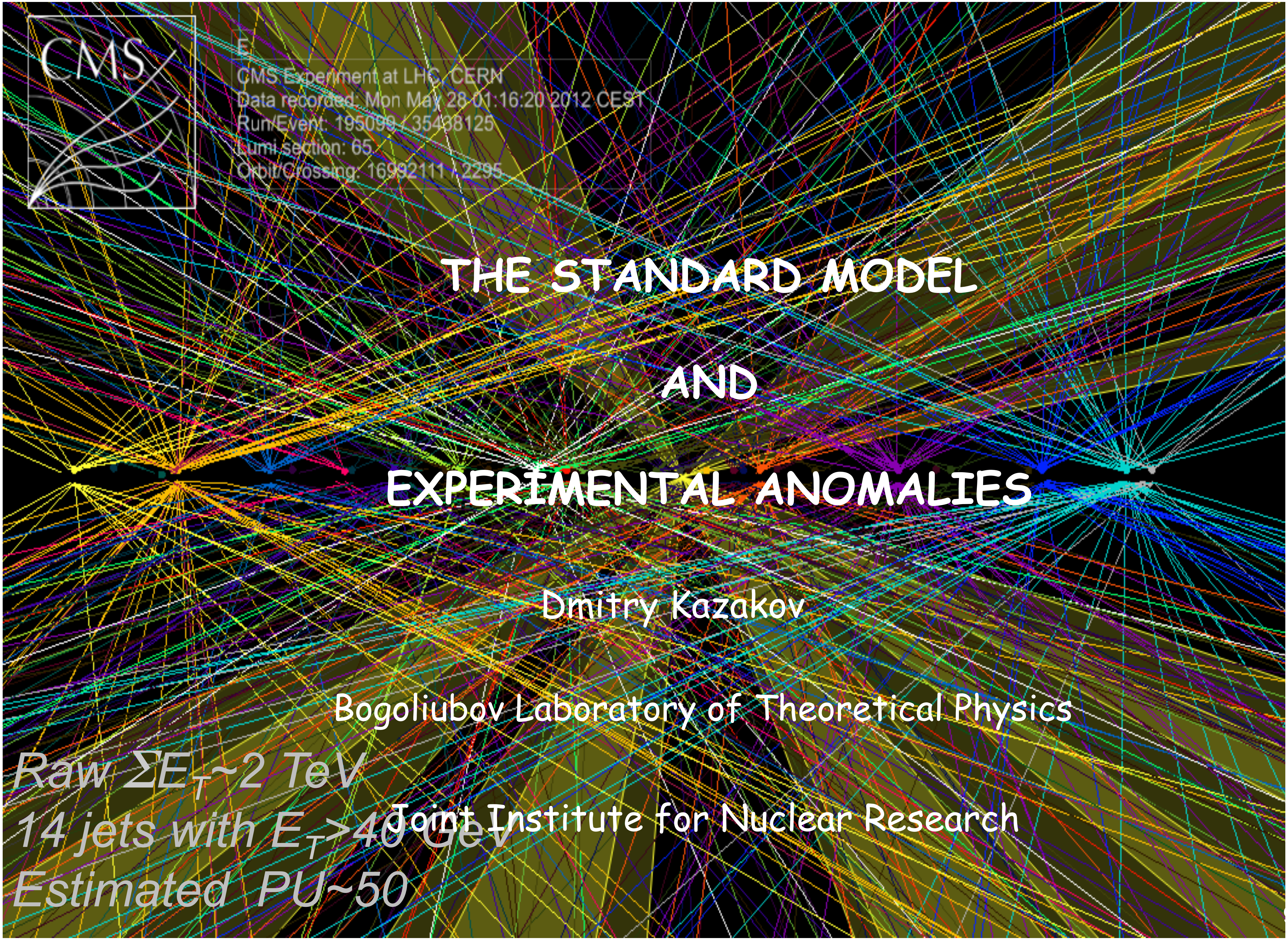


THE STANDARD MODEL

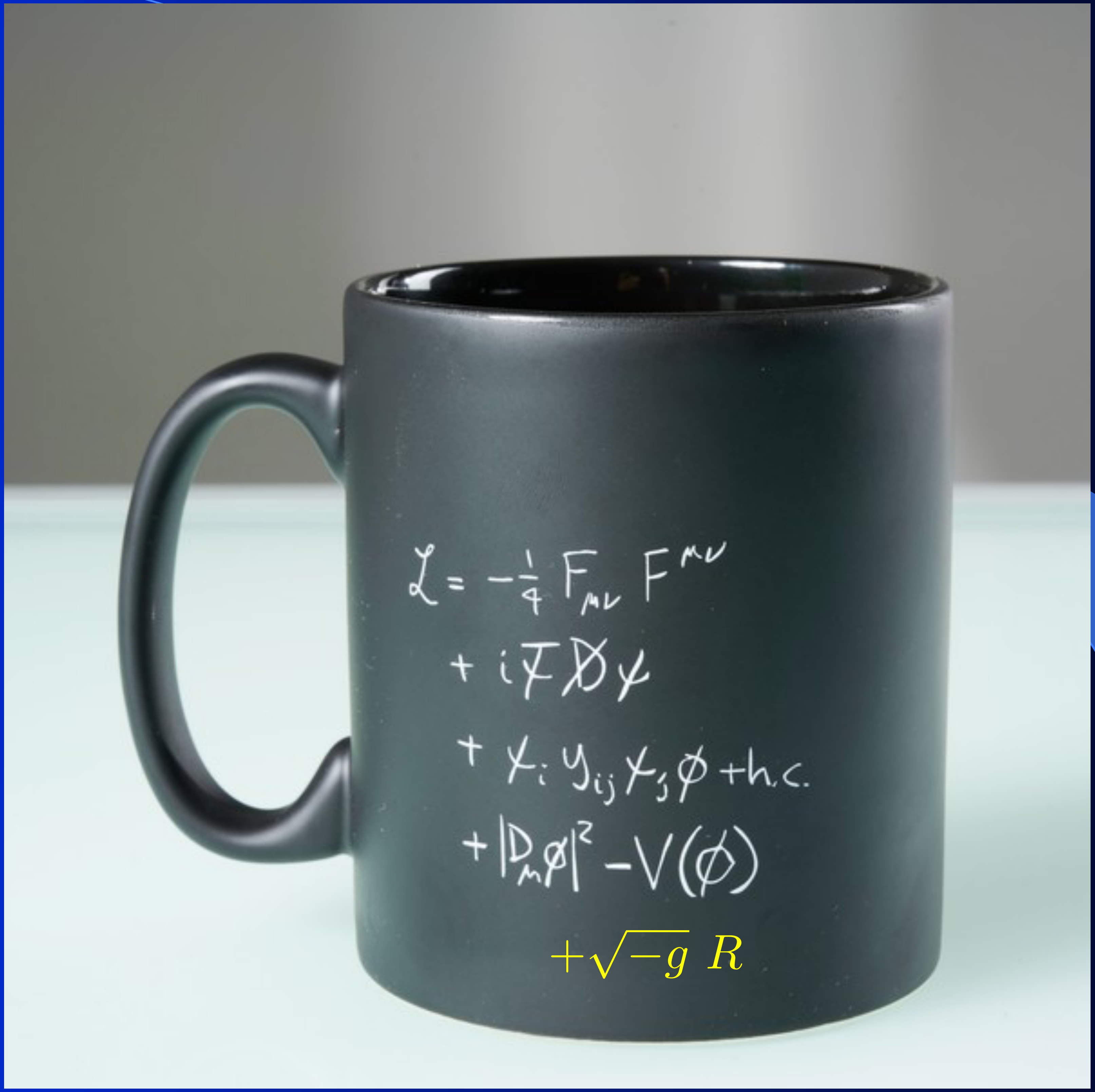
AND

EXPERIMENTAL ANOMALIES

Dmitry Kazakov

Bogoliubov Laboratory of Theoretical Physics

Joint Institute for Nuclear Research



Утренний кофе теоретика

Higgs sector

SUSY Higgs Bosons

SM

$$H = \begin{pmatrix} H^0 \\ H^- \end{pmatrix} = \begin{pmatrix} \mathrm{v} + \frac{S+iP}{\sqrt{2}} \\ H^- \end{pmatrix} = \exp(i\frac{\vec{\xi}\vec{\sigma}}{2})\begin{pmatrix} \mathrm{v} + \frac{S}{\sqrt{2}} \\ 0 \end{pmatrix}$$

4=2+2=3+1

$$H \rightarrow H' = \exp(i\frac{\vec{\alpha}\vec{\sigma}}{2})H \xrightarrow{(\vec{\alpha}=-\vec{\xi})} H' = \begin{pmatrix} \mathrm{v} + \frac{S}{\sqrt{2}} \\ 0 \end{pmatrix}$$

MSSM

8=4+4=3+5

$$H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix} = \begin{pmatrix} \mathrm{v}_1 + \frac{S_1+iP_1}{\sqrt{2}} \\ H_1^- \end{pmatrix}, \quad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix} = \begin{pmatrix} H_2^+ \\ \mathrm{v}_2 + \frac{S_2+iP_2}{\sqrt{2}} \end{pmatrix},$$

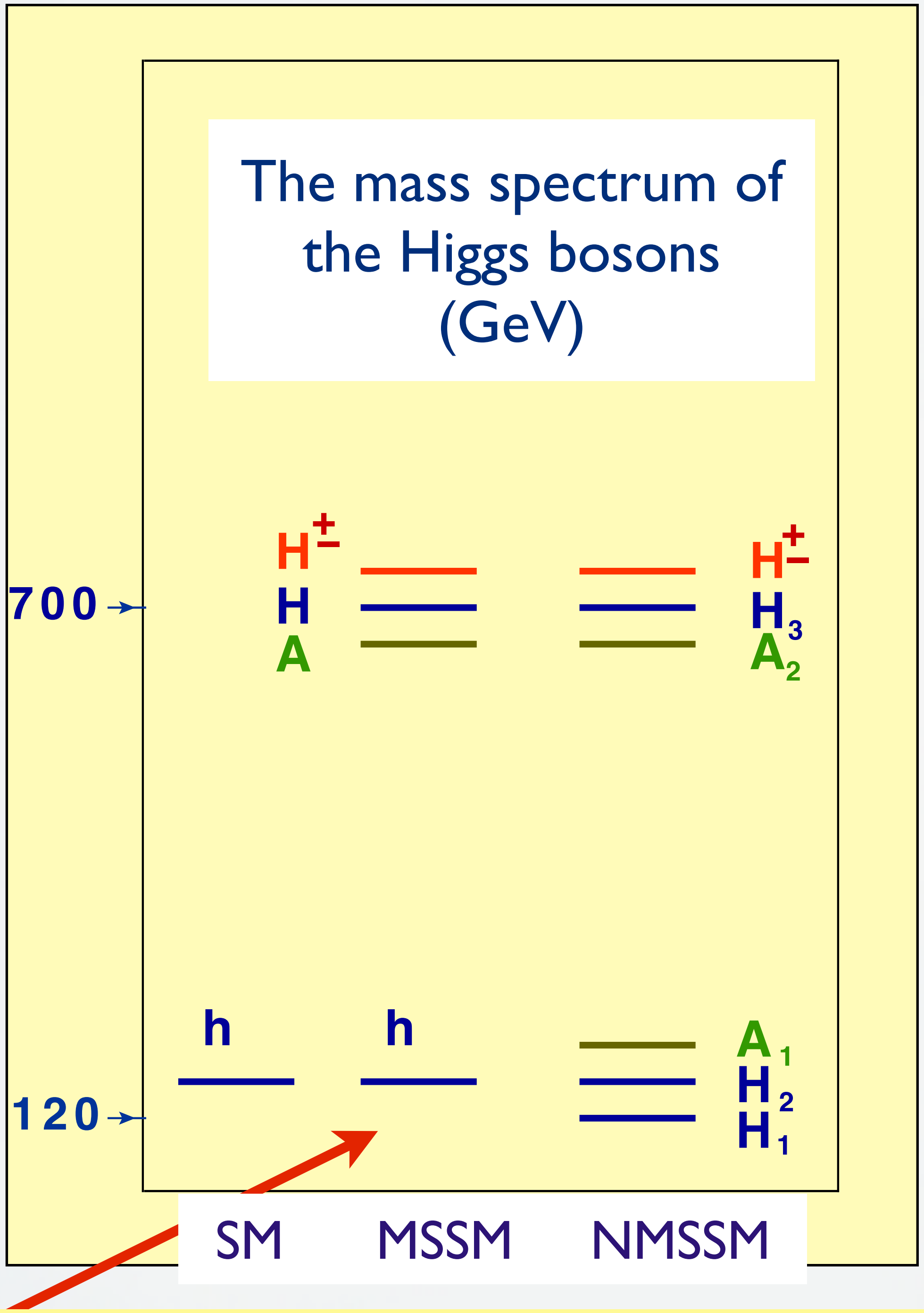
$\mathrm{v}_1^2+\mathrm{v}_2^2=\mathrm{v}^2$, $\mathrm{v}_2/\mathrm{v}_1 \equiv \tan\beta$

NMSSM

+2 $S+P$

The Higgs Sector: Alternatives

Model	Particle content
SM	h CP-even
2HDM/MSSM	h,H CP-even A CP-odd $H^{\pm}$
NMSSM	H_1,H_2,H_3 CP-even A_1,A_2 CP-odd $H^{\pm}$
Composite	h CP-even + excited states

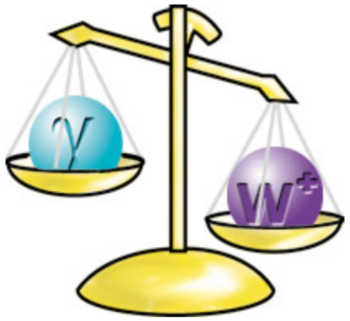

The mass spectrum of the Higgs bosons (GeV)

It may well be that we see one of these states

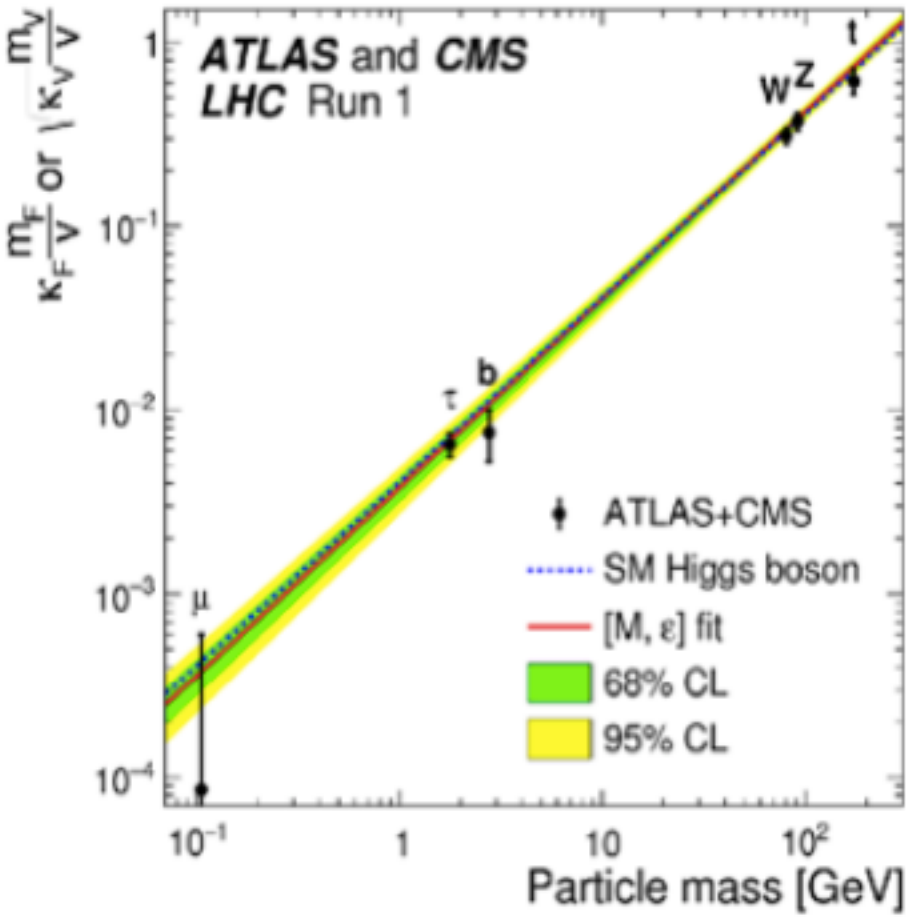
One has to check the presence or absence of heavy Higgs bosons

EXTENDED HIGGS SECTOR

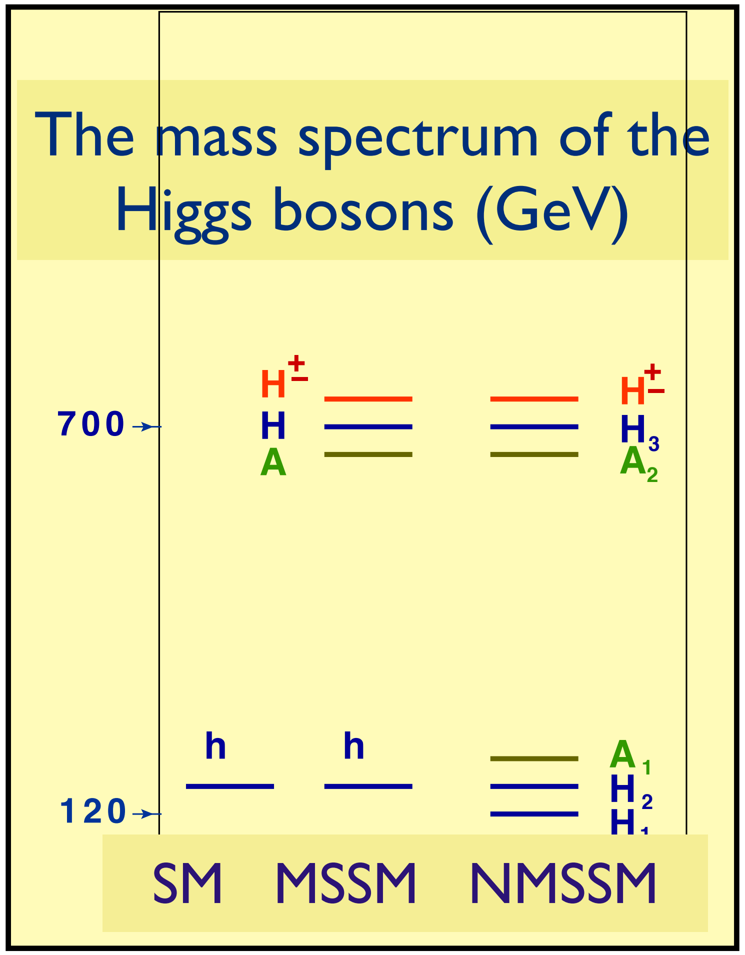
How to probe?



- Probe deviations from the SM Higgs couplings



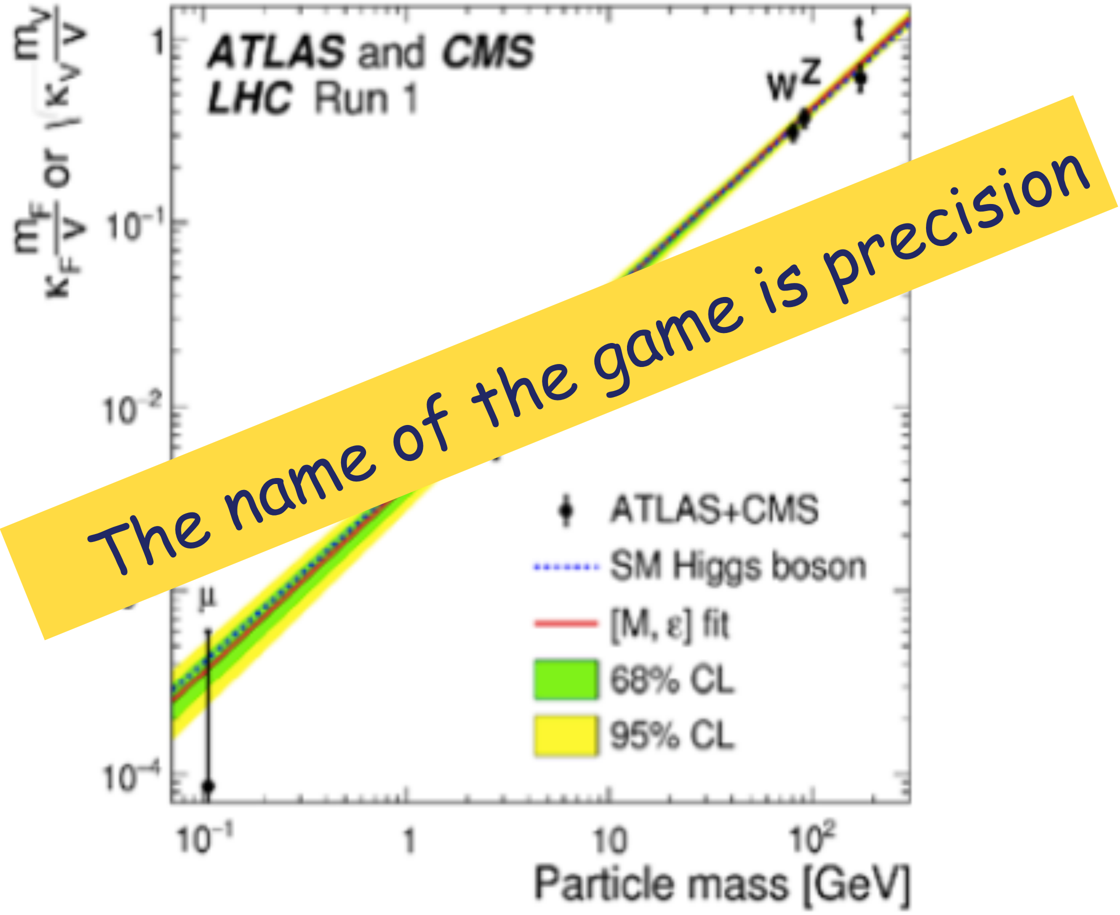
- Perform direct search for additional scalars



EXTENDED HIGGS SECTOR

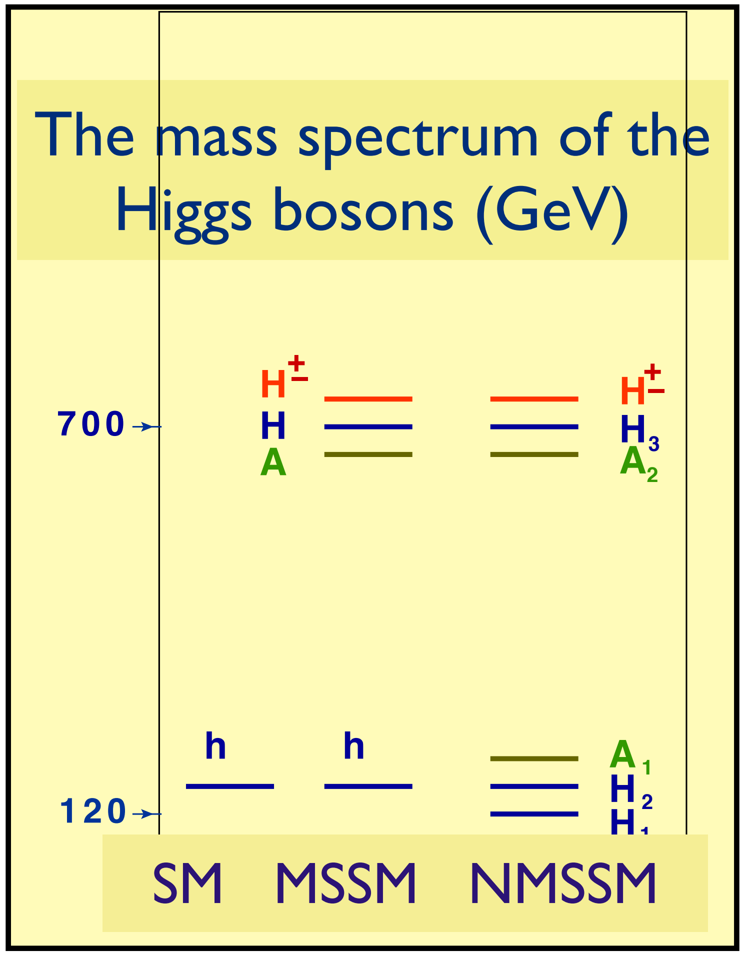
How to probe?

- Probe deviations from the SM Higgs couplings



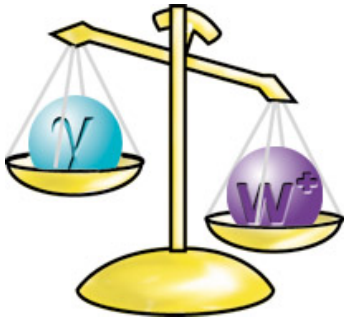
The name of the game is precision

- Perform direct search for additional scalars



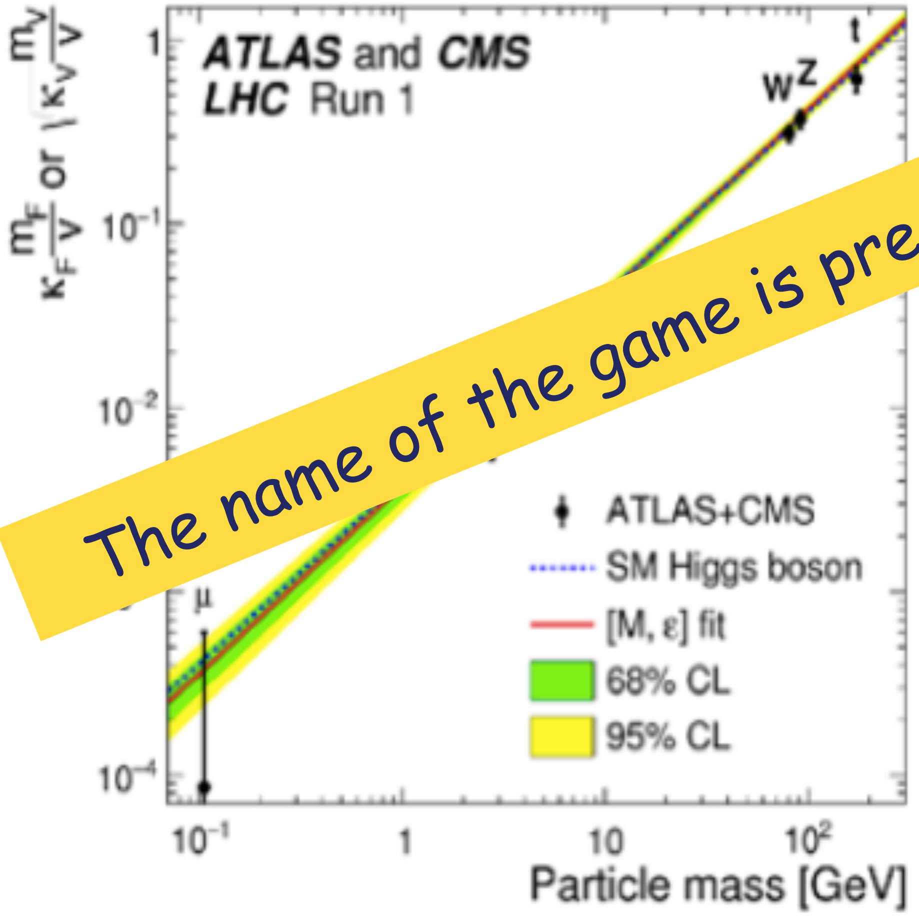
The mass spectrum of the Higgs bosons (GeV)

EXTENDED HIGGS SECTOR



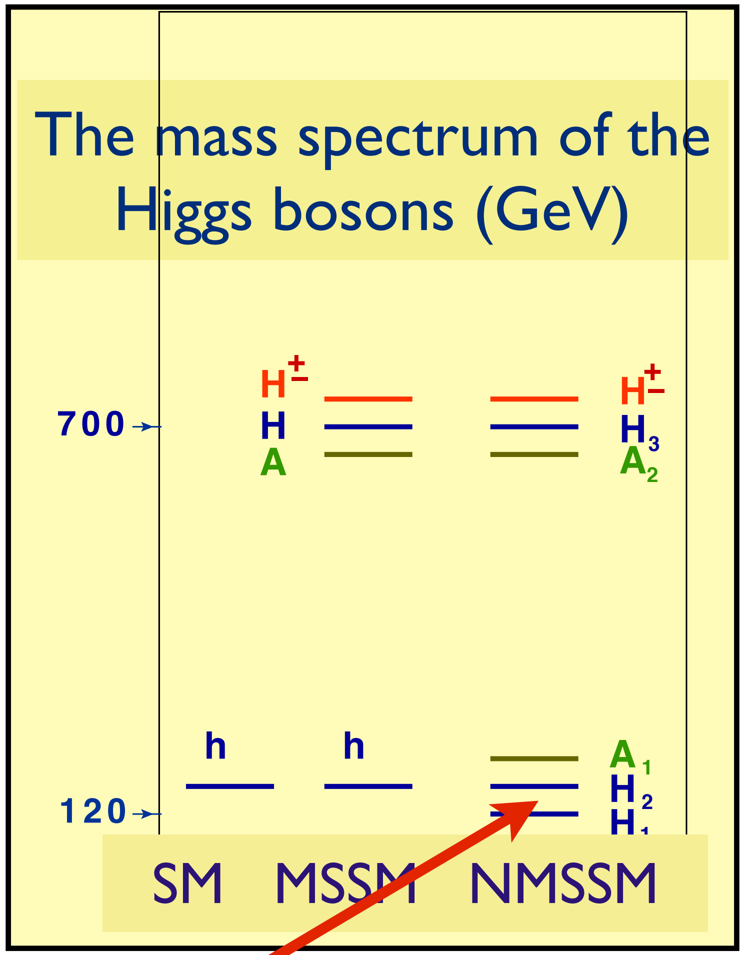
How to probe?

- Probe deviations from the SM Higgs couplings



The name of the game is precision

- Perform direct search for additional scalars

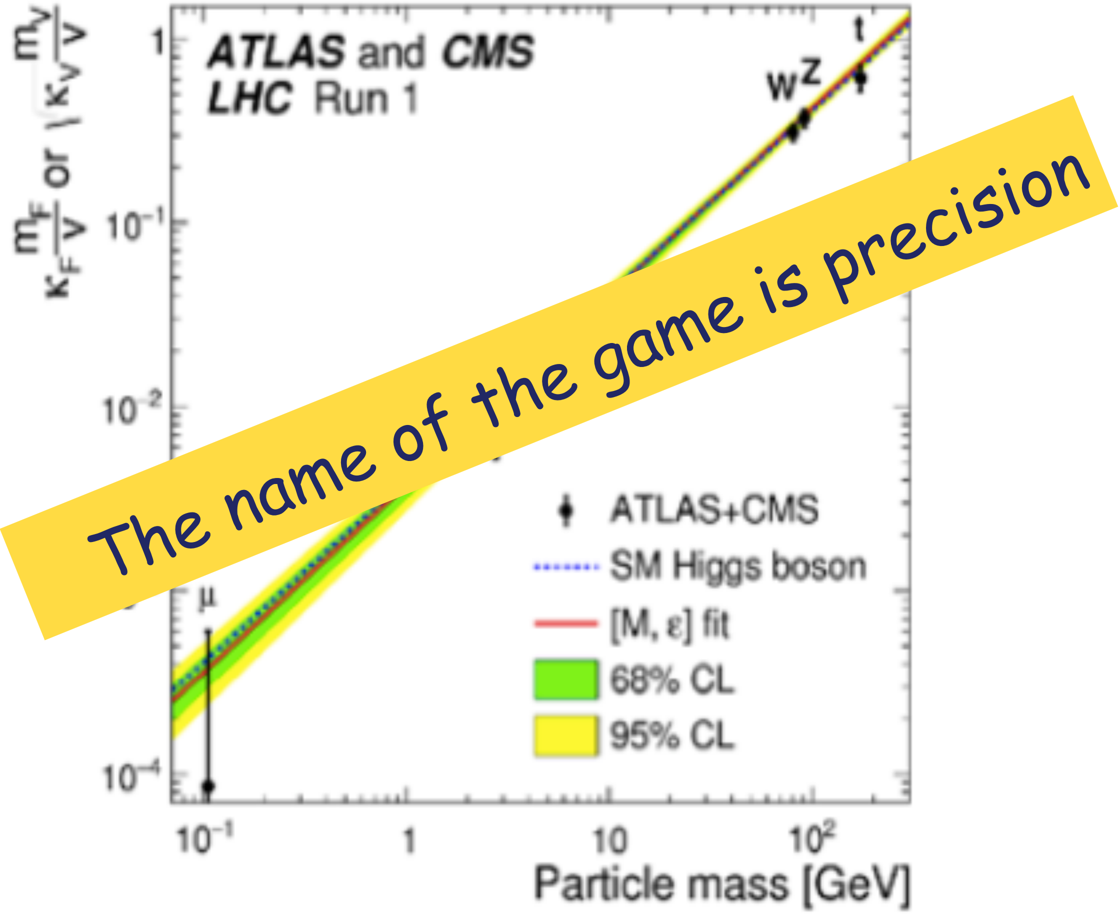

The mass spectrum of the Higgs bosons (GeV)

We may have found one of these states

EXTENDED HIGGS SECTOR

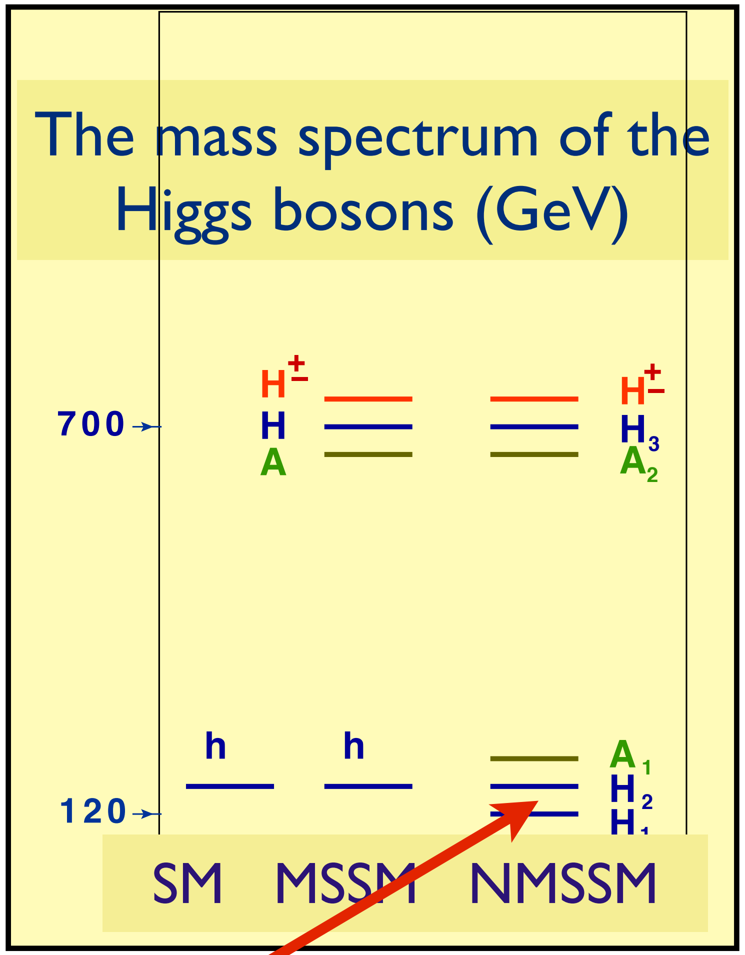
How to probe?

