.3 | 450 GeV | m(χ̃1^0)>0.2×m(χ̃1^±), λ133≠0 | 1405.5086
g̃g̃, g̃→qqq | 0 | 4-5 large-R jets | - | 14.8 | 1.08 TeV | BR(t)=BR(b)=BR(c)=0% | ATLAS-CONF-2016-057
g̃g̃, g̃→qqχ̃1^0, χ̃1^0 → qqq | 0 | 4-5 large-R jets | - | 14.8 | 1.55 TeV | m(χ̃1^0)=800 GeV | ATLAS-CONF-2016-057
g̃g̃, g̃→t̃1t, t̃1→bs | 2 e,μ (SS) | 0-3 b | Yes | 13.2 | 1.3 TeV | m(t̃1)<750 GeV | ATLAS-CONF-2016-037
t̃1t̃1, t̃1→bs | 0 | 2 jets + 2 b | - | 15.4 | 410 GeV | 450-510 GeV | ATLAS-CONF-2016-022, ATLAS-CONF-2016-084
t̃1t̃1, t̃1→bℓ | 2 e,μ | 2 b | - | 20.3 | 0.4-1.0 TeV | BR(t̃1→be/μ)>20% | ATLAS-CONF-2015-015
Other
Scalar charm, c̃→cχ̃1^0 | 0 | 2 c | Yes | 20.3 | 510 GeV | m(χ̃1^0)<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]

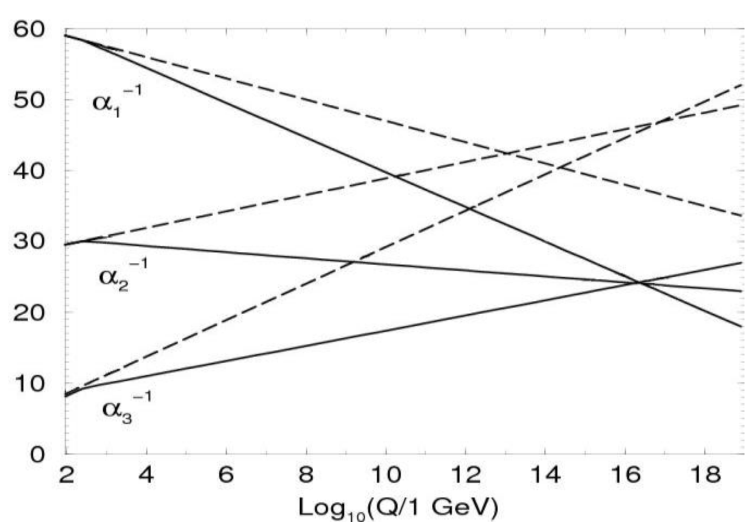
Even when we abandon the naturalness, still there are some indications that SUSY may not be too far away from the weak scale.

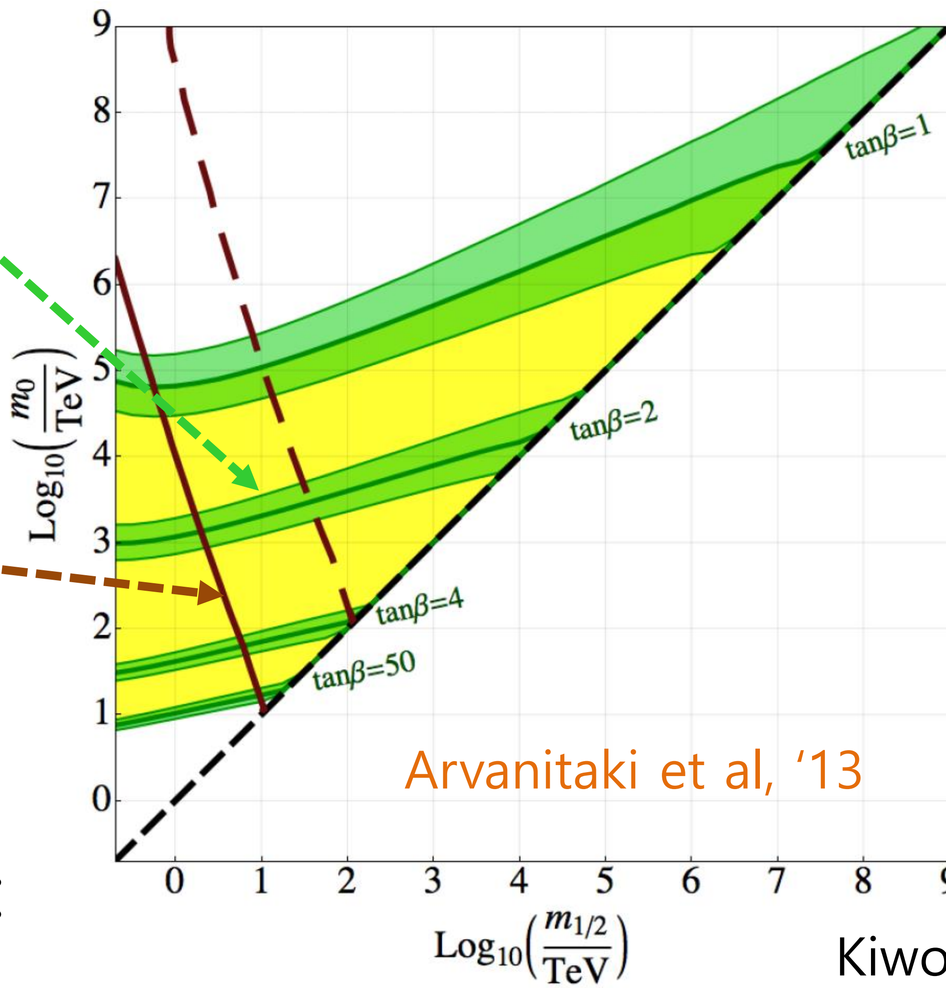
* Higgs mass = 125 GeV: $m_h^2 = M_Z^2 \cos^2 2\beta + \frac{3y_t^2 m_t^2}{4\pi^2} \ln\left(\frac{m_{\rm stop}}{m_t}\right) + \ldots$

➔ squark and slepton masses:

m_0 < 1000 TeV for tanβ > 2

* Gauge coupling unification:





➔ Higgsino and gaugino masses:

$m_{1/2}$ < 10 TeV

Kiwoon Choi

(ICHEP 2016, Chicago)

Future SUSY Searches

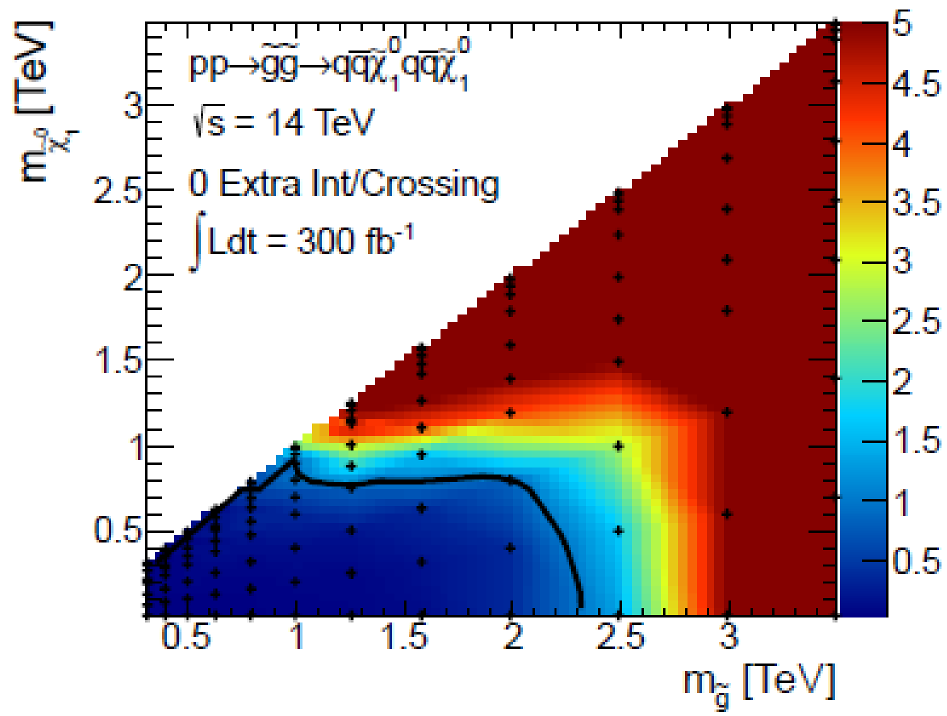
SUSY is certainly a compelling candidates of BSM physics, so we should keep searching for her without leaving any stone unturned.

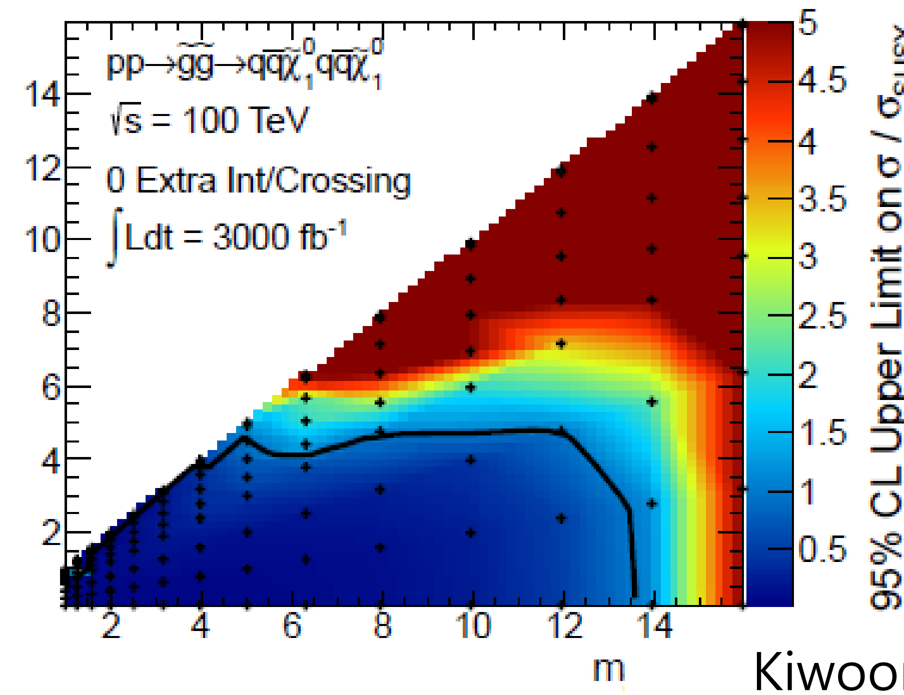
* Taking the gauge coupling unification seriously, SUSY may have some chance to be seen at LHC, and a good chance at the FCC:

High luminosity LHC

Cohen et al, '13

100 TeV collider

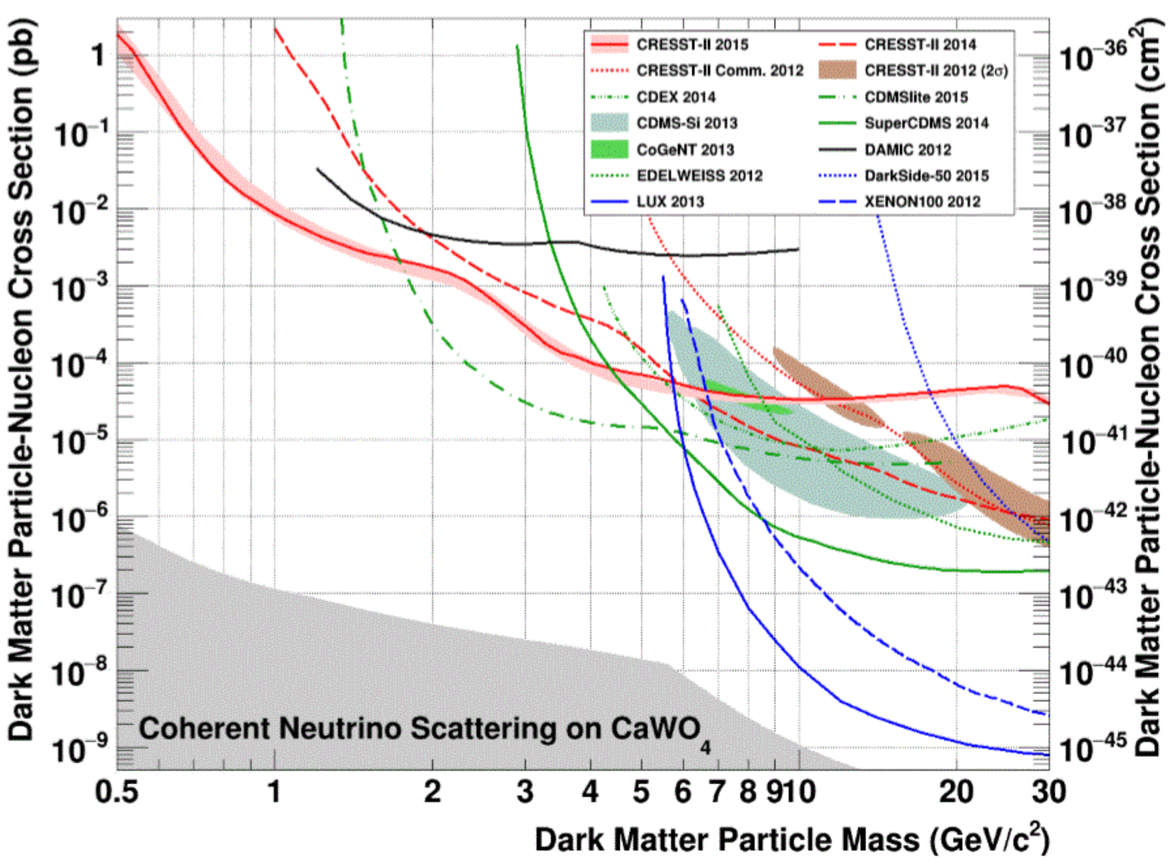




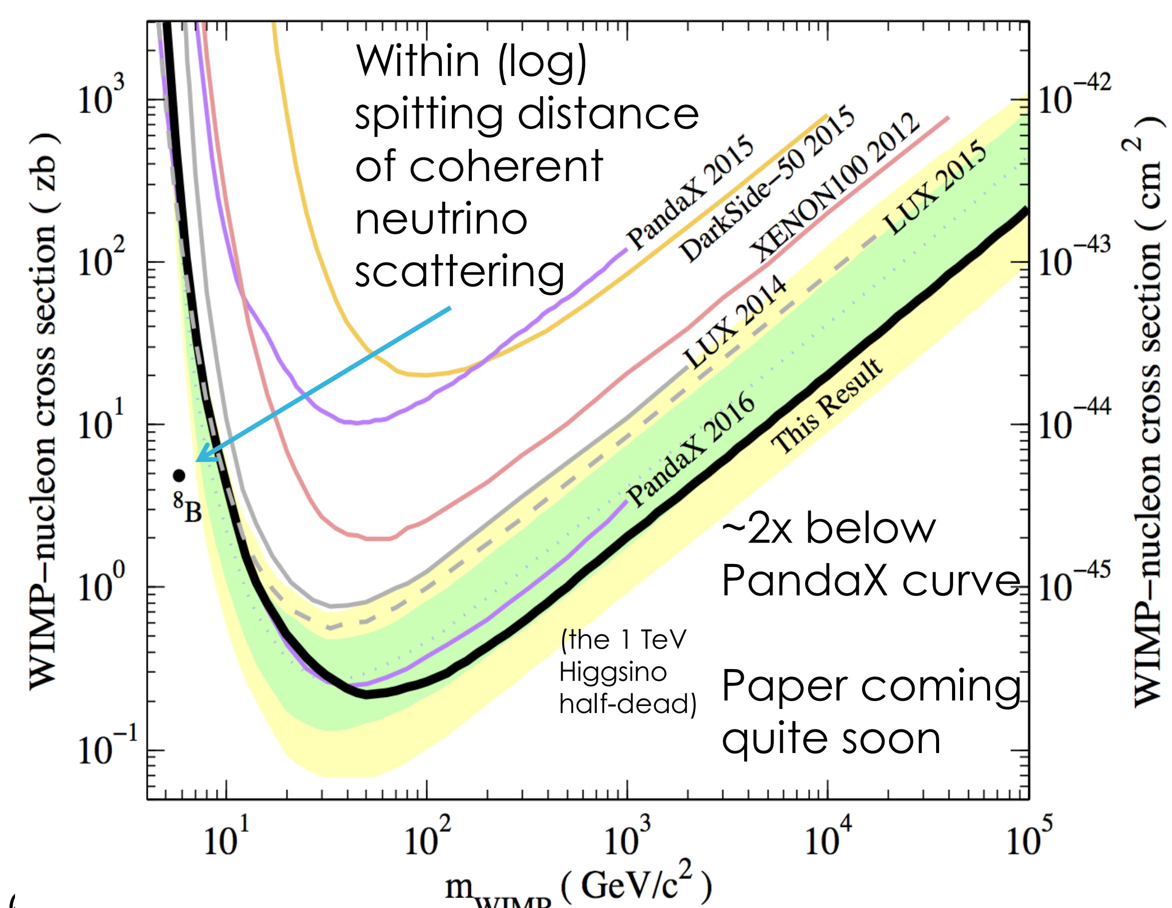
Kiwoon Choi

(ICHEP 2016, Chicago)

