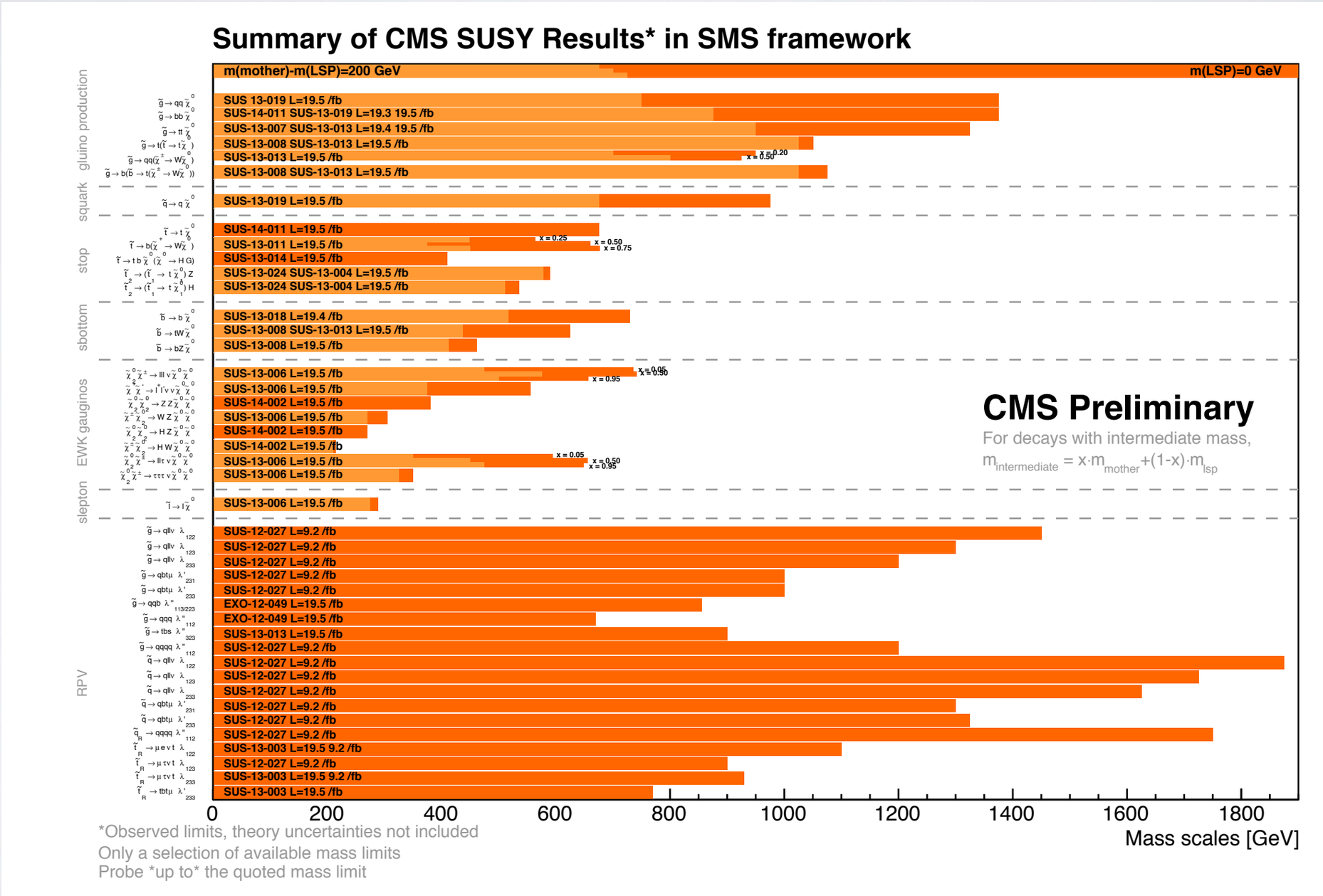
NEW IDEAS FOR DISPLACED PHYSICS AT THE LHC

Eric Kuflik
Cornell University

with
Csaba Csaki (Cornell)
Salvator Lombardo (Cornell)
Oren Slone (Tel Aviv)
Tomer Volansky (Tel Aviv)

BEEN LOOKING…



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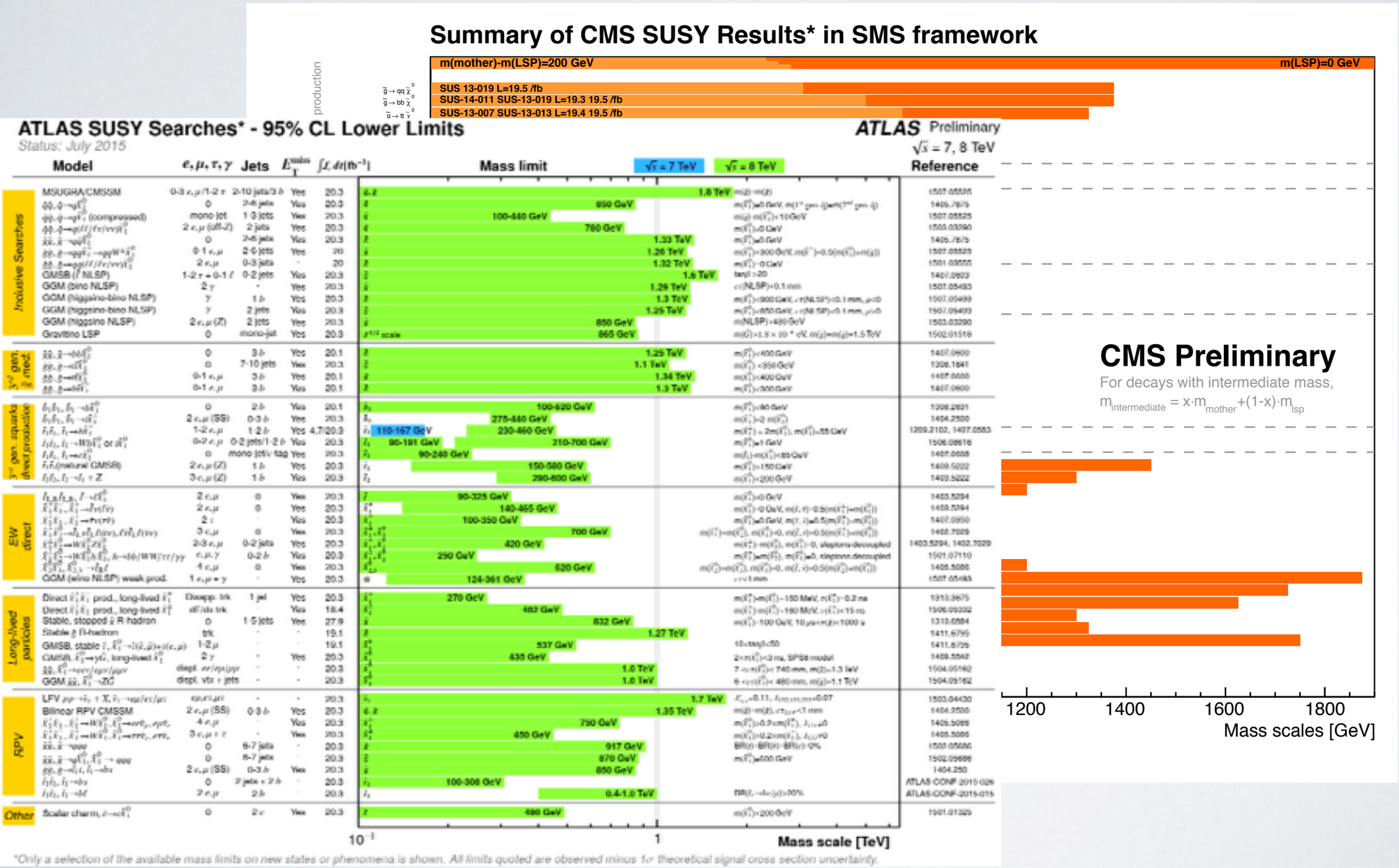

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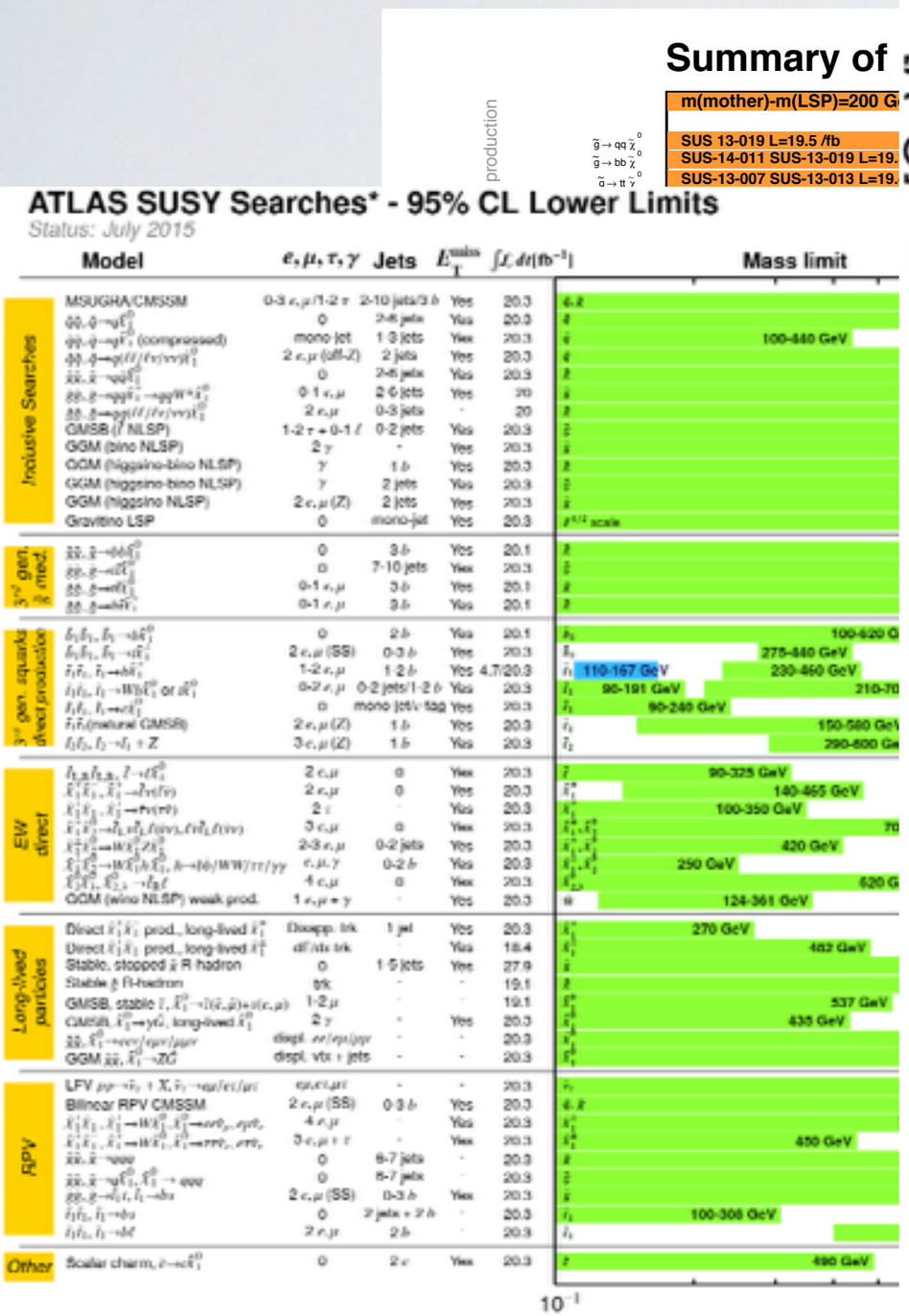

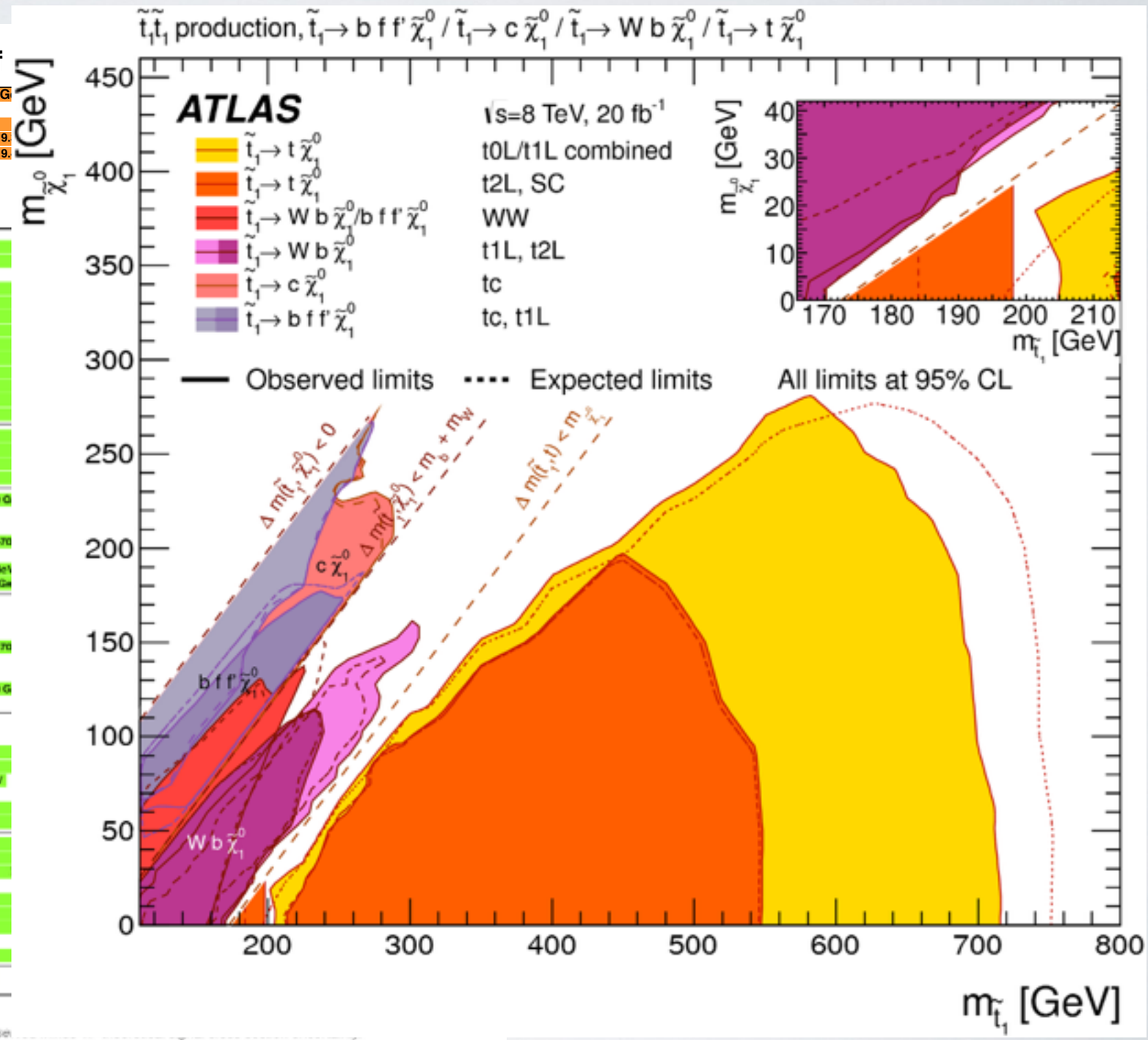

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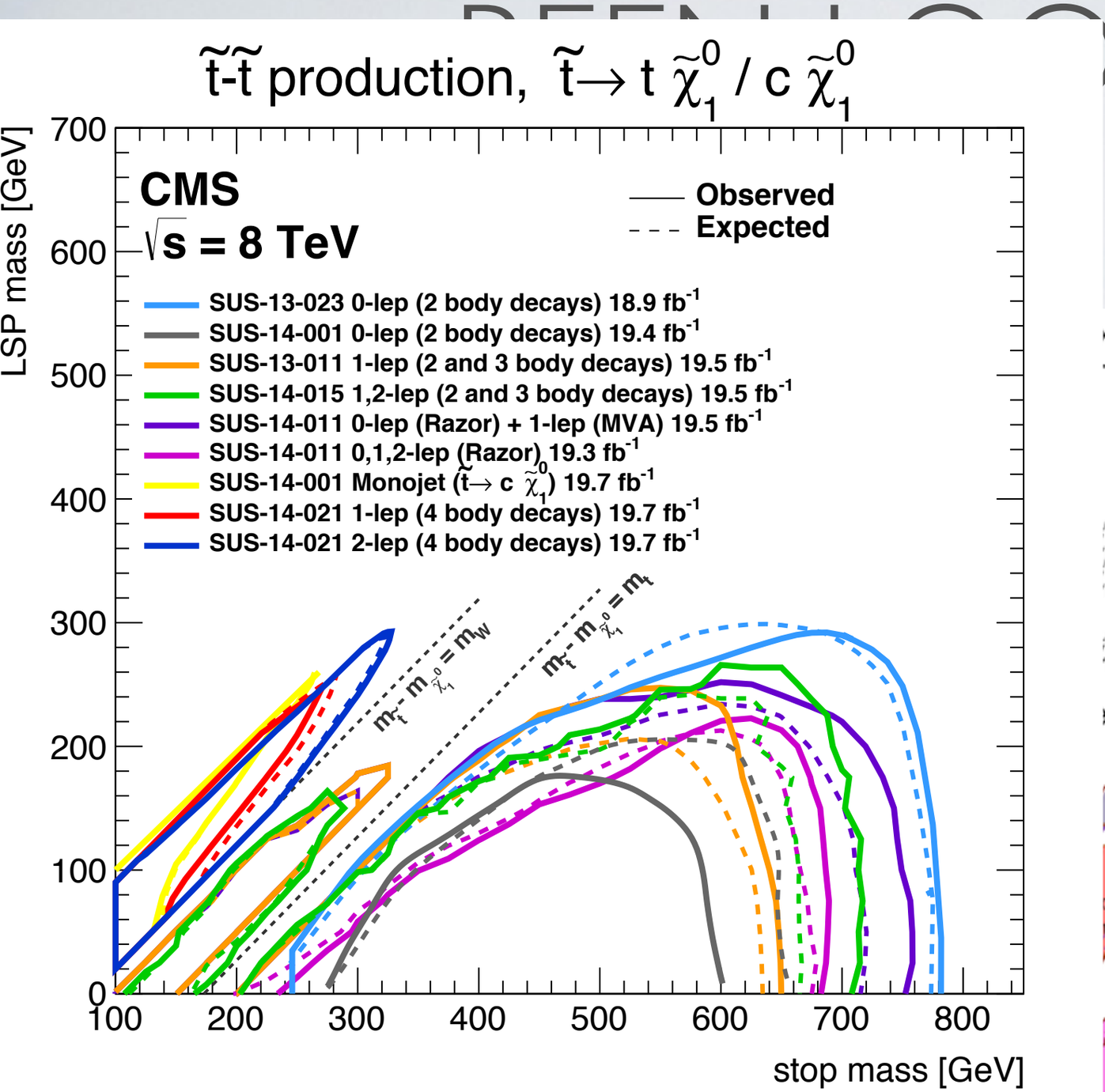

