Characterizing New Physics with Polarized Beams at High Energy Hadron Colliders

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Outline

1. Motivations
2. Physics at polarized hadron colliders
3. Physics case: Monotop signature
4. Conclusions

Status of New Physics searches at the LHC

- **After 3 years of data taking at the LHC:**
  - **No experimental evidence** of **New physics has been found**
  - **ATLAS and CMS have probed extensively** the **TeV region**
  - **Mass exclusion limits** of many **BSM particles** have been **pushed higher and higher in energy**
  - **Significant portions** of the **parameter space** of **many simplified models** have been **excluded**

- ***e.g.* Summary plots for ATLAS:**

ATLAS Exotics Searches* - 95% CL Exclusion

Status: ICHEP 2014

ATLAS Preliminary

$\int \mathcal{L}\, dt$ = (1.0 - 20.3) fb^{-1} $\sqrt{s}$ = 7, 8 TeV

	Model	ℓ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt$[fb^{-1}]	Mass limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	1-2 j	Yes	4.7	M_D 4.37 TeV	$n = 2$	1210.4491
	ADD non-resonant $\ell\ell$	$2e, \mu$	–	–	20.3	M_S 5.2 TeV	$n = 3$ HLZ	ATLAS-CONF-2014-030
	ADD QBH $\to \ell q$	$1\, e, \mu$	1 j	–	20.3	M_{th} 5.2 TeV	$n = 6$	1311.2006
	ADD QBH	–	2 j	–	20.3	M_{th} 5.82 TeV	$n = 6$	to be submitted to PRD
	ADD BH high N_{trk}	$2\, \mu$ (SS)	–	–	20.3	M_{th} 5.7 TeV	$n = 6$, $M_D = 1.5$ TeV, non-rot BH	1308.4075
	ADD BH high $\sum p_T$	$\geq 1\, e, \mu$	≥ 2 j	–	20.3	M_{th} 6.2 TeV	$n = 6$, $M_D = 1.5$ TeV, non-rot BH	1405.4254
	RS1 $G_{KK} \to \ell\ell$	$2\, e, \mu$	–	–	20.3	G_{KK} mass 2.68 TeV	$k/\overline{M}_{Pl} = 0.1$	1405.4123
	RS1 $G_{KK} \to WW \to \ell\nu\ell\nu$	$2\, e, \mu$	–	Yes	4.7	G_{KK} mass 1.23 TeV	$k/\overline{M}_{Pl} = 0.1$	1208.2880
	Bulk RS $G_{KK} \to ZZ \to \ell\ell qq$	$2\, e, \mu$	2 j / 1 J	–	20.3	G_{KK} mass 730 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2014-039
	Bulk RS $G_{KK} \to HH \to b\bar{b}b\bar{b}$	–	4 b	–	19.5	G_{KK} mass 590-710 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2014-005
	Bulk RS $g_{KK} \to t\bar{t}$	$1\, e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	14.3	g_{KK} mass 2.0 TeV	BR = 0.925	ATLAS-CONF-2013-052
	S^1/Z_2 ED	$2\, e, \mu$	–	–	5.0	$M_{KK} \approx R^{-1}$ 4.71 TeV		1209.2535
	UED	$2\, \gamma$	–	Yes	4.8	Compact. scale R^{-1} 1.41 TeV		ATLAS-CONF-2012-072
Gauge bosons	SSM $Z' \to \ell\ell$	$2\, e, \mu$	–	–	20.3	Z' mass 2.9 TeV		1405.4123
	SSM $Z' \to \tau\tau$	$2\, \tau$	–	–	19.5	Z' mass 1.9 TeV		ATLAS-CONF-2013-066
	SSM $W' \to \ell\nu$	$1\, e, \mu$	–	Yes	20.3	W' mass 3.28 TeV		ATLAS-CONF-2014-017
	EGM $W' \to WZ \to \ell\nu\, \ell'\ell'$	$3\, e, \mu$	–	Yes	20.3	W' mass 1.52 TeV		1406.4456
	EGM $W' \to WZ \to qq\ell\ell$	$2\, e, \mu$	2 j / 1 J	–	20.3	W' mass 1.59 TeV		ATLAS-CONF-2014-039
	LRSM $W'_R \to t\bar{b}$	$1\, e, \mu$	2 b, 0-1 j	Yes	14.3	W' mass 1.84 TeV		ATLAS-CONF-2013-050
	LRSM $W'_R \to t\bar{b}$	$0\, e, \mu$	≥ 1 b, 1 J	–	20.3	W' mass 1.77 TeV		to be submitted to EPJC
CI	CI $qqqq$	–	2 j	–	4.8	Λ 7.6 TeV	$\eta = +1$	1210.1718
	CI $qq\ell\ell$	$2\, e, \mu$	–	–	20.3	Λ 21.6 TeV	$\eta_{LL} = -1$	ATLAS-CONF-2014-030
	CI $uutt$	$2\, e, \mu$ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	Λ 3.3 TeV	$\lvert C \rvert = 1$	ATLAS-CONF-2013-051
DM	EFT D5 operator (Dirac)	$0\, e, \mu$	1-2 j	Yes	10.5	M_* 731 GeV	at 90% CL for $m(\chi) < 80$ GeV	ATLAS-CONF-2012-147
	EFT D9 operator (Dirac)	$0\, e, \mu$	1 J, ≤ 1 j	Yes	20.3	M_* 2.4 TeV	at 90% CL for $m(\chi) < 100$ GeV	1309.4017
LQ	Scalar LQ 1st gen	$2\, e$	≥ 2 j	–	1.0	LQ mass 660 GeV	$\beta = 1$	1112.4828
	Scalar LQ 2nd gen	$2\, \mu$	≥ 2 j	–	1.0	LQ mass 685 GeV	$\beta = 1$	1203.3172
	Scalar LQ 3rd gen	$1\, e, \mu, 1\, \tau$	1 b, 1 j	–	4.7	LQ mass 534 GeV	$\beta = 1$	1303.0526
Heavy quarks	Vector-like quark $TT \to Ht + X$	$1\, e, \mu$	≥ 2 b, ≥ 4 j	Yes	14.3	T mass 790 GeV	T in (T,B) doublet	ATLAS-CONF-2013-018
	Vector-like quark $TT \to Wb + X$	$1\, e, \mu$	≥ 1 b, ≥ 3 j	Yes	14.3	T mass 670 GeV	isospin singlet	ATLAS-CONF-2013-060
	Vector-like quark $TT \to Zt + X$	$2/\geq 3\, e, \mu$	$\geq 2/\geq 1$ b	–	20.3	T mass 735 GeV	T in (T,B) doublet	ATLAS-CONF-2014-036
	Vector-like quark $BB \to Zb + X$	$2/\geq 3\, e, \mu$	$\geq 2/\geq 1$ b	–	20.3	B mass 755 GeV	B in (B,Y) doublet	ATLAS-CONF-2014-036
	Vector-like quark $BB \to Wt + X$	$2\, e, \mu$ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	B mass 720 GeV	B in (T,B) doublet	ATLAS-CONF-2013-051
Excited fermions	Excited quark $q^* \to q\gamma$	$1\, \gamma$	1 j	–	20.3	q^* mass 3.5 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1309.3230
	Excited quark $q^* \to qg$	–	2 j	–	20.3	q^* mass 4.09 TeV	only u^* and d^*, $\Lambda = m(q^*)$	to be submitted to PRD
	Excited quark $b^* \to Wt$	1 or 2 e, μ	1 b, 2 j or 1 j	Yes	4.7	b^* mass 870 GeV	left-handed coupling	1301.1583
	Excited lepton $\ell^* \to \ell\gamma$	$2\, e, \mu, 1\, \gamma$	–	–	13.0	ℓ^* mass 2.2 TeV	$\Lambda = 2.2$ TeV	1308.1364
Other	LSTC $a_T \to W\gamma$	$1\, e, \mu, 1\, \gamma$	–	Yes	20.3	a_T mass 960 GeV		to be submitted to PLB
	LRSM Majorana ν	$2\, e, \mu$	2 j	–	2.1	N^0 mass 1.5 TeV	$m(W_R) = 2$ TeV, no mixing	1203.5420
	Type III Seesaw	$2\, e, \mu$	–	–	5.8	$N^\pm$ mass 245 GeV	$\lvert V_e \rvert$=0.055, $\lvert V_\mu \rvert$=0.063, $\lvert V_\tau \rvert$=0	ATLAS-CONF-2013-019
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	$2\, e, \mu$ (SS)	–	–	4.7	$H^{\pm\pm}$ mass 409 GeV	DY production, BR($H^{\pm\pm} \to \ell\ell$)=1	1210.5070
	Multi-charged particles	–	–	–	4.4	multi-charged particle mass 490 GeV	DY production, $\lvert q \rvert = 4e$	1301.5272
	Magnetic monopoles	–	–	–	2.0	monopole mass 862 GeV	DY production, $\lvert g \rvert = 1 g_D$	1207.6411