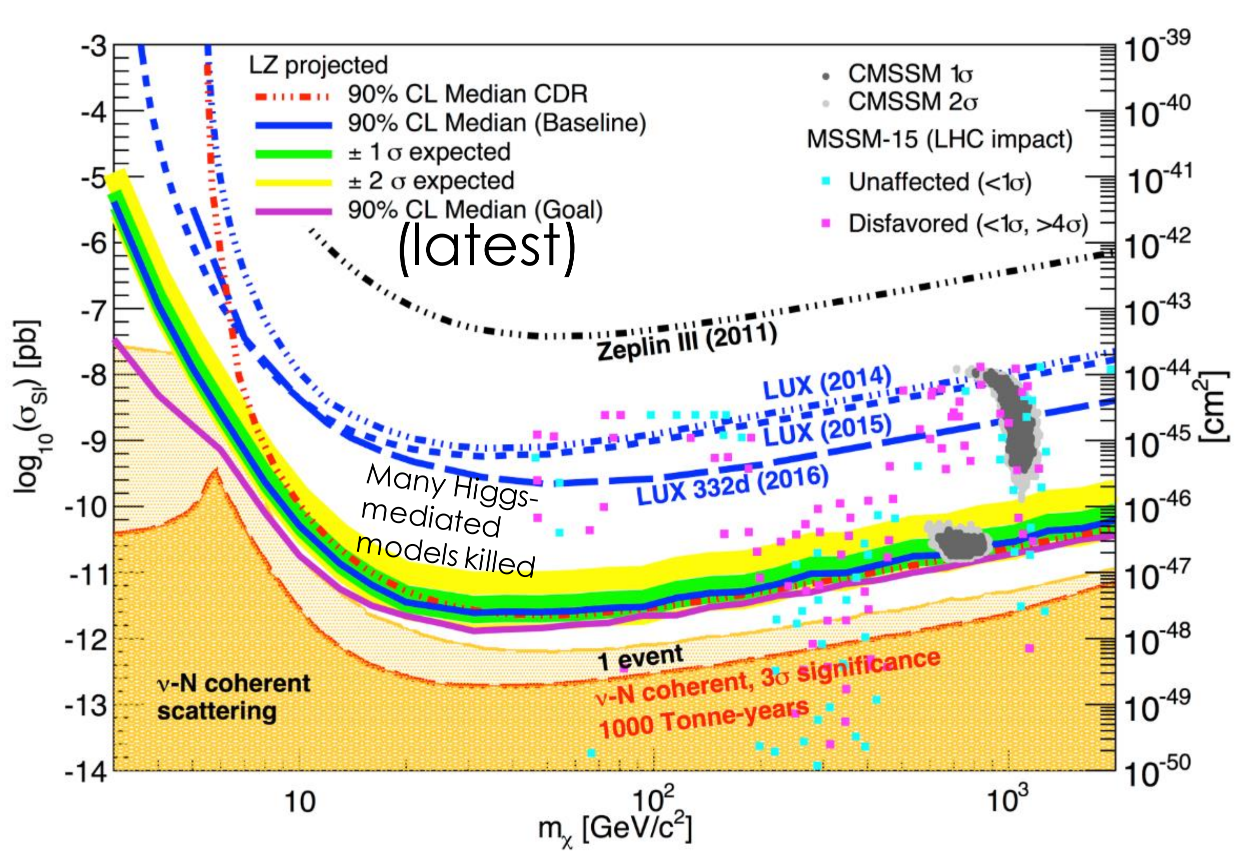
Dark Matter Searches



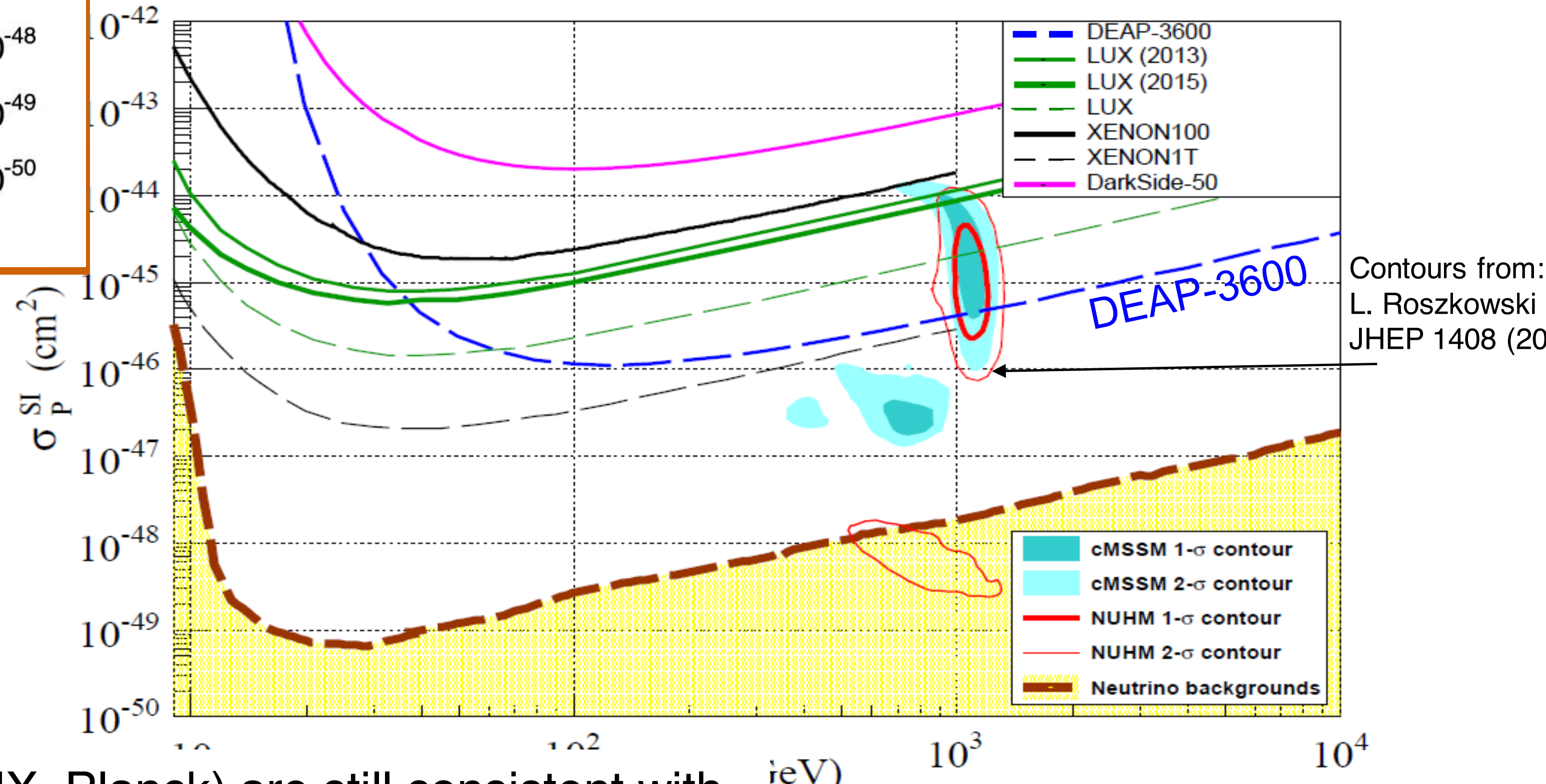
CRESST-II



Future DM Searches



Physics reach

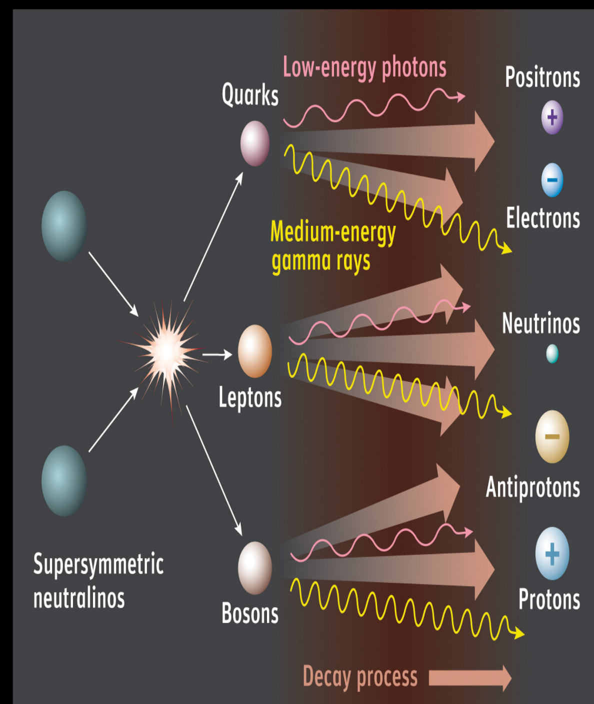


- All available experimental data combined (LHC, LUX, Planck) are still consistent with even the simplest versions of SUSY (cMSSM, NUHM)
- Remaining parameter space is directly probed by direct WIMP searches with tonne scale detectors: DEAP-3600, XENON1T, LUX/LZ
- Complementarity with LHC (cMSSM/NUHM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

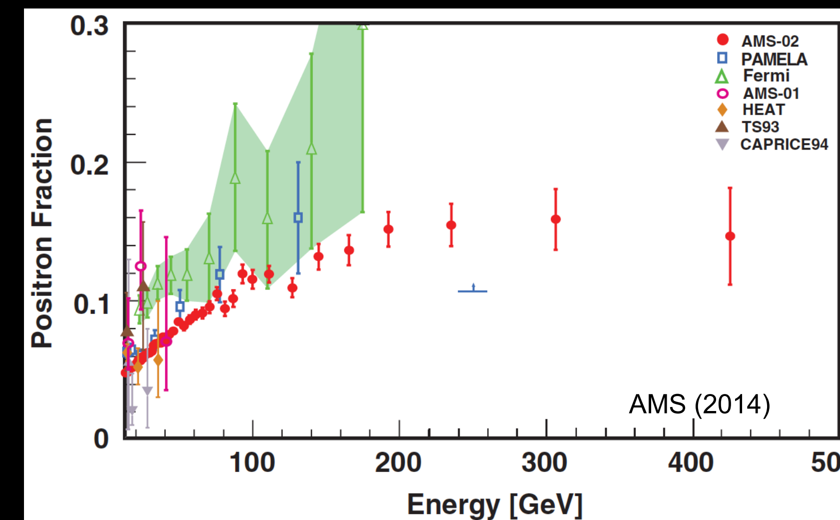
Indirect Detection of DM

INDIRECT DETECTION

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

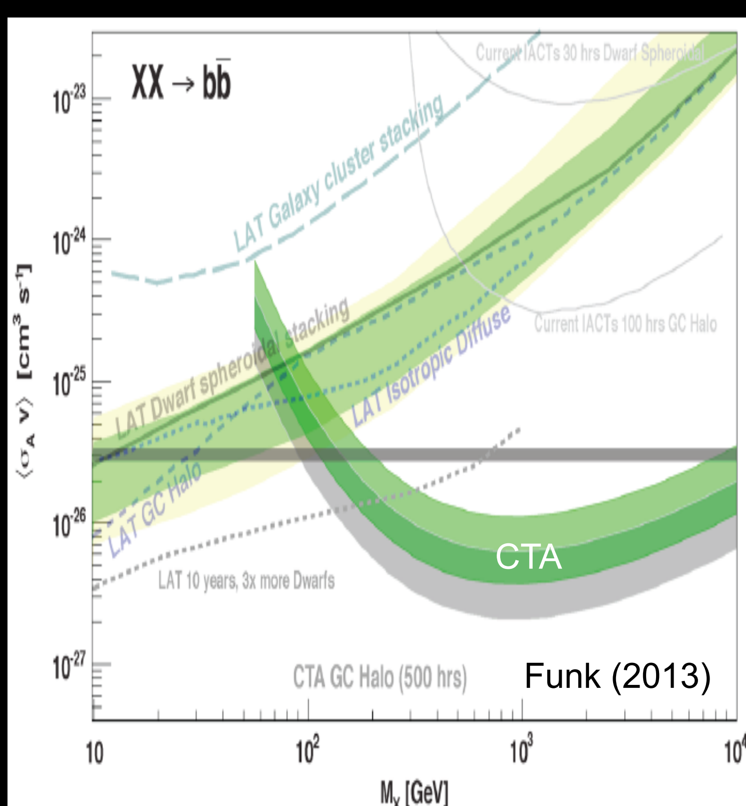


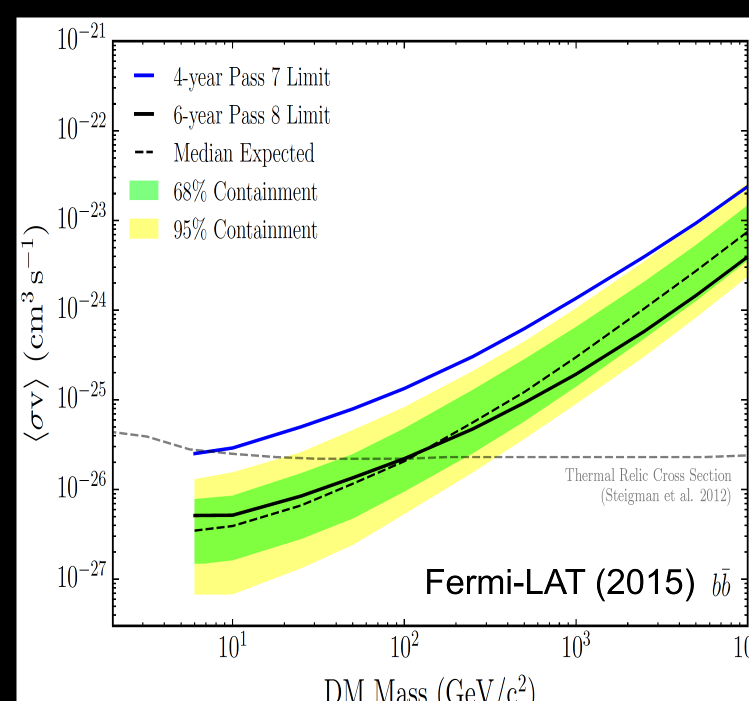
INDIRECT DM: POSITRON RESULTS



- 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

Not from the SM:
- axion (axino)
- neutralino
- sneutrino
- gravitino
- heavy photon
- heavy pseudo-goldstone
- light sterile higgs

mSUGRA

Dark Matter/New Physics

The Dark Matter is made of:

- Macro objects – Not seen
- New particles – right heavy neutrino — not favorable but possible

Not from the SM:

- axion (axino) — might be invisible (?)
- neutralino — mSUGRA — detectable in 3 spheres
- sneutrino — less theory favorable
- gravitino — might be undetectable (?)
- heavy photon
- heavy pseudo-goldstone — possible, but not related to the other models
- light sterile higgs

Dark Matter/New Physics

The Dark Matter is made of:

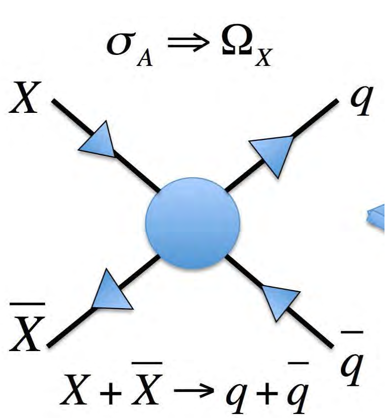
- Macro objects – Not seen
- New particles – right heavy neutrino — not favorable but possible

Not from the SM:

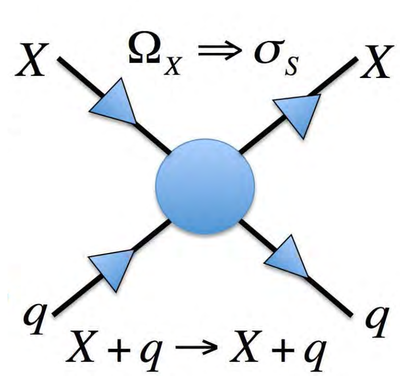
- axion (axino) — might be invisible (?)
- neutralino (mSUGRA) — detectable in 3 spheres
- sneutrino — less theory favorable
- gravitino — might be undetectable (?)
- heavy photon
- heavy pseudo-goldstone — possible, but not related to the other models
- light sterile higgs

WIMP

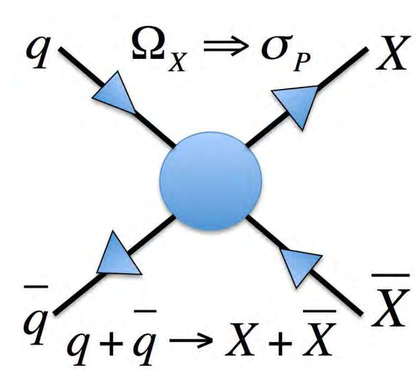
Annihilation in the halo



Scattering on a target



Creation at the LHC



Dark Matter/New Physics

The Dark Matter is made of:

- Macro objects – Not seen
- New particles – right heavy neutrino — not favorable but possible

Not from the SM:

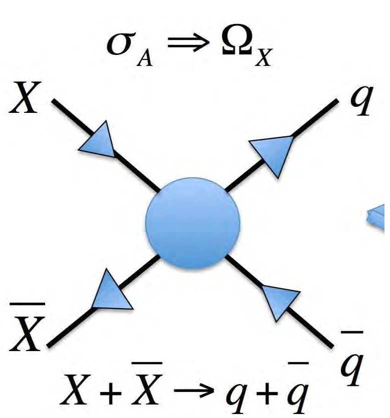
- axion (axino) — might be invisible (?)
- neutralino — mSUGRA — detectable in 3 spheres
- sneutrino — less theory favorable
- gravitino — might be undetectable (?)
- heavy photon
- heavy pseudo-goldstone
- light sterile higgs

possible, but not related to the other models

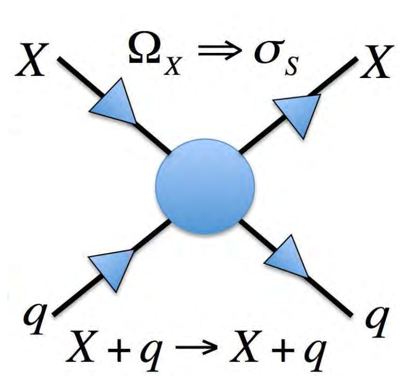
WIMP is our chance !

WIMP

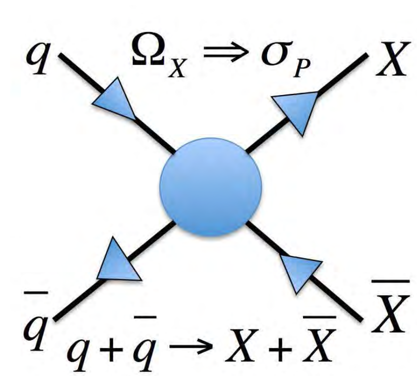
Annihilation in the halo



Scattering on a target



Creation at the LHC



Dark Matter/New Physics

The Dark Matter is made of:

- Macro objects – Not seen
- New particles – right heavy neutrino — not favorable but possible

Not from the SM:

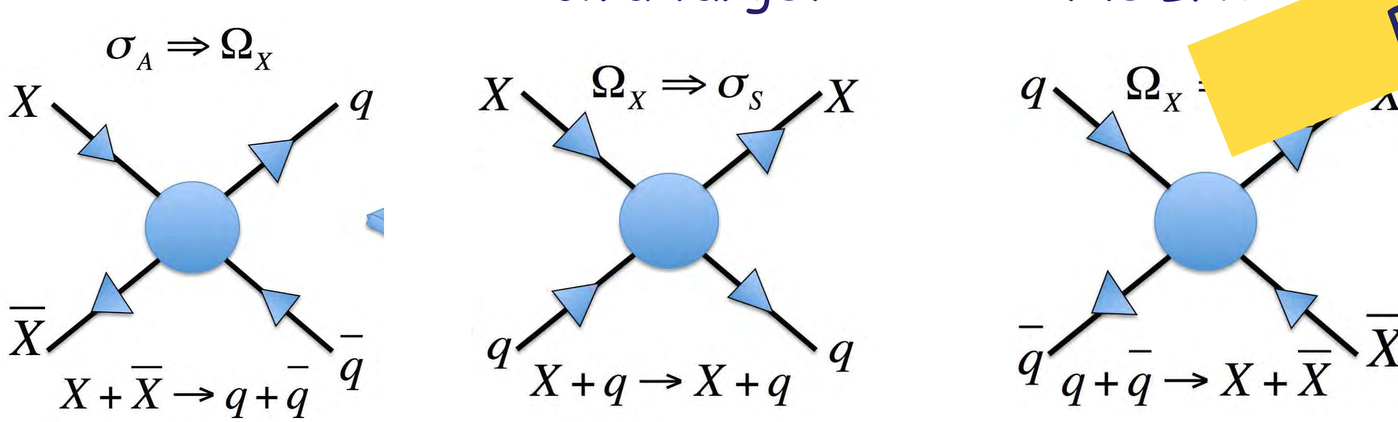
- axion (axino) — might be invisible (?)
- neutralino — mSUGRA — detectable in 3 spheres
- sneutrino — less theory favorable
- gravitino — might be undetectable (?)
- heavy photon — possible, but not related to the other models
- heavy pseudo-goldstone
- light sterile higgs

WIMP is our chance !