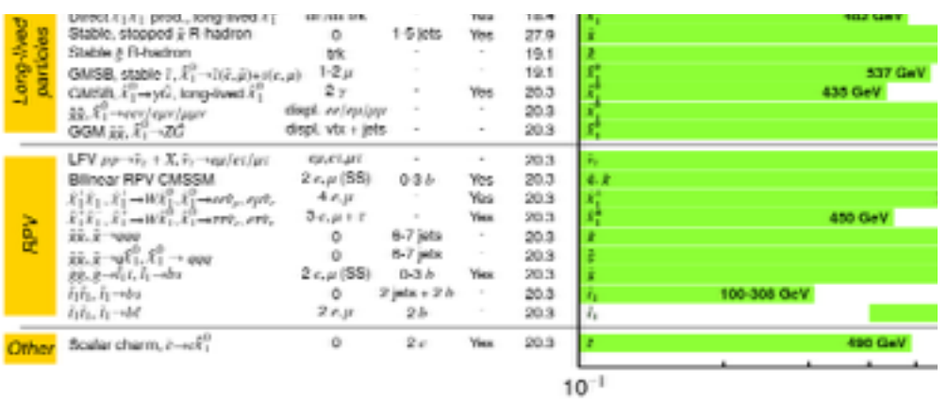

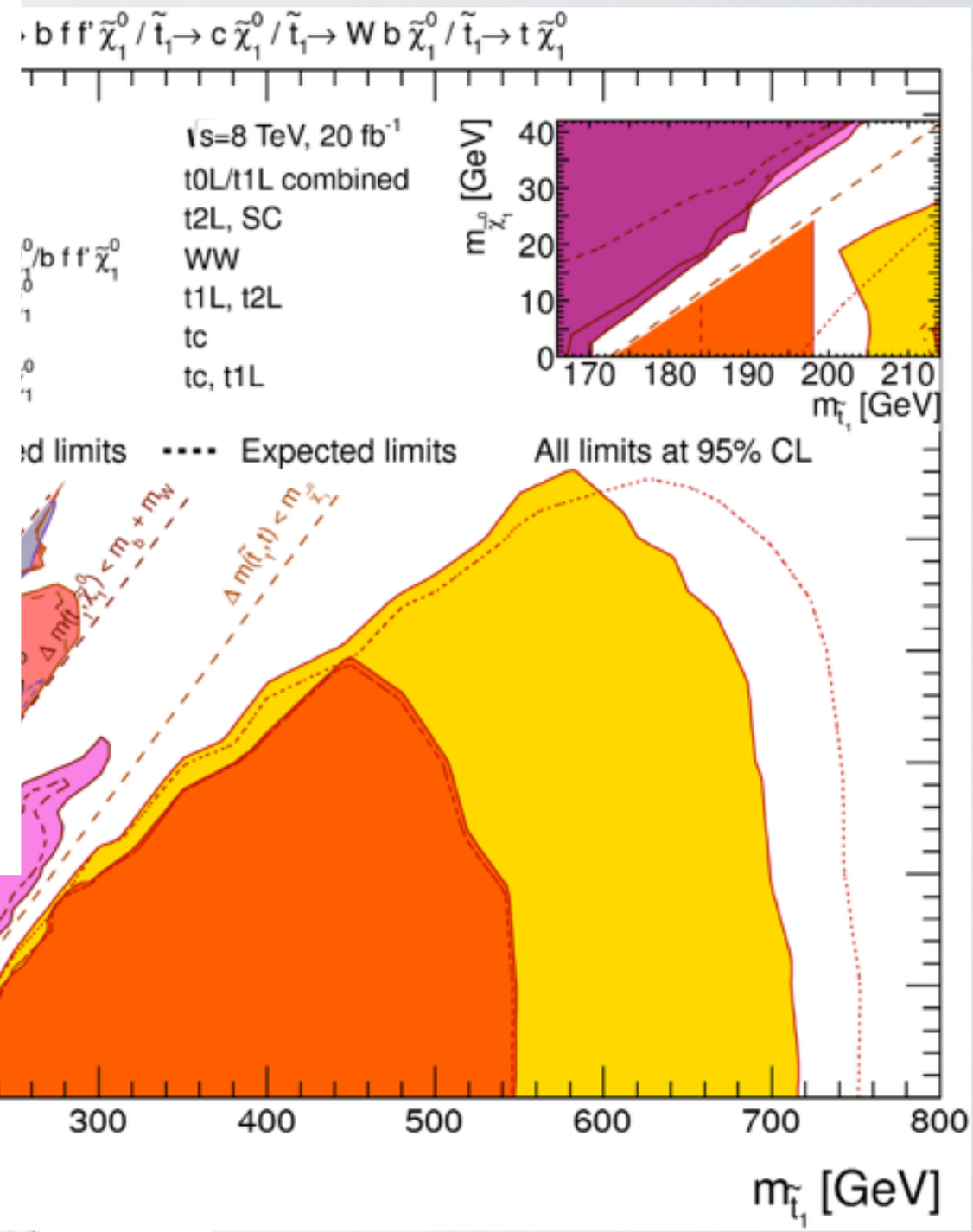

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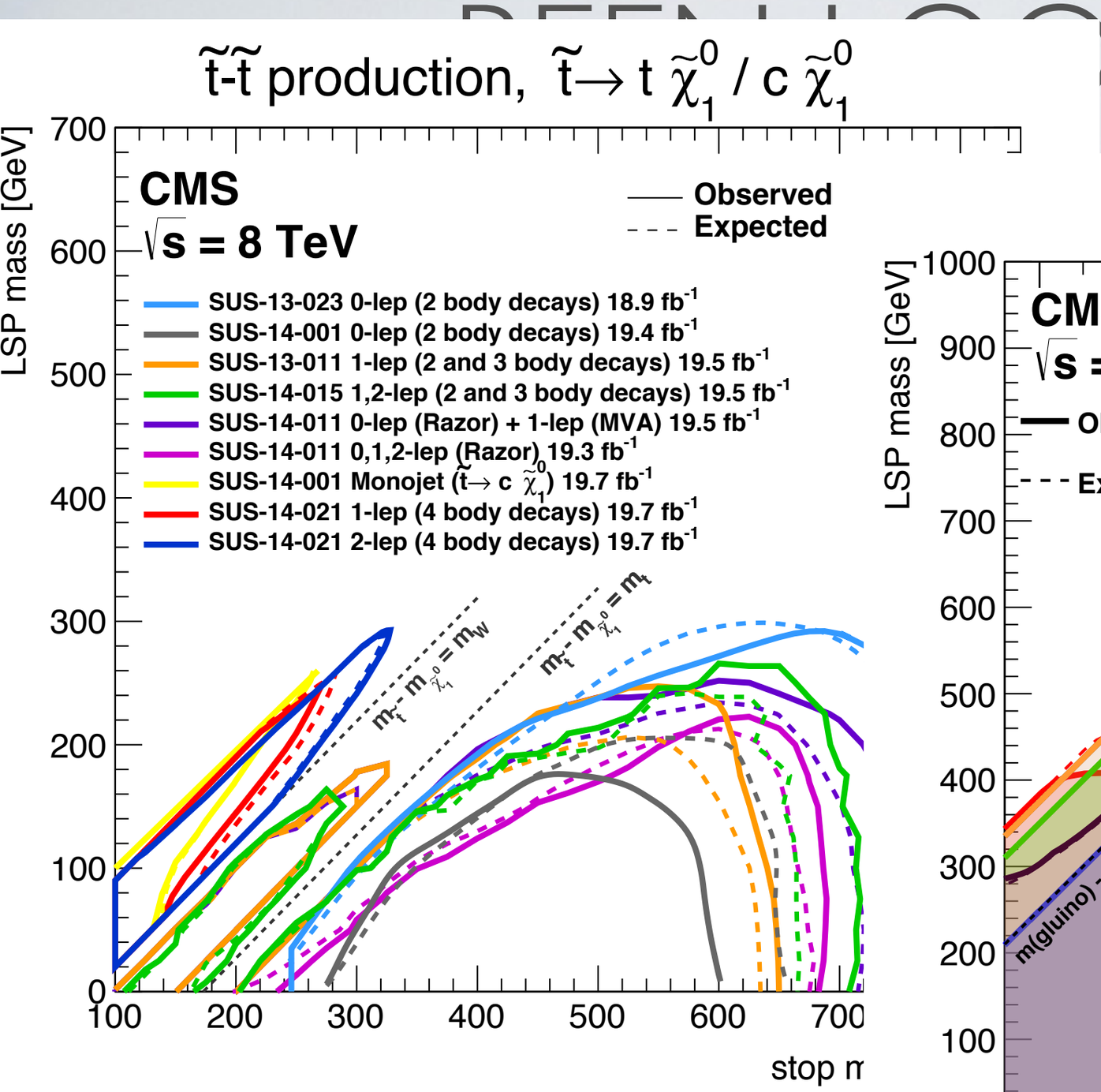
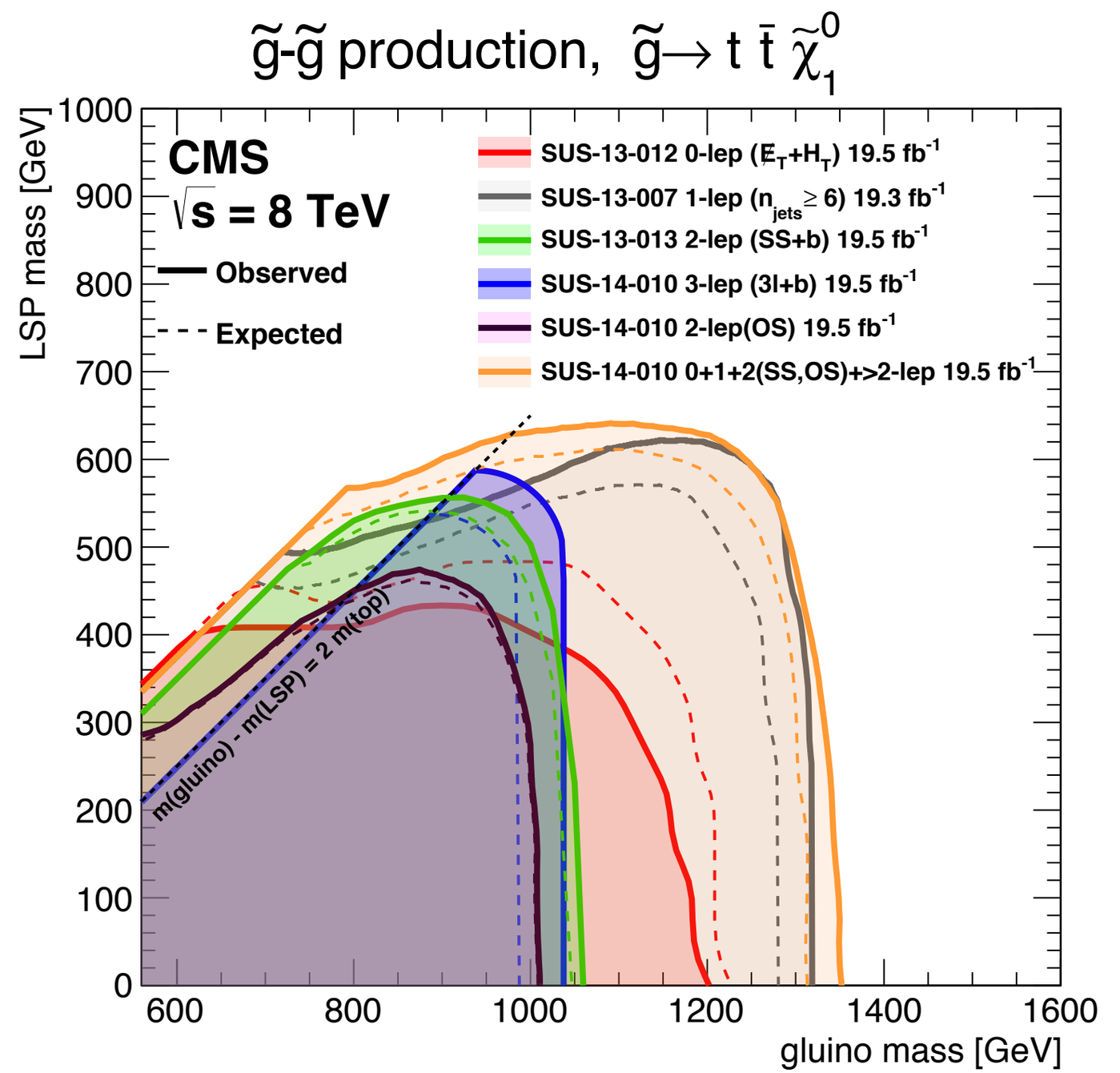
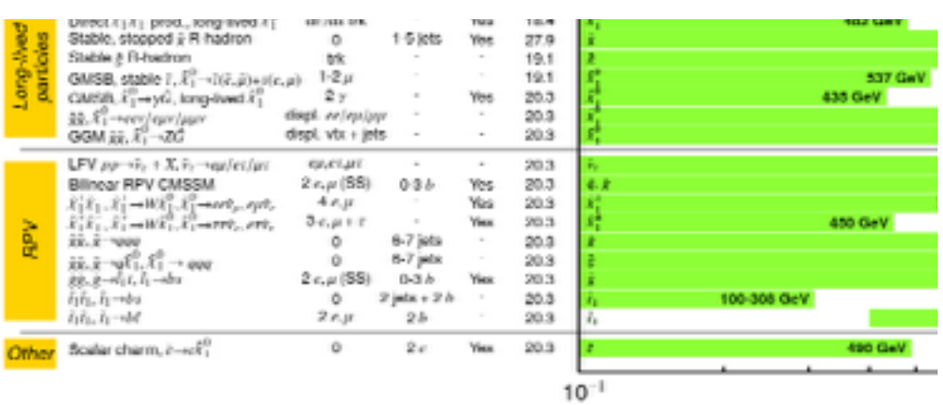
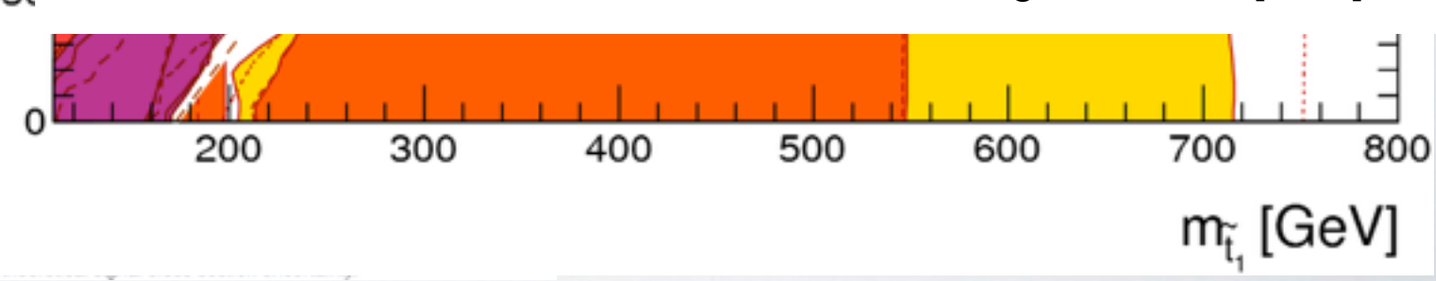




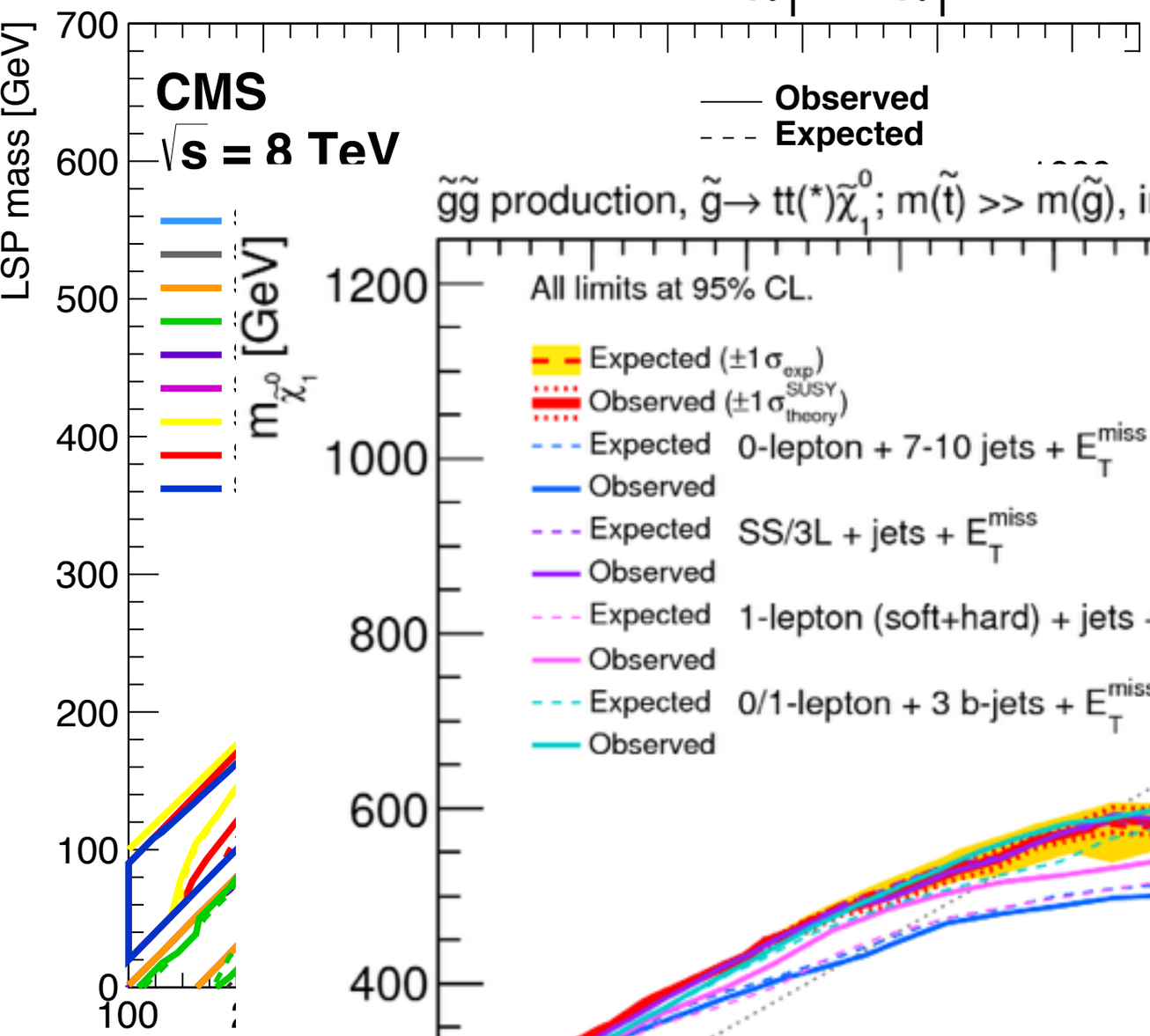




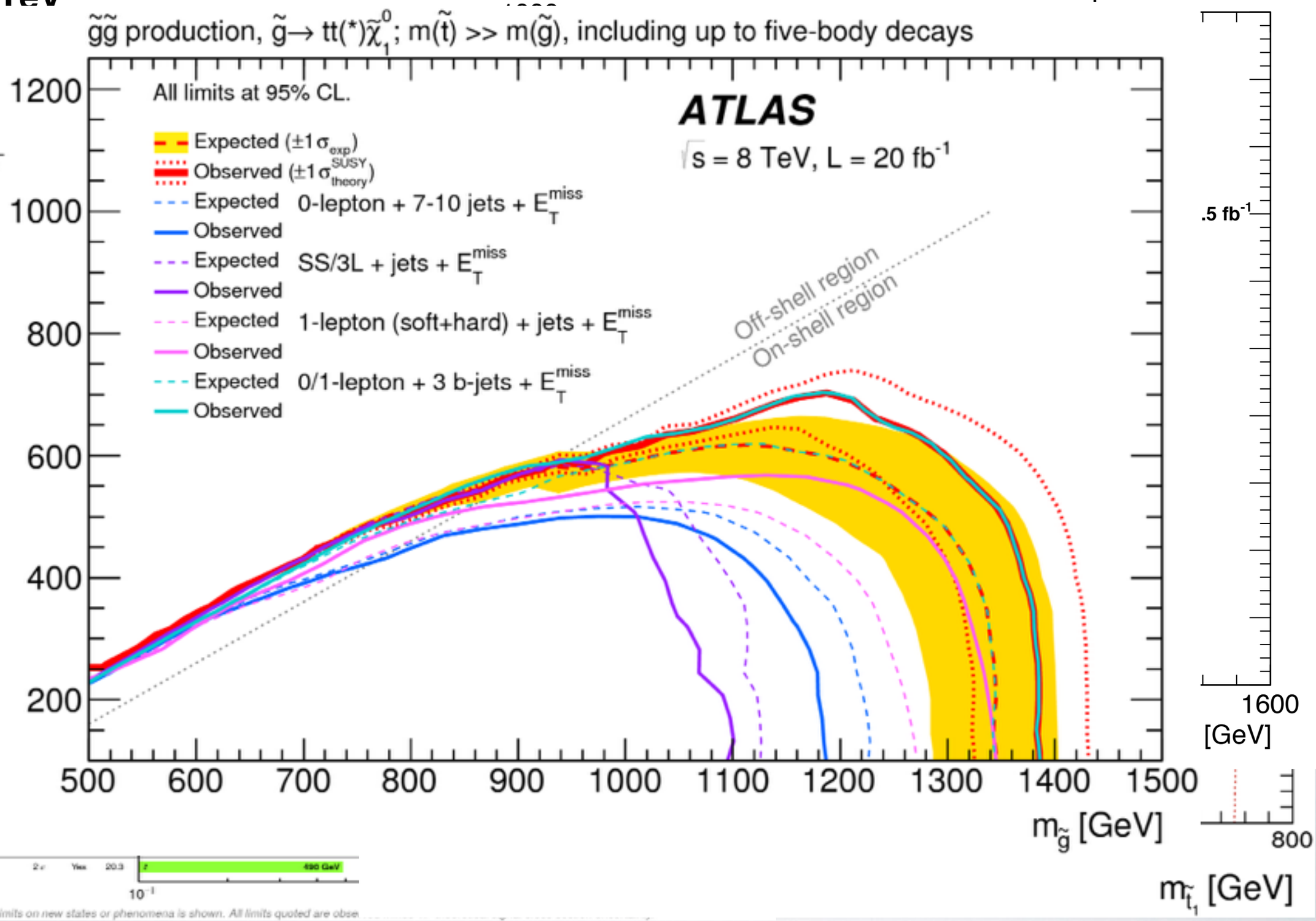
*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are obse

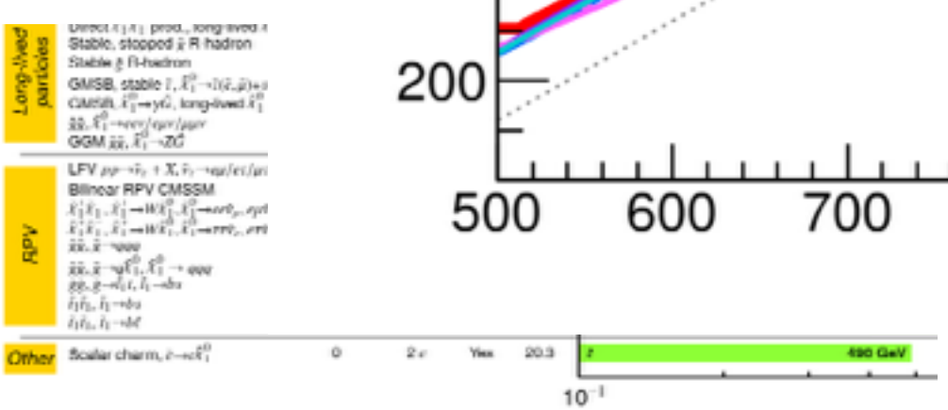
BEEN LOOKING…

$\tilde{t}$-$\tilde{t}$ production, $\tilde{t} \to t\,\tilde{\chi}_1^0 \,/\, c\,\tilde{\chi}_1^0$



