QCD ISSUES

IN SEARCHES FOR

SUPERSYMMETRY

WITH THE ATLAS DETECTOR

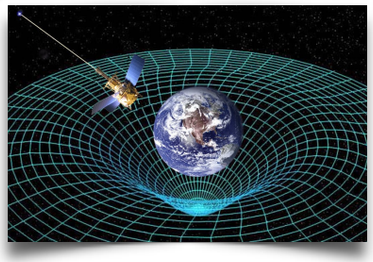
July 15th, 2019

VERONIKA MAGERL (FOR THE ATLAS-COLLABORATION)

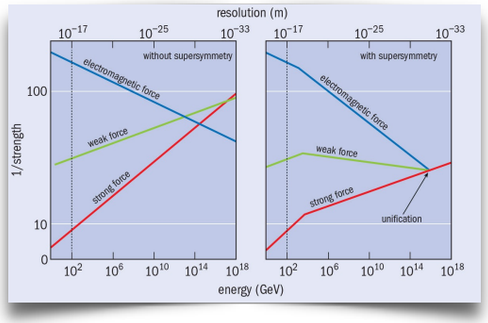
BMBF-Forschungsschwerpunkt ATLAS-EXPERIMENT
Physik bei höchsten Energien mit dem ATLAS-Experiment am LHC
FSP 103 ATLAS

WHY SUPERSYMMETRY

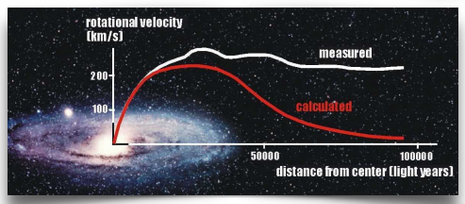
GRAVITY

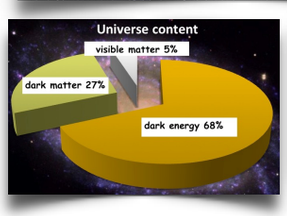


UNIFICATION OF COUPLINGS

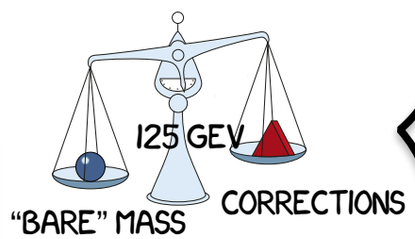


DARK MATTER



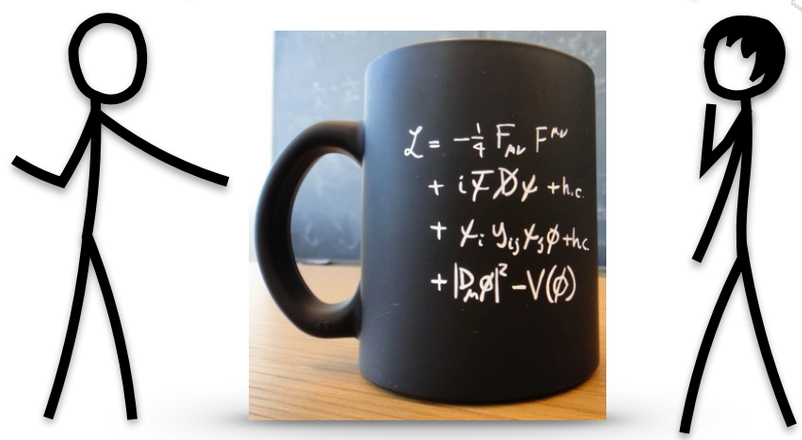


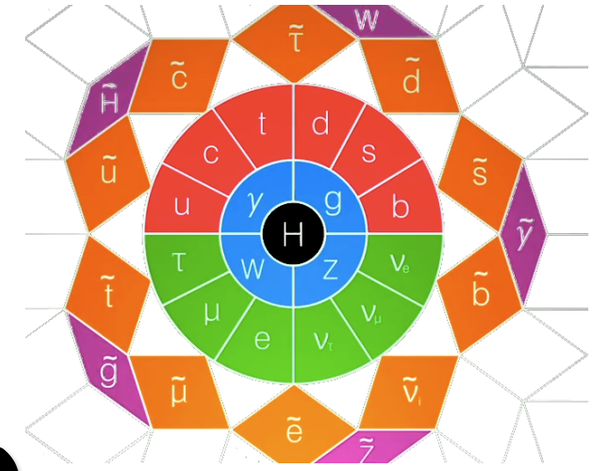
HIERARCHY PROBLEM



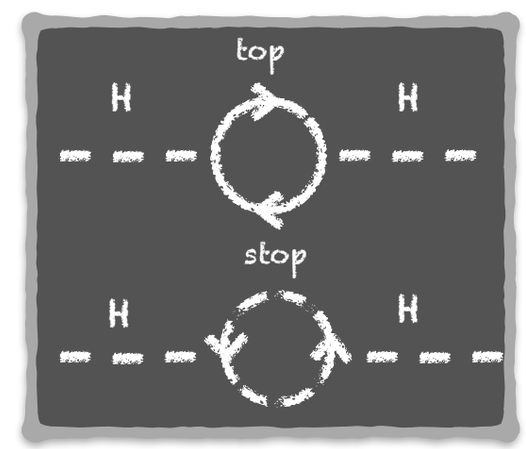
OK, WE HAVE THIS NICE STANDARD MODEL BUT WHAT ABOUT ALL THIS?

WELL, SUSY COULD FIX IT FOR US ...





"Particle Fever" (Levinson and Kaplan)



- interesting theoretical framework providing various different BSM scenarios e.g. MSSM
- each fermionic SM particle has a bosonic superpartner and vice versa
  ⇒ doubled number of particles

SUPERSYMMETRY AT LHC

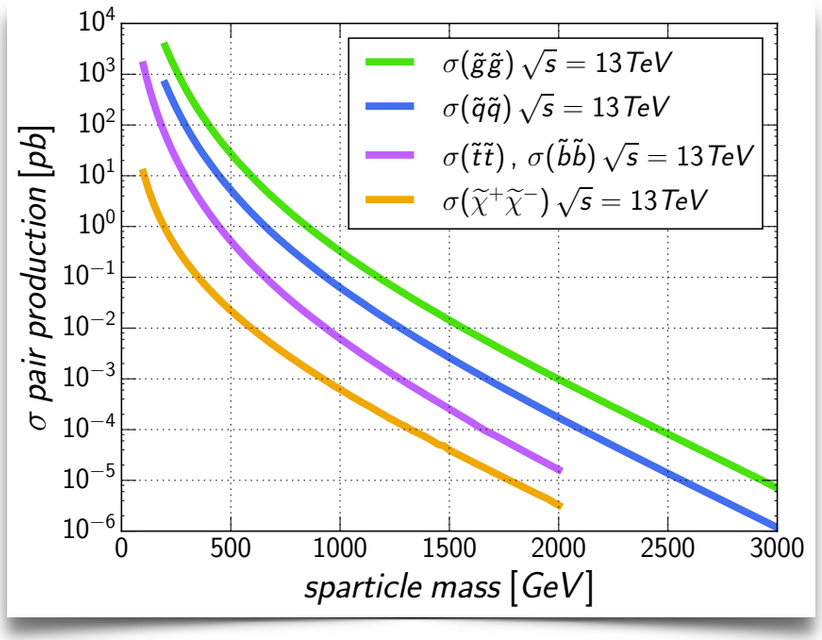
- if SUSY is present at the TeV scale → within the MSSM strongly coupling sparticles like gluinos ($\tilde{g}$) may be produced at the LHC at high rate

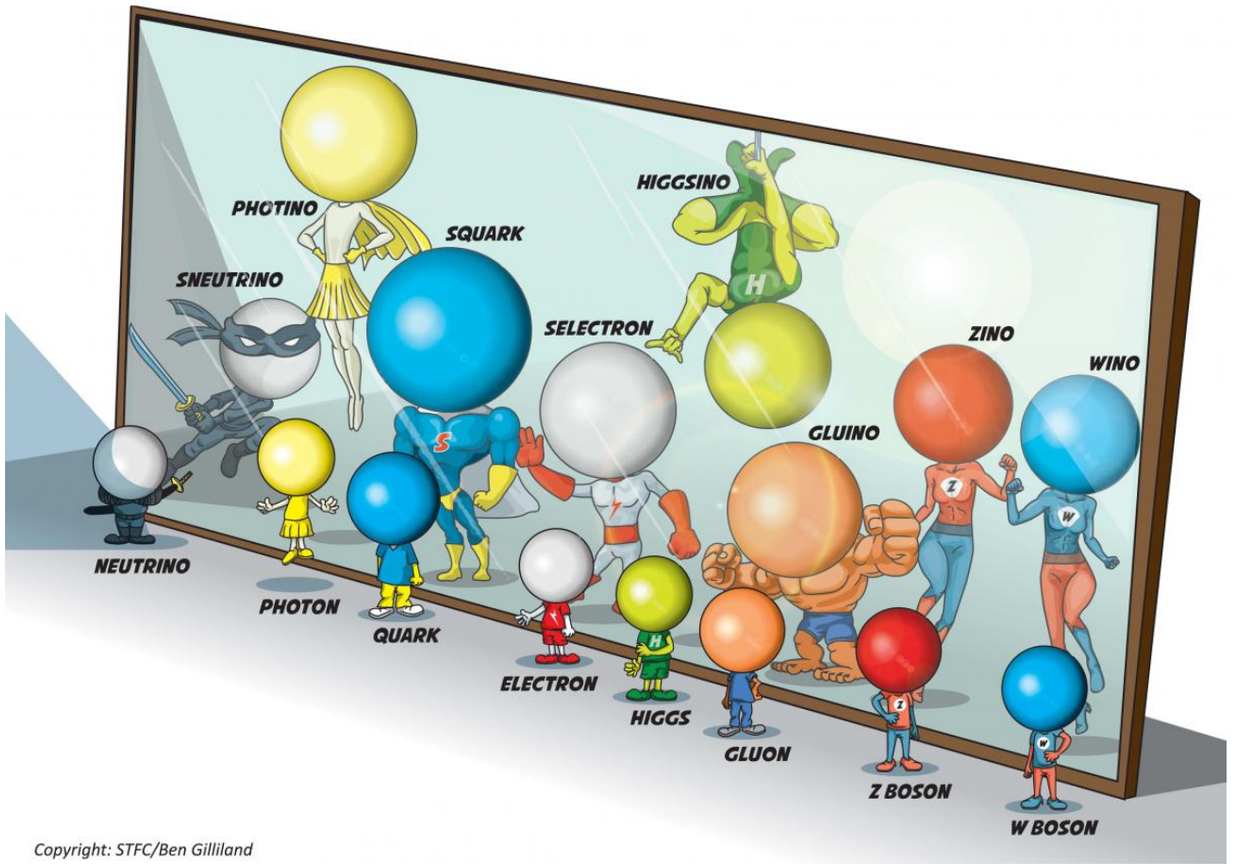
- under R-Parity Conservation (RPC) gluinos can decay directly or via cascades into final states with
  - Quarks (jets)
  - Missing Transverse Energy (MET) carried away by undetected Lightest Supersymmetric Particle (LSP)

- under R-Parity Violation (RPV) the LSP itself can decay further into SM particles

- other models like Split SUSY include long-lived particles

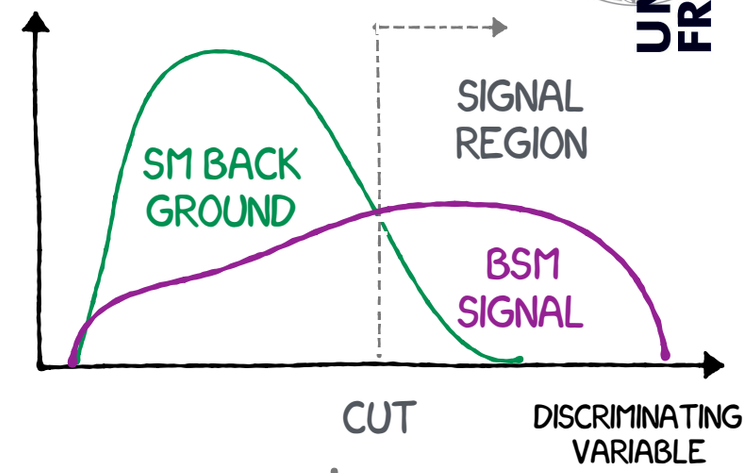
- many different possible realisations
  ⇒ rich landscape of channels to design searches

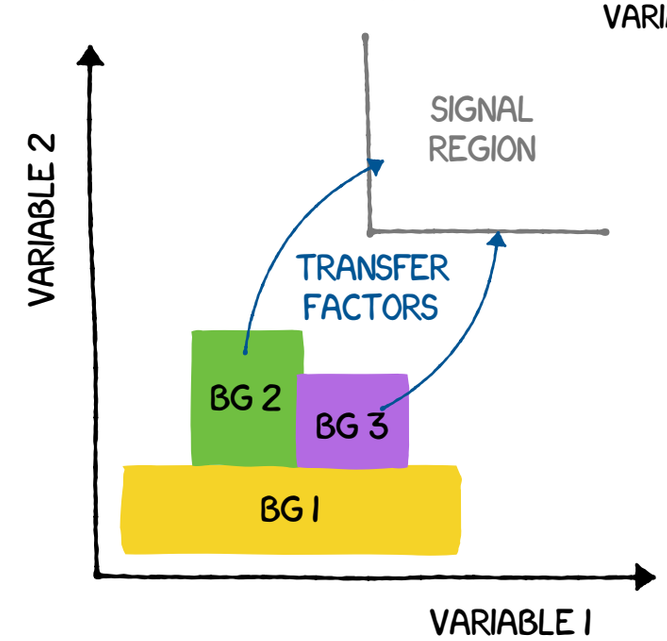


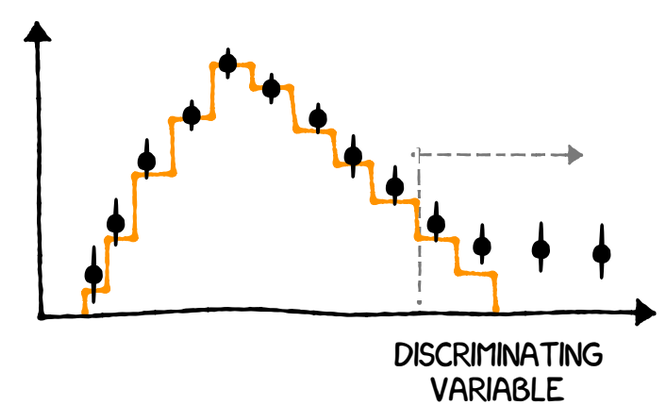


GENERAL ANALYSIS STRATEGY

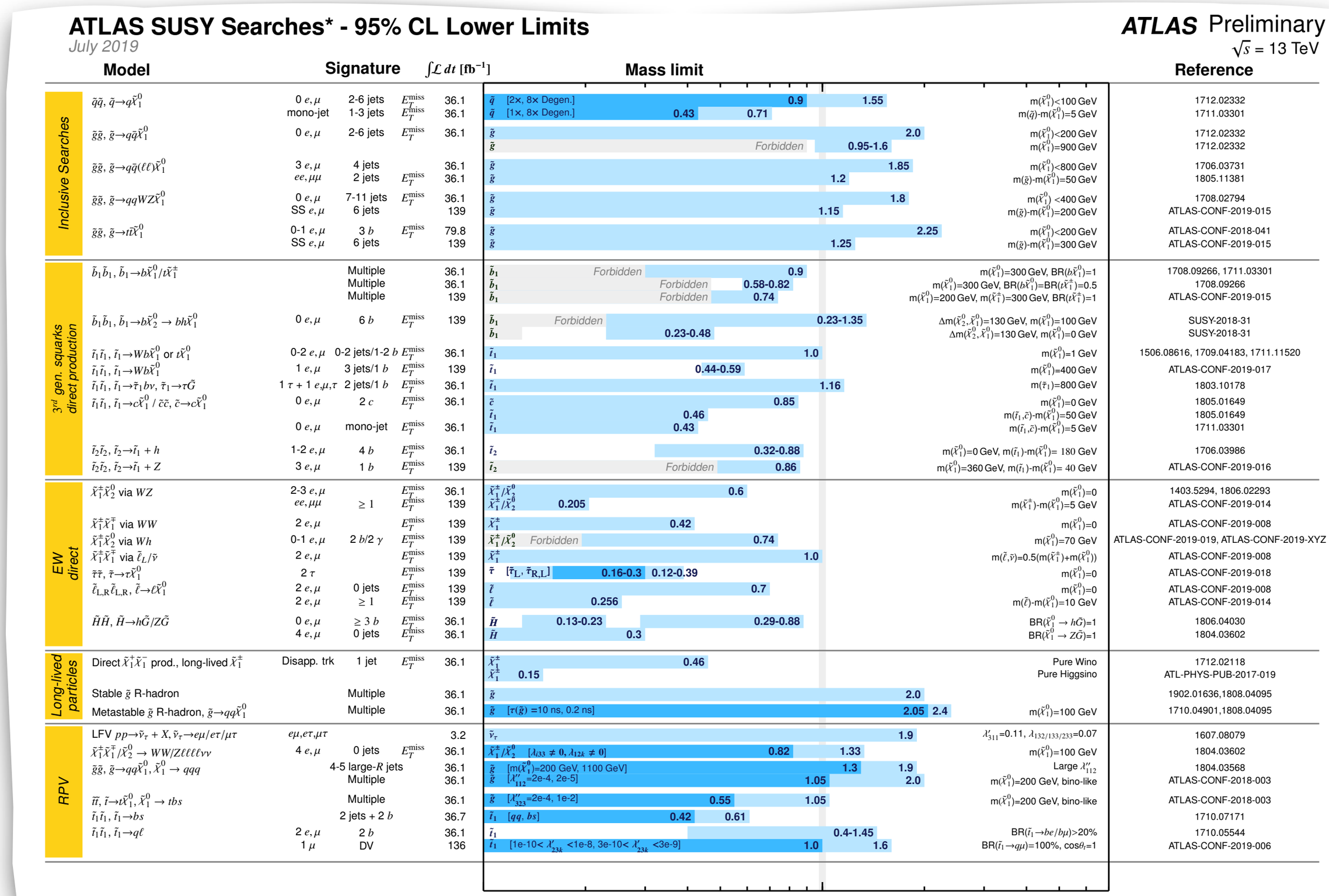
- find variables to discriminate between signal and background → define signal regions
- use control regions to enhance SM process → estimate expected background yield in the signal region:
  - purely MC based
  - data driven methods (e.g. template fit methods, jet smearing, …)
- cross check background prediction using validation regions closer to signal regions
- QCD enters in different ways but from analysis point of view we talk about jets:
  - need to be reconstructed (from topo-clusters in calorimeter, from particle flow, reclustered from smaller jets, …)
  - need to be calibrated (mass, energy, resolution, …)
- unblinding → compare data and BG prediction for each signal region to look for an excess
- no significant excess is found → set limits for particular simplified model



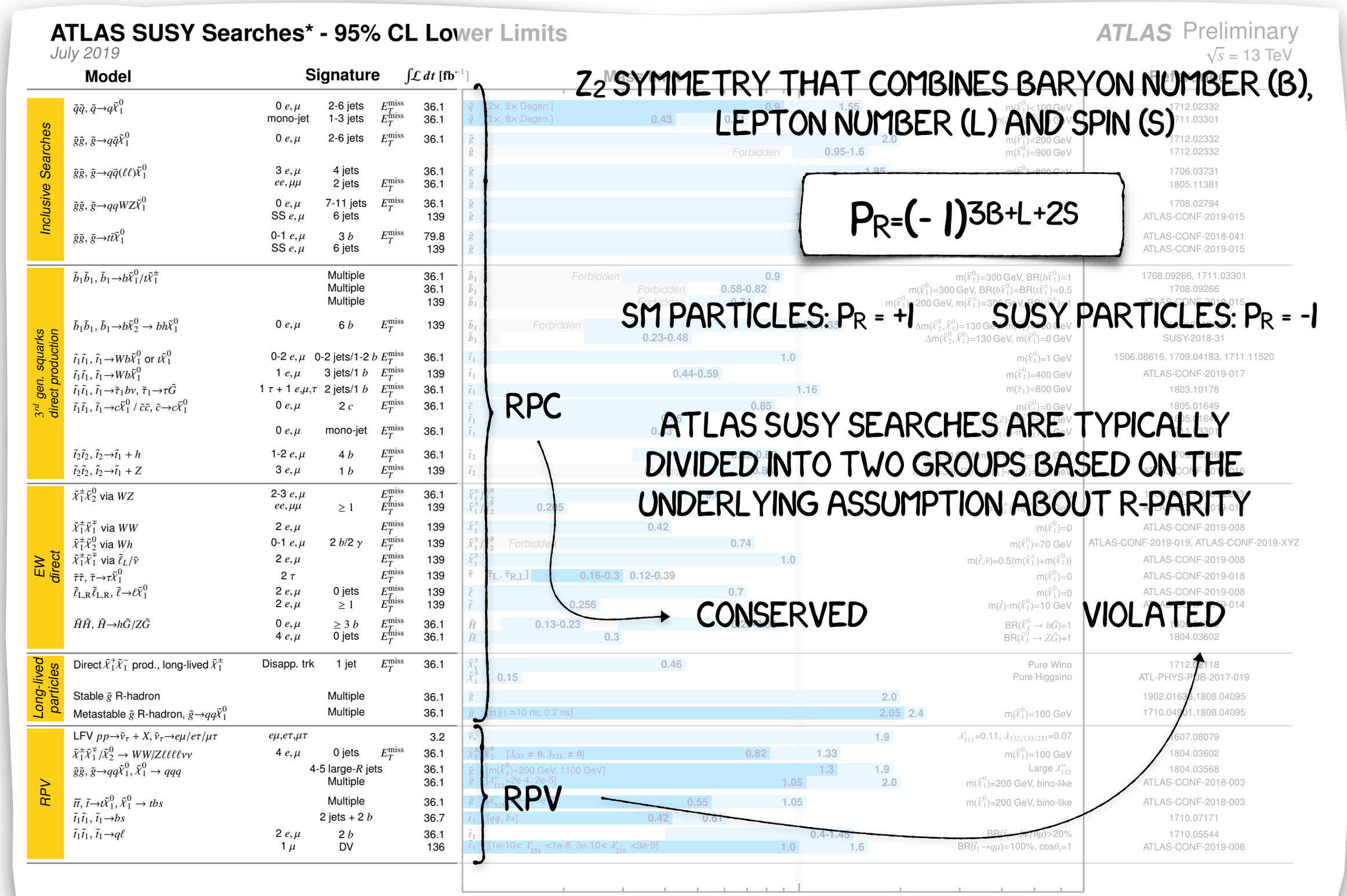




THE ATLAS SUSY SEARCH PROGRAM . . .



