SUSY highlights -- current results and future prospects

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on behalf of the CMS and ATLAS collaborations

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

25th Rencontres Vietnam
Qui Nhon, Vietnam 2018
Windows on the Universe

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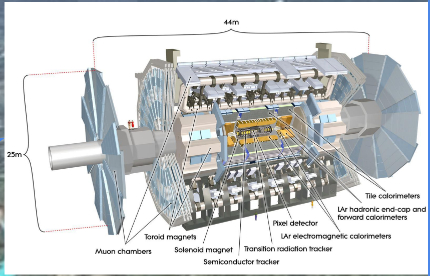
ATLAS EXPERIMENT

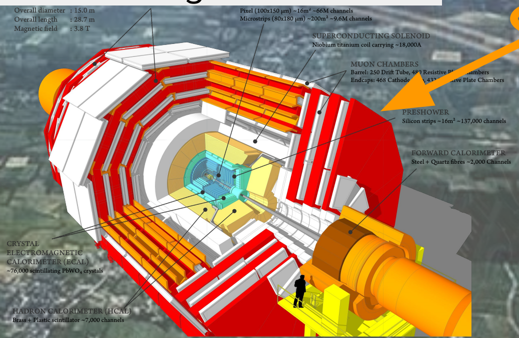
CMS
Compact Muon Solenoid

Detectors on the Large Hadron Collider

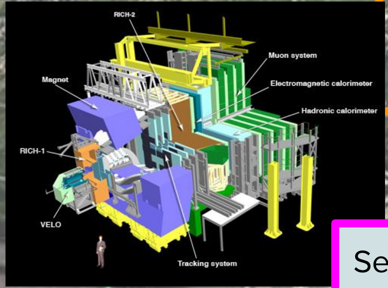
A Toroidal LHC ApparatuS:
25m high (vs 15m in CMS), 25 m wide, and 46m long
The inner detector has 3 air core **toroidal magnets** and one solenoidal magnet .



Compact Muon Solenoid
14000 tons: 1.5* Eiffel tower weight, half the size of ATLAS
Largest superconducting and most powerful solenoid magnet ever made



LHC beauty:
A single-arm **forward** spectrometer designed for the study of particles containing b or c quarks.



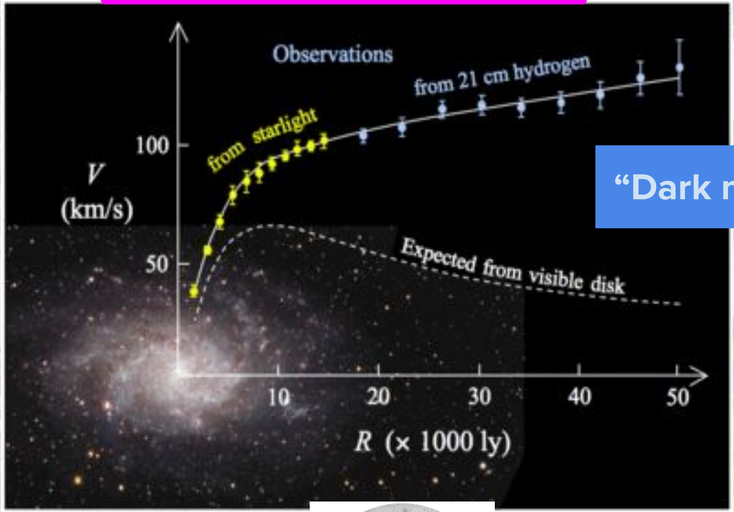
Other detectors: MoEDAL, TOTEM, LHCforward, ALICE

See also detector status talks yesterday by J. Butler (CMS), T. Nayak (ALICE), G. Passaleva (LHCb), A. Polini (ATLAS)

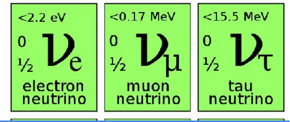
https://cms-docdb.cern.ch/cgi-bin/PublicDocDB/RetrieveFile?docid=11514&version=1&filename=cms_120918_03.png

Beyond the standard model of particle physics (BSM)

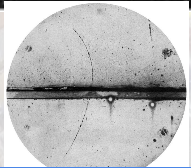
Unexplained phenomena



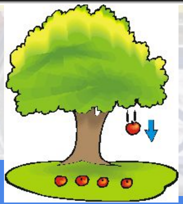
"Dark matter"



Neutrino masses



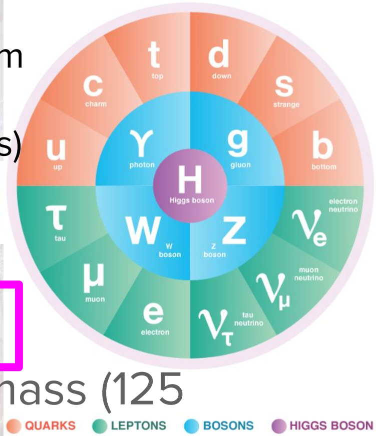
Matter/anti matter asymmetry



Gravity

Standard Model: internal symmetries from which follow matter (quarks, particles leptons) and force carriers (gauge bosons)

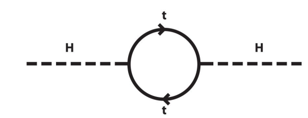
Internal symmetry: SU(3) x SU(2) x U(1)



Theoretically unsatisfactory

- the value of the Higgs mass (125 GeV) despite its large quantum corrections

$$(m_H)^2 = (m_0)^2 + \mathcal{O}(10^{19})\ \text{GeV} = (125\ \text{GeV})^2$$



- Vanishing strong CP violating term
- Mass hierarchy
- Three generations
- ...

See talk by GIno Isidori yesterday

https://upload.wikimedia.org/wikipedia/commons/thumb/6/69/PositronDiscovery.jpg/800px-PositronDiscovery.jpg

https://science.energy.gov/~/media/hep/images/research/Frontiers/Standard_Model.png

https://upload.wikimedia.org/wikipedia/commons/thumb/e/ec/M33_rotation_curve_HI.gif/400px-M33_rotation_curve_HI.gif

http://idahoptv.org/sciencetrek/topics/gravity/images/tree_and_apple.png

http://www.science20.com/files/images/particles.png

Physics beyond the standard model: supersymmetry

- Required symmetry in supergravity
- The only possible way to combine spacetime and internal symmetries

Internal symmetries: SU(3) x SU(2) x U(1)

Space-time symmetries: **Poincaré group**

Translations $[P_\mu, P_\nu] = 0$

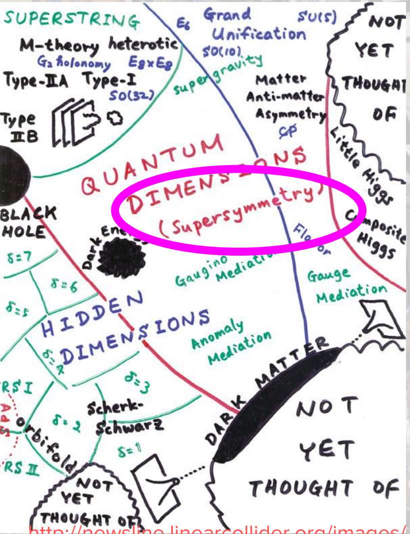
$$\frac{1}{i}[M_{\mu\nu}, P_\rho] = \eta_{\mu\rho}P_\nu - \eta_{\nu\rho}P_\mu$$

$$\frac{1}{i}[M_{\mu\nu}, M_{\rho\sigma}] = \eta_{\mu\rho}M_{\nu\sigma} - \eta_{\mu\sigma}M_{\nu\rho} - \eta_{\nu\rho}M_{\mu\sigma} + \eta_{\nu\sigma}M_{\mu\rho},$$

Lorentz group (boosts, rotations)

$$\{Q_\alpha, \bar{Q}_\beta\} = 2\gamma^\mu_{\alpha\beta}P_\mu$$

Poincaré algebra
SUSY algebra



There are many BSM models!

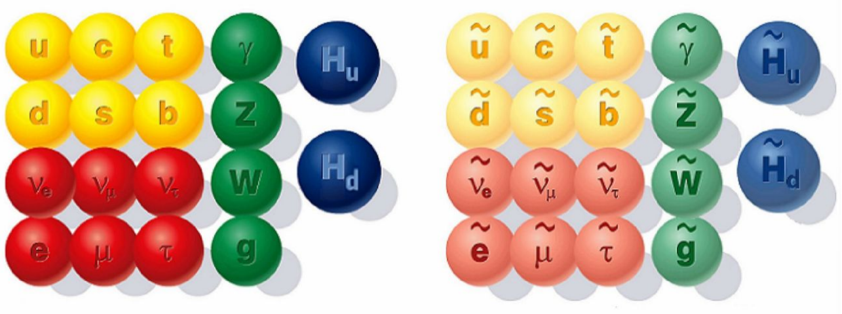
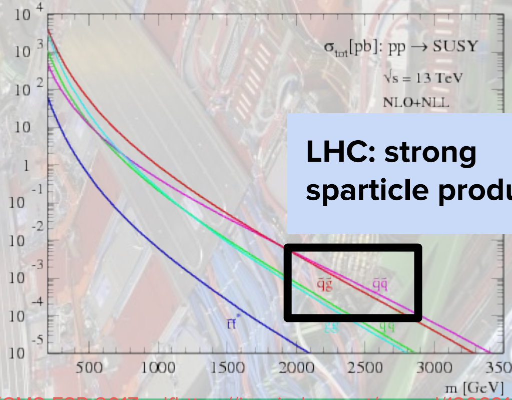


Figure: Jan Heisig, DESY

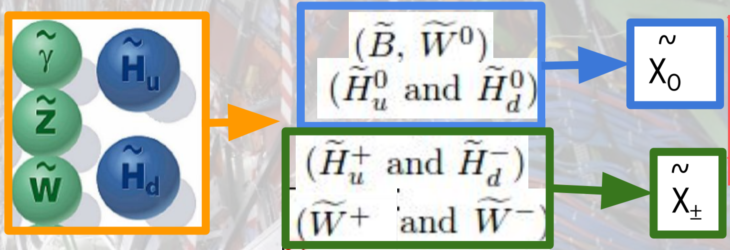


LHC: strong sparticle production

http://newsline.linearcollider.org/images/2010/20100401_dc_2.jpg

https://indico.cern.ch/event/647001/contributions/2691416/attachments/1535782/2405800/CMS-FSP-2017.pdf https://inspirehep.net/record/1306918/plots#0

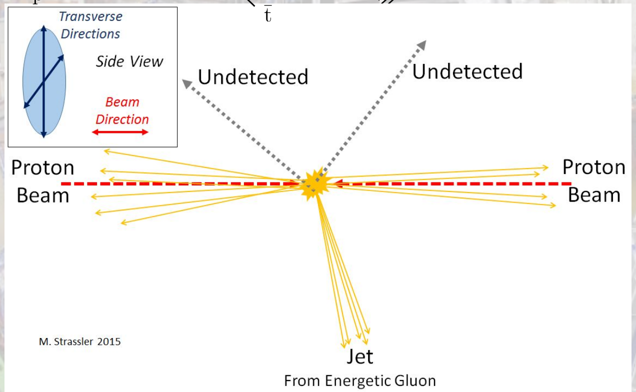
Searching for supersymmetry



Higgsinos and weak gauginos mix to neutralino, chargino

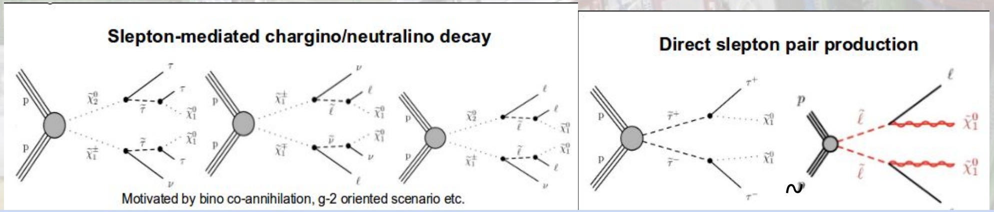
https://arxiv.org/pdf/hep-ph/9709356.pdf

Classic strong SUSY searches:



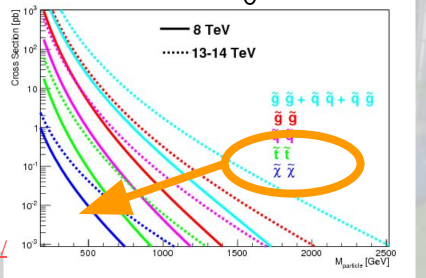
Search for gluino and squark pair production in multijet and multilepton events with a lot of **missing transverse momentum**!

Classic electroweakino searches:



R-parity conserving (RPC): lightest SUSY particle (e.g. χ_0^1) is stable

- $WZ : 2\ell + \text{jets} + p_T^{miss}$
- $WZ : 3\ell + p_T^{miss}$
- $Wh : 1\ell + bb + p_T^{miss}$



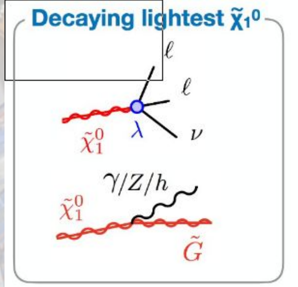
https://cds.cern.ch/record/2291346/files/fig_susy_crossections.png

One can search also for resonance search ('bump hunt'), angular distributions, deviations in standard model observables...

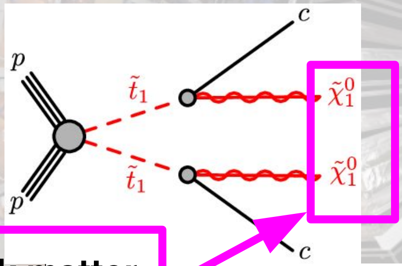
https://profmattstrassler.com/articles-and-posts/relativity-space-astronomy-and-cosmology/dark-matter/searching-for-dark-matter-at-the-lhc/ https://indico.cern.ch/event/689399/contributions/2945161/attachments/1691950/2722452/SUSY2018_Camacho.pdf https://indico.cern.ch/event/689399/contributions/3005411/attachments/1692317/2723139/BasilSchneider_20180724_SUSY.pdf

New strategies

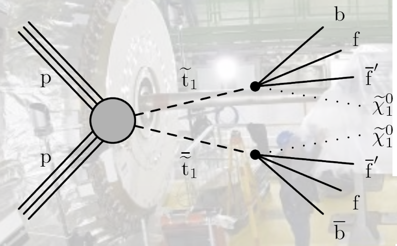
R-parity **violating** (RPV): LSP decays

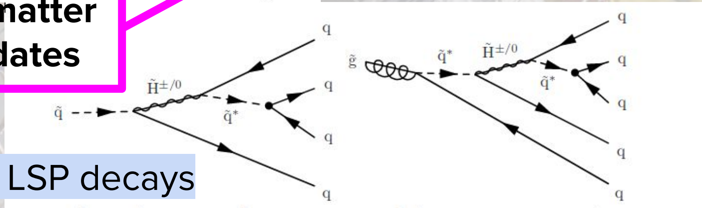


Small mass splittings, new final state particles and RPV SUSY:



Dark matter candidates

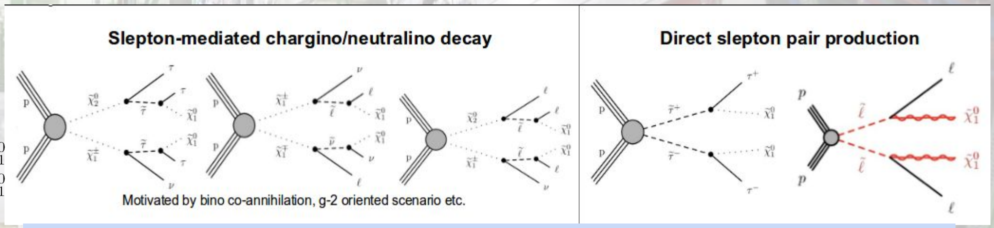




RPV LSP decays

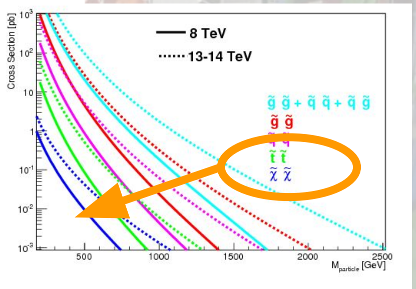
Gluino and squark pair production with multijet and multilepton final states -- very **little missing transverse momentum**!

Smaller mass electroweakinos:



R-parity conserving (RPC): lightest sparticle (LSP) is stable

- WZ : ! jets + p_T^{miss}
- WZ : p_T^{miss}
- Wh : $bb + p_T^{\text{miss}}$



Very soft leptons! How to trigger?

https://cds.cern.ch/record/2291346/files/fig_susy_crossections.png

https://indico.cern.ch/event/689399/contributions/2945157/attachments/1691972/2722396/20180724_-_Strong_SUSY.pdf

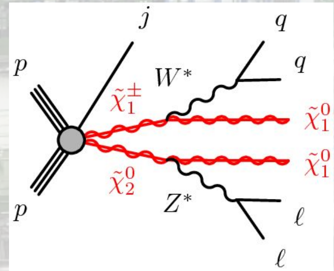
https://indico.cern.ch/event/689399/contributions/2945161/attachments/1691950/2722452/SUSY2018_Camacho.pdf

https://indico.cern.ch/event/689399/contributions/3005411/attachments/1692317/2723139/BasilSchneider_20180724_SUSY.pdf

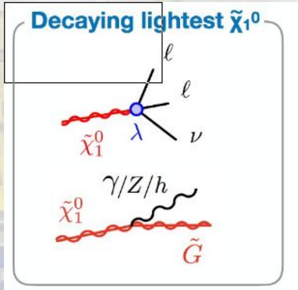
Searching for supersymmetry

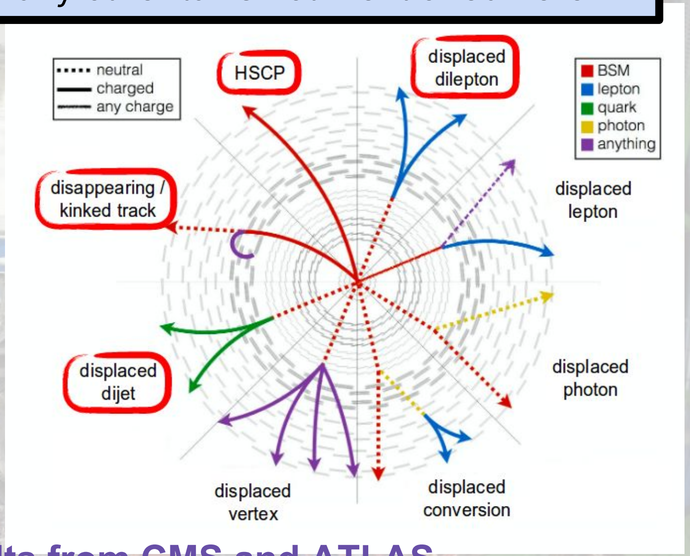
Not covered here:
SUSY Higgs searches
See talk on Wednesday by Nikolina Ilic
SM, DM results (need interpretation!):
E.g. Maria Cepeda and Gino Isidori on Wednesday, Vasiliki Kouskoura on Friday
And many other talks not mentioned here

Searches refined in run 2:



- Compressed mass spectra
- Lower cross sections
- Broaden class of models of supersymmetry to e.g. RPV (tougher background)
- More complex signatures (longlived)
- More third generation production and final states





➔ Will improve for run 3 and HL-LHC!

Will now show highlights up to now only: a selection of recent results from CMS and ATLAS

CMS public results: https://cms-results.web.cern.ch/cms-results/public-results/publications/

ATLAS public results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic

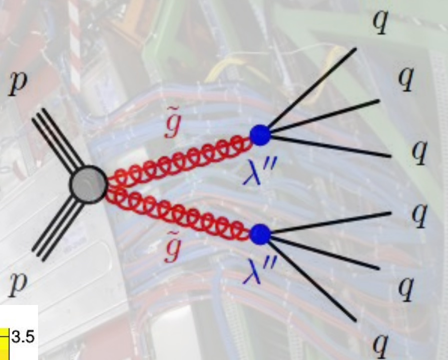
https://indico.cern.ch/event/689399/contributions/2945161/attachments/1691950/2722452/SUSY2018_Camacho.pdf

https://indico.cern.ch/event/517268/contributions/2041293/attachments/1272363/1886050/Antonelli_CMS_LLP_May12.pdf

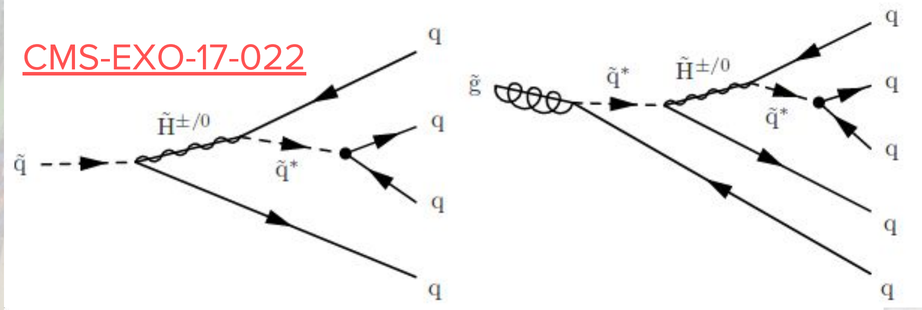
Strong sparticle production

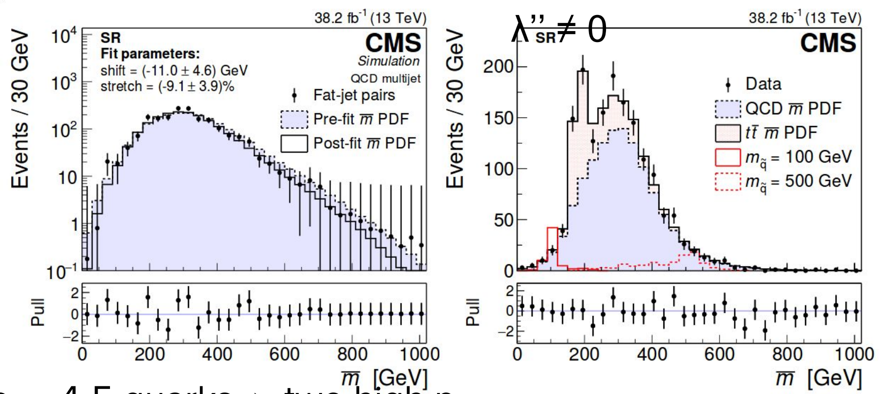
See also talks by
Antonia Strubig this afternoon
Anshul Kapoor on Wednesday
And also talks on vector-like quarks by
Erich Varnes this afternoon
Stéphanie Beauceron this afternoon

Hadronic RPV resonance search



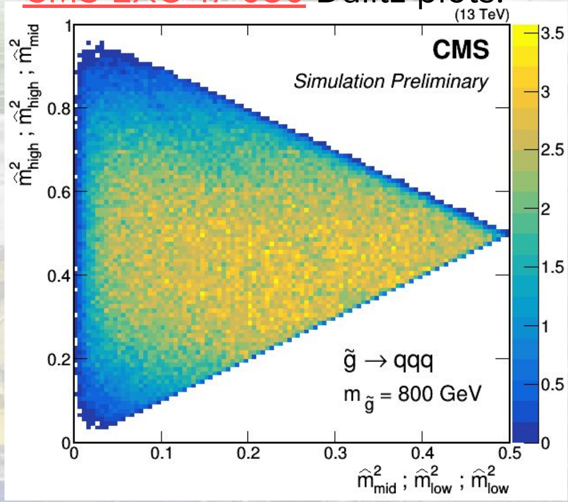
CMS-EXO-17-022

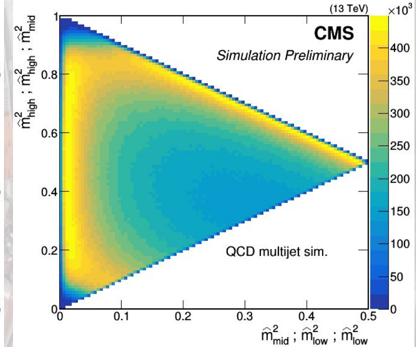




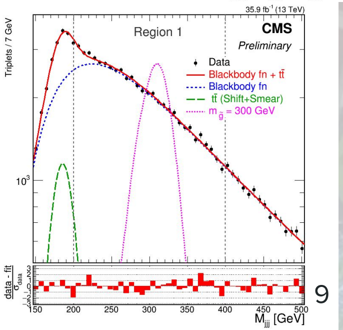
- 4-5 quarks → two high p_T (>400GeV) fat jets (CA, R=1.2) with substructure (τ_{43} < 0.8, τ_{42} < 0.45) → suppresses QCD multijet background
- Experimentally challenging light quark mode for masses < 400 GeV

CMS-EXO-17-030 Dalitz plots:





Uses **data scouting** for low masses:
High level trigger selection with 2kHz rate for a sum of jet transverse momenta HT>410 (not all event info saved)



http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/EXO-17-030

Charm tagging

Selection: ≥ 2 jets, ≥ 1 c-jet, $p_{T,miss}$ > 500 GeV.

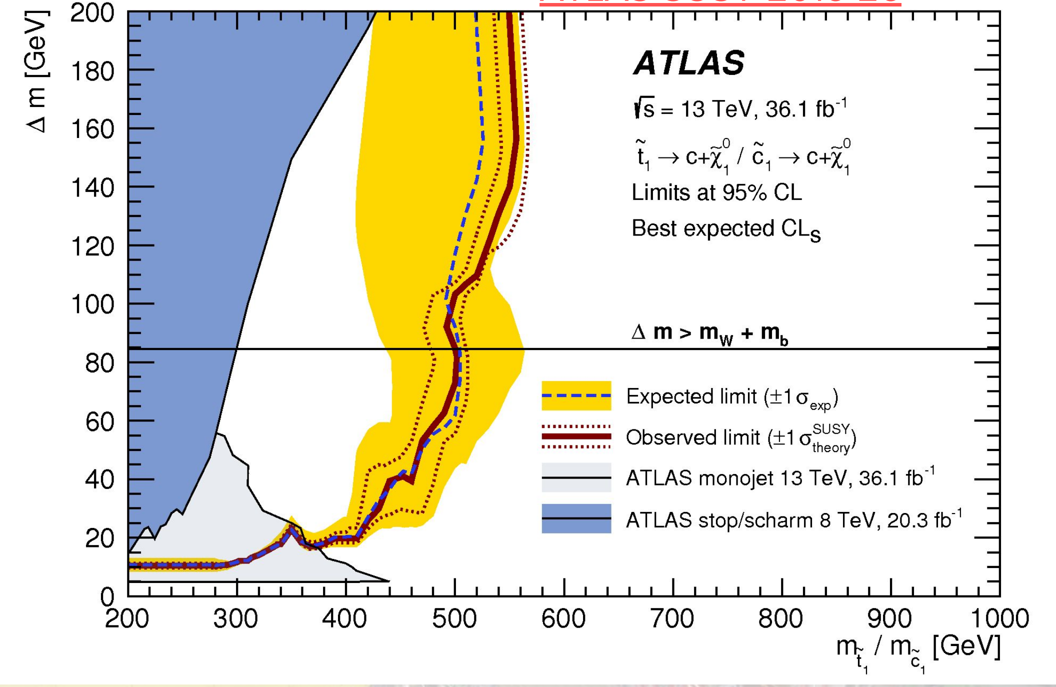
In compressed region:

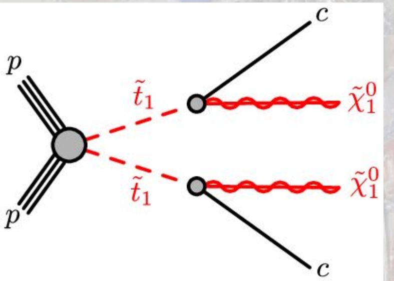
ISR selection: ≥ 3 jets with leading jet not c-tagged

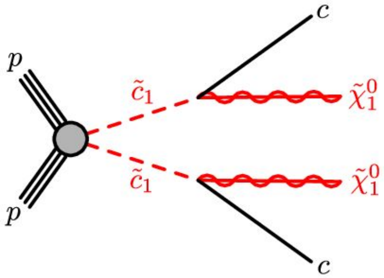
Charm tagging with MVA in tight working point 18% efficient, and

- b-jet rejection factor 20
- Light-flavor rejection factor 200
- Hadronic τ-jet rejection factor 6

ATLAS-SUSY-2016-26



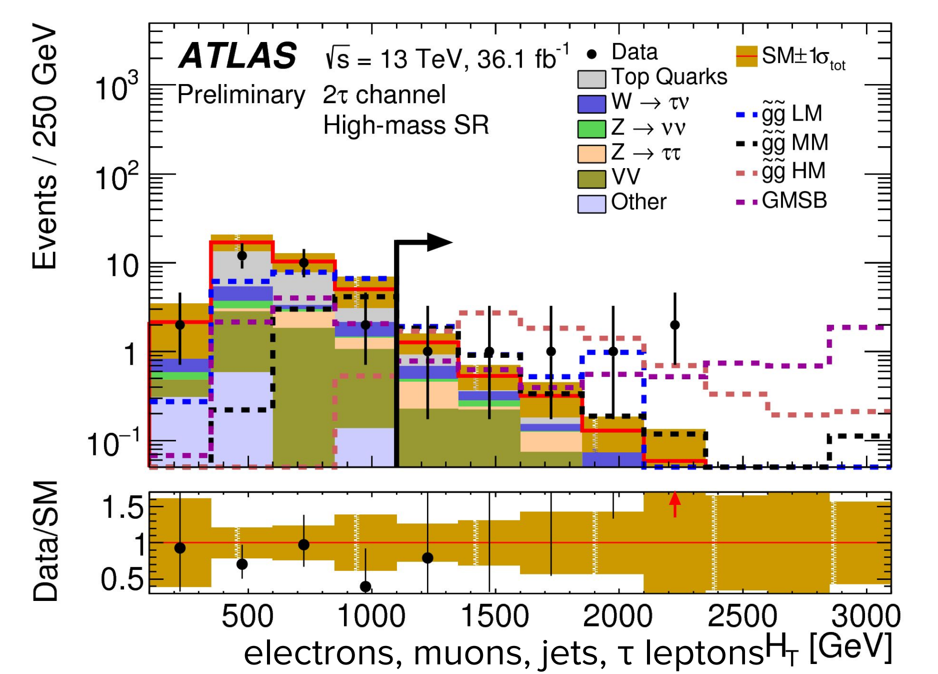




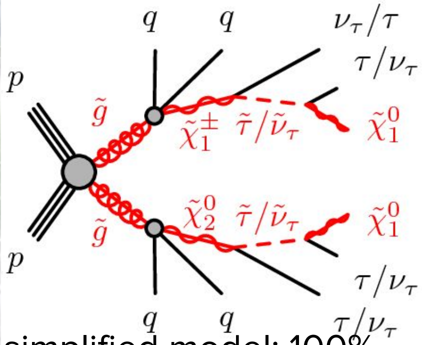
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2016-26

ATLAS=SUSY-2016-30

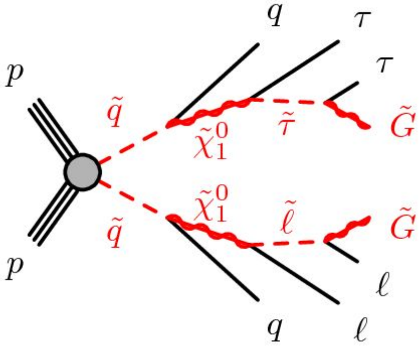
New results in tau and lepton final state from ATLAS



electrons, muons, jets, τ leptons



simplified model: 100% branching ratios

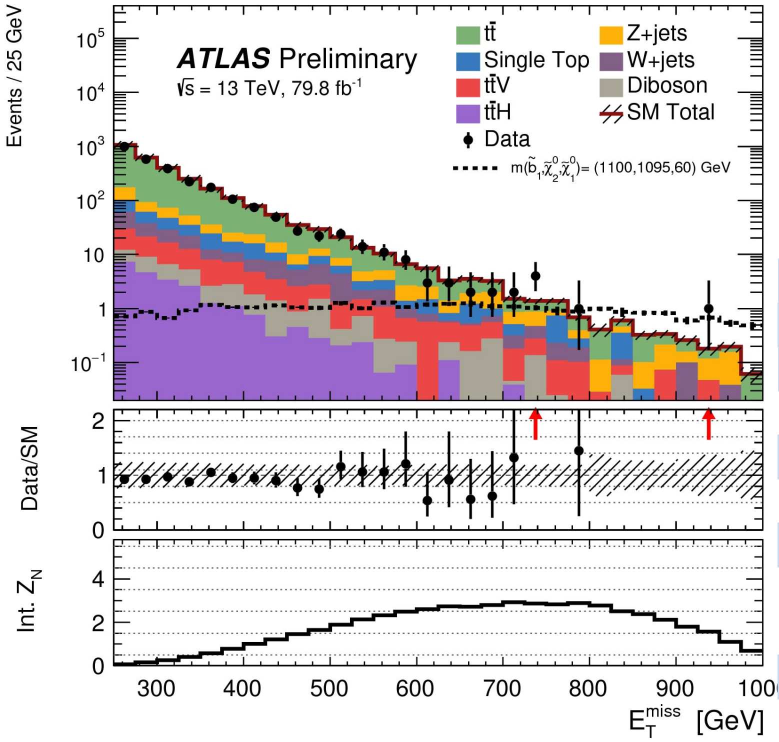


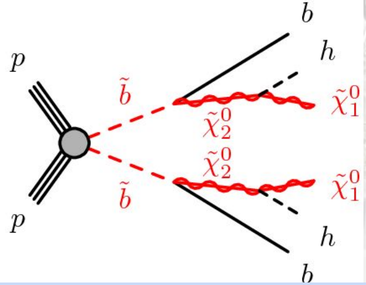
Gravity-mediated SUSY breaking (GMSB) model

