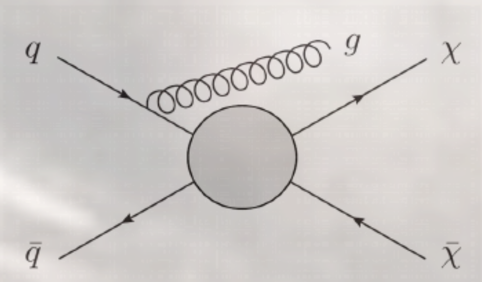
Imperial College London

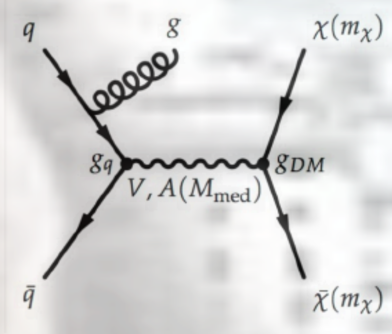
SUSY & DARK MATTER @ LHC

Oliver Buchmueller, Imperial College London

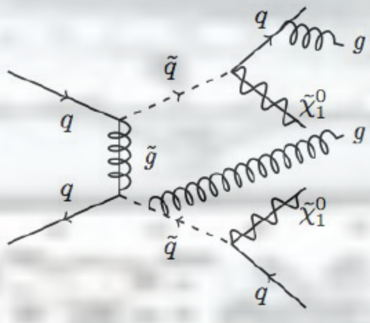
GALILEO GALILEI INSTITUTE WORKSHOP: "COLLIDER PHYSICS AND THE COSMOS" SEP 6, 2017



EFTs



Simplified Models



UV-complete Models

Simplicity vs. Complexity

Finding the right balance is a challenge!

Characterisation of Dark Matter searches at colliders

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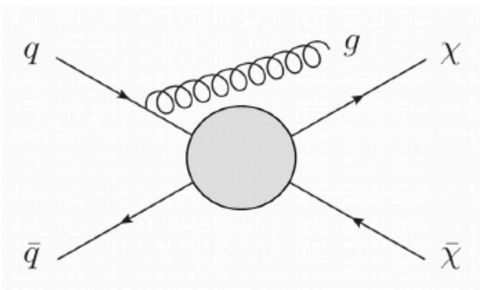

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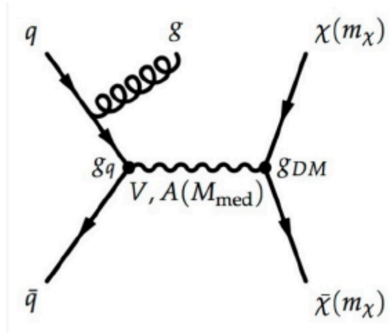

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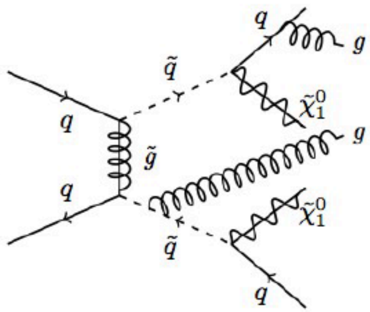

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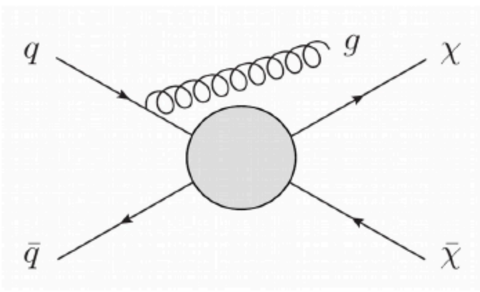

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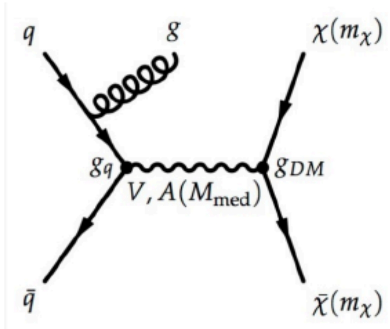

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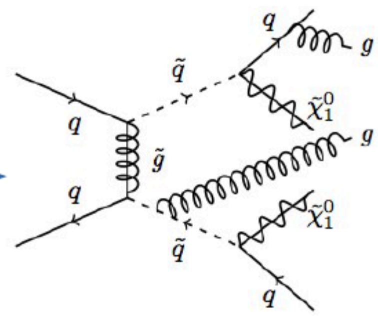


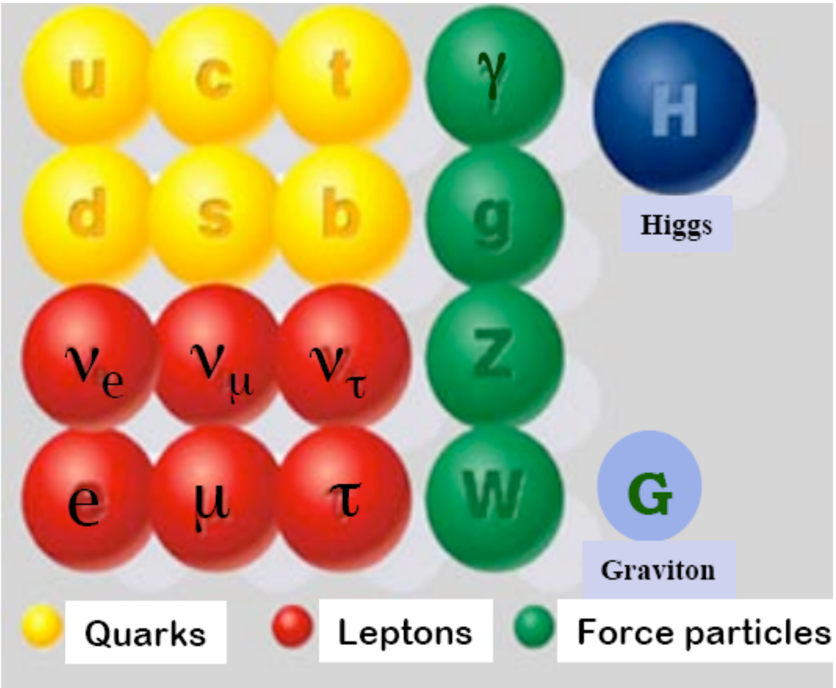
UV-complete Models

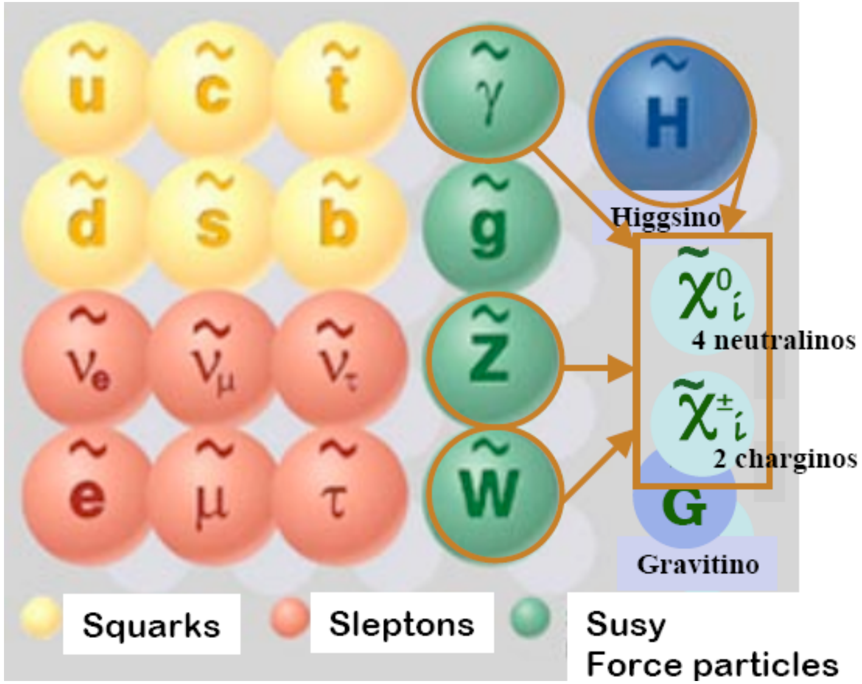
Supersymmetry

Extension of the Standard Model: Introduce a new symmetry

Spin ½ matter particles (fermions) ⇔ Spin 1 force carriers (bosons)

Standard Model particles **SUSY particles**





New Quantum number: R-parity: $R_p = (-1)^{B+L+2s}$ = +1 SM particles

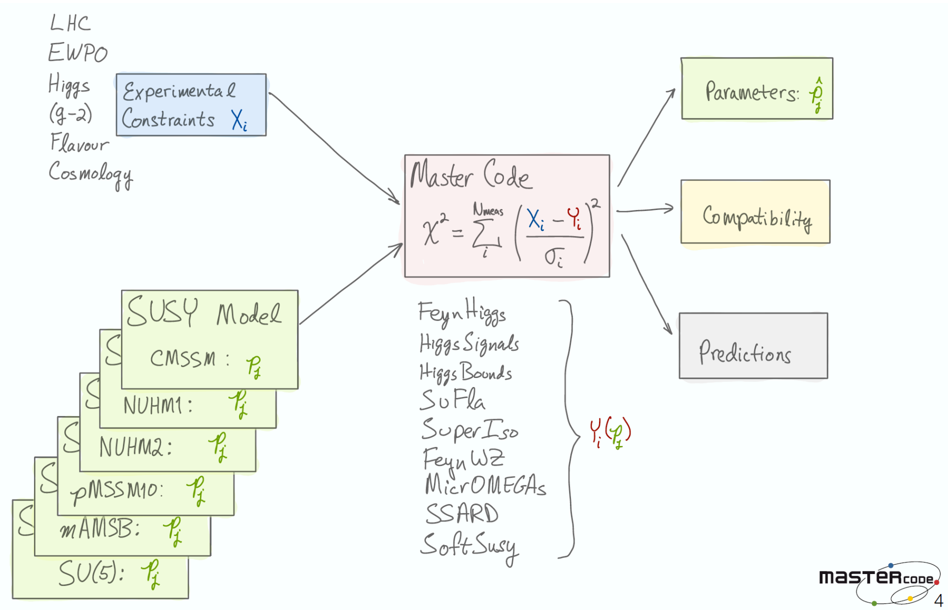
- 1 SUSY particles

R-parity conservation:

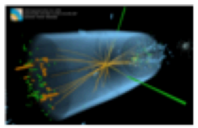
- SUSY particles are produced in pairs
- The lightest SUSY particle (LSP) is stable

Dark Matter in Supersymmetry with MasterCode

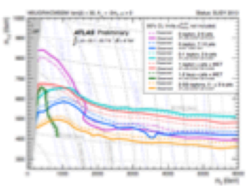
Global Fit to indirect and direct constraints on SUSY!



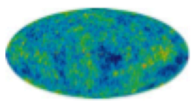
Direct Constraints	Indirect Constraints	Dark Matter Constraints
Lightest Higgs	Mw, Z-pole, $(g-2)_\mu$, Electroweak observables	CMB
SUSY particles	Flavour observables	Direct Detection



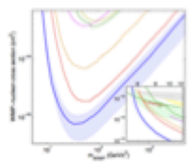
Lightest Higgs



SUSY particles



CMB



Direct Detection

Source:
http://mastercode.web.cern.ch/mastercode/

Observable	Source Th./Ex.	Constraint	$\Delta\chi^2$ (CMSSM)	$\Delta\chi^2$ (NUHM1)	$\Delta\chi^2$ ("SM")
m_t [GeV]	[43]	173.2 ± 0.90	0.05	0.06	-
$\Delta\alpha^{(5)}_{had}(M_Z)$	[42]	0.02749 ± 0.00010	0.009	0.004	-
M_Z [GeV]	[44]	91.1875 ± 0.0021	2.7×10^{-5}	0.26	-
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$A_{fb}(\ell)$	[26] / [44]	0.01714 ± 0.00095	0.72	0.69	0.81
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R_b	[26] / [44]	0.21629 ± 0.00066	0.26	0.29	0.27
R_c	[26] / [44]	0.1721 ± 0.0030	0.002	0.002	0.002
$A_{fb}(b)$	[26] / [44]	0.0992 ± 0.0016	7.17	7.37	6.63
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A_ℓ(SLD)	[26] / [44]	0.1513 ± 0.0021	3.16	3.03	3.51
$\sin^2\theta^\ell_w(Q_{fb})$	[26] / [44]	0.2324 ± 0.0012	0.63	0.64	0.59
M_W [GeV]	[26] / [44]	$80.399 \pm 0.023 \pm 0.010_{SUSY}$	1.77	1.39	2.08
$a_\mu^{EXP} - a_\mu^{SM}$	[53] / [42,54]	$(30.2 \pm 8.8 \pm 2.0_{SUSY}) \times 10^{-10}$	4.35	1.82	11.19 (N/A)
M_h [GeV]	[28] / [55,56]	$> 114.4[\pm1.5_{SUSY}]$	0.0	0.0	0.0
$BR^{EXP/SM}_{b\to s\gamma}$	[45] / [46]	$1.117 \pm 0.076_{EXP}$ $\pm 0.082_{SM} \pm 0.050_{SUSY}$	1.83	1.09	0.94
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$BR^{EXP/SM}_{K\to\mu\nu}$	[29] / [48]	$1.008 \pm 0.014_{EXP+TH}$	0.39	0.42	0.33
$BR^{EXP/SM}_{K\to\pi\nu\bar\nu}$	[49] / [50]	< 4.5	0.0	0.0	0.0
$\Delta M^{EXP/SM}_{B_s}$	[49] / [51,52]	$0.97 \pm 0.01_{EXP} \pm 0.27_{SM}$	0.02	0.02	0.01
$\frac{\Delta M^{EXP/SM}_{B_s}}{\Delta M^{EXP/SM}_{B_d}}$	[29] / [46,51,52]	$1.00 \pm 0.01_{EXP} \pm 0.13_{SM}$	$\ll 0.01$	0.33	$\ll 0.01$
$\Delta\epsilon^{EXP/SM}_K$	[49] / [51,52]	$1.08 \pm 0.14_{EXP+TH}$	0.27	0.37	0.33
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$H/A, H^\pm$	[21]	$(M_A, \tan\beta)$ plane	0.0	0.0	N/A
Total χ^2/d.o.f. p-values	All	All	28.8/22 15%	27.3/21 16%	32.7/23 (21.5/22) 9% (49%)

Dark Matter in Supersymmetry with MasterCode

Global Fit to indirect and direct constraints on SUSY!

LHC
EWPO

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[m]Institute for Particle Physics, ETH Zürich, CH–8093 Zürich, Switzerland

[n]DESY, Notkestrasse 85, D–22607 Hamburg, Germany

b.cern.ch/mastercode/

…straint	$\Delta\chi^2$ (CMSSM)	$\Delta\chi^2$ (NUHM1)	$\Delta\chi^2$ ("SM")
± 0.90	0.05	0.06	-
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± 0.037	2.50	2.57	2.54
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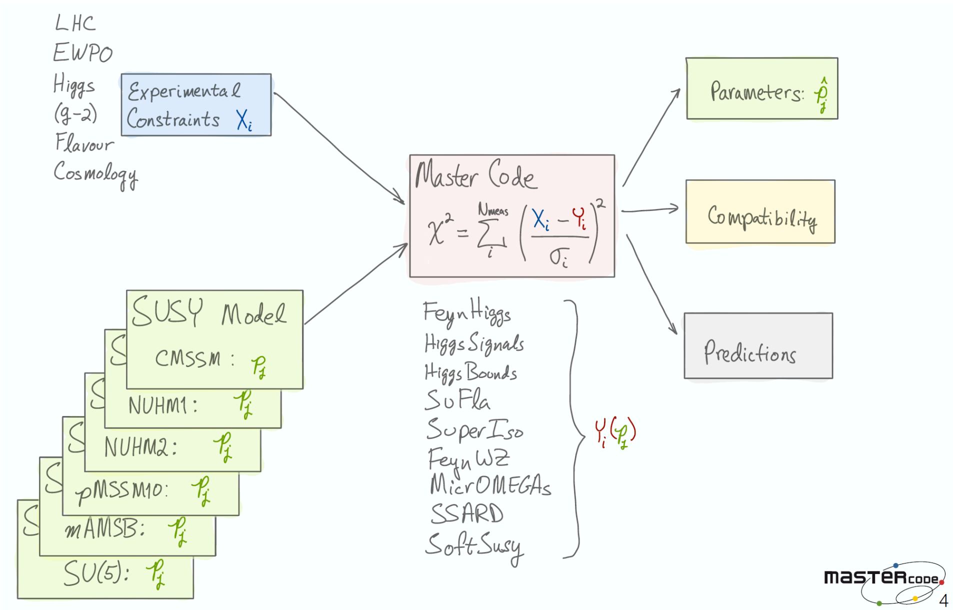

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Direct Constraints | Indirect Constraints | Dark Matter Constraints

Other "global Fitters" with similar studies are:

Fittino group: [see e.g. arXiv:1508.05951]
http://flcwiki.desy.de/Fittino

Gambit group: [see e.g. arXiv:1705.07917]
https://gambit.hepforge.org

SuperBayeS: [see e.g. arXiv:1507.07008]