$\sqrt{s}$ = 7 TeV | $\sqrt{s}$ = 8 TeV

10^{-1} 1 10 **Mass scale [TeV]**

*Only a selection of the available mass limits on new states or phenomena is shown.

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: ICHEP 2014

ATLAS Preliminary

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

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.7 TeV	$m(\tilde{q})=m(\tilde{g})$	1405.7875
	MSUGRA/CMSSM	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.2 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	any $m(\tilde{q})$	1308.1841
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 850 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	1405.7875
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.33 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	1405.7875
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.18 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}^{\pm})=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e, μ	0-3 jets	-	20.3	$\tilde{g}$ 1.12 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-089
	GMSB ($\tilde{\ell}$ NLSP)	2 e, μ	2-4 jets	Yes	4.7	$\tilde{g}$ 1.24 TeV	$\tan\beta$<15	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde{g}$ 1.6 TeV	$\tan\beta$ >20	1407.0603
	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde{g}$ 1.28 TeV	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2014-001
	GGM (wino NLSP)	1 $e, \mu + \gamma$	-	Yes	4.8	$\tilde{g}$ 619 GeV	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$ 900 GeV	$m(\tilde{\chi}_1^0)$>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e, μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$ 690 GeV	m(NLSP)>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale 645 GeV	$m(\tilde{G})>10^{-4}$ eV	ATLAS-CONF-2012-147
3rd gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$ 1.25 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	1407.0600
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	$m(\tilde{\chi}_1^0)$ <350 GeV	1308.1841
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	1407.0600
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	1407.0600
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$ 100-620 GeV	$m(\tilde{\chi}_1^0)$<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}_1^{\pm}$	2 e, μ (SS)	0-3 b	Yes	20.3	$\tilde{b}_1$ 275-440 GeV	$m(\tilde{\chi}_1^{\pm})$=2 $m(\tilde{\chi}_1^0)$	1404.2500
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	1-2 e, μ	1-2 b	Yes	4.7	$\tilde{t}_1$ 110-167 GeV	$m(\tilde{\chi}_1^0)$=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e, μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 130-210 GeV	$m(\tilde{\chi}_1^0)$ =$m(\tilde{t}_1)$-$m(W)$-50 GeV, $m(\tilde{t}_1)$<<$m(\tilde{\chi}_1^{\pm})$	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e, μ	2 jets	Yes	20.3	$\tilde{t}_1$ 215-530 GeV	$m(\tilde{\chi}_1^0)$=1 GeV	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	0	2 b	Yes	20.1	$\tilde{t}_1$ 150-580 GeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}_1^{\pm})$-$m(\tilde{\chi}_1^0)$=5 GeV	1308.2631
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e, μ	1 b	Yes	20	$\tilde{t}_1$ 210-640 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1407.0583
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{t}_1$ 260-640 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1406.1122
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 90-240 GeV	$m(\tilde{t}_1)$-$m(\tilde{\chi}_1^0)$<85 GeV	1407.0608
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e, μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$ 150-580 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + Z$	3 e, μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$ 290-600 GeV	$m(\tilde{\chi}_1^0)$<200 GeV	1403.5222
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	20.3	$\tilde{\ell}$ 90-325 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e, μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 140-465 GeV	$m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})$+$m(\tilde{\chi}_1^0)$)	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 100-350 GeV	$m(\tilde{\tau},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})$+$m(\tilde{\chi}_1^0)$)	1407.0350
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e, μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 700 GeV	$m(\tilde{\chi}_1^{\pm})$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})$+$m(\tilde{\chi}_1^0)$)	1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$	2-3 e, μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 420 GeV	$m(\tilde{\chi}_1^{\pm})$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0h\tilde{\chi}_1^0$	1 e, μ	2 b	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 285 GeV	$m(\tilde{\chi}_1^{\pm})$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	ATLAS-CONF-2013-093
	$\tilde{\chi}_2^0\tilde{\chi}_3^0, \tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	4 e, μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$ 620 GeV	$m(\tilde{\chi}_2^0)$=$m(\tilde{\chi}_3^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_2^0)$+$m(\tilde{\chi}_1^0)$)	1405.5086
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 270 GeV	$m(\tilde{\chi}_1^{\pm})$-$m(\tilde{\chi}_1^0)$=160 MeV, $\tau(\tilde{\chi}_1^{\pm})$=0.2 ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$ 832 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	1310.6584
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	15.9	$\tilde{\chi}_1^0$ 475 GeV	10<$\tan\beta$<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	4.7	$\tilde{\chi}_1^0$ 230 GeV	0.4<$\tau(\tilde{\chi}_1^0)$<2 ns	1304.6310
	$\tilde{q}\tilde{q}, \tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$ 1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, $m(\tilde{\chi}_1^0)$=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e + \mu$	2 e, μ	-	-	4.6	$\tilde{\nu}_\tau$ 1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e(\mu) + \tau$	1 $e, \mu + \tau$	-	-	4.6	$\tilde{\nu}_\tau$ 1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	2 e, μ (SS)	0-3 b	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.35 TeV	$m(\tilde{q})$=$m(\tilde{g})$, $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e, μ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 750 GeV	$m(\tilde{\chi}_1^0)$>0.2×$m(\tilde{\chi}_1^{\pm})$, $\lambda_{121}\neq0$	1405.5086
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e, \mu + \tau$	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 450 GeV	$m(\tilde{\chi}_1^0)$>0.2×$m(\tilde{\chi}_1^{\pm})$, $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\to\tilde{t}_1t, \tilde{t}_1\to bs$	2 e, μ (SS)	0-3 b	Yes	20.3	$\tilde{g}$ 850 GeV		1404.250
Other	Scalar gluon pair, sgluon$\to q\bar{q}$	0	4 jets	-	4.6	sgluon 100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon$\to t\bar{t}$	2 e, μ (SS)	2 b	Yes	14.3	sgluon 350-800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale 704 GeV	$m(\chi)$<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

