NLO (S)QCD corrections in R-symmetric supersymmetry

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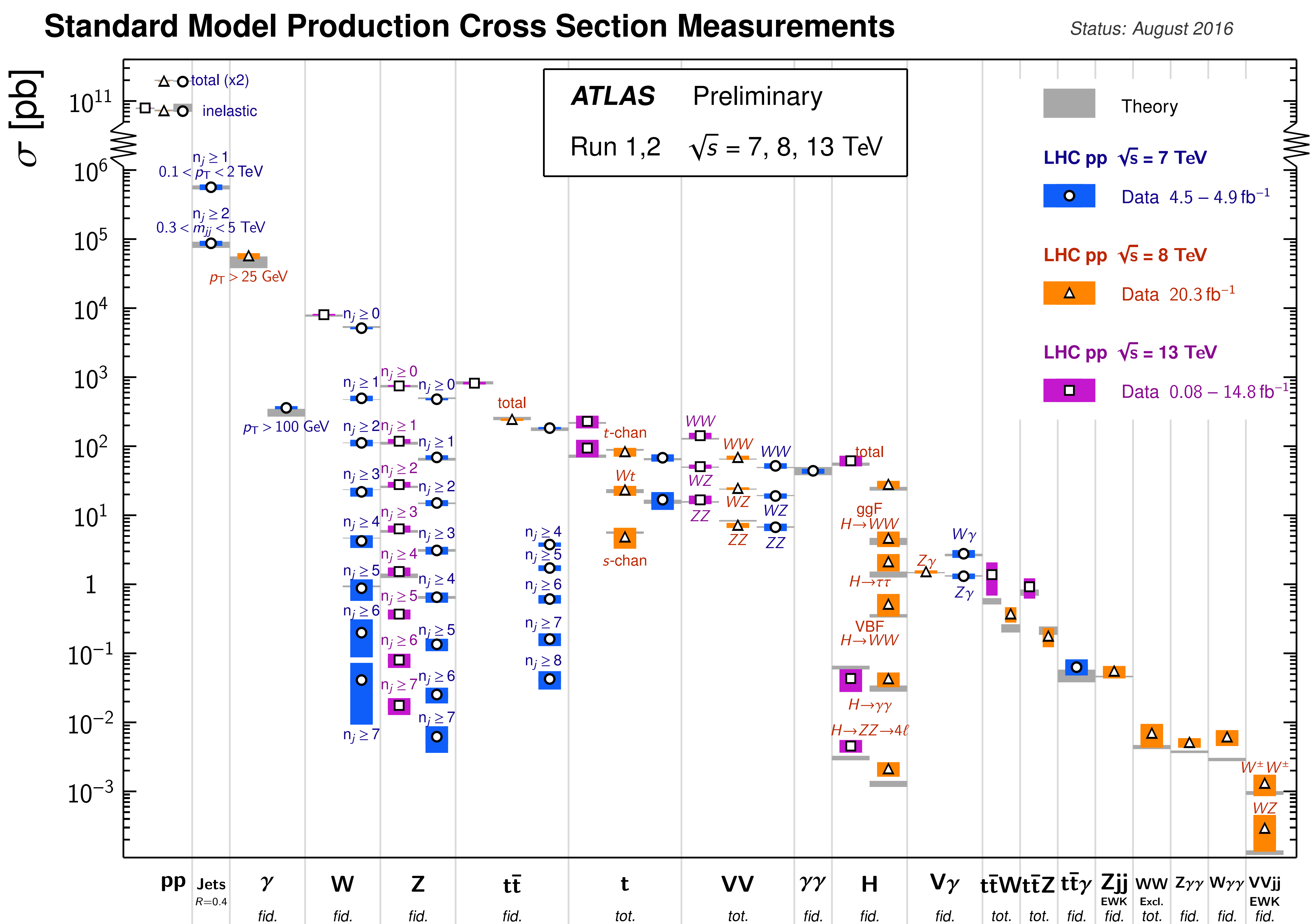
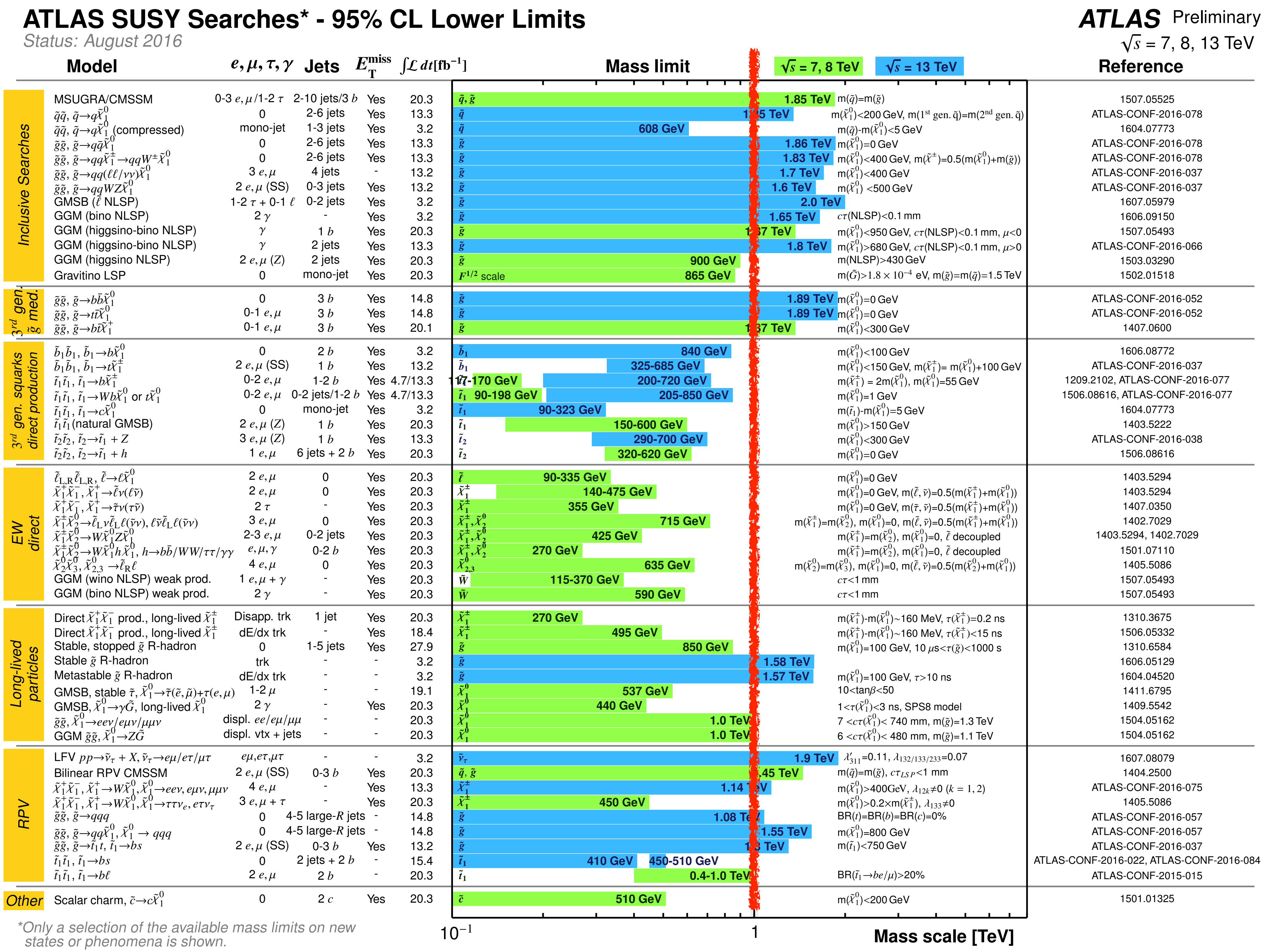
in collaboration with Philip Dießner, Jan Kalinowski, Sebastian Liebschner and Dominik Stöckinger