SUSY particles | Flavour observables | Direct Detection

MasterCode: The two worlds of SUSY models

"Soft scale" ⟷ "GUT scale"

pMSSM10

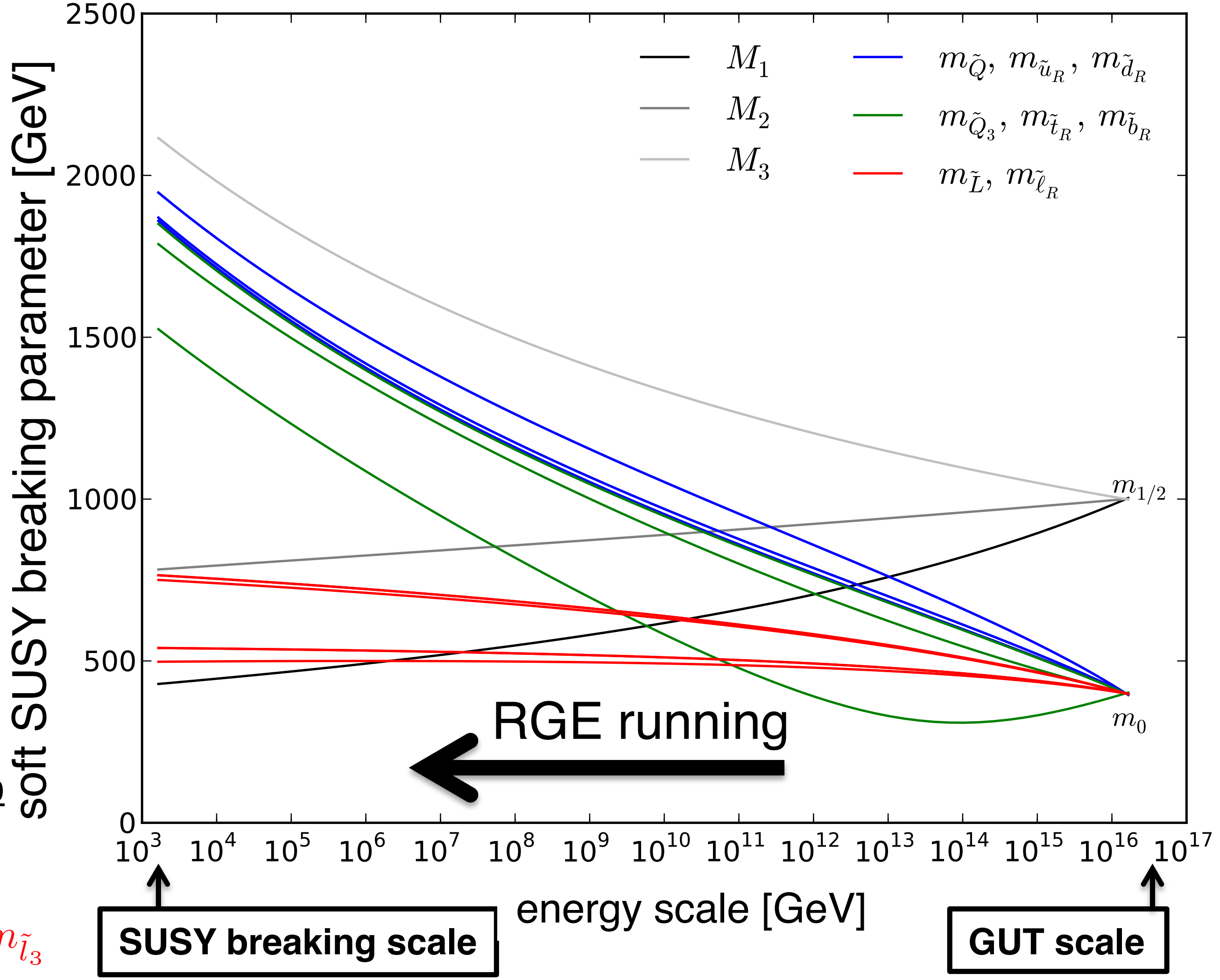
M_1, M_2, M_3, $m_{\tilde{q}_{12}}$, $m_{\tilde{q}_3}$, $m_{\tilde{\ell}}$, A, M_A, $\tan\beta$, μ

arXiv:1504.03260

pMSSM11

$m_{\tilde{l}} \rightarrow m_{\tilde{l}_{12}}, m_{\tilde{l}_3}$

in preparation



CMSSM

$m_0, \; m_{1/2},$

$A_0, \; \tan\beta$

arXiv:1312.5250

NUHM1

$m^2_{H_u} = m^2_{H_d}$

arXiv:1312.5250

NUHM2

$m^2_{H_u} \neq m^2_{H_d}$

arXiv:1408.4060

SU5

$m_0 \rightarrow m_5, m_{10}$

arXiv:1610.10084

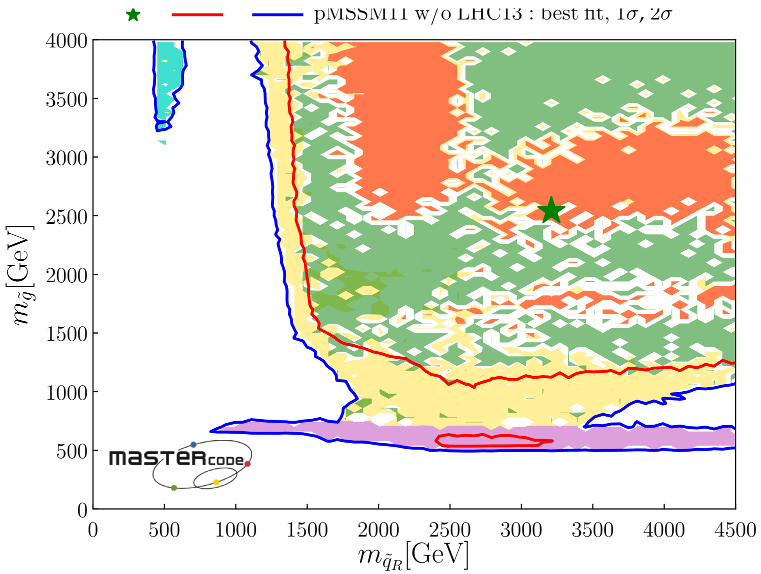
AMSB

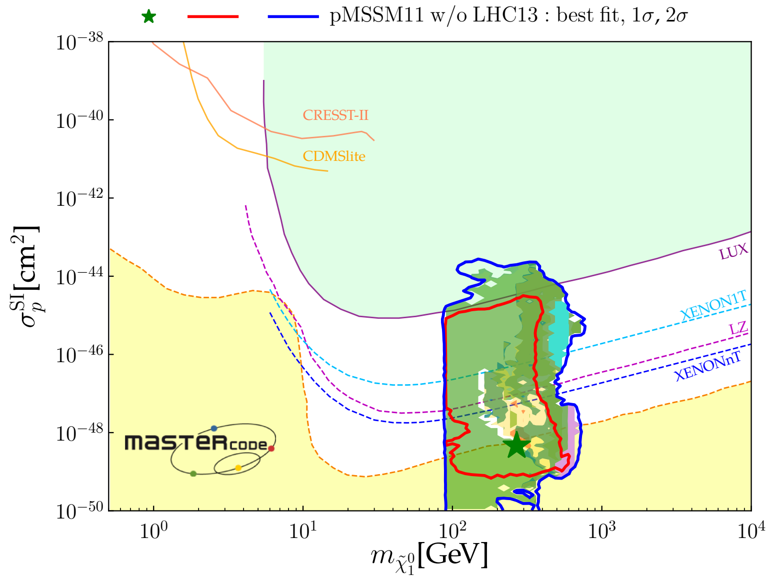
$m_0, m_{3/2}, tan\beta$

arXiv:1612.05210

pMSSM11: Status LHC RUN 1 (pre-LHC 13 TeV)

stau coann. | $\tilde{\chi}_1^{\pm}$ coann. | slep coann | gluino coann. | squark coann.





DM mechanisms:

To satisfy cosmological DM density constraint requires, in general, specific relations between sparticle masses that suppress the relic density via coannihilation effects and/or rapid annihilations through direct channel resonances.

Define indicative measures to highlight different DM mechanisms in the preferred regions of the fit:

$\left(\frac{M_{\tilde{\tau}}}{m_{\chi_1^0}} - 1\right) < 0.15$ **Stau coannihilation**

$\left(\frac{M_{\tilde{l}}}{m_{\chi_1^0}} - 1\right) < 0.15$ **Slepton Co-annihilation**

$\left(\frac{M_{\chi_1^{\pm}}}{m_{\chi_1^0}} - 1\right) < 0.25$ **Chargino Co-annihilation**

$\left(\frac{M_{\tilde{g}}}{m_{\chi_1^0}} - 1\right) < 0.25$ **Gluino Co-annihilation**

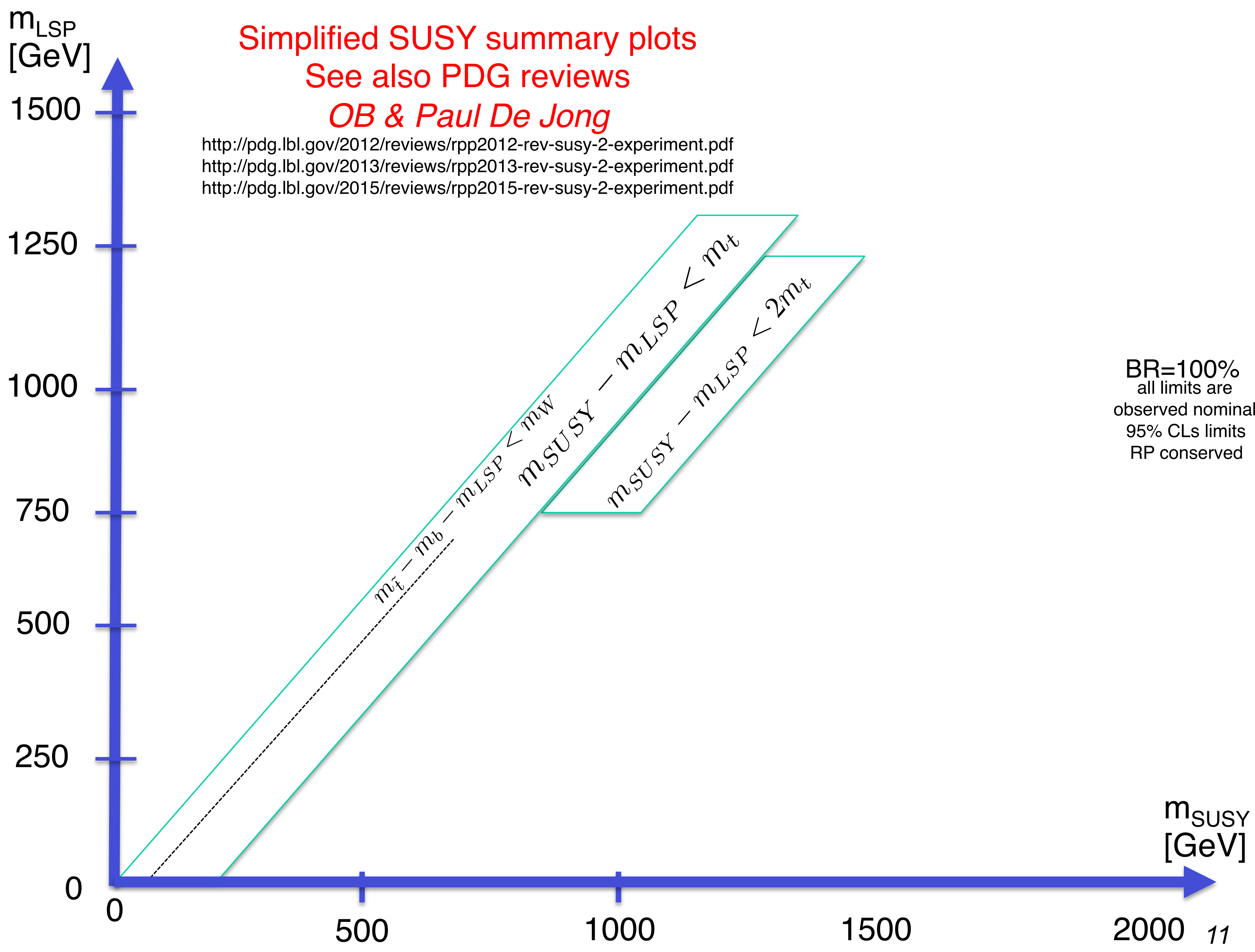
$\left(\frac{M_{\tilde{q}}}{m_{\chi_1^0}} - 1\right) < 0.20$ **Squark Co-annihilation**

$\left|\frac{M_B}{m_{\chi_1^0}} - 2\right| < 0.4$ **B = h, Z or H/A funnel**

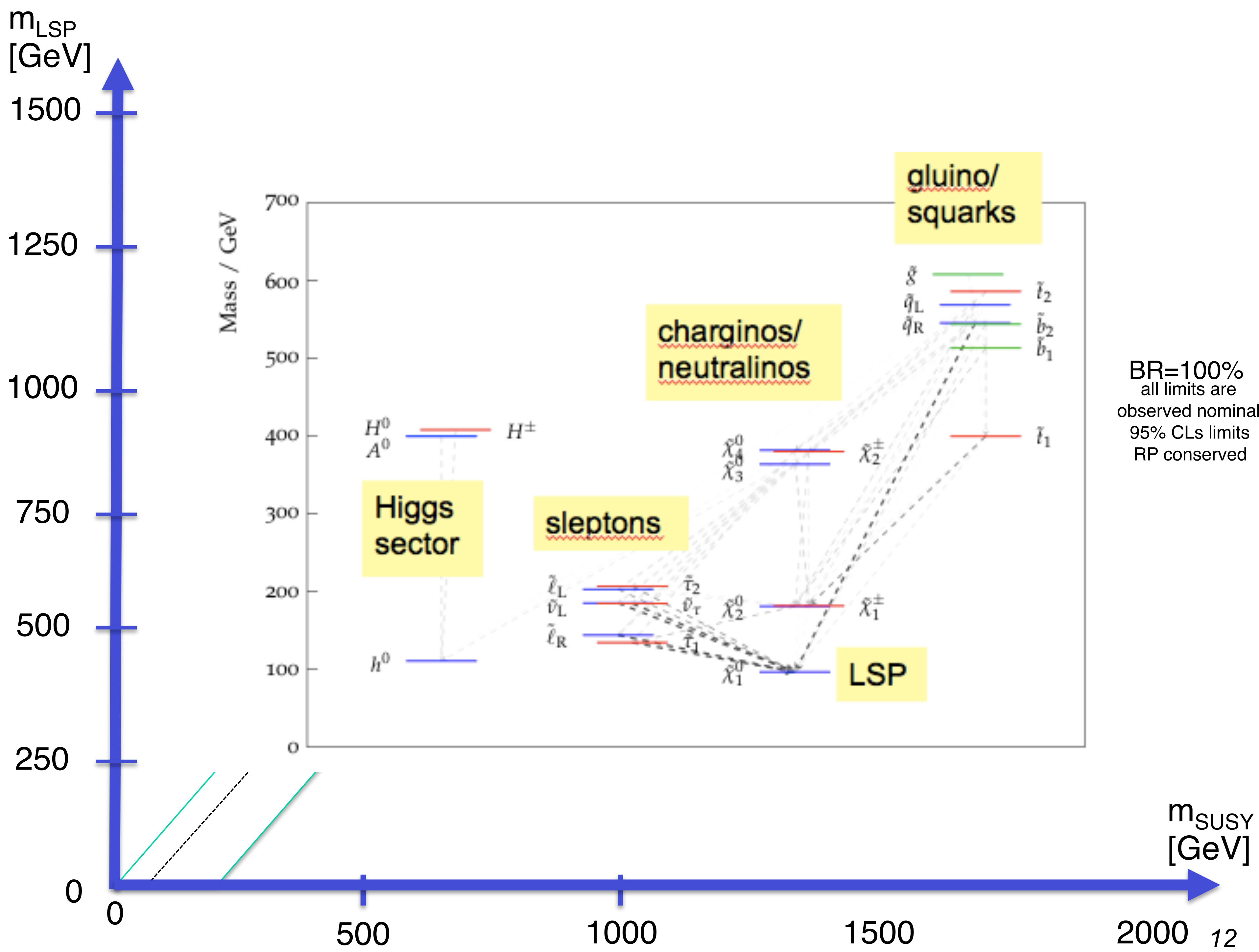
$\left|\frac{\mu}{m_{\chi_1^0}} - 1\right| < 0.30$ **Higgsino enriched "focus-point" like**

Hybrid regions:
In addition to the `primary' regions where only one of the conditions is satisfied, there can also be `hybrid' regions where more than one condition is satisfied. If present, these are indicated using combined colours.

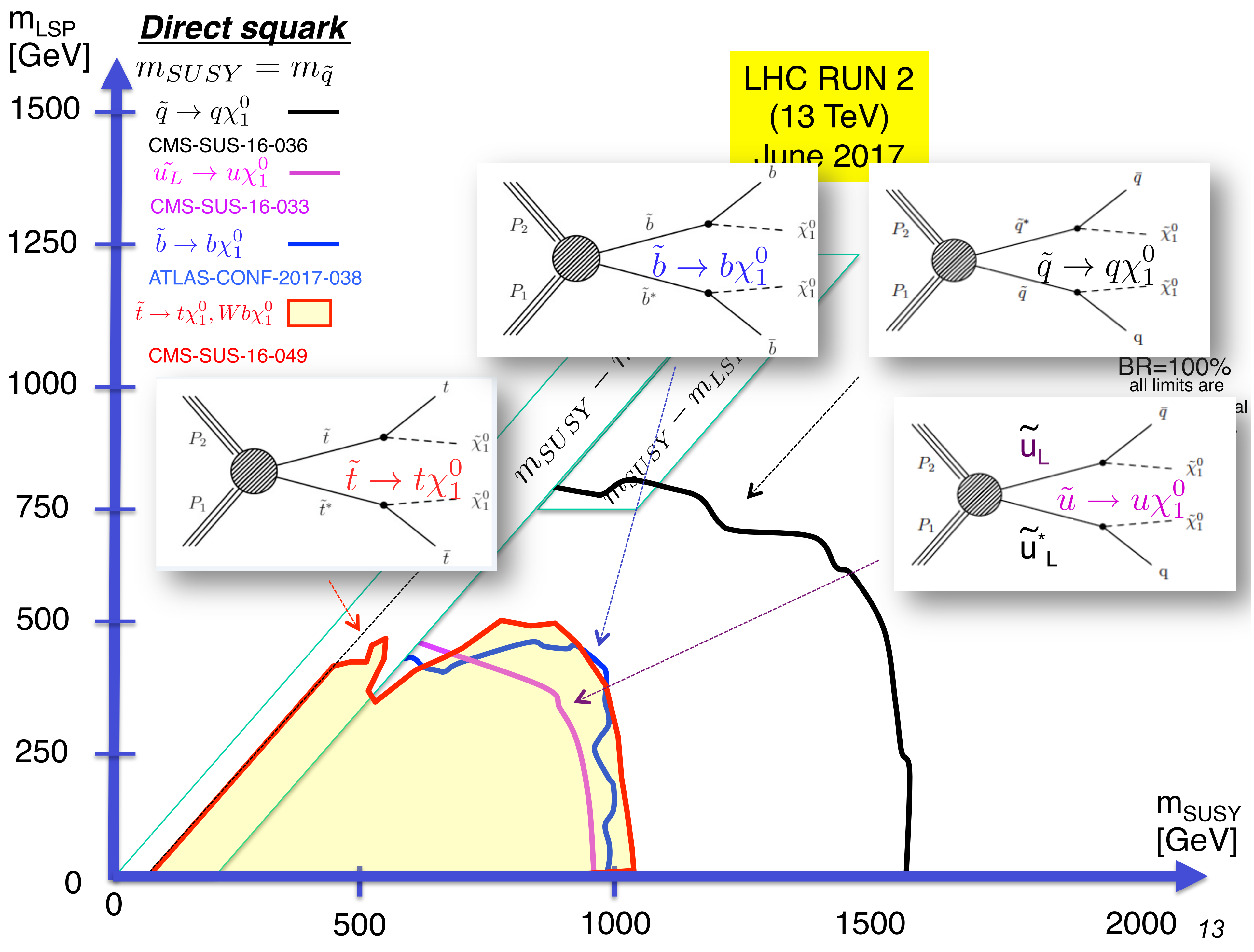
See also arXiv:1508.01173 for further details



