Searching for Physics beyond the Standard Model

Research Seminar, Lund University

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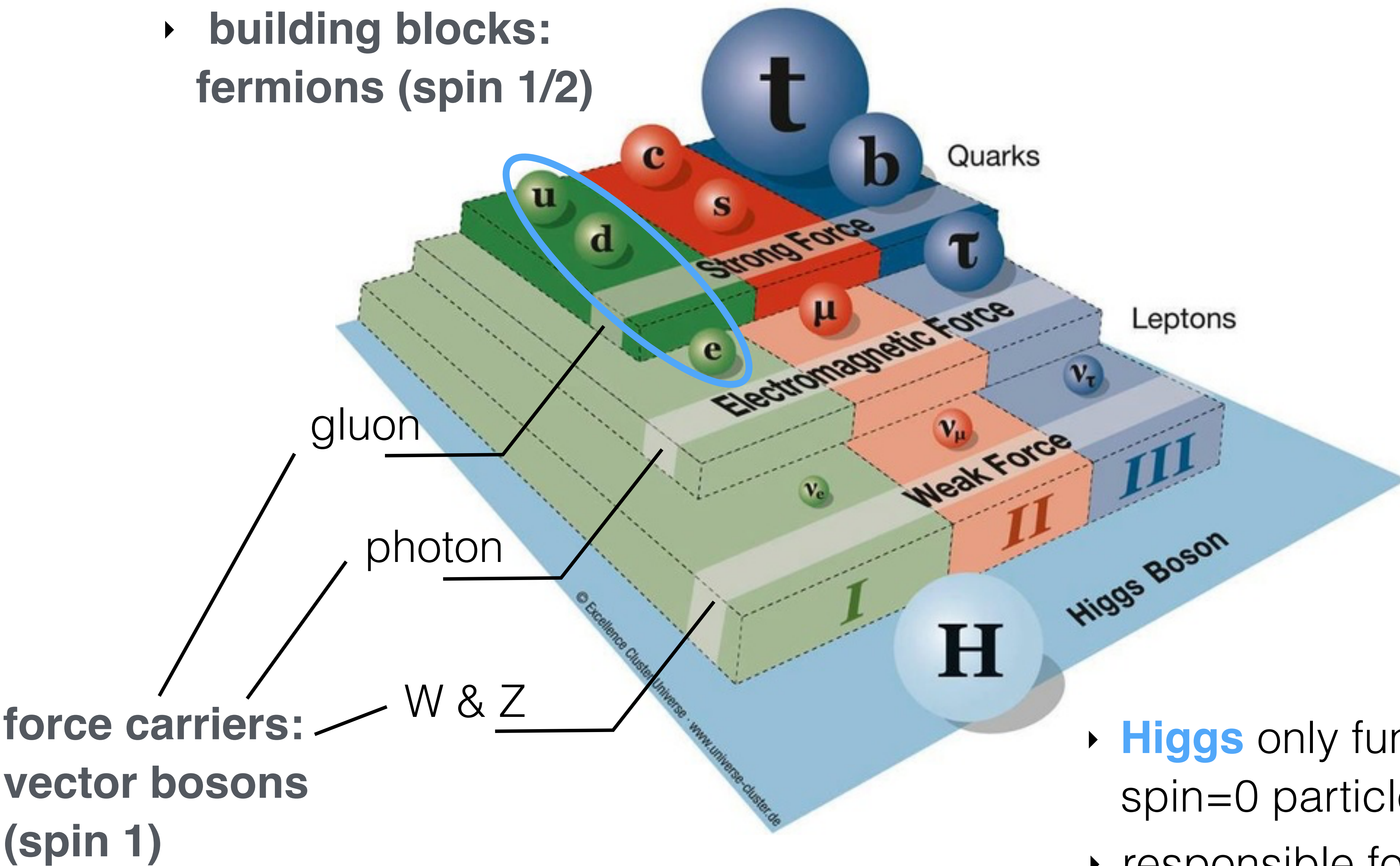
15 Nov 2016

Standard Model

- fundamental particles and their interactions



- **Higgs** only fundamental spin=0 particle
- responsible for masses of fundamental particles

Open Questions

https://apod.nasa.gov/apod/ap060824.html

- What is Dark Matter/Energy?

https://www.research.vt.edu/resmag/sciencecol/2002asymmetry.html

- Where is the anti-matter?
- Why so different interaction strengths?
- Why similarities between quark and lepton sector?
- several more…

Hypothetical Solutions

- various theories addressing one or several of the open questions
  - Supersymmetry, extra dimensions, Grand Unification…
- most predict **new particles** with masses at the **TeV scale**
- experiments look for evidence of such particles
  - production of new particles at colliders
  - observation of processes not present in the SM
  - deviation from prediction in precision measurements

Hypothetical Solutions

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this talk

Outline

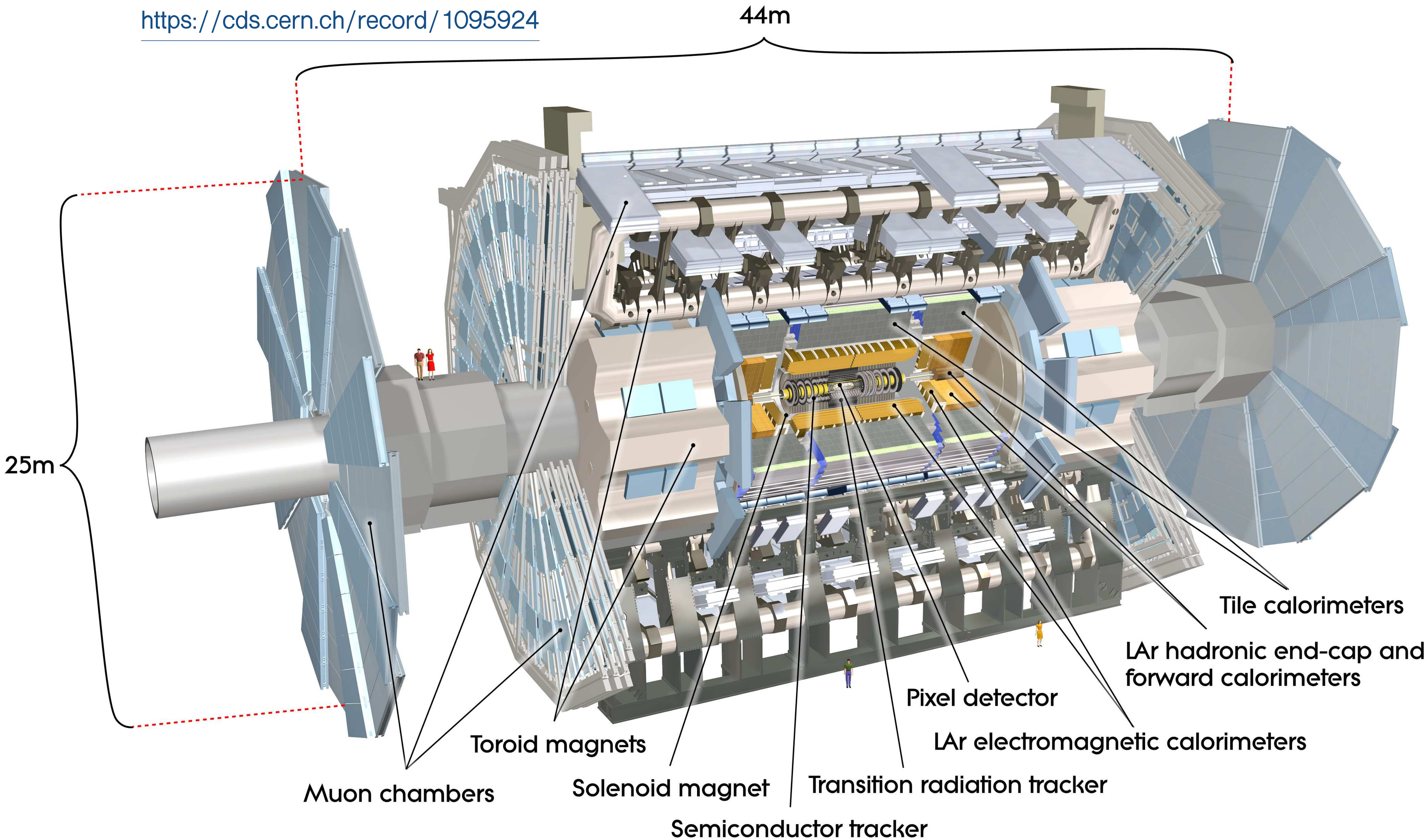
<u>Search for Dark Matter candidates</u>

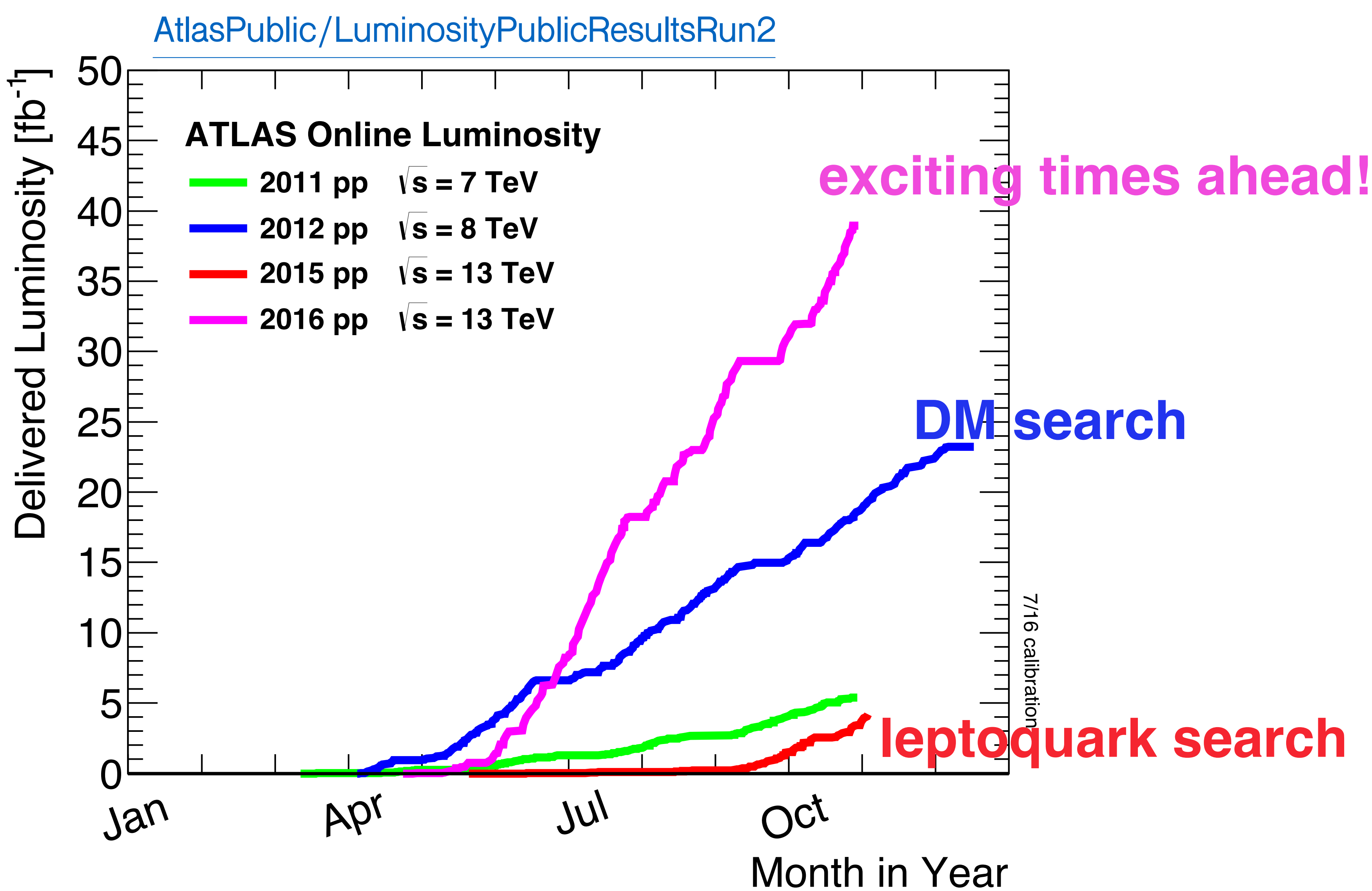
- WIMP Dark Matter
- collider mono-X signature
- ATLAS mono-jet analysis
- interpretation of results
- outlook and future plans

<u>Other Searches for new physics</u>

- ATLAS search for scalar leptoquarks
- phenomenological study on baryon number violation

https://cds.cern.ch/record/1095924




AtlasPublic/LuminosityPublicResultsRun2
ATLAS Online Luminosity
2011 pp √s = 7 TeV
2012 pp √s = 8 TeV
2015 pp √s = 13 TeV
2016 pp √s = 13 TeV
exciting times ahead!
DM search
leptoquark search
Delivered Luminosity [fb-1]
50
45
40
35
30
25
20
15
10
5
0
Jan
Apr
Jul
Oct
Month in Year
7/16 calibration

Search for Dark Matter Candidates

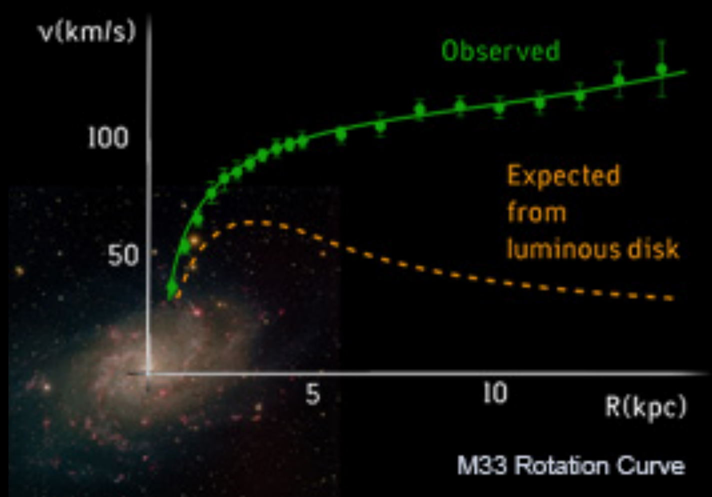
- using 20 fb^{-1} of $\sqrt{s}$ = 8 TeV ATLAS data

Springer Theses (2016) 978-3-319-41044-9

and EPJC 75 (2015) 299

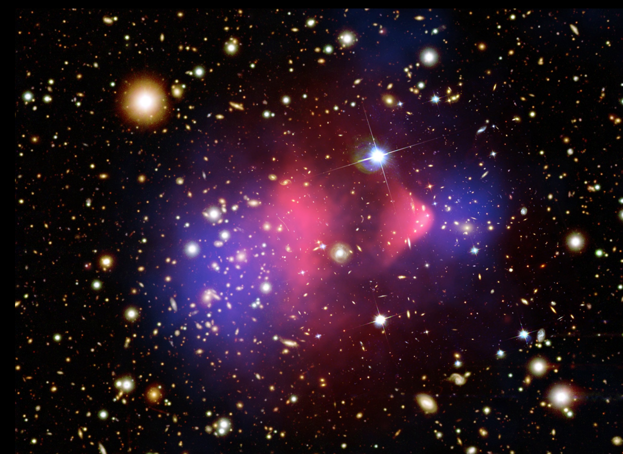
Why Dark Matter?

rotation velocity curves of stars in galaxies



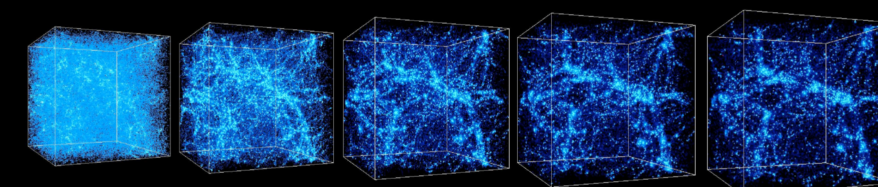
© M33 Image: NOAO, AURA, NSF, T.A.Rector.

galaxy clusters



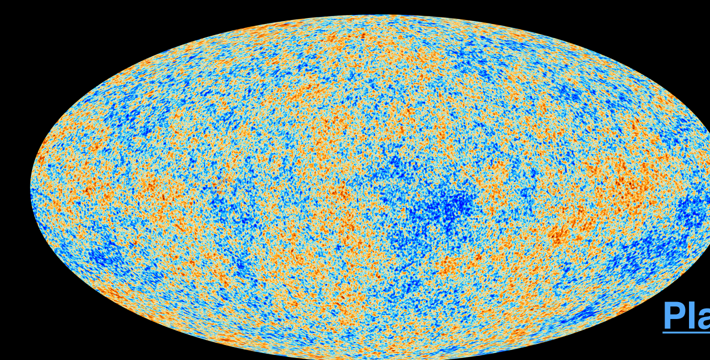
https://apod.nasa.gov/apod/ap060824.html

structure formation



http://cosmicweb.uchicago.edu/filaments.html

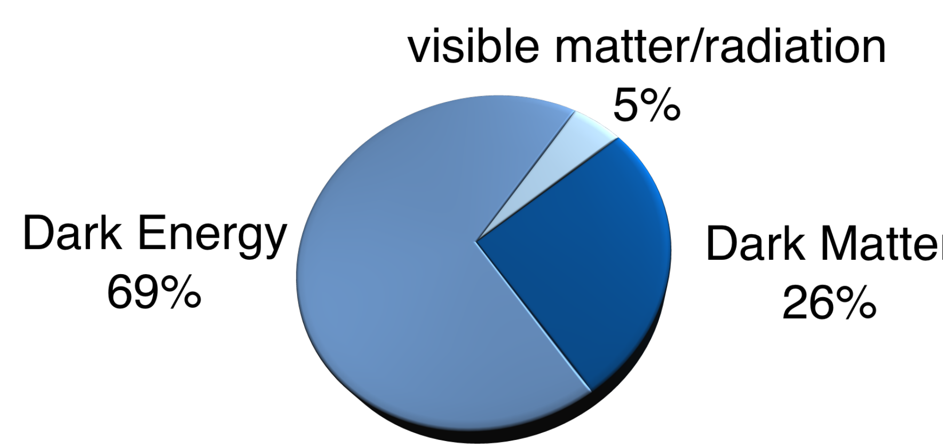
cosmic microwave background



Planck

- compelling **evidence** for existence of non-luminous matter on largely different **cosmological** scales => "**Dark Matter**"

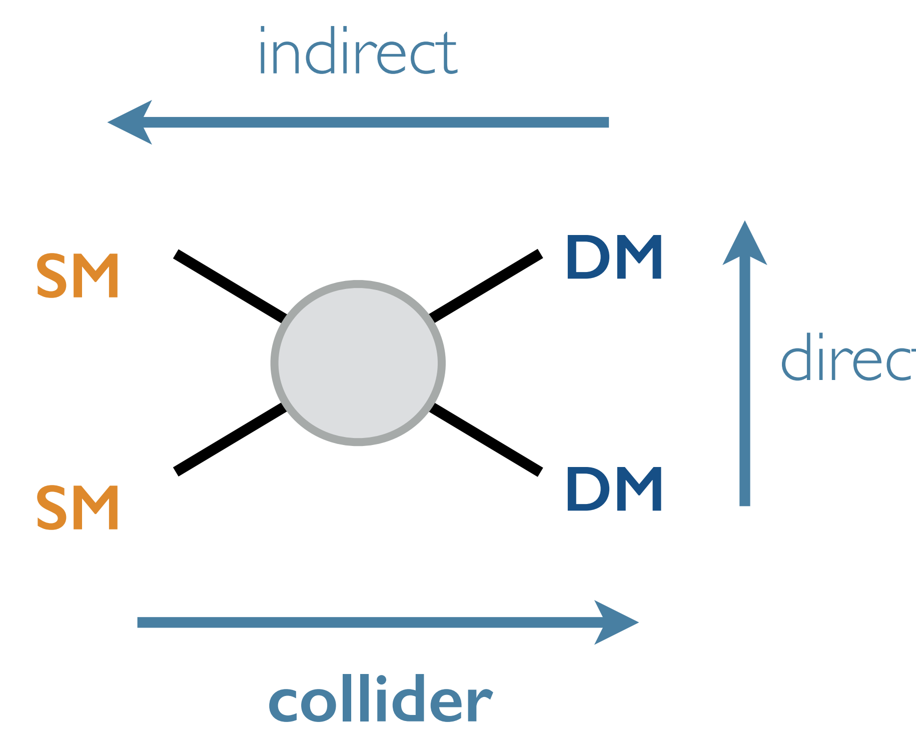
- **~1/4** of the universe's matter-energy budget
  - ~5 times as much as 'normal' matter

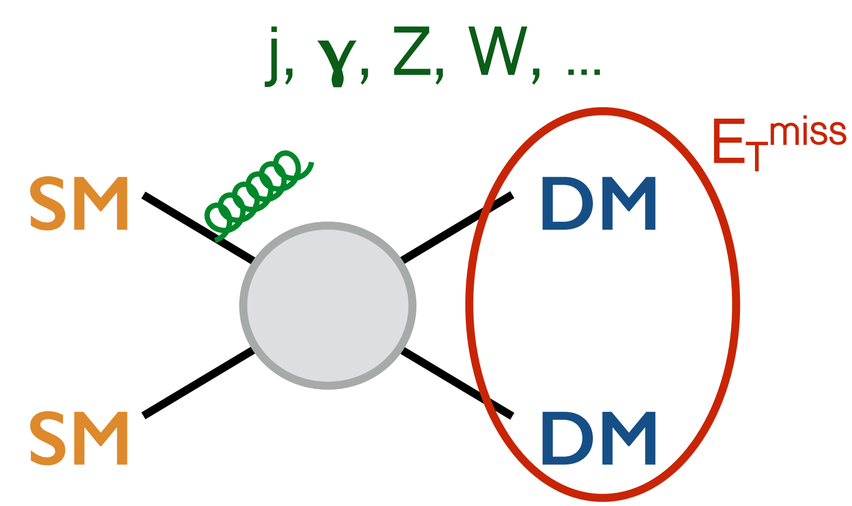


Planck

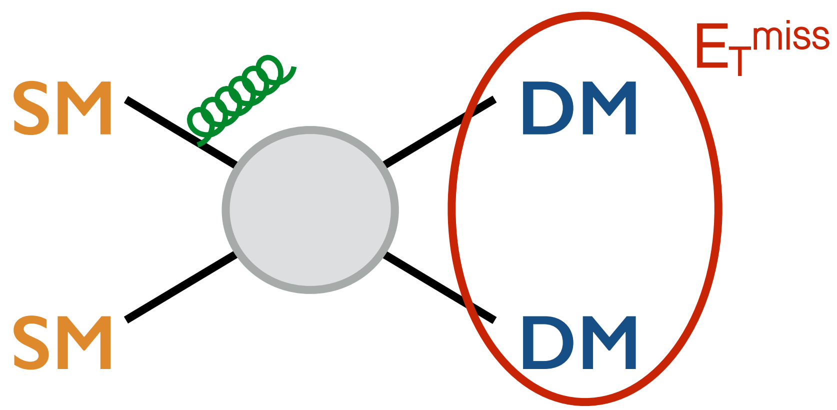
Dark Matter Searches

- **no viable candidate** within Standard Model (SM)
- popular generic class of new particles:
  weakly interacting massive particles (**WIMP**s)
  - broad search programme, mainly 3 approaches
  - **interacting** = interacting non-gravitationally
  - **weakly** interacting
    —> escape collider experiment undetected
    - **additional** (high pT) object to **trigger** on
      - missing transverse energy ($\mathbf{E_T^{miss}}$)
        from recoiling WIMPs
      - => "mono-X" searches
  - **massive** —> can account for relic density

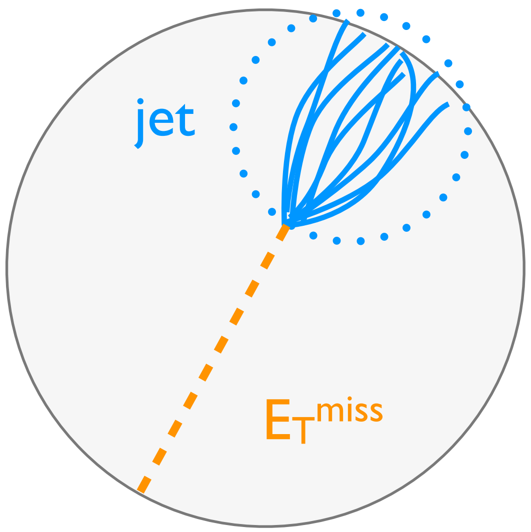




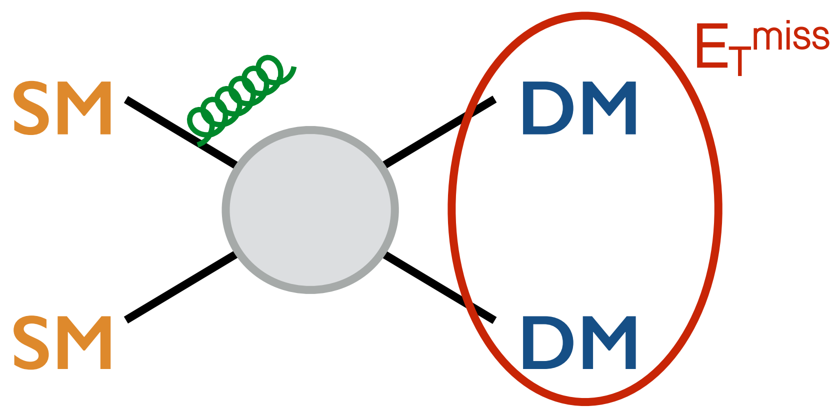
Monojet Signature



- highly energetic **jet**
  + large **missing E_T**



Monojet Signature



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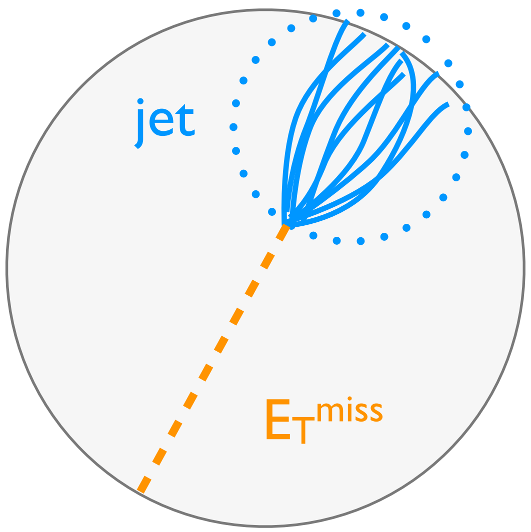
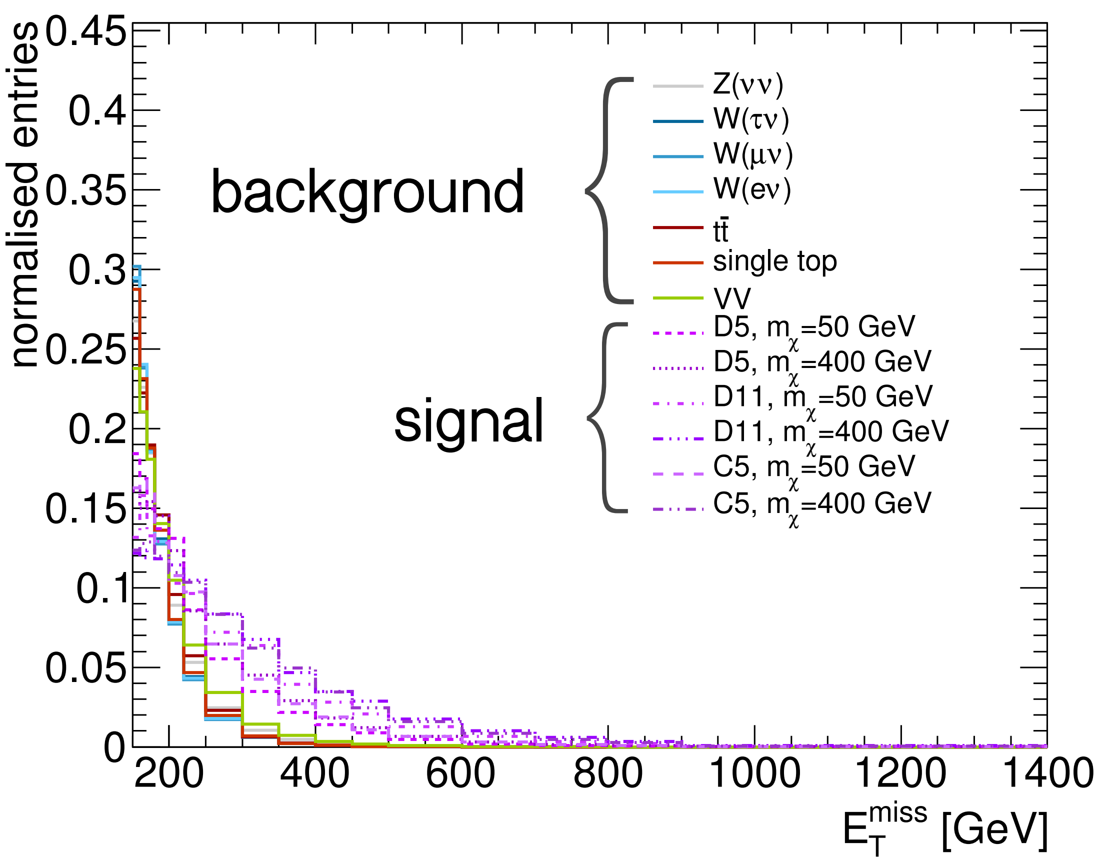




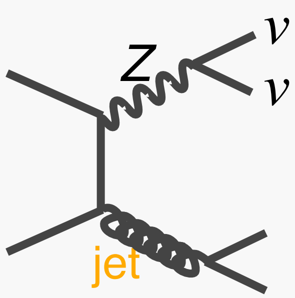
- larger WIMP mass => higher E_T^{miss}
- missing E_T as discriminant variable
- “cut&count” experiment

=> search for excess over SM prediction at high E_T^{miss}

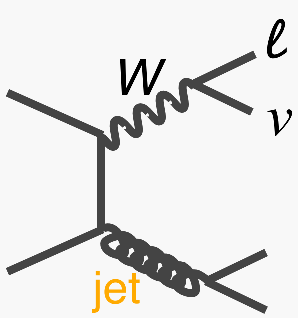
SM Backgrounds

- various **SM processes** can lead to the **same signature**

semi-data driven



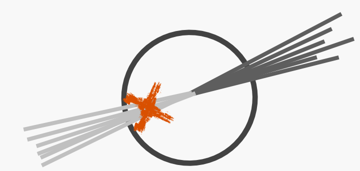
- Z(νν) + jet
  irreducible, largest contribution



- W(lν) + jet
  leptons not identified
  hadronic tau-decay

data driven

- Multi–jet



- Non–collision background (NCB)
  beam halo, cosmic muons...