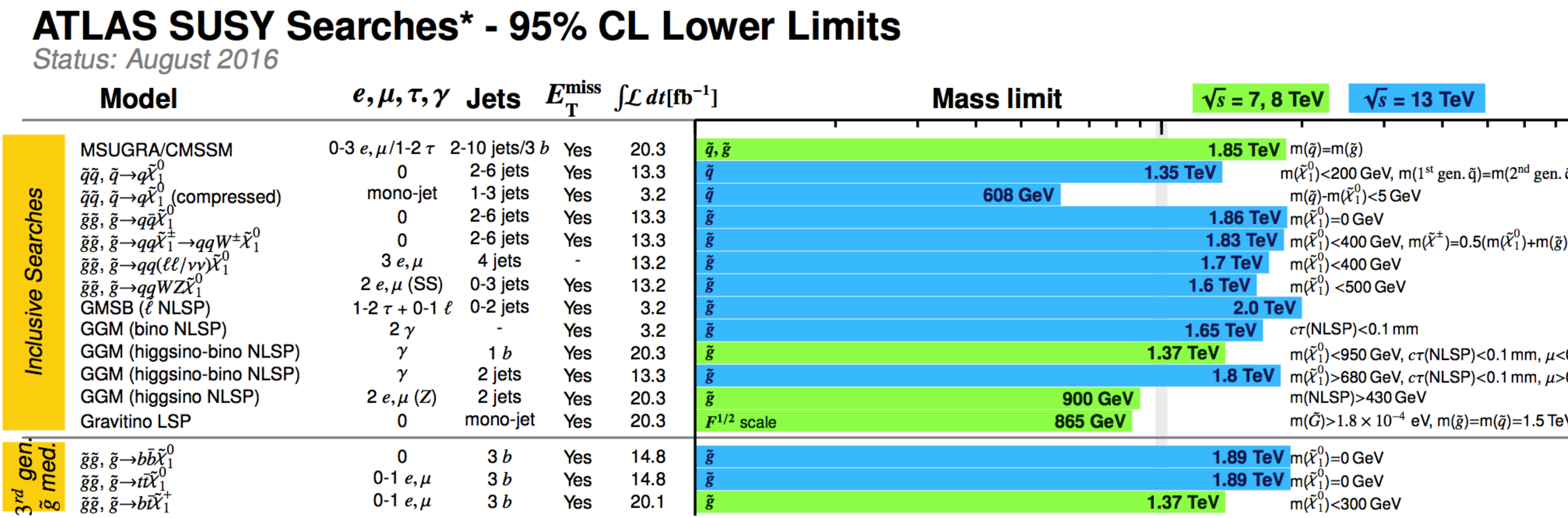
Triumph of the Standard Model



"SUSY" status at the beginning of Run II



Fine print: MSSM status at the beginning of Run II



ATLAS SUSY Searches* - 95% CL Lower Limits

Status: August 2016

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$\sqrt{s}$ = 7, 8 TeV　$\sqrt{s}$ = 13 TeV

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MSUGRA/CMSSM

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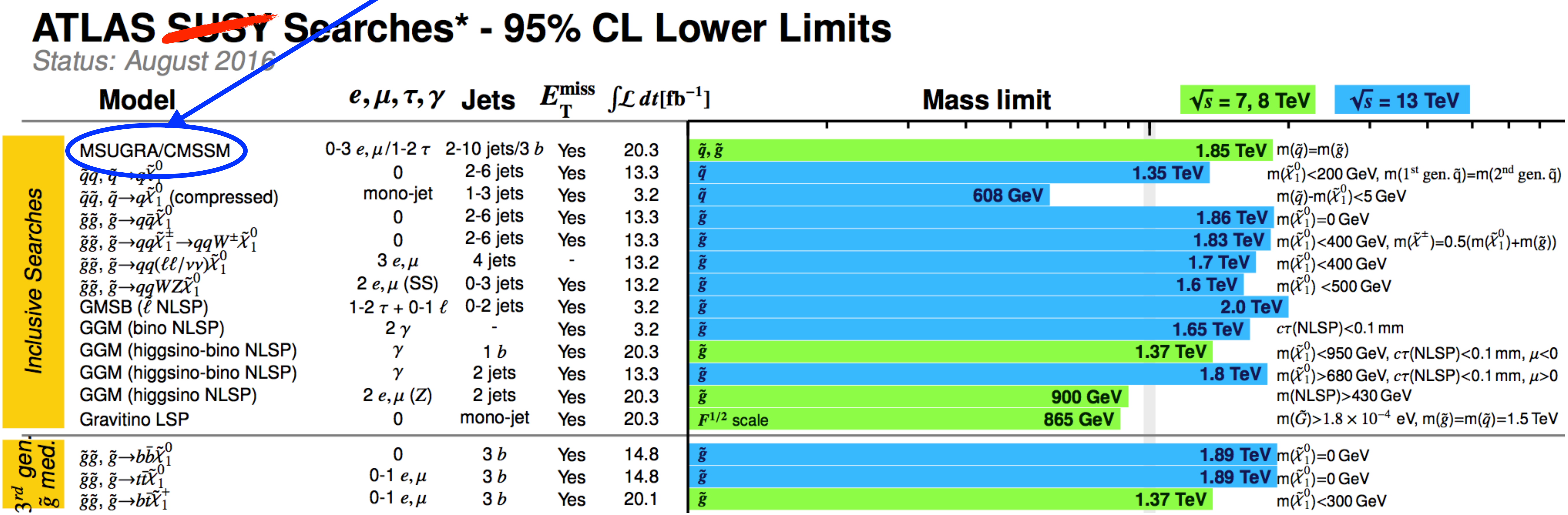

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those limits are model dependent and can be much weaker

Landscape of supersymmetric models

MSSM

Landscape of supersymmetric models

singlet extended SSM

SUSY with R-parity violation

additional U(1)'s

MSSM

R-symmetry

models with Dirac gauginos

triplet extended SSM

and many others....