- Probe deviations from the SM Higgs couplings



The name of the game is precision

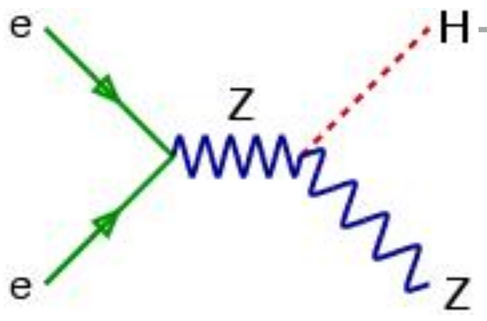
- Perform direct search for additional scalars


The mass spectrum of the Higgs bosons (GeV)

We may have found one of these states

One has to check the presence or absence of heavy Higgs bosons

PRECISION PHYSICS OF THE HIGGS BOSONS

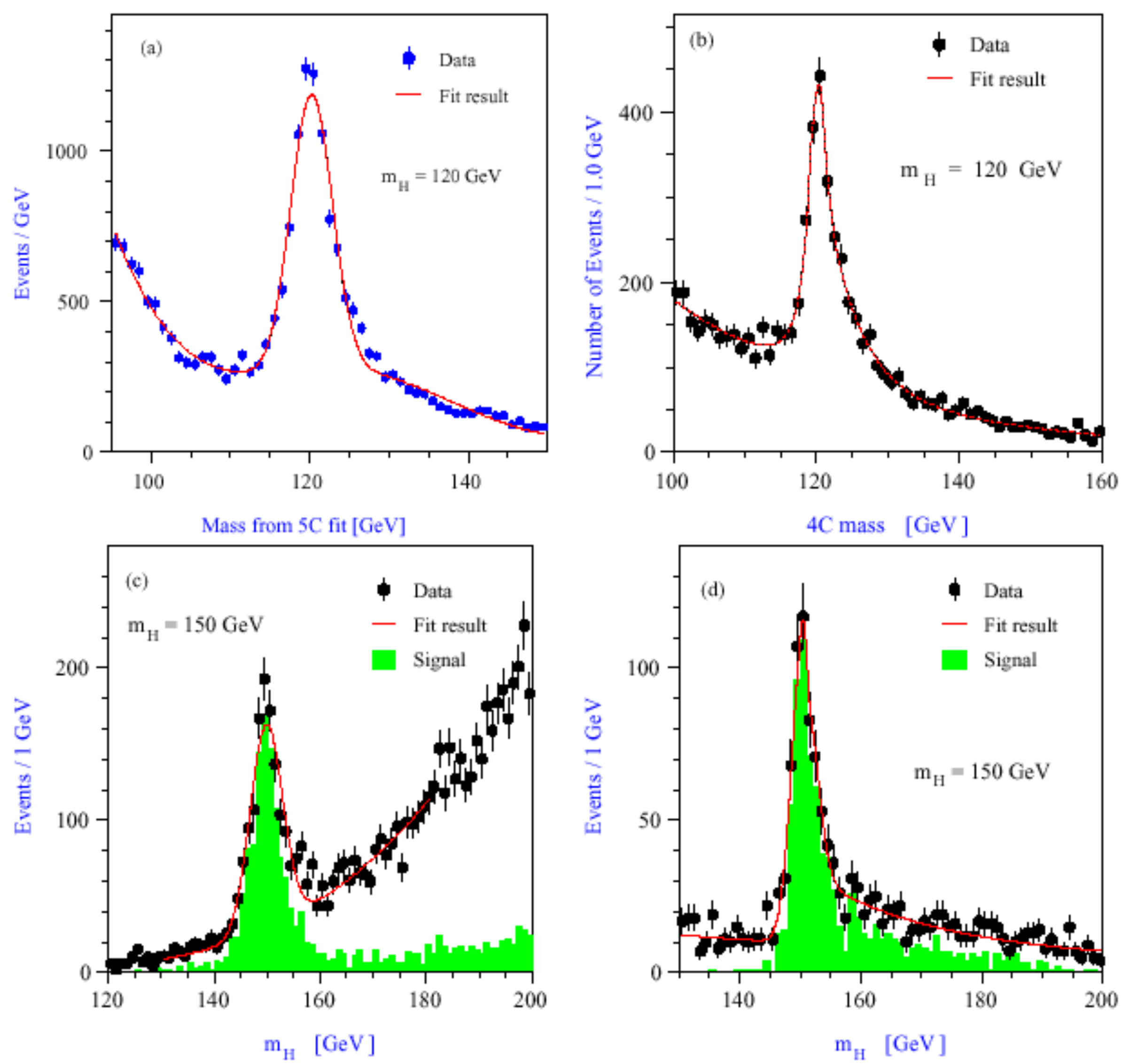


$\rightarrow b\bar{b}q\bar{q}$

ee -> HZ diff. decay channels

Int Linear Collider

$\rightarrow W^+W^-q\bar{q}$

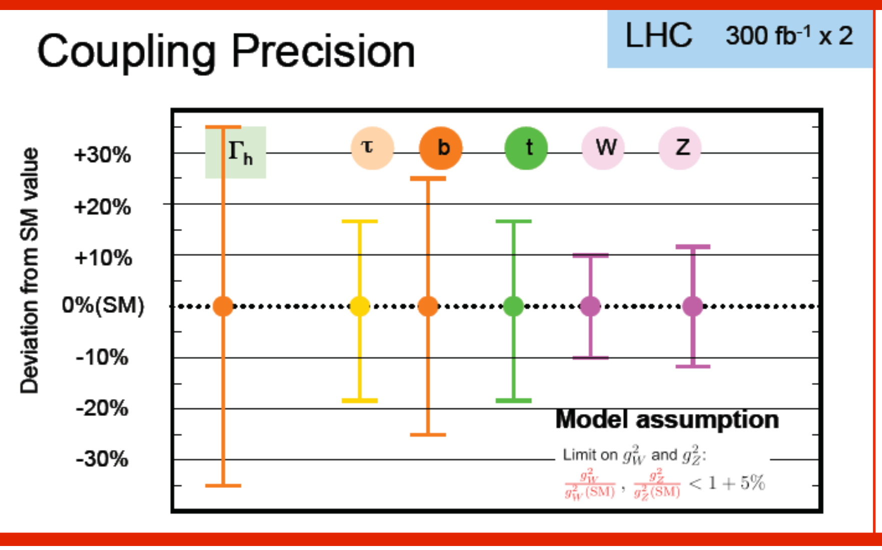


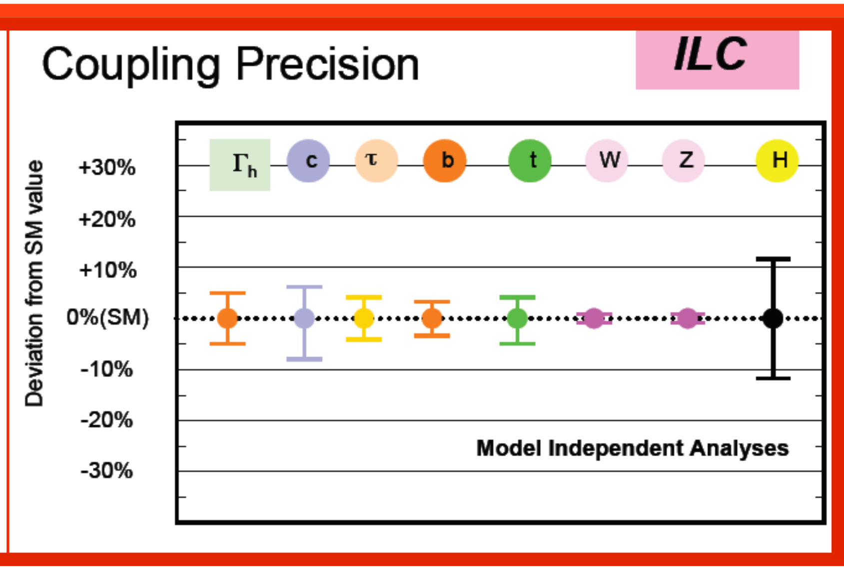
$\rightarrow q\bar{q}\ell^+\ell^-$

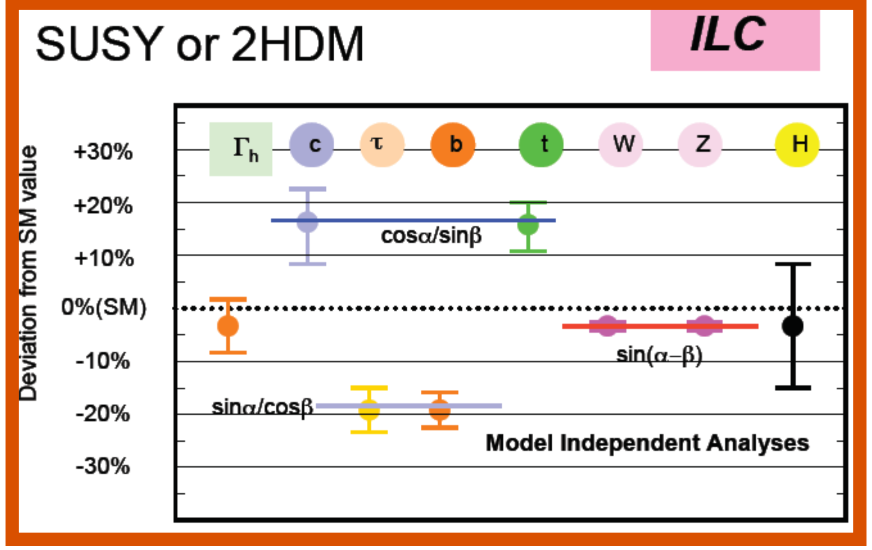
Δm_H = 40 MeV

$\rightarrow W^+W^-\ell^+\ell^-$

Δm_H = 70 MeV

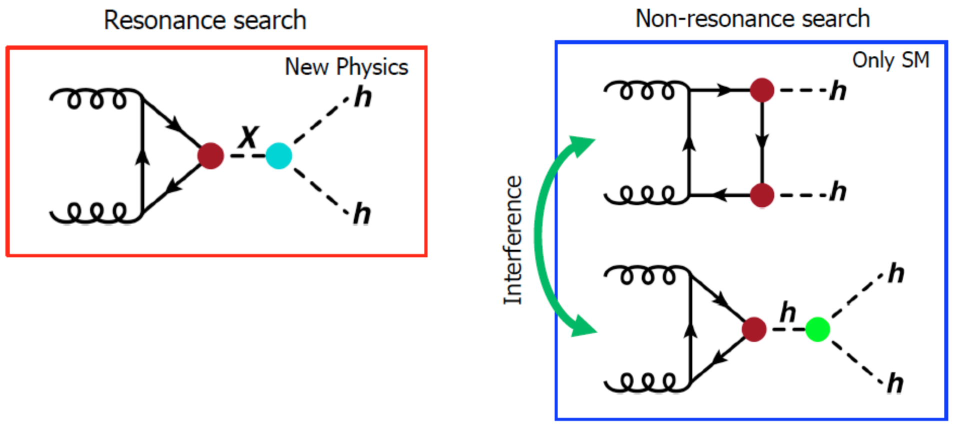




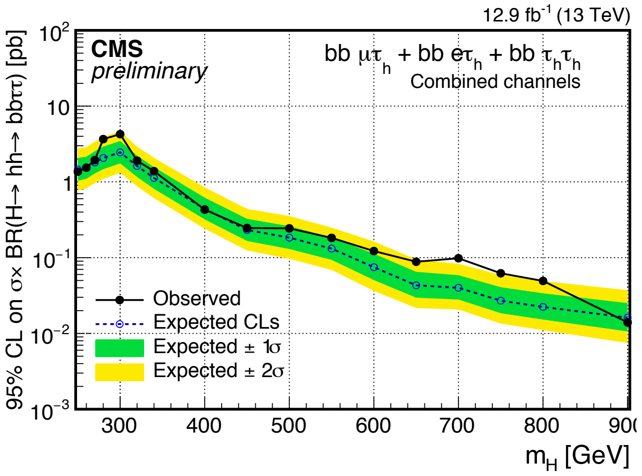


EXTRA HIGGS BOSONS

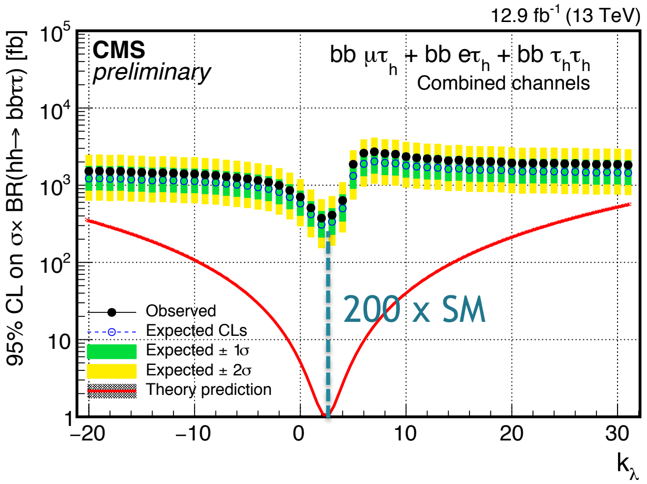
Higgs→hh→bbττ



Resonant

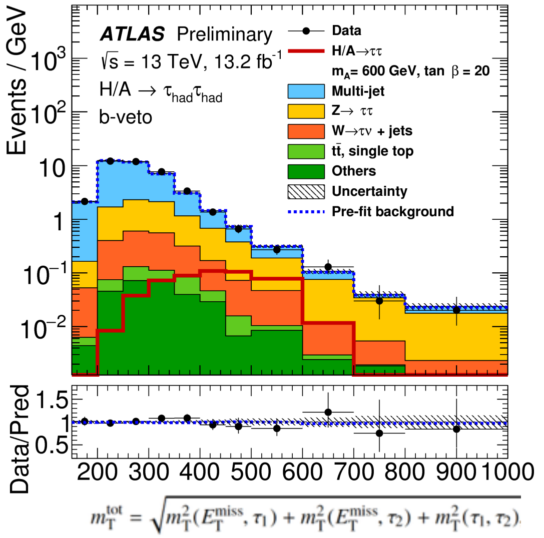


Non-Resonant

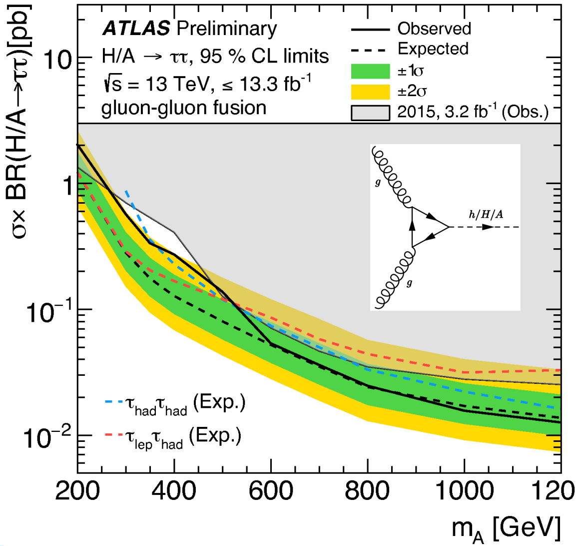


200 x SM

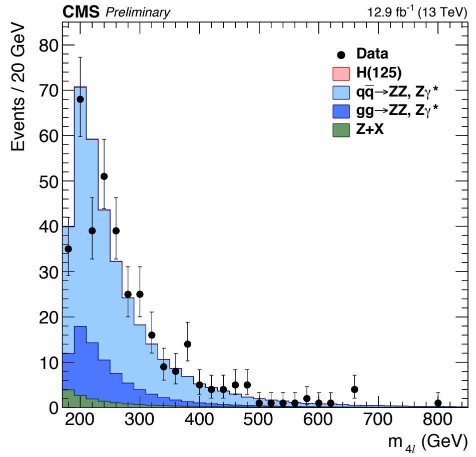
Heavy Higgs→ττ

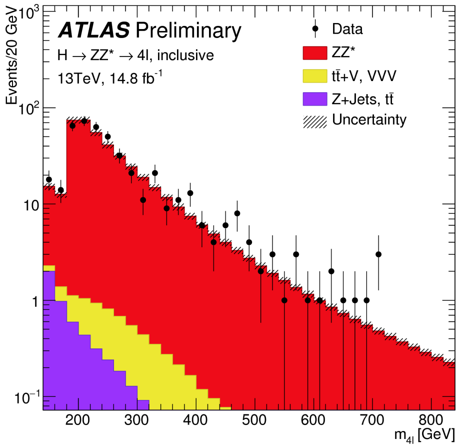


$m_T^{tot} = \sqrt{m_T^2(E_T^{miss}, \tau_1) + m_T^2(E_T^{miss}, \tau_2) + m_T^2(\tau_1, \tau_2)}$

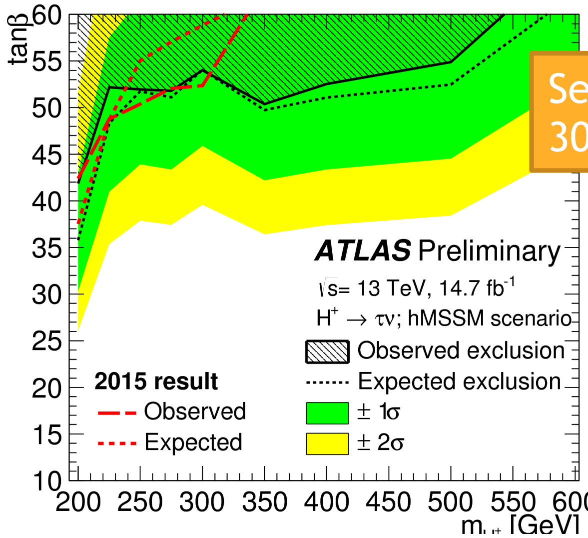


Heavy Higgs→ZZ→4l



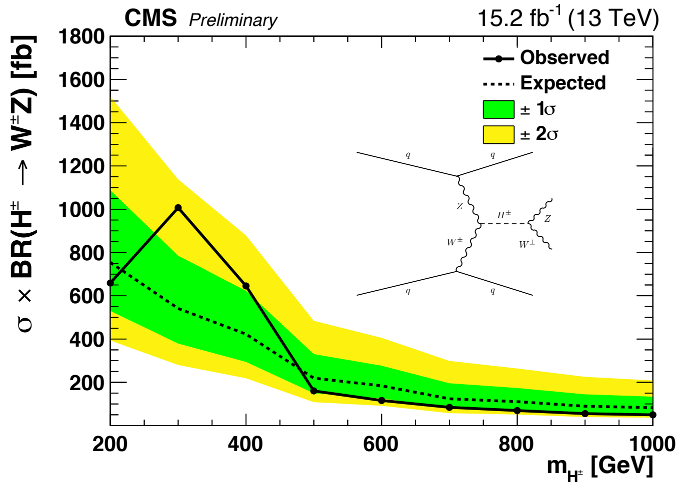


Charged Higgs



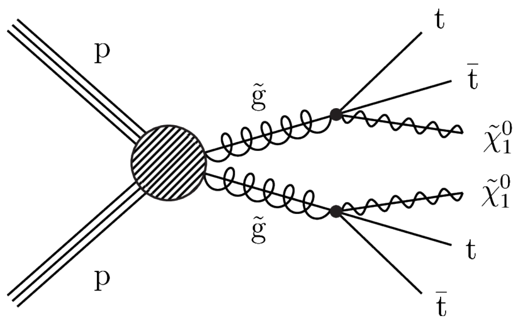
Search for H±→tb
300<$m_{H^\pm}$<1000 GeV