$\sqrt{s}$ = 7 TeV full data | $\sqrt{s}$ = 8 TeV partial data | $\sqrt{s}$ = 8 TeV full data

10^{-1} 1 Mass scale [TeV]

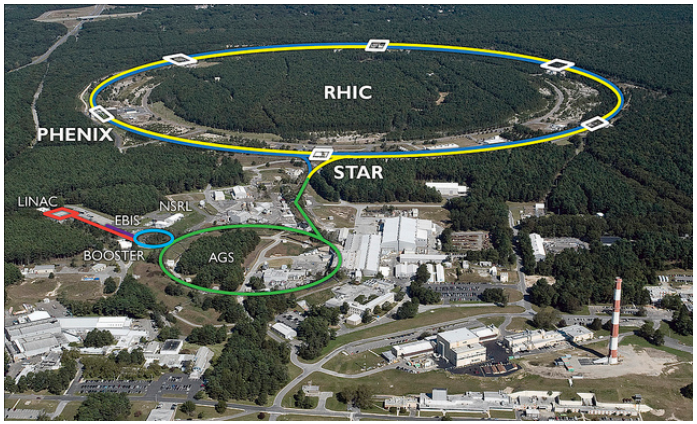
*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

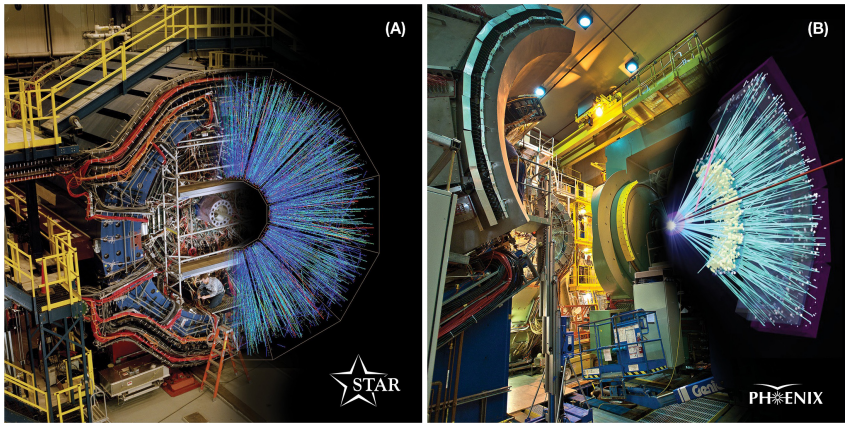
What's next?

- **The range of those searches will be increased by:**
  - The **upcoming run** at **13** and **14 TeV**
  - The **proposed** (and **very popular**) **High-Luminosity upgrade**
- **If New Physics has to be discovered in the coming years:**
  - **Goal** will be to **characterize** the **properties** of the new **d.o.f.**
    - e.g. masses, couplings and spins
- **However in most studies at hadron colliders...**
  - **Experimental analyses motivated** by theoretical arguments
    - Imply **key-final state signatures** that should be looked for
  - **Signatures not typical** of a given **theory/scenario**
    - **Famous example**: MSSM and UED models
- **Disentangling BSM theories with same signature is hard**

Why using polarized beams for New Physics searches?

- **Because it precisely solves the previous issue**





- **Because the technology is already there and working:**
  - c.f. **RHIC** (Relativistic Heavy Ion Collider) in **BNL**
    - **Polarization rate** of proton beams at RHIC $\sim$ **70-80%**
- **Because we have the theoretical knowledge:**
  - **A few BSM** phenomenological **studies** were **lead** at **RHIC**
  - **Most** of those **studies** were also **considering**
    - **Polarization upgrades** of the TeVatron and/or the LHC

Future Accelerators & Polarized beams

- **A polarized LHC is now quite unlikely to be realized**
  - **Technologically feasible** but...
    - Would **require** to **replace** the **full injector chain**

- **The situation is different for the recently proposed FCC**
  - **If New physics** is **discovered** at the **LHC**
    - ➟ **Strong motivation** for a **polarized mode** of the **FCC**

1 Motivations

2 Physics at polarized hadron colliders

3 Physics case: Monotop signature

4 Conclusions

Parton distributions & Parton luminosities

- **Unpolarized and polarized PDFs are defined as:**

$$
\begin{aligned}
f_{a/p}(x, Q^2) &= f^+_{a/p}(x, Q^2) + f^-_{a/p}(x, Q^2) \\
\Delta f_{a/p}(x, Q^2) &= f^+_{a/p}(x, Q^2) - f^-_{a/p}(x, Q^2)
\end{aligned}
$$

- **Parton luminosities are defined from the PDFs:**

$$
\begin{aligned}
\mathcal{L}_{ij} &= \frac{1}{S}\int_\tau^1 \frac{dx}{x}\frac{1}{1+\delta_{ij}}\left[f_{i/p}\left(x, Q^2\right) f_{j/p}\left(\frac{\tau}{x}, Q^2\right) + f_{i/p}\left(\frac{\tau}{x}, Q^2\right) f_{j/p}\left(x, Q^2\right)\right] \\
\mathcal{L}^L_{ij} &= \frac{1}{S}\int_\tau^1 \frac{dx}{x}\frac{1}{1+\delta_{ij}}\left[f_{i/p}\left(x, Q^2\right) \Delta f_{j/p}\left(\frac{\tau}{x}, Q^2\right) + f_{i/p}\left(\frac{\tau}{x}, Q^2\right) \Delta f_{j/p}\left(x, Q^2\right)\right] \\
\mathcal{L}^{LL}_{ij} &= \frac{1}{S}\int_\tau^1 \frac{dx}{x}\frac{1}{1+\delta_{ij}}\left[\Delta f_{i/p}\left(x, Q^2\right) \Delta f_{j/p}\left(\frac{\tau}{x}, Q^2\right) + \Delta f_{i/p}\left(\frac{\tau}{x}, Q^2\right) \Delta f_{j/p}\left(x, Q^2\right)\right]
\end{aligned}
$$

Cross sections & Longitudinal spin asymmetries

- **Cross sections at parton level are defined as:**

$$\begin{aligned}
\hat{\sigma}_0 &= \frac{1}{4}\left[\hat{\sigma}^{\uparrow\uparrow} + \hat{\sigma}^{\downarrow\downarrow} + \hat{\sigma}^{\uparrow\downarrow} + \hat{\sigma}^{\downarrow\uparrow}\right] \\
\hat{\sigma}_L &= \frac{1}{4}\left[\hat{\sigma}^{\uparrow\uparrow} - \hat{\sigma}^{\downarrow\downarrow} - \hat{\sigma}^{\uparrow\downarrow} + \hat{\sigma}^{\downarrow\uparrow}\right] \\
\hat{\sigma}_{LL} &= \frac{1}{4}\left[\hat{\sigma}^{\uparrow\uparrow} + \hat{\sigma}^{\downarrow\downarrow} - \hat{\sigma}^{\uparrow\downarrow} - \hat{\sigma}^{\downarrow\uparrow}\right]
\end{aligned}$$