R-symmetry

Fayet; Salam and Strathdee, ...

- additional symmetry of the SUSY algebra allowed by the Haag - Łopuszański - Sohnius theorem

- for N=1 it is a global $U_R(1)$ symmetry under which the SUSY generators are charged

- implies that the spinorial coordinates are also charged

$$Q_R(\theta) = 1, \; \theta \to e^{\imath\alpha}\theta$$

- Lagrangian invariance
  - Kähler potential invariant if R-charge of vector superfield is 0
  - R-charge of the superpotential must be 2
  - soft-breaking terms must have R-charge 0

Low-energy R-symmetry realization

R charges of component fields

	Q_R	scalar	vector	fermionic
vector superfield	0	-	0	1
chiral superfield	Q	Q	-	$Q-1$

- freedom in the choice of chiral superfield charge
- we choose SM fields to have R=0 ➜ Higgs superfields $Q_R=0$, lepton and quark superfields have $Q_R=+1$
- with the above assignment R-symmetry forbids
  - $\mu \hat{H}_u \hat{H}_d$
  - $\lambda \hat{E}\hat{L}\hat{L}, \kappa \hat{U}\hat{D}\hat{D}, e\hat{H}\hat{L}$
  - soft SUSY breaking Majorana masses and trilinear scalar couplings
- flavor problem ameliorated but now gauginos and higgsinos are masses
  ➜ possible solution - Dirac gauginos

One way to fix it: Dirac masses
Minimal R-Symmetric Supersymmetric Standardmodel (MRSSM)
Kribs et.al. arXiv:0712.2039

			$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_R$
Additional fields:	Singlet	$\hat{S}$	1	1	0	0
	Triplet	$\hat{T}$	1	3	0	0
	Octet	$\hat{O}$	8	1	0	0
	R-Higgses	$\hat{R}_u$	1	2	$-1/2$	2
		$\hat{R}_d$	1	2	$1/2$	2

other realizations:

...

Davies, March-Russell, McCullough (2011)
Lee, Raby, Ratz, Schieren, Schmidt-Hoberg, Vaudrevange (2011)
Frugiuele, Gregoire (2012)

...

MRSSM lagrangian

- Superpotential — Choi, Choudhury, Freitas, Kalinowski, Zerwas (2011)

$$W = \mu_d \hat{R}_d \hat{H}_d + \mu_u \hat{R}_u \hat{H}_u$$
$$+ \Lambda_d \hat{R}_d \hat{T} \hat{H}_d + \Lambda_u \hat{R}_u \hat{T} \hat{H}_u + \lambda_d \hat{S} \hat{R}_d \hat{H}_d + \lambda_u \hat{S} \hat{R}_u \hat{H}_u$$
$$- Y_d \hat{d} \hat{q} \hat{H}_d - Y_e \hat{e} \hat{l} \hat{H}_d + Y_u \hat{u} \hat{q} \hat{H}_u$$

  - μ-type terms
  - terms with λ, Λ couplings generate quartic Higgs couplings in the potential
  - MSSM-like Yukawa terms

- Allowed soft SUSY-breaking terms
  - conventional MSSM B_μ-term: $V \ni B_\mu (H_d^- H_u^+ - H_d^0 H_u^0) + \text{h.c.}$
  - Dirac mass terms for gauginos $M^D \tilde{g}\tilde{g}'$
  - scalar soft masses $m^2 |\Phi|^2$

Particle content summary: MSSM vs. MRSSM

different number of physical states **completely new states**

	Higgs				R-Higgs		
	CP-even	CP-odd	charged	charginos	neutral	charged	sgluon
MSSM	2	1	1	2	0	0	0
MRSSM	4	3	3	2+2	2	2	1