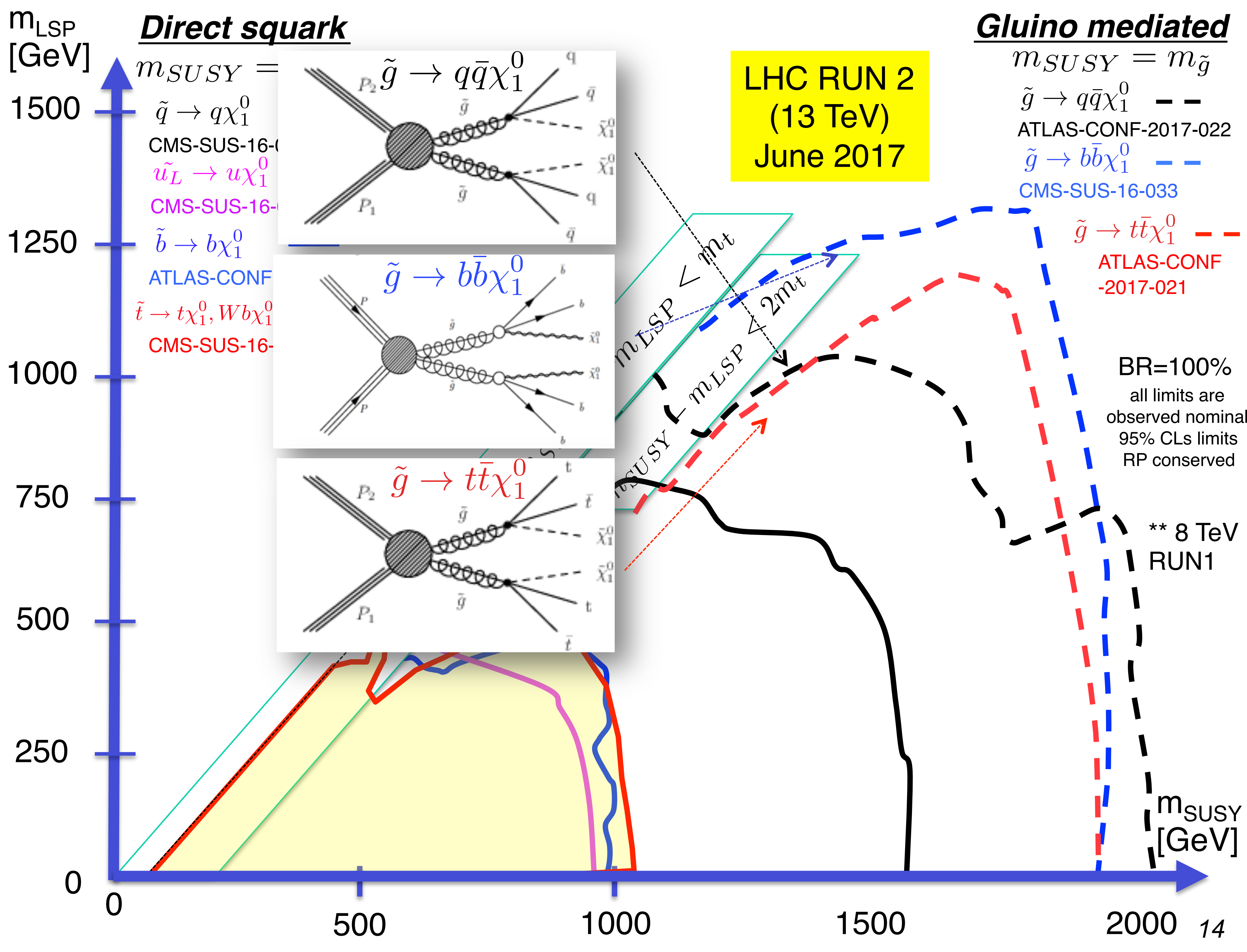
Simplified SUSY summary plots
See also PDG reviews
OB & Paul De Jong
http://pdg.lbl.gov/2012/reviews/rpp2012-rev-susy-2-experiment.pdf
http://pdg.lbl.gov/2013/reviews/rpp2013-rev-susy-2-experiment.pdf
http://pdg.lbl.gov/2015/reviews/rpp2015-rev-susy-2-experiment.pdf
m_LSP [GeV]
1500
1250
1000
750
500
250
0
$m_{\tilde{t}} - m_b - m_{LSP} < m_W$
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved
m_SUSY [GeV]
0
500
1000
1500
2000



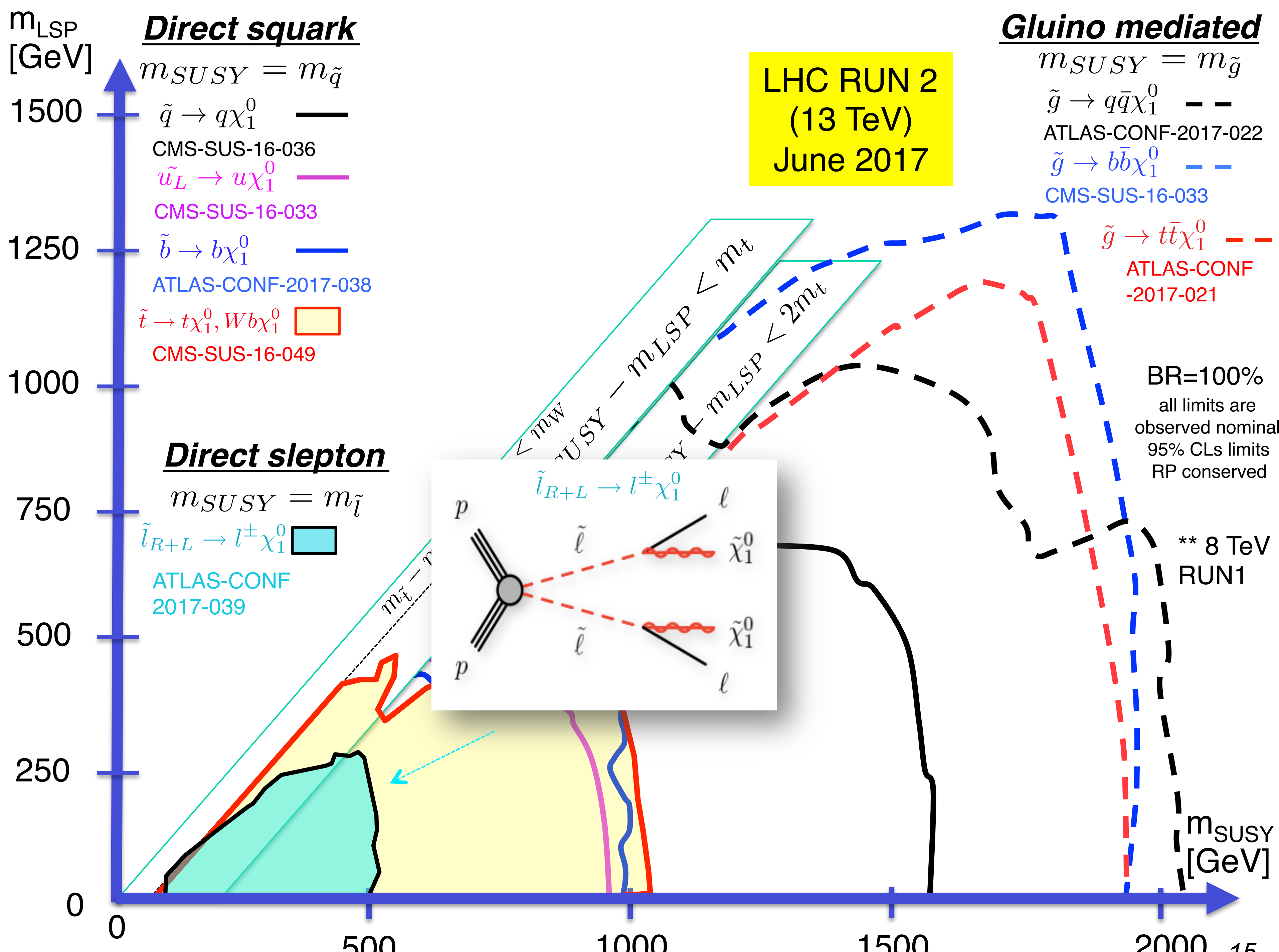
m_LSP [GeV]
1500
1250
1000
750
500
250
0
0
500
1000
1500
2000
m_SUSY [GeV]
Mass / GeV
700
600
500
400
300
200
100
0
gluino/ squarks
charginos/ neutralinos
Higgs sector
sleptons
LSP
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved



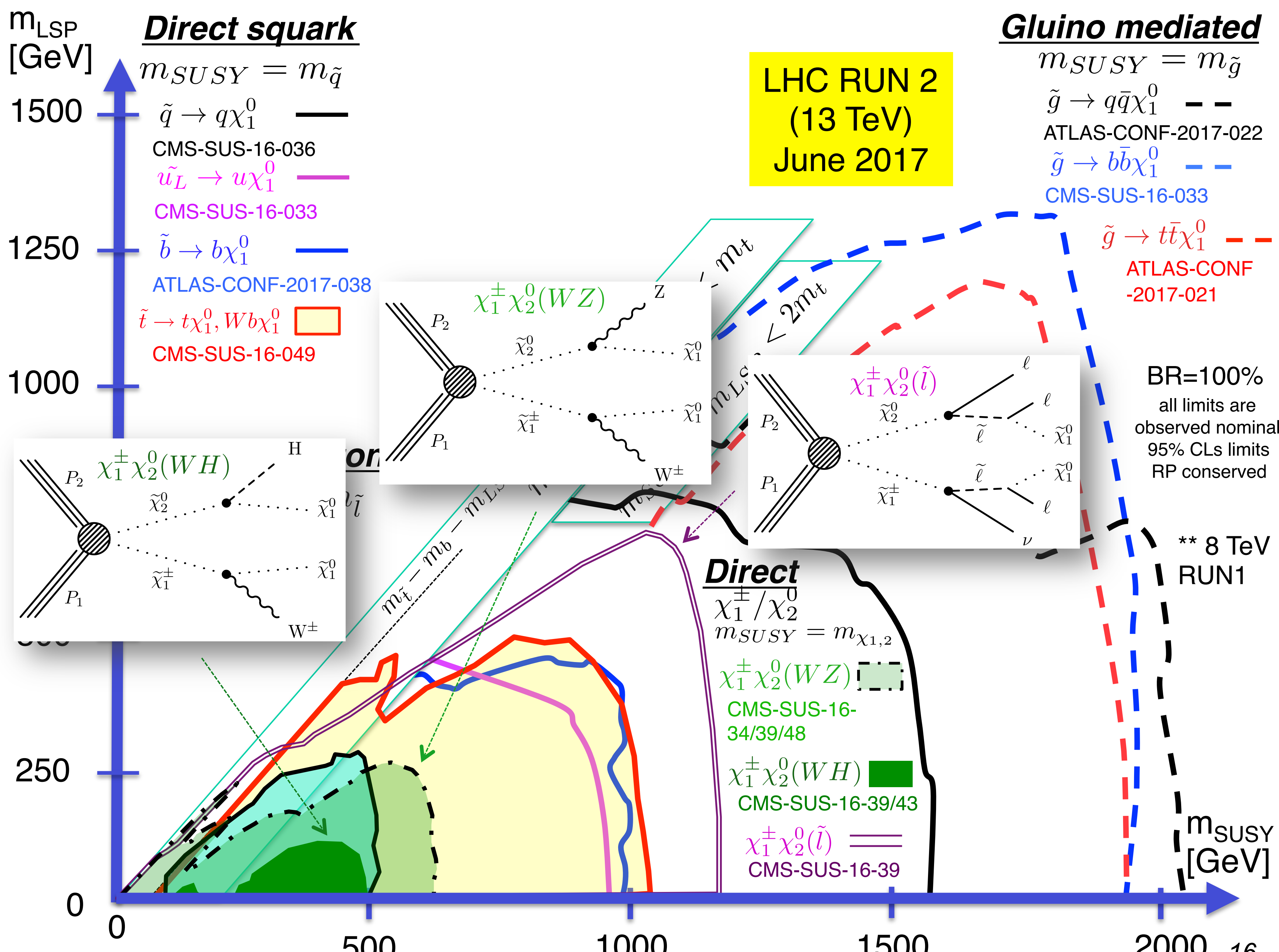
m_{LSP} [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \to q\chi_1^0$
CMS-SUS-16-036
$\tilde{u}_L \to u\chi_1^0$
CMS-SUS-16-033
$\tilde{b} \to b\chi_1^0$
ATLAS-CONF-2017-038
$\tilde{t} \to t\chi_1^0, Wb\chi_1^0$
CMS-SUS-16-049
LHC RUN 2
(13 TeV)
June 2017
BR=100%
all limits are
$\tilde{t} \to t\chi_1^0$
$\tilde{b} \to b\chi_1^0$
$\tilde{q} \to q\chi_1^0$
$\tilde{u} \to u\chi_1^0$
$\tilde{u}_L$
$\tilde{u}^*_L$
$m_{SUSY} [GeV]$
1500
1250
1000
750
500
250
0
0
500
1000
1500
2000



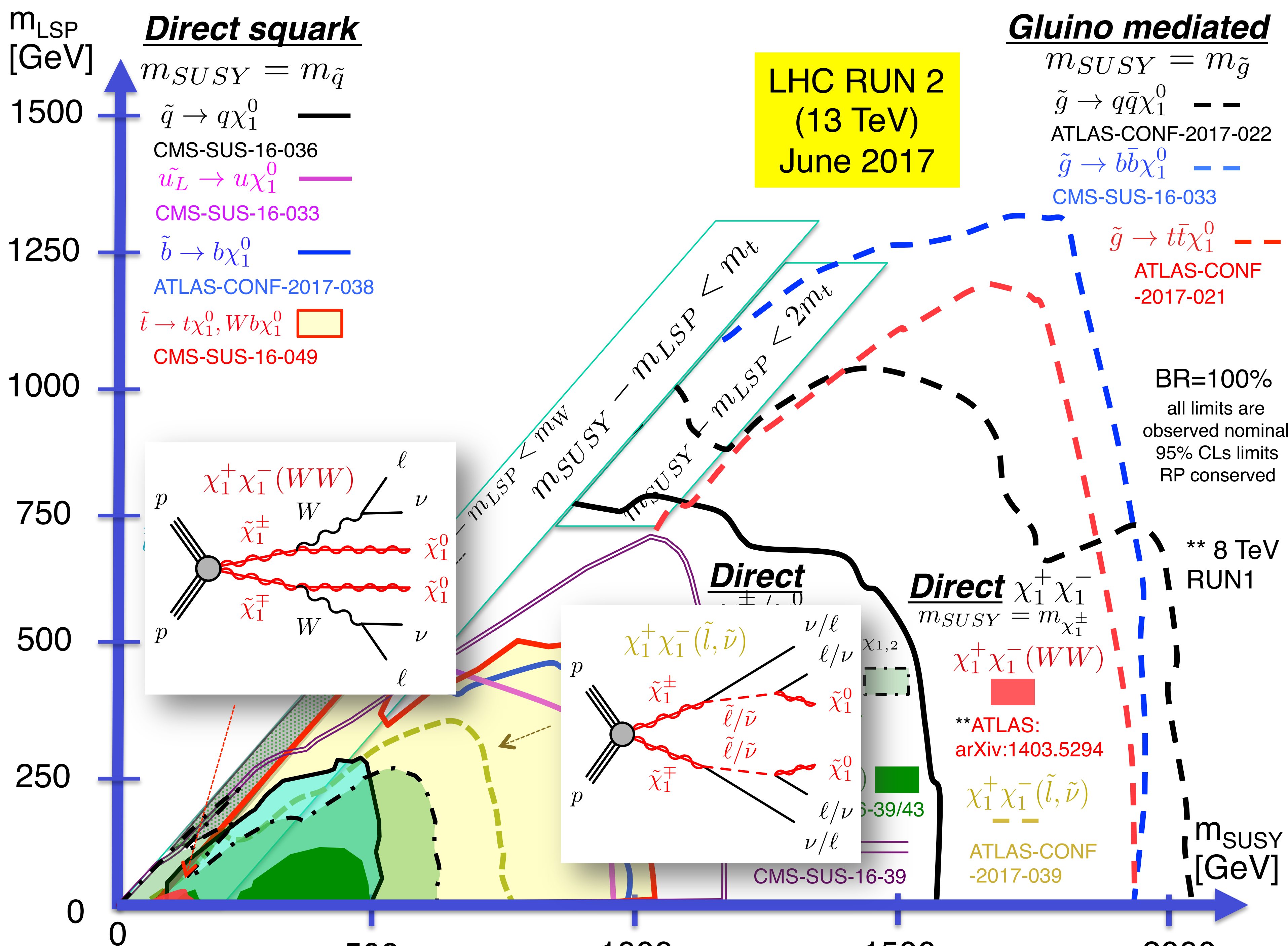
Direct squark
Gluino mediated
m_{LSP} [GeV]
m_{SUSY} [GeV]
$m_{SUSY} =$
$\tilde{q} \to q\chi_1^0$
CMS-SUS-16-
$\tilde{u_L} \to u\chi_1^0$
CMS-SUS-16-
$\tilde{b} \to b\chi_1^0$
ATLAS-CONF
$\tilde{t} \to t\chi_1^0, Wb\chi_1^0$
CMS-SUS-16-
$\tilde{g} \to q\bar{q}\chi_1^0$
$\tilde{g} \to b\bar{b}\chi_1^0$
$\tilde{g} \to t\bar{t}\chi_1^0$
LHC RUN 2
(13 TeV)
June 2017
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \to q\bar{q}\chi_1^0$
ATLAS-CONF-2017-022
$\tilde{g} \to b\bar{b}\chi_1^0$
CMS-SUS-16-033
$\tilde{g} \to t\bar{t}\chi_1^0$
ATLAS-CONF
-2017-021
$m_{LSP} < m_t$
$m_{LSP} < 2m_t$
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved
** 8 TeV
RUN1
1500
1250
1000
750
500
250
0
0
500
1000
1500
2000

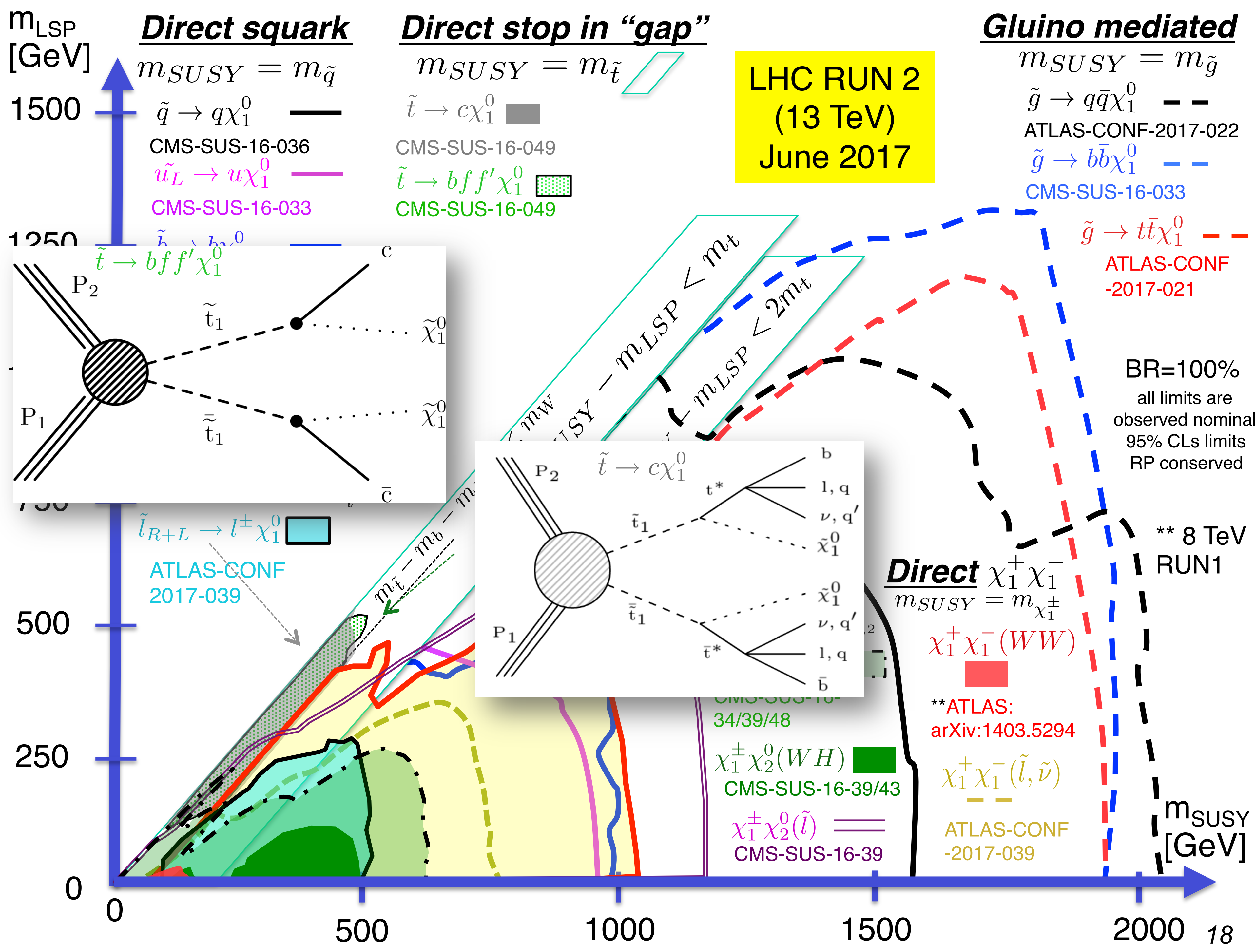


m_{LSP} [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \to q\chi_1^0$
CMS-SUS-16-036
$\tilde{u}_L \to u\chi_1^0$
CMS-SUS-16-033
$\tilde{b} \to b\chi_1^0$
ATLAS-CONF-2017-038
$\tilde{t} \to t\chi_1^0, Wb\chi_1^0$
CMS-SUS-16-049
LHC RUN 2
(13 TeV)
June 2017
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \to q\bar{q}\chi_1^0$
ATLAS-CONF-2017-022
$\tilde{g} \to b\bar{b}\chi_1^0$
CMS-SUS-16-033
$\tilde{g} \to t\bar{t}\chi_1^0$
ATLAS-CONF
-2017-021
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
$< m_W$
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved
Direct slepton
$m_{SUSY} = m_{\tilde{l}}$
$\tilde{l}_{R+L} \to l^\pm\chi_1^0$
ATLAS-CONF
2017-039
$\tilde{l}_{R+L} \to l^\pm\chi_1^0$
** 8 TeV
RUN1
m_{SUSY} [GeV]
1500
1250
1000
750
500
250
0
0
500
1000
1500
2000