But we have to look elsewhere !

WIMP

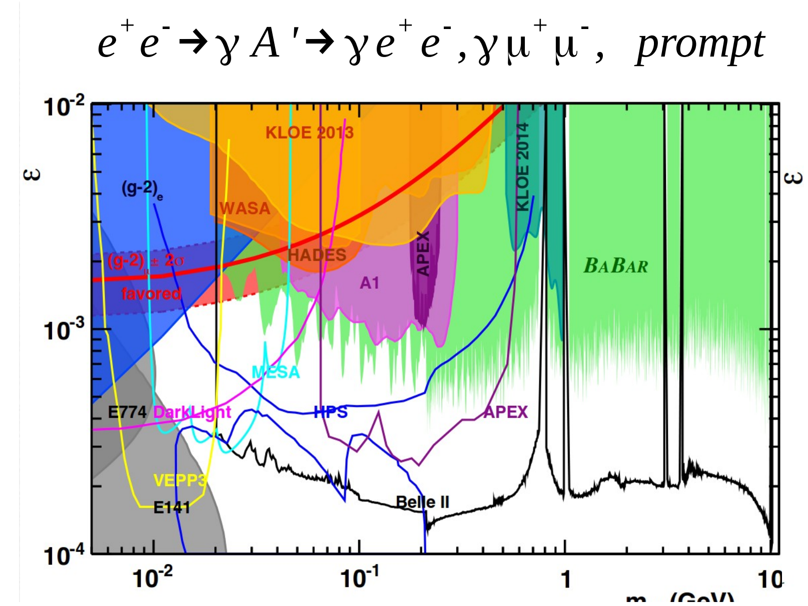
Annihilation in the halo | Scattering on a target | Creation at the LHC



Dark Matter/New Physics

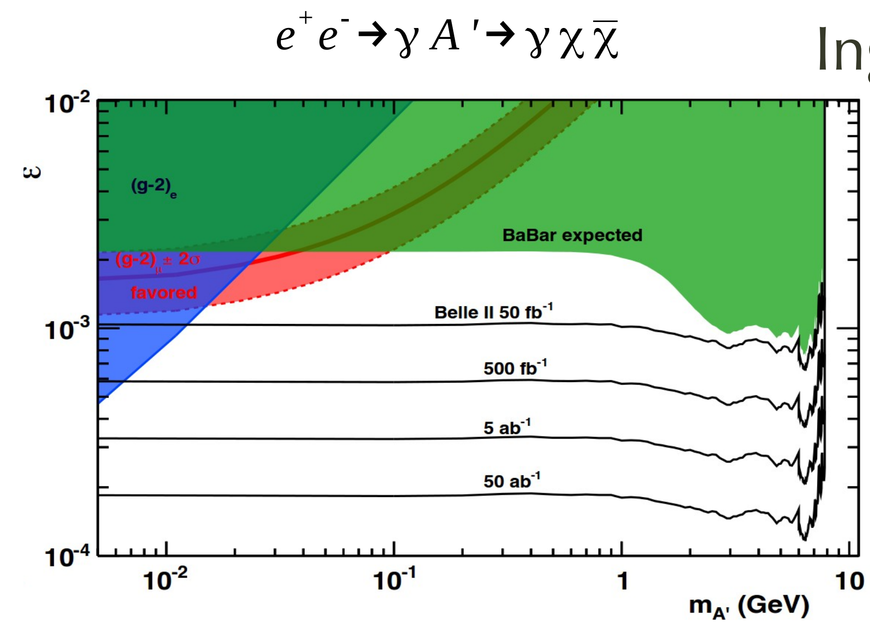
SIMPs(strong interacting massive particle)

- 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



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.



- **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.

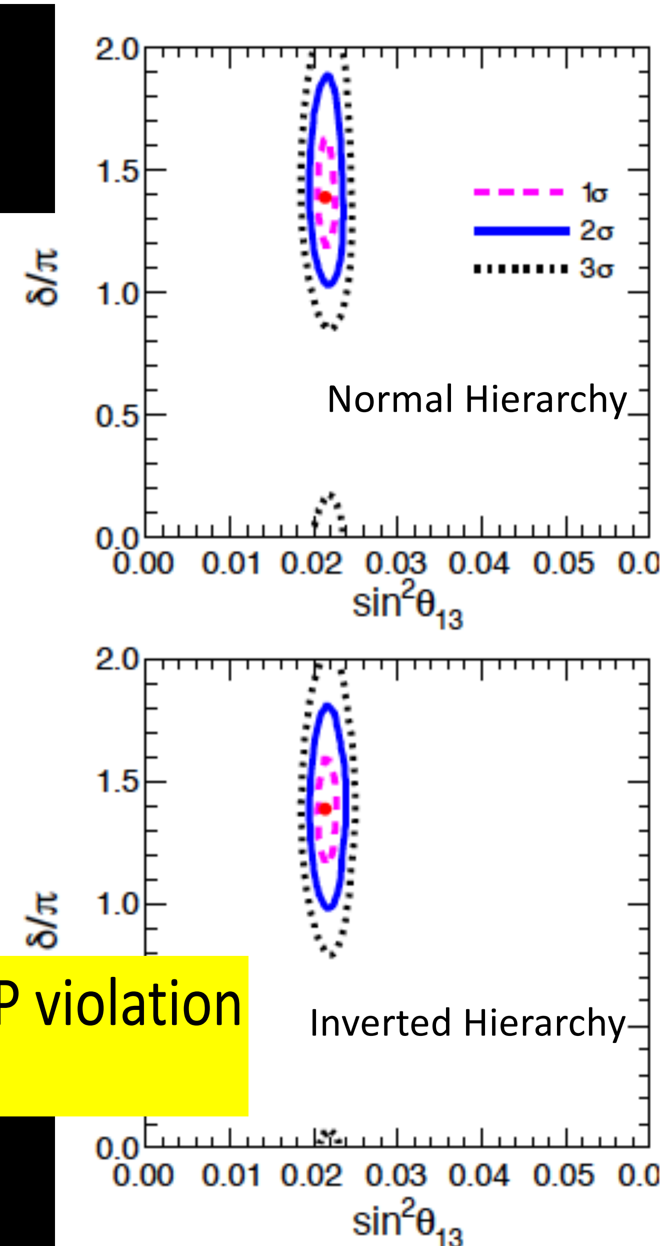
Generation 2 expts

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



Neutrino Physics

Long Baseline Experiments

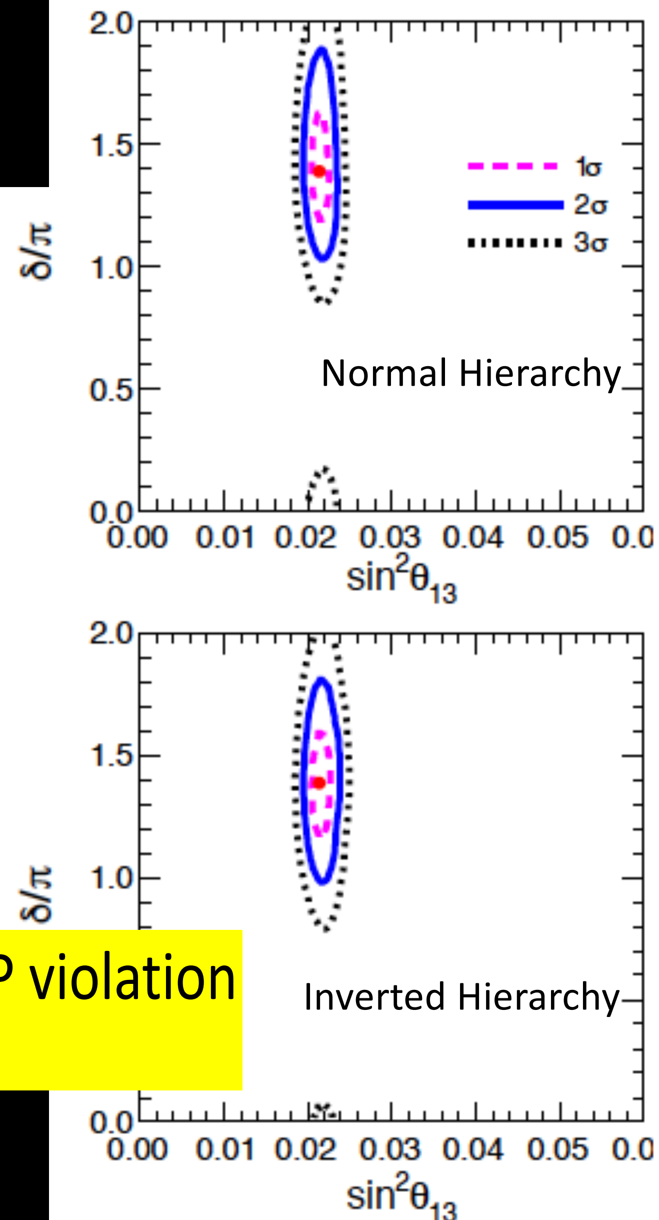
Long baseline oscillation experiments: an international campaign to test the 3-flavor paradigm, measure CP violation and go beyond.

Generation 2 expts

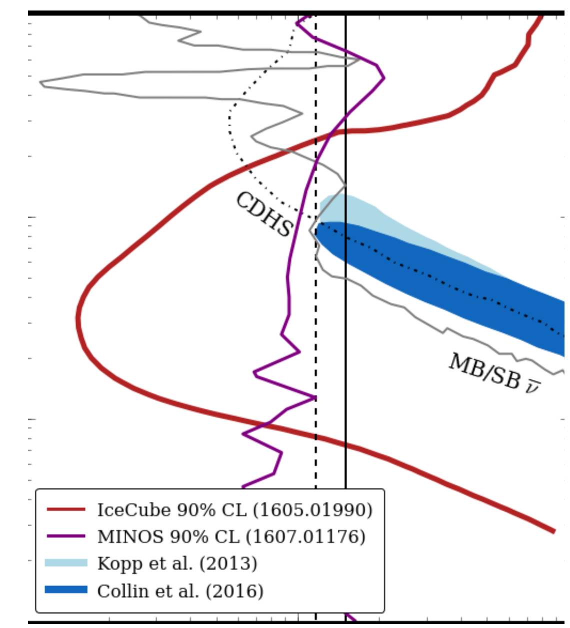
By combining with SK in a global fit
Marrone @ Neutrino 2016

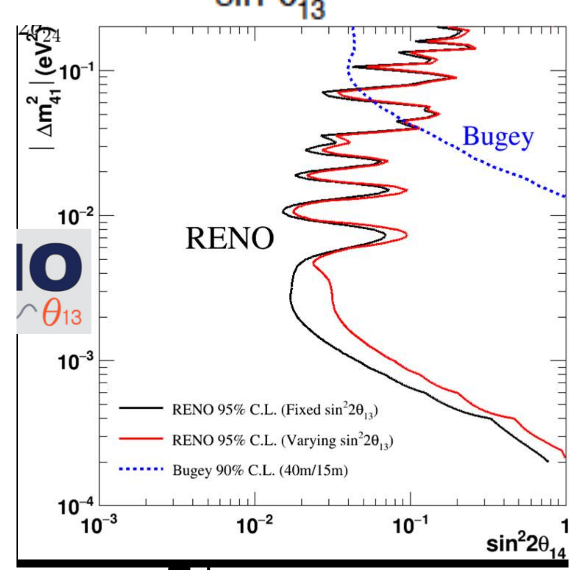
CP conservation excluded at >2 σ

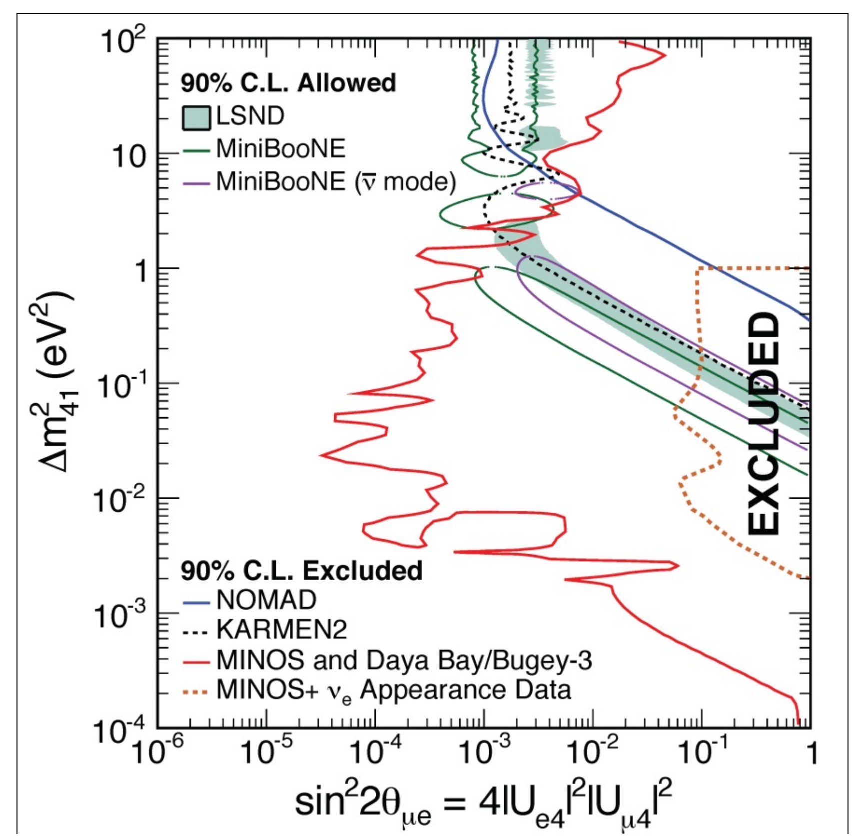
For the first time robust indication of CP violation in the leptonic sector



No evidence for sterile neutrinos







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

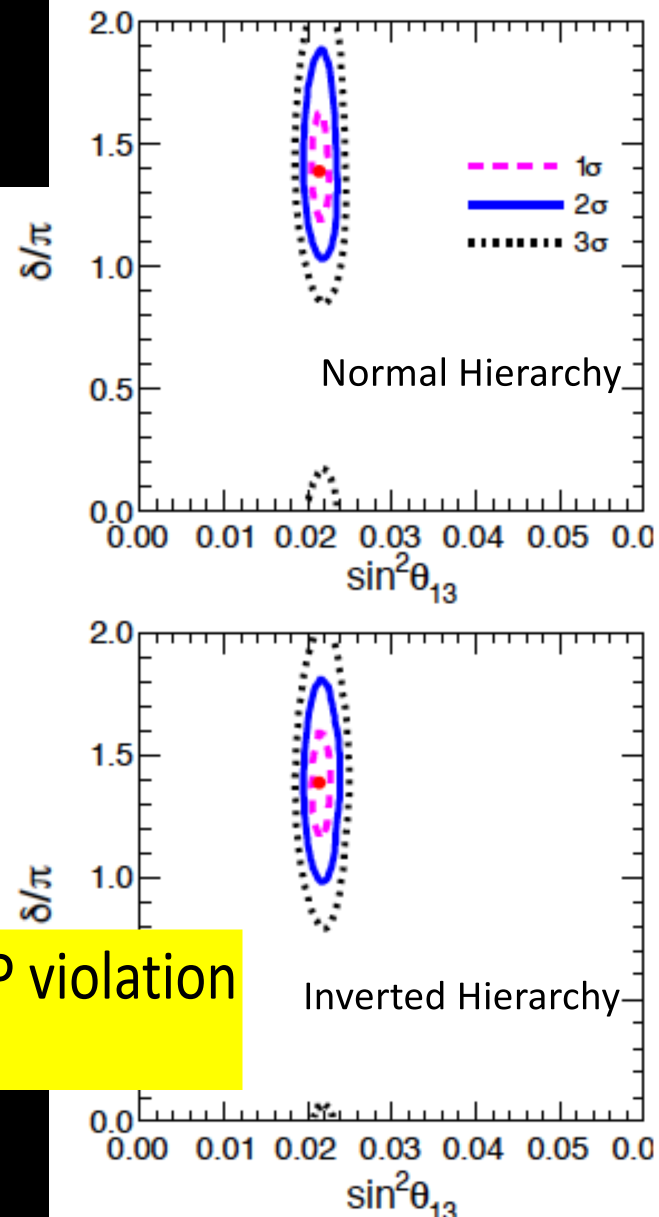
T2K NOvA

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

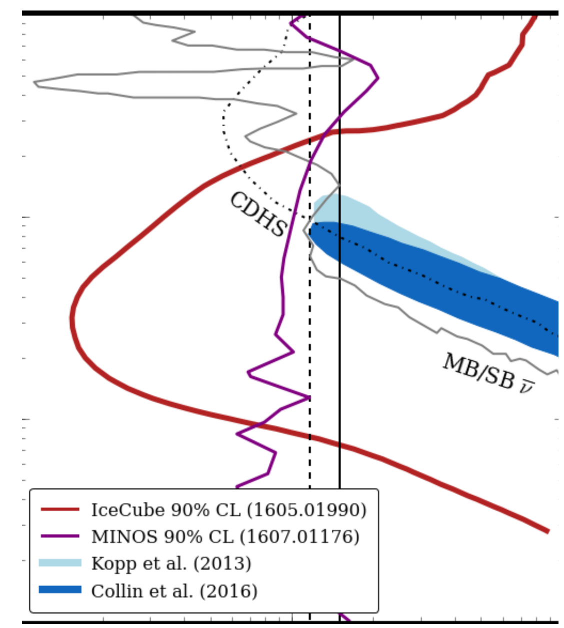
CP conservation excluded at >2 σ

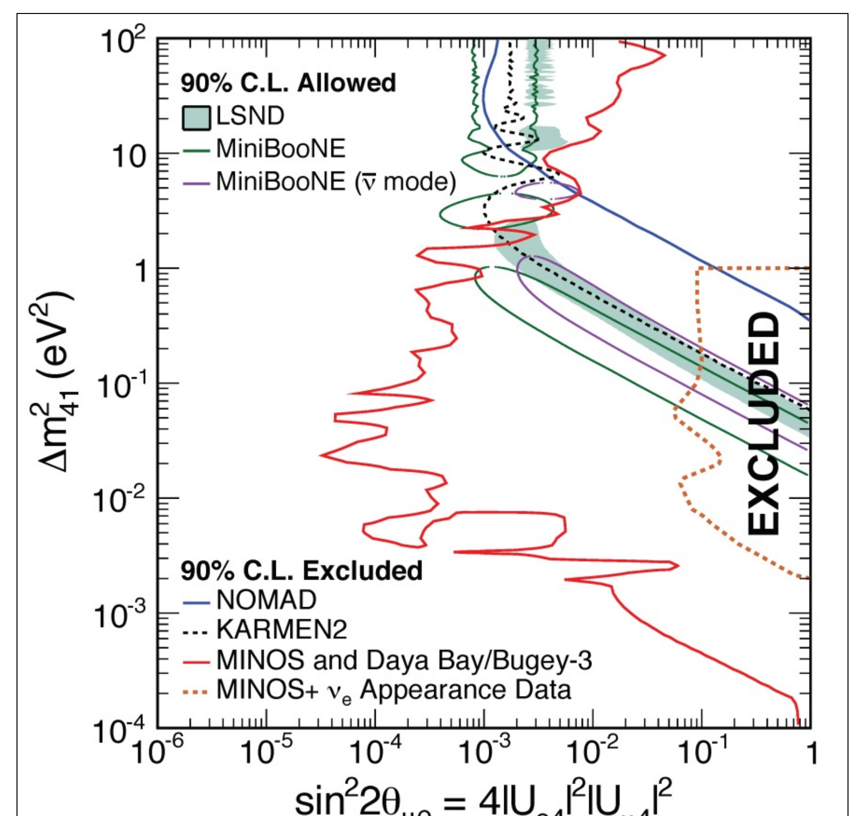
For the first time robust indication of CP violation in the leptonic sector