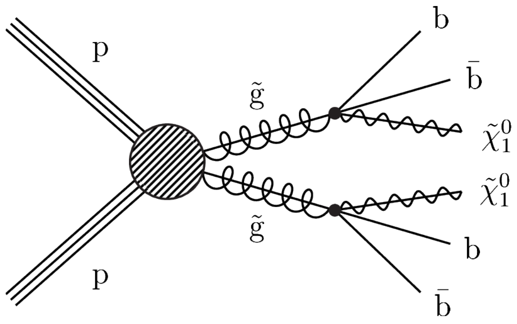
Search for H±WZ

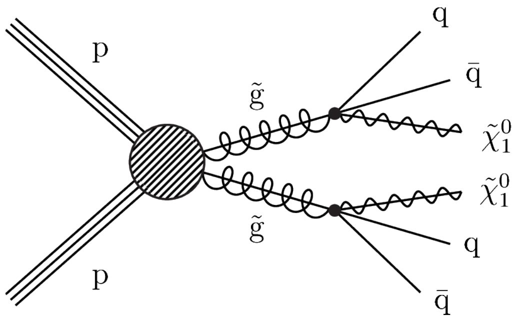


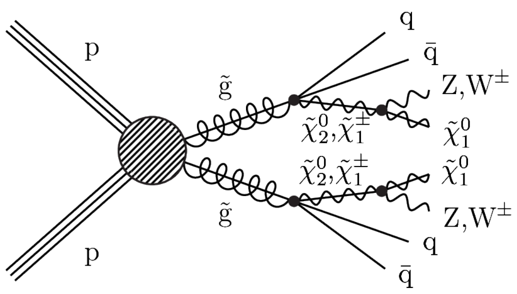
SUSY Searches

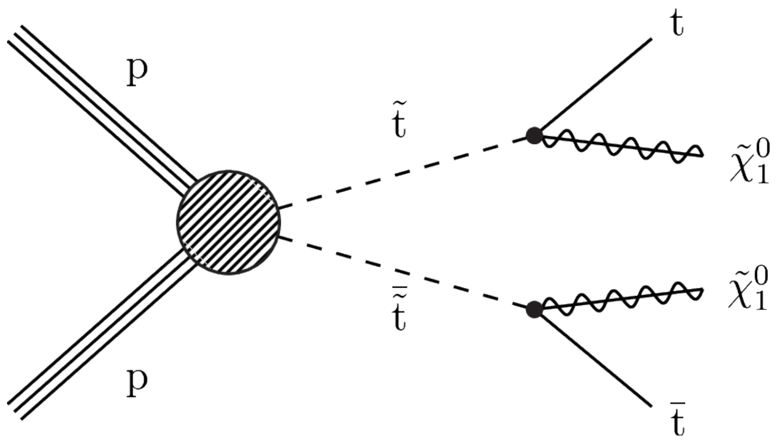
SUSY PRODUCTION

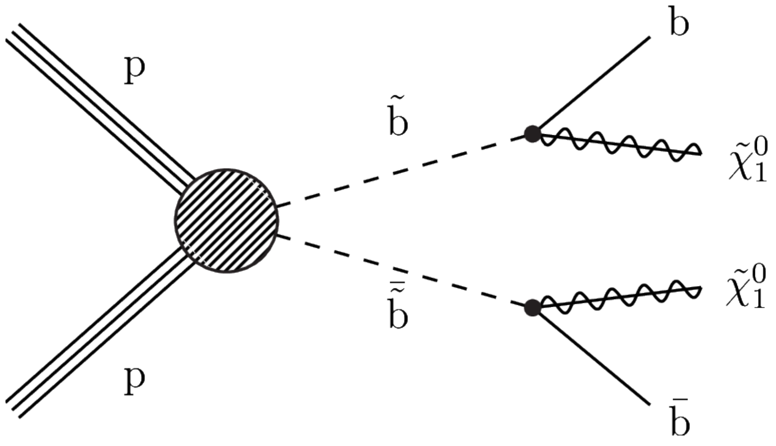


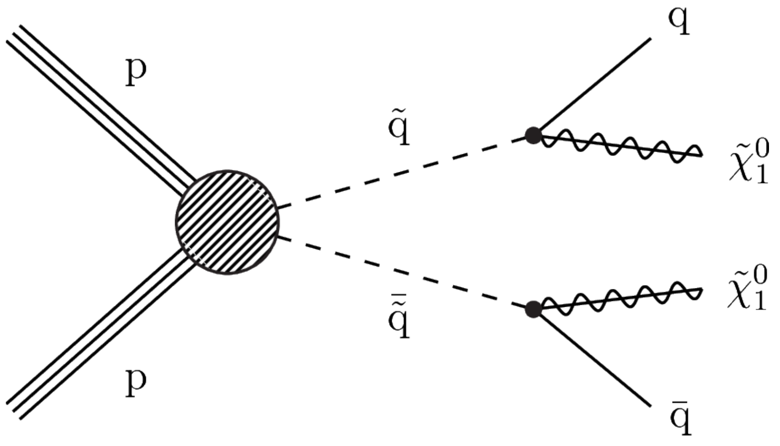




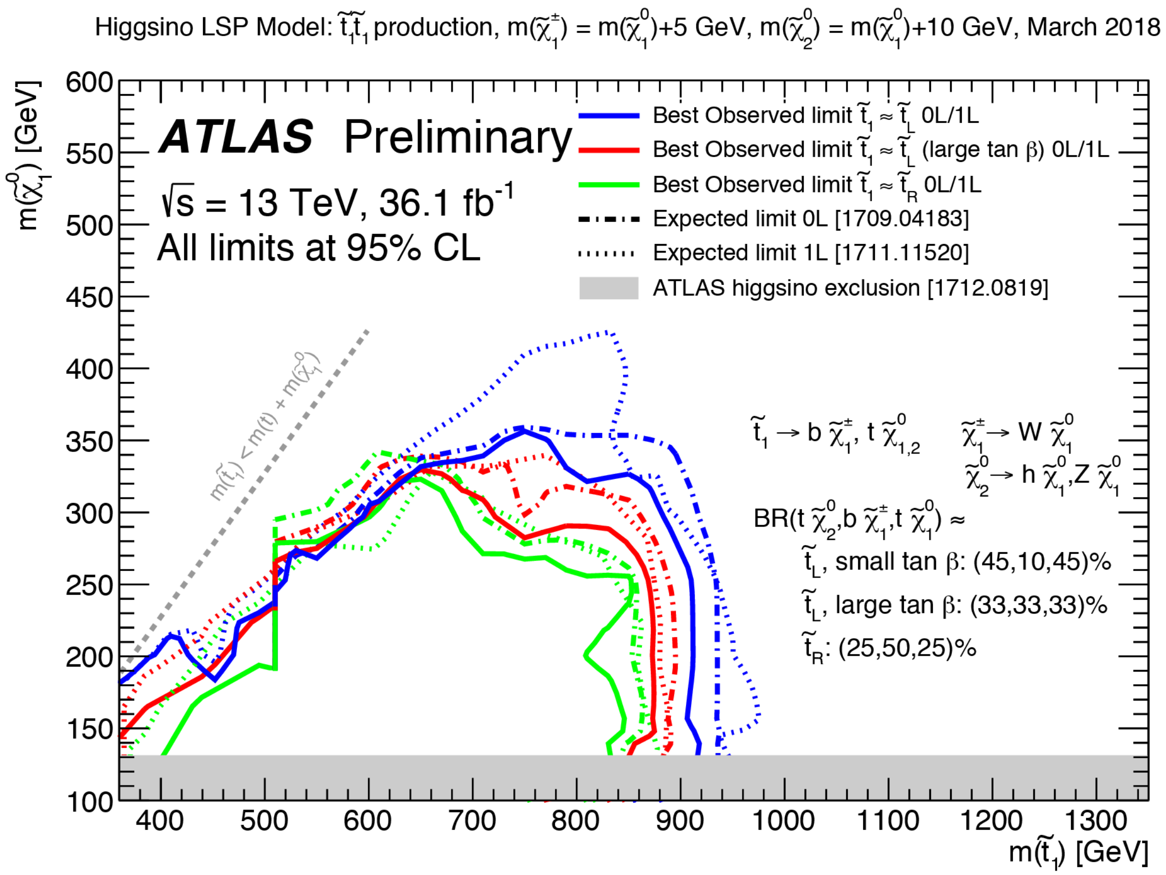


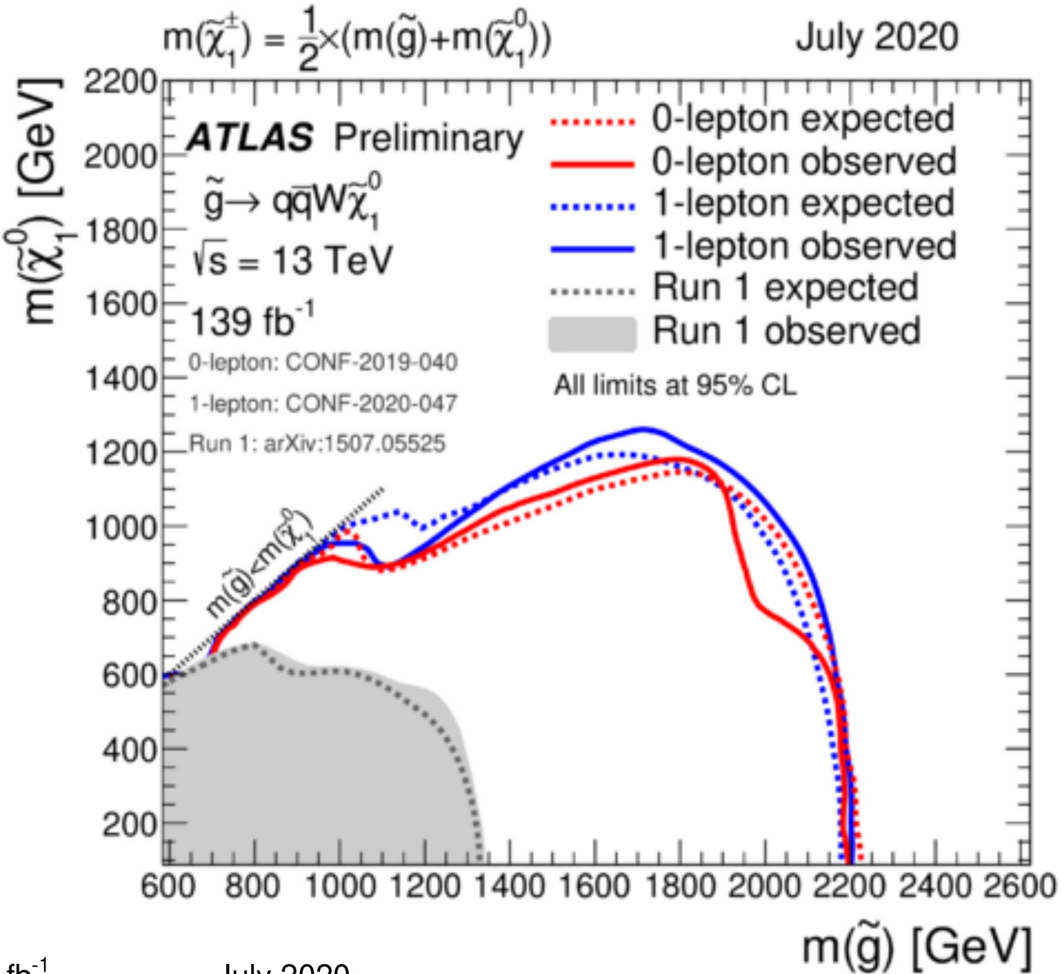


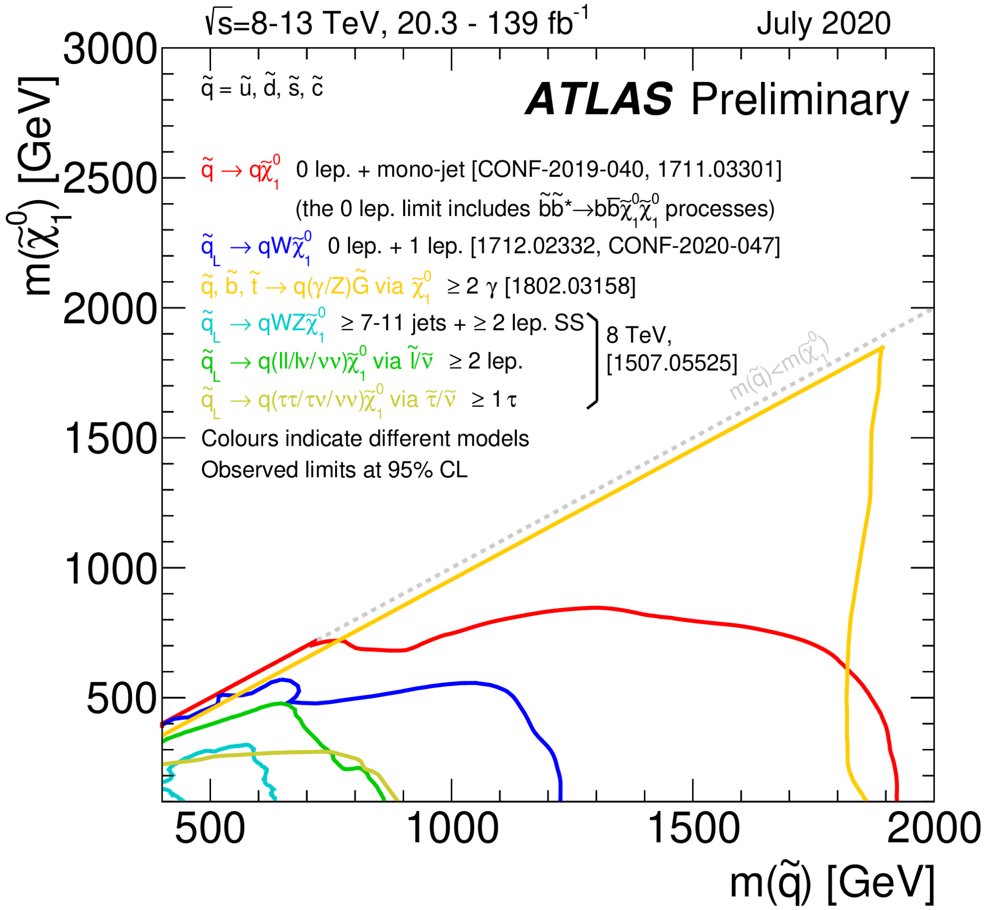




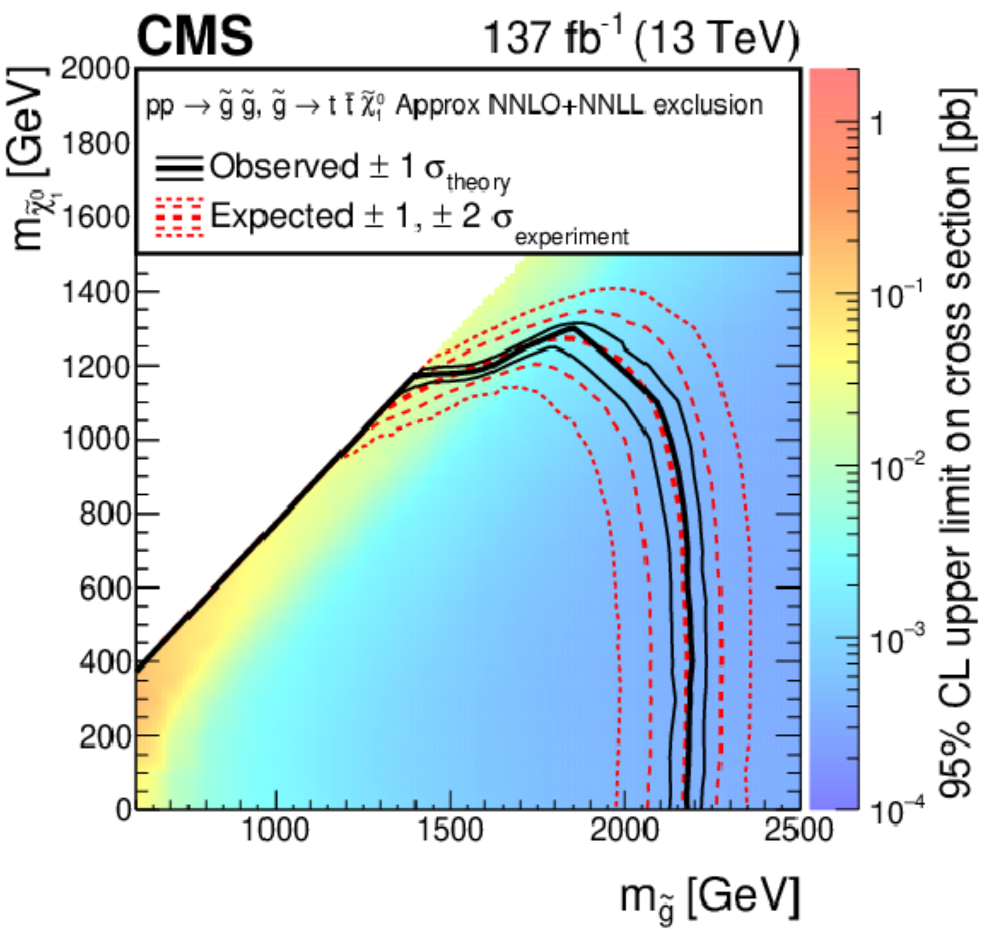
SUSY LIMITS


Higgsino LSP Model: $\tilde{t}_1\tilde{t}_1$ production, $m(\tilde{\chi}_1^\pm) = m(\tilde{\chi}_1^0)$+5 GeV, $m(\tilde{\chi}_2^0) = m(\tilde{\chi}_1^0)$+10 GeV, March 2018
ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
All limits at 95% CL
Best Observed limit $\tilde{t}_1 \approx \tilde{t}_L$ 0L/1L
Best Observed limit $\tilde{t}_1 \approx \tilde{t}_L$ (large tan β) 0L/1L
Best Observed limit $\tilde{t}_1 \approx \tilde{t}_R$ 0L/1L
Expected limit 0L [1709.04183]
Expected limit 1L [1711.11520]
ATLAS higgsino exclusion [1712.0819]
$\tilde{t}_1 \to b\,\tilde{\chi}_1^\pm,\ t\,\tilde{\chi}_{1,2}^0$
$\tilde{\chi}_1^\pm \to W\,\tilde{\chi}_1^0$
$\tilde{\chi}_2^0 \to h\,\tilde{\chi}_1^0, Z\,\tilde{\chi}_1^0$
BR($t\,\tilde{\chi}_2^0$,$b\,\tilde{\chi}_1^\pm$,$t\,\tilde{\chi}_1^0$) ≈
$\tilde{t}_L$, small tan β: (45,10,45)%
$\tilde{t}_L$, large tan β: (33,33,33)%
$\tilde{t}_R$: (25,50,25)%
$m(\tilde{t}_1) < m(t) + m(\tilde{\chi}_1^0)$
$m(\tilde{\chi}_1^0)$ [GeV]
100 150 200 250 300 350 400 450 500 550 600
400 500 600 700 800 900 1000 1100 1200 1300
$m(\tilde{t}_1)$ [GeV]

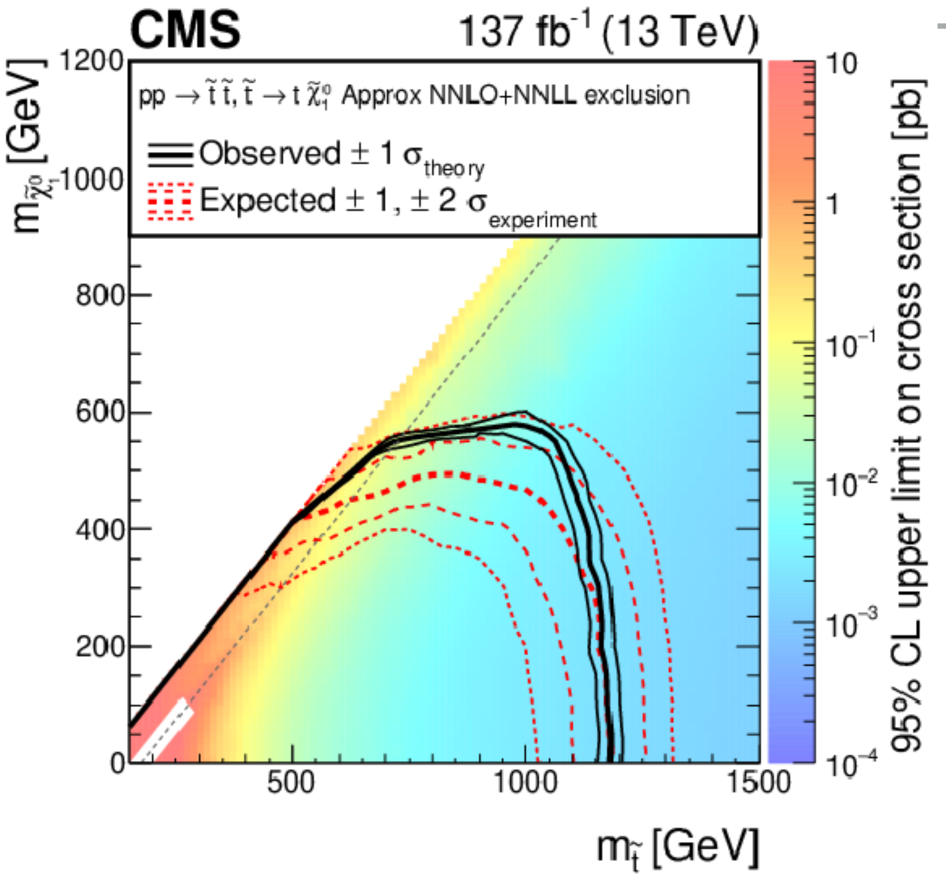

$m(\tilde{\chi}_1^\pm) = \frac{1}{2}\times(m(\tilde{g})+m(\tilde{\chi}_1^0))$
July 2020
ATLAS Preliminary
$\tilde{g} \to q\bar{q}W\tilde{\chi}_1^0$
$\sqrt{s}$ = 13 TeV
139 fb^{-1}
0-lepton: CONF-2019-040
1-lepton: CONF-2020-047
Run 1: arXiv:1507.05525
0-lepton expected
0-lepton observed
1-lepton expected
1-lepton observed
Run 1 expected
Run 1 observed
All limits at 95% CL
$m(\tilde{g})<m(\tilde{\chi}_1^0)$
$m(\tilde{\chi}_1^0)$ [GeV]
200 400 600 800 1000 1200 1400 1600 1800 2000 2200
600 800 1000 1200 1400 1600 1800 2000 2200 2400 2600
$m(\tilde{g})$ [GeV]


$\sqrt{s}$=8-13 TeV, 20.3 - 139 fb^{-1}
July 2020
$\tilde{q} = \tilde{u}, \tilde{d}, \tilde{s}, \tilde{c}$
ATLAS Preliminary
$\tilde{q} \to q\tilde{\chi}_1^0$ 0 lep. + mono-jet [CONF-2019-040, 1711.03301]
(the 0 lep. limit includes $\tilde{b}\tilde{b}^* \to b\bar{b}\tilde{\chi}_1^0\tilde{\chi}_1^0$ processes)
$\tilde{q}_L \to qW\tilde{\chi}_1^0$ 0 lep. + 1 lep. [1712.02332, CONF-2020-047]
$\tilde{q}, \tilde{b}, \tilde{t} \to q(\gamma/Z)\tilde{G}$ via $\tilde{\chi}_1^0$ ≥ 2 γ [1802.03158]
$\tilde{q}_L \to qWZ\tilde{\chi}_1^0$ ≥ 7-11 jets + ≥ 2 lep. SS
$\tilde{q}_L \to q(ll/l\nu/\nu\nu)\tilde{\chi}_1^0$ via $\tilde{l}/\tilde{\nu}$ ≥ 2 lep.
$\tilde{q}_L \to q(\tau\tau/\tau\nu/\nu\nu)\tilde{\chi}_1^0$ via $\tilde{\tau}/\tilde{\nu}$ ≥ 1 τ
8 TeV, [1507.05525]
Colours indicate different models
Observed limits at 95% CL
$m(\tilde{q})<m(\tilde{\chi}_1^0)$
$m(\tilde{\chi}_1^0)$ [GeV]
500 1000 1500 2000 2500 3000
500 1000 1500 2000
$m(\tilde{q})$ [GeV]

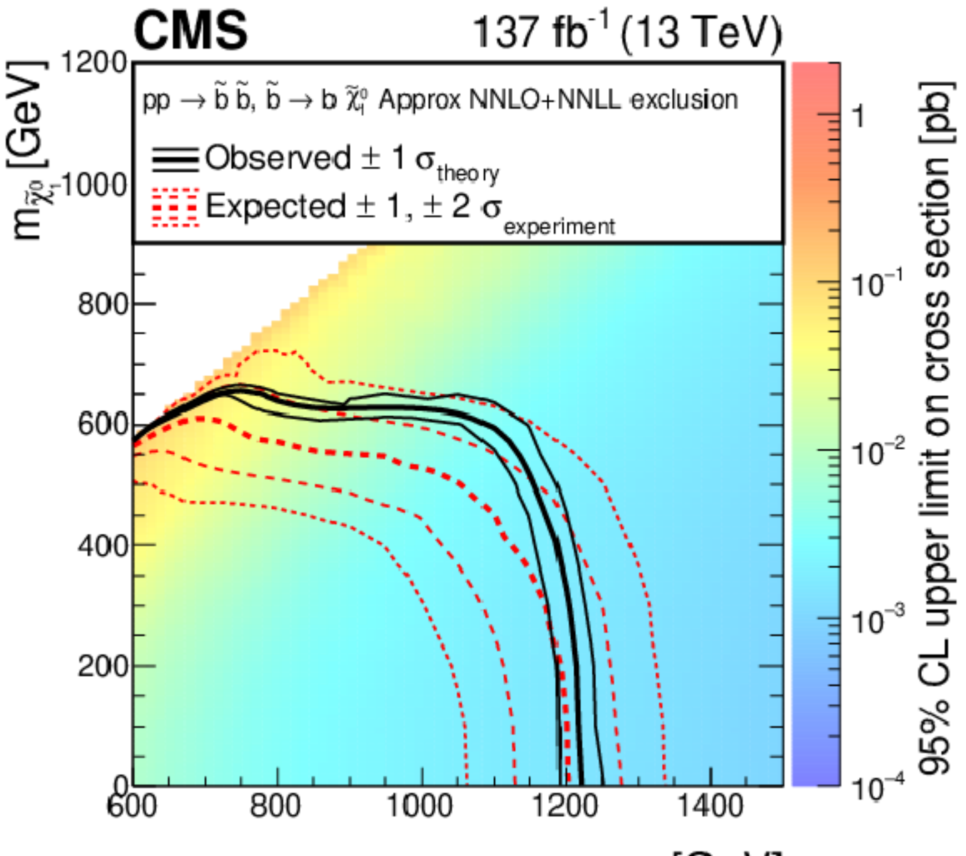
SUSY LIMITS



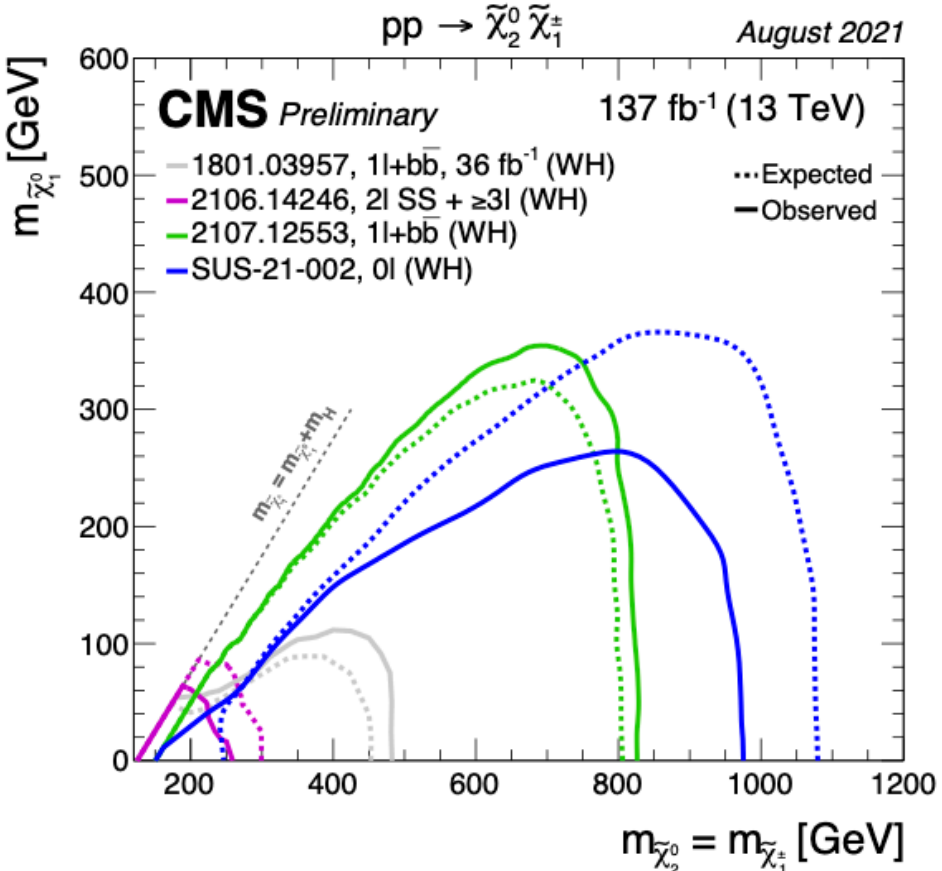
CMS
137 fb^{-1} (13 TeV)
pp → $\tilde{g}\tilde{g}$, $\tilde{g} \to t\bar{t}\tilde{\chi}^0_1$ Approx NNLO+NNLL exclusion
Observed ± 1 σ_{theory}
Expected ± 1, ± 2 $\sigma_{experiment}$
$m_{\tilde{\chi}^0_1}$ [GeV]
0
200
400
600
800
1000
1200
1400
1600
1800
2000
1000
1500
2000
2500
$m_{\tilde{g}}$ [GeV]
95% CL upper limit on cross section [pb]
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}



CMS
137 fb^{-1} (13 TeV)
pp → $\tilde{t}\bar{\tilde{t}}$, $\tilde{t} \to t\tilde{\chi}^0_1$ Approx NNLO+NNLL exclusion
Observed ± 1 σ_{theory}
Expected ± 1, ± 2 $\sigma_{experiment}$
$m_{\tilde{\chi}^0_1}$ [GeV]
0
200
400
600
800
1000
1200
500
1000
1500
$m_{\tilde{t}}$ [GeV]
95% CL upper limit on cross section [pb]
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}



CMS
137 fb^{-1} (13 TeV)
pp → $\tilde{b}\bar{\tilde{b}}$, $\tilde{b} \to b\tilde{\chi}^0_1$ Approx NNLO+NNLL exclusion
Observed ± 1 σ_{theory}
Expected ± 1, ± 2 $\sigma_{experiment}$
$m_{\tilde{\chi}^0_1}$ [GeV]
0
200
400
600
800
1000
1200
600
800
1000
1200
1400
95% CL upper limit on cross section [pb]
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}

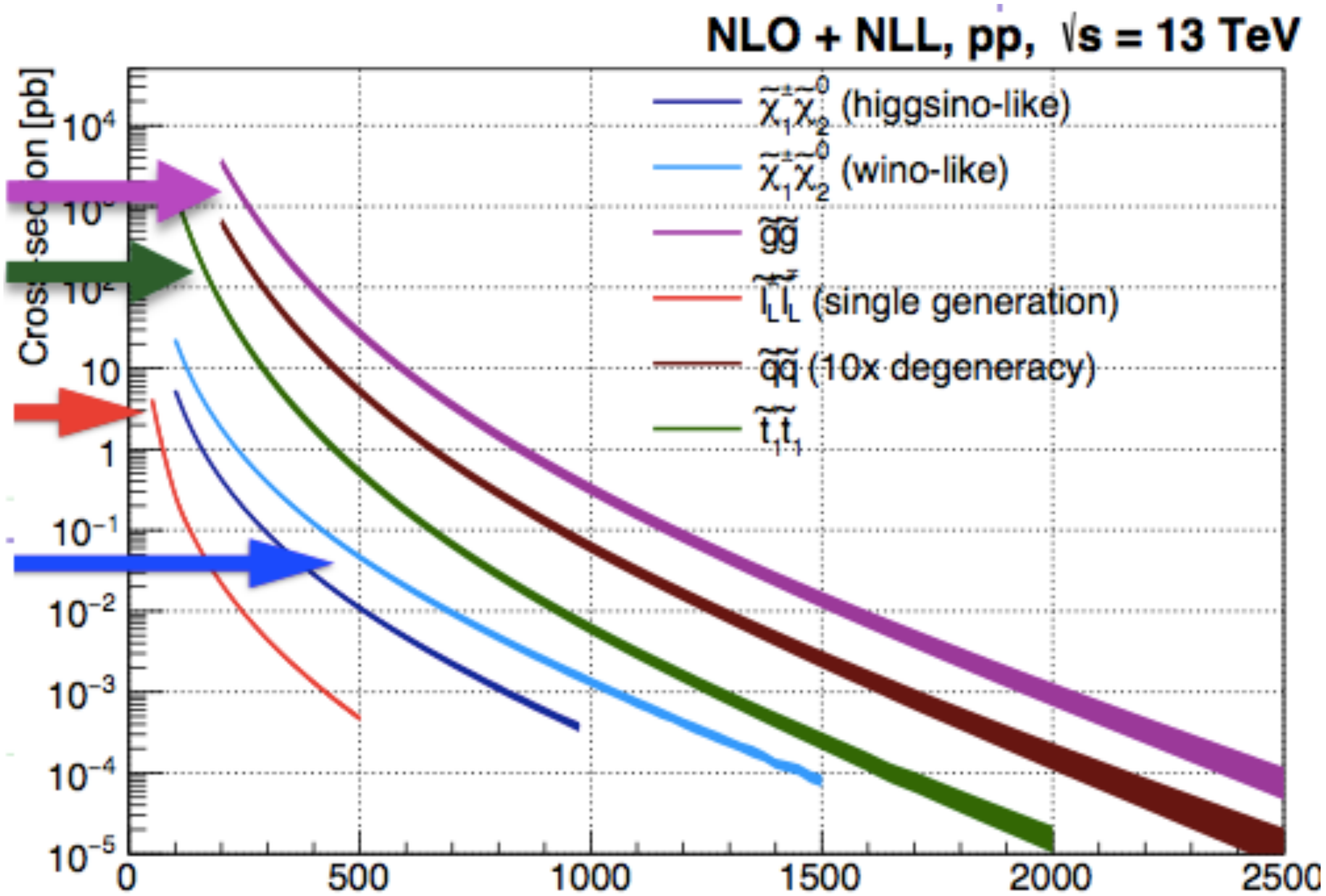


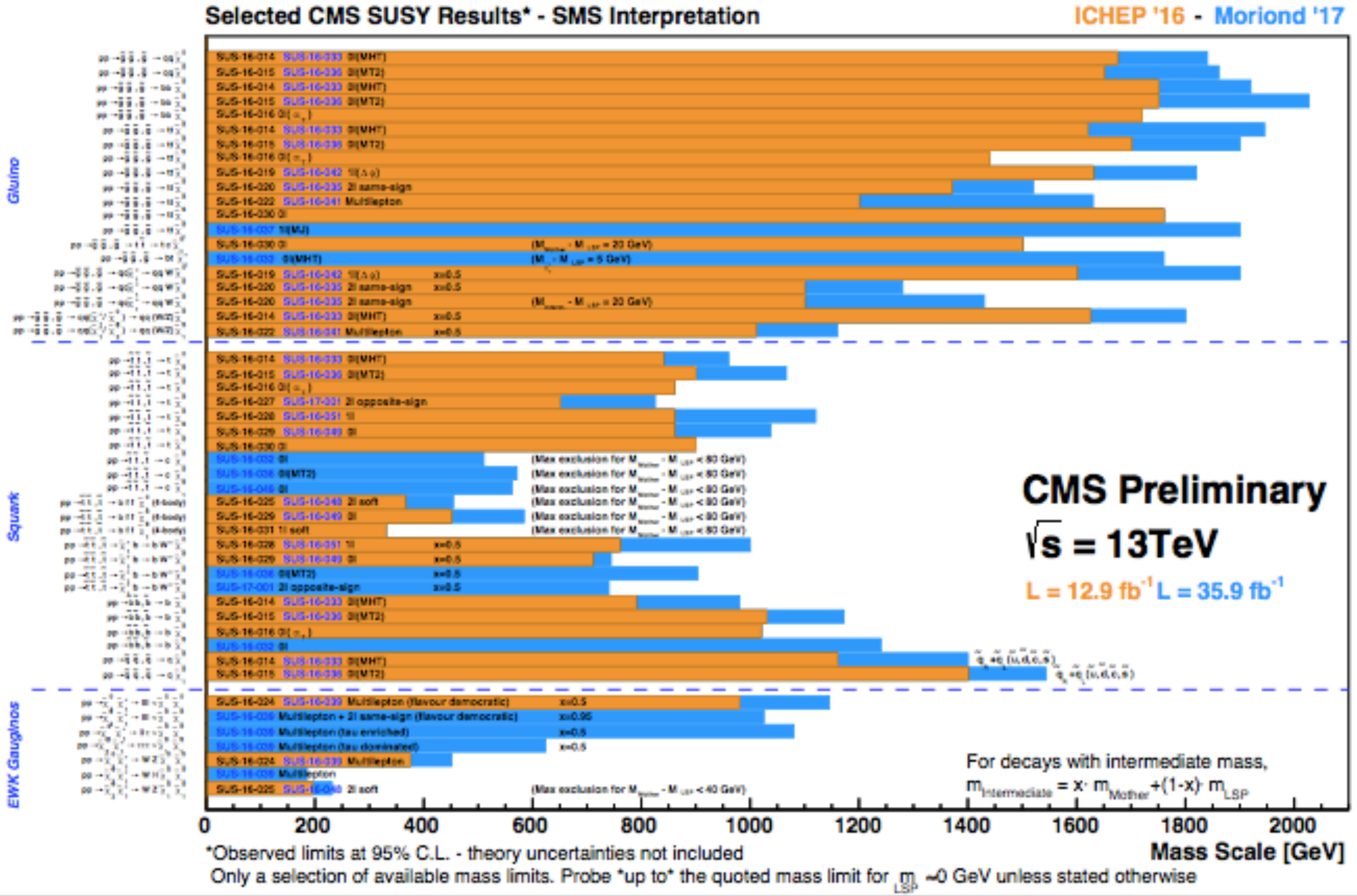
pp → $\tilde{\chi}^0_2\tilde{\chi}^\pm_1$
August 2021
CMS Preliminary
137 fb^{-1} (13 TeV)
1801.03957, 1l+b$\bar{b}$, 36 fb^{-1} (WH)
2106.14246, 2l SS + ≥3l (WH)
2107.12553, 1l+b$\bar{b}$ (WH)
SUS-21-002, 0l (WH)
Expected
Observed
$m_{\tilde{\chi}^0_2} = m_{\tilde{\chi}^0_1} + m_H$
$m_{\tilde{\chi}^0_1}$ [GeV]
0
100
200
300
400
500
600
200
400
600
800
1000
1200
$m_{\tilde{\chi}^0_2} = m_{\tilde{\chi}^\pm_1}$ [GeV]

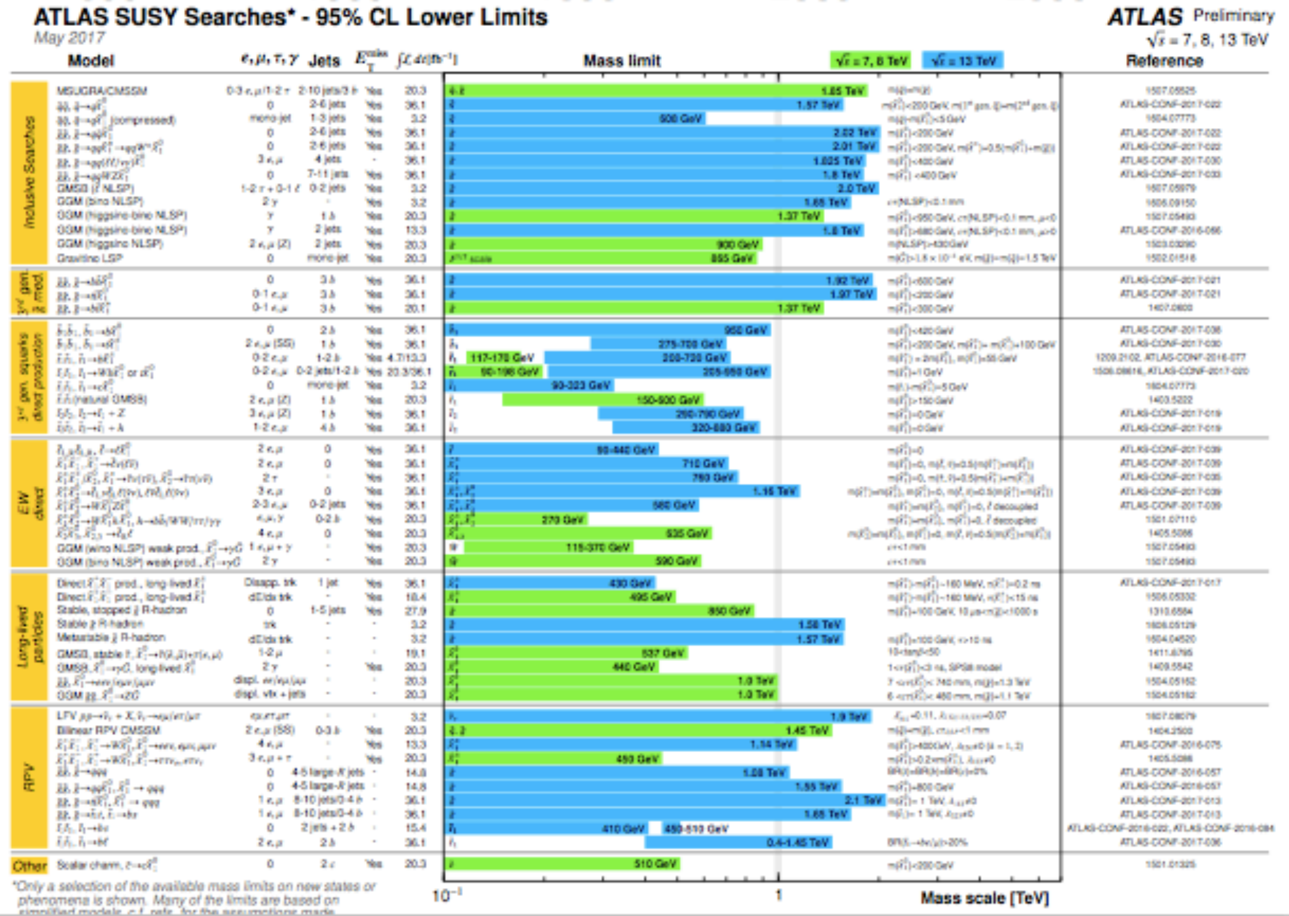
SUSY SEARCHES

Strong production
(gluinos, squarks)

EWK production
(charginos, neutralinos, sleptons)



