Experimental Constraints on Baryon Number Violation in Supersymmetry

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collaboration with

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Baryon Number Violation & R-parity violating SUSY

- baryon number (B) "accidentally" conserved at perturbative level in SM
- **baryon number violation** (BNV) needed for baryogenesis (Sakharov)
  - intrinsic to many BSM theories
  - e.g. R-parity violation (RPV) in generic SUSY

$$\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \boxed{\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k}$$

leptons only | leptons + quarks | quarks only => **pure BNV**

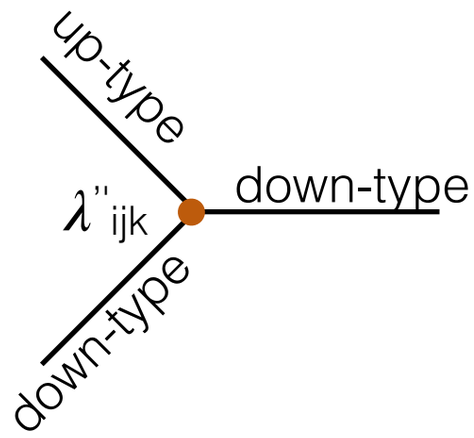
  - R-parity conservation **imposed** by setting all **Yukawa couplings** $\lambda^{(')/('')}$**=0**
    - stable LSP (Dark Matter), stable proton
    - typical signature with large missing energy
  - can set one $\lambda''\neq 0$, proton still stable (p decay violates B and L)

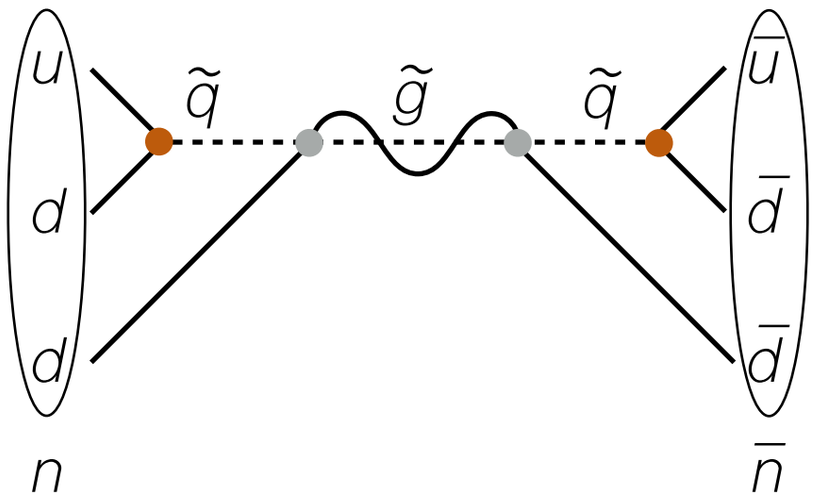
- one (of few) observables for pure BNV: **n-$\bar{\text{n}}$** oscillations (**Δ**B=2)
  - experiment proposed at European Spallation Source (ESS), Lund, Sweden

n-$\bar{n}$ oscillations in RPV SUSY

- BNV term

$$\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k$$



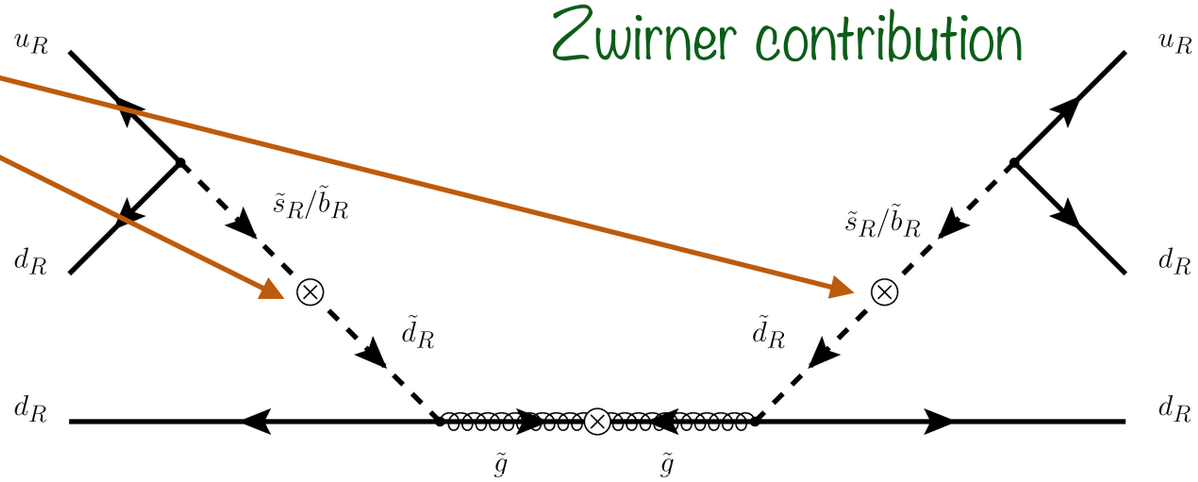


- simplest ansatz: u and d quarks + sparticles —> λ''_{11X}

- $\lambda''_{ijk} = -\lambda''_{ikj}$ => $\lambda''_{111} = 0$
  - n–$\bar{n}$ oscillation via λ''_{112} and λ''_{113} (λ''_{uds}, λ''_{udb})
    - => also need **flavour mixing**
    - encoded in e.g.

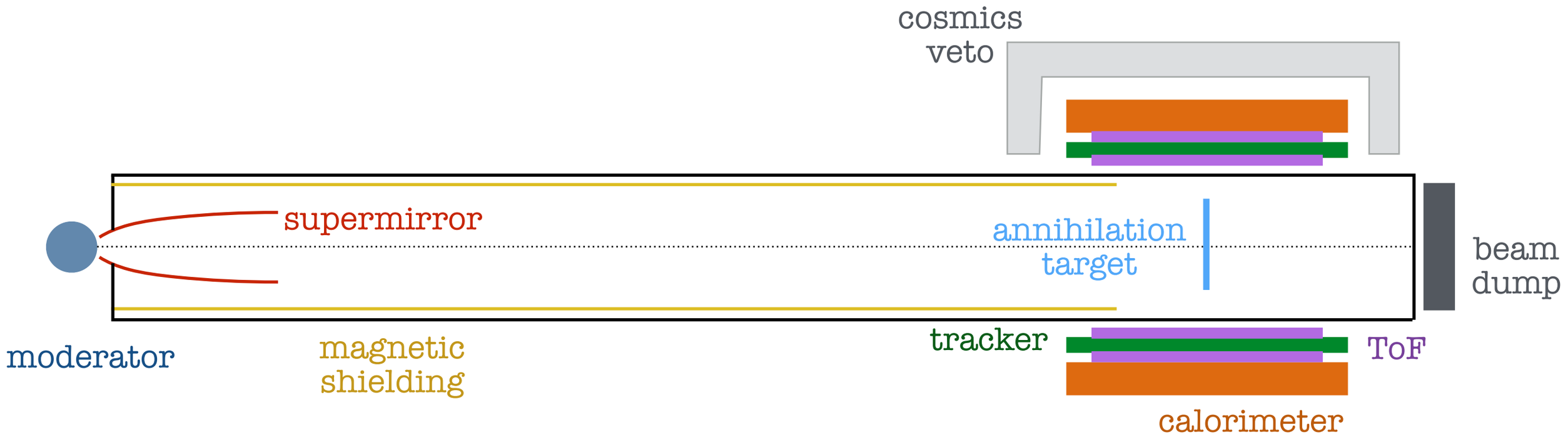
$$\left(\delta^d_{RR}\right)_{12} \equiv m^2_{\tilde{s}_R\tilde{d}_R}/m^2_{\tilde{d}_R}$$

(analogously for sbottom)



Observation Principle

- cold neutrons from ESS (v<1000m/s)
- **annihilate** with neutrons in target nuclei
  - —> many **pions**, typically 5, total energy ~2 GeV
- thin annihilation target, e.g. carbon —> $\sigma_{annihilation}/\sigma_{n\text{-}interaction}$ ~10^6
- (cylindrical) detector with **tracking** (vertex finding), **calorimeter**, ToF



- current limit: t_{osc}^{free} > 0.86x10^{8}s (ILL Grenoble, 1994)
- ESS experiment: factor ~1000 **greater sensitivity** to transition probability
  - => factor ~30 in oscillation time