$\tilde{g}$-$\tilde{g}$ production, $\tilde{g} \to t\,\bar{t}\,\tilde{\chi}_1^0$





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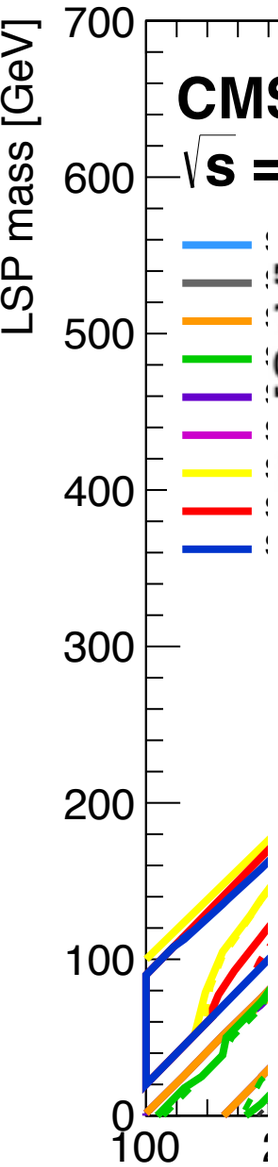
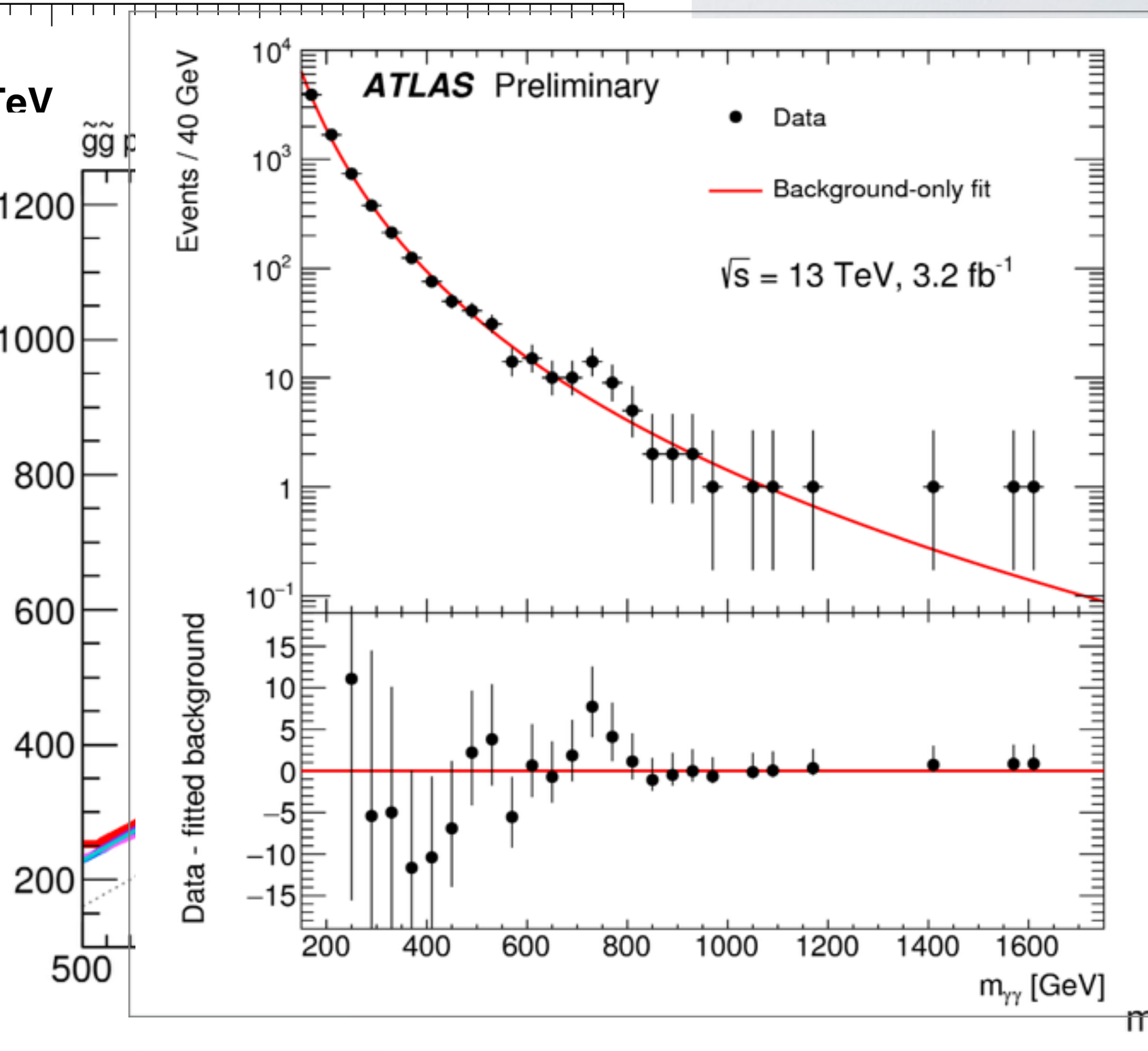
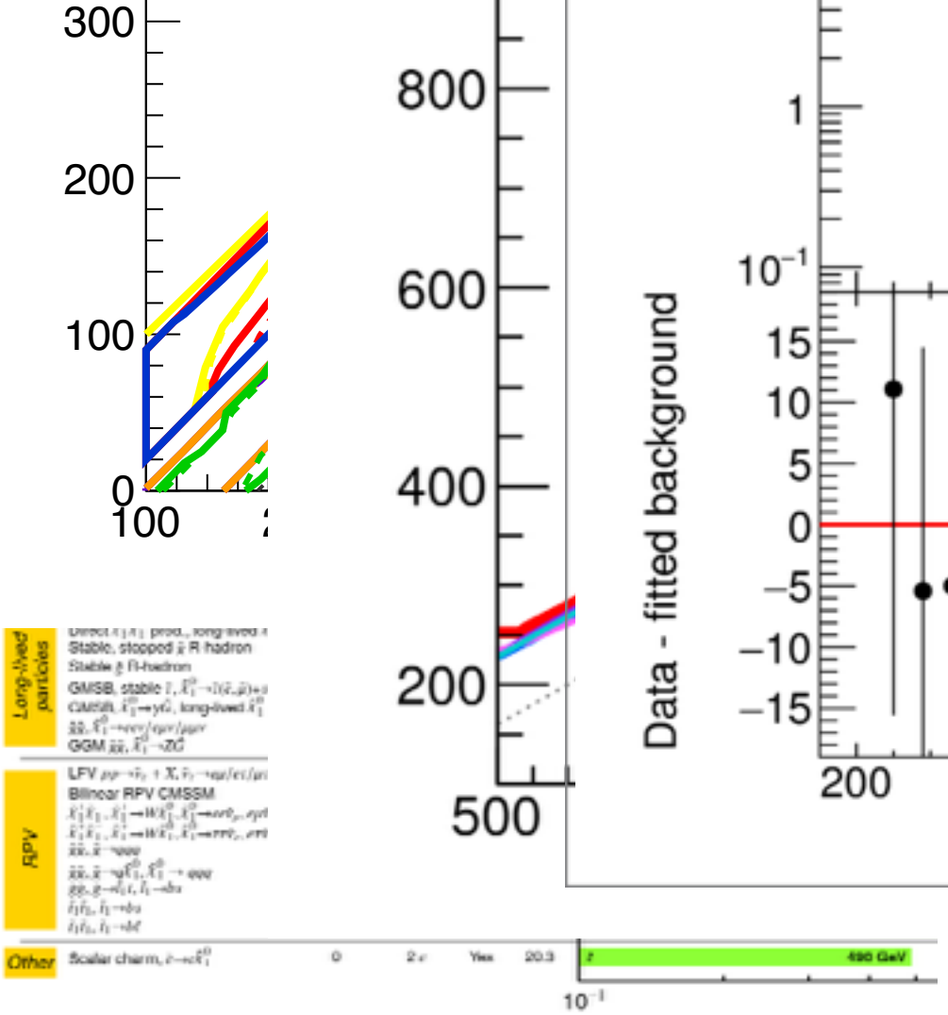
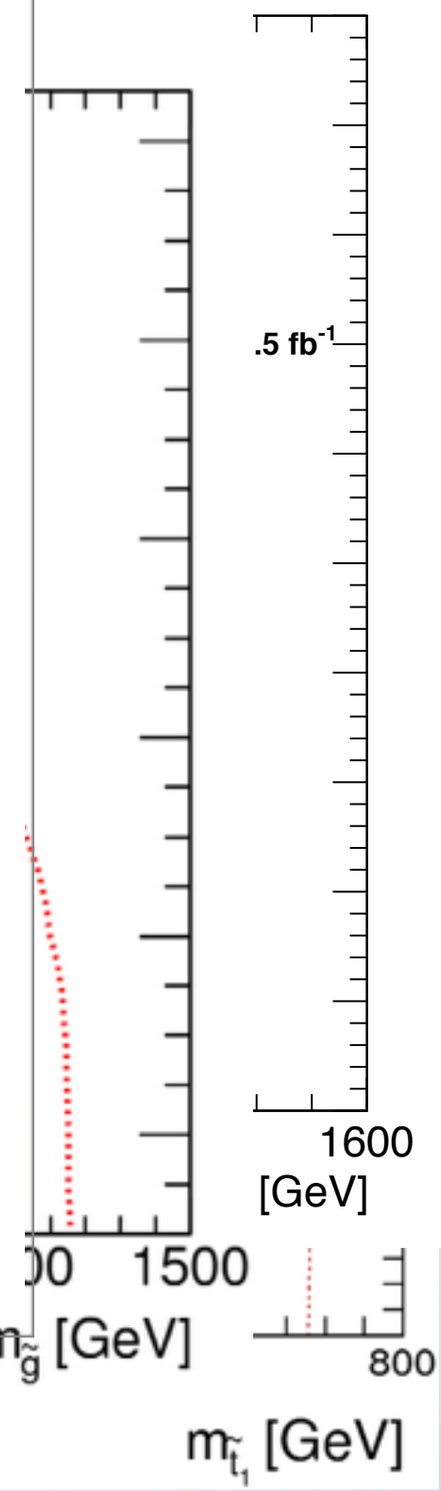
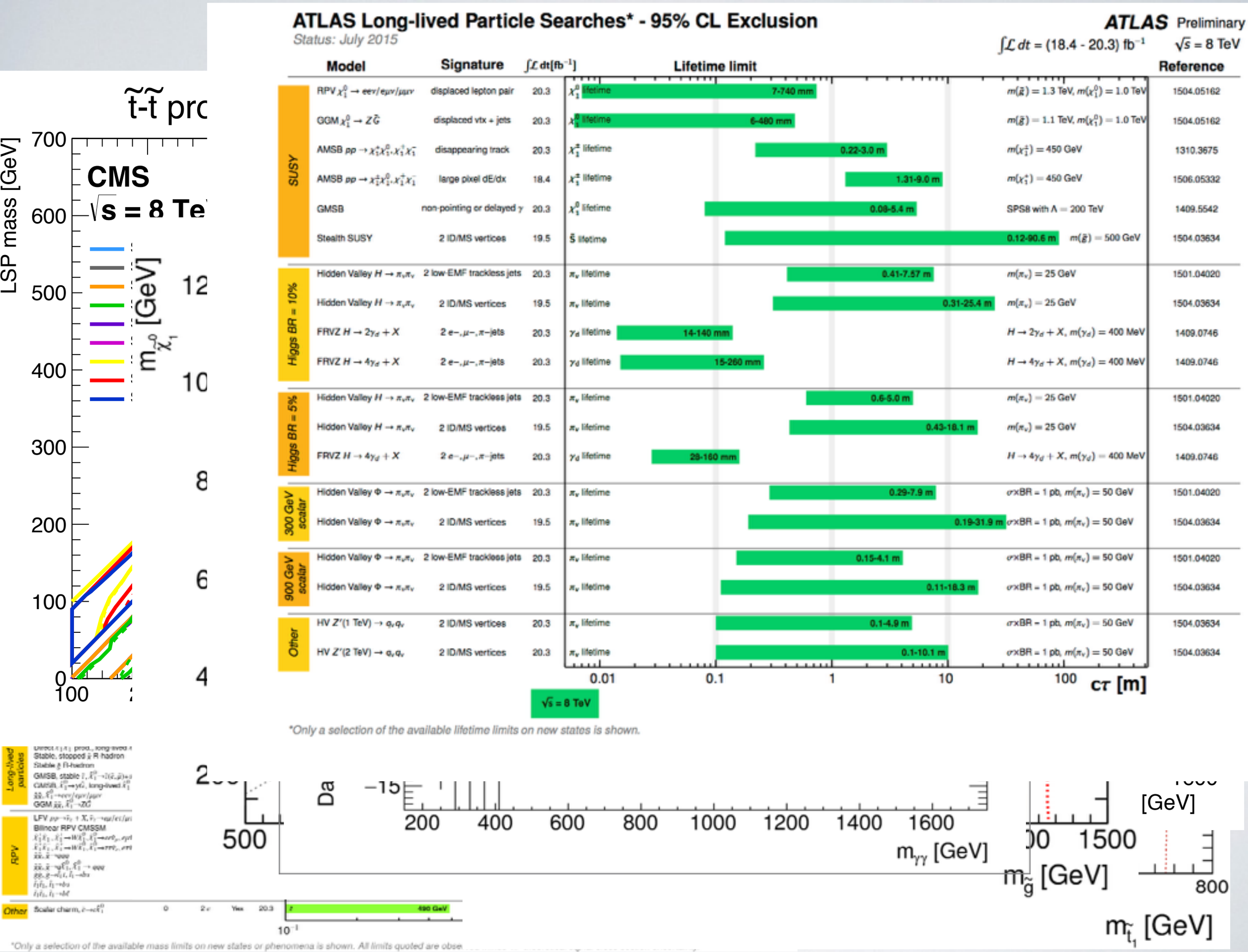
$\tilde{t}$-$\tilde{t}$ production, $\tilde{t} \rightarrow t\,\tilde{\chi}_1^0 \,/\, c\,\tilde{\chi}_1^0$

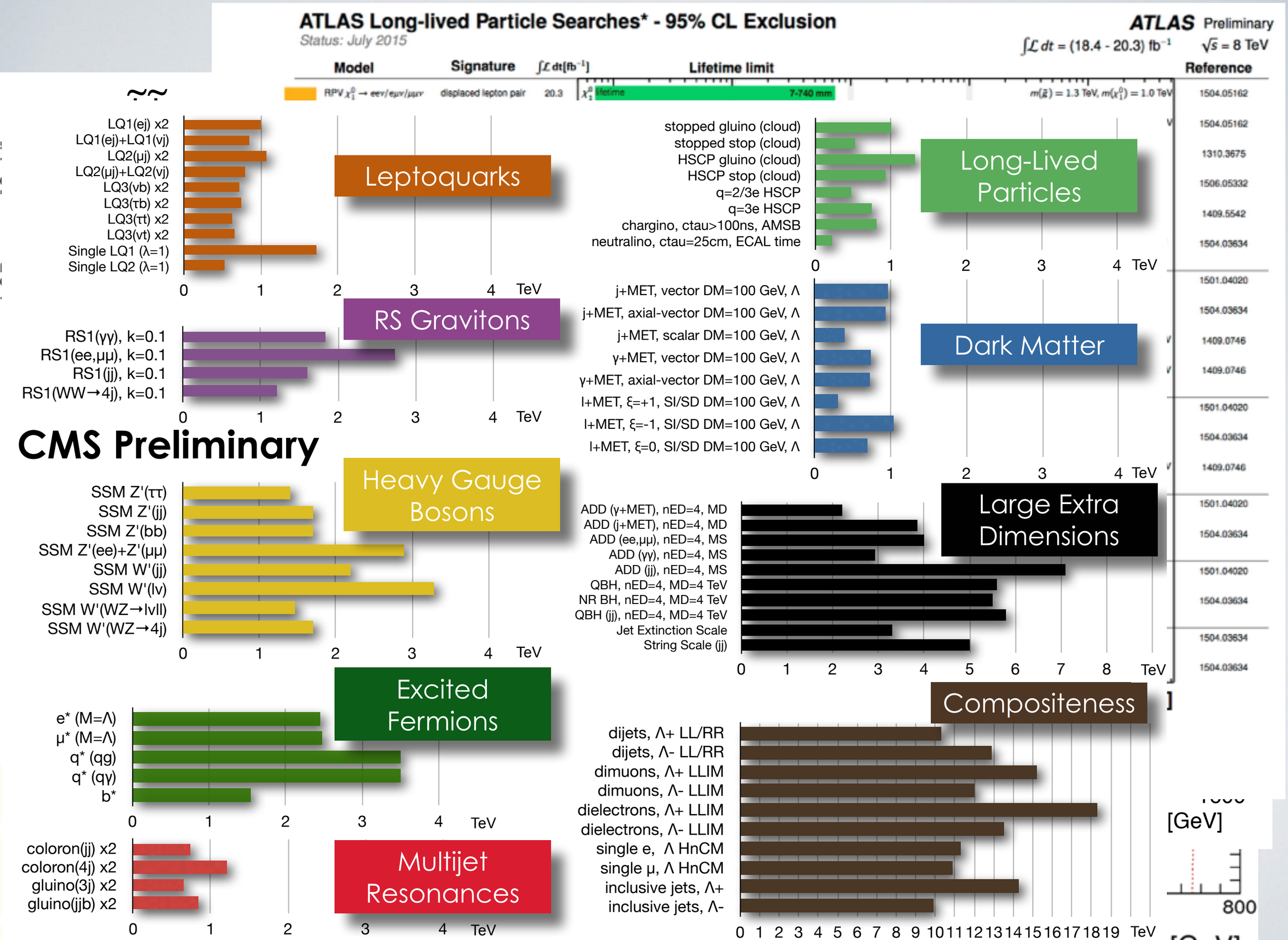









ATLAS Long-lived Particle Searches* - 95% CL Exclusion
Status: July 2015
ATLAS Preliminary
$\int \mathcal{L}\,dt = (18.4 - 20.3)\ \mathrm{fb}^{-1}$
$\sqrt{s} = 8$ TeV
Model
Signature
$\int \mathcal{L}\,dt[\mathrm{fb}^{-1}]$
Lifetime limit
Reference
SUSY
RPV $\chi_1^0 \to ee\nu/e\mu\nu/\mu\mu\nu$ displaced lepton pair 20.3 χ_1^0 lifetime 7-740 mm $m(\tilde{g}) = 1.3$ TeV, $m(\chi_1^0) = 1.0$ TeV 1504.05162
GGM $\chi_1^0 \to Z\tilde{G}$ displaced vtx + jets 20.3 χ_1^0 lifetime 6-480 mm $m(\tilde{g}) = 1.1$ TeV, $m(\chi_1^0) = 1.0$ TeV 1504.05162
AMSB $pp \to \chi_1^\pm\chi_1^0, \chi_1^+\chi_1^-$ disappearing track 20.3 $\chi_1^\pm$ lifetime 0.22-3.0 m $m(\chi_1^\pm) = 450$ GeV 1310.3675
AMSB $pp \to \chi_1^\pm\chi_1^0, \chi_1^+\chi_1^-$ large pixel dE/dx 18.4 $\chi_1^\pm$ lifetime 1.31-9.0 m $m(\chi_1^\pm) = 450$ GeV 1506.05332
GMSB non-pointing or delayed γ 20.3 χ_1^0 lifetime 0.09-5.4 m SPS8 with $\Lambda = 200$ TeV 1409.5542
Stealth SUSY 2 ID/MS vertices 19.5 $\tilde{S}$ lifetime 0.12-90.6 m $m(\tilde{g}) = 500$ GeV 1504.03634
Higgs BR = 10%
Hidden Valley $H \to \pi_v\pi_v$ 2 low-EMF trackless jets 20.3 π_v lifetime 0.41-7.57 m $m(\pi_v) = 25$ GeV 1501.04020
Hidden Valley $H \to \pi_v\pi_v$ 2 ID/MS vertices 19.5 π_v lifetime 0.31-25.4 m $m(\pi_v) = 25$ GeV 1504.03634
FRVZ $H \to 2\gamma_d + X$ 2 $e-,\mu-,\pi-$jets 20.3 γ_d lifetime 14-140 mm $H \to 2\gamma_d + X$, $m(\gamma_d) = 400$ MeV 1409.0746
FRVZ $H \to 4\gamma_d + X$ 2 $e-,\mu-,\pi-$jets 20.3 γ_d lifetime 15-260 mm $H \to 4\gamma_d + X$, $m(\gamma_d) = 400$ MeV 1409.0746
Higgs BR = 5%
Hidden Valley $H \to \pi_v\pi_v$ 2 low-EMF trackless jets 20.3 π_v lifetime 0.6-5.0 m $m(\pi_v) = 25$ GeV 1501.04020
Hidden Valley $H \to \pi_v\pi_v$ 2 ID/MS vertices 19.5 π_v lifetime 0.43-18.1 m $m(\pi_v) = 25$ GeV 1504.03634
FRVZ $H \to 4\gamma_d + X$ 2 $e-,\mu-,\pi-$jets 20.3 γ_d lifetime 29-160 mm $H \to 4\gamma_d + X$, $m(\gamma_d) = 400$ MeV 1409.0746
300 GeV scalar
Hidden Valley $\Phi \to \pi_v\pi_v$ 2 low-EMF trackless jets 20.3 π_v lifetime 0.29-7.9 m $\sigma\times$BR = 1 pb, $m(\pi_v) = 50$ GeV 1501.04020
Hidden Valley $\Phi \to \pi_v\pi_v$ 2 ID/MS vertices 19.5 π_v lifetime 0.19-31.9 m $\sigma\times$BR = 1 pb, $m(\pi_v) = 50$ GeV 1504.03634
900 GeV scalar
Hidden Valley $\Phi \to \pi_v\pi_v$ 2 low-EMF trackless jets 20.3 π_v lifetime 0.15-4.1 m $\sigma\times$BR = 1 pb, $m(\pi_v) = 50$ GeV 1501.04020
Hidden Valley $\Phi \to \pi_v\pi_v$ 2 ID/MS vertices 19.5 π_v lifetime 0.11-18.3 m $\sigma\times$BR = 1 pb, $m(\pi_v) = 50$ GeV 1504.03634
Other
HV Z'(1 TeV) $\to q_v q_v$ 2 ID/MS vertices 20.3 π_v lifetime 0.1-4.9 m $\sigma\times$BR = 1 pb, $m(\pi_v) = 50$ GeV 1504.03634
HV Z'(2 TeV) $\to q_v q_v$ 2 ID/MS vertices 20.3 π_v lifetime 0.1-10.1 m $\sigma\times$BR = 1 pb, $m(\pi_v) = 50$ GeV 1504.03634
0.01
0.1
1
10
100
$c\tau$ [m]
$\sqrt{s} = 8$ TeV
*Only a selection of the available lifetime limits on new states is shown.
$\tilde{t}$-$\tilde{t}$ prod
CMS
$\sqrt{s} = 8$ Te
LSP mass [GeV]
$m_{\tilde{\chi}_1^0}$ [GeV]
Long-lived particles
RPV
Other
Stable, stopped $\tilde{g}$ R hadron
Stable $\tilde{g}$ R-hadron
Bilinear RPV CMSSM
Scalar charm, $\tilde{c} \to c\tilde{\chi}_1^0$
0
2 e
Yes
20.3
490 GeV
10^{-1}
*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are obse
Da
$m_{\gamma\gamma}$ [GeV]
$m_{\tilde{g}}$ [GeV]
$m_{\tilde{t}_1}$ [GeV]