	neutralino	gluino	
MSSM	4	1	**Majorana fermions**
MRSSM	4	1	**Dirac fermions**

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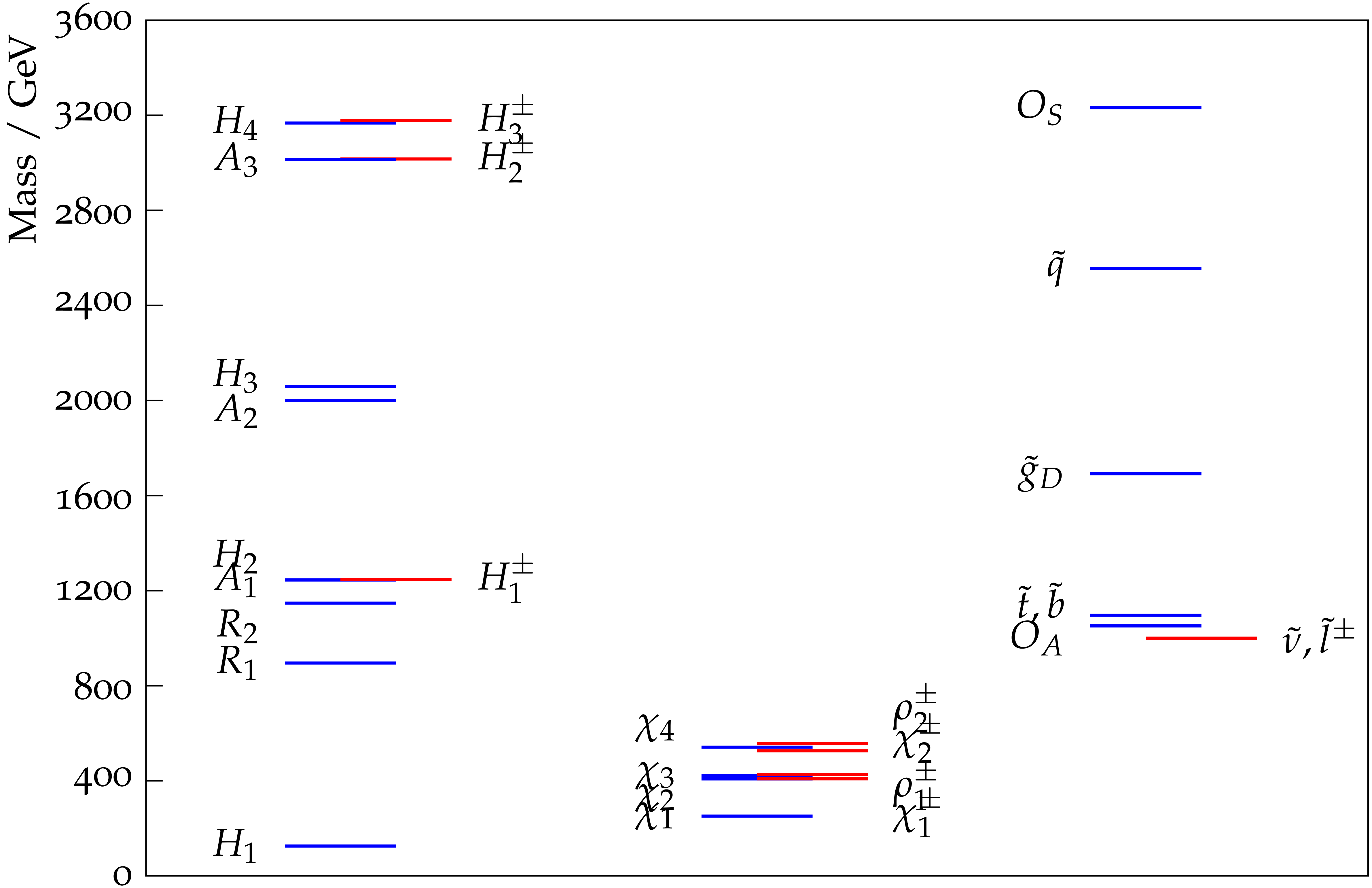
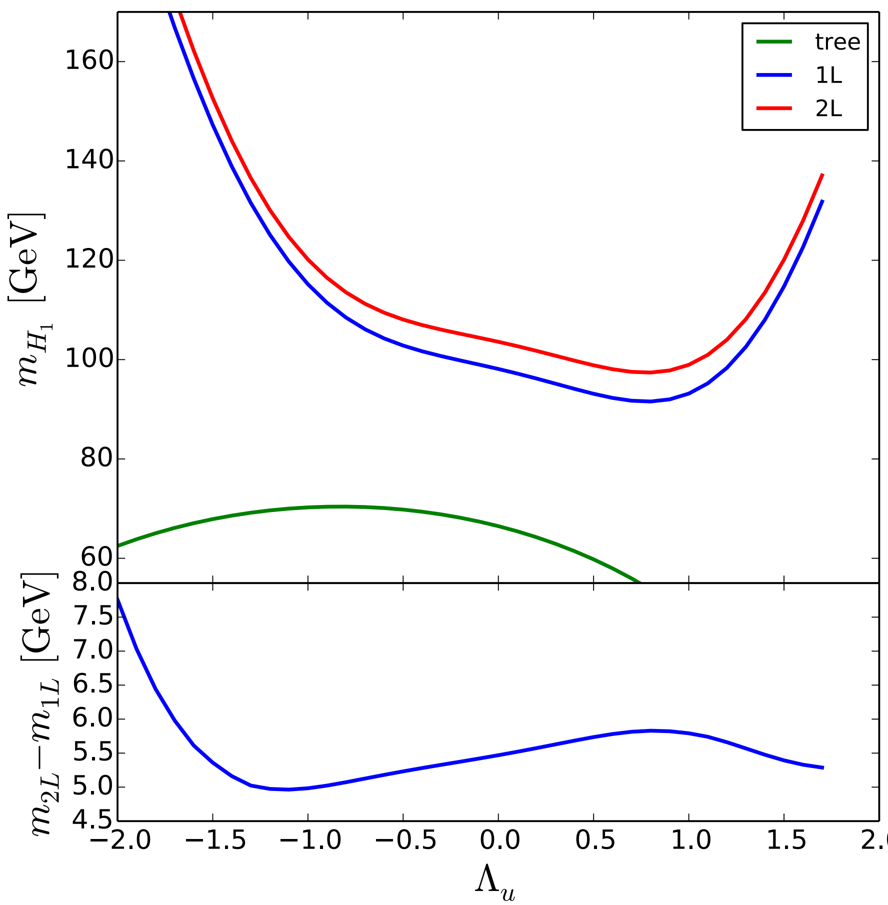
most important difference from the point of view of direct searches of supersymmetry at the LHC

Exemplary mass spectrum

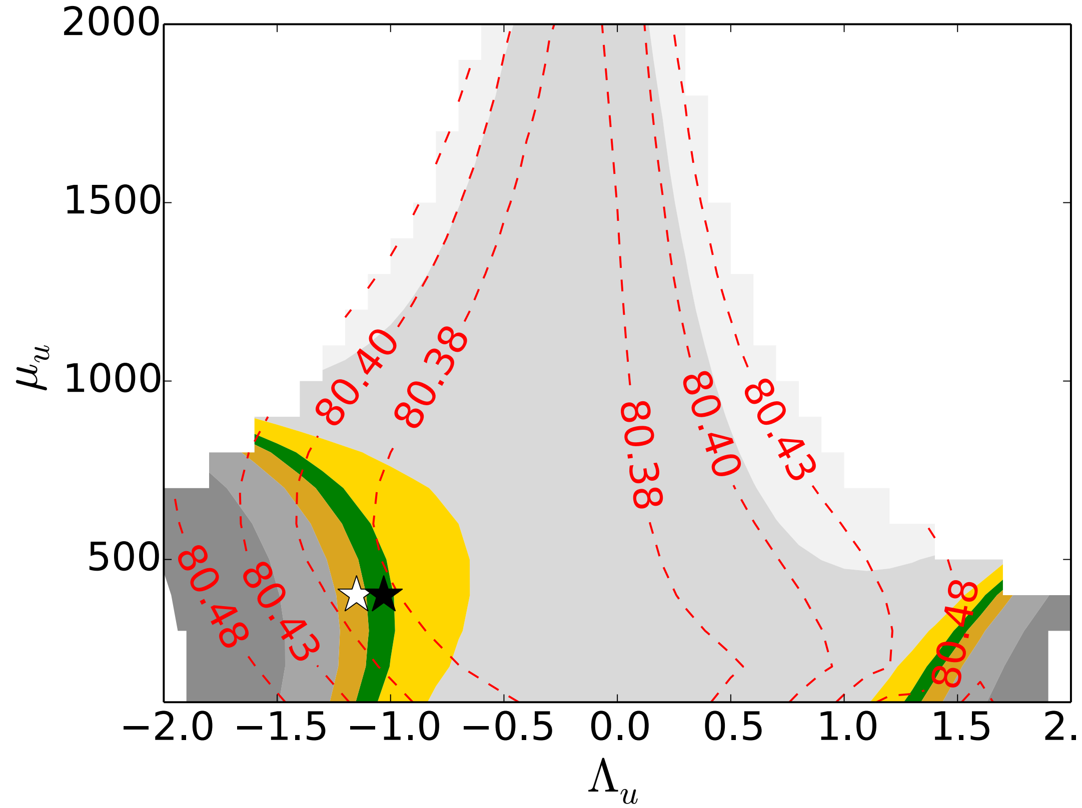


EW sector of the MRSSM (status)