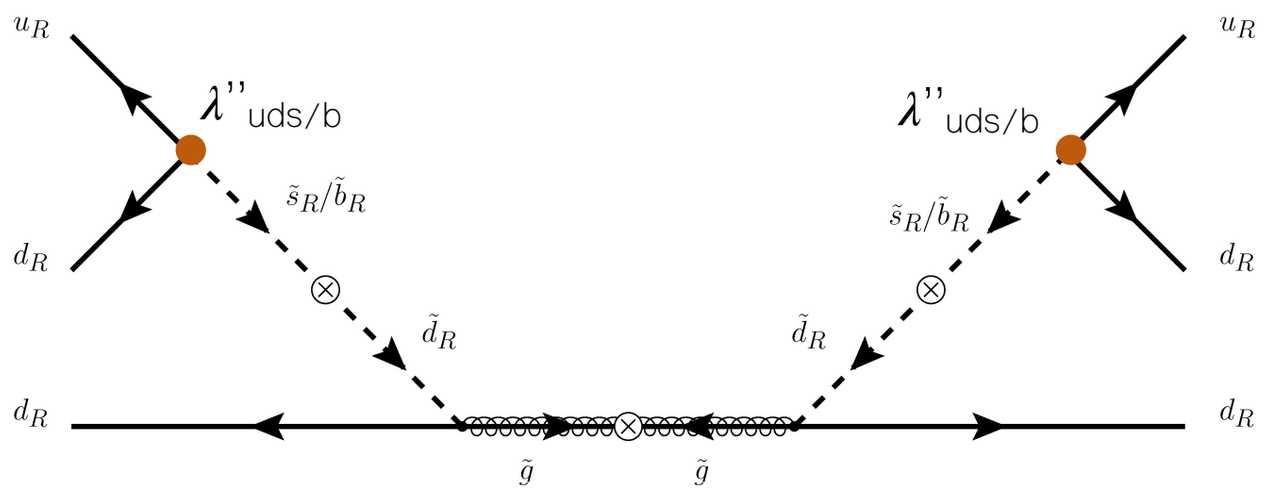
This Project

- study pure BNV processes in framework of RPV SUSY
- **complementarity** of LHC and flavour/low energy constraints
- quantification of **potential** of proposed n–n̄ search

Simplified RPV SUSY Model(s)

- consider only sparticles and coupling relevant for a given process
  - all other sparticles decoupled, all other couplings = 0

- e.g. Zwirner contribution



several others considered in paper, both strong and electroweak production

- only **gluino** and 2 **right-handed down-type squarks** (degenerate)
  - => two parameters: $m_{\tilde{g}}$ and $m_{\tilde{q}}$
    - $m_{\tilde{g}} > m_{\tilde{q}}$: $\tilde{g} \longrightarrow \tilde{q}q$, $\tilde{q} \longrightarrow qq$
    - $m_{\tilde{q}} > m_{\tilde{g}}$: $\tilde{q} \longrightarrow \tilde{g}q$, $\tilde{g} \longrightarrow qqq$

RPV SUSY @ LHC

- not “traditional" SUSY signature with large missing energy
- dependence on decay length of lightest sparticles

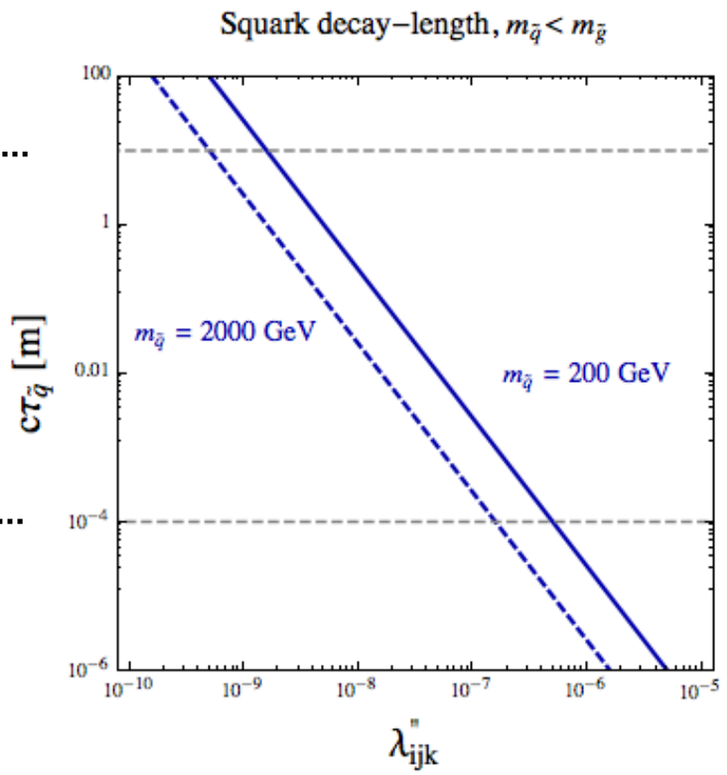
$$\Gamma(\tilde{q} \to qq) = \frac{(\lambda'')^2}{8\pi} m_{\tilde{q}}$$

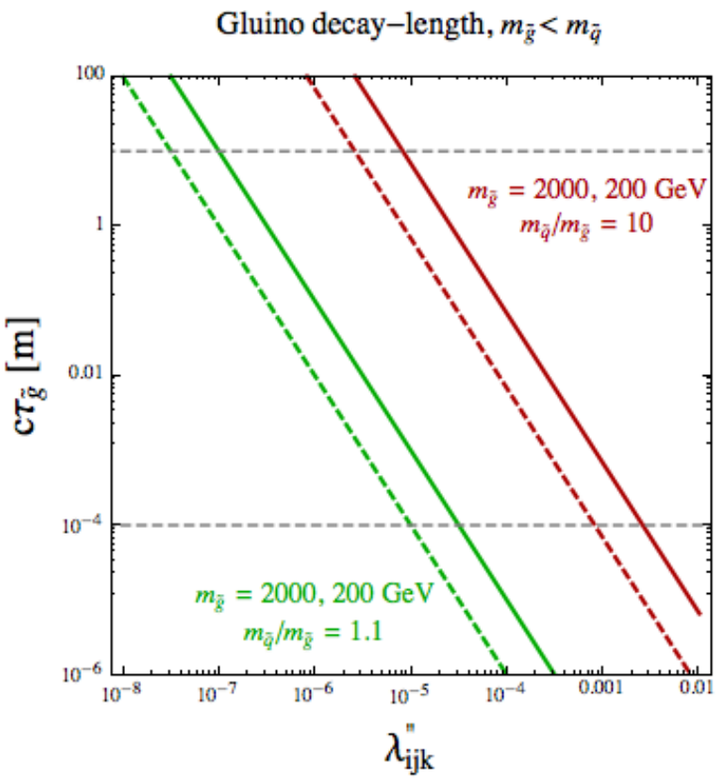
$$\Gamma(\tilde{g} \to qqq) = \frac{\alpha_s(\lambda'')^2}{256\pi^3} \frac{m_{\tilde{g}}^5}{m_{\tilde{q}}^4}$$

long-lived

displaced jets

prompt (many jets)





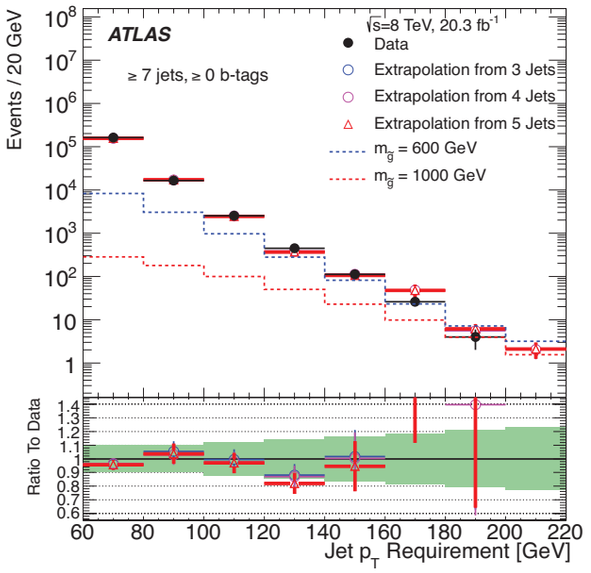
prompt decay with couplings as small as 10^{-7}

larger couplings needed to get prompt decay

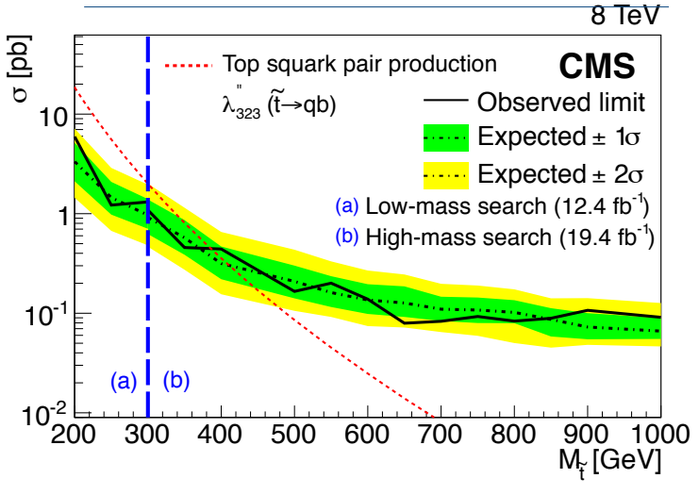
Experimental Constraints

- **LHC** results (recasted)