ATLAS Long-lived Particle Searches* - 95% CL Exclusion
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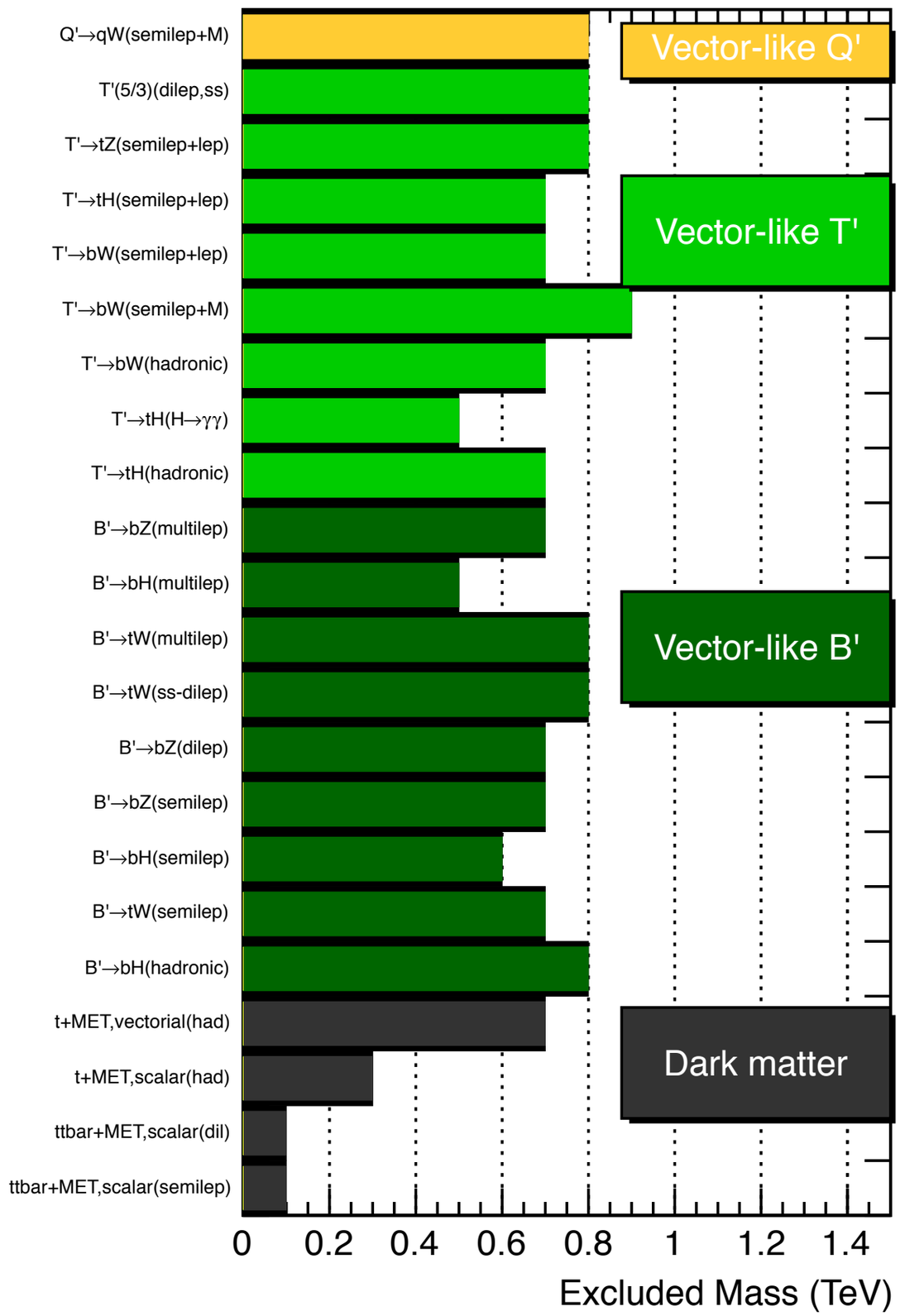
∫ℒ dt = (18.4 - 20.3) fb⁻¹
√s = 8 TeV
Model
Signature
∫ℒ dt[fb⁻¹]
Lifetime limit
Reference
RPV χ̃⁰₁ → eeν/eμν/μμν
displaced lepton pair
20.3
lifetime
7-740 mm
m(g̃) = 1.3 TeV, m(χ̃⁰₁) = 1.0 TeV
1504.05162
Leptoquarks
LQ1(ej) x2
LQ1(ej)+LQ1(νj)
LQ2(μj) x2
LQ2(μj)+LQ2(νj)
LQ3(νb) x2
LQ3(τb) x2
LQ3(τt) x2
LQ3(νt) x2
Single LQ1 (λ=1)
Single LQ2 (λ=1)
Long-Lived Particles
stopped gluino (cloud)
stopped stop (cloud)
HSCP gluino (cloud)
HSCP stop (cloud)
q=2/3e HSCP
q=3e HSCP
chargino, ctau>100ns, AMSB
neutralino, ctau=25cm, ECAL time
1504.05162
1310.3675
1506.05332
1409.5542
1504.03634
RS Gravitons
RS1(γγ), k=0.1
RS1(ee,μμ), k=0.1
RS1(jj), k=0.1
RS1(WW→4j), k=0.1
Dark Matter
j+MET, vector DM=100 GeV, Λ
j+MET, axial-vector DM=100 GeV, Λ
j+MET, scalar DM=100 GeV, Λ
γ+MET, vector DM=100 GeV, Λ
γ+MET, axial-vector DM=100 GeV, Λ
l+MET, ξ=+1, SI/SD DM=100 GeV, Λ
l+MET, ξ=-1, SI/SD DM=100 GeV, Λ
l+MET, ξ=0, SI/SD DM=100 GeV, Λ
1501.04020
1504.03634
1409.0746
CMS Preliminary
Heavy Gauge Bosons
SSM Z'(ττ)
SSM Z'(jj)
SSM Z'(bb)
SSM Z'(ee)+Z'(μμ)
SSM W'(jj)
SSM W'(lν)
SSM W'(WZ→lνll)
SSM W'(WZ→4j)
Large Extra Dimensions
ADD (γ+MET), nED=4, MD
ADD (j+MET), nED=4, MD
ADD (ee,μμ), nED=4, MS
ADD (γγ), nED=4, MS
ADD (jj), nED=4, MS
QBH, nED=4, MD=4 TeV
NR BH, nED=4, MD=4 TeV
QBH (jj), nED=4, MD=4 TeV
Jet Extinction Scale
String Scale (jj)
Excited Fermions
e* (M=Λ)
μ* (M=Λ)
q* (qg)
q* (qγ)
b*
Compositeness
dijets, Λ+ LL/RR
dijets, Λ- LL/RR
dimuons, Λ+ LLIM
dimuons, Λ- LLIM
dielectrons, Λ+ LLIM
dielectrons, Λ- LLIM
single e, Λ HnCM
single μ, Λ HnCM
inclusive jets, Λ+
inclusive jets, Λ-
Multijet Resonances
coloron(jj) x2
coloron(4j) x2
gluino(3j) x2
gluino(jjb) x2
TeV
[GeV]
800

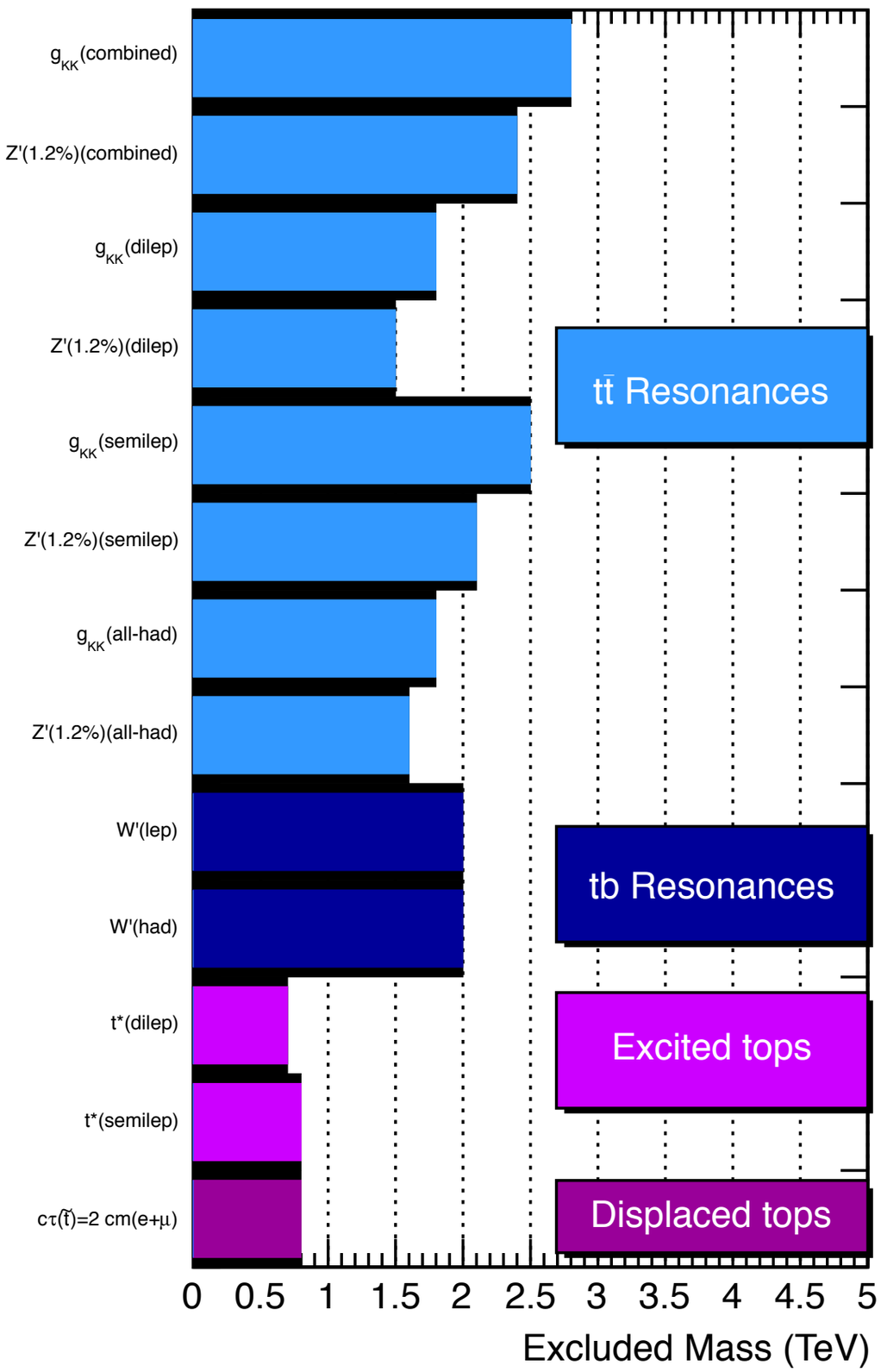
ATLAS Long-lived Particle Searches* - 95% CL Exclusion

ATLAS Preliminary

CMS Searches for New Physics Beyond Two Generations (B2G)

95% CL Exclusions (TeV)





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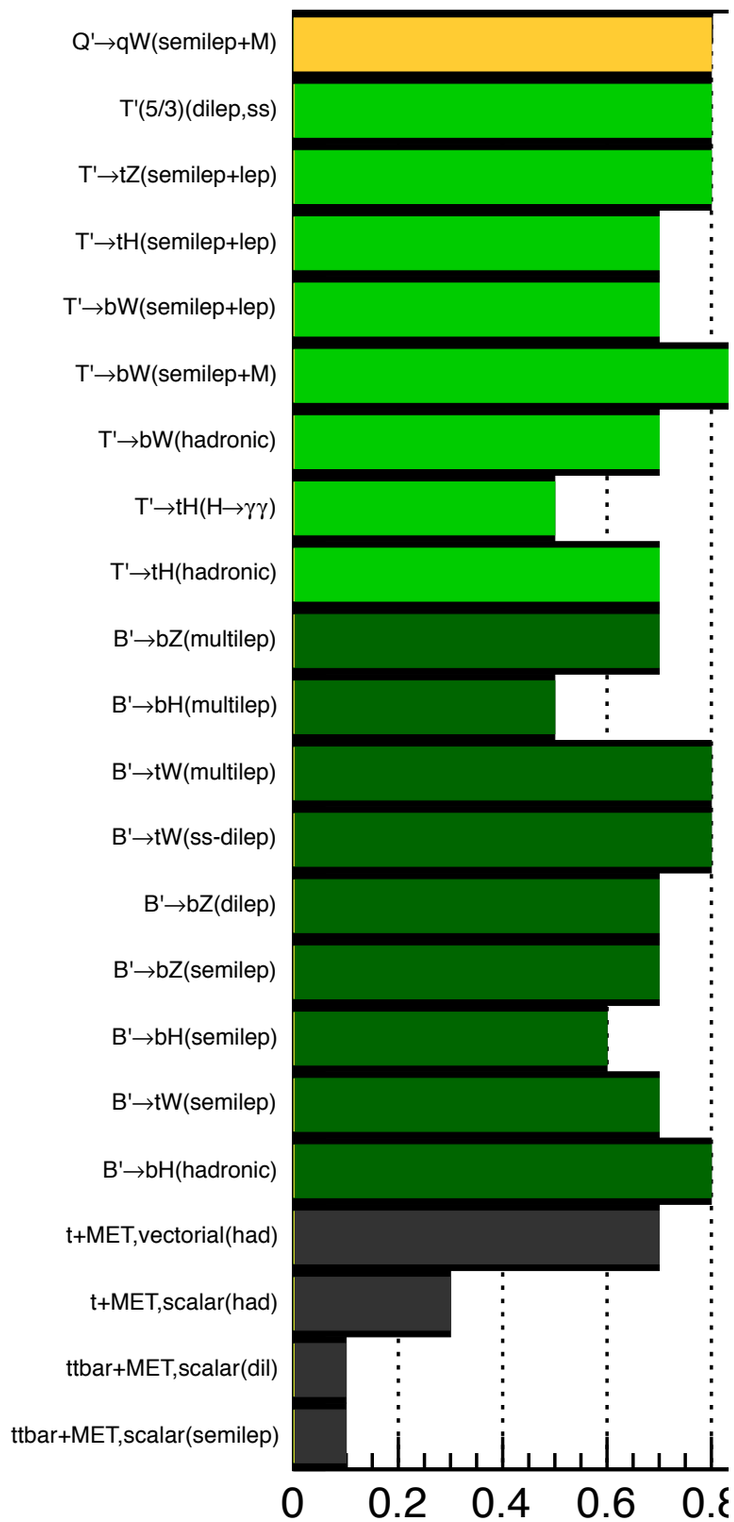