- The SM-like Higgs boson mass in the MRSSM has been calculated including full 1-loop and leading 2-loop corrections[1,2]
- Impact of EWPO was analyzed[1]
- MRSSM can predicts correct dark matter relic density while being in agreement with dark matter direct detection bounds[3]
- Its EW signatures were checked against available 7 and 8 TeV data[3]



✦ tree-level result
✦ 1-loop quantum correction
✦ leading 2-loop corrections



1. P. Dießner, J. Kalinowski, W. Kotlarski and D. Stöckinger, JHEP **1412** (2014) 124

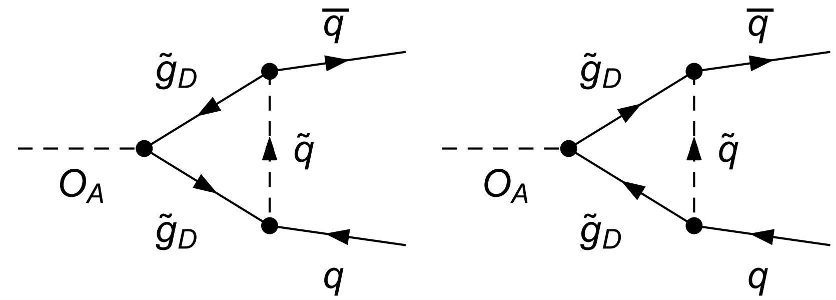
2. P. Dießner, J. Kalinowski, W. Kotlarski and D. Stöckinger, Adv. High Energy Phys. **2015** (2015) 760729

3. P. Dießner, J. Kalinowski, W. Kotlarski and D. Stöckinger, JHEP **1603** (2016) 007

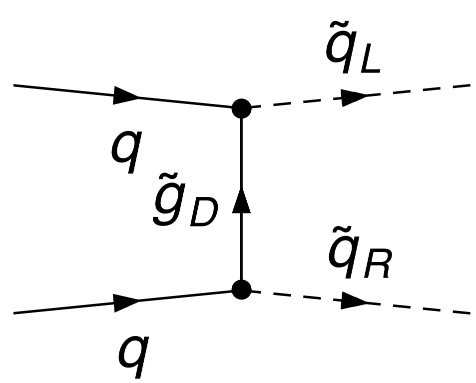
MRSSM signatures at the LHC

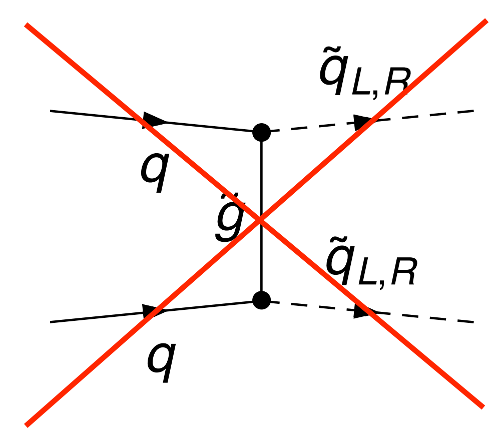
- sgluon pair production $pp \to OO$
  - complex fields O split by D-term contribution into scalar (S) and pseudoscalar (A) parts

$$m^2_{O_A} = m^2_O \qquad\qquad m^2_{O_S} = m^2_O + 4(M^D_O)^2$$

  - O_S naturally heavy, O_A might decay into quarks through loop-induced coupling
  - 

  - Coupling proportional to m_q. If O_A is lighter than other SUSY particles but $m_{O_A} > 2m_t$ O_A decays exclusively to top quarks

- same sign squark pair production $pp \to \tilde{q}_L \tilde{q}_R$
  - diagram present in the MRSSM 

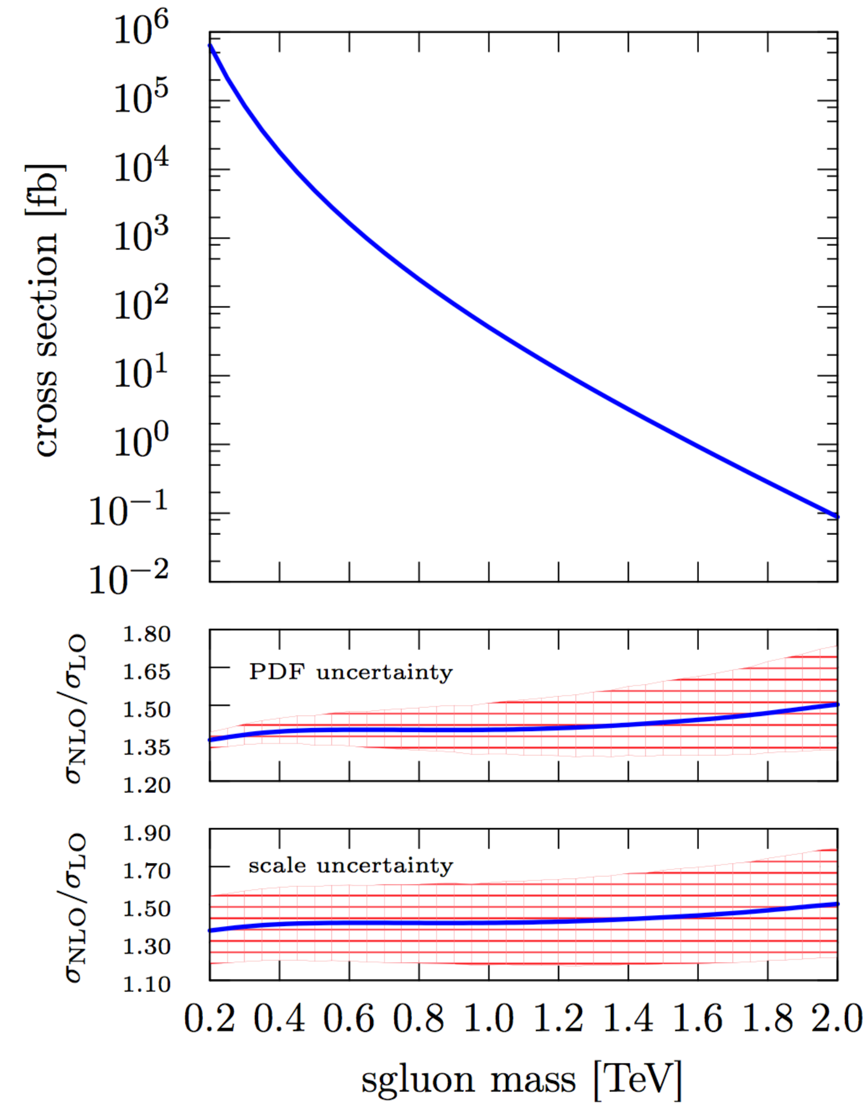
MSSM diagram with Majorana mass insertion doesn't exist 