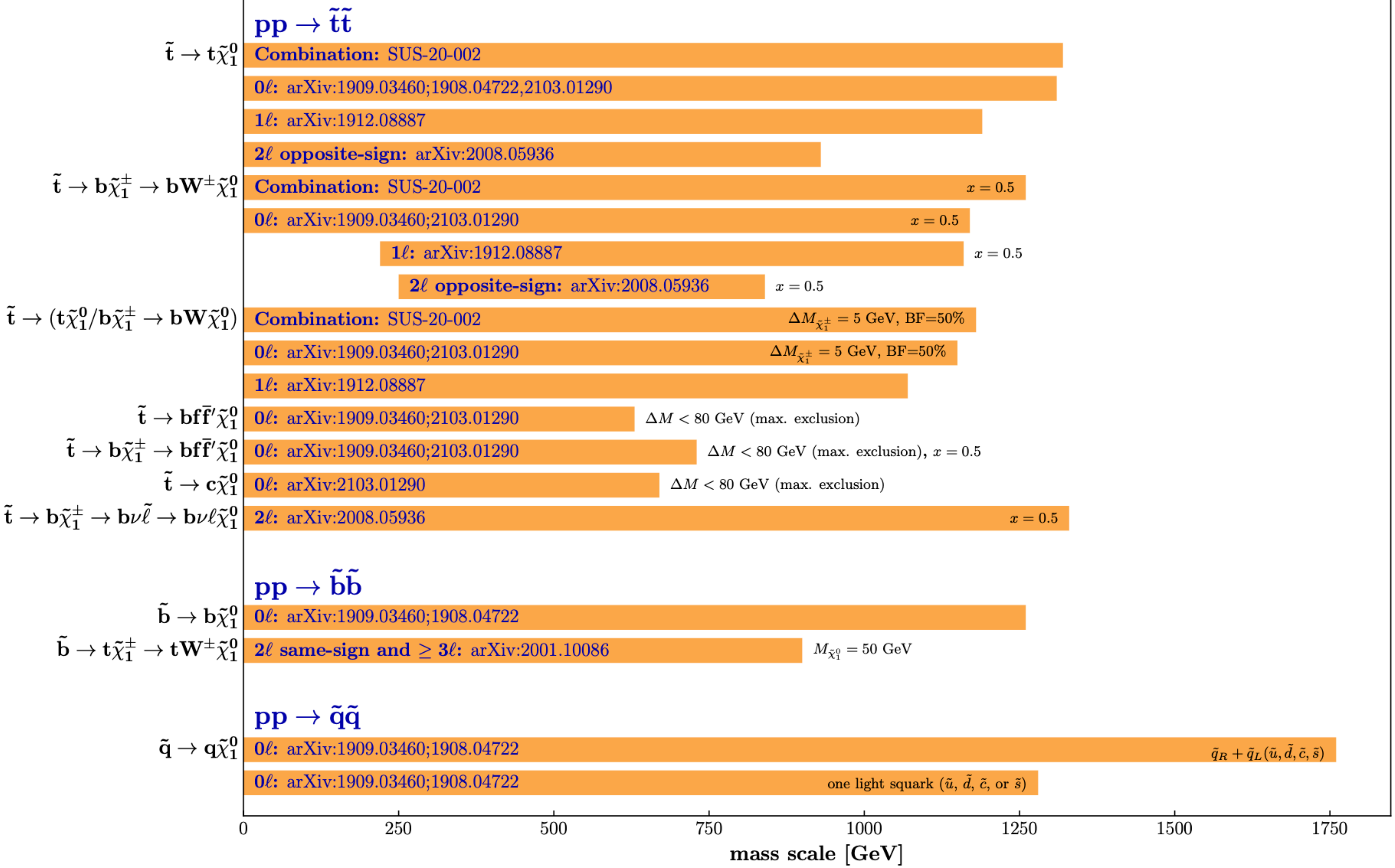




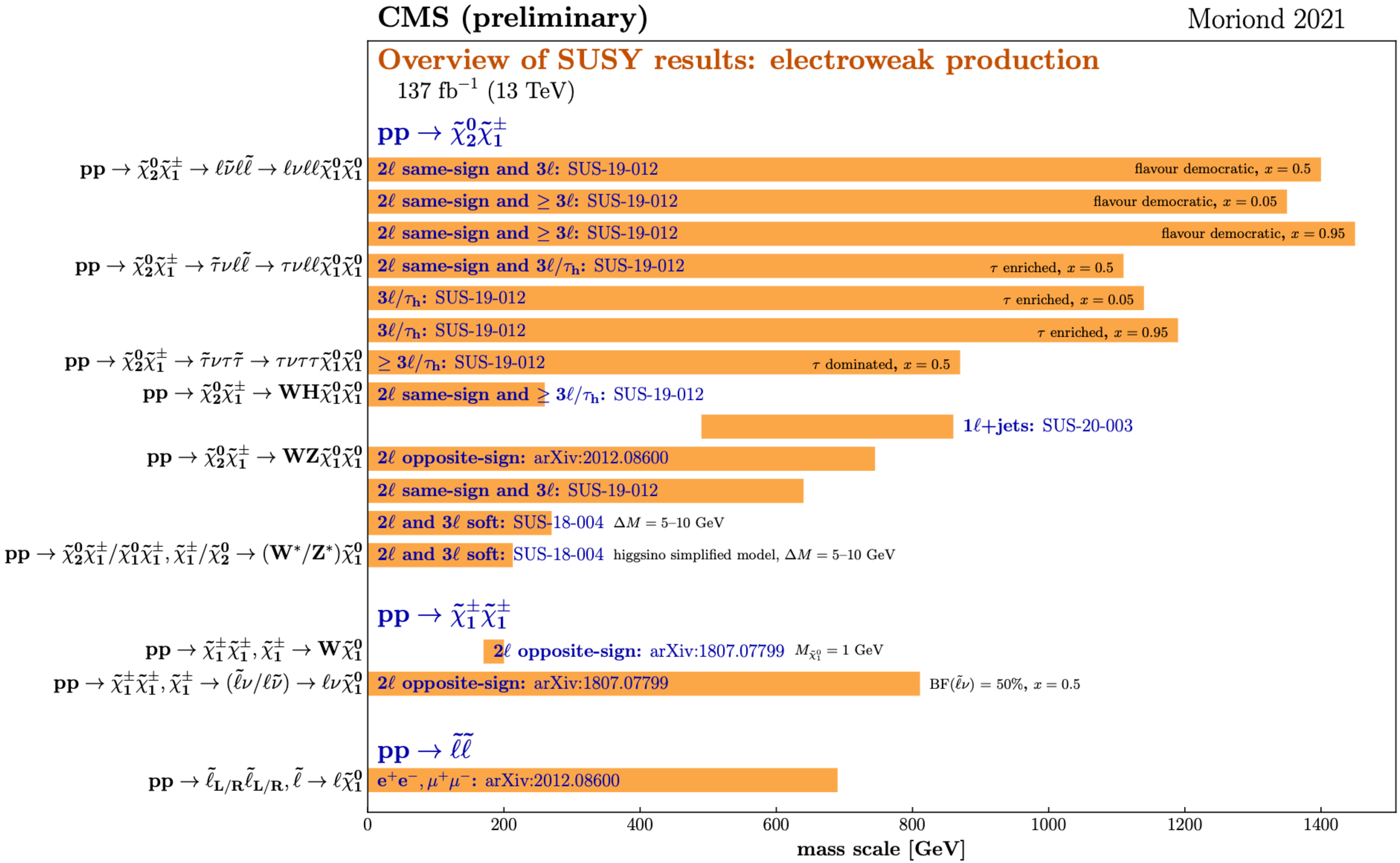
CMS (preliminary) Moriond 2021

Overview of SUSY results: squark pair production

137 fb^{-1} (13 TeV)



Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe **up to** the quoted mass limit for light LSPs unless stated otherwise. The quantities ΔM and x represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to ΔM, respectively, unless indicated otherwise.



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mass scale [GeV]

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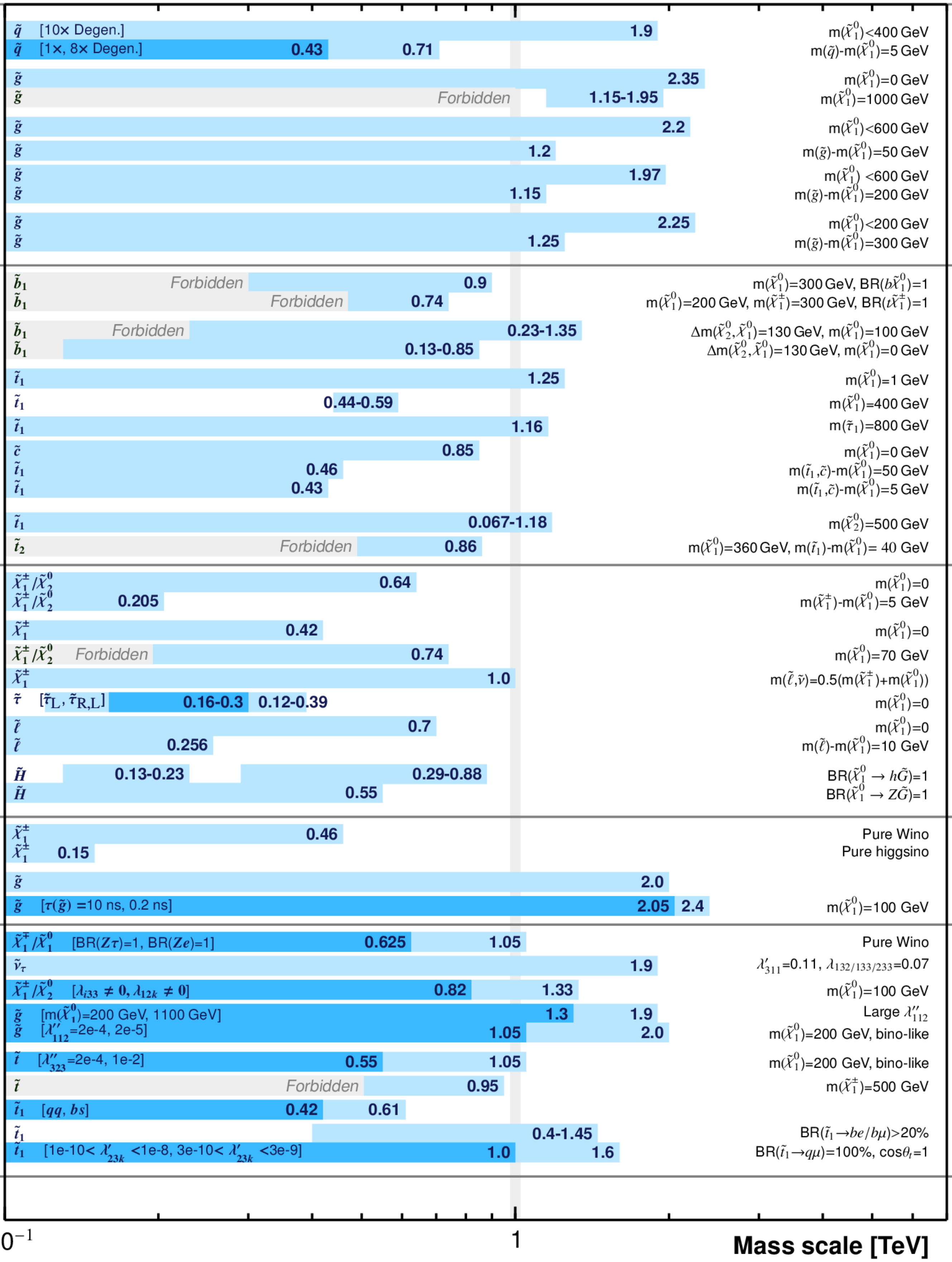
ATLAS SUSY Searches* - 95% CL Lower Limits

July 2020

ATLAS Preliminary

$\sqrt{s}$ = 13 TeV



	Model	Signature			$\int\mathcal{L}\,dt$ [fb^{-1}]	Mass limit			Reference
Inclusive Searches	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$	0 e,μ	2-6 jets	$E_T^{\rm miss}$	139	$\tilde{q}$ [10× Degen.]	1.9	m($\tilde{\chi}^0_1$)<400 GeV	ATLAS-CONF-2019-040
		mono-jet	1-3 jets	$E_T^{\rm miss}$	36.1	$\tilde{q}$ [1×, 8× Degen.]	0.43 0.71	m($\tilde{q}$)-m($\tilde{\chi}^0_1$)=5 GeV	1711.03301
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0 e,μ	2-6 jets	$E_T^{\rm miss}$	139	$\tilde{g}$	2.35	m($\tilde{\chi}^0_1$)=0 GeV	ATLAS-CONF-2019-040
						$\tilde{g}$	Forbidden 1.15-1.95	m($\tilde{\chi}^0_1$)=1000 GeV	ATLAS-CONF-2019-040
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}W\tilde{\chi}^0_1$	1 e,μ	2-6 jets		139	$\tilde{g}$	2.2	m($\tilde{\chi}^0_1$)<600 GeV	ATLAS-CONF-2020-047
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}^0_1$	$ee,\mu\mu$	2 jets	$E_T^{\rm miss}$	36.1	$\tilde{g}$	1.2	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=50 GeV	1805.11381
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}^0_1$	0 e,μ	7-11 jets	$E_T^{\rm miss}$	139	$\tilde{g}$	1.97	m($\tilde{\chi}^0_1$) <600 GeV	ATLAS-CONF-2020-002
		SS e,μ	6 jets		139	$\tilde{g}$	1.15	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=200 GeV	1909.08457
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e,μ	3 b	$E_T^{\rm miss}$	79.8	$\tilde{g}$	2.25	m($\tilde{\chi}^0_1$)<200 GeV	ATLAS-CONF-2018-041
		SS e,μ	6 jets		139	$\tilde{g}$	1.25	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=300 GeV	1909.08457
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}^0_1/t\tilde{\chi}^\pm_1$		Multiple		36.1	$\tilde{b}_1$	Forbidden 0.9	m($\tilde{\chi}^0_1$)=300 GeV, BR($b\tilde{\chi}^0_1$)=1	1708.09266, 1711.03301
			Multiple		139	$\tilde{b}_1$	Forbidden 0.74	m($\tilde{\chi}^0_1$)=200 GeV, m($\tilde{\chi}^\pm_1$)=300 GeV, BR($t\tilde{\chi}^\pm_1$)=1	1909.08457
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}^0_2\to bh\tilde{\chi}^0_1$	0 e,μ	6 b	$E_T^{\rm miss}$	139	$\tilde{b}_1$	Forbidden 0.23-1.35	Δm($\tilde{\chi}^0_2,\tilde{\chi}^0_1$)=130 GeV, m($\tilde{\chi}^0_1$)=100 GeV	1908.03122
		2 τ	2 b	$E_T^{\rm miss}$	139	$\tilde{b}_1$	0.13-0.85	Δm($\tilde{\chi}^0_2,\tilde{\chi}^0_1$)=130 GeV, m($\tilde{\chi}^0_1$)=0 GeV	ATLAS-CONF-2020-031
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}^0_1$	0-1 e,μ	$\geq$ 1 jet	$E_T^{\rm miss}$	139	$\tilde{t}_1$	1.25	m($\tilde{\chi}^0_1$)=1 GeV	ATLAS-CONF-2020-003, 2004.14060
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}^0_1$	1 e,μ	3 jets/1 b	$E_T^{\rm miss}$	139	$\tilde{t}_1$	0.44-0.59	m($\tilde{\chi}^0_1$)=400 GeV	ATLAS-CONF-2019-017
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to\tilde{\tau}_1 b\nu$, $\tilde{\tau}_1\to\tau\tilde{G}$	1 τ + 1 e,μ,τ	2 jets/1 b	$E_T^{\rm miss}$	36.1	$\tilde{t}_1$	1.16	m($\tilde{\tau}_1$)=800 GeV	1803.10178
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}^0_1$ / $\tilde{c}\tilde{c}$, $\tilde{c}\to c\tilde{\chi}^0_1$	0 e,μ	2 c	$E_T^{\rm miss}$	36.1	$\tilde{c}$	0.85	m($\tilde{\chi}^0_1$)=0 GeV	1805.01649
						$\tilde{t}_1$	0.46	m($\tilde{t}_1,\tilde{c}$)-m($\tilde{\chi}^0_1$)=50 GeV	1805.01649
		0 e,μ	mono-jet	$E_T^{\rm miss}$	36.1	$\tilde{t}_1$	0.43	m($\tilde{t}_1,\tilde{c}$)-m($\tilde{\chi}^0_1$)=5 GeV	1711.03301
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}^0_2$, $\tilde{\chi}^0_2\to Z/h\tilde{\chi}^0_1$	1-2 e,μ	1-4 b	$E_T^{\rm miss}$	139	$\tilde{t}_1$	0.067-1.18	m($\tilde{\chi}^0_2$)=500 GeV	SUSY-2018-09
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ	1 b	$E_T^{\rm miss}$	139	$\tilde{t}_2$	Forbidden 0.86	m($\tilde{\chi}^0_1$)=360 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}^0_1$)= 40 GeV	SUSY-2018-09
EW direct	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via WZ	3 e,μ		$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$	0.64	m($\tilde{\chi}^0_1$)=0	ATLAS-CONF-2020-015
		$ee,\mu\mu$	$\geq$ 1 jet	$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$	0.205	m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=5 GeV	1911.12606
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ via WW	2 e,μ		$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1$	0.42	m($\tilde{\chi}^0_1$)=0	1908.08215
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via Wh	0-1 e,μ	2 b/2 γ	$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$	Forbidden 0.74	m($\tilde{\chi}^0_1$)=70 GeV	2004.10894, 1909.09226
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e,μ		$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1$	1.0	m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	1908.08215
	$\tilde{\tau}\tilde{\tau}$, $\tilde{\tau}\to\tau\tilde{\chi}^0_1$	2 τ		$E_T^{\rm miss}$	139	$\tilde{\tau}$ [$\tilde{\tau}_L$, $\tilde{\tau}_{R,L}$]	0.16-0.3 0.12-0.39	m($\tilde{\chi}^0_1$)=0	1911.06660
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}^0_1$	2 e,μ	0 jets	$E_T^{\rm miss}$	139	$\tilde{\ell}$	0.7	m($\tilde{\chi}^0_1$)=0	1908.08215
		$ee,\mu\mu$	$\geq$ 1 jet	$E_T^{\rm miss}$	139	$\tilde{\ell}$	0.256	m($\tilde{\ell}$)-m($\tilde{\chi}^0_1$)=10 GeV	1911.12606
	$\tilde{H}\tilde{H}$, $\tilde{H}\to h\tilde{G}/Z\tilde{G}$	0 e,μ	$\geq$ 3 b	$E_T^{\rm miss}$	36.1	$\tilde{H}$	0.13-0.23 0.29-0.88	BR($\tilde{\chi}^0_1\to h\tilde{G}$)=1	1806.04030
		4 e,μ	0 jets	$E_T^{\rm miss}$	139	$\tilde{H}$	0.55	BR($\tilde{\chi}^0_1\to Z\tilde{G}$)=1	ATLAS-CONF-2020-040
Long-lived particles	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	Disapp. trk	1 jet	$E_T^{\rm miss}$	36.1	$\tilde{\chi}^\pm_1$	0.46	Pure Wino	1712.02118
						$\tilde{\chi}^\pm_1$	0.15	Pure higgsino	ATL-PHYS-PUB-2017-019
	Stable $\tilde{g}$ R-hadron		Multiple		36.1	$\tilde{g}$	2.0		1902.01636,1808.04095
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}^0_1$		Multiple		36.1	$\tilde{g}$ [$\tau(\tilde{g})$ =10 ns, 0.2 ns]	2.05 2.4	m($\tilde{\chi}^0_1$)=100 GeV	1710.04901,1808.04095
RPV	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_1$, $\tilde{\chi}^\pm_1\to Z\ell\to\ell\ell\ell$	3 e,μ			139	$\tilde{\chi}^\mp_1/\tilde{\chi}^0_1$ [BR($Z\tau$)=1, BR(Ze)=1]	0.625 1.05	Pure Wino	ATLAS-CONF-2020-009
	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu,e\tau,\mu\tau$			3.2	$\tilde{\nu}_\tau$	1.9	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_2\to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0 jets	$E_T^{\rm miss}$	36.1	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ [$\lambda_{i33}\neq 0$, $\lambda_{12k}\neq 0$]	0.82 1.33	m($\tilde{\chi}^0_1$)=100 GeV	1804.03602
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to qqq$		4-5 large-R jets		36.1	$\tilde{g}$ [m($\tilde{\chi}^0_1$)=200 GeV, 1100 GeV]	1.3 1.9	Large λ''_{112}	1804.03568
			Multiple		36.1	$\tilde{g}$ [λ''_{112}=2e-4, 2e-5]	1.05 2.0	m($\tilde{\chi}^0_1$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}$, $\tilde{t}\to t\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to tbs$		Multiple		36.1	$\tilde{t}$ [λ''_{323}=2e-4, 1e-2]	0.55 1.05	m($\tilde{\chi}^0_1$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}$, $\tilde{t}\to b\tilde{\chi}^\pm_1$, $\tilde{\chi}^\pm_1\to bbs$		$\geq$ 4b		139	$\tilde{t}$	Forbidden 0.95	m($\tilde{\chi}^\pm_1$)=500 GeV	ATLAS-CONF-2020-016
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$		2 jets + 2 b		36.7	$\tilde{t}_1$ [qq, bs]	0.42 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to q\ell$	2 e,μ	2 b		36.1	$\tilde{t}_1$	0.4-1.45	BR($\tilde{t}_1\to be/b\mu$)>20%	1710.05544
		1 μ	DV		136	$\tilde{t}_1$ [1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k} <3e-9]	1.0 1.6	BR($\tilde{t}_1\to q\mu$)=100%, cosθ_t=1	2003.11956

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

Neutrinos

DIRAC OR MAJORANA?

$$\nu_D = \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} \qquad \nu_{M_1} = \begin{pmatrix} \xi_1 \\ \xi_1^* \end{pmatrix}, \quad \nu_{M_2} = \begin{pmatrix} \xi_2 \\ \xi_2^* \end{pmatrix}$$

Mass martix

$$\begin{array}{ccc} & L & R & \\ \mathcal{M} = \Big(& 0 & m_D & \Big) \; L \\ & m_D^* & M & \;\; R \end{array}$$

Majorana term

Mass eigenvalues

$$m_1 \approx \frac{m_D^* m_D}{M} \qquad m_2 \approx M$$

Light

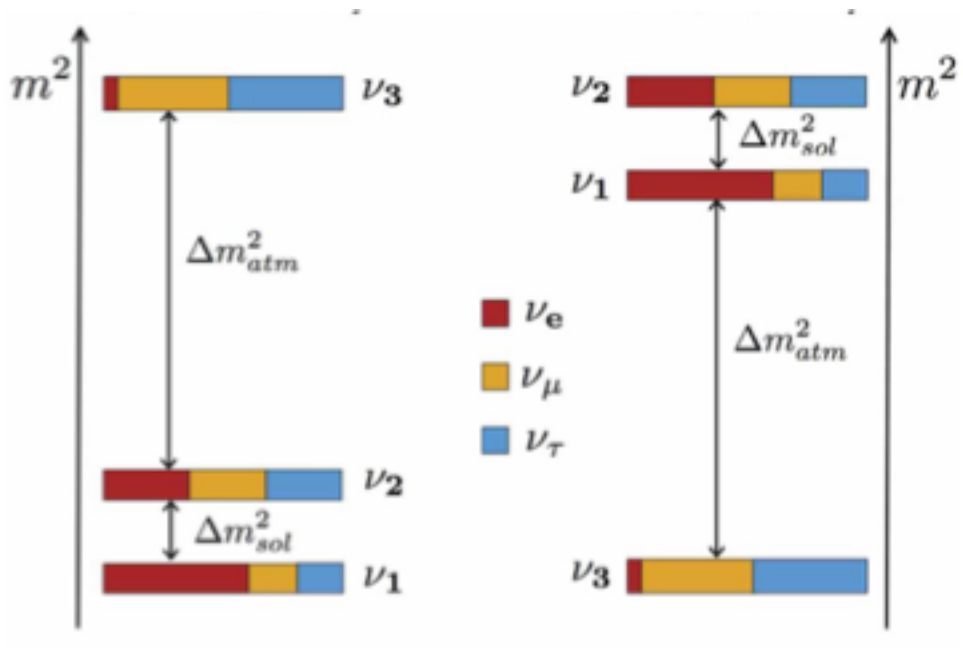
Heavy

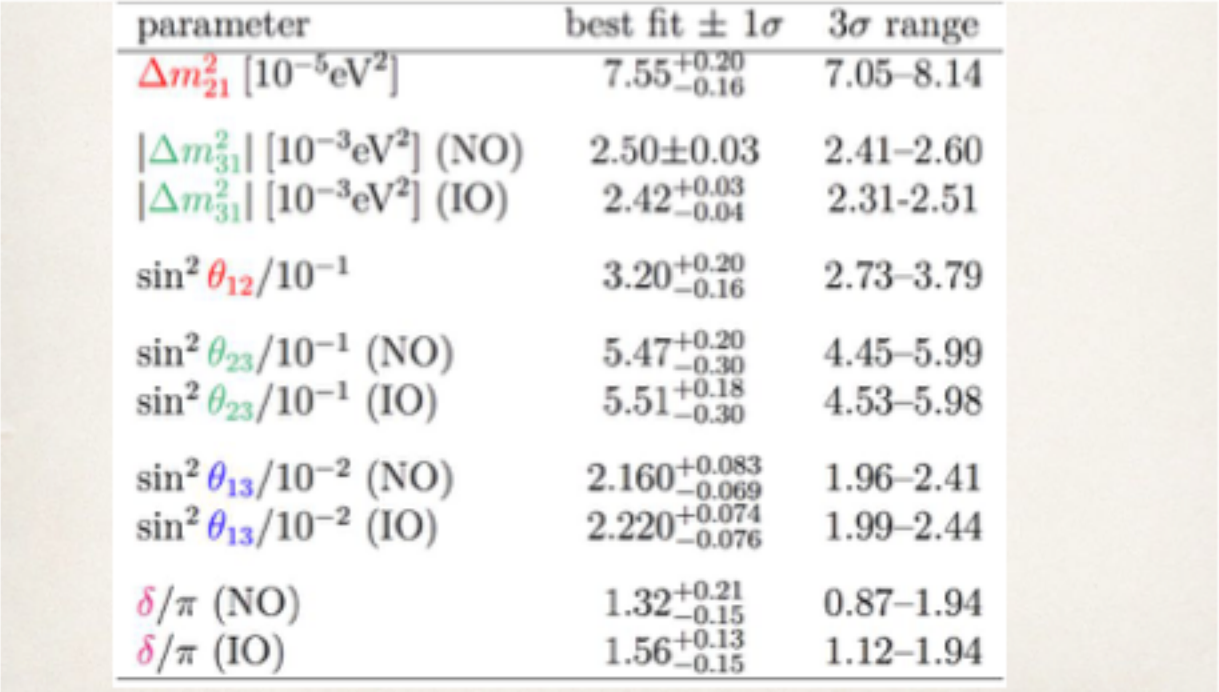
$$\boxed{\begin{array}{c} \nu_D \neq \nu_D^* \\ m_{\nu_L} = m_{\nu_R} \end{array}}$$

?

$$\boxed{\begin{array}{c} \nu_M = \nu_M^* \\ m_{\nu_{M_1}} \neq m_{\nu_{M_2}} \end{array}}$$

Neutrino Physics





parameter	best fit ± 1σ	3σ range
Δm^2_{21} [10^{-5}eV^2]	$7.55^{+0.20}_{-0.16}$	7.05–8.14
$\lvert\Delta m^2_{31}\rvert$ [10^{-3}eV^2] (NO)	2.50±0.03	2.41–2.60
$\lvert\Delta m^2_{31}\rvert$ [10^{-3}eV^2] (IO)	$2.42^{+0.03}_{-0.04}$	2.31-2.51
$\sin^2\theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	2.73–3.79
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.45–5.99
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.53–5.98
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	1.96–2.41
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	1.99–2.44
δ/π (NO)	$1.32^{+0.21}_{-0.15}$	0.87–1.94
δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.12–1.94

de Salas et al, 1708.01186

- Absolute value of neutrino masses ?
- Mass hierarchy?
- Dirac or Majorana?
- Fourth sterile neutrino?
- Neutrino dark matter?

$$\boxed{0.06\ eV < \sum m_\nu < 0.12\ eV}$$

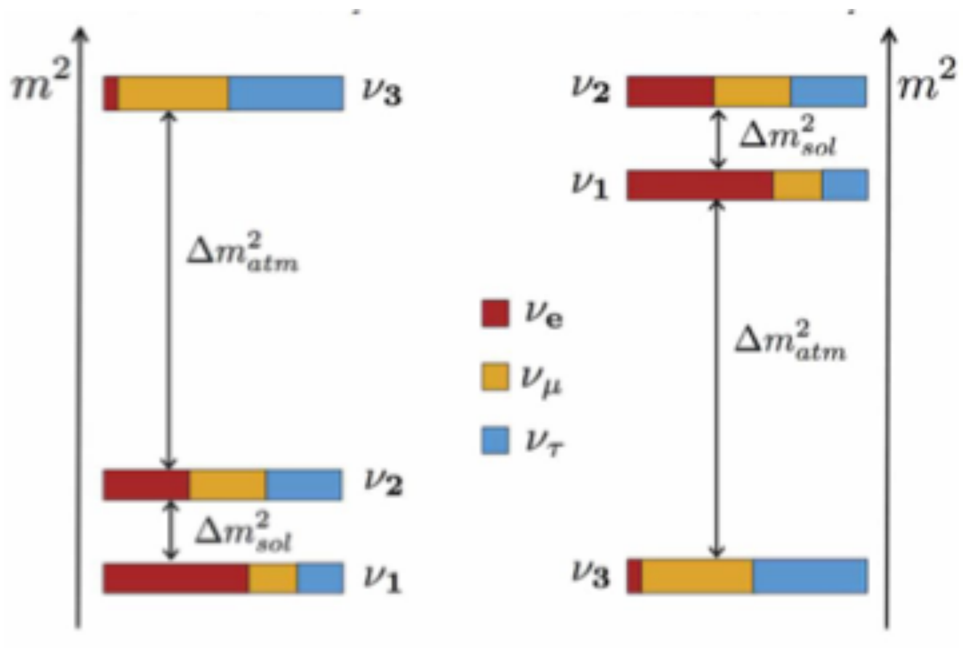
-osc

CMB

PMNS-matrix parameters are measured with high accuracy of few %

- Normal hierarchy favoured at 3.1 σ
- Nonzero CP phase favoured
- Upper octant favoured

Neutrino Physics



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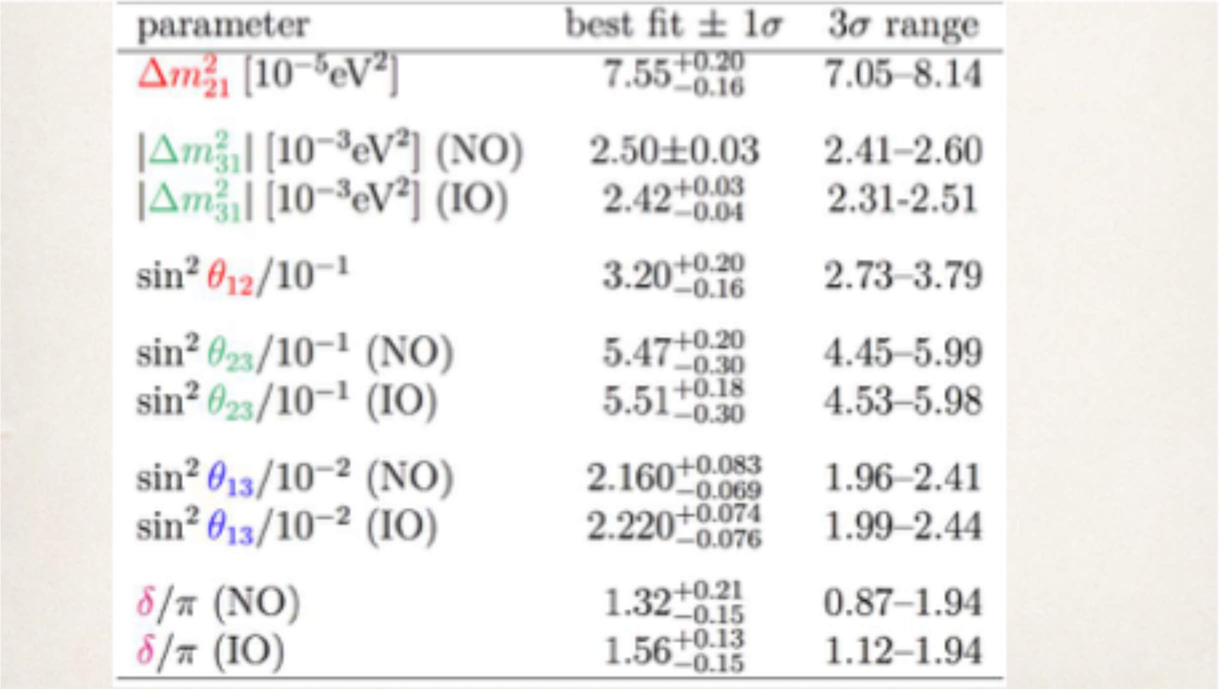

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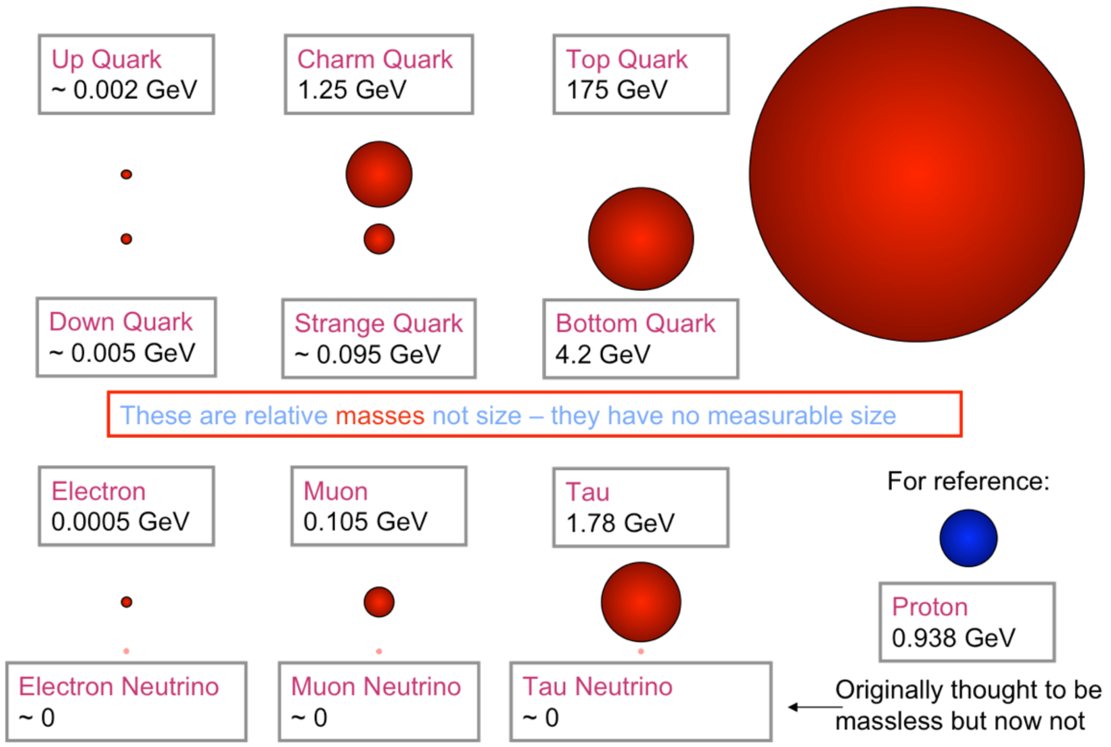
BEYOND THE STANDARD MODEL: THE MASS SPECTRUM AND MIXINGS

- Mass spectrum?

$$m_{quark} = y_{quark} \cdot v$$
$$m_{lepton} = y_{lepton} \cdot v$$
$$m_W = g/\sqrt{2} \cdot v$$
$$m_Z = \sqrt{g^2 + g'^2}/\sqrt{2} \cdot v$$
$$m_H = \sqrt{\lambda} \cdot v$$
$$m_\gamma = 0$$
$$m_{gluon} = 0$$

SM



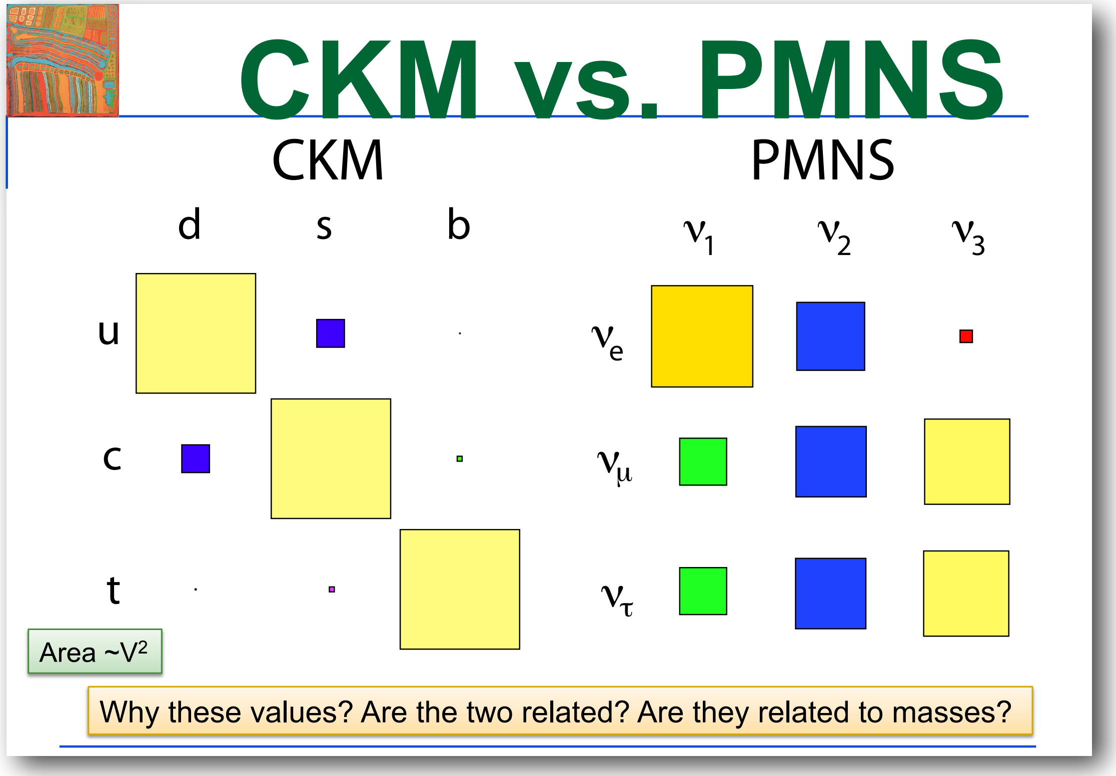
These are relative masses not size – they have no measurable size

For reference:

Originally thought to be massless but now not

- Mixing Matrices?