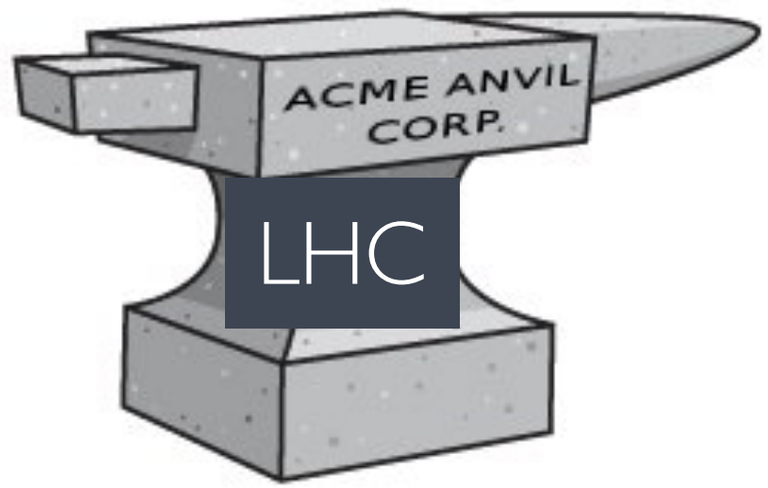

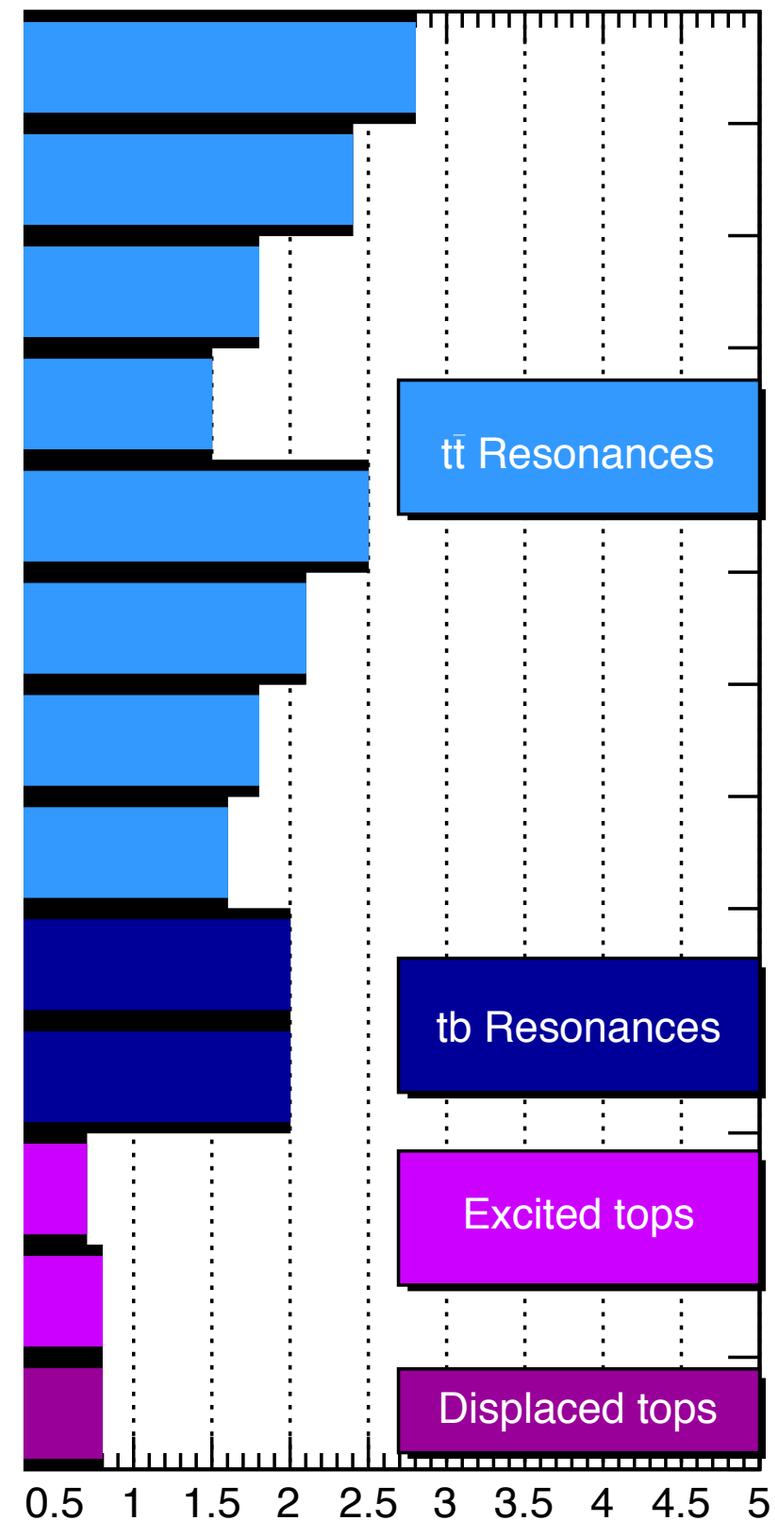

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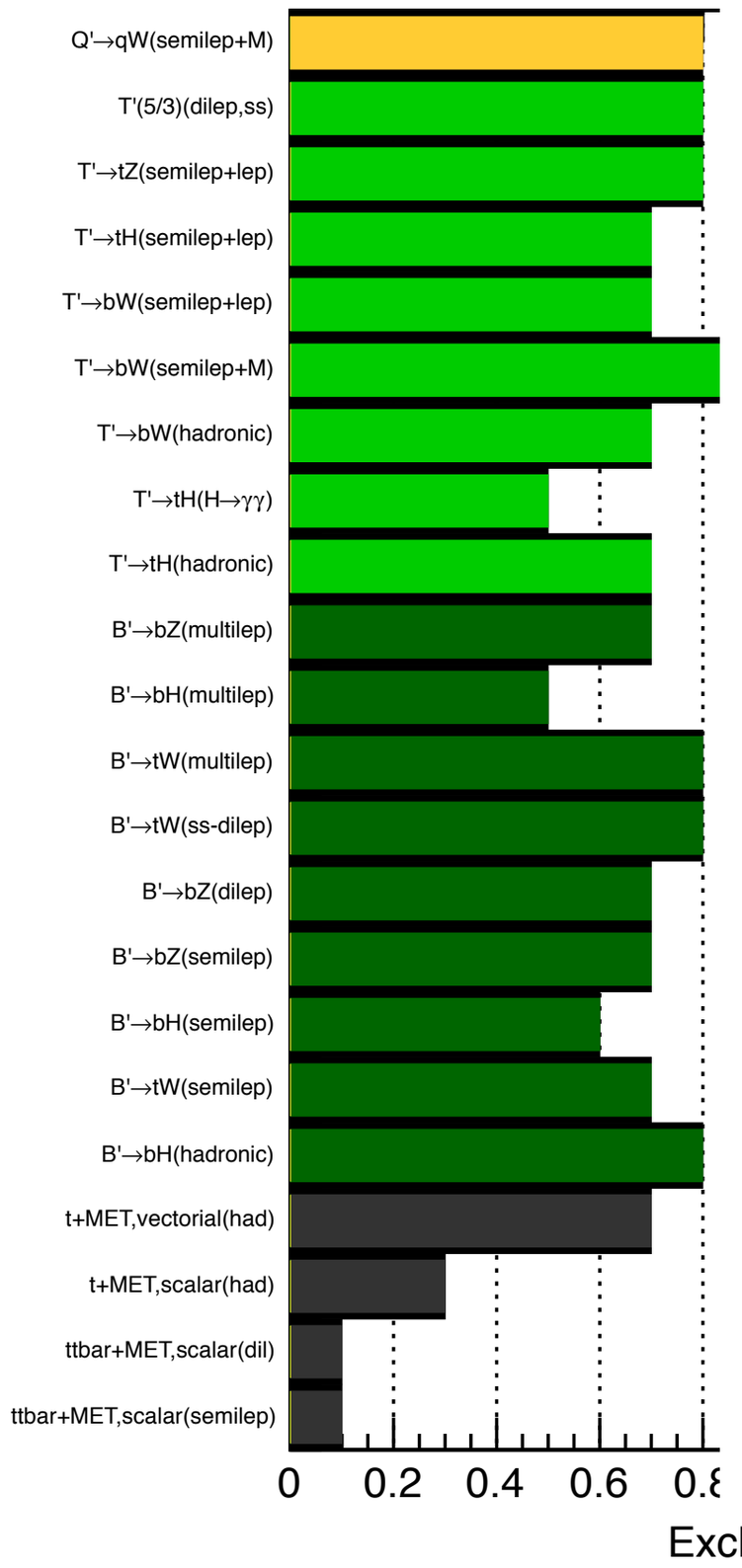
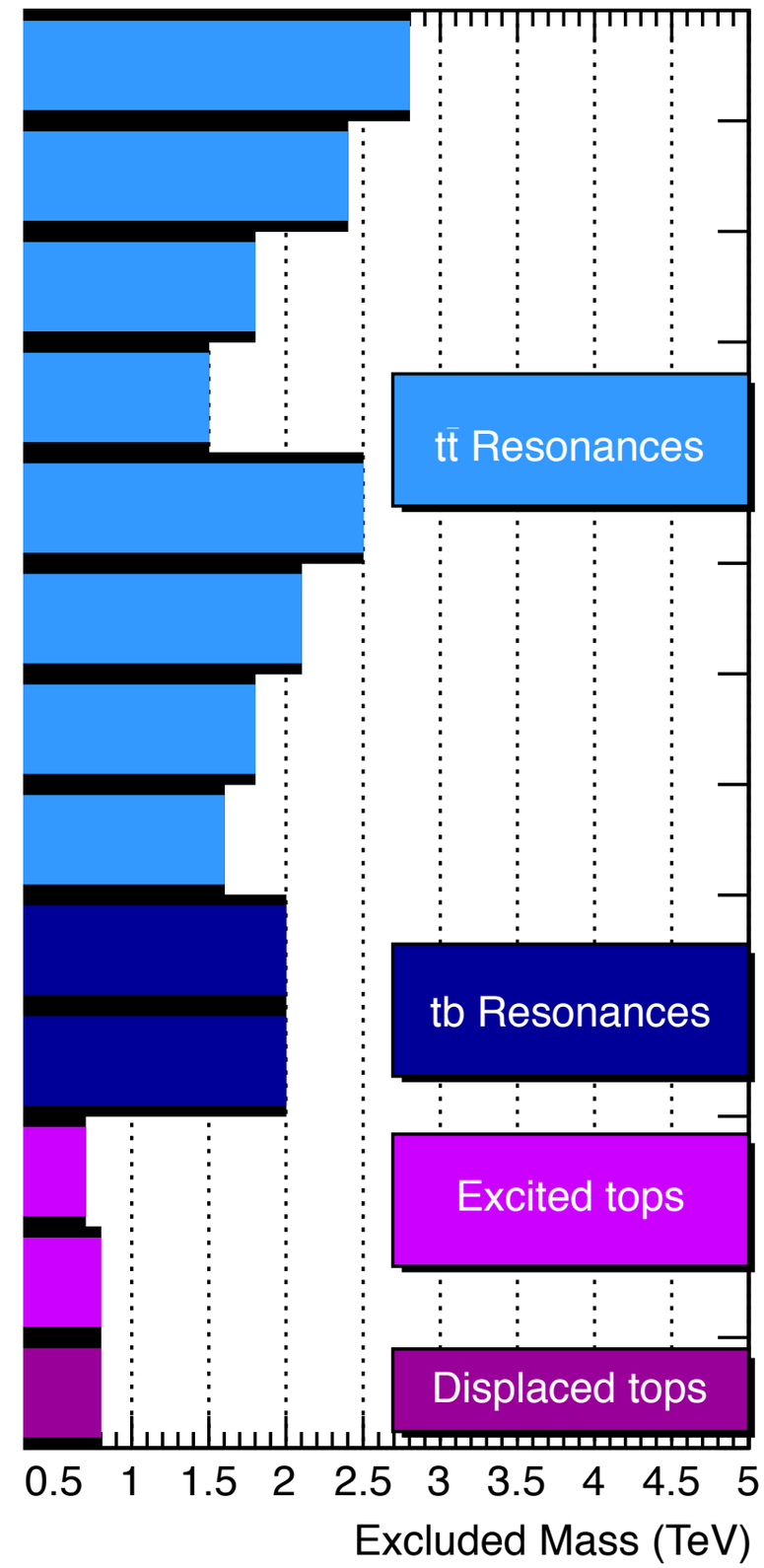


LHC

Naturalness



OUTLINE

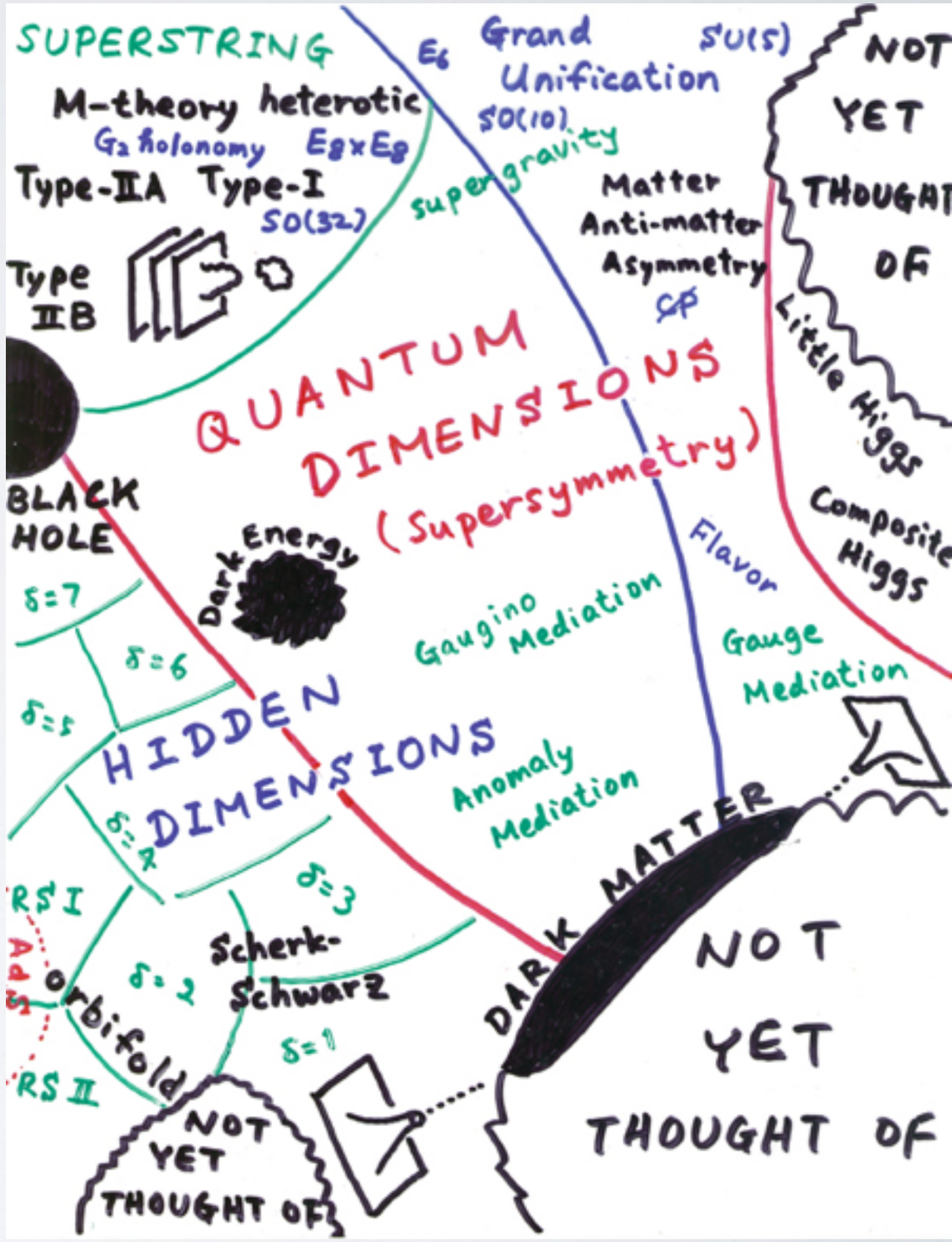
Non-Standard Theories

1. **Dynamical R-Parity Violation**

2. **Neutral Naturalness**

Non-Standard Signatures

3. **Long lived particles**



Hitoshi Murayama, 2003

LONG LIVED PARTICLES

FROM

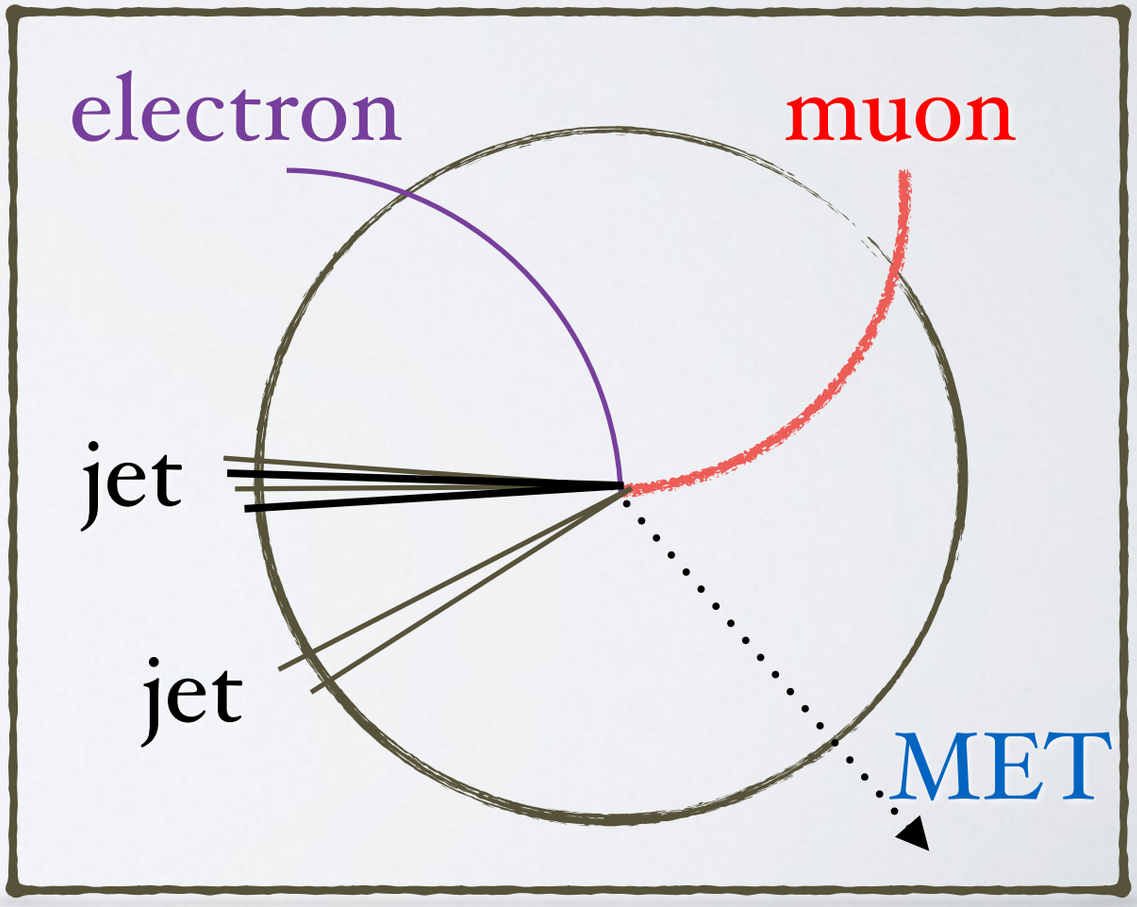
DYNAMICAL R-PARITY VIOLATION

C. Csaki, EK, T. Volansky, Phys.Rev.Lett. 112 (2014) 131801
C. Csaki, EK, O. Slone, T. Volansky, JHEP 1506 (2015) 045

WHERE IS SUPERSYMMETRY?

LHC Bounds typically assume large missing-energy, because the LSP is stable

Assumption of R-parity conservation



R-PARITY VIOLATION

Standard Operators

$$W = \lambda \left(L L \bar{e} + L Q \bar{d} + \bar{u} \bar{d} \bar{d} \right)$$

Couplings have to be very small

R-PARITY VIOLATION

C. Csaki, **EK**, T. Volansky, Phys.Rev.Lett. 112 (2014) 131801

Instead of only considering

$$W = \lambda \left(L L \bar{e} + L Q \bar{d} + \bar{u} \bar{d} \bar{d} \right)$$

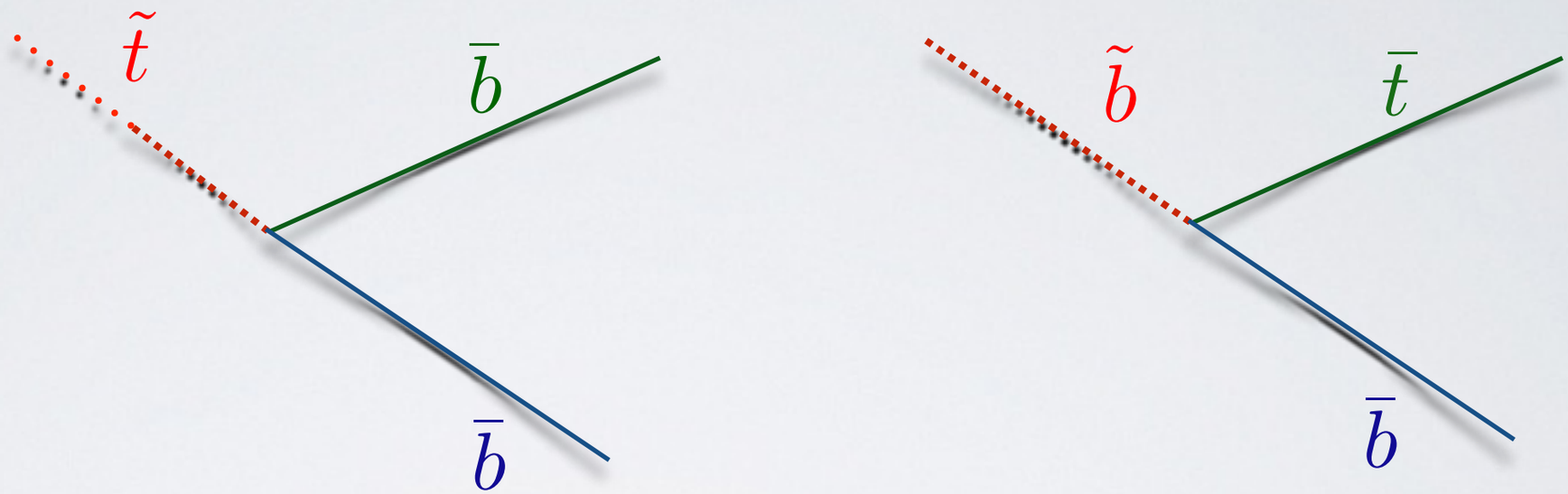
Let's also consider

$$K = \frac{1}{M} \left(\bar{u} \bar{e} \bar{d}^\dagger + Q \bar{u} L^\dagger + Q Q \bar{d}^\dagger \right)$$

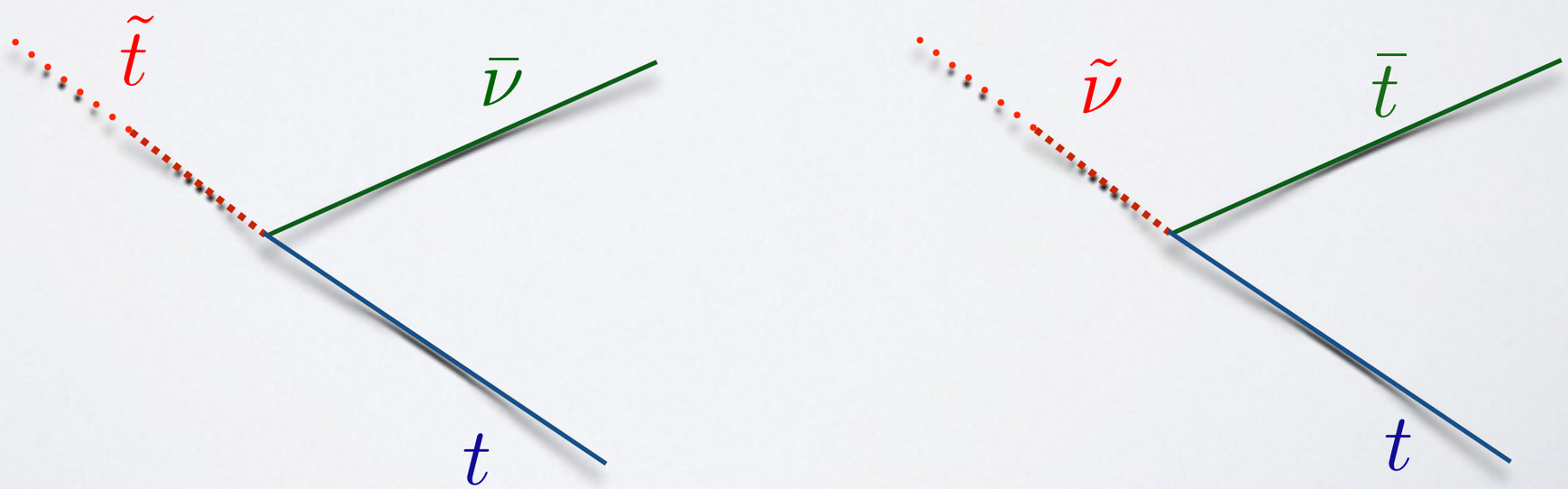
If we know R-parity violating operators are small,
why do we only consider renormalizable ones?

EXOTIC LSP DECAYS

$QQ\bar{d}^*$:



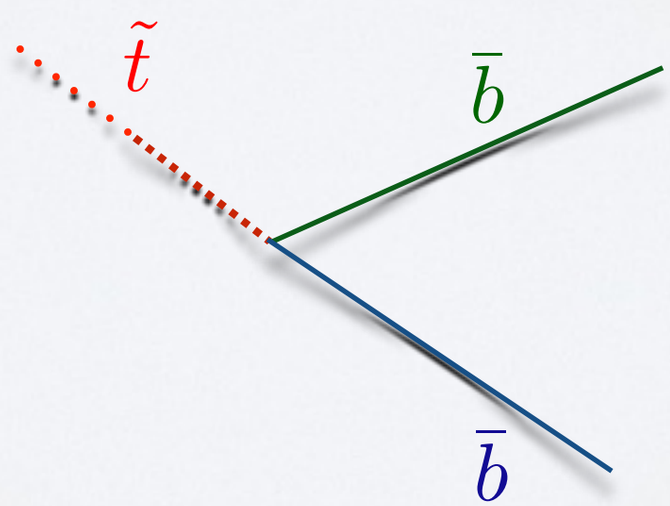
$Q\bar{u}L^*$:



LONG LIVED LSP

LSP decays to 3rd generation particles, and in much of the parameter space is displaced

$$c\tau_{\tilde{t}\to\tilde{b}\tilde{b}} \sim 10 \text{ cm} \left(\frac{300 \text{ GeV}}{m_{\tilde{t}}}\right)\left(\frac{M}{10^9 \text{ GeV}}\right)$$



LONG LIVED PARTICLES

FROM

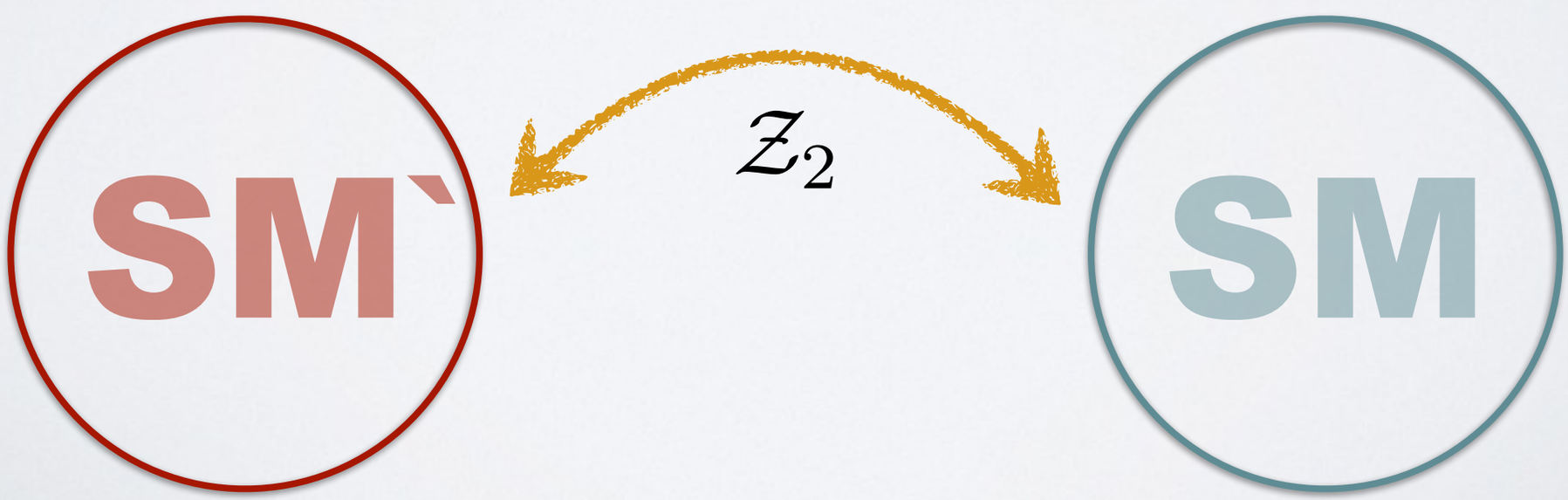
NEUTRAL NATURALNESS

THE TWIN HIGGS

Z. Chacko, H. Goh, R. Harnik, Phys.Rev.Lett. 96 (2006) 231802 [hep-ph/0506256]

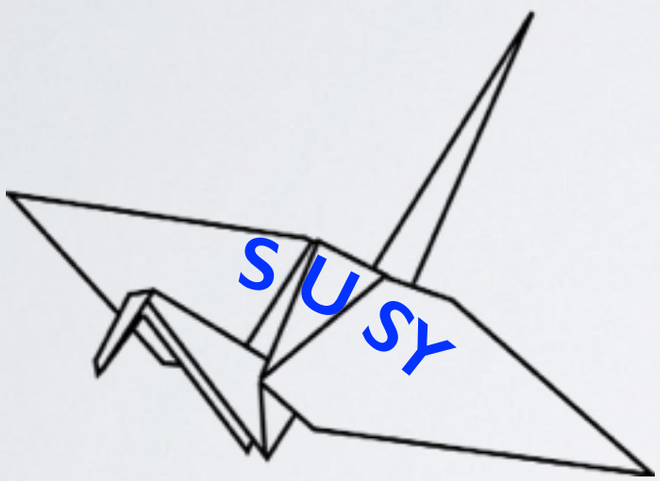
- Introduce a full copy of the SM, with same interaction strengths

