Non-standard SUSY searches at the LHC

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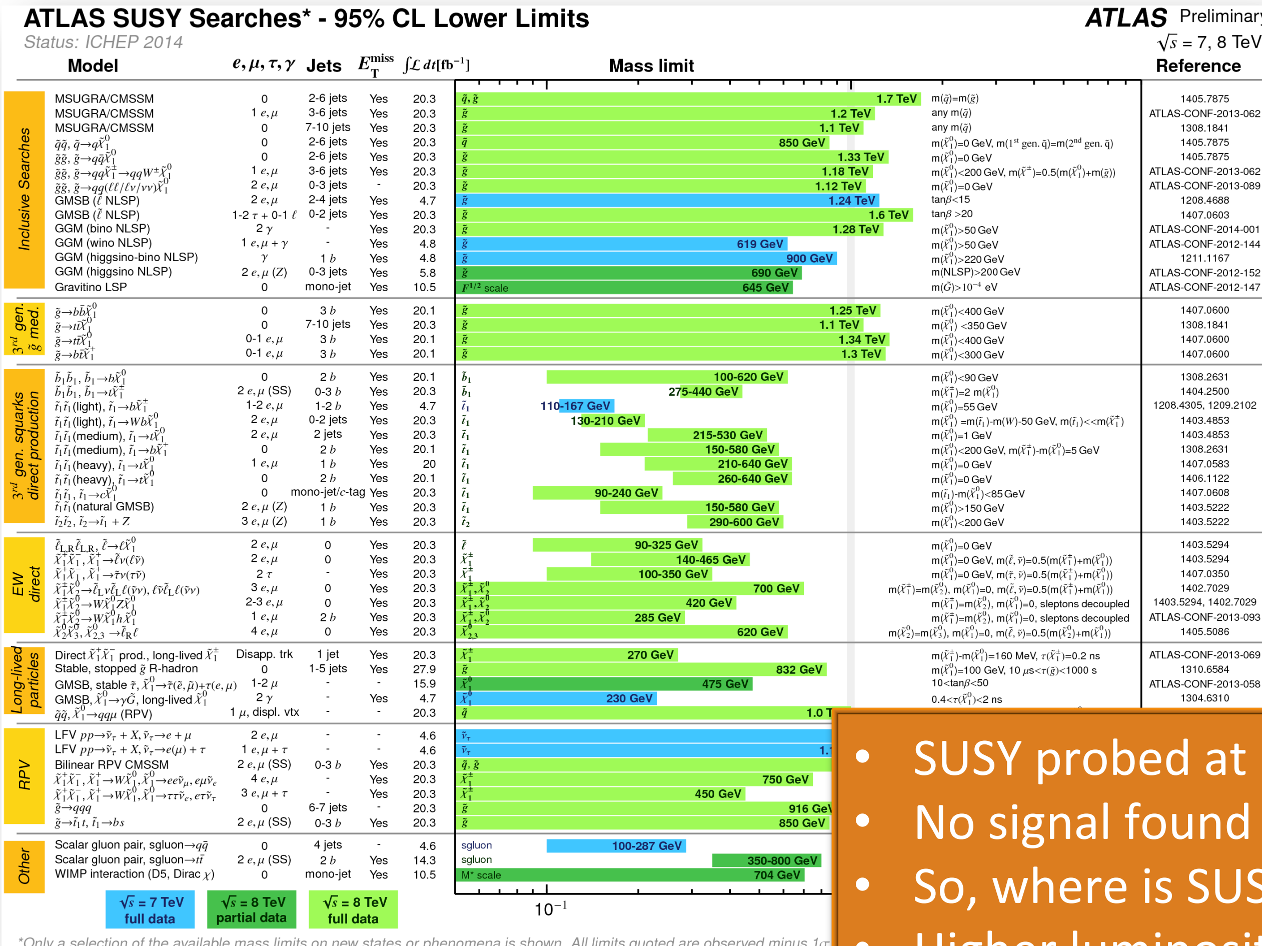
IFIC Valencia

Physics Challenges in the face of LHC-14
IFT, Madrid, 15 – 26 September 2014

SUSY @ LHC : The current picture



- SUSY probed at LHC up to ~ 1 TeV
- No signal found yet
- So, where is SUSY?
- Higher luminosity and energy of future LHC runs will certainly improve the reach
- Is this enough?

"Alternative SUSY"

- Alternative from the experimental point-of-view
  ➜ high missing transverse momentum not necessary
  - R-parity violating (RPV) signatures
  - long-lived particles (LLP)
- Why overlooked so far?
  - R-parity always provides a dark matter candidate; in RPV in some cases (gravitino, axino)
  - signatures from stable particles require large effort to be probed
    - ATLAS & CMS optimised for promptly decaying particles
    - need to take care many aspects of analysis (trigger, reconstruction, non-collision background, …) from scratch
  - difficult to organise RPV searches in coherent way
    - many couplings ➔ many combinations of final states
    - prompt vs. delayed LSP decays
    - consider one non-zero coupling at a time versus complete RPV model

R-parity violation

- R-parity: $R = (-1)^{3(B-L)+2s}$ → $R = \begin{cases} +1, \text{ for SM particles} \\ -1, \text{ for superpartners} \end{cases}$

L-number violating terms

$$W_{\not{R}p} = \lambda_{ijk}\hat{L}_i\hat{L}_j\hat{E}^C_k + \lambda'_{ijk}\hat{L}_i\hat{Q}_j\hat{D}^C_k + \epsilon_i\hat{L}_i\hat{H}_u + \lambda''_{ijk}\hat{U}^C_i\hat{D}^C_j\hat{D}^C_k$$

bilinear terms

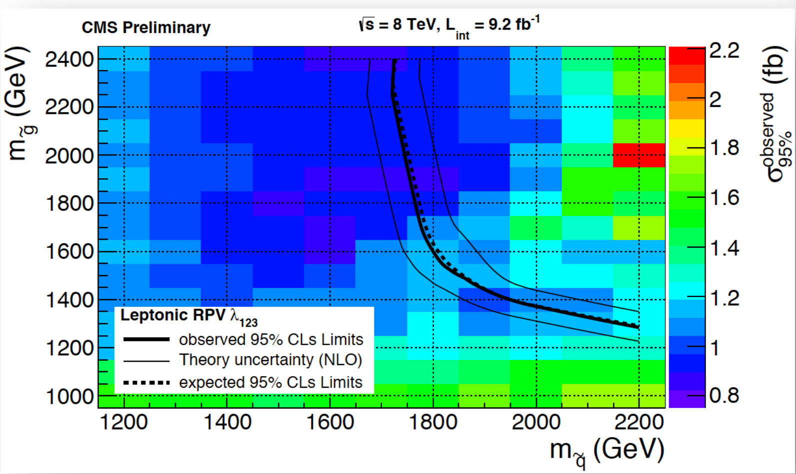
B-number violating terms

- R-parity conservation hinted but not required by proton stability
- Phenomenological consequences of RPV:
  - LSP may be charged and/or carry color (e.g. sleptons, squarks)
  - LSP is not stable
    - potentially long LSP lifetime
    - transverse missing energy in colliders may or may not be large

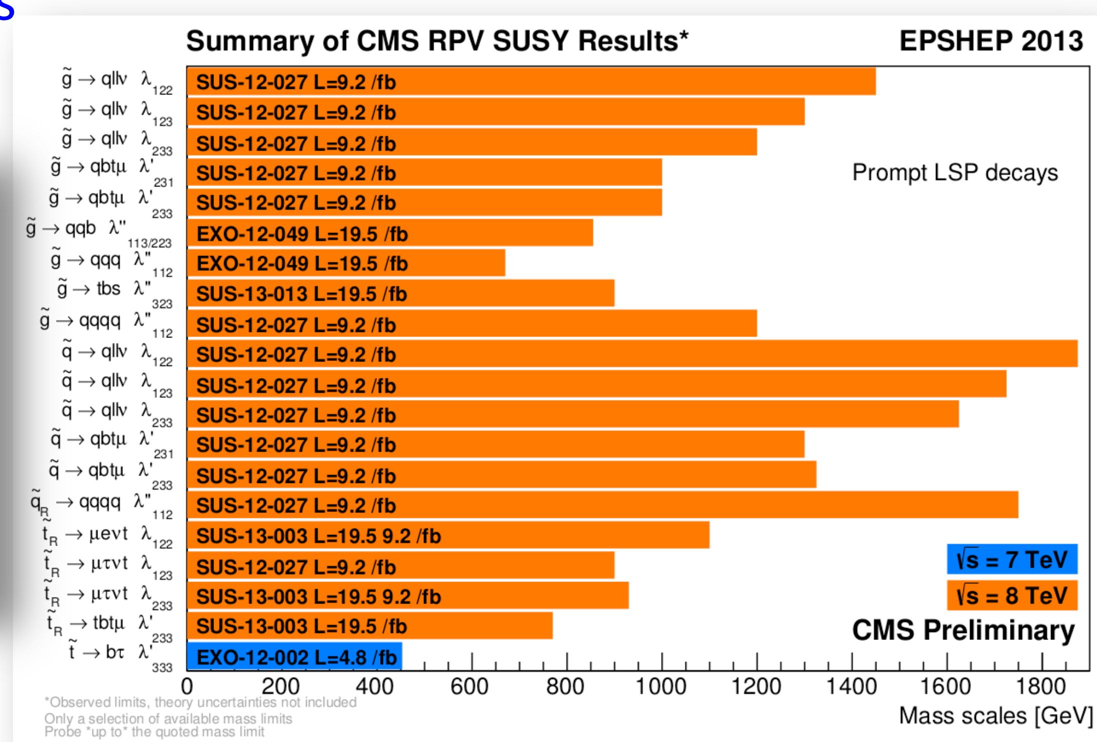
A whole new landscape of phenomenological possibilities opens up…