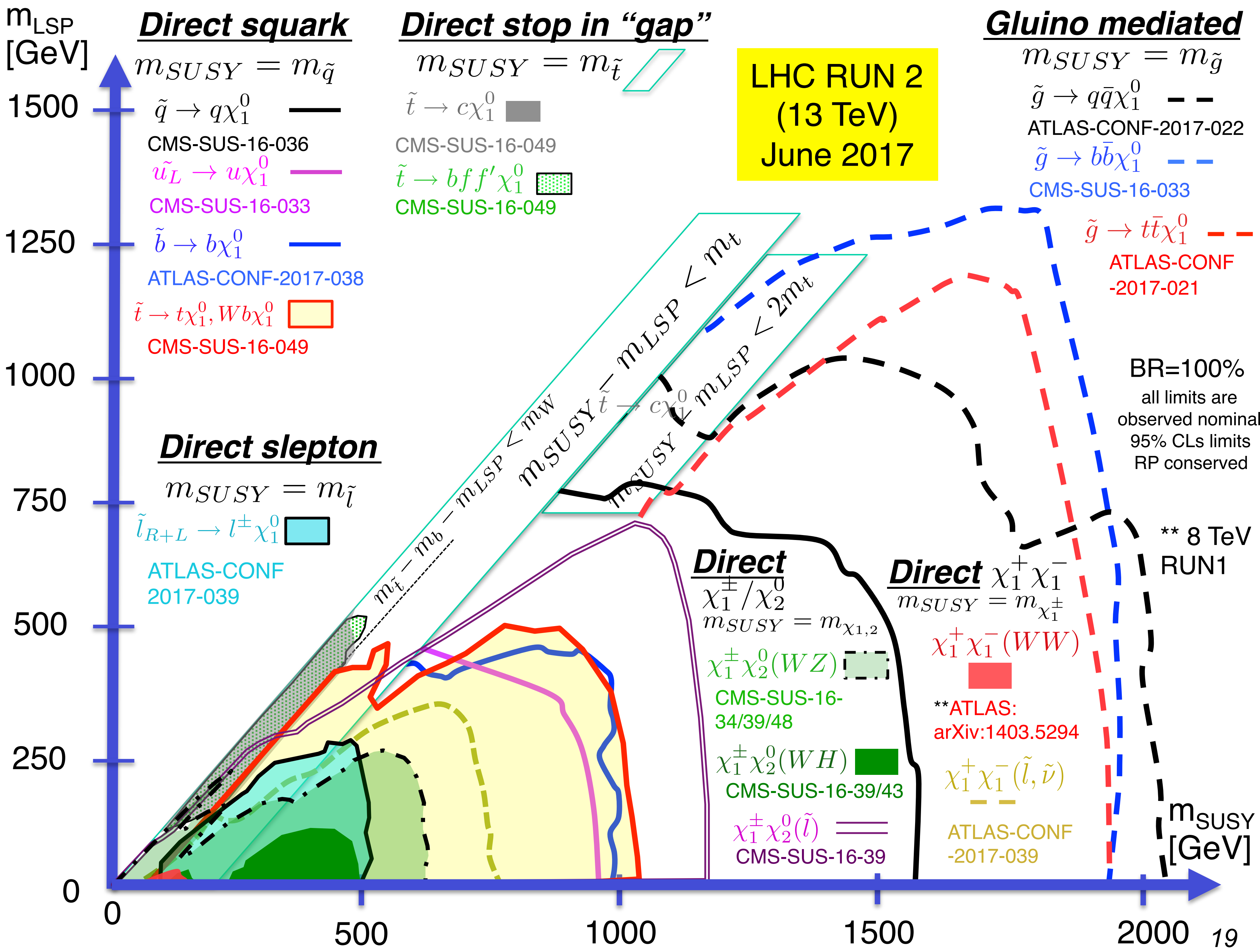


m_LSP [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \to q\chi_1^0$
CMS-SUS-16-036
$\tilde{u_L} \to u\chi_1^0$
CMS-SUS-16-033
$\tilde{b} \to b\chi_1^0$
ATLAS-CONF-2017-038
$\tilde{t} \to t\chi_1^0, Wb\chi_1^0$
CMS-SUS-16-049
LHC RUN 2
(13 TeV)
June 2017
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \to q\bar{q}\chi_1^0$
ATLAS-CONF-2017-022
$\tilde{g} \to b\bar{b}\chi_1^0$
CMS-SUS-16-033
$\tilde{g} \to t\bar{t}\chi_1^0$
ATLAS-CONF
-2017-021
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved
** 8 TeV
RUN1
$\chi_1^\pm\chi_2^0(WZ)$
$\chi_1^\pm\chi_2^0(WH)$
$\chi_1^\pm\chi_2^0(\tilde{l})$
Direct
$\chi_1^\pm/\chi_2^0$
$m_{SUSY} = m_{\chi_{1,2}}$
$\chi_1^\pm\chi_2^0(WZ)$
CMS-SUS-16-
34/39/48
$\chi_1^\pm\chi_2^0(WH)$
CMS-SUS-16-39/43
$\chi_1^\pm\chi_2^0(\tilde{l})$
CMS-SUS-16-39
$m_{\tilde{t}} - m_b - m_{LSP}$
$< 2m_t$
$- m_t$
m_SUSY [GeV]
0
250
1000
1250
1500
500
1000
1500
2000

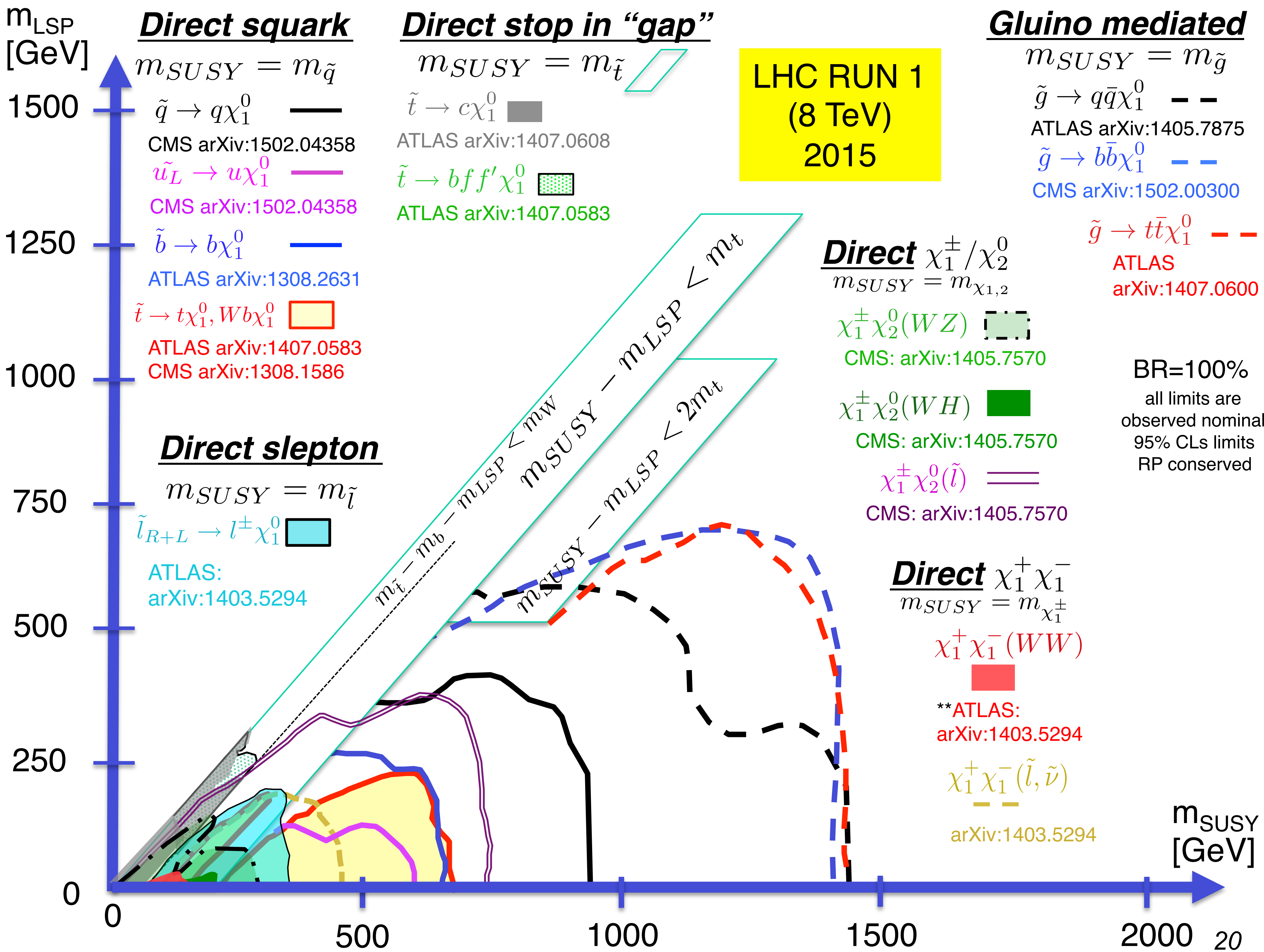

mLSP [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \rightarrow q\chi_1^0$
CMS-SUS-16-036
$\tilde{u_L} \rightarrow u\chi_1^0$
CMS-SUS-16-033
$\tilde{b} \rightarrow b\chi_1^0$
ATLAS-CONF-2017-038
$\tilde{t} \rightarrow t\chi_1^0, Wb\chi_1^0$
CMS-SUS-16-049
LHC RUN 2
(13 TeV)
June 2017
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \rightarrow q\bar{q}\chi_1^0$
ATLAS-CONF-2017-022
$\tilde{g} \rightarrow b\bar{b}\chi_1^0$
CMS-SUS-16-033
$\tilde{g} \rightarrow t\bar{t}\chi_1^0$
ATLAS-CONF
-2017-021
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
$m_{SUSY} - m_{LSP} < m_W$
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved
** 8 TeV
RUN1
Direct
Direct $\chi_1^+\chi_1^-$
$m_{SUSY} = m_{\chi_1^\pm}$
$\chi_1^+\chi_1^-(WW)$
**ATLAS:
arXiv:1403.5294
$\chi_1^+\chi_1^-(\tilde{l},\tilde{\nu})$
ATLAS-CONF
-2017-039
CMS-SUS-16-39
-39/43
$\chi_1^+\chi_1^-(WW)$
$\chi_1^+\chi_1^-(\tilde{l},\tilde{\nu})$
mSUSY [GeV]
1500
1250
1000
750
500
250
0
0
500
1000
1500
2000



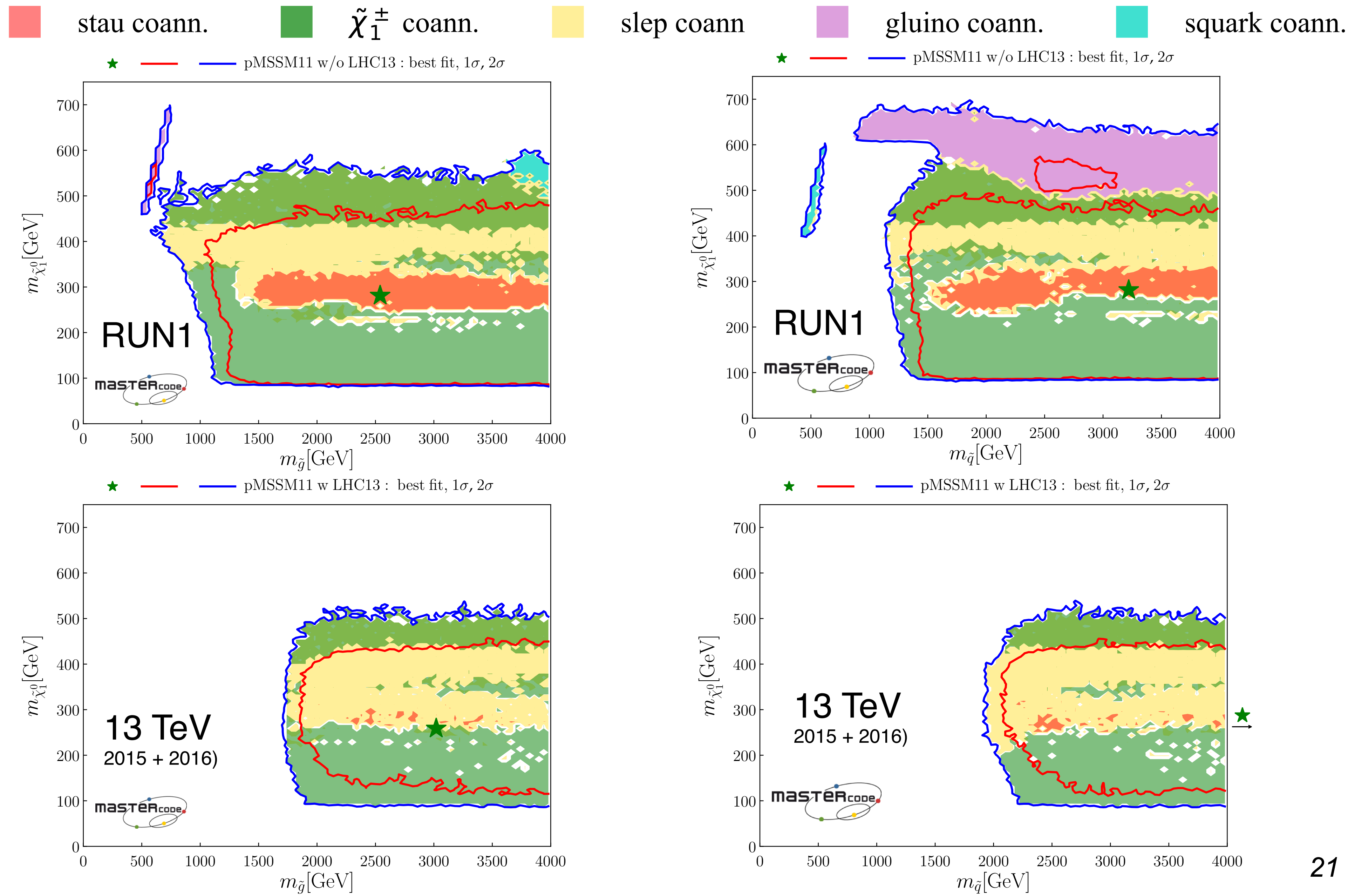
m_LSP [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \rightarrow q\chi_1^0$
CMS-SUS-16-036
$\tilde{u}_L \rightarrow u\chi_1^0$
CMS-SUS-16-033
Direct stop in "gap"
$m_{SUSY} = m_{\tilde{t}}$
$\tilde{t} \rightarrow c\chi_1^0$
CMS-SUS-16-049
$\tilde{t} \rightarrow bff'\chi_1^0$
CMS-SUS-16-049
LHC RUN 2
(13 TeV)
June 2017
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \rightarrow q\bar{q}\chi_1^0$
ATLAS-CONF-2017-022
$\tilde{g} \rightarrow b\bar{b}\chi_1^0$
CMS-SUS-16-033
$\tilde{g} \rightarrow t\bar{t}\chi_1^0$
ATLAS-CONF
-2017-021
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved
** 8 TeV
RUN1
$m_{SUSY} - m_{LSP} < m_t$
$m_{LSP} < 2m_t$
$m_{\tilde{t}} - m_b - m_W$
$\tilde{l}_{R+L} \rightarrow l^{\pm}\chi_1^0$
ATLAS-CONF
2017-039
Direct $\chi_1^+\chi_1^-$
$m_{SUSY} = m_{\chi_1^{\pm}}$
$\chi_1^+\chi_1^-(WW)$
**ATLAS:
arXiv:1403.5294
34/39/48
$\chi_1^{\pm}\chi_2^0(WH)$
CMS-SUS-16-39/43
$\chi_1^{\pm}\chi_2^0(\tilde{l})$
CMS-SUS-16-39
$\chi_1^+\chi_1^-(\tilde{l},\tilde{\nu})$
ATLAS-CONF
-2017-039
m_SUSY [GeV]
0
250
500
1500
0
500
1000
1500
2000