} *only at low E_T^{miss}*

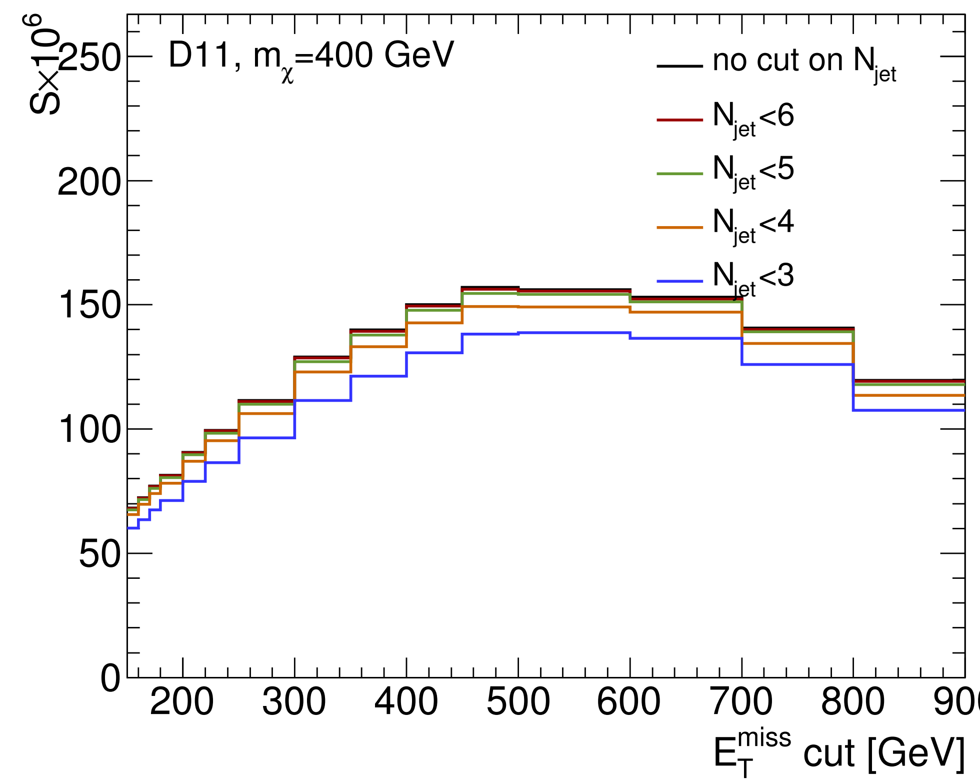
simulation based

- Z(ℓℓ)+jets
- single top
- $t\bar{t}$
- Diboson (VV)

- introduce **dedicated cuts** for suppression

Optimised Event Selection

- high-p_T jet (anti-kt algorithm, distance parameter 0.4)
- large missing E_T
- separation between E_T^{miss} & jets ($|\Delta\phi|>1.0$)
- lepton veto



+ optimisation

=> no restriction on jet multiplicity

=> asymmetric cuts:

leading jet $p_T > 120$ GeV

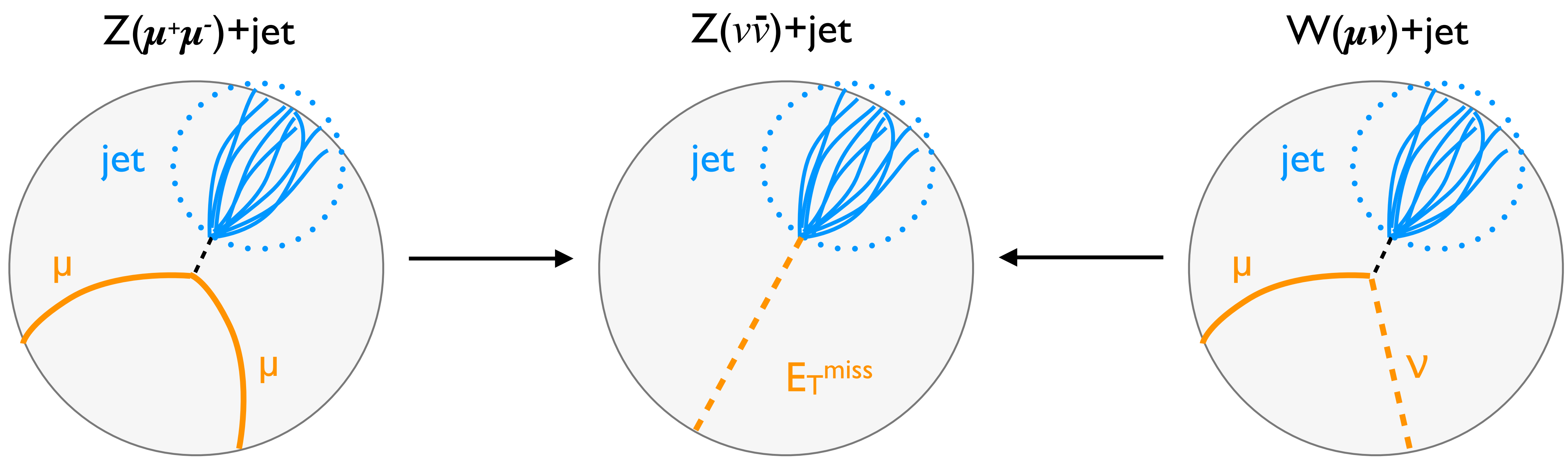
8 inclusive signal regions (SR1 - SR8) for cut&count:

150, 200, 250, 300, 350, 400, 500, 600 GeV < E_T^{miss}

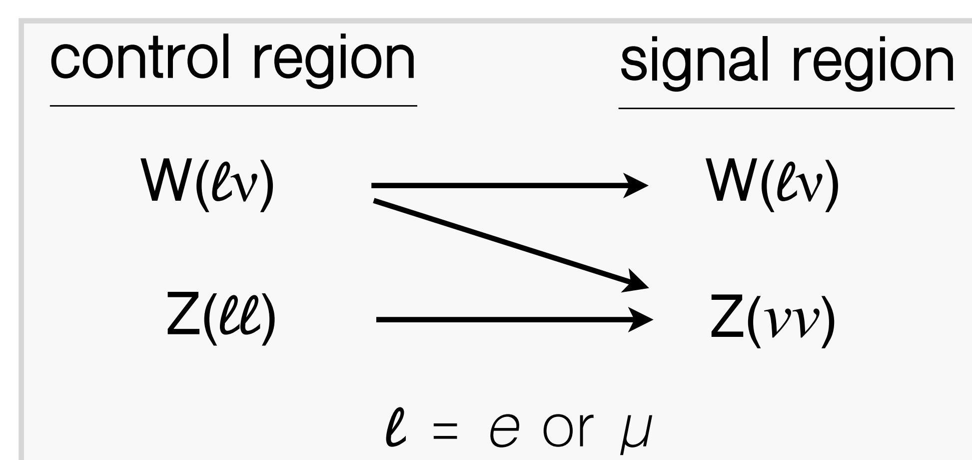
W/Z Estimation - Idea

- **main backgrounds** => precise estimation essential
- use W/Z+jets events in **data** to **normalise** simulation & **correct shape** of distributions
- for Z(νν): "treat leptons as missing E_T"

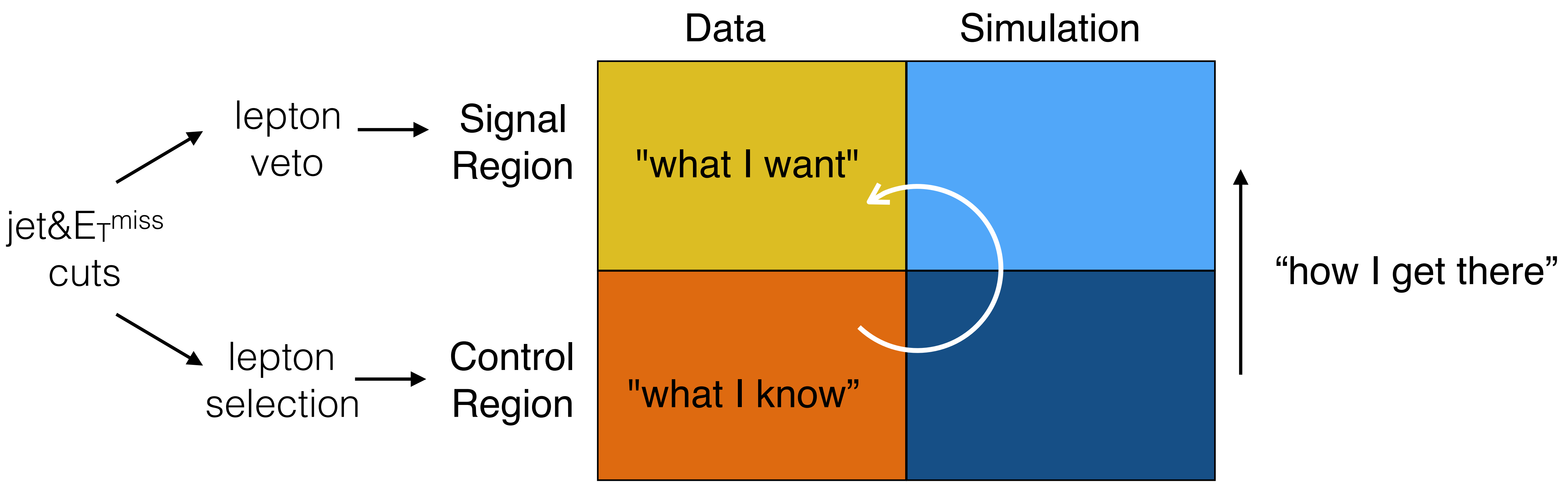
example:
muon channel



- 4 **control region** (CR) processes:
  W&Z+jets with decay into e or μ
- 4 estimates for Z(νν) —> **combination**!
- W+jets events for estimation of W+jets



W/Z Estimation - Procedure



- simulation only in **ratios**

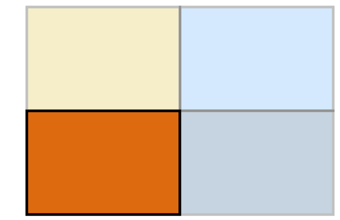
  => **reduce** systematic uncertainties (e.g. luminosity)

- applied **bin-by-bin**

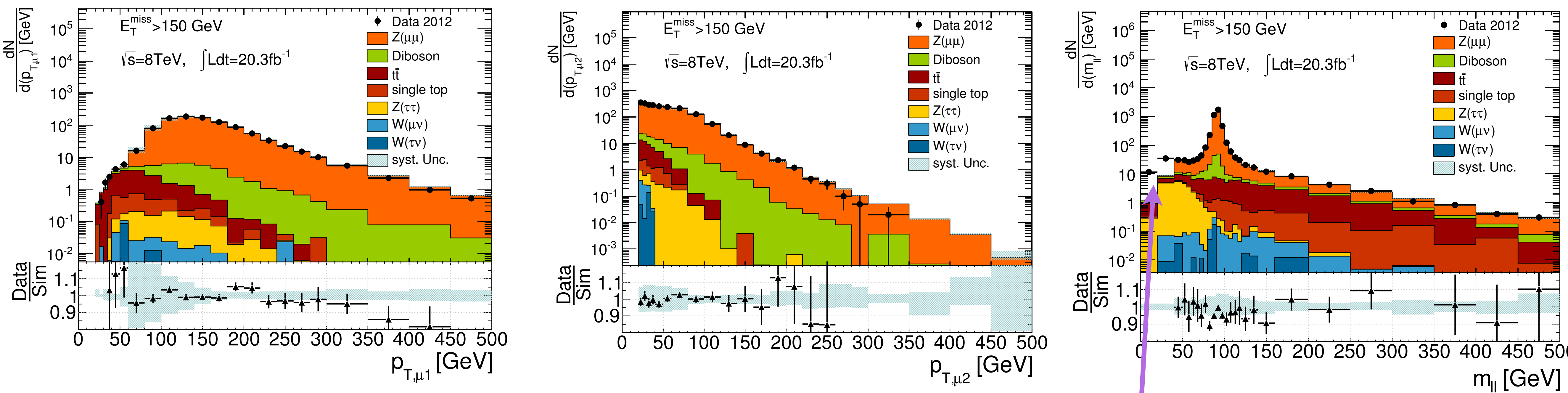
  => correct normalisation & shape

CR example

- **control region specific** variables (lepton, boson) need to be modelled well
  (jet/E_T^{miss} variables "protected" by transfer factor method)



- some control plots from Z(μμ) control region with E_T^{miss} > 150GeV (CR1)



generator cut on invariant mass

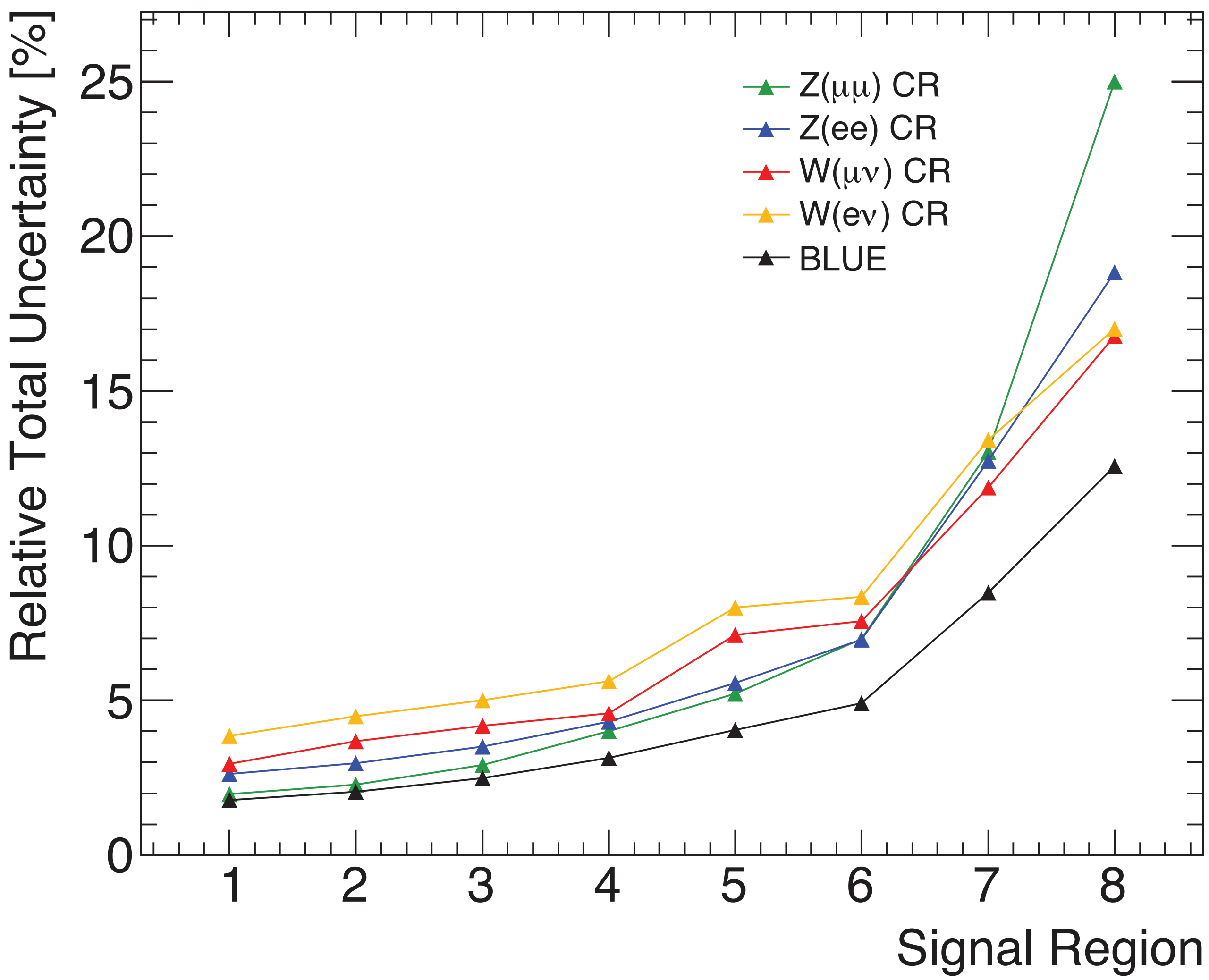
- simulation normalised to data (factor 0.92)

- agreement between data and prediction within uncertainties

  => **'good' control region**

Combination

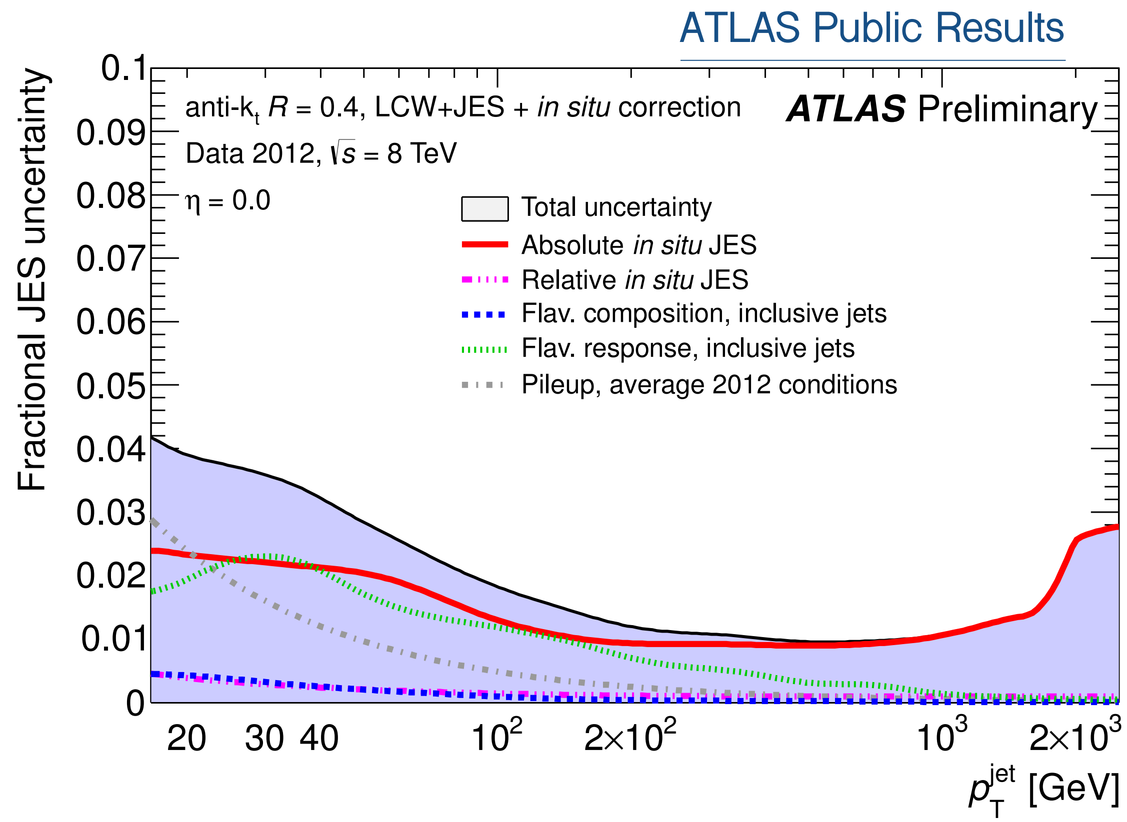
- using ‘best linear unbiased estimator’ (**BLUE**) method



- total uncertainty reduced by combination

Reduction of Systematics

- example: **jet energy scale** (propagated to E_T^{miss})

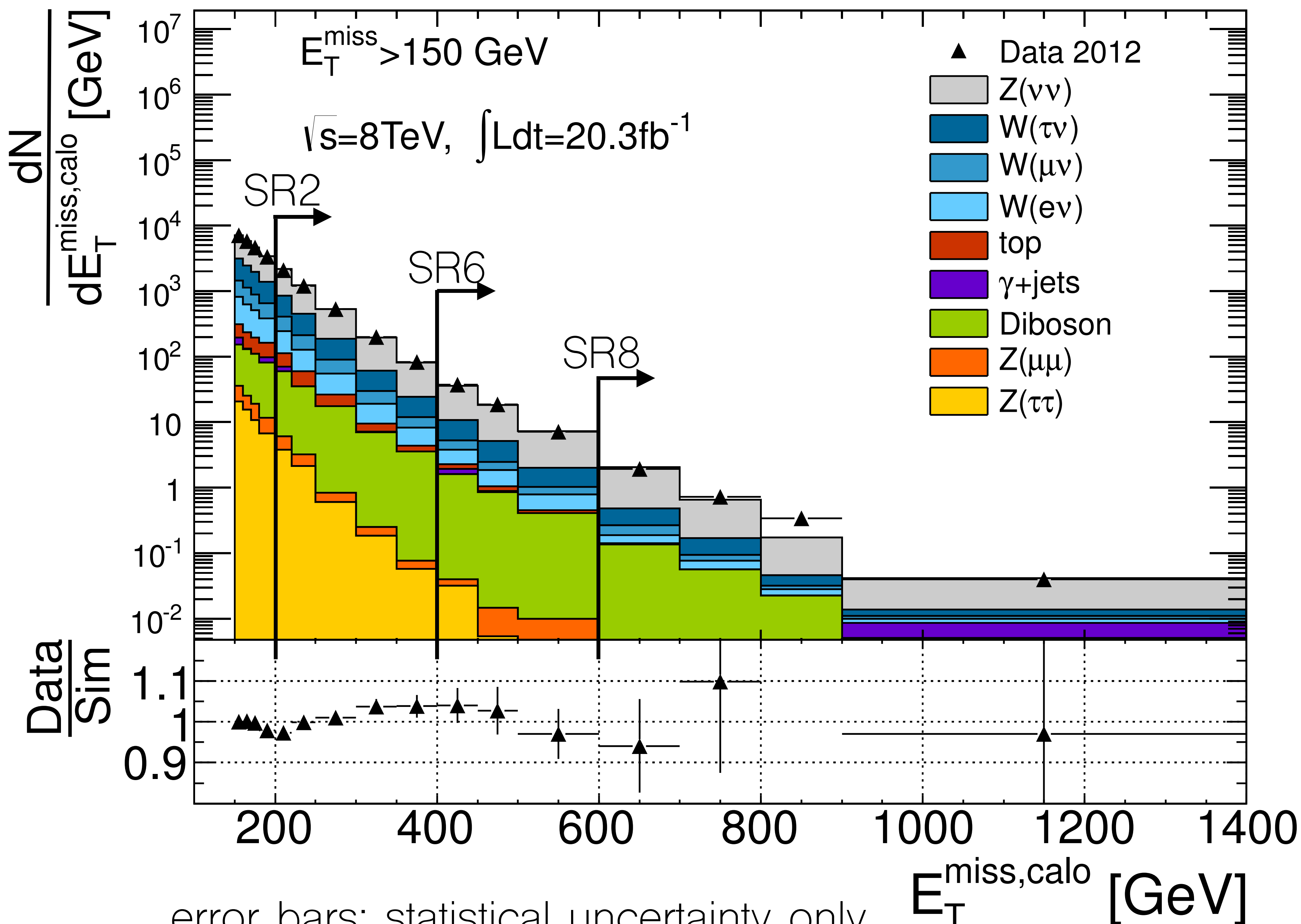


  - depends on η and p_T of the jets, 1-10%
  - raw simulation: ~10%
  - data-driven estimates: 0.5-4%
  - combined Z(νν) estimate: ≤1% (3% SR8)
  - final background estimate: ~1%

many systematics reduced by use of simulation ratios and Z(νν) combination

8 inclusive signal regions (SR1 - SR8) for cut&count:

150, 200, 250, 300, 350, 400, 500, 600 GeV < E_T^{miss}

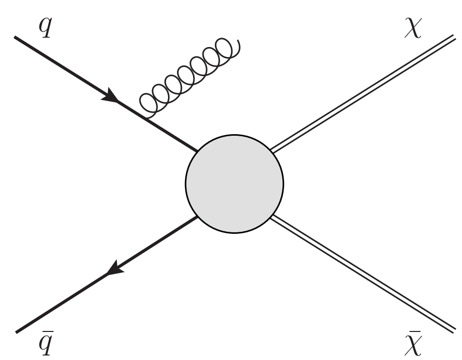


error bars: statistical uncertainty only

- **no significant deviation from SM prediction**

Signal Description

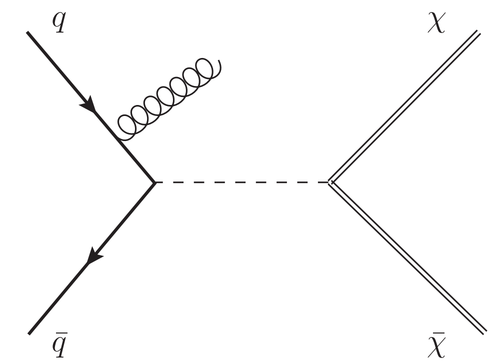
Effective Field Theory (EFT)



minimal assumptions:

- WIMPs only new particles in reach of LHC
- mediator too heavy to be produced on-shell
  - integrated out —> contact interaction
- only two parameters:
  - suppression scale **M_***
  - WIMP mass **m_χ**
- consider subset of possible operators
- straight-forward **conversion** into non-collider parameters
- **applicability** questionable at LHC energies