ICHEP 2016 -- I. Shipsey

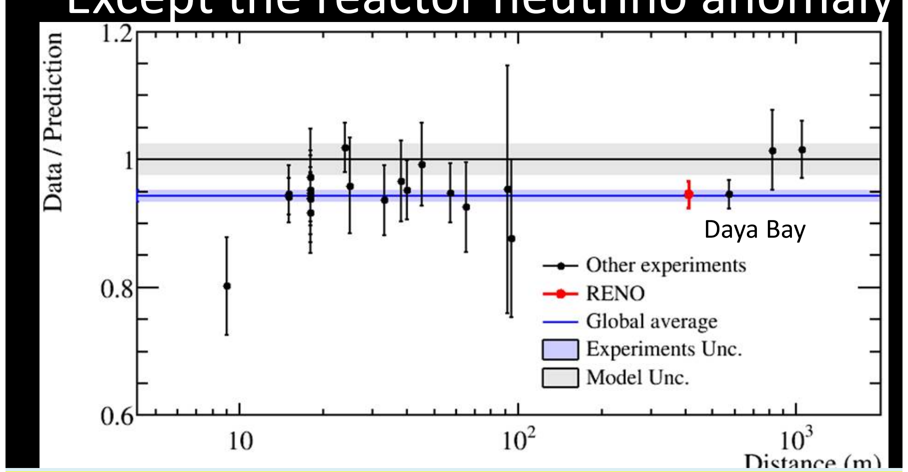


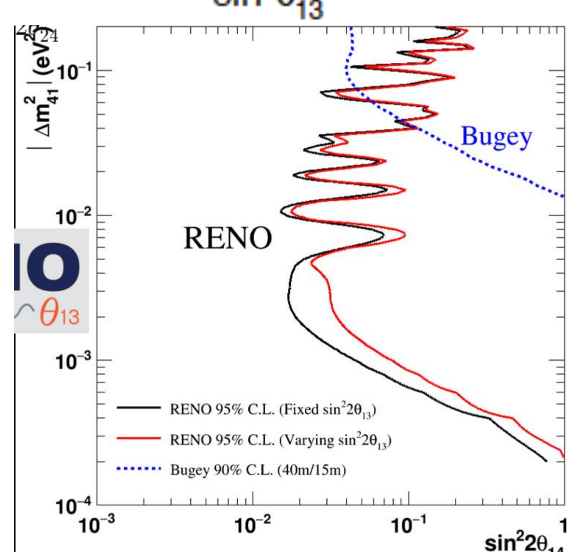
No evidence for sterile neutrinos





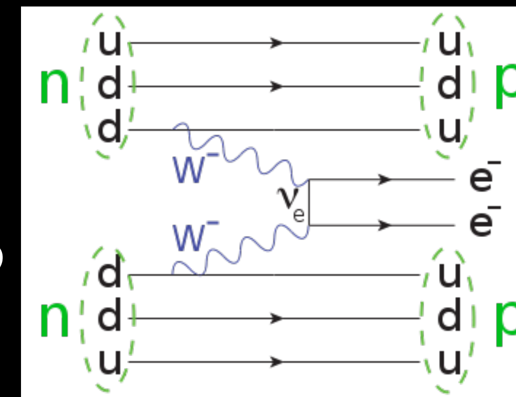
Except the reactor neutrino anomaly

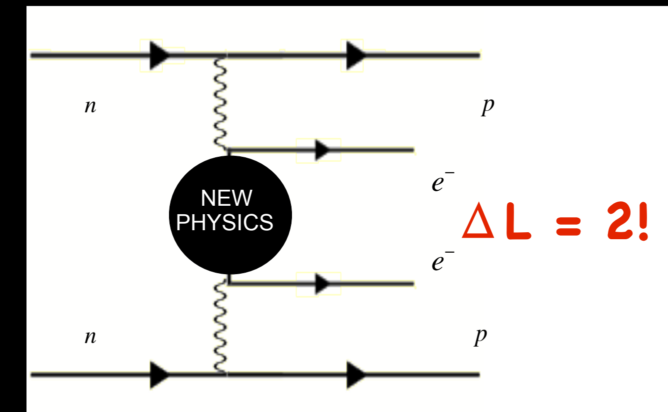




$0\beta\beta\nu$

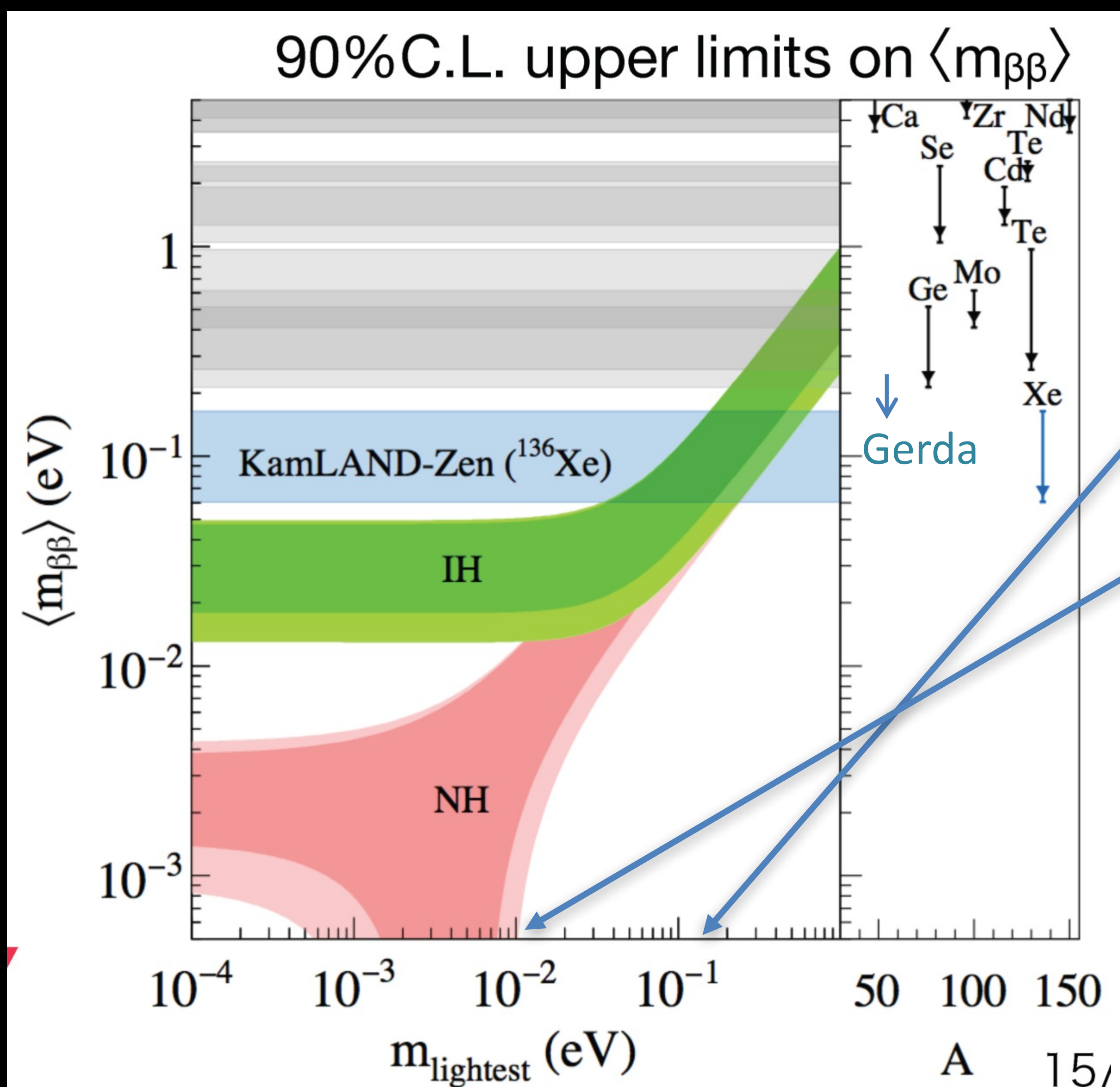
Is ν Dirac or Majorana?





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

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



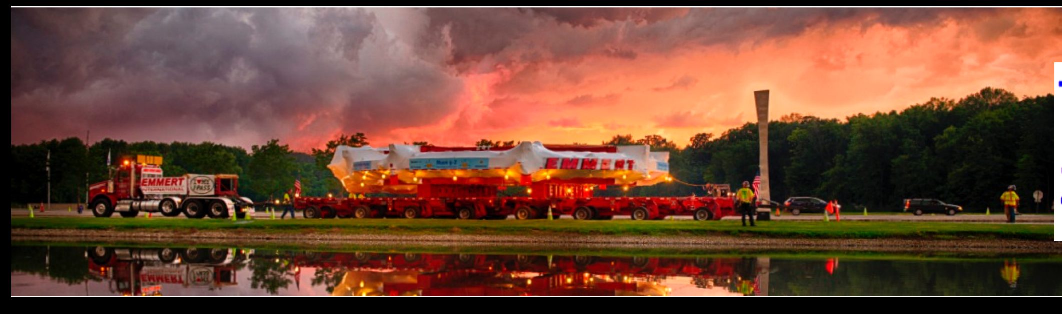
knowledge of the neutrino mixing parameters provides a firm prediction for the range of values of the parameter $m_{\beta\beta}$ in both hierarchies (NH favored)

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

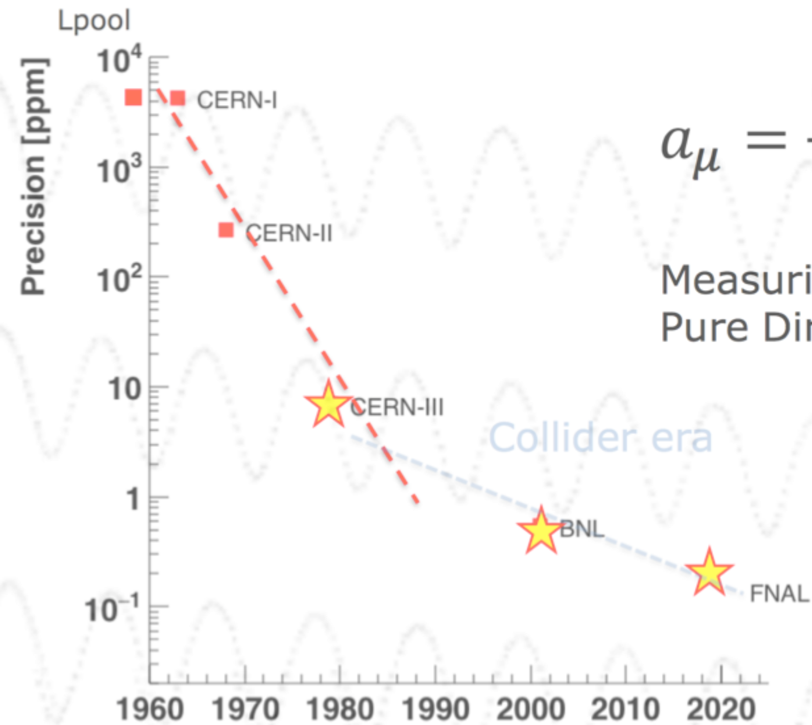
Therefore, it is timely and compelling to embark on a renewed discovery quest to observe neutrinoless double beta decay.

g-2



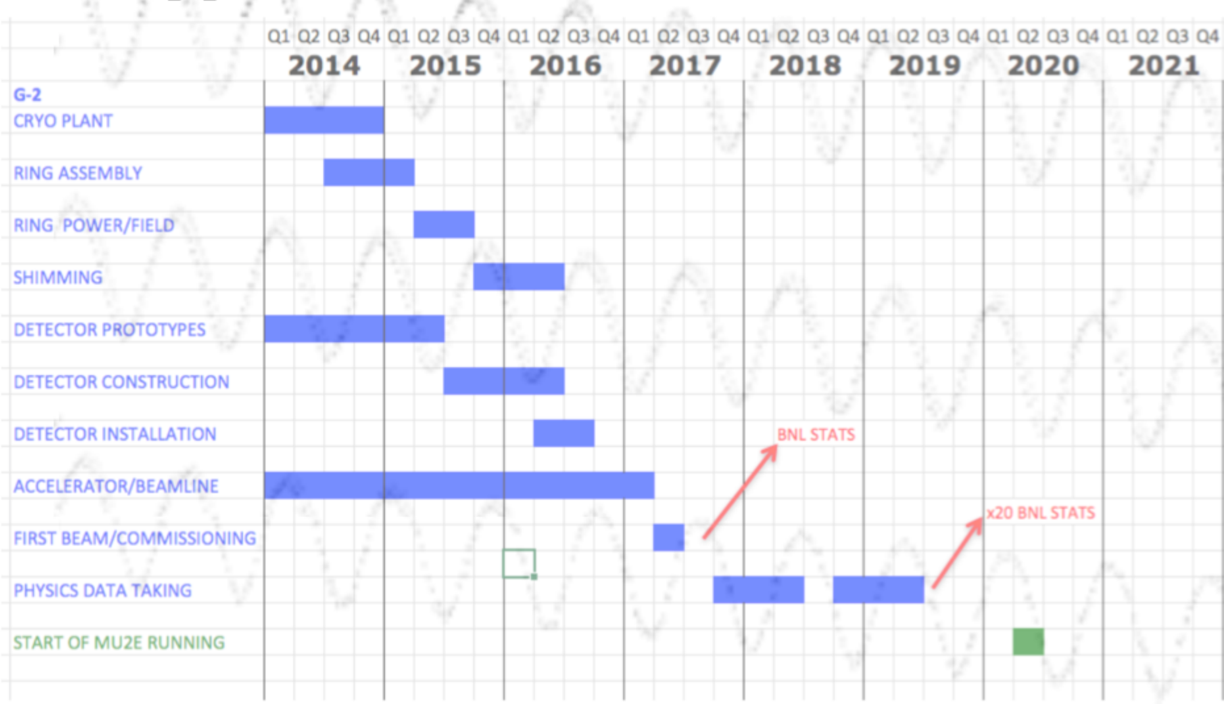
Theory: 12,672 Feynman Diagrams
2.00231930436356 ± 0.00000000000154

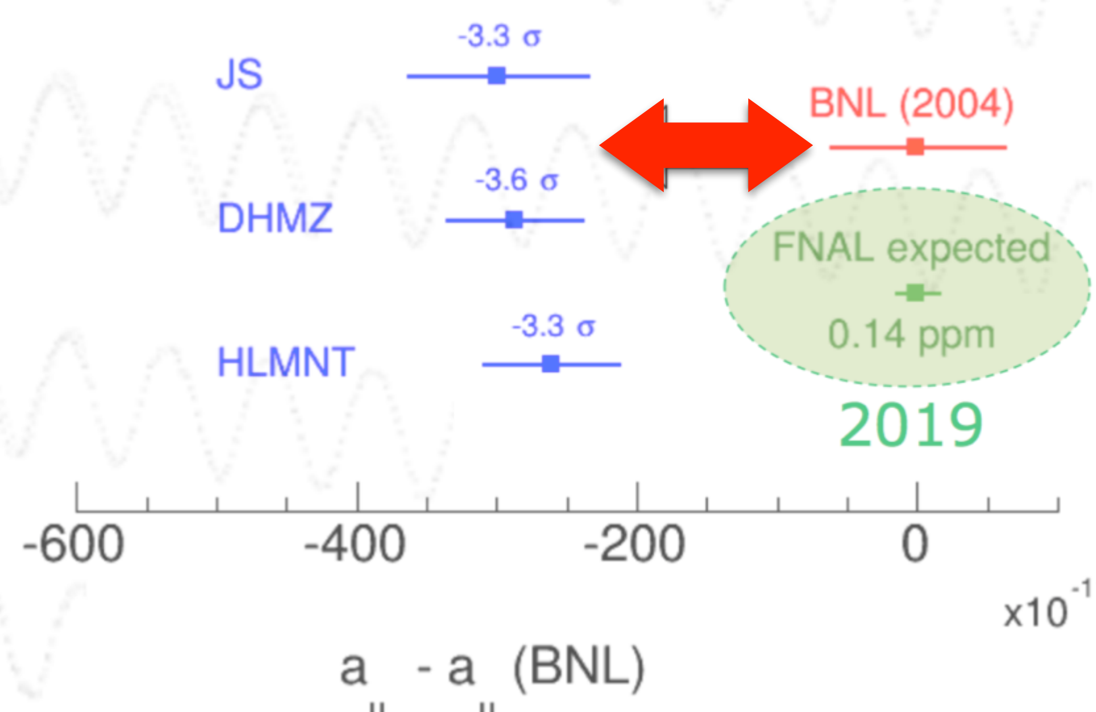
- Experiment construction on schedule and on budget.
- Improved experimental design.
- Improved simulaton.
- Aims to reduce error from 0.2ppm to 0.07ppm.