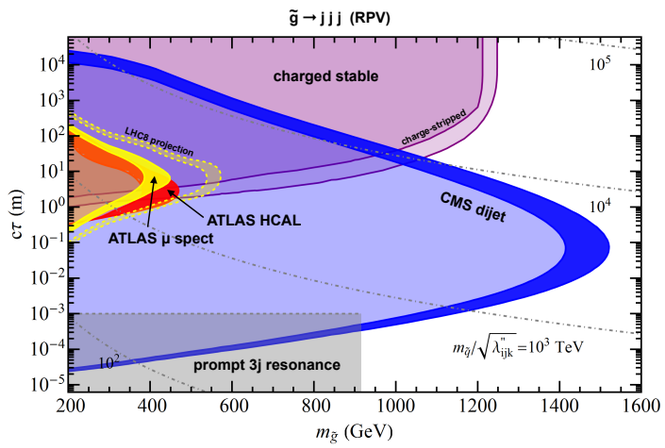
ATLAS multijet, arxiv:1502.05686



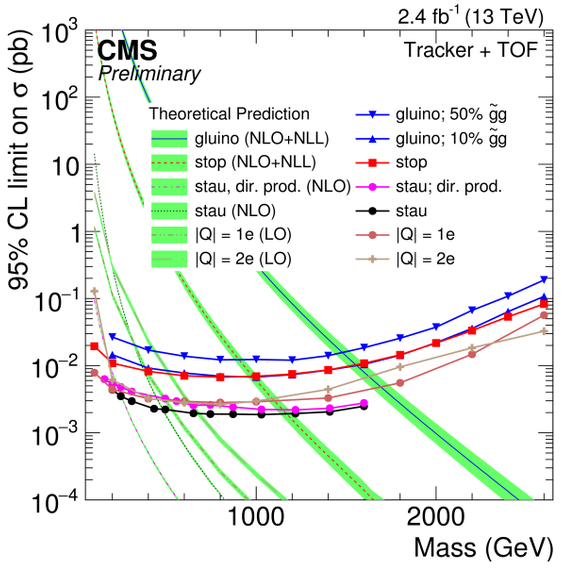
CMS di-jet pair, arxiv:1412.7706



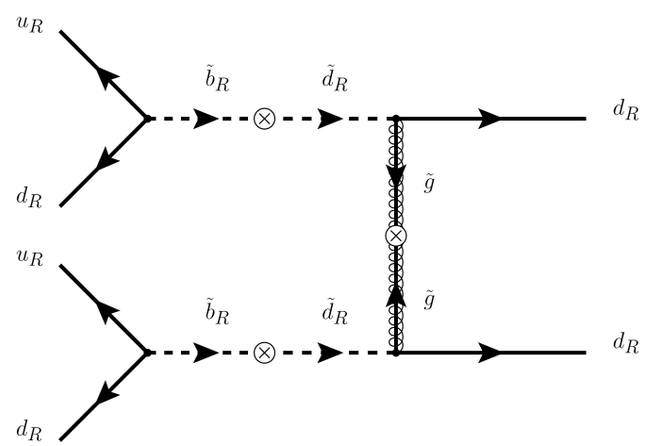
Liu&Tweedie, arxiv:1503.05923



CMS-PAS-EXO-15-010



- **flavour/CP violation** (e.g. K- or B-meson oscillations)
  - strong constraints for 1-2 mixing
- other **ΔB=2** processes: **di-nucleon decay**
  - NN—>KK, NN—>**ππ**

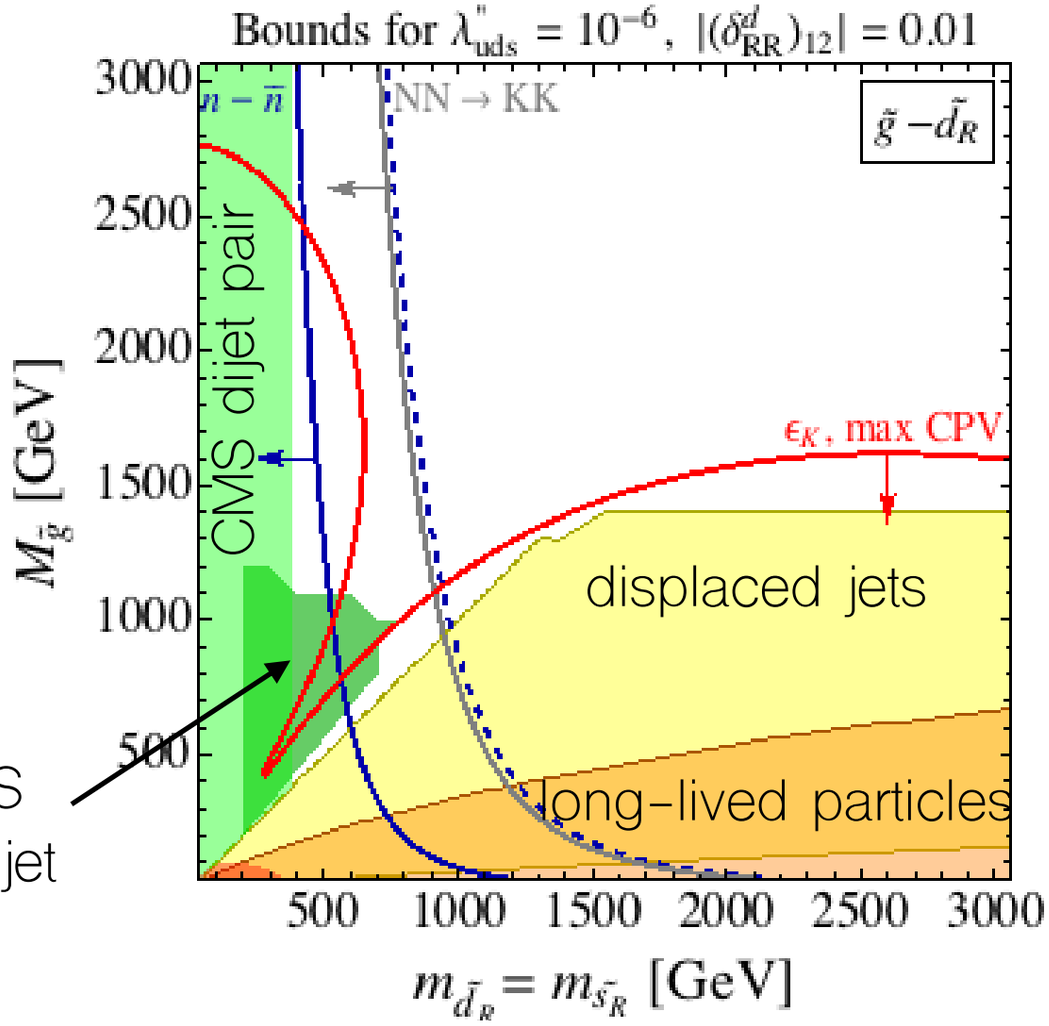


- SuperKamiokande searches with ^{16}O —> t > 10^{32}y —> t_{osc}^{free} > 2.7x10^{8}s