- **Cross sections at hadron level are defined as:**

$$\begin{aligned}
\sigma_0 &= f_{i/p} \otimes f_{j/p} \otimes \hat{\sigma}_{0,ij} = \mathcal{L}_{ij} \otimes \left[\hat{s}\ \hat{\sigma}_{0,ij}\right], \\
\sigma_L &= f_{i/p} \otimes \Delta f_{j/p} \otimes \hat{\sigma}_{L,ij} = \mathcal{L}^L_{ij} \otimes \left[\hat{s}\ \hat{\sigma}_{L,ij}\right], \\
\sigma_{LL} &= \Delta f_{i/p} \otimes \Delta f_{j/p} \otimes \hat{\sigma}_{LL,ij} = \mathcal{L}^{LL}_{ij} \otimes \left[\hat{s}\ \hat{\sigma}_{LL,ij}\right]
\end{aligned}$$

- **Spin asymmetries are defined as ratios of cross sections:**

$$A_L = \frac{\sigma_L}{\sigma_0} \qquad A_{LL} = \frac{\sigma_{LL}}{\sigma_0}$$

1 Motivations

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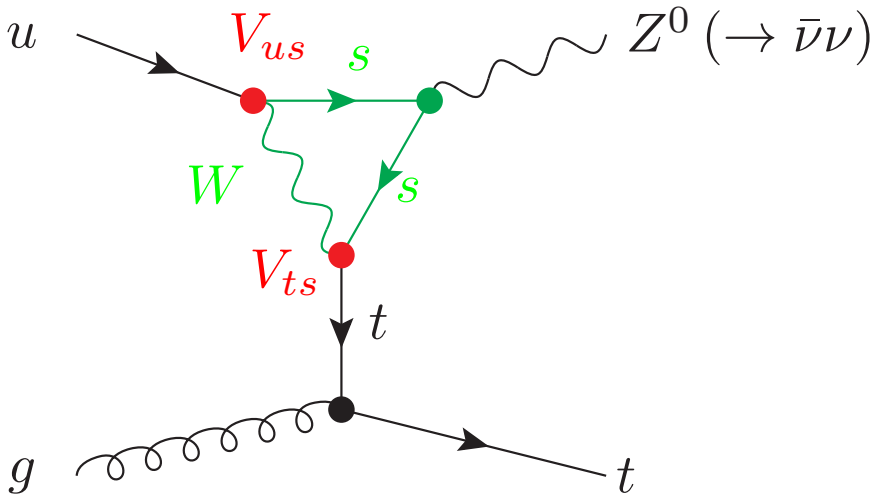
Monotop production in the Standard model

[Fuks, Andrea, Maltoni arXiv:11066199]

- Final state signature : $t + \not{E}_T \longrightarrow bjj + \not{E}_T \;\; / \;\; bl + \not{E}_T$
- Production mode $\longrightarrow$ **subdominant contribution**
  - **GIM suppressed:** $V_{us} \simeq 0.23$, $V_{ts} \simeq 0.04$
  - **Loop-suppressed**
  - **Branching ratio**: $\mathrm{BR}(Z \to \nu\bar{\nu}) \simeq 0.2$
- **Observing monotop means observing New Physics**

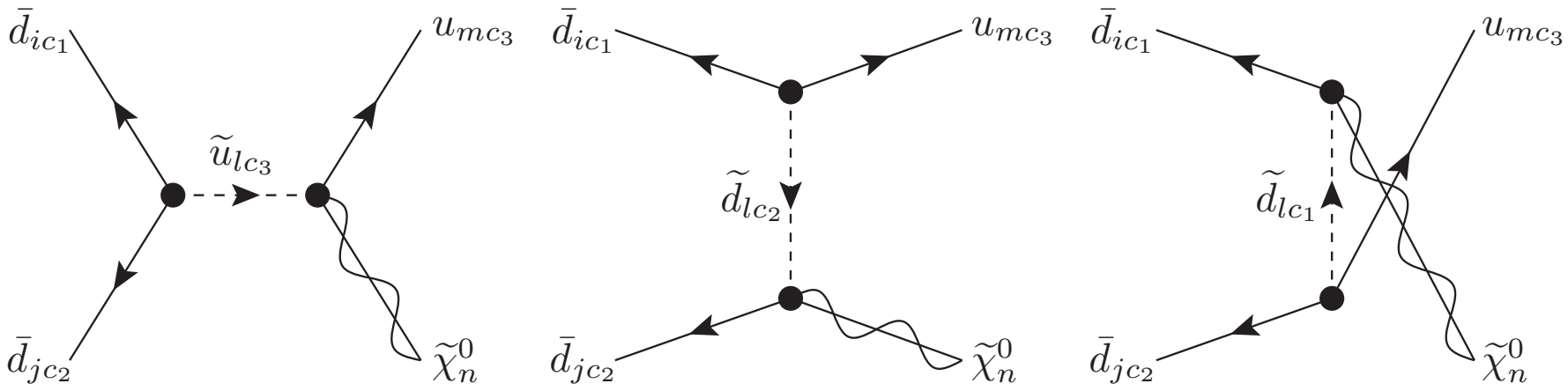


Monotop production in the RPV-MSSM

- **Production @ tree-level through squark exchange**

$$pp \to \widetilde{q} \to \widetilde{\chi}_1^0 + t$$

  - **6 diagrams** in the **flavor conserving case**
  - $\not{E}_T$ associated to the lightest neutralino
    - Kinematic condition: $m_t > m_{\chi_1^0} \Rightarrow$ Long-lived neutralino
    - Decay far outside of the detector due to its long lifetime

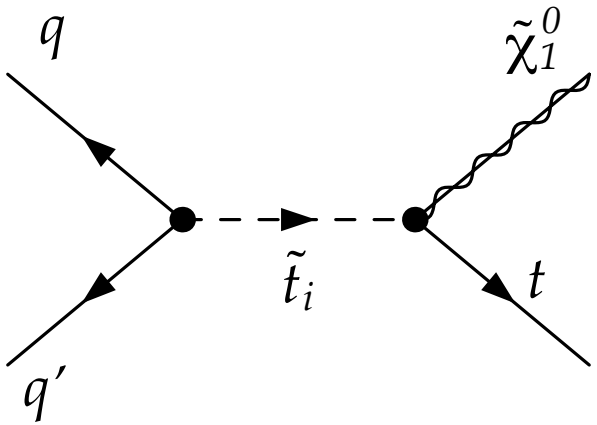


Monotop production in the RPV-MSSM

- **Production @ tree-level through $\widetilde{t}_1$ exchange**

$$pp \to \widetilde{t}_1 \to \widetilde{\chi}_1^0 + t$$

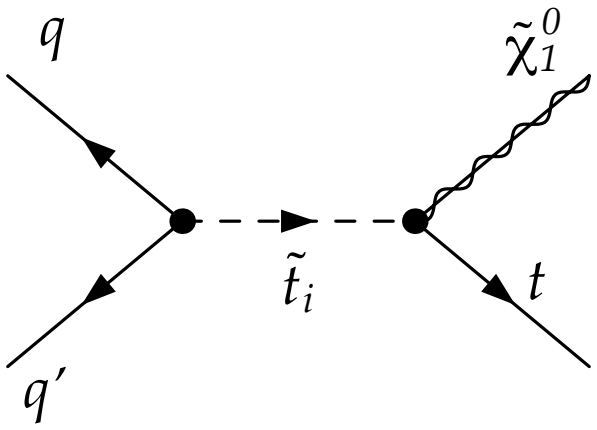
  - **Non-resonant channels** are **subdominant** (NWA)
  - **Assume $\widetilde{t}_2$ contribution** is **negligible**