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

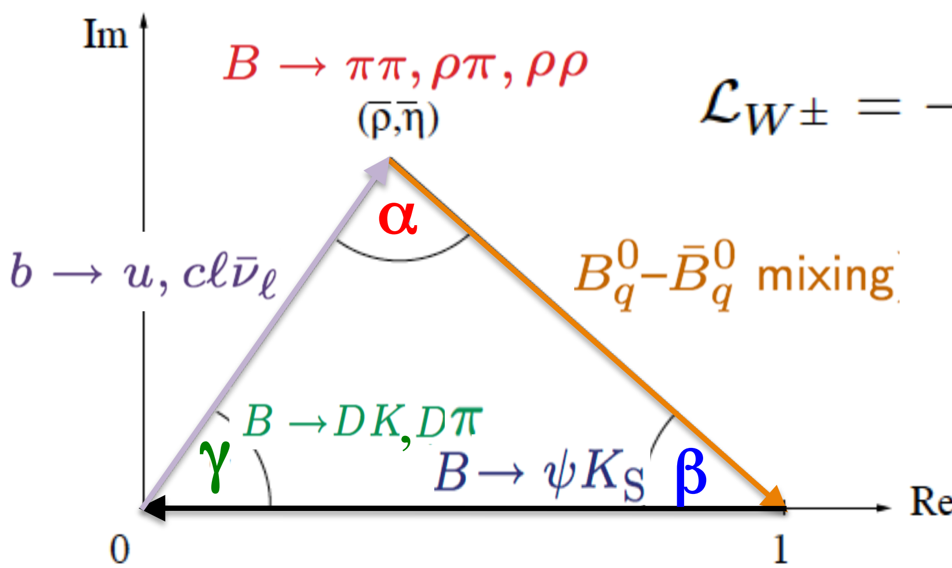
Measuring deviations from Pure Dirac prediction





The CKM Unitarity Triangle

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



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

From CKM matrix unitarity

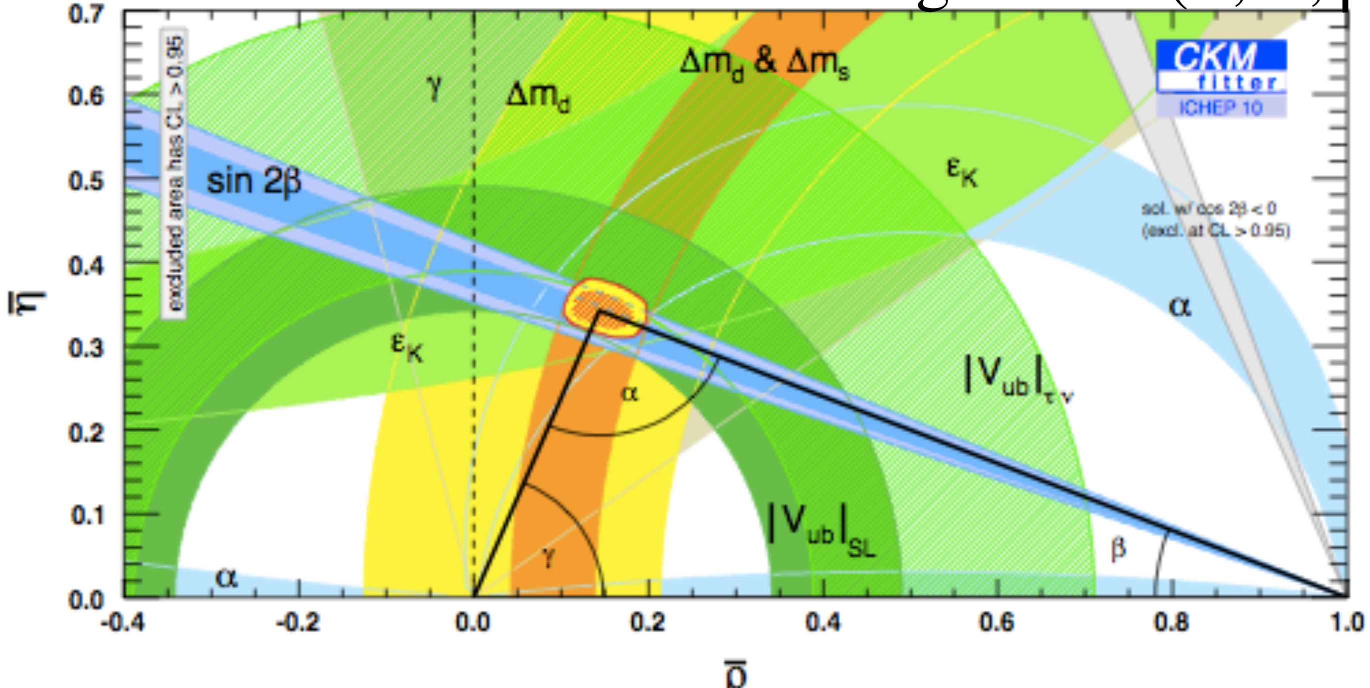
$$V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0$$

- 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)

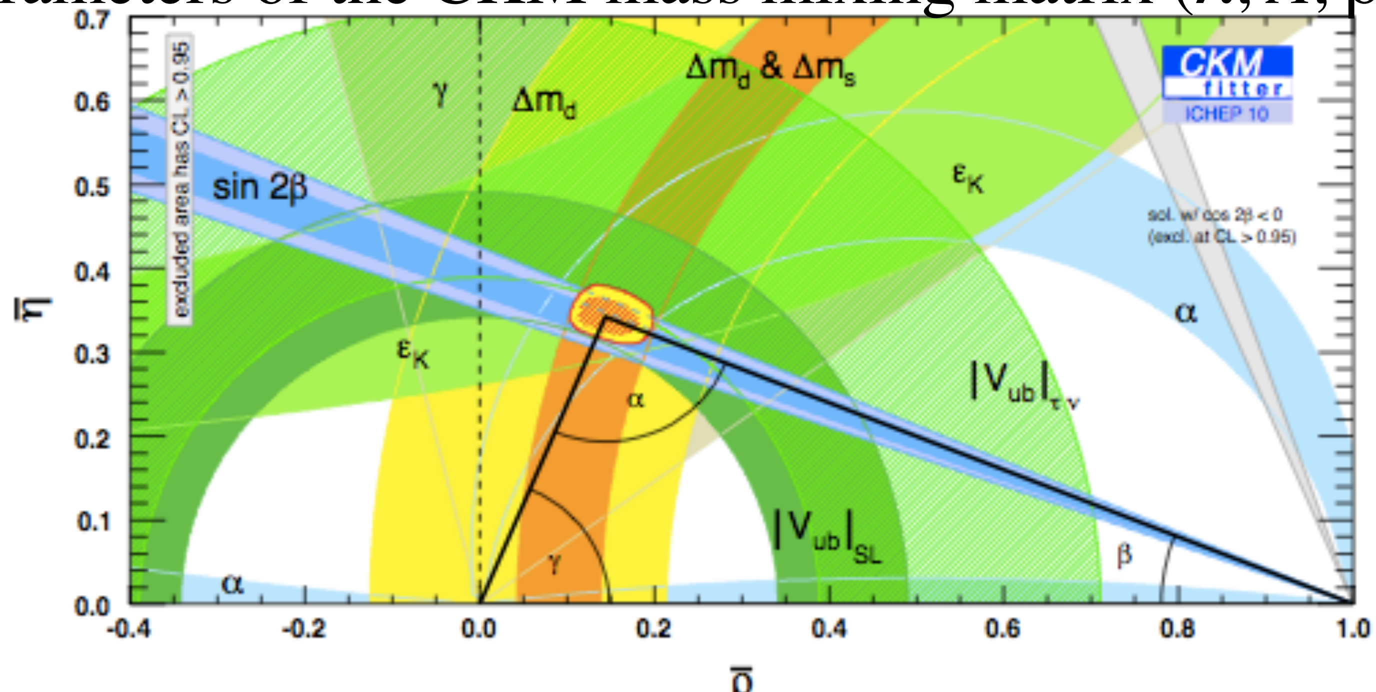


- From this plot, we know already either new physics energy scale is >> TeV (far beyond LHC) or the flavour structure of new physics is very special.

Quark flavor physics

Triumph of the CKM description

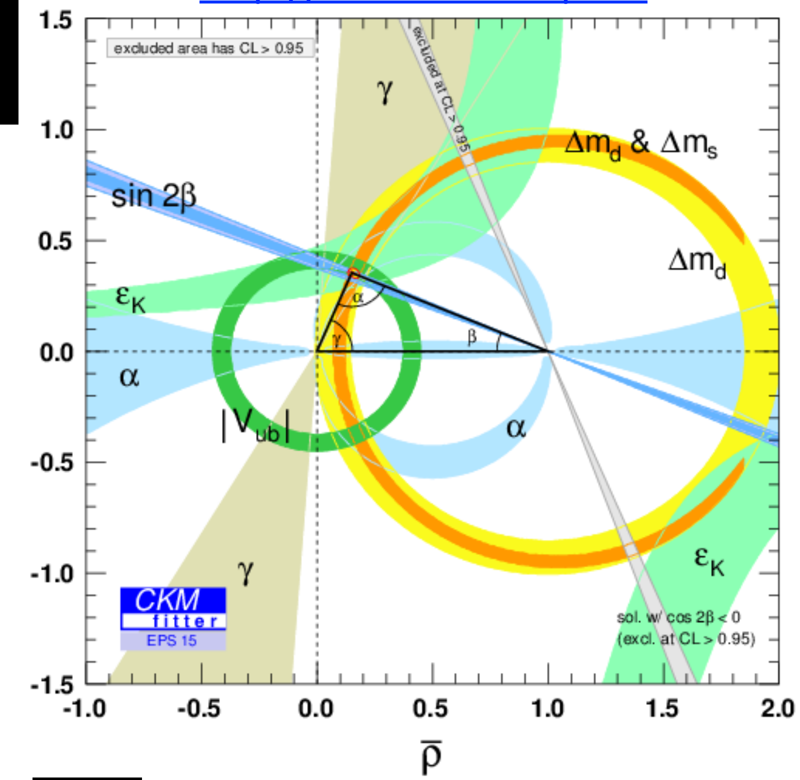
- All the flavour changing processes are described by the four parameters of the CKM mass mixing matrix (λ, A, ρ, η)



- 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.

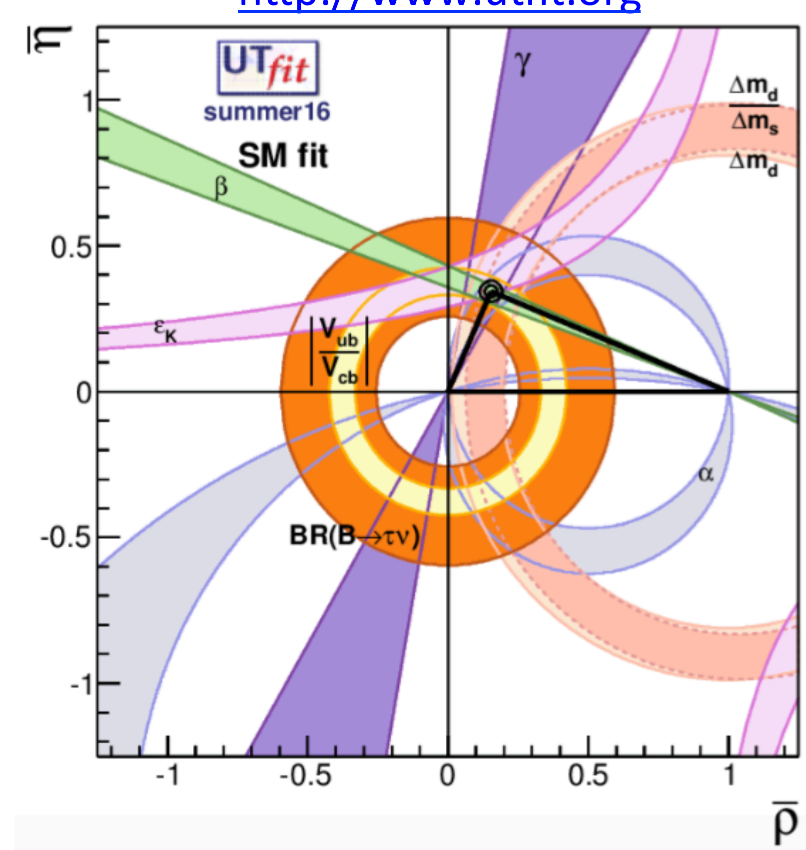
ICHEP 2016 -- I. Shipsey

http://ckmfitter.in2p3.fr



2015->2016

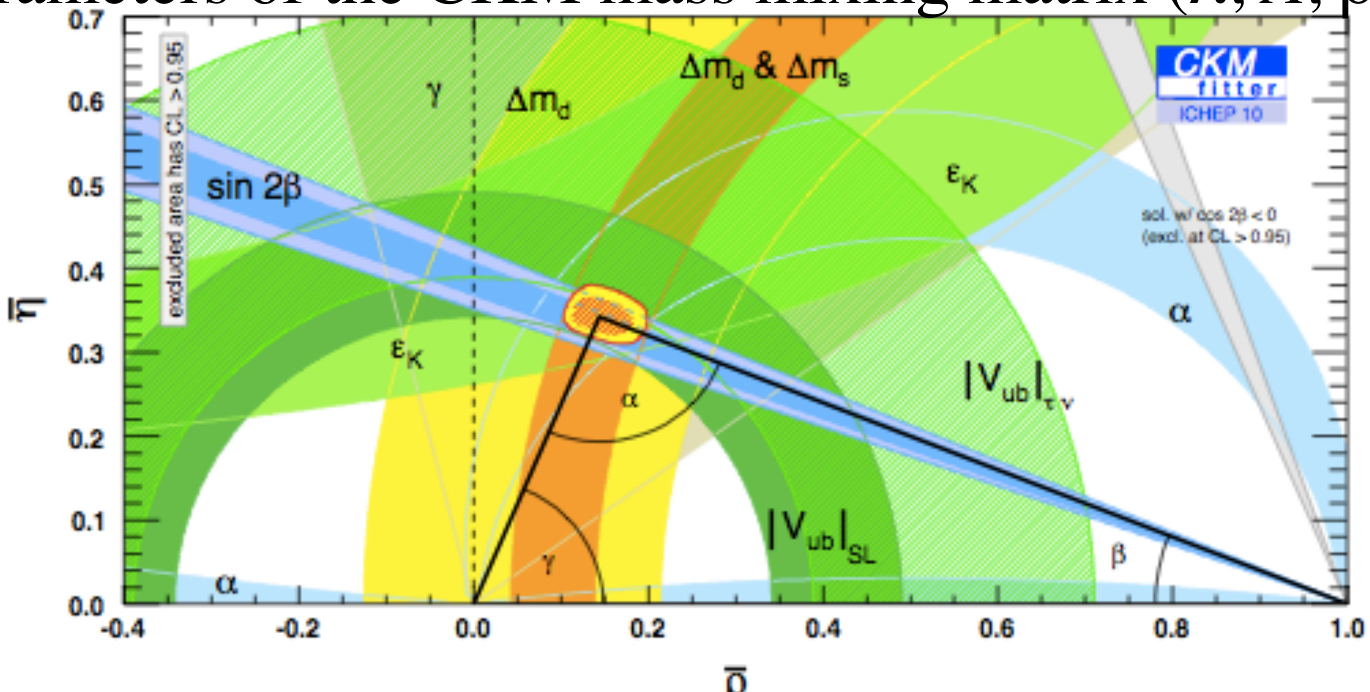
http://www.utfit.org



Quark flavor physics

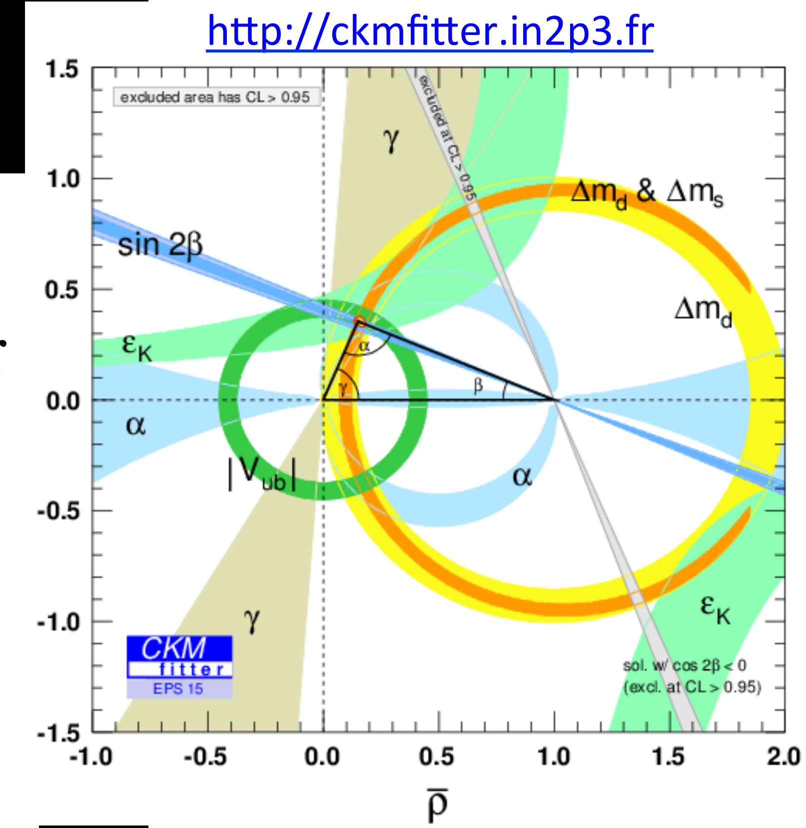
Triumph of the CKM description

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

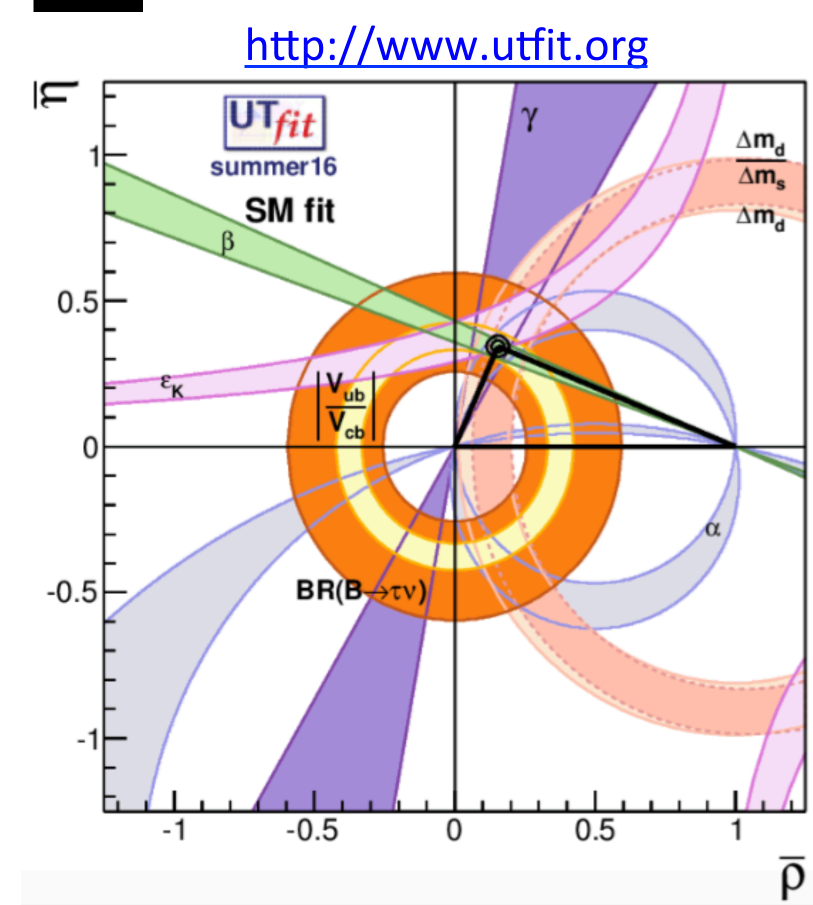


- From this plot, we know already either new physics energy scale is >> TeV (far beyond LHC) or the flavour structure o new physics is very special.