Simplified Model

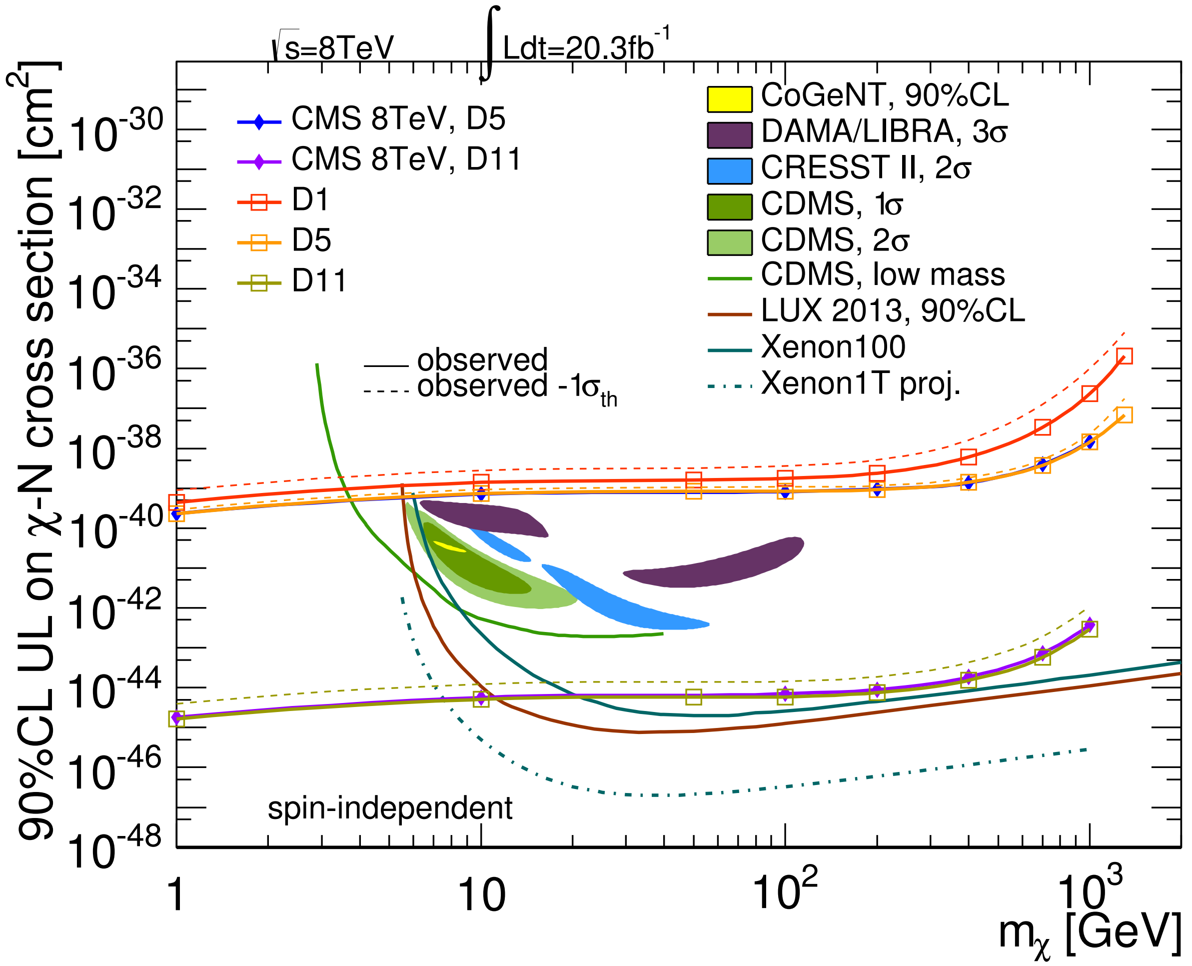


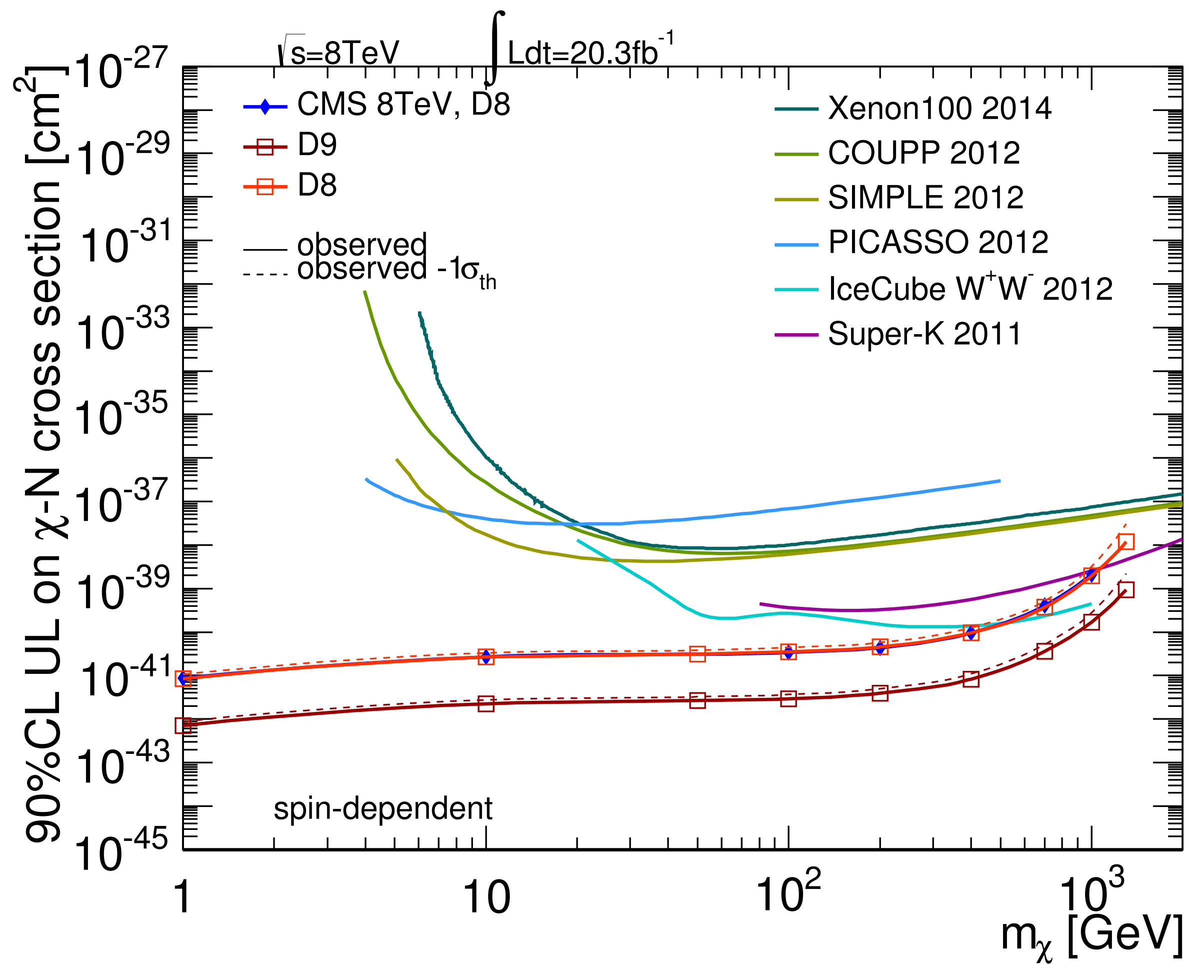
less general

- s-channel vector mediator
- larger number of parameters:
  - mass M_{Med}
  - width Γ_{Med}
  - couplings g_{SM}, g_{DM}
  - WIMP mass m_χ
- comparison with non-collider more involved
- **no concerns about validity**
- default for run-2

Comparing to other Experiments

- **upper** limits on WIMP-nucleon-scattering cross section



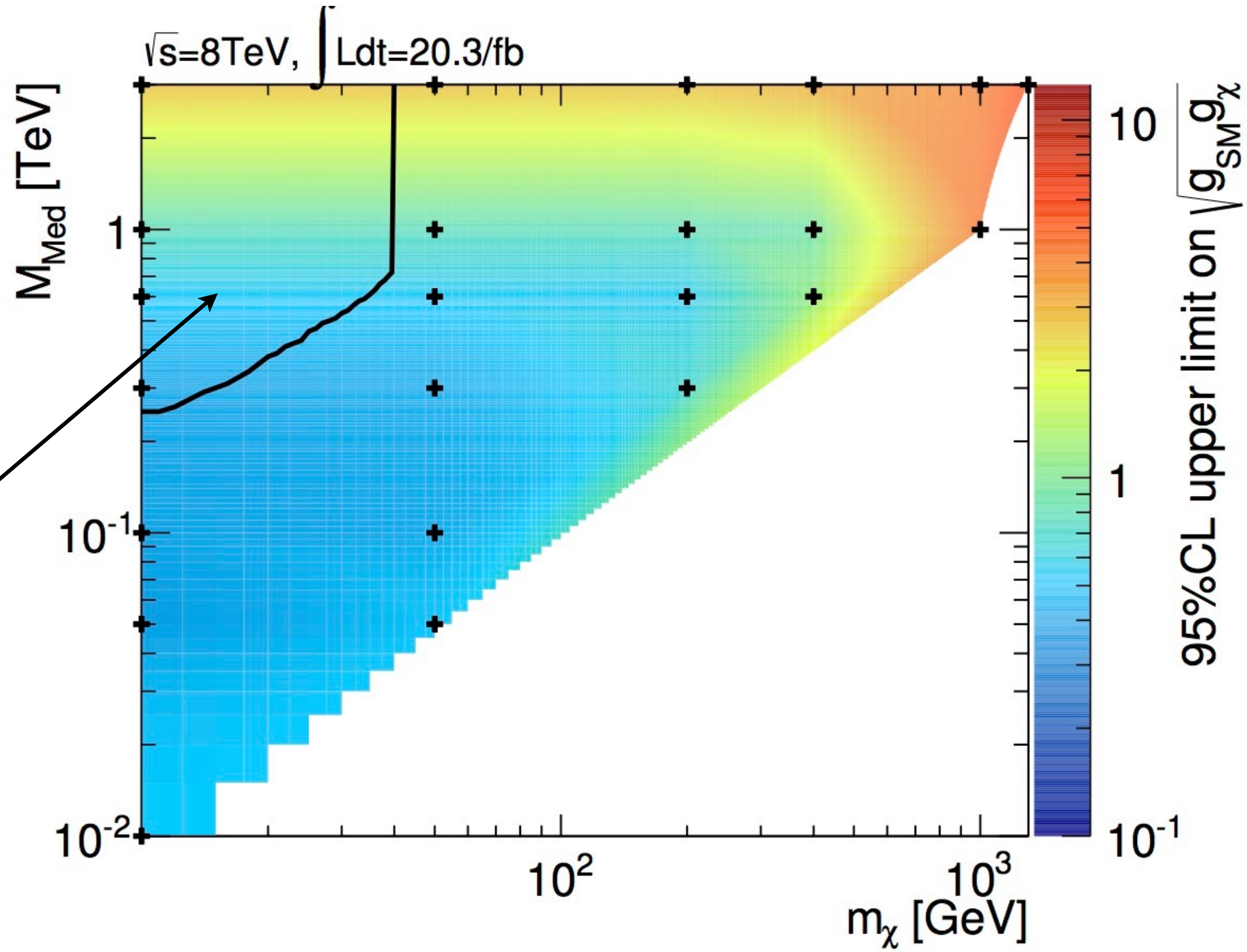


- **spin-independent:** collider limits stronger at low WIMP masses
- **spin-dependent:** collider limits stronger over large range of WIMP mass

- ATLAS and CMS very similar
- **some of the strongest collider limits** (especially gg-operator)
- **improvement** wrt previous result: factor ~3-10

Limits on Vector Mediator Model

- limits on √($g_{SM}g_\chi$)



- lower limits from relic abundance above upper limits derived here

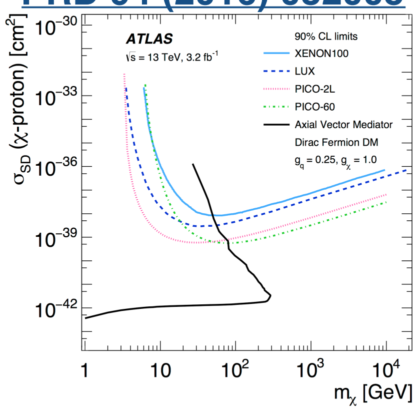
=> parameter space excluded (for WIMPs with standard production mechanism)

=> connection to astrophysics

- shift to simplified models for run-2 **ATLAS/CMS DM Forum report**
- **suite of mono-X searches**, ATLAS & CMS

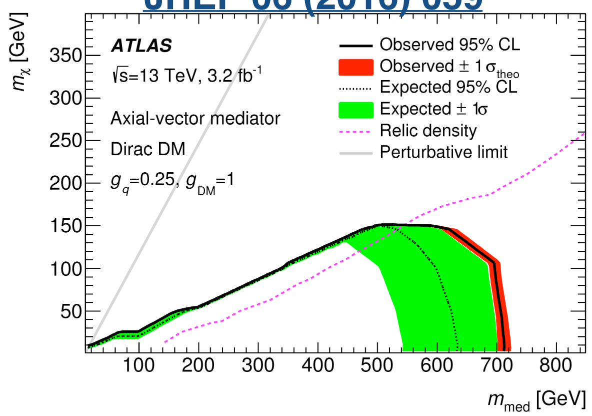
X=j

PRD 94 (2016) 032005



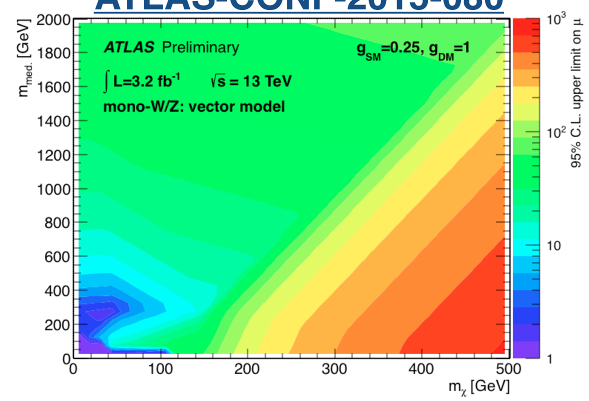
X=γ

JHEP 06 (2016) 059



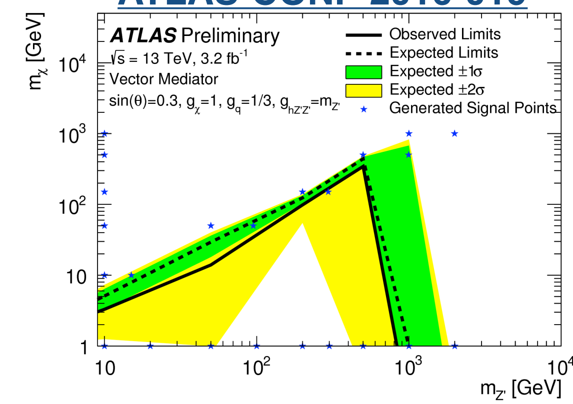
X=W/Z

ATLAS-CONF-2015-080



X=H

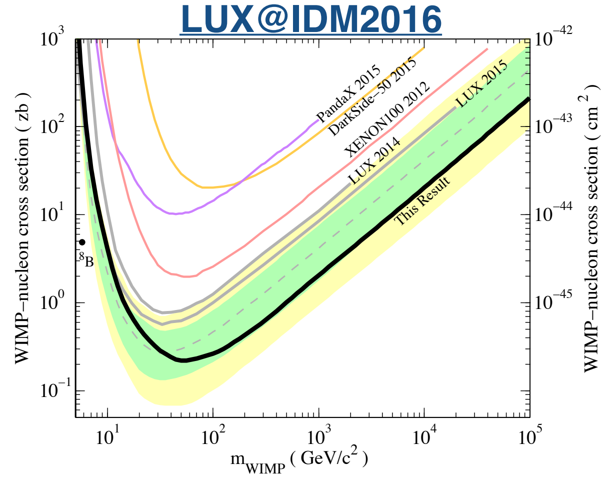
ATLAS-CONF-2016-019



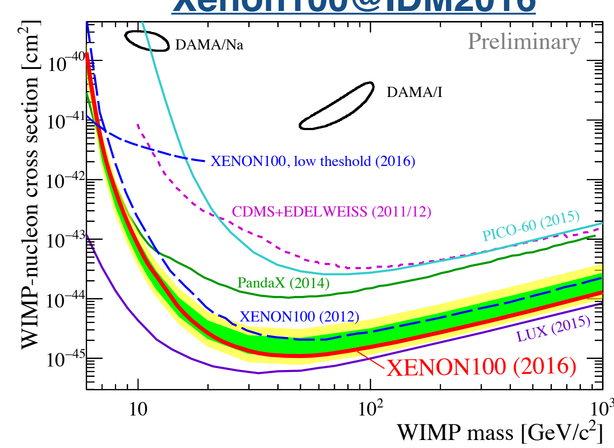
- for some models: **DM WG recommendations**

- many recent results from **direct detection** experiments

LUX@IDM2016



Xenon100@IDM2016



...

so far no unambiguous signal anywhere

Outlook & Future Plans - ATLAS

- LHC run-2 holds **great potential** for mono-X searches
  - particularly interesting: **mono-Higgs** searches
    - probe **different models** than other mono-X searches
      - comparisons to other experiments?
      - collaboration with phenomenologists
    - **new** after Higgs discovery
      - room for **improvements**
        - H—>bb (largest branching ratio)
          - alternative background estimation
          - b-tagging in boosted regime
      - **unexplored** channels
        - H—>WW (2nd largest BR)
          - sub-structure techniques, “di-boson tagging"

- **exciting field with ample room for development**
  - **my goal for the next years of LHC operation**

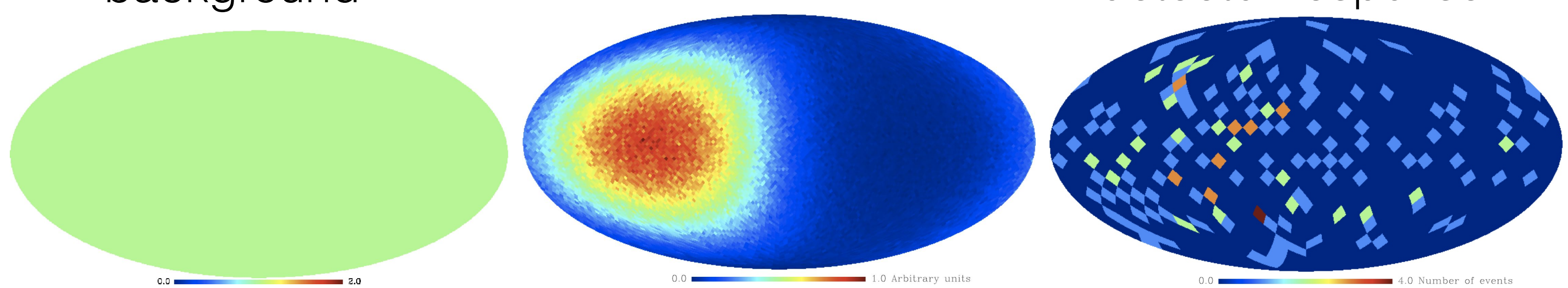
Outlook & Future Plans - Direct Detection

- next generation DD experiments will (almost) reach "**neutrino floor**" (irreducible neutrino background)

- **directional direct detection**
  - study direction of recoil

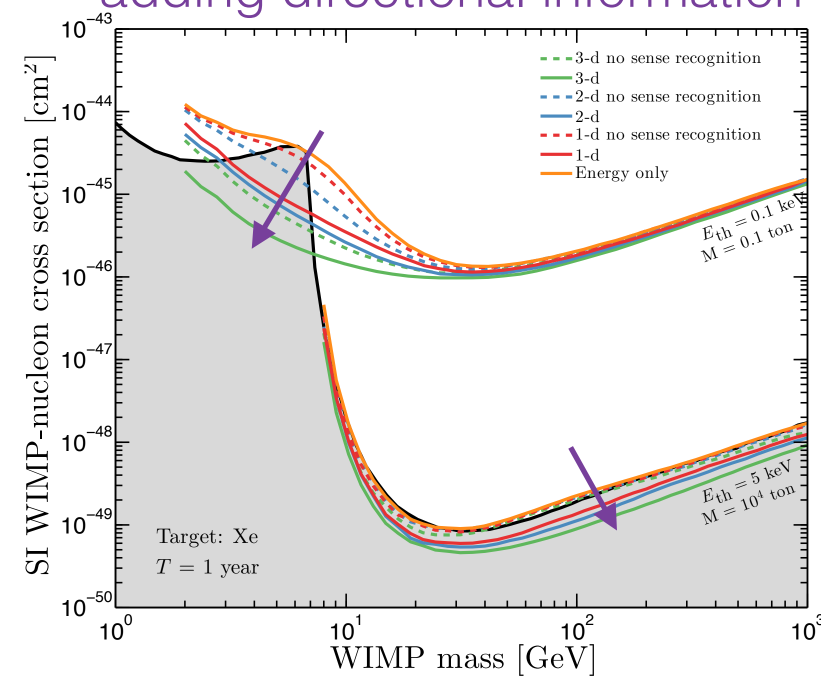
background signal detector response

arxiv:1304.2255



- distinguish between models
- reach beyond neutrino floor

adding directional information



arxiv:1602.03781

- **“dual use” —> promising future concept**
- **plan to get active in this area**

Search for Scalar Leptoquarks

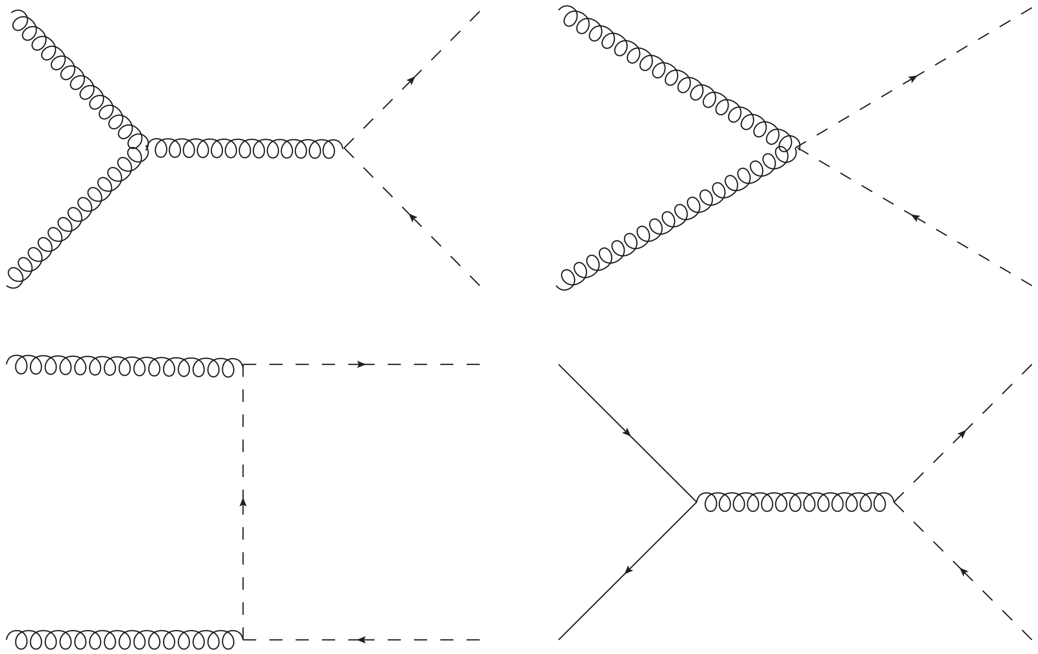
- using 3.2 fb^{-1} of $\sqrt{s}$ = 13 TeV ATLAS data

NJP 18 (2016) 093016

Leptoquarks

- similarities in SM lepton & quark sector
- **leptoquarks** (LQ) provide connection, e.g. in unification theories, compositeness

- carry lepton **and** baryon number
    - couple to lepton-quark pair
    - typically assumed: from the same generation
        - => "LQs of a certain generation"

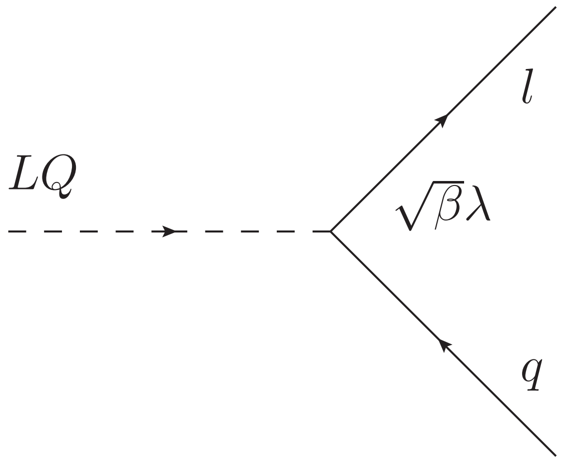


- here: **pair** production of **scalar** LQs
    - essentially strong production
    - cross section depends ~only on mass

LQ Signature

- decay into lepton + quark
  - branching fraction into charged lepton: β
  - coupling parameter: λ

$$\lambda_\ell = \sqrt{\beta}\lambda \qquad \lambda_\nu = \sqrt{1-\beta}\lambda$$



- pair production => 3 possible final states

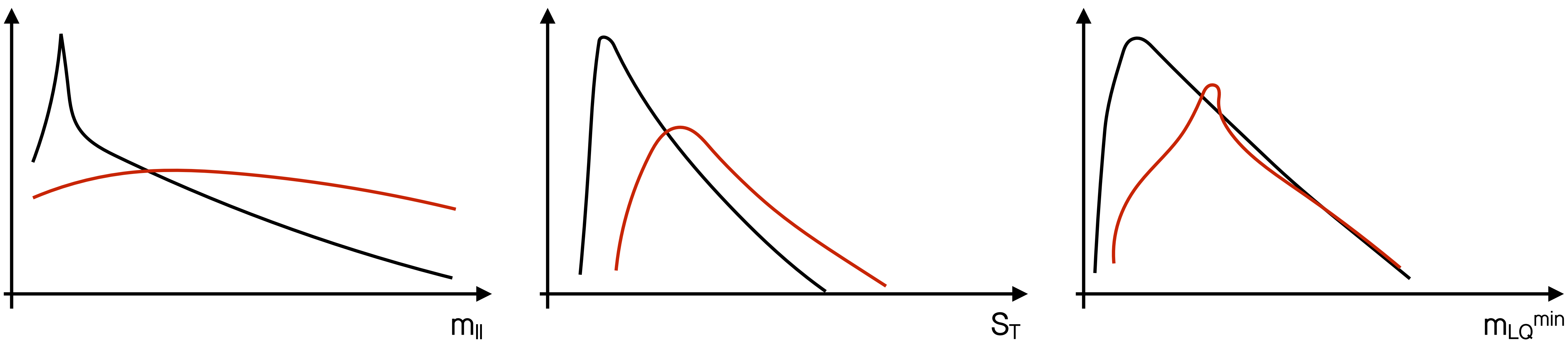
final state	**qqll**	qqlν	qqνν
xsec*BR scales as	**β^2**	$2(1-\beta)\beta$	$(1-\beta)^2$