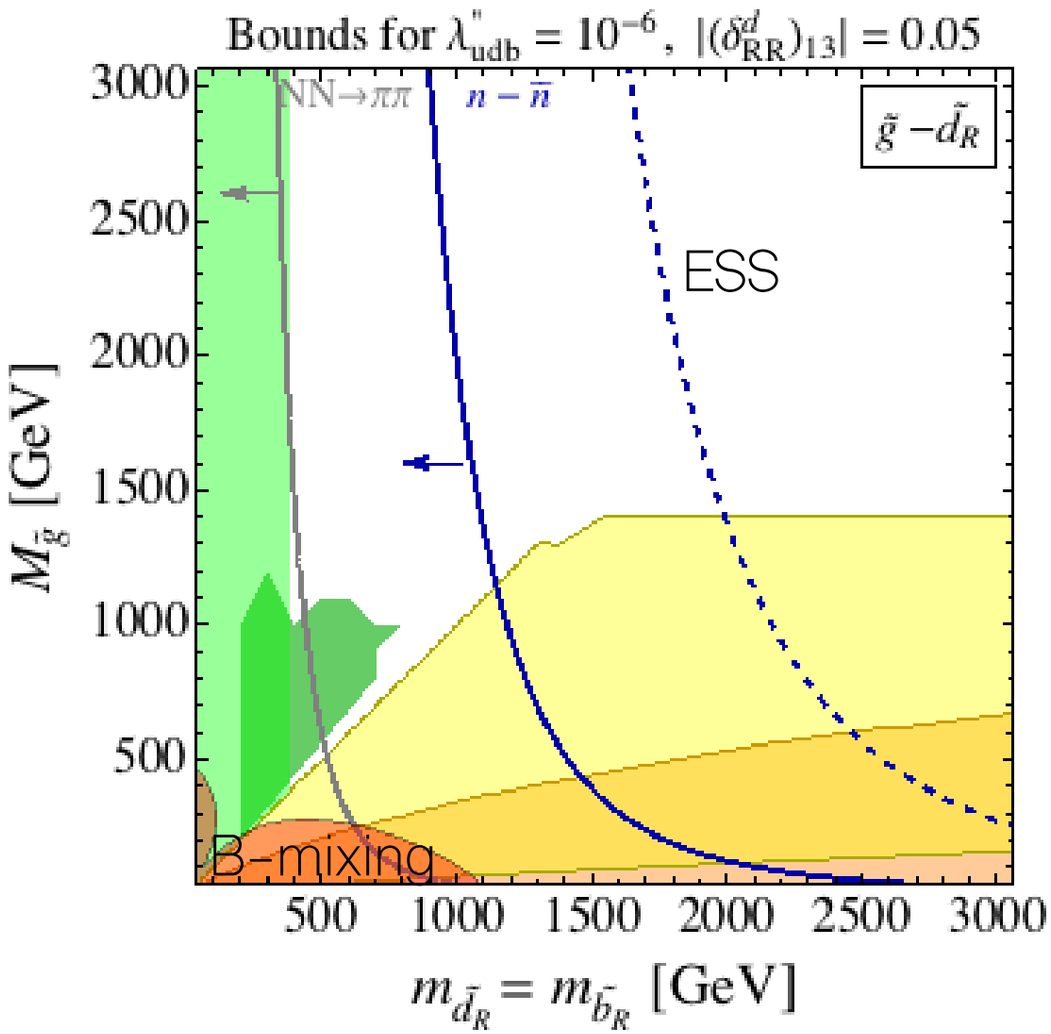
Results - Mass Plain

- $\lambda'' = 10^{-6}$

udS



udb

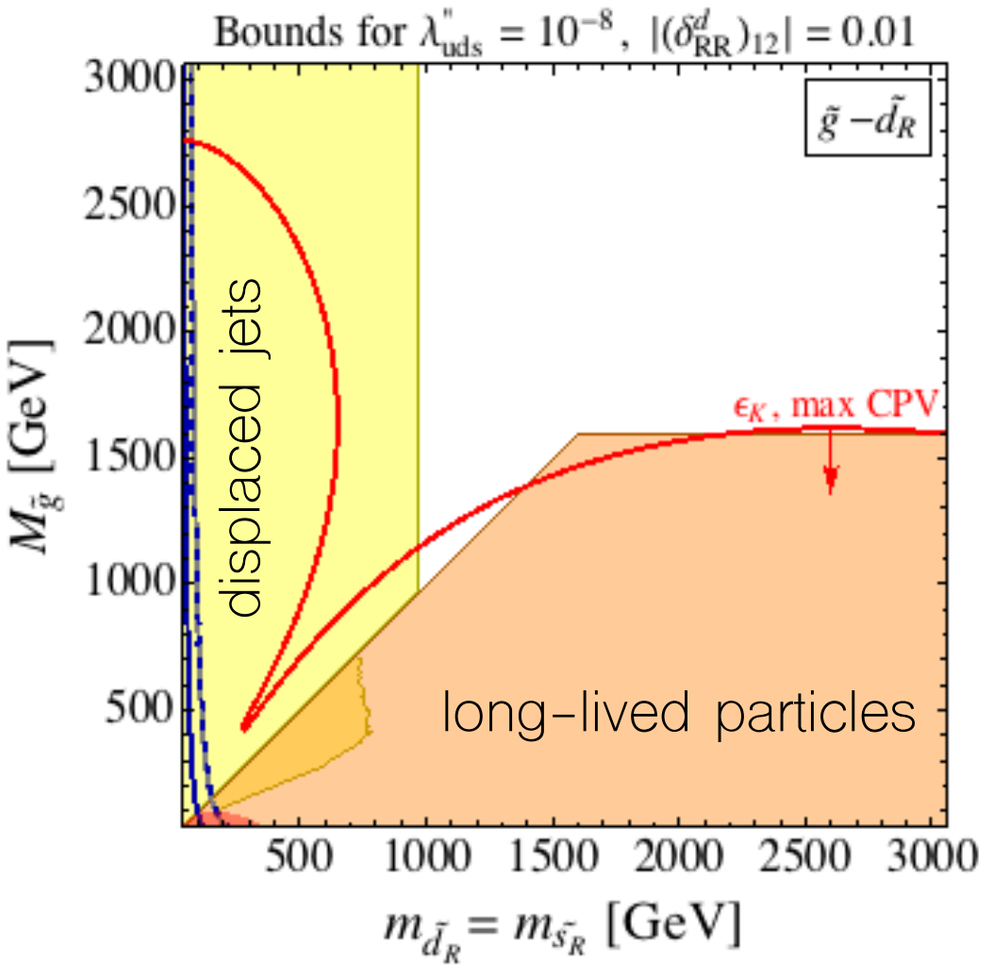


- LHC bounds similar in both cases
- other constraints weaker for udb
- ESS experiment can exclude further parameter space