Bottom-up approach: inclusive analysis

- All coupling types considered: λ (purely leptonic), λ´, λ´´ (purely hadronic)
- Many combinations of objects in final state: 0, 1, 2 leptons, taus, b-jets
- Signal regions cover all space in terms of kinematic variables
- Limits set for many couplings yet for limited decay chains

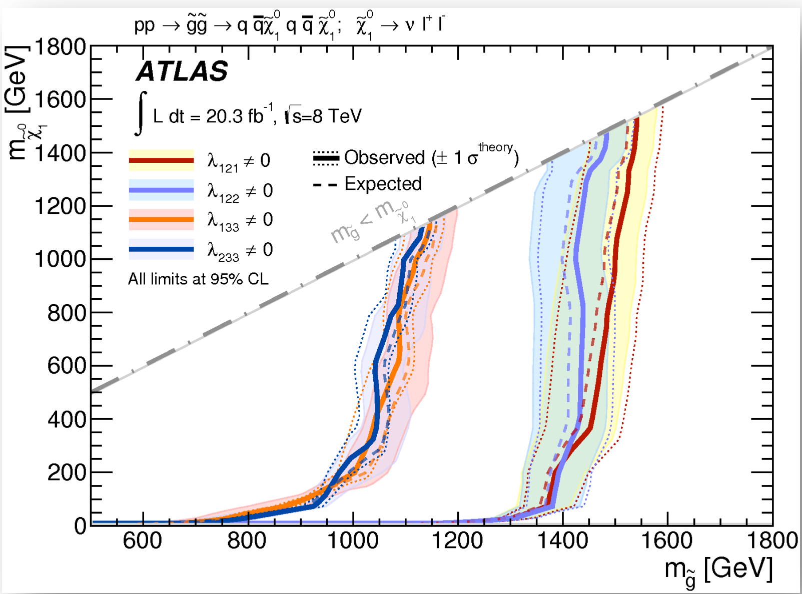


CMS-PAS-SUS-12-027

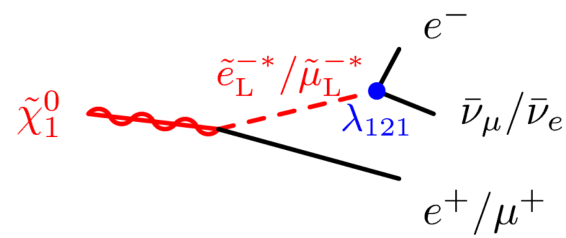


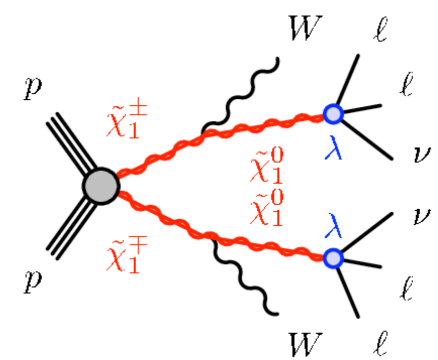
Target specific decay chain / coupling: 4 leptons

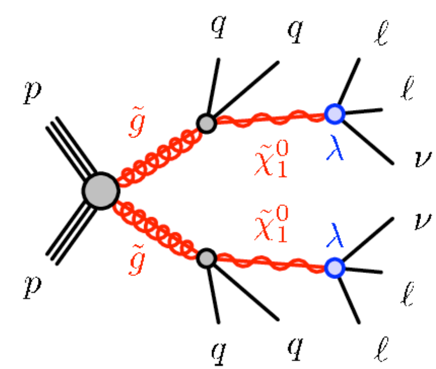
- Neutralino decays into 2 charged leptons and a neutrino
  - 4 charged leptons (flavours determined by λ_{ijk} choice)
  - RPV signal selection via Z-veto and effective mass
- RPV-optimised analysis enhances discovery reach yet much effort needed to cover more couplings



Phys. Rev. D. 90, 052001 (2014)







Top-bottom approach: bilinear RPV

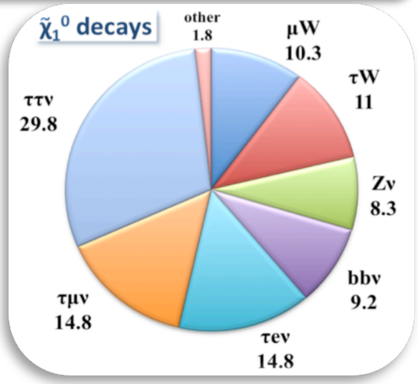
- Consider a well-motivated RPV model…
- Bilinear RPV introduces **neutrino masses** in an intrinsically supersymmetric way
  - EW symmetry is broken by Higgs and sneutrino VEVs
  - neutrinos mix with neutralinos
  - a "low-scale" seesaw mechanism renders neutrinos massive

$$W_{\text{bRPV}} = W^{\text{MSSM}} + \epsilon_i \hat{L}_i \hat{H}_u$$
$$V_{\text{soft}} = V_{\text{soft}}^{\text{MSSM}} - B_i \epsilon_i \tilde{L}_i H_u$$

- Direct connection between model phenomenology and neutrino parameters

Valle, Hirsch, Porod, Romao, Diaz, *et al.*

$$\tan^2\theta_{\text{atm}} \simeq \left|\frac{\Lambda_\mu}{\Lambda_\tau}\right|^2 \simeq \frac{BR(\tilde{\chi}_1^0 \to \mu^\pm W^\mp)}{BR(\tilde{\chi}_1^0 \to \tau^\pm W^\mp)}$$

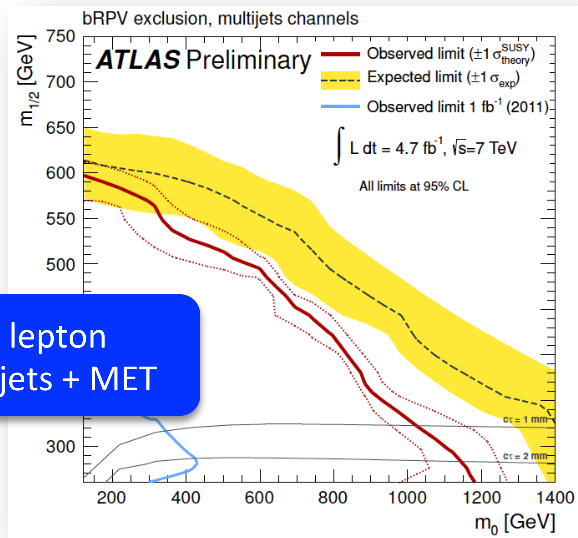


- Well-defined LHC phenomenology thanks to constraints from neutrino measurements
- Large MET due to copious **neutrino** production
  → conventional MET-based searches applicable to bRPV SUSY