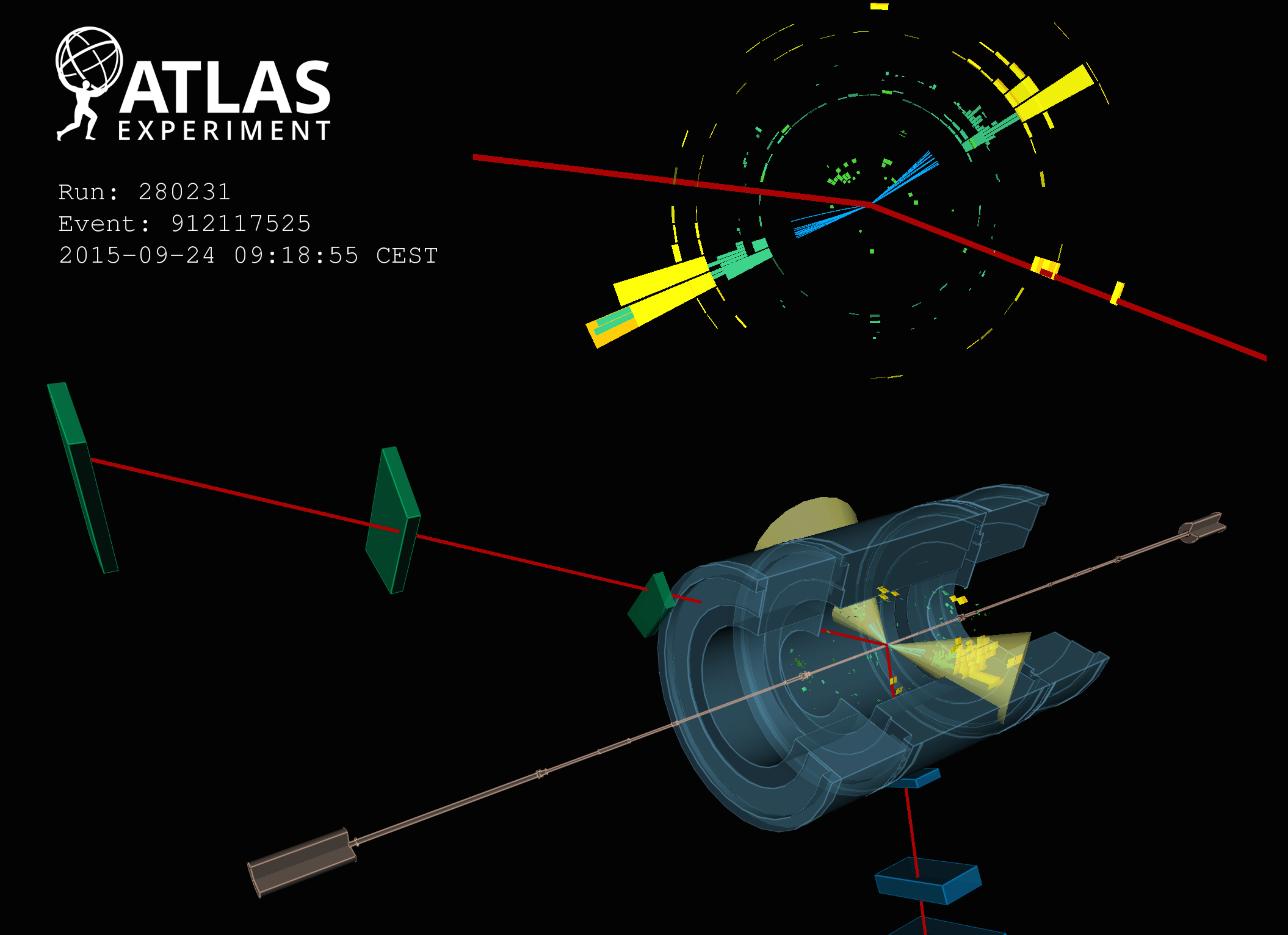
LQ 2015

l=e or μ => LQs of 1st or 2nd generation

Main Kinematic Variables

- final state: **≥2 jets, 2 charged (high-p_T), same flavour leptons** (e,μ)
- main SM backgrounds: **Z/γ***+jets ("DY+jets") and **$t\bar{t}$**
- discriminant variables:
  - dilepton invariant mass, **m_{ll}**
  - scalar p_T sum of leptons and jets, **S_T**
  - (minimum) invariant lepton-jet (“LQ") mass, **m_{LQ}^{min}**
    - for combination with smallest mass difference

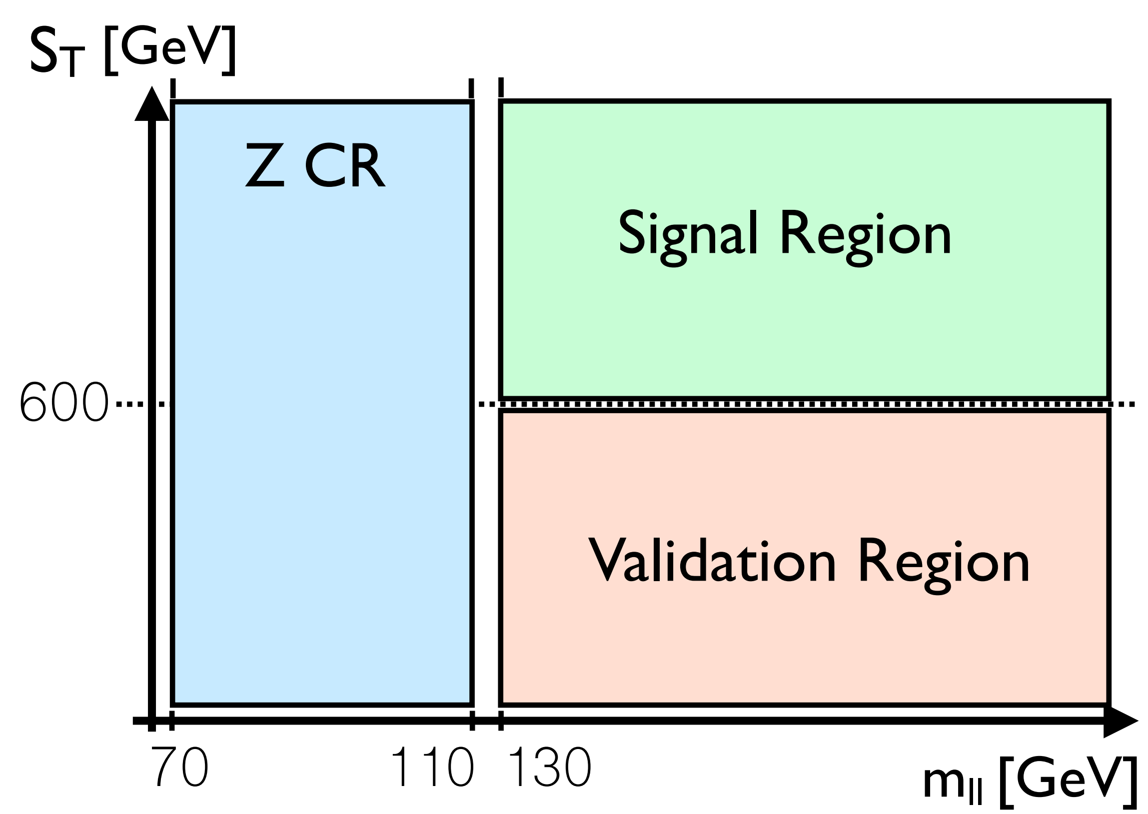




https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2015-19/

Analysis Strategy

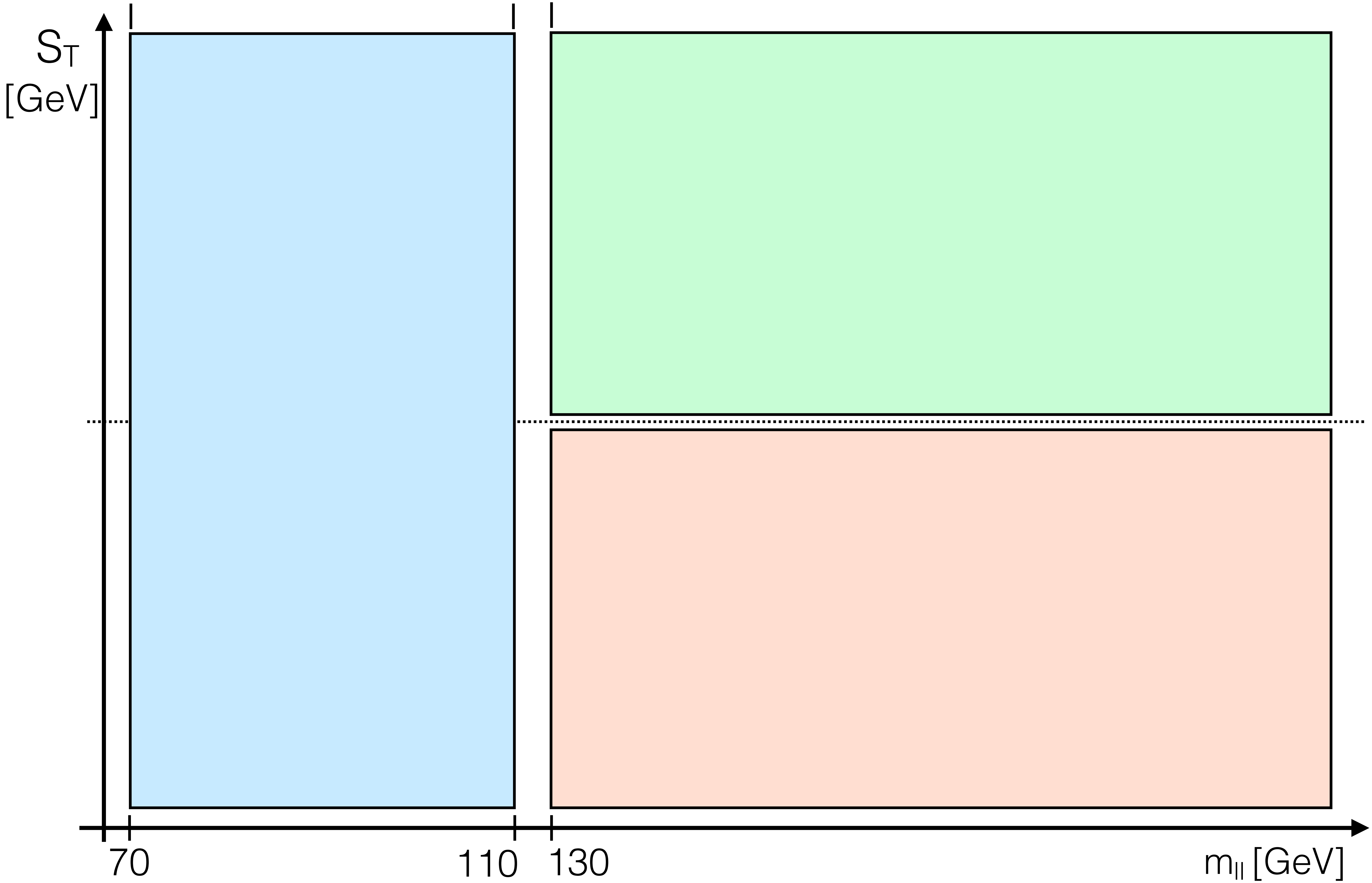
- need to predict background expectation in extreme region of phase space
  - **signal region**: m_{ll}>130 GeV, S_T>600 GeV, 10 bins in m_{LQ}^{min}
- use well-known regions to constrain them — "**control region**"
  - DY+jets CR: only look at **Z-peak**, i.e. m_{ll} in [70,110] GeV
  - $t\bar{t}$ CR: use electron-muon events
- other (small) backgrounds taken from MC directly or estimated from data
- perform combined **fit** to CRs (1-bin) and SR
  - normalisation factors
- check in **validation region**
  - m_{ll}>130 GeV and S_T < 600 GeV



Uncertainties

- experimental
  - most relevant:
    - object energy scales & resolution
    - lepton efficiency description
  - few %, 10% at most
- theoretical/modelling
  - background modelling: 20-30%
  - signal PDF/scales: 10-35%

Data-to-Simulation Comparisons



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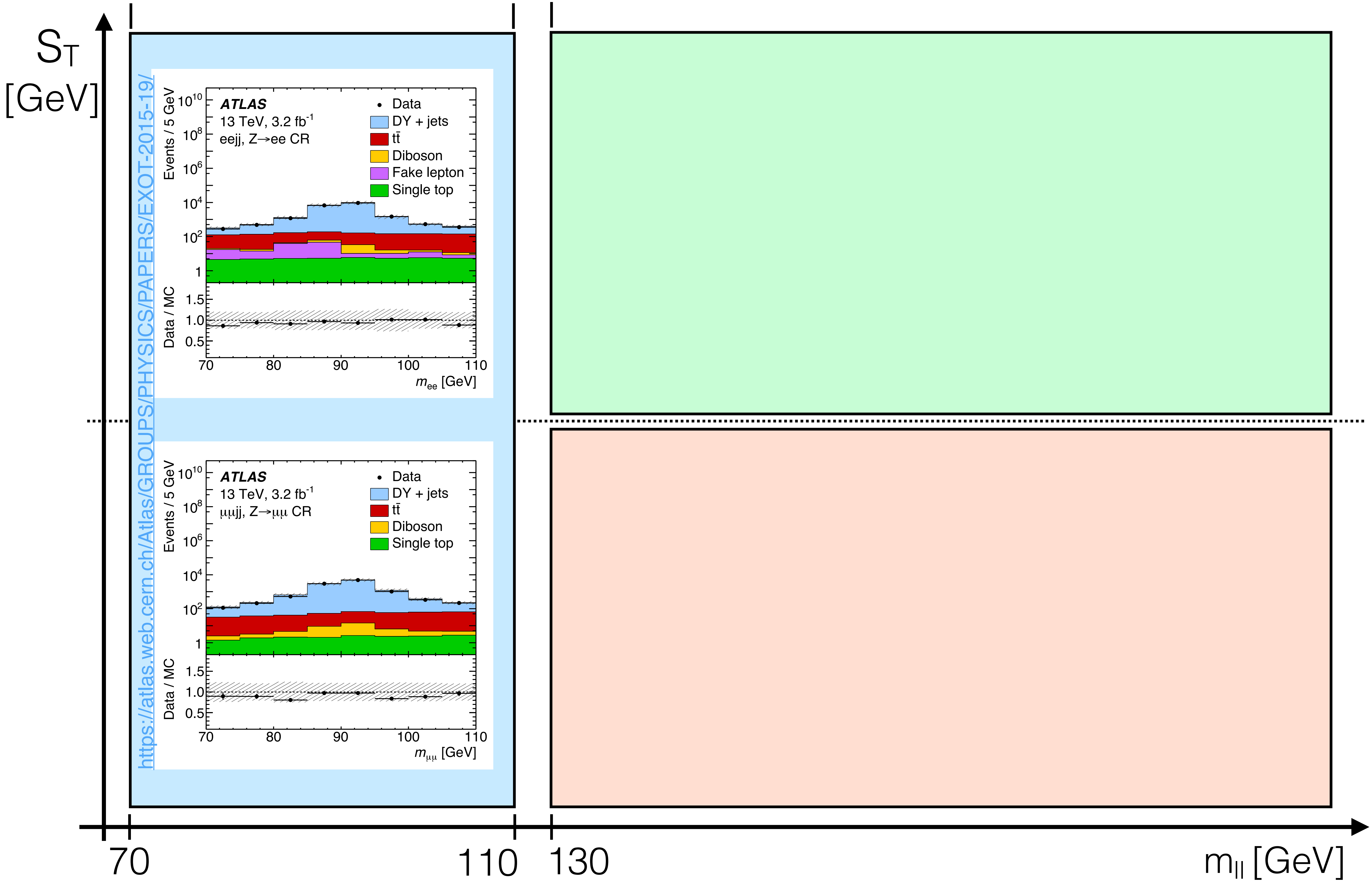

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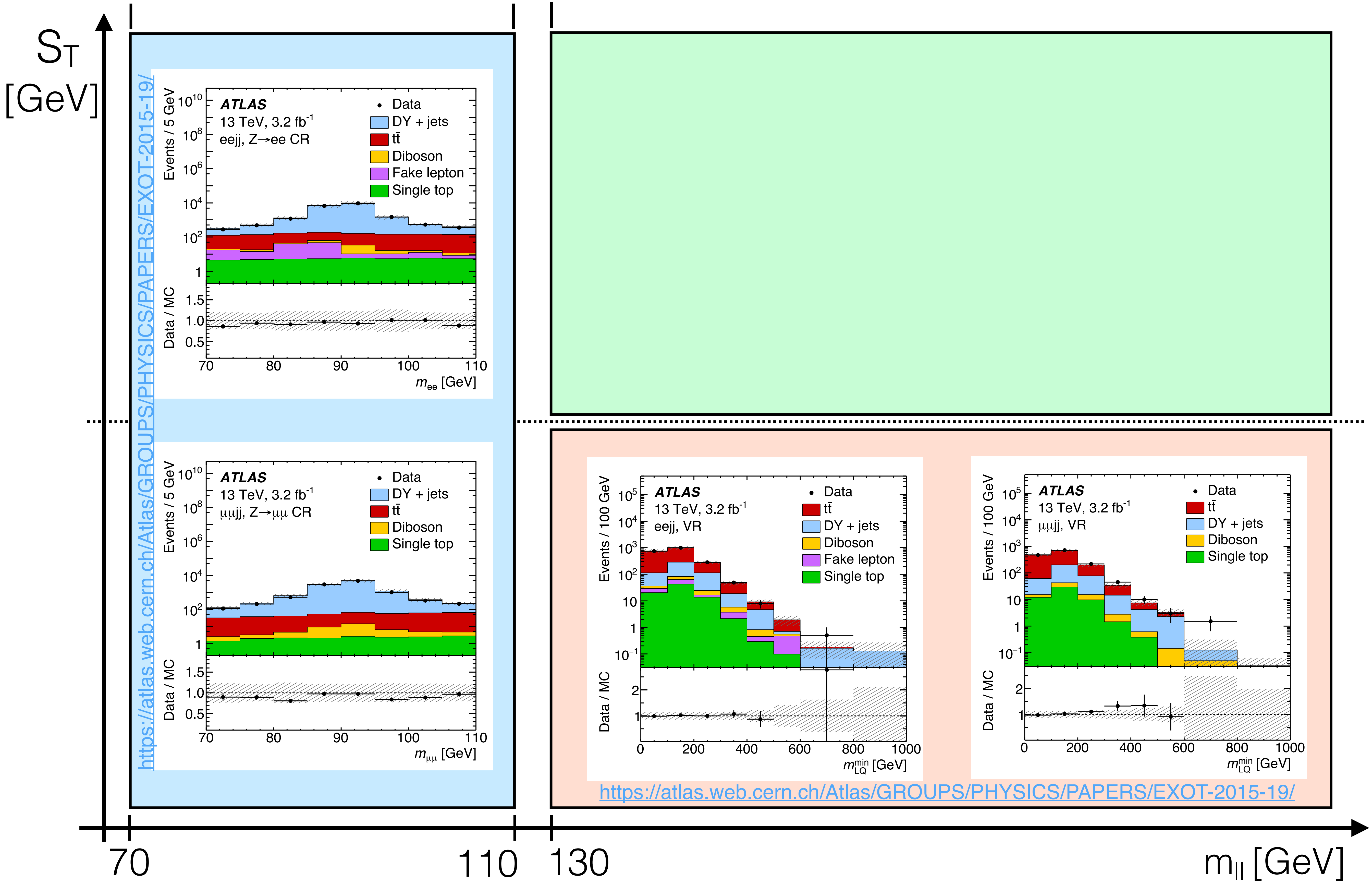

Data-to-Simulation Comparisons

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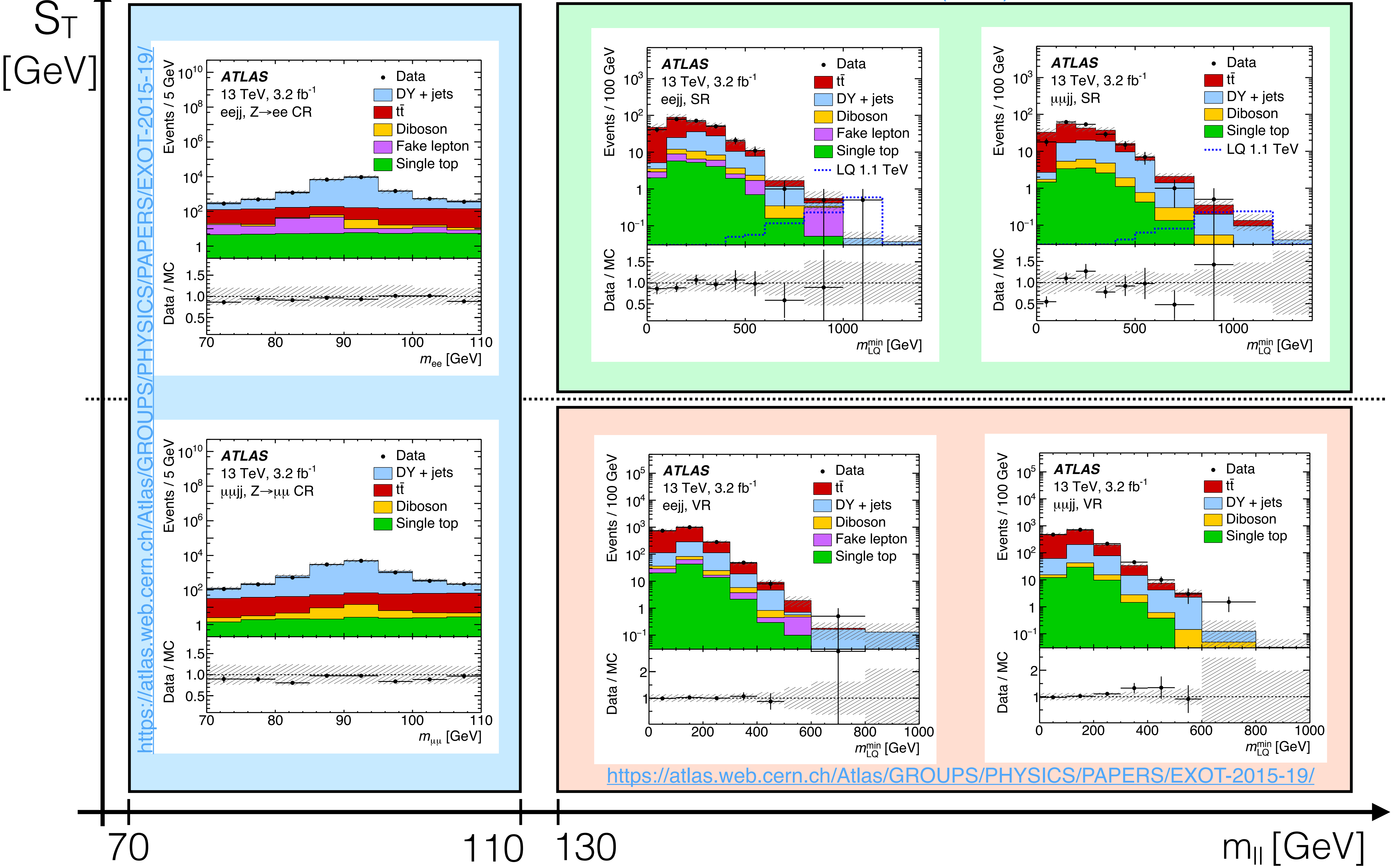
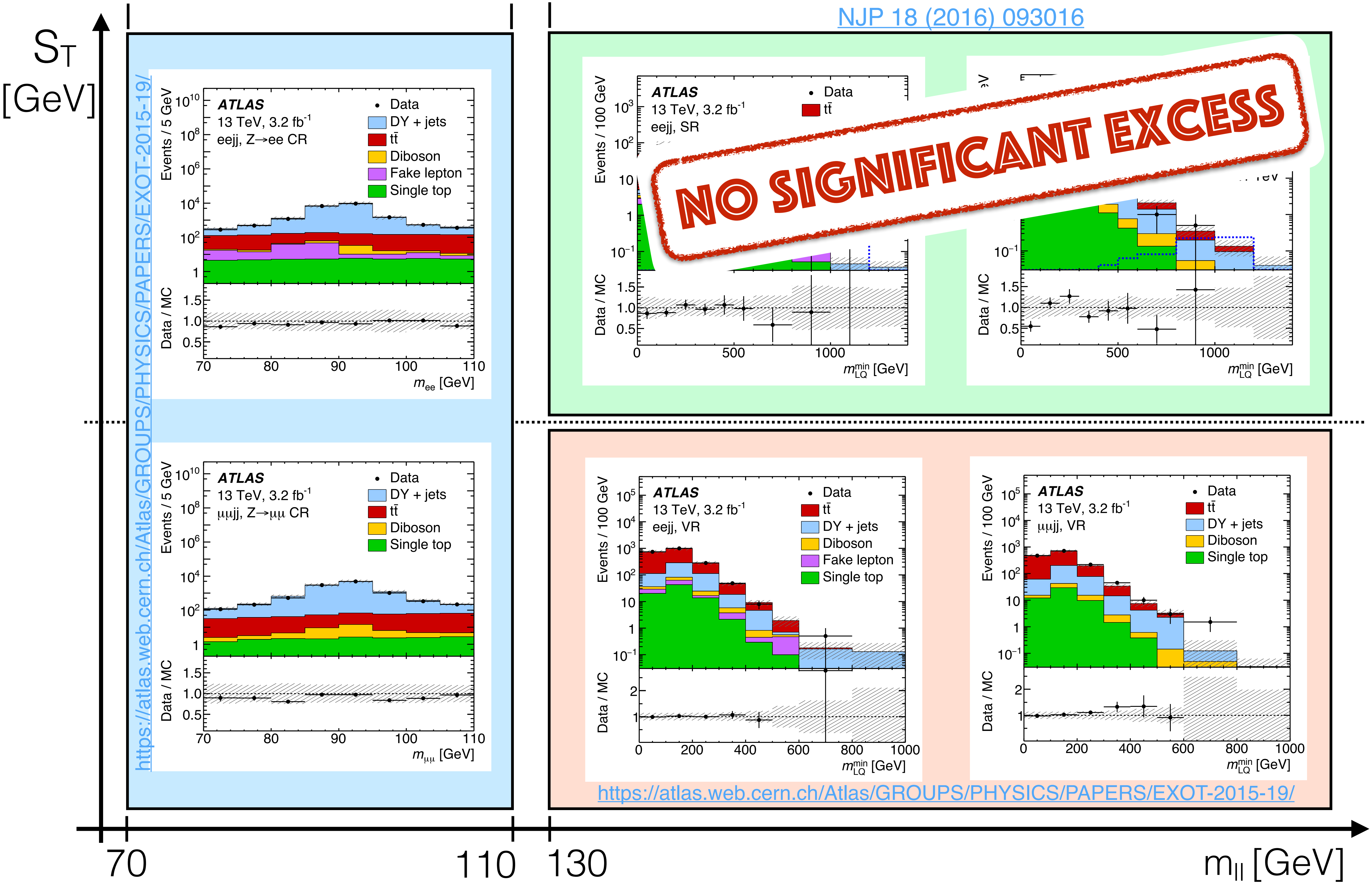
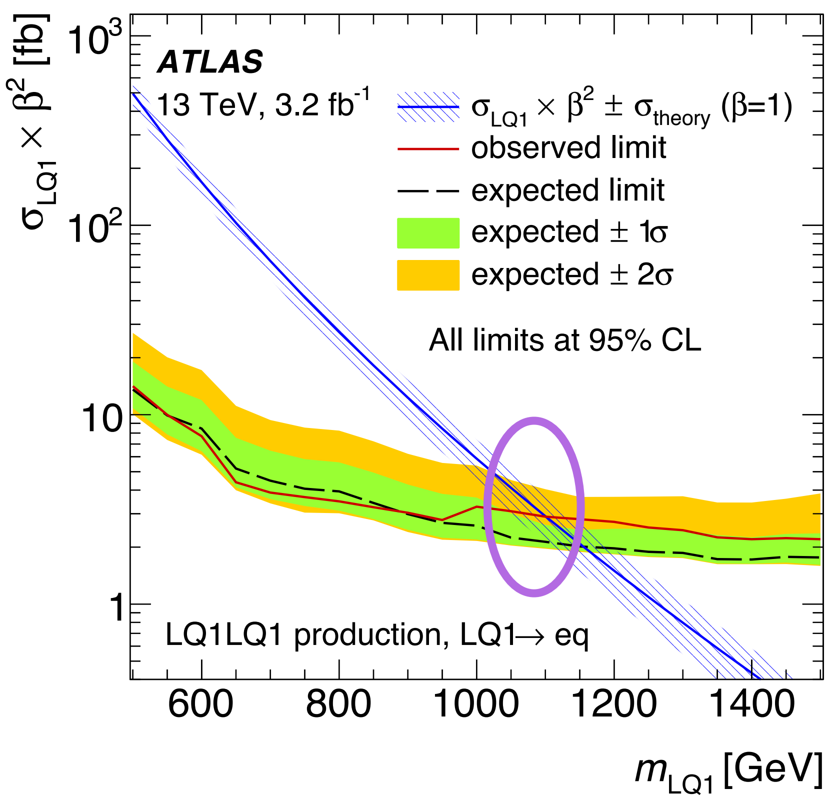