...AND R-PARITY



Z_2 SYMMETRY THAT COMBINES BARYON NUMBER (B), LEPTON NUMBER (L) AND SPIN (S)

$$P_R = (-1)^{3B+L+2S}$$

SM PARTICLES: $P_R = +1$ SUSY PARTICLES: $P_R = -1$

RPC

ATLAS SUSY SEARCHES ARE TYPICALLY DIVIDED INTO TWO GROUPS BASED ON THE UNDERLYING ASSUMPTION ABOUT R-PARITY

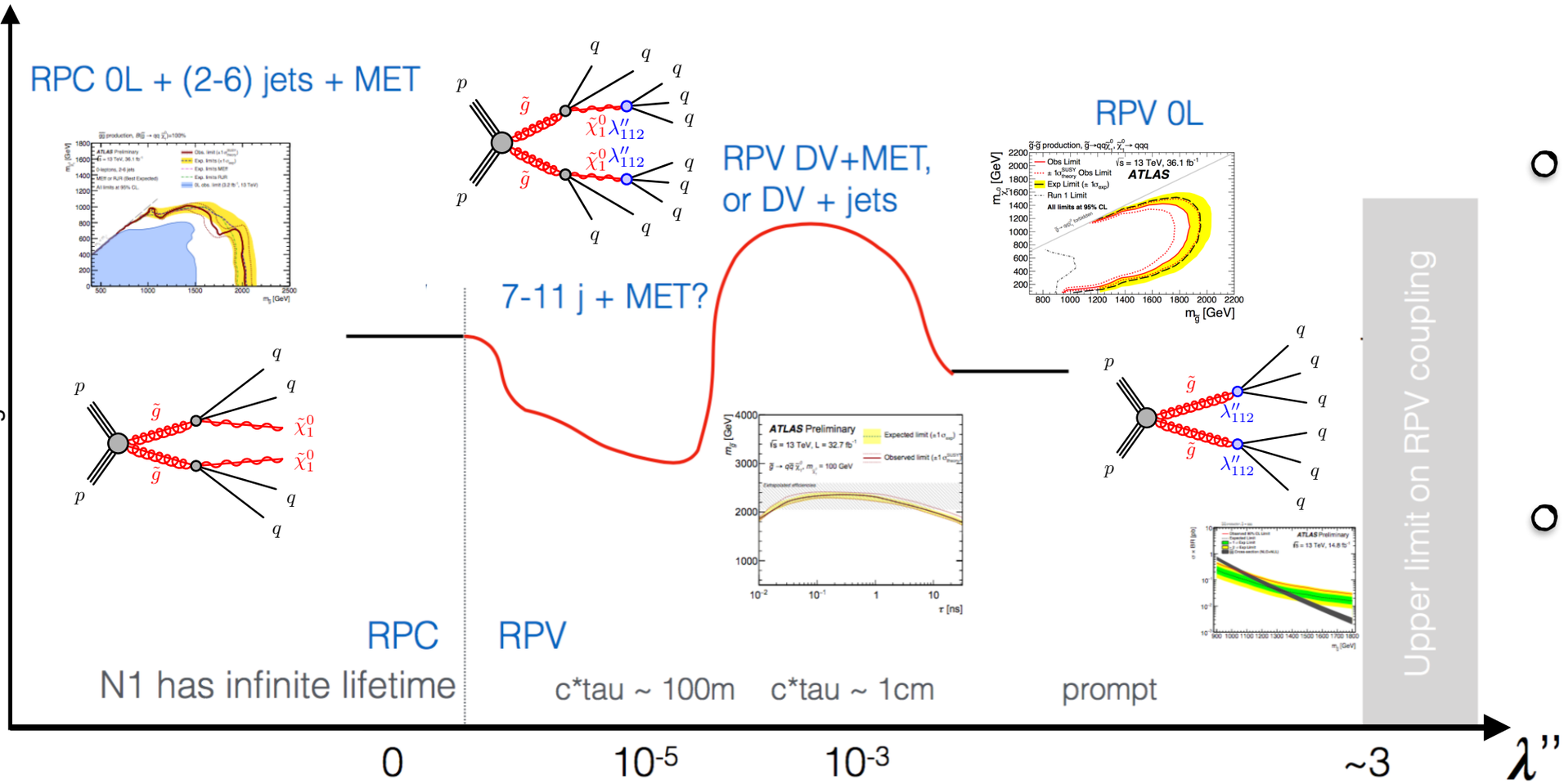
CONSERVED

VIOLATED

RPV

WHAT'S IN BETWEEN?

- close the gap between phase space covered by dedicated RPC SUSY analyses and by those targeting prompt RPV models



- → slowly increase strength of RPV coupling ⇒ covering a rich phenomenology
- different analyses are sensitive in various regions

ATLAS CONF Note

April 18, 2018

ATLAS-CONF-2018-003

Reinterpretation of searches for supersymmetry in models with variable *R*-parity-violating coupling strength and long-lived *R*-hadrons

R-PARITY CONSERVING (RPC) SPLIT SUPERSYMMETRY
=> LONG LIVED GLUINOS

R-PARITY VIOLATING (RPV) SUPERSYMMETRY
=> LONG LIVED NEUTRALINOS

MULTIJET LL NEUTRALINO MODELS

- most generic superpotential → Yukawa couplings can cause lepton-number (L) and baryon-number (B) violation

$$\mathcal{W}_{\mathrm{RPV}} = \frac{\lambda_{ijk}}{2} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \frac{\lambda''_{ijk}}{2} \bar{U}_i \bar{D}_j \bar{D}_k + \kappa_i L_i H_u$$

- RPV couplings λ, λ', λ'' are removed in many SUSY models by imposing R-parity
  ⇒ R-parity-conserving (RPC) models → lightest SUSY particle (LSP) is stable
- but at least some of these couplings might not be zero
  ⇒ R-parity-violating (RPV) models → lightest SUSY particle (LSP) decays promptly

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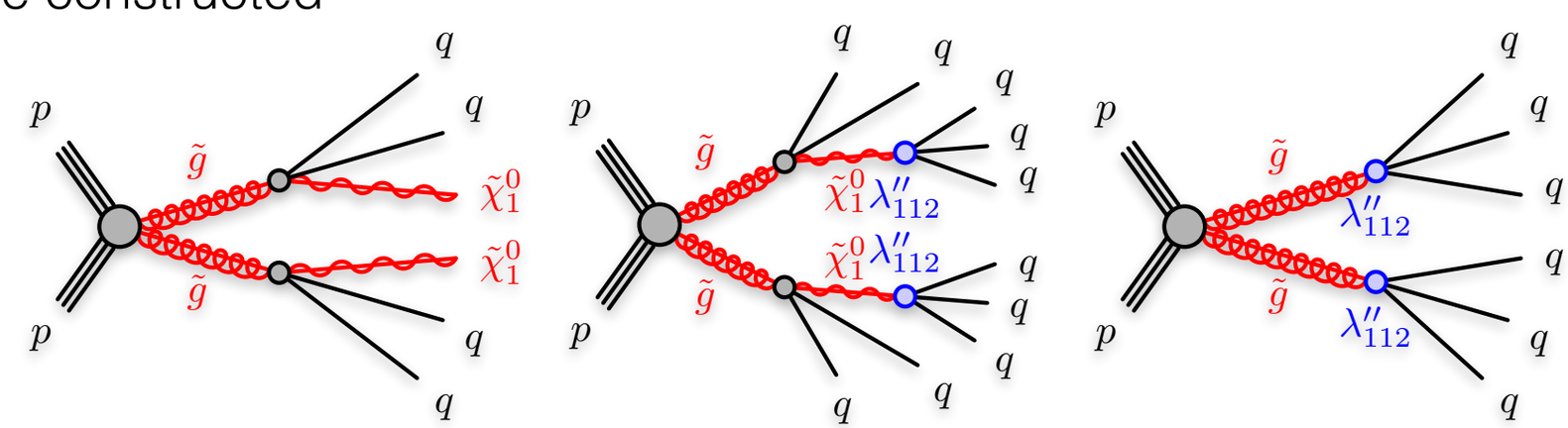
INTRODUCTION OF NON-ZERO RPV COUPLINGS -> LSP CAN BECOME A LONG-LIVED PARTICLE

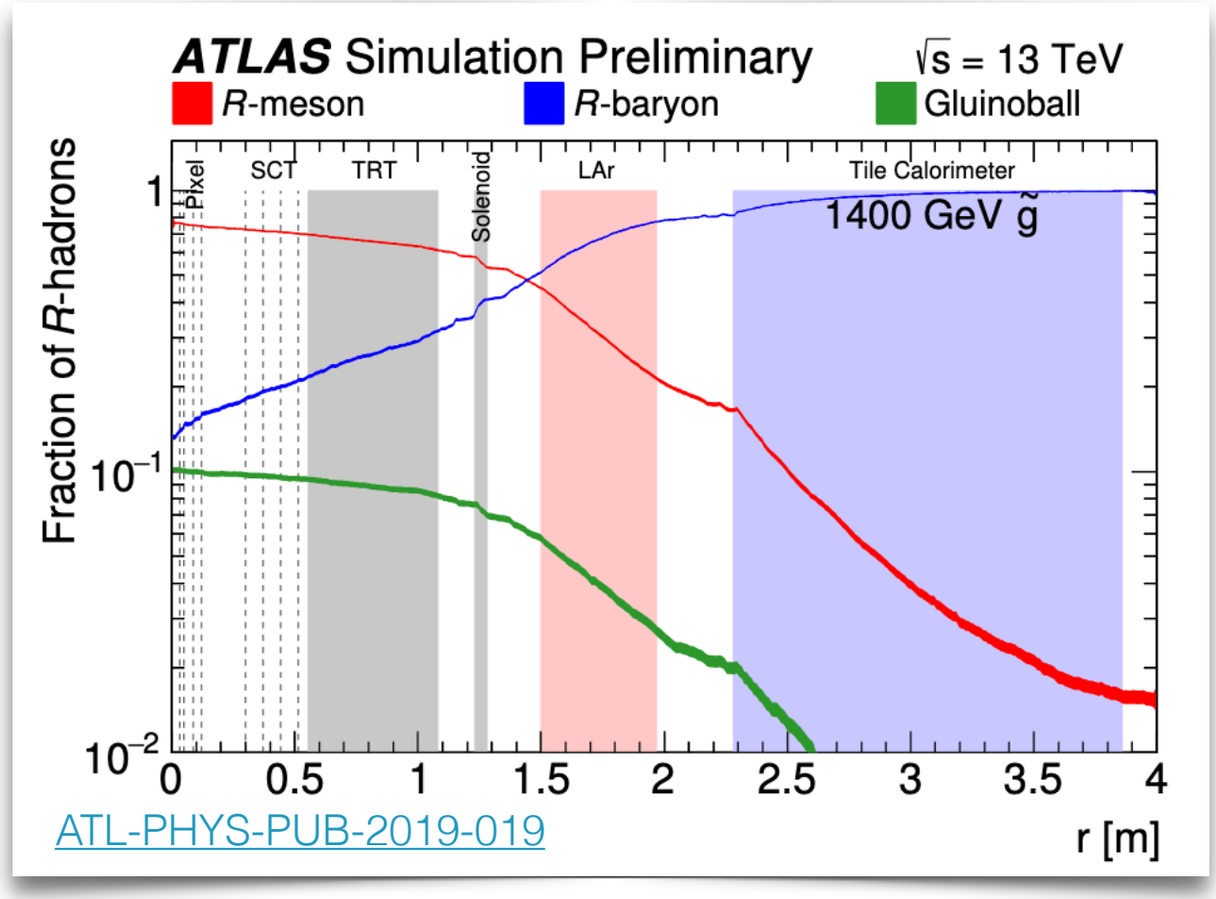
- sets of simplified models can be constructed
  e.g. Gqq-model:

=> FINAL STATES WITH POTENTIALLY DISPLACED JETS



LONG-LIVED GLUINO MODEL

- based on Split SUSY scenario assuming RPC
  - SUSY breaking occurs at high scales
  - scalar particles acquire mass at this scale
    ⇒ at LHC only gluinos and EWeakinos
  - squark mediated gluino decays are suppressed
    ⇒ gluinos are metastable massive particles
- gluinos hadronize into color singlet states called R-hadron:
  - gluinoballs, meson-like, baryon-like
  - change their charge and light quark system while traversing the detector
- properties (mass, lifetime, decays, …) of the R-hadron are largely dominated by the gluino



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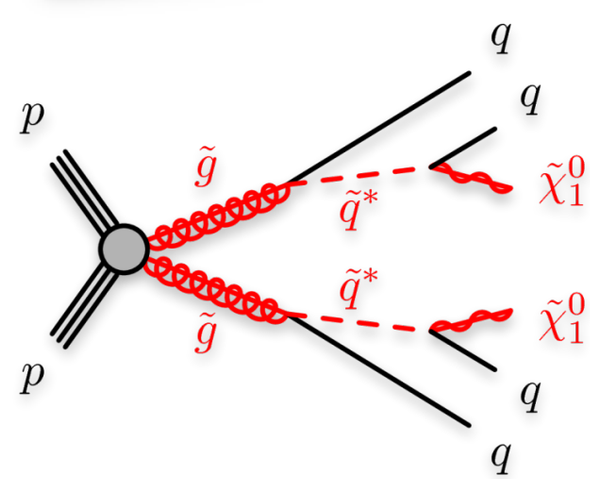


=> DETECTOR SIGNATURES WITH (DISPLACED) JETS

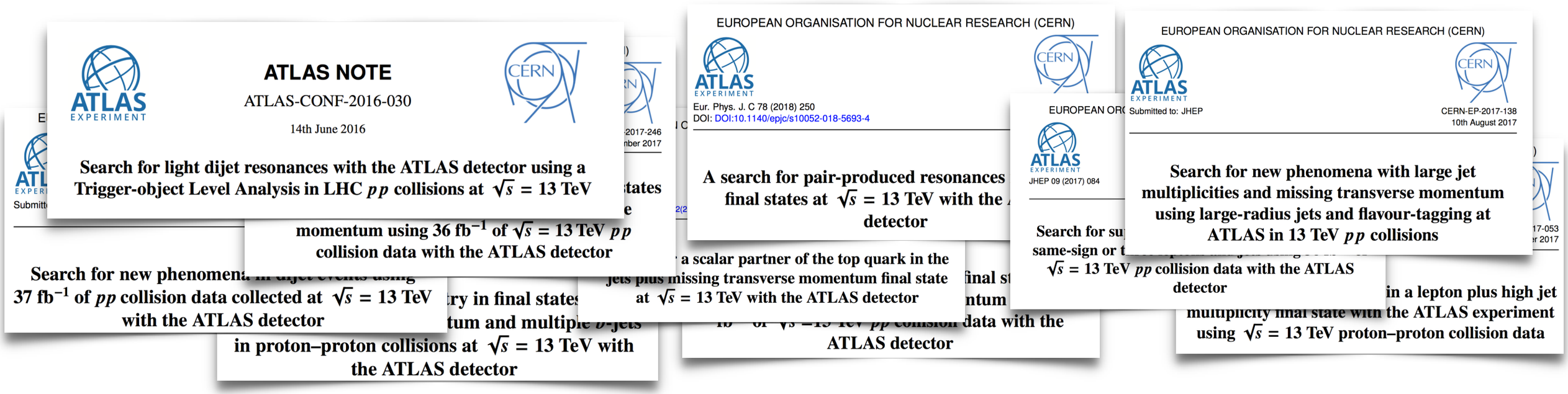
CONTRIBUTING ANALYSES

- reinterpretation of the LL gluino models was performed in the RPC 0L inclusive 2-6 jets analysis
- in total 10 different analyses contributed to the reinterpretation of the LL neutralino models

RPC 0-lepton, 7-11 jets
RPC 0-lepton, 2-6 jets (modified)
RPC stop 0-lepton and 1-lepton

RPC multi-b
RPC and RPV SS/3L
RPV 1-lepton

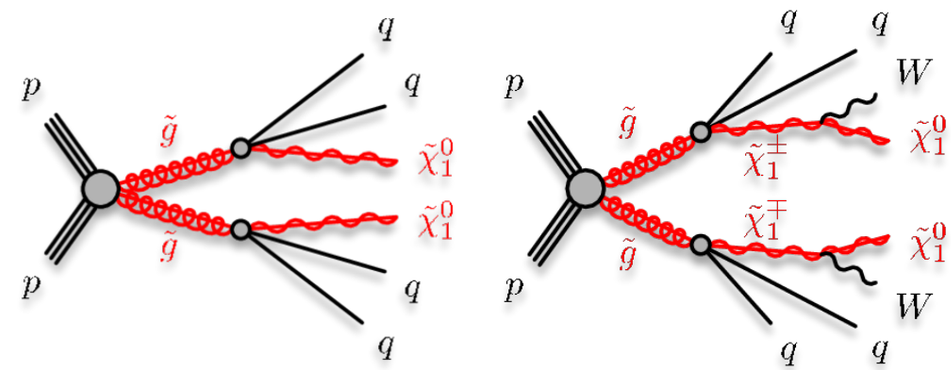
RPV stop dijet pairs
Dijet and trigger-level-analysis (TLA)



ASSESS SENSITIVITY IN LL SCENARIOS
-> STUDY JET RESPONSE AND RECONSTRUCTION EFFICIENCY

RPC 0-LEPTON ANALYSIS

- studies mainly performed in RPC 0L inclusive 2-6 jets analysis (Phys. Rev. D 97, 112001)



- search for strongly produced sparticles e.g. RPC limit of Gqq (λ'' = 0) in fully hadronic final states with large MET

$$\not{E}_T > 250 \text{ GeV}$$

- M_{eff} based cut & count approach using discriminating variable

MAIN OBSERVABLE:

$$M_{eff} = \sum_{i=1}^{n} |p_T^{(i)}| + \not{E}_T$$

- use MC based estimation for major background processes V+jets and Top

$$\Delta\Phi(\text{JET},\not{E}_T),\ H_T = \sum_{i=1}^{n} |p_T^{(i)}|,\ \not{E}_T/\sqrt{H_T}, \ldots$$

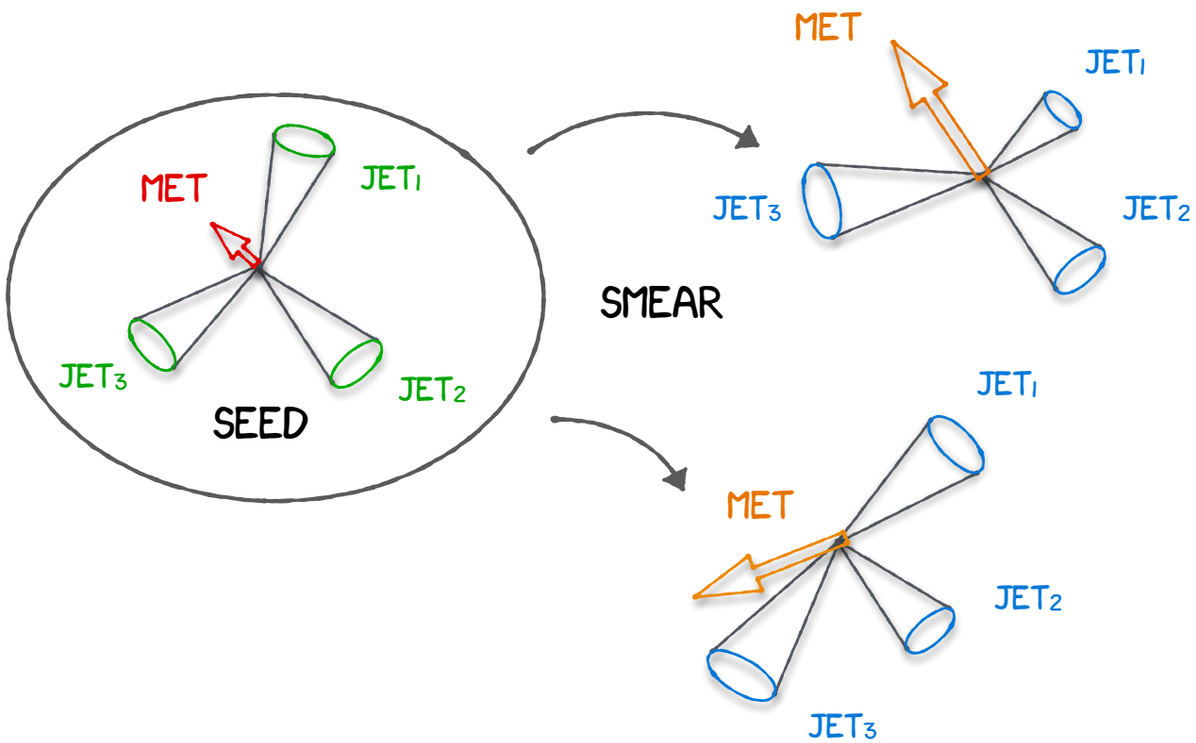
- QCD background is suppressed by high MET cut and cut on $\Delta\Phi$ but tricky to estimate
  - dominated by mis-measurement of multiple jets leading to fake MET
  - huge amount of MC events needed to effectively simulated mis-measurement from detector effects
  - inaccuracy of simulation for large MET due hard-to-model features like JER dependency, time dependency etc.

=> FULLY DATA-DRIVEN JET SMEARING

JET SMEARING METHOD

- basic idea: create "pseudo-data" where events have large amount of fake MET
- construct jet response map derived from well-measured dijet events in MC
- select good "seed event" well-measured event in data
- multiply each jet in this event 1000 times with a random number created from response map

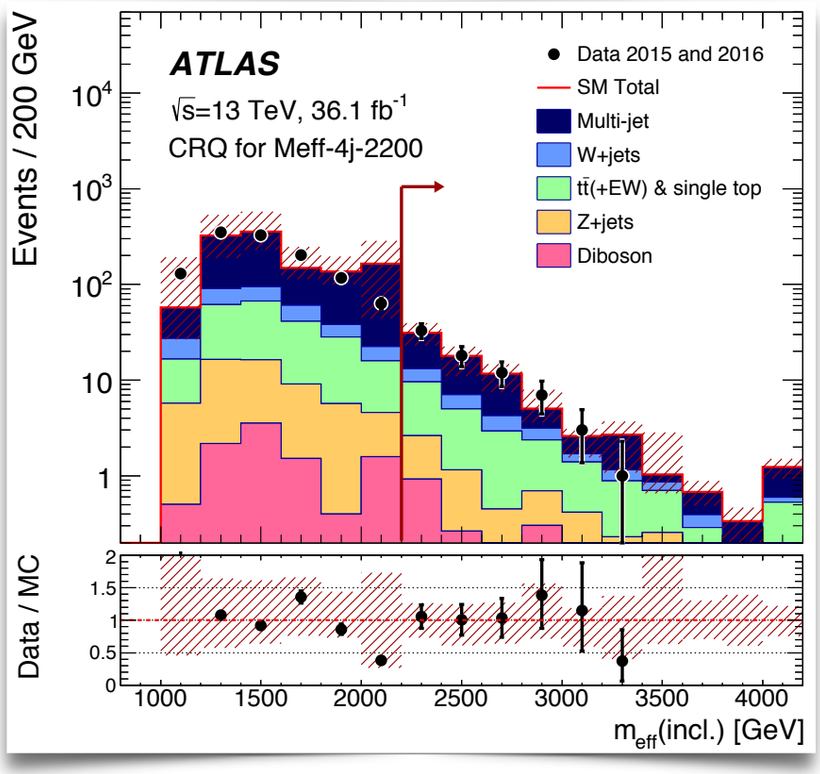
  → altered jet energy

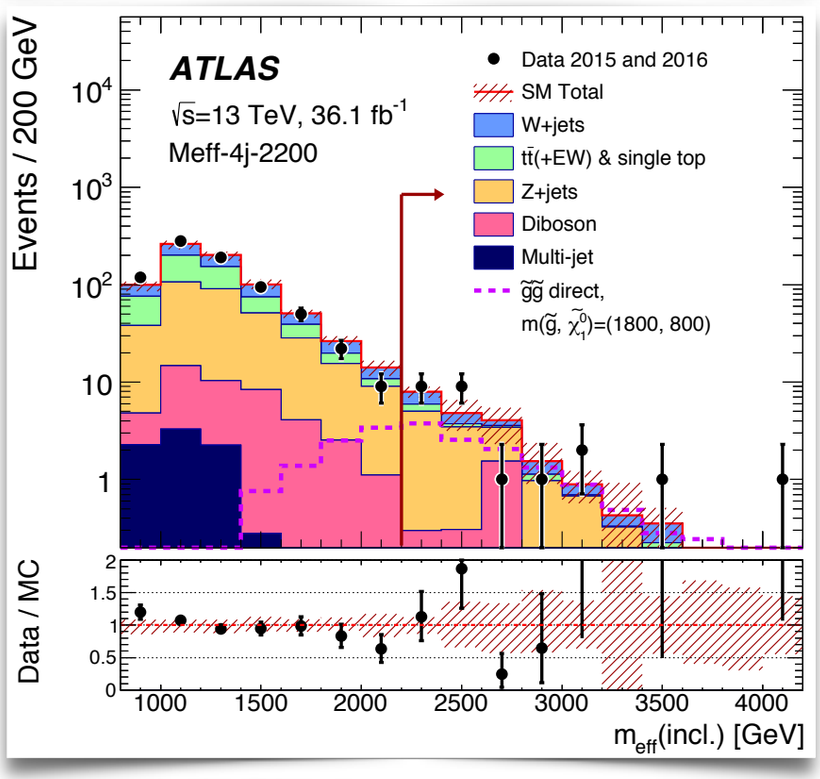


- single or multiple up/down fluctuations of the jets in the original seed ⇒
  - ΔΦ(MET, jet) can be large
  - alignment of jet and MET can be lost