ATLAS results on bRPV SUSY

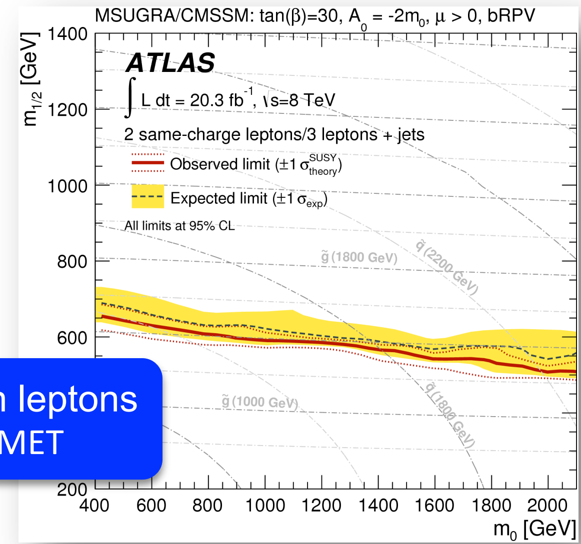
- So far, interpretation of results from searches targeting R-parity conserving SUSY in mSUGRA-bRPV

ATLAS-CONF-2012-140



one lepton
+ multijets + MET

2 same-sign leptons
+ jets + MET



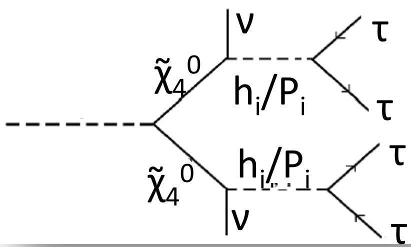
JHEP 1406 (2014) 035

Possibilities for 13 / 14 TeV run (just some thoughts):

- embed bRPV couplings in an attractive SUSY scenario, e.g. natural pMSSM
- design analysis customised for such models (also sensitive to trilinear RPV)
- **What about other RPV models?** see e.g.:
  - L. Covi's talk on decaying dark matter [arXiv:1403.4923]
  - Y. Nakai' talk on warped natural SUSY [arXiv:1407.5095]

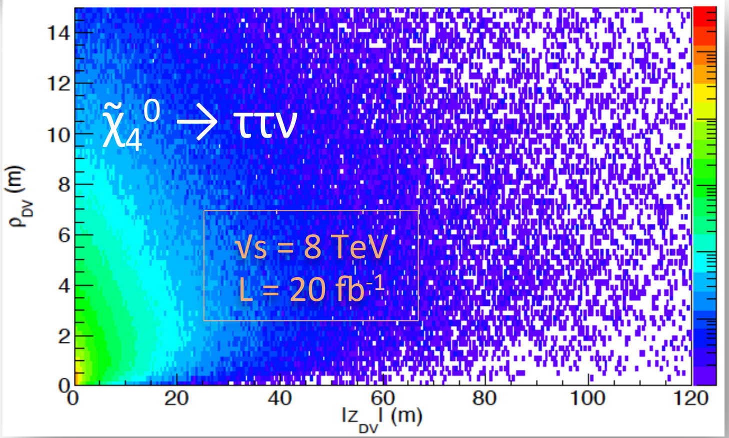
RPV model: μνSSM

- μνSSM: μ-from-ν Supersymmetric Standard Model
  - R-parity breaking terms
  - → neutrino masses
  - → evades μ-problem
- Very rich phenomenology
  - many Higgs bosons and gauginos
  - → enlarged Higgs sector can easily accommodate a 125-GeV Higgs boson
  - long neutralino lifetimes → **(extremely) displaced vertices**
  - **multileptons / multitaus**



Muñoz, López-Fogliani, Ruiz de Austri, Fidalgo, Roy, Ghosh, Dey *et al.*

Position of LSP decay in LHC detector



Ghosh, López-Fogliani, VAM, Muñoz, Ruiz de Austri, **Phys.Rev. D88 (2013) 015009**

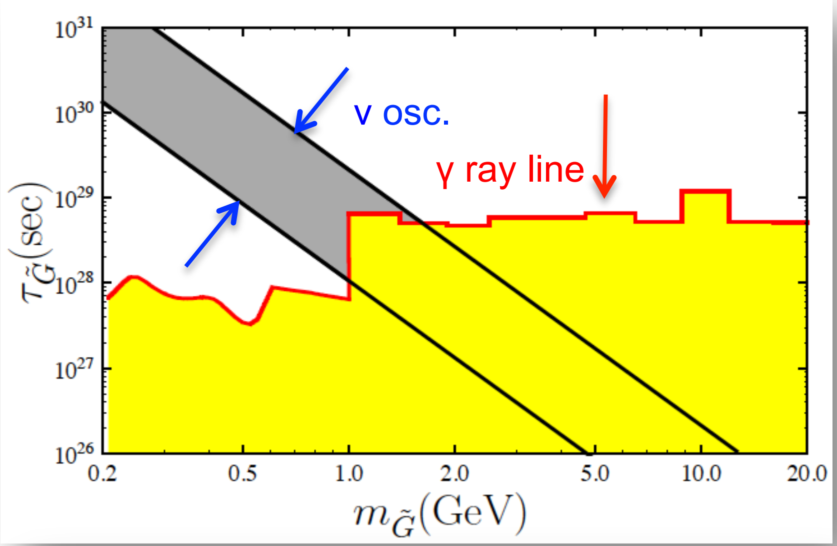
May serve as an inspiration for looking for other prompt or displaced signatures at 14-TeV LHC (other models may profit, too)

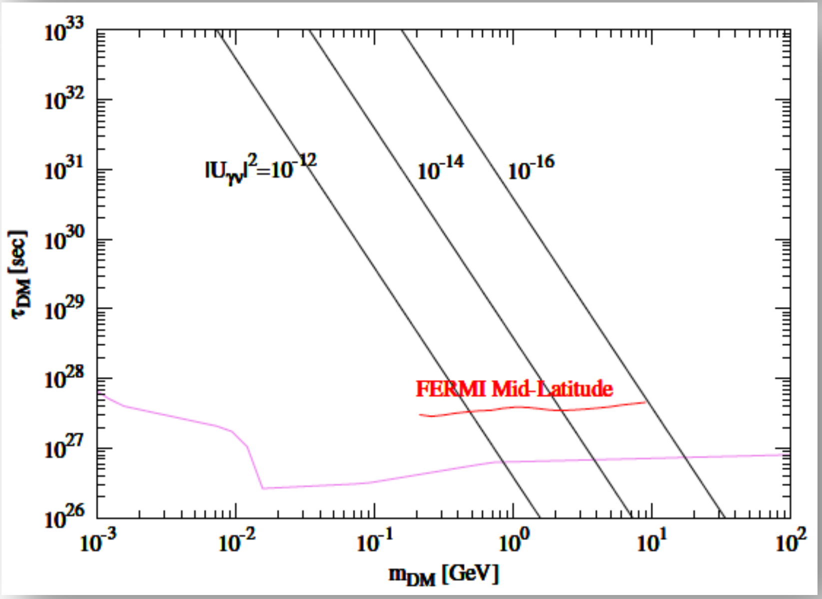
What about RPV and dark matter?

- Gravitivo LSP with cosmologically-long lifetime
  - signal: monochromatic gamma-rays $\tilde{G} \to \gamma\nu$
  - constrained by
    - ν-oscillations
    - DM relic density $\Omega_\chi h^2$
    - γ-ray line searches
- If lightest neutralino is the NLSP

$$\tilde{\chi}_1^0 \to h^0 \nu_i, \qquad \tilde{\chi}_1^0 \to W^\pm l_i^\mp,$$
$$\tilde{\chi}_1^0 \to \gamma \nu_i, \qquad \tilde{\chi}_1^0 \to Z^0 \nu_i.$$

- (Long-lived) neutralino can also decay to 3 fermions





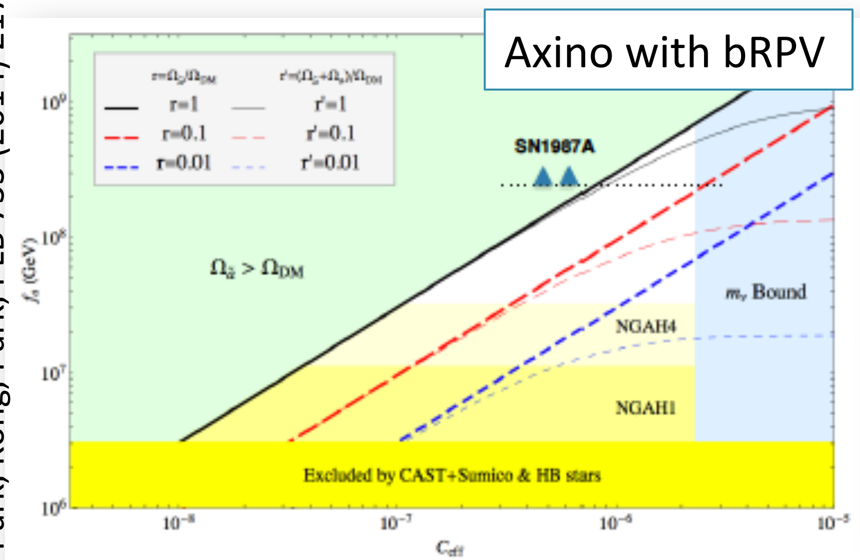
Restrepo et al, PRD85 (2012) 023523 Choi et al, JCAP 1003 (2010) 028