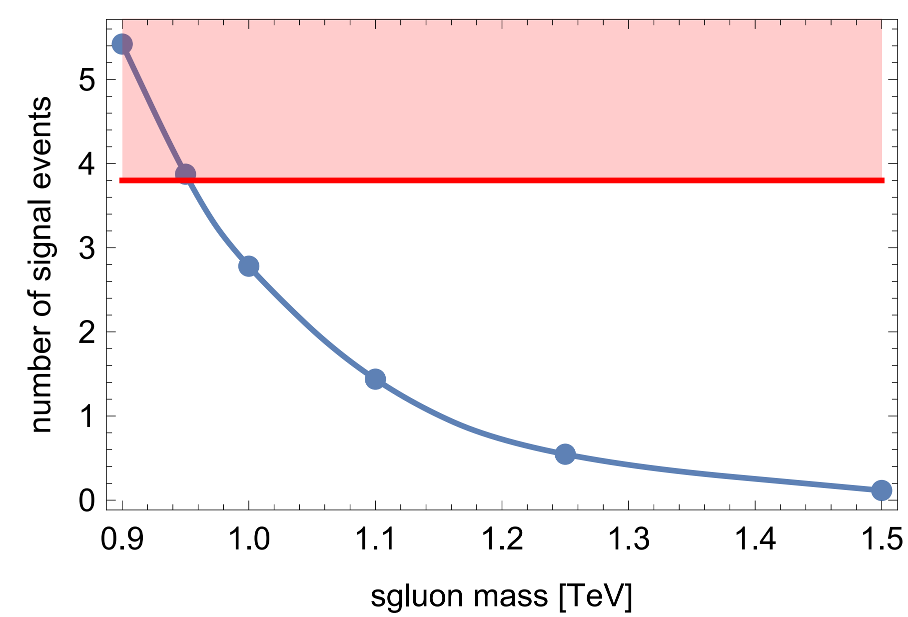
- Dirac gluino $\tilde{g}_D$ pair production, with cross section roughly twice as large as in the MSSM

Sgluon pair production at 13 TeV LHC

W. Kotlarski [arXiv:1608.00915]

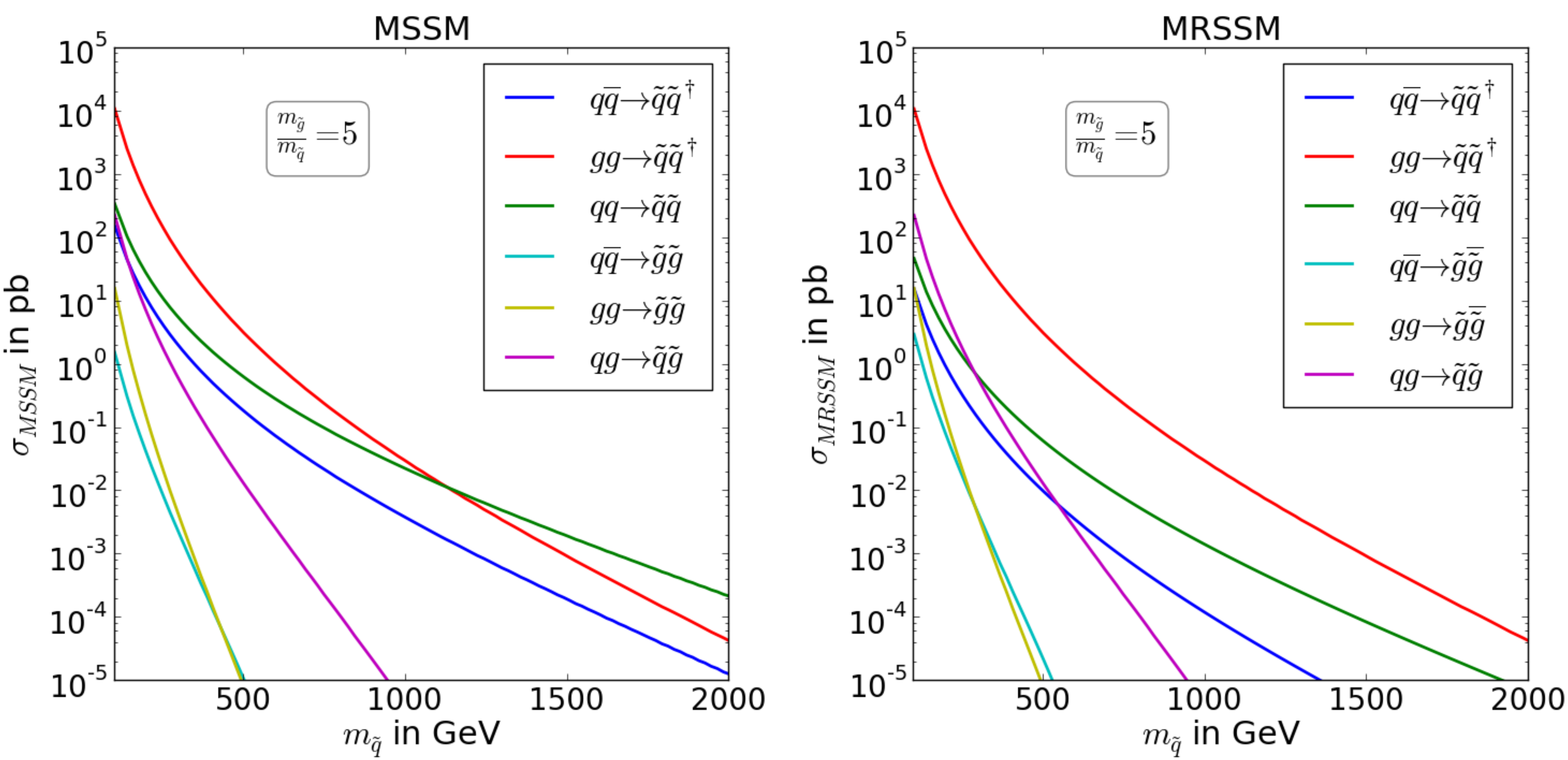
- Analysis of the sgluon pair production with subsequent decay into $t\bar{t}$ pairs. Recasting ATLAS search in the same-sign lepton channel using 3.2/fb of integrated luminosity
- Signal simulated at NLO using **MadGraph5_aMC@NLO** + **FeynRules** + **NLOCT** and matched to parton shower in the MC@NLO scheme
- Detector response parametrized using **Delphes3**
- Analysis validated on background processes $t\bar{t}l^+l^-, t\bar{t}l^\pm\nu$
- Mass of pair produced real sgluons decaying with $\mathrm{BR}(O \to t\bar{t}) = 1$ excluded up to 950 GeV