- Quark-Lepton Symmetry
- Strong difference in parameters



CKM vs. PMNS

Area ~V²

Why these values? Are the two related? Are they related to masses?

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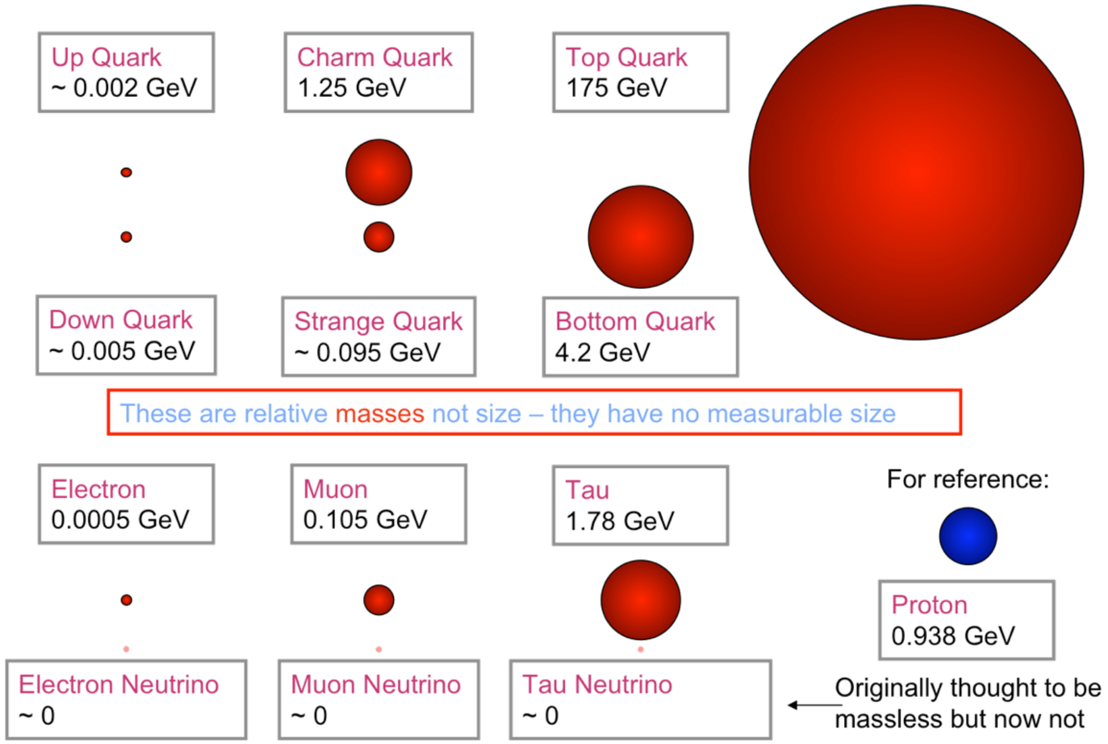

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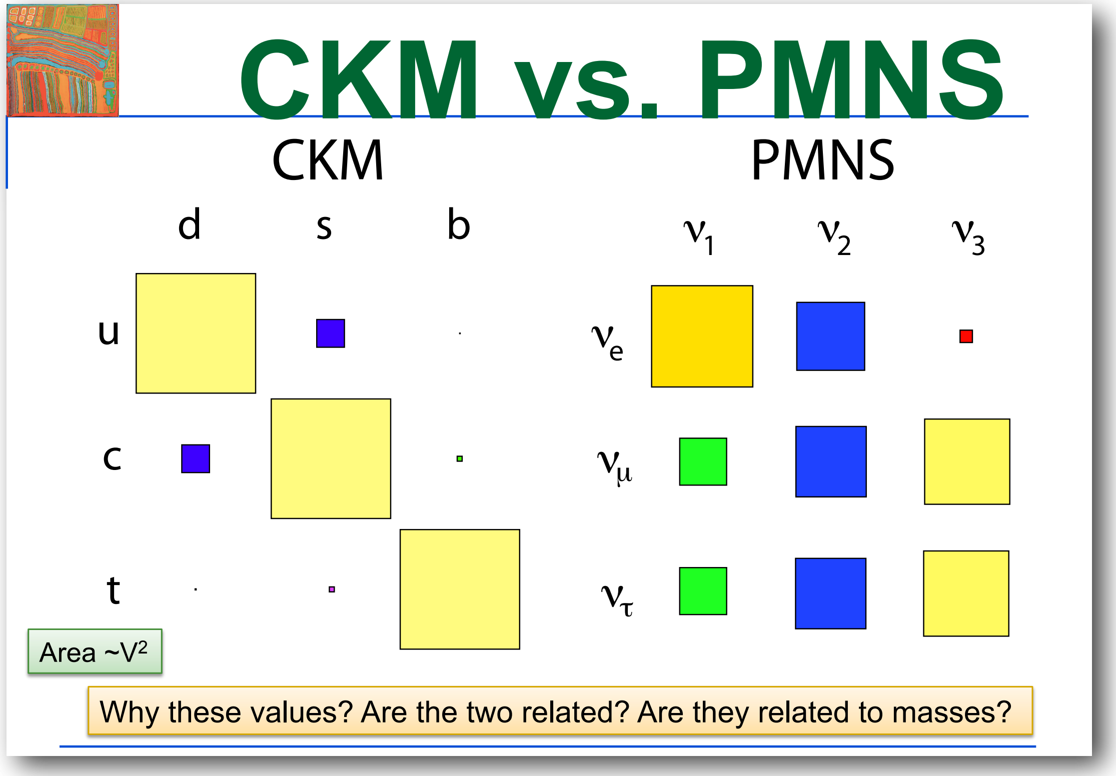

CKM vs. PMNS

CKM

PMNS

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BEYOND THE STANDARD MODEL: THE MASS SPECTRUM AND MIXINGS

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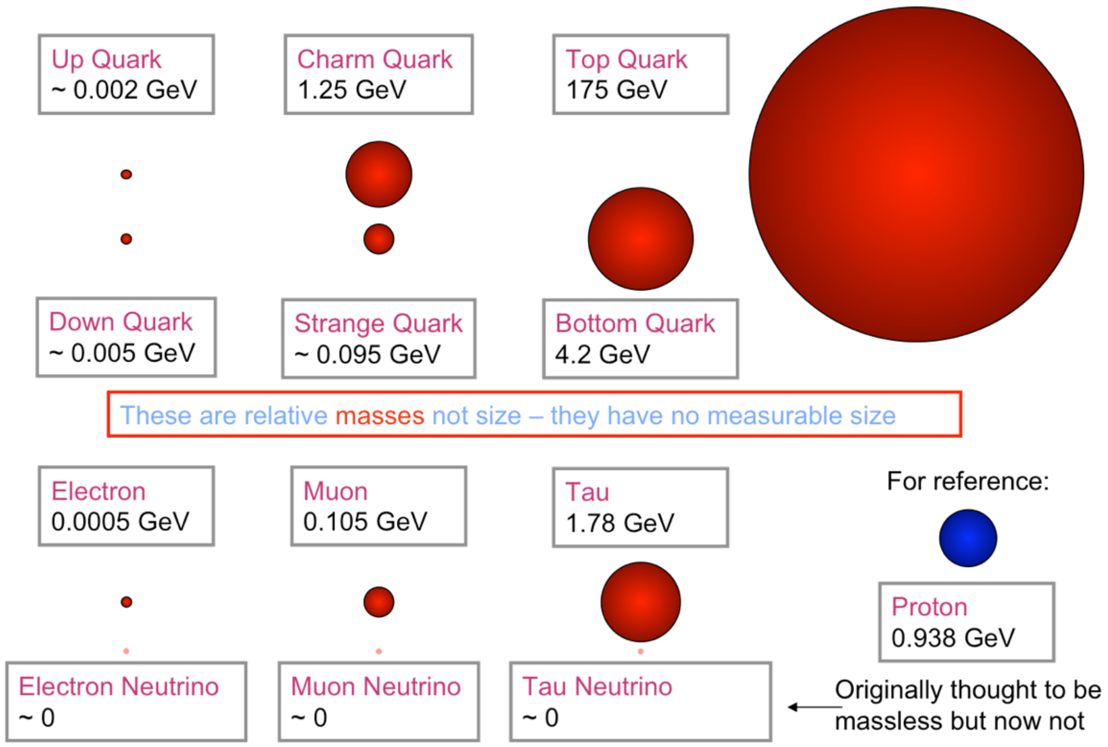

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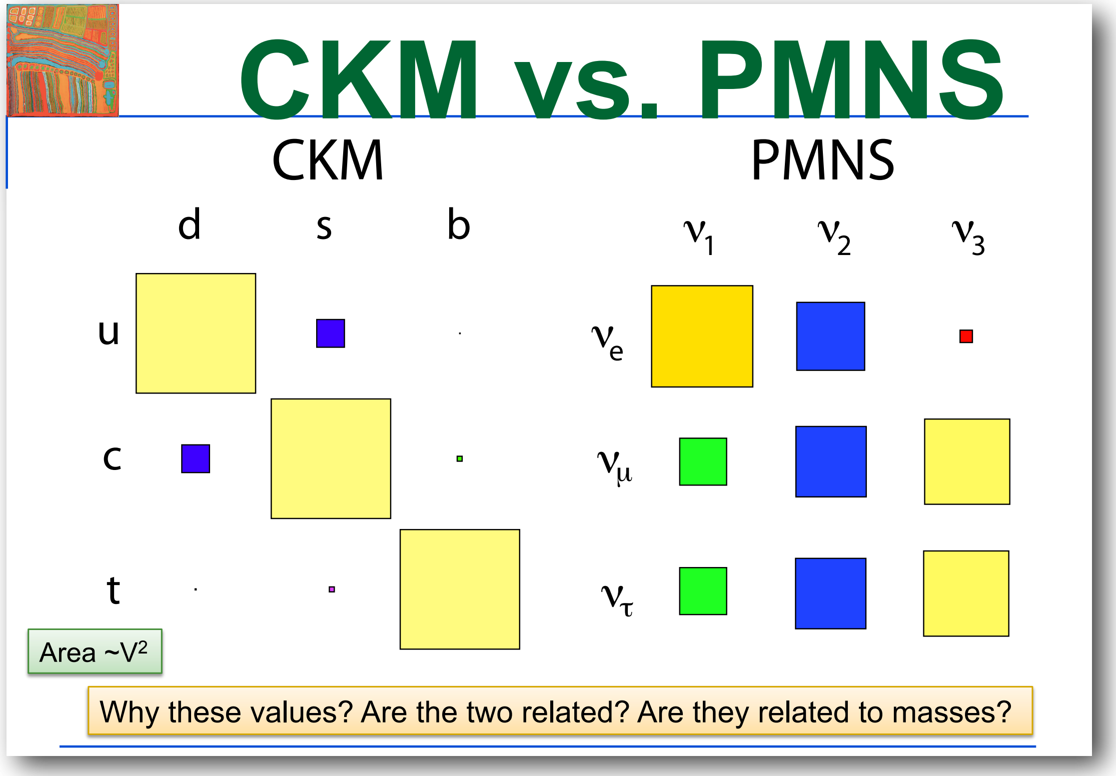

CKM vs. PMNS

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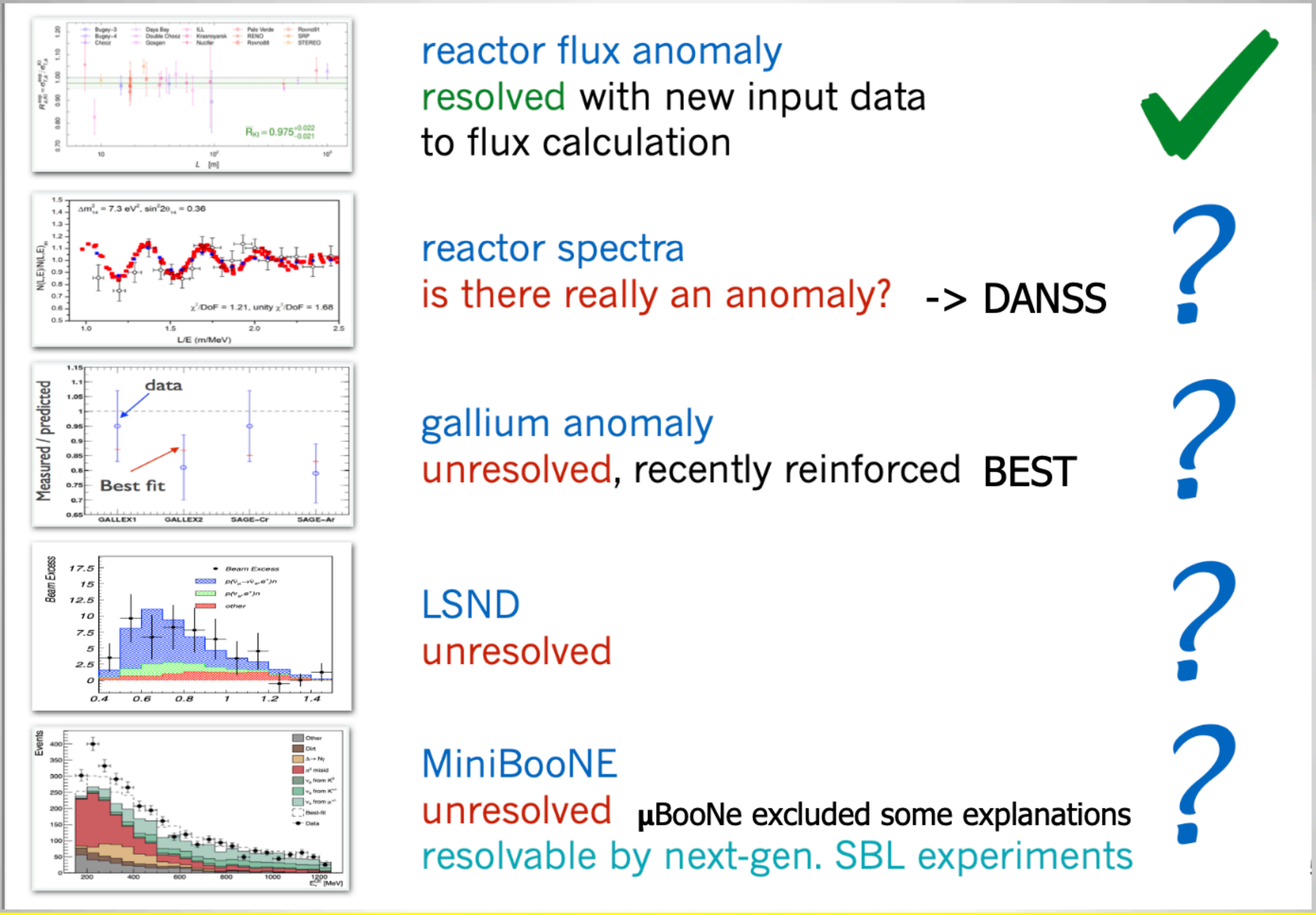
$$J_{CP} = \frac{1}{8} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos \theta_{13} \sin \delta$$

Neutrino Anomalies

Albert De Roeck



reactor flux anomaly
resolved with new input data
to flux calculation ✓

reactor spectra
is there really an anomaly? -> DANSS ?

gallium anomaly
unresolved, recently reinforced BEST ?

LSND
unresolved ?

MiniBooNE
unresolved μBooNe excluded some explanations
resolvable by next-gen. SBL experiments ?

More details in the backup

- Jury still out on many of these anaomalies. No clear picture emerging yet.
- Simple sterile neutrino would not fit all the data. Tensions on all sides…
- Future: Reactor experiments continuing or new ones (eg JSNS²) or new experiments at the FNAL short neutrino baseline… (ICARUS, SBND)

Sterile Neutrinos

Several anomalies around in the community since some years…
Additional sterile neutrinos as a possible candidate explanation

☑ Very generic extension of SM

- ○ can be leftover of extended gauge multiplet

☑ Useful phenomenological tool

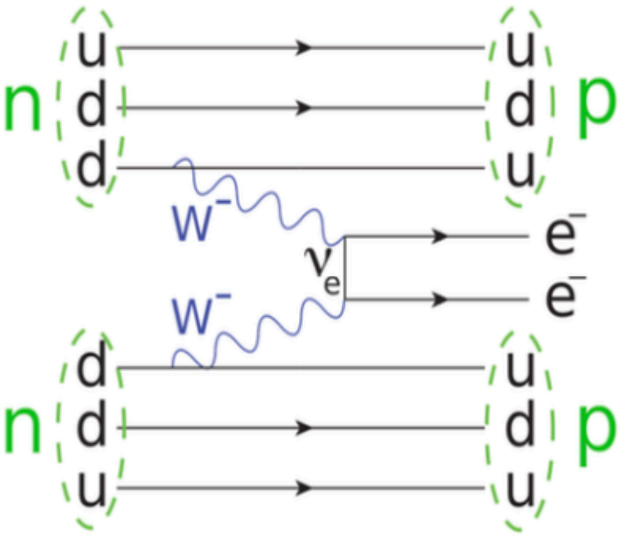
- ○ can explain ν masses (seesaw mechanism, $m \sim$ TeV…M_{Pl})
- ○ can explain cosmic baryon asymmetry (leptogenesis, $m \gg 100$ GeV)
- ○ can explain dark matter ($m \sim$ keV)
- ○ can explain oscillation anomalies ($m \sim$ eV)
  Promote mixing matrix to 4 x 4, oscillation formula unchanged:

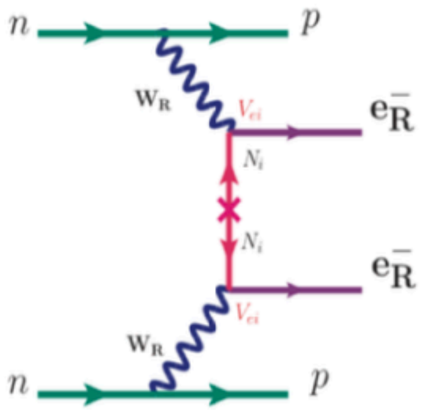
$$P_{\alpha\to\beta} = \sum_{j,k} U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k} \exp\left[-i(E_j - E_k)T\right]$$

Neutrinoless Double Beta Decay

The question is still unanswered:

Are neutrinos their own antiparticles?





Left-Right Symmetric Model,
M_{W_R} ~ 2 TeV, M_N = 1 TeV,
g_R ~ 2/3 g_L

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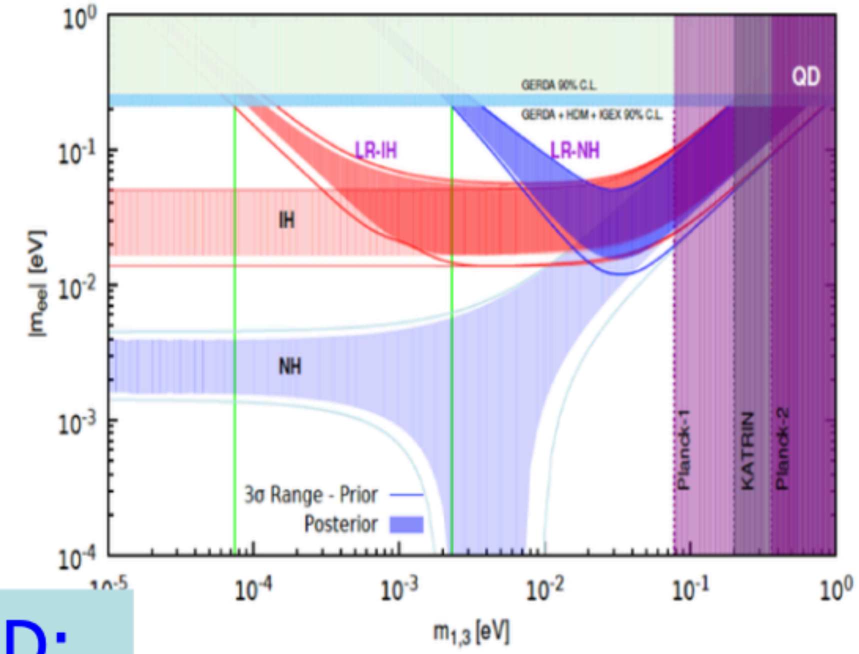


Ton scale 0nuBB experiments will cover the inverted hierarchy by 2035

Many experiments operating, planned or in R&D:
LEGEND, SNO+, NEXT, CUPID, THEIA…

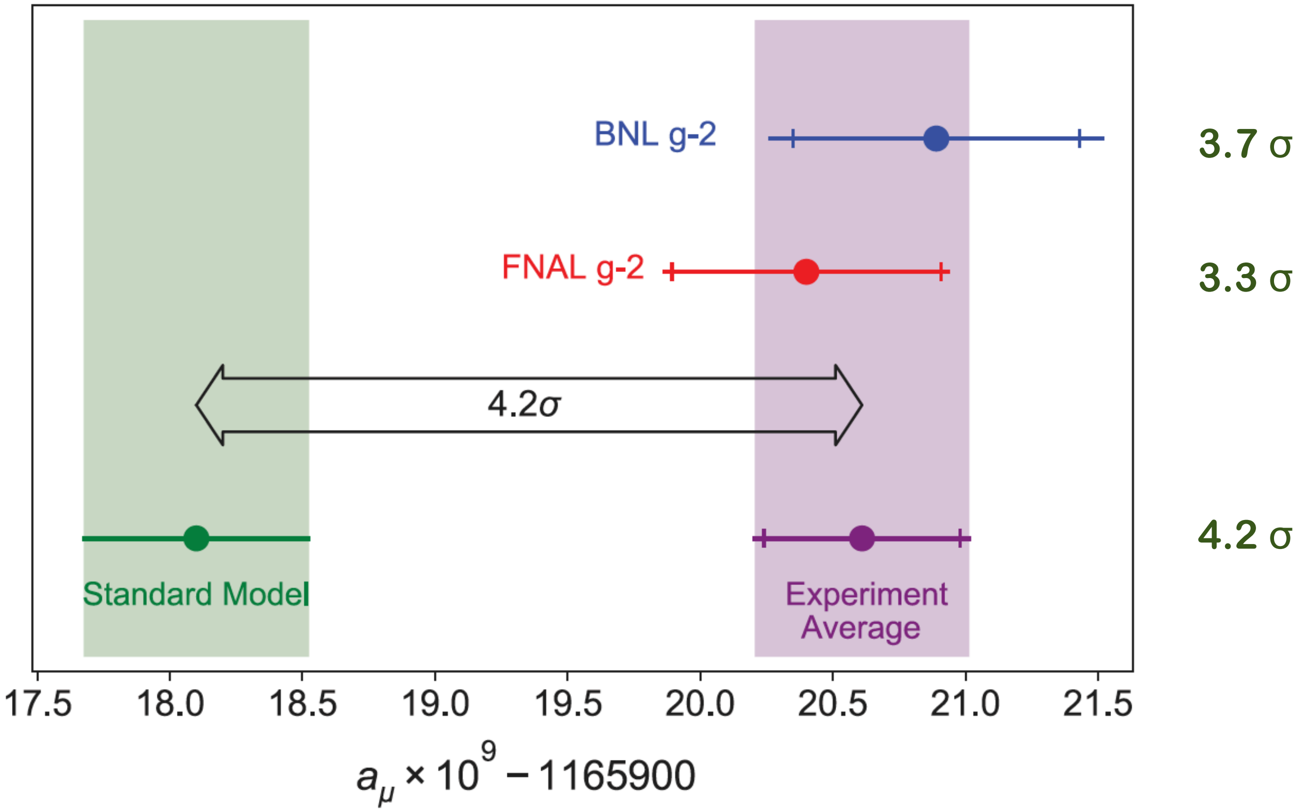
Summary

- In ~10 years from now, oscillation will mostly be understood: mass hierarchy and CP phase will be known
- Neutrino absolute masses may be measured in ~20 years, through cosmology, beta decays and double beta decays
- Majorana neutrino nature maybe determined in ~30 years
- Sterile neutrinos are unlikely the cause of reactor and Ga anomalies, but still possible for the LSND anomaly
- A new era of astrophysics with multi-messengers, including neutrinos
- Many new projects will start within 10 years
- A bright future

g-2

Experimental status

- **April 7th 2021: Muon $g-2$ experiment at FNAL confirms BNL!**



$a_\mu^{EXP} = (116592089 \pm 63) \times 10^{-11}$ [0.54ppm] BNL E821

$a_\mu^{EXP} = (116592040 \pm 54) \times 10^{-11}$ [0.46ppm] FNAL E989 Run 1

$a_\mu^{EXP} = (116592061 \pm 41) \times 10^{-11}$ [0.35ppm] WA

- **FNAL aims at 16 × 10^{-11}. First 4 runs completed, 5th in progress.**
- **Muon $g-2$ proposal at J-PARC: Phase-1 with similar BNL precision.**

“Old muon g-2 puzzle”

New Physics for the muon $g-2$: at which scale?

- **Δa_μ discrepancy at $\sim 4.2\,\sigma$ level:**

$$\Delta a_\mu = a_\mu^{\rm EXP} - a_\mu^{\rm SM} \equiv a_\mu^{\rm NP} = (2.51 \pm 0.59) \times 10^{-9}$$

$$\Delta a_\mu \equiv a_\mu^{\rm NP} \approx (a_\mu^{\rm SM})_{weak} \approx \frac{m_\mu^2}{16\pi^2 v^2} \approx 2 \times 10^{-9}$$

  - NP is at the weak scale ($\Lambda \approx v$) and weakly coupled to SM particles.*
  - NP is very light ($\Lambda \lesssim 1$ GeV) and feebly coupled to SM particles.
  - NP is very heavy ($\Lambda \gg v$) and strongly coupled to SM particles.

*Favoured by the *hierarchy problem* and by a WIMP DM candidate but disfavoured by the LEP and LHC bounds (supersymmetry being the most prominent example).

[For a through compilation of models, see Athron, Balazs, Jacob, Kotlarski, Stockinger, Stockinger-Kim, ’21.]