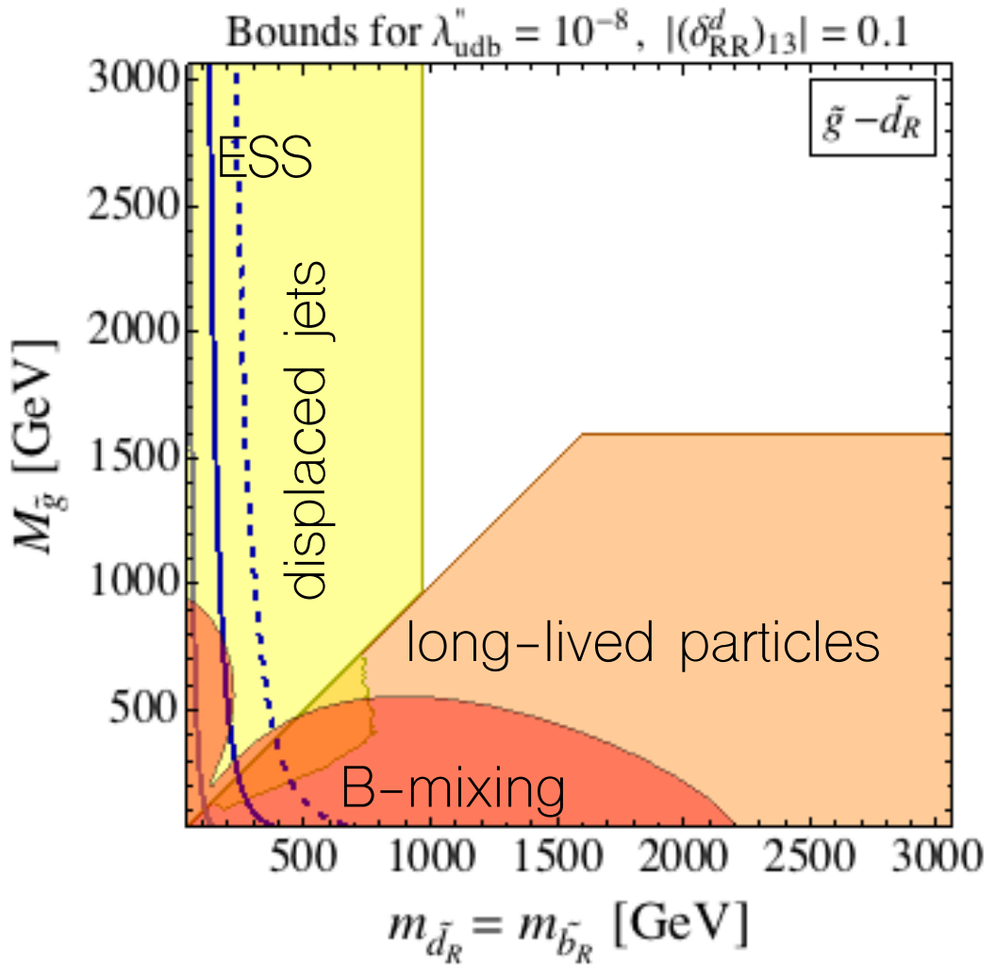
Results - Mass Plain

- λ'' = 10^{-8} —> non-prompt

uds



udb

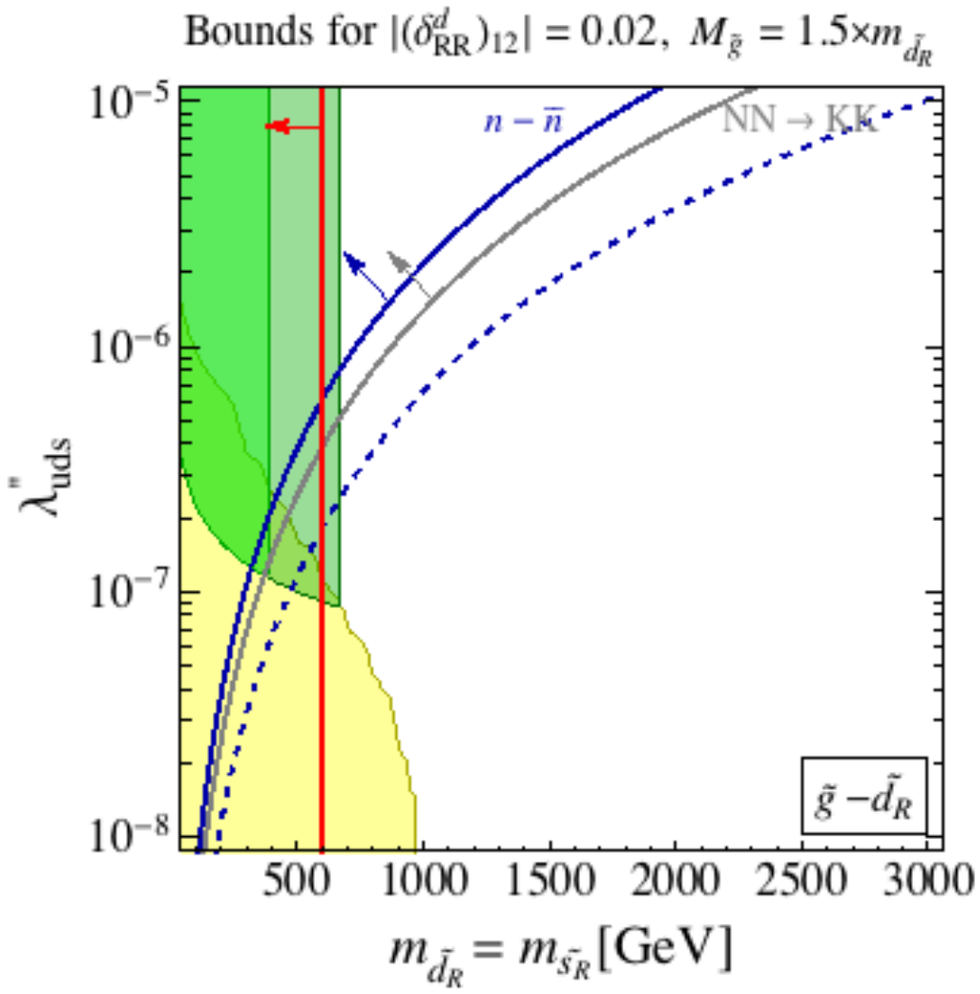


- LHC bounds similar in both cases
- other constraints weaker for udb
- ESS does not extend exclusion

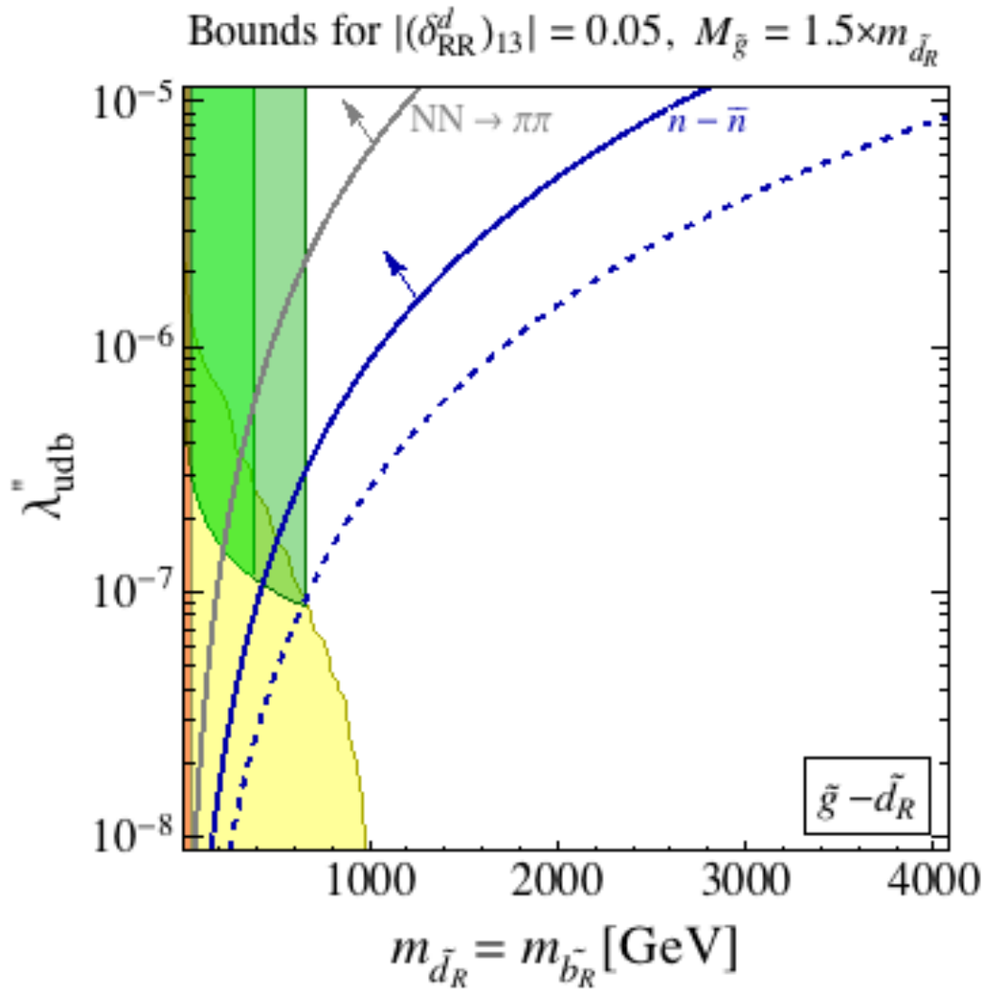
Results - Coupling Vs. Mass

- gluino mass = 1.5 squark mass

uds



udb

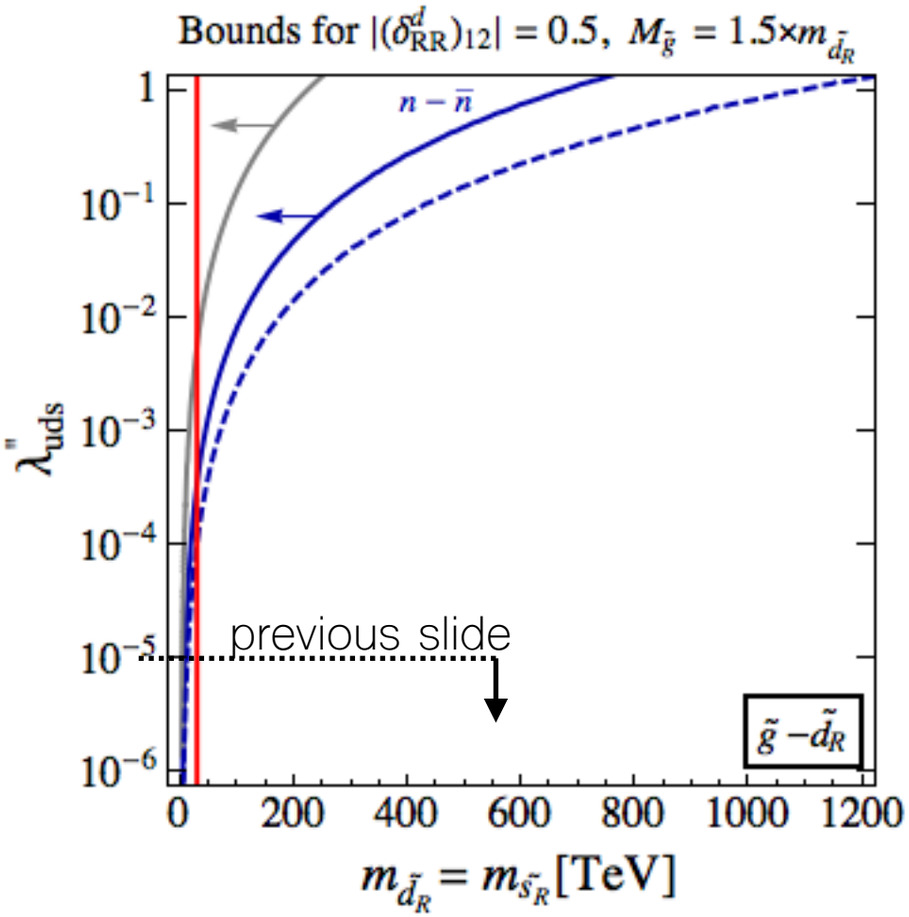


- for lambda not too small potentially large gain by ESS experiment

Results - "Best Case Scenario"