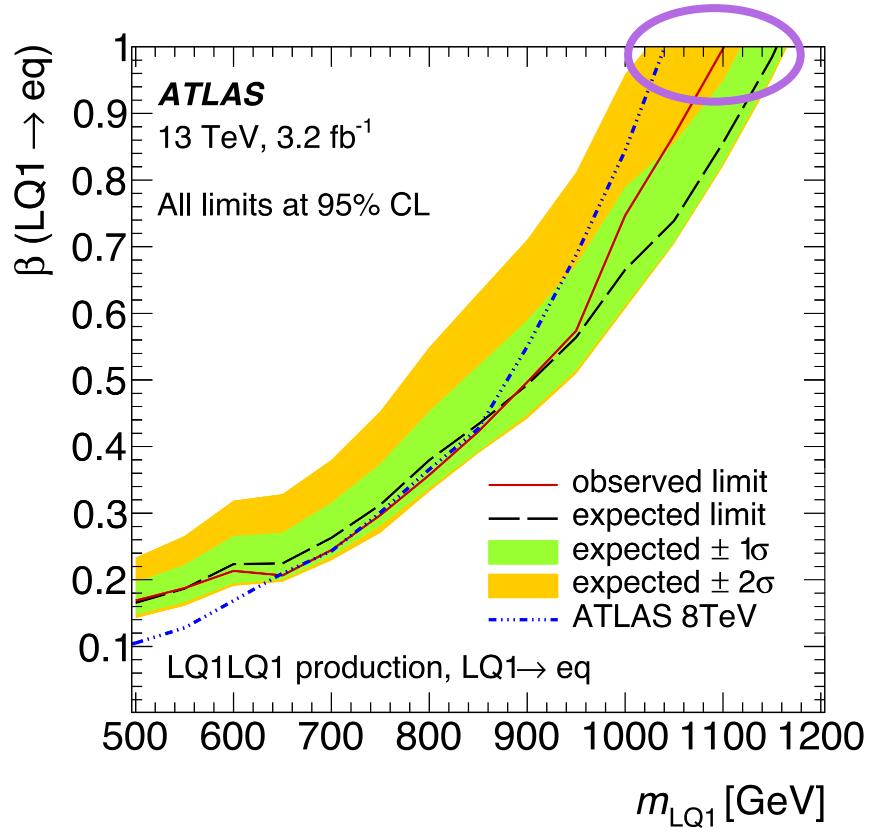
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2015-19/

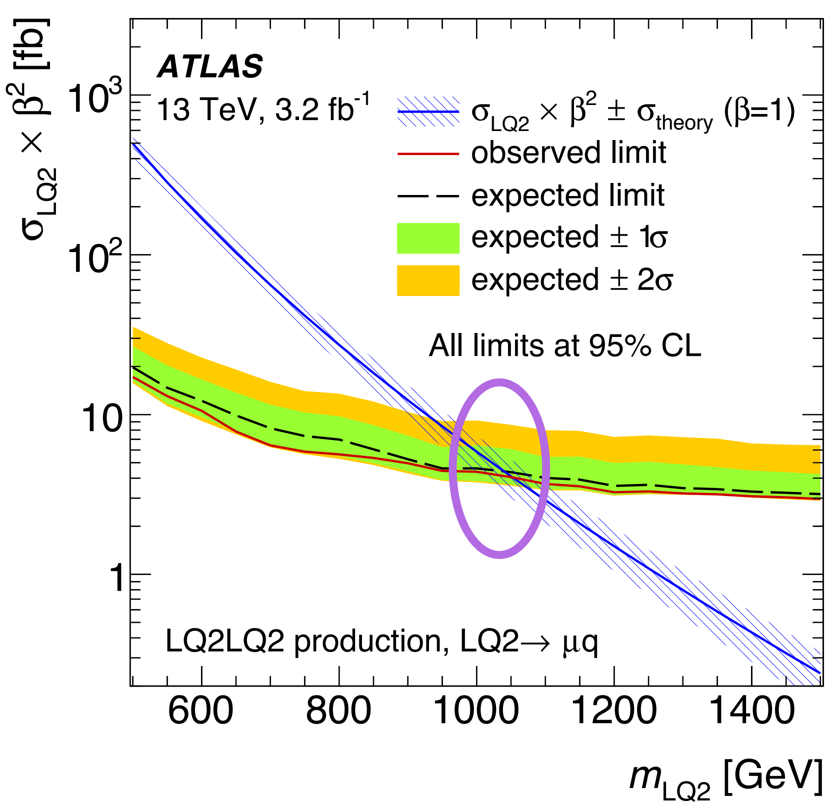
Data-to-Simulation Comparisons

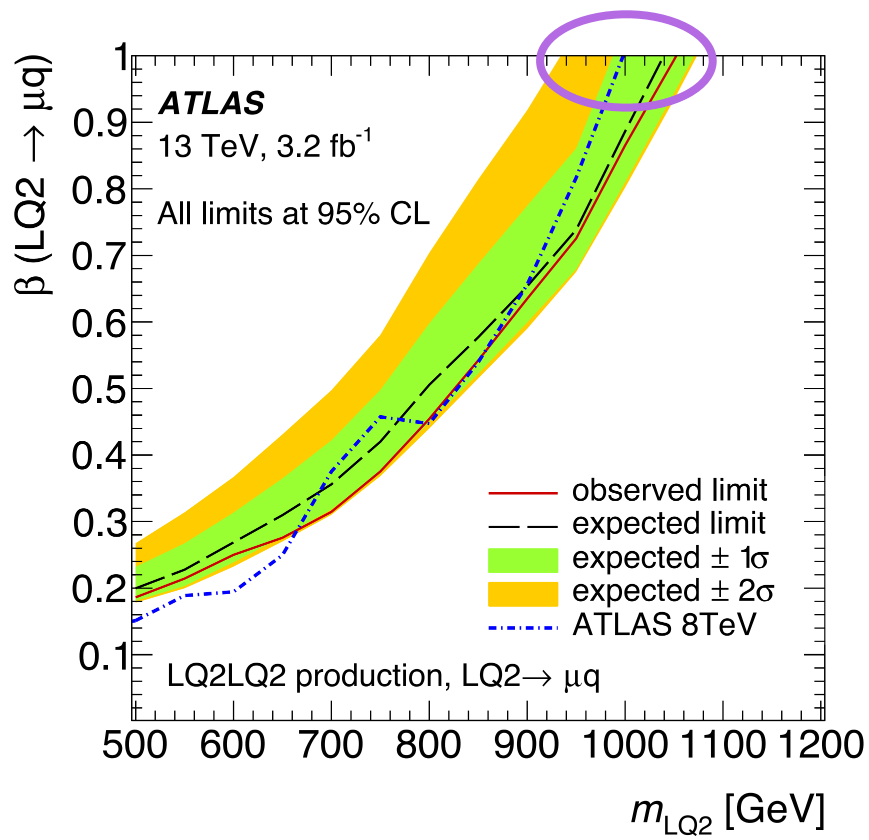


Exclusion Bounds



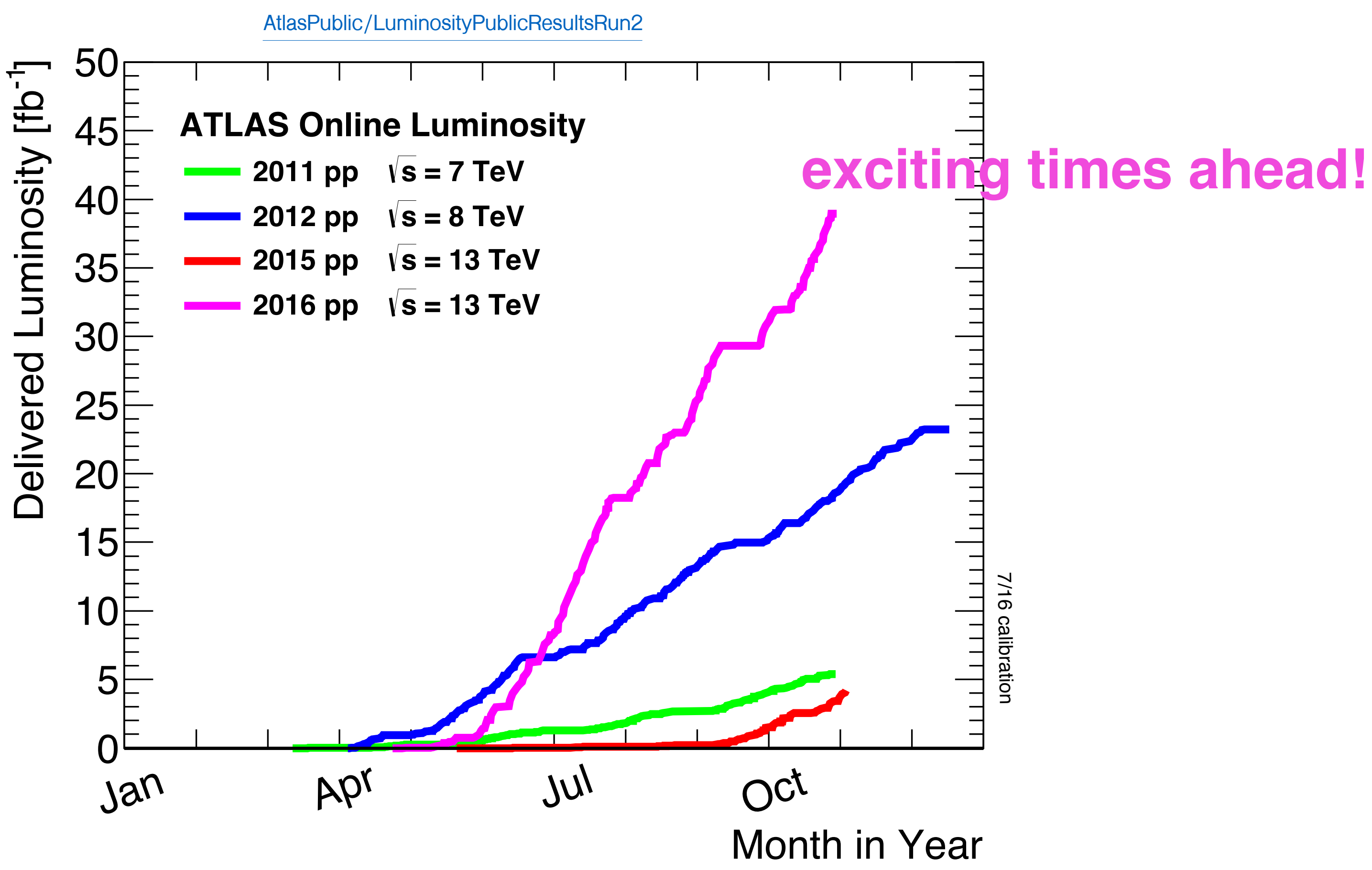






Outlook

- first results at 13 TeV with 3.2/fb
  - llqq channel
- great potential for full 13 TeV data set ~40/fb
  - include lv channel
  - extend spectrum of models



Experimental Constraints on Baryon Number Violation in Supersymmetry

- study pure BNV processes in framework of RPV SUSY
- complementarity of LHC and flavour/low energy constraints
- quantification of potential of proposed n-$\bar{n}$ search

collaboration with
L. Calibbi, G. Ferretti, D. Milstead, C. Petersson

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Baryon Number Violation

- **baryon number violation** (BNV) for baryogenesis (Sakharov)
  - intrinsic to many BSM theories
  - e.g. R-parity violation (RPV) 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**

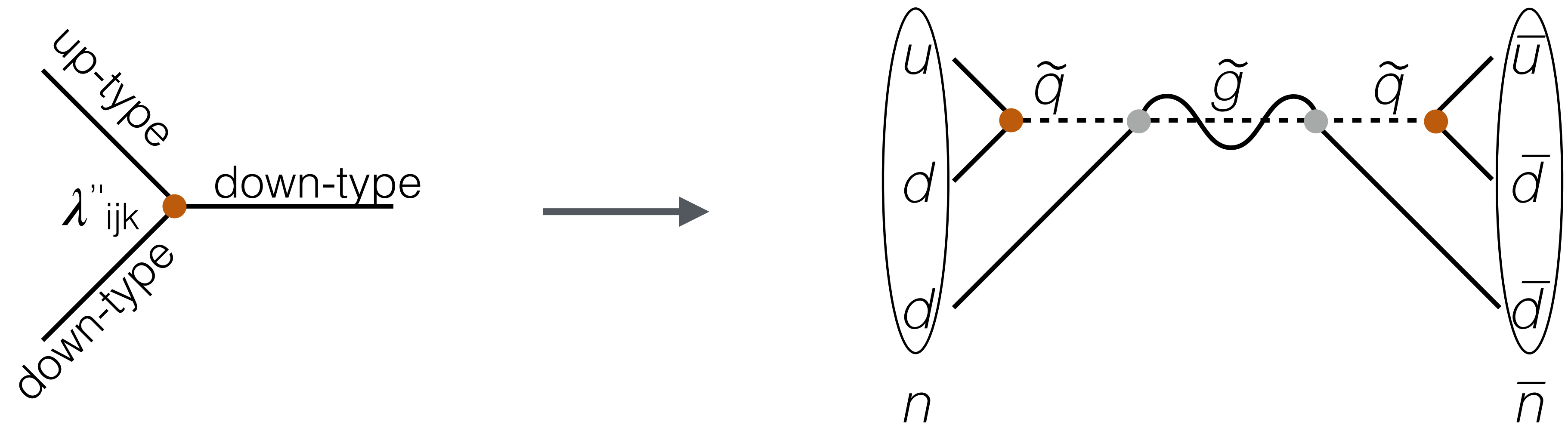
  - most common SUSY models: set all **Yukawa couplings** $\lambda^{(')/('')}=0$
  - can set one **$\lambda''\neq 0$**, proton still stable (p decay violates B and L)

- one (of few) observables for pure BNV: **n-n̄ oscillations** ($\Delta B=2$)
  - current limit: $t_{osc}^{free} > 0.86\times10^8$s (ILL Grenoble, 1994)
  - experiment proposed at European Spallation Source (ESS)
    - factor ~1000 **greater sensitivity** to transition probability
      - => factor ~30 in oscillation time

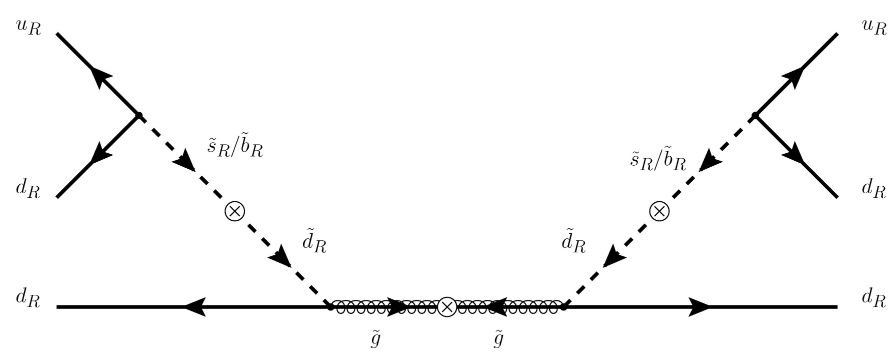
Neutron-Antineutron Oscillations in RPV SUSY

- BNV term

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



- several possible processes, e.g. "Zwirner contribution"

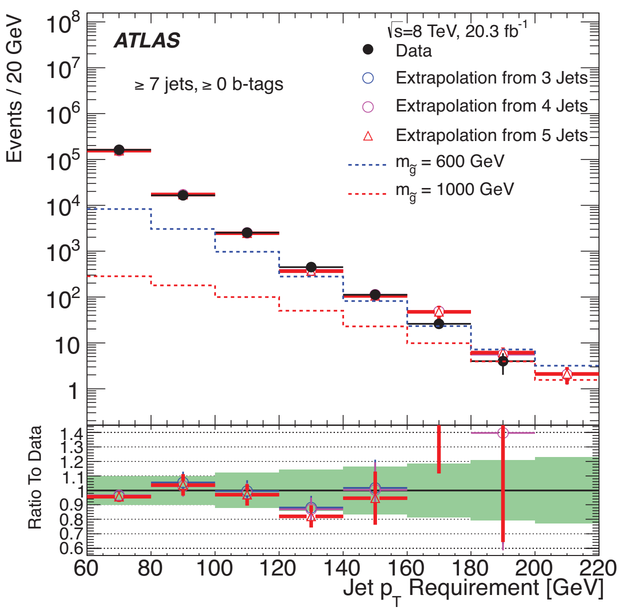


- consider only couplings and sparticles relevant for a given process
  - all other masses decoupled, all other couplings = 0
- LHC signature depends on decay length of lightest sparticles
  - prompt decays (many jets), displaced jets, long-lived particles

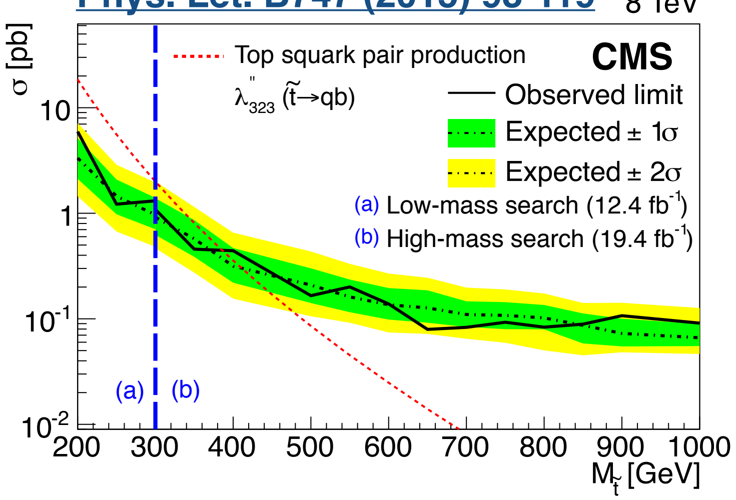
Existing Contraints

- LHC results (recasted)

Phys. Rev. D 91, 112016



Phys. Let. B747 (2015) 98-119



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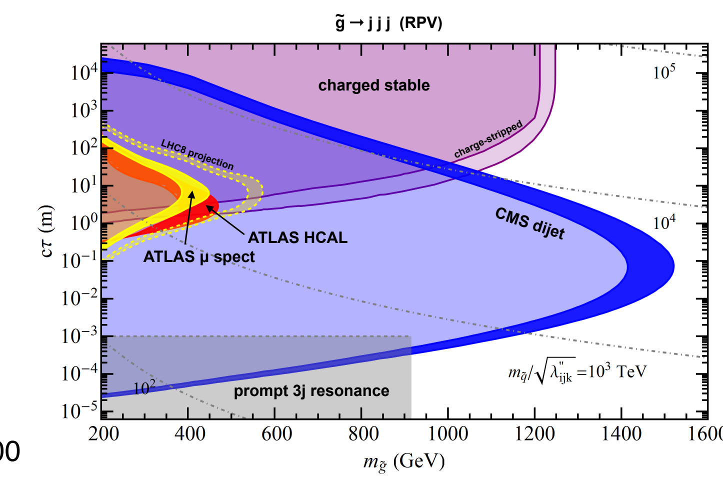
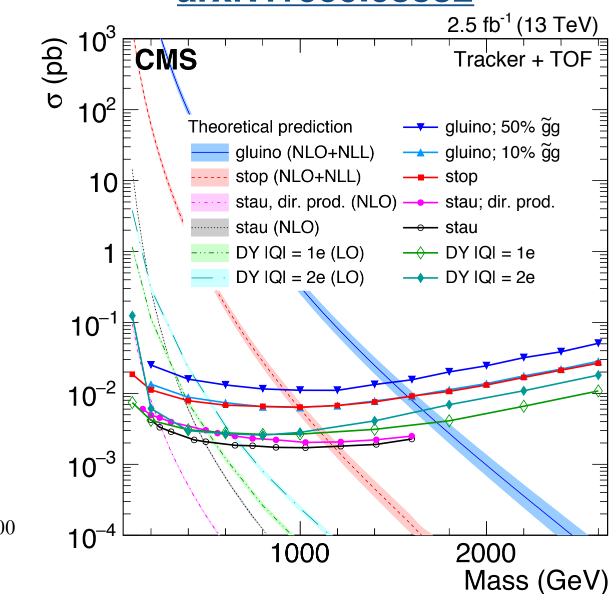
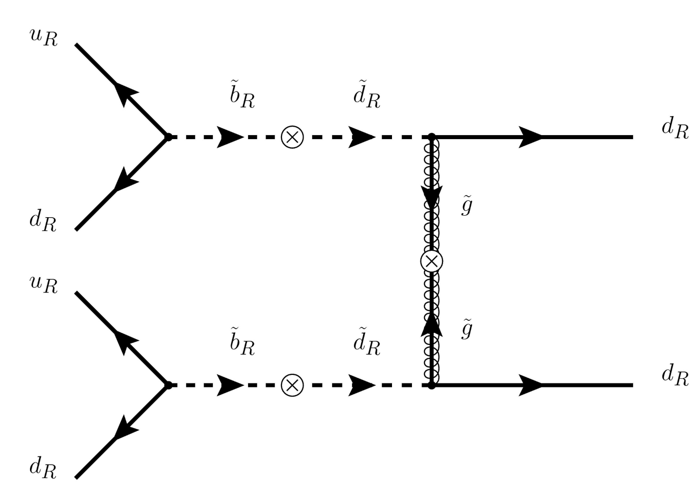


arxiv:1609.08382



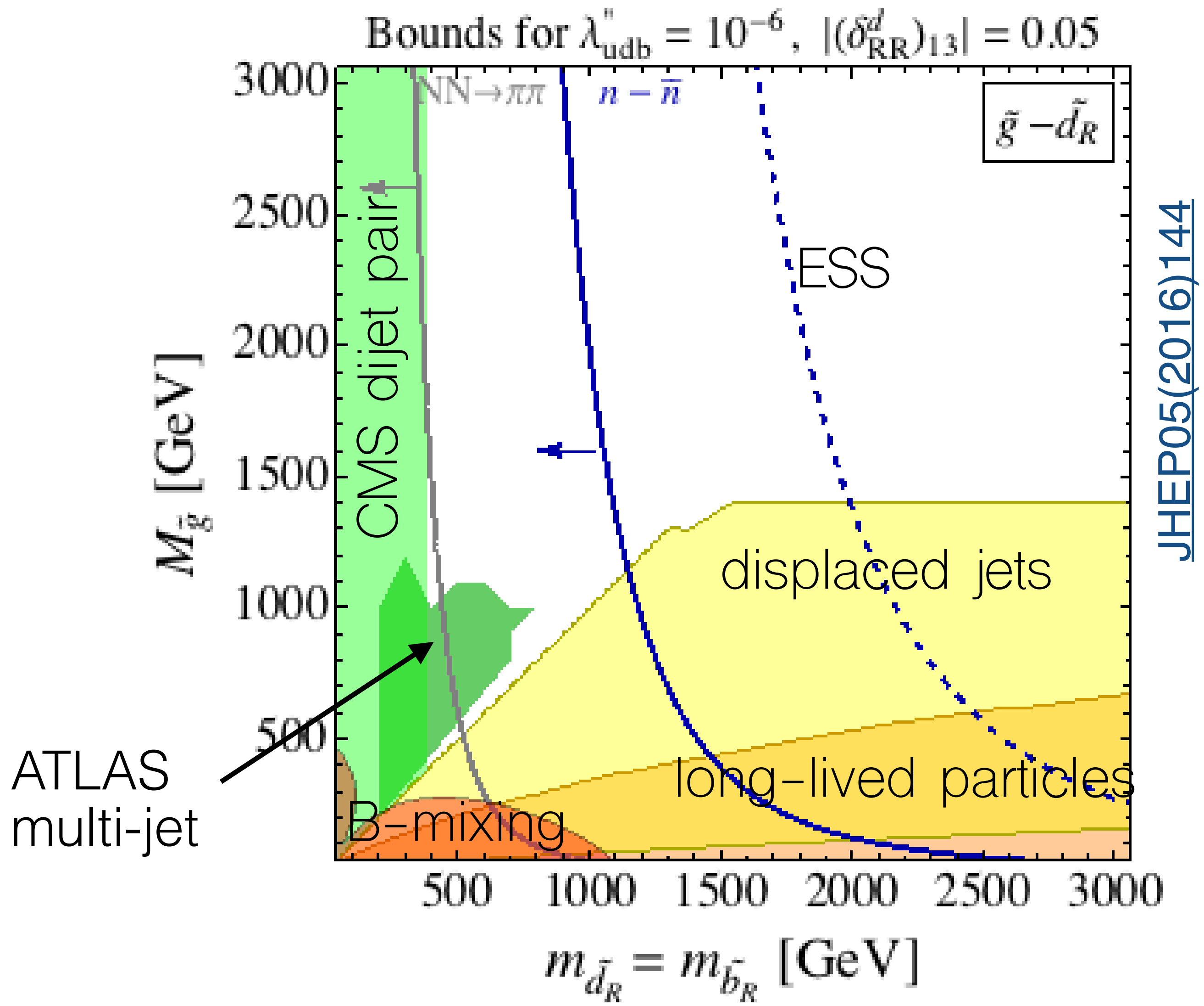
- **flavour/CP violation** (e.g. K- or B-meson oscillations)
  - strong constraints for 1-2 mixing



- other ΔB=2 processes: **di-nucleon decay**
  - NN—>KK, NN—>ππ
  - SuperKamiokande searches with ^{16}O —> t > 10^{32}y —> t_{osc}^{free} > 2.7x10^8s