$\Lambda \approx v$: SUSY and the muon $(g-2)$

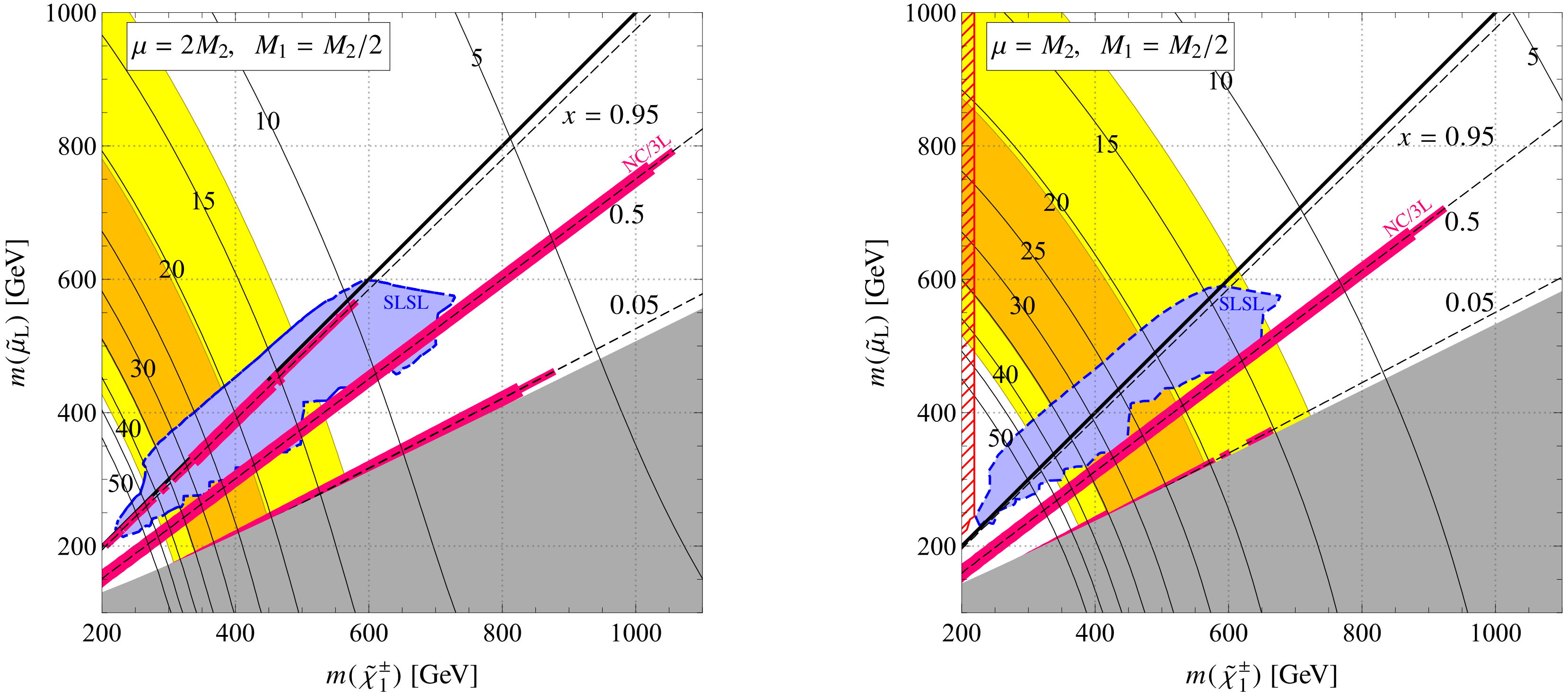
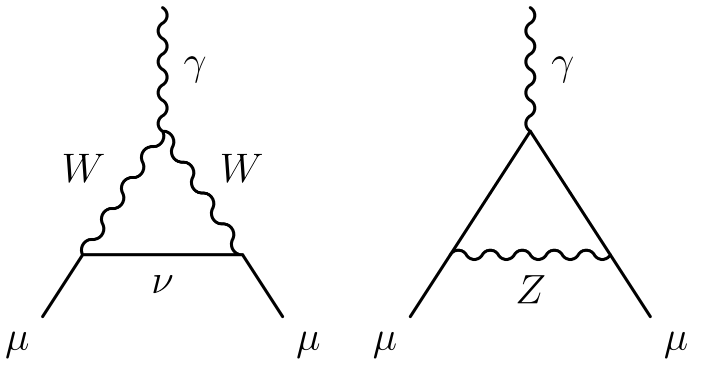
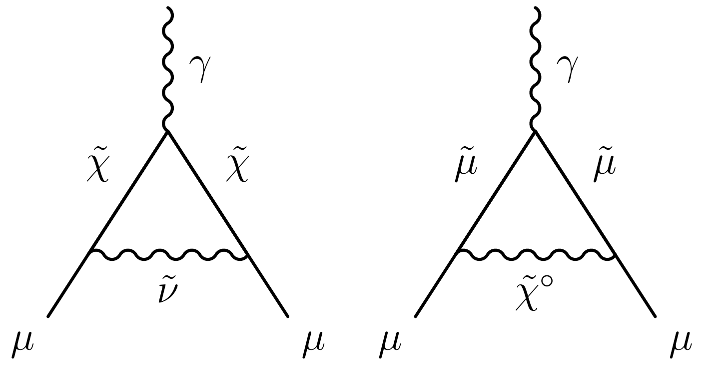


Figure: LHC Run 2 bounds on SUSY scenario for the muon $g-2$ anomaly for $\tan\beta = 40$. Orange (yellow) regions satisfy the muon $g-2$ anomaly at the 1σ (2σ) level [Endo et al., '20].





$$(a_\mu^{\rm SM})_{weak} \approx \frac{g^2 m_\mu^2}{32\pi^2 M_W^2} \approx 2 \times 10^{-9}$$

$$a_\mu^{\rm SUSY} \approx \frac{g^2 m_\mu^2 \tan\beta}{32\pi^2 \tilde m^2} \underbrace{\approx 2 \times 10^{-9}}_{\tilde m = 500{\rm GeV}\ \&\ \tan\beta = 40}$$

$\Lambda \lesssim 1$ GeV: Axion-like Particles and the muon $(g-2)$

Axion-like Particle effective Lagrangian

$$\mathcal{L} = e^2 C_{\gamma\gamma} \frac{a}{\Lambda} F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{c_{\mu\mu}}{2}\frac{\partial^\nu a}{\Lambda}\bar{\mu}\gamma_\nu\gamma_5\mu$$

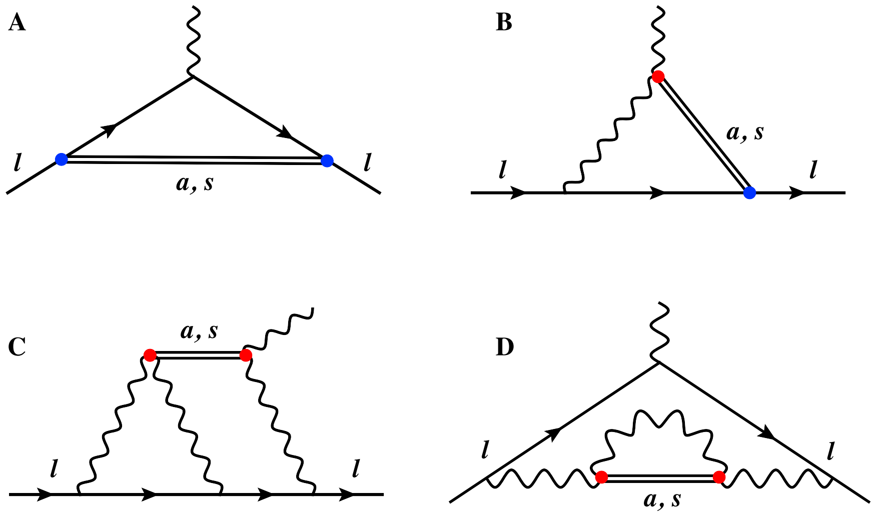


Figure: Contributions of a scalar 's' and a pseudoscalar 'a' ALP to the $(g-2)_\ell$.

[Marciano, Masiero, PP, Passera '16]

[Cornella, P.P., Sumensari '19]

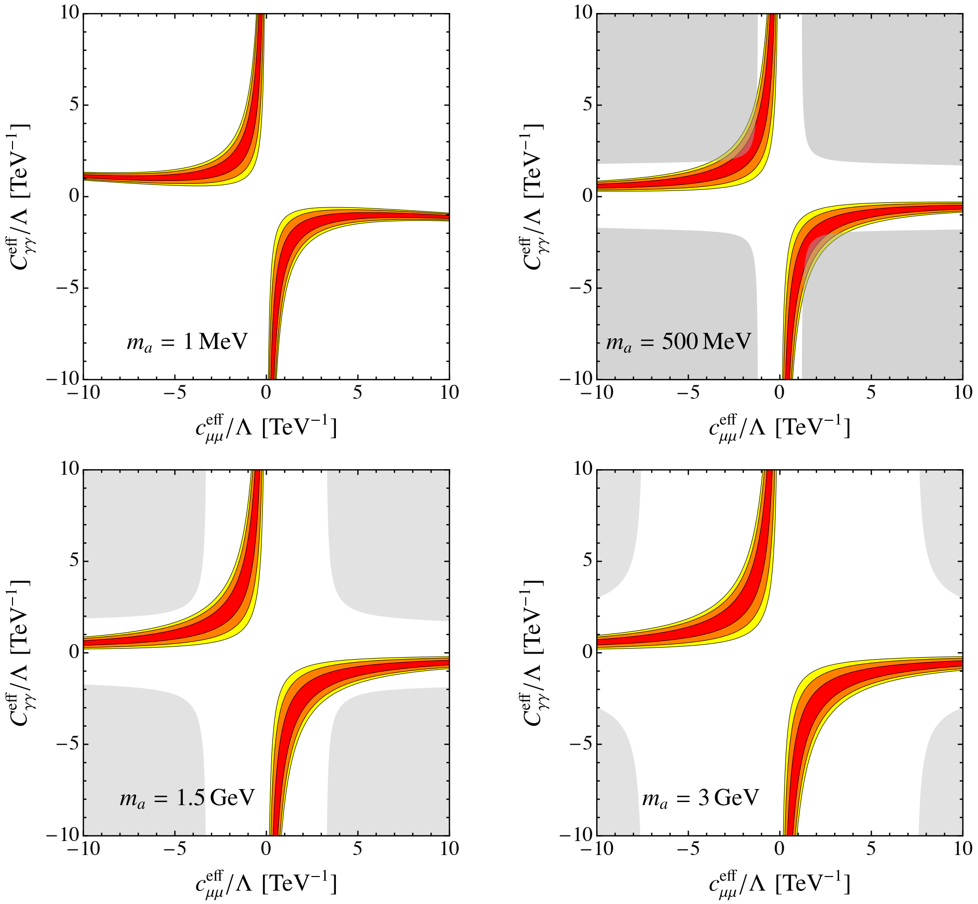


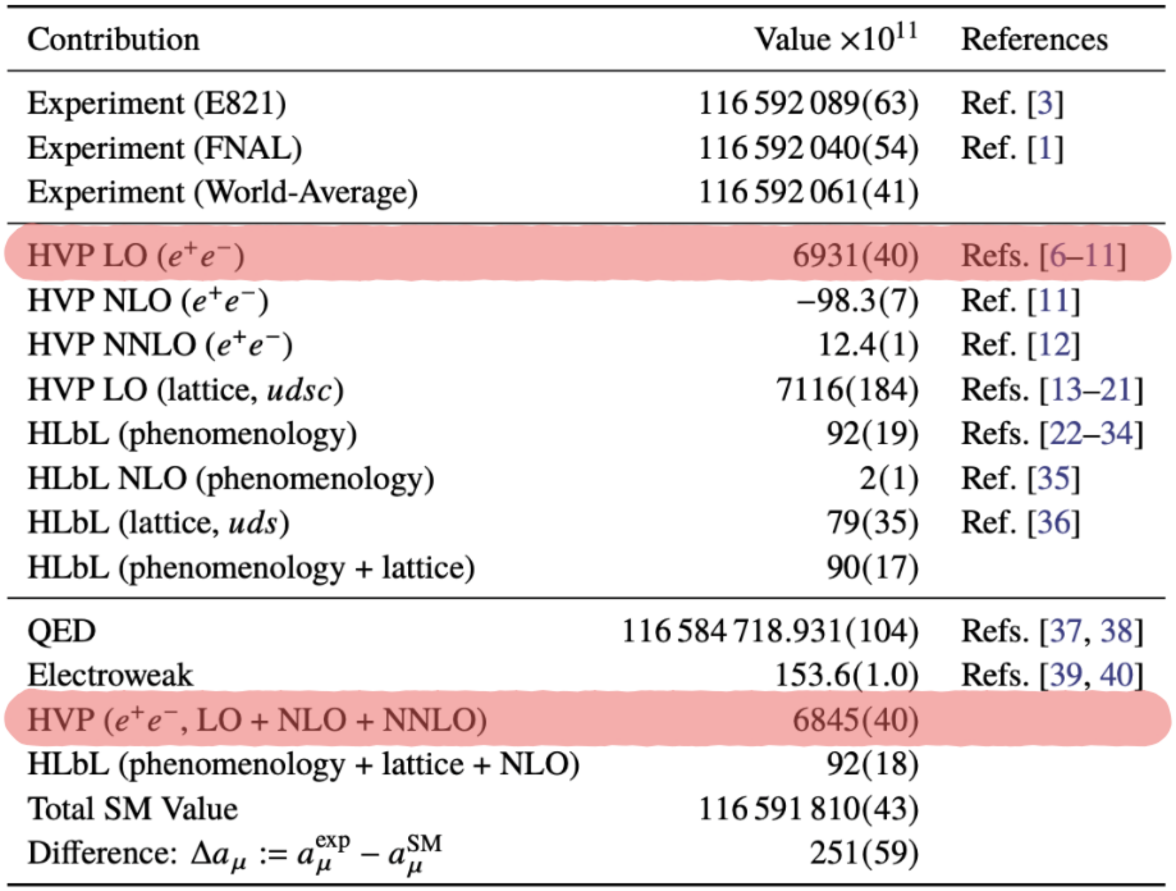
Figure: Δa_μ regions favoured at 68% (red), 95% (orange) and 99% (yellow) CL. Gray regions are excluded by the BaBar search $e^+e^- \to \mu^+\mu^- + \mu^+\mu^-$ [Bauer, Neubert, Thamm, '17]

$$\Delta a_\mu = \frac{m_\mu^2}{\Lambda^2}\left[\frac{12\alpha^3}{\pi} C_{\gamma\gamma}^2 \ln^2\frac{\Lambda^2}{m_\mu^2} - \frac{(c_{\mu\mu})^2}{16\pi^2} h_1\left(\frac{m_a^2}{m_\mu^2}\right) - \frac{2\alpha}{\pi} c_{\mu\mu} C_{\gamma\gamma} \ln\frac{\Lambda^2}{m_\mu^2}\right]$$

Breakdown of SM contributions

- a_μ from WP20 (w/o BMWc lattice result)

[Colangelo EPS-HEP2021 proceeding]

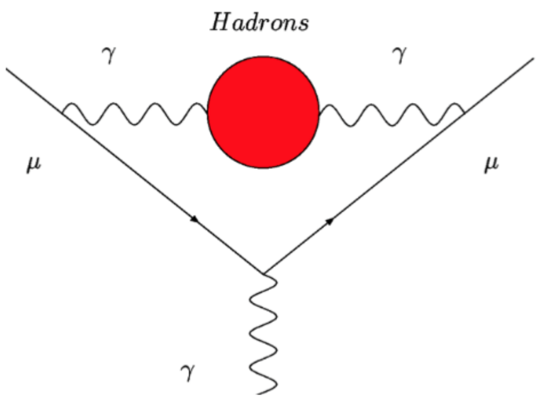


Contribution	Value $\times 10^{11}$	References
Experiment (E821)	116 592 089(63)	Ref. [3]
Experiment (FNAL)	116 592 040(54)	Ref. [1]
Experiment (World-Average)	116 592 061(41)	
HVP LO (e^+e^-)	6931(40)	Refs. [6–11]
HVP NLO (e^+e^-)	−98.3(7)	Ref. [11]
HVP NNLO (e^+e^-)	12.4(1)	Ref. [12]
HVP LO (lattice, $udsc$)	7116(184)	Refs. [13–21]
HLbL (phenomenology)	92(19)	Refs. [22–34]
HLbL NLO (phenomenology)	2(1)	Ref. [35]
HLbL (lattice, uds)	79(35)	Ref. [36]
HLbL (phenomenology + lattice)	90(17)	
QED	116 584 718.931(104)	Refs. [37, 38]
Electroweak	153.6(1.0)	Refs. [39, 40]
HVP (e^+e^-, LO + NLO + NNLO)	6845(40)	
HLbL (phenomenology + lattice + NLO)	92(18)	
Total SM Value	116 591 810(43)	
Difference: $\Delta a_\mu := a_\mu^{\text{exp}} - a_\mu^{\text{SM}}$	251(59)	

→ HVP LO is the bottle-neck of the SM prediction

HLO contribution from $e^+e^- \to$ *hadrons*

- dominated by $e^+e^- \to \pi^+\pi^-$ channel (70% of the full hadronic)



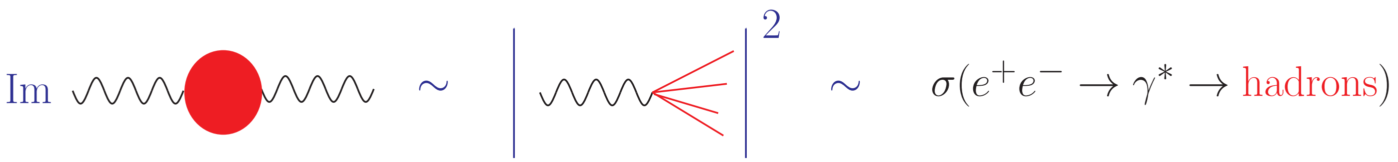
$$(a_\mu^{\text{HVP}})_{e^+e^-} = \frac{\alpha}{\pi^2}\int_{m_{\pi^0}^2}^{\infty} \frac{ds}{s} K(s)\,\text{Im}\,\Pi_{\text{had}}(s) = \frac{1}{4\pi^3}\int_{m_{\pi^0}^2}^{\infty} ds\, K(s)\sigma_{\text{had}}(s)$$

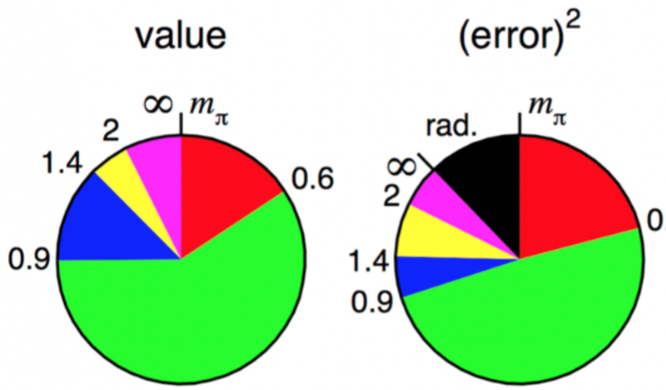
dispersion relations

optical theorem

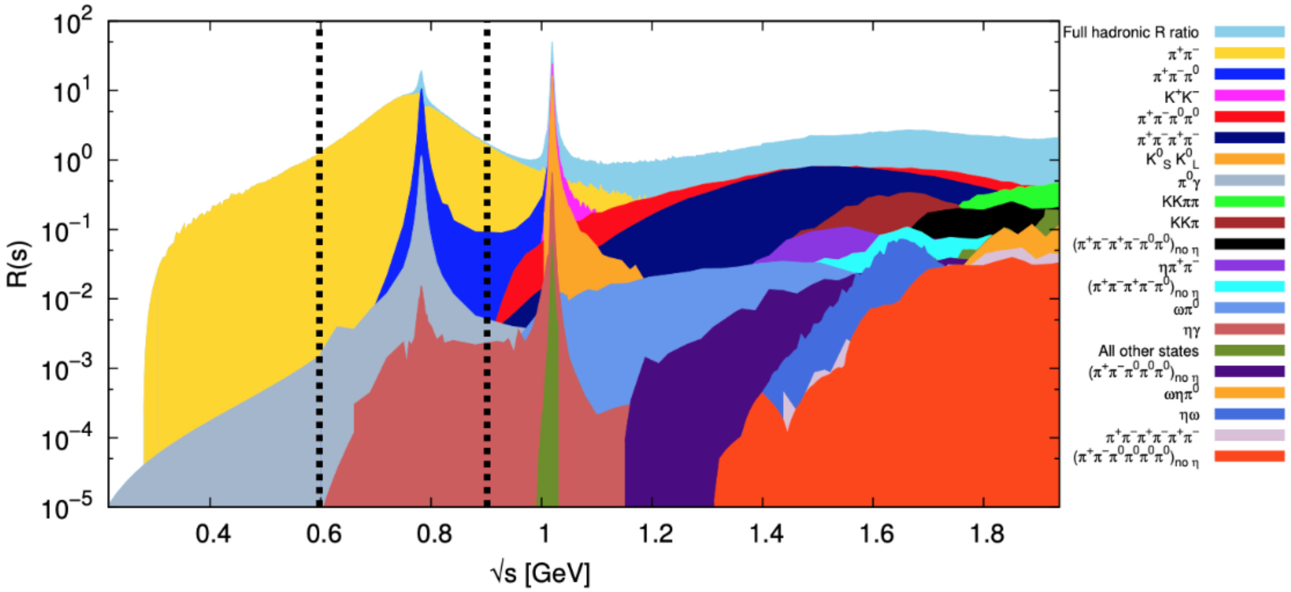
kernel function

$K(s) \approx m_\mu^2/3s$ for $\sqrt{s} \gg m_\mu$





Keshavarzi, Nomura, Teubner 2018



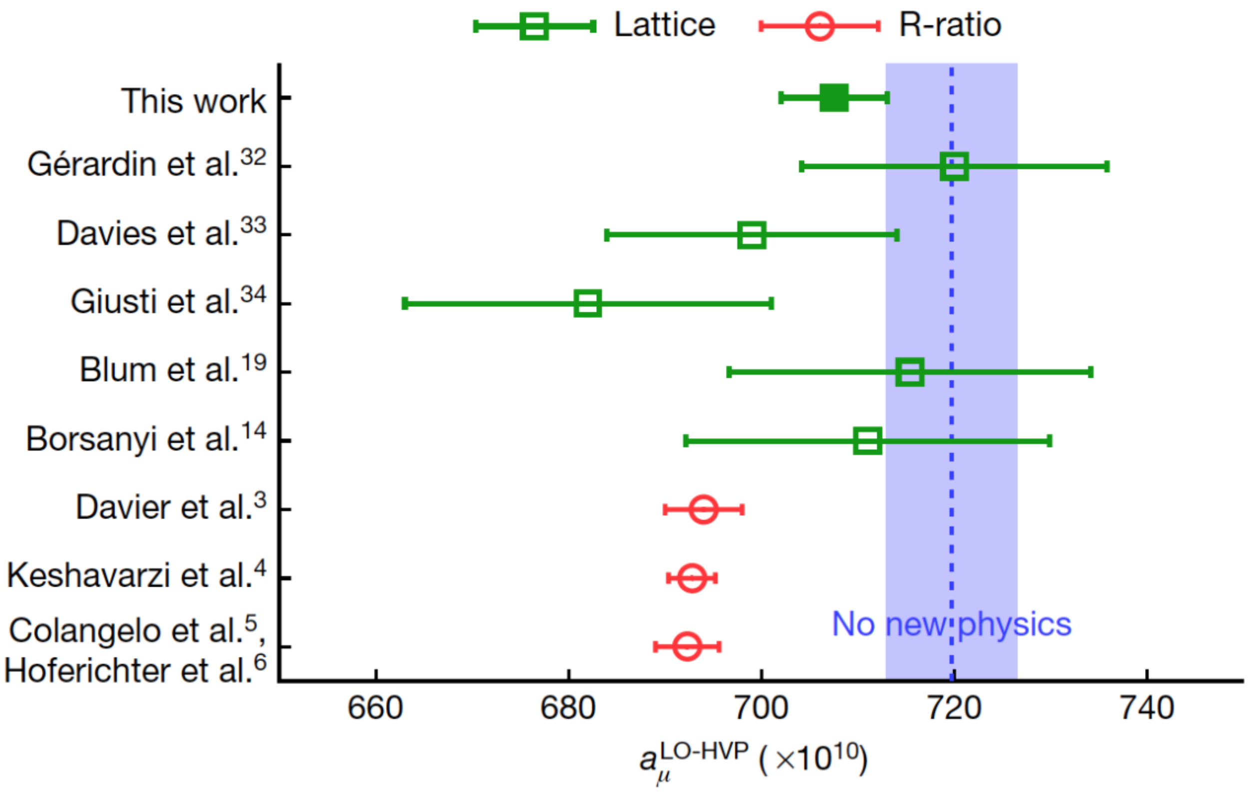
$$a_{\mu,e^+e^-}^{\text{HLO}} = 6931(40) \times 10^{-11}(0.6\%)$$ [WP20]

HLO contribution from lattice QCD

- **Great progress also in lattice QCD, where spacetime is modeled as a discrete grid of points. The BMW collaboration reached a 0.8% precision!**

$$a_\mu^{HLO} = 7075(23)_{stat}(50)_{syst}\ [55]_{tot} \times 10^{-11}$$

- **2–2.5σ tension with the “data-driven” evaluations.**



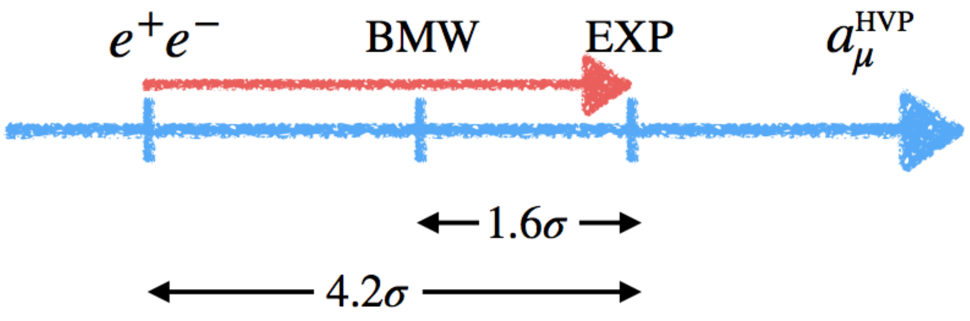
Borsanyi et al (BMWc), Nature 2021

"New muon g-2 puzzle"

$$(a_\mu^{\rm HVP})_{\rm EXP} = a_\mu^{\rm EXP} - a_\mu^{\rm SM,\,rest}$$

$$(a_\mu^{\rm HVP})_{e^+e^-}^{\rm WP20} = 6931(40) \times 10^{-11}$$

$$(a_\mu^{\rm HVP})_{\rm BMW} = 7075(55) \times 10^{-11}$$



"new puzzle": if BMW is correct, the "old" g-2 discrepancy (4.2σ) would be basically gone

→ *however, this brings in a new tension with e^+e^- data (2.2σ)*

Here, NP in $\sigma_{\rm had}(e^+e^- \to \text{hadrons})$ such that [LDL, Masiero, Paradisi, Passera 2112.08312]

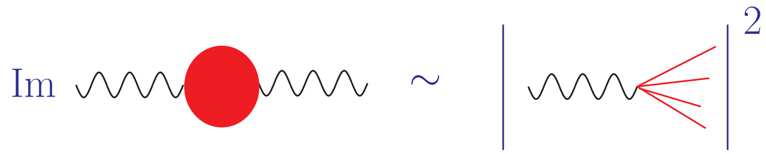
1. $(a_\mu^{\rm HVP})_{e^+e^-}^{\rm WP20} \approx (a_\mu^{\rm HVP})_{\rm EXP}$
2. the approximate agreement between BMW and EXP is not spoiled
3. w/o a direct contribution $a_\mu^{\rm NP}$ (i.e. NP not in muons)

Consequences of the BMW result

- **Can Δa_μ be due to missing contributions in $\sigma(e^+e^- \to had)$?**
  - An upward shift of $\sigma(s)$ also induces an increase of $\Delta\alpha^{(5)}_{\rm had}(M_Z)$ defined by:

$$\alpha(M_Z) = \frac{\alpha}{1 - \Delta\alpha(M_Z) - \Delta\alpha^{(5)}_{\rm had}(M_Z) - \Delta\alpha_{\rm top}(M_Z)}$$

$$a_\mu^{\rm HLO} \simeq \frac{m_\mu^2}{12\pi^3}\int_{4m_\pi^2}^{\infty} ds\, \frac{\sigma(s)}{s}\,, \qquad \Delta\alpha^{(5)}_{\rm had} = \frac{M_Z^2}{4\pi\alpha^2}\int_{4m_\pi^2}^{\infty} ds\, \frac{\sigma(s)}{M_Z^2 - s}$$



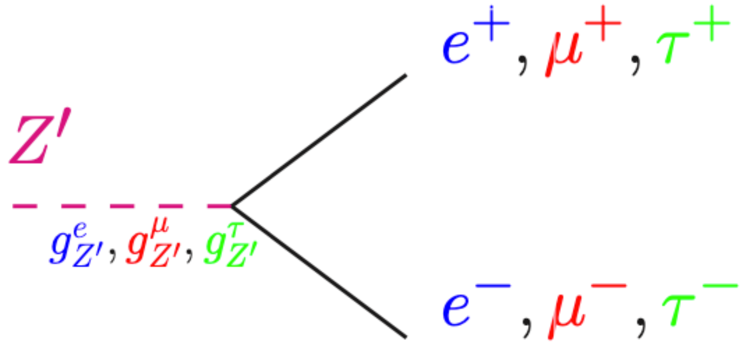
$\sim \quad \sigma(e^+e^- \to \gamma^* \to \mathrm{hadrons})$

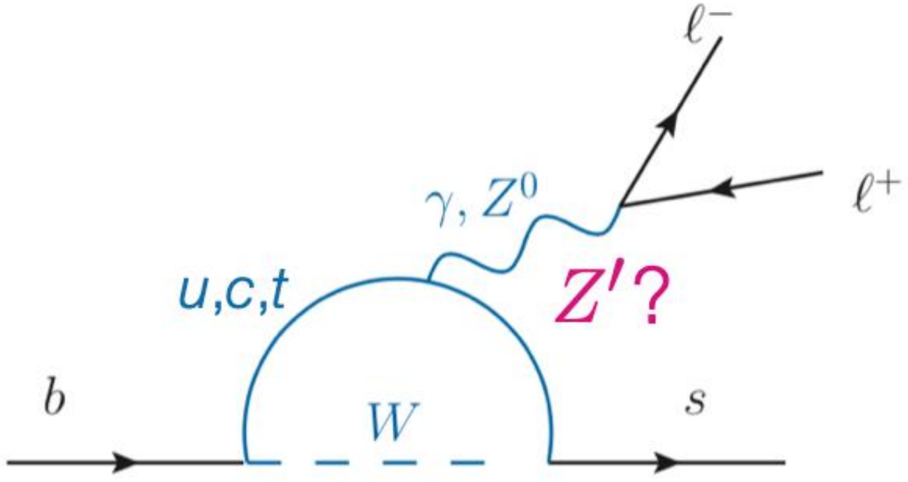
- **A change in $\sigma(e^+e^- \to had)$ is strongly disfavoured by:**
  - **EW-fit for $\sqrt{s} \gtrsim 1$ GeV** [Marciano, Passera, Sirlin, '08, Keshavarzi, Marciano, Passera, Sirlin, '20, Crivellin, Hoferichter, Manzari, Montull, '20]. A shift of $\sigma(e^+e^- \to had)$ to accomodate the Δa_μ anomaly would necessarely require new physics to show up in the EW-fit!
- **A check of the BMW results by other lattice QCD (LQCD) coll. is worth.**
- **LQCD coll. should provide $\Delta\alpha^{\rm LQCD}_{\rm had}$ to be compared with $\Delta\alpha^{e^+e^-}_{\rm had}$.**

Flavor Anomaly

Lepton Flavour Universality (LFU)

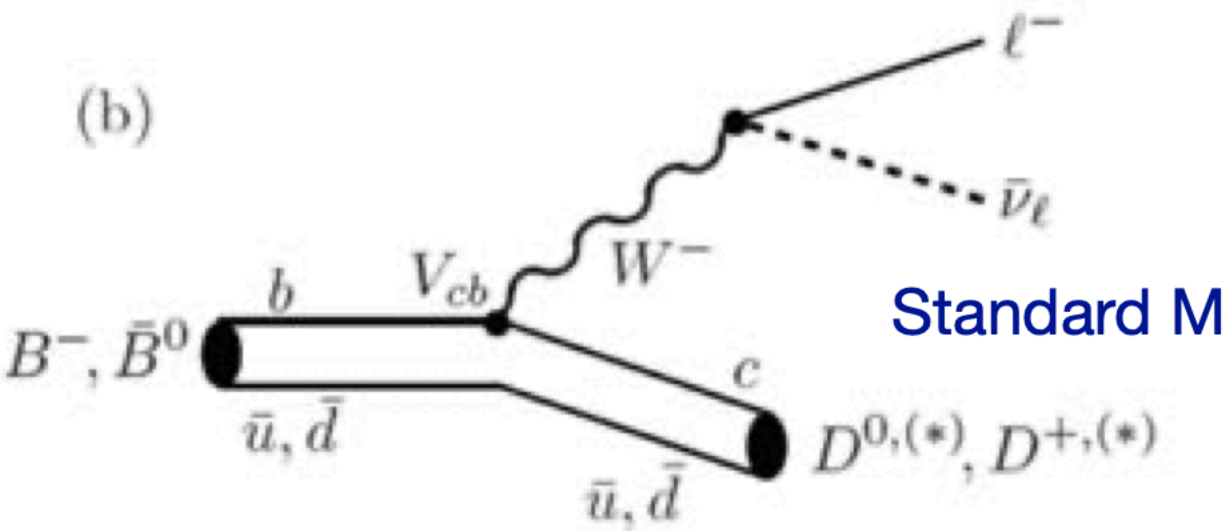
- LFU is a cornerstone of the SM : charged leptons (e, μ , τ) couple in a universal way to the SM gauge bosons
- If NP couples in a non-universal way to the three lepton families, then we might see differences in rates of rare decays involving different lepton pairs (e.g. e/μ or μ/τ)
- Hence - LFU is tested in $b \rightarrow s\ \ell^+\ell^-$ transitions. These are FCNC's with amplitudes involving loop diagrams





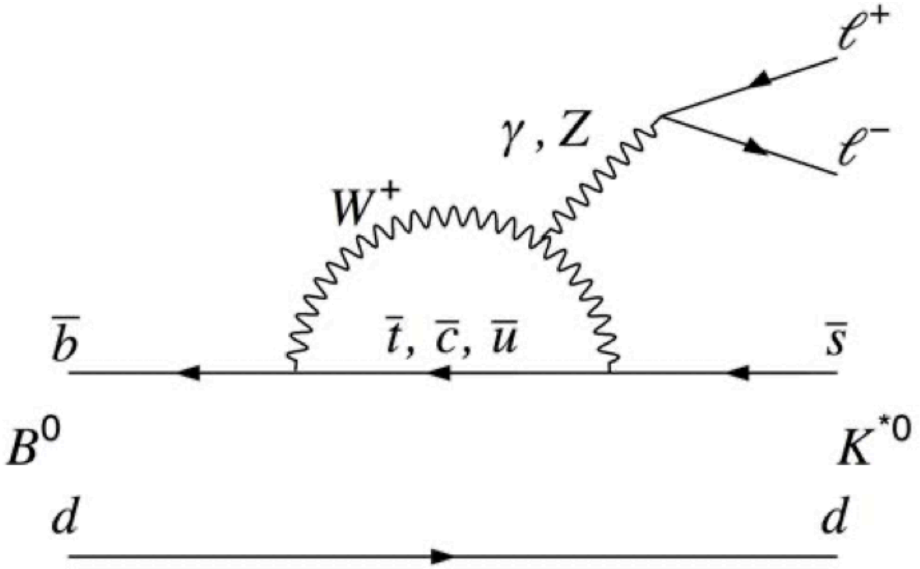
LEPTON (NON) UNIVERSALITY (?!)