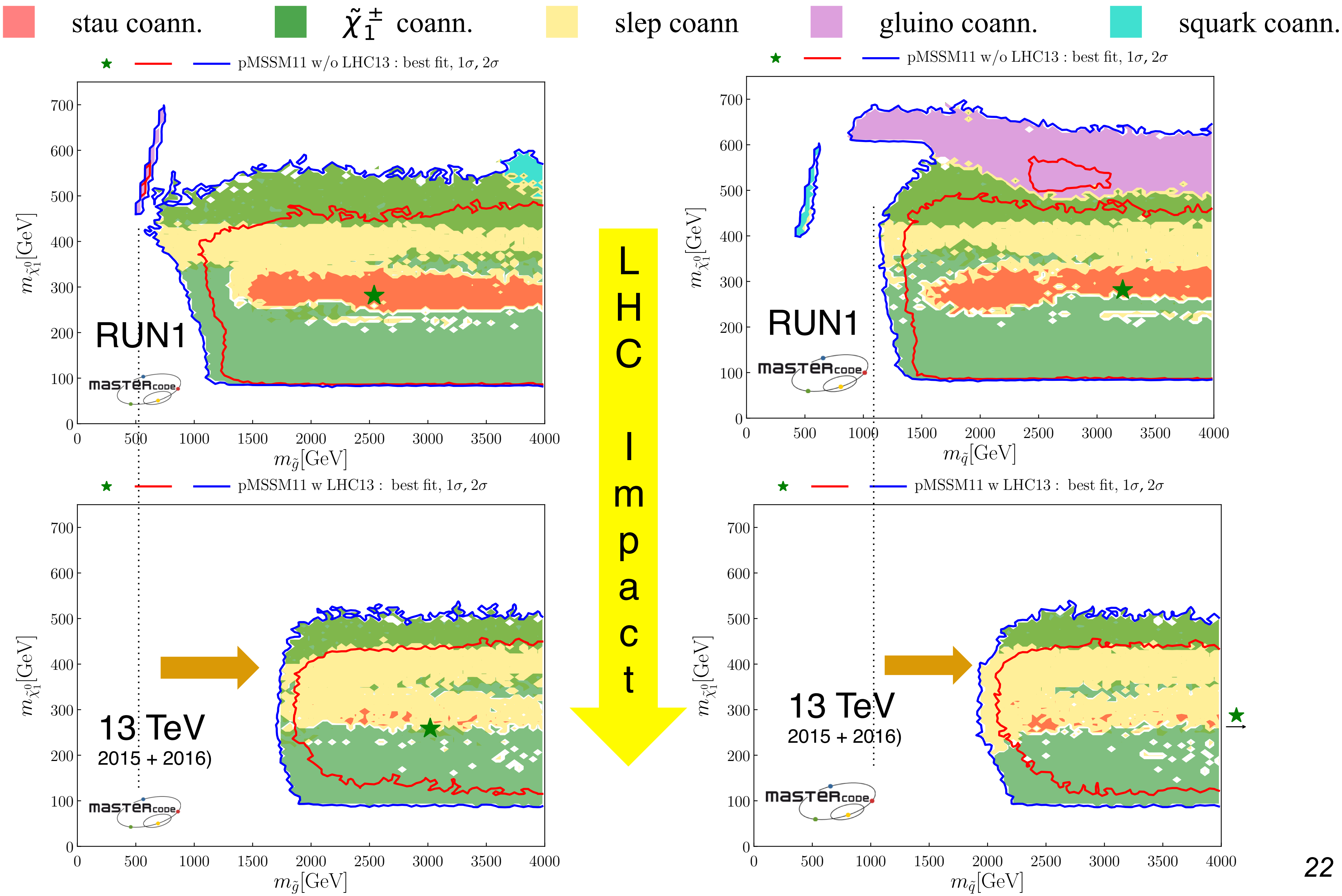
m_{LSP} [GeV]
1500
1250
1000
750
500
250
0
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \to q\chi_1^0$
CMS-SUS-16-036
$\tilde{u}_L \to u\chi_1^0$
CMS-SUS-16-033
$\tilde{b} \to b\chi_1^0$
ATLAS-CONF-2017-038
$\tilde{t} \to t\chi_1^0, Wb\chi_1^0$
CMS-SUS-16-049
Direct stop in "gap"
$m_{SUSY} = m_{\tilde{t}}$
$\tilde{t} \to c\chi_1^0$
CMS-SUS-16-049
$\tilde{t} \to bff'\chi_1^0$
CMS-SUS-16-049
LHC RUN 2
(13 TeV)
June 2017
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \to q\bar{q}\chi_1^0$
ATLAS-CONF-2017-022
$\tilde{g} \to b\bar{b}\chi_1^0$
CMS-SUS-16-033
$\tilde{g} \to t\bar{t}\chi_1^0$
ATLAS-CONF -2017-021
$m_{\tilde{t}} - m_b - m_{LSP} < m_W$
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
$\tilde{t} \to c\chi_1^0$
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved
Direct slepton
$m_{SUSY} = m_{\tilde{l}}$
$\tilde{l}_{R+L} \to l^{\pm}\chi_1^0$
ATLAS-CONF 2017-039
Direct $\chi_1^{\pm}/\chi_2^0$
$m_{SUSY} = m_{\chi_{1,2}}$
$\chi_1^{\pm}\chi_2^0(WZ)$
CMS-SUS-16-34/39/48
$\chi_1^{\pm}\chi_2^0(WH)$
CMS-SUS-16-39/43
$\chi_1^{\pm}\chi_2^0(\tilde{l})$
CMS-SUS-16-39
Direct $\chi_1^+\chi_1^-$
$m_{SUSY} = m_{\chi_1^{\pm}}$
$\chi_1^+\chi_1^-(WW)$
**ATLAS: arXiv:1403.5294
$\chi_1^+\chi_1^-(\tilde{l},\tilde{\nu})$
ATLAS-CONF -2017-039
** 8 TeV RUN1
m_{SUSY} [GeV]
0
500
1000
1500
2000


m_{LSP} [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \to q\chi_1^0$
CMS arXiv:1502.04358
$\tilde{u_L} \to u\chi_1^0$
CMS arXiv:1502.04358
$\tilde{b} \to b\chi_1^0$
ATLAS arXiv:1308.2631
$\tilde{t} \to t\chi_1^0, Wb\chi_1^0$
ATLAS arXiv:1407.0583
CMS arXiv:1308.1586
Direct stop in "gap"
$m_{SUSY} = m_{\tilde{t}}$
$\tilde{t} \to c\chi_1^0$
ATLAS arXiv:1407.0608
$\tilde{t} \to bff'\chi_1^0$
ATLAS arXiv:1407.0583
LHC RUN 1
(8 TeV)
2015
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \to q\bar{q}\chi_1^0$
ATLAS arXiv:1405.7875
$\tilde{g} \to b\bar{b}\chi_1^0$
CMS arXiv:1502.00300
$\tilde{g} \to t\bar{t}\chi_1^0$
ATLAS
arXiv:1407.0600
Direct $\chi_1^{\pm}/\chi_2^0$
$m_{SUSY} = m_{\chi_{1,2}}$
$\chi_1^{\pm}\chi_2^0(WZ)$
CMS: arXiv:1405.7570
$\chi_1^{\pm}\chi_2^0(WH)$
CMS: arXiv:1405.7570
$\chi_1^{\pm}\chi_2^0(\tilde{l})$
CMS: arXiv:1405.7570
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved
Direct slepton
$m_{SUSY} = m_{\tilde{l}}$
$\tilde{l}_{R+L} \to l^{\pm}\chi_1^0$
ATLAS:
arXiv:1403.5294
$m_{SUSY} - m_{LSP} < m_t$
$m_{\tilde{t}} - m_b - m_{LSP} < m_W$
$m_{SUSY} - m_{LSP} < 2m_t$
Direct $\chi_1^+\chi_1^-$
$m_{SUSY} = m_{\chi_1^{\pm}}$
$\chi_1^+\chi_1^-(WW)$
**ATLAS:
arXiv:1403.5294
$\chi_1^+\chi_1^-(\tilde{l},\tilde{\nu})$
arXiv:1403.5294
1500
1250
1000
750
500
250
0
0
500
1000
1500
2000
m_{SUSY} [GeV]

pMSSM11: RUN1 vs 13 TeV (2015 + 2016)



pMSSM11: RUN1 vs 13 TeV (2015 + 2016)



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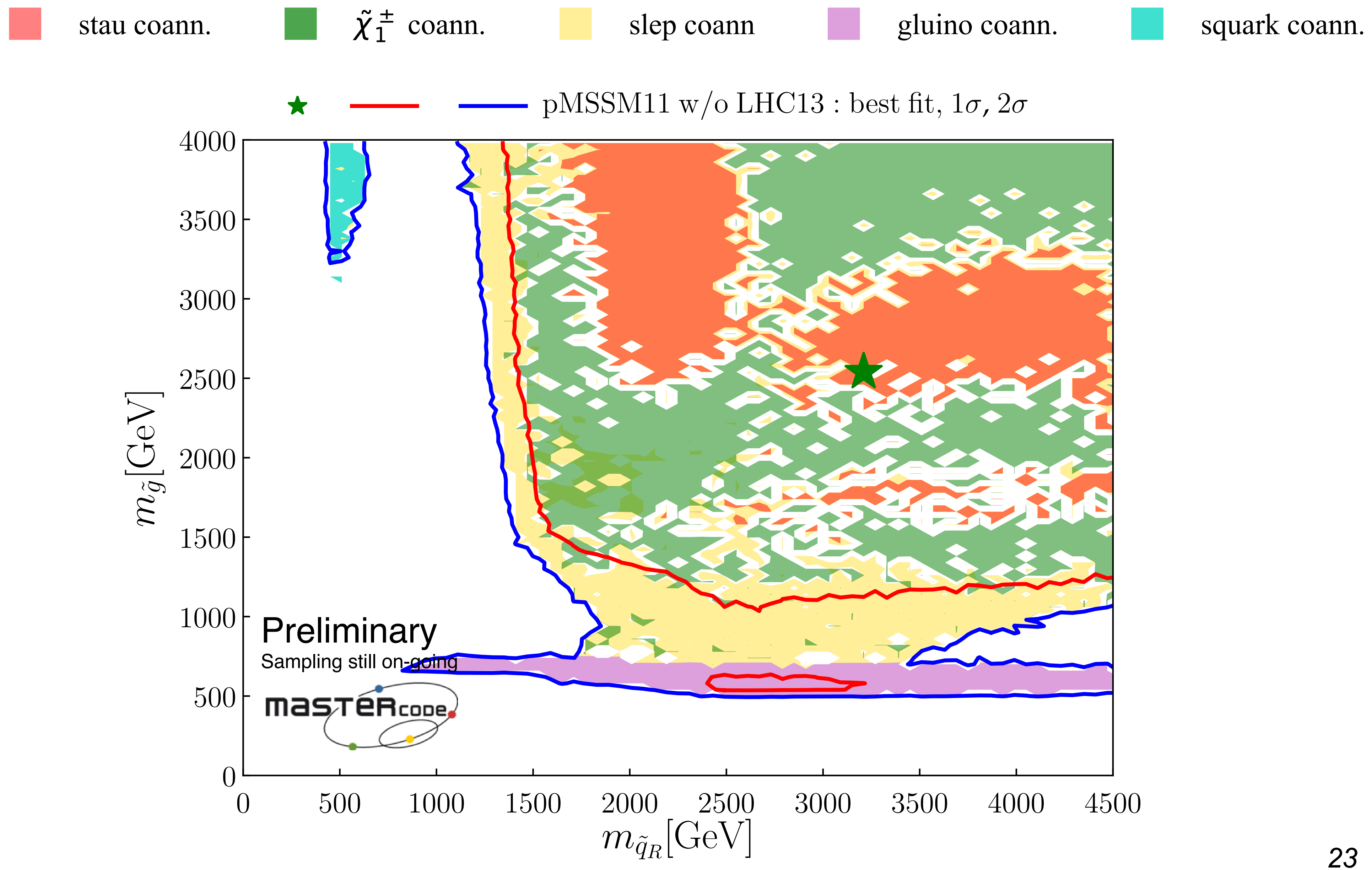
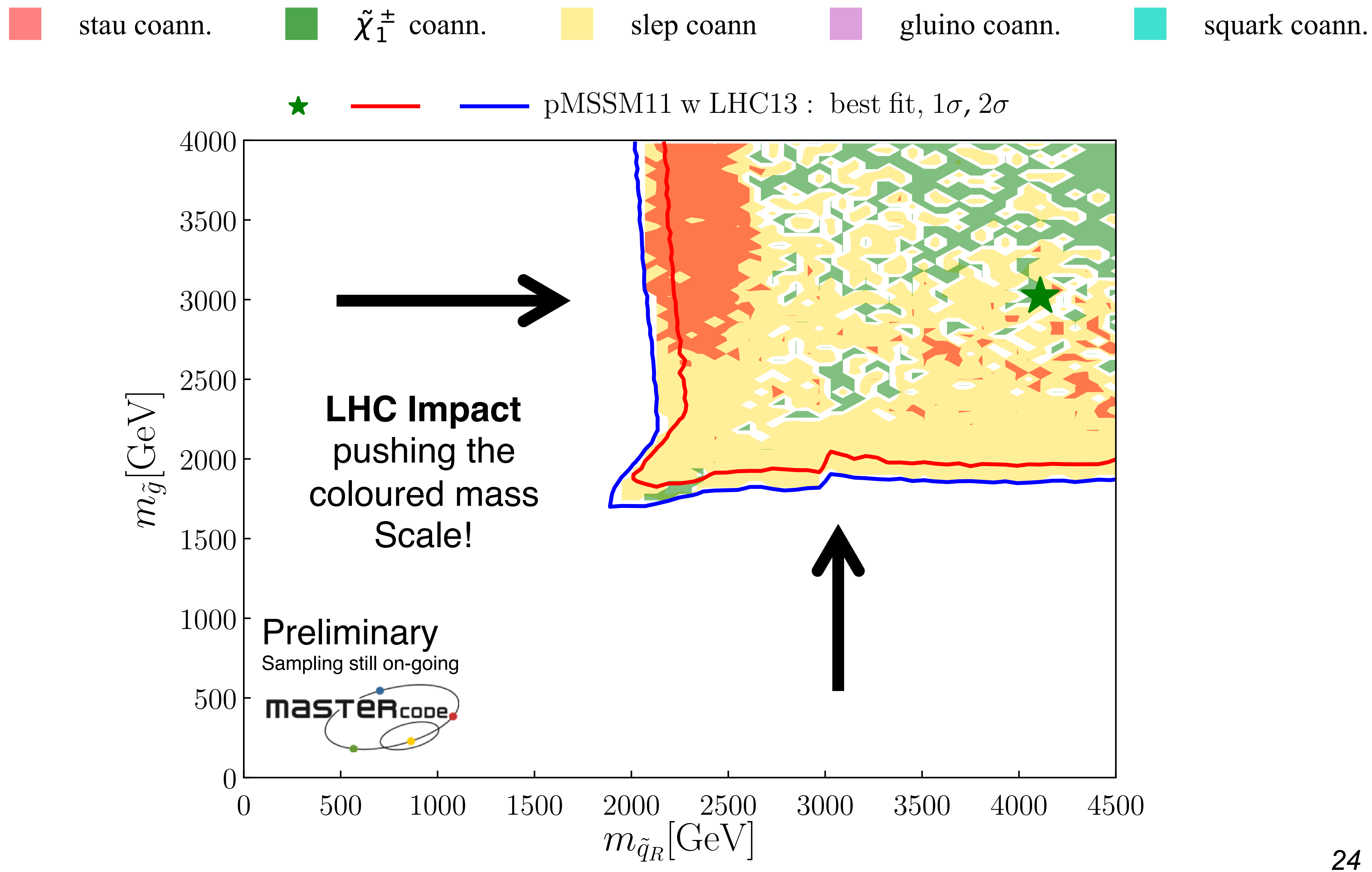
Gluino vs Squark: LHC RUN 1

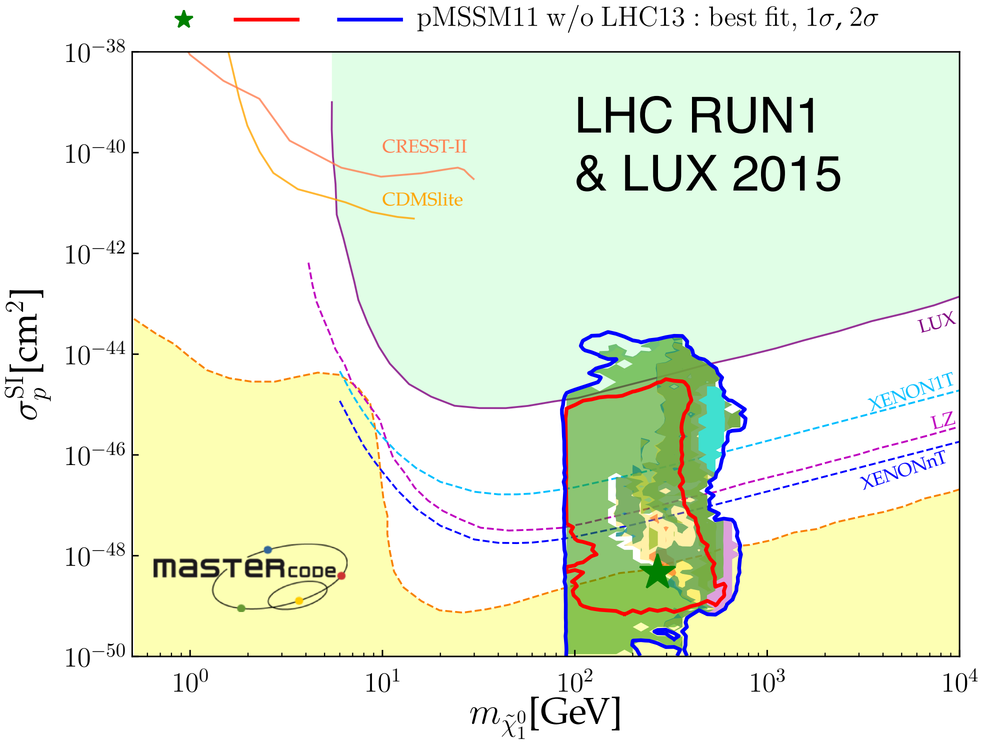


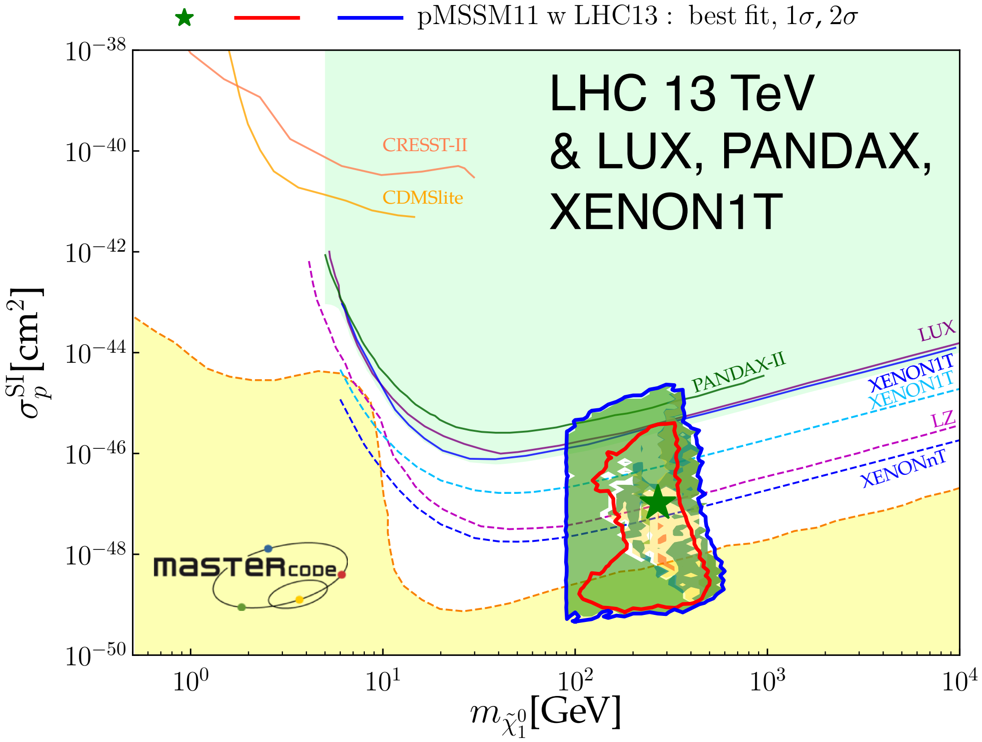
Gluino vs Squark: LHC RUN 2 (2015 + 2016 data)