$$\hat{\sigma}^{h_1 h_2}_{RPV}(\bar{q}_j \bar{q}_k \to t\tilde{\chi}_1^0) = \frac{(1-h_1)(1-h_2)\pi \left|\lambda''_{3jk} \sin\theta_{\tilde{t}}\right|^2}{6} \times \mathrm{BR}\left(\tilde{t} \to t\tilde{\chi}_1^0\right) \times \delta\left(\hat{s} - m_{\tilde{t}}^2\right)$$

Monotop production in the RPV-MSSM

- **Dominant channels are ds and $\bar{d}\bar{s}$**



Spin asymmetries for the process + charge conjugate

$$A_L^{\bar{d}\bar{s}+ds} = \frac{\mathcal{L}_{ds}^{L} - \mathcal{L}_{\bar{d}\bar{s}}^{L}}{\mathcal{L}_{ds} + \mathcal{L}_{\bar{d}\bar{s}}} \quad \text{and} \quad A_{LL}^{\bar{d}\bar{s}+ds} = \frac{\mathcal{L}_{ds}^{LL} + \mathcal{L}_{\bar{d}\bar{s}}^{LL}}{\mathcal{L}_{ds} + \mathcal{L}_{\bar{d}\bar{s}}}$$

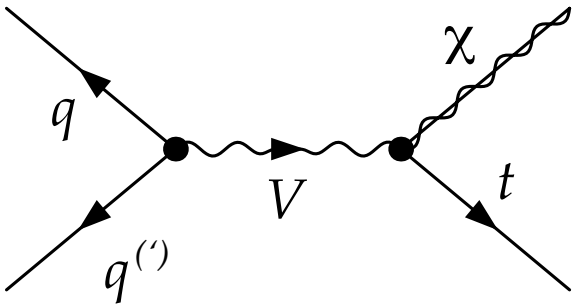
Monotop production in the Hylogenesis model

[arXiv:1008.2399], [arXiv:1106.4320]

- **Provides a theoretical mechanism for generating:**
  - **Baryon Asymmetry in the Universe** (BAU)
  - **Dark Matter** (DM)
- **Lagrangian:**

$$\mathcal{L}_{\rm hylo} = \frac{1}{2}\kappa_{ij}\ \bar{d}_i^c \gamma^\mu d_j V_\mu + \text{h.c.}\ ,$$

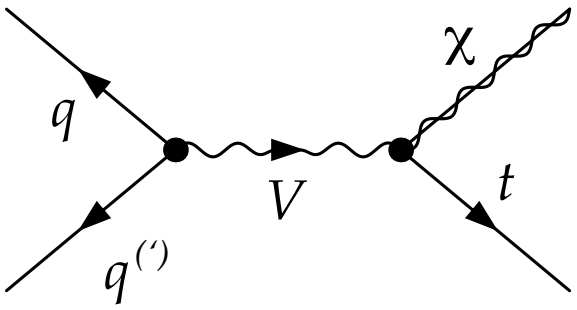
- **Monotop originates from the decay of a vector resonance**



$$\hat{\sigma}^{h_1 h_2}_{\rm hylo}(\bar{q}_j \bar{q}_k \to t\chi) = \frac{2(1-h_1 h_2)\pi \left|\kappa_{jk}\right|^2}{3} \times \text{BR}\Big(V \to t\chi\Big) \times \delta\Big(\hat{s} - m_V^2\Big)$$

Monotop production in the Hylogenesis model

- **Dominant channels are dd and $\bar{d}\bar{d}$**



Spin asymmetries for the process + charge conjugate

$$A_L^{\bar{d}\bar{d}+dd} = 0\,, \qquad A_{LL}^{\bar{d}\bar{d}+dd} = -\frac{\mathcal{L}_{dd}^{LL} + \mathcal{L}_{\bar{d}\bar{d}}^{LL}}{\mathcal{L}_{dd} + \mathcal{L}_{\bar{d}\bar{d}}}$$

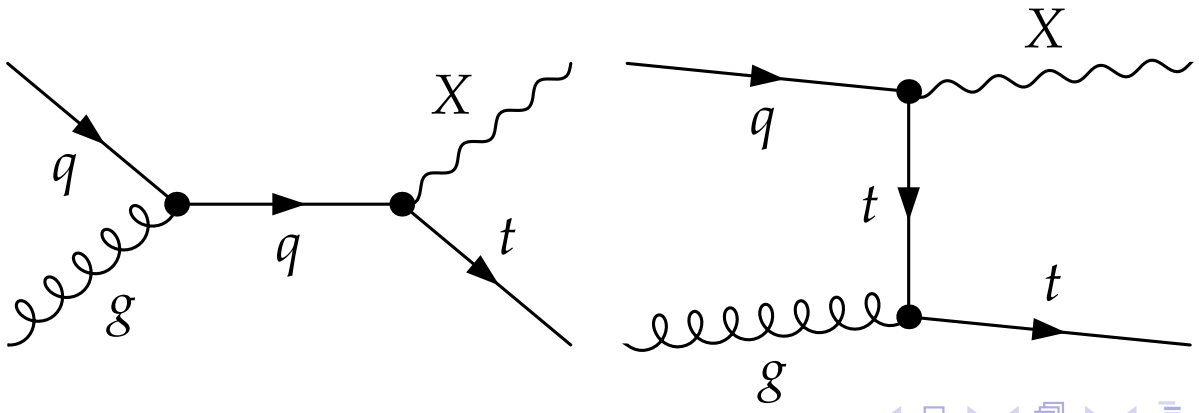
Monotop production in the X-model

[arXiv:1107.0623], [arXiv:1310.7600]

- **Provides a candidate for Dark matter**
  - **Top quark couple** to a new **neutral heavy resonance** X
  - X **resonance strongly couples** to some **new hidden sector**
  - X **resonance** decays into **particles** of the **hidden sector**
  - X **resonance** mediates **FCNCs at tree-level**
- **Lagrangian:**