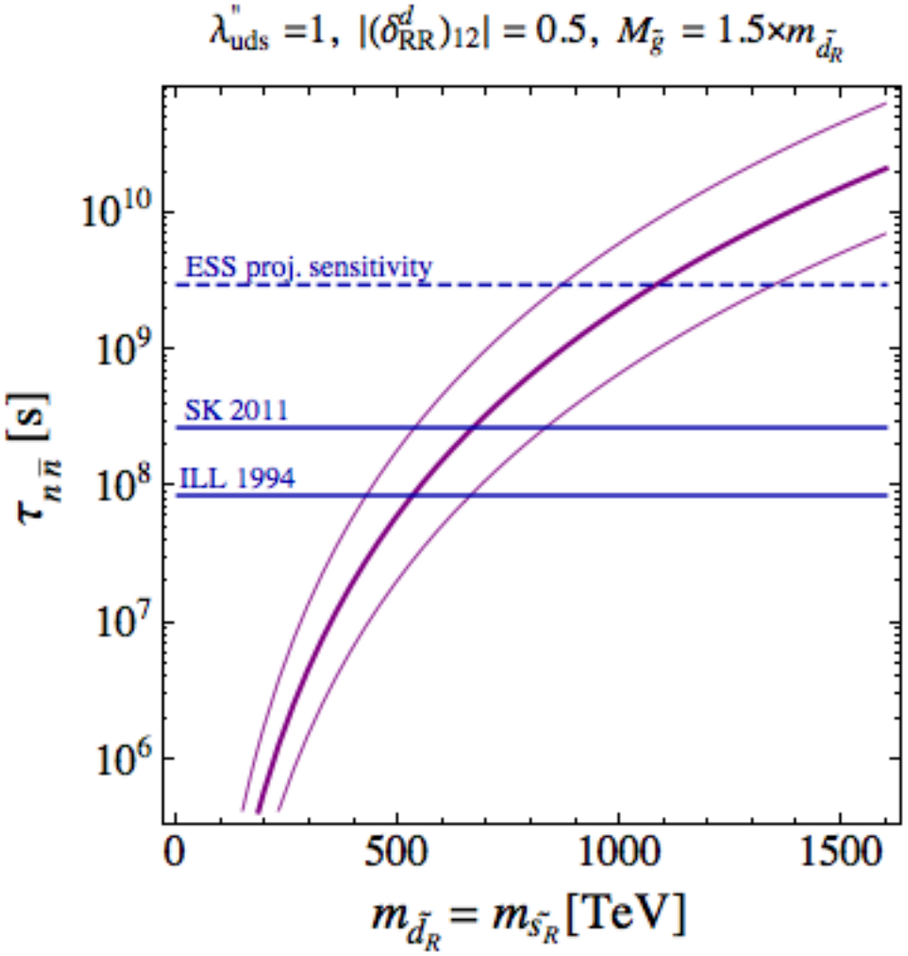
- λ''~O(1), large flavour mixing

coupling vs mass



- ε_K cuts up to ~30TeV
- n-$\bar{n}$ stronger than dinucleon

oscillation time vs mass



- large uncertainty from nuclear matrix element
- ESS experiment can extend mass reach

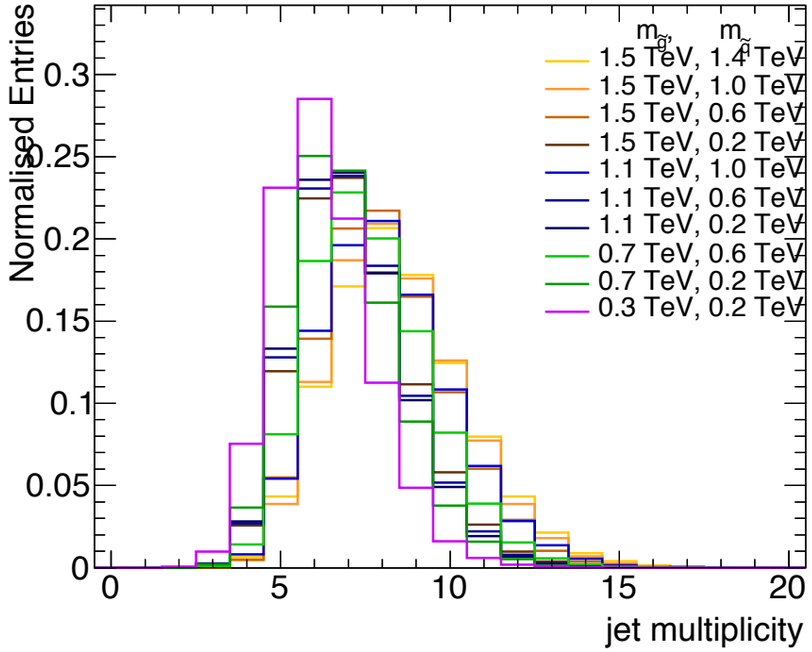
Summary

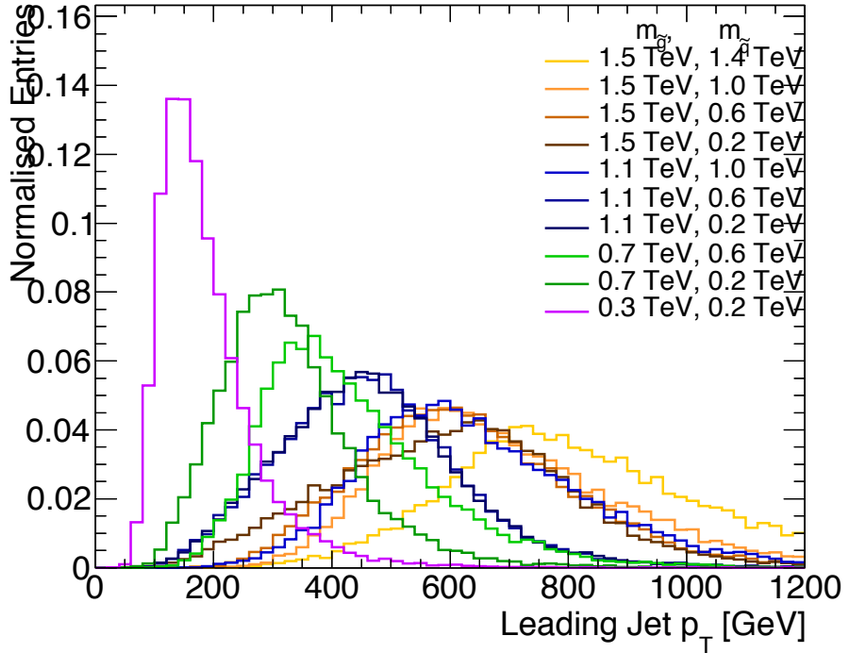
- BNV well motivated (experiment/theory)
- n-$\bar{n}$ oscillations high precision observable for pure BNV
- strong bounds from LHC in certain kinematic region
- complementary results from precision flavour measurements
- dedicated BNV experiments considerably extend reach in mass & coupling

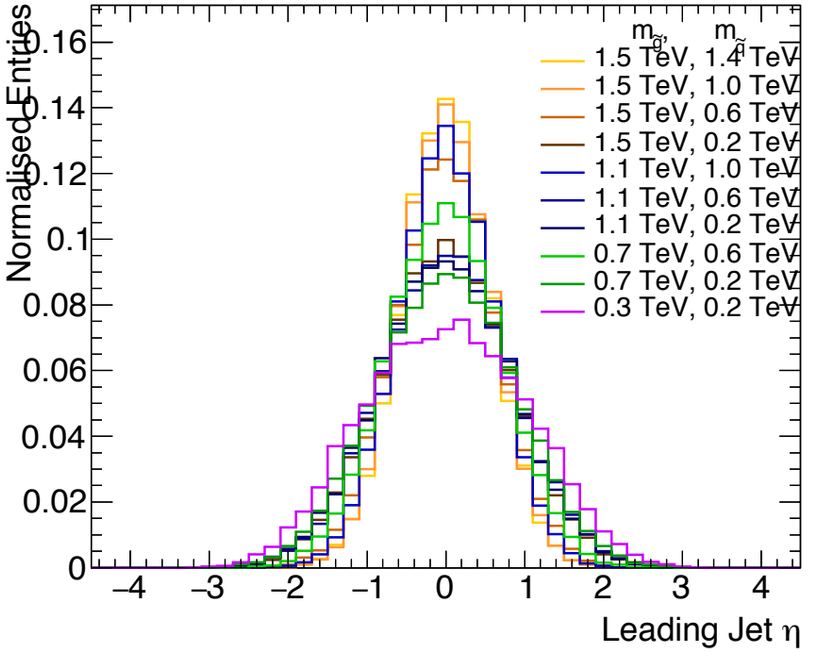
Additional Material

Simulation

- using MadGraph+Pythia8+Delphes (default ATLAS card)
- mass scan ($m_{\tilde{g}}$>$m_{\tilde{q}}$)
  - $m_{\tilde{g}}$: 0.3 –1.5 TeV
  - $m_{\tilde{q}}$: 0.2 – 1.4 TeV
- cross section for each mass configuration obtained from Prospino
- example: $\tilde{g}\tilde{q}$-production