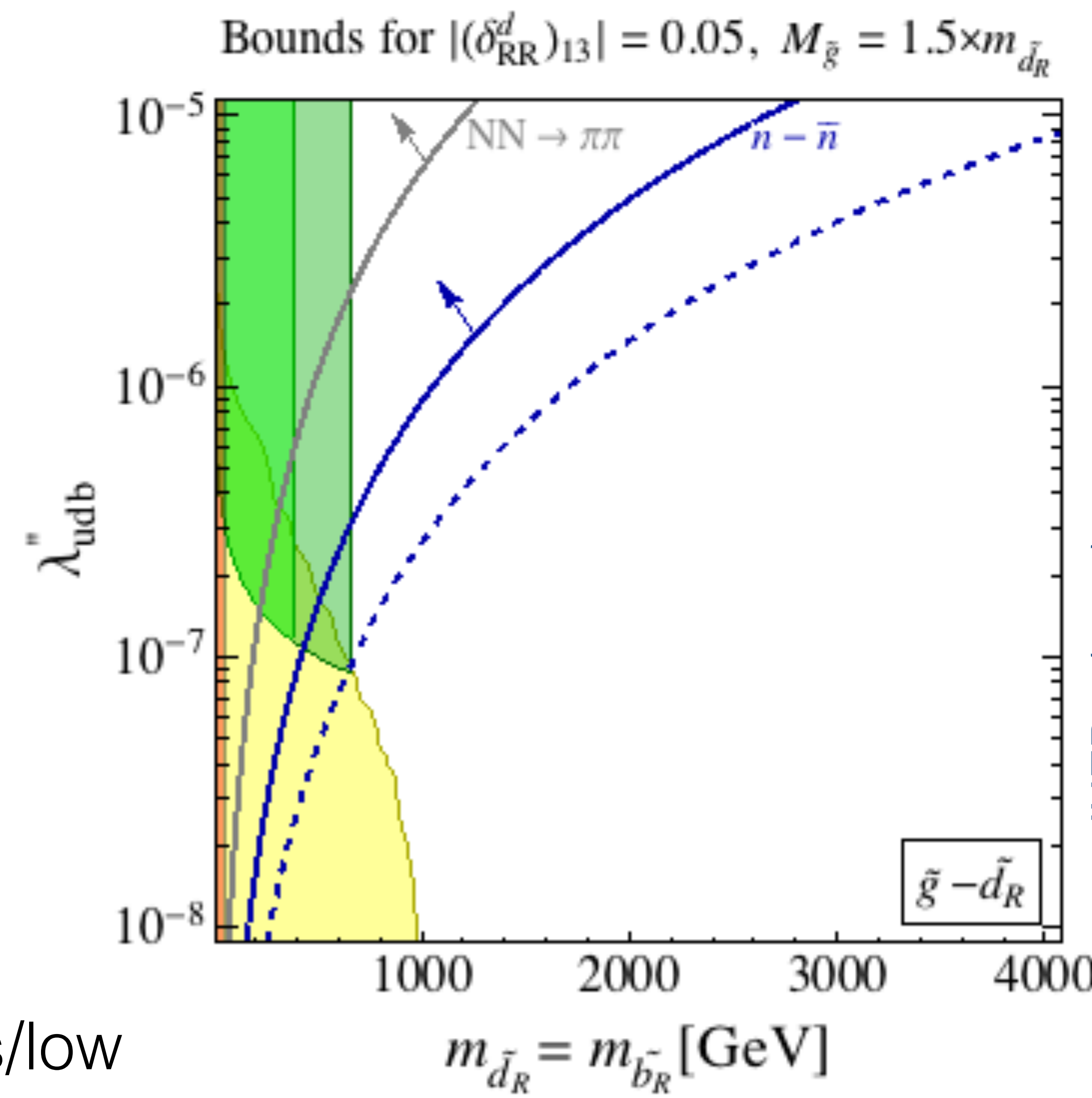
Results: $\lambda_{udb}'' = 10^{-6}$

- prompt decay



- ESS experiment can exclude further parameter space

Results: $m_{\tilde{g}} = 1.5m_{\tilde{q}}$



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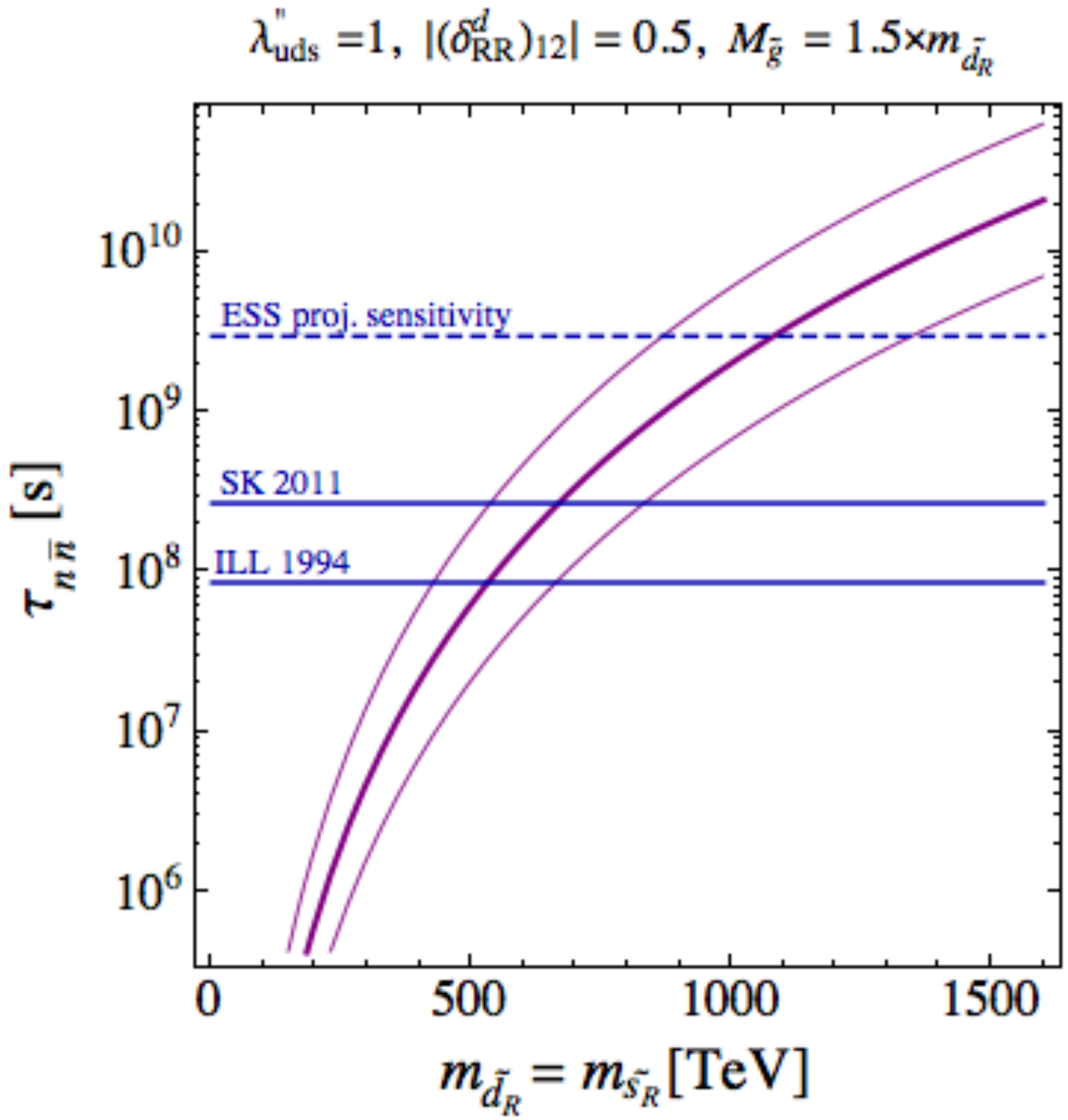
- for lambda not too small large gain by ESS experiment

- at low couplings/low masses LHC dominates

Oscillation Time as Function of Mass Scale

- best case scenario



- large uncertainty from nuclear matrix element
- reach up to mass scales of hundreds of TeV

Conclusion

- Baryon number violation well motivated (experiment and theory)
- n-$\bar{n}$ oscillations high precision observable for pure baryon number violation
- strong constraints from LHC in certain regions of parameter space
- complementary results from flavour experiments
- ESS experiment can extend reach considerably

Summary

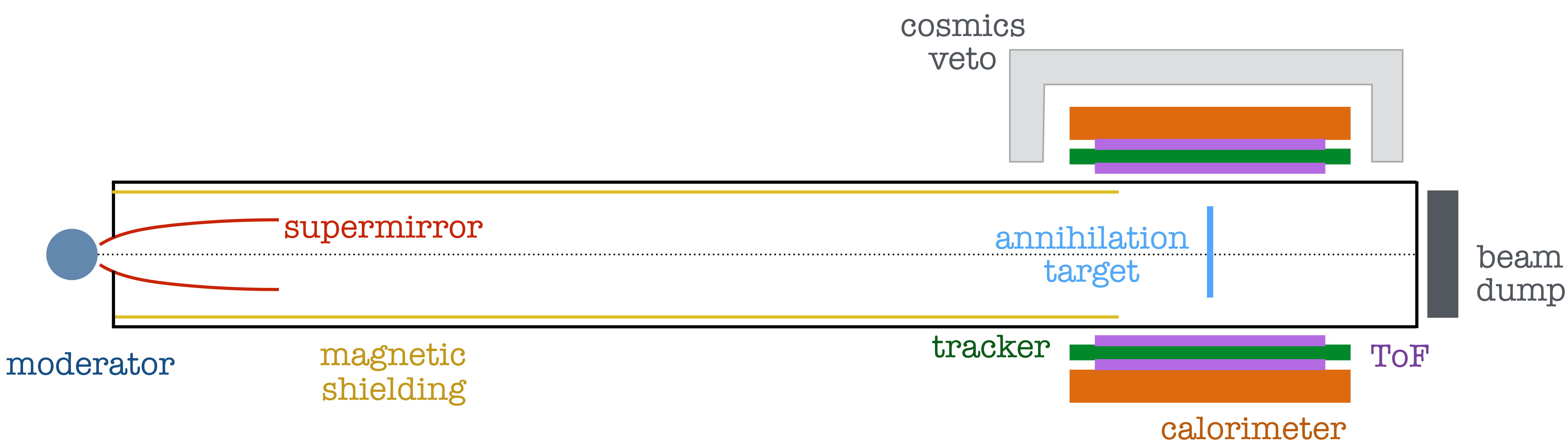
- SM leaves various questions unanswered
- many answers suggest new particles at TeV scale
- presented searches I made important contributions to
  - search for WIMP Dark Matter
  - search for leptoquarks
  - study on potential of n-$\bar{n}$ experiment
- so far, no convincing hint for new physics found
- future plans:
  - Dark Matter search in mono-Higgs channels
  - explore interplay between results from different experiments
  - Directional Direct Detection

Additional Material

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 —> $\sigma_{annihilation}/\sigma_{n-interaction}$ ~10^6
- (cylindrical) detector with **tracking** (vertex finding), **calorimeter**, **ToF**



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

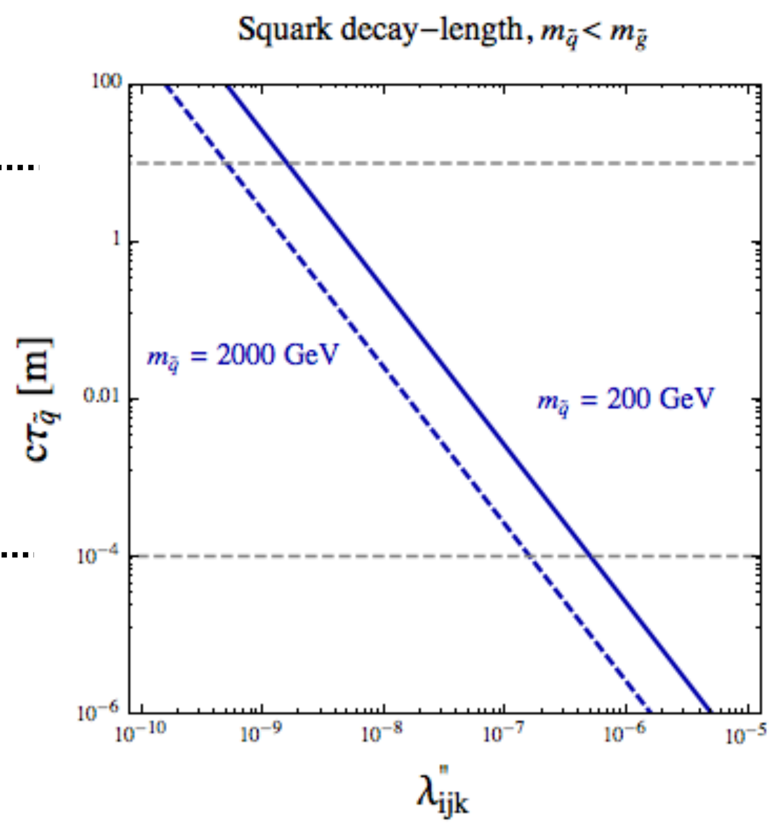
$$\Gamma(\tilde{q} \to qq) = \frac{(\lambda'')^2}{8\pi} m_{\tilde{q}}$$

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

long-lived

displaced jets

prompt (many jets)



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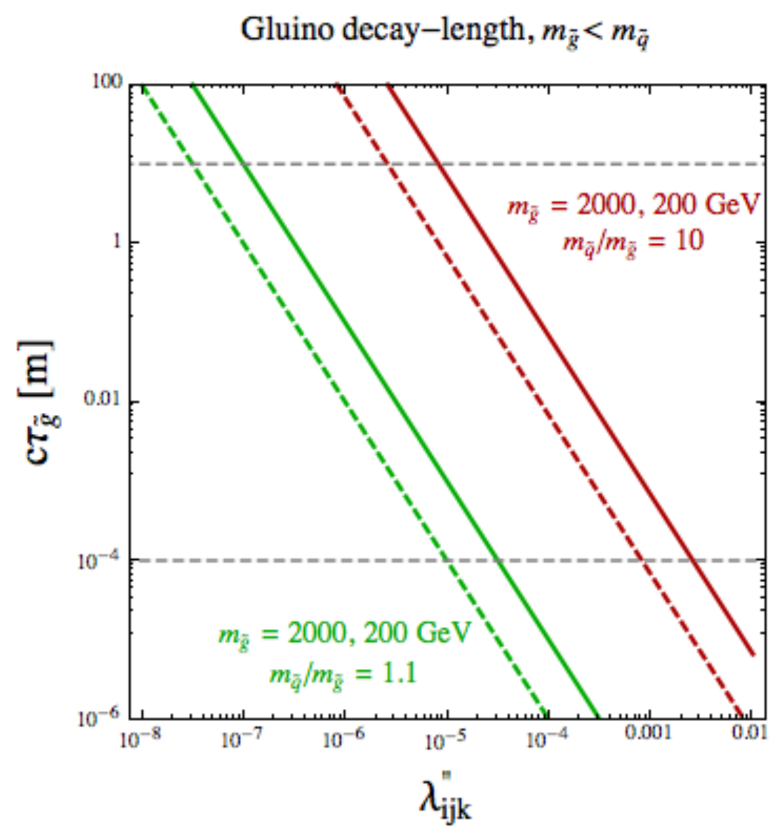

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prompt decay with couplings as small as 10^{-7}

larger couplings needed to get prompt decay

Models considered

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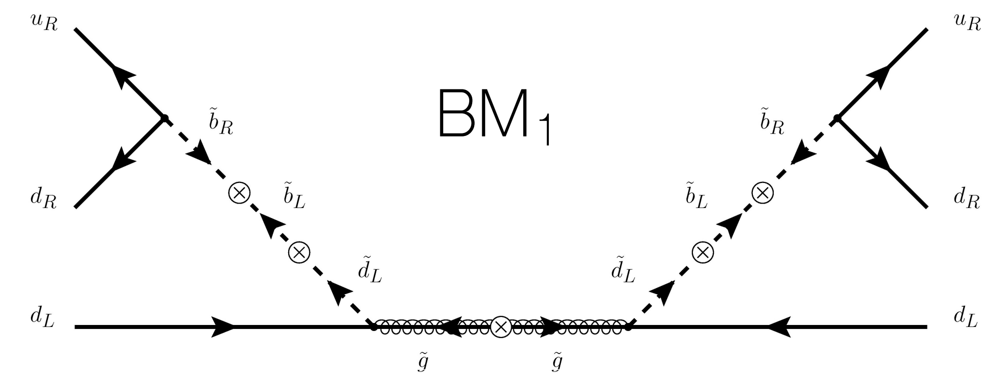
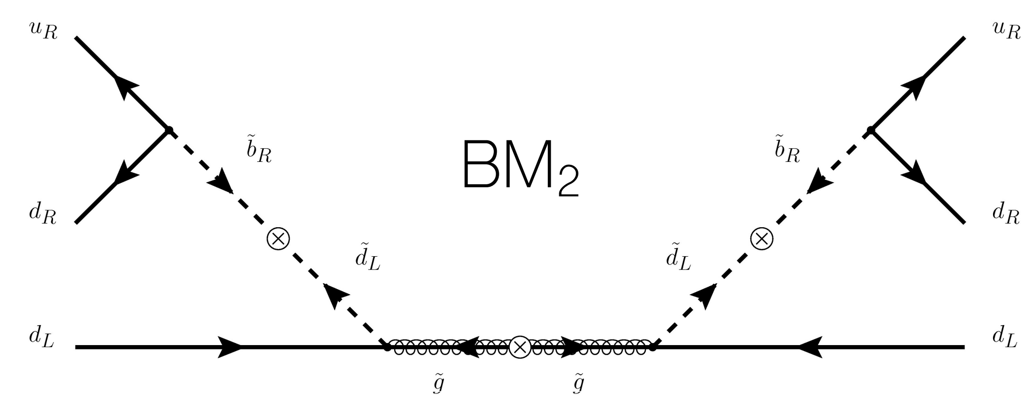
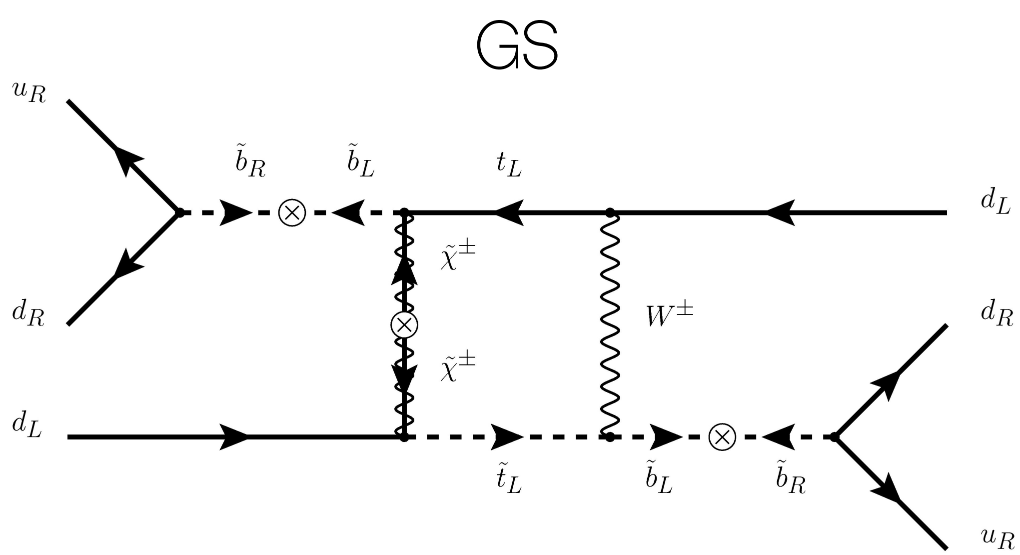
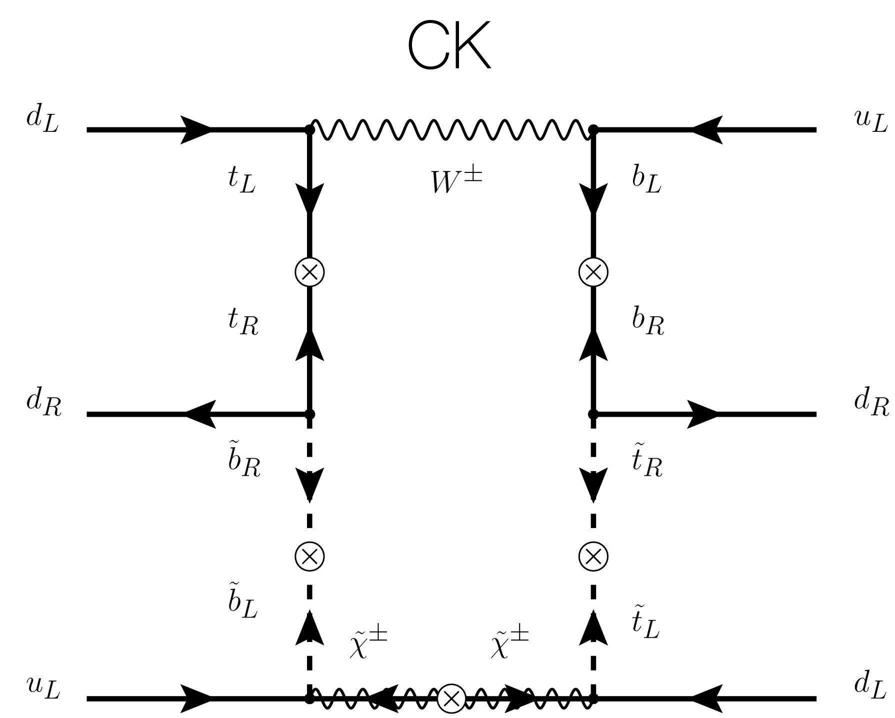
- relevant subset of large number of possibilities

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	$\tilde{\chi}^\pm, (\tilde{\chi}^0), \tilde{b}_R, \tilde{t}_R, \tilde{b}_L, (\tilde{t}_L)$	$\lambda''_{tdb}, (A_b - \mu \tan\beta), (A_t - \mu \cot\beta)$