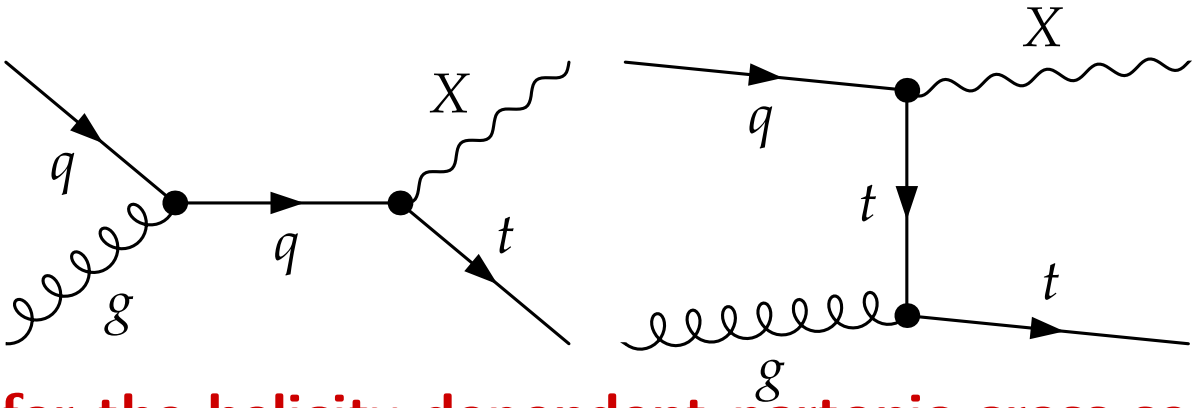
$$\mathcal{L}_X = g_X^i \bar{u}_i \gamma^\mu P_R t X_\mu + \text{h.c.}$$

- **Monotop originates from non-resonant diagrams**



Monotop production in the X-model

- **Non-resonant diagrams ⇒ Cannot apply the NWA**



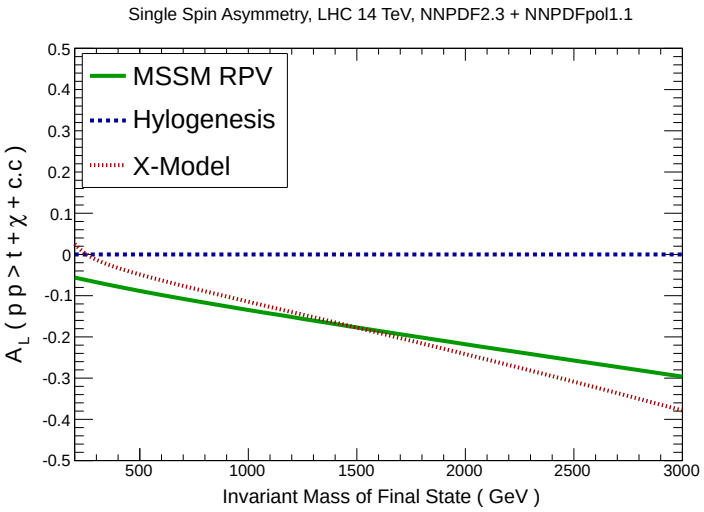
- **Result for the helicity-dependent partonic cross-section:**

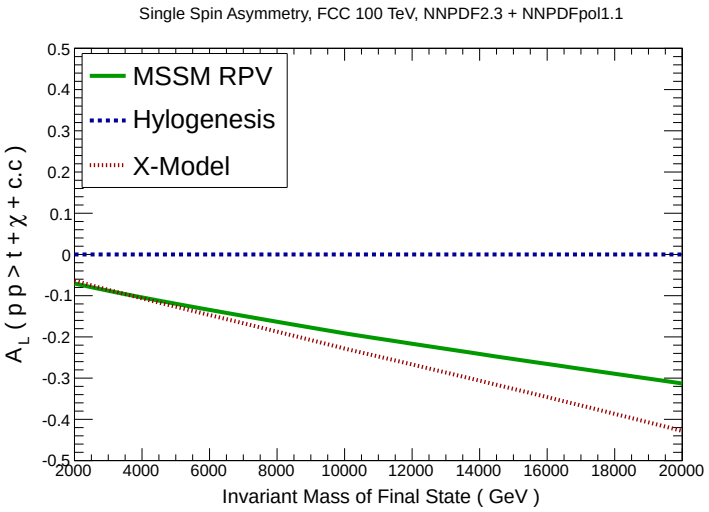
$$\frac{\mathrm{d}\hat{\sigma}_X^{h,\lambda}}{\mathrm{d}t}(u_i g \to tX) = \frac{1}{16\pi s^2}\frac{g_s^2 g_X^{i2}}{12 s m_X^2 (t-m_t^2)^2}(1+h)\Big[C_1 + C_2\lambda\Big]$$

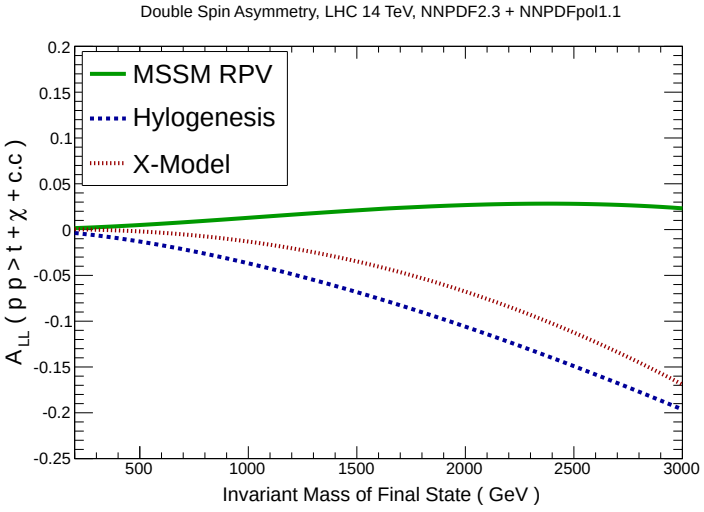
  - No simple expression for A_L and A_{LL}

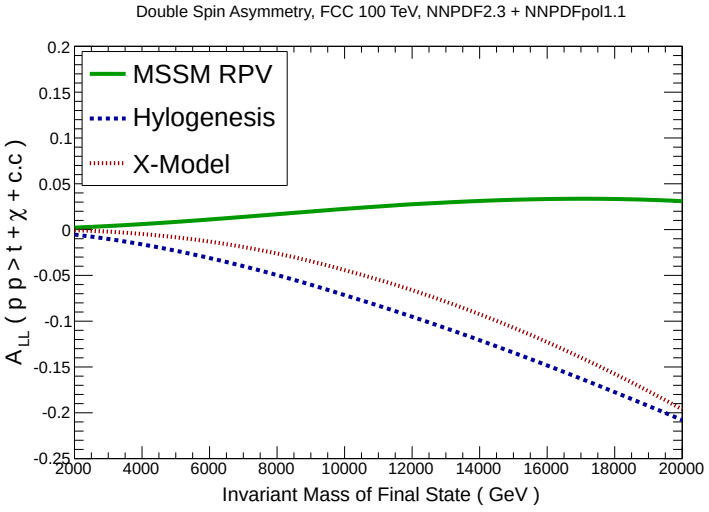
- **Dominant channel ⇒** ug

Numerical Results









Conclusions

Take-home messages

- **Polarized beams are technologically feasible**
- **Polarized beams** allow to disentangle **BSM theories** with the **same final-state signature**
- **If New Physics** is discovered at the LHC or at the HL-LHC
  - ➟ **Strong motivation** for a **polarized FCC**
- Assuming polarized PDF uncertainties are improved
  - ➟ **Measurement** of A_L with a 5% precision enough to distinguish between the three models