Away from LHC: γ-ray lines & RPV SUSY

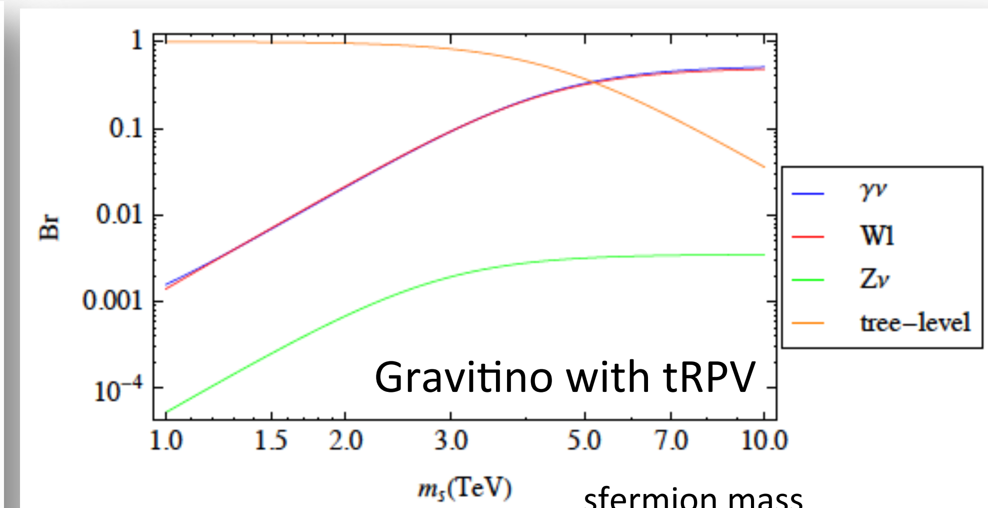
- 130-GeV γ-line in Fermi-LAT
  - axino with bilinear RPV [Endo et al, PLB 721 (2013) 111]
  - gravitino with trilinear RPV [Liew, PLB 724 (2013) 88]

$$\tilde{G} \to \gamma\nu$$

- Recently, 3.5 keV X-ray emission line observed in galaxy clusters
  - **axino with RPV** [Choi & Seto, PLB 735 (2014) 92; Liew, JCAP 1405 (2014) 044]
  - **gravitino, bino, or hidden sector photino in RPV** [Kolda & Unwin, PRD 90 (2014) 023535; Bomark & Roszkowski, PRD 90 (2014) 011701]

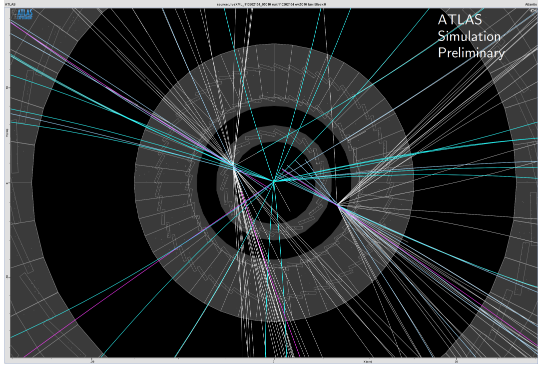


Park, Kong, Park, PLB 733 (2014) 217

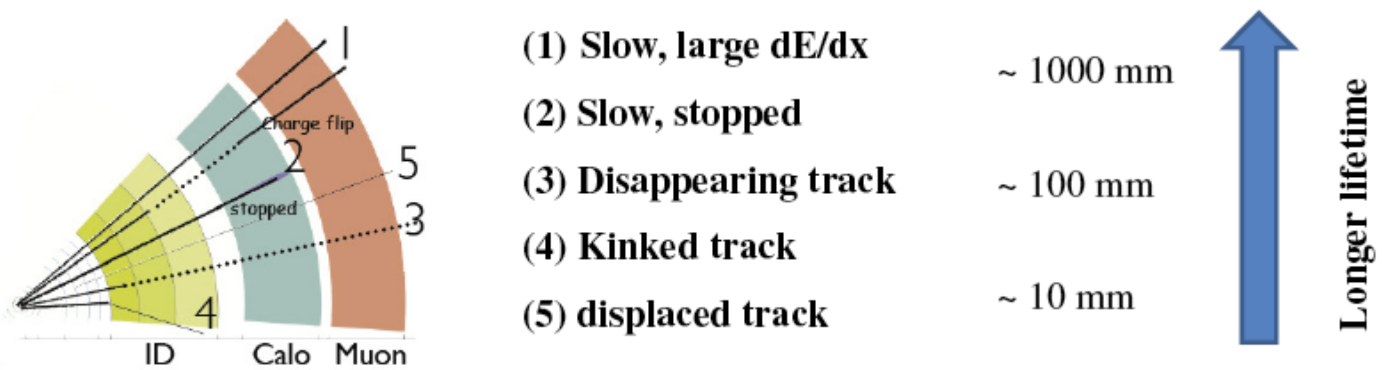


Liew, Phys.Lett. B724 (2013) 88

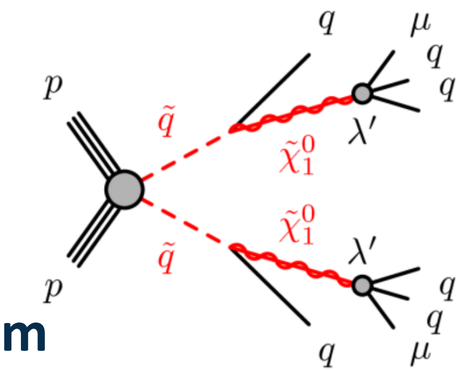
Stable or metastable particles



- Long-lived decays of spartners possible in several frameworks, including
  - nearly conserved symmetry
    - e.g. long lived gluinos or squarks that hadronise before decaying → R-hadrons in Split SUSY
  - low coupling between the particle and the final state
    - e.g. weak RPV couplings
  - Mass degeneracy between the particle and the final state
- Depending on the lifetime, different detection techniques involving various objects: tracks, photons, leptons, …