- τ often rejected with ttbar, Wt backgrounds; here 40-60% τ id eff.
- Events with ((1τ and p_T^{miss}>400GeV) or (>1τ and p_T^{miss}>180GeV)) and >1 jet
- Background normalization and top modelling largest syst. Uncertainties
- No significant deviation (2σ excess)

Bottom squark pair production to Higgs

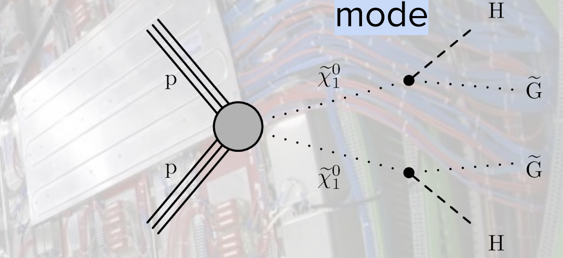
ATLAS-CONF-2018-40



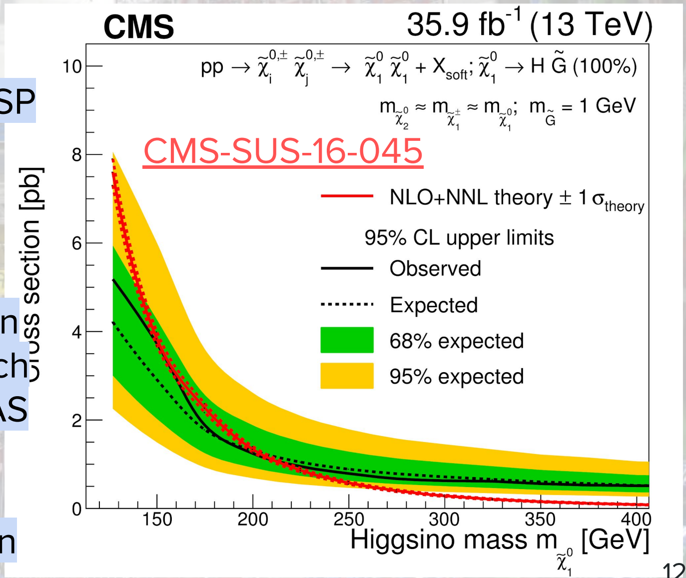


On-shell higgs with large enough $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$

In CMS: EW production mode



- GMSB goldstino LSP
- ATLAS: h → bb
- CMS: at least one H → γγ
- H, h: Standard Model Higgs boson
- First search for such a scenario in ATLAS in Run 2
- Small excess in compressed region with soft b-jets



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2018-40 http://cms-results.web.cern.ch/cms-results/public-results/publications/SUS-16-045/

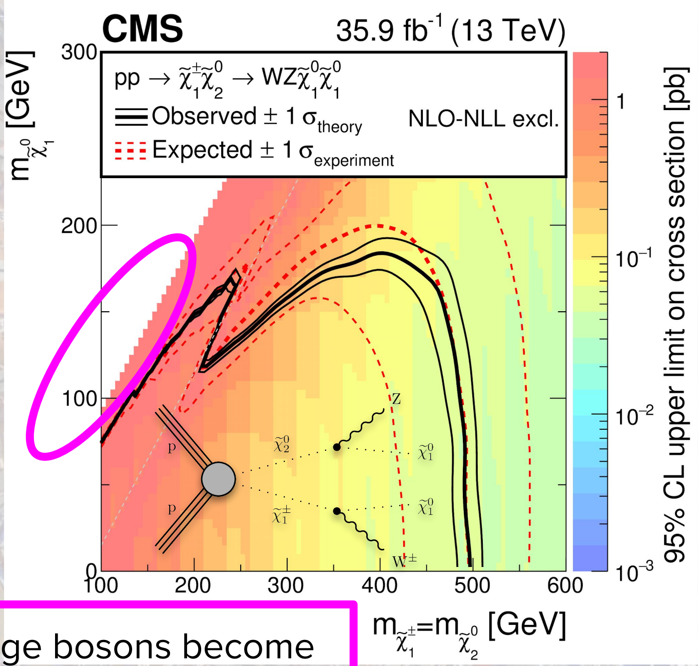
Electroweak sparticle production

See talk by
Sarah Williams this afternoon

CMS-SUS-17-004

ATLAS-SUSY-2017-03

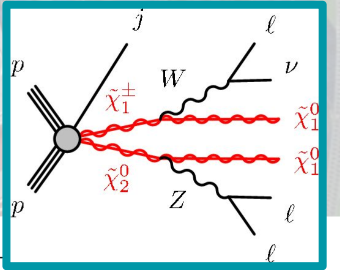
Multileptons from electroweakino pair production

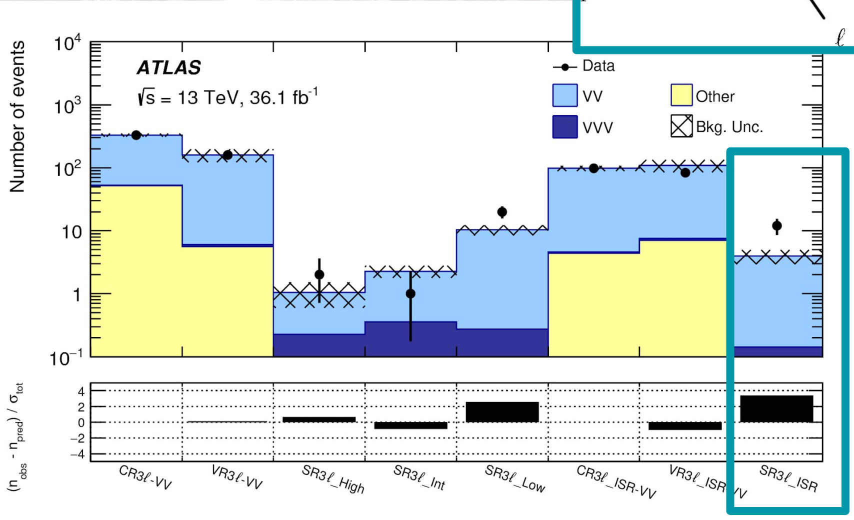


Gauge bosons become off-shell ➔ soft leptons

Classic WZ mediated electroweakino search typically not sensitive close to diagonal

RJR or **Recursive jigsaw reconstruction** uses kinematic observables computed in different reference frames for enhanced sensitivity





High, intermediate: large masses ➔ large mass splittings

Low: smaller masses

3σ

https://indico.cern.ch/event/689399/contributions/2945161/attachments/1691950/2722452/SUSY2018_Camacho.pdf

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2017-03/

ATLAS-SUSY-2016-25

CMS-SUS-16-048

Off-shell gauge bosons

μ ≈ higgsino mass

Natural SUSY has light higgsino:

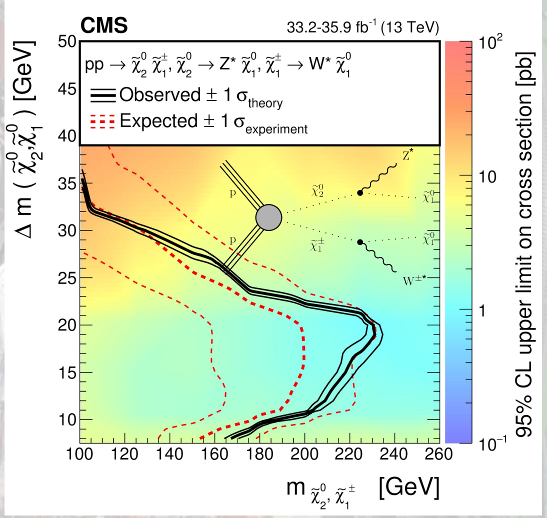
tree-level:

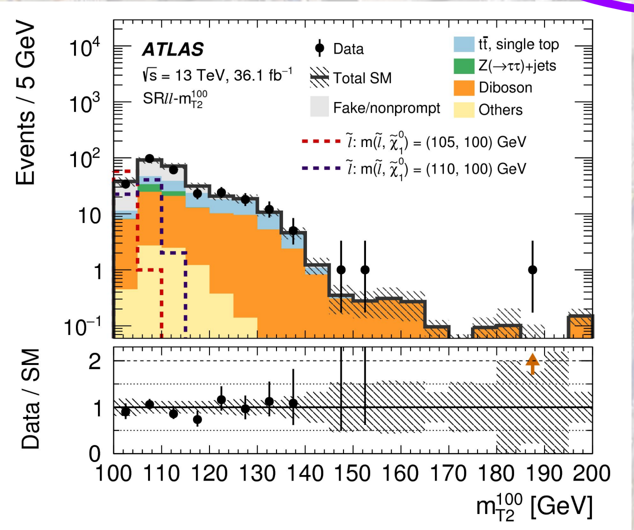
$$-\frac{m_Z^2}{2} = \boxed{|\mu^2|} + m_{H_u}^2 + \mathcal{O}\left(\frac{1}{\tan^2\beta}\right)$$

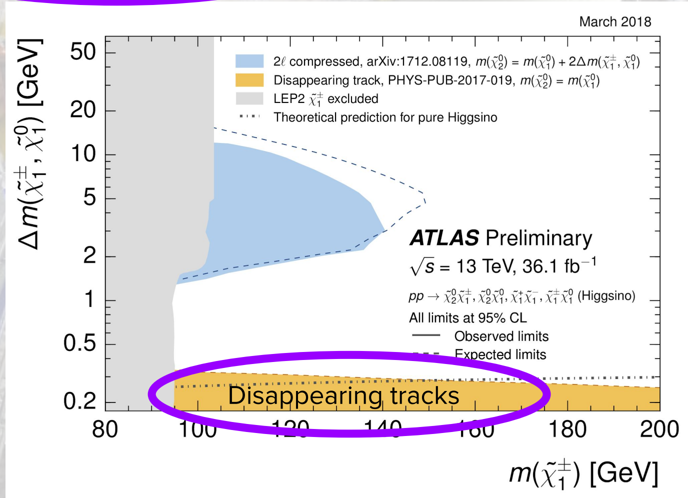
Then if n1, n2 higgsinolike:

- ➜ small mass splittings
- ➜ very soft leptons

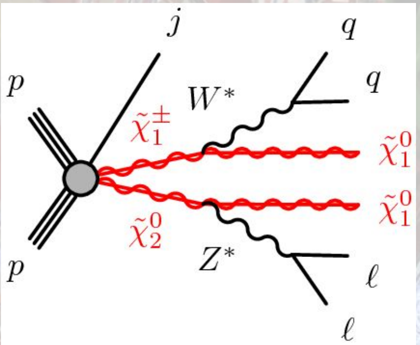
Very very soft leptons: disappearing tracks







Sensitive to low mass splittings (soft leptons)

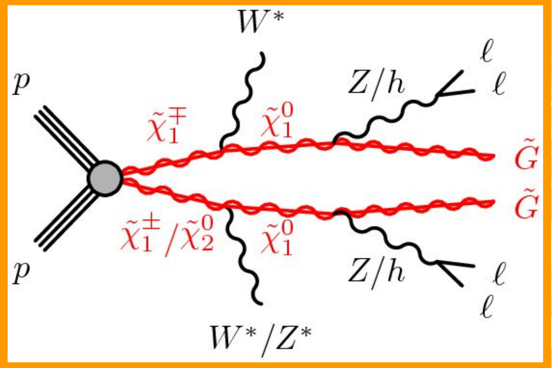


See also CMS-PAS-SUS-17-002

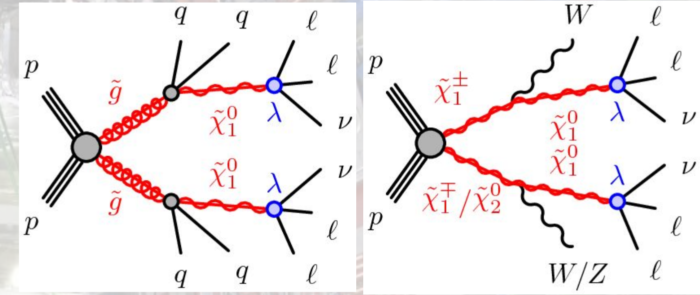
>=4 leptons, 0 - 2 hadronically decaying taus
Mild excess observed (2.3 σ) in 0 tau, on-shell Z

RPC + RPV to leptons

ATLAS-SUSY-2016-21



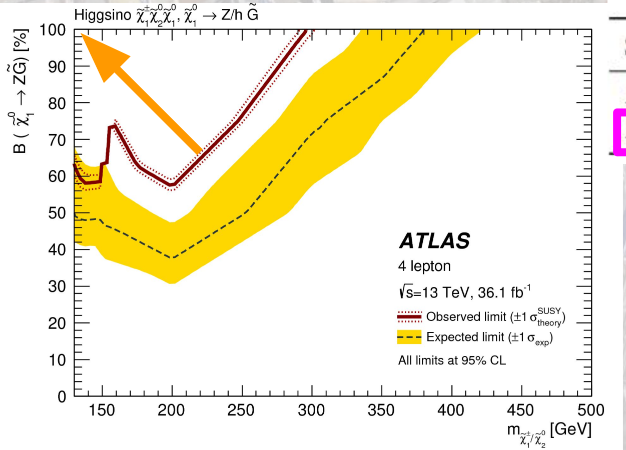
RPC wino decay, gauginos decaying via ZZ
Decay products from offshell W*, Z* cannot easily be triggered on



RPV simplified model
NLSP production

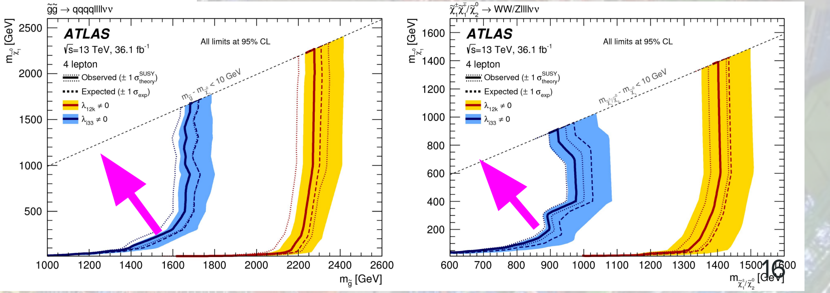
$$\frac{1}{2}\lambda_{ijk}L_iL_j\bar{E}_k + \lambda'_{ijk}L_iQ_j\bar{D}_k + \frac{1}{2}\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k + \kappa_i L_i H_2,$$

λ_{ijk}: 27 RPV couplings in superpotential



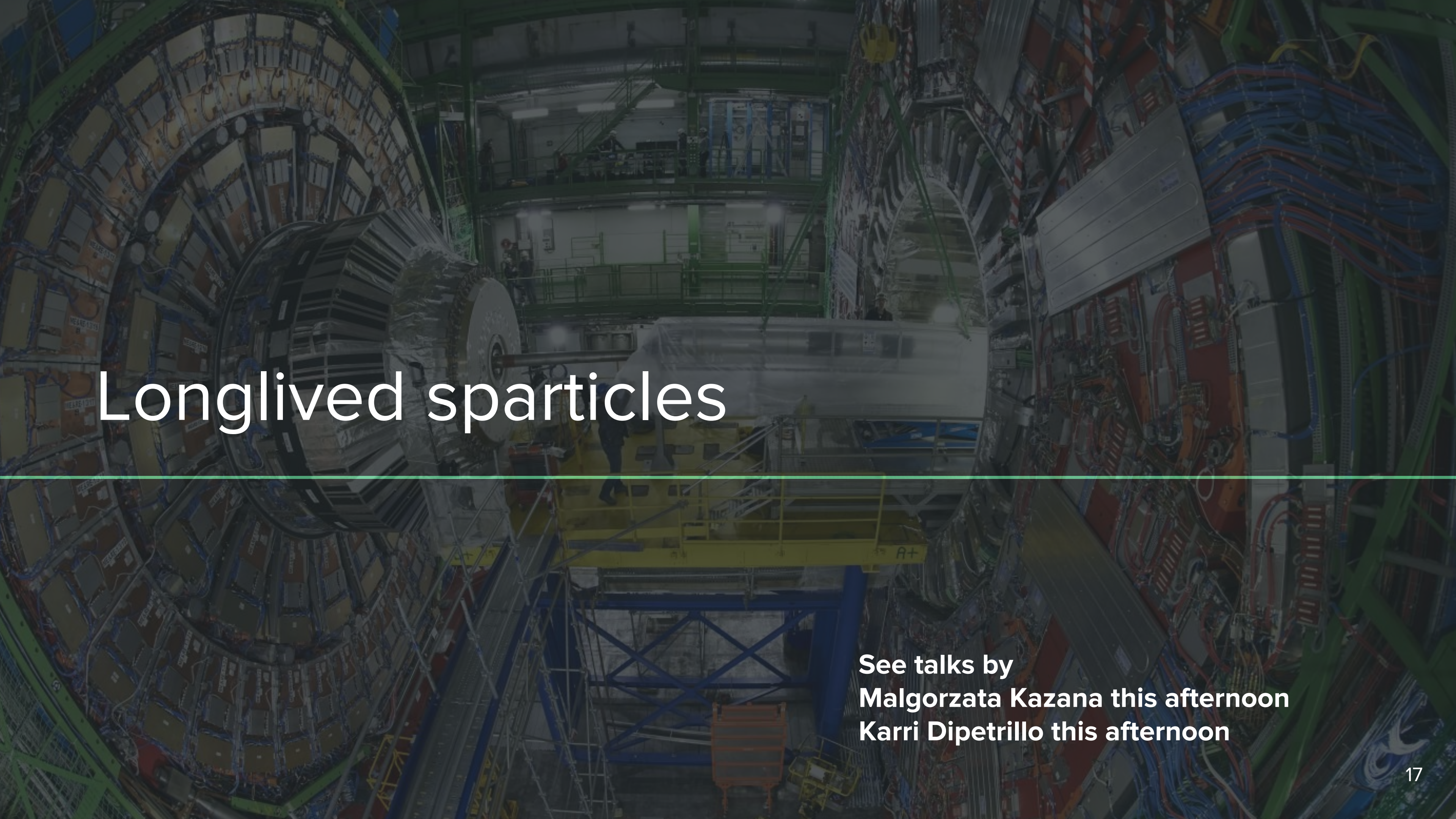
Scenario	$\tilde{\chi}_1^0$ branching ratios		
$LL\bar{E}12k$	$e^+e^-\nu$ (1/4)	$e^{\pm}\mu^{\mp}\nu$ (1/2)	$\mu^+\mu^-\nu$ (1/4)
$LL\bar{E}i33$	$e^{\pm}\tau^{\mp}\nu$ (1/4)	$\tau^+\tau^-\nu$ (1/2)	$\mu^{\pm}\tau^{\mp}\nu$ (1/4)

Less sensitivity for 3rd gen RPV coupling



https://indico.cern.ch/event/689399/contributions/2945161/attachments/1691950/2722452/SUSY2018_Camacho.pdf

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2016-21/

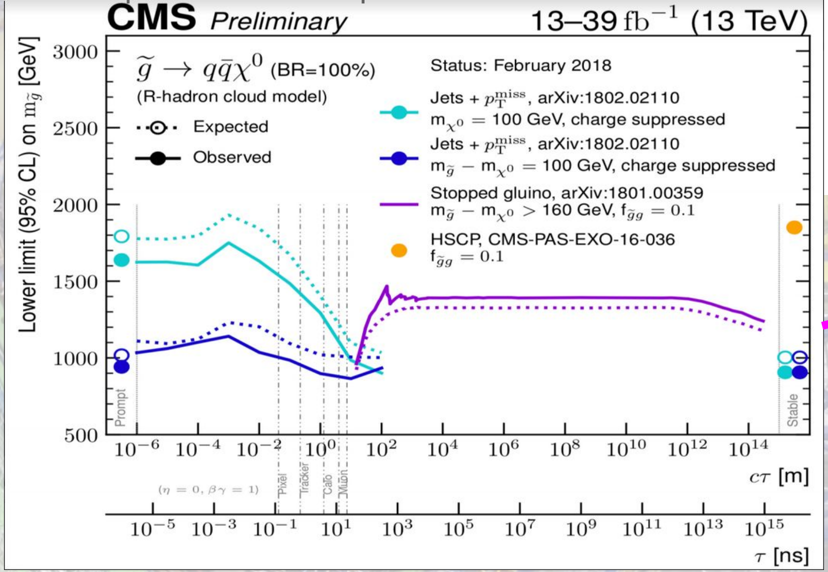


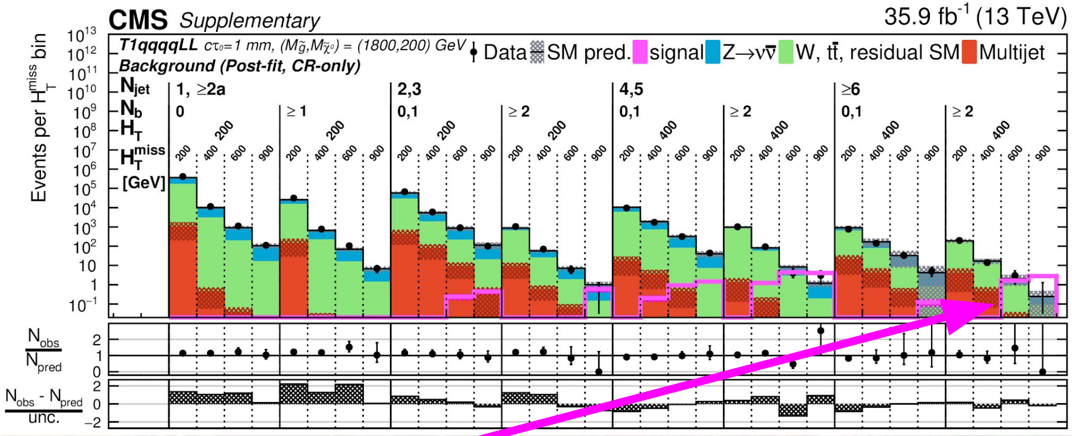
Longlived sparticles

See talks by
Malgorzata Kazana this afternoon
Karri Dipetrillo this afternoon

Longlived gluinos in split supersymmetry

CMS-PAS-EXO-16-036 heavy stable charged particle search with dE/dx
CMS-SUS-16-038 CMS inclusive search with jets and missing transverse momentum using α_T with split SUSY interpretation





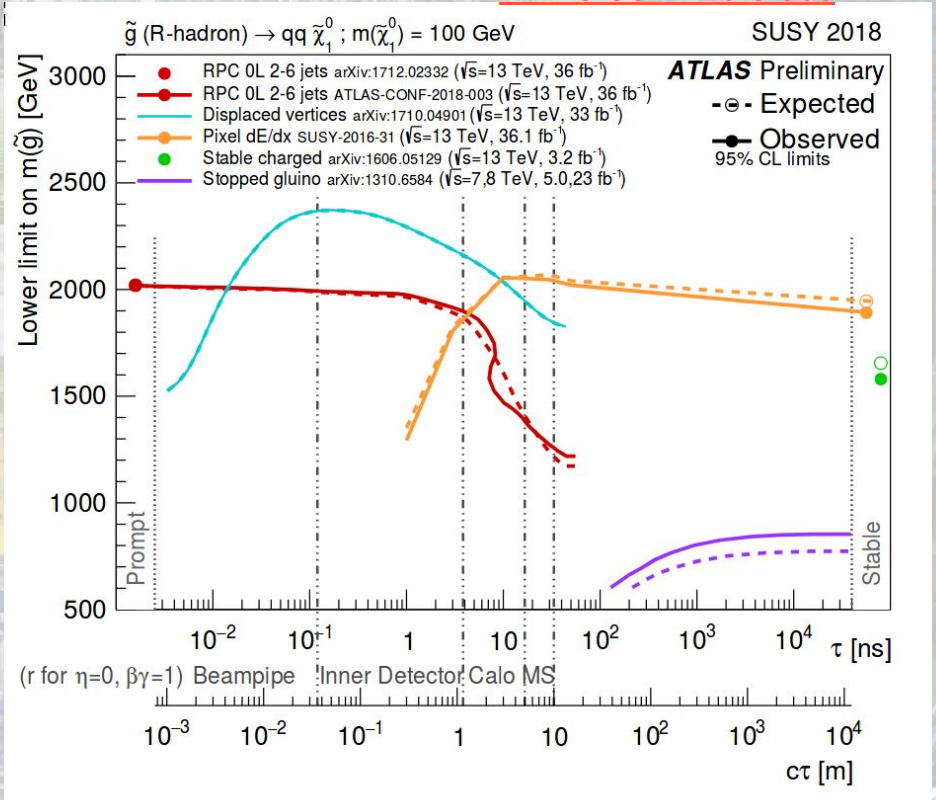
HSCP searches will benefit from tracker phase 2 upgrade (see e.g. CMSTDR014) and muon phase 2 upgrade (see e.g. CMSTDR016)

http://cms-results.web.cern.ch/cms-results/public-results/publications/SUS-16-038/

Split SUSY and R-Hadrons

Split SUSY: has light sfermions and higgs, rest heavy.
Heavy quarks make gluino longlived.
If cτ > 1 picosecond:
➜ 'R-hadron' or bound color-singlet state containing squarks or gluons.
The R-Hadron eventually decays to quark, antiquark and LSP.

ATLAS reinterpretation of SUSY searches in RPV models and R-hadron models
ATLAS-CONF-2018-003



https://arxiv.org/pdf/hep-ph/0611040.pdf
https://arxiv.org/pdf/hep-ph/0406088.pdf
https://arxiv.org/pdf/hep-th/0405159.pdf
https://arxiv.org/abs/1802.02110v2
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY/ATLAS_SUSY_LLP/ATLAS_SUSY_LLP.pdf
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2018-003/

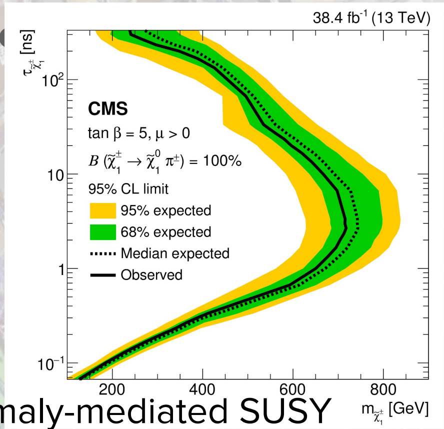
ATLAS-SUSY-2018-06

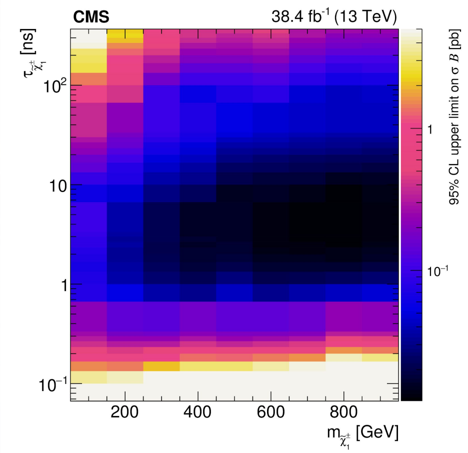
CMS-EXO-16-044

Disappearing tracks

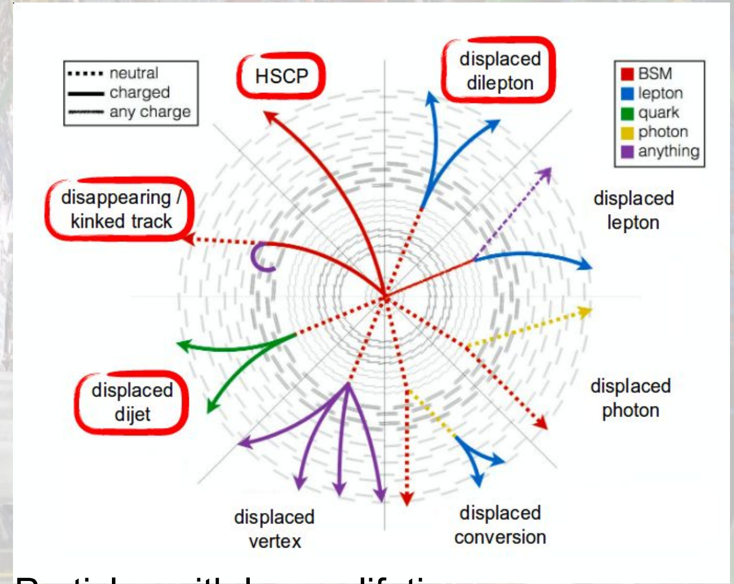
- No missing inner or middle hits
- p_T^{miss} > 70 GeV on level 1 trigger (L1), >50GeV isolated track on high level trigger (HLT)
- Calorimeter constraint makes leptons reconstructed as charged hadrons unlikely

rou



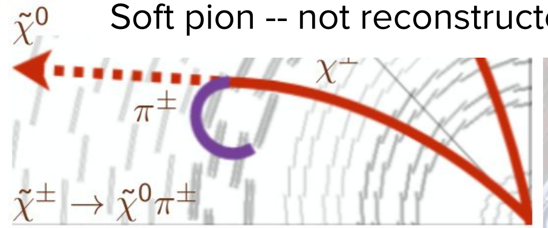


Anomaly-mediated SUSY breaking (AMSB) model



Particles with longer lifetimes decay in characteristic ways in our detector (or outside!)