- The "Twin" fields play the role of canceling the quadratic divergence



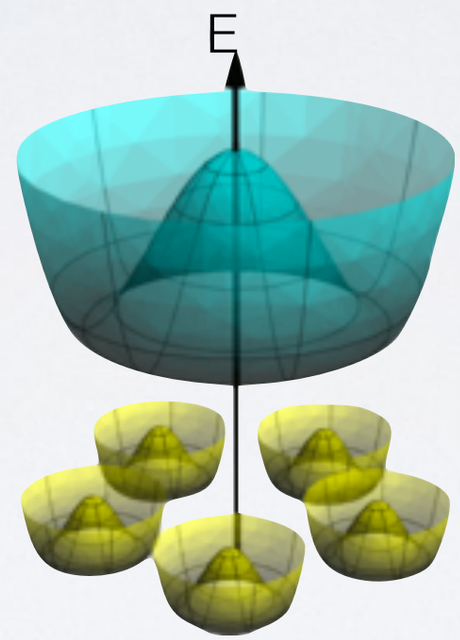
NEUTRAL NATURALNESS

Naturalness models of top partner
that are neutral under QCD



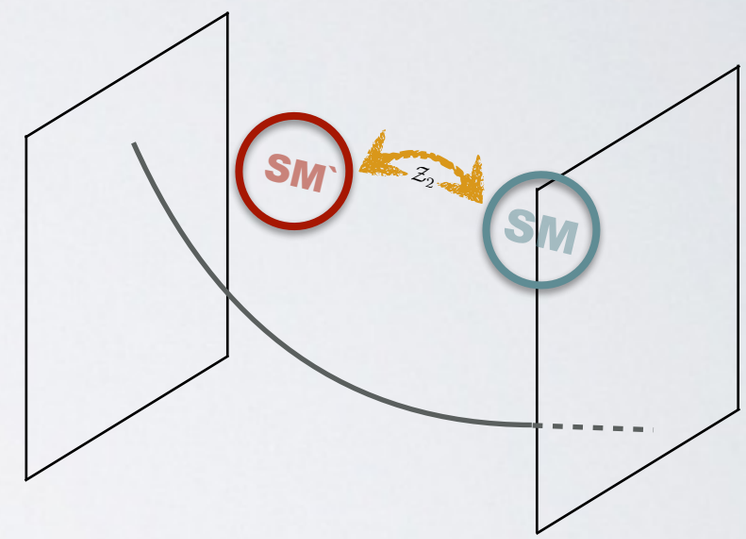
Folded Supersymmetry

G. Burdman, Z. Chacko,
H. Goh, R. Harnik



Orbifold Higgs

N. Craig, S. Knapen, P. Longhi

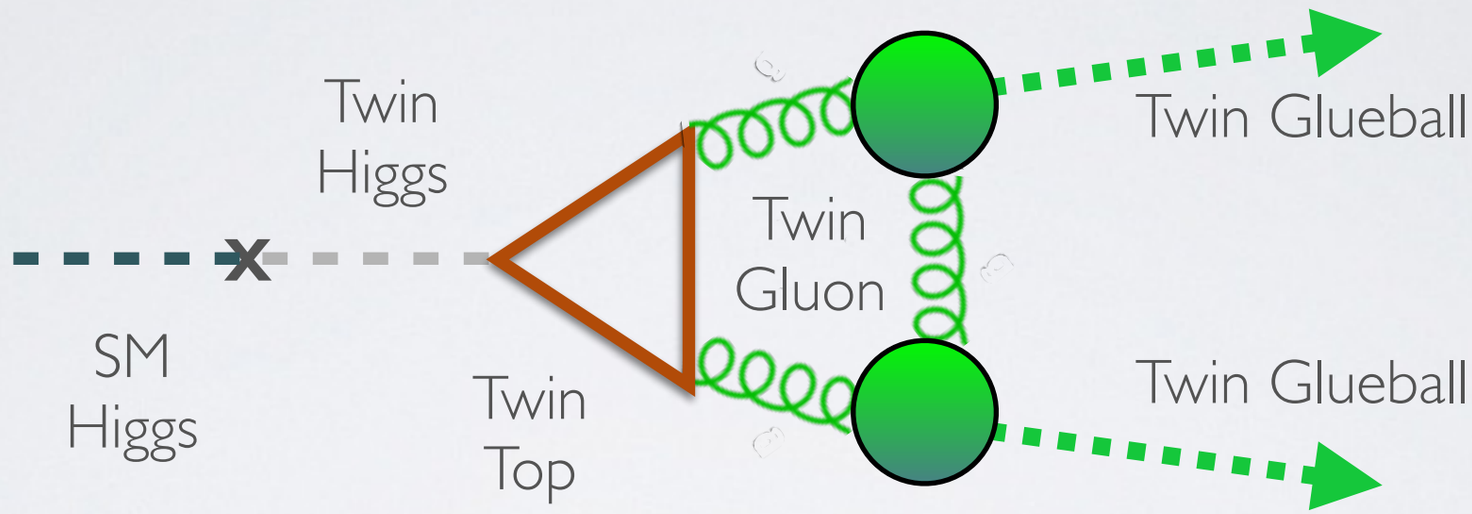


Holographic Twin Higgs

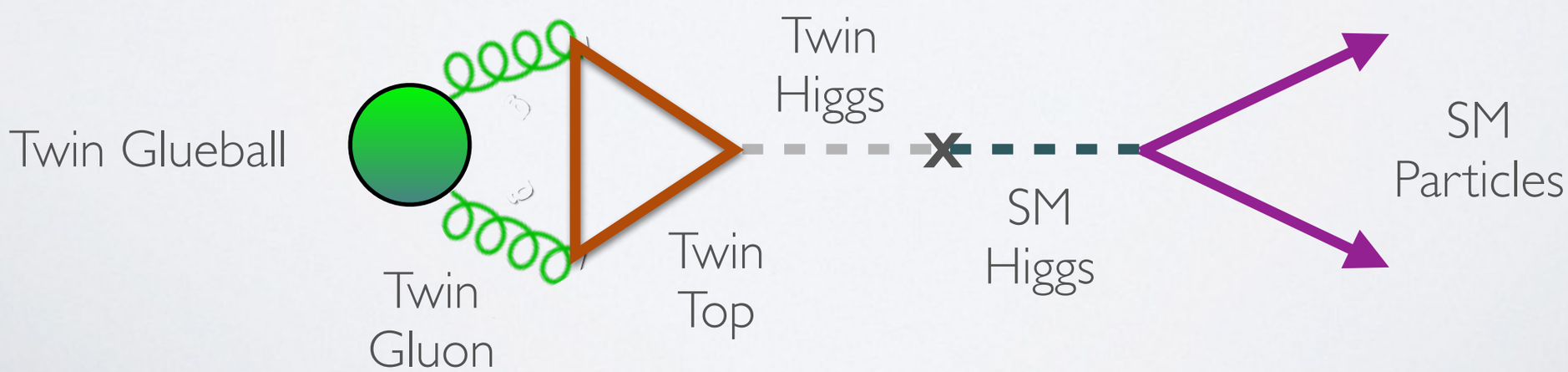
M. Geller, O. Telem

DISPLACED HIGGS

The SM Higgs can decay into Twin glueballs



Which then decay back to the SM



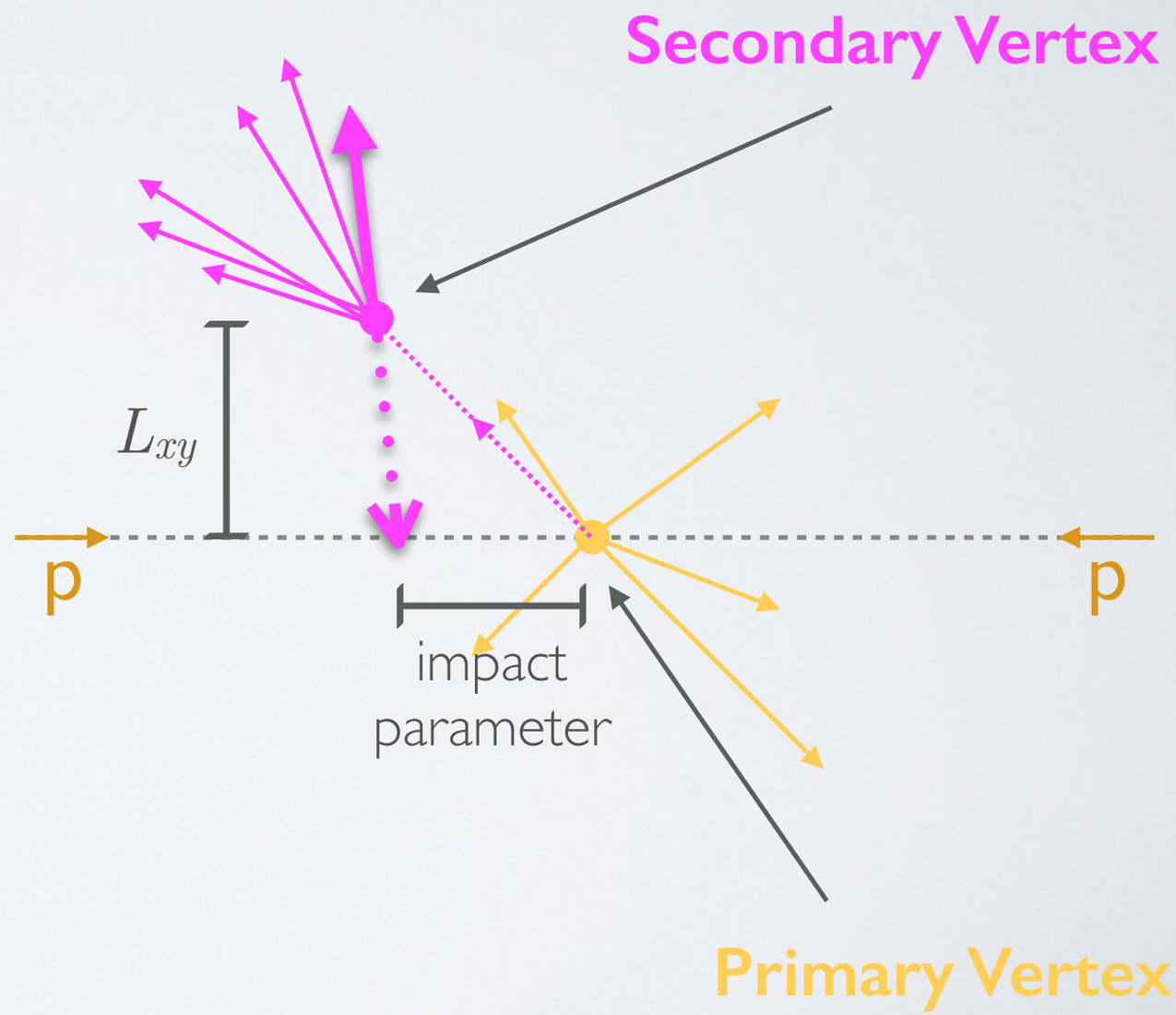
The search for displaced Higgs decays will be one of the most important tasks for Run II

DISPLACED SEARCHES AT THE LHC

DISPLACED VERTEX

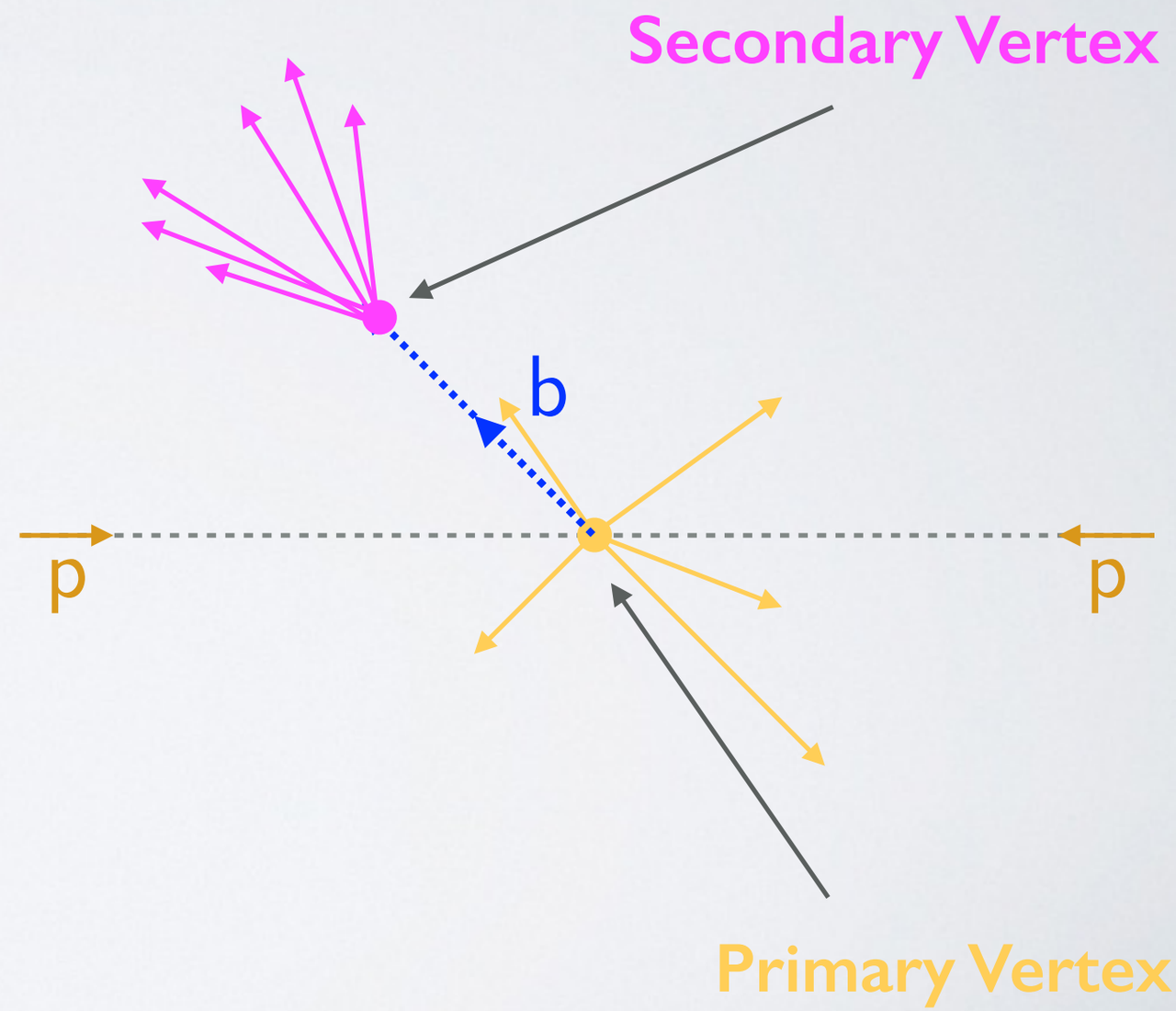
- Search for a vertex in the tracker that is not aligned with beam axis
- Sensitive to
  $L_{xy} \sim 50$ cm
  IP ~ 0.5 mm to 30 cm
- No Level 1 triggers

  Triggers require other hard objects



DISPLACED VERTEX

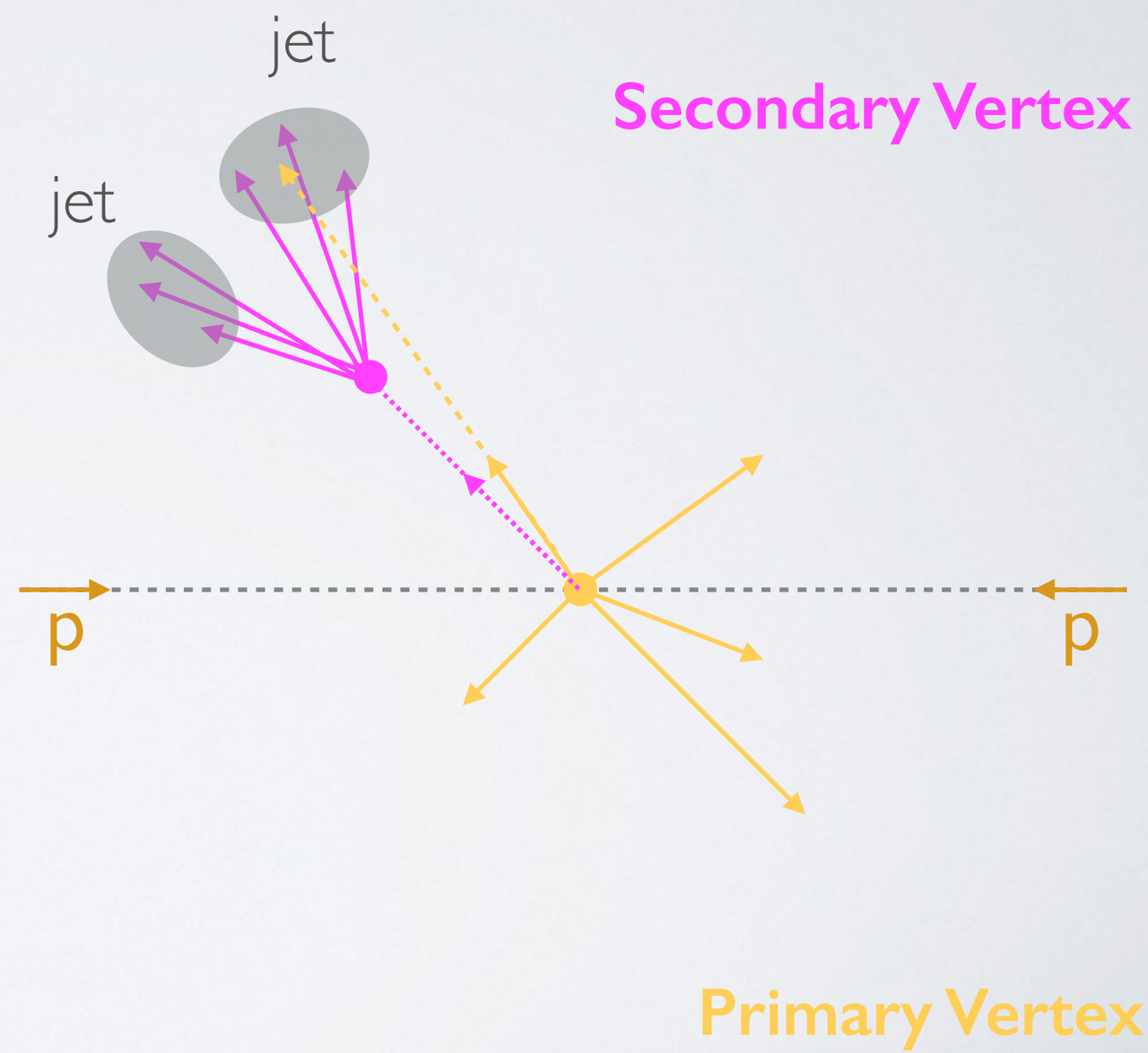
- Search for a vertex in the tracker that is not aligned with beam axis
- Backgrounds include:
  - Crossing tracks
  - Interactions with detector material
  - b-jets ($c\tau \sim 0.5$ mm)



CMS DISPLACED DIJET

Search for long-lived neutral particles decaying to quark-antiquark pairs in proton-proton collisions at sqrt(s) = 8 TeV