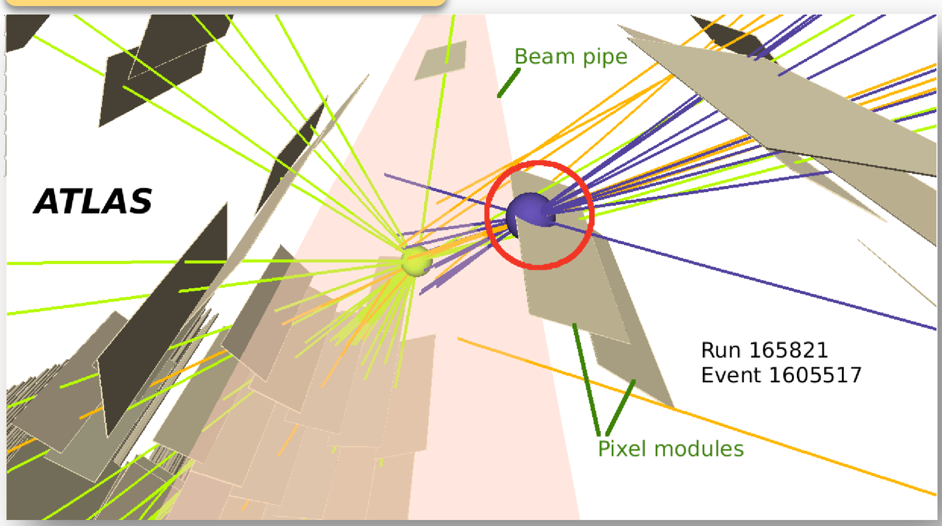


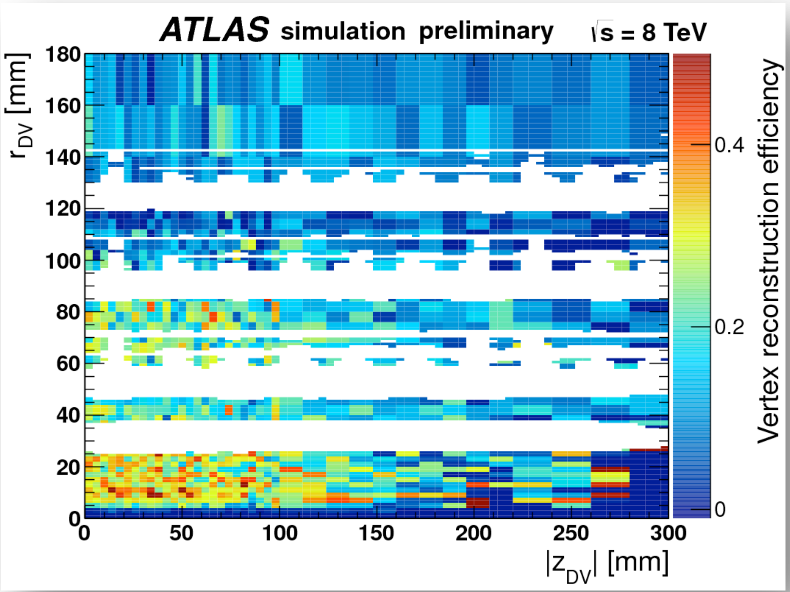
Displaced vertices: analysis



- RPV: LSP decays 4 – 180 mm from the interaction point for couplings $\lambda'_{2ij} \neq 0$
- Search for high-impact-parameter vertices: **$|d_0| > 2$ mm**
  - trigger: high-p_T muon
  - SM-particle late decays ➞ require high mass & high track multiplicity
  - overlap of high-p_T track with hadronic interaction vertex ➞ veto to vertices reconstructed within regions of high-density material

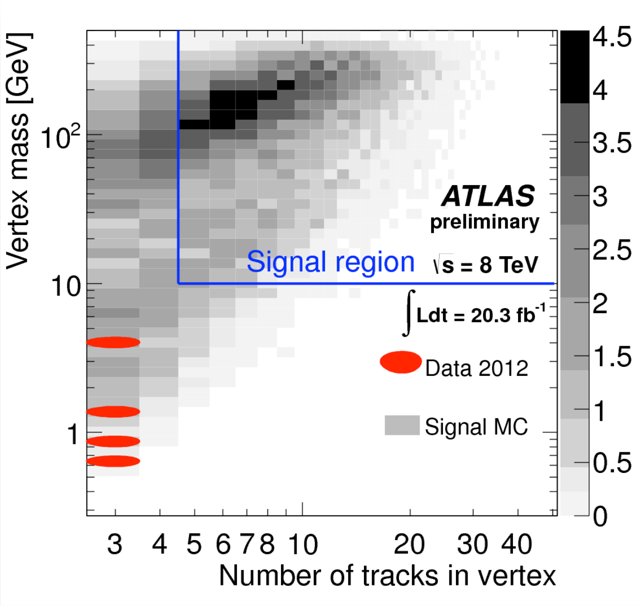
ATLAS-CONF-2013-092



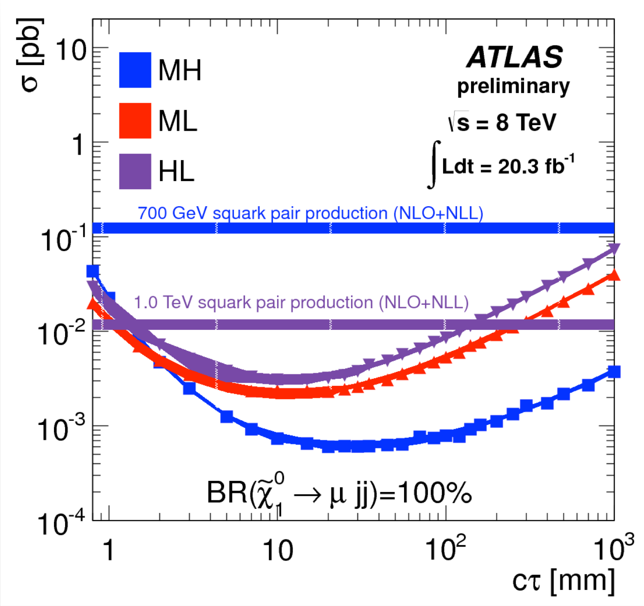


Displaced vertices: results

- Number of events passing selected requirements except for m_{DV} and $N_{DVtracks}$
- No data events observed in the signal region



- Upper exclusion limits at 95% CL
- Depend on masses and LSP lifetime
- Excluded: **σ×BR > 0.8 — 5.4 fb**



ATLAS-CONF-2013-092

For 13 / 14 TeV run:

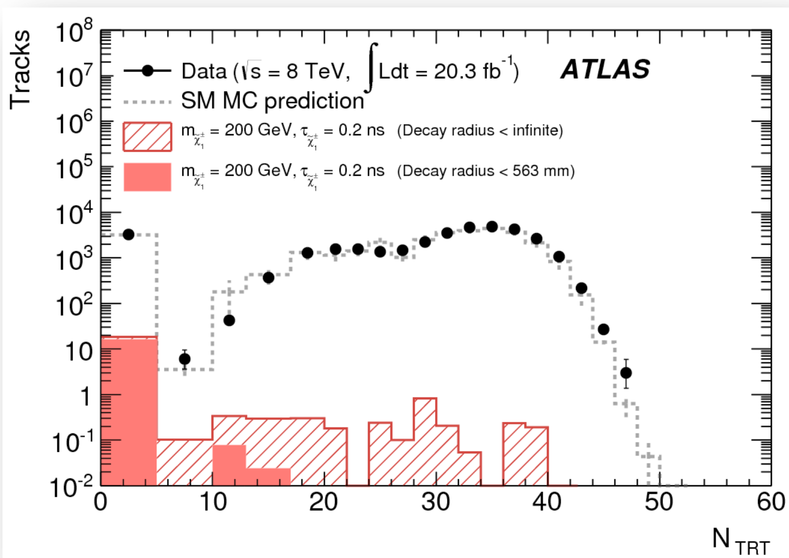
- dedicated DV trigger
- new final states (also for Run-I final analysis): e+jets, ν+jets, …
- new "complete" RPV models to motivate/interpret analysis (not just λ′ couplings)

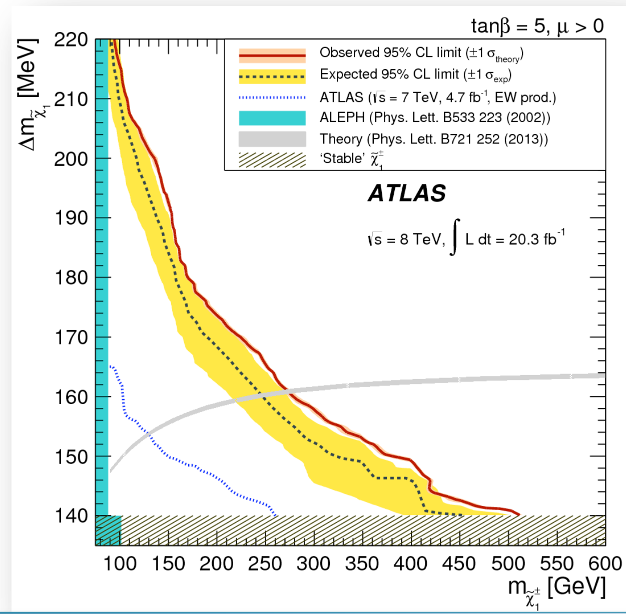
Disappearing track search

$$\tilde{\chi}_1^{\pm} \rightarrow \tilde{\chi}_1^{0} + \pi^{\pm}$$

- Meta-stable next-to-lightest particles may be created, fly some distance, and disappear / decay within the inner detector
- Searching for tracks with:
  - inner silicon detector: Well measured
  - **outer straw tracks (TRT)**: Low (<5) number of hits

Chargino mass below 270 GeV excluded in decoupled Anomaly Mediated SUSY Breaking (AMSB)