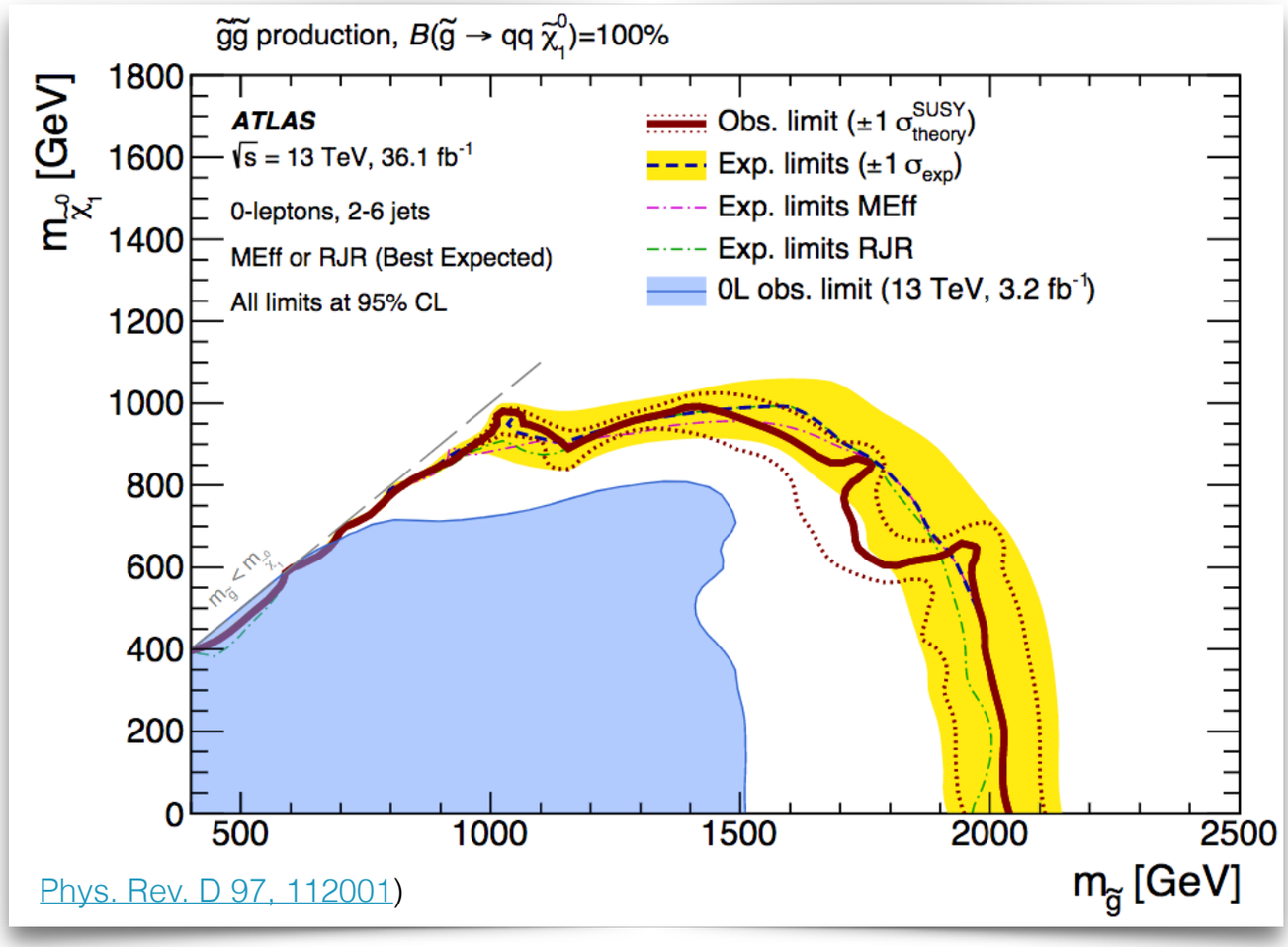
$$\underbrace{\begin{pmatrix} E_0 \\ \vec{p}_0 \end{pmatrix}, \begin{pmatrix} E_1 \\ \vec{p}_1 \end{pmatrix} \cdots \begin{pmatrix} E_m \\ \vec{p}_m \end{pmatrix}}_{\text{(seed event)}} \longrightarrow \underbrace{\left\{ \begin{matrix} \begin{pmatrix} a_0 \cdot E_0 \\ a_0 \cdot \vec{p}_0 \end{pmatrix}, & \begin{pmatrix} a_1 \cdot E_1 \\ a_1 \cdot \vec{p}_1 \end{pmatrix} & \cdots & \begin{pmatrix} a_m \cdot E_m \\ a_m \cdot \vec{p}_m \end{pmatrix} \\ \begin{pmatrix} b_0 \cdot E_0 \\ b_0 \cdot \vec{p}_0 \end{pmatrix}, & \begin{pmatrix} b_1 \cdot E_1 \\ b_1 \cdot \vec{p}_1 \end{pmatrix} & \cdots & \begin{pmatrix} b_m \cdot E_m \\ b_m \cdot \vec{p}_m \end{pmatrix} \\ \vdots & \vdots & & \vdots \\ \begin{pmatrix} n_0 \cdot E_0 \\ n_0 \cdot \vec{p}_0 \end{pmatrix}, & \begin{pmatrix} n_1 \cdot E_1 \\ n_1 \cdot \vec{p}_1 \end{pmatrix} & \cdots & \begin{pmatrix} n_m \cdot E_m \\ n_m \cdot \vec{p}_m \end{pmatrix} \end{matrix} \right.}_{\text{(pseudo events)}}$$

MULTIJET ESTIMATION AND RESULTS





- estimation of QCD background works well → good agreement between data and BG (within the given uncertainties) in CRQ
- only limited contribution of multi jet in SR → effectively suppressed by cuts on ΔΦ(MET, jet) and high M_{eff}-cut
- exclusion limit on gluino mass around 2 TeV on RPC limit of Gqq



- needed to be **modified** to **increase sensitivity** in **LL scenarios**

RPC 0-LEPTON IN LL SCENARIOS

- jet cleaning cuts relying on track information were modified since displaced jets might miss associated tracks → high inefficiency in LL scenarios

- jet calibration with standard reconstruction software assuming objects are projective
- signal jets in both long-lived scenarios originate from displaced vertices DV

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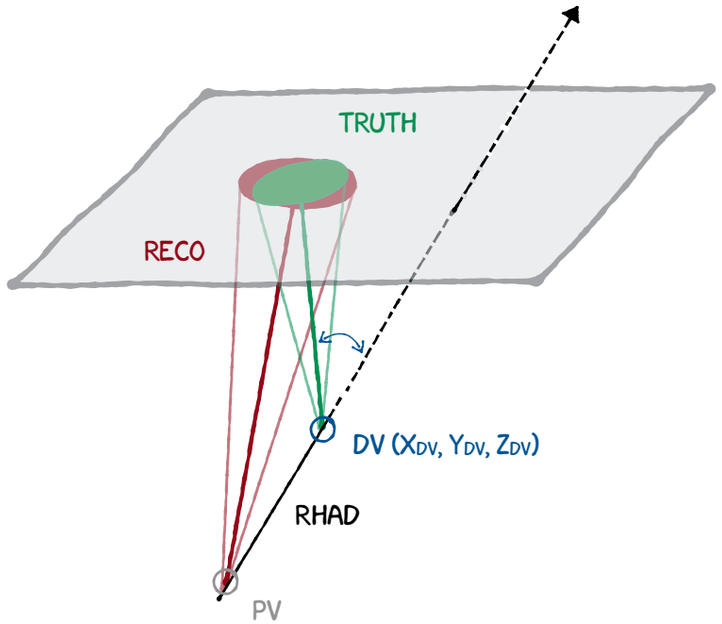

DEDICATED UNCERTAINTIES ON JET ENERGY SCALE AND JET ENERGY RESOLUTION

- studied p_T response as function of radial decay position R_{DEC} of the associated LL particle

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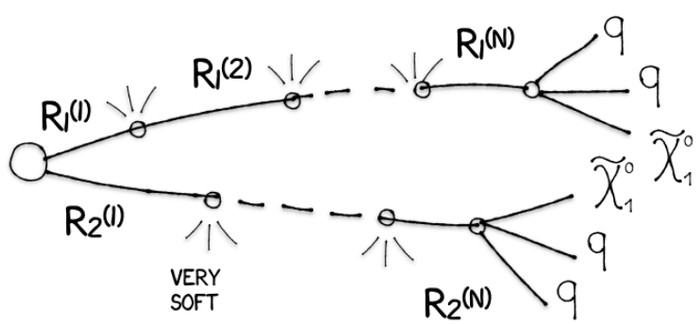
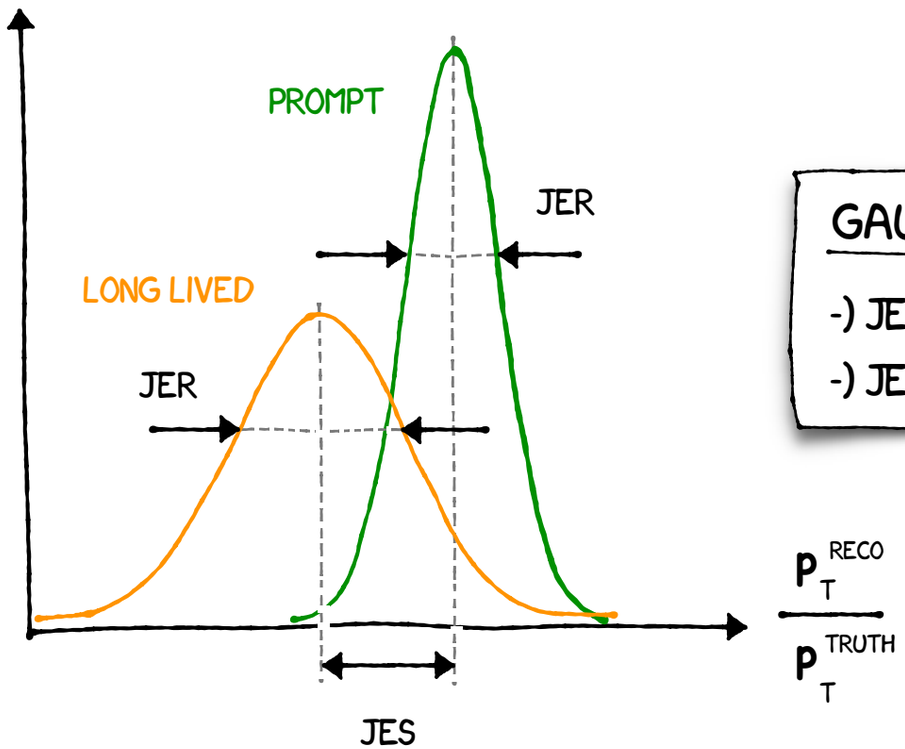


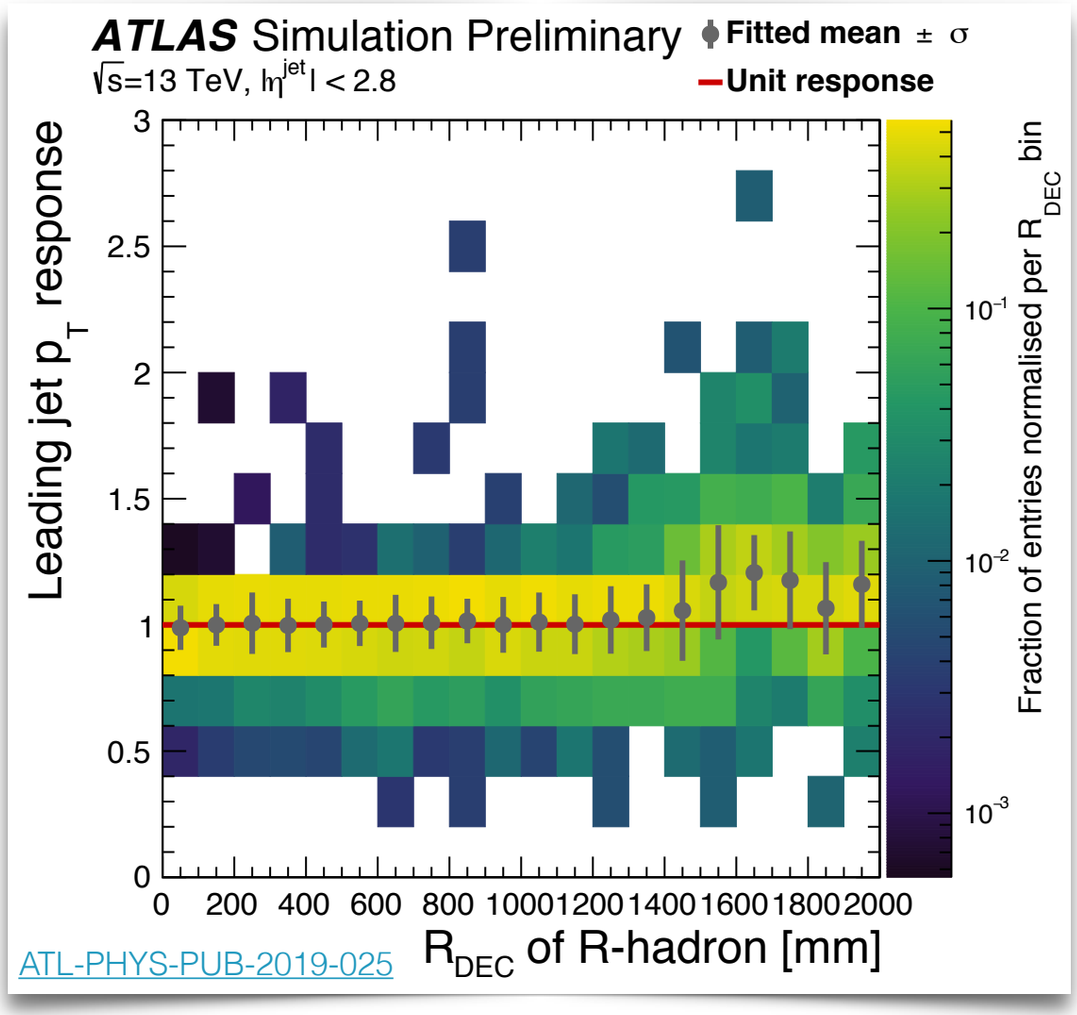


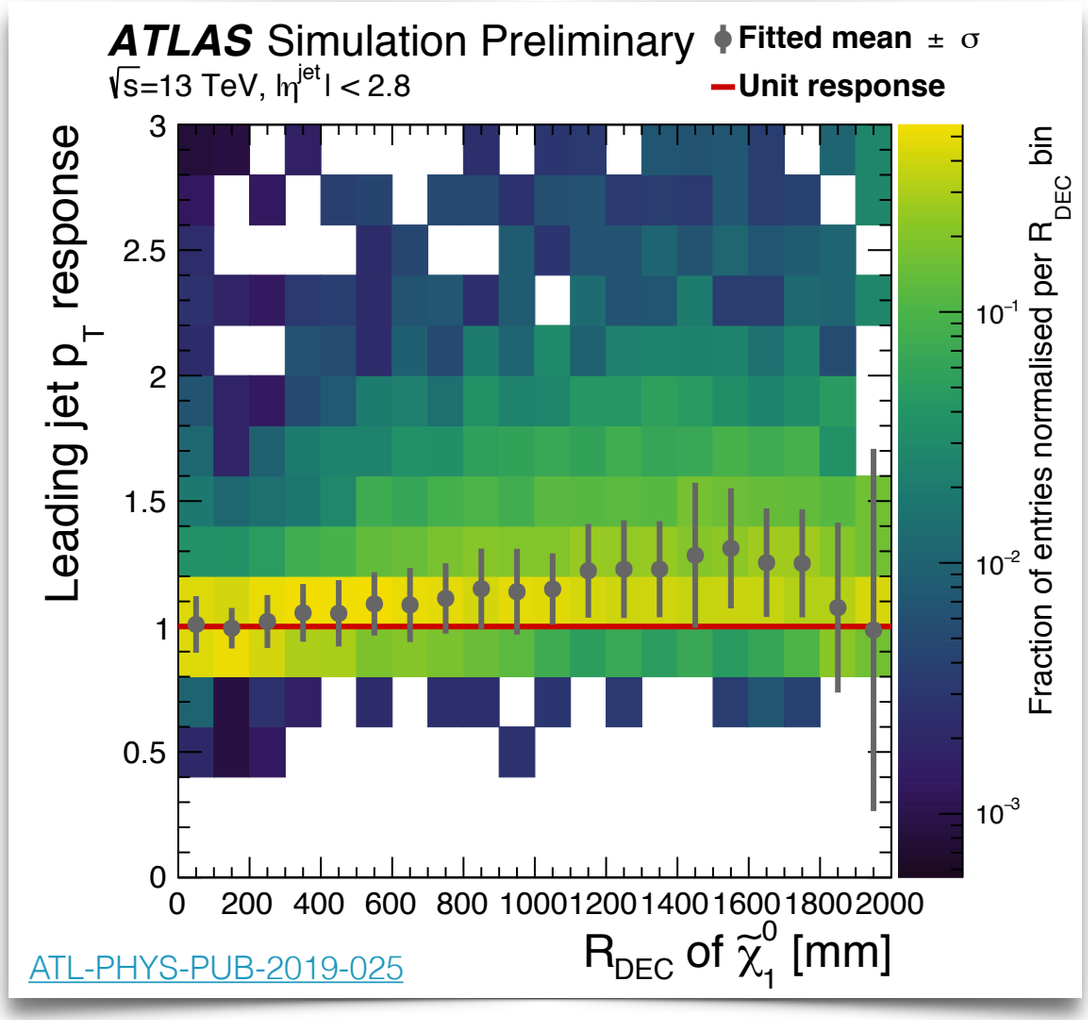
GAUSS-FIT

-) JES = DEVIATION OF MEAN

-) JER = DEVIATION OF WIDTH

TRANSVERSE MOMENTUM RESPONSE

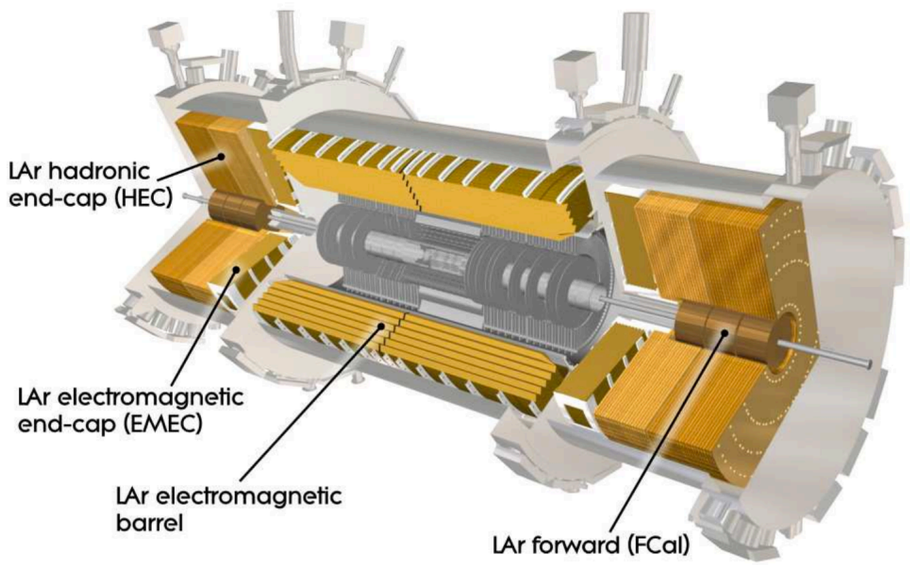




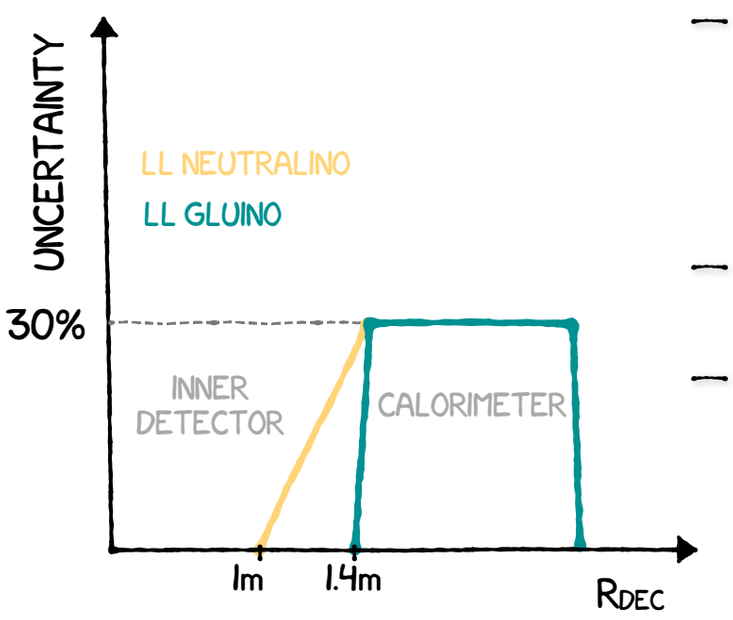
- R-hadrons: fitted mean of response is extremely stable until the decays start to occur outside inner detector ($R_{DEC} \approx 1.4$m)
- LL neutralinos: shift with respect to 1 already in inner detector ($R_{DEC} \approx 1.0$m)
- lower jet activity in R-hadron model ⇒ reduction non-Gaussian tails from near-by jets via isolation
- in addition need to check reconstruction efficiency

JET RECONSTRUCTION EFFICIENCY

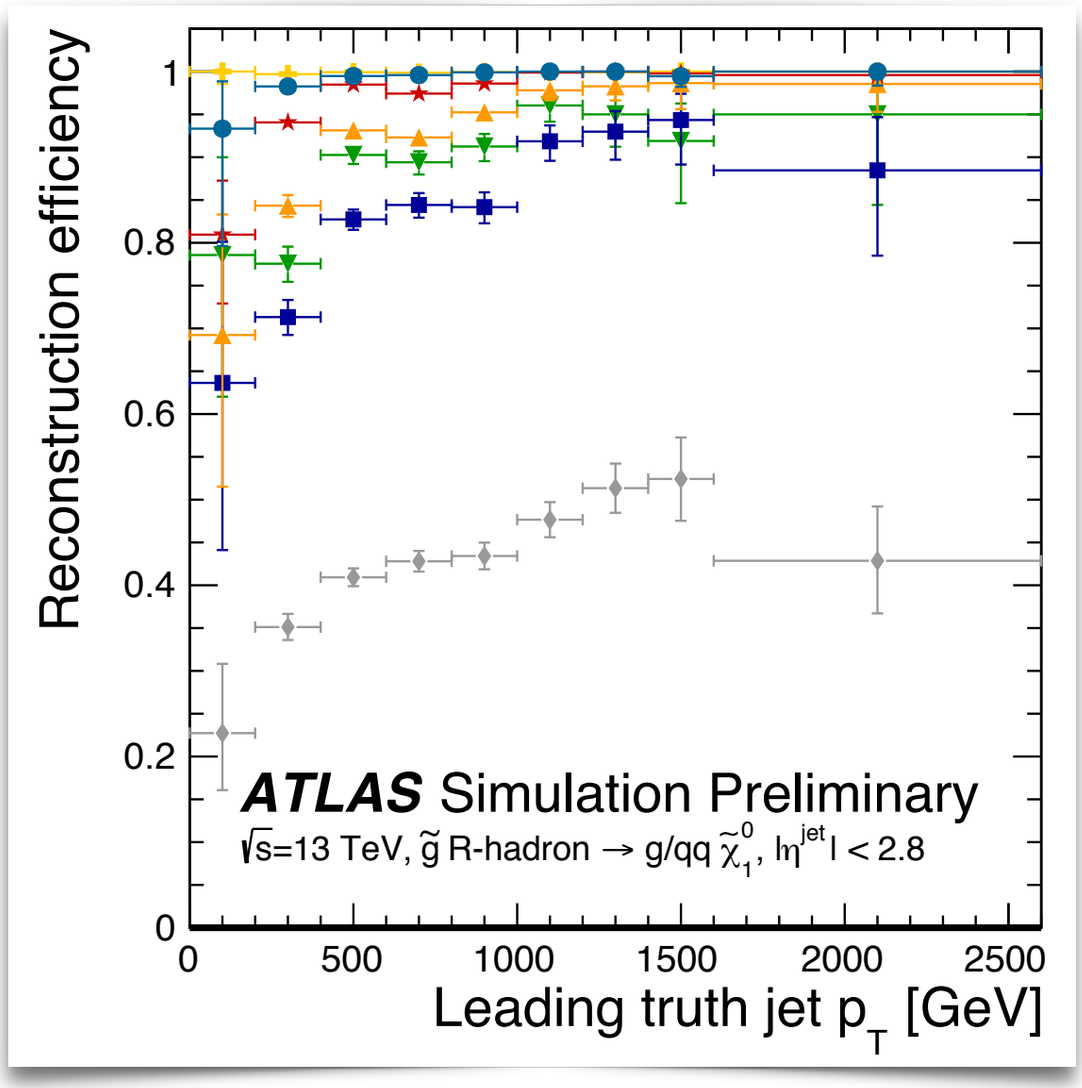
- study the jet reconstruction efficiency as function of truth jet p_T in bins of R_{DEC}



- additional systematic uncertainties driven by R_{DEC}:

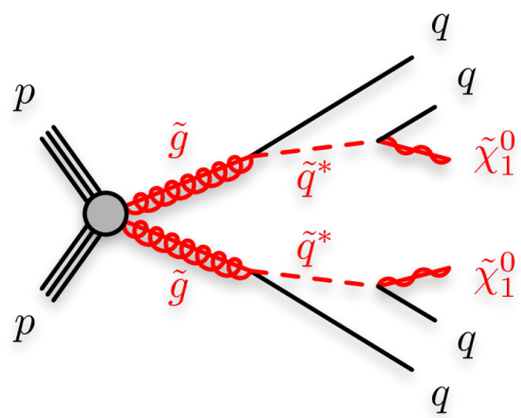


- from 0% to 30% between R_{DEC} threshold and calorimeter
- flat 30% inside calorimeter
- no additional uncertainty after calorimeter → jets produced there are not reconstructed

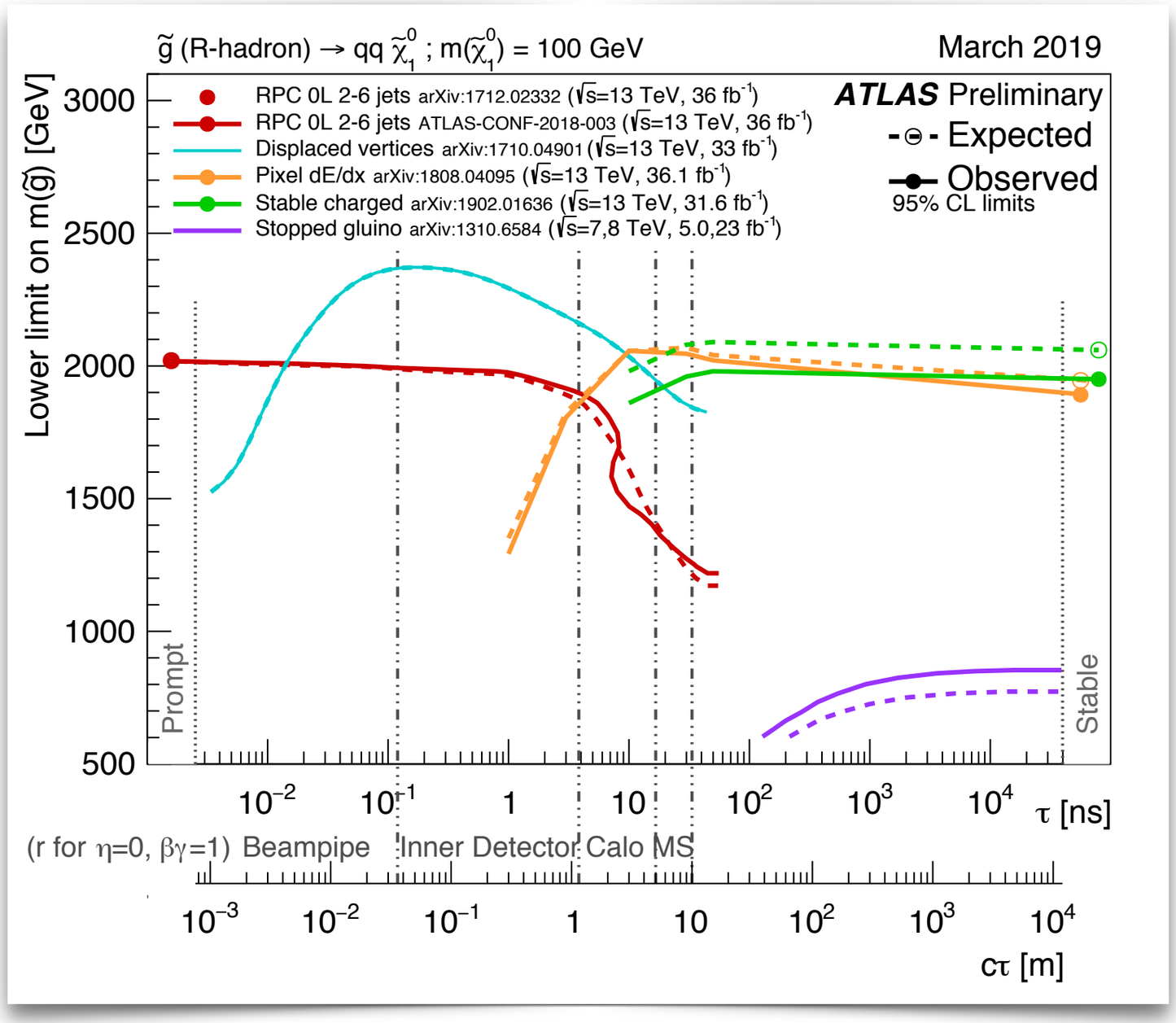


RESULTS R-HADRON MODEL

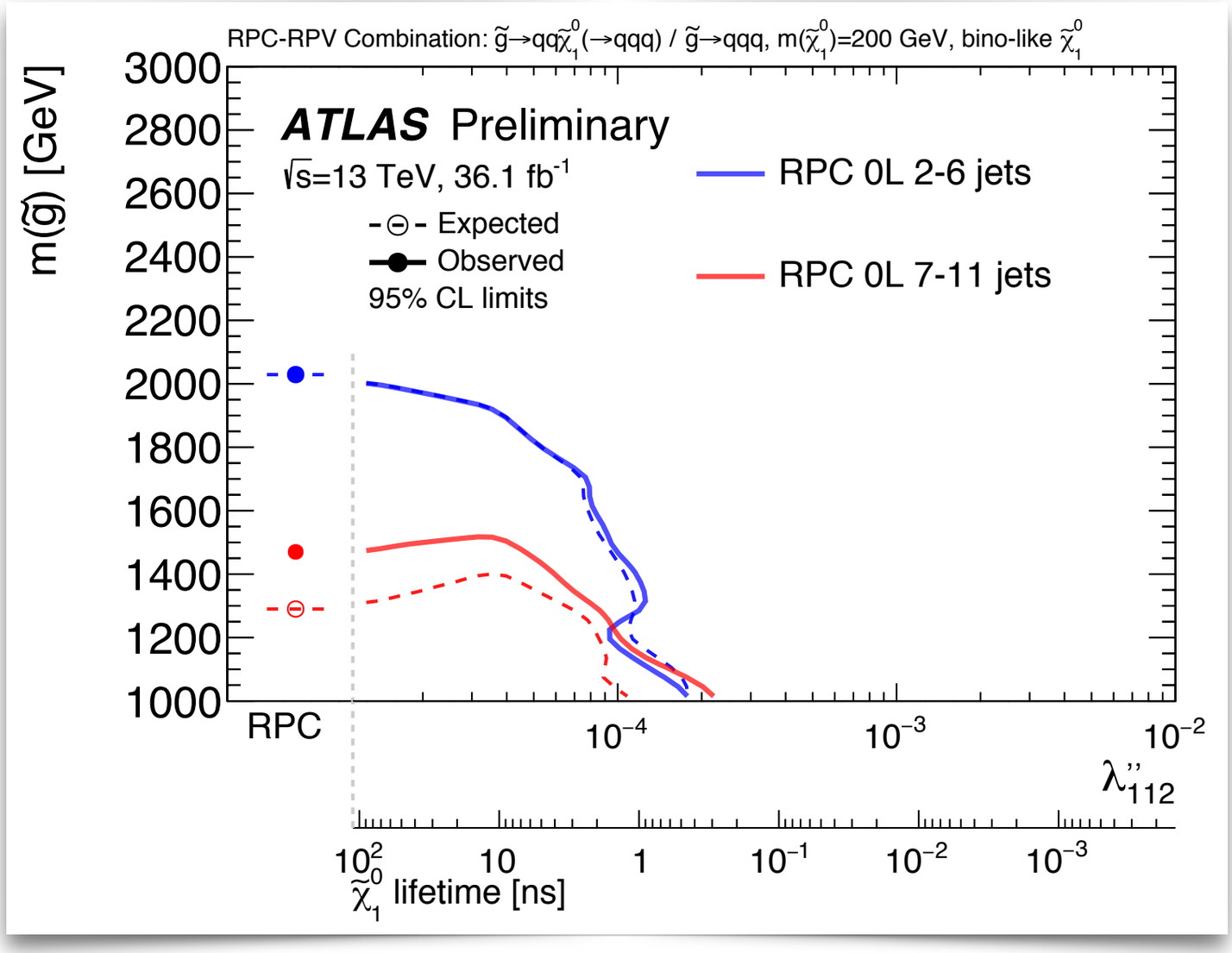
- summary plot including ATLAS results of several LL particle searches
- observed and expected limits on gluino mass as function of the lifetime



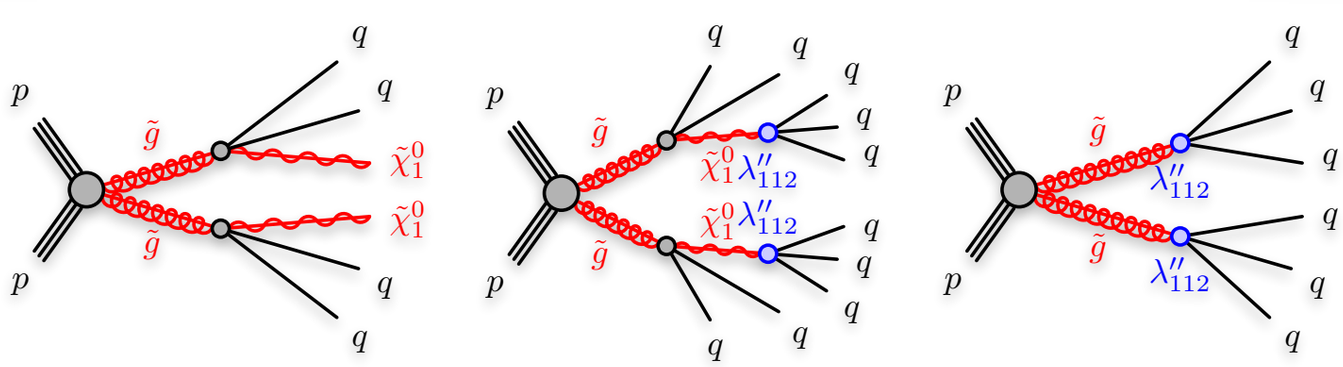
- **RPC 0L 2-6 jet** re-interpretation:
  - places strongest limits for lowest lifetime
  - provides strong limits until R-hadron decays in calorimeter
- **DV + MET** (latest paper):
  - best exclusion power for moderate lifetimes
- **Pixel dE/dx** (early Run 2 analysis) and **Stable charged** (recent paper):
  - reconstructed R-hadron track



RESULTS Gqq MODEL



- observed and expected limits on gluino mass as a function of neutralino lifetime and equivalent λ''_{112} coupling strength
- **RPC 0L 2-6 jet** strongest limits on this model
  - with increased RPV coupling MET is reduced → sensitivity decreases
- **RPC 0L 7-11 jet** sets weaker limits
  - moderate jet multiplicity for large neutralino lifetimes reduces efficiency

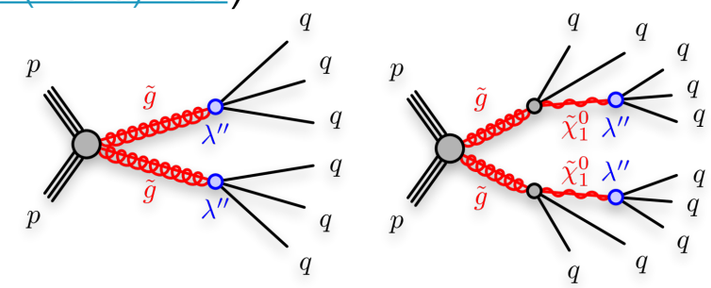


- intermediate and large values of λ''_{112} not covered →

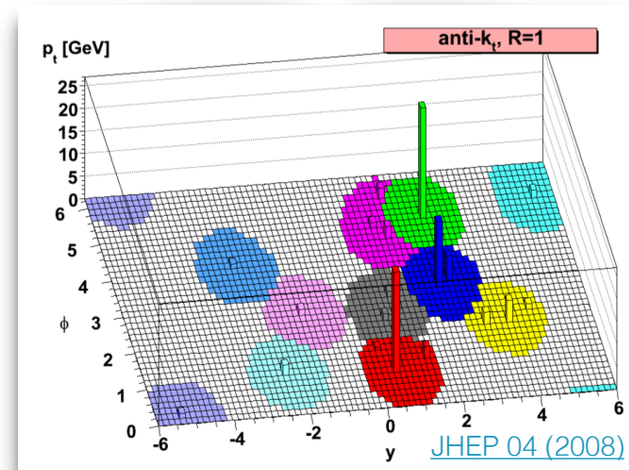
  RPV 0-lepton analysis (not shown) is expected to be sensitive

RPV 0-LEPTON ANALYSIS

- ATLAS search for pair produced gluinos in RPV limit of Gqq (Phys. Lett. B 785 (2018) 136)
- major background processes:
  - signal has high jet multiplicity ⇒ QCD multijet dominant ⇒ data-driven method
  - other SM backgrounds found to be negligible from MC studies



- use signal jets (EMtopo **Anti-k_t** jets) with 2 different radii:
  - **R=0.4** (small-R jets) ⇒ used for b-tag based event classification
  - **R=1.0** (large-R jets) ⇒ used to build main observables:



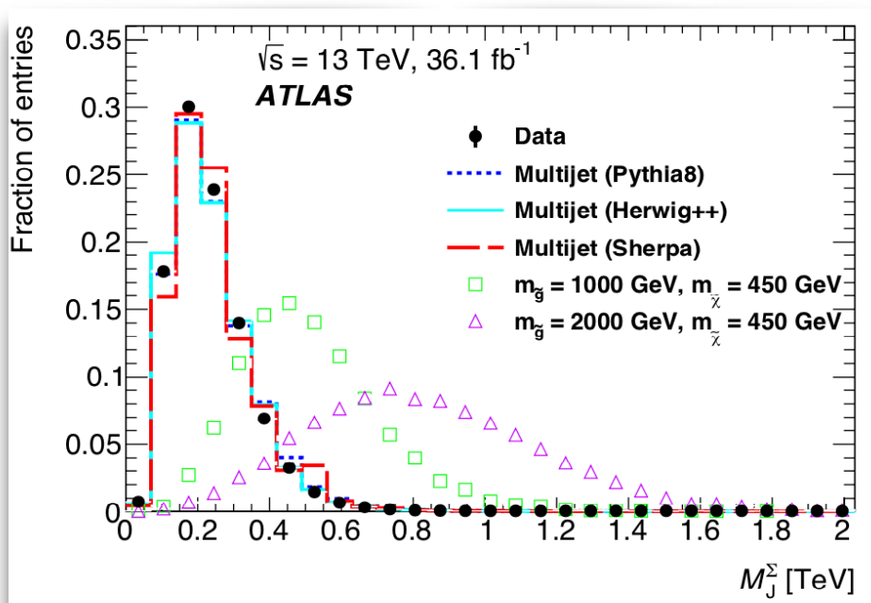
JHEP 04 (2008)

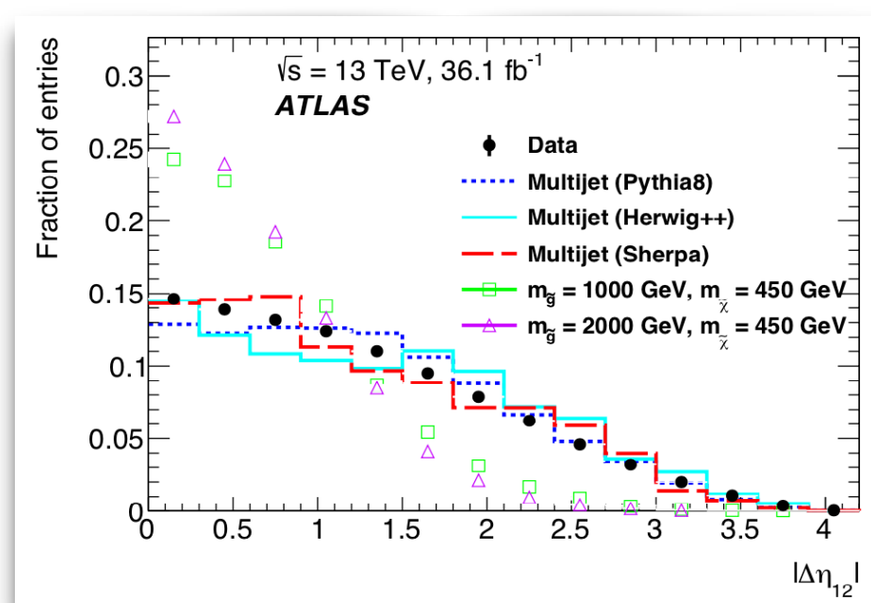
$$M_J^{\Sigma} = \sum_{i=1}^{4} m_{JET}^{(i)} \quad \text{AND} \quad |\Delta\eta_{12}|$$

sum of jet mass (sensitive to high mass gluinos)

=>

CONSTRUCT SR





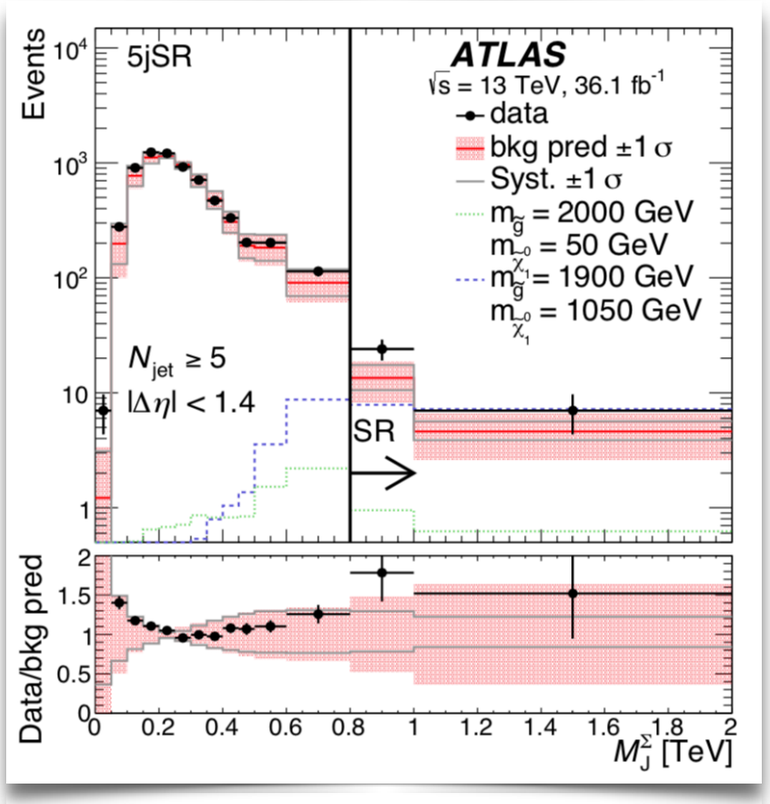
jets in signal are more central than in SM multijet

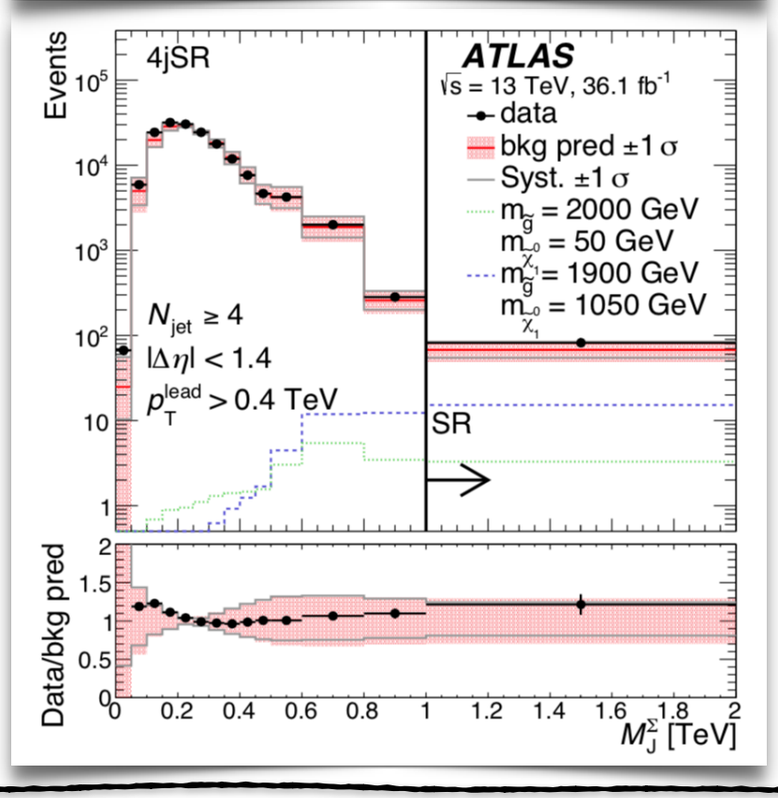
=>

CONSTRUCT CR

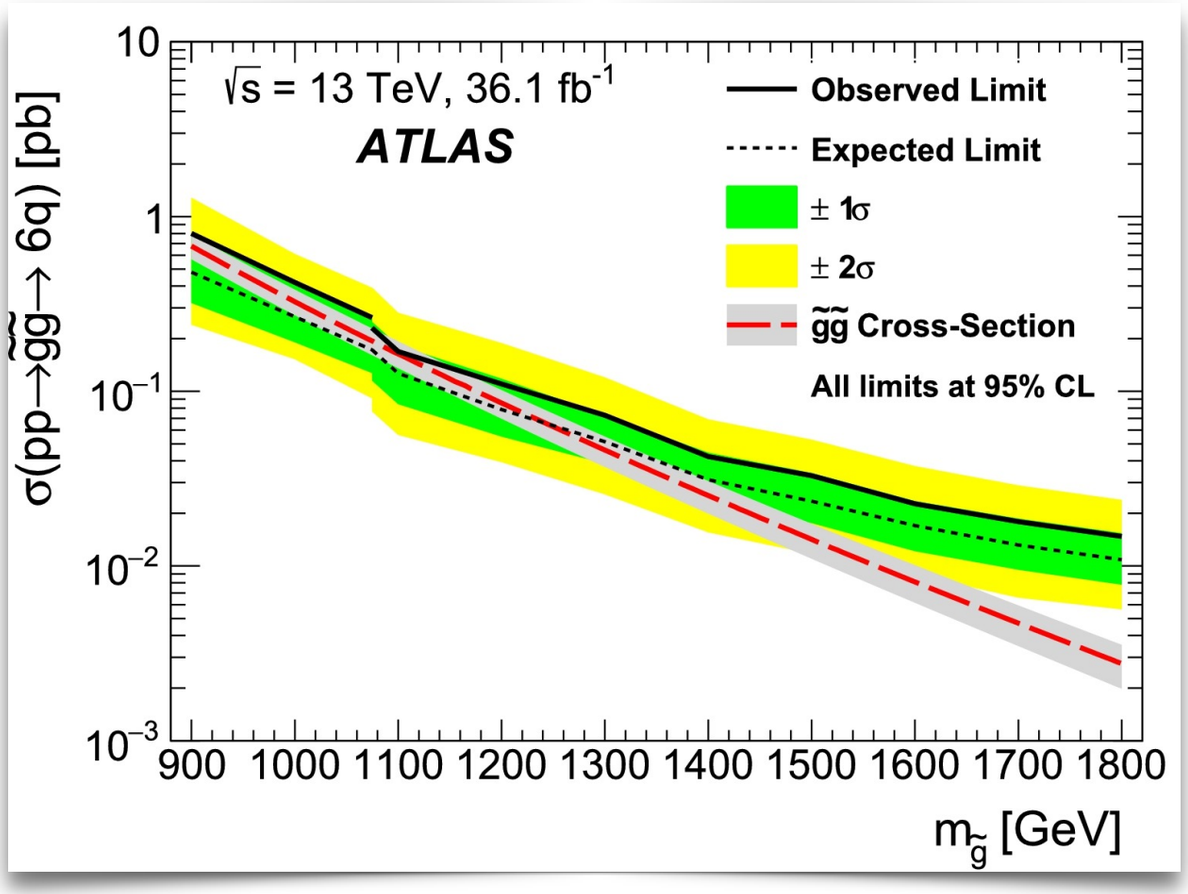
MASS TEMPLATE METHOD

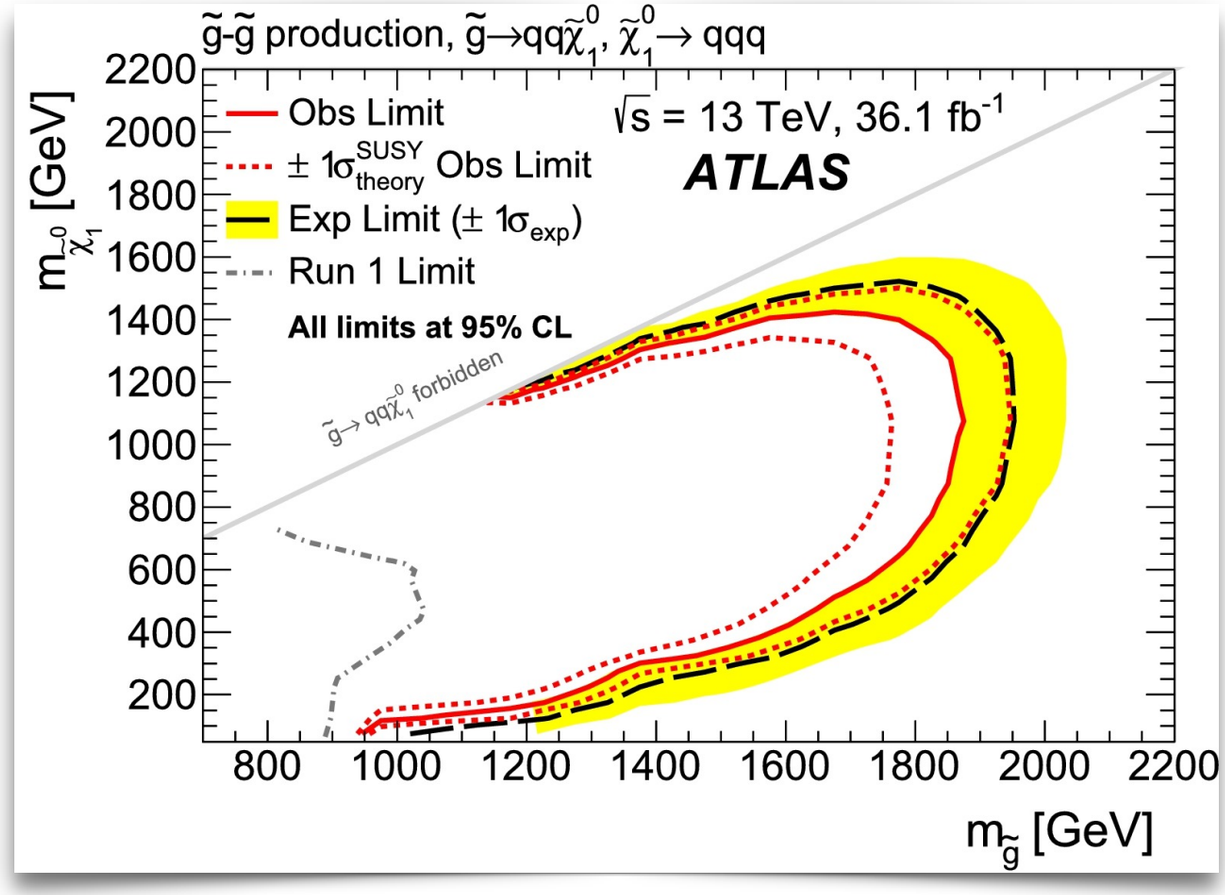
- M_J^{Σ} → employ fully data-driven jet mass template method
  - single-jet mass templates extracted from CRs binned in $|\eta|$ and p_T
  - probability density function for jet in given bin to have certain mass
- from template generate random mass for each jet and construct M_J^{Σ} distribution
  - templates generated from control sample of QCD events ⇒ shape of M_J^{Σ} matches multijet background
- jet mass template method applied to data
  - in VR → good agreement of observed and predicted M_J^{Σ} distributions
  - in SR => **NO SIGNIFICANT EXCESS**
- define threshold of M_J^{Σ} to maximise sensitivity for statistical interpretation