ICHEP 2016 -- I. Shipsey



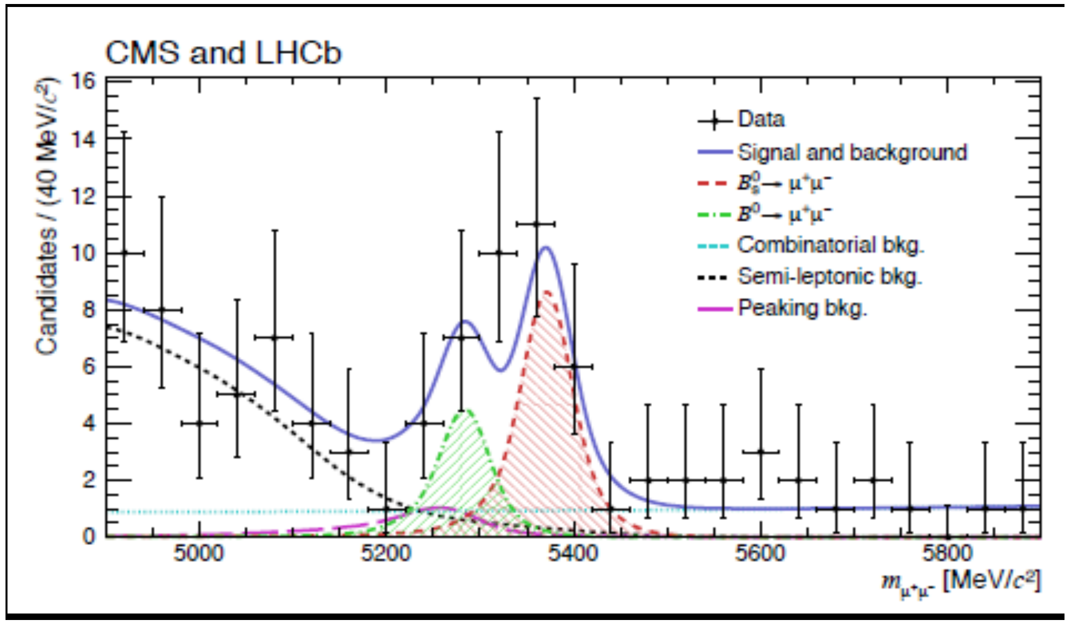
2015->2016



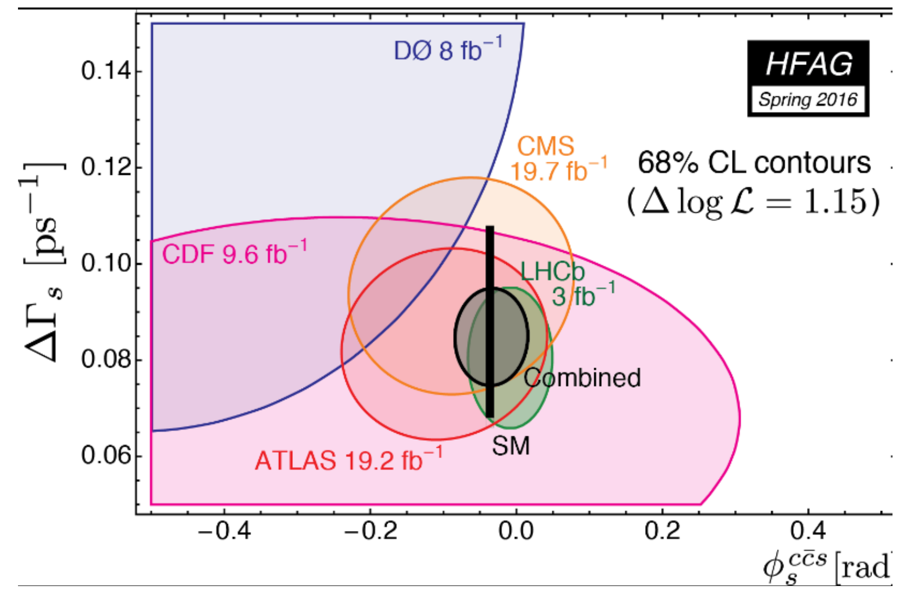
- Great success of the Standard Model CKM picture!
  - All of the measurements agree in a highly profound way
  - In the presence of relevant New Physics effects, the various contours would cross each other in a single point

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

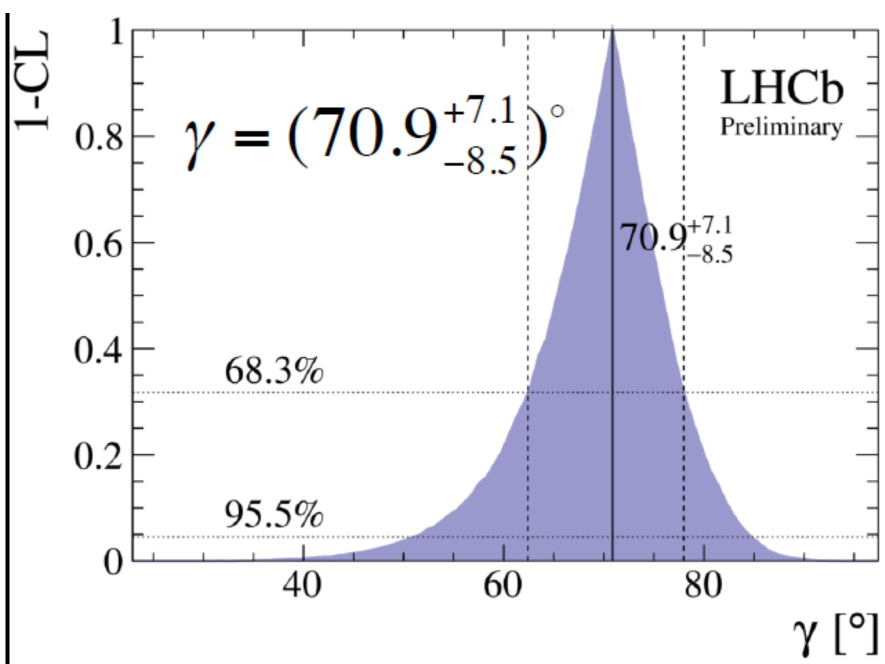
Observation of $B_s \rightarrow \mu\mu$



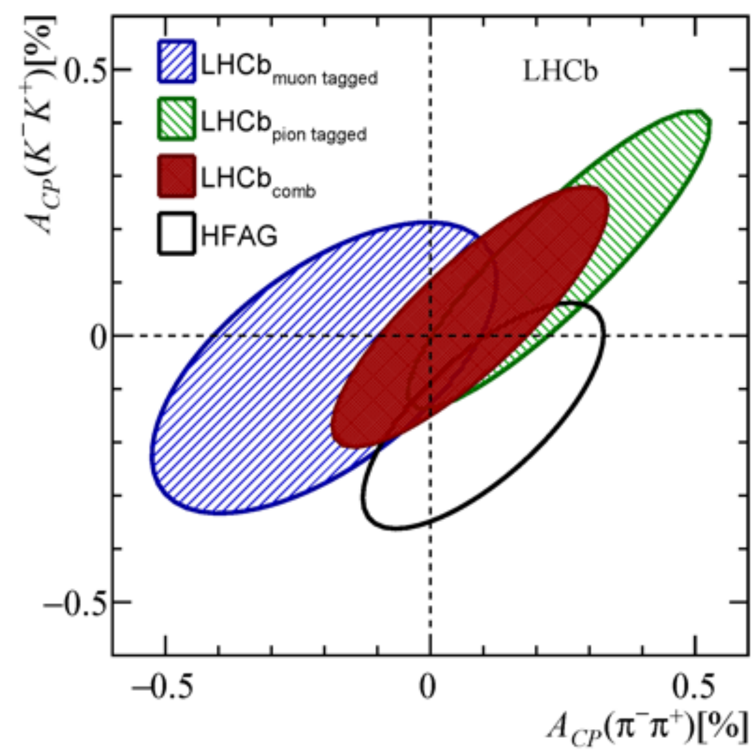
Precise studies of CPV in the B_s system



Great steps forward in knowledge of unitarity triangle angle γ (ϕ_3)

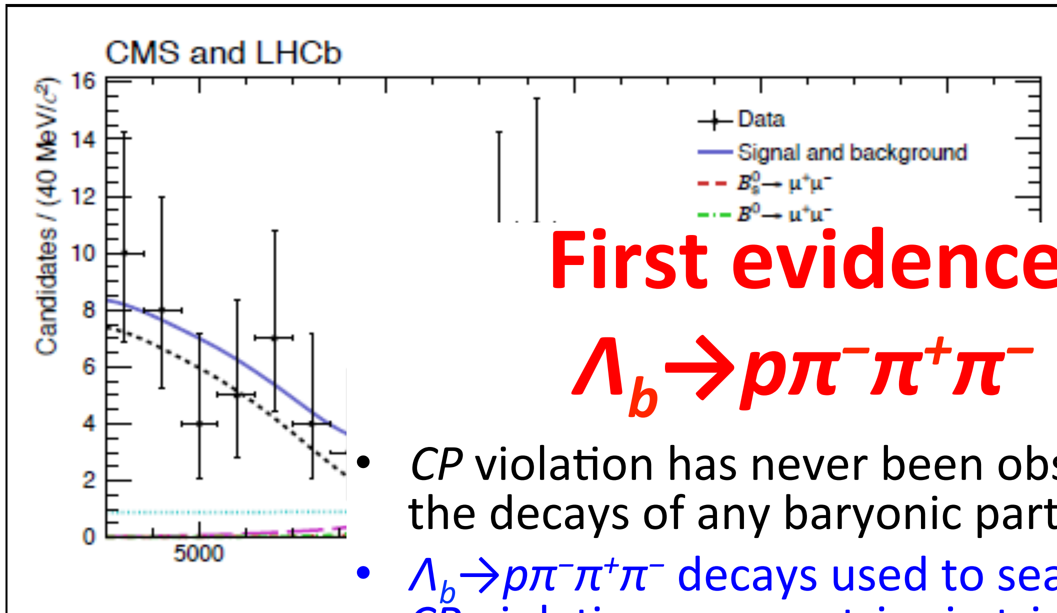


Probing for CPV in charm with per mille precision

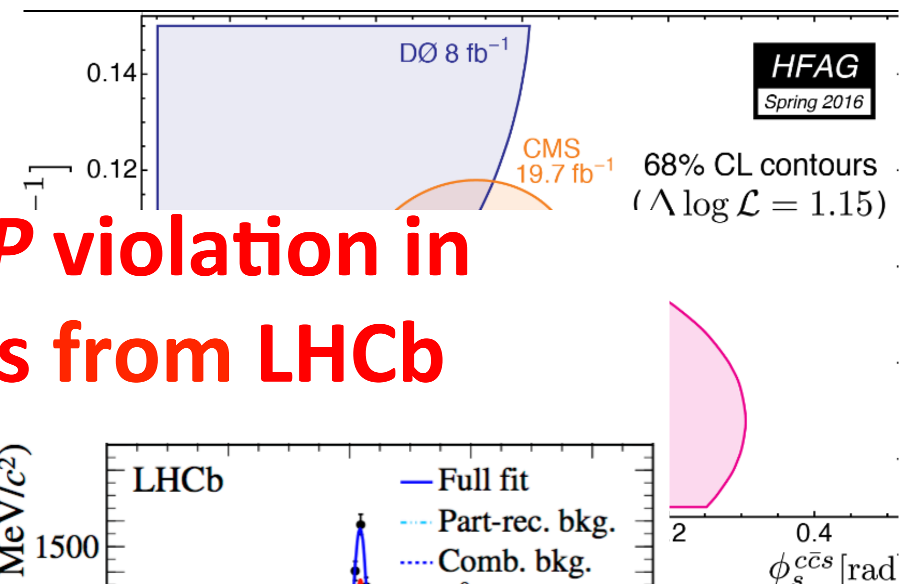


Flavour physics at the LHC a great success, with run-1 delivering in all important topics

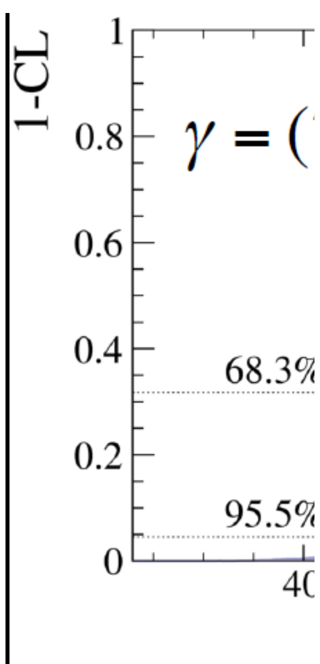
Observation of $B_s \to \mu\mu$



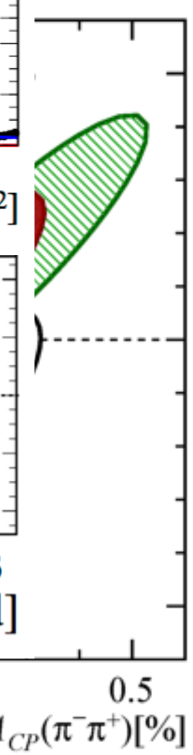
Precise studies of CPV in the B_s system



Great st... of unitar...

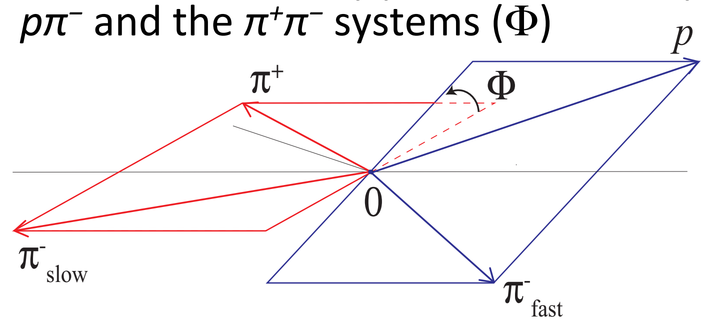


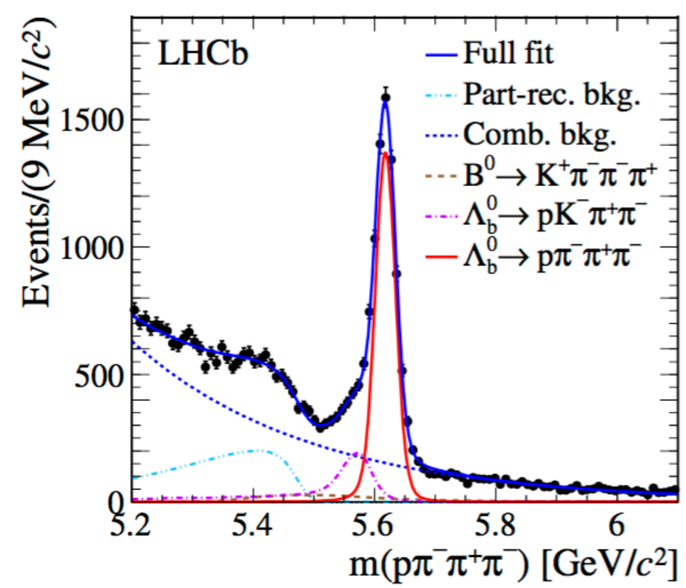
...th per mille precision

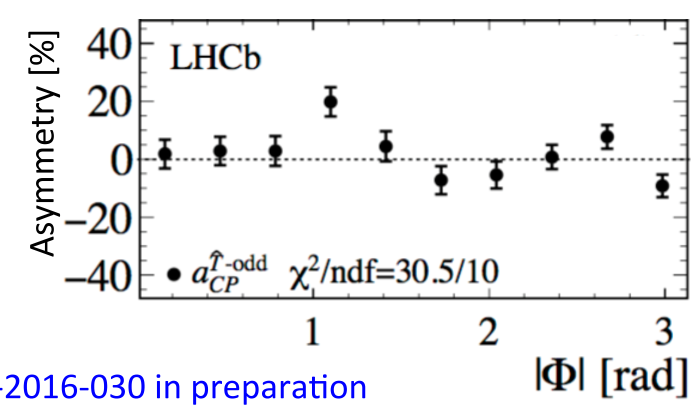


First evidence for *CP* violation in $\Lambda_b \to p\pi^-\pi^+\pi^-$ decays from LHCb

- *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)







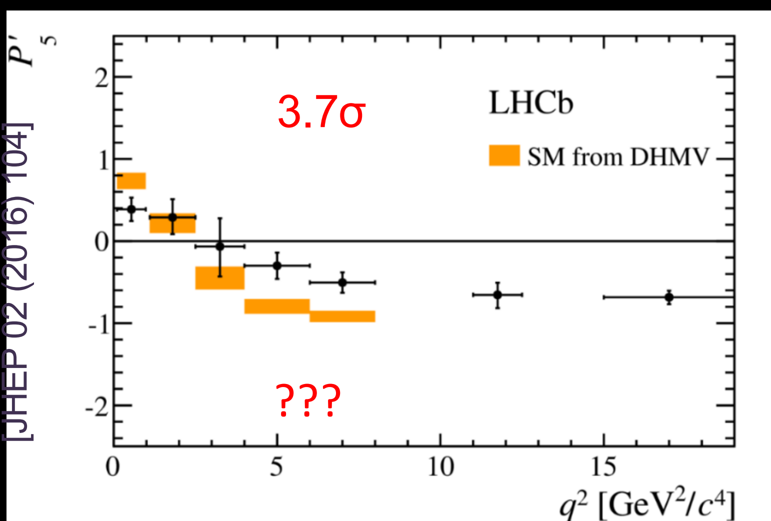
- An evidence for *CP* violation at the 3.3σ level is found
- This represents the first evidence of *CP* violation in the baryon sector

LHCb-PAPER-2016-030 in preparation

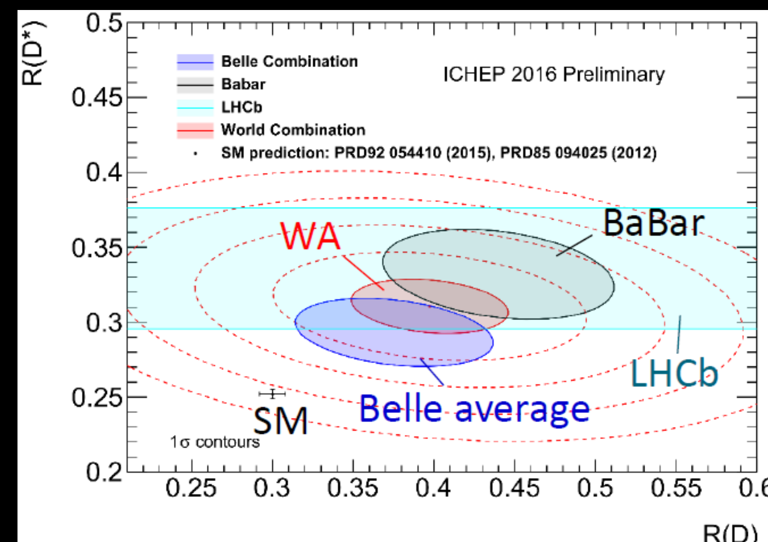
But some intriguing anomalies have emerged from LHC-b and the B-factories