Charged currents at tree level



Standard Model

Neutral currents at one-loop level



$$R_{D^{(*)}} = \frac{BR(B \to D^{(*)}\tau\nu_\tau)}{BR(B \to D^{(*)}\mu\nu_\mu)}$$ 3.8σ

$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)}\mu\mu)}{BR(B \to K^{(*)}ee)}$$ 2.5σ

$$\mathcal{R}(D)_{SM} = 0.299 \pm 0.003$$

$$\mathcal{R}(D^*)_{SM} = 0.258 \pm 0.005$$

$$\mathcal{R}(K^*)_{SM} = 1.0$$

Several R-ratio measurements

- Compare the rates of $B \longrightarrow X_s e^+e^-$ and $B \longrightarrow X_s\, \mu^+\mu^-$

  [*where B is* B^+, B^0, B^0_s , Λ^0_b and X_s is K^+, K^{*0}, ϕ , pK . . .]
- This allows precise testing of lepton flavour universality
- We can construct the ratio :

$$\boldsymbol{R_X} = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\mathcal{B}(B_q \to X_s \mu^+\mu^-)}{dq^2}\, dq^2}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\mathcal{B}(B_q \to X_s e^+e^-)}{dq^2}\, dq^2} = 1 \pm \mathcal{O}(1\,\%)$$

- Small theoretical uncertainties because hadronic uncertainties cancel
- This ratio is unity in the SM, neglecting lepton masses, with QED corrections at the % level

- Five different ratios published so far by LHCb:

  $X_s = K^+$, K^0_S, K^{*0}, K^{*+} and pK^-

Several R-ratio measurements

- Compare the rates of $B \longrightarrow X_s e^+ e^-$ and $B \longrightarrow X_s \mu^+ \mu^-$

  [*where B is* B^+, B^0, B^0_s, Λ^0_b and X_s is K^+, K^{*0}, ϕ, pK . . .]
- This allows precise testing of lepton flavour universality
- We can construct the ratio :

$$R_X = \int^{q^2_{\max}} \frac{d\mathcal{B}(B_q \to X_s \mu^+\mu^-)}{dq^2} dq^2$$

- Small theoretical uncertainties because hadronic uncertainties cancel

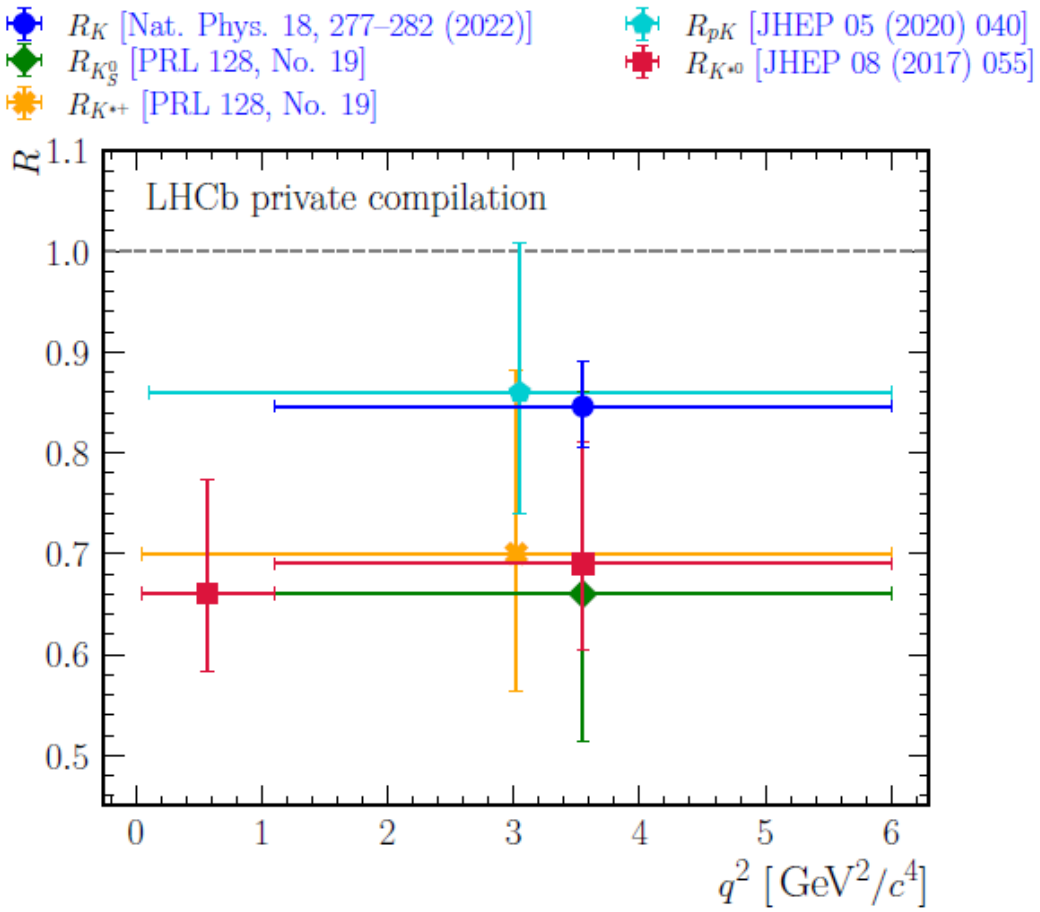
- Actually measure double ratios which significantly reduce systematic uncertainties:

$$R_X = \frac{\mathcal{B}\left(B_q \to X_s \mu^+\mu^-\right)}{\mathcal{B}\left(B_q \to X_s J/\psi(\mu^+\mu^-)\right)} \cdot \frac{\mathcal{B}\left(B_q \to X_s J/\psi(e^+e^-)\right)}{\mathcal{B}\left(B_q \to X_s e^+e^-\right)}$$

- Five different ratios published so far by LHCb:

  $X_s = K^+$, K^0_S, K^{*0}, K^{*+} and pK^-

LFU results : R_x



R_K (9/fb) 3.1 σ from SM

$R_{K^{*+}}$ (9/fb) 1.4 σ NEW

R_{K0s} (9/fb) 1.5 σ NEW

$R_{K^{*0}}$ low-q^2 (3/fb) 2.1 σ

$R_{K^{*0}}$ central-q^2 (3/fb) 2.4 σ

R_{pK} (5/fb) <1 σ

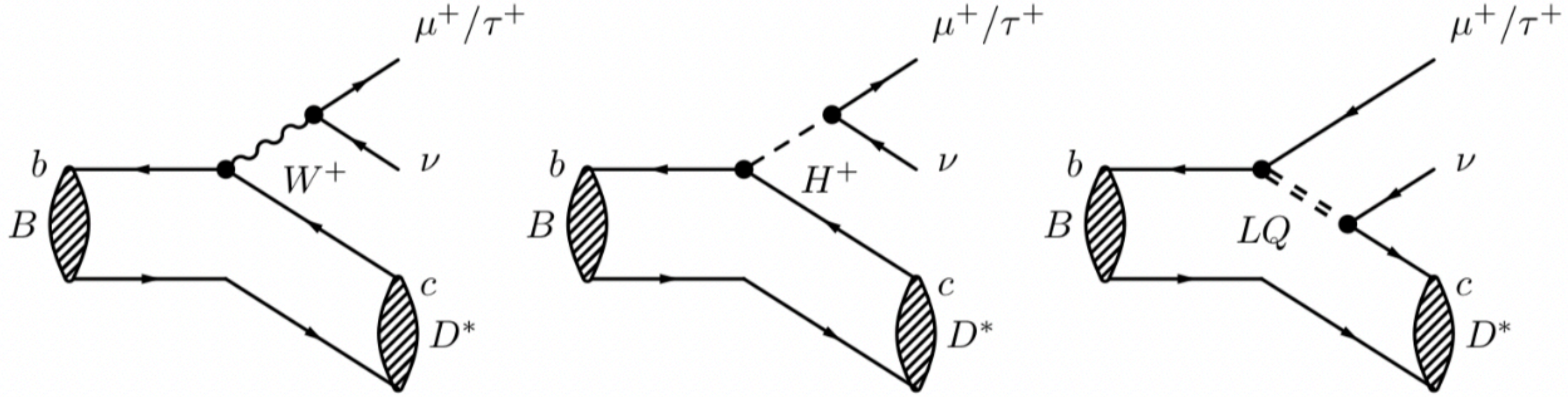
- All measurements have values less than unity
- The puzzle persists → we eagerly await Belle-II & CMS results
- LHCb is now focused on completing a combined analysis of RK & RK* with the Run 1+2 dataset. This work has led to a deeper understanding of systematics which will be reflected in the final result.

LFU studies in $B^0 \longrightarrow D^{(*)-}\tau^+\nu_\tau$ decays

- Different class of decays (tree-level charged current with V_{cb} suppression)
- Not at all rare: $B(B^0 \longrightarrow D^{*-}\tau^+\nu_\tau) \sim 1\%$, the problem is the background.
- Lepton-universality ratio R(D*) :

$$R(D^*) = \frac{B(B^0 \to D^{*-}\tau^+\nu_\tau)}{B(B^0 \to D^{*-}\mu^+\nu_\mu)}$$

- may be sensitive to any NP model coupling preferentially to third generation leptons



- Ratios predicted theoretically at ~1%:

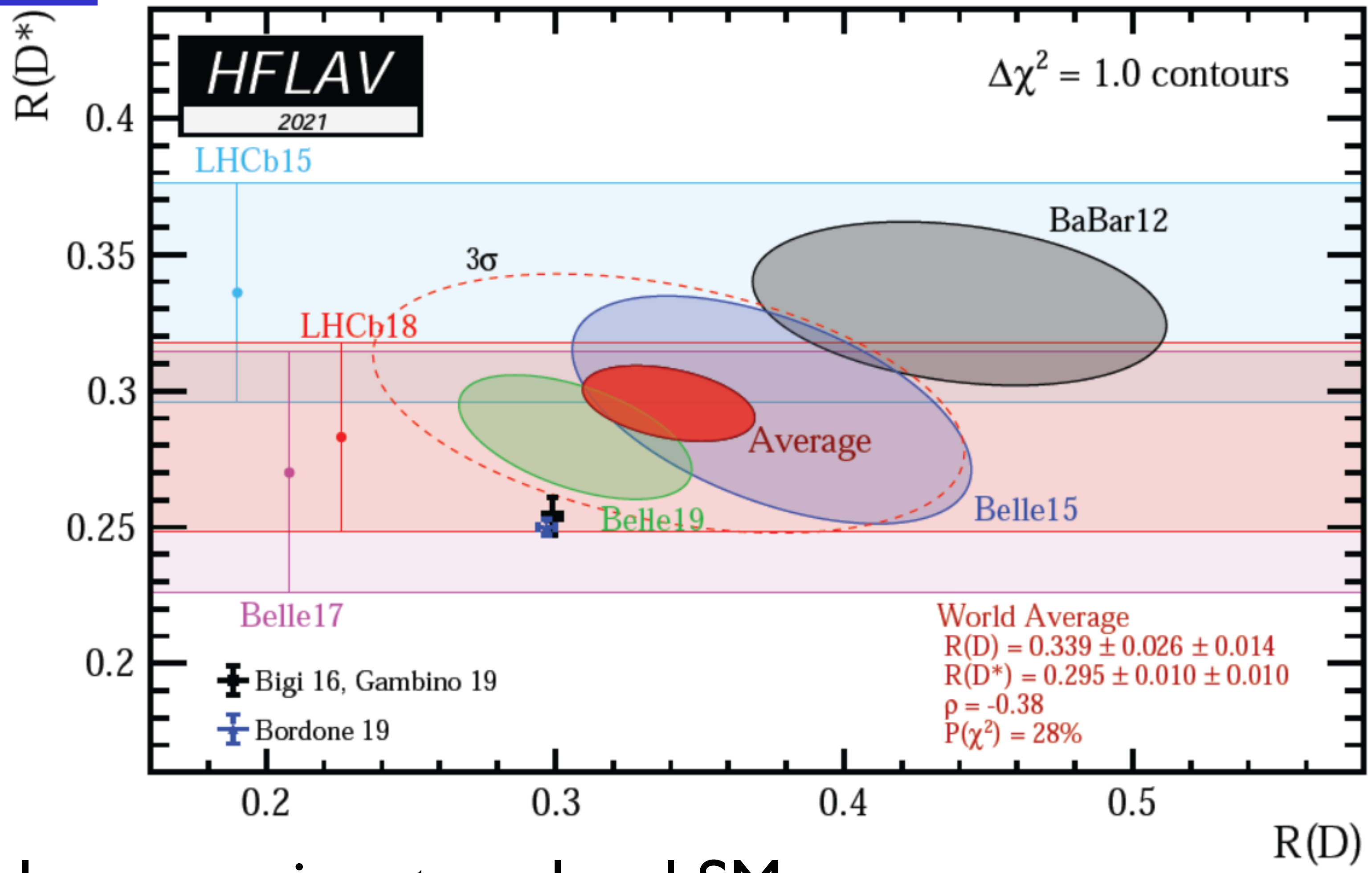
  $R(D)_{SM} = 0.299 \pm 0.003$ $R(D^*)_{SM} = 0.258 \pm 0.005$

- Anomolies first observed by Belle and BaBar

HFLAV 2019 average of theoretical predictions

R(D) vs R(D*)

- All experiments see an excess wrt SM predictions
- Combining R(D)/R(D*) average ~3.4 σ tension with SM



- Intriguing as anomaly occurs in a tree-level SM process

- New LHCb result

$R(\Lambda_c) = 0.242 \pm 0.026 \pm 0.040 \pm 0.059(\text{ext})$

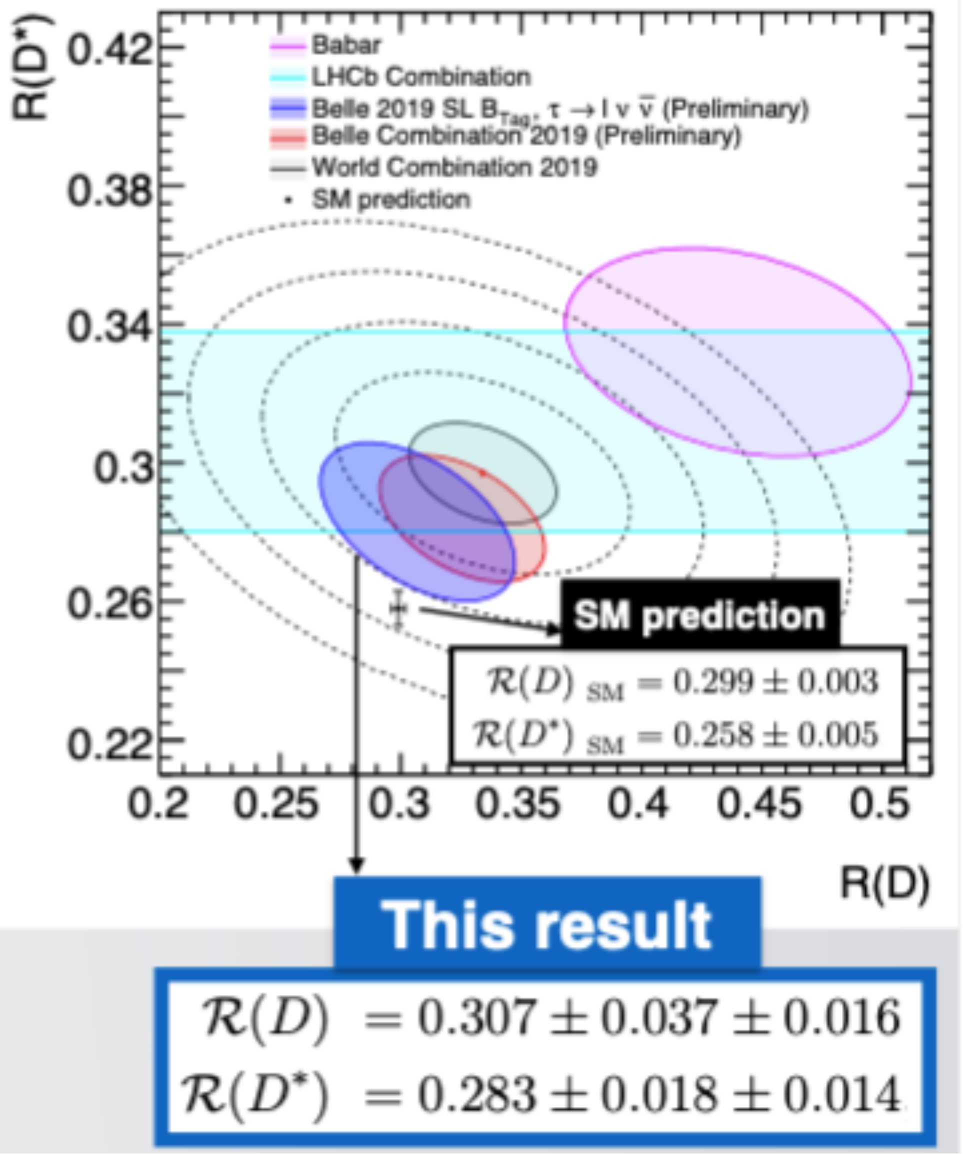
arxiv:2201:03497

Measurement is consistent with SM (~1σ "low") [SM=0.324±0.004].

THE STANDARD MODEL: THE STATUS AND OPEN QUESTIONS

Anomalies in B-meson decays: experiment ≠ the SM predictions

D-mesons



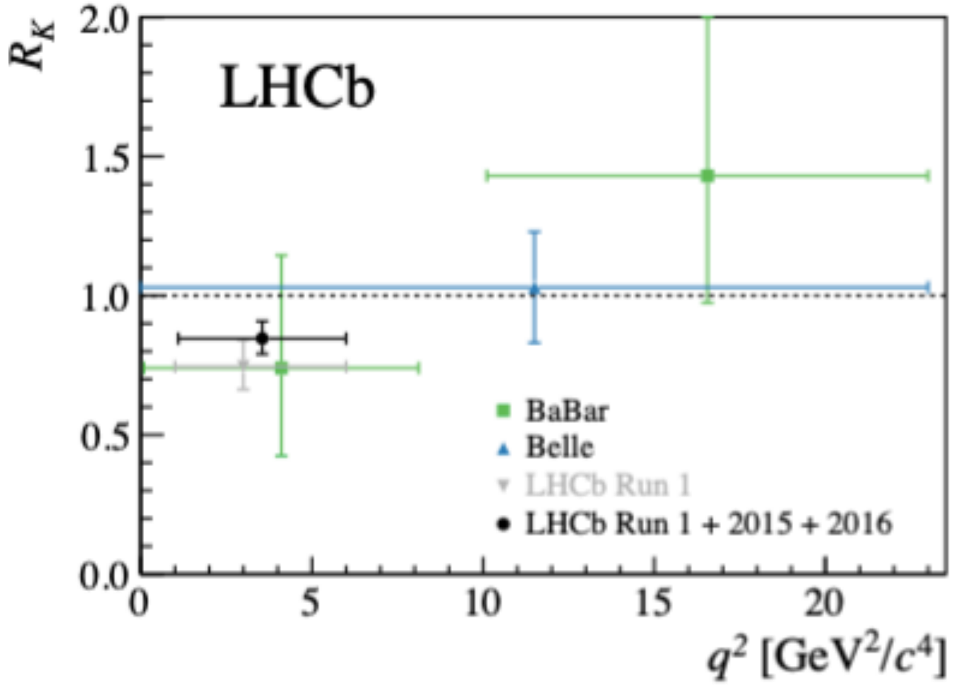
$\mathcal{R}(D)_{\text{SM}} = 0.299 \pm 0.003$

$\mathcal{R}(D^*)_{\text{SM}} = 0.258 \pm 0.005$

This result

$$\mathcal{R}(D) = 0.307 \pm 0.037 \pm 0.016$$
$$\mathcal{R}(D^*) = 0.283 \pm 0.018 \pm 0.014$$

K-mesons



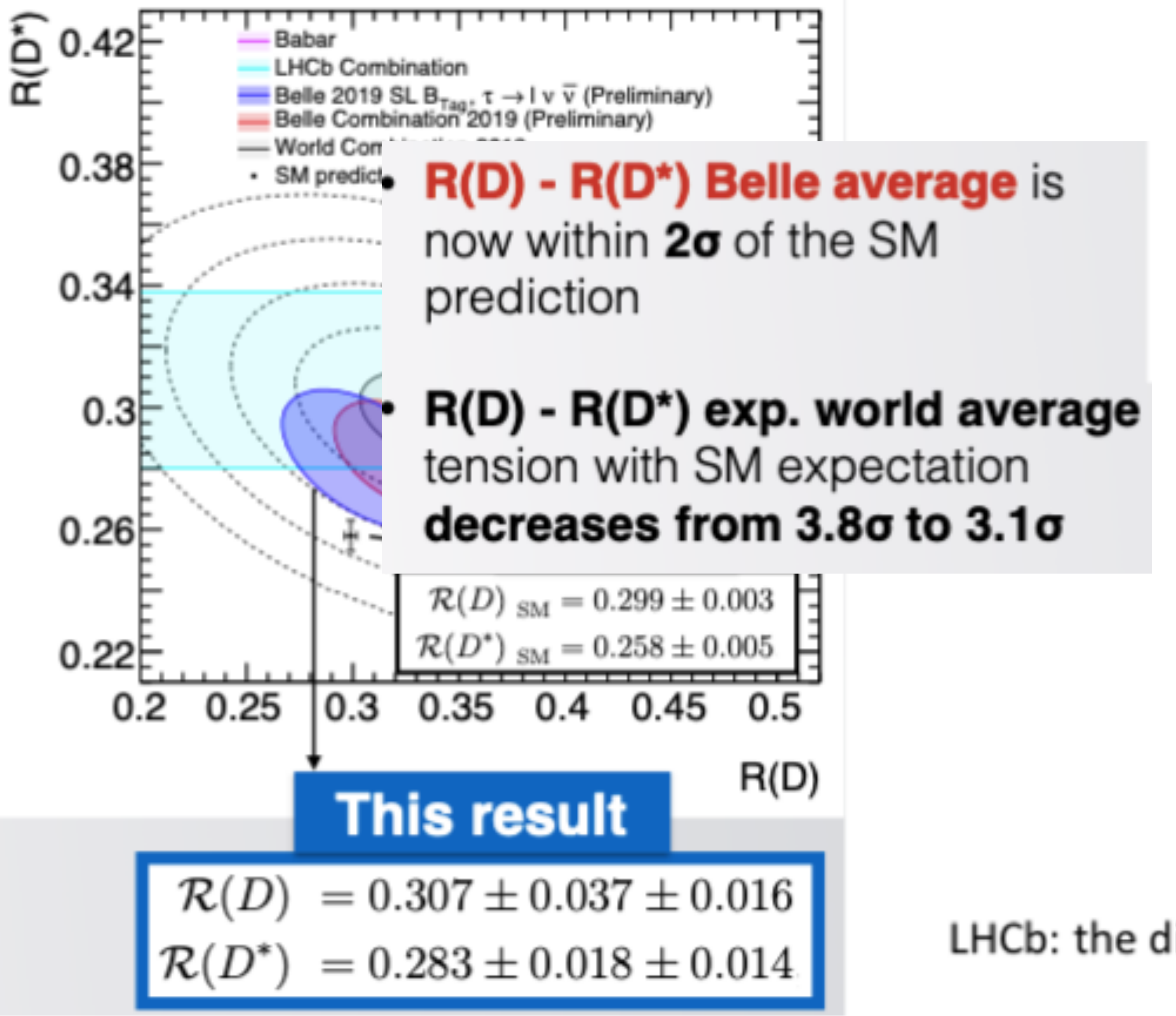
Combined Run1 + Run2

$$R_K = 0.846\,^{+0.060}_{-0.054}(\text{stat.})\,^{+0.016}_{-0.014}(\text{syst.})$$

LHCb: the discrepancy present in $B_s \to \phi\mu\mu$ and $\Lambda_b \to \Lambda\mu\mu$

Anomalies in B-meson decays: experiment ≠ the SM predictions

D-mesons



- **R(D) - R(D*) Belle average** is now within **2σ** of the SM prediction
- **R(D) - R(D*) exp. world average** tension with SM expectation **decreases from 3.8σ to 3.1σ**

This result

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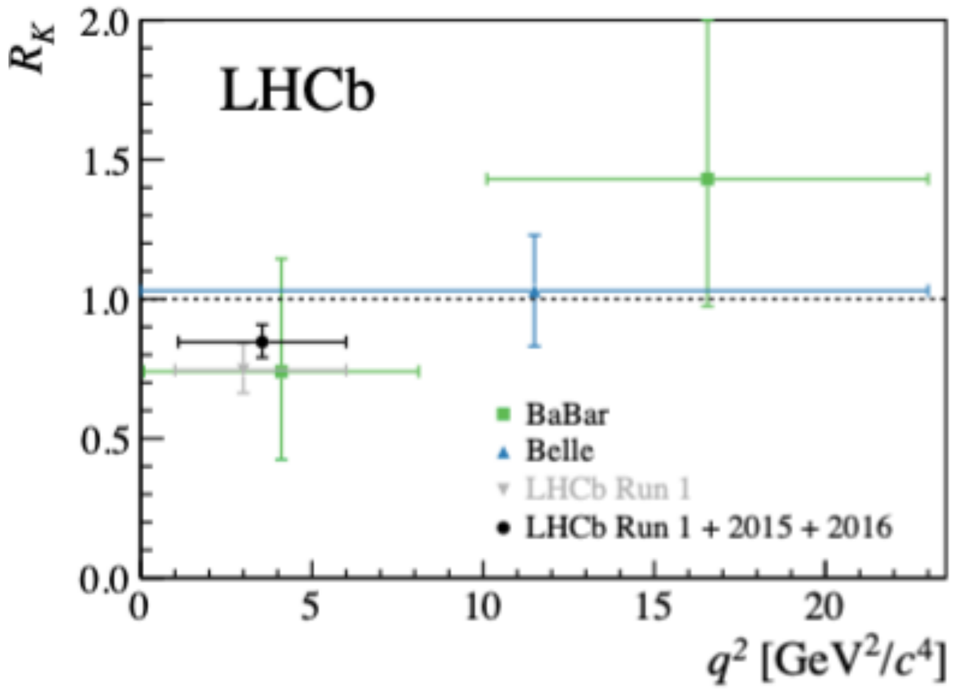
K-mesons



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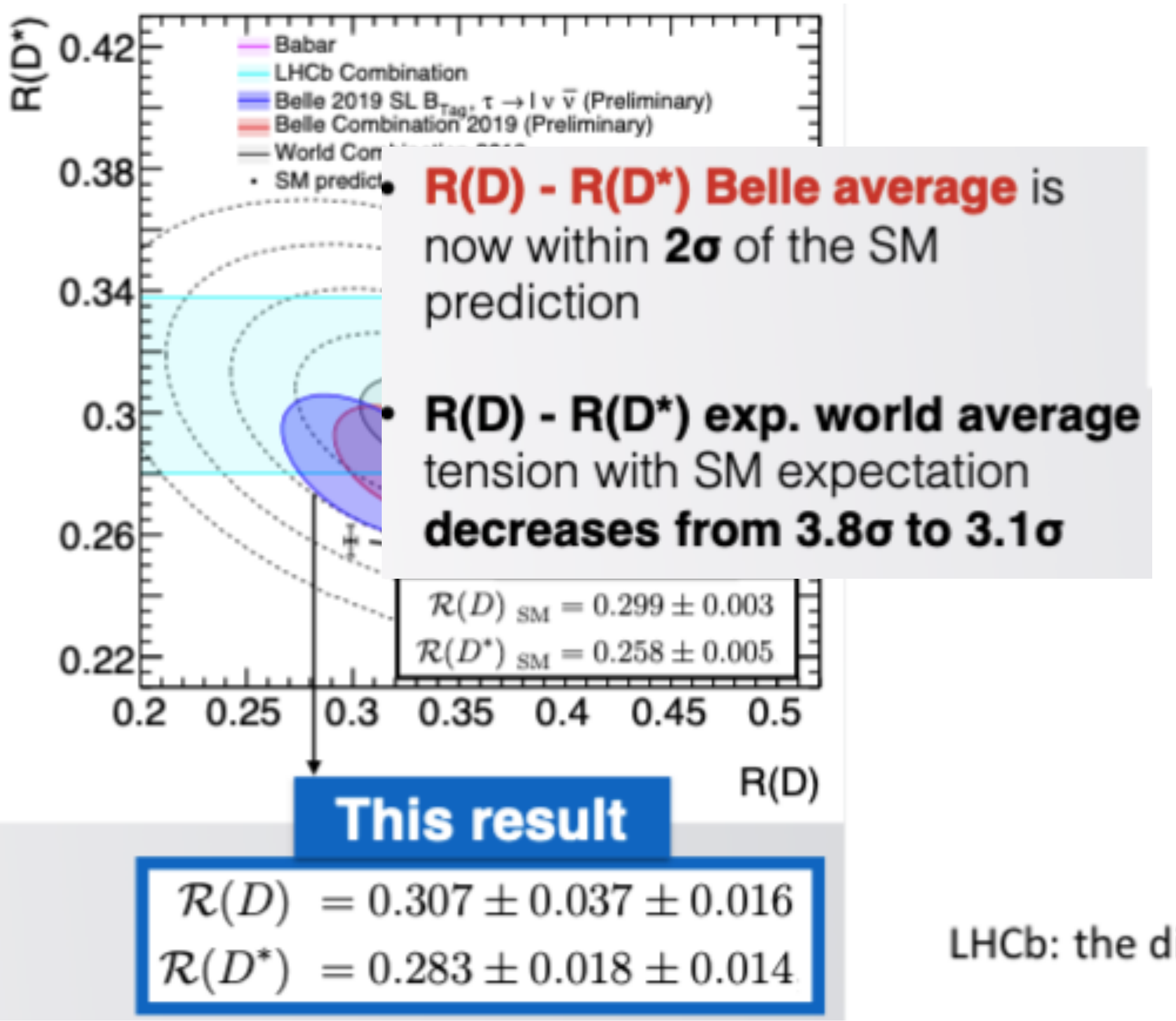

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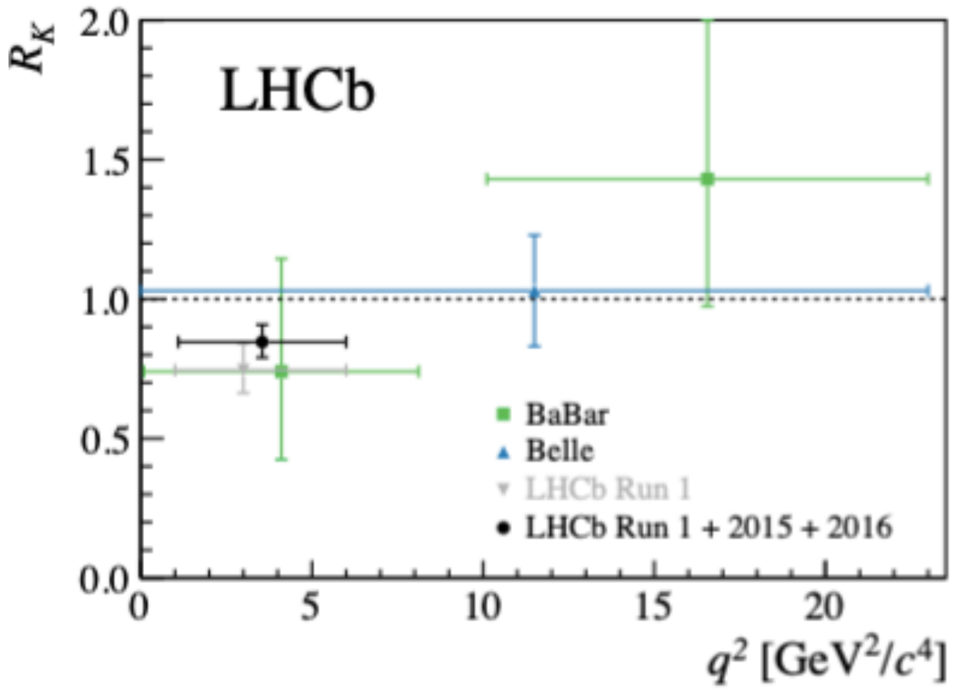
This result

$$\mathcal{R}(D) = 0.307 \pm 0.037 \pm 0.016$$
$$\mathcal{R}(D^*) = 0.283 \pm 0.018 \pm 0.014$$

K-mesons



Combined Run1 + Run2

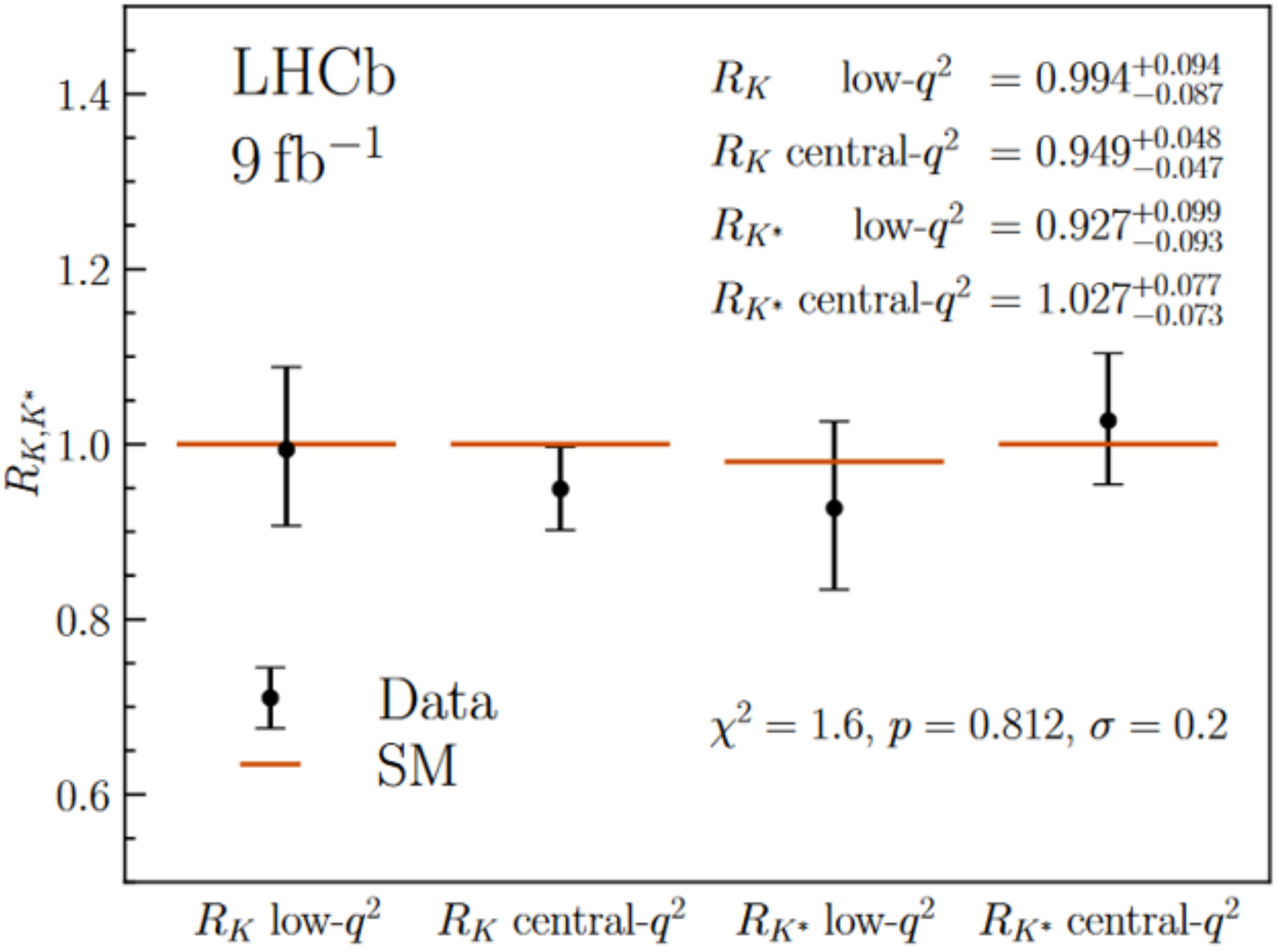
$$R_K = 0.846\ ^{+0.060}_{-0.054}\,(\text{stat.})\ ^{+0.016}_{-0.014}\,(\text{syst.})$$

LHCb: the discrepancy present in $B_s \to \phi\mu\mu$ and $\Lambda_b \to \Lambda\mu\mu$

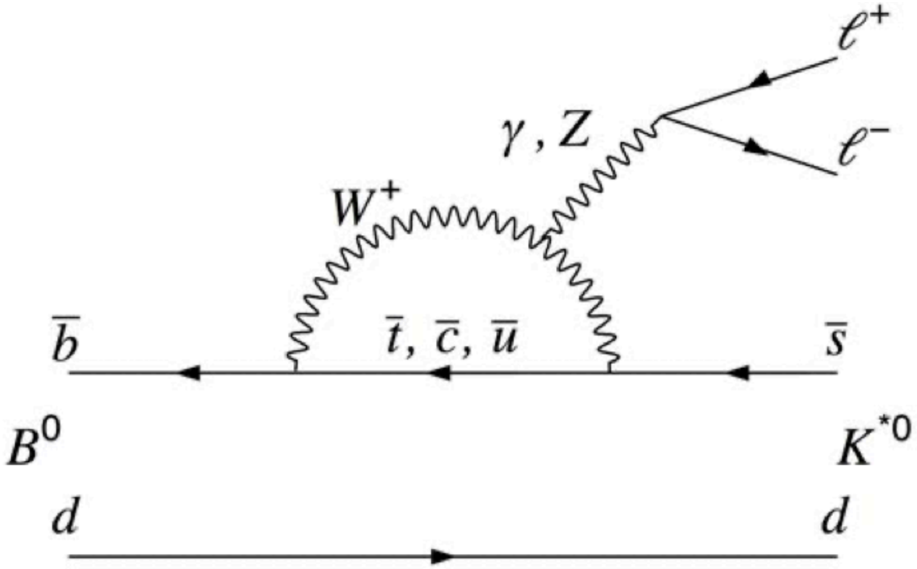
Discrepancy may increase but may decrease ….