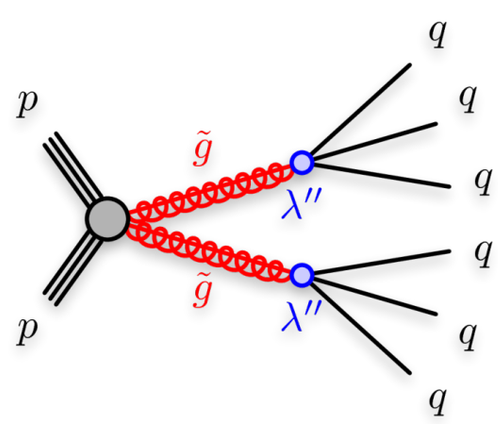
EXCLUSION LIMITS



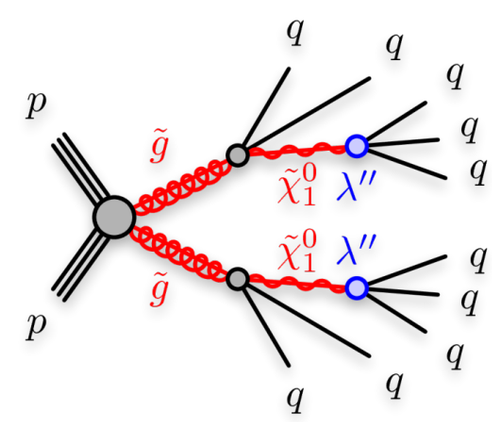


- no specific range of gluino mass is excluded for due to upward fluctuation in SR ⇒

  set 95% CL upper limit on the production cross section



- 95% CL limits given in gluino-neutralino mass-plane exclude gluino masses between 1 and 1.9 TeV



SUMMARY

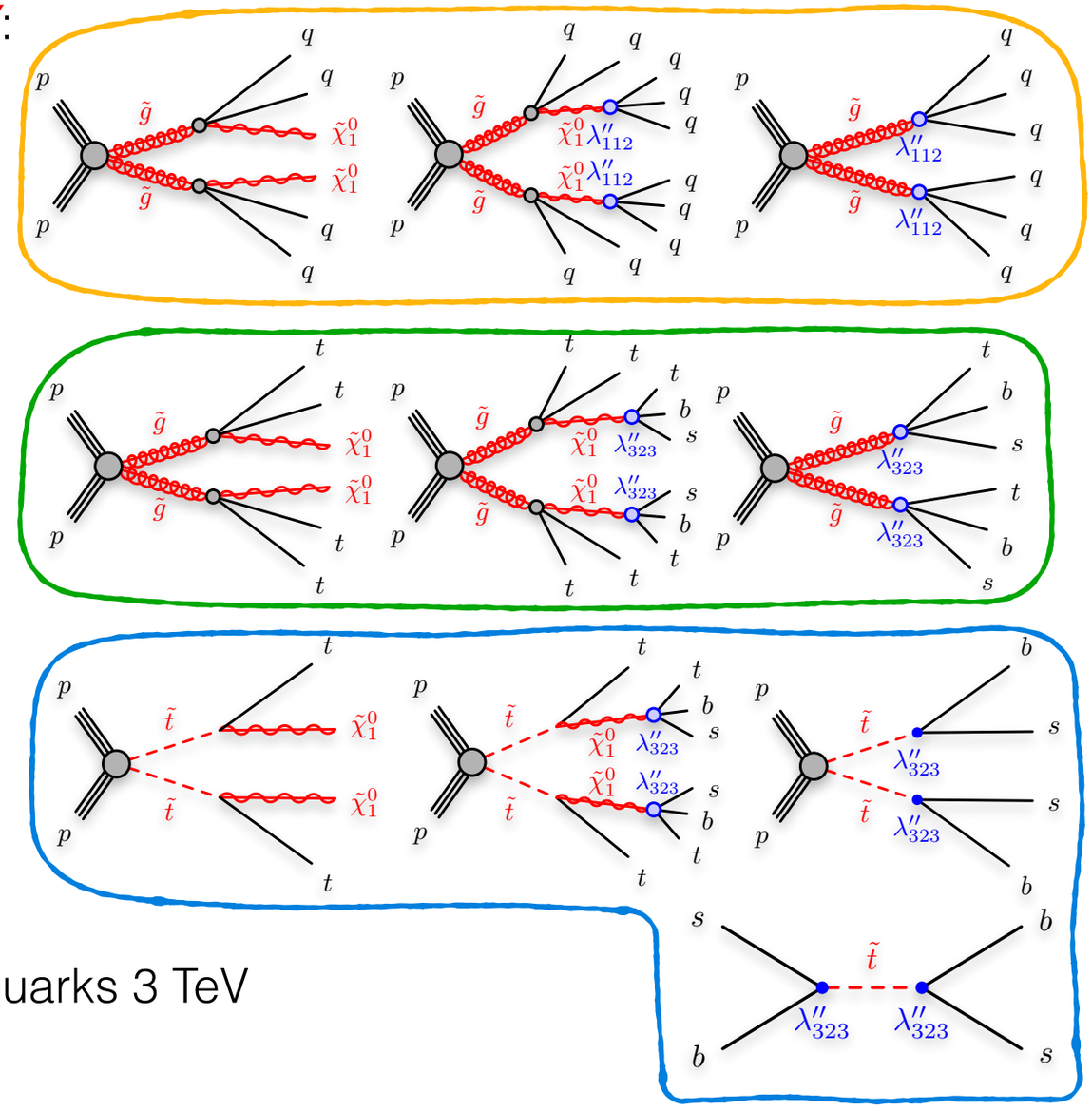
- presented a brief glimpse on the many faces of QCD in various ATLAS SUSY searches manifested as:
  - smeared jets to estimate the comparably minor but nevertheless tricky multijet background in fully RPC searches
  - kinematic scale uncertainties of displaced jets in reinterpretation of analyses in non-Standard SUSY scenarios
  - exploitation of event jet mass and rapidity balance to estimate dominant QCD background in pure RPV searches
- the ATLAS SUSY group continues to explore the supersymmetric phase-space in particular of non-vanilla SUSY models to further push the frontier
- many exciting new results based on the full Run2 data set are in preparation

THANKS FOR YOUR ATTENTION
AND
STAY TUNED!

BACK UP

LONG-LIVED NEUTRALINO MODELS

- scenarios inspired by minimal flavour violation (MFV) SUSY:
  - no L-violating couplings
    λ=0 and λ'=0
  - only one non-zero B-violating coupling
    $\lambda''_{ijk} \neq 0$
- LSP is assumed to be the lightest neutralino:
  - purely Bino-like
  - fixed mass of 200 GeV
  - lifetime depends on choice of squark masses and value of coupling strength



Gqq-Model: $\lambda''_{112} \neq 0$, masses of 1st and 2nd generation squarks 3 TeV
→ multi jet final state

Gtt-Model: $\lambda''_{323} \neq 0$ (favoured by MFV models) masses of 3rd generation squarks 2.4 TeV
→ final states including b-jets and leptons

Stop-Model: $\lambda''_{323} \neq 0$ light mostly right-handed stop → final states including b-jets and leptons

NEUTRALINO LIFETIMES

- correspondence between lifetime or BR and coupling strength is determined by the choice of the squark masses ⇒ mean decay length of bino-like neutralino LSP can be numerically estimated:

$$L(cm) = \frac{0.9\beta\gamma}{\lambda''^2}\left(\frac{m_{\tilde{q}}}{100GeV}\right)^4\left(\frac{1GeV}{m_{\tilde{\chi}_1^0}}\right)^5$$

- theoretical upper limits on λ'' can be obtained from:
  - RGE of superpotential parameters
  - requirement of couplings being perturbative up to GUT scale ⇒ $\lambda'' < \sqrt{4\pi}$

$$\Longrightarrow \quad \lambda''_{112} \leq 1.25, \quad \lambda''_{323} \leq 1.07$$

- experimental limits from low-energy measurements
  e.g. Phys. Rev. Lett. 112, 131803 (Di-nucleon decay analysis)

$$\lambda''_{112} \leq 5 \times 10^{-7}\left(\frac{m_{\tilde{q}_R}}{1\,TeV}\right)^2\sqrt{\frac{m_{\tilde{g}}}{1\,TeV}}$$

exclusion of lifetimes below 100 ns for 200 GeV neutralinos for gluino masses up to 5 TeV

- this does not effect RPV couplings for different choices of flavour indices ⇒

- limits for the Gqq model could be reinterpreted in any other combination of i, j, k as long as $i \neq 3$ since no b-tagging is used in the analyses contributing

SIGNAL PRODUCTION DETAILS

- production of long lived gluino samples:
  - gluino production and hadronization into R-hadrons is simulated with PYTHIA 6
  - specialised GEANT4 routines simulate the propagation of the R-hadrons through the detector
  - PYTHIA routines decay the R-hadron into quarks and LSP
- production of long-lived neutralino samples:
  - full detector simulation GEANT4
  - overlaid with pile-up simulated with PYTHIA 8 (using A2 set of tuneable parameters)
  - LO generated with MadGraph5 interfaced with PYTHIA 8 (up to 2 partons in matrix element and A14 tune)
  - production cross-sections at NLO in strong couplings + soft-gluon emission at NLL (squark contributions are not considered for gluino production)
  - cross-sections for stop resonant production at NLO in strong couplings
  - computation of lifetime and branching ratios is performed with SARAH and SPheno

Model name	Gqq	Gtt	Stop	*R*-hadron
Coupling	λ''_{112}	λ''_{323}	λ''_{323}	–
Decay	$\tilde{g} \to qq\tilde{\chi}_1^0$ $\tilde{g} \to qq\tilde{\chi}_1^0(\to qqq)$ $\tilde{g} \to qqq$	$\tilde{g} \to tt\tilde{\chi}_1^0$ $\tilde{g} \to tt\tilde{\chi}_1^0(\to tbs)$ $\tilde{g} \to tbs$	$\tilde{t}_1 \to t\tilde{\chi}_1^0$ $\tilde{t}_1 \to t\tilde{\chi}_1^0(\to tbs)$ $\tilde{t}_1 \to bs$	$\tilde{g} \to qq\tilde{\chi}_1^0$
Other colored sparticle masses	$m(\tilde{q}) = 3$ TeV $m(\tilde{t}, \tilde{b}) = 5$ TeV	$m(\tilde{q}) = 5$ TeV $m(\tilde{t}, \tilde{b}) = 2.4$ TeV	$m(\tilde{q}, \tilde{g}) = 3$ TeV $m(\tilde{t}_2, \tilde{b}) = 3$ TeV	$m(\tilde{q}, \tilde{t}, \tilde{b}) \approx$ PeV
LSP	The LSP is bino-like, $m(\tilde{\chi}_1^0) = 200$ GeV			$m(\tilde{\chi}_1^0) = 100$ GeV

light flavoured squarks are assumed to be mass-degenerate

$(\tilde{q} = \tilde{u}, \tilde{d}, \tilde{s}, \tilde{c})$

as well as left- and right-handed squarks

$(\tilde{q} = \tilde{q}_1, \tilde{q}_2)$

except for stop-model where the right-handed stop is light

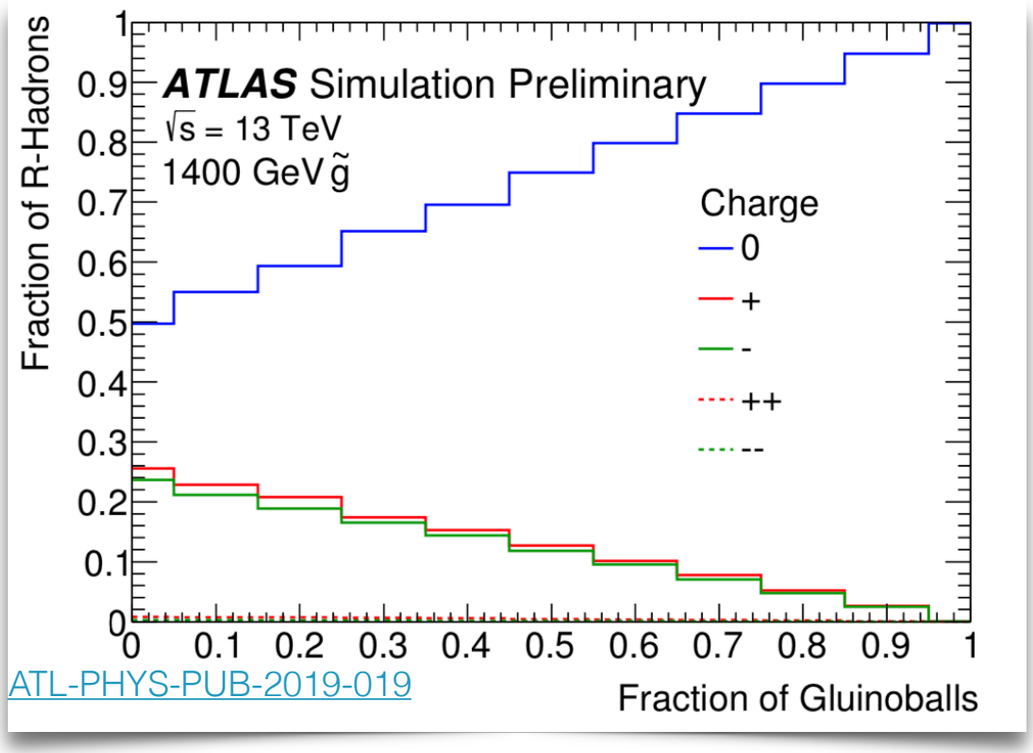
R-HADRON MASS SPECTRUM

- moving from Pythia6 with customised hadronisation routines to Pythia8 → most important parameters:
  - R-hadron mass-spectrum
  - gluinoball fraction (gluino gluon boundstates
- R-hadron masses are described in many theoretical models, e.g. MIT bag, lattice QCD, …
- Pythia6 used 3 different pheno models to derive the mass spectrum
- Pythia8 includes simple sum over constituent masses with offset of 200MeV to represent the gluon cloud surrounding the gluino
  - m_i constituent mass of parton i
  - F_i coulor SU(3) matrices
  - S_i spin SU(2) matrices
  - k is obtained from fitting SM baryon mass spectra → for mesons 0.043 GeV^3 for baryons 0.026 GeV^3

$$m_{\text{hadron}} = \sum_i m_i - k \underbrace{\sum_{i \neq j} \frac{(\mathbf{F}_i \cdot \mathbf{F}_j)(\mathbf{S}_i \cdot \mathbf{S}_j)}{m_i m_j}}_{\text{SPLITTING TERM}}$$

- mass calculation for R-mesons only lightest states (J=1) -> spin and charge play only minor role in hadronisation
- mass calculation for R-baryon → neglect add splitting term only for lightest states

R-HADRON SIMULATION



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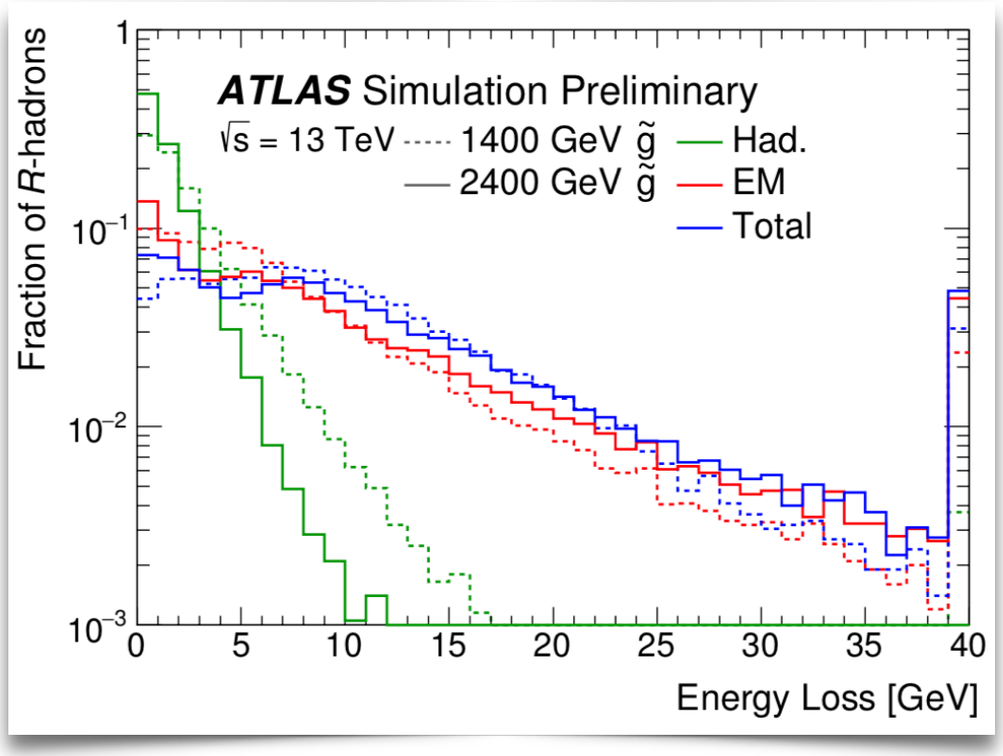
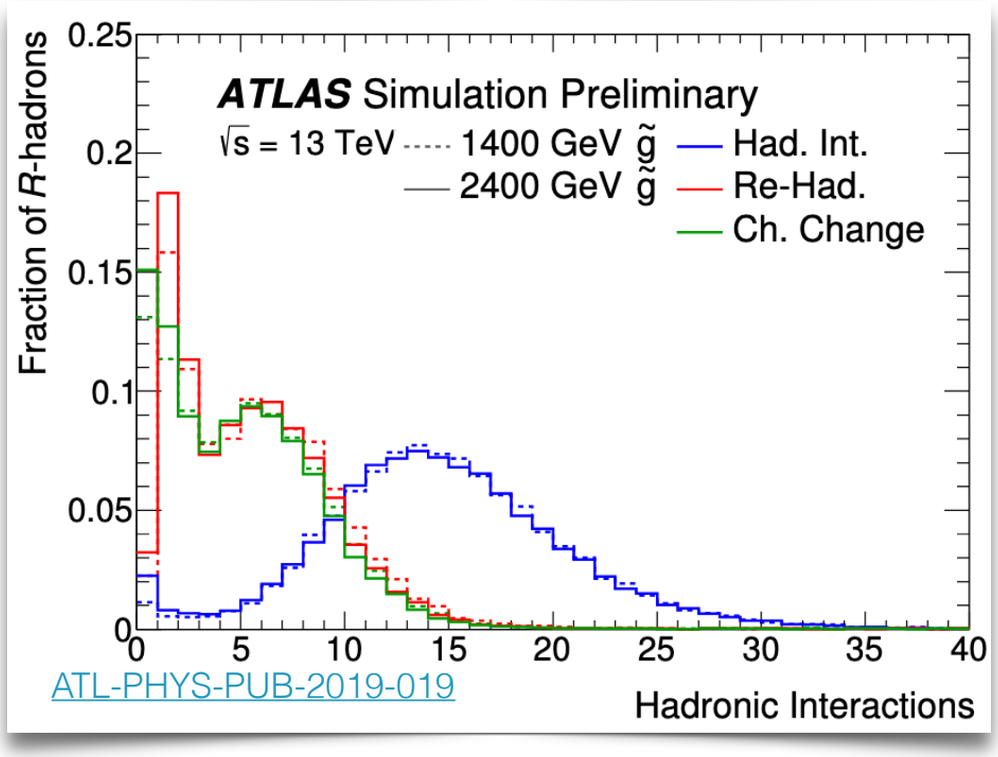
- in production: the more gluinoballs the more neutral R-hadrons
- specialised `GEANT4` routines simulate the propagation of the R-hadrons through the detector
- assume large lifetimes → little energy loss due to hadronic interactions but
  - change of electric charge ("Ch. Change")
  - change of light-quark system ("Re-Had.")