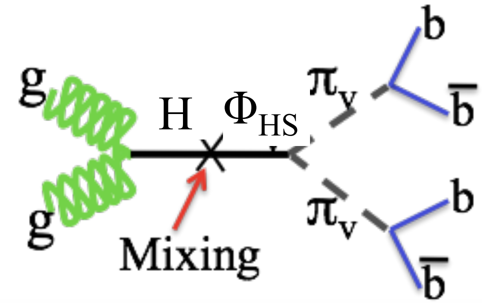


Phys. Rev. D 88 (2013) 112006

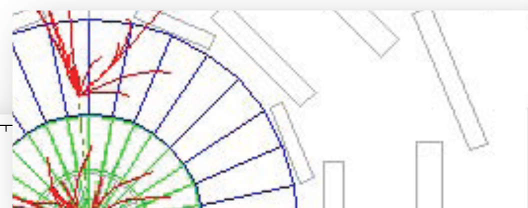
In view of the ATLAS inner detector upgrade in future HL-LHC (no TRT), such analyses have to be completely redesigned
➔ should get the most out of Run II

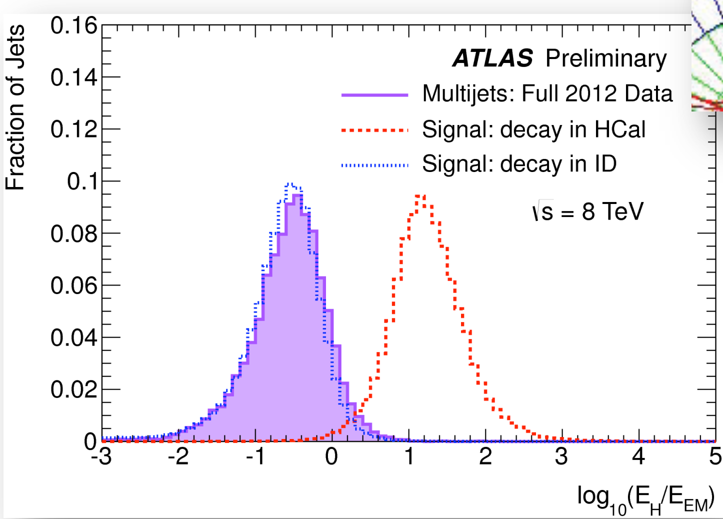
Non SUSY LLP: Hidden Valley neutral particle

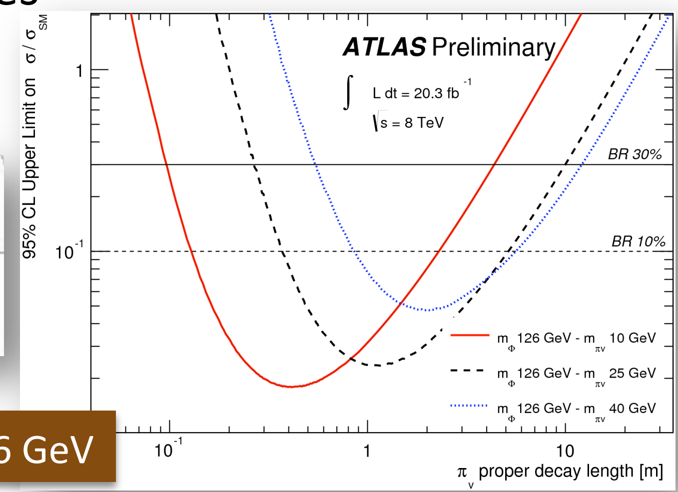
ATLAS-CONF-2014-041



- Hidden Valley (HV) weakly coupled to SM via heavy communicator scalar $\mathbf{\Phi_{HS}}$
  - Φ_{HS} Higgs or a Higgs-like scalar
  - HV can alter the branching fractions for Higgs decay
- Signature: If π_v long-lived, will give rise to final states with π_v decaying in hadronic calorimeter (HCal) or the outer edge of electromagnetic (EM) calorimeter



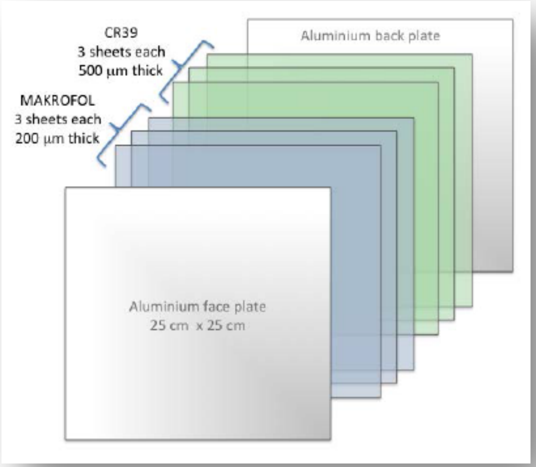




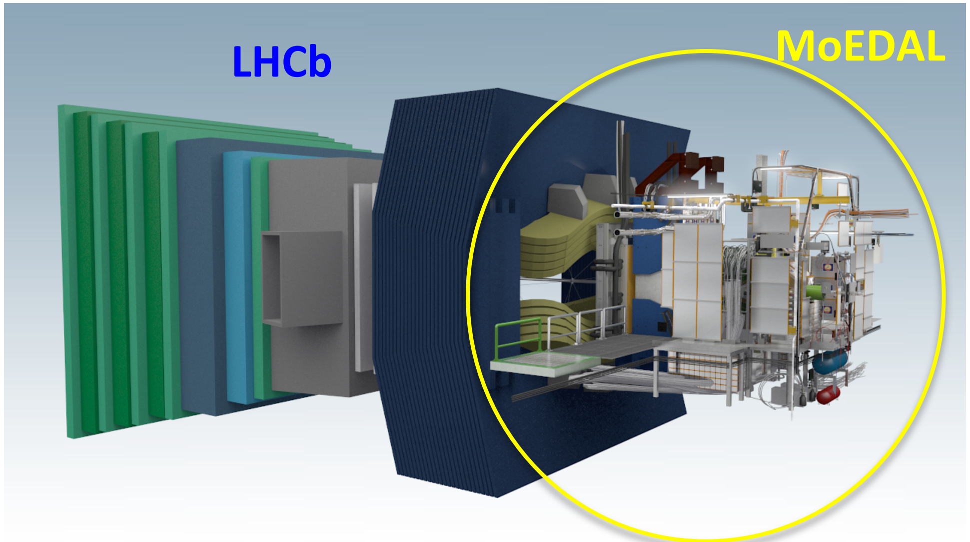
m_Φ = 126 GeV

No significant excess was observed
➜ limits set in Hidden Valley scenario
➜ **analysis may be sensitive to other (SUSY) scenarios, μνSSM ?**

MoEDAL experiment



- One step further: dedicated experiment at LHC to observe highly-ionising (meta-)stable states
  - monopoles, dyons
  - **SUSY stable particles**
  - multiply-charged particles, e.g. doubly charged Higgs
  - black-hole remnants, Q-balls, …
- Complementary to ATLAS & CMS experiments



MoEDAL is unlike any other LHC experiment:
- mostly passive detectors; no trigger; no readout
- the largest deployment of passive **Nuclear Track Detectors** at an accelerator
- the 1st time **trapping detectors** will be deployed as a detector

MoEDAL detectors are being installed to be ready for LHC Run II

Summary & outlook

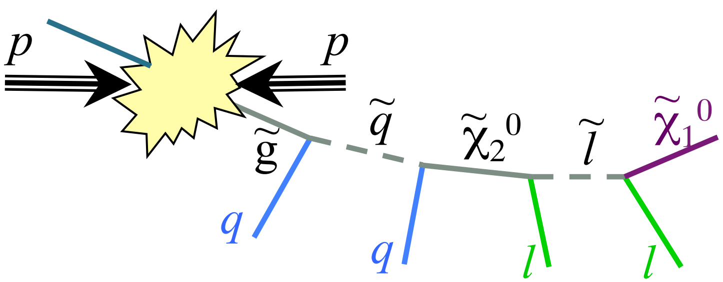
- R-parity violating and long-lived decays in SUSY
  - lead to collider signatures not predicted by conventional RPC searches
  - effort to cover them with dedicated analyses
  - in Run I we have barely scratched the surface of it
- Search approaches for 14-TeV LHC
  - reinterpretations of existing RPC analyses
    - help identify uncovered regions and carry out RPV-targeted analysis
  - prompt RPV searches
    - typically target high multiplicity final states & resonant production
    - probe more final states
  - searches for long-lived decays
    - exploiting the full potential of the detector
    - new operating conditions may require redesign existing analyses/triggers…
    - new ideas for theorists welcomed!!

… for 13-14 TeV run in 2015

Backup…

How do we search for SUSY at LHC?

- SUSY (more than) duplicates spectrum of particle states w.r.t. Standard Model
- Simplest extension of SM (MSSM) has > 100 new parameters
- Sparticles decay into (b/c-)jets, leptons, taus, photons, invisible (MET), …



- How do we decide on what to search for?
- How to interpret the results?