Soft pion -- not reconstructed

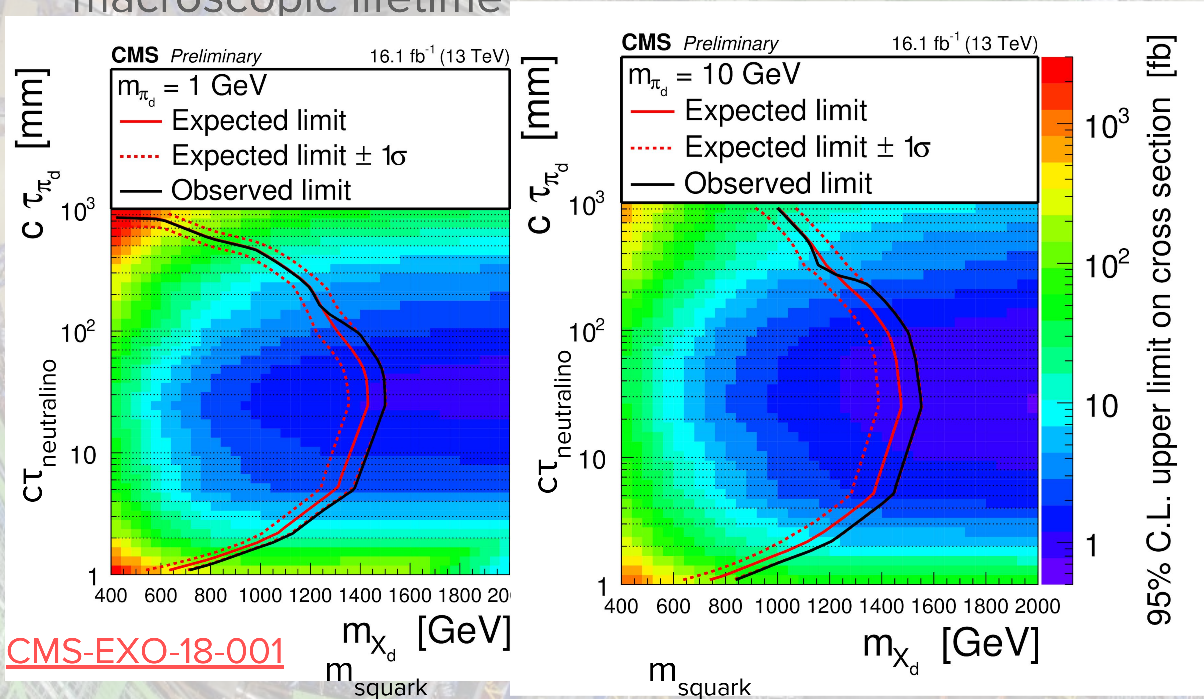


https://indico.cern.ch/event/686555/contributions/2969867/attachments/1680800/2700286/ICHEP2018_LLP_Escalante.pdf

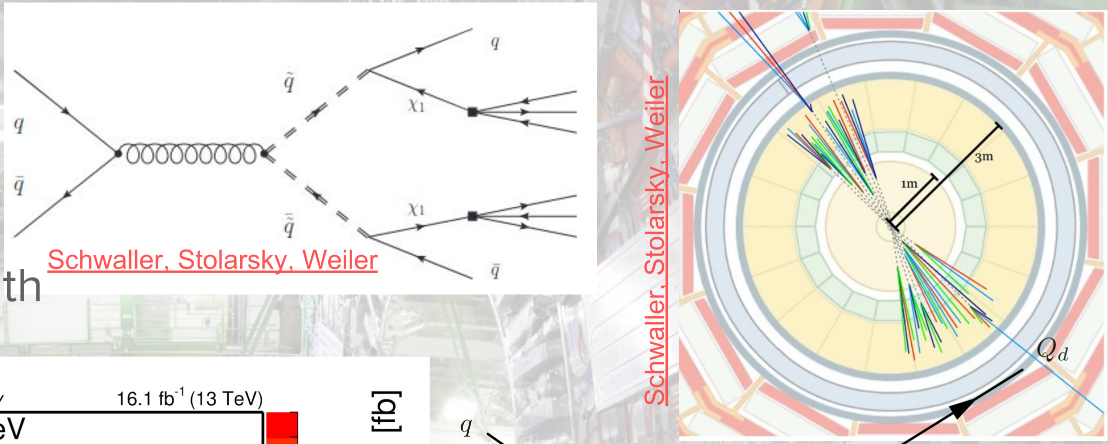
https://indico.cern.ch/event/517268/contributions/2041293/attachments/1272363/1886050/Antonelli_CMS_LLP_May12.pdf

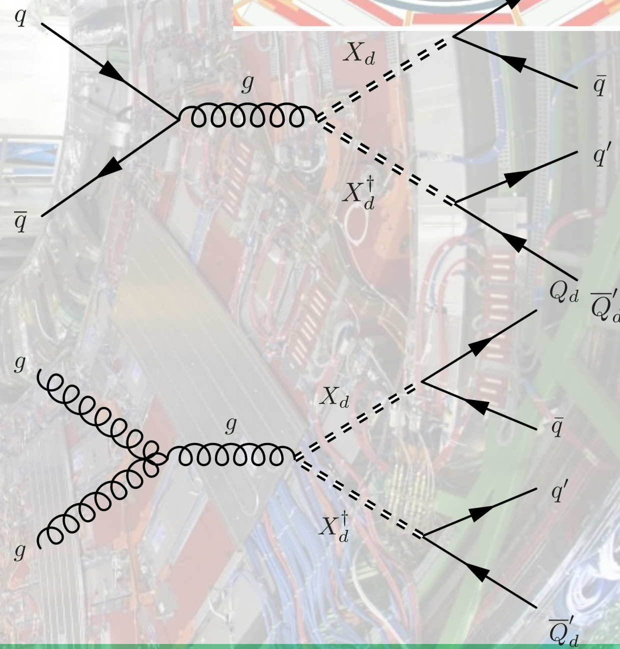
Emerging jets

SUSY: RPV decay of neutralino with macroscopic lifetime



CMS-EXO-18-001

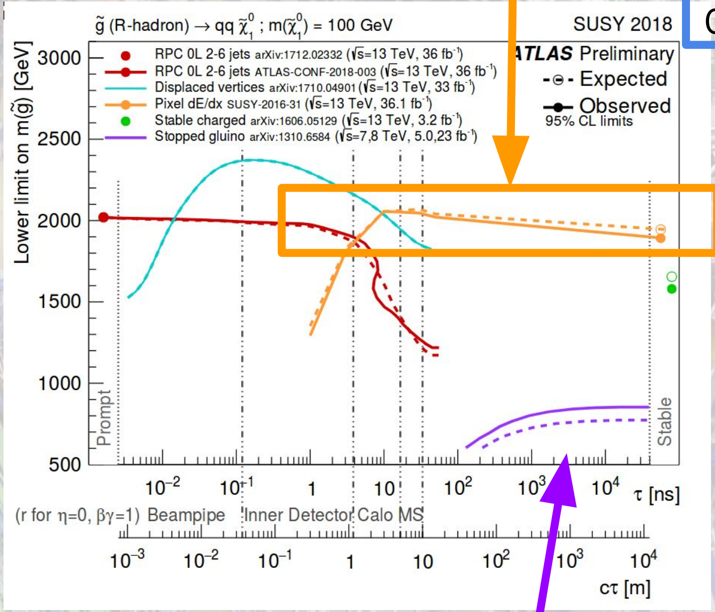




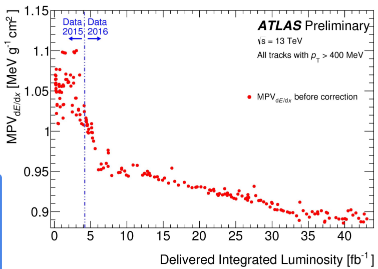
ATLAS-SUSY-2016-031

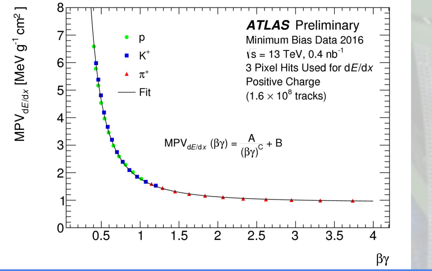
Heavy charged longlived

Pixel dE/dx measurement

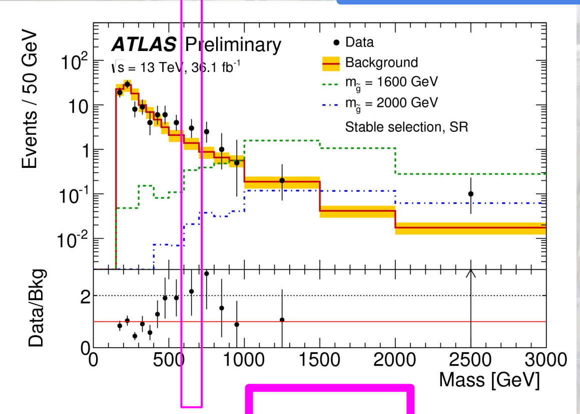


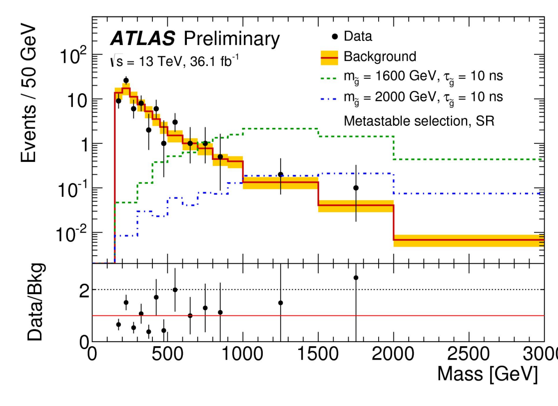
0.3 < ßγ < 0.9
Too long time over threshold < 0.3
0.9 > SM background





Most probably value dE/dx $(MPV)_{dE/dx}$ correction (radiation damage, kaons, traversed thickness)





2.4σ

Stable: no muon veto, decay outside ATLAS detector
p_T often not in $E_{T,miss}$ (no reco)
➔ use ISR

Metastable: isolated, high momentum, high dE/dx tracks that do not reach muon spectrometer (1ns to tens of ns)

ATLAS-CONF-2018-003

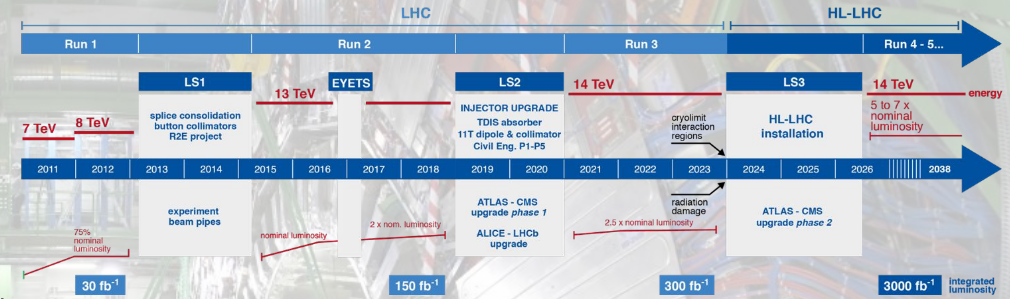
ATLAS-SUSY-2013-03

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2016-31/

Beyond LHC run 2

See also talk by
Isobel Ojalvo on Thursday

Run 3 and HL-LHC

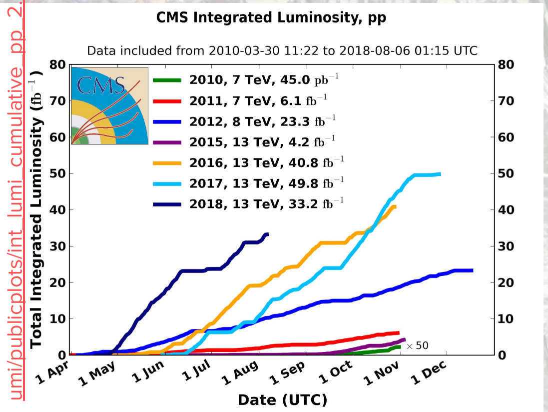


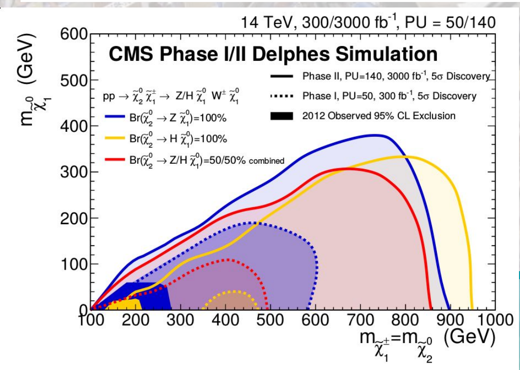
https://project-hl-lhc-industry.web.cern.ch/content/project-schedule

Now: 13TeV, 80fb-1
Run 2 expected: 150fb-1
LHC run 3: 14TeV, 300 fb-1
HL-LHC: 14TeV, 3000fb-1

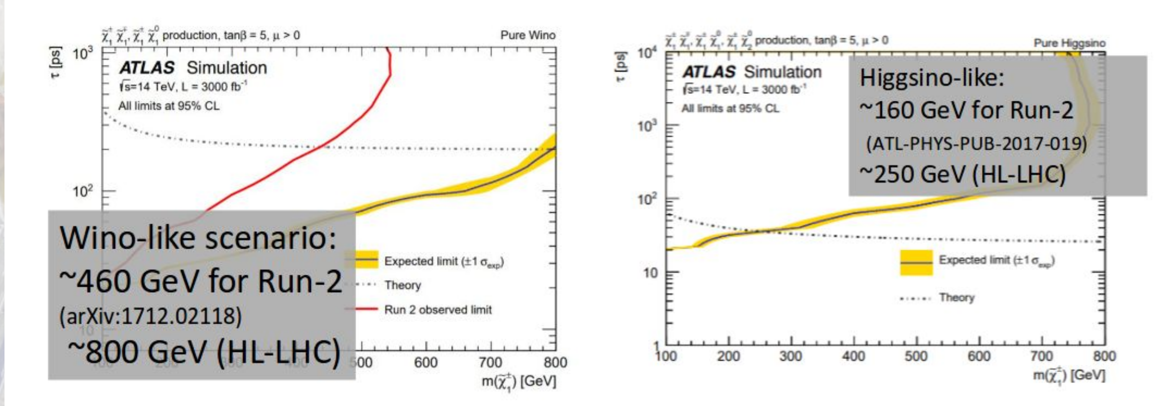
HL-LHC: L1 trigger rate from 100kHz to 750kHz

https://cms-service-lumi.web.cern.ch/cms-service-lumi/publicplots/int_lumi_cumulative_pp_2.png





CMS-TDR-15-02



Wino-like scenario:
~460 GeV for Run-2
(arXiv:1712.02118)
~800 GeV (HL-LHC)

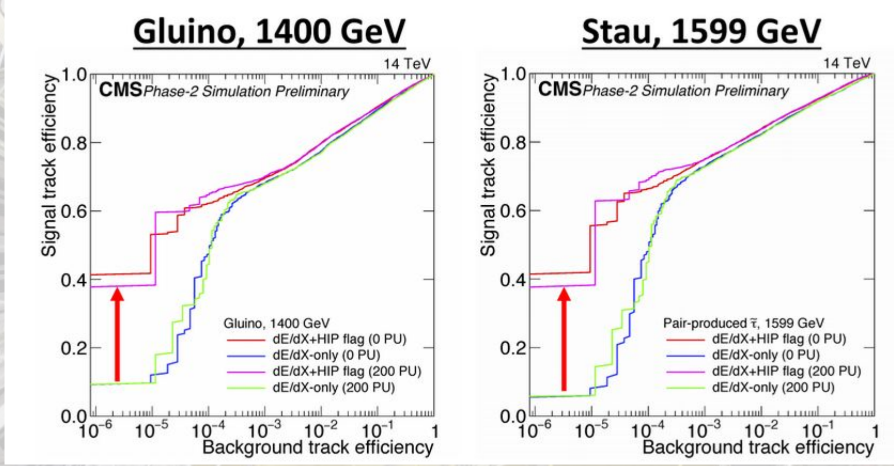
Higgsino-like:
~160 GeV for Run-2
(ATL-PHYS-PUB-2017-019)
~250 GeV (HL-LHC)

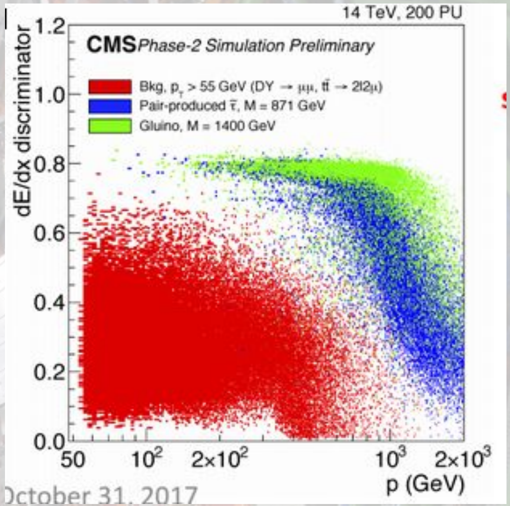
- Reach larger mass particles
- Search for low-cross section models

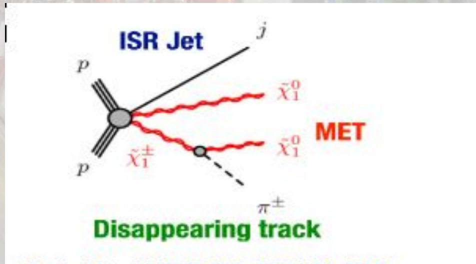
140 pileup ➔ degradation in trigger efficiency, b-tagging, MET resolution

https://indico.cern.ch/event/689399/contributions/3005916/attachments/1692207/2722880/BSMPhysicsHLLHC.pdf

What can we expect from HL-LHC?

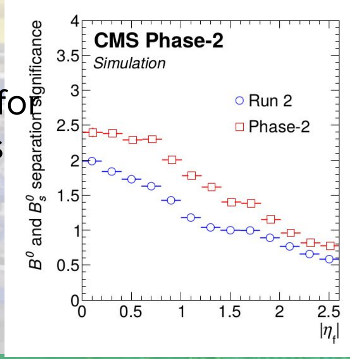






- Flag for ionizing particles in outer tracker
- Excellent dE/dx resolution in inner tracker (CMS-TDR-014)
- Muon time of flight system to distinguish HCSPs from muons (CMS-TDR-016)

See talk by Lars Eklund for current B physics results

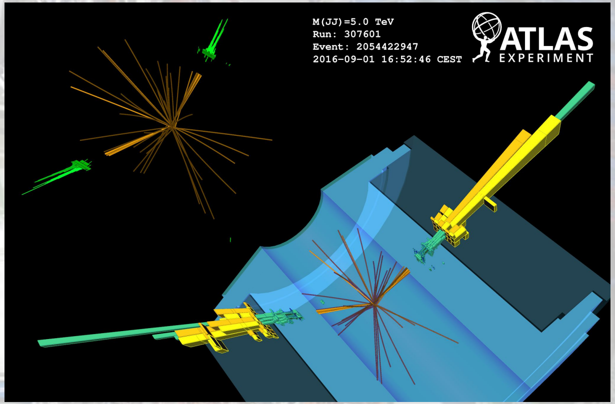


With new tracker an improved mass resolution makes Bs→ mumu better distinguishable from B0→ mumu (CMS-TDR-014).

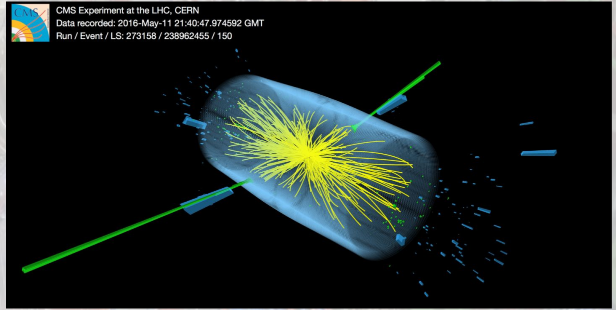
Small mass splitting between chargino and neutralino → longlived charginos

Summary and Outlook

Summary and outlook



- Data taking at LHC successful at both ATLAS and CMS;
- Many new search techniques;
- New searches for SUSY models with more complicated signatures;
- Several excesses seen but no clear sign of new physics;
- In run 3 more statistics can lead to better sensitivity in searches for models with low cross sections like electroweak SUSY searches;
- In the HL-LHC track-triggers can help look for more unconventional signatures.



Note that there is also a well-advanced e^+e^- collider program, see e.g. Jie Gao's talk yesterday

https://www.researchgate.net/profile/Raquel_Gomez-Ambrosio/publication/323966523/figure/fig17/AS:607356689842176@1521816527028/Transverse-section-of-the-CMS-detector.png

Additional material or long version

SUSY highlights -- current results and future prospects

Jory Sonneveld
on behalf of the CMS and ATLAS collaborations

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

jory.sonneveld@cern.ch

25th Rencontres Vietnam
Qui Nhon, Vietnam 2018
Windows on the Universe

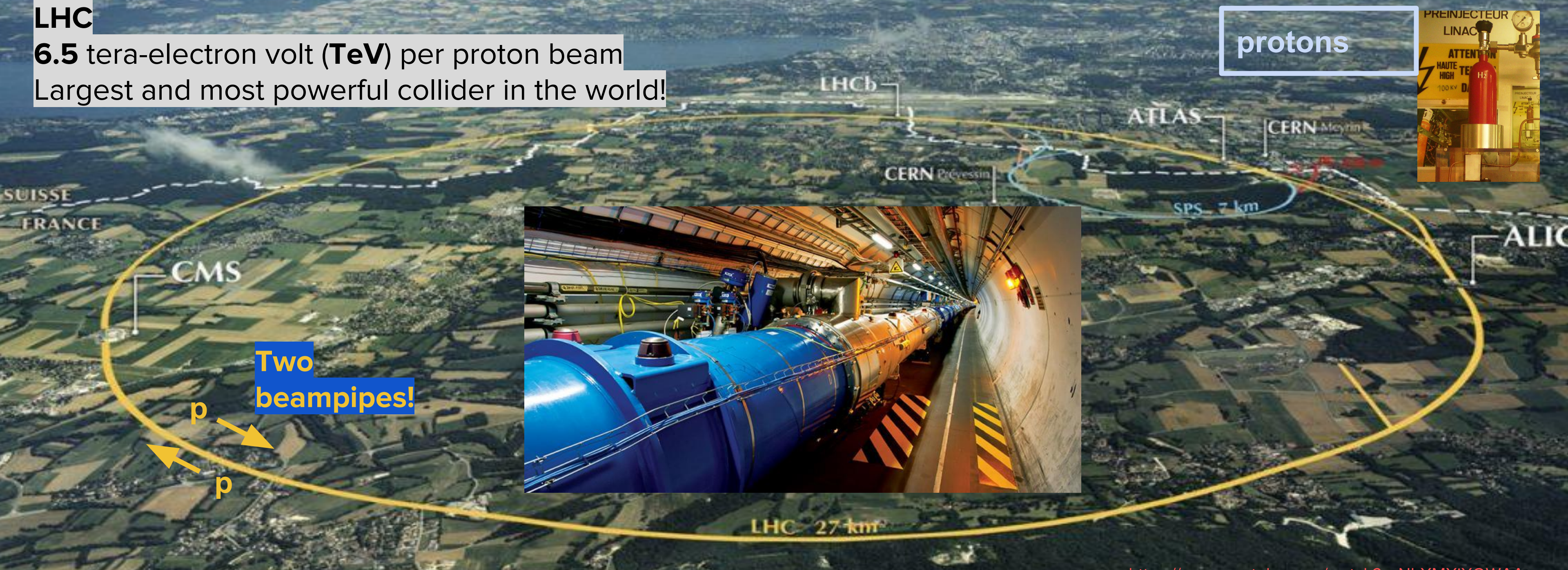
ATLAS EXPERIMENT

CMS Compact Muon Solenoid

Large Hadron Collider

Hadron: composite particle made of quarks held together by the strong force

LHC
6.5 tera-electron volt (**TeV**) per proton beam
Largest and most powerful collider in the world!



protons

Two beampipes!

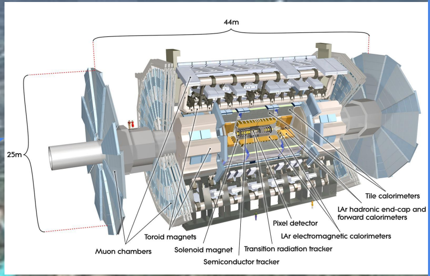
p

p

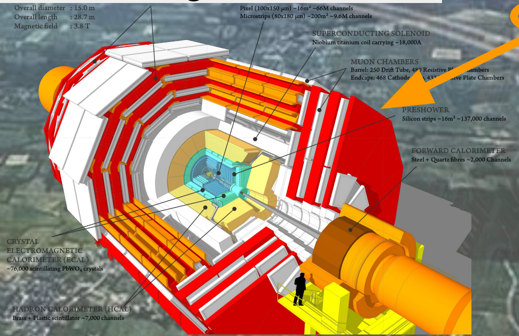
https://cdn.zmescience.com/wp-content/uploads/2015/05/cern-lhc-aerial.jpg
H t tp://s ites.uci.edu/energyobserver/files/2012/11/lhc-aerial.jpg
https://upload.wikimedia.org/wikipedia/commons/6/62/CERN_LHC_Proton_Source.JPG
https://www.youtube.com/watch?v=NhXMXiXOWAA
https://home.cern/sites/home.web.cern.ch/files/image/inline-images/old/lhc_long_1.jpg

Detectors on the Large Hadron Collider

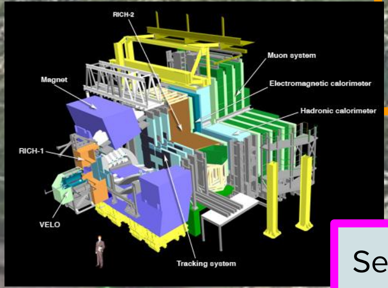
A Toroidal LHC ApparatuS:
25m high (vs 15m in CMS), 25 m wide, and 46m long
The inner detector has 3 air core **toroidal magnets** and one solenoidal magnet .



Compact Muon Solenoid
14000 tons: 1.5* Eiffel tower weight, half the size of ATLAS
Largest superconducting and most powerful solenoid magnet ever made



LHC beauty:
A single-arm **forward** spectrometer designed for the study of particles containing b or c quarks.

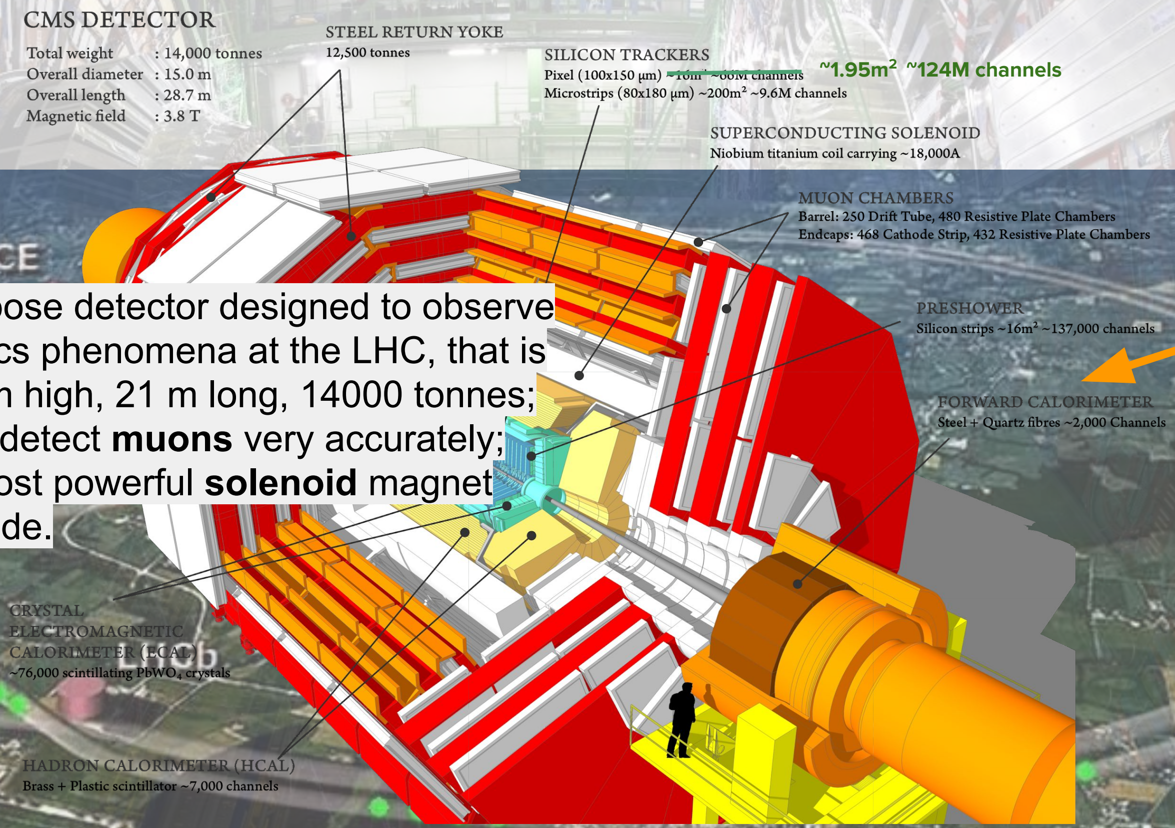


Other detectors: MoEDAL, TOTEM, LHCforward, ALICE

See also detector status talks yesterday by J. Butler (CMS), T. Nayak (ALICE), G. Passaleva (LHCb), A. Polini (ATLAS)

https://cms-docdb.cern.ch/cgi-bin/PublicDocDB/RetrieveFile?docid=11514&version=1&filename=cms_120918_03.png

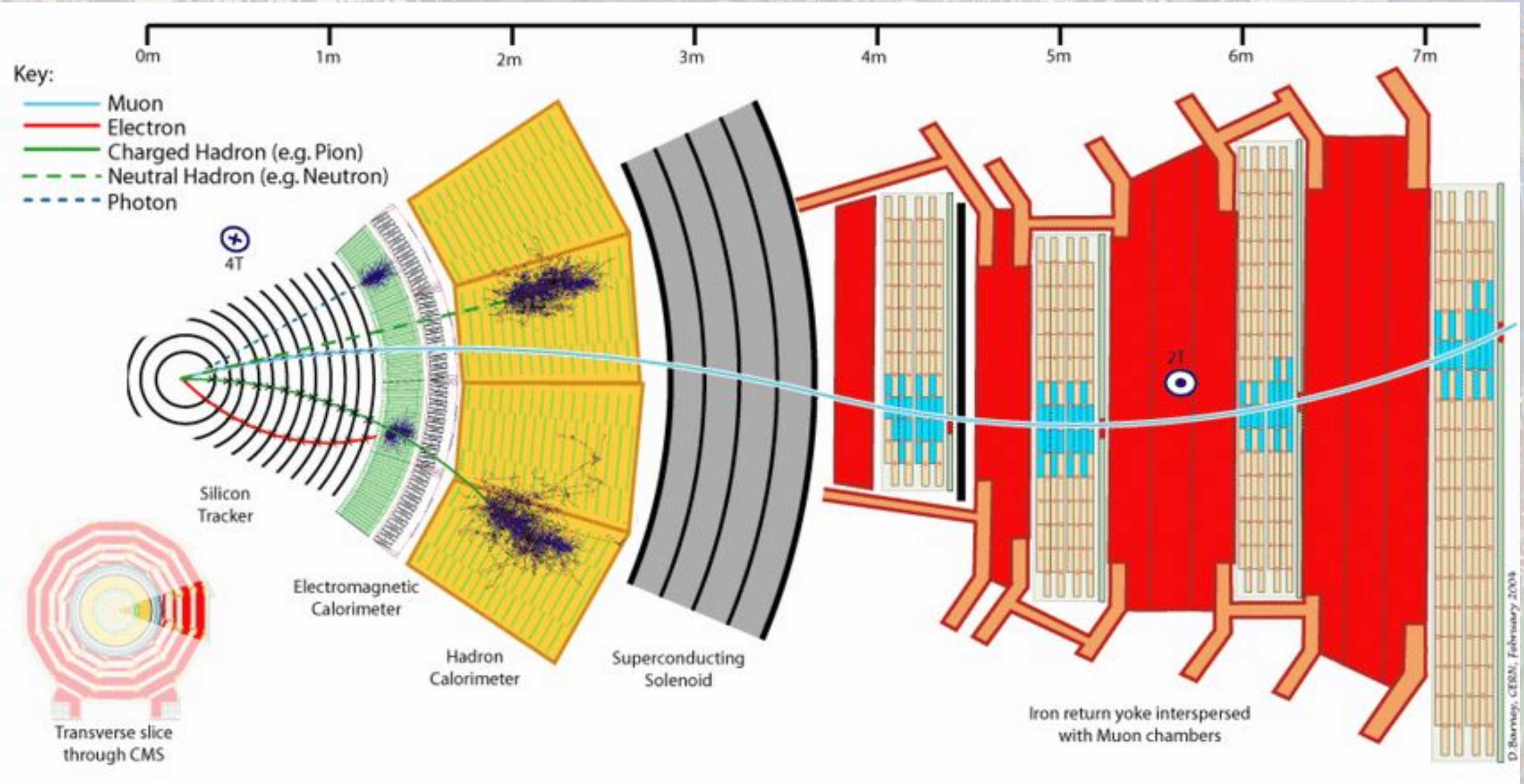
Compact Muon Solenoid



CMS:
A general-purpose detector designed to observe any new physics phenomena at the LHC, that is **compact**: 15 m high, 21 m long, 14000 tonnes;
Is designed to detect **muons** very accurately;
and has the most powerful **solenoid** magnet (3.8T) ever made.

https://cms-docdb.cern.ch/cgi-bin/PublicDocDB/RetrieveFile?docid=11514&version=1&filename=cms_120918_03.png

Detecting particles with CMS

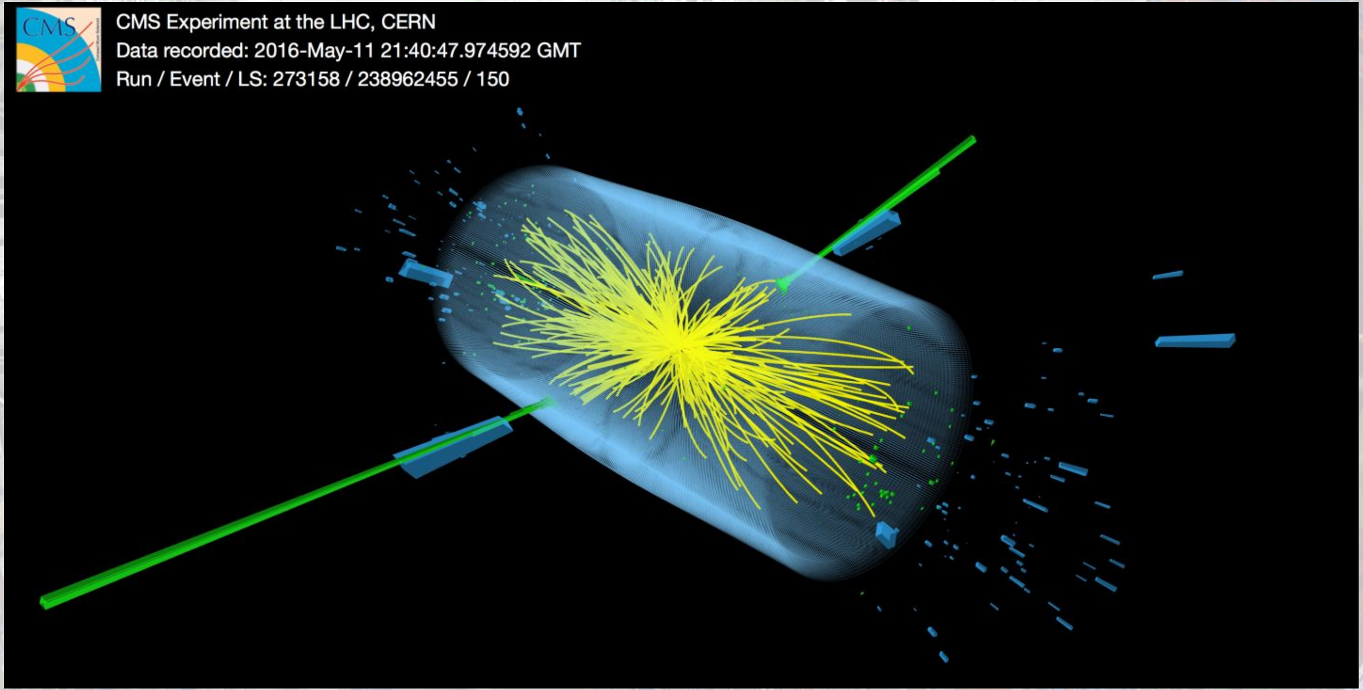


https://www.researchgate.net/profile/Raquel_Gomez-Ambrosio/publication/323966523/figure/fig17/AS:607356689842176@1521816527028/Transverse-section-of-the-CMS-detector.png

Large mass dijet event in CMS

Barrel: central cylindrical part
Endcap: at both ends of CMS

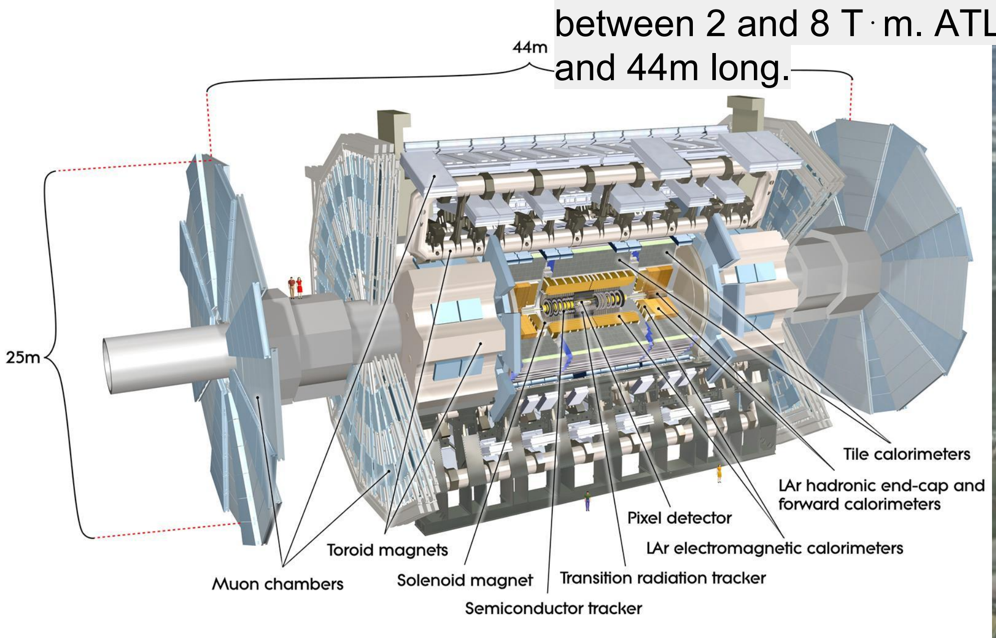
The mass of the di-jet system is 7.7 TeV. Both jets are reconstructed in the **barrel** region and each have transverse momenta of over 3 TeV.



https://cds.cern.ch/record/2203615/files/Mjjgt6_v1.png?subformat=icon-1440 https://cds.cern.ch/record/2203615

A toroidal LHC ApparatuS

ATLAS:
A general-purpose detector designed to observe any new physics phenomena at the LHC a central solenoid magnet of 2T as well as three **toroidal** barrel and endcap magnets that vary between 2 and 8 T·m. ATLAS is 25m in diameter and 44m long.