Anomalous behaviour
In b→sl+l- observables

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

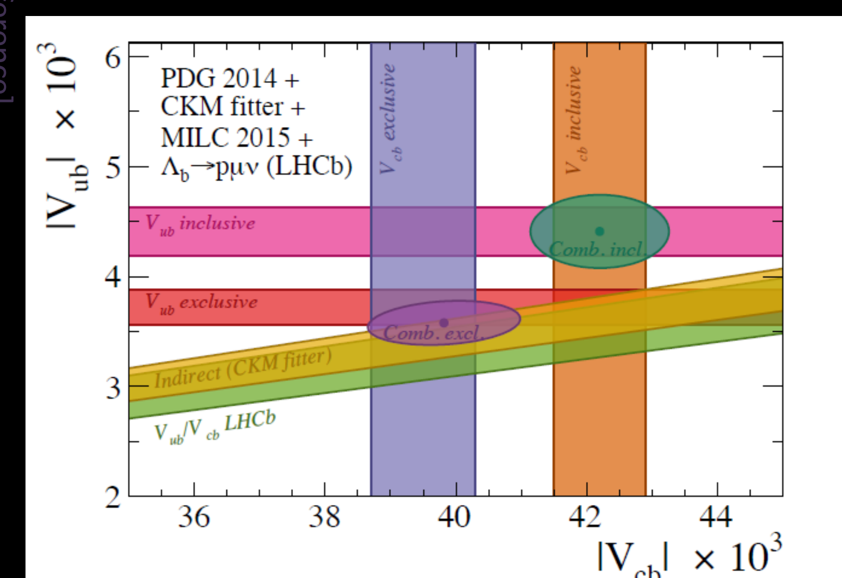


Hints of lepton universality violation in B→D(*)lν …



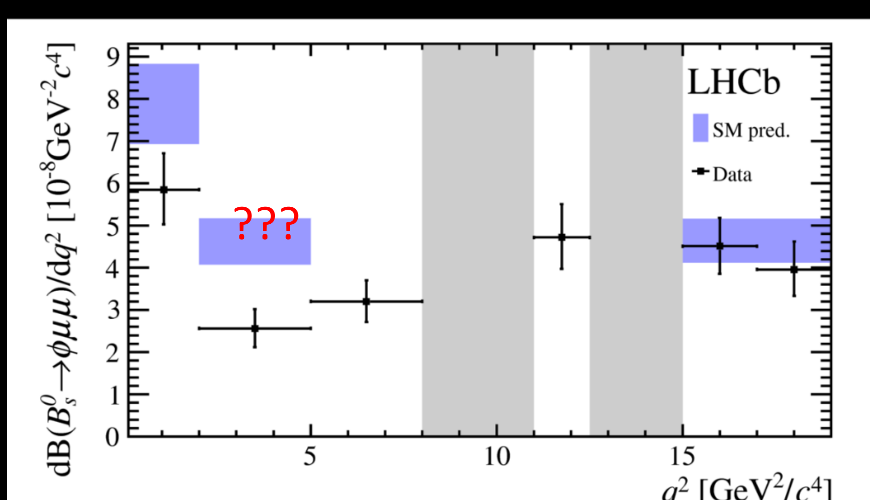
[Y. Sato, this conference]

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

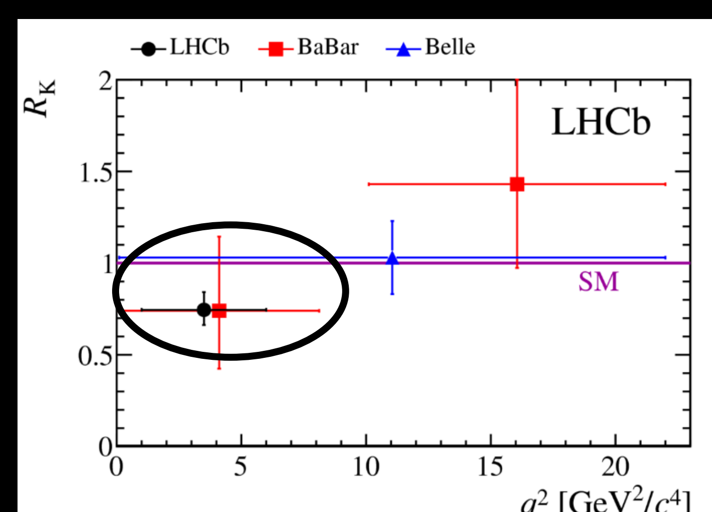


[JHEP 09 (2015) 179]

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



…and in B→Kl+l-

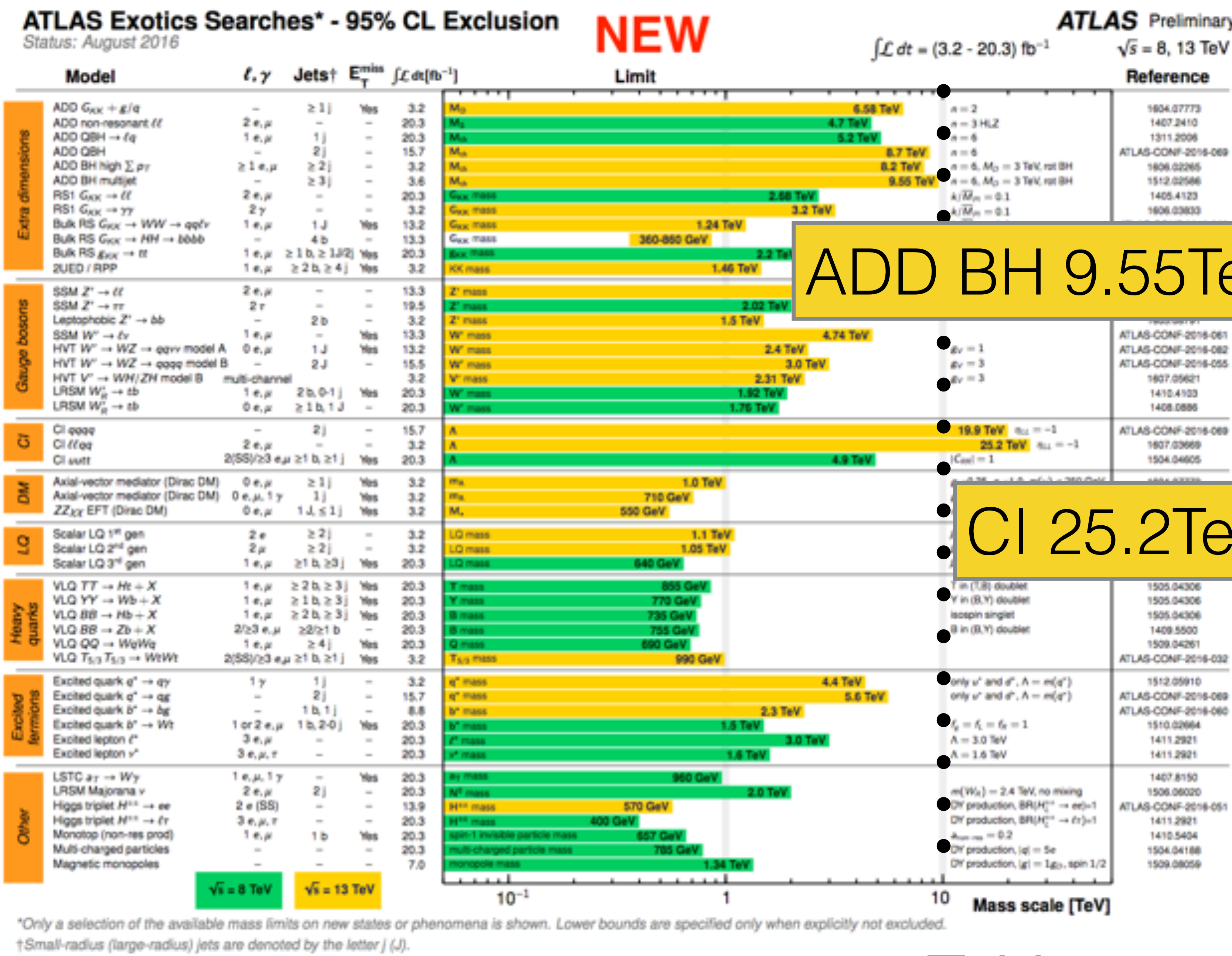


[PRL 113 (2014) 151601]

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

Exotics … What to say?

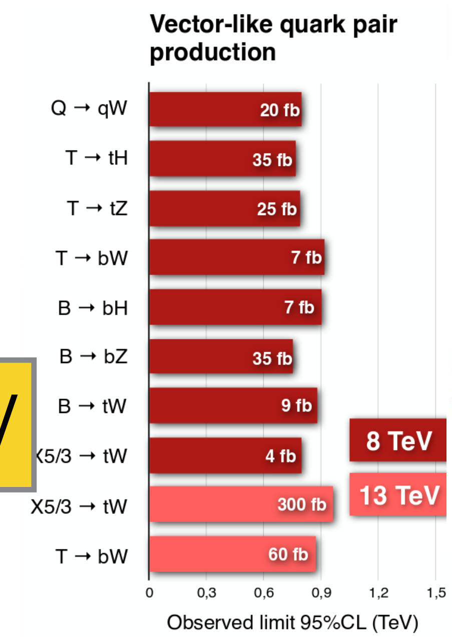
- Up to 25% mass limit increase by extending 2015 to 2016
- ~50% of the analyses updated to Run2

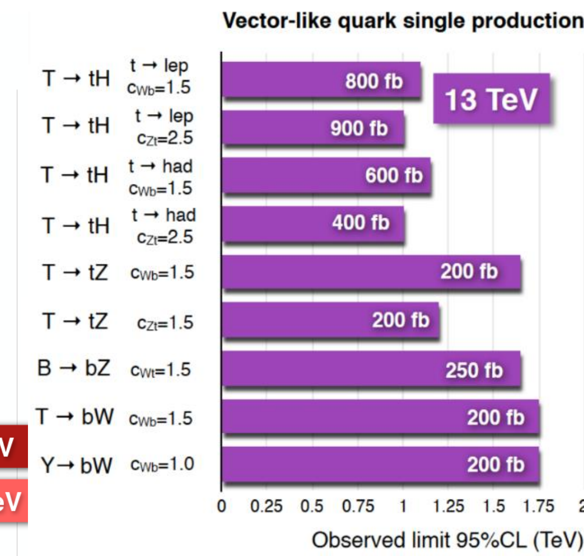


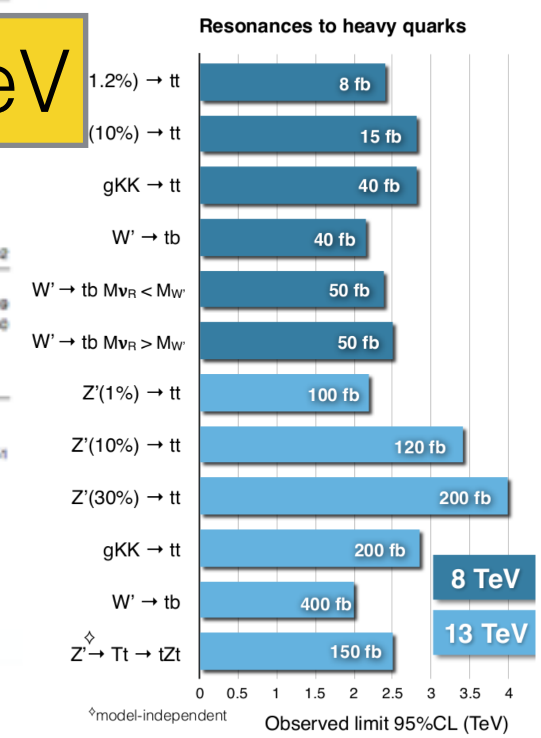
ADD BH 9.55TeV

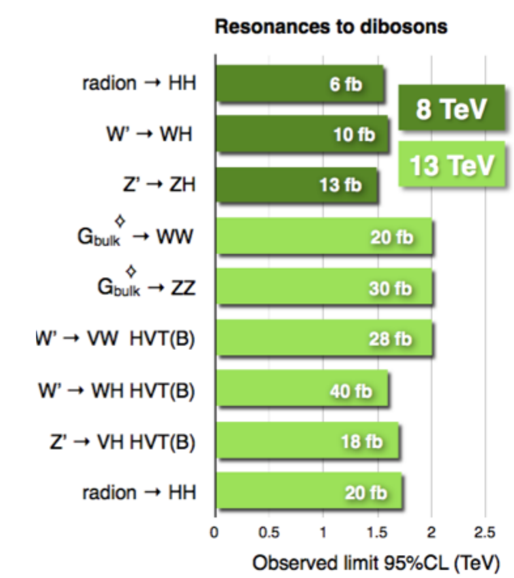
CI 25.2TeV

10TeV

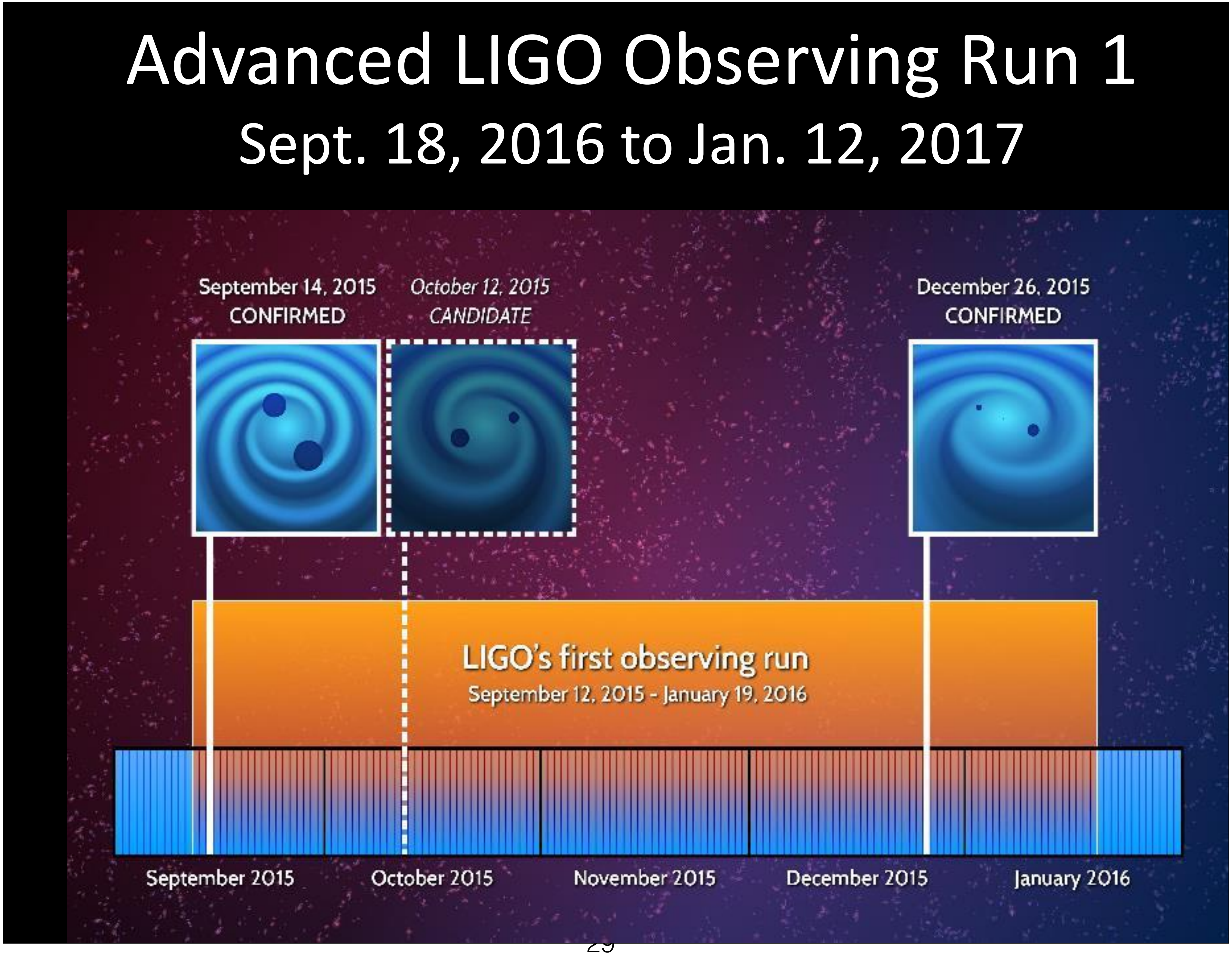




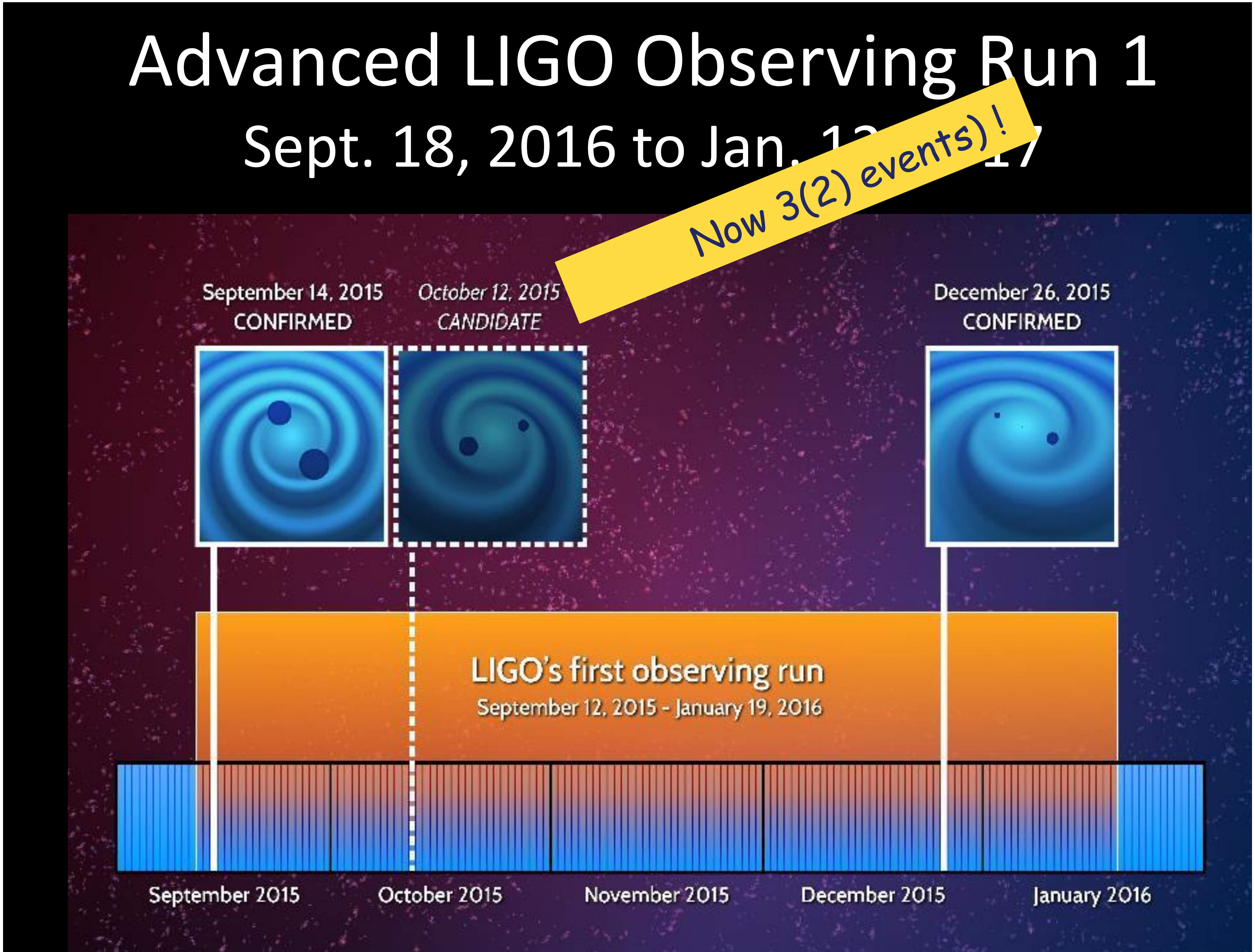




Gravitational Waves! Amazing!