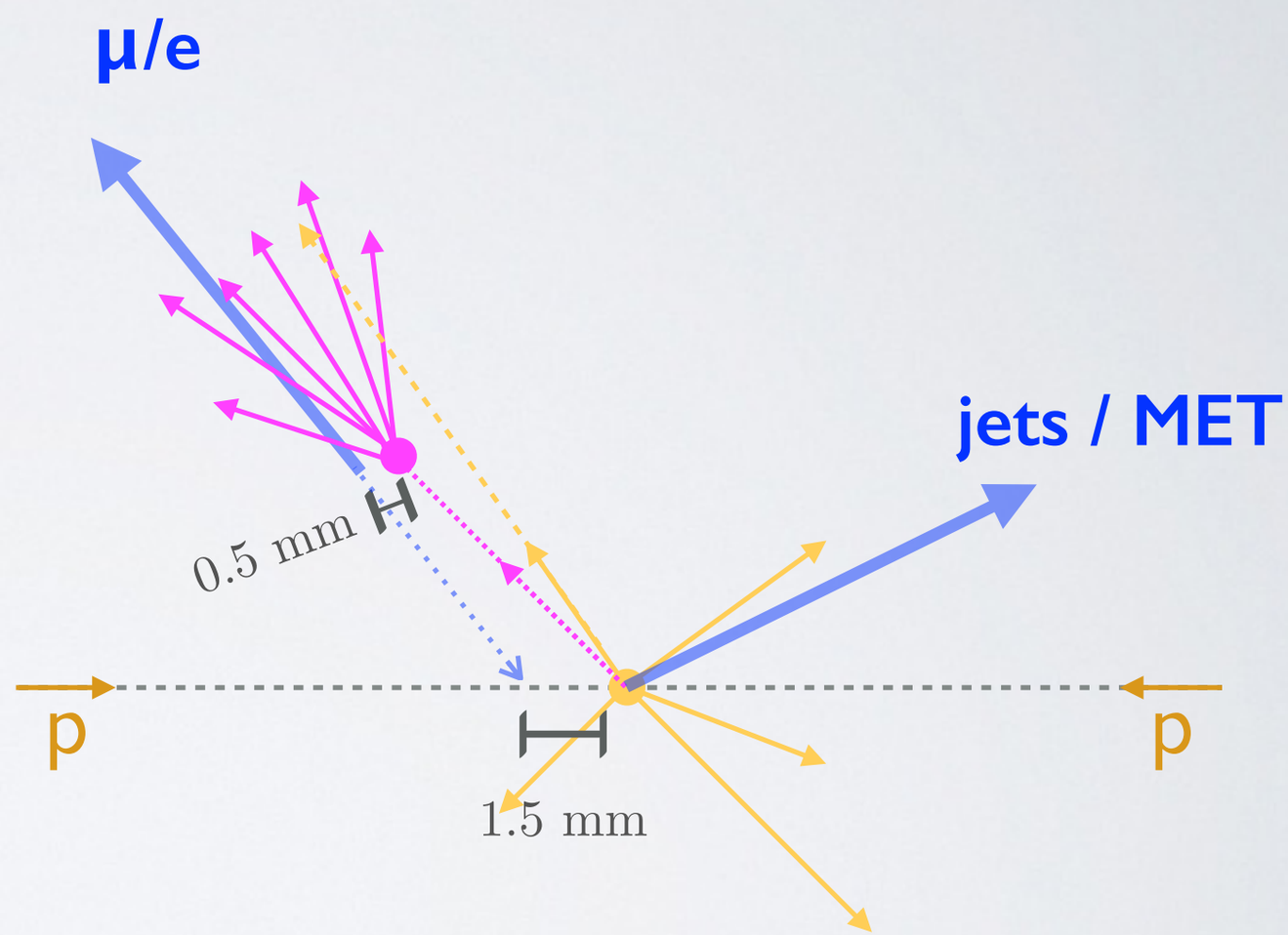
- Search for 2 displaced jets with p_T > 60 GeV (Leptons also counted as jets)
- Important cuts
  - H_T > 350 GeV (trigger)
  - m_{DV} > 4 GeV (no b's)
  - N_{tracks} > 4, 5
  - At most one prompt (IP <0.5 mm) track per jet
  - Dijet consistent with DV



ATLAS DV + *muon/e/jets/MET*

Search for massive, long-lived particles using multitrack displaced vertices or displaced lepton pairs in pp collisions at sqrt(s) = 8 TeV with the ATLAS detector

- Search for displaced vertex with
  - $N_{tracks} > 5$
  - $m_{DV} > 10$ GeV
- Trigger/cut on associated object
  - muon, $p_T > 55$ GeV
  - electron, $p_T > 125$ GeV
  - MET > 180 GeV
  - Jets 4, 5 or 6, $p_T > 65, 60, 55$ GeV



LHC PROBES OF DRPV

C. Csaki, E. Kuflik, S. Lombardo, O. Slone, T. Volansky JHEP 1508 (2015) 016

RPV SCENARIOS

- Looked at cases motivated by naturalness
- Light stops, gluinos, and higgsinos
- Only considered direct production of LSPs

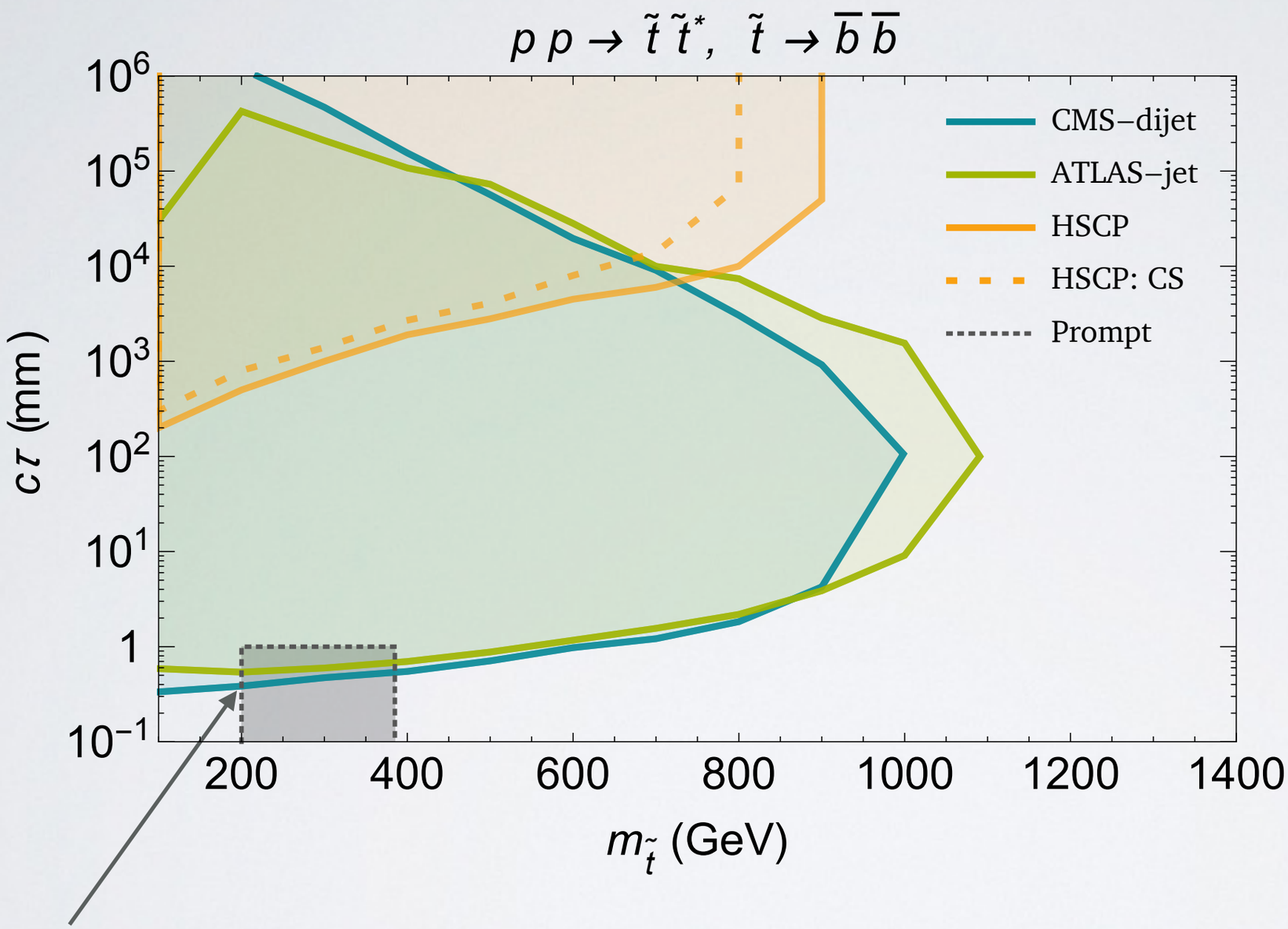
Topologies		
LSP	Decay	Operator
$\tilde{t}$	$\bar{d}\,\bar{d}'$	λ'', η''
	$u\,\bar{\nu}$	η'
	$d\,\ell^+$	λ', η
$\tilde{g}$	$t\,d\,d' + c.c$	λ'', η''
	$t\,\bar{u}\,\bar{\nu} + c.c$	η'
	$t\bar{d}\,\ell^- + c.c$	λ', η
$\tilde{H}^0/\tilde{H}^\mp$	$(t/b)\,d\,d' + c.c$	λ'', η''
	$(t/b)\,\bar{u}\,\bar{\nu} + c.c$	η'
	$(t/b)\,\bar{d}\,\ell^- + c.c$	λ', η

RECAST

- Feynrules→Madgraph→Pythia→Delphes
- Applied cuts and vertex reconstruction procedure for ATLAS+ CMS displaced vertex searches
- Use displaced tracking efficiency
- Recast HSCP at parton level
- Prompt searches applied directly

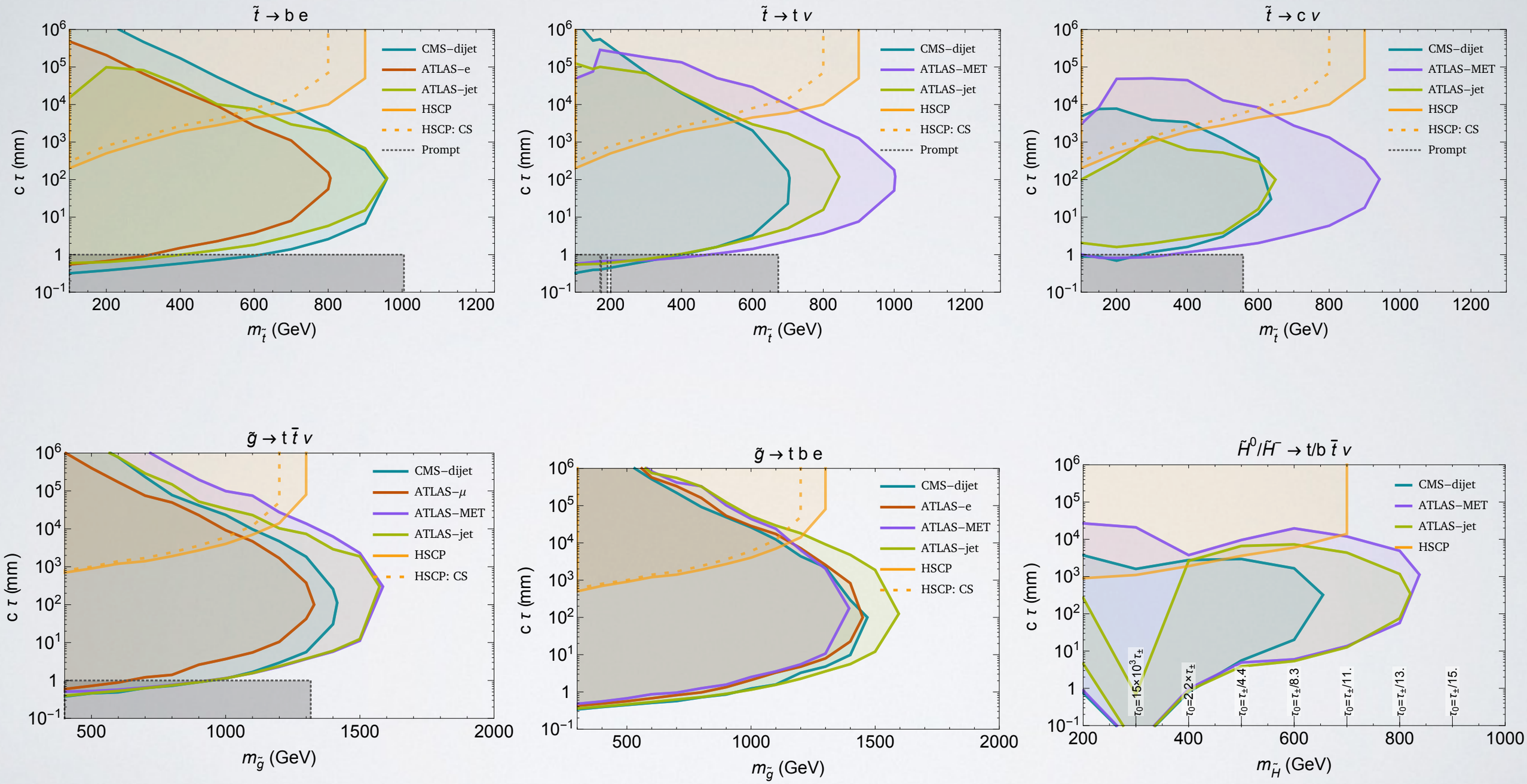
Topologies		
LSP	Decay	Operator
$\tilde{t}$	$\bar{d}\,\bar{d}'$	λ'', η''
	$u\,\bar{\nu}$	η'
	$d\,\ell^+$	λ', η
$\tilde{g}$	$t\,d\,d' + c.c$	λ'', η''
	$t\,\bar{u}\,\bar{\nu} + c.c$	η'
	$t\bar{d}\,\ell^- + c.c$	λ', η
$\tilde{H}^0/\tilde{H}^\mp$	$(t/b)\,d\,d' + c.c$	λ'', η''
	$(t/b)\,\bar{u}\,\bar{\nu} + c.c$	η'
	$(t/b)\,\bar{d}\,\ell^- + c.c$	λ', η

EXAMPLE



C. Csaki, **EK**, S. Lombardo, O. Slone, T. Volansky JHEP 1508 (2015) 016

Search for pair-produced resonances decaying to jet pairs in proton-proton collisions at sqrt(s) = 8 TeV (CMS, 1412.7706)



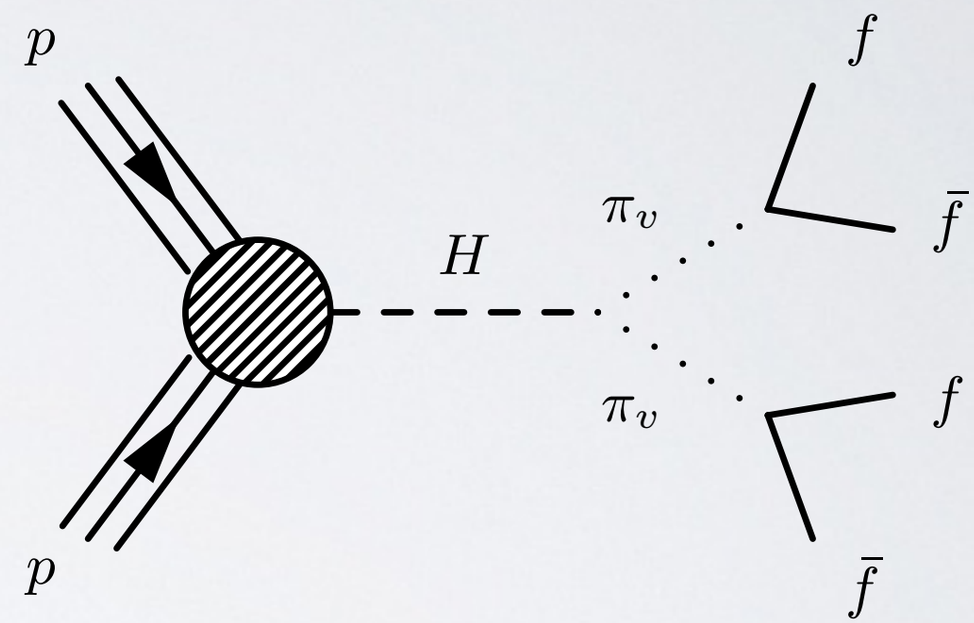
C. Csaki, **EK**, S. Lombardo, O. Slone, T. Volansky JHEP 1508 (2015) 016

PROBES OF DISPLACED HIGGS

C. Csaki, EK, S. Lombardo, O. Slone Phys.Rev. D92 (2015) 073008

DISPLACED HIGGS

- Look for Higgs decay to two light particles
- Light particles decay to SM pairs
- Assume branching ratios proportional to Higgs couplings.

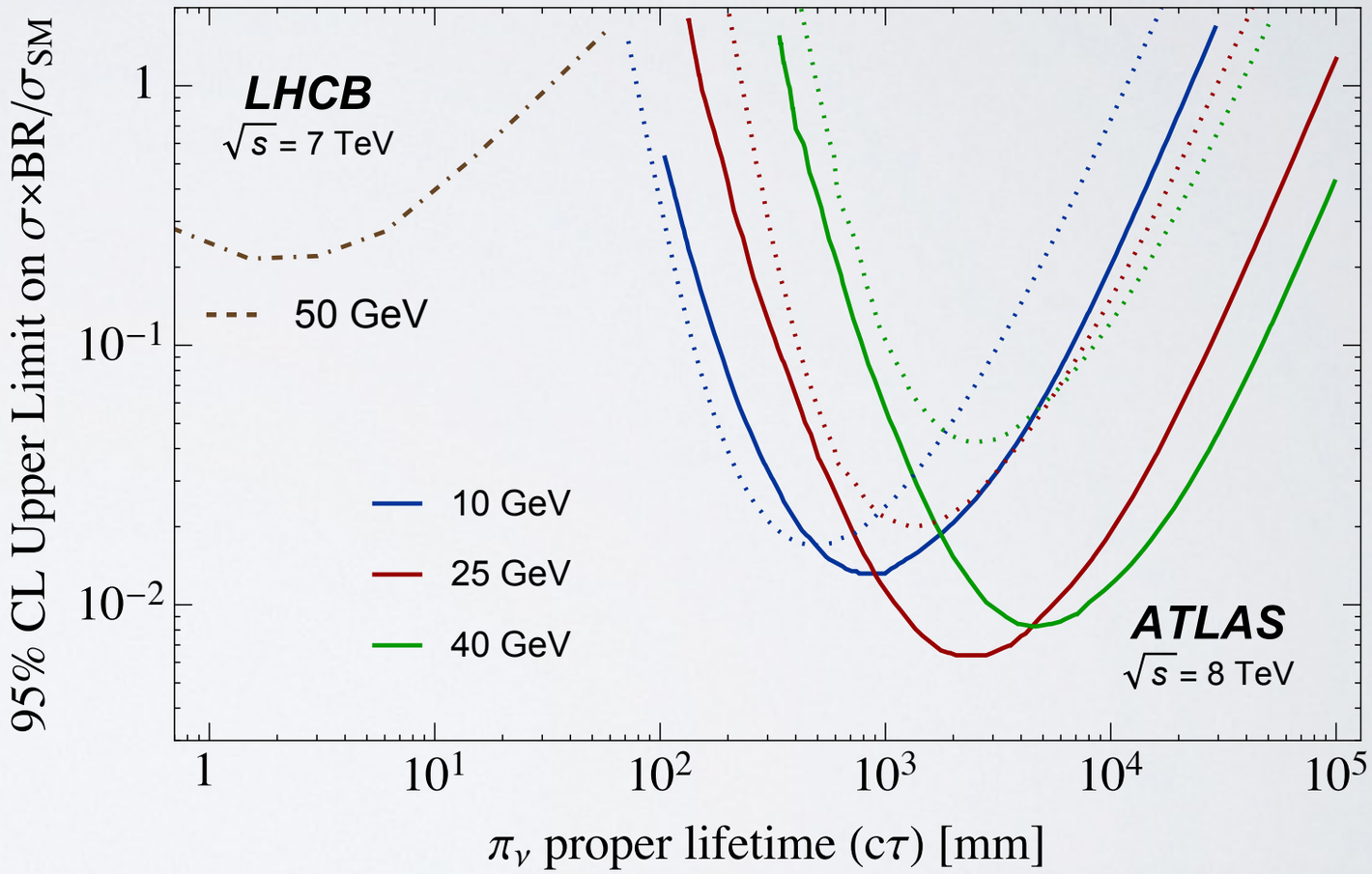


$$m_{\pi_\nu} = 10,\ 25,\ 40\ \mathrm{GeV}$$

EXISTING CONSTRAINTS

- ATLAS search for decays in the HCAL
- ATLAS search for decays in the muon system
- LHCB search for displaced vertices (0.26 fb^{-1})

(Bartlomiej Rachwal @ 17:20)



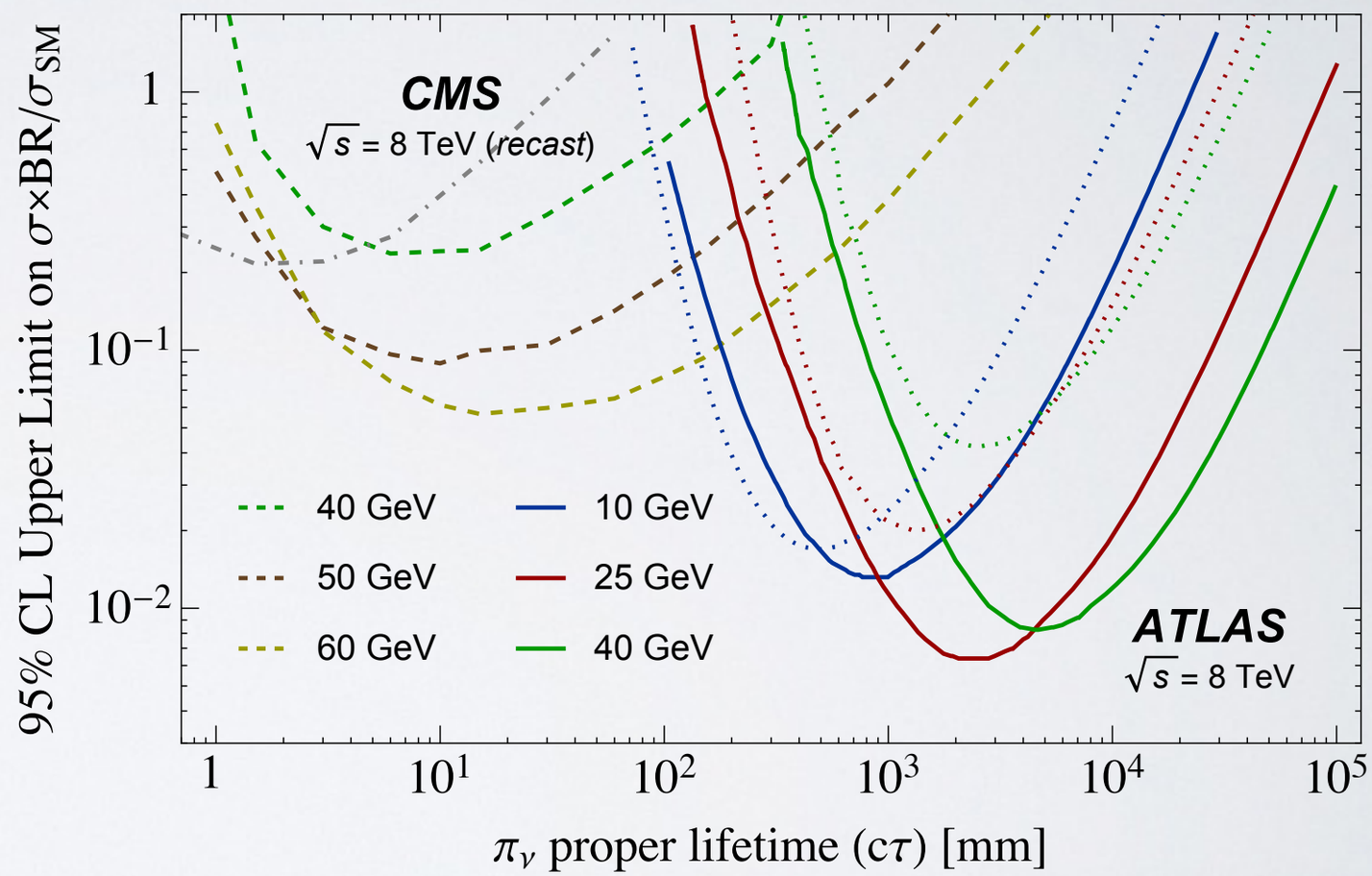
Twin Higgs: BR~10^{-4}

EXISTING CONSTRAINTS

- ATLAS DV search is not sensitive due to strong triggers for leptons, jets and MET
- Recast CMS dijet analysis - dedicated displaced trigger allows some coverage, but $H_T > 350$ GeV decreases efficiency.
- Picks up boosted Higgs or w/ISR