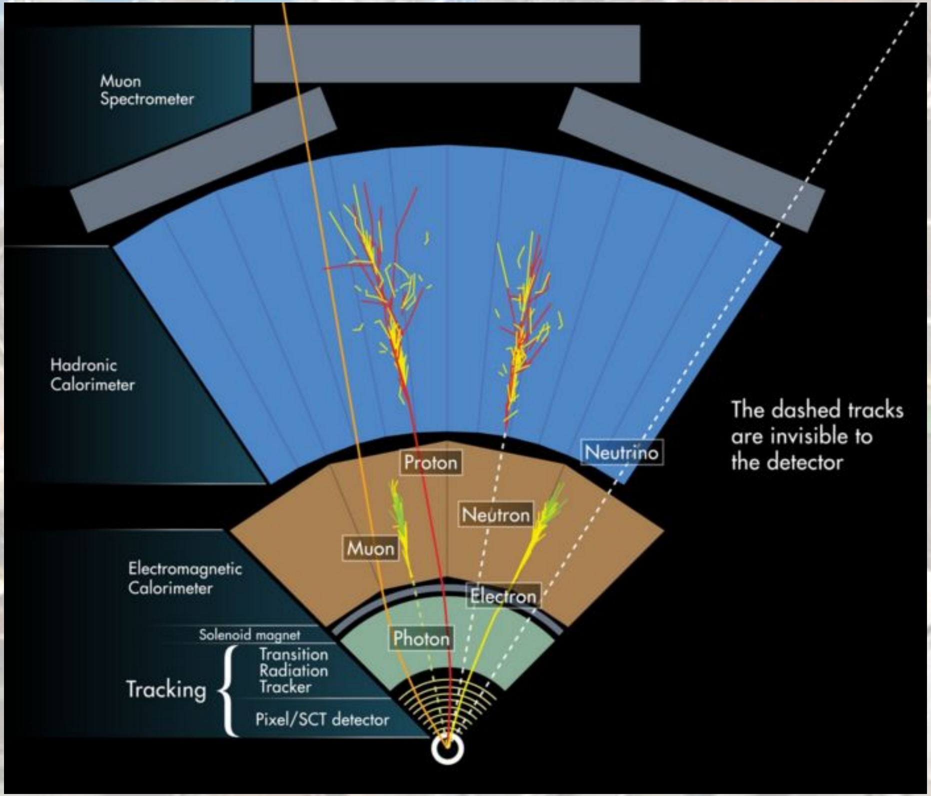


https://atlas.cern/sites/atlas-public.web.cern.ch/files/magnet-head.jpg http://mediaarchive.cern.ch/MediaArchive/Photo/Public/2008/0803012/0803012_01/0803012_01-A4-at-144-dpi.jpg

Detecting particles with the ATLAS detector

Transition radiation tracker
A combination of a straw detector and transition radiation detector. Particles travelling close to the speed of light leave most transition radiation, such as electrons and positrons.

Toroidal magnets bend charged particles also outside the hadronic calorimeter (HCAL). Nonuniform magnetic field.

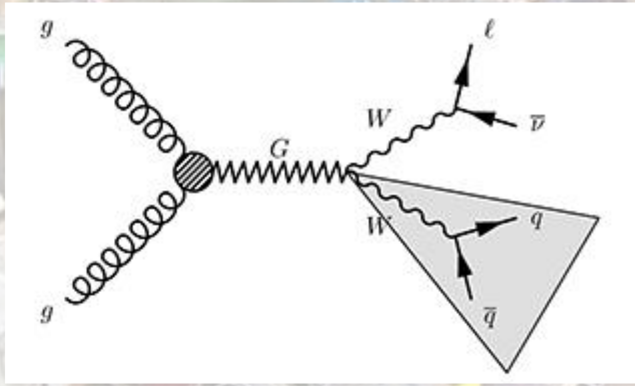


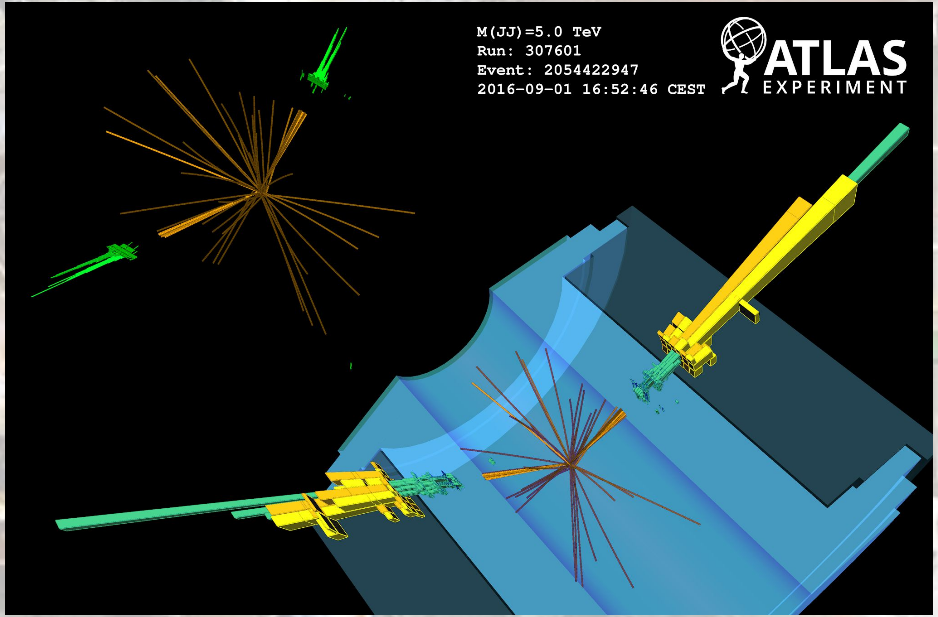
http://collider.physics.ox.ac.uk/img/layers.png

Detecting particles with the ATLAS detector

Very accurate jet resolution!

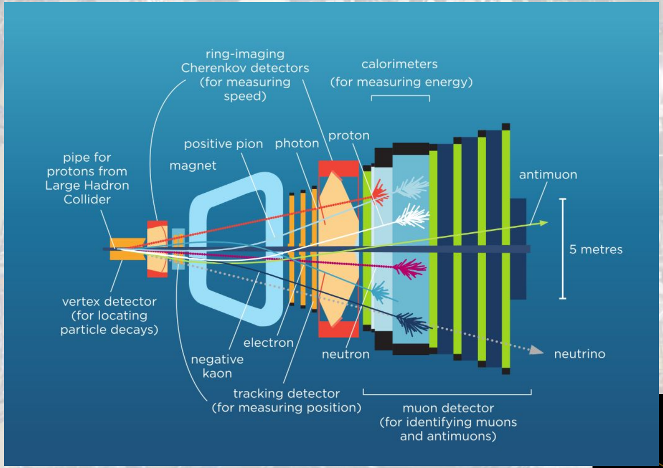
Searching for a diboson resonance: **boosted** bosons are detected as one jet.

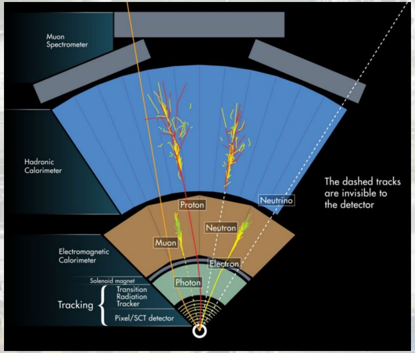


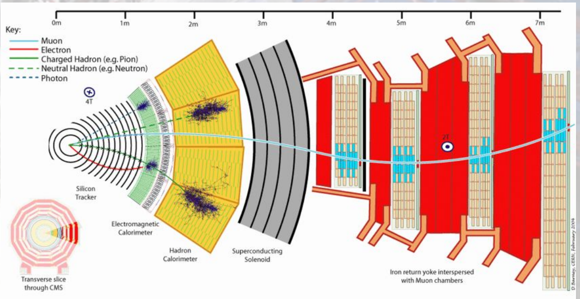


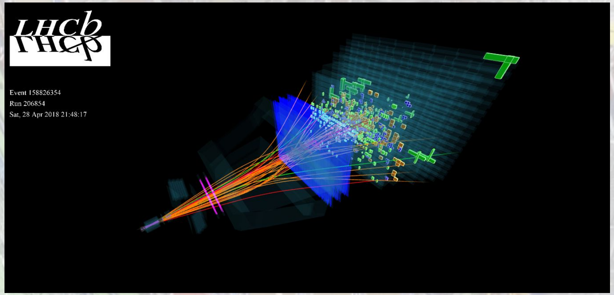
https://physikseminar.desy.de/sites2009/site_physikseminar/content/e408/e232819/e232905/e232907/Feynman_CMS-Kombi.jpg https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2018-016/fig_16.png

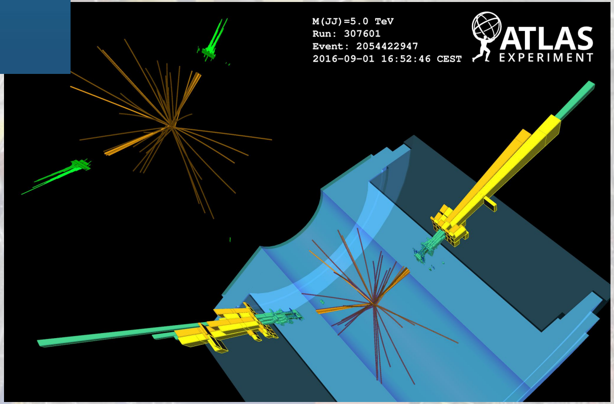
Detecting particles at the LHC

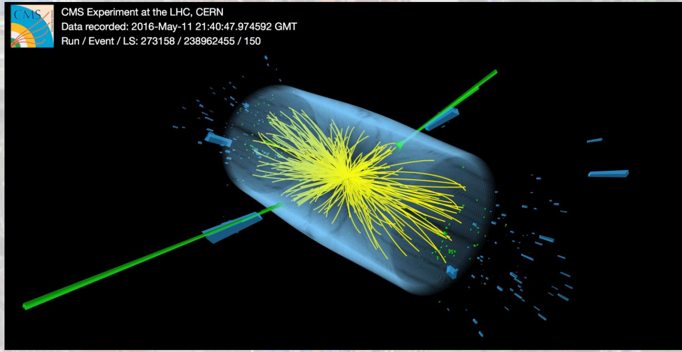












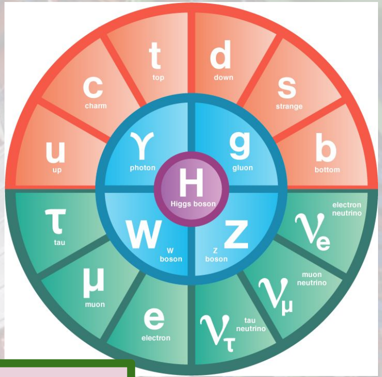
LHCb b-jet event

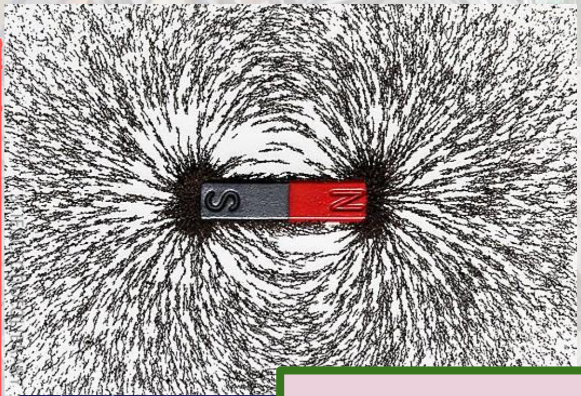
ATLAS dijet event

CMS dijet event

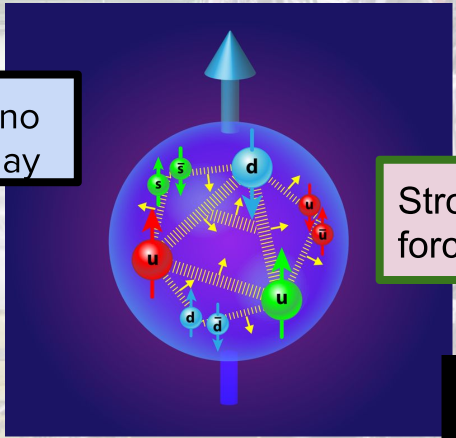
https://www.researchgate.net/profile/Raquel_Gomez-Ambrosio/publication/323966523/figure/fig17/AS:607356689842176@1521816527028/Transverse-section-of-the-CMS-detector.ppm

The standard model of particle physics





See talk by GIno Isidori yesterday

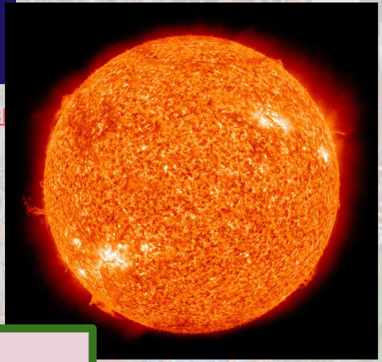


Strong nuclear force

https://physics.aps.org/assets/89b4f0e0-b8
b70d-d90f744d1790/e23_2.png

electromagnetism

What are we made of?
How do particles get mass?



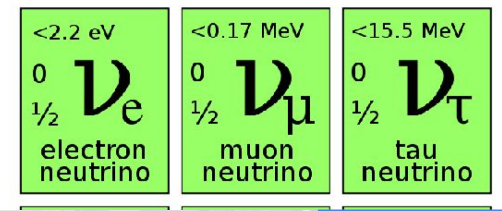
Weak nuclear force

https://upload.wikimedia.org/wikipedia/commons/thumb/3/33/Lightning.0257.jpg/1200px-Lightning.0257.jpg

http://blog.science4you.es/wp-content/uploads/2016/08/5magnet.jpg

https://upload.wikimedia.org/wikipedia/commons/thumb/b/b4/The_Sun_by_the_Atmospheric_Imaging_Assembly_of_NASA%27s_Solar_Dynamics_Observatory_-_20100819.jpg/800px-The_Sun_by_the_Atmospheric_Imaging_Assembly_of_NASA%27s_Solar_Dynamics_Observatory_-_20100819.jpg

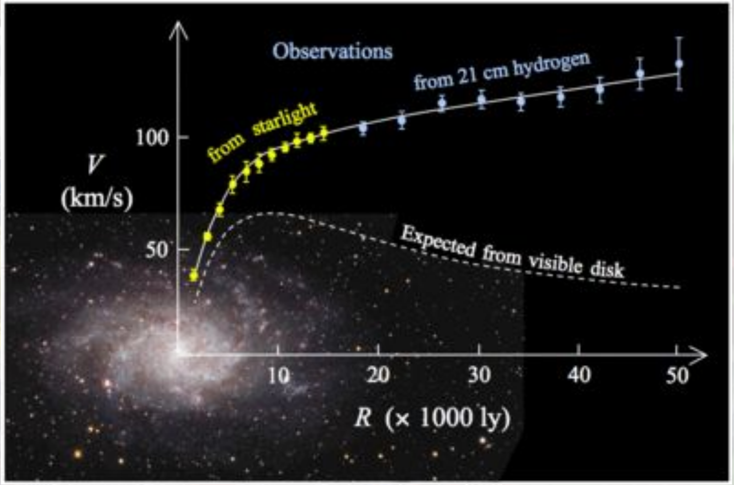
Unexplained phenomena in the standard model of particle physics



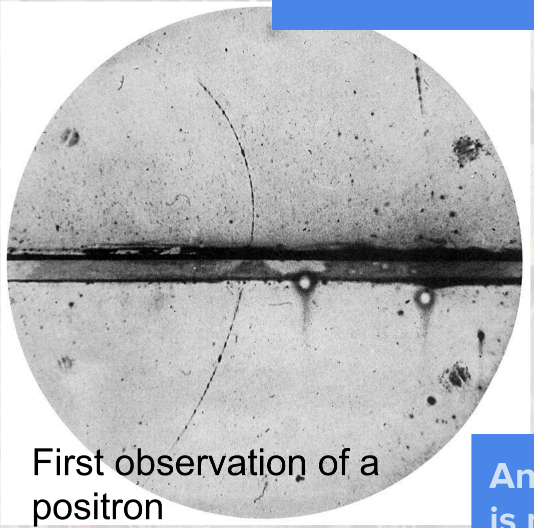
See talk by GIno Isidori yesterday

See also galaxy rotation simulation and observation

https://upload.wikimedia.org/wikipedia/commons/transcoded/3/33/Galaxy_rotation_under_the_influence_of_dark_matter.ogv/Galaxy_rotation_under_the_influence_of_dark_matter.ogv.360p.webm



Neutrino masses



First observation of a positron

Gravity

Antimatter: where is most of it?

"Dark matter"

https://upload.wikimedia.org/wikipedia/commons/thumb/6/69/PositronDiscovery.jpg/800px-PositronDiscovery.jpg

http://idahoptv.org/sciencetrek/topics/gravity/images/tree_and_apple.png

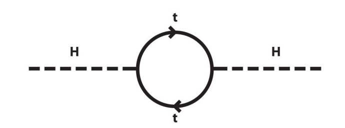
http://www.science20.com/files/images/particles.png

https://upload.wikimedia.org/wikipedia/commons/thumb/e/ec/M33_rotation_curve_HI.gif/400px-M33_rotation_curve_HI.gif

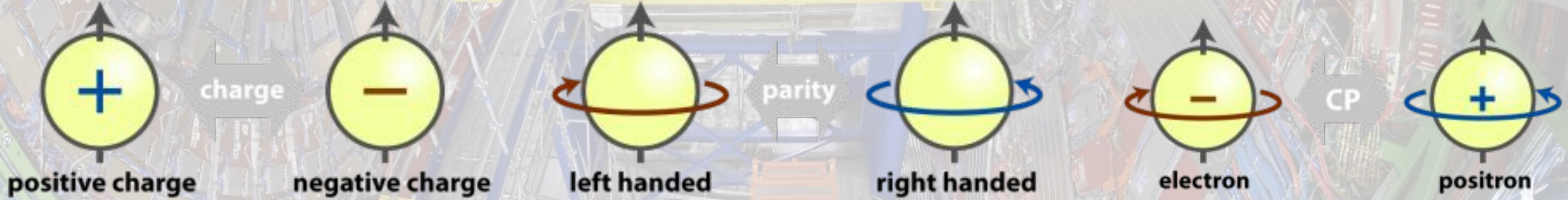
This standard model can be theoretically unsatisfactory

- the value of the Higgs mass (125 GeV) despite its large quantum corrections:

$$(m_H)^2 = (m_0)^2 + \mathcal{O}(10^{19})\ \mathrm{GeV} = (125\ \mathrm{GeV})^2$$



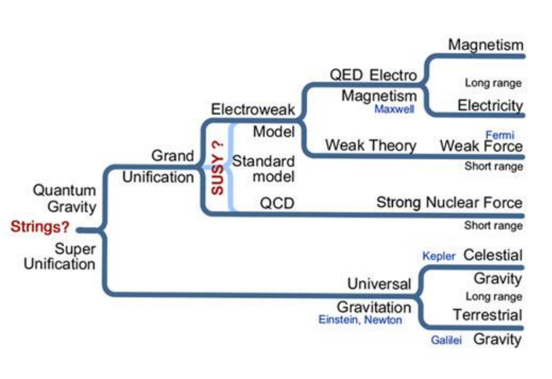
- vanishing term of the theory describing the strong force that breaks the combined symmetry of particle-antiparticle exchange (charge conjugation) and spatial coordinate inversion (parity, or 'mirror' symmetry): **CP violating** term
- ... and more



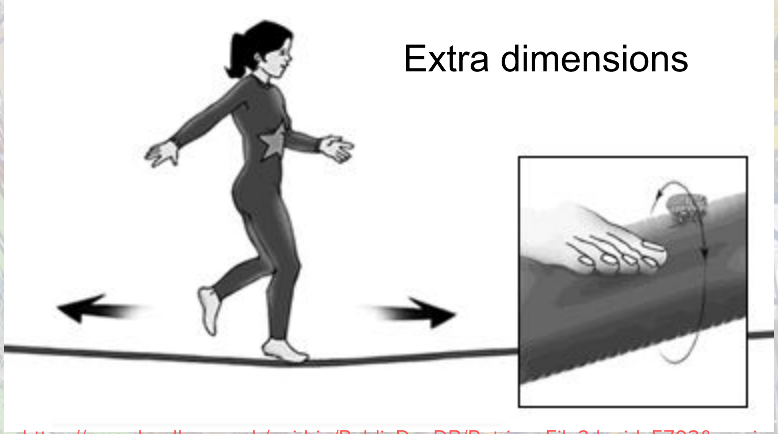
CP violation: why is there so much more matter than antimatter in the universe?

https://www.quantumdiaries.org/2011/11/14/what-exactly-is-cp-violation/ http://scienceblogs.com/startswithabang/files/2013/05/1000px-Hqmc-vector.png

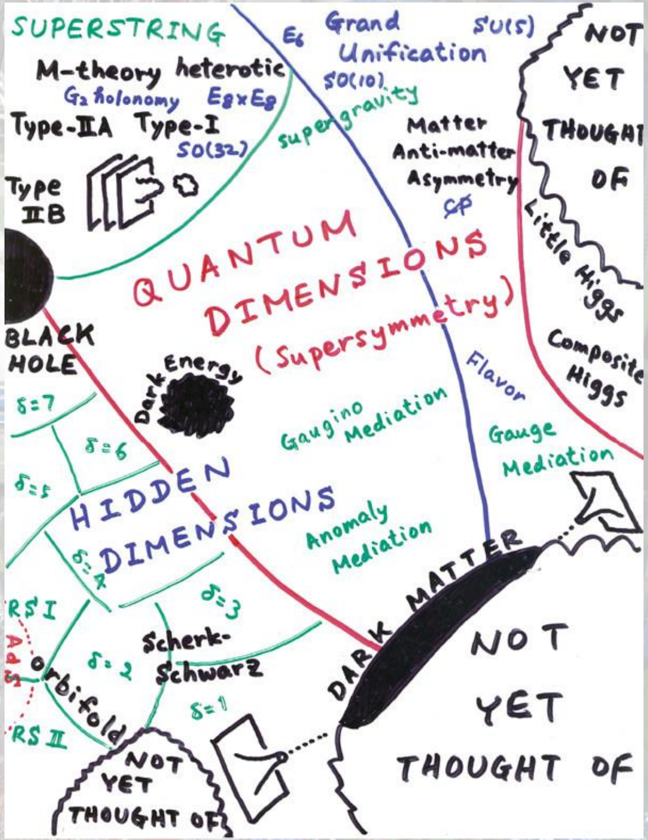
Physics beyond the standard model



Theory of everything?



“BSM”
“New physics”



https://cms-docdb.cern.ch/cgi-bin/PublicDocDB/RetrieveFile?docid=5703&version=1&filename=Susy_1.4.jpg http://newsline.linearcollider.org/images/2010/20100401_dc_2.jpg
https://www.eurekalert.org/features/doe/images/dbnl-gil053102.gif

Physics beyond the standard model: supersymmetry

- Required symmetry in supergravity
- The only possible way to combine spacetime and internal symmetries

Internal symmetries: SU(3) x SU(2) x U(1)

Space-time symmetries: **Poincaré group**

Translations $[P_\mu, P_\nu] = 0$

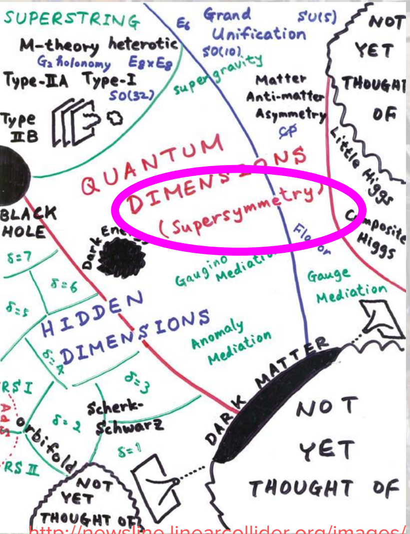
$$\frac{1}{i}[M_{\mu\nu}, P_\rho] = \eta_{\mu\rho}P_\nu - \eta_{\nu\rho}P_\mu$$

$$\frac{1}{i}[M_{\mu\nu}, M_{\rho\sigma}] = \eta_{\mu\rho}M_{\nu\sigma} - \eta_{\mu\sigma}M_{\nu\rho} - \eta_{\nu\rho}M_{\mu\sigma} + \eta_{\nu\sigma}M_{\mu\rho},$$

Lorentz group (boosts, rotations)

$$\{Q_\alpha, \bar{Q}_\beta\} = 2\gamma^\mu_{\alpha\beta}P_\mu$$

Poincaré algebra
SUSY algebra



There are many BSM models!

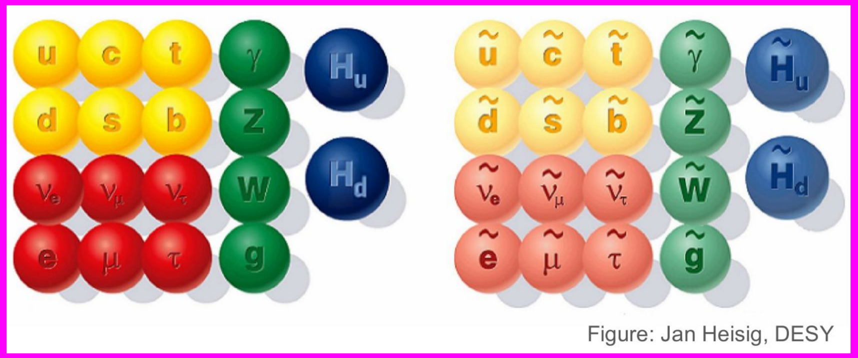
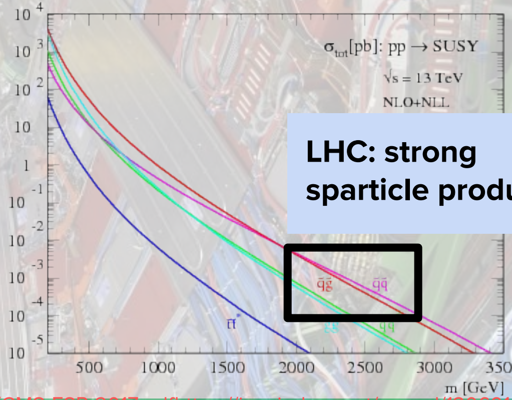


Figure: Jan Heisig, DESY



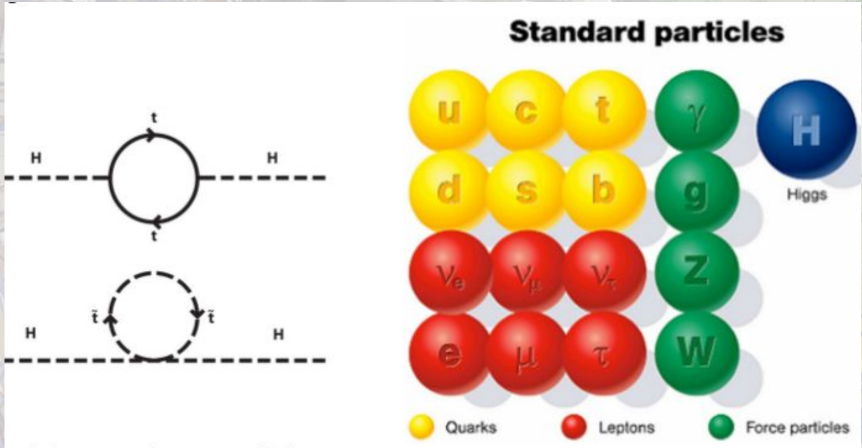
LHC: strong sparticle production

http://newsline.linearcollider.org/images/2010/20100401_dc_2.jpg

https://indico.cern.ch/event/647001/contributions/2691416/attachments/1535782/2405800/CMS-FSP-2017.pdf https://inspirehep.net/record/1306918/plots#0

The big vs the little hierarchy problem

Big or gauge hierarchy problem:



hierarchy problem:

$$(m_H)^2 = (m_0)^2 + \mathcal{O}(10^{19})\ \text{GeV}$$
$$= (125\ \text{GeV})^2$$

Little hierarchy problem:

Superpartners are not *that* light: loop corrections are reduced but only to about 10%. Some unnaturalness still remains.