SUSY @ LHC: The strategy

Theoretical model space

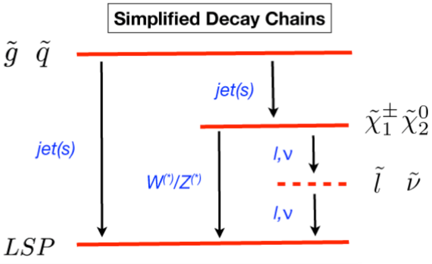
breaking mechanism, R parity, MGUT unification, ..
(N)MSSM, mSUGRA, GMSB, …

Top down

Define model and search for it in suitable final states

Bottom up

Define topology (decay chain) and interpret results in (m_X, m_Y) plane
➜ **simplified topologies**



Experimental signature space

MET ? + n jets + m leptons, taus, Meff, mT, …

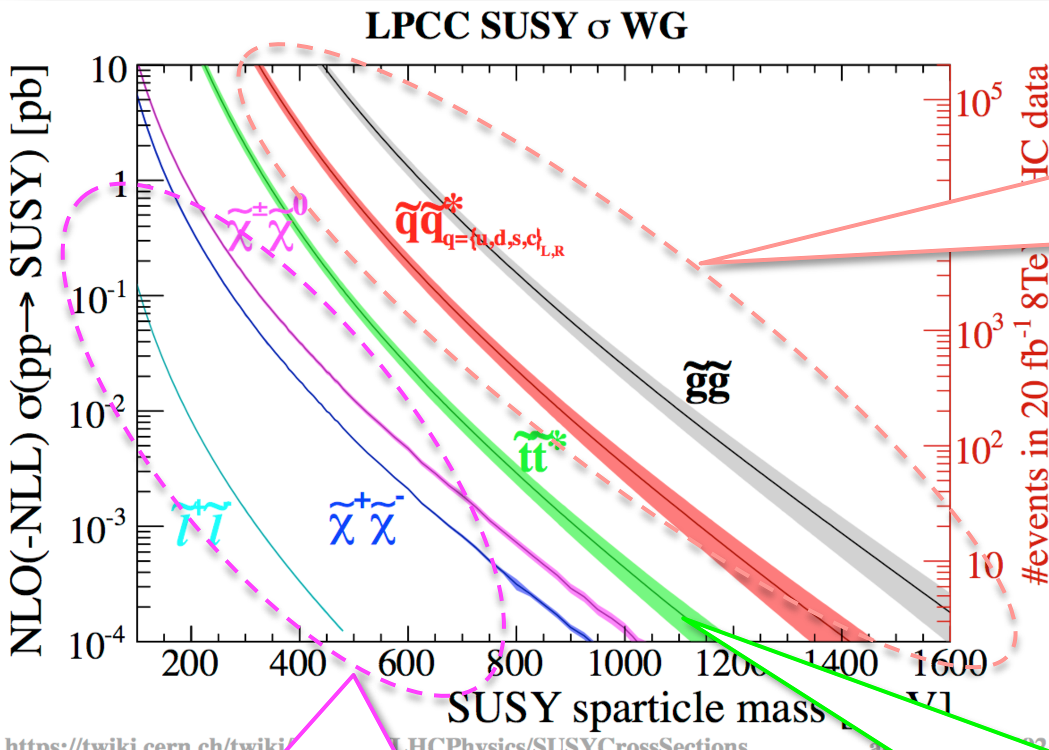
SUSY @ LHC: The organisation

Following previous paradigm, we divide analyses into separate(*) signatures

- R-parity conserving (RPC) signatures:
  - sparticles produced in pairs, each decays to (WIMP) LSP, mostly lightest neutralino or gravitino
  - one invisible LSP per decay chain → MET
- R-parity violating (RPV) signatures:
  - resonances or multijets / multileptons: single sparticle production or LSP decay
  - Displaced vertices from late LSP decay
- Long-lived particles from:
  - weak couplings, e.g. RPV, gravitino
  - heavy mediator sparticles, e.g., heavy squarks in split SUSY
  - mass degeneracy, e.g. m(chargino) ~ m(LSP) in AMSB

(*) Limits not clearly defined, e.g. RPV delayed decays

SUSY searches @ LHC



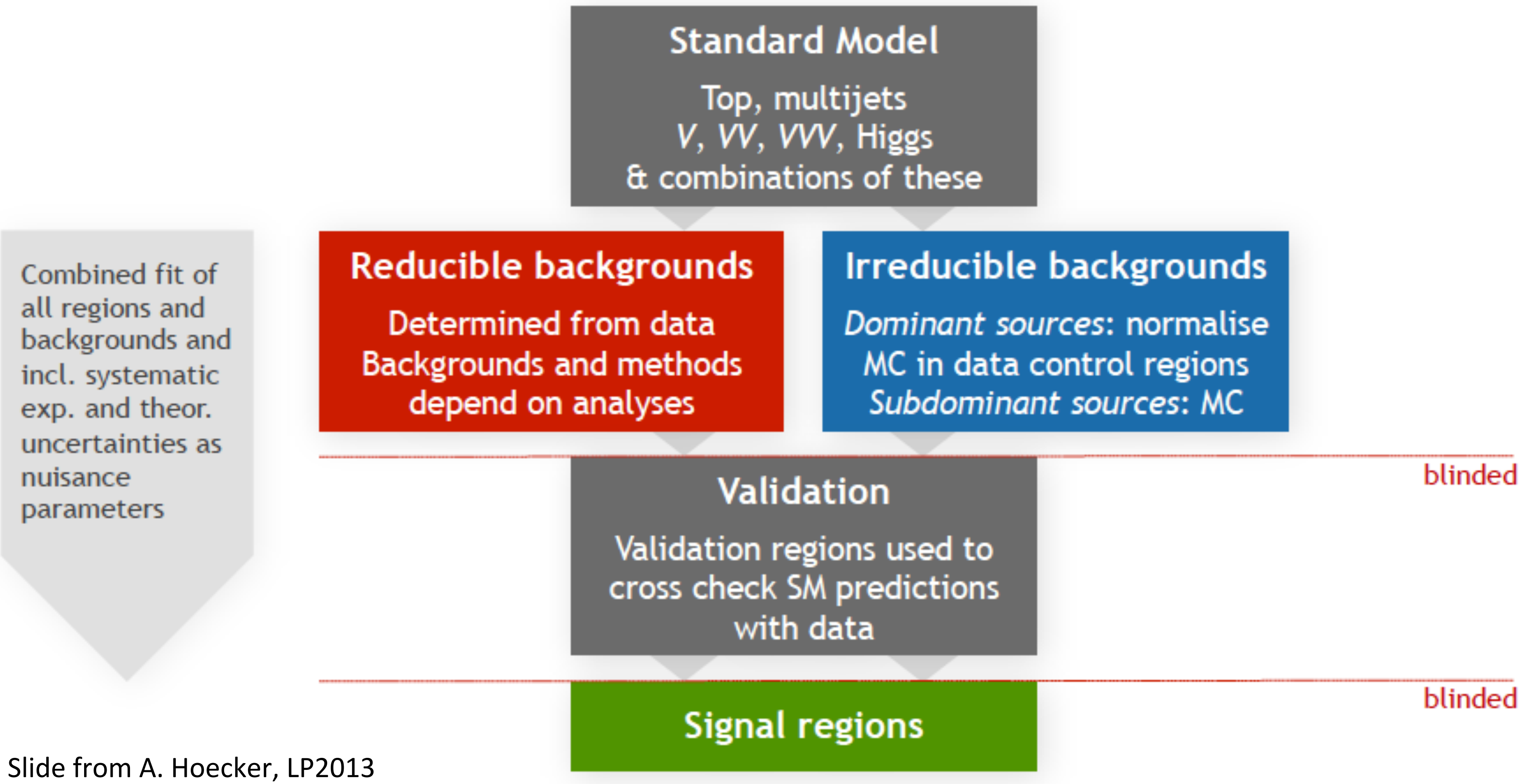
Strong-production channels
- Copious production at hadron colliders
- E_T^{miss}-based generic search channels
- Plus more exotic channels

Third-generation sparticle searches
- Expected from naturalness to be *O*(<TeV)
- Expected lighter than other squarks due to mixing
- Can search for more specific final states

Leptons/photons searches
- colored spartners too heavy
  → direct gaugino production
- pertinent for gauge-mediated models

SUSY @ LHC: The technique

Background estimation mostly based on data-driven techniques



Slide from A. Hoecker, LP2013

What about dark matter?