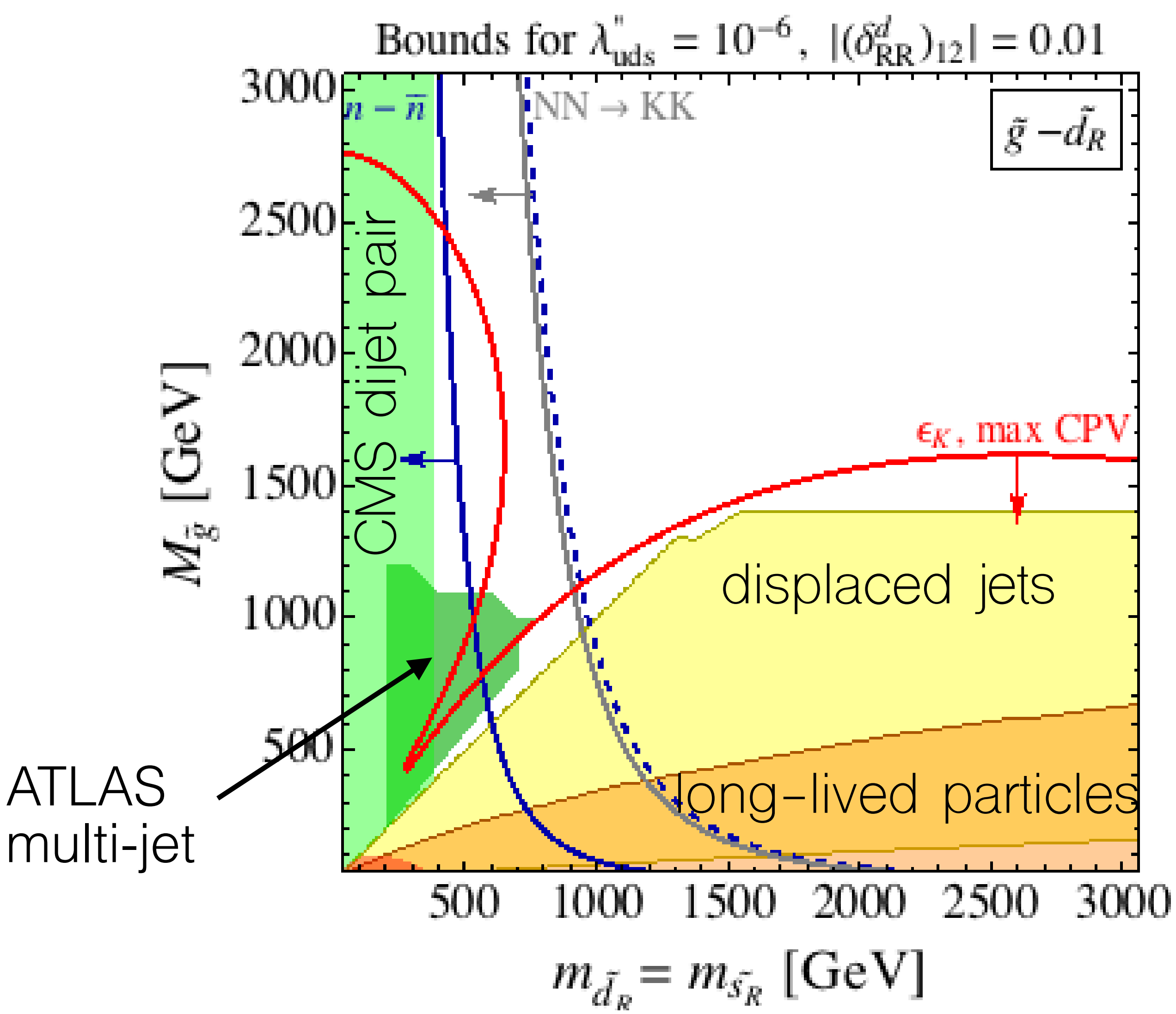




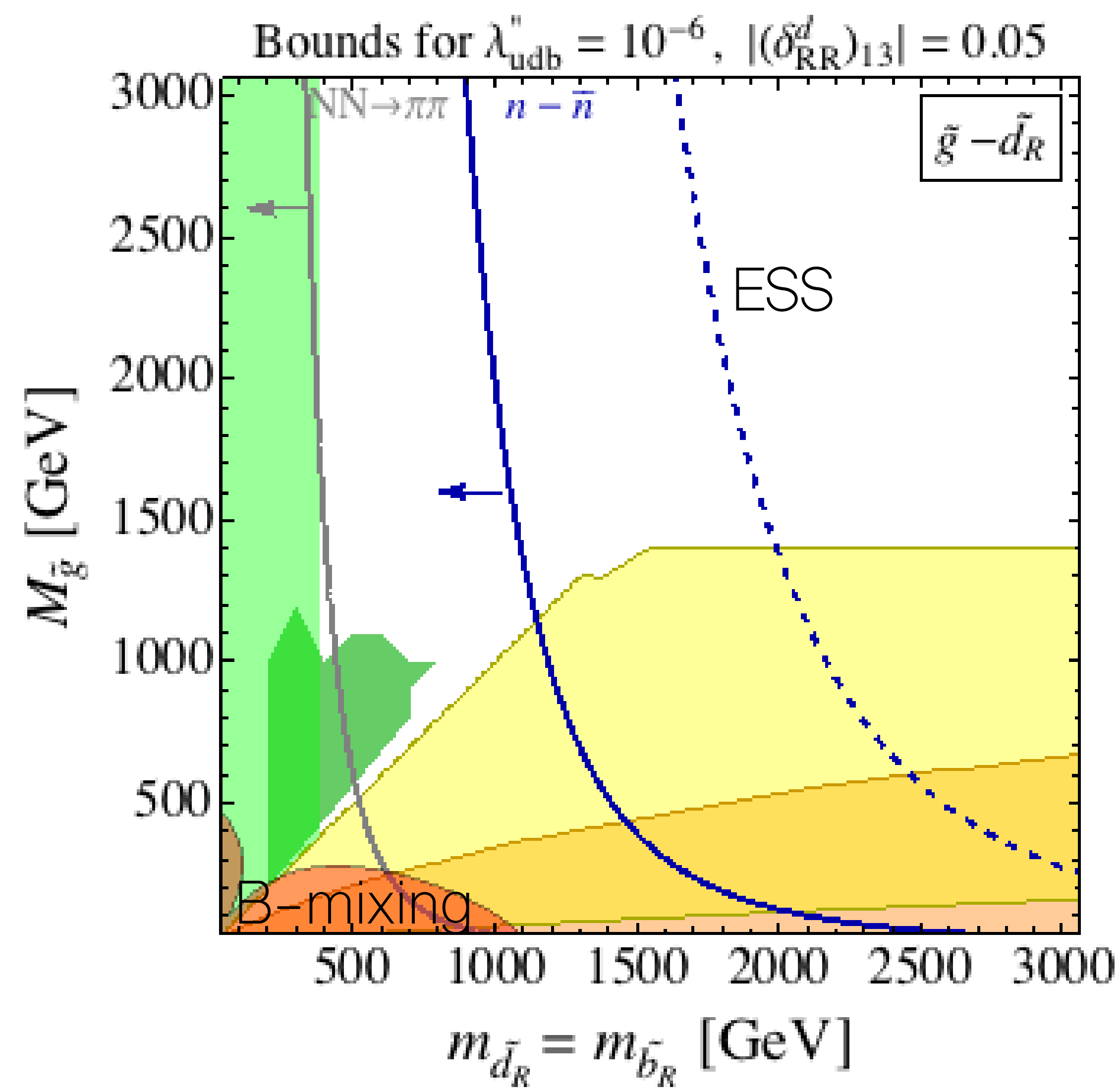


- prompt decay

uds



udb



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

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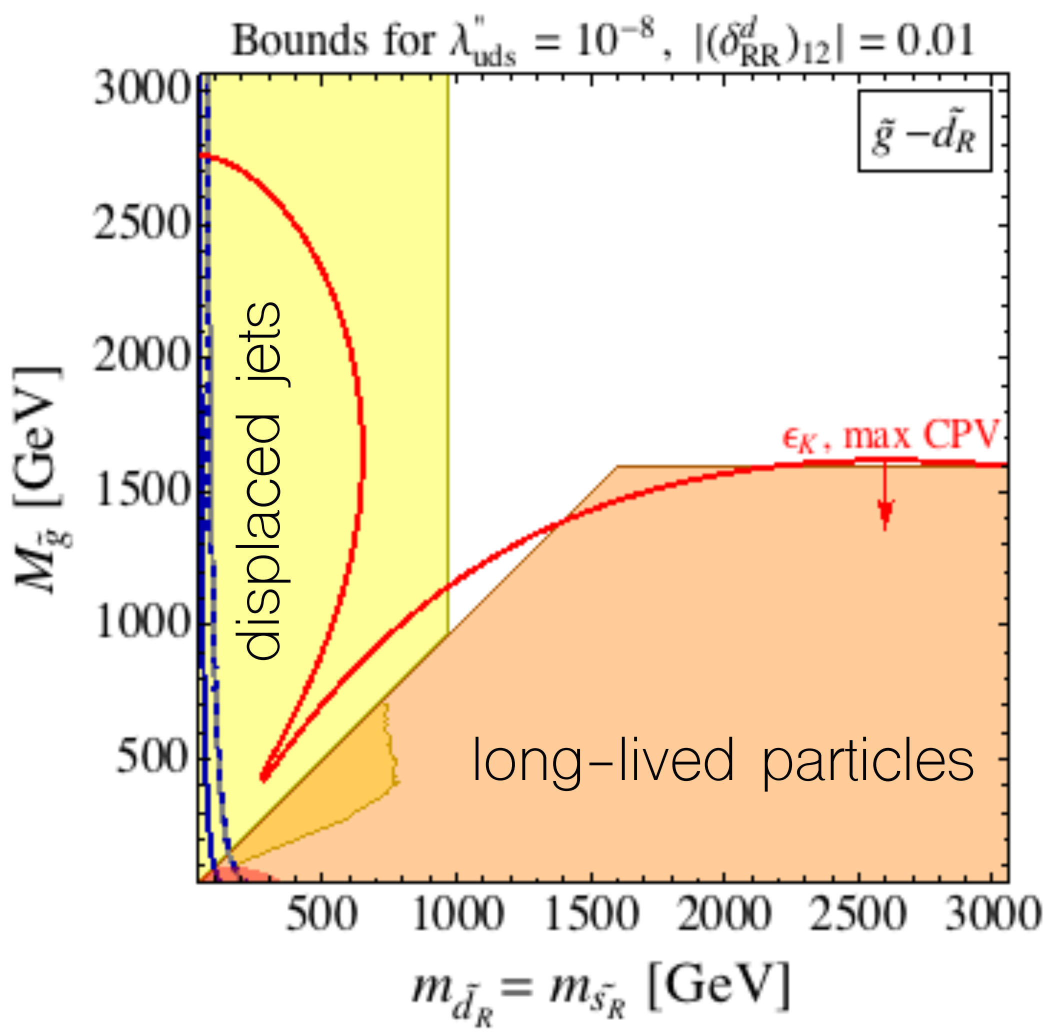
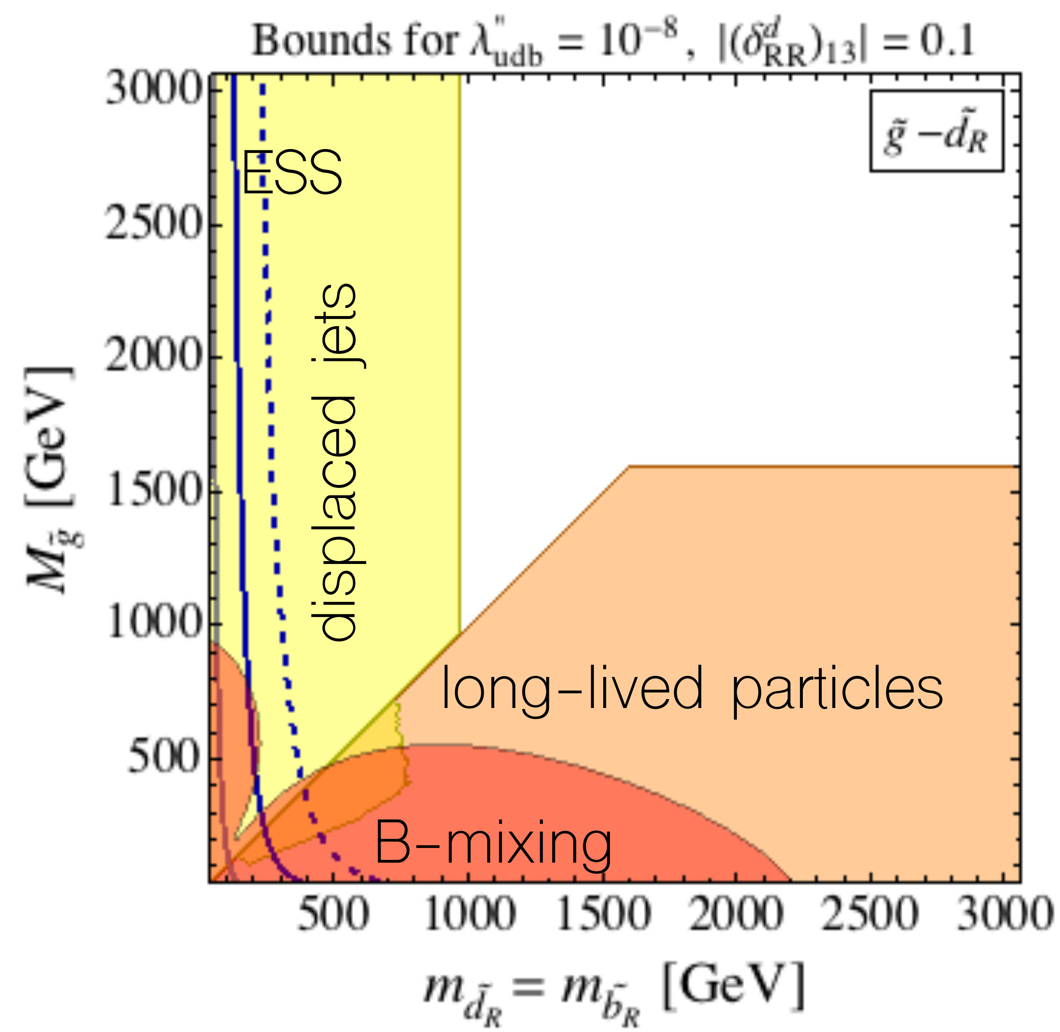
- non-prompt!





- LHC bounds similar in both cases
- other constraints weaker for ud**b**
- ESS does not extend exclusion beyond LHC sensitivity

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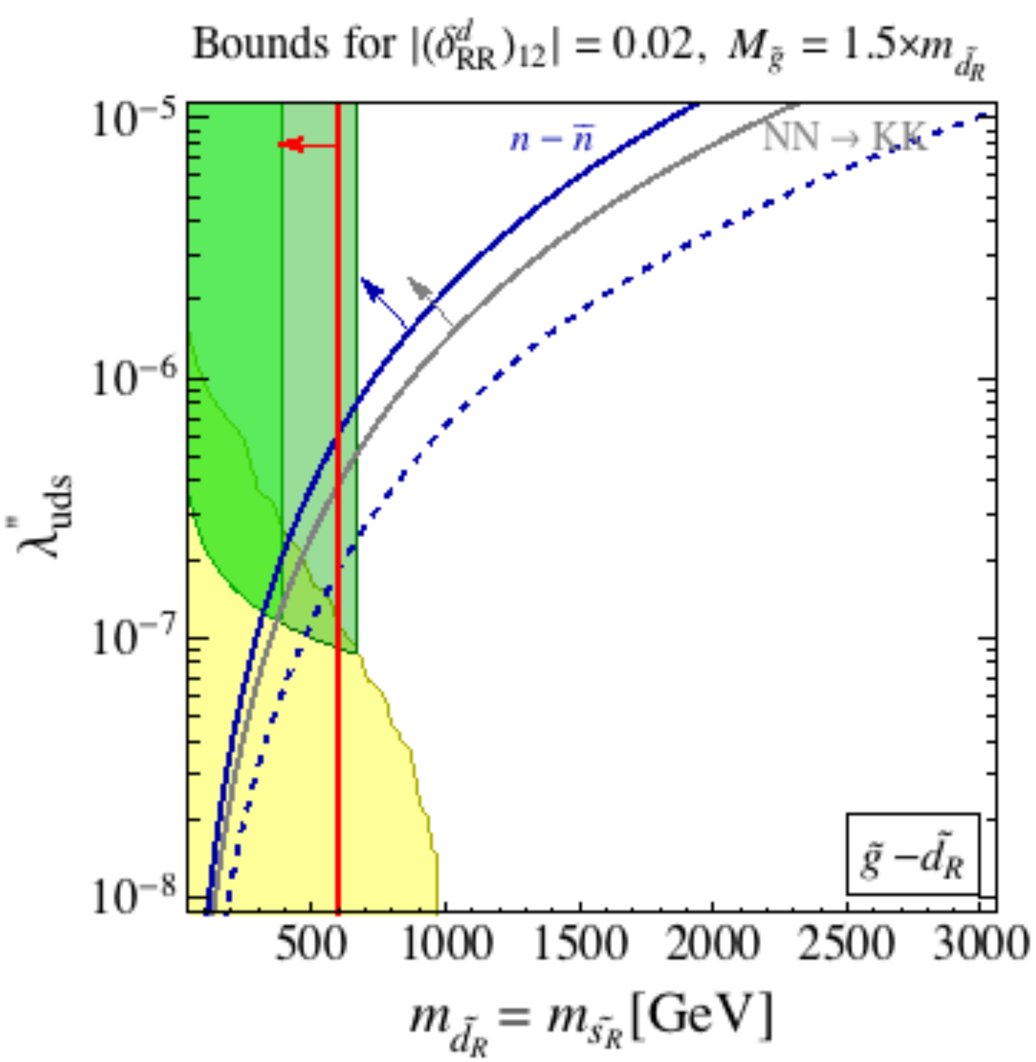
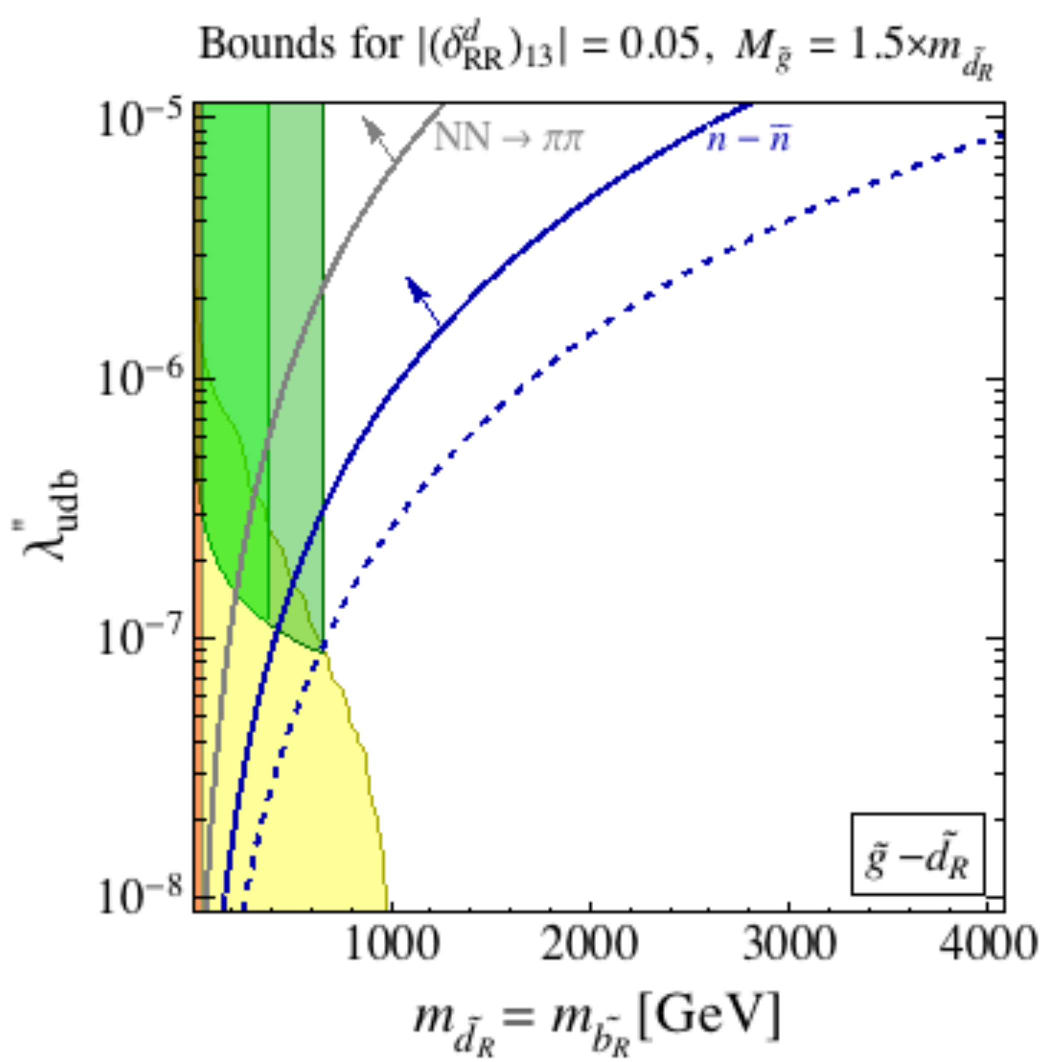
uds



udb



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

Bounds for BM models

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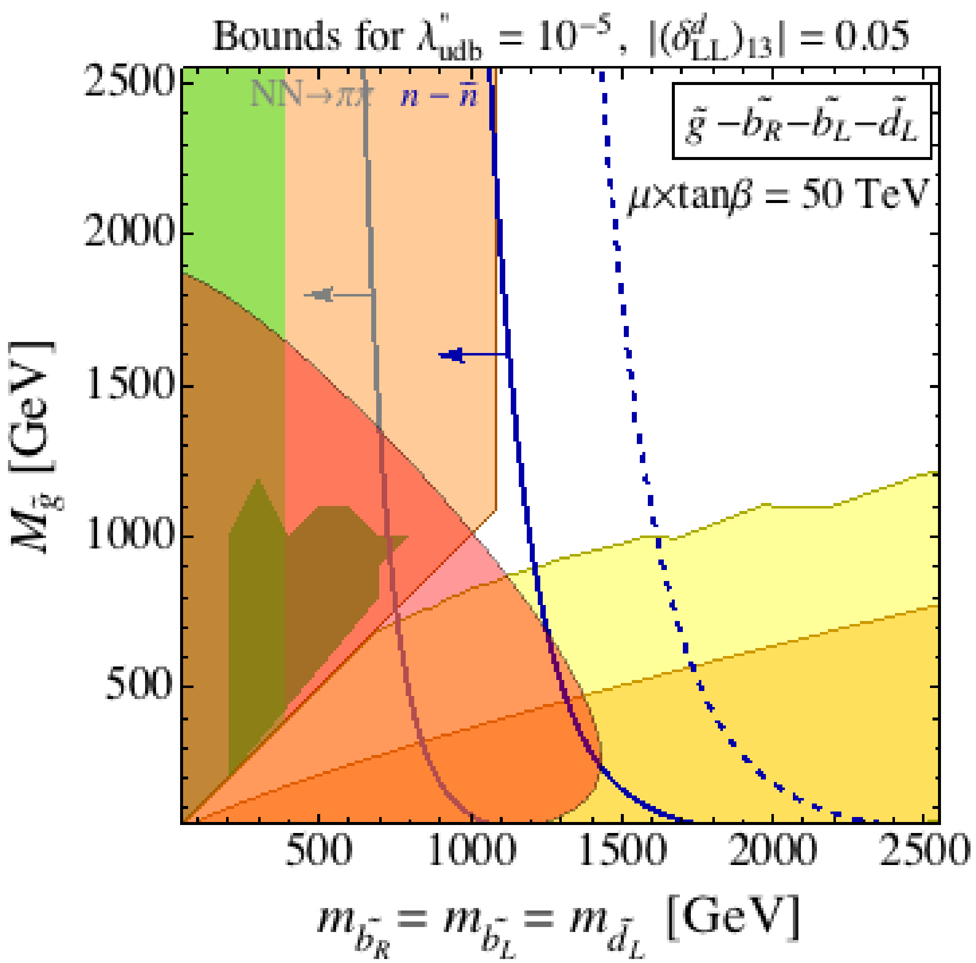
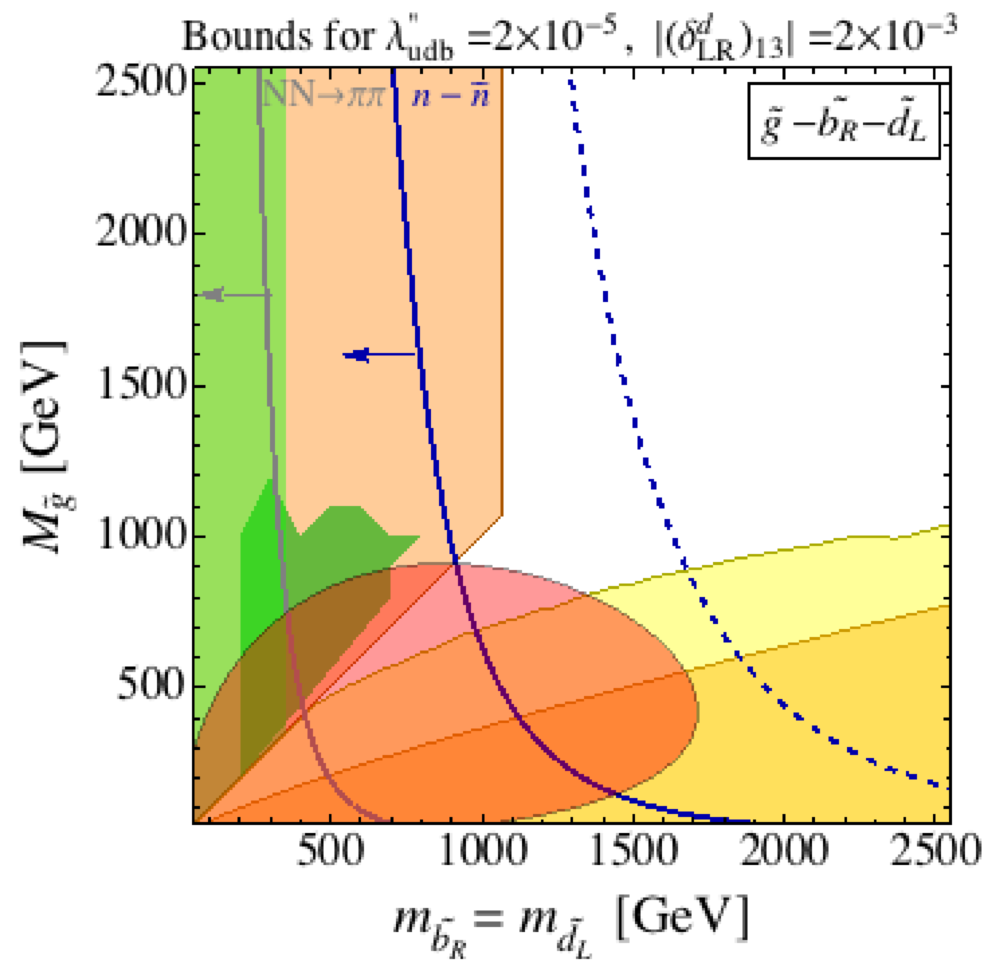
- bounds for BM$_1$ and BM$_2$ (MFV —> flavour mixing via detour)
  - red: constraints from $b \to d\gamma$





Bounds for GS model

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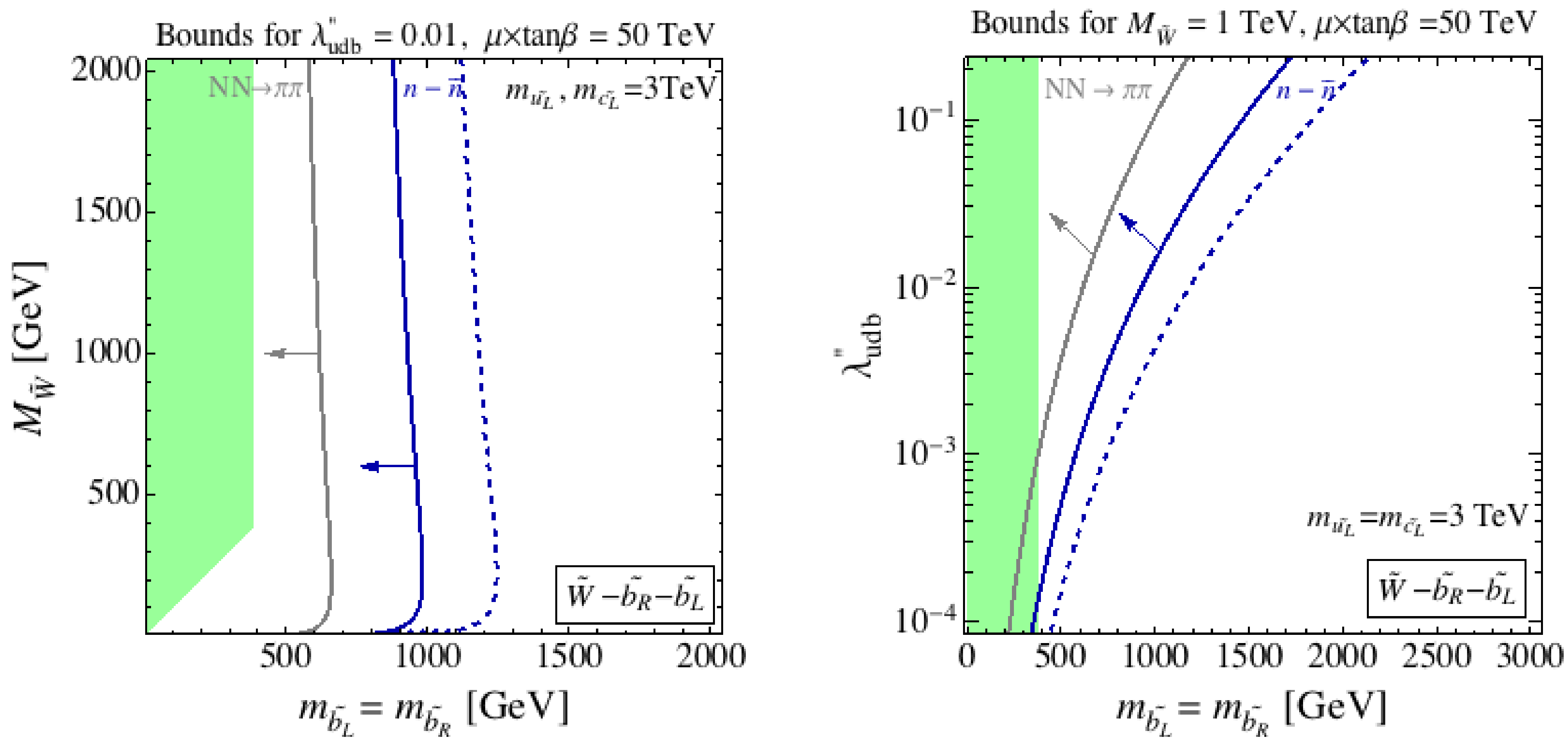
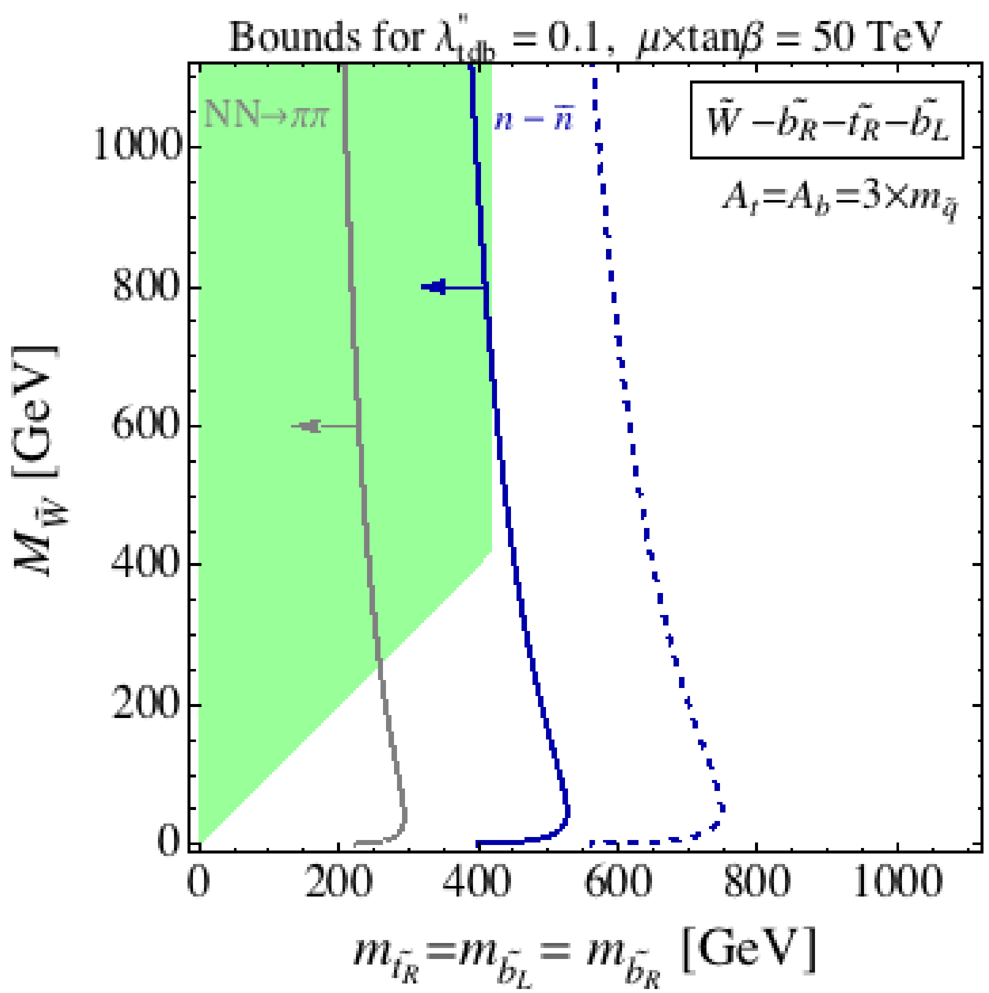
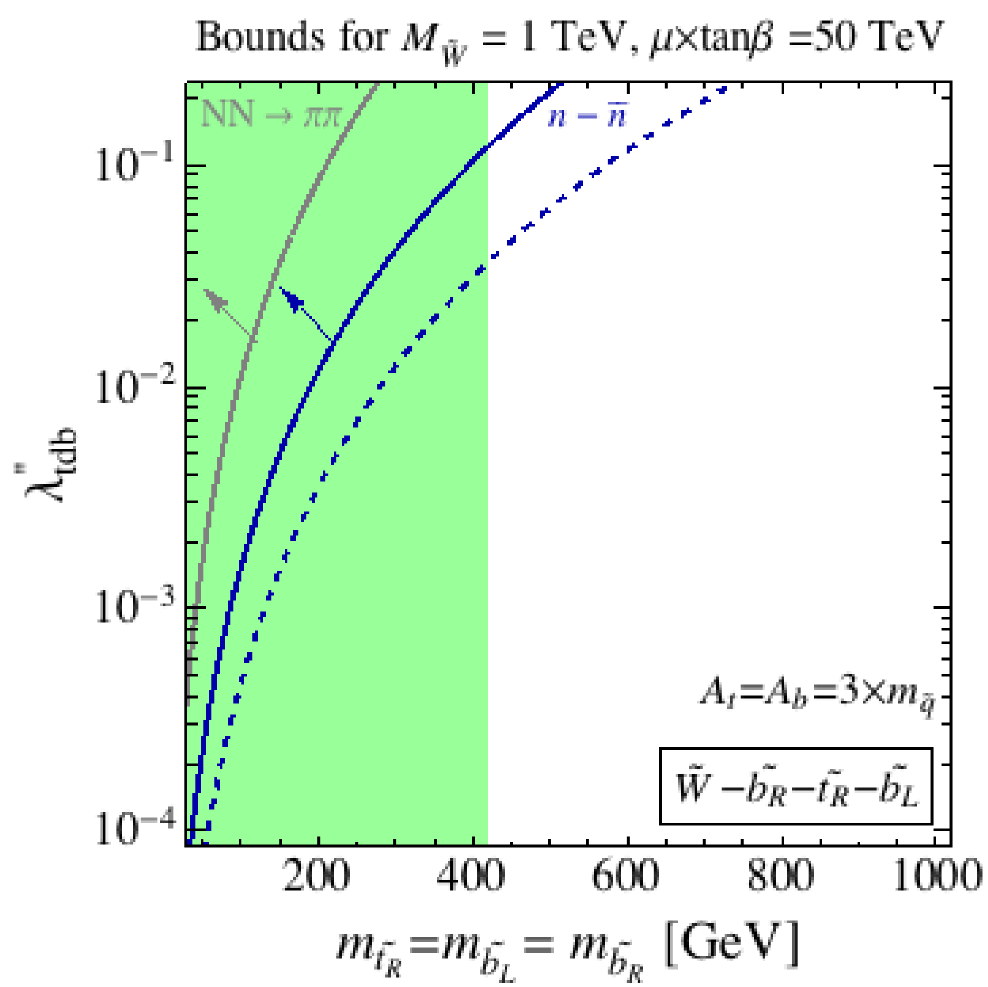
- MFV by construction, no relevant bounds from flavour constraints
- LHC: only squark mass bound