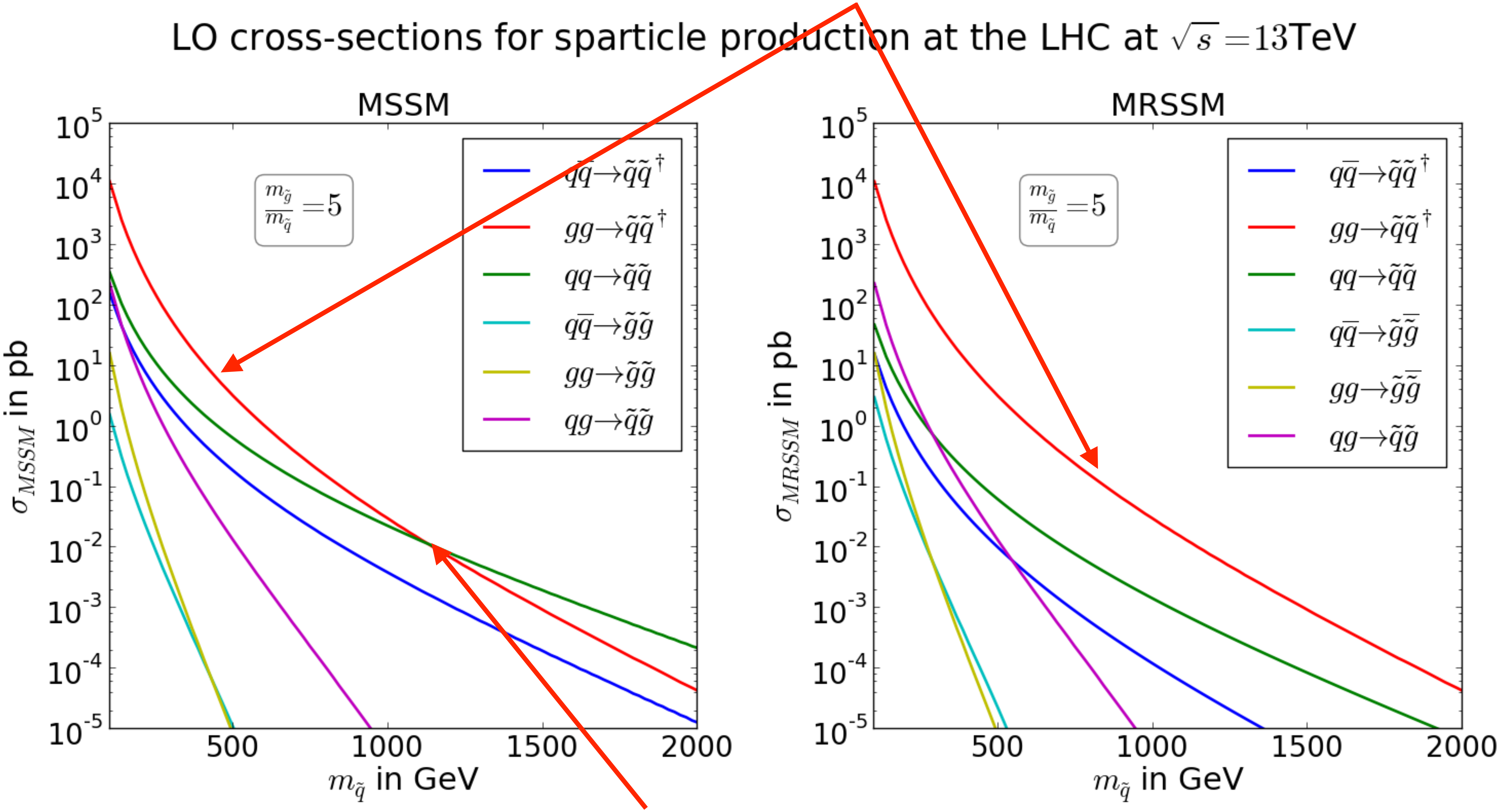
Leading order analysis

LO cross-sections for sparticle production at the LHC at $\sqrt{s}=13$TeV



Leading order analysis

while the red lines are the same



squark anti-squark pair production becomes subdominant

NLO corrections

Detour - regularization in SUSY theories

- dimensional regularization (DREG) breaks supersymmetry

	gluon		Majorana gluino
	g^μ		$\tilde{g}$
degrees of freedom in **4**-dimensions			
	4-2=2	=	2
degrees of freedom in **D**-dimensions			
	D-2	$\neq$	2

- Solution - use dimensional reduction (DRED). In DRED, momenta are continued from 4 to D dimensions, while gauge fields and γ-matrices remain 4-dimensional objects.

- PDF are fitted in the $\overline{\text{MS}}$ scheme. Not trivial to combine them with matrix elements regularized using DRED.

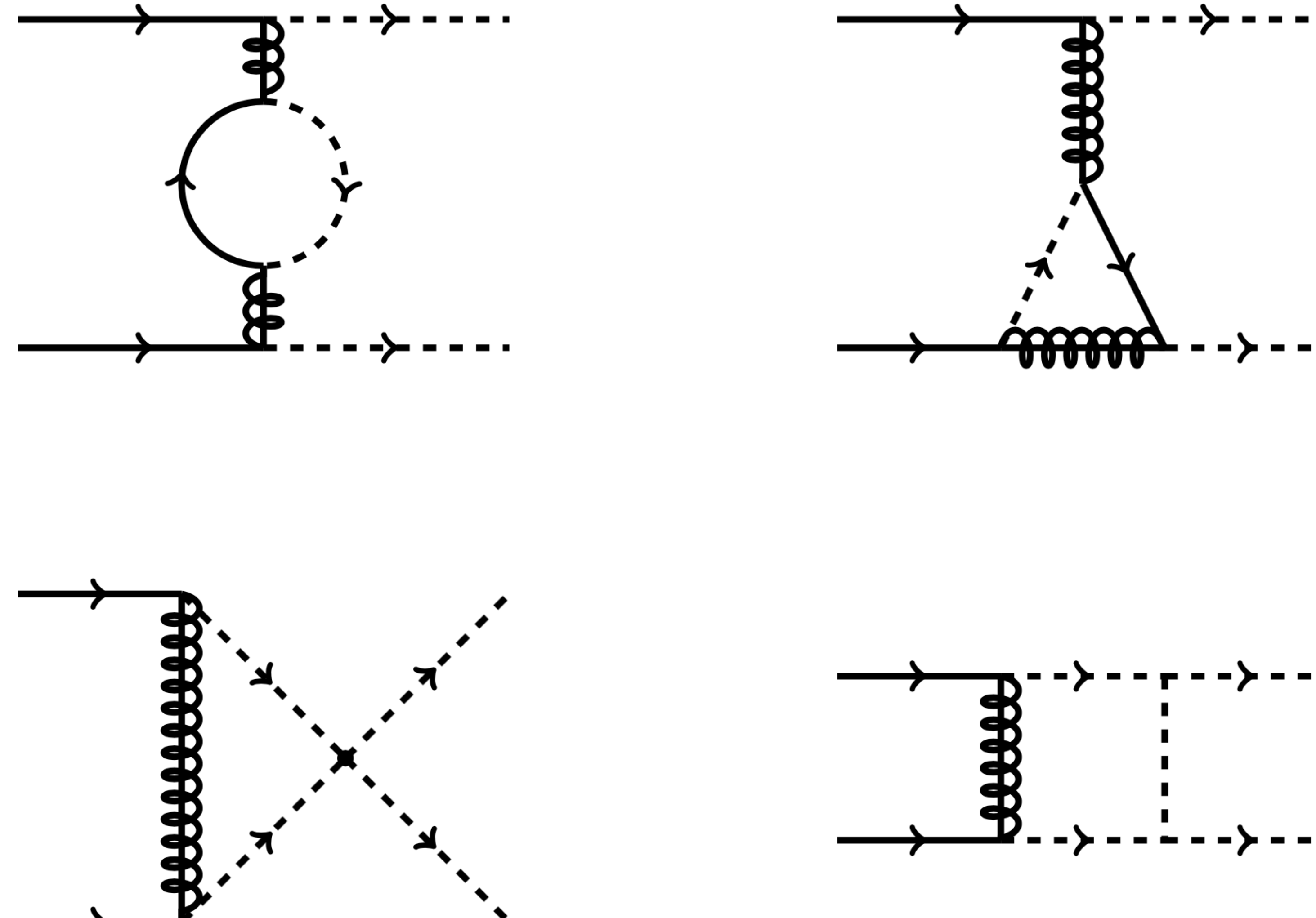
- Solution: do the calculation in the $\overline{\text{MS}}$ scheme and derive $\overline{\text{MS}} \to \overline{\text{DR}}$ transition terms by matching off-shell Green's functions calculated in both schemes. This fixes UV-part without altering the IR one.