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ANALYSES OVERVIEW

- exemplary characteristics of most sensitive SR for all contributing analyses:
  - simplified MET significance $E_T^{miss}/\sqrt{H_T}$ with H_T is the scalar sum of the jet p_T
  - effective mass $M_{eff} = E_T^{miss} + H_T$
  - mass asymmetry between dijet pairs $\mathcal{A}$
  - rapidity seperation $|y^*|$

Analysis name	Leptons	Jets / b-tags	E_T^{miss} requirement	Representative cuts	Model targeted
RPC 0-lepton, 2-6 jets	0	≥ 4 / –	$E_T^{miss}/m_{eff} > 0.2$	$m_{eff} > 3000$ GeV	Gqq, R-hadron
RPC 0-lepton, 7-11 jets	0	≥ 7 / – ≥ 11 / ≥ 2	$E_T^{miss}/\sqrt{H_T} > 5$ GeV$^{1/2}$	–	Gqq Gtt
RPC multi-b	0 1	≥ 7 / ≥ 3 ≥ 5 / ≥ 3	$E_T^{miss} > 350$ GeV $E_T^{miss} > 500$ GeV	$m_{eff} > 2600$ GeV $m_{eff} > 2200$ GeV	Gtt
RPV 1-lepton	1	≥ 10 / ≥ 4	–	–	Gtt, stop
RPC Stop 0-lepton	0	≥ 4 / ≥ 2	$E_T^{miss} > 400$ GeV	$m_{jet,R=1.2} > 120$ GeV	stop
RPC Stop 1-lepton	1	≥ 4 / ≥ 1	$E_T^{miss} > 250$ GeV	$m_T > 160$ GeV	stop
RPC and RPV same-sign and three leptons	2 SS or 3	≥ 6 / ≥ 2 ≥ 6 / ≥ 2	$E_T^{miss}/m_{eff} > 0.15$ –	$m_{eff} > 1800$ GeV $m_{eff} > 2000$ GeV	Gtt, stop
RPV stop dijet pairs	–	≥ 4 / ≥ 2	–	$\mathcal{A} < 0.05$	stop
Dijet and TLA	–	≥ 2 / –	–	$\lvert y^* \rvert < 0.6$	stop

b-TAGGING UNCERTAINTIES

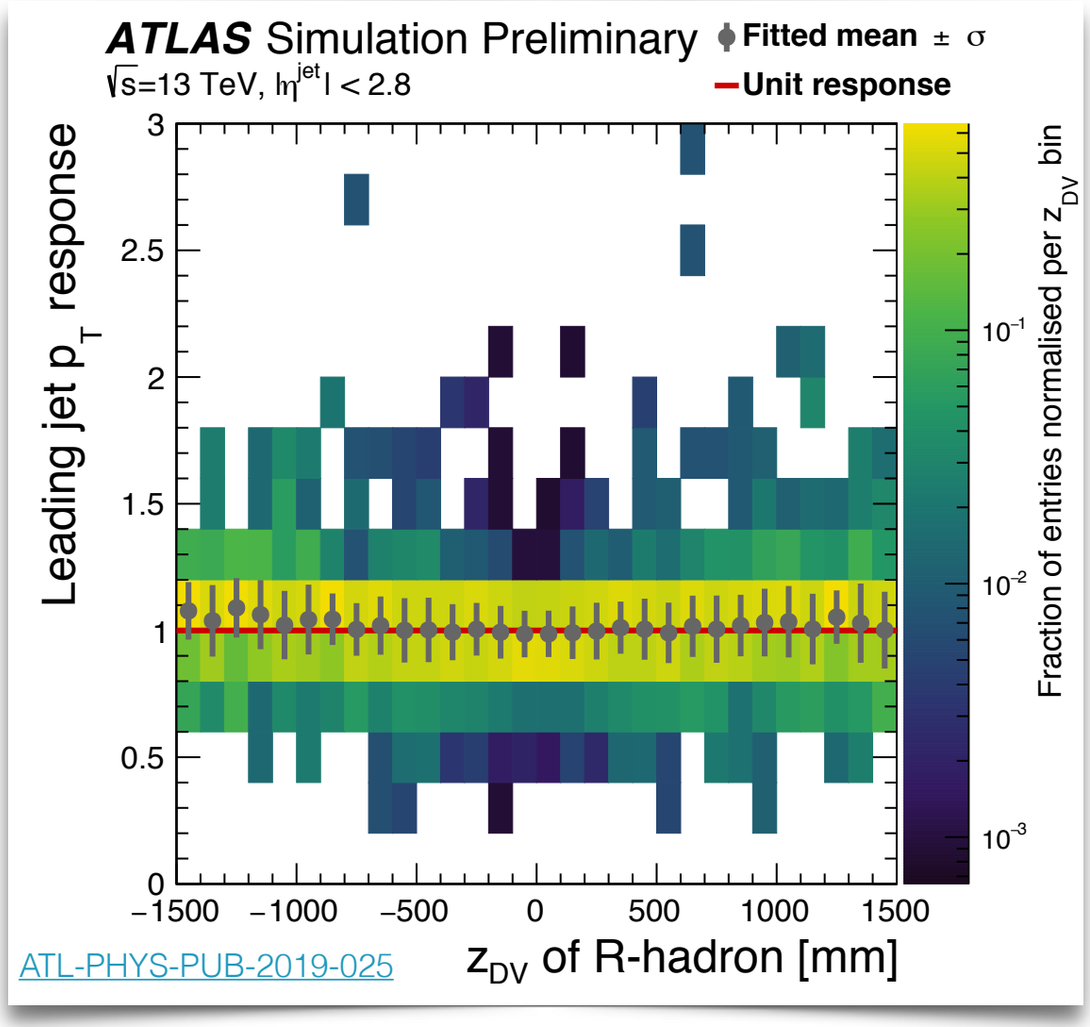
- b-tagging efficiency is affected by additional decay length due to non-zero life-time:
  - for jets originating after the innermost pixel layer it degrades rapidly
  - for decay lengths of order of millimetres → efficiency improves
    (e.g. $\tau_{LSP} \approx 0.01$ns (ttbar) 85%(75%) for b-jets and 20%(<1%) for light-jets)

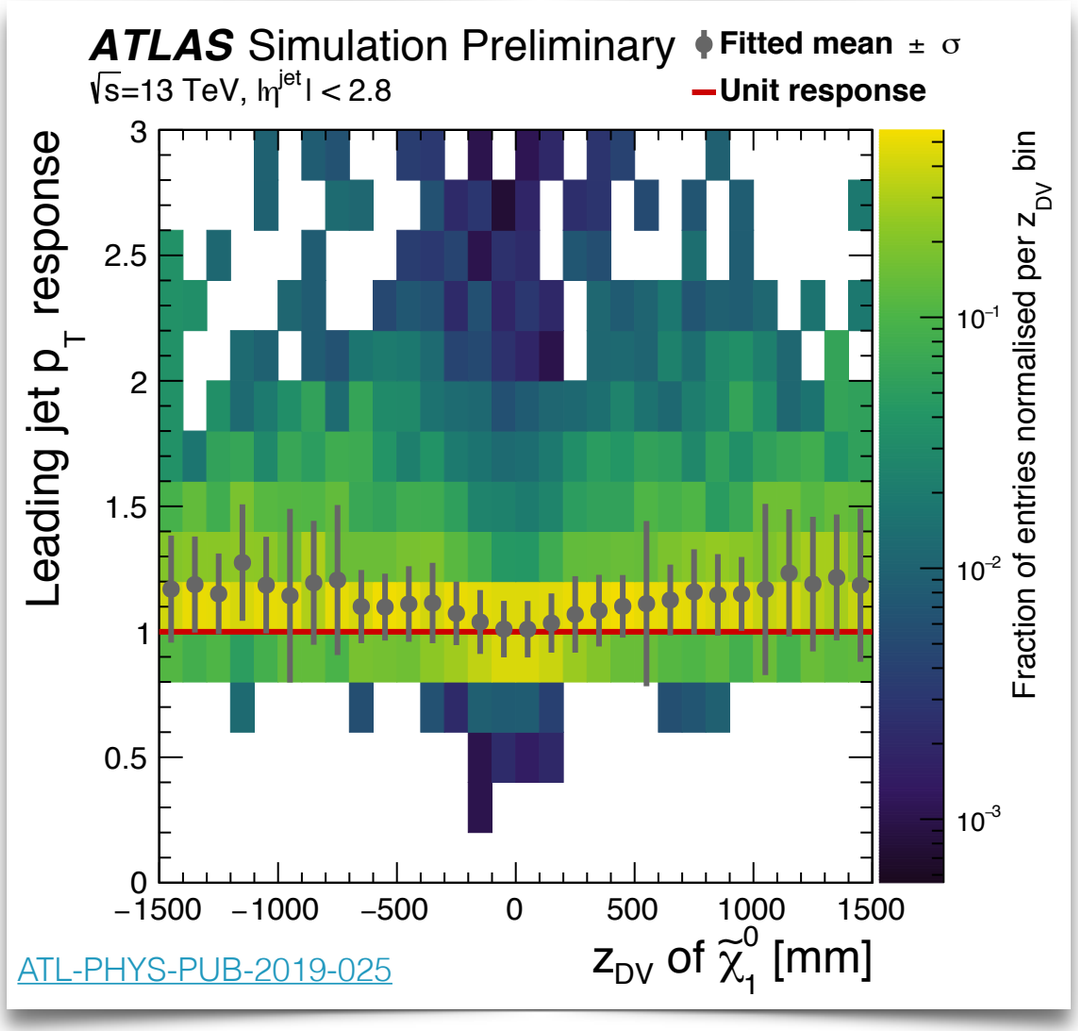
  ⟹ UNCERTAINTY TO COVER MIS-TAGGED LIGHT JETS

- using a a bottom-up approach following ATL-COM-PHYS-2017-192 (light flouver b-tagging calibration)
  - adjusted underlying tracking observables in MC samples to match data and propagated effect to b-tagging observables:
    - impact-parameter resolution
    - track reconstruction efficiency
    - fake-rate
  - b-tagging is re-evaluated on adjusted MC ⇒ modified b-tagging efficiency
  - uncertainties on tracking modelling are propagated to efficiency
  - difference between nominal and adjusted efficiency is taken as additional uncertainty

extra uncertainties growing with LSP lifetime e.g. 10% when selecting 2 b-jets, 20% for 4 b-jets for τ_{LSP} = 1ns

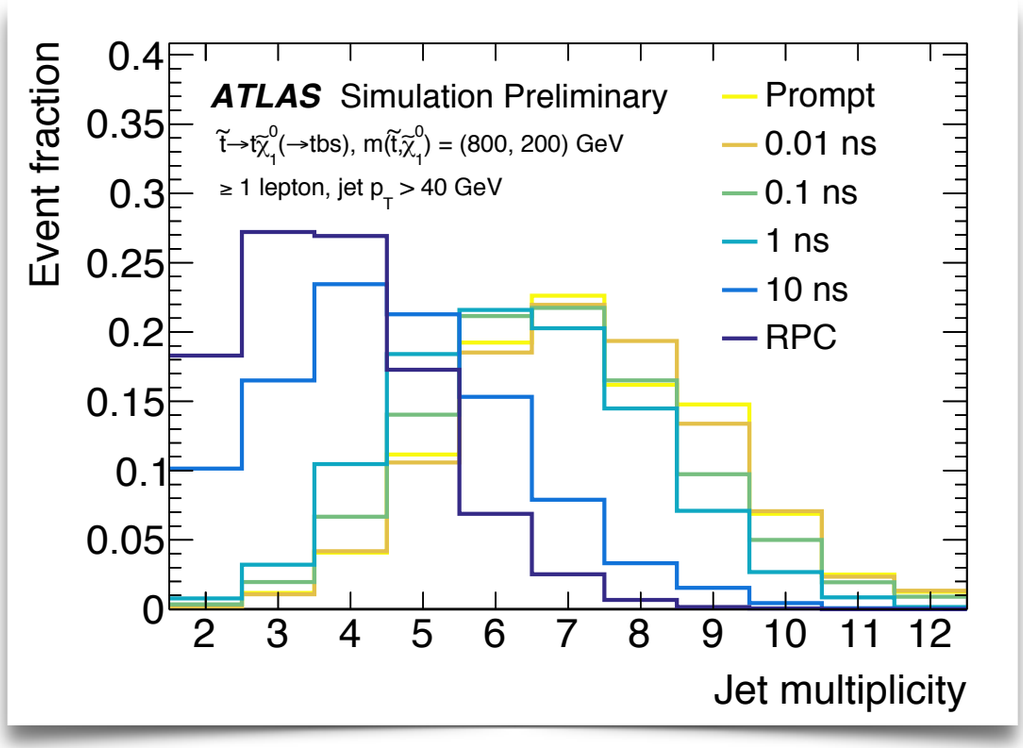
TRANSVERSE MOMENTUM RESPONSE

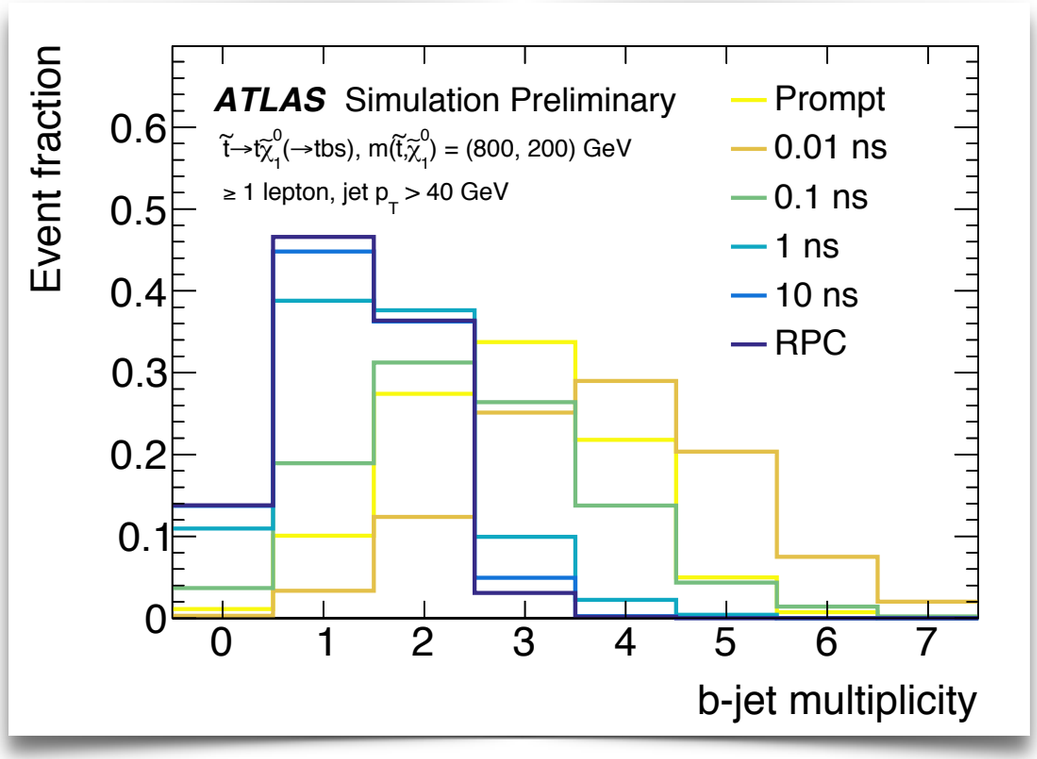


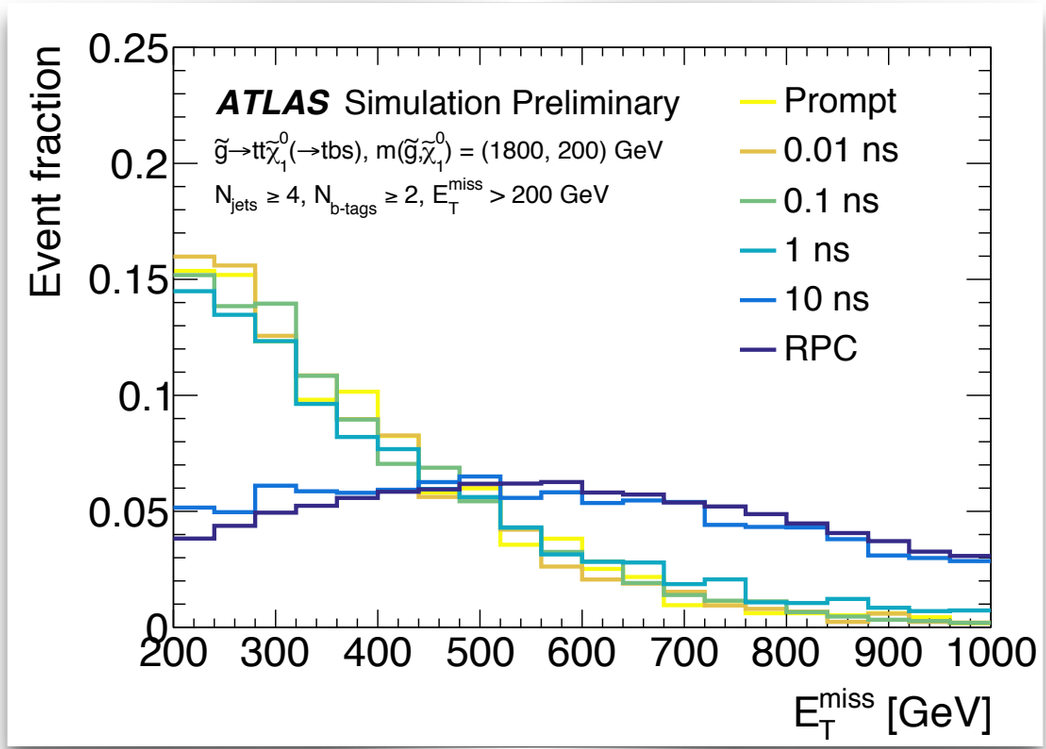


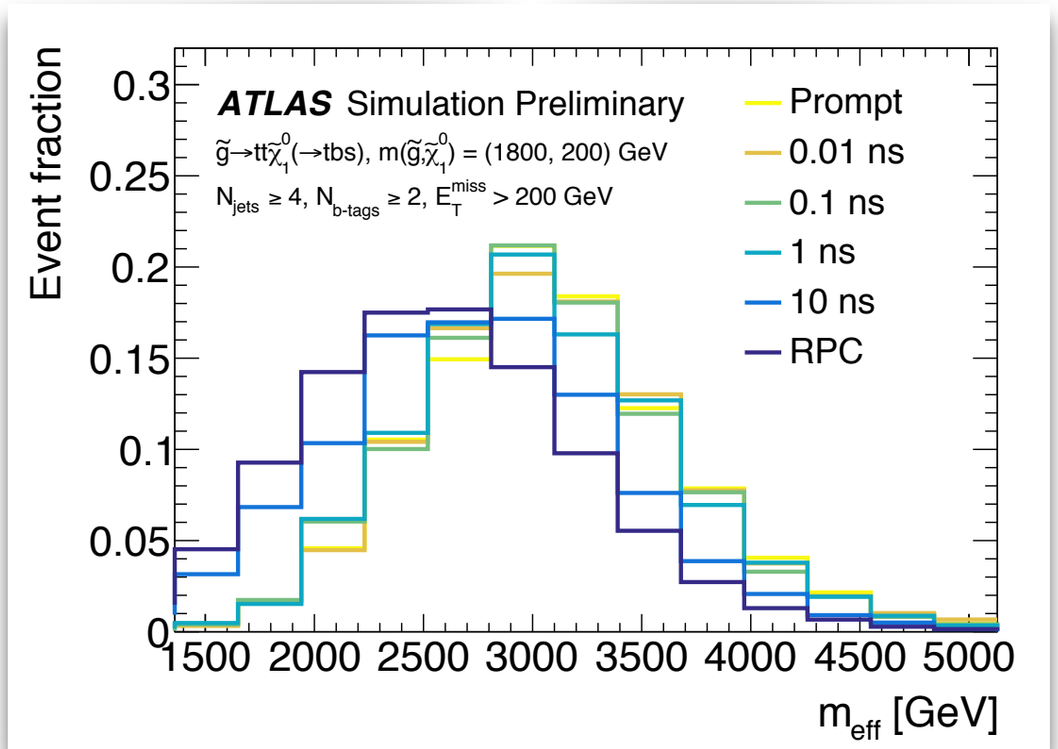
- for **LL neutralinos** there is an upwards shift of the mean due to non-Gaussian tails of response distribution caused disturbing near-by jets effects from higher jet multiplicity
- deviation for longitudinal displacements with $|z_{DV}| < 1.5$m is negligible for **LL gluinos**
- to estimate the additional experimental uncertainties → need to check the reconstruction efficiency

EFFECT OF LIFETIME ON BASIC VARIABLES



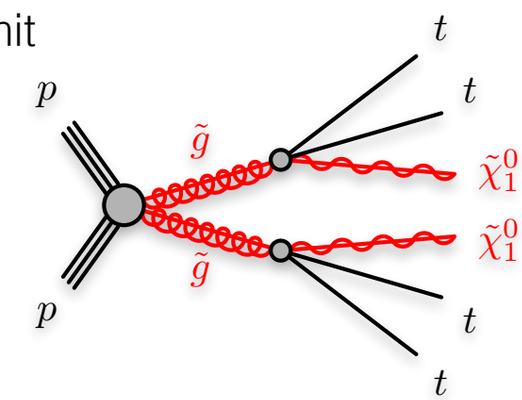




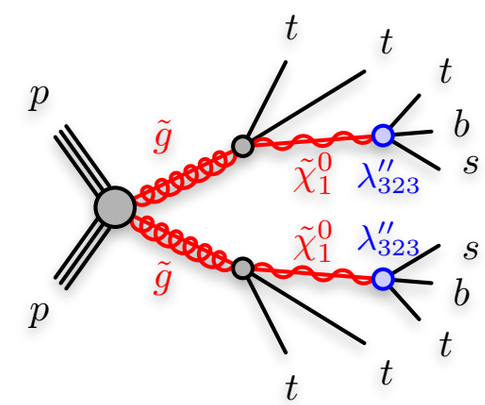


ANALYSES SENSITIVE TO Gtt

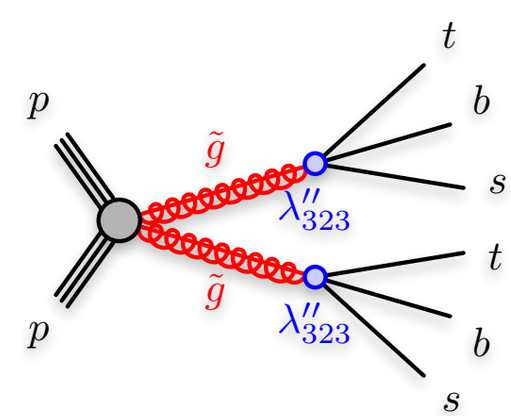
- RPC multi-b
  - targets gluinos decaying to top and neutralino → equivalent to the Gtt model in RPC limit
  - requires final states with zero or one lepton, high jet and b-jet multiplicity, moderate MET and large m_{eff}
  - gluino masses up to 2 TeV are excluded for a 200 GeV neutralino mass



- RPV 1-lepton
  - searches for gluinos and stops in RPV models with at least one lepton final states, very high jet multiplicity and either no or many b-jets
  - limits are set on gluino mass for two models similar to Gtt model in RPV limit (prompt LSP decay, 100% BR gluino ⟶ tt neutralino or gluino ⟶ tbs)
  - limits are set on stop mass around 1 TeV for models equivalent to RPV top-model (prompt LSP decay, 100% BR stop ⟶ t neutralino ⟶ tbs)

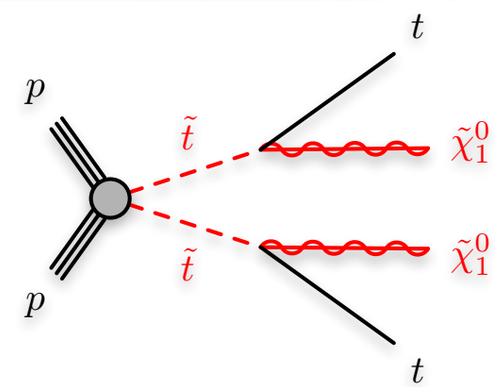


- RPC and RPV same-sign and 3-leptons (SS/3L)
  - covers a large variety of RPC and RPV models including:
    - three distinct regimes of Gtt model
    - final states compatible with top model in RPV limit
  - requirement of two same-sign or three leptons efficiently suppresses SM BG
    ⇒ SRs are designed with and without MET covering RPC and RPV scenarios

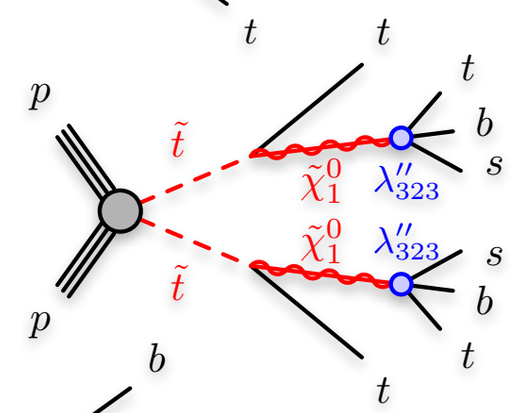


ANALYSES SENSITIVE TO stop-MODEL

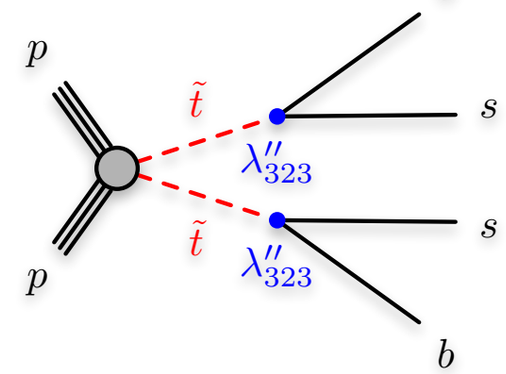
- RPC stop 0-lepton and 1-lepton
  - both search for stop pair production in ttbar + MET final states with tops decaying all hadronically/semi-leptonically
  - exclusion limits on the stop mass around 1 TeV for a model equivalent to RPC limit of stop model