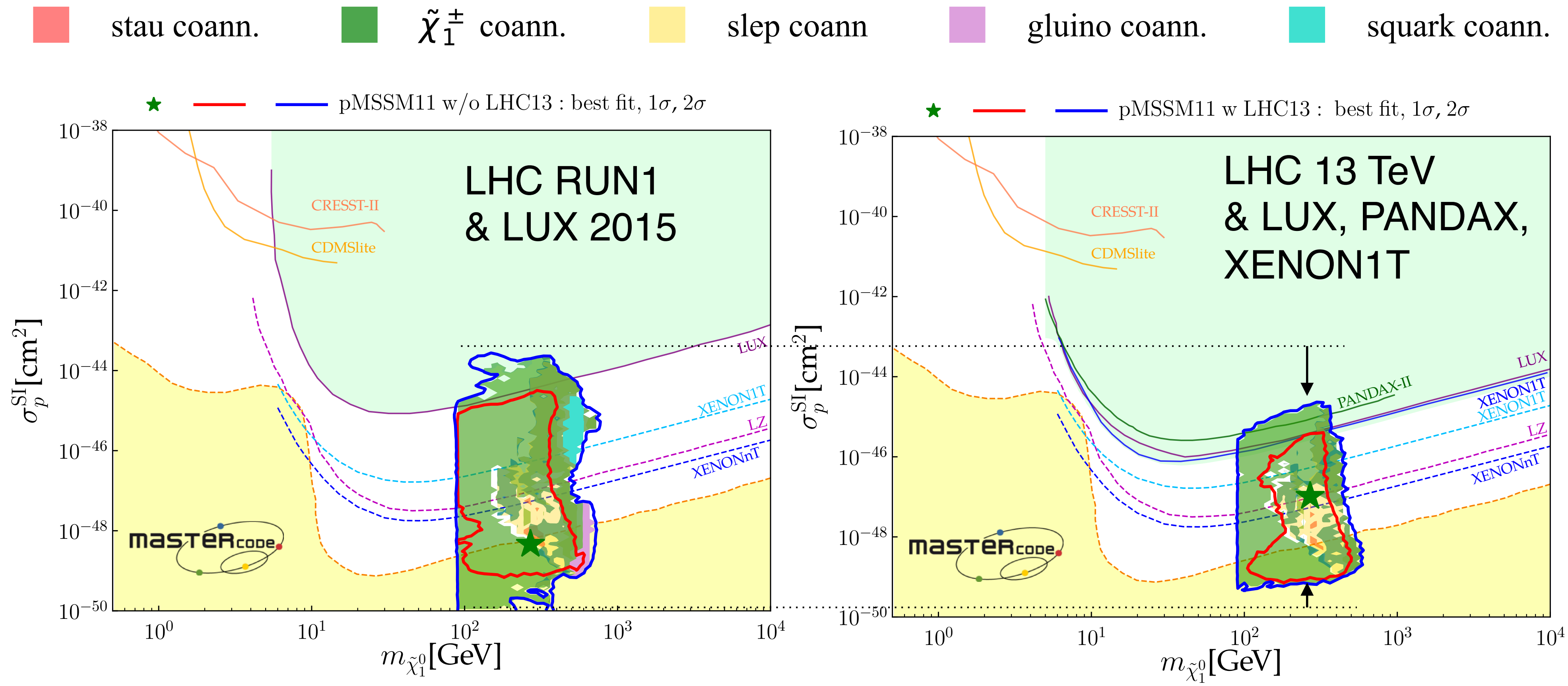
pMSSM11: σ_{SI} vs m_{DM}

stau coann. | $\tilde{\chi}_1^\pm$ coann. | slep coann | gluino coann. | squark coann.





pMSSM11: σ_{SI} vs m_{DM}



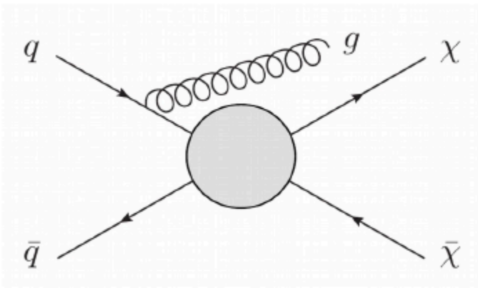
Clear complementarity of collider and DD constraints:

- Collider covers regions not easily or not at all accessible to DD experiments (i.e. low m_{DM} and also very small σ_{SI})
- On the other hand, DD experiments push strongly the preferred region to lower σ_{SI} (and will continue to do so in the future)

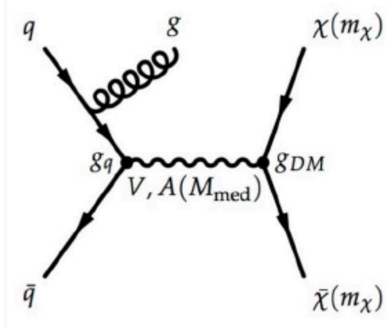
Characterisation of Dark Matter searches at colliders

Simplicity vs. Complexity

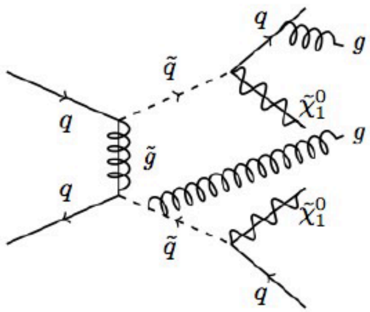
Finding the right balance is a challenge!



EFTs



Simplified Models



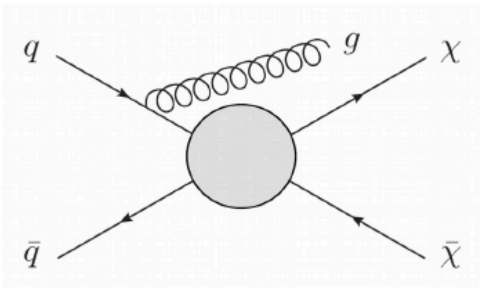
UV-complete Models

Characterisation of Dark Matter searches at colliders

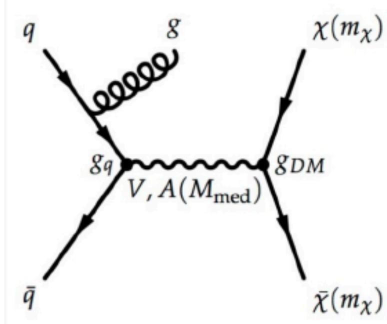
Simplicity vs. Complexity

Finding the right balance is a challenge!

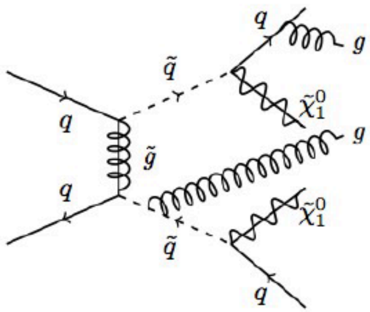
Main part of of this is covered in Caterina's talk



EFTs



Simplified Models



UV-complete Models

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SIMPLIFIED MODELS AND LONG-LIVED PARTICLE SIGNATURES AT THE LHC

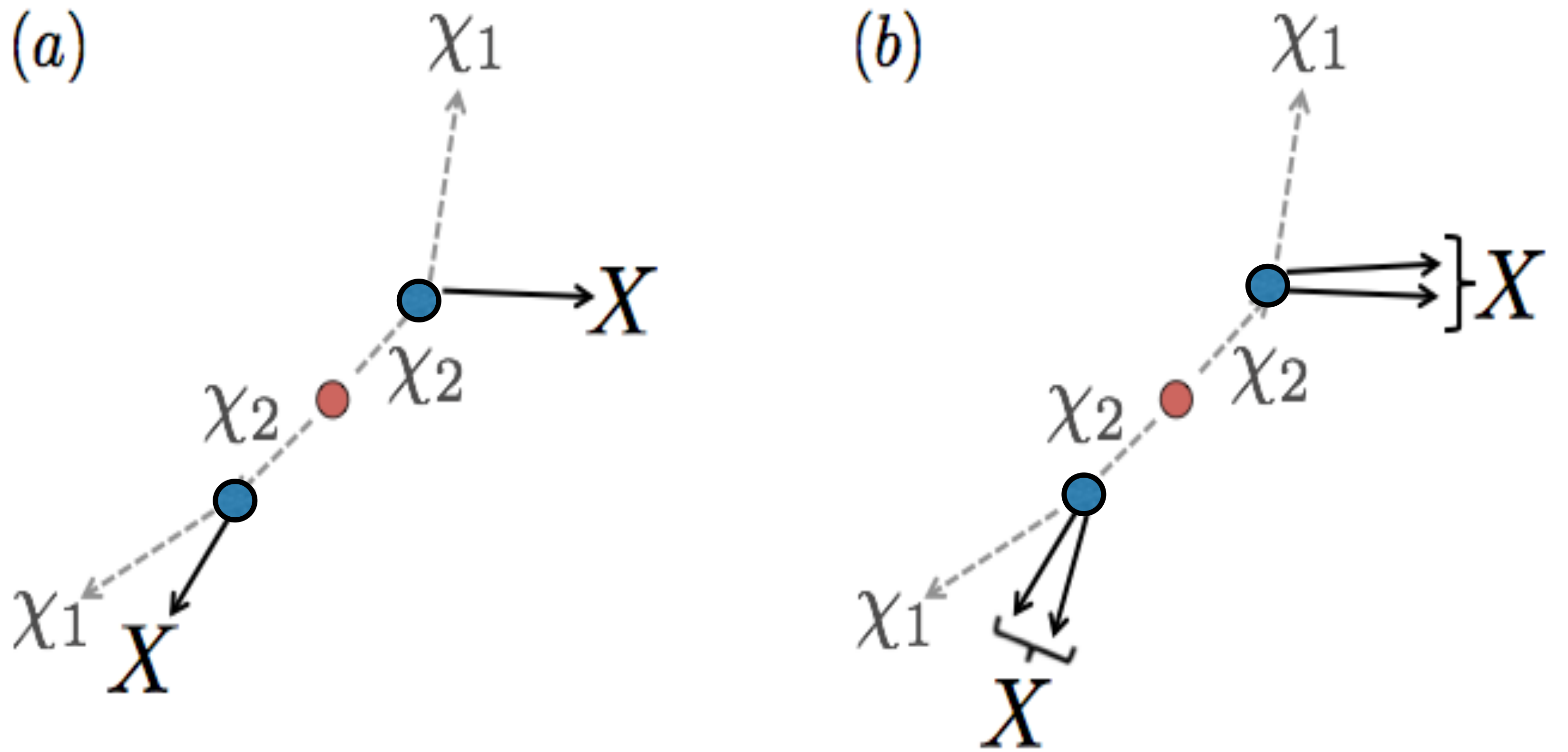
Based on:

Simplified Models for Displaced Dark Matter Signatures

Oliver Buchmueller, Albert De Roeck, Matthew McCullough, Kristian Hahn, Kevin Sung, Pedro Schwaller, Tien-Tien Yu

arXiv:170406515

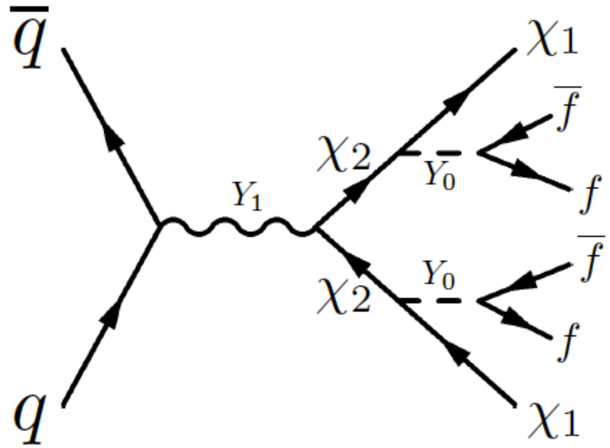
WANTED:
Systematic programme for displaced vertex searches



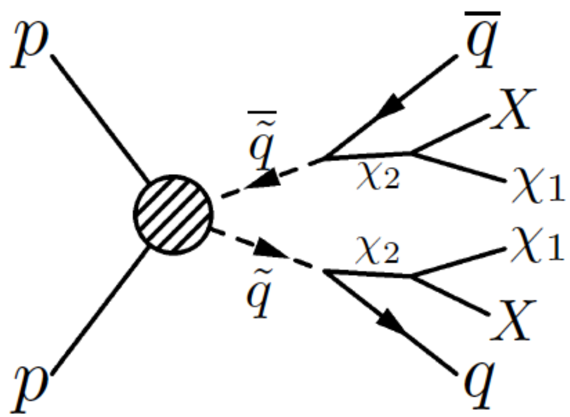
WANTED:
Systematic programme for displaced vertex searches

Production through simplified models: DM or SUSY

Example: simplified DM



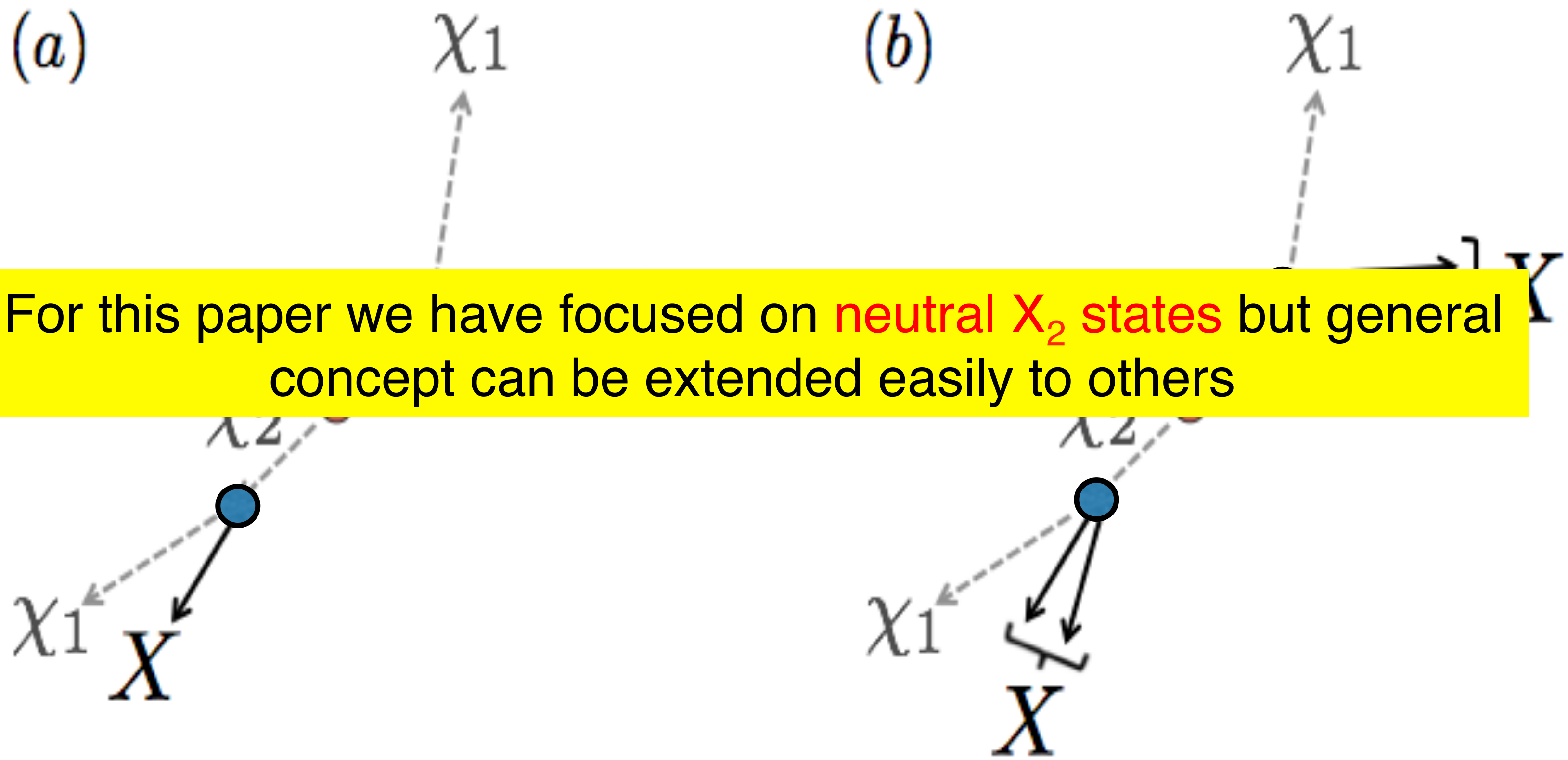
Example: simplified SUSY



Advantage:
Can revert to a large and well understood portfolio of simplified models that are already in use by the experiments!

http://feynrules.irmp.ucl.ac.be/wiki/DMsimp
https://github.com/ksung25/DisplacedDM

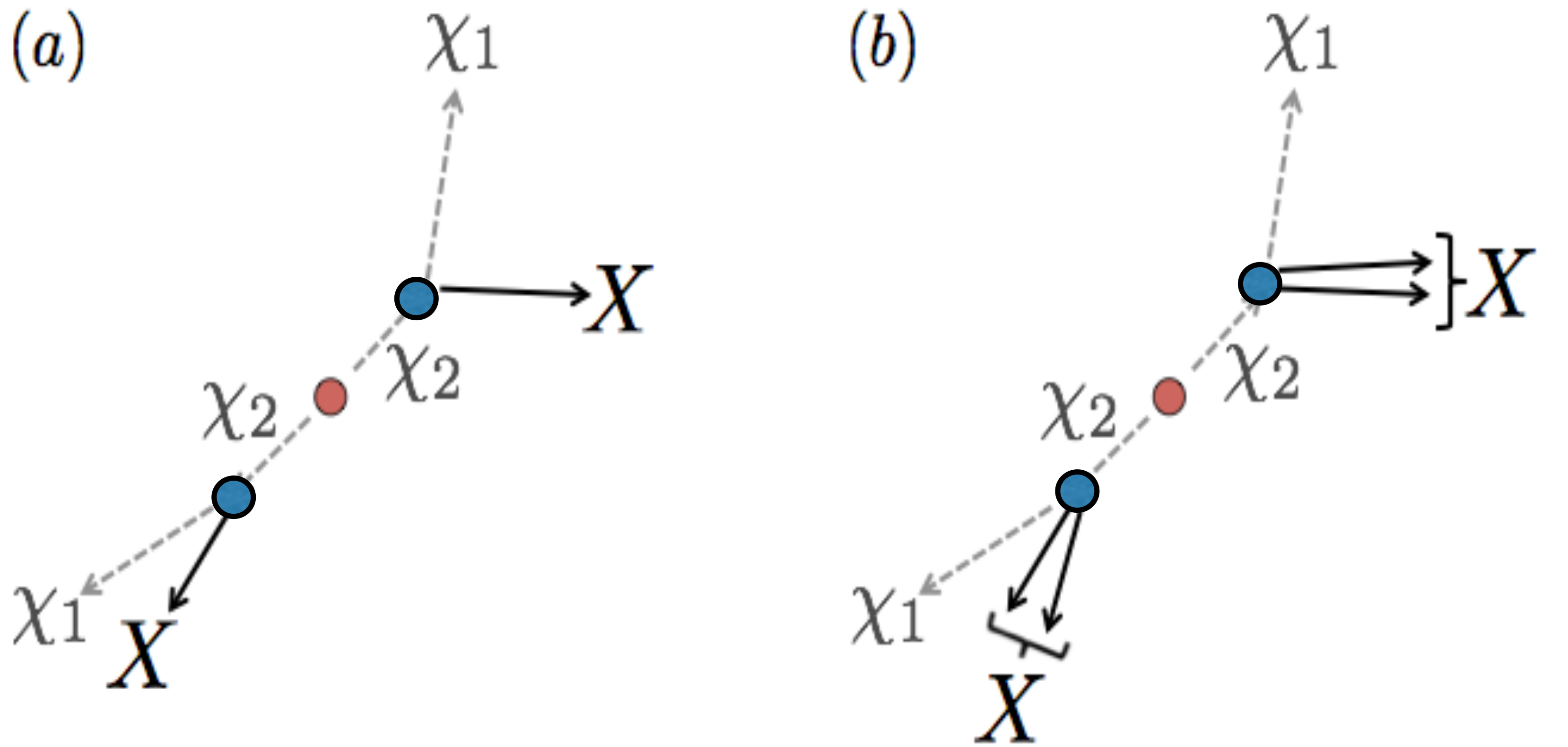
WANTED: Systematic programme for displaced vertex searches



For this paper we have focused on neutral X_2 states but general concept can be extended easily to others