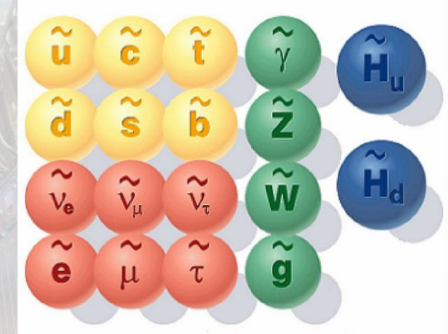


Figure: Jan Heisig, DESY

https://arxiv.org/pdf/hep-ph/0007265.pdf Giudice, Barbieri

The cosmological constant problem

The cosmological constant problem or vacuum catastrophe is the 120 orders of magnitude difference between the observed vacuum energy density and the predicted zero point density by quantum field theory

The stringy landscape with many hidden sectors can solve the cosmological constant problem and gauge hierarchy problem at the same time

Adding an axion can also solve the strong CP problem by a chiral superfield containing an axion, axino (fermionic superpartner), and dilaton (scalar superpartner). The axino is often the LSP and a candidate for cold dark matter.

https://arxiv.org/pdf/hep-ph/0410252.pdf axion + high scale susy

https://arxiv.org/abs/hep-ph/0402220 RPV axinos (Hooper)

What is a simplified model?

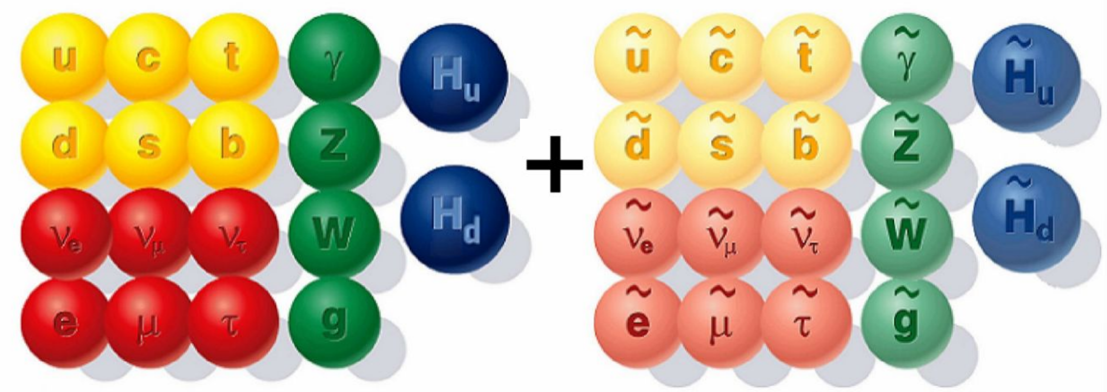
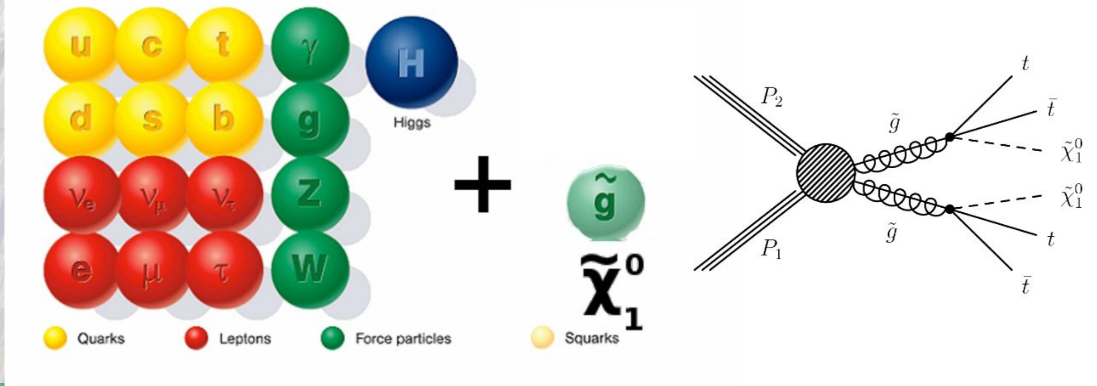
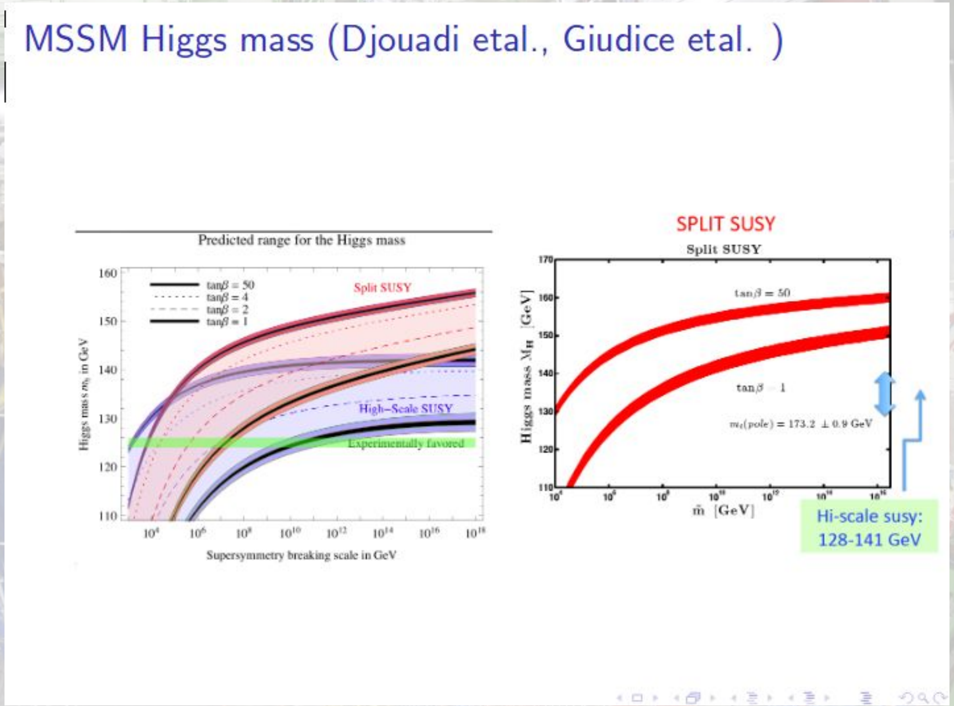


Figure: Jan Heisig, DESY

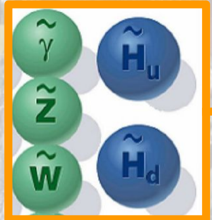


Split SUSY and the Higgs mass

https://indico.cern.ch/event/689399/contributions/3005379/attachments/1690861/2720690/StopGrinoDks-v1.pdf



Searching for supersymmetry



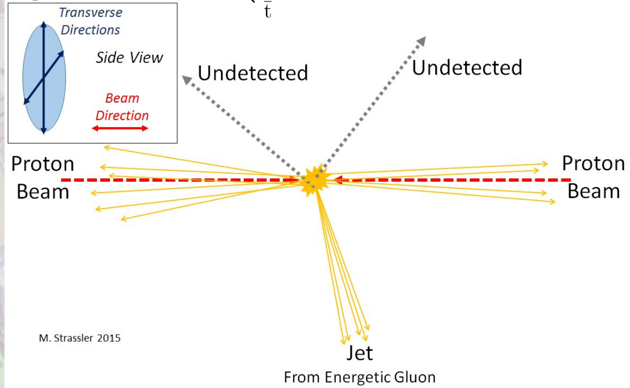
$(\tilde{B}, \widetilde{W}^0)$
$(\tilde{H}_u^0$ and $\tilde{H}_d^0)$ → $\tilde{\chi}_0$

$(\tilde{H}_u^+$ and $\tilde{H}_d^-)$
$(\widetilde{W}^+$ and $\widetilde{W}^-)$ → $\tilde{\chi}_\pm$

https://arxiv.org/pdf/hep-ph/9709356.pdf

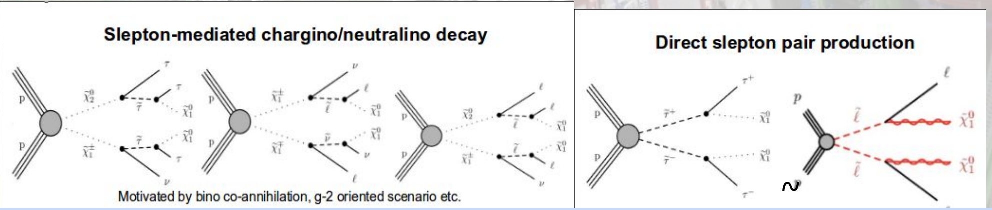
Higgsinos and weak gauginos mix to neutralino, chargino

Classic strong SUSY searches:



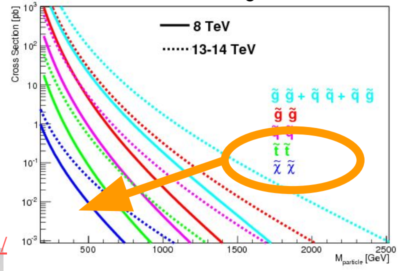
Search for gluino and squark pair production in multijet and multilepton events with a lot of **missing transverse momentum**!

Classic electroweakino searches:



R-parity conserving (RPC): lightest SUSY particle (e.g. χ_0^1) is stable

- $WZ : 2\ell$ + jets + p_T^{miss}
- $WZ : 3\ell + p_T^{miss}$
- $Wh : 1\ell + bb + p_T^{miss}$



https://cds.cern.ch/record/2291346/files/fig_susy_crossections.png

One can search also for resonance search ('bump hunt'), angular distributions, deviations in standard model observables...

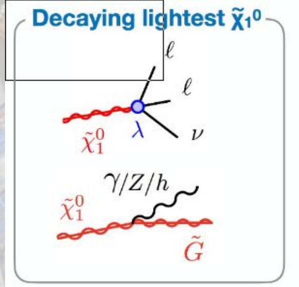
https://profmattstrassler.com/articles-and-posts/relativity-space-astronomy-and-cosmology/dark-matter/searching-for-dark-matter-at-the-lhc/

https://indico.cern.ch/event/689399/contributions/2945161/attachments/1691950/2722452/SUSY2018_Camacho.pdf

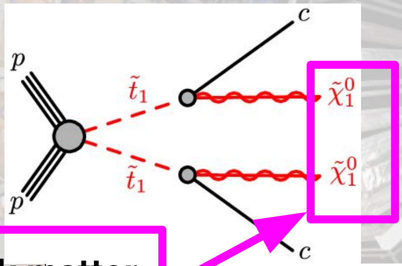
https://indico.cern.ch/event/689399/contributions/3005411/attachments/1692317/2723139/BasilSchneider_20180724_SUSY.pdf

New strategies

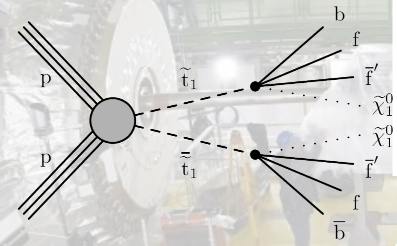
R-parity **violating** (RPV): LSP decays

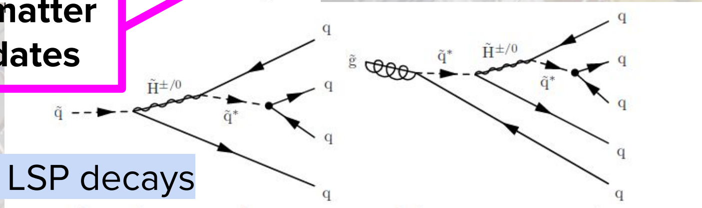


Small mass splittings, new final state particles and RPV SUSY:



Dark matter candidates

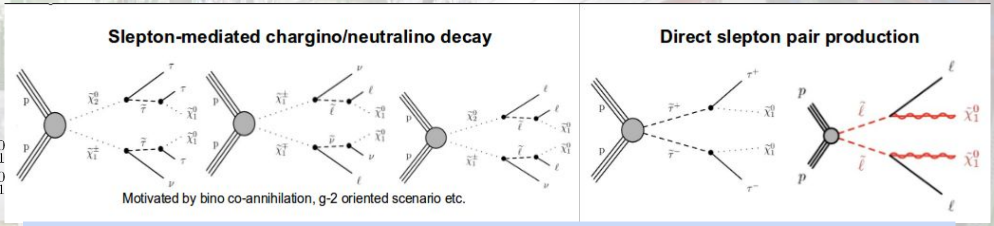




RPV LSP decays

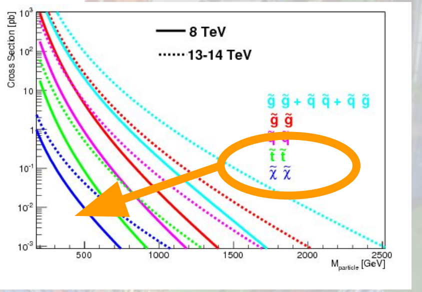
Gluino and squark pair production with multijet and multilepton final states -- very **little missing transverse momentum**!

Smaller mass electroweakinos:



R-parity conserving (RPC): lightest sparticle (LSP) is stable

- WZ : jets + $p_T^{\rm miss}$
- WZ : $p_T^{\rm miss}$
- Wh : $bb + p_T^{\rm miss}$



Very soft leptons! How to trigger?

https://cds.cern.ch/record/2291346/files/fig_susy_crossections.png

https://indico.cern.ch/event/689399/contributions/2945157/attachments/1691972/2722396/20180724_-_Strong_SUSY.pdf

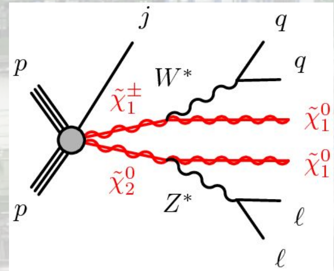
https://indico.cern.ch/event/689399/contributions/2945161/attachments/1691950/2722452/SUSY2018_Camacho.pdf

https://indico.cern.ch/event/689399/contributions/3005411/attachments/1692317/2723139/BasilSchneider_20180724_SUSY.pdf

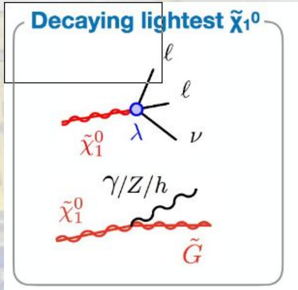
Searching for supersymmetry

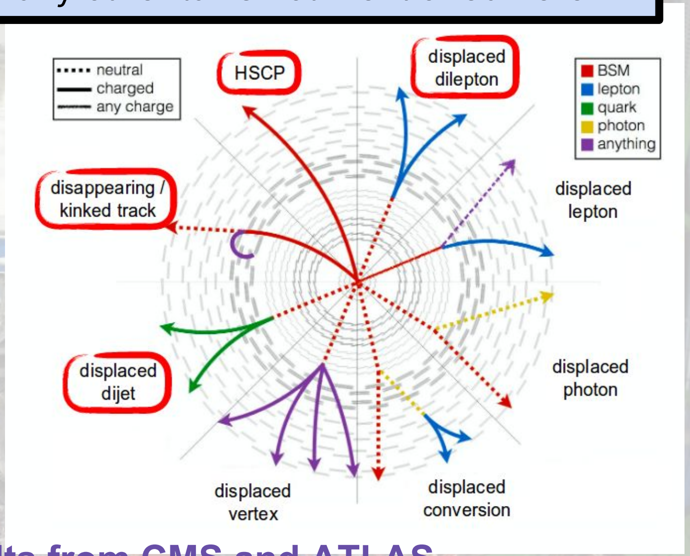
Not covered here:
SUSY Higgs searches
See talk on Wednesday by Nikolina Ilic
SM, DM results (need interpretation!):
E.g. Maria Cepeda and Gino Isidori on Wednesday, Vasiliki Kouskoura on Friday
And many other talks not mentioned here

Searches refined in run 2:



- Compressed mass spectra
- Lower cross sections
- Broaden class of models of supersymmetry to e.g. RPV (tougher background)
- More complex signatures (longlived)
- More third generation production and final states





→ Will improve for run 3 and HL-LHC!

Will now show highlights up to now only: a selection of recent results from CMS and ATLAS

CMS public results: https://cms-results.web.cern.ch/cms-results/public-results/publications/

ATLAS public results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic

https://indico.cern.ch/event/689399/contributions/2945161/attachments/1691950/2722452/SUSY2018_Camacho.pdf

https://indico.cern.ch/event/517268/contributions/2041293/attachments/1272363/1886050/Antonelli_CMS_LLP_May12.pdf

Strong sparticle production

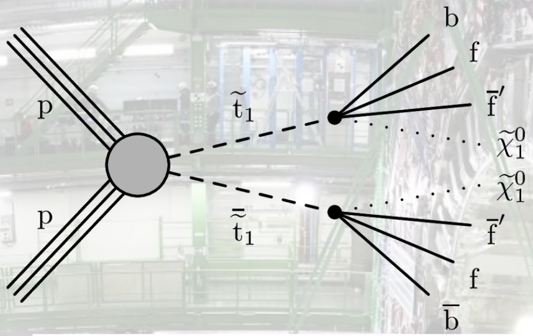
See also talks by
Antonia Strubig this afternoon
Anshul Kapoor on Wednesday
And also talks on vector-like quarks by
Erich Varnes this afternoon
Stéphanie Beauceron this afternoon

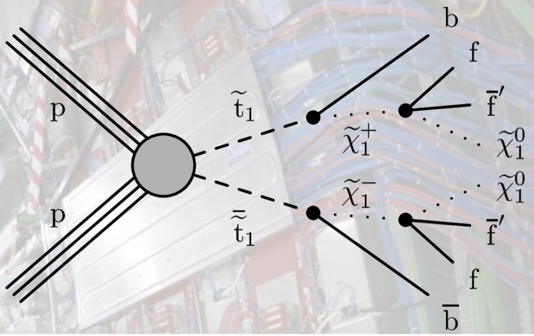
CMS-SUS-17-005

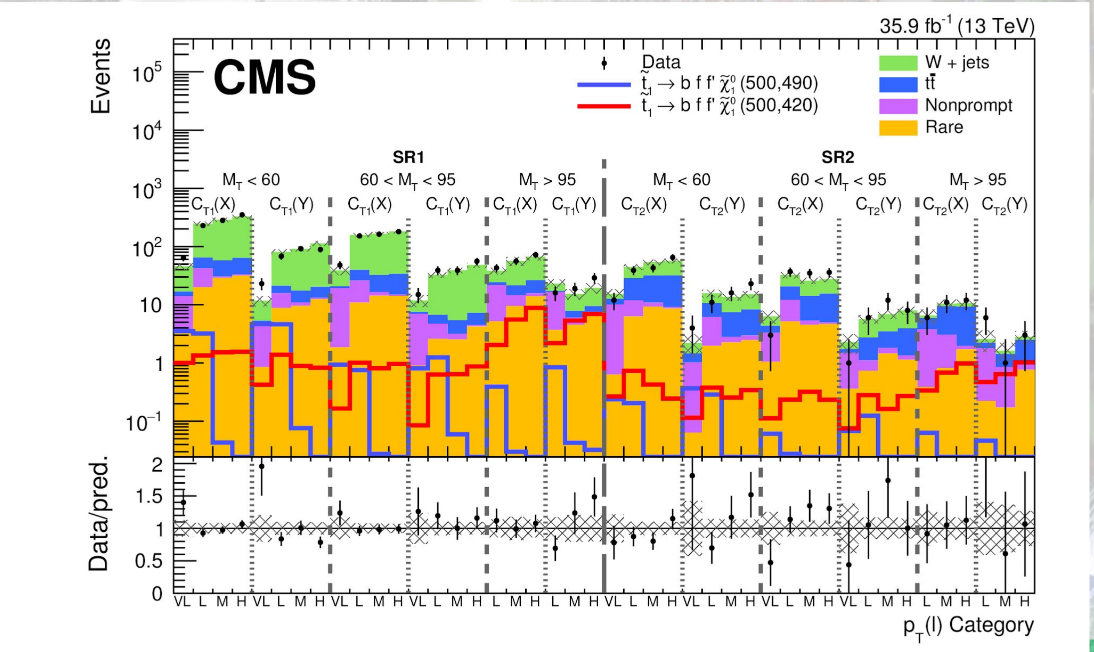
Light stops

At low mass splittings, the stop may not decay in a conventional way:

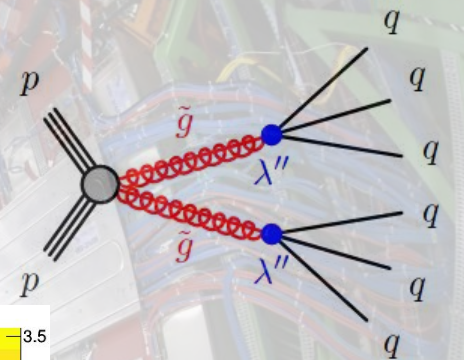
- ISR jet > 100(110) GeV
- $p_T$miss > 300 (200) GeV
- Multivariate technique and sequential selection
- Sensitive to stop masses up to 540GeV, Δm 40GeV in sequential selection



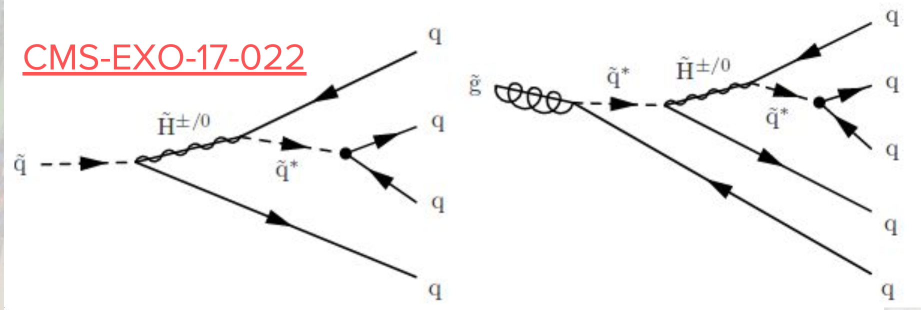


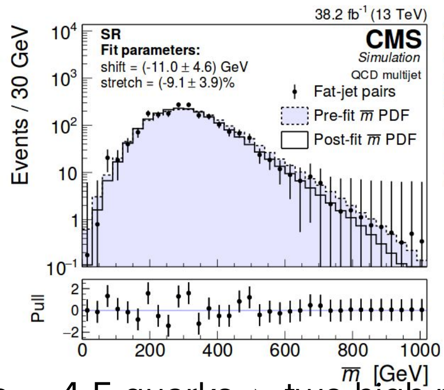


Hadronic RPV resonance search

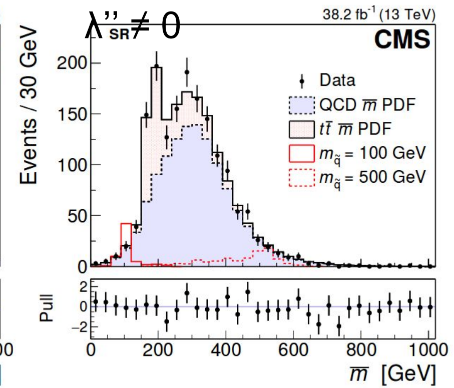


CMS-EXO-17-022

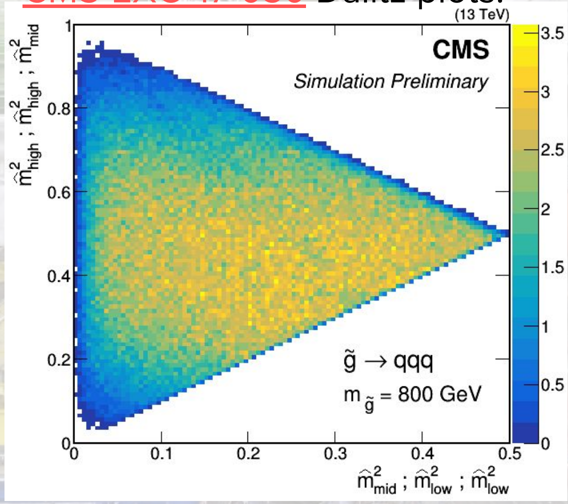


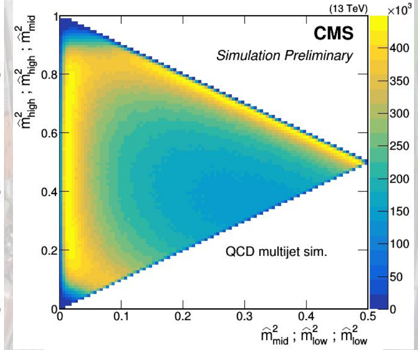


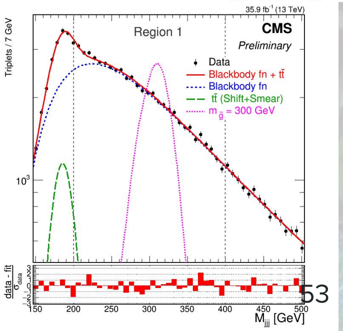
$\lambda'' \neq 0$



CMS-EXO-17-030 Dalitz plots:







- 4-5 quarks → two high p_T (>400GeV) fat jets (CA, R=1.2) with substructure (τ_{43} < 0.8, τ_{42} < 0.45) → suppresses QCD multijet background
- Experimentally challenging light quark mode for masses < 400 GeV

Uses **data scouting** for low masses:
High level trigger selection with 2kHz rate for a sum of jet transverse momenta HT>410 (not all event info saved)

http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/EXO-17-030

Charm tagging

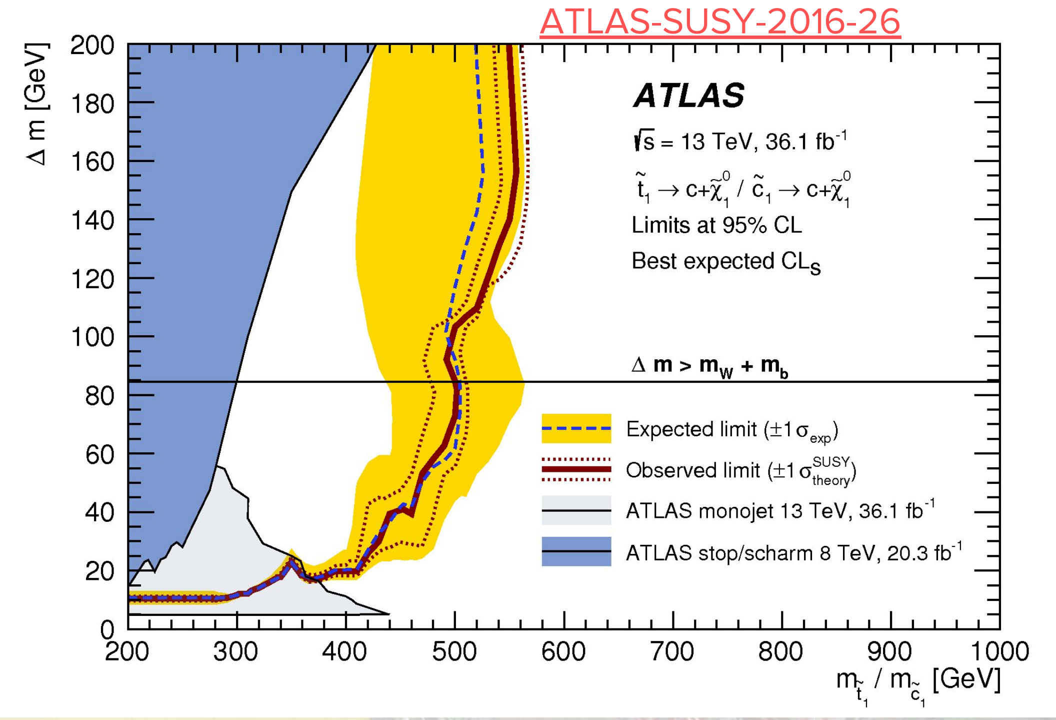
Selection: ≥ 2 jets, ≥ 1 c-jet, $p_{T,miss}$ > 500 GeV.

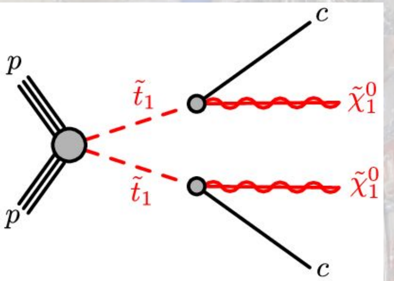
In compressed region:

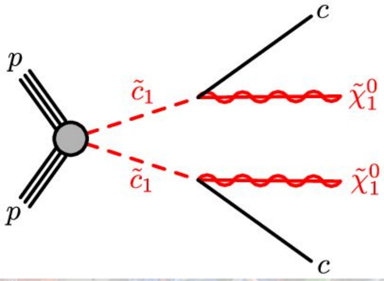
ISR selection: ≥ 3 jets with leading jet not c-tagged

Charm tagging with MVA in tight working point 18% efficient, and

- b-jet rejection factor 20
- Light-flavor rejection factor 200
- Hadronic τ-jet rejection factor 6







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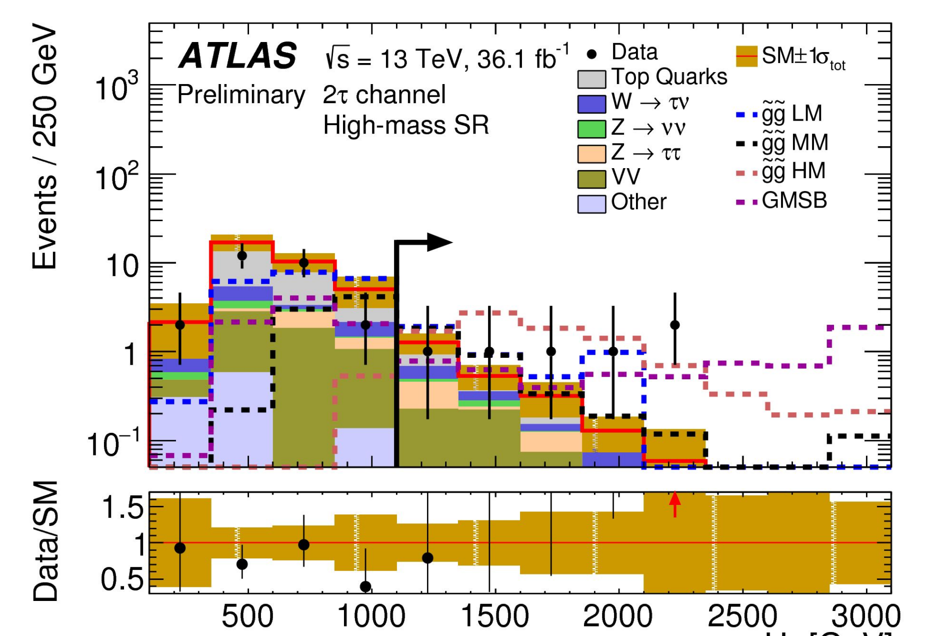
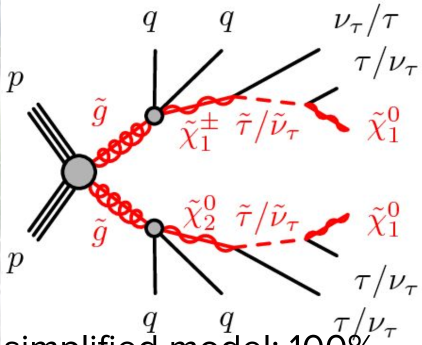
ATLAS=SUSY-2016-30

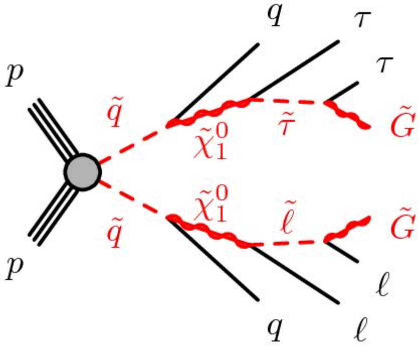
New results in tau and lepton final state from ATLAS



electrons, muons, jets, τ leptons



simplified model: 100% branching ratios



Gravity-mediated SUSY breaking (GMSB) model

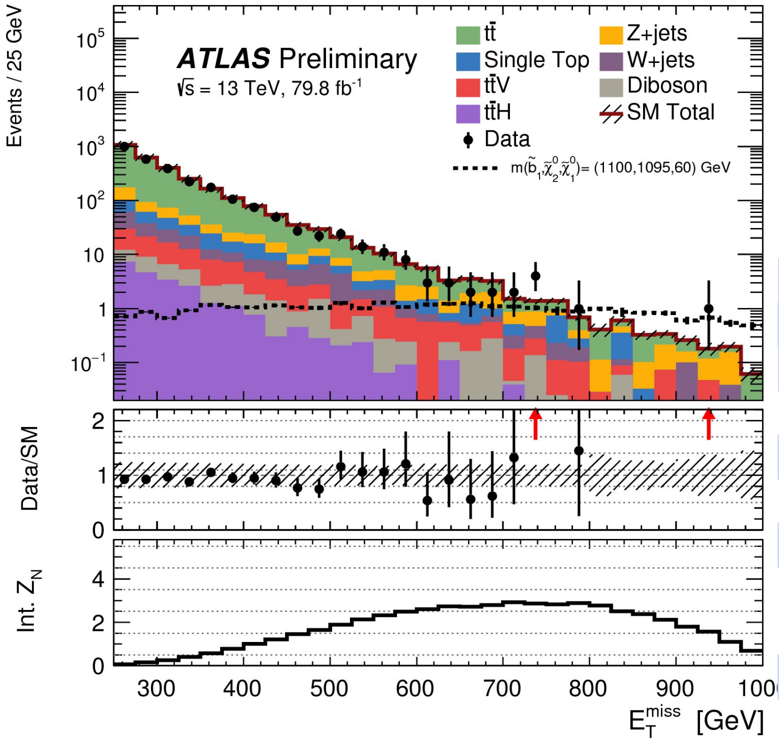
- τ often rejected with ttbar, Wt backgrounds; here 40-60% τ id eff.
- Events with ((1τ and p_T^{miss}>400GeV) or (>1τ and p_T^{miss}>180GeV)) and >1 jet
- Background normalization and top modelling largest syst. Uncertainties
- No significant deviation (2σ excess)