- Gravitivo LSP with cosmologically-long lifetime
  - signal: monochromatic gamma-rays $\tilde{G} \to \gamma\nu$
  - constrained by
    - ν-oscillations
    - DM relic density $\Omega_\chi h^2$
    - γ-ray line searches
- If lightest neutralino is the NLSP

$$\tilde{\chi}_1^0 \to h^0 \nu_i, \qquad \tilde{\chi}_1^0 \to W^\pm l_i^\mp,$$
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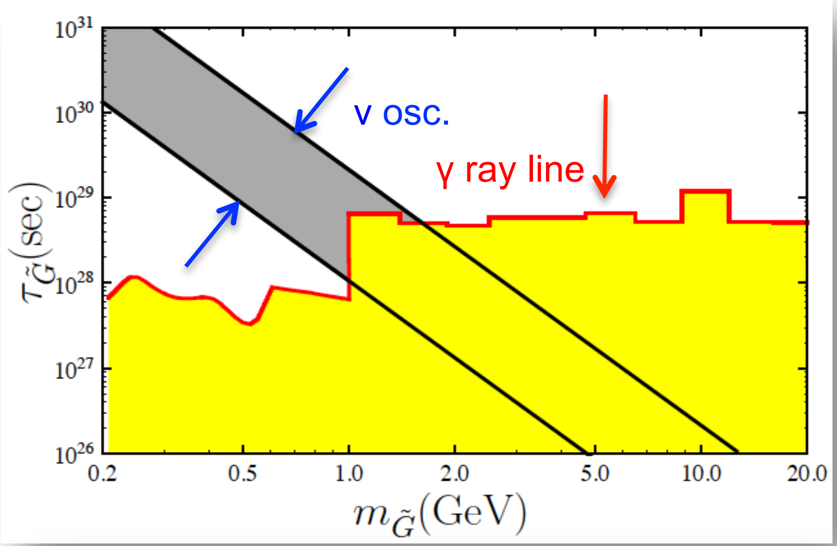
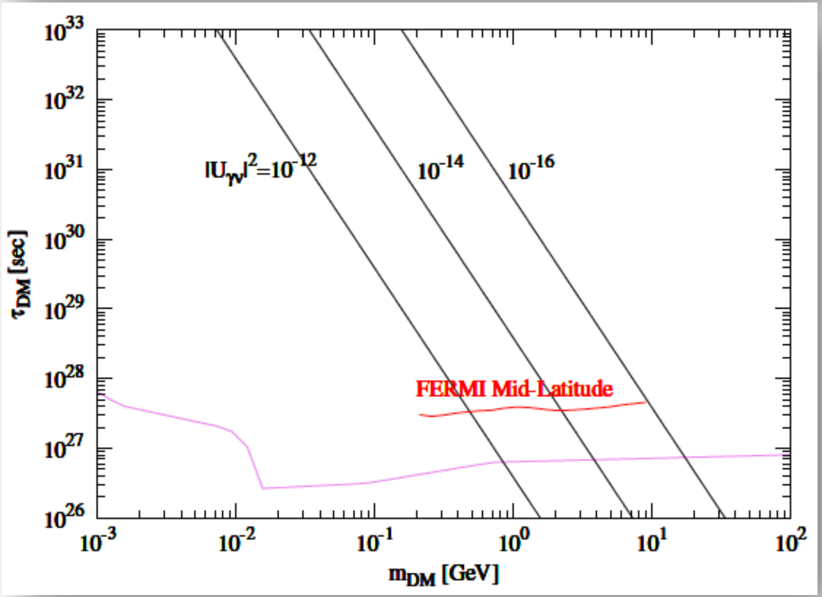
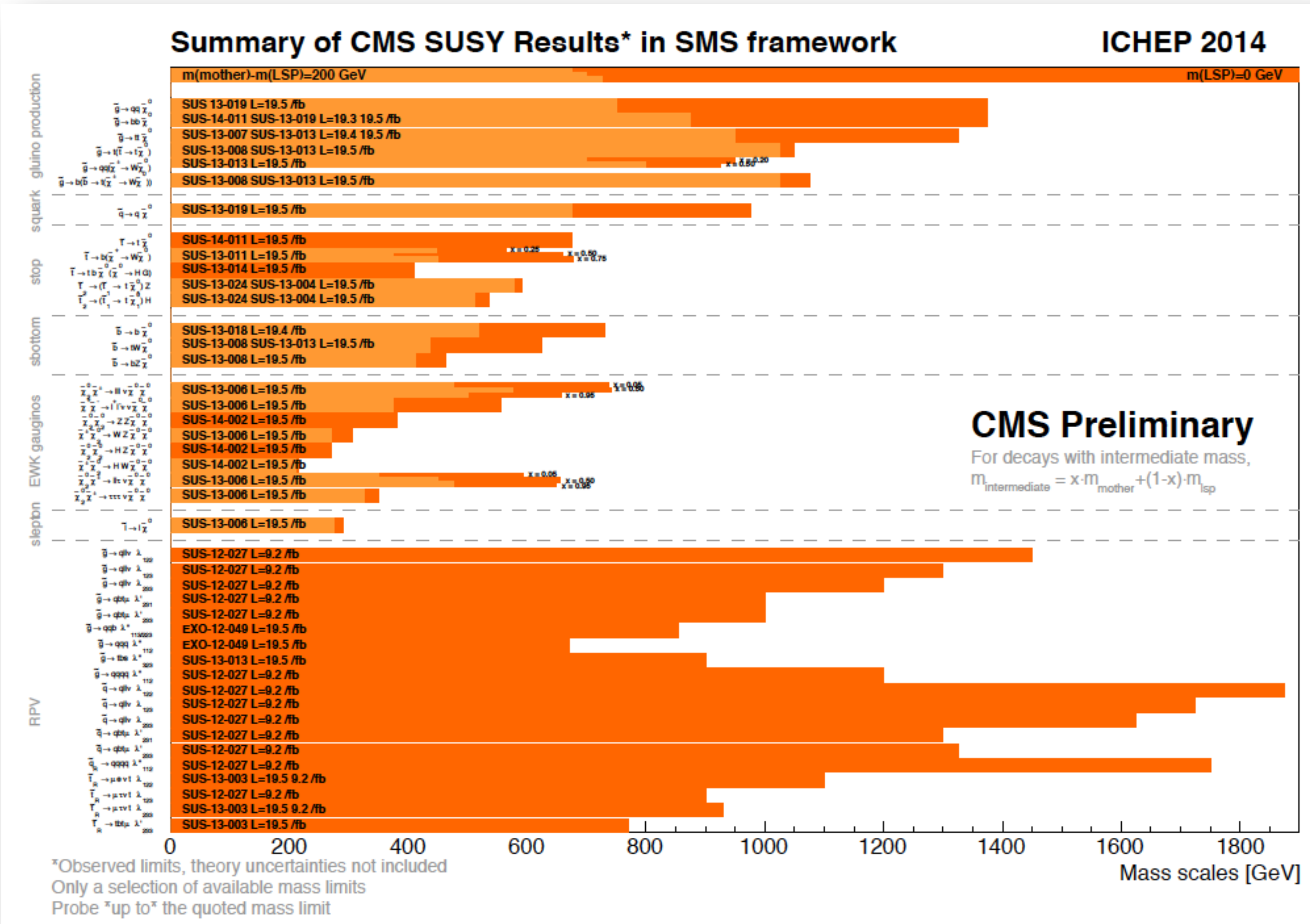
- (Long-lived) neutralino can also decay to 3 fermions



Restrepo et al, PRD85 (2012) 023523



Choi et al, JCAP 1003 (2010) 028


Summary of CMS SUSY Results* in SMS framework
ICHEP 2014
m(mother)-m(LSP)=200 GeV
m(LSP)=0 GeV
gluino production
squark
stop
sbottom
EWK gauginos
slepton
RPV
SUS 13-019 L=19.5 /fb
SUS-14-011 SUS-13-019 L=19.3 19.5 /fb
SUS-13-007 SUS-13-013 L=19.4 19.5 /fb
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SUS-13-018 L=19.4 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
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SUS-12-027 L=9.2 /fb
SUS-13-003 L=19.5 9.2 /fb
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CMS Preliminary
For decays with intermediate mass,
m_intermediate = x·m_mother + (1-x)·m_lsp
0
200
400
600
800
1000
1200
1400
1600
1800
Mass scales [GeV]
*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit

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