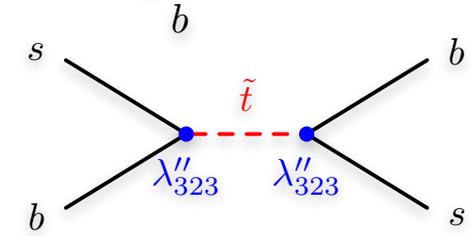


- RPV stop dijet pairs
  - targeting stop pair production decaying to b and s similar to the top model with very high RPV coupling
  - requires two jet pairs with large mass and low mass asymmetry
  - limit on stop mass up to 610 GeV for BR(stop ⟶ bs)=100%



- offline dijet and trigger-level-analysis (TLA)
  - considering single stop resonant production pp ⟶ stop$_1$ ⟶ bs ⇒
  - di-jet final state ⇒ both search for localised excess in dijet mass spectrum
    - no signal samples → limits on generic gaussian resonances are reinterpreted
    - width-to-mass ratio is found to be 5 - 7% over entire range of stop masses
  - experimental limits on a generic gaussian resonance with width 7% are used for the reinterpretation

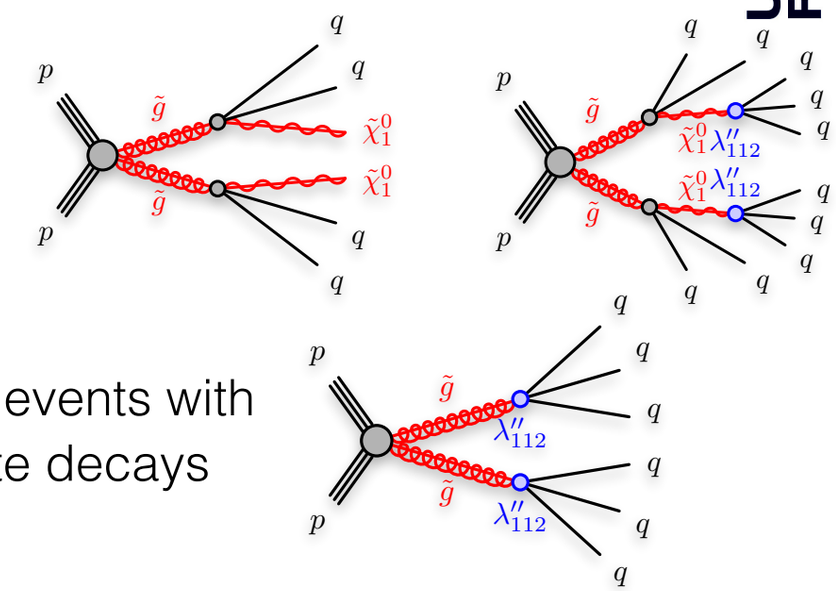




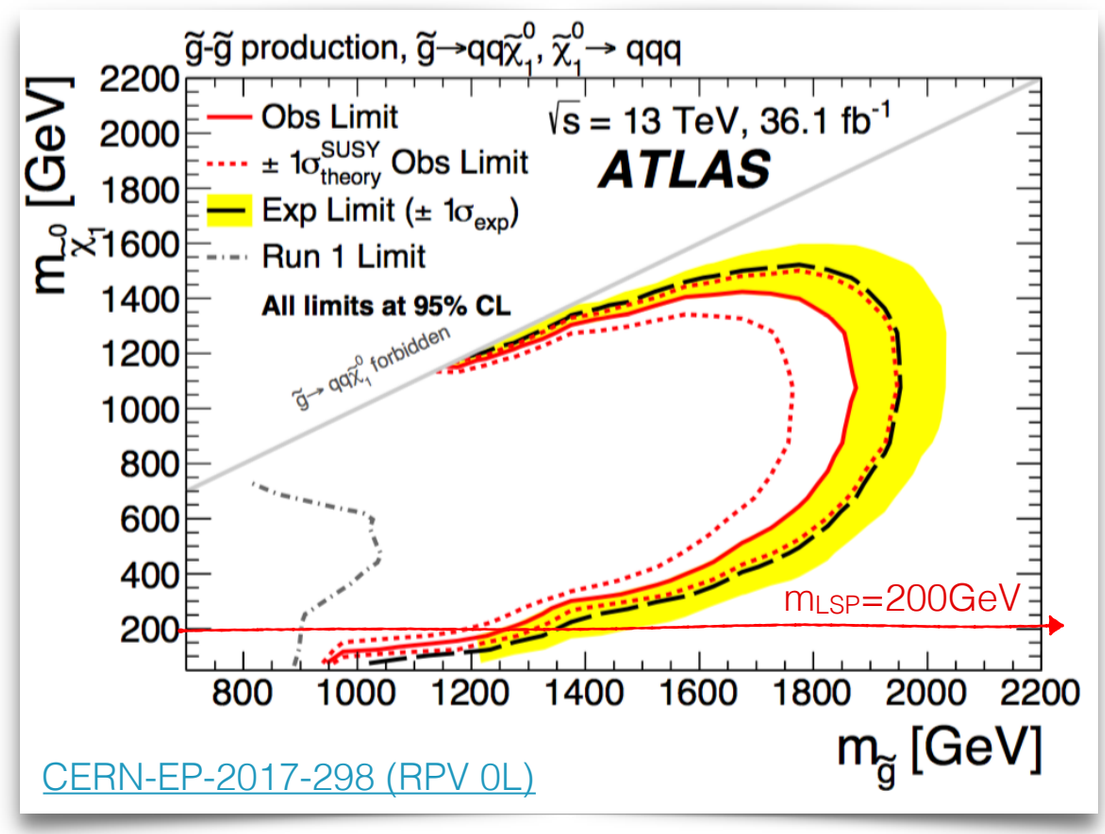
$\sigma_{single} \sim (\lambda''_{323})^2$

ANALYSES SENSITIVE TO Gqq

- RPC 0-lepton, 7-11 jets
  - searches for gluinos which decay via long decay chains, yielding a final state with high jet multiplicity and moderate MET
  - targeted models do not match models considered in this note
  - potential sensitivity to the Gqq and Gtt due to high jet multiplicity in events with moderate λ'' and moderate MET from misreconstructed jets from late decays



- RPV 0-lepton (**not included in this note**)
  - searches for gluinos decaying hadronically to final states without MET in RPV scenarios
  - correspond to RPV limit of Gqq model → but λ'' are considered simultaneously, here only $\lambda''_{112} \neq 0$
  - for gluino ⟶ qq neutralino a limit of 1.2 TeV is set on the gluino mass for neutralino mass of 200 GeV
  - for gluino ⟶ qqq upper limits on σ × BR are provided varying depending on the gluino mass from 0.8 fb^{-1} at 900 GeV to 0.011 fb^{-1} at 1.8 TeV



CERN-EP-2017-298 (RPV 0L)

THE RPC 0L (2-6 JETS) ANALYSIS

- RPC 0-lepton, 2-6 jets searches for pair production of squarks or gluinos in final states with jets and MET and lepton veto (e, mu)

  $\not{E}_T > 250$ GeV

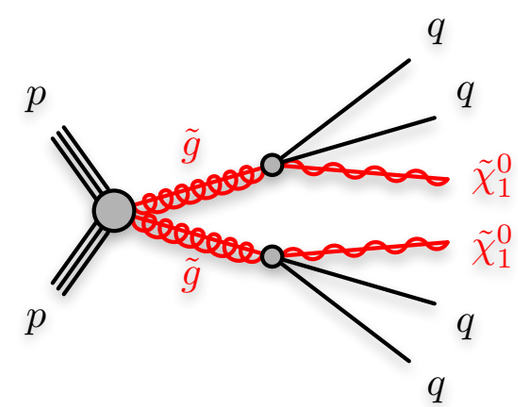
- using two different analysis strategies:

  $$M_{eff} = \sum_{i=1}^{n} |p_T^{(i)}| + \not{E}_T$$

  - M_{eff} based cut & count approach main discriminating variable
  - recursive jigsaw reconstruction (RJR) not considered here

- exclusion limit on gluino mass around 2 TeV on RPC limit of Gqq ($\lambda'' = 0$)

  → reported in latest publication



- jet cleaning cuts are based on jet charged particle fraction (ratio of scalar sum of associated track p_T to jet p_T)

  ⇒ high inefficiency for long-lived signals (e.g. 96.5% signal loss for τ_{LSP} = 1ns)

  - modified based on longitudinal calorimeter-sampling profile as used e.g. in DV + MET analysis
  - signal and background yields in all signal and control regions show minimal change (SR < 4% and CR < 2%) wrt latest public results

OBJECT DEFINITION IN RPC 0-L ANALYSIS

Jets

Cut	Value/description
Baseline jet	
Algorithm	anti-k_t4Topo $R = 0.4$
Acceptance	$p_T > 20$ GeV, $\|\eta\| < 2.8$
Pileup suppression	$p_T > 60$ GeV $\|\|$ $\|\eta\| > 2.4$ $\|\|$ JVT > 0.59
b-jet	
b-tagging algorithm	MV2c10 at 77% efficiency point
Acceptance	$p_T > 50$ GeV , $\|\eta\| < 2.5$
Reclustered jet	
Algorithm	anti-k_t $R = 1.0$
Input	Baseline jets with $p_T > 25$ GeV

Photons

Cut	Value/description
Baseline photon	
Acceptance	$p_T > 25$ GeV, $\|\eta\| < 2.37$
Quality	Loose
Overlap	$\Delta R(\gamma, \text{jet}) > 0.4$
Signal photon	
Quality	Tight
Isolation	FixedCutTight

Leptons

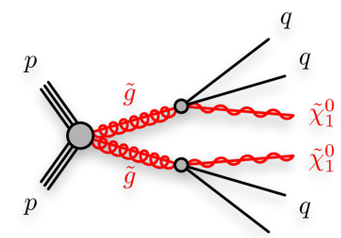
Cut	Value/description
Baseline electron	
Algorithm	AuthorElectron
Acceptance	$p_T > 7$, GeV, $\|\eta^{\text{clust}}\| < 2.47$
Quality	LooseLH
Overlap	$\Delta R(e, \text{jet}) > 0.4$
Signal Electron	
Acceptance	$p_T > 7GeV$
Quality	TightLL
Isolation	GradientLoose
Track	$\|z_0^{PV} \cdot \sin\theta\| < 0.5$ mm
	$\|d_0^{PV}\|/\sigma(d_0^{PV}) < 5$

Cut	Value/description
Baseline muon	
Acceptance	$p_T > 7GeV, \|\eta\| < 2.7$
Quality	Medium
Overlap	$\Delta R(\mu, \text{jet}) > 0.4$
Signal muon	
Acceptance	$p_T > 7GeV$
Isolation	GradientLoose
Track	$\|z_0^{PV} \cdot \sin\theta\| < 0.5$ mm
	$\|d_0^{PV}\|/\sigma(d_0^{PV}) < 3$

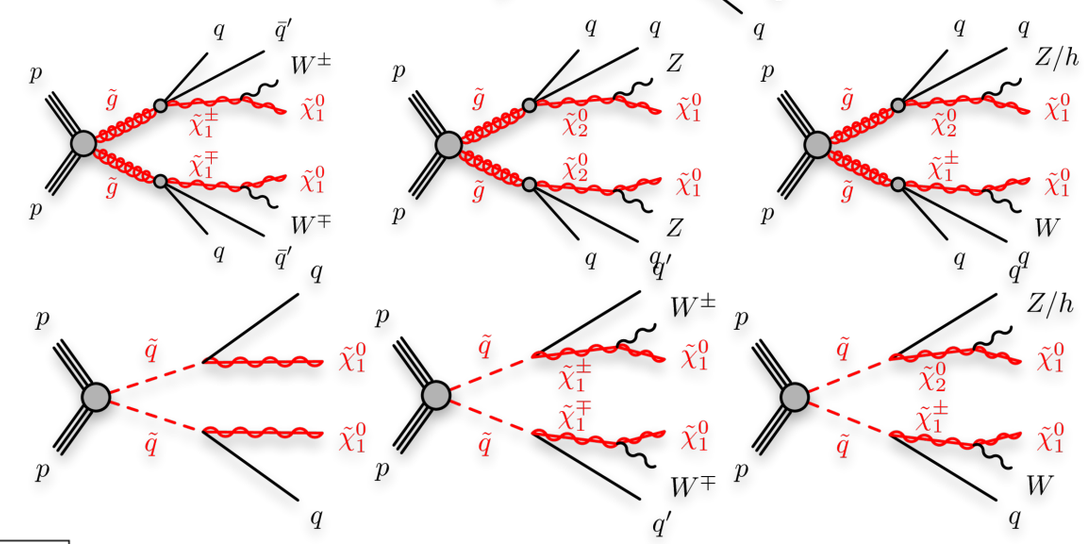
0L M_{eff} BASED SIGNAL REGIONS

Targeted signal	$\tilde{q}\tilde{q}, \tilde{q} \to q\tilde{\chi}_1^0$							
Requirement	Signal Region [**Meff-**]							
	2j-1200	**2j-1600**	**2j-2000**	**2j-2400**	**2j-2800**	**2j-3600**	**2j-2100**	**3j-1300**
E_T^{miss} [GeV] >	250							
$p_T(j_1)$ [GeV] >	250	300	350				600	700
$p_T(j_2)$ [GeV] >	250	300	350				50	
$p_T(j_3)$ [GeV] >	–							50
$\lvert\eta(j_{1,2})\rvert$ <	0.8	1.2				–		
$\Delta\phi(\text{jet}_{1,2,(3)}, \vec{E}_T^{miss})_{min}$ >	0.8						0.4	
$\Delta\phi(\text{jet}_{i>3}, \vec{E}_T^{miss})_{min}$ >	0.4						0.2	
$E_T^{miss}/\sqrt{H_T}$ [GeV$^{1/2}$] >	14	18					26	16
m_{eff}(incl.) [GeV] >	1200	1600	2000	2400	2800	3600	2100	1300

M_{eff} based cut & count analysis 24 SRs optimised for direct and onestep gluino and squark decays including 2 specialised regions targeting final states with boosted W



Targeted signal	$\tilde{g}\tilde{g}, \tilde{g} \to q\bar{q}\tilde{\chi}_1^0$						
Requirement	Signal Region [**Meff-**]						
	4j-1000	**4j-1400**	**4j-1800**	**4j-2200**	**4j-2600**	**4j-3000**	**5j-1700**
E_T^{miss} [GeV] >	250						
$p_T(j_1)$ [GeV] >	200						700
$p_T(j_4)$ [GeV] >	100				150		50
$p_T(j_5)$ [GeV] >	–						50
$\lvert\eta(j_{1,2,3,4})\rvert$ <	1.2	2.0					–
$\Delta\phi(\text{jet}_{1,2,(3)}, \vec{E}_T^{miss})_{min}$ >	0.4						
$\Delta\phi(\text{jet}_{i>3}, \vec{E}_T^{miss})_{min}$ >	0.4						0.2
$E_T^{miss}/m_{eff}(N_j)$ >	0.3	0.25			0.2		0.3
Aplanarity >	0.04						–
m_{eff}(incl.) [GeV] >	1000	1400	1800	2200	2600	3000	1700



Targeted signal	$\tilde{g}\tilde{g}, \tilde{g} \to q\bar{q}W\tilde{\chi}_1^0$ and $\tilde{q}\tilde{q}, \tilde{q} \to qW\tilde{\chi}_1^0$						
Requirement	Signal Region [**Meff-**]						
	5j-1600	**5j-2000**	**5j-2600**	**6j-1200**	**6j-1800**	**6j-2200**	**6j-2600**
E_T^{miss} [GeV] >	250						
$p_T(j_1)$ [GeV] >	200						
$p_T(j_6)$ [GeV] >	50				100		
$\lvert\eta(j_{1,\ldots,6})\rvert$ <	–			2.0		–	
$\Delta\phi(\text{jet}_{1,2,(3)}, \vec{E}_T^{miss})_{min}$ >	0.4		0.8	0.4			
$\Delta\phi(\text{jet}_{i>3}, \vec{E}_T^{miss})_{min}$ >	0.2	0.4		0.2			
$E_T^{miss}/m_{eff}(N_j)$ >	0.15	–		0.25	0.2		0.15
$E_T^{miss}/\sqrt{H_T}$ [GeV$^{1/2}$] >	–	15	18	–			
Aplanarity >	0.08	–			0.04	0.08	
m_{eff}(incl.) [GeV] >	1600	2000	2600	1200	1800	2200	2600

Targeted signal	$\tilde{g}\tilde{g}, \tilde{g} \to q\bar{q}W\tilde{\chi}_1^0$ and $\tilde{q}\tilde{q}, \tilde{q} \to qW\tilde{\chi}_1^0$	
Requirement	Signal Region [**Meff-**]	
	2jB-1600	**2jB-2400**
E_T^{miss} [GeV] >	250	
p_T(Large-R j_1) [GeV] >	200	
p_T(Large-R j_2) [GeV] >	200	
m(Large-R j_1) [GeV]	[60,110]	
m(Large-R j_2) [GeV]	[60,110]	
$\Delta\phi(\text{jet}_{1,2,(3)}, \vec{E}_T^{miss})_{min}$ >	0.6	
$\Delta\phi(\text{jet}_{i>3}, \vec{E}_T^{miss})_{min}$ >	0.4	
$E_T^{miss}/\sqrt{H_T}$ [GeV$^{1/2}$] >	20	
m_{eff}(incl.) [GeV] >	1600	2400

0L CONTROL REGIONS

CR	SR background	CR process	CR selection (Meff-based)	CR selection (RJR-based)
Meff/RJR-CRγ	$Z(\rightarrow \nu\bar{\nu})$+jets	γ+jets	Isolated photon	Isolated photon
Meff/RJR-CRQ	Multi-jet	Multi-jet	SR with reversed requirements on (i) $\Delta\phi(\text{jet}, \boldsymbol{E}_{\text{T}}^{\text{miss}})_{\text{min}}$ and (ii) $E_{\text{T}}^{\text{miss}}/m_{\text{eff}}(N_{\text{j}})$ or $E_{\text{T}}^{\text{miss}}/\sqrt{H_{\text{T}}}$	$\Delta_{\text{QCD}} < 0$ reversed requirement on $H_{1,1}^{\text{PP}}$ (RJR-S/G) or $R_{\text{ISR}} < 0.5$ (RJR-C)
Meff/RJR-CRW	$W(\rightarrow \ell\nu)$+jets	$W(\rightarrow \ell\nu)$+jets	30 GeV$< m_{\text{T}}(\ell, E_{\text{T}}^{\text{miss}}) <$ 100 GeV, b-veto	
Meff/RJR-CRT	$t\bar{t}$(+EW) and single top	$t\bar{t} \rightarrow b\bar{b}qq'\ell\nu$	30 GeV$< m_{\text{T}}(\ell, E_{\text{T}}^{\text{miss}}) <$ 100 GeV, b-tag	

Z + JETS BG ESTIMATION

- **irreducible Z $\longrightarrow \nu\nu$ generates large MET**
  ⇒ constrained by usage of γ + jets sample with $p_T(\gamma) > 150$GeV
  treating the reconstructed photon as invisible in calculation of MET

  - for **$p_T(\gamma) \gg m_Z$ → kinematic properties of events are very similar to those in Z + jets**
    usage of LO γ + jets cross sections ⇒ large theoretical uncertainties ⇒
    reduced by applying a correction factor κ (κ is a function of n_{JETS}) to events:

1.41 (2j) < κ < 2.26 (6j)

$$N_{SR}^{Z\nu\nu,pred} = N_{CRY}^{\gamma+jets,data} \cdot \frac{N_{SR}^{Z\nu\nu,MC}}{N_{CRY}^{\gamma+jets,MC} \cdot k}$$

κ gives difference between data and MC of γ + jets / Z + jets and cancels dependence on total cross-section calculation

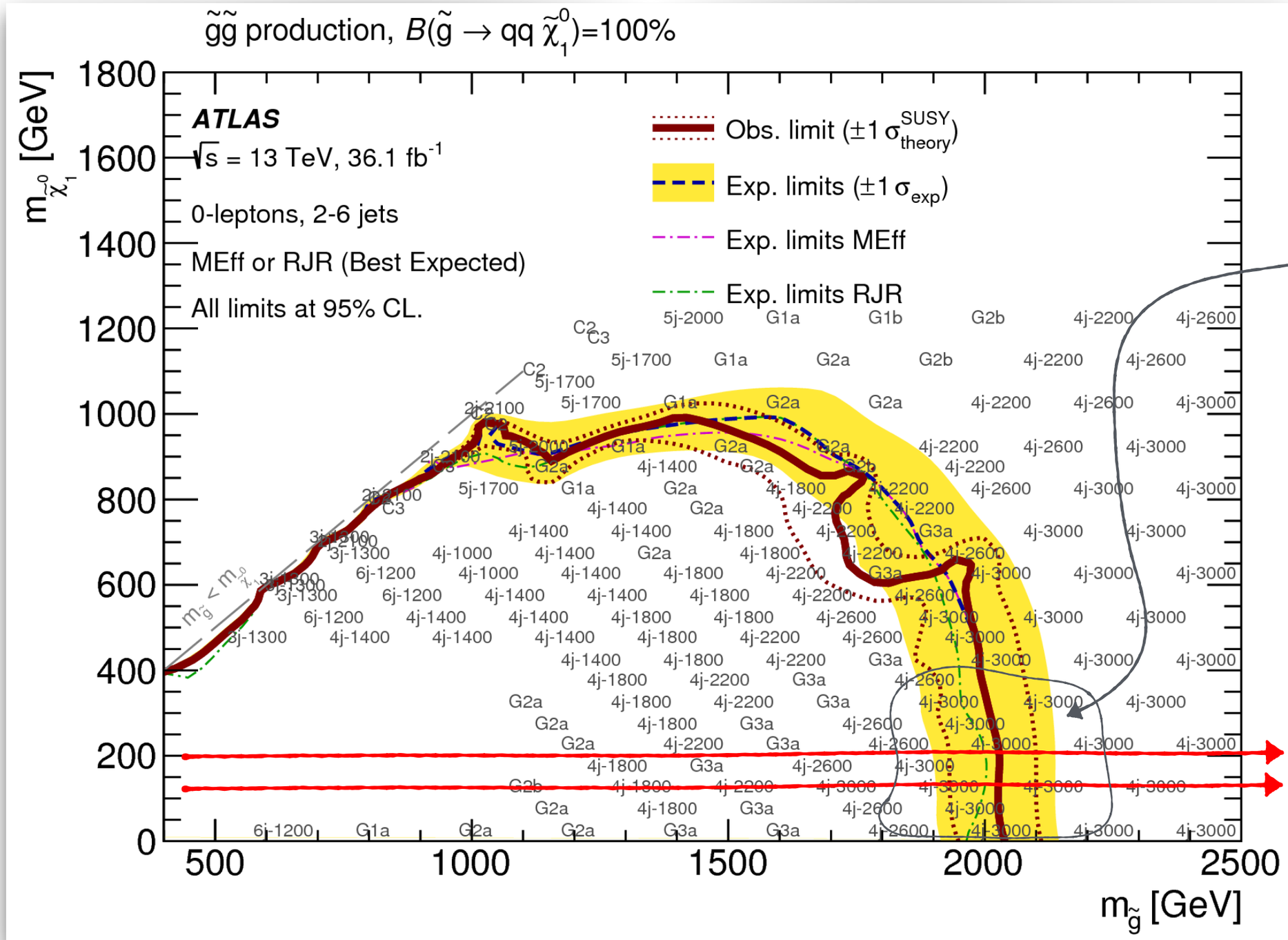
- κ is determined by comparing CRY observations with those in a highly populated aux. CR

  - 2e or 2μ contributing to MET
  - m_Z-25GeV < minvar. < m_Z +25GeV
  - MET > 250GeV
  - Meff > 1200GeV
  - MET/$\sqrt{H_T}$ > 14 $\sqrt{\text{GeV}}$

$$\kappa = \left(\frac{N_{\text{CRYVL}}^{\gamma+jets,data}}{N_{\text{CRZVL}}^{Z\ell\ell,data}}\right) \Big/ \left(\frac{N_{CRYVL}^{\gamma+jets,MC}}{N_{\text{CRZVL}}^{Z\ell\ell,MC}}\right) = \frac{N_{\text{CRYVL}}^{\gamma+jets,data} . N_{\text{CRZVL}}^{Z\ell\ell,MC}}{N_{CRYVL}^{\gamma+jets,MC} . N_{\text{CRZVL}}^{Z\ell\ell,data}}$$

$$= \frac{\left(N_{\text{CRYVL}}^{data} - N_{\text{CRYVL}}^{bkg}\right) . N_{\text{CRZVL}}^{Z\ell\ell,MC}}{N_{CRYVL}^{\gamma+jets,MC} . \left(N_{\text{CRZVL}}^{data} - N_{\text{CRZVL}}^{bkg}\right)}$$

BEST SIGNAL REGIONS FOR DIRECT GLUINO DECAY



most sensitive SRs in relevant region of mass plane:

M_{eff}-4j-3000

RJR-SRs have best sensitivity in compressed region

both LL scenarios consider very light LSP:

RPV: m_{LSP}=200GeV

R-hadron: m_{LSP}=100GeV

=> ONLY M_{EFF}-BASED SRs CONSIDERED FOR REINTERPRETATION

MULTIJET BACKGROUND

- the QCD background in analysis with high MET cut is dominated by the mis-measurement of multiple jets leading to fake MET
  - hadronisation (particularly for heavy-flavour quarks) produces real MET in form of neutrinos
  - hadronisation of partons is not fully reconstructed by ATLAS
    - imperfect hadronic calorimeters (limited by granularity) → no perfect measurement of energy
    - jet radius may not contain all particles → some may be lost due to interaction with non-detector material
    - particles from various different sources may enter into jet cone (reduced by OR and event cleaning)
    - very high energetic jets can punch through to muon system ⇒ fake MET
    - although vetoed regions with dead material (damages, electronics, …) in calorimeters ⇒ fake MET

- why not just use MC as for other SM BGs but a fully data-driven method instead?
  - amount of simulated events to have such significant mis-measurement from detector effects is enormous → lack of statistic in high MET tails
  - inaccuracy of simulation of events with large MET due hard-to-model features like JER dependency, time dependency etc.