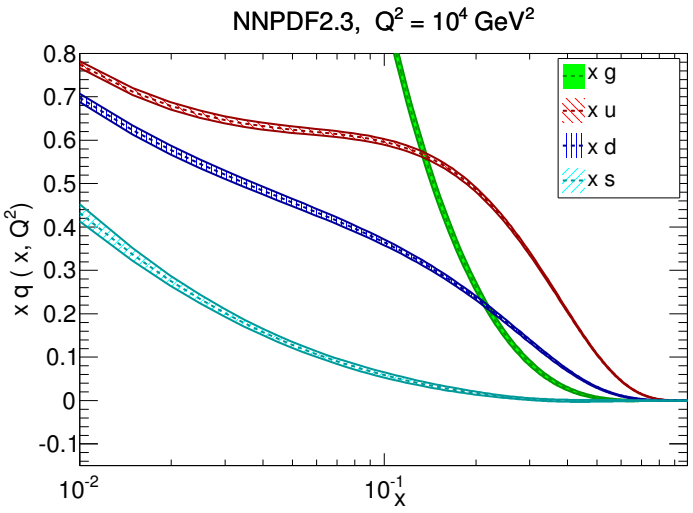
What remains to be done:

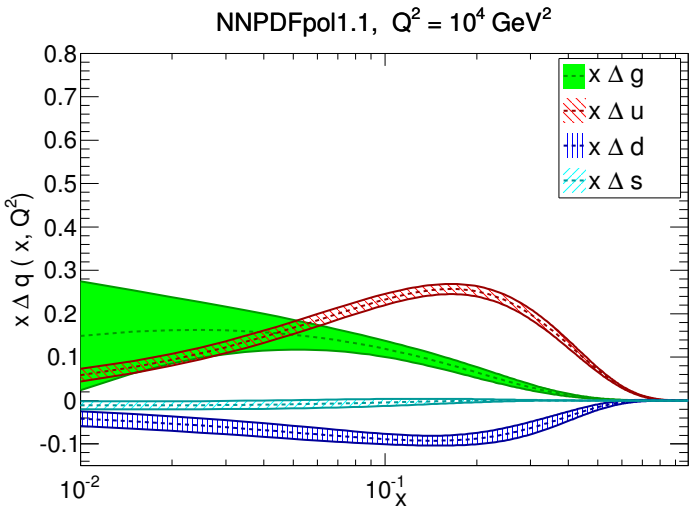
- **Study other BSM scenarios**
- **Estimate** effects of **finite polarization** of the **beams**
- **Include W and Z bosons** in the **DGLAP** evolution equations

Thanks for your attention

Back-up slides

Polarized Parton Distribution Functions



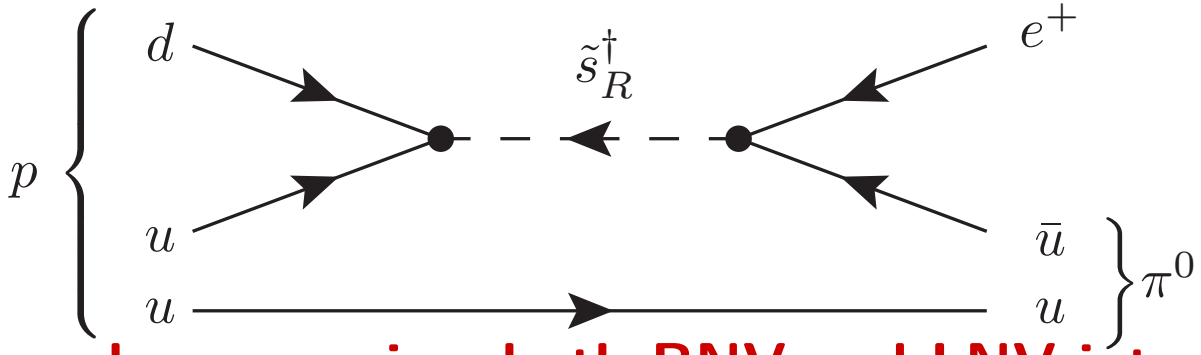


- **Polarized PDFs are smaller than unpolarized ones**
- **At small-x polarized PDFs are largely suppressed**
- **Polarized distributions Δu and Δd have opposite signs**
- **Important consequences for spin asymmetries:**
  - **Sizable only** at **medium** and **large-x**
    - i.e. for final-state with large invariant masses (New Physics)
  - Behave **differently** depending on the **initial partonic state**
    - i.e. give discriminating power between BSM scenarios

Motivations for R-Parity Violating SUSY

R-Parity

- **Forbids both BNV** and **LNV interactions** in the MSSM
- **Imposed** to avoid **fast proton decay:** $\tau_p \gtrsim 10^{33}$ years



- **Proton decay requires both BNV and LNV interactions**
  - **R-parity conservation** is **too restrictive**
  - **Either BNV** or **LNV** are **allowed** $\Rightarrow$ **No proton decay**
- **RPV-MSSM with BNV model features**
  - **BNV** + lepton number conservation **compatible** with a **GUT**
  - **Provides** the **third Sakharov condition** $\Rightarrow$ **BAU**
- **Price to pay:** Extremely difficult to accommodate DM

The model

- **BNV superpotential:**

$$W_{BNV} = \frac{1}{2}\lambda''_{ijk} U^i D^j D^k + W_{MSSM}$$

  - λ''_{ijk}: BNV couplings $\Rightarrow$ 9 new free independent parameters
  - U, D: Superfields
  - i, j and k : Flavor indices

- **BNV Lagrangian:**

$$\begin{aligned}\mathcal{L}_{U_i U_j D_k} &= -\frac{1}{2}\lambda''_{ijk}\varepsilon^{c_1 c_2 c_3}\Big(\widetilde{u}^{0\dagger}_{lc_3} R^u_{l(k+3)} \bar{\Psi}^d_{Dic_1} P_L \Psi^{d\ c}_{Djc_2} \\ &+ \widetilde{d}^{0\dagger}_{lc_2} R^d_{l(k+3)} \bar{\Psi}^u_{Dic_1} P_L \Psi^{d\ c}_{Dkc_2} + \bar{\Psi}^u_{Dic_1} P_L \Psi^{d\ c}_{Djc_2} R^d_{l(k+3)} \widetilde{d}^{0\dagger}_{lc_3}\Big) + \text{h.c.}\end{aligned}$$

Constraints on BNV couplings

Present experimental constraints on λ''_{ijk} couplings:

- Neutron dipole moment [Slavich arXiv:0008270]
- Antinucleon oscillations, double nucleon decays
- Rare hadronic decays of B-mesons, K-K systems
- **Observed flux of cosmic rays antiprotons :** [Gondolo arXiv:9704411]

$$\lambda''_{ijk} < 10^{-19} - 10^{-24}$$

- **Yet... Not applicable** to λ''_{3jk} if the **top quark** is **heavier than the Lightest Supersymmetric Particle (LSP)**
  - λ''_{3jk} is left **almost unconstrained** [Barbier et al.]
- **Enforce MFV** $\Rightarrow$ **Only** λ''_{312} is **sizable** $\sim \mathcal{O}(0.1)$