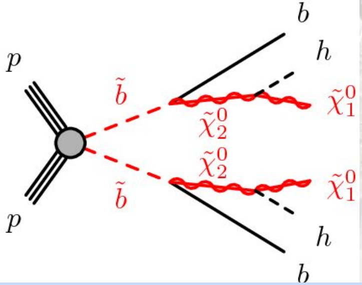
Bottom squark pair production to Higgs

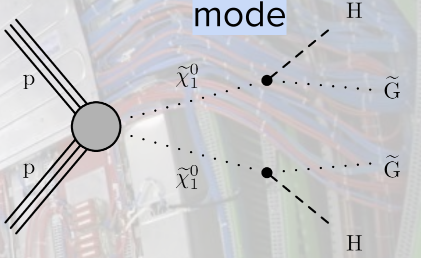
On-shell higgs with large enough $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$

In CMS: EW production mode

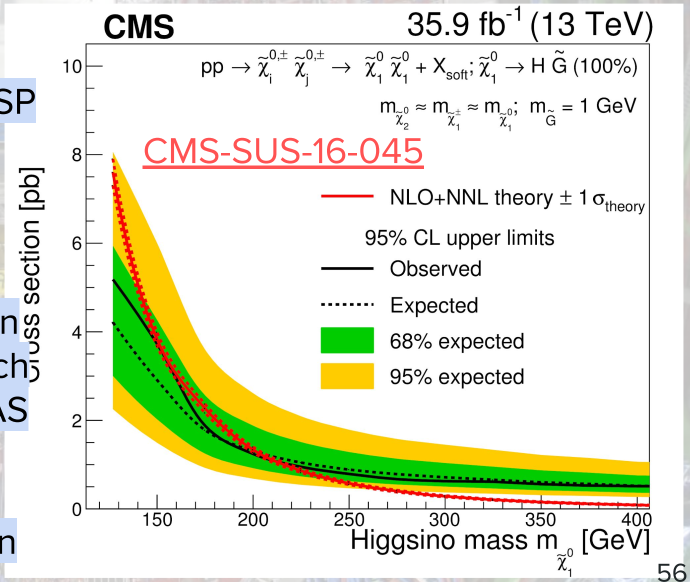
ATLAS-CONF-2018-40







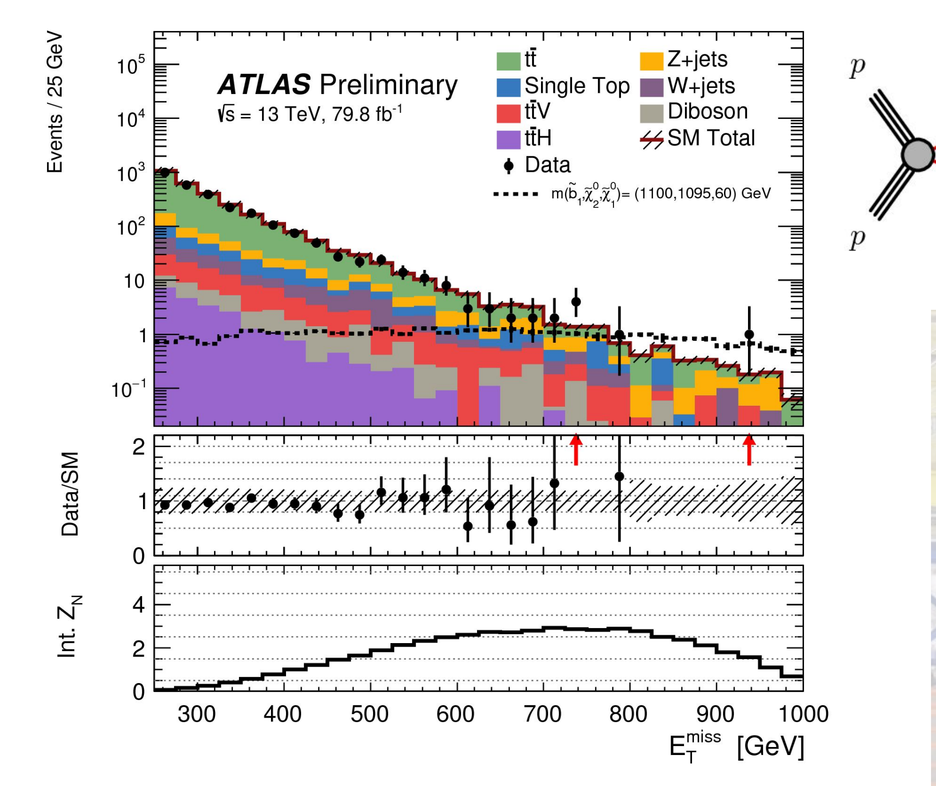
- GMSB goldstino LSP
- ATLAS: h → bb
- CMS: at least one H → γγ
- H, h: Standard Model Higgs boson
- First search for such a scenario in ATLAS in Run 2
- Small excess in compressed region with soft b-jets

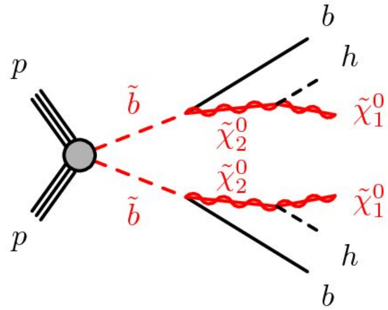


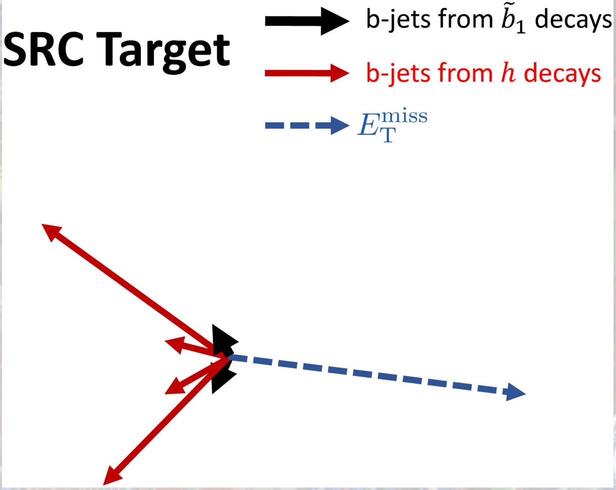
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2018-40 http://cms-results.web.cern.ch/cms-results/public-results/publications/SUS-16-045/

On-shell higgs with large enough $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$

Bottom squark pair production to Higgs







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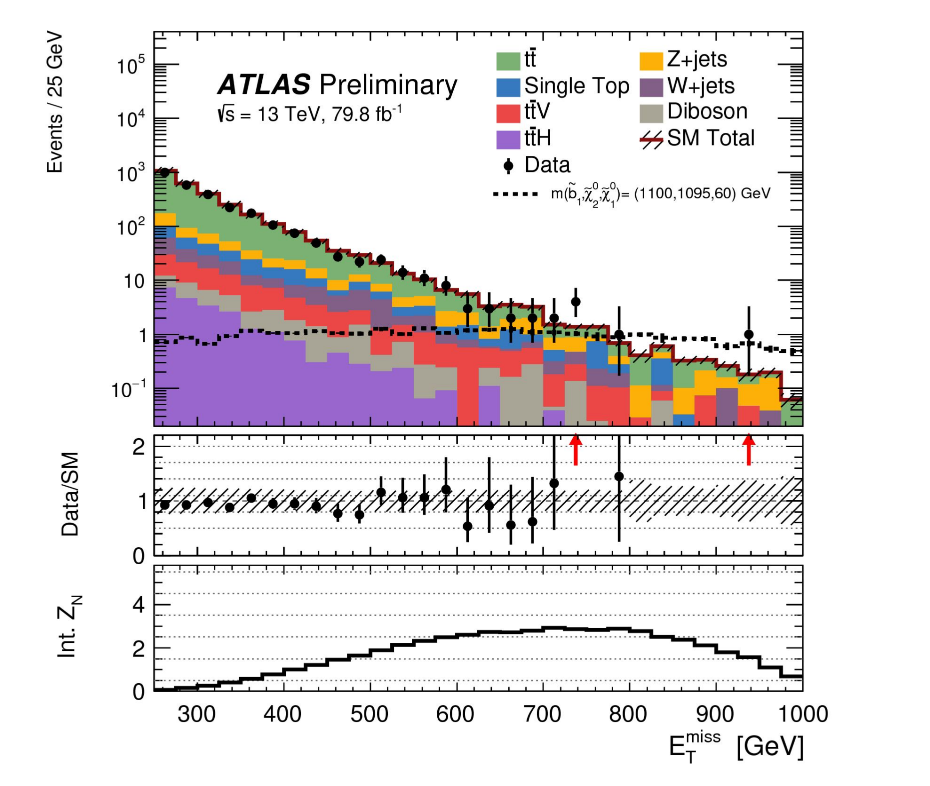
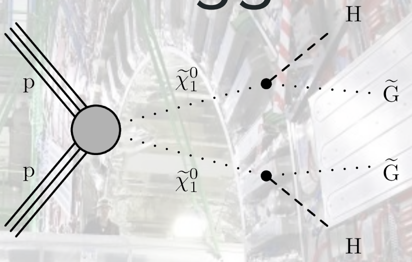
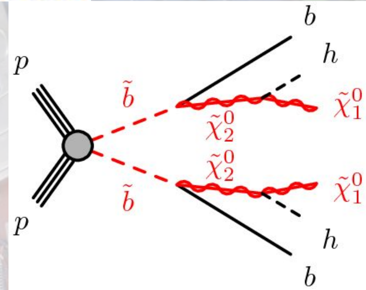
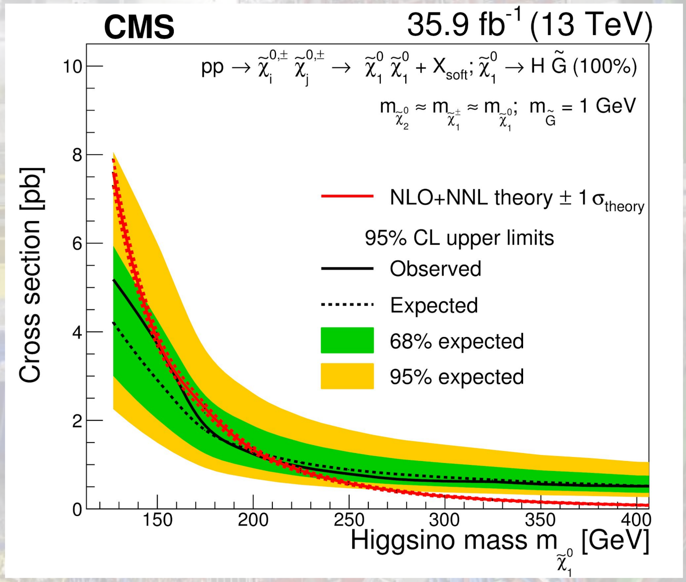
On-shell higgs with large enough $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$

Bottom squark pair production to Higgs









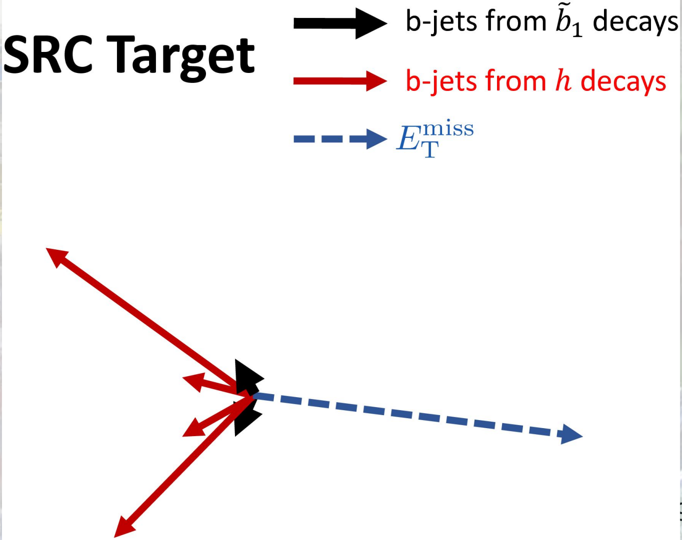
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2018-40 http://cms-results.web.cern.ch/cms-results/public-results/publications/SUS-16-045/

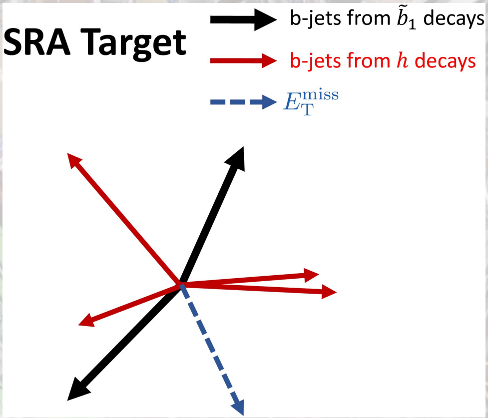
Bottom squark pair production to Higgs

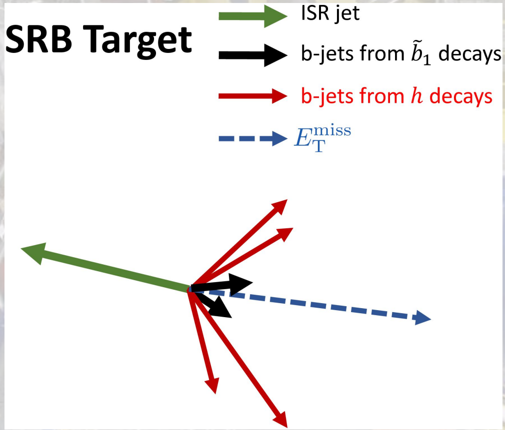
Bottom-squark pair production with the ATLAS detector in final states containing Higgs bosons, b-jets and missing transverse momentum in pp collisions at s√=13 TeV

Variable	SRC25	SRC27	SRC30	SRC32
N_{leptons} (baseline)			$= 0$	
N_{jets}			≥ 4	
$N_{\text{b-jets}}$			≥ 3	
$E_{\text{T}}^{\text{miss}}$ [GeV]			> 250	
$\min \Delta\phi(\text{jet}_{1-4}, \mathbf{p}_{\text{T}}^{\text{miss}})$ [rad]			> 0.4	
$\mathcal{S}$	> 25	> 27	> 30	> 32

$$\mathcal{S} = \sqrt{\frac{|\mathbf{p}_{\text{T}}^{\text{miss}}|^2}{\sigma_{\text{L}}^2(1 - \rho_{\text{LT}}^2)}}.$$





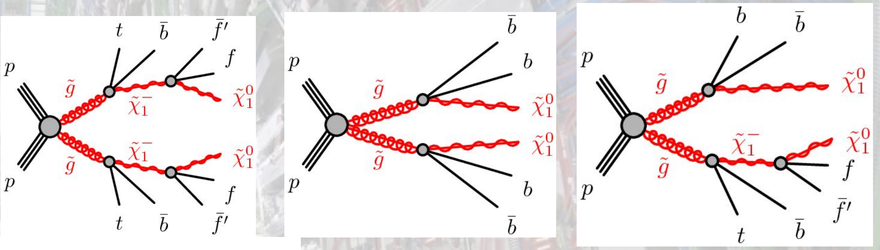


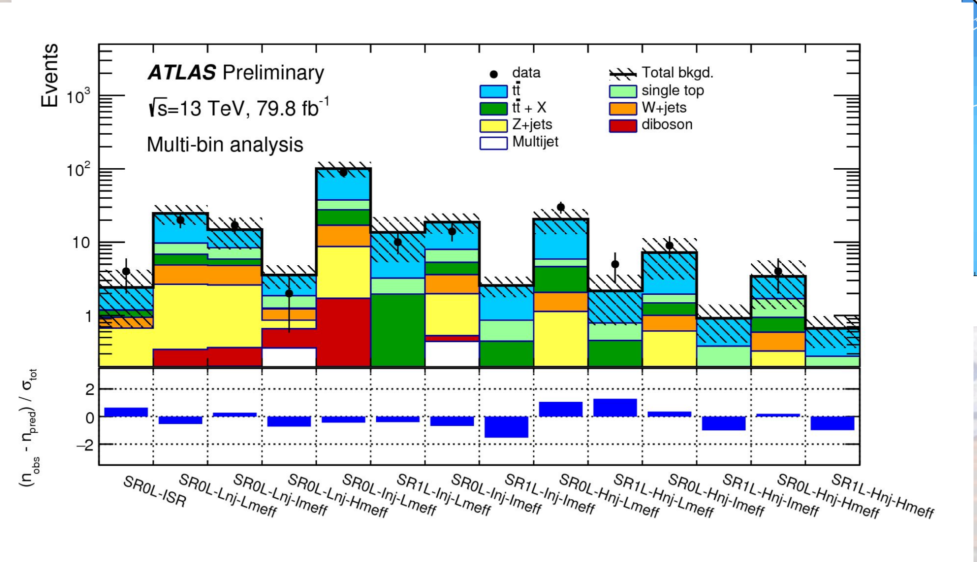
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2018-40

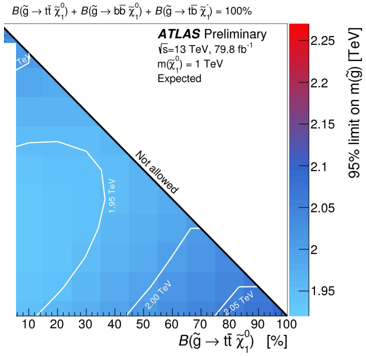
Gluino-mediated stop and sbottom pair production

ATLAS inclusive search with b-jets and missing transverse momentum

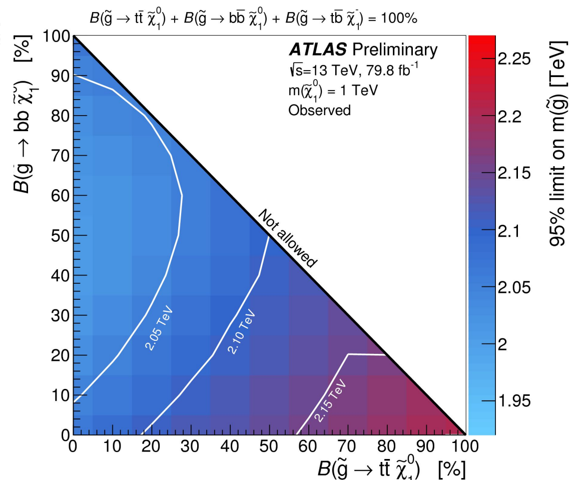
Search with stop-mediated decay similar results for m(gluino) close to m(LSP)







expected



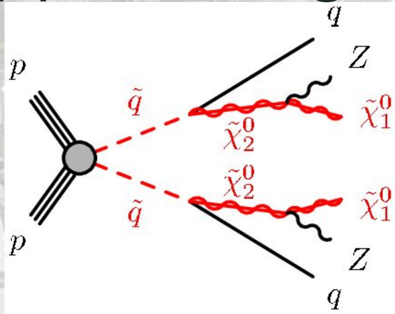
observed

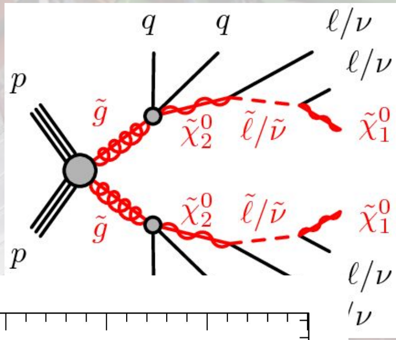
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2018-041/

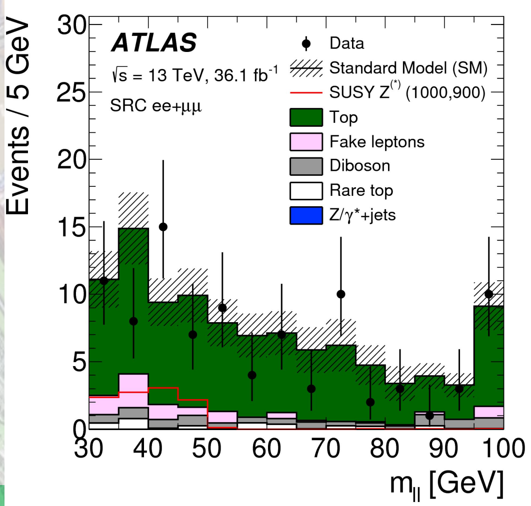
ATLAS-SUSY-2016-33

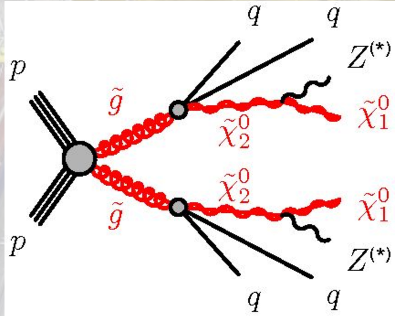
Soft same flavor opposite sign dileptons

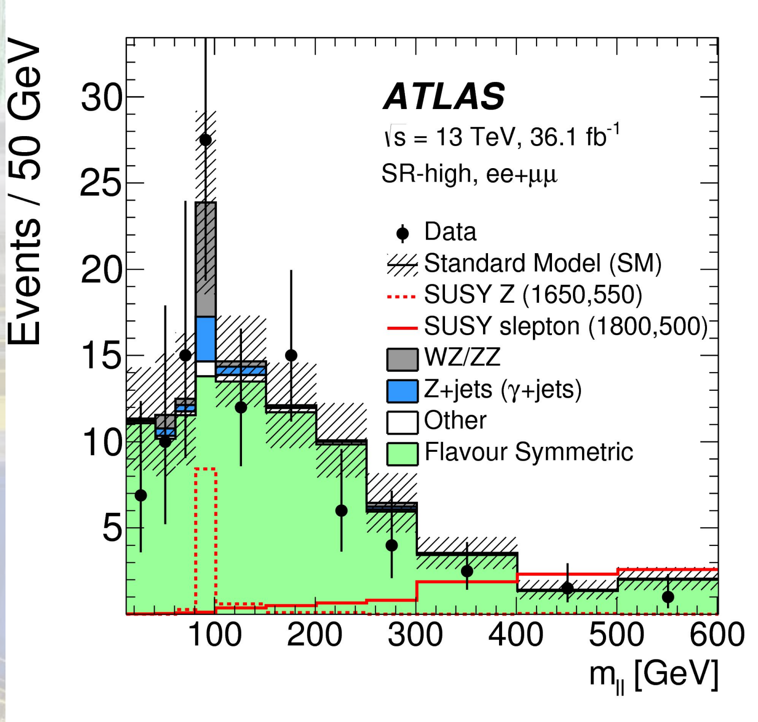
- Soft dilepton region: p_T> 7 GeV only (high p_T region: 25GeV)
- Missing transverse energy trigger for soft dilepton region
- Data-driven flavor-symmetric background estimates (ttbar, WW, Wt, Z→ ττ)











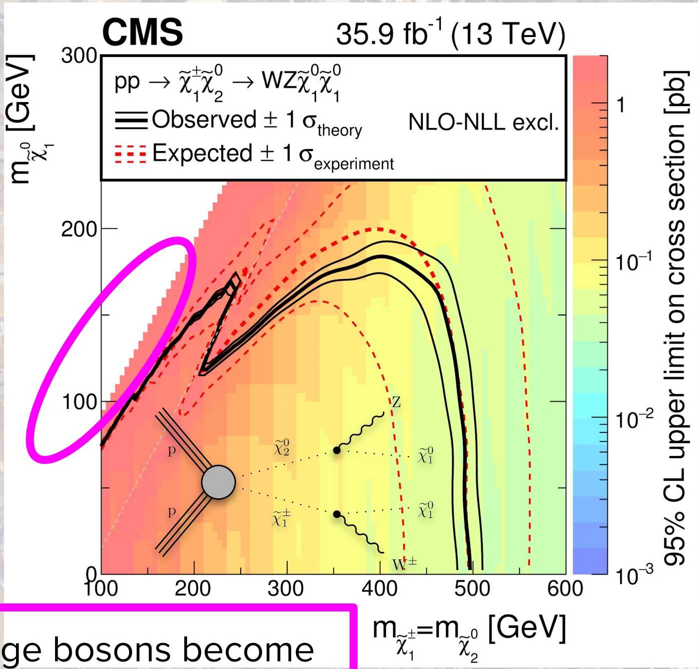
Electroweak sparticle production

See talk by
Sarah Williams this afternoon

CMS-SUS-17-004

ATLAS-SUSY-2017-03

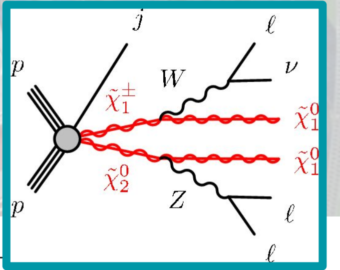
Multileptons from electroweakino pair production

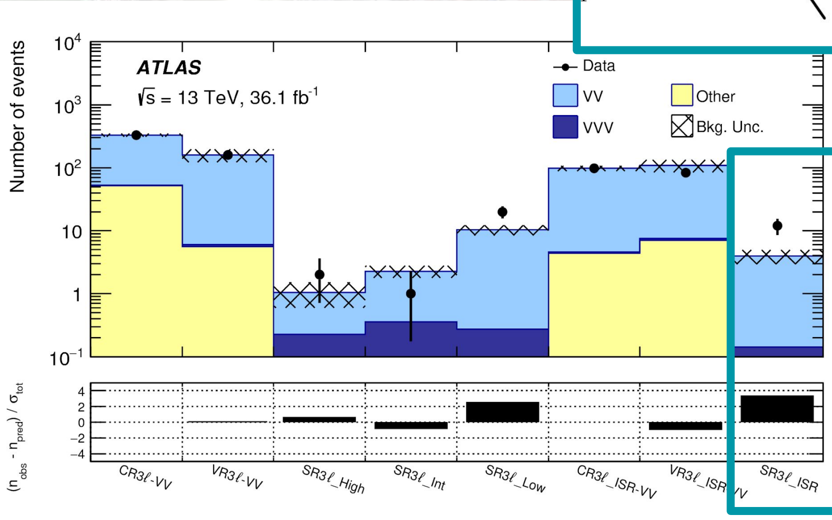


Gauge bosons become off-shell → soft leptons

Classic WZ mediated electroweakino search typically not sensitive close to diagonal

RJR or **Recursive jigsaw reconstruction** uses kinematic observables computed in different reference frames for enhanced sensitivity





3σ

High, intermediate: large masses → large mass splittings

Low: smaller masses

https://indico.cern.ch/event/689399/contributions/2945161/attachments/1691950/2722452/SUSY2018_Camacho.pdf

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2017-03/

ATLAS-SUSY-2016-25

CMS-SUS-16-048

Off-shell gauge bosons

μ ≍ higgsino mass

Natural SUSY has light higgsino:

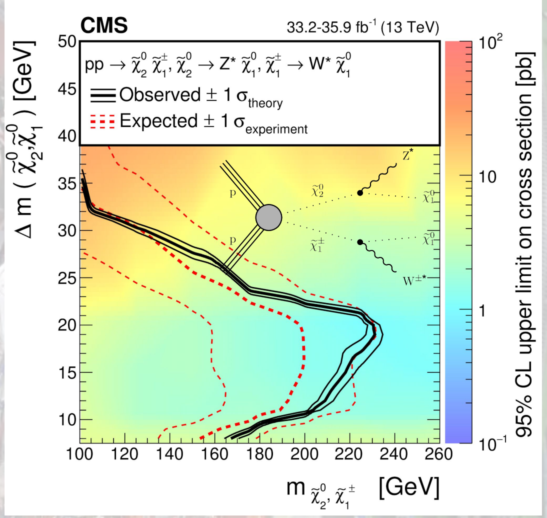
Then if n1, n2 higgsinolike:

- ➜ small mass splittings
- ➜ very soft leptons

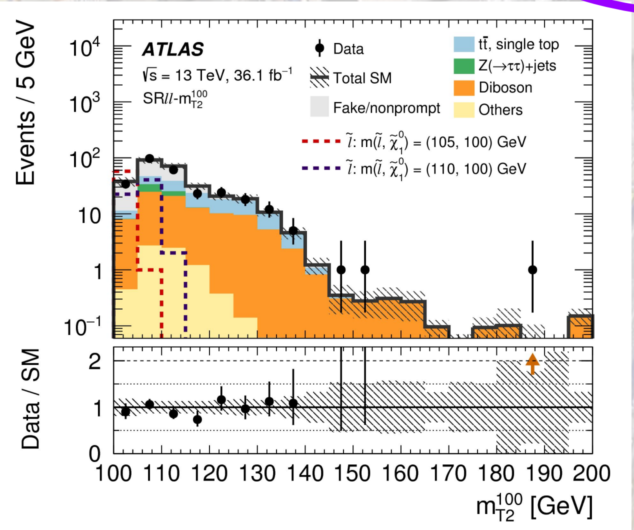
Very very soft leptons: disappearing tracks

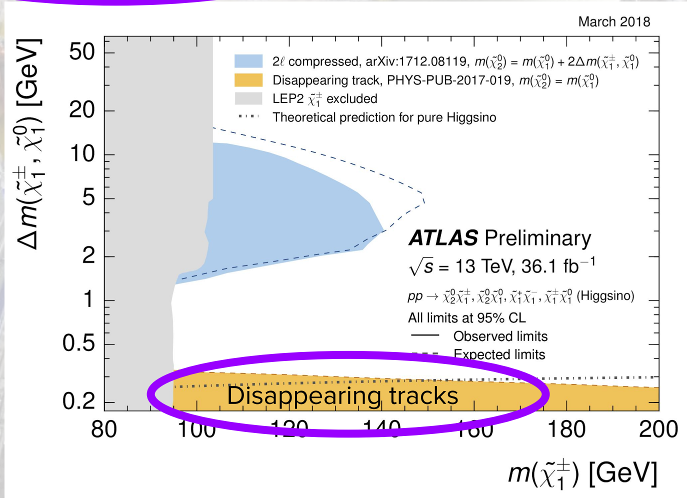
tree-level:

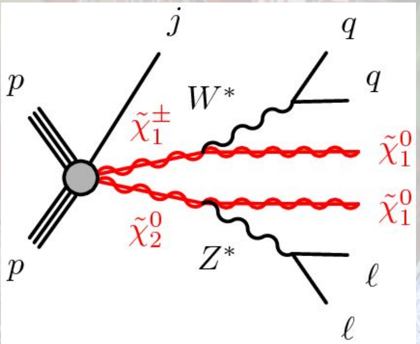
$$-\frac{m_Z^2}{2} = \boxed{|\mu^2|} + m_{H_u}^2 + \mathcal{O}\left(\frac{1}{\tan^2\beta}\right)$$



Sensitive to low mass splittings (soft leptons)







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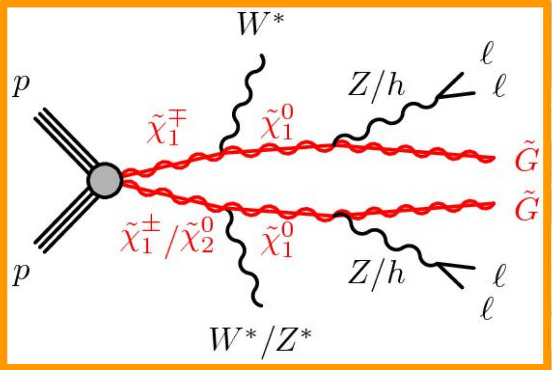
See also CMS-PAS-SUS-17-002

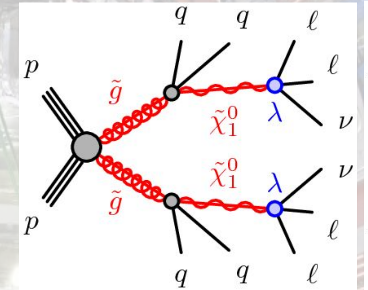
>=4 leptons, 0 - 2 hadronically decaying taus
Mild excess observed (2.3 σ) in 0 tau, on-shell Z

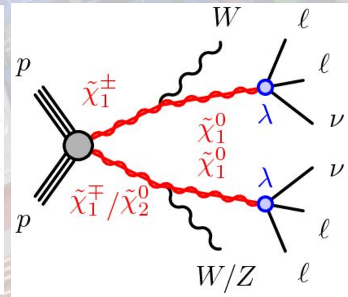
RPC + RPV to leptons

ATLAS-SUSY-2016-21



RPC wino decay, gauginos decaying via ZZ
Decay products from offshell W*, Z* cannot easily be triggered on

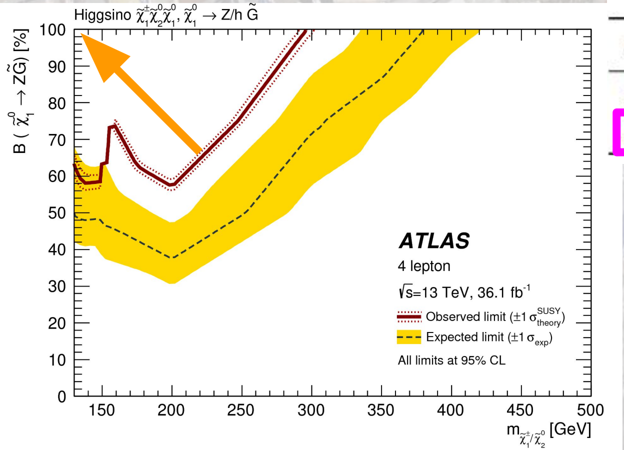




RPV simplified model
NLSP production

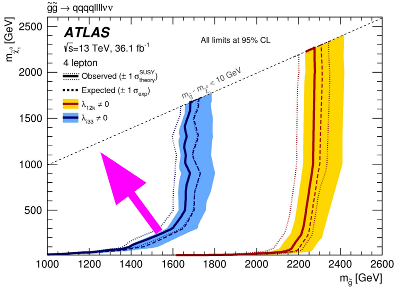
$$\frac{1}{2}\lambda_{ijk}L_iL_j\bar{E}_k + \lambda'_{ijk}L_iQ_j\bar{D}_k + \frac{1}{2}\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k + \kappa_iL_iH_2,$$

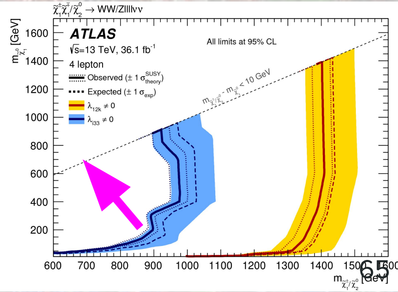
λ_{ijk}: 27 RPV couplings in superpotential



Scenario	$\tilde{\chi}_1^0$ branching ratios		
$LL\bar{E}12k$	$e^+e^-\nu$ (1/4)	$e^\pm\mu^\mp\nu$ (1/2)	$\mu^+\mu^-\nu$ (1/4)
$LL\bar{E}i33$	$e^\pm\tau^\mp\nu$ (1/4)	$\tau^+\tau^-\nu$ (1/2)	$\mu^\pm\tau^\mp\nu$ (1/4)

Less sensitivity for 3rd gen RPV coupling





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https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2016-21/

Electroweak SUSY: low-mass neutralino/chargino?