DV ANALYSIS OVERVIEW

- Event Selection:
  - preselection:
    - Draw RPVLL filtering (standard tracking not sufficient)
    - SUSY15 skimming
  - additional cuts:
    - at least one primary vertex with $N_{trk} \geq 2$
    - NCB cuts $F_{EM} > 0.8$ or $F_{MAX} > 0.96 \Rightarrow$ event vetoed
    - MET > 250 GeV
    - at least one displaced vertex with $N_{trk} \geq 2 \Rightarrow$ kills SM BG
  - tracking:
    modified tracking algorithm with loosened cuts ⇒
    TrackParticles = standard tracks + additional tracks
- Main BG: basically no SM BG but BG from detector
  - hadronic interactions → particles interact with detector material
  - merged vertices → two close decay vertices are mistakenly merged to one DV
  - randomly crossing tracks → mistakenly reconstructed as part of crossed vertex

Phys. Rev. D 97, 052012

Submitted to: Phys. Rev. D.

CERN-EP-2017-202
October 16, 2017

Search for long-lived, massive particles in events with displaced vertices and missing transverse momentum in $\sqrt{s}$ = 13 TeV *pp* collisions with the ATLAS detector

DISPLACED VERTEX:

-) LIES IN FIDUCIAL VOLUMEN

-) DISTANCE IN (x, y) > 4mm FROM PV

-) NOT IN REGION OF DENSE MATERIAL

-) SR DV: MORE THAN 5 TRACKS AND INVERSE MASS > 10 GeV

PIXEL dE/dx ANALYSIS

- search for massive charged long-lived particles:
  - are produced at low velocities v << c ⇒
  - have specific ionisation distinguishable from SM particles
- measure ionisation energy loss dE/dx in ATLAS' Pixel subsystem
  - average energy loss of massive, charged particles in matter is expected to follow the Bethe–Bloch distribution

    ⇒ expressed as a function of the βγ of the LLPs

    (p_i … calibration constants measured in data)

$$(\mathrm{d}E/\mathrm{d}x)_{\mathrm{MPV}}(\beta\gamma) = \frac{p_1}{\beta^{p_3}} \ln(1 + [p_2\beta\gamma]^{p_5}) - p_4$$

  - ionisation signature is used for event selection and for mass calculation ⇒

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

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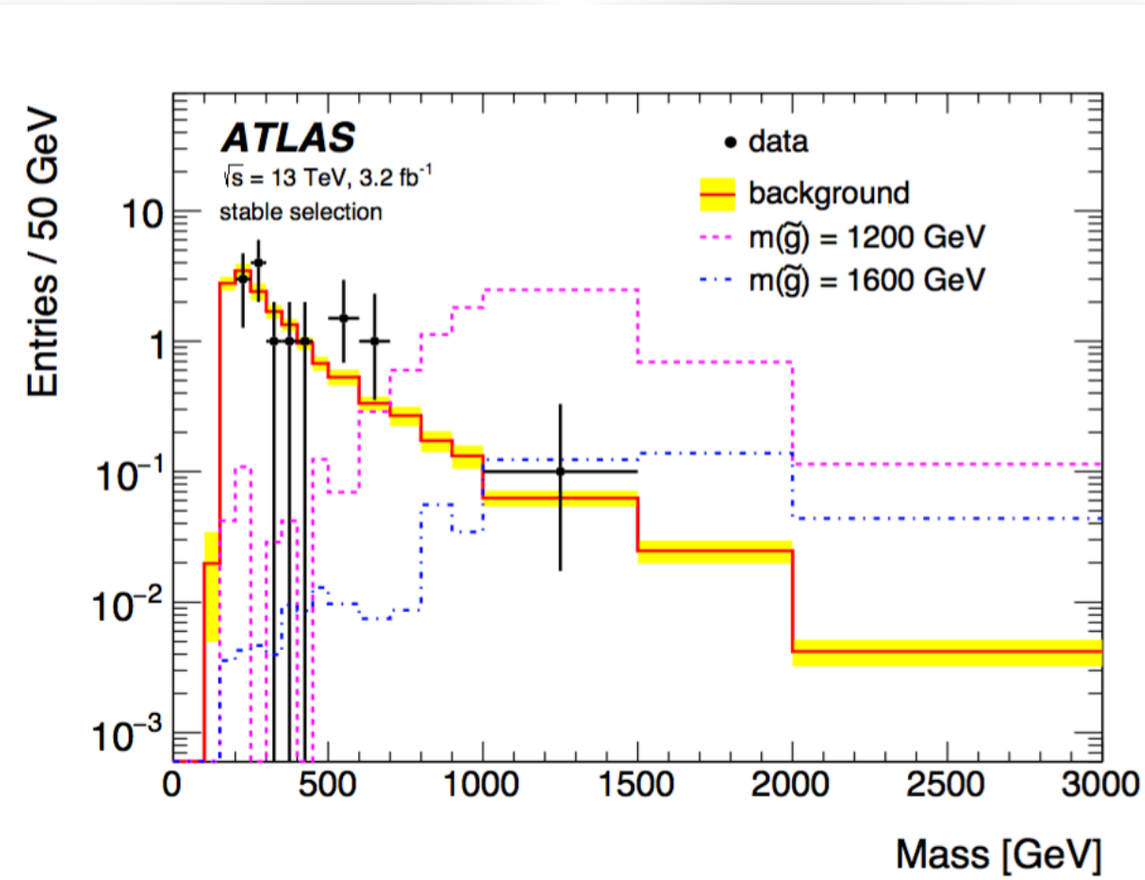
8th July 2016

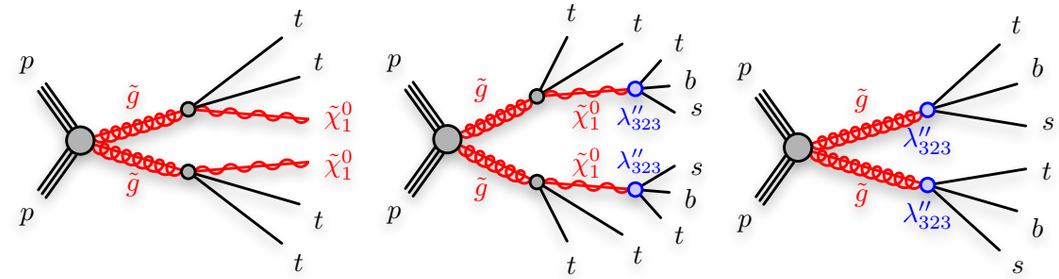
Search for metastable heavy charged particles with large ionization energy loss in *pp* collisions at $\sqrt{s}$ = 13 TeV using the ATLAS experiment

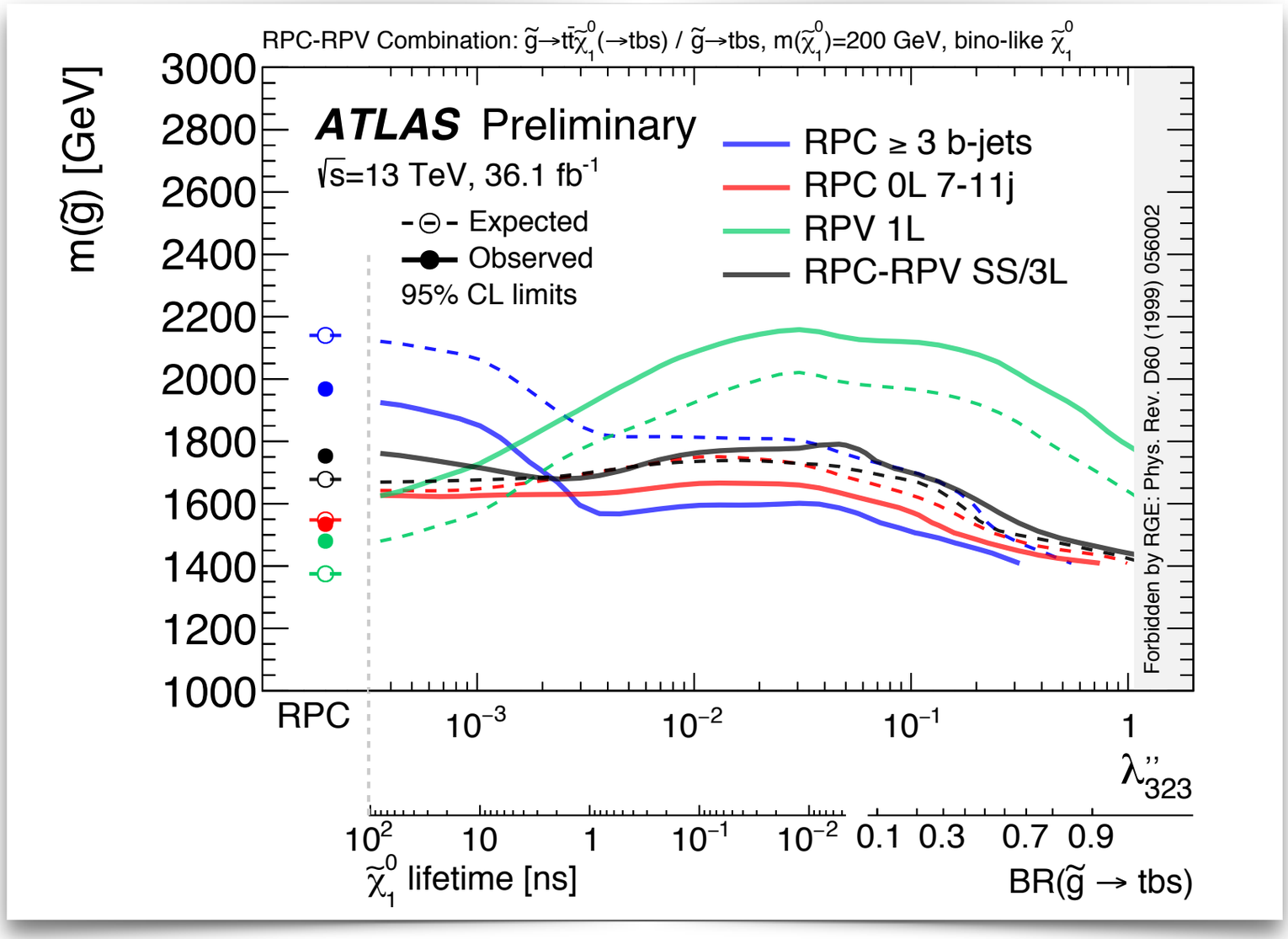


ESTIMATED CANDIDATE MASS IS FINAL SEARCH DISCRIMINANT

RESULTS Gtt MODEL

- observed and expected limits on gluino mass shown as a function of neutralino lifetime and gluino branching ratio, as well as equivalent λ''_{323} coupling strength





- entire λ''_{323} range is covered effectively by various analyses

  ⇒ gluino mass limit ≥ 1.8 TeV

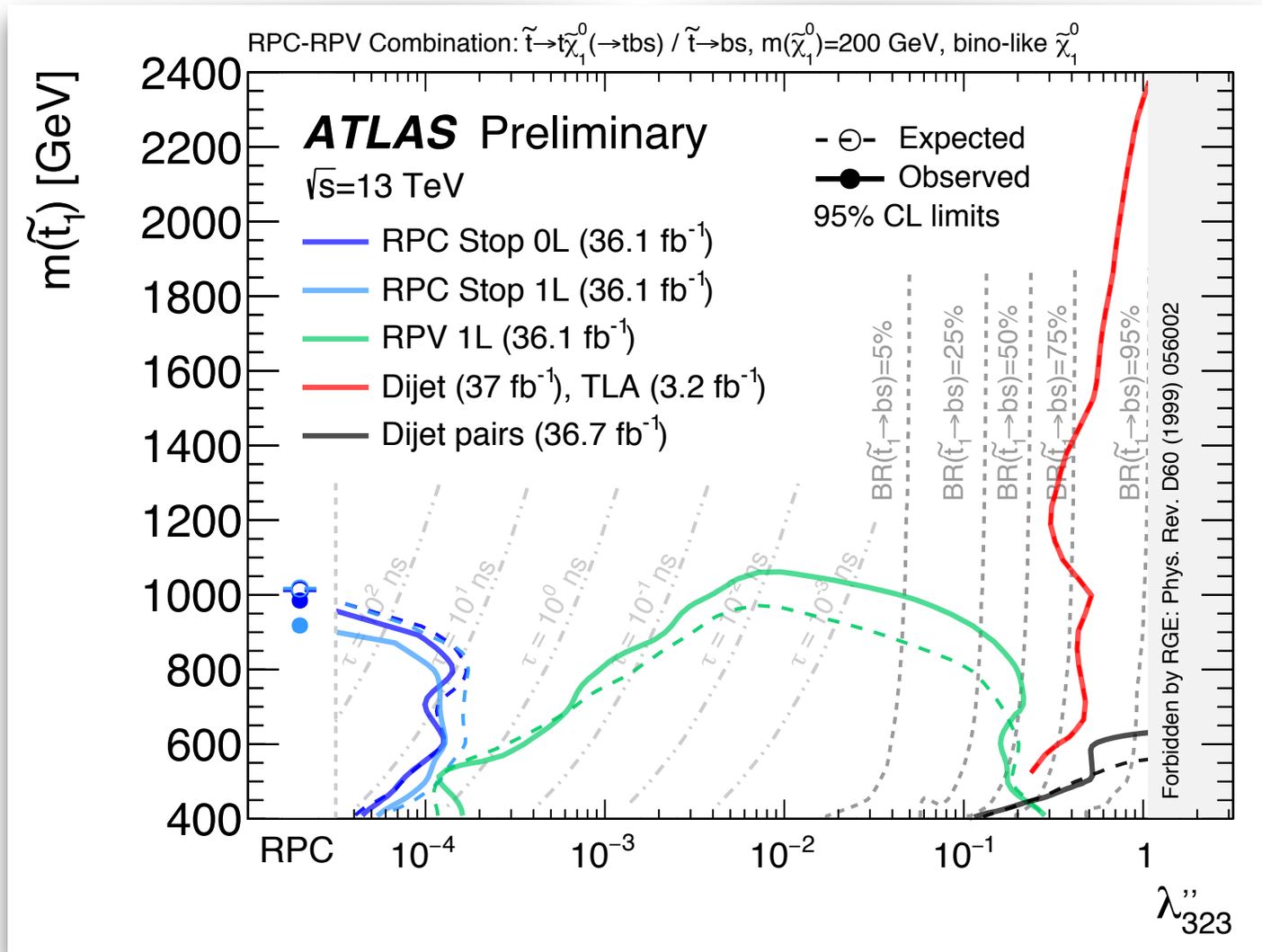
- **RPC multi-b** sets strongest limits for RPC scenario and large lifetimes

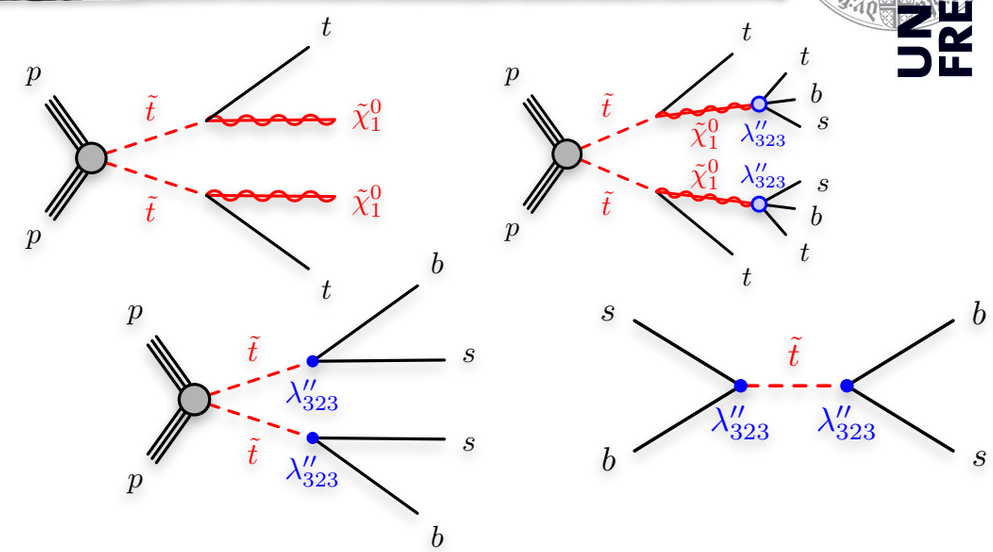
- **RPV 1L** analysis is most powerful for moderate and high values of λ''_{323}

- strong limits from **RPC 0L 7-11** and **SS/3L** throughout the entire λ''_{323} range

RESULTS stop MODEL

- observed and expected limits on stop mass as a function λ''_{323} coupling strength
- neutralino lifetime contours and BR (stop ⟶ bs) are overlaid since they depend on coupling value and stop mass





- entire λ''_{323} range is covered but with fluctuating sensitivity ⇒ no consistent limit
- **RPC stop 0L** and **1L** set strongest limits in RPC scenario and for low λ''
- **RPV 1L** begins setting limits for slightly higher values of λ''
- **dijet and TLA** analysis sets extremely strong limits for high values of λ'' due to sensitivity to stop resonance production

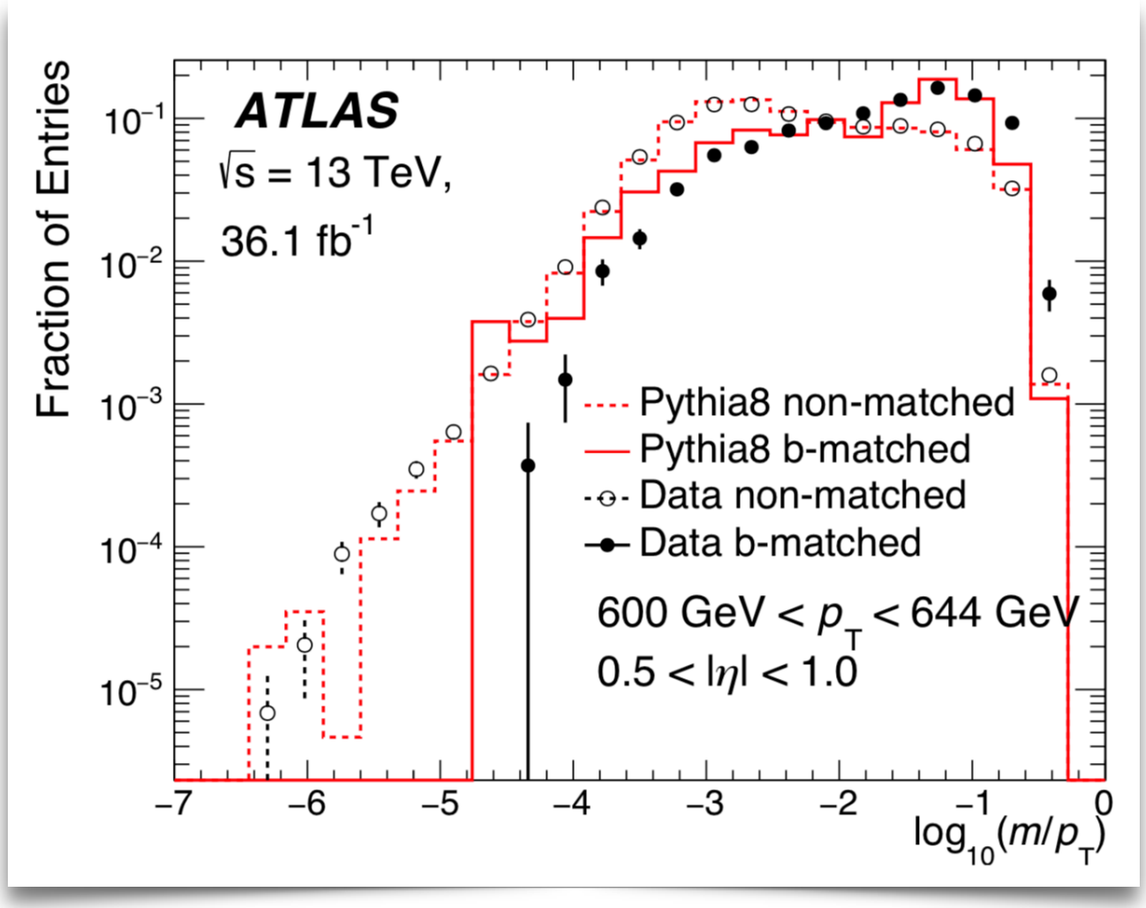
$$m_{\tilde{t}} = 500\,GeV \text{ and } \lambda''_{323} = 1 \Rightarrow \sigma_{single} > 100 \times \sigma_{pair}$$

- weakest limits occur between analyses → for $\tau_{LSP} \approx 1$ ns and BR (stop ⟶ bs) ≈ 60%

MASS TEMPLATE METHOD

- M_J^{Σ} → possible to employ the fully data-driven jet mass template method to estimate QCD background:
  - single-jet mass templates extracted from pure CRs
  - probability for jet in given p_T and $|\eta|$ bin to have certain mass
  - assume that templates depend only on $|\eta|$, p_T and b-matching status and are valid in CR and SR
- from jet mass template generate a random jet mass for each jet in the different regions and construct M_J^{Σ} distribution
  - templates generated in CRs (binned in $|\eta|$, p_T and b-matching status)

    ⇒ shape of M_J^{Σ} matches multijet background



- 120 jet mass templates are created → example jet mass template distribution: data and MC multijet samples for b-matched and non-matched jets
- predicted M_J^{Σ} distribution is normalised to observation in region (0.2 TeV < M_J^{Σ} < 0.6 TeV) where signal contamination < statistical uncertainty on BG
- Uncertainties on jet mass prediction (derived from UDRs) propagated to predicted M_J^{Σ} distribution

RPV MULTIJET SEARCH - UNCERTAINTIES

- predicted M_J^{Σ} distribution is normalised to observation in region (0.2 TeV < M_J^{Σ} < 0.6 TeV) where signal contamination < statistical uncertainty on BG
- statistical uncertainties arises from finite sample size in CR and jet mass randomisation (quantified through pseudo-experiments)
- systematic uncertainties are estimated in uncertainty determination regions (UDRs) in data → difference between predicted and observed jet masses provides estimate of size of systematic uncertainty
  - jet mass templates are assumed to only depend on a given number of observables (jet p_T, $|\eta|$, and b-matching information)
  - jet mass templates are created for each of these observables with a given bin width
  - jets in the same event are assumed to be uncorrelated with each other, such that their masses can be modelled independently
  - statistical fluctuations in the jet mass templates are propagated to BG yield prediction in SR → considered as systematic uncertainty
- from study of jet mass response (ratio of average observed jet mass to average predicted jet mass) in UDRs difference between predicted and observed jet mass distributions can be quantified
  - difference between UDRs in same p_T and $|\eta|$ bin can be compensated by scale factor with size given by response
  - scaling up and down predicted jet mass in the UDRs by this response gives variations in predicted M_J^{Σ} distributions
- Uncertainties on jet mass prediction propagated to predicted M_J^{Σ} distribution and cover the difference to observed one