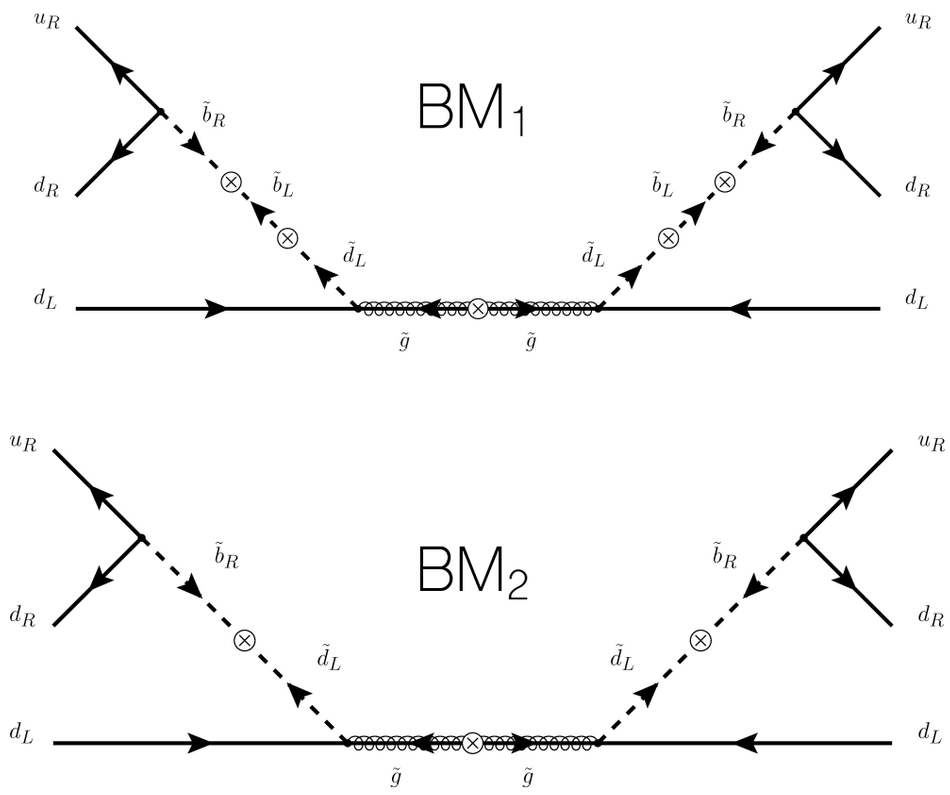


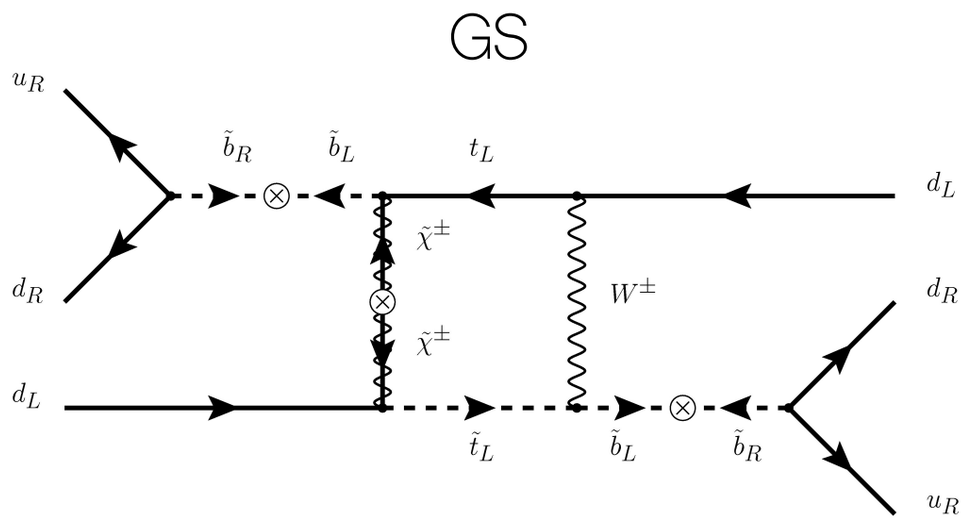
- higher masses => more jets, higher jet p_T, more central jets

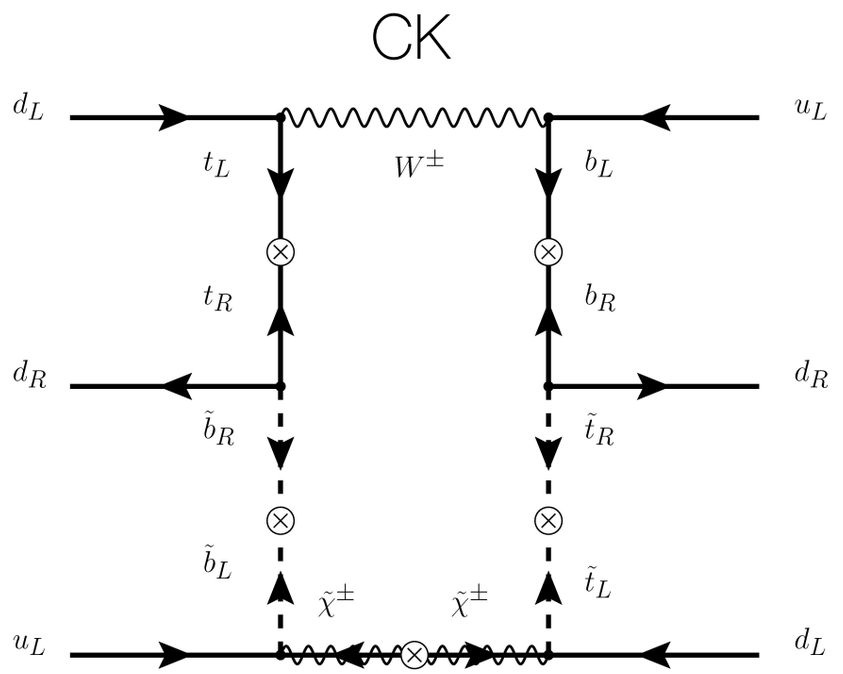
Models considered

- relevant subset of large number of possibilities

Model	Sparticle content	Couplings probed
Z_1	$\tilde{g}, \tilde{d}_R, \tilde{s}_R$	$\lambda''_{uds}, (\delta^d_{RR})_{21}$
Z_2	$\tilde{g}, \tilde{d}_R, \tilde{b}_R$	$\lambda''_{udb}, (\delta^d_{RR})_{31}$
BM_1	$\tilde{g}, \tilde{b}_R, \tilde{b}_L, (\tilde{t}_L), \tilde{d}_L, (\tilde{u}_L)$	$\lambda''_{udb}, (\delta^d_{LL})_{31}, (A_b - \mu \tan\beta)$
BM_2	$\tilde{g}, \tilde{b}_R, \tilde{d}_L, (\tilde{u}_L)$	$\lambda''_{udb}, (\delta^d_{LR})_{31}$
GS	$\tilde{\chi}^\pm, (\tilde{\chi}^0), \tilde{b}_R, \tilde{b}_L, (\tilde{t}_L)$	$\lambda''_{udb}, (A_b - \mu \tan\beta)$
CK	$\tilde{\chi}^\pm, (\tilde{\chi}^0), \tilde{b}_R, \tilde{t}_R, \tilde{b}_L, (\tilde{t}_L)$	$\lambda''_{tdb}, (A_b - \mu \tan\beta), (A_t - \mu \cot\beta)$