MSSM-EW ($M_1, M_2, \mu, \tan\beta$ + 2 nuisances) scans in progress

decouple everything except $\chi^{0,\pm}$

- free (EW scale) parameters:

$$M_1, M_2, \mu, \tan\beta, \quad \alpha_S, m_t$$

- focus: impact of collider data

various LEP cross-section limits

ATLAS multi-lepton: 2-3 leptons + 0-5 jets

ATLAS RJ: 2-3 leptons, recursive jigsaw variables

ATLAS 4lep: at least 4 leptons

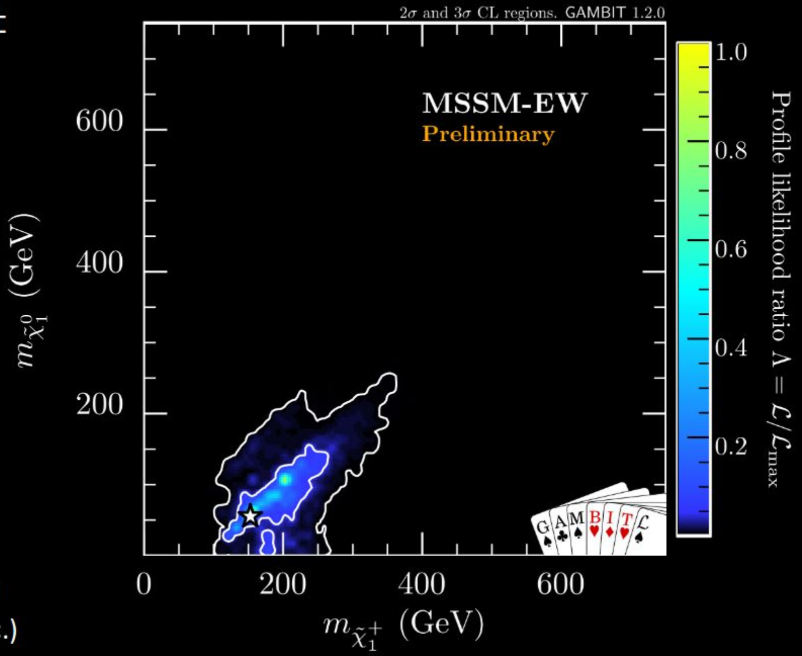
ATLAS 3b: higgsinos in double-Higgs final states

CMS multi-lepton: (similar to ATLAS)

CMS 1lep(H)bb: 1 lepton plus bbar from H

CMS 2SFOSlep-soft: two SFOS leptons (virtual W/Z)

CMS 2SFOSlep: two SFOS leptons (on-shell W/Z dec.)



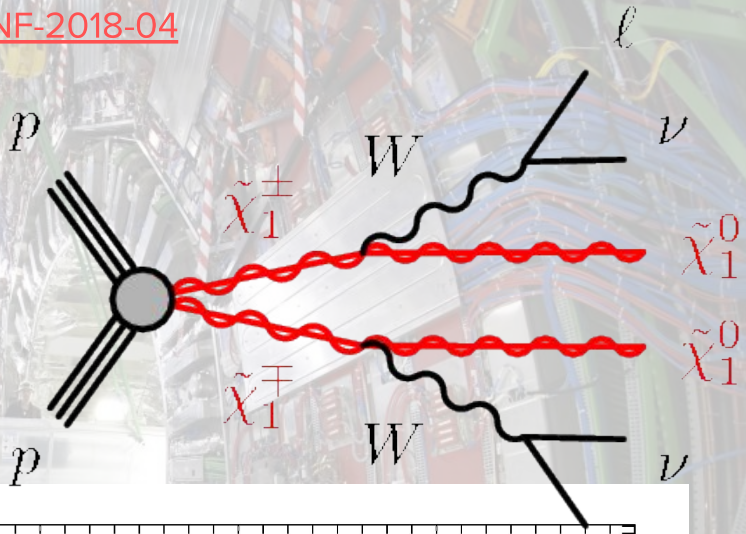
C Balázs | 2018 Jul 27 SUSY18 | page 28 of 36

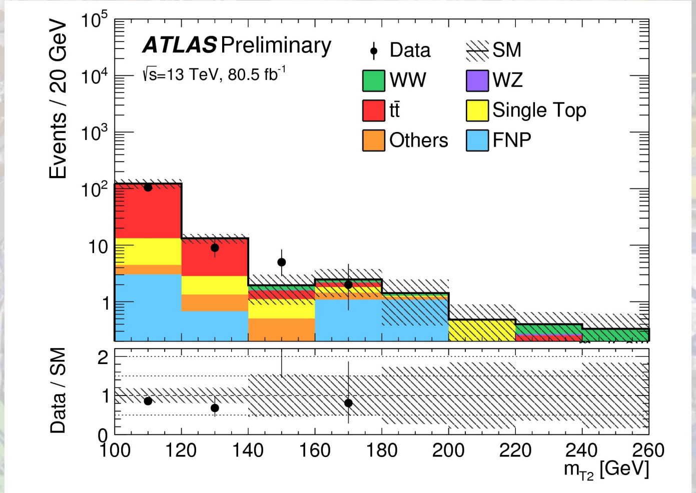
https://indico.cern.ch/event/689399/contributions/3005486/attachments/1692595/2723584/SUSY-GAMBIT.pdf

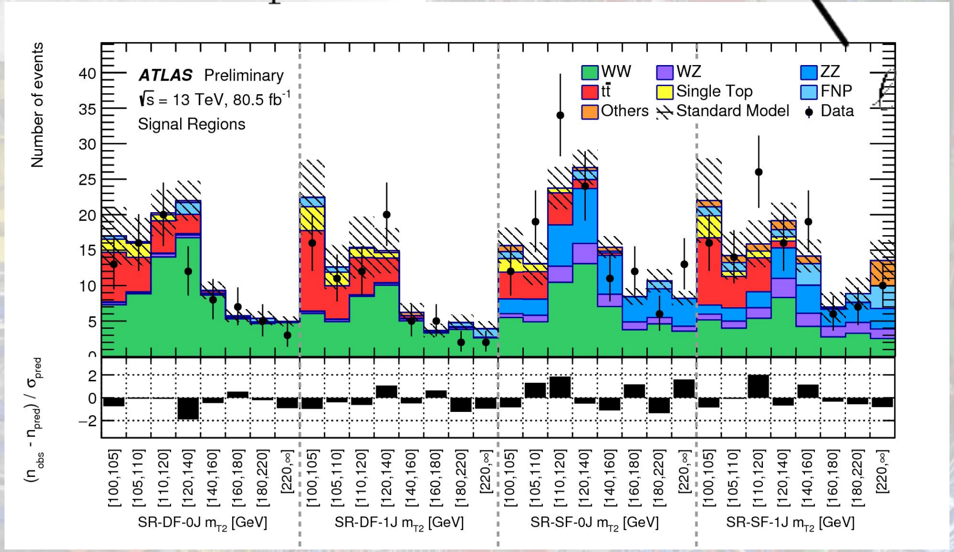
ATLAS-CONF-2018-042

Chargino pair production

- 2 OS leptons: m(ll) > 25 GeV, p_T>25GeV
- Missing transverse momentum: p_T^{miss} > 110GeV
- No b-jets
- MC backgrounds with likelihood fit to data for normalization







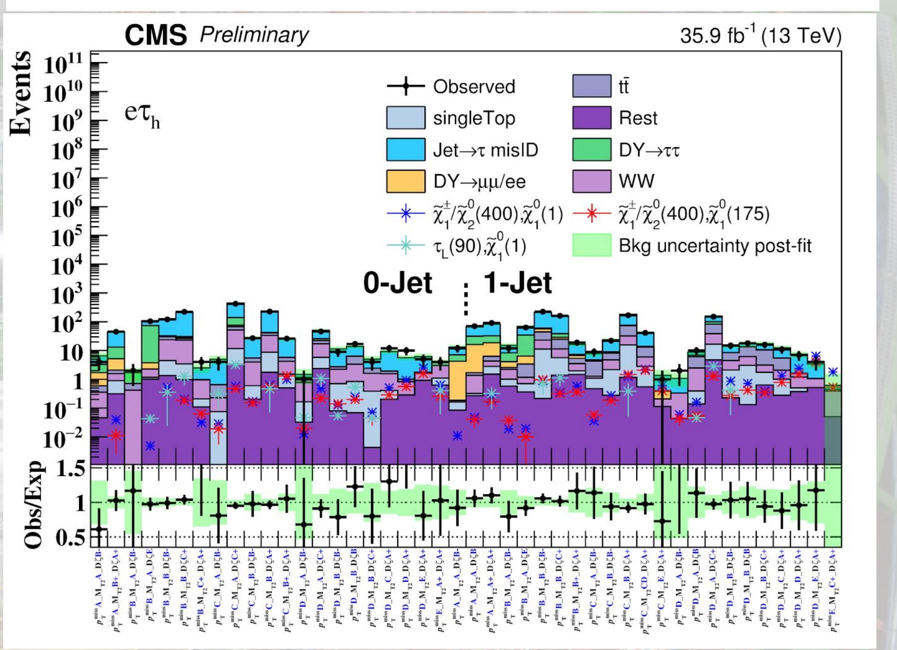
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2018-042

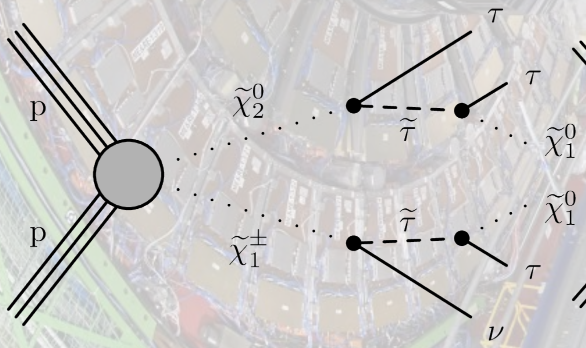
CMS-PAS-SUS-17-002

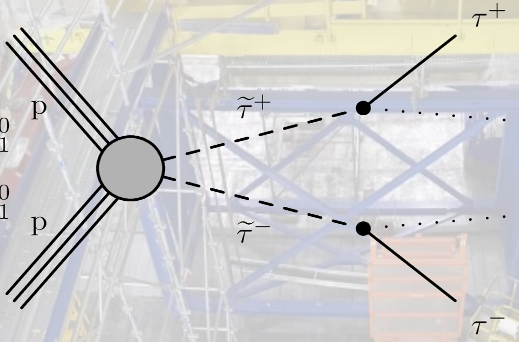
Hadronic and leptonic tau

Combination of leptonic and hadronic channels

$p_T(\tau)$ > 20 GeV





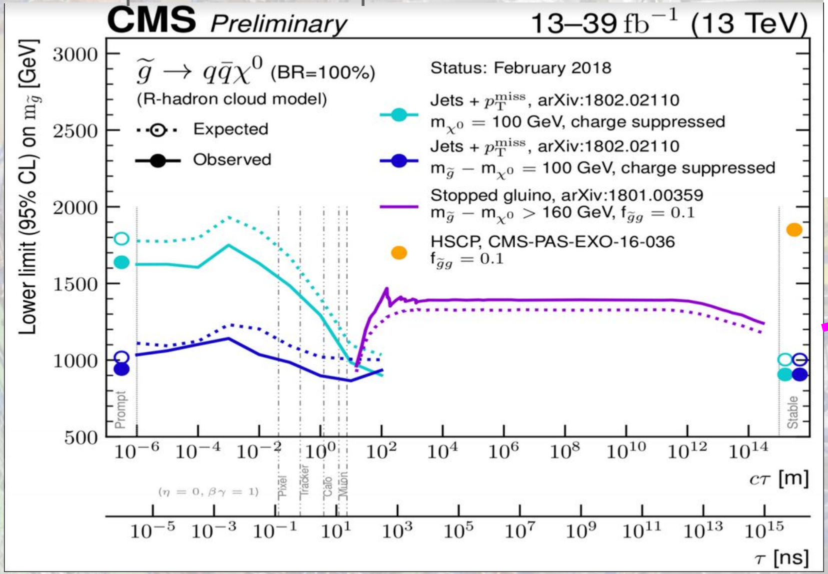


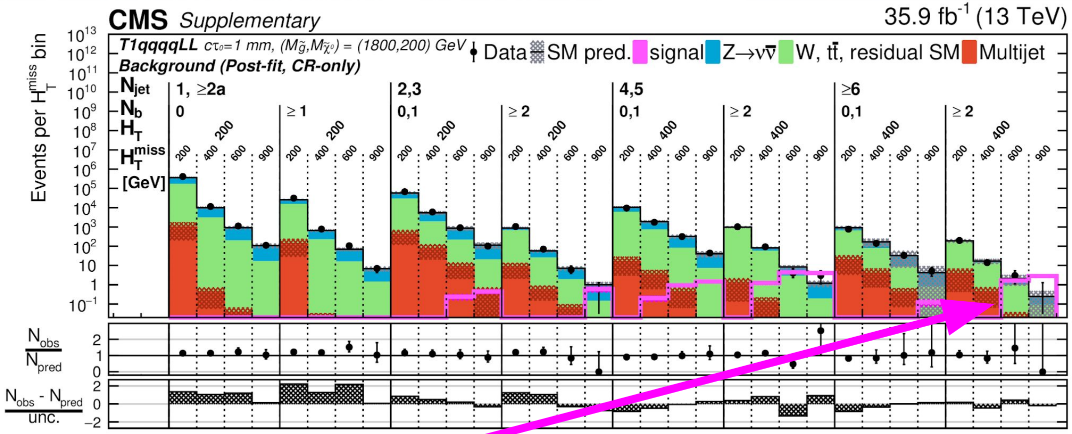
Longlived sparticles

See talks by
Malgorzata Kazana this afternoon
Karri Dipetrillo this afternoon

Longlived gluinos in split supersymmetry

CMS-PAS-EXO-16-036 heavy stable charged particle search with dE/dx
CMS-SUS-16-038 CMS inclusive search with jets and missing transverse momentum using α_T with split SUSY interpretation





HSCP searches will benefit from tracker phase 2 upgrade (see e.g. CMSTDR014) and muon phase 2 upgrade (see e.g. CMSTDR016)

http://cms-results.web.cern.ch/cms-results/public-results/publications/SUS-16-038/

Split SUSY and R-Hadrons

ATLAS reinterpretation of SUSY searches in RPV models and R-hadron models

ATLAS-CONF-2018-003

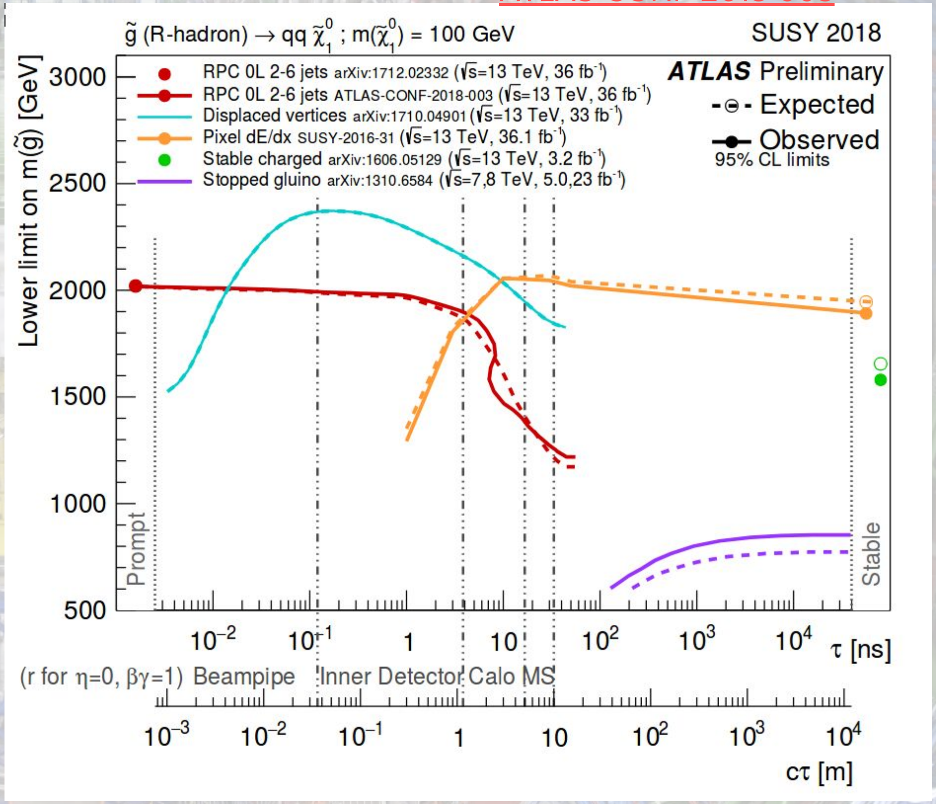
Split SUSY: has light sfermions and higgs, rest heavy.

Heavy quarks make gluino longlived.

If $c\tau > 1$ picosecond:

➜ 'R-hadron' or bound color-singlet state containing squarks or gluons.

The R-Hadron eventually decays to quark, antiquark and LSP.



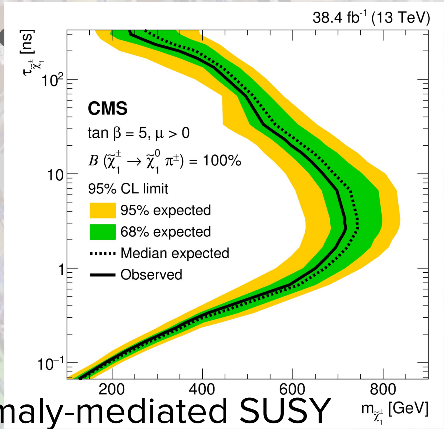
https://arxiv.org/pdf/hep-ph/0611040.pdf
https://arxiv.org/pdf/hep-ph/0406088.pdf
https://arxiv.org/pdf/hep-th/0405159.pdf
https://arxiv.org/abs/1802.02110v2

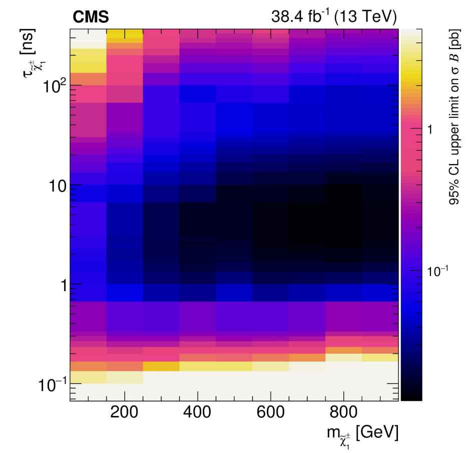
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY/ATLAS_SUSY_LLP/ATLAS_SUSY_LLP.pdf
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2018-003/

[ATLAS-SUSY-2018-06](#) [CMS-EXO-16-044](#)

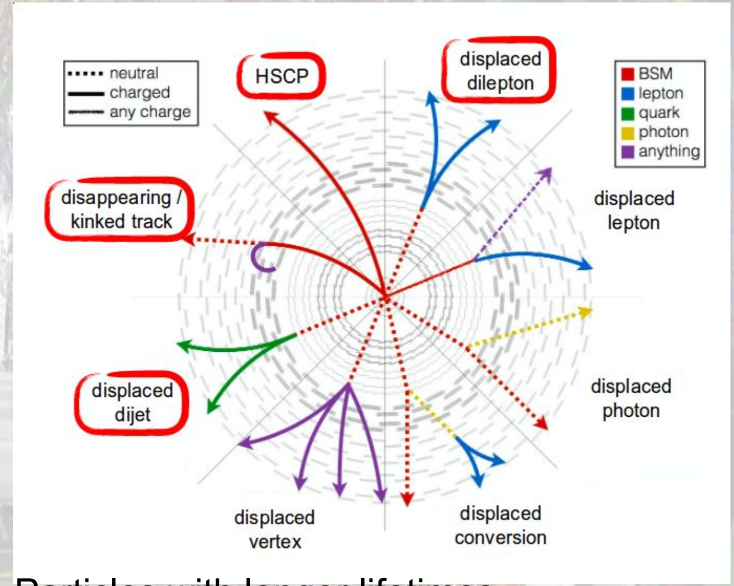
Disappearing tracks

- No missing inner or middle hits
- p_T^{miss} > 70 GeV on level 1 trigger (L1), >50GeV isolated track on high level trigger (HLT)
- Calorimeter constraint makes leptons reconstructed as charged hadrons unlikely
- … rou



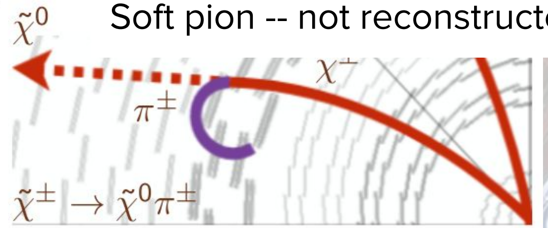


Anomaly-mediated SUSY breaking (AMSB) model



Particles with longer lifetimes decay in characteristic ways in our detector (or outside!)

Soft pion -- not reconstructed

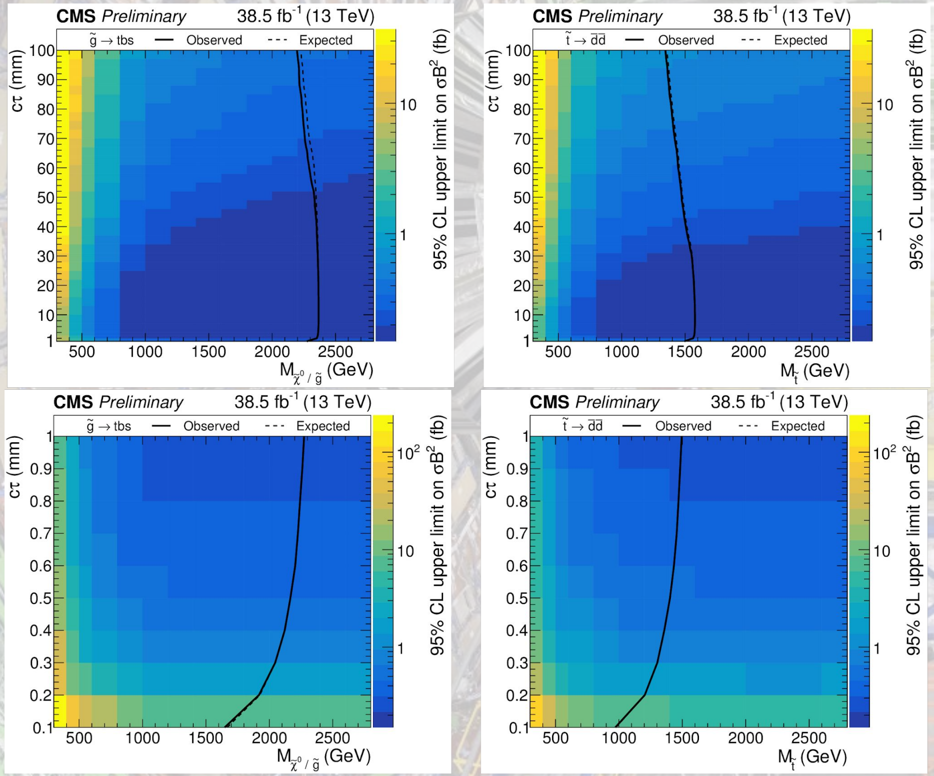


https://indico.cern.ch/event/686555/contributions/2969867/attachments/1680800/2700286/ICHEP2018_LLP_Escalante.pdf

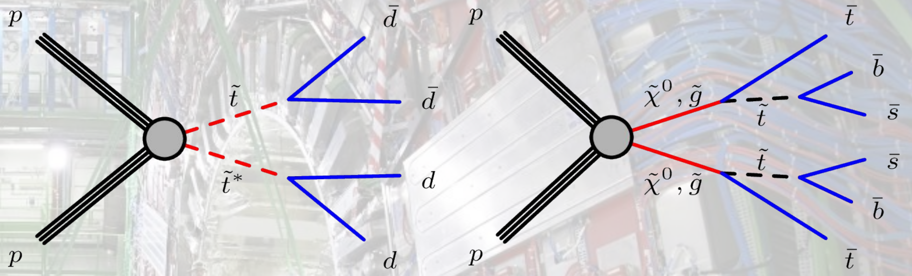
https://indico.cern.ch/event/517268/contributions/2041293/attachments/1272363/1886050/Antonelli_CMS_LLP_May12.pdf

ATLAS-SUSY-2018-08 CMS-EXO-17-018

Displaced vertices



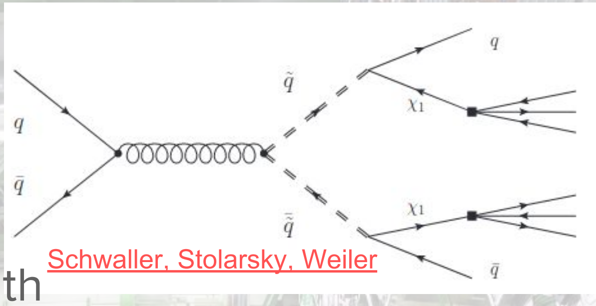
Multiple jets and multiple tracks



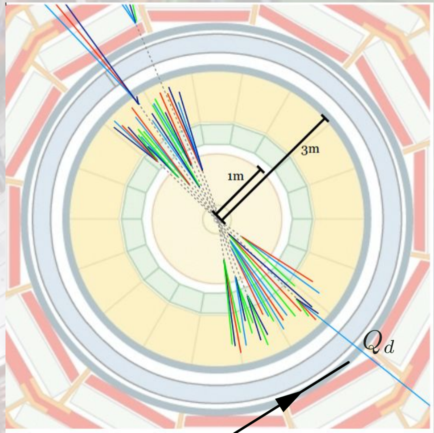
- RPV SUSY model with neutralino or gluino LSP
- Final states with multiple charged particles
- Longlived stops or gluinos/neutralinos
- Lifetimes of 0.1-100mm within beam pip radius
- Sensitive to shorter lifetimes than previous analyses

Emerging jets

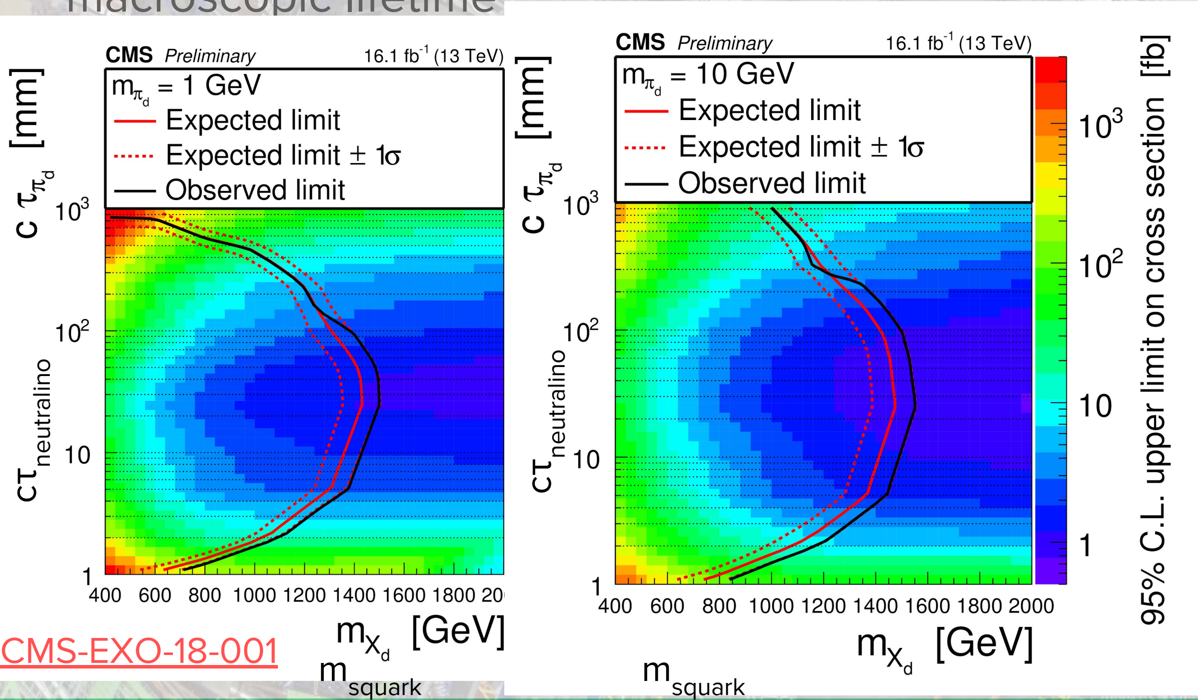
SUSY: RPV decay of neutralino with macroscopic lifetime