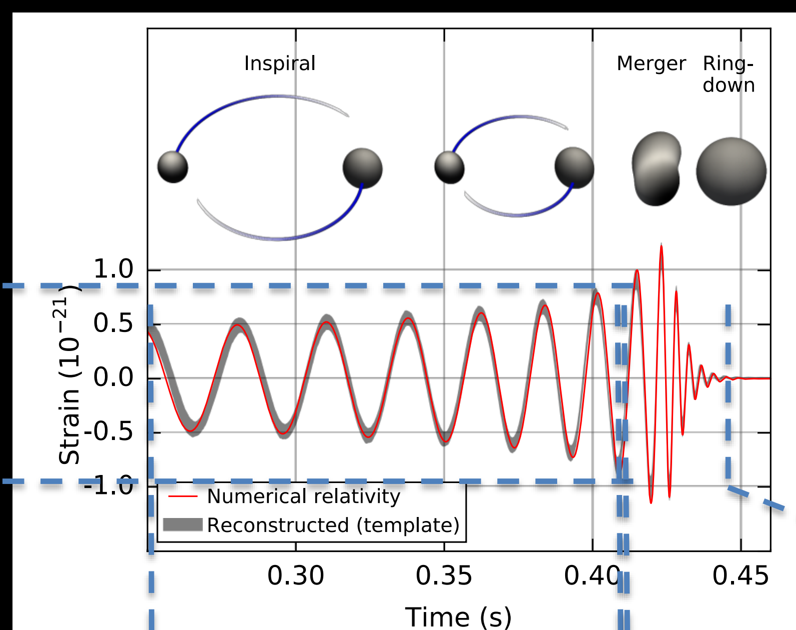


Gravitational Waves! Amazing!



Gravitational Waves

What does the signal tell us about the source?

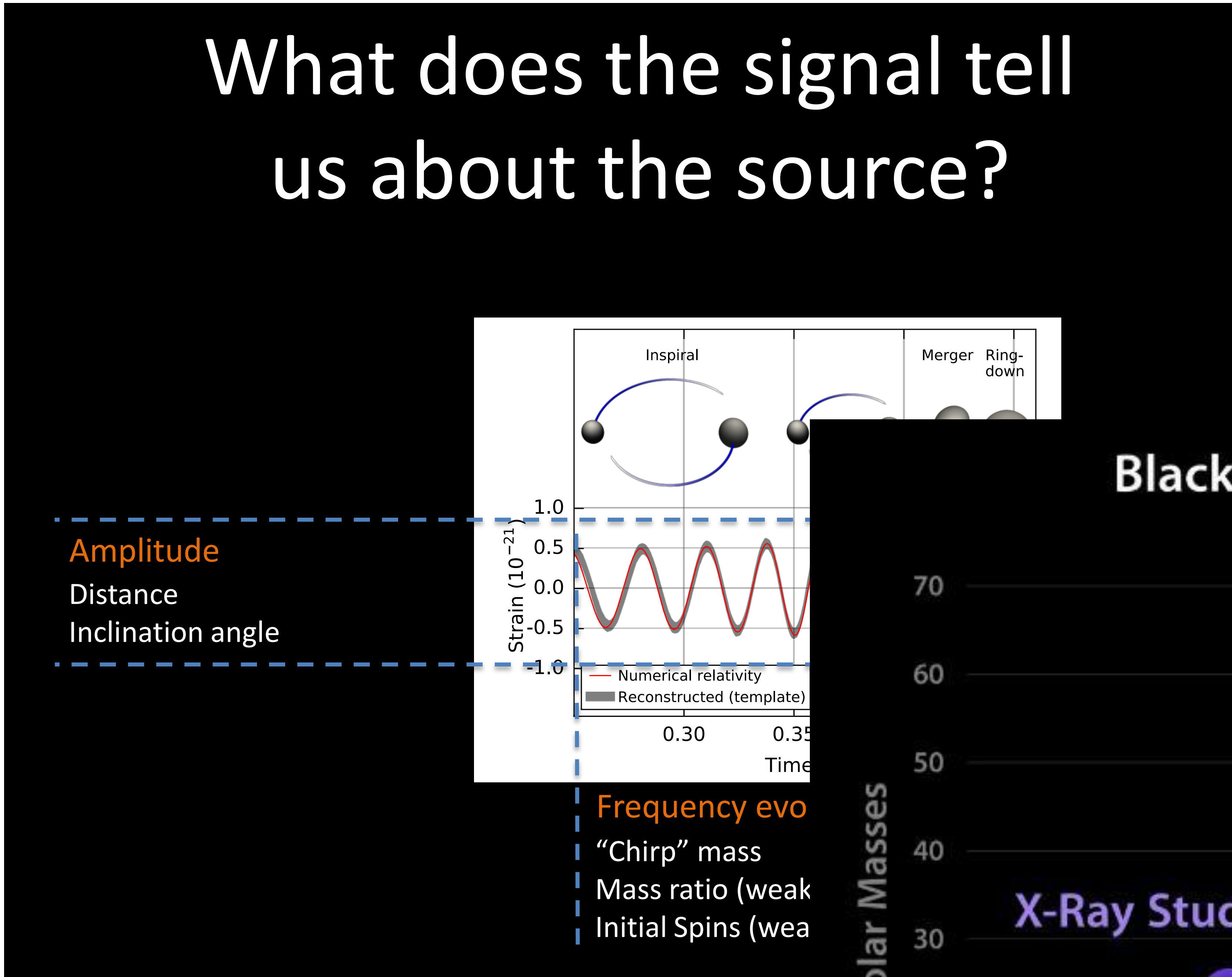


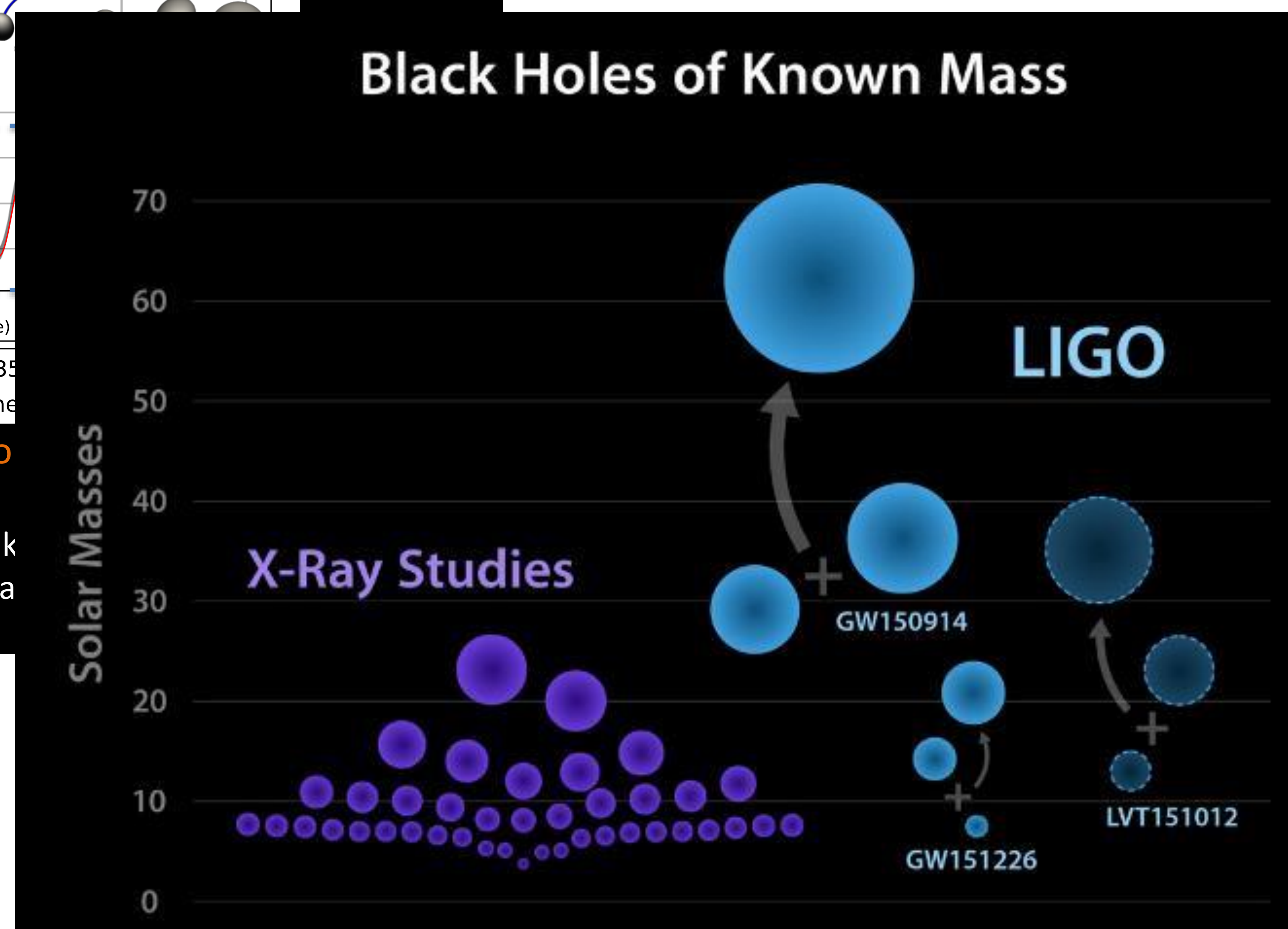
Amplitude
Distance
Inclination angle

Frequency evolution
"Chirp" mass
Mass ratio (weaker)
Initial Spins (weakest)

Frequency and decay time
Final mass
Final spin

Gravitational Waves





Probing Dark Energy

Equation of state

$$p = w\rho$$

pressure density

$w = 0$ Non-rel matter

$w = 1/3$ Ultra-rel matter

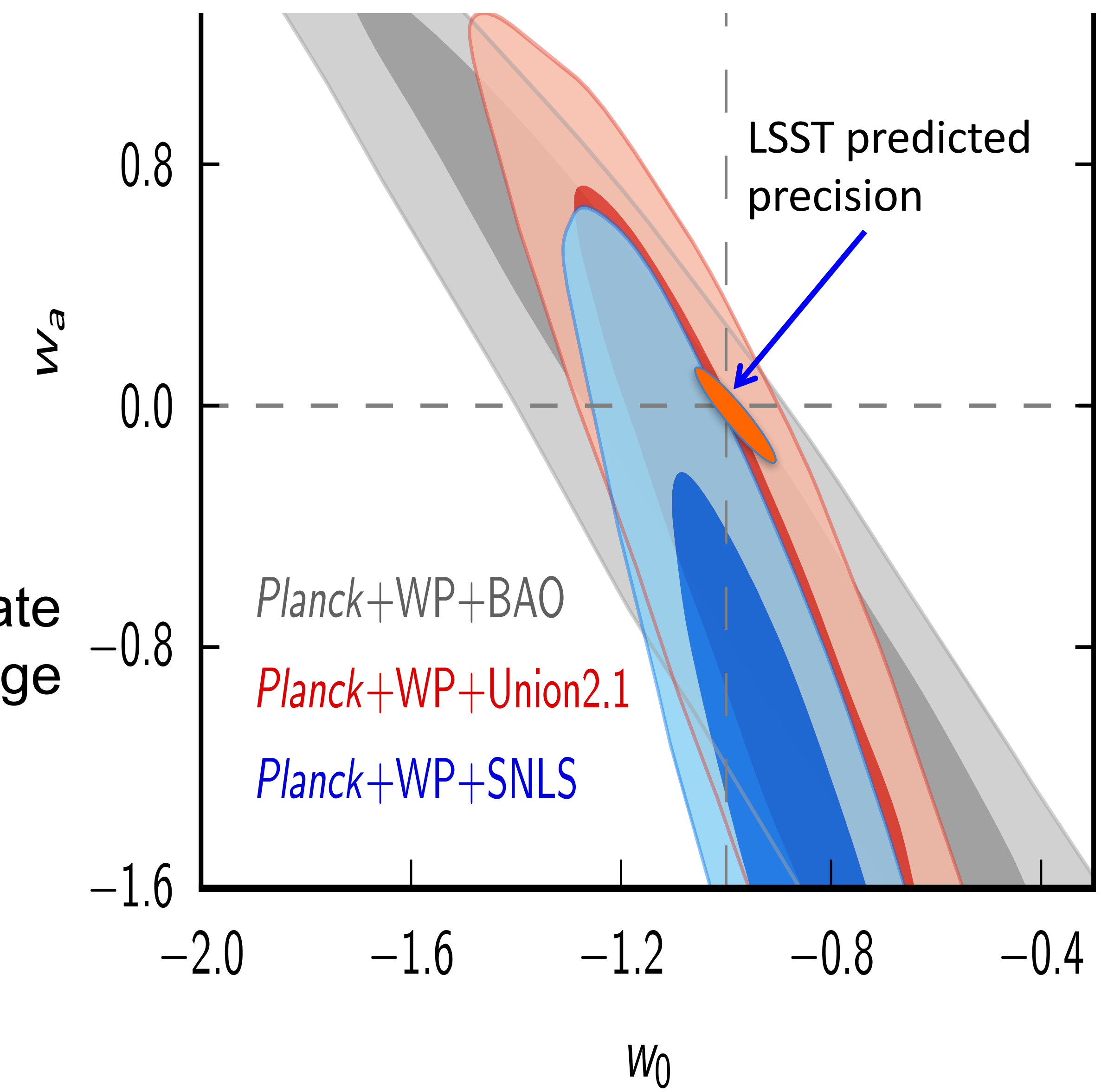
$w = -1$ Vacuum

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

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

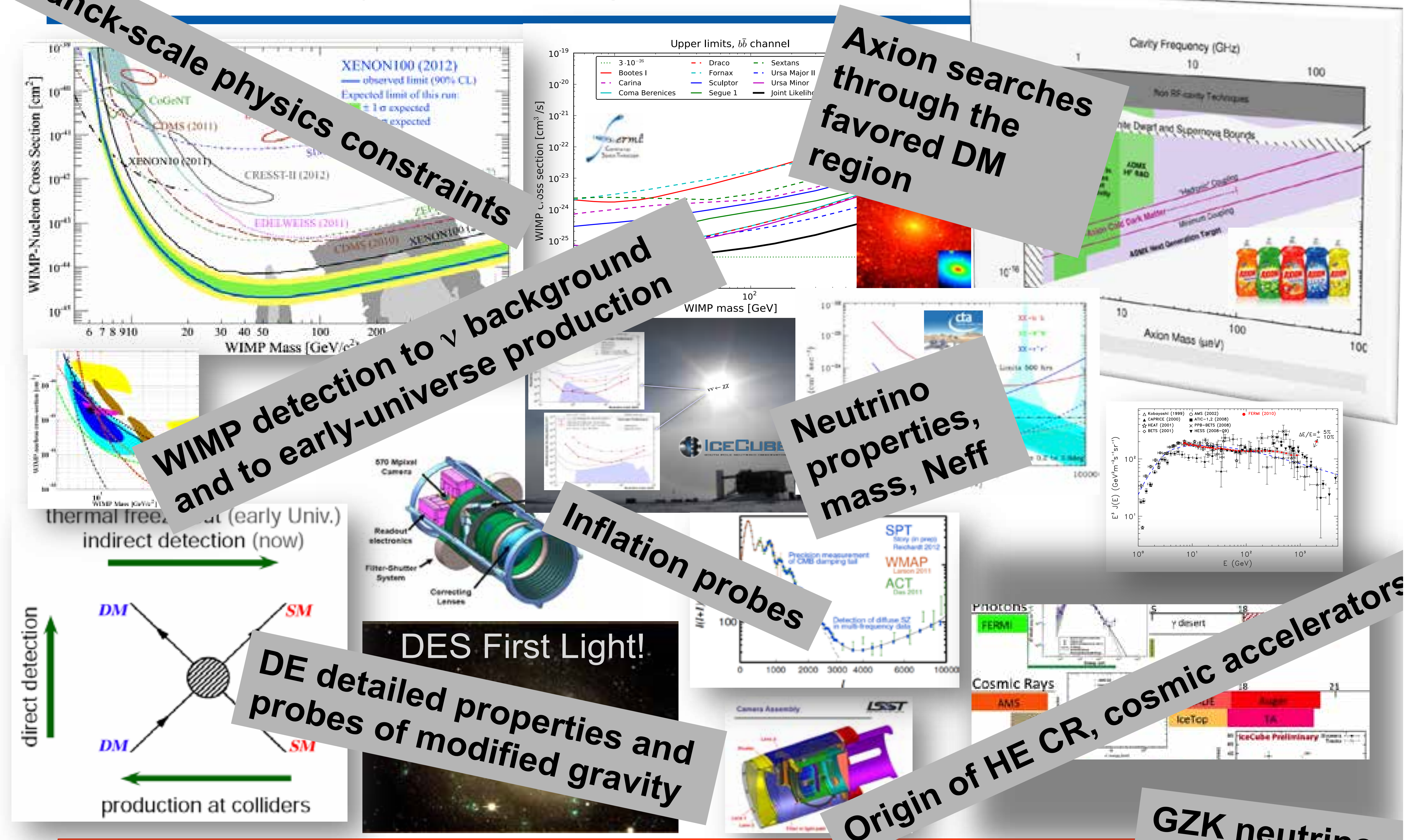
$$\rho = a^{-3(1+w_0+w_1)}e^{-\frac{3w_1 z}{1+z}}$$

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_LV_L cross-section at high $M(V_LV_L)$? 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*** ***<u>discoveries</u>*** beyond the SM, and/or ***<u>answers</u>*** 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