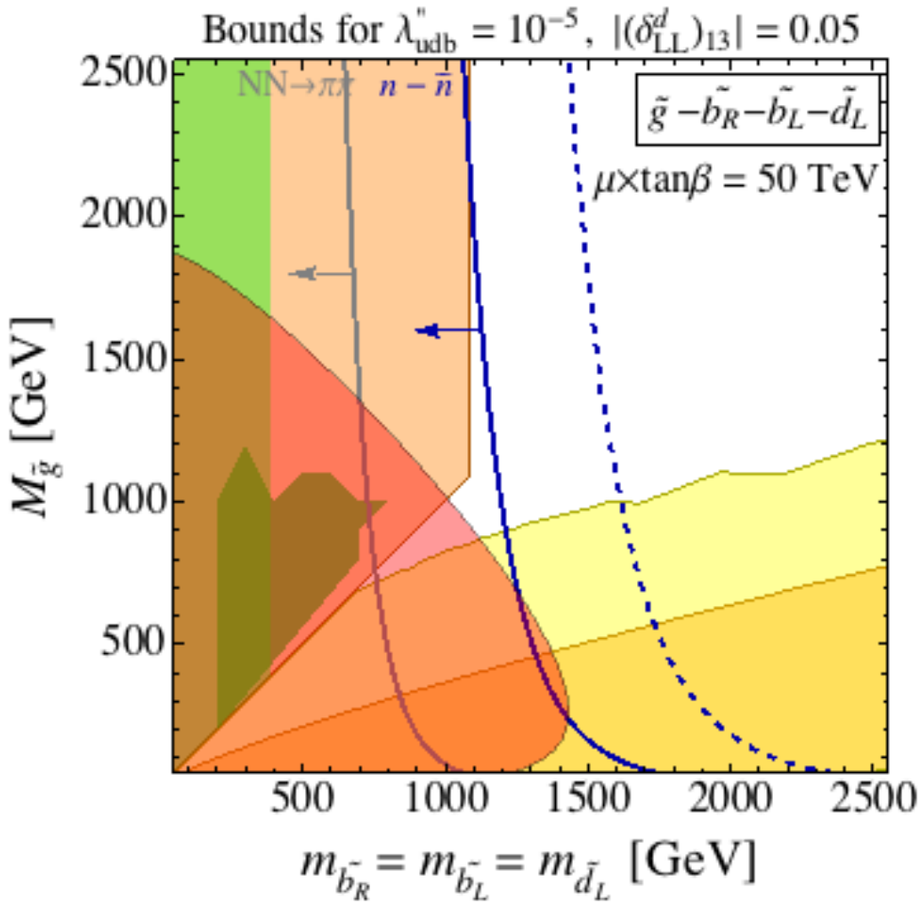


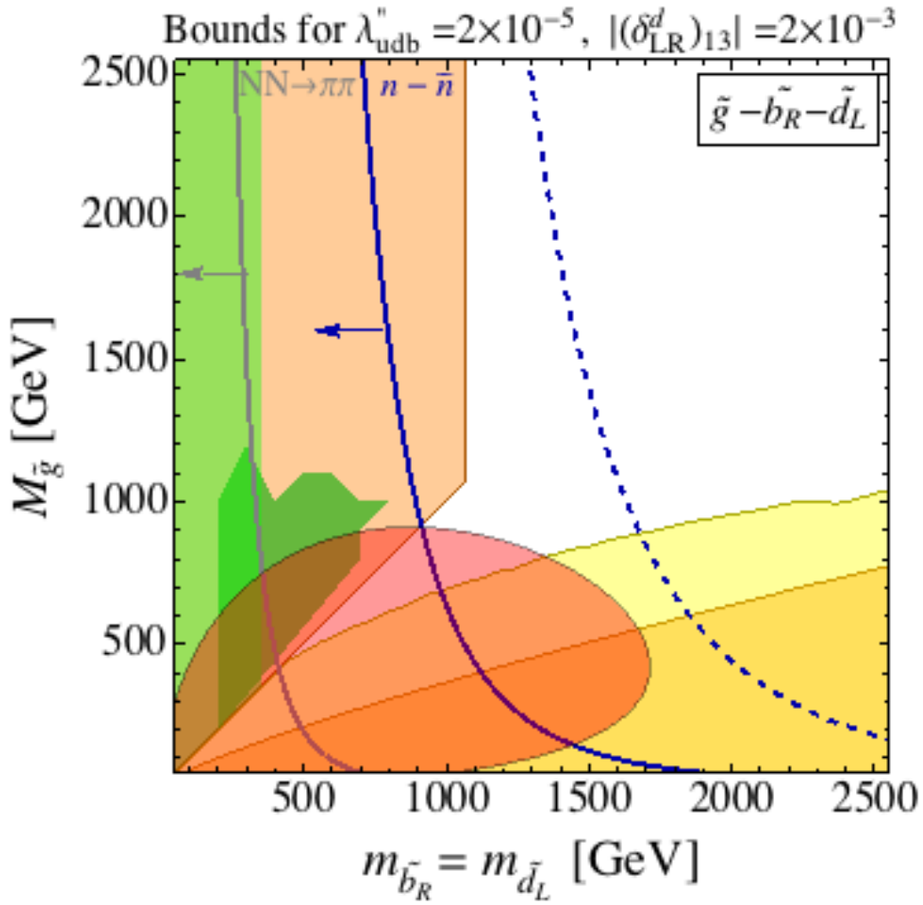




Bounds for BM models

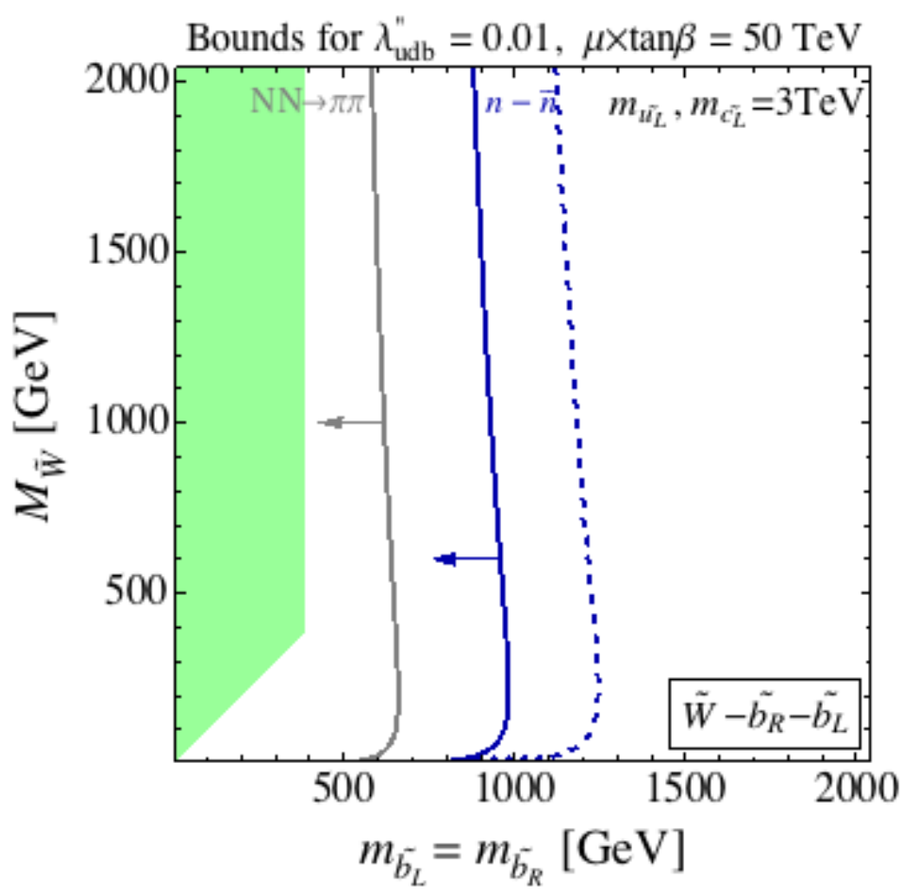
- bounds for BM_1 and BM_2 (MFV —> flavour mixing via detour)
  - red: constraints from $b \rightarrow d\gamma$

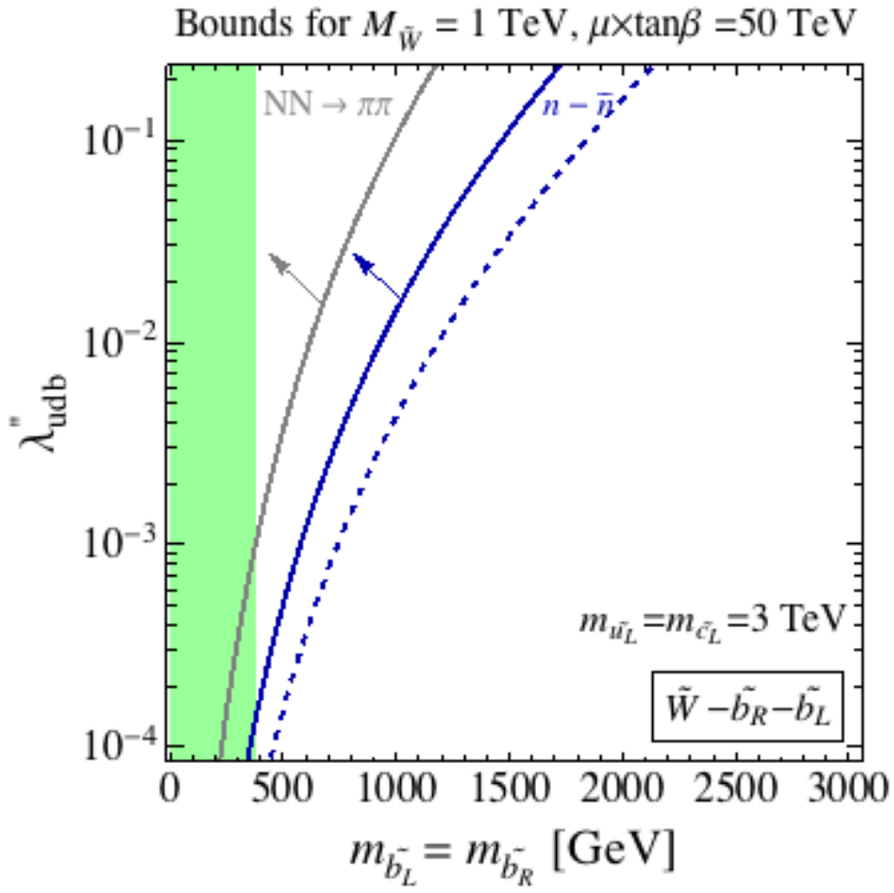




Bounds for GS model

- MFV by construction, no relevant bounds from flavour constraints
- LHC: only squark mass bound





Bounds for CK model

- MFV by construction, no relevant bounds from flavour constraints
- LHC: only squark mass bound