8 TeV

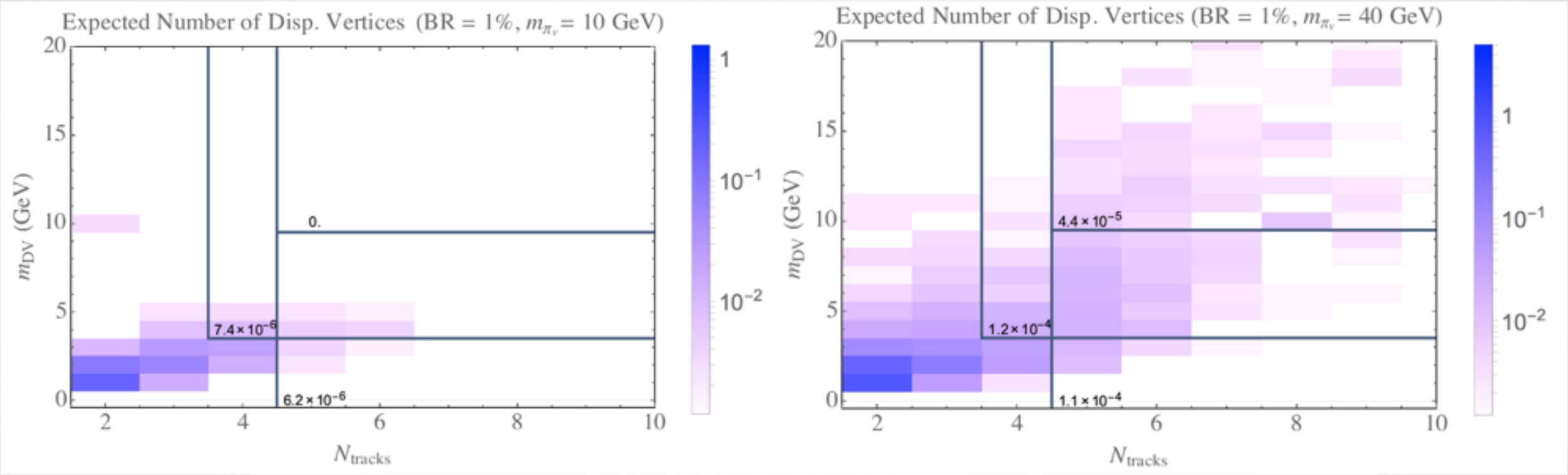
Recast: C. Csaki, EK, S. Lombardo, O. Slone



Twin Higgs: BR~10^{-4}

RUN I SHORTCOMINGS

- Run I strategies not sufficient:
  - Triggers were too strong - required more energy than a typical Higgs event
  - Cuts on the displaced vertex too strong for light objects
- Need a more model-dependent search for lighter objects



Propose new search strategies.

RUN II - TRIGGERS

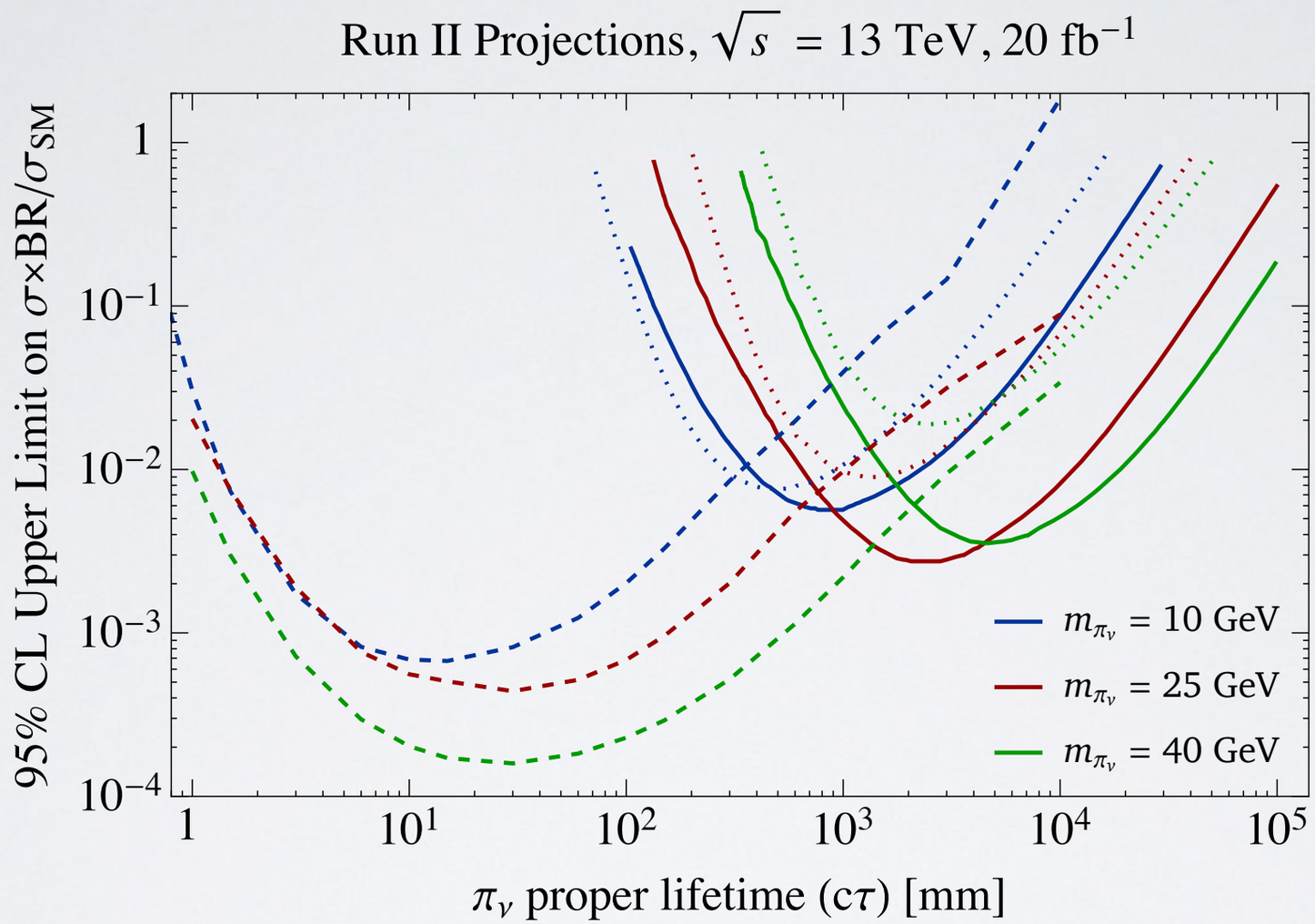
- New CMS dijet trigger best for 1 mm to 10 cm. But new 4 x larger impact parameter than Run I
- For lifetimes smaller than 1 mm, use prompt triggers

Trigger	Trigger Requirement
Displaced jet	$H_T > 175$ GeV or three jets with $p_T^{j_{1,2,3}} > (92, 76, 64)$ GeV, $\lvert\eta_{j_{1,2,3}}\rvert < (5.2, 5.2, 2.6)$ with $\lvert\eta_{j_1}\rvert$ or $\lvert\eta_{j_2}\rvert < 2.6$, and two of the three jets satisfying $m_{jj} > 500$ GeV, and $\Delta\eta > 3.0$. A displaced jet satisfying $p_T > 40$ GeV, at most 1 prompt track (2D IP $<$ 2.0 mm) [a], and at least 2 displaced tracks.
Inclusive VBF	Two jets with $\lvert\eta_{j_1,j_2}\rvert > 2$, $\eta_{j_1} \cdot \eta_{j_2} < 0$, $\lvert\eta_{j_1} - \eta_{j_2}\rvert > 3.6$ and $m_{j_1,j_2} > 1000$ GeV.
VBF, h $\rightarrow b\bar{b}$	Three jets with $p_T^{j_{1,2,3}} > (112, 80, 56)$ GeV and $\lvert\eta_{j_{1,2,3}}\rvert < (5.2, 5.2, 2.6)$ and at least one of the two first jets with $\lvert\eta_{j_1}\rvert$ or $\lvert\eta_{j_2}\rvert < 2.6$.
Isolated Lepton	One lepton with $p_T > 25$ GeV, $\lvert\eta\rvert < 2.4$, and 3D IP < 1 mm. Isolation requires the summed p_T of all tracks with $p_T > 1$ and within $\Delta R < 0.2$ of the lepton is less than 10% of the lepton p_T.
Trackless jets	A jet with $p_T > 40$ GeV and $\lvert\eta\rvert < 2.5$ matched with a muon with $p_T > 10$ GeV within $\Delta R = 0.4$. No tracks with $p_T > 0.8$ GeV in the ID within a $\Delta\phi \times \Delta\eta$ region of 0.2×0.2.

PROPOSED SEARCH STRATEGIES

- **Search I**: Single DV with $m_{DV} \geq 10$ GeV and $N_{tracks} \geq 5$ tracks based on ATLAS search. Good for high mass ≥ 40 GeV
- **Search II**: One DV with $N_{tracks} \geq 5$, no mass requirement (allow softer objects), but reproduce Higgs and intermediate particle masses
- **Search III**: Single DV with $m_{DV} \geq 4$ GeV and $N_{tracks} \geq 4$ tracks based on CMS search.
- **Search IV**: Same DV requirements as III but within a displaced jet with 2-prong substructure.
- **Search V**: Search for 2 DVs ($N_{tracks} \geq 5$) in the same event, comparable to an ATLAS search.

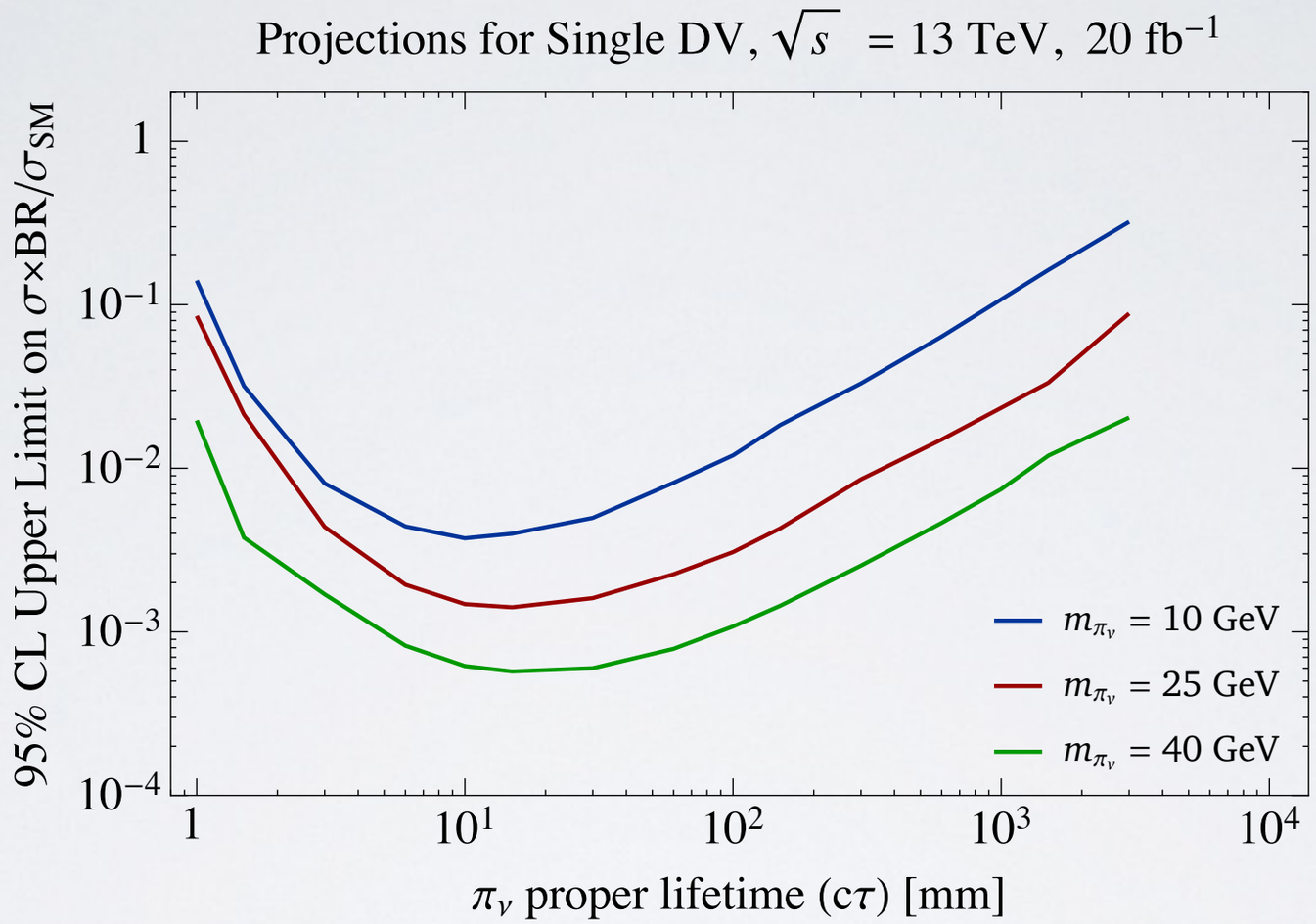
COMBINED PROJECTIONS



C. Csaki, **EK**, S. Lombardo, O. Slone Phys.Rev. D92 (2015) 073008

Can probe

SINGLE DV

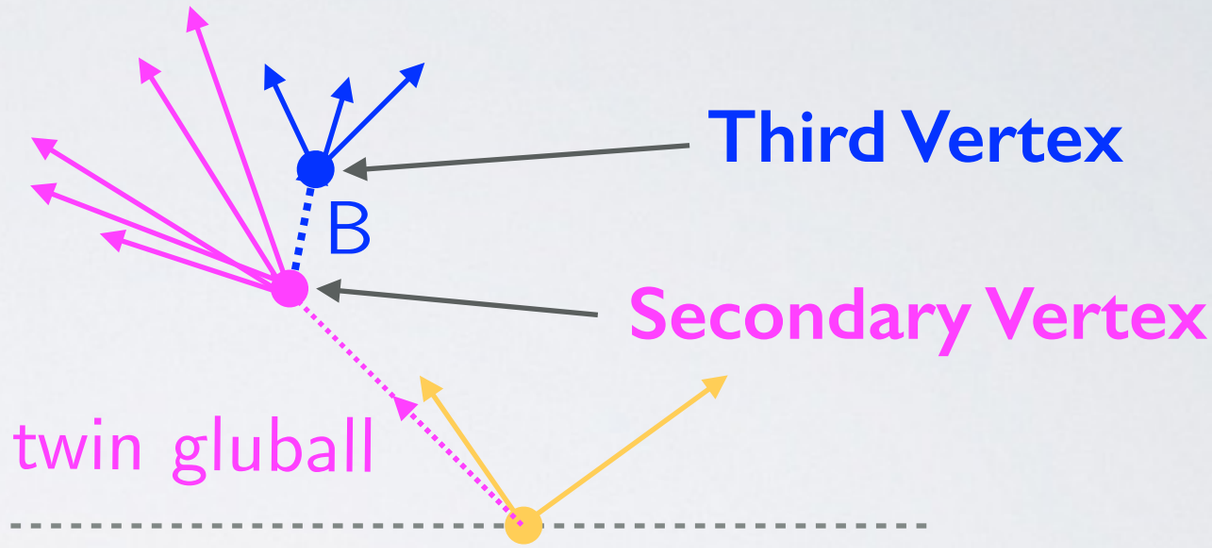


- **Combined Search III and IV**: sensitivity for case with just **one displaced vertex**, assuming the second particle just escapes the detector.

Unconstrained by existing DV searches

WHAT CAN WE DO?

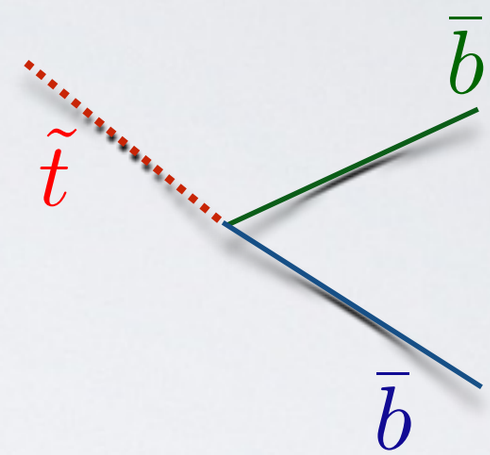
- Look for a third vertex from the B-decay.
- Improve triggers



- Robust model independent searches are excellent, but designed search could improve the reach.
- "LHCb has a unique coverage for long-lived particles with relatively small mass and lifetime, because its trigger makes only modest requirements on transverse momentum." - LHCb-PAPER-2014-062

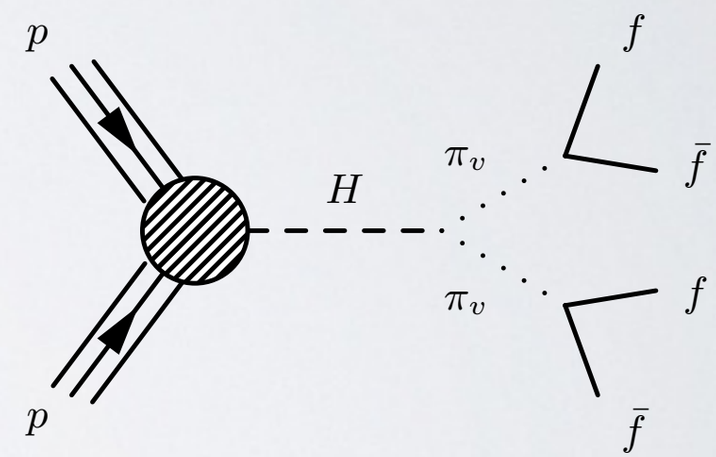
SUMMARY

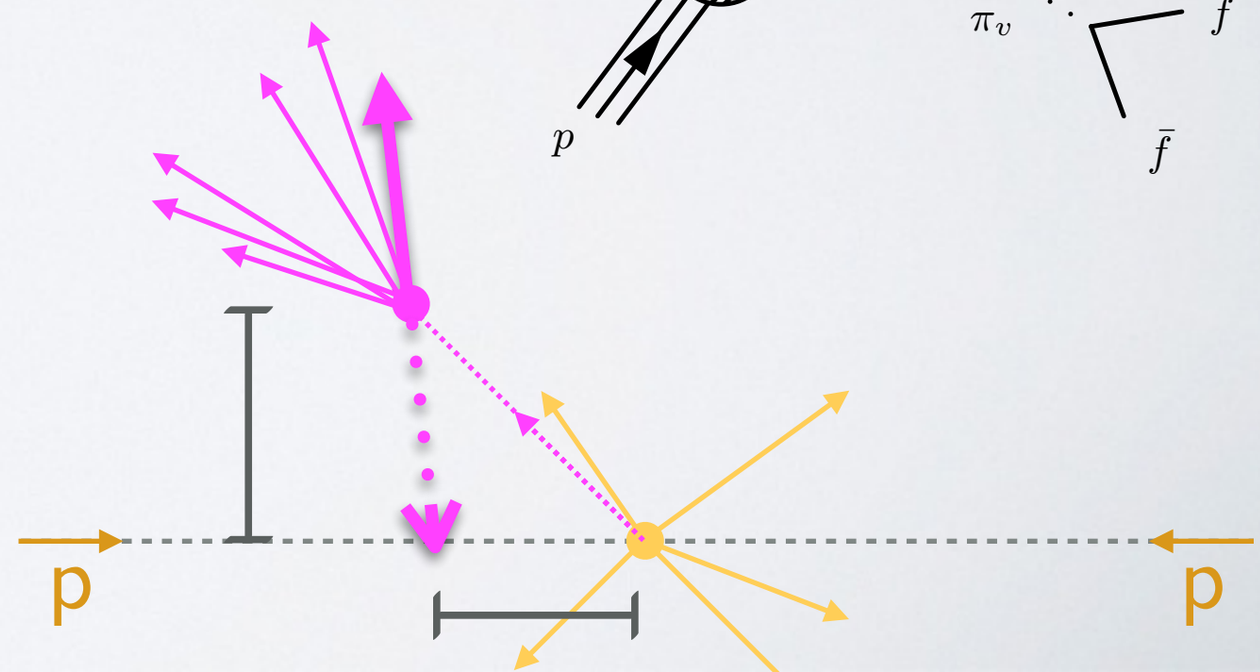
Non-Standard Theories



1. **Dynamical R-Parity Violation**

2. **The Twin Higgs**



Non-Standard Signatures

3. **Long lived particles**