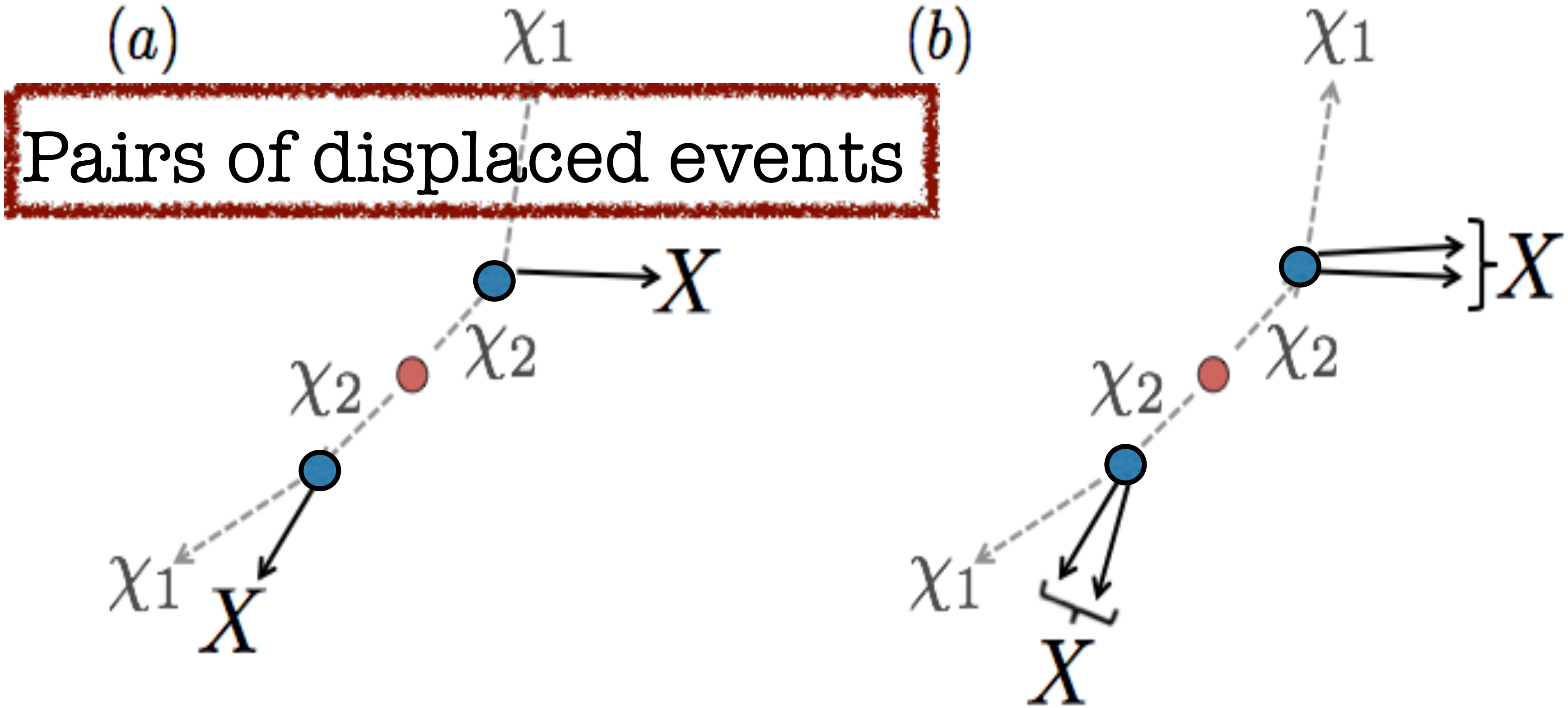
Production through simplified models: DM or SUSY

Experimental Signature

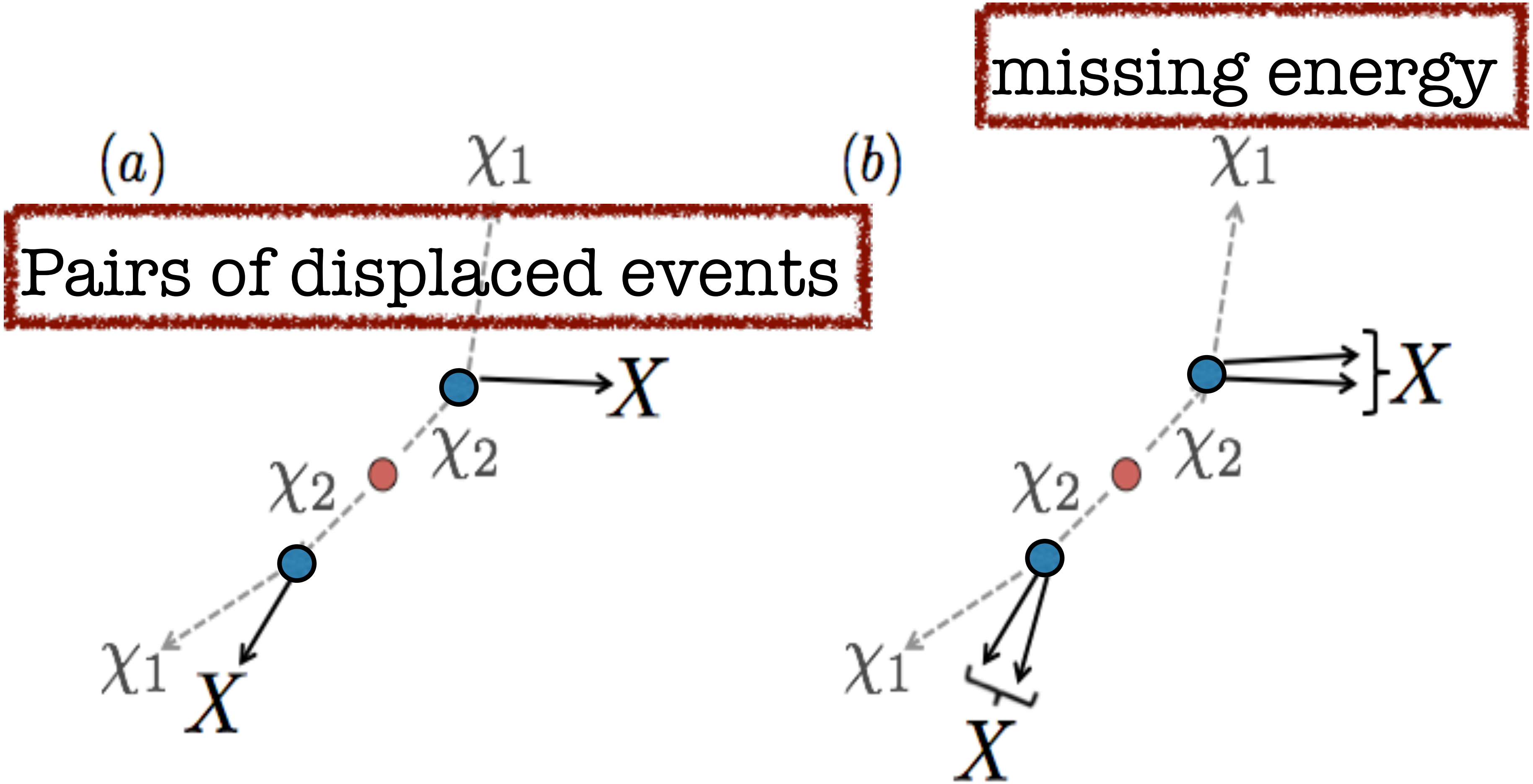


Experimental Signature

Pairs of displaced events



Experimental Signature



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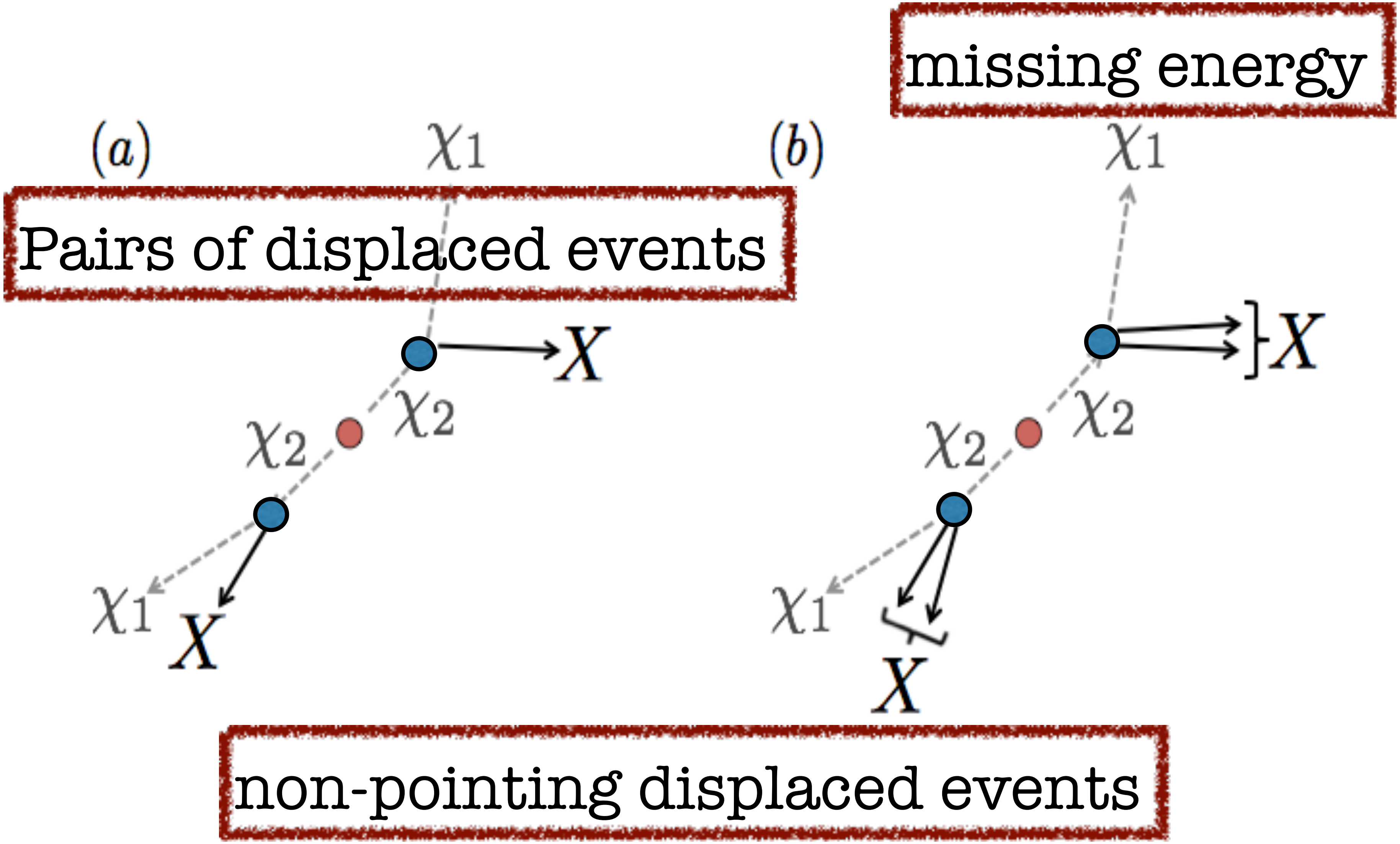

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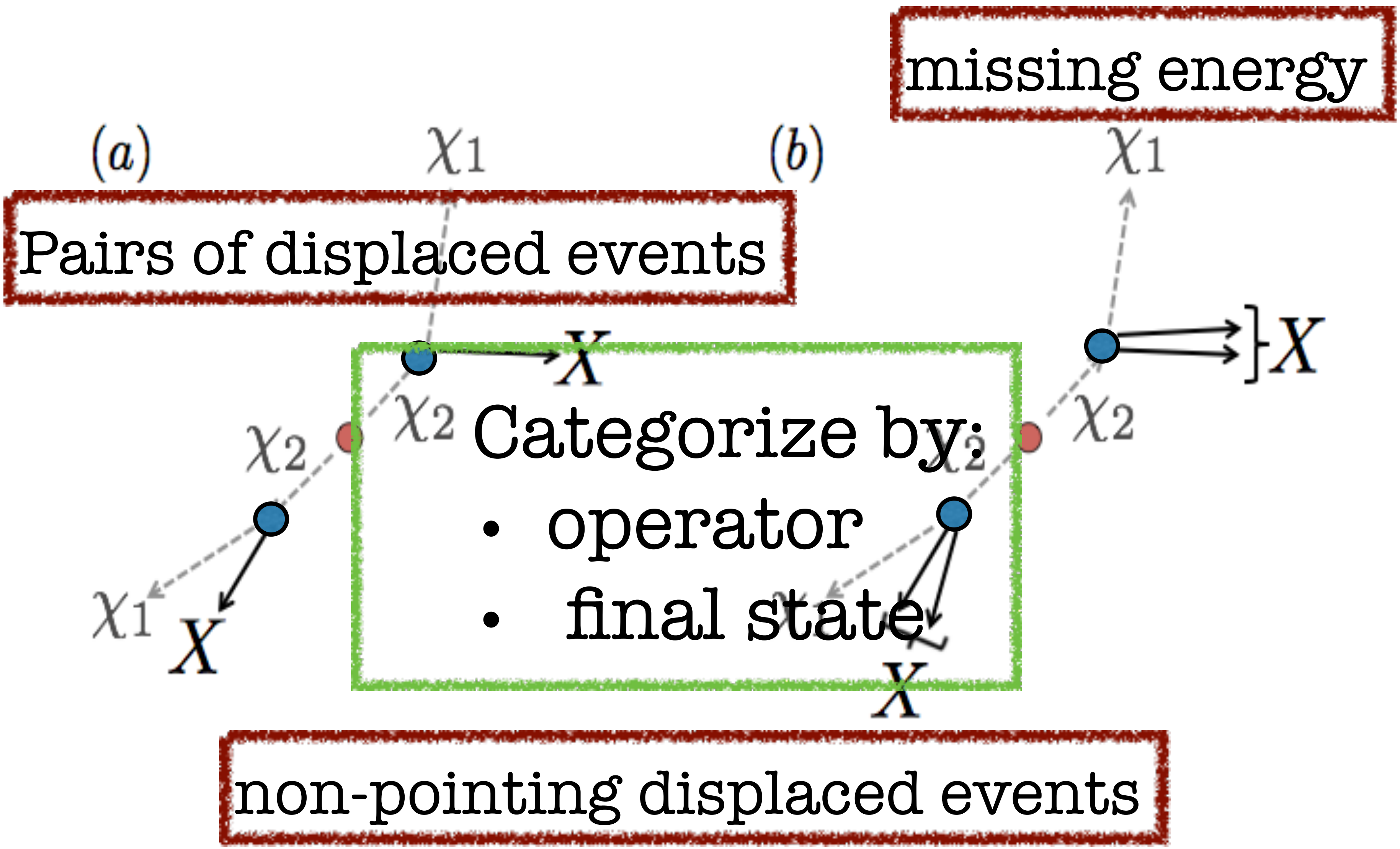


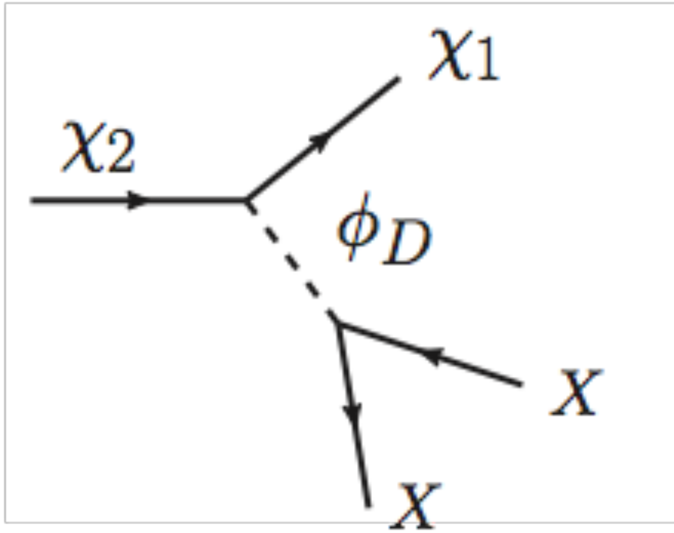
Example Operators

$$\chi_2 \to \chi_1 + X$$

final state X	$\mathcal{O}_F$	$\mathcal{O}_S$
γ/γ^*	$\frac{1}{\Lambda}\overline{\chi}_2\sigma_{\mu\nu}\chi_1 F^{\mu\nu}$	$\frac{1}{\Lambda^2}(\partial_\mu\phi_2\partial_\nu\phi_1)F^{\mu\nu}$
Z	$\frac{1}{\Lambda}\overline{\chi}_2\sigma_{\mu\nu}\chi_1 Z^{\mu\nu}$	$\frac{1}{\Lambda^2}(\partial_\mu\phi_2\partial_\nu\phi_1)Z^{\mu\nu}$
h	$\overline{\chi}_2\chi_1 h$	$\Lambda\phi_2\phi_1 h$
jj	$\frac{1}{\Lambda^3}\overline{\chi}_2\chi_1 \mathrm{Tr}[G^{\mu\nu}G_{\mu\nu}]$	$\frac{1}{\Lambda^2}\phi_2\phi_1 \mathrm{Tr}[G^{\mu\nu}G_{\mu\nu}]$
$\bar{l}l$	$\frac{1}{\Lambda^2}\bar{l}l\overline{\chi}_2\chi_1$	$\frac{1}{\Lambda}\phi_2\phi_1\bar{l}l$
$\bar{b}b$	$\frac{1}{\Lambda^2}\bar{b}b\overline{\chi}_2\chi_1$	$\frac{1}{\Lambda}\phi_2\phi_1\bar{b}b$
$\bar{t}t$	$\frac{1}{\Lambda^2}\bar{t}t\overline{\chi}_2\chi_1$	$\frac{1}{\Lambda}\phi_2\phi_1\bar{t}t$

*can also have diboson final states

Light Mediator



final state	$\mathcal{O}_{DM} + \mathcal{O}_{SM}$
$\bar{f}f$	$-g_{12}Z'_\mu\bar{\chi}_1\gamma^\mu\chi_2 - g_q Z'_\mu\bar{l}\gamma^\mu l$ $-g_{12}Z'_\mu\bar{\chi}_1\gamma^\mu\gamma_5\chi_2 - g_q Z'_\mu\bar{l}\gamma^\mu\gamma_5 l$ $-g_{12}\phi\bar{\chi}_1\chi_2 - g_q\phi\bar{l}l$ $-ig_{12}\phi\bar{\chi}_1\gamma^5\chi_2 - g_q\phi\bar{l}\gamma^5 l$ $-(g_1\tilde{l}^*\bar{\chi}_1 l + g_2\tilde{l}^*\bar{\chi}_2 l + h.c.)$

Parameters

Simplified DM Models		
Variables	DM candidate	Interaction
m_ϕ	Dirac	Vector
m_1	Majorana	Axial-Vector
g_χ	Scalar-real	Scalar
g_ϕ	Scalar-complex	Pseudoscalar
Extension Displaced Signature		
τ , m_2	Decay of $\chi_2 \to \chi_1 X$	

DM simplified models program

proposed extension

or $m_2 - m_1$

Minimal Set of Final States to cover Experimentally

$\not{E}_T$ plus displaced X system					
dMETs	dMET_{jj}	$\mathrm{dMET}_{e^+e^-}$	$\mathrm{dMET}_{\mu^+\mu^-}$	$\mathrm{dMET}_{\tau^+\tau^-}$	dMET_{γ}
X	*jet*-pair	e-pair	μ-pair	τ-pair	γ

Table 4. Minimal set of dMETs searches for neutral displaced SM particles. To facilitate the trigger acceptance for these topologies, especially for soft X systems, the dMETs can be combined with an ISR signature, such as an additional hard jet or hard γ. A list of basic operators that would give rise to such topologies is shown in Table 2.