Uncertainty of baryon contribution might be crucial!

THE LHCB RECENT RESULTS



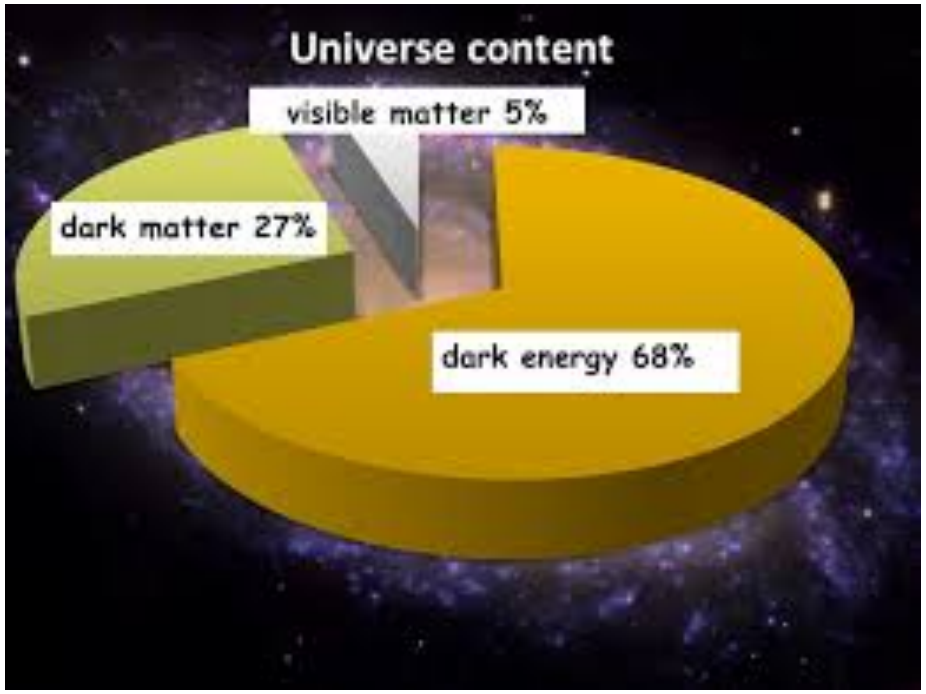
$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)}\mu\mu)}{BR(B \to K^{(*)}ee)}$$

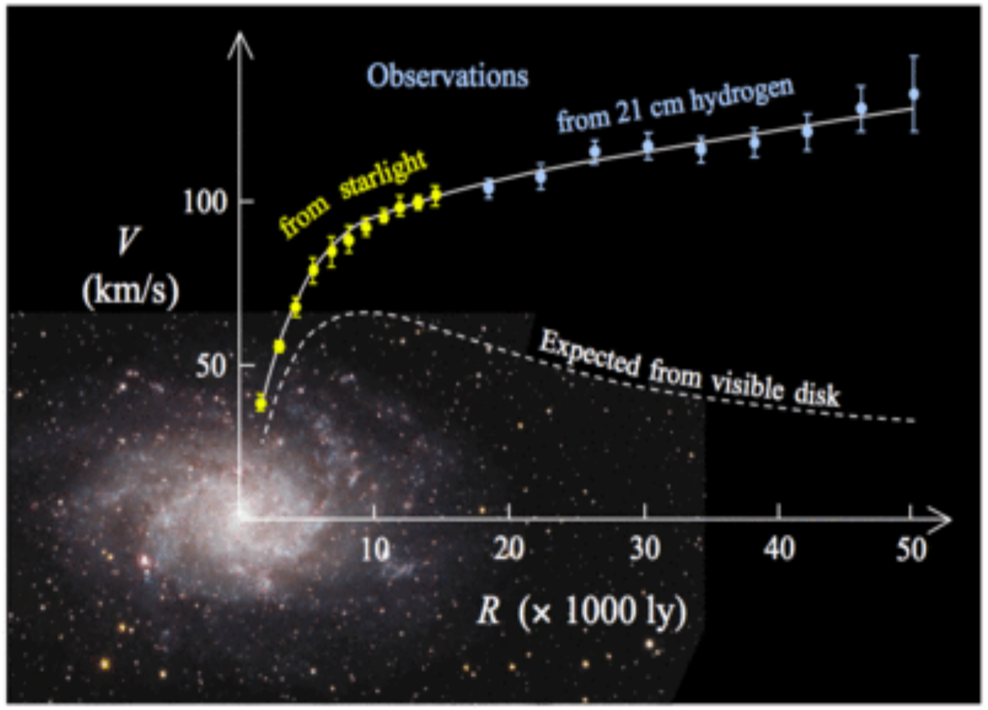


$$\mathcal{R}(K^*)_{SM} = 1.0$$

Dark matter

Тёмная материя



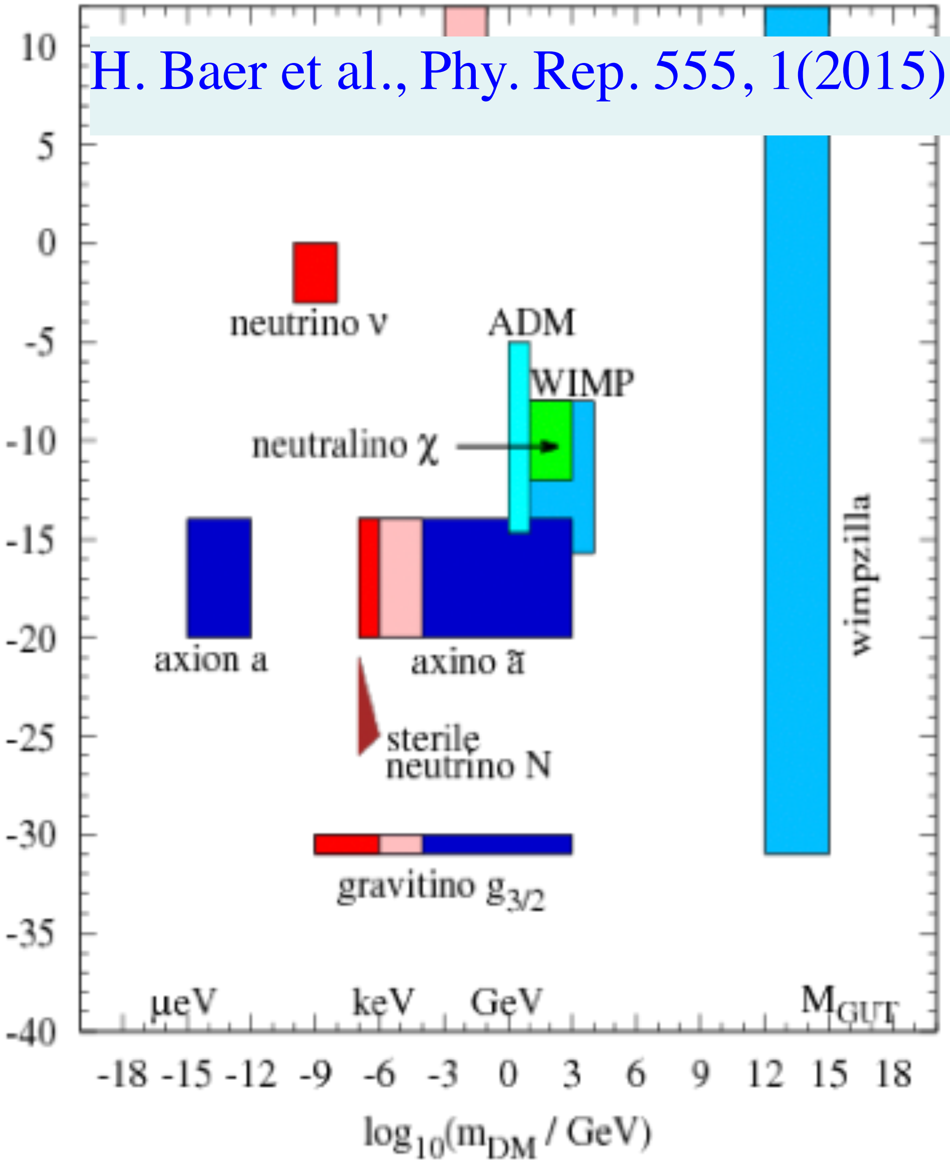


СТАНДАРТНАЯ МОДЕЛЬ: ПУТИ РАЗВИТИЯ - ТЁМНАЯ МАТЕРИЯ

Главная проблема: 85% материи является тёмной и остаётся невидимой!
Совместимо ли это с Стандартной моделью?

Требует ли это модификации СМ или добавление гравитации?

- Много кандидатов в разбросов масс в несколько порядков
  - **MOND** (Problems: large scales, Bullet cluster)
  - **Primordial black holes** (LIGO, but constraints)
  - **Fuzzy** (very light bosons)
  - **Warm** (KeV sterile)
  - **WIMP**
  - **Axions/ALPs**
  - **Dark sector**
  - **Gravitinos**
  - **Moduli**
  - **Wimpzillas**

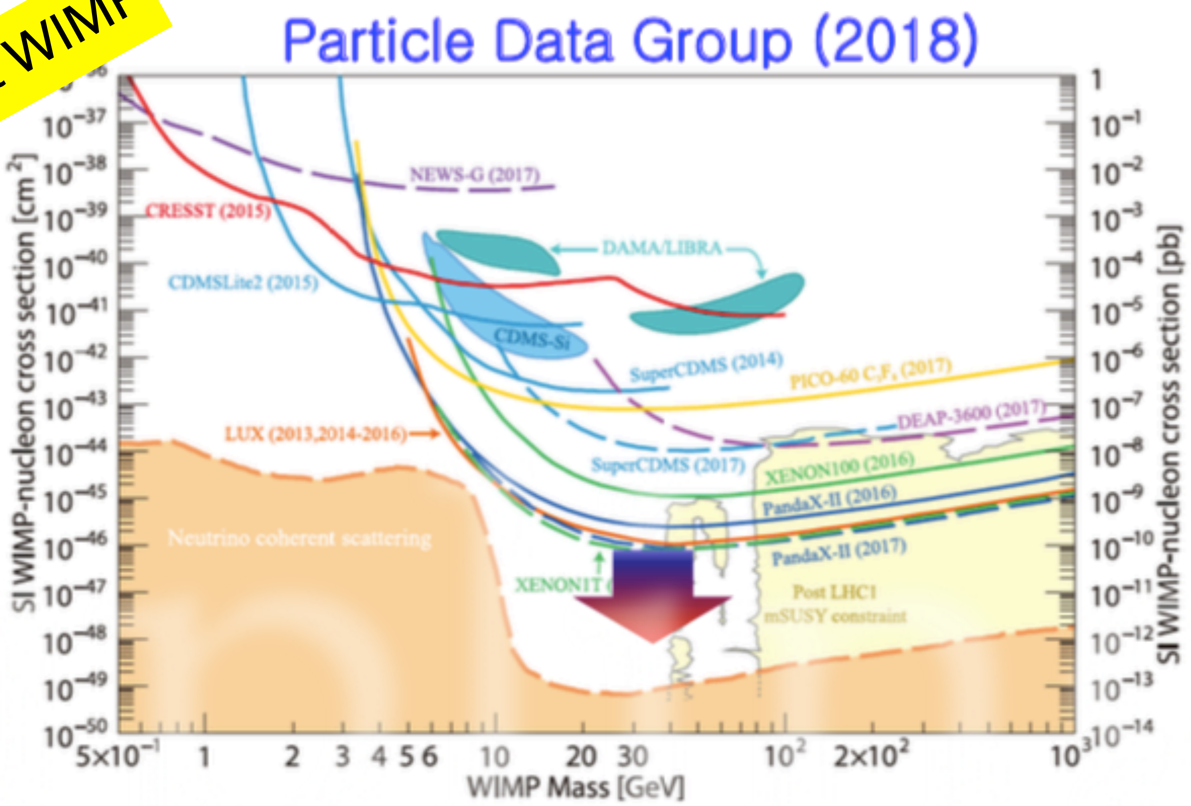


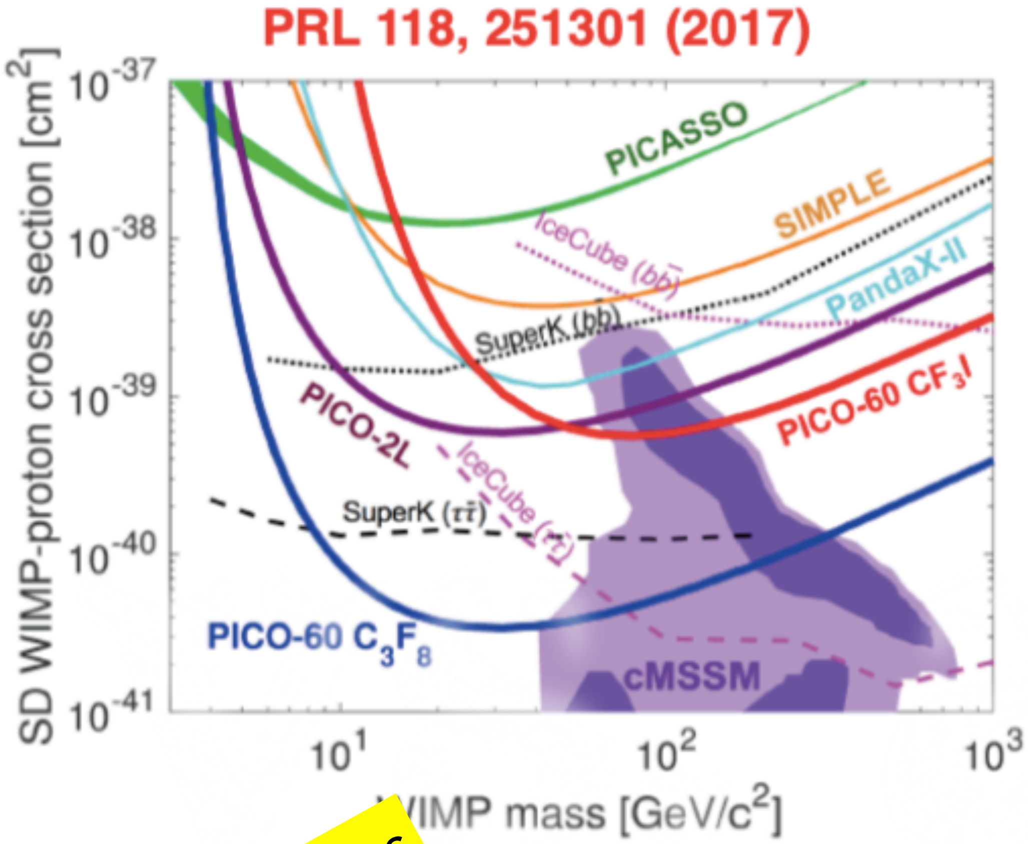
H. Baer et al., Phy. Rep. 555, 1(2015)

- Прямые, косвенные и коллайдерные поиски тёмной материи

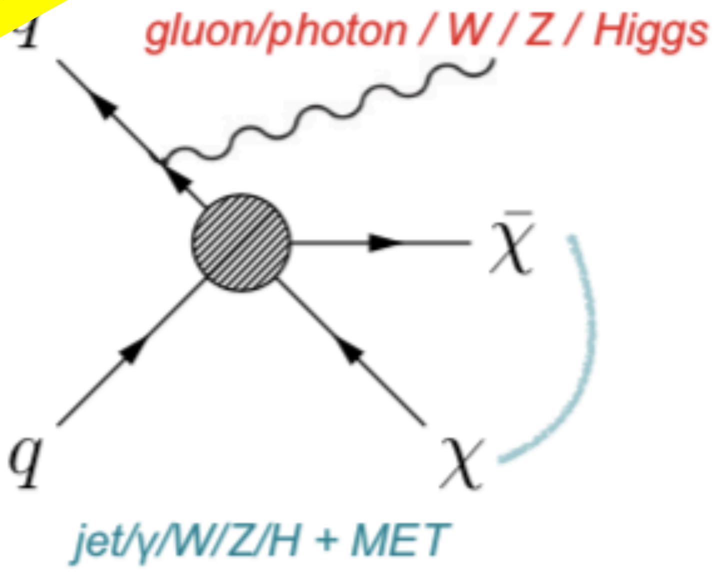
BEYOND THE STANDARD MODEL: DARK MATTER SEARCHES

Direct WIMP





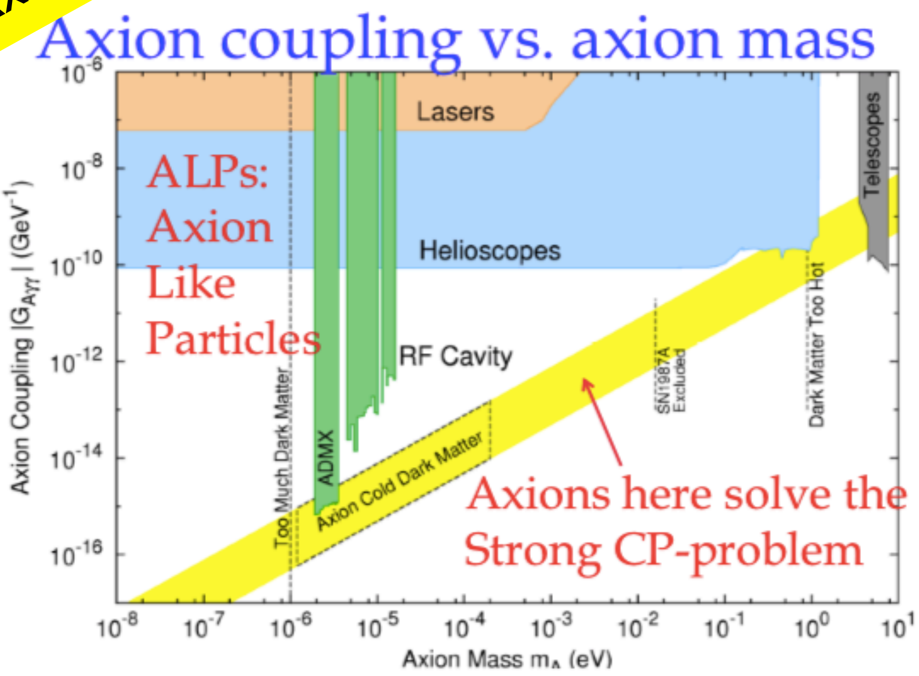
Colliders WIMP



- **mono-jet**
  - most general signature, constraints on many mode
- **mono-photon**
  - more challenging for background estimation
  - less powerful: EW vs. strong interaction
- **mono-W/Z leptonic**
  - clean signature and simple trigger
  - penalized by W/Z branching fraction
- **mono-W/Z hadronic**
  - larger statistics with larger background
- **tt+MET/bb+MET and mono-top**
  - more complicated experimentally
  - powerful in some scenarios
- **mono-Higgs**
  - powerful in some scenarios

D. del Re

Axion-likes

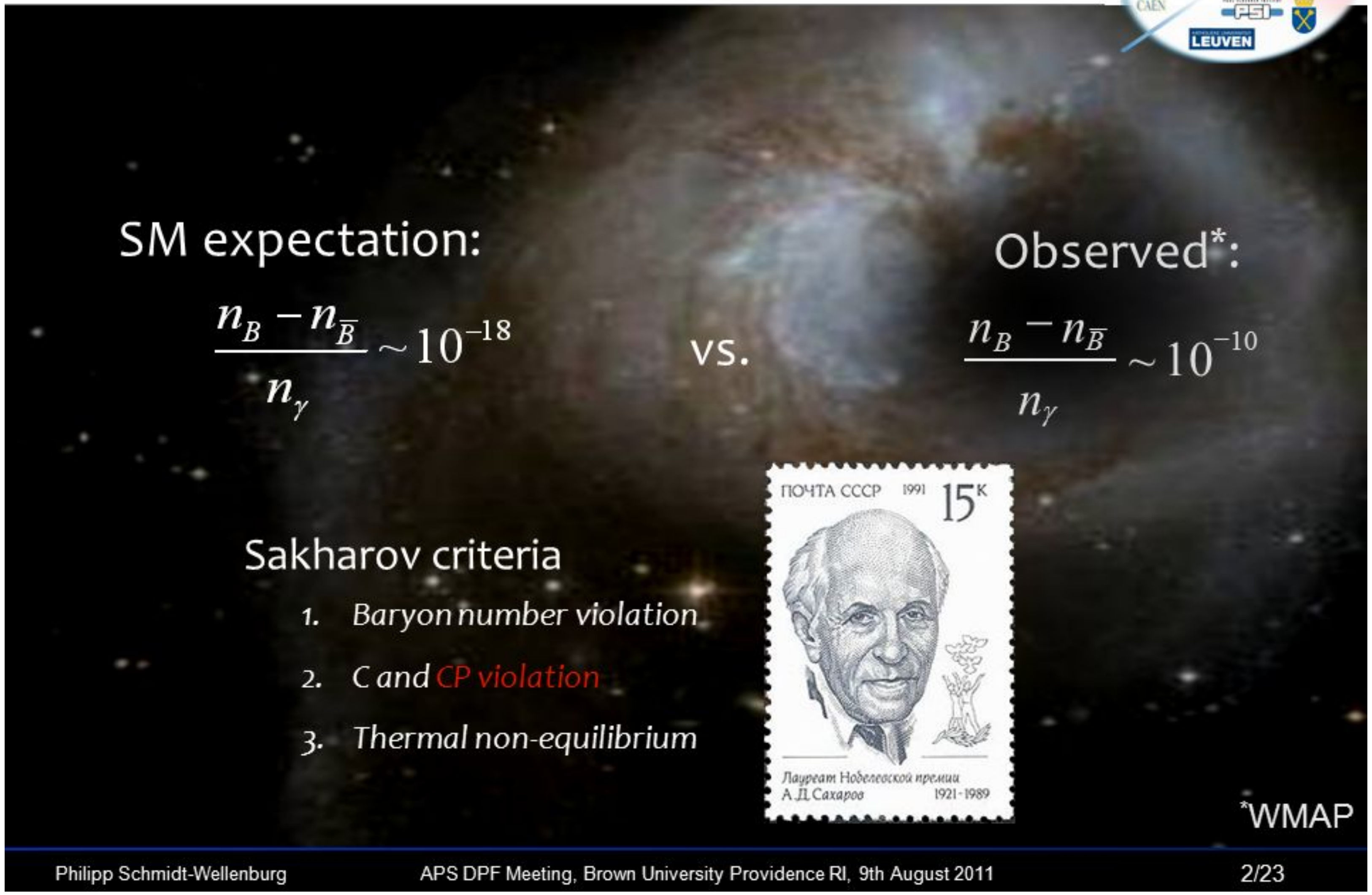


Y. Semertzidis

Baryon Asymmetry of the Universe

СТАНДАРТНАЯ МОДЕЛЬ: КОНЦЕПТУАЛЬНАЯ ПРОБЛЕМА

Барионная асимметрия Вселенной



SM expectation:

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-18}$$

vs.

Observed*:

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-10}$$

Sakharov criteria

1. *Baryon number violation*
2. *C and CP violation*
3. *Thermal non-equilibrium*

*WMAP

Philipp Schmidt-Wellenburg APS DPF Meeting, Brown University Providence RI, 9th August 2011 2/23

- Барионное число сохраняется в СМ с экспоненциальной точностью
- Нарушение барионного числа имеет место в Теориях Великого Объединения и в моделях Пати-Салама (лептон = четвертый цвет)

Новые частицы = лептокварки, расширенный хиггсовский сектор

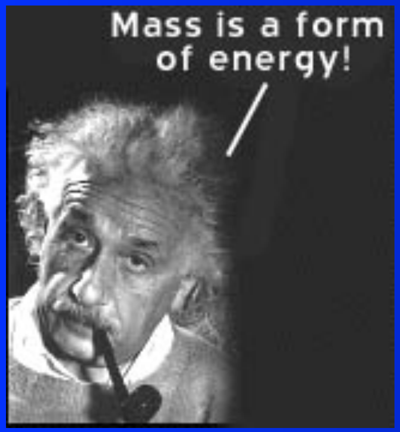
$$B = \frac{N_q - N_{\bar{q}}}{3} \qquad \cancel{B}$$

- Нарушение CP инвариантности в СМ достигается за счёт фаз в матрицах смешивания СКМ и PMNS $\longleftrightarrow$ $\cancel{CP}$
- BAU требует бо́льшего CP нарушения чем есть в СМ
- Возможен бариогенезис через лептогенезис
- В расширенных моделях (2HDM, SUSY, etc) существуют новые фазовые факторы

Gravity

Задача № 3:

Как проквантовать гравитацию?



Общая теория Относительности

$$Action = \int d^4x\sqrt{-g}\left[\frac{c^4}{16\pi G}(R-2\Lambda)+\mathcal{L}_M\right]$$

$$R_{\mu\nu}-\frac{1}{2}g_{\mu\nu}R=\frac{8\pi G}{c^2}T_{\mu\nu} \quad \Longrightarrow \quad R_{\mu\nu}-\frac{1}{2}g_{\mu\nu}R+g_{\mu\nu}\Lambda=\frac{8\pi G}{c^2}T_{\mu\nu}$$

тензор Риччи

тензор энергии-импульса материи

скалярная кривизна

Космологическая постоянная

Космологическая постоянная есть вакуумная энергия = Λ^4

Приводит к антигравитации, что порождает ускоренное расширение Вселенной

Чтобы получить ~ 70 % вклада в энергетический баланс Вселенной Λ должна быть порядка 10^{-3} эв.

?!

Квантование

$$\underset{\substack{\Uparrow \\ \text{метрика}}}{g_{\mu\nu}} = g_{\mu\nu}^{clasic} + \underset{\substack{\Uparrow \\ \text{квантовые флуктуации (гравитон)}}}{h_{\mu\nu}}$$

Проблемы:

- Лишние степени свободы: духи
- Рост вероятностей с энергией: $\sim E^2/M_{Pl}^2$
- Наличие бесконечного числа бесконечностей: неперенормируемость

Квантование

$$g_{\mu\nu} = g_{\mu\nu}^{clasic} + h_{\mu\nu}$$

метрика квантовые флуктуации (гравитон)

Проблемы:

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- Рост вероятностей с энергией: $\sim E^2/M_{Pl}^2$
- Наличие бесконечного числа бесконечностей: неперенормируемость

Пути решения:

- Модификация сектора материи (суперсимметрия)
- Модификация гравитации (высшие члены по кривизне)
- Нелокальная теория (струна)
- Обуздание неперенормируемости

Квантование

$$g_{\mu\nu} = g_{\mu\nu}^{clasic} + h_{\mu\nu}$$

метрика

квантовые флуктуации (гравитон)

<u>Проблемы:</u>

- Лишние степени свободы: духи
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?!

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метрика   квантовые флуктуации (гравитон)

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- Обуздание неперенормируемости

?!

Решение пока отсутствует

Квантование

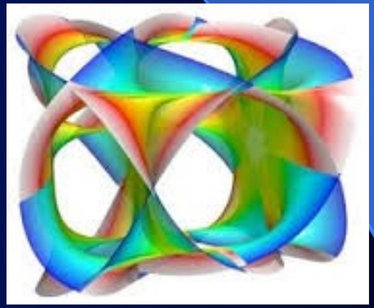
Модификация ОТО

$$R \to R + R^2 + R_{\mu\nu}R^{\mu\nu}$$

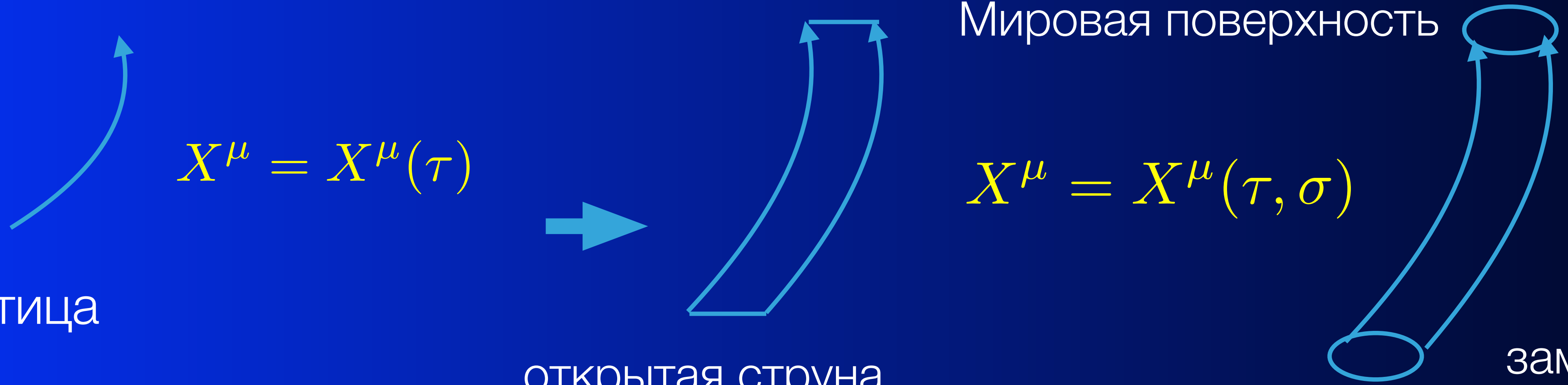
скалярная кривизна тензор Риччи

Изменение космологических сценариев

Поляризация гравитационных волн



Новая парадигма: Теория струн



Мировая линия

$$X^\mu = X^\mu(\tau)$$

частица

открытая струна

Мировая поверхность

$$X^\mu = X^\mu(\tau, \sigma)$$

замкнутая струна

Частицы есть моды колебаний релятивистской струны