Virtual matrix element - technical side

- **FeynArts** model containing renormalization constants and $\overline{\mathrm{MS}} \to \overline{\mathrm{DR}}$ transition counterterms

- Amplitude generated using **FeynArts** and evaluated in **FormCalc** in terms of Passarino - Veltman loop functions

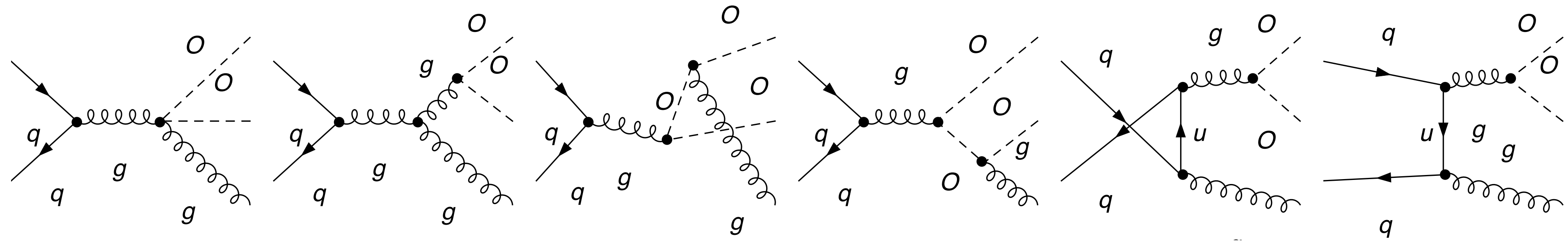
- Check of UV-finiteness



After renormalization the result is UV-finite but still IR divergent

Real emissions

- IR divergences cancelled after including real emission diagrams (Kinoshita-Lee-Nauenberg theorem) and through mass factorization, e.g.



- Split real emission phase space as (two-cut phase space slicing)

$$
\begin{aligned}
\sigma_R &= \int d\sigma_R \\
&= \int_S d\sigma_R + \int_H d\sigma_R \\
&= \int_S d\sigma_R + \int_{HC} d\sigma_R + \int_{H\overline{C}} d\sigma_R
\end{aligned}
$$

split gluon phase space according to its softness

split hard gluon phase space according to its collinearity

- S and HC parts integrated analytically in D-dimension
  - soft and collinear part (S) is the source of $\epsilon_{\rm IR}^{-2}$, $\epsilon_{\rm IR}^{-1}$
  - hard-collinear part (HC) is the source of $\epsilon_{\rm IR}^{-1}$

Framework's validation

- check of UV- and IR-finiteness, check of result independence on the phase space slicing parameters

- check of the selected MSSM processes against MadGrapgh5_aMC@NLO + FeynRules + NLOCT

  - ϵ expansion of the virtual matrix elements

  - total NLO cross sections

- sgluon pair production within an effective model (SM + octet)

- For MRSSM, independent implementation into MadGraph5_aMC@NLO + GoSam framework using UFO model with a hand encoded counterterms

- Following processes were already validated (more are on the way):

  - $pp \to OO$

  - $pp \to \tilde{q}_L \tilde{q}_R$

Preliminary results for $uu \to u_L u_R (+g)$

- Parameter point:

$$\sqrt{S} = 13 \text{ TeV}, m_{\tilde{q}} = 1.5 \text{ TeV}, m_{\tilde{g}_D} = 1 \text{ TeV}, \mu_R = \mu_F = m_{\tilde{q}}$$

  - LO result with MMHT2014lo68cl PDFs

$$\sigma^{\text{LO}}_{\text{MRSSM}} = \sigma^{\text{LO}}_{\text{MSSM}} = 6.379 \pm 0.004\, fb$$

  - NLO result with MMHT2014nlo68cl PDFs

$$\sigma^{\text{NLO}}_{\text{MSSM}} = 9.441 \pm 0.002\, fb$$

$$\sigma^{\text{NLO}}_{\text{MRSSM}} = 9.93 \pm 0.01\, fb$$

Summary and outlook

- MRSSM presents a viable alternative to the MSSM, without some of the MSSM drawbacks
    - 125 GeV SM-like Higgs boson with ~1 TeV stops
    - in agreement with EW precision observables, dark matter searches and collider bounds
- Its collider phenomenology might be quite different from the MSSM
- I presented first calculation of the SQCD NLO correction to $2 \to 2$ processes at the LHC within the R-symmetric SUSY
- Standalone `C++` code, called `RSymSQCD`, allowing to calculate NLO cross sections for selected $2 \to 2$ processes is in the preparation. Version 0.1, containing processes involving squarks: $pp \to \tilde{q}_i \tilde{q}_j^{(*)}, i, j \in \{L, R\}$ should become public before the end of this year

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Thank you!