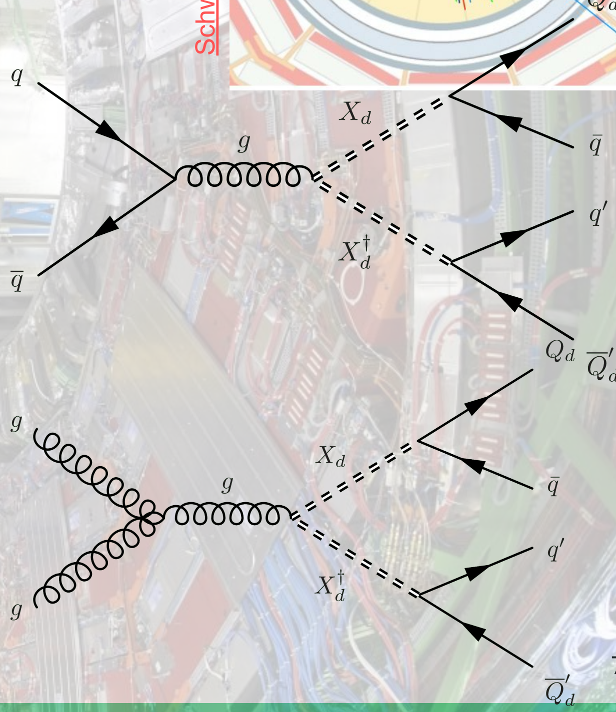
Schwaller, Stolarsky, Weiler



Schwaller, Stolarsky, Weiler



CMS-EXO-18-001

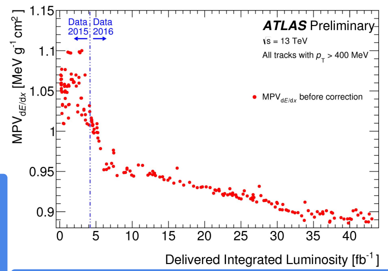


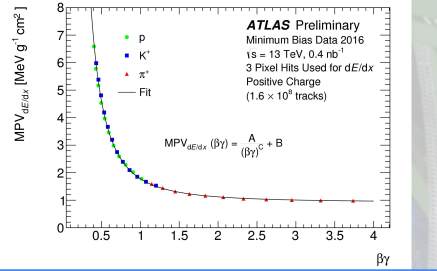
ATLAS-SUSY-2016-031

Heavy charged longlived

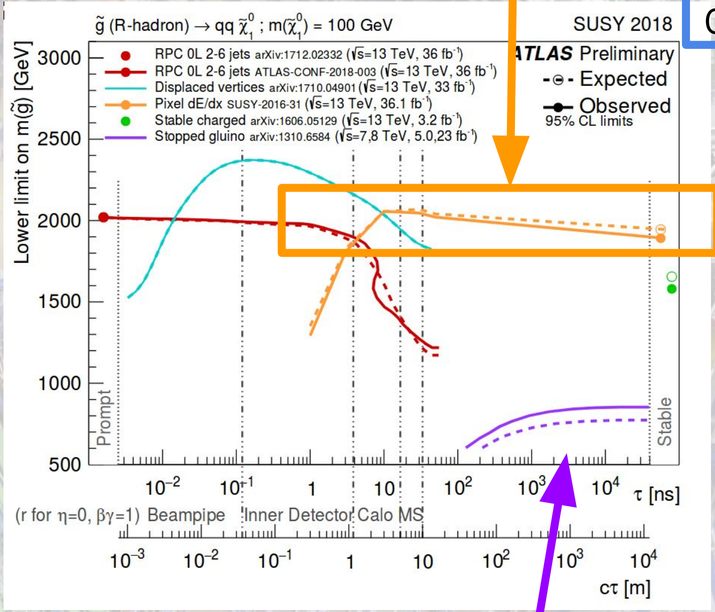
Pixel dE/dx measurement

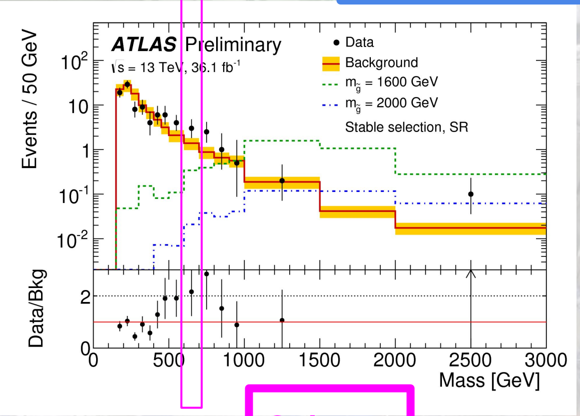
0.3 < ßγ < 0.9
Too long time over threshold < 0.3
0.9 > SM background

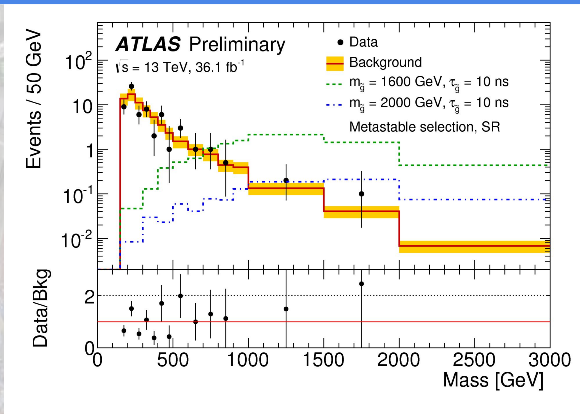




Most probably value dE/dx $(MPV)_{dE/dx}$ correction (radiation damage, kaons, traversed thickness)







2.4σ

Stable: no muon veto, decay outside ATLAS detector
p_T often not in $E_{T,miss}$ (no reco)
➜ use ISR

Metastable: isolated, high momentum, high dE/dx tracks that do not reach muon spectrometer (1ns to tens of ns)

ATLAS-CONF-2018-003

ATLAS-SUSY-2013-03

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2016-31/

SUSY Higgses

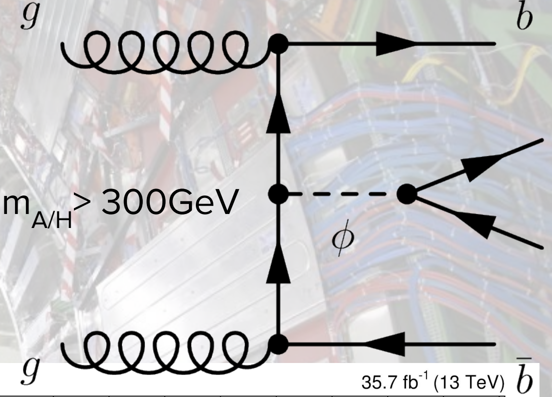
More Higgses?

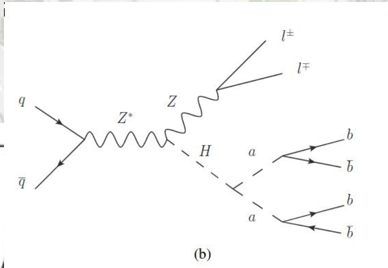
See talk by Nikolina Ilic on BSM Higgs searches

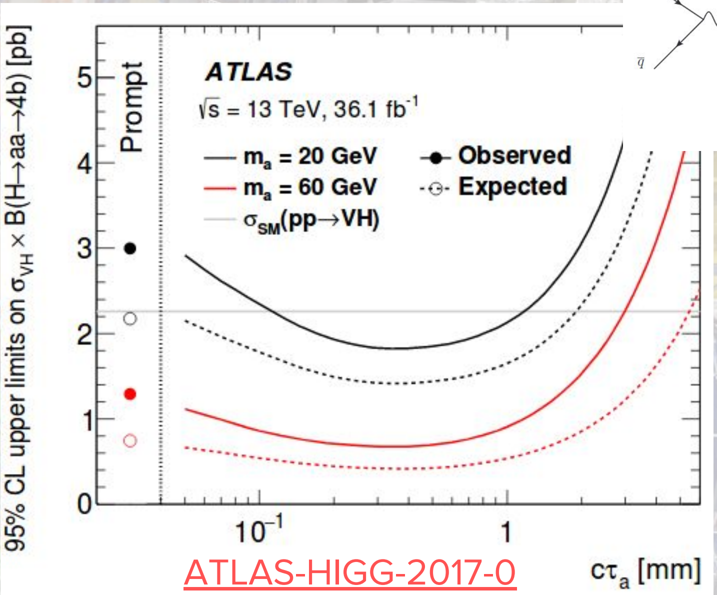
Searches for beyond the Standard Model Higgs(es)

a up to 6mm, 20-60GeV

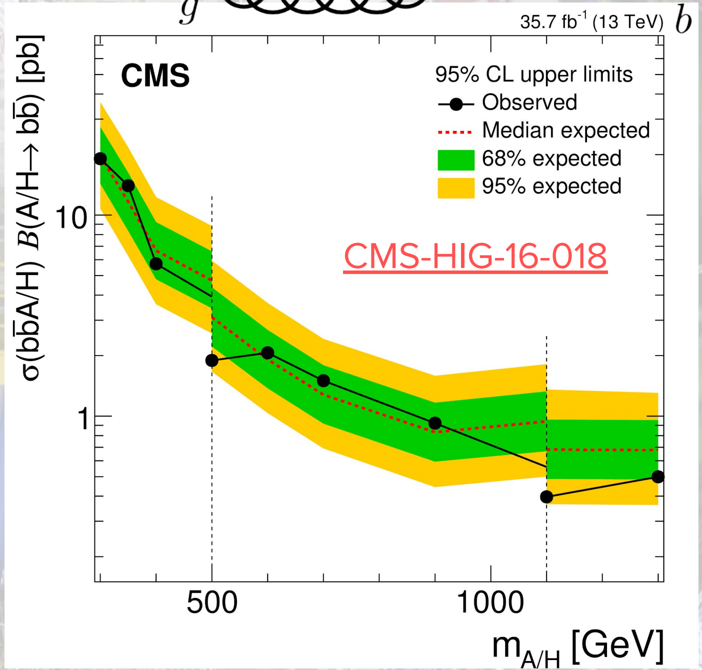
MSSM $m_{A/H}$ > 300GeV







[ATLAS-HIGG-2017-0](https://arxiv.org/pdf/1806.07355.pdf)



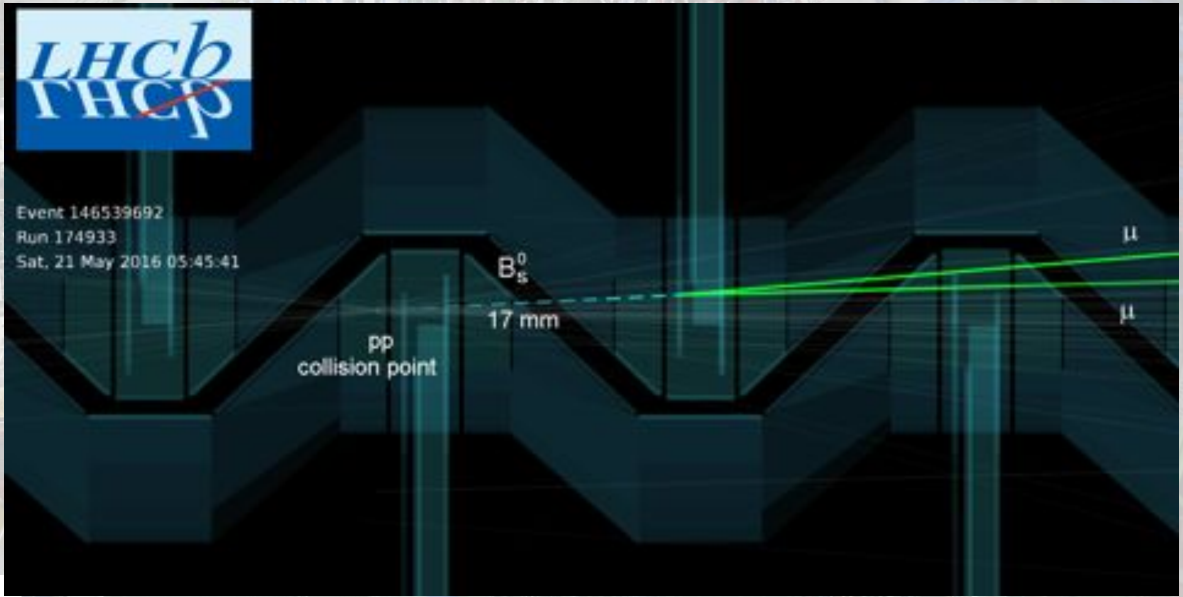
CMS-HIG-16-018

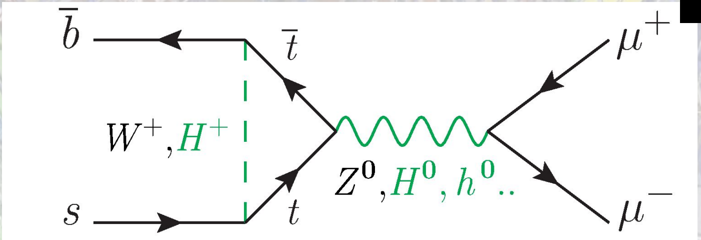
https://arxiv.org/pdf/1806.07355.pdf

http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-16-018/index.html

Precision measurements

Beyond the standard model: $B^0_{(s)} \to \mu\mu$





BSM?

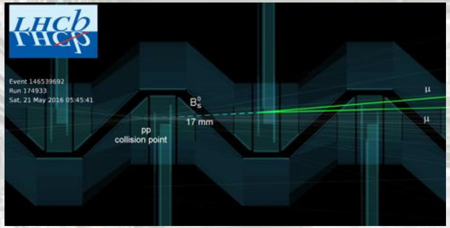
https://www.hep.physik.uni-siegen.de/atlas/pics/feynman_dig_Bs-MuMu.png

https://www.hep.physik.uni-siegen.de/atlas/atlas_bphys_en.html

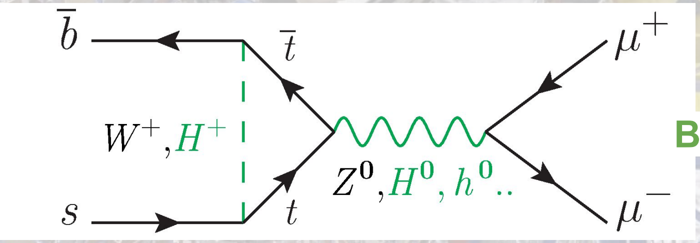
http://lhcb-public.web.cern.ch/lhcb-public/Images2017/BsMuMuVertex_s.png

Beyond the standard model: $B^0_{(s)} \rightarrow \mu\mu$

Everything consistent with standard model predictions.



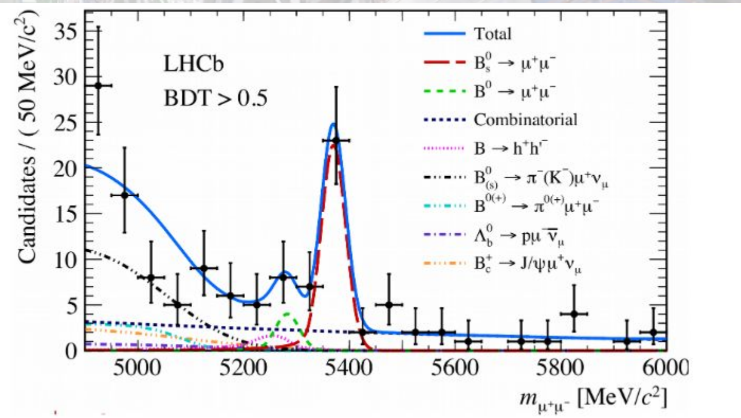
http://lhcb-public.web.cern.ch/lhcb-public/Images2017/BsMuMuVertex_s.png

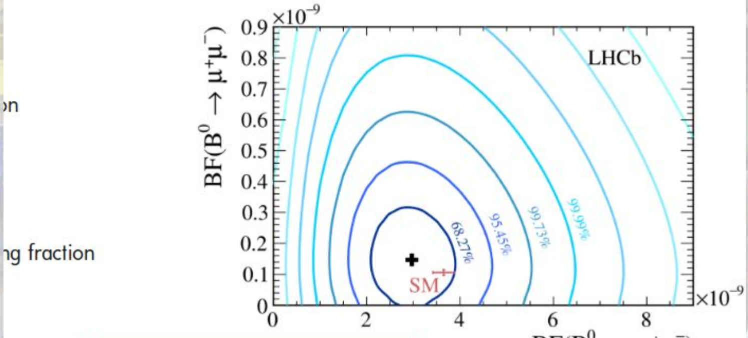


BSM?

https://www.hep.physik.uni-siegen.de/atlas/atlas_bphys_en.html

https://www.hep.physik.uni-siegen.de/atlas/pics/feynman_dig_Bs-MuMu.png

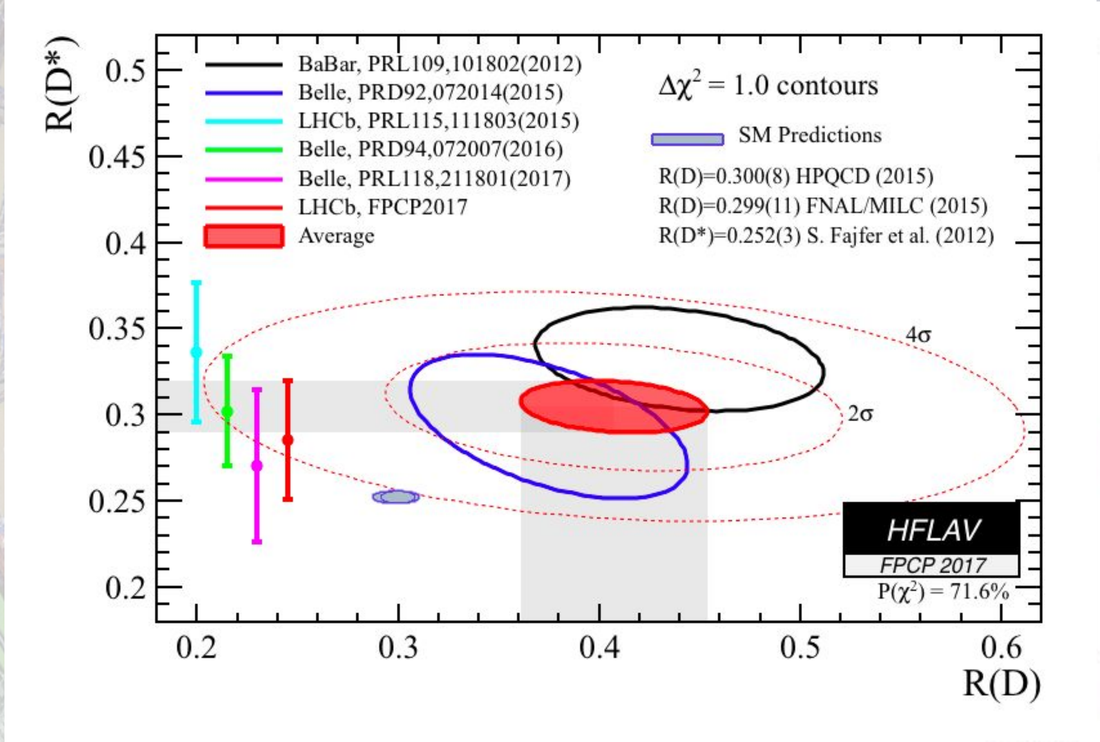




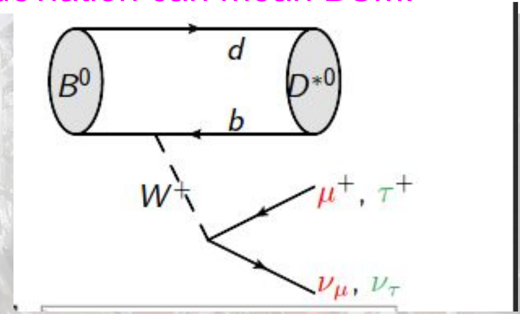
PRL 118, 191801 (2017)

https://indico.cern.ch/event/681549/contributions/2920113/attachments/1661525/2662168/LHCP_Machefert_030618.pdf

Tests of the standard model: lepton universality



LHCb can measure **branching fractions** very precisely: any deviation can mean BSM!



- Combined R_D, R_{D*} deviate from SM by ~4σ
(http://www.slac.stanford.edu/xorg/hflav/semi/fpcp17/RDRDs.html)

Observables:

$$R(D^*) = \frac{BF(B \to D^* \tau \nu)}{BF(B \to D^* \mu \nu)} \overset{SM}{=} 0.252 \pm 0.003$$

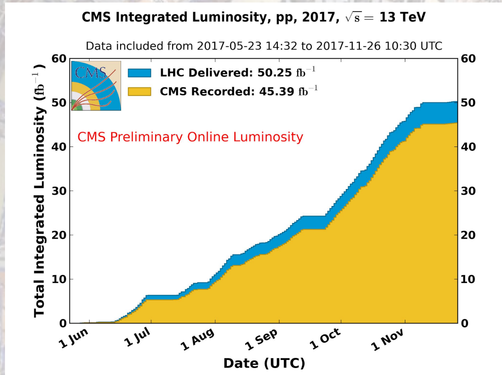
https://indico.cern.ch/event/681549/contributions/2944422/attachments/1664288/2667701/LHCP2018_THumair.pdf
https://indico.cern.ch/event/681549/contributions/2833189/attachments/1660728/2660649/passaleva-LHCb.pdf

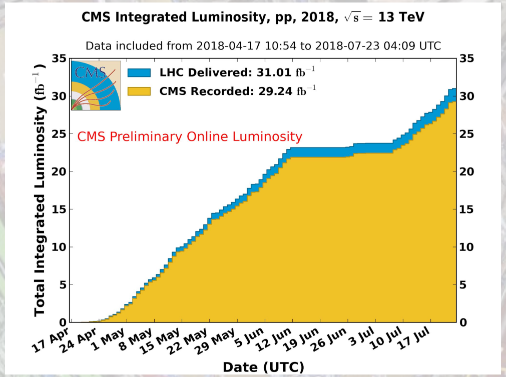
http://www.slac.stanford.edu/xorg/hflav/semi/fpcp17/r_dtaunu/rdrds_fpcp2017.png

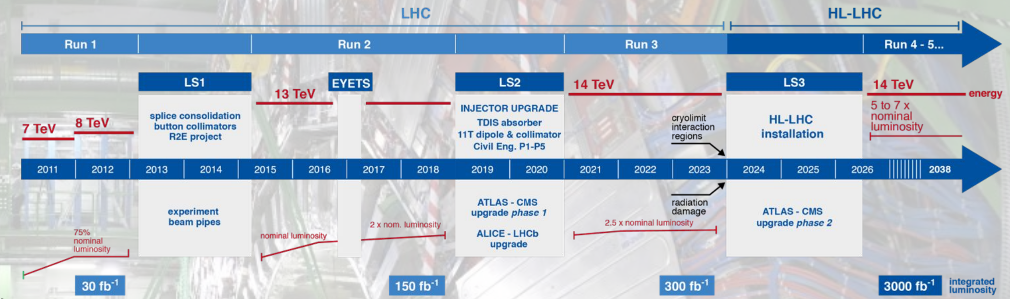
Beyond LHC run 2

See also talk by
Isobel Ojalvo on Thursday

Run 3 and HL-LHC







https://project-hl-lhc-industry.web.cern.ch/content/project-schedule

Now: 13TeV, 80fb-1
Run 2 expected: 150fb-1
LHC run 3: 14TeV, 300 fb-1
HL-LHC: 14TeV, 3000fb-1

CMS:

- **Run 3:** new GEM
- Track-trigger
- Pixel to η=3.8
- RPC timing
- HGCAL
- Possible minimum ionizing particle timing detector
- … and much more!

https://indico.cern.ch/event/647676/contributions/2721136

ATLAS:

- **Run 3:** New Small Wheel (NSW) with Micromegas (MM) and small strips Thin Gap Chambers (sTGCs)
- **Run 3:** RPC upgrade
- Track-trigger
- Pixel to η=4
- Trigger includes monitored drift tube
- Possible forward timing detector
- … and much more!

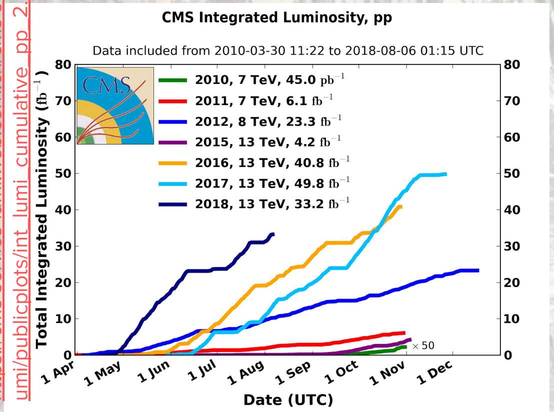
https://indico.cern.ch/event/647676/contributions/2721135/

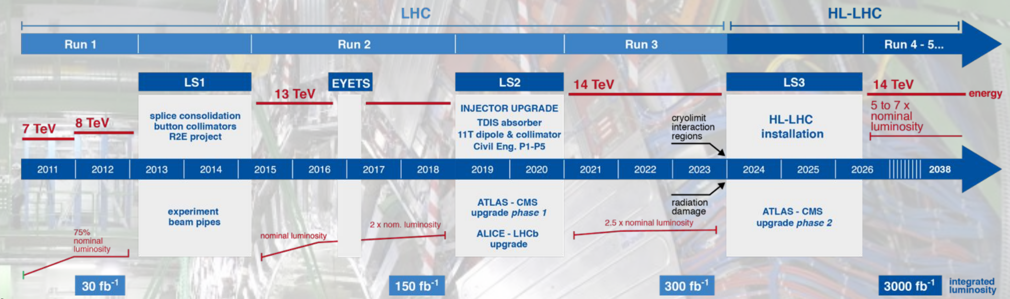
L1 trigger rate from 100kHz to 750kHz

https://cms-service-lumi.web.cern.ch/cms-service-lumi/publicplots/int_lumi_per_day_cumulative_pp_2017OnlineLumi.png
https://cms-service-lumi.web.cern.ch/cms-service-lumi/publicplots/int_lumi_per_day_cumulative_pp_2018OnlineLumi.png

Run 3 and HL-LHC

https://cms-service-lumi.web.cern.ch/cms-service-lumi/publicplots/int_lumi_cumulative_pp_2.png





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Now: 13TeV, 80fb-1
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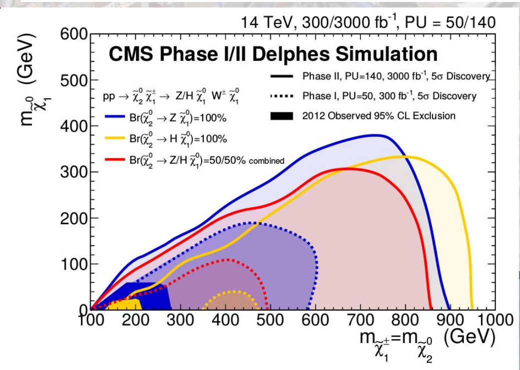
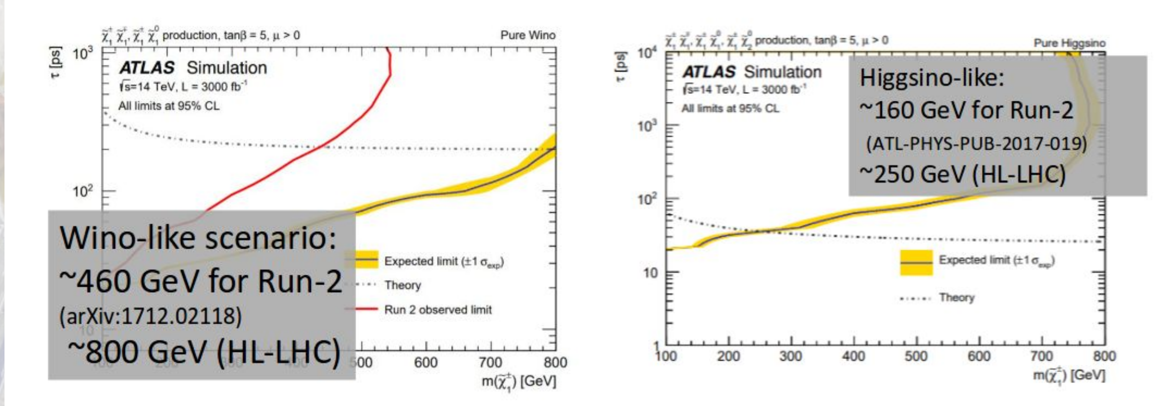
HL-LHC: 14TeV, 3000fb-1

HL-LHC: L1 trigger rate from 100kHz to 750kHz



CMS-TDR-15-02

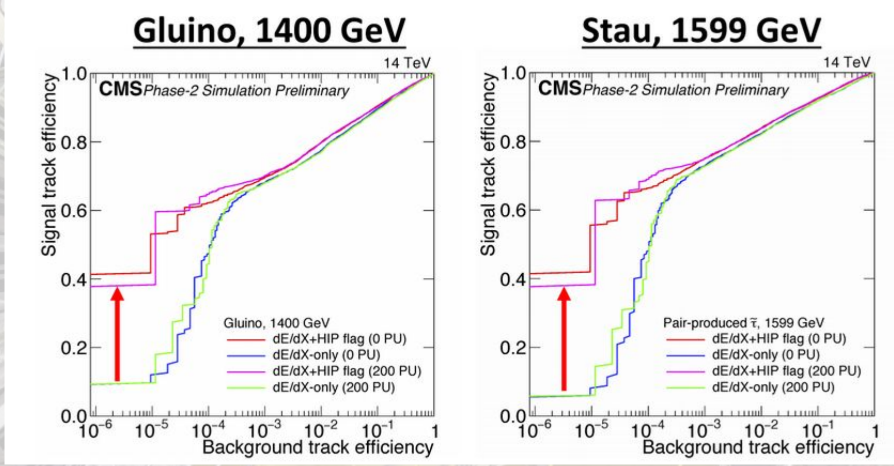


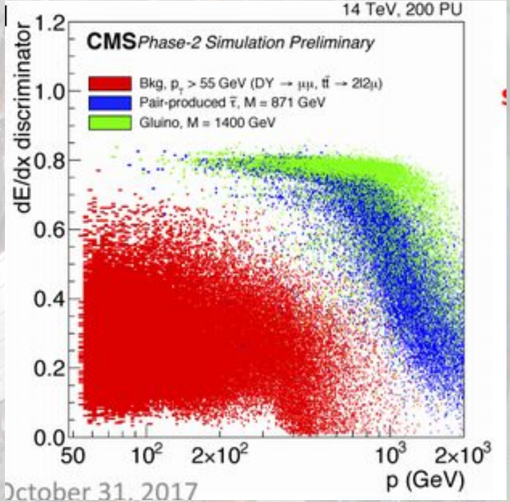
- Reach larger mass particles
- Search for low-cross section models

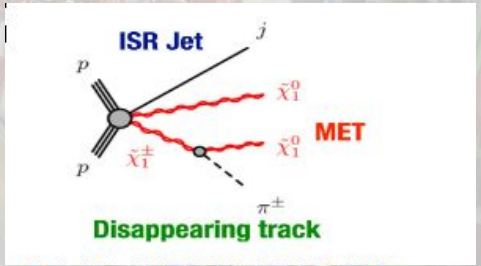
140 pileup → degradation in trigger efficiency, b-tagging, MET resolution

https://indico.cern.ch/event/689399/contributions/3005916/attachments/1692207/2722880/BSMPhysicsHLLHC.pdf

What can we expect from HL-LHC?

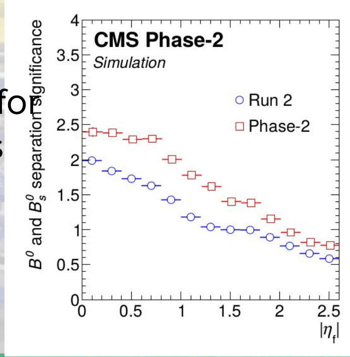






- Flag for ionizing particles in outer tracker
- Excellent dE/dx resolution in inner tracker (CMS-TDR-014)
- Muon time of flight system to distinguish HCSPs from muons (CMS-TDR-016)

See talk by Lars Eklund for current B physics results



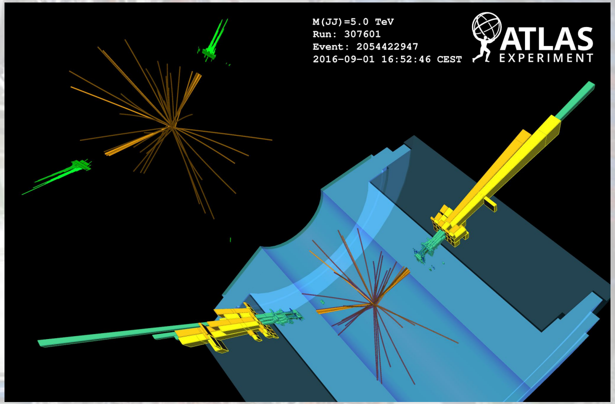
With new tracker an improved mass resolution makes Bs→ mumu better distinguishable from B0→ mumu (CMS-TDR-014).

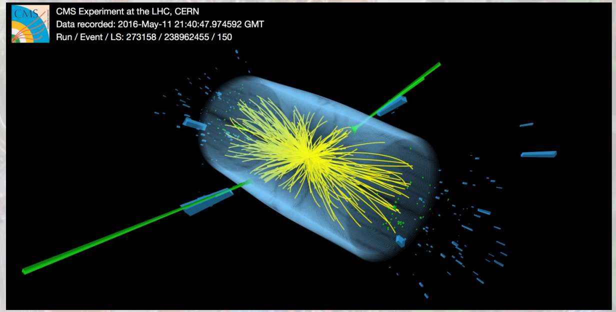
Small mass splitting between chargino and neutralino → longlived charginos

Summary and Outlook

Summary and outlook

- Data taking at LHC successful at both ATLAS and CMS;
- Many new search techniques;
- New searches for SUSY models with more complicated signatures;
- Several excesses seen but no clear sign of new physics;
- In run 3 more statistics can lead to better sensitivity in searches for models with low cross sections like electroweak SUSY searches;
- In the HL-LHC track-triggers can help look for more unconventional signatures.





Note that there is also a well-advanced e^+e^- collider program, see e.g. Jie Gao's talk yesterday

https://www.researchgate.net/profile/Raquel_Gomez-Ambrosio/publication/323966523/figure/fig17/AS:607356689842176@1521816527028/Transverse-section-of-the-CMS-detector.png