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





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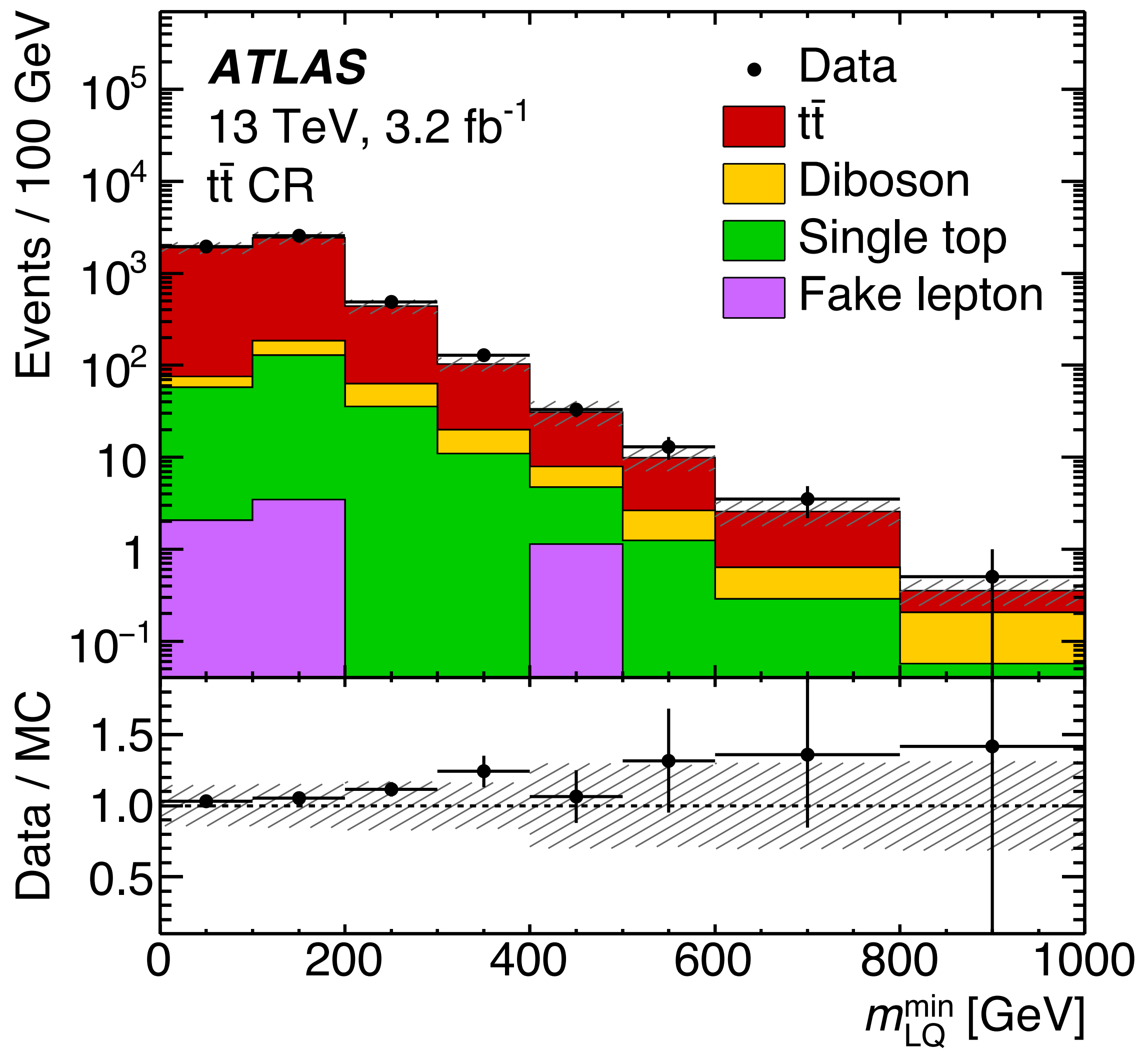
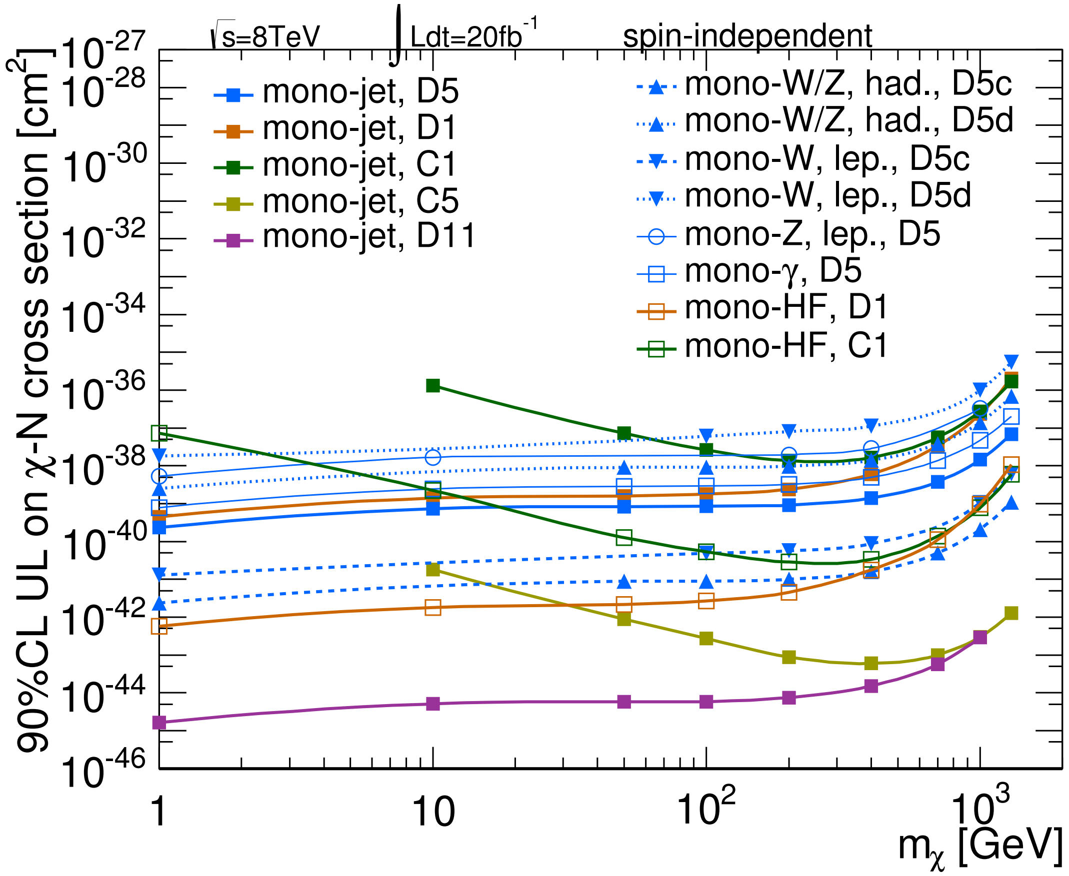
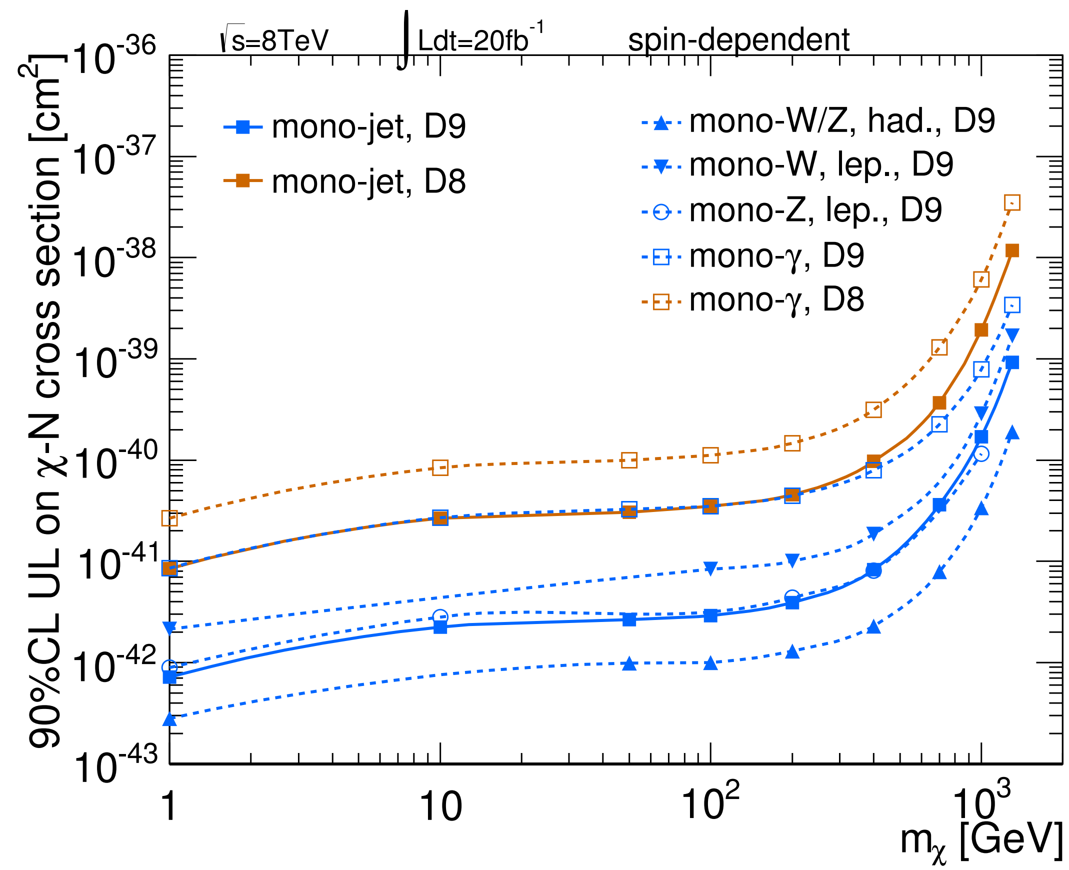


Comparison to other ATLAS Results

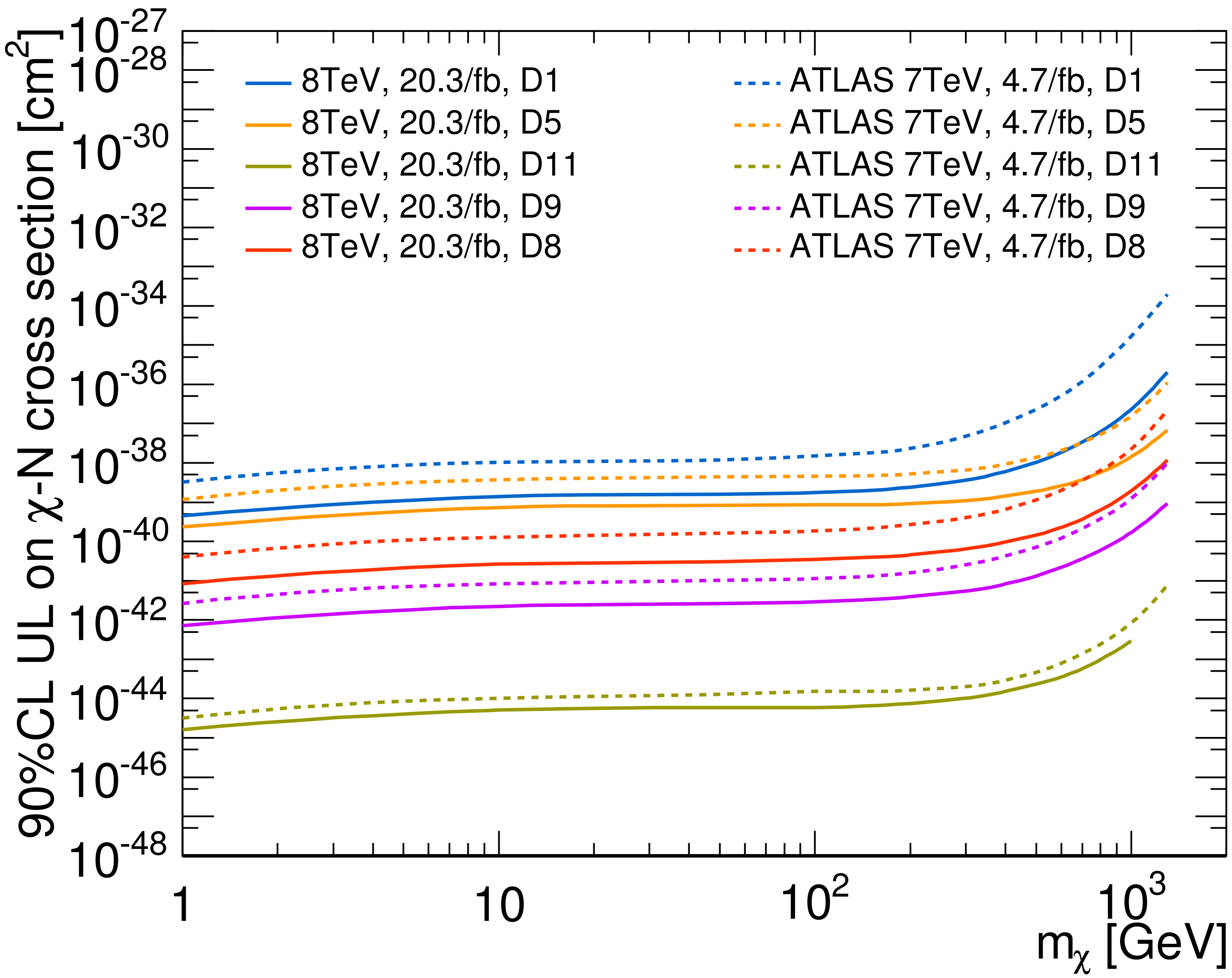


- only mono-jet can test gg-operator (strongest limits)
- for D5, constructive interference can occur -> mono-W surpass mono-jet
- for operators involving quark masses, mono-HF stronger limits
- mono-W/Z hadr. best limits for spin-dependent operator D9



EFT - Comparison to Previous Mono-Jet Result

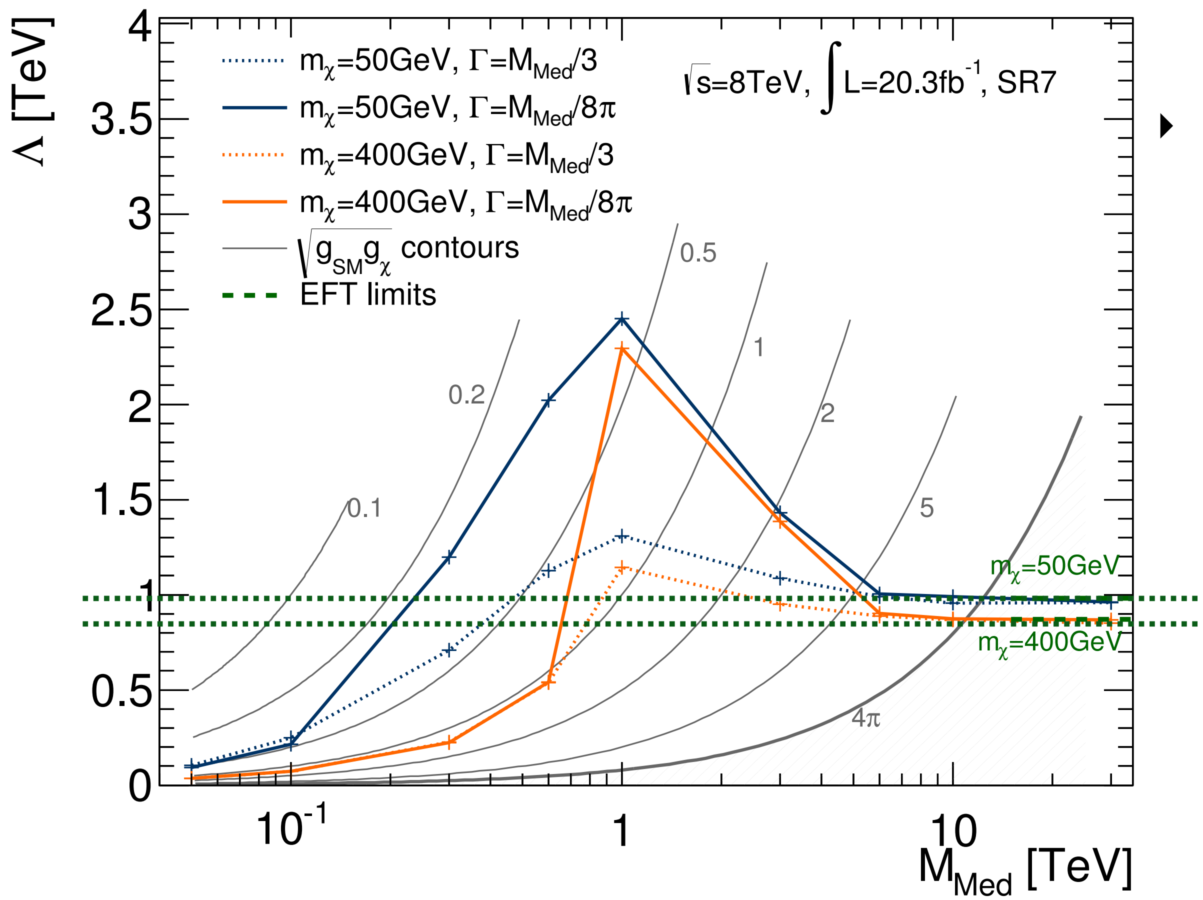
- **upper** limits on WIMP-nucleon-scattering cross section



clear improvement compared to 7TeV result

Simplified Model Limits 1

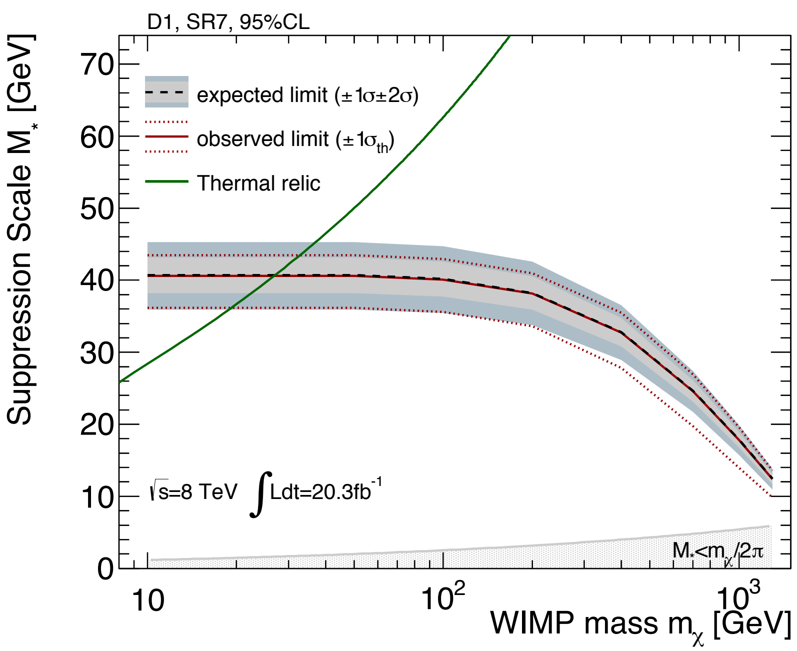
- limits taken from SR with best expected limit

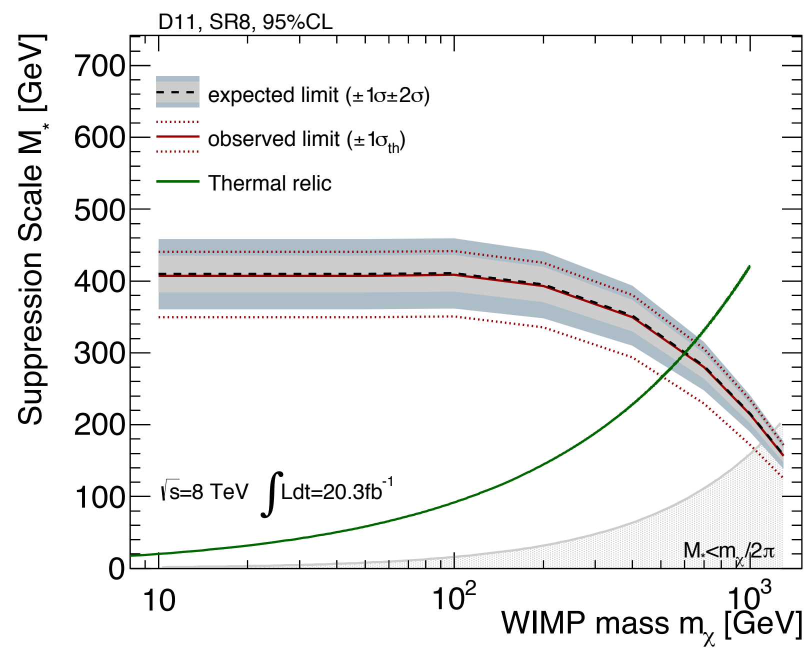


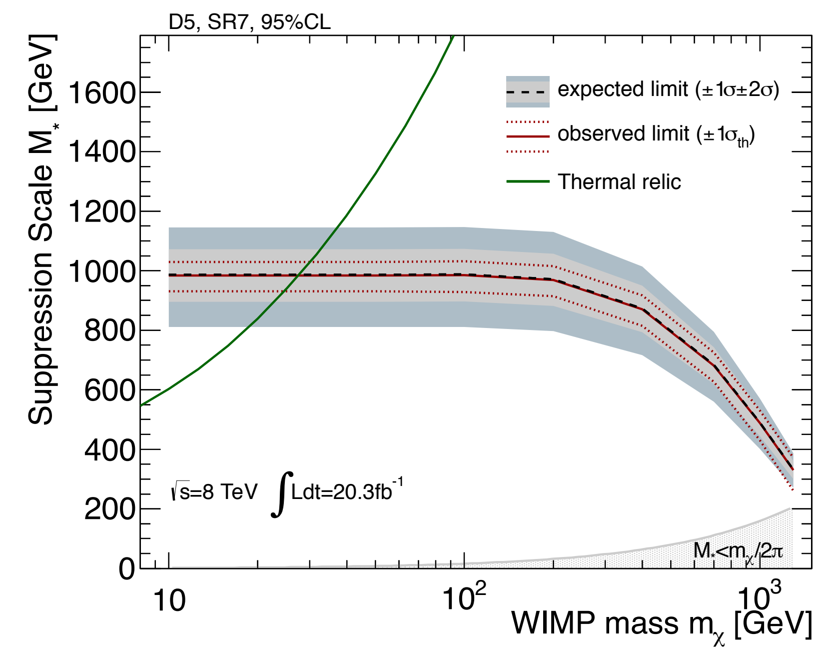
- limits on $\Lambda = M_{Med}/\sqrt{(g_{SM} g_\chi)}$
  - high M_{Med}: EFT regime
  - medium M_{Med}: on-shell production, strong limits
  - low M_{Med}: off-shell production, weak limits

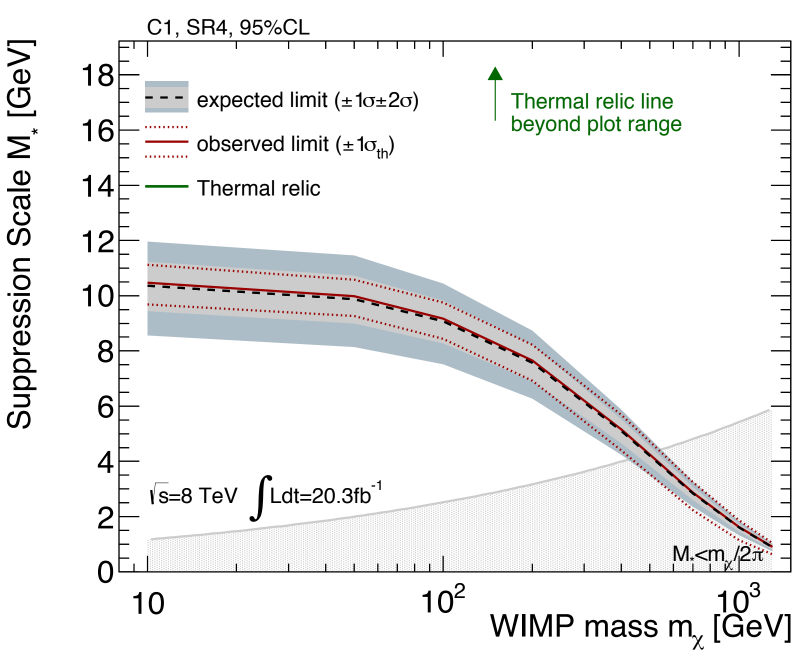
EFT - Limits on M* , SI

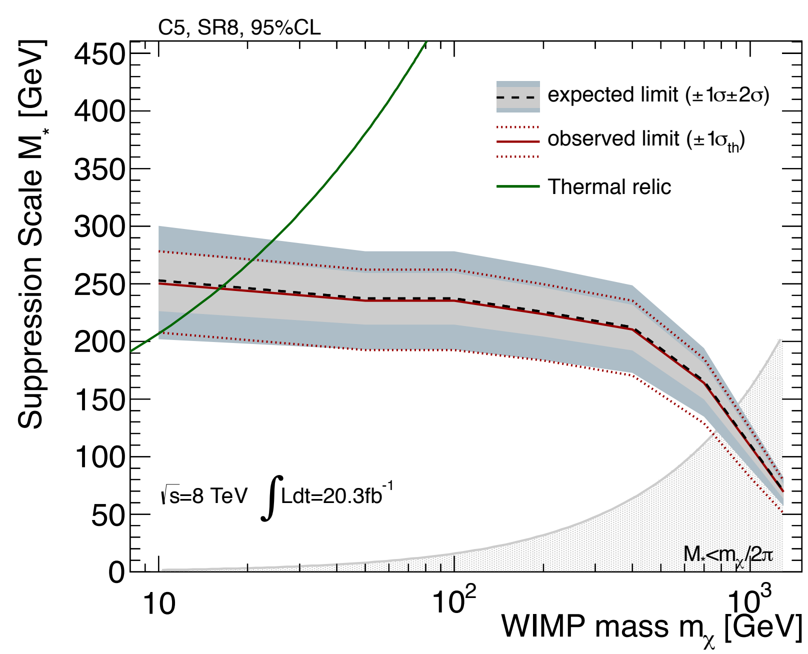
- limits taken from SR with best expected limit











EFT - Limits on M*, SD

- limits taken from SR with best expected limit