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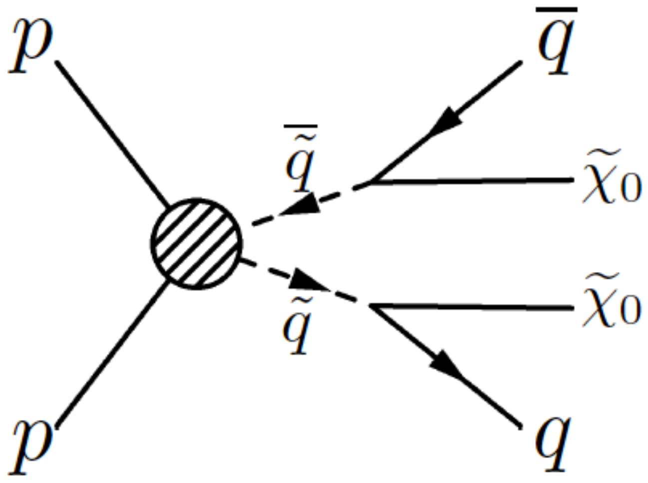
dMETγ: displaced gamma with MET is the only of these signature that is currently covered with a dedicated analysis by experiments.

Simulation in a nutshell

Simulation

1) Chose simplified Model for production



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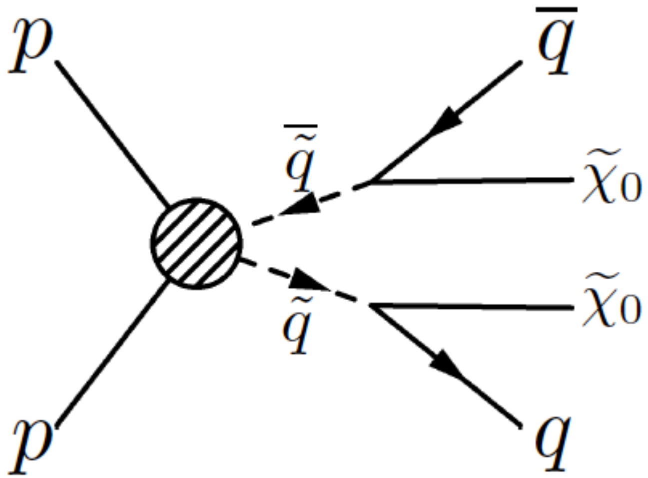

2) Chose ansatz to add long-lived particle and decay:

final state X	$\mathcal{O}_F$	$\mathcal{O}_S$
γ	$\frac{1}{\Lambda}\overline{\chi}_2\sigma_{\mu\nu}\chi_1 F^{\mu\nu}$	$\frac{1}{\Lambda^2}(\phi_2\partial_\mu\partial_\nu\phi_1)F^{\mu\nu}$
Z	$\frac{1}{\Lambda}\overline{\chi}_2\sigma_{\mu\nu}\chi_1 Z^{\mu\nu}$	$\frac{1}{\Lambda^2}(\phi_2\partial_\mu\partial_\nu\phi_1)Z^{\mu\nu}$
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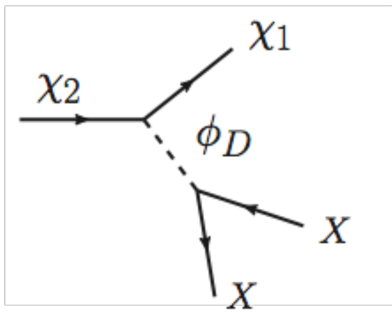
$\bar{b}b$	$\frac{1}{\Lambda^2}\bar{b}b\overline{\chi}_2\chi_1$	$\frac{1}{\Lambda}\phi_2\phi_1\bar{b}b$
$\bar{t}t$	$\frac{1}{\Lambda^2}\bar{t}t\overline{\chi}_2\chi_1$	$\frac{1}{\Lambda}\phi_2\phi_1\bar{t}t$

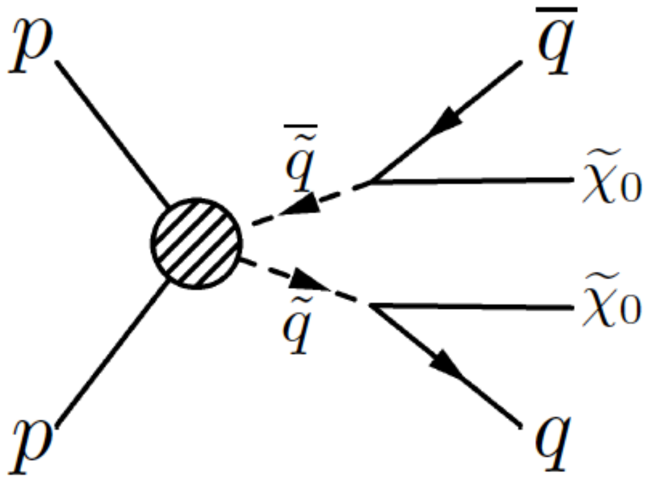
EFT like decay



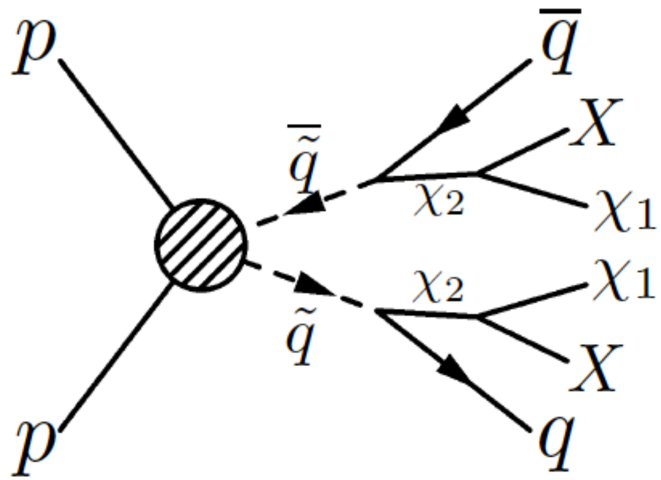
Resolved (light) mediator

Simulation in a nutshell

1) Chose simplified Model for production



3) Simulate full chain



2) Chose ansatz to add long-lived particle and decay:

final state X	$\mathcal{O}_F$	$\mathcal{O}_S$
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Z	$\frac{1}{\Lambda}\overline{\chi}_2\sigma_{\mu\nu}\chi_1 Z^{\mu\nu}$	$\frac{1}{\Lambda^2}(\phi_2\partial_\mu\partial_\nu\phi_1)Z^{\mu\nu}$
h	$\overline{\chi}_2\chi_1 h$	$\Lambda\phi_2\phi_1 h$
jj	$\frac{1}{\Lambda^3}\overline{\chi}_2\chi_1\mathrm{Tr}[G^{\mu\nu}G_{\mu\nu}]$	$\frac{1}{\Lambda^2}\phi_2\phi_1\mathrm{Tr}[G^{\mu\nu}G_{\mu\nu}]$
$\bar{l}l$	$\frac{1}{\Lambda^2}\bar{l}l\overline{\chi}_2\chi_1$	$\frac{1}{\Lambda}\phi_2\phi_1\bar{l}l$
$\bar{b}b$	$\frac{1}{\Lambda^2}\bar{b}b\overline{\chi}_2\chi_1$	$\frac{1}{\Lambda}\phi_2\phi_1\bar{b}b$
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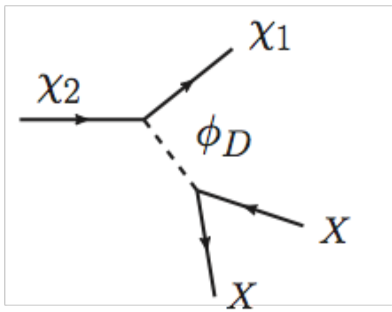
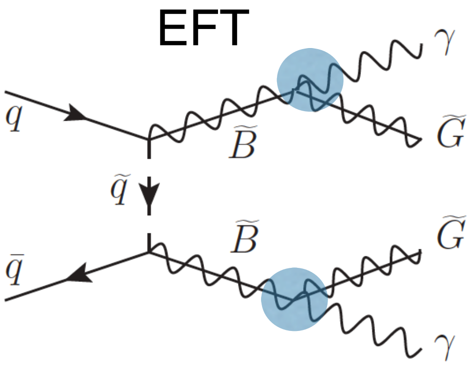
EFT like decay



Resolved (light) mediator

Example: EFT like decay for X_2 -> γ X_1



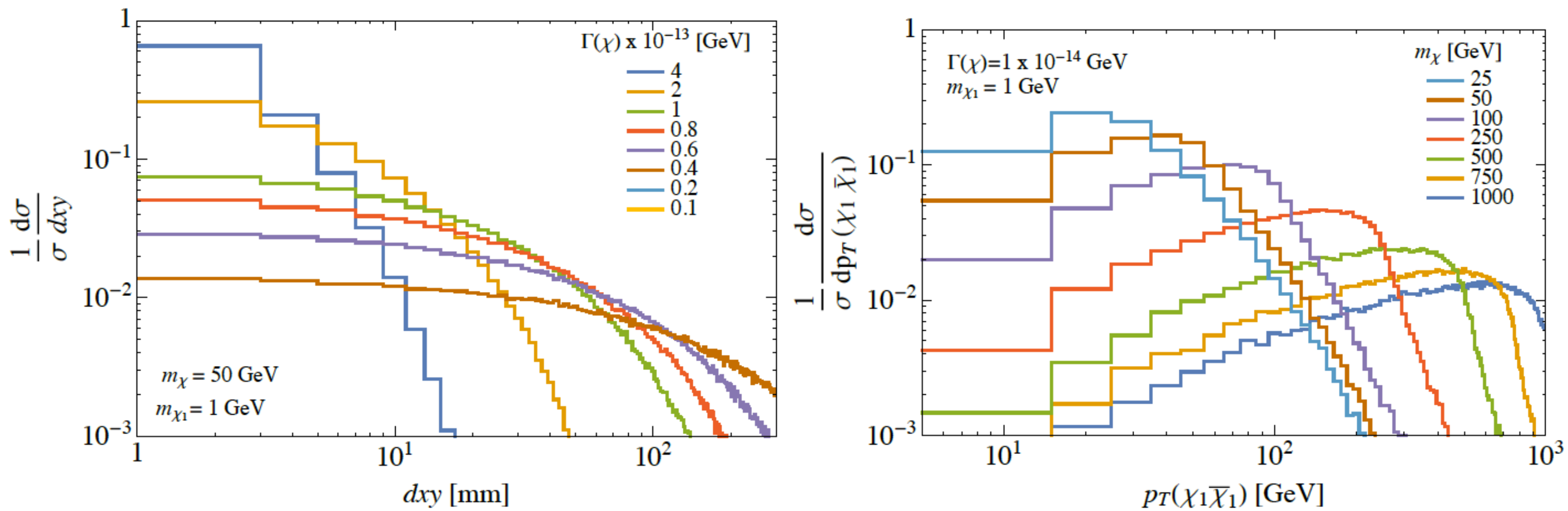
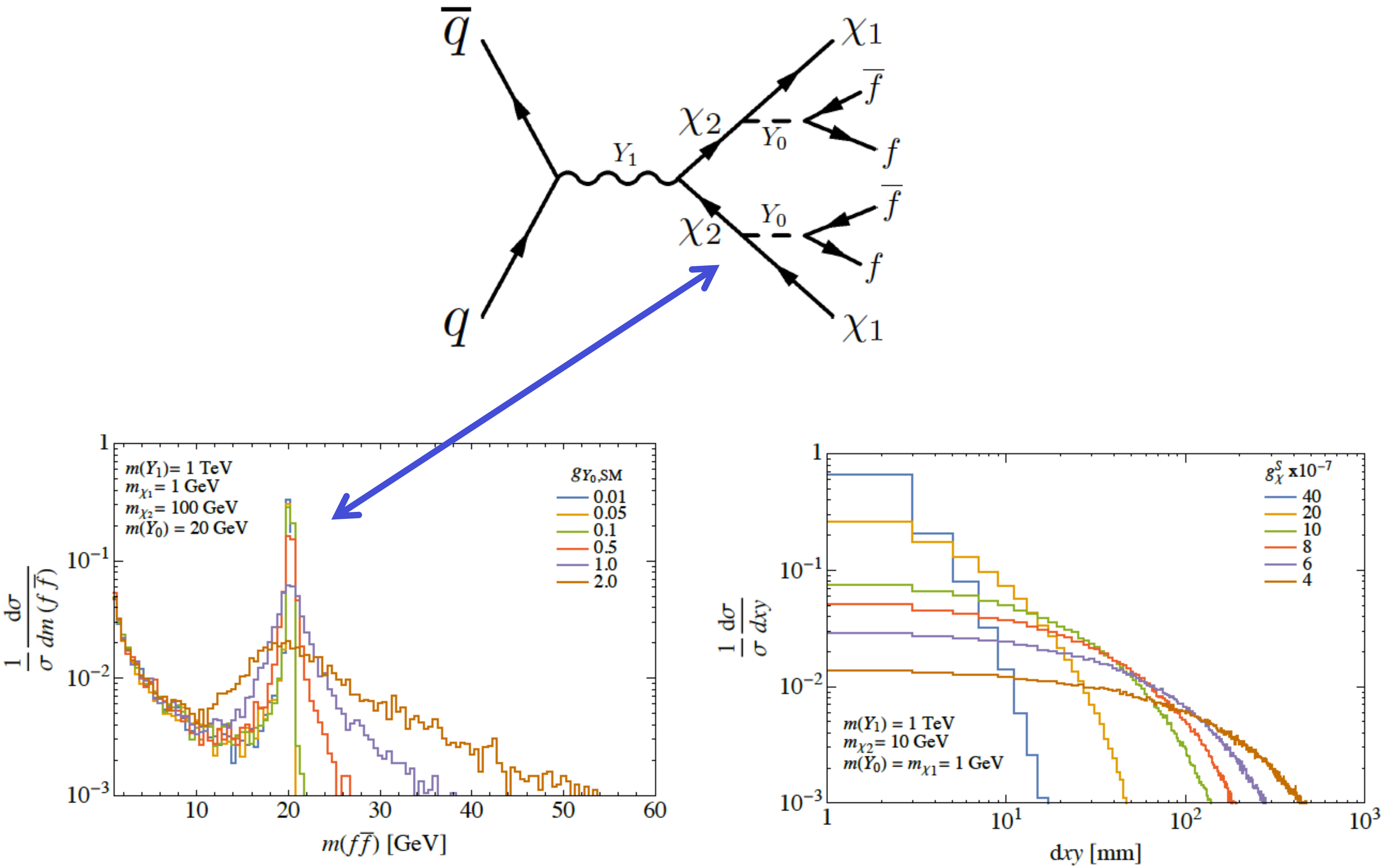


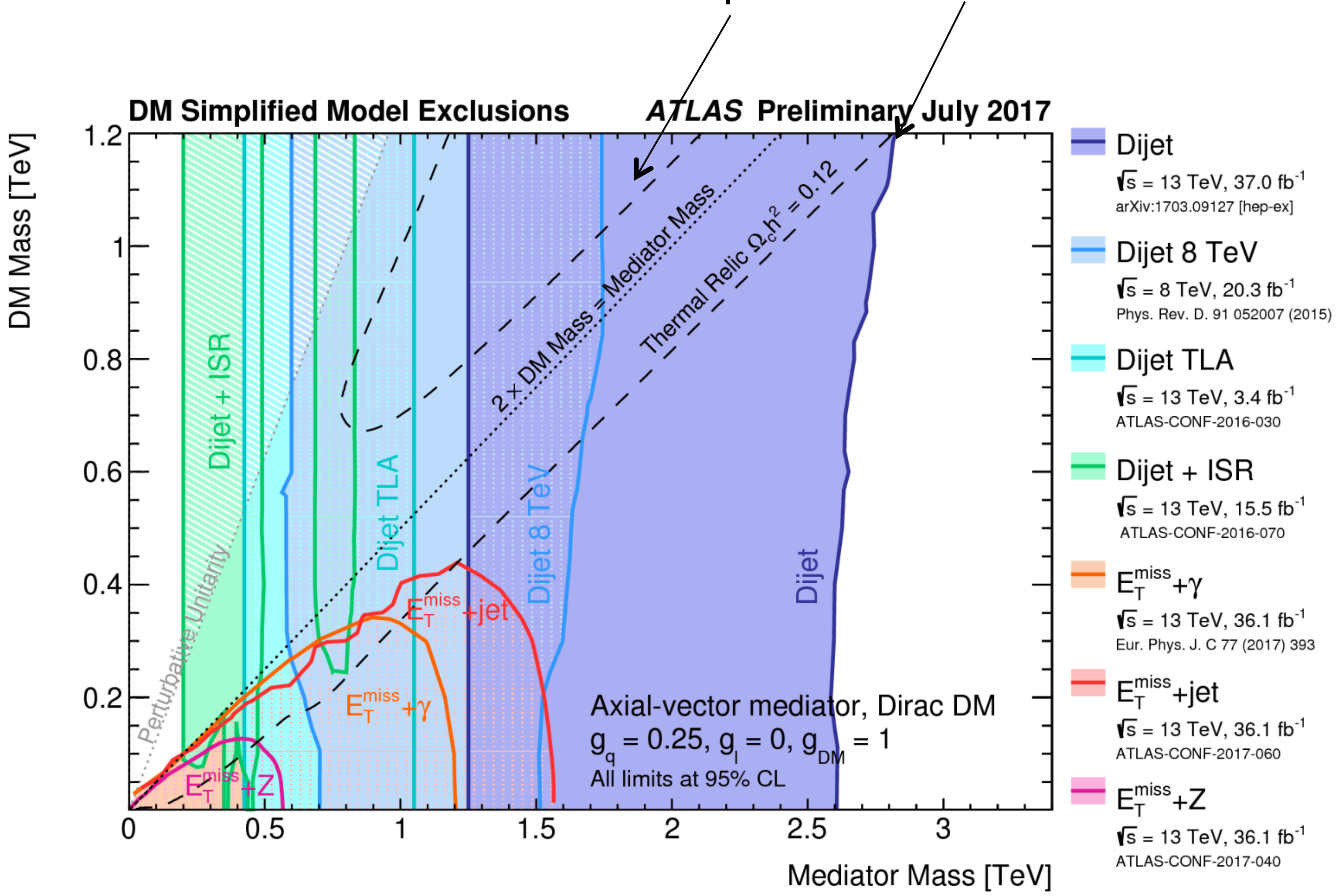
Figure 10. Left: the transverse impact parameter of $\chi_1\gamma$ vertices for a range of χ widths. Right: the transverse momentum of the DM system ($p_{\mathrm{T}}(\chi_1\bar{\chi_1})$) for various χ masses. Other parameters in the GMSB model are fixed as per the panel headings. The distributions in both panels are unit-normalised.

Example: Resolved decay for X_2 -> Y_0 X_1 -> ff X_1



How to calculate the relic for these models?

For the standard simplified models we calculate the relic – would like to do the same for the those with LL particles involved.



Simulation

1. **Add the new particle content to the original DM simplified model.**

   For an EFT decay model, this is simply the new, stable DM particle χ_1.

   For the simplified decay model the mediating particle must also be included.

2. **Add new interactions to the original model.**

   These can either be single-parameter EFT operators, or interaction terms involving a mediator.

3. **Configure the relevant particle masses and couplings in the MG5 aMC@NLO param card.dat to achieve displaced decays.**

4. **Generate the pp → $\chi\bar{\chi}$ in process MG5 aMC@NLO, which will result in an LHE file that contains the necessary width information in the SLHA header.**

5. **Pass the resulting LHE to Pythia, which will perform the $\chi \to \chi_1 X$ decay using the SLHA information.**

More details are provided in arXiv:1704.06515