Monotop production in the RPV-MSSM

- **Helicity-dependent partonic cross section**

Full $2 \to 2$ process

$$\frac{d\hat{\sigma}_{h_a h_b}}{dt} = \frac{\alpha}{12 s_W^2 c_W^2 s^2} \sum_{l,o=1,2}^{6} \Bigg[(1-h_a)(1-h_b) \Bigg(\frac{Q_{lo}^{ss}}{s_l s_o} + \frac{Q_{lo}^{tt-}}{t_l t_o} + \frac{Q_{lo}^{uu-}}{u_l u_o} + \frac{Q_{lo}^{st}}{s_l t_o} + \frac{Q_{lo}^{su}}{s_l u_o} + \frac{Q_{lo}^{tu}}{t_l u_o} \Bigg) + (1-h_a)(1+h_b) \frac{Q_{lo}^{tt+}}{t_l t_o} + (1+h_a)(1-h_b) \frac{Q_{lo}^{uu+}}{u_l u_o} \Bigg]$$

- **Compactified expression** of the **cross section**
- h_a and $h_b \Longrightarrow$ **helicities** of **incoming particles**
- Q^{ss}: interferences between diagrams in the s-channel

Analytical expressions of the charges

$$
\begin{aligned}
Q_{lo}^{ss} &= s \; C_{d_i d_j \tilde{u}_l} C^*_{d_i d_j \tilde{u}_o} \Bigg[\left(s - m^2_{q_m} - m^2_{\tilde{\chi}^0_n} \right) \Big(L_{u_m \tilde{u}_l \tilde{\chi}^0_n} L^*_{u_m \tilde{u}_o \tilde{\chi}^0_n} \\
&+ R_{u_m \tilde{u}_l \tilde{\chi}^0_n} R^*_{u_m \tilde{u}_o \tilde{\chi}^0_n} \Big) - 2 m_{u_m} m_{\tilde{\chi}^0_n} \left(L_{u_m \tilde{u}_l \tilde{\chi}^0_n} R^*_{u_m \tilde{u}_o \tilde{\chi}^0_n} + R_{u_m \tilde{u}_l \tilde{\chi}^0_n} L^*_{u_m \tilde{u}_o \tilde{\chi}^0_n} \right) \Bigg] \\
Q_{lo}^{tt+} &= C_{u_m d_i \tilde{d}_l} C^*_{u_m d_i \tilde{d}_o} \left(t - m^2_{u_m} \right) \left(t - m^2_{\tilde{\chi}^0_n} \right) \left(L_{d_j \tilde{d}_l \tilde{\chi}^0_n} L^*_{d_j \tilde{d}_o \tilde{\chi}^0_n} \right) \\
Q_{lo}^{tt-} &= C_{u_m d_i \tilde{d}_l} C^*_{u_m d_i \tilde{d}_o} \left(t - m^2_{u_m} \right) \left(t - m^2_{\tilde{\chi}^0_n} \right) \left(R_{d_j \tilde{d}_l \tilde{\chi}^0_n} R^*_{d_j \tilde{d}_o \tilde{\chi}^0_n} \right) \\
Q_{lo}^{uu+} &= C_{u_m d_j \tilde{d}_l} C^*_{u_m d_j \tilde{d}_o} \left(u - m^2_{u_m} \right) \left(u - m^2_{\tilde{\chi}^0_n} \right) \left(L_{d_i \tilde{d}_l \tilde{\chi}^0_n} L^*_{d_i \tilde{d}_o \tilde{\chi}^0_n} \right)
\end{aligned}
$$

Analytical expressions of the charges

$$
\begin{aligned}
Q_{lo}^{uu-} &= C_{u_m d_j \widetilde{d}_l} C^*_{u_m d_j \widetilde{d}_o} \left(u - m^2_{u_m}\right)\left(u - m^2_{\widetilde{\chi}^0_n}\right)\left(R_{d_i \widetilde{d}_l \widetilde{\chi}^0_n} R^*_{d_i \widetilde{d}_o \widetilde{\chi}^0_n}\right) \\
Q_{lo}^{st} &= 2 m_{\widetilde{\chi}^0_n} m_{u_m} s \Re\left(C_{d_i d_j \widetilde{u}_l} L_{u_m \widetilde{u}_l \widetilde{\chi}^0_n} C^*_{u_m d_i \widetilde{d}_o} R^*_{d_j \widetilde{d}_o \widetilde{\chi}^0_n}\right) \\
&+ 2 s t \Re\left(C_{d_i d_j \widetilde{u}_l} R_{u_m \widetilde{u}_l \widetilde{\chi}^0_n} C^*_{u_m d_i \widetilde{d}_o} R^*_{d_j \widetilde{d}_o \widetilde{\chi}^0_n}\right) \\
Q_{lo}^{su} &= -2 m_{\widetilde{\chi}^0_n} m_{u_m} s \Re\left(C_{d_i d_j \widetilde{u}_l} L_{u_m \widetilde{u}_l \widetilde{\chi}^0_n} C^*_{u_m d_j \widetilde{d}_o} R^*_{d_i \widetilde{d}_o \widetilde{\chi}^0_n}\right) \\
&- 2 u s \Re\left(C_{d_i d_j \widetilde{u}_l} R_{u_m \widetilde{u}_l \widetilde{\chi}^0_n} C^*_{u_m d_j \widetilde{d}_o} R^*_{d_i \widetilde{d}_o \widetilde{\chi}^0_n}\right) \\
Q_{lo}^{ut} &= 2\left(m^2_{\widetilde{\chi}^0_n} m^2_{u_m} - u t\right) \Re\left(C_{u_m d_i \widetilde{d}_l} R_{d_j \widetilde{d}_l \widetilde{\chi}^0_n} C^*_{u_m d_j \widetilde{d}_o} R^*_{d_i \widetilde{d}_o \widetilde{\chi}^0_n}\right)
\end{aligned}
$$

Full expressions for the couplings

$$
\begin{aligned}
L_{\tilde{u}_j u_k \tilde{\chi}_i^0} &= \left[(e_q - T_q^3)\, s_W\, N_{i1} + T_q^3\, c_W\, N_{i2} \right] R_{jk}^{u*} + \frac{m_{u_k}\, c_W\, N_{i4}\, R_{j(k+3)}^{u*}}{2\, m_W\, \sin\beta} \\
R_{\tilde{u}_j u_k \tilde{\chi}_i^0} &= -e_q\, s_W\, N_{i1}^*\, R_{j(k+3)}^{u*} + \frac{m_{u_k}\, c_W\, N_{i4}^*\, R_{jk}^{u*}}{2\, m_W\, \sin\beta} \\
L_{\tilde{d}_j d_k \tilde{\chi}_i^0} &= \left[(e_q - T_q^3)\, s_W\, N_{i1} + T_q^3\, c_W\, N_{i2} \right] R_{jk}^{d*} + \frac{m_{d_k}\, c_W\, N_{i4}\, R_{j(k+3)}^{d*}}{2\, m_W\, \sin\beta} \\
R_{\tilde{d}_j d_k \tilde{\chi}_i^0} &= -e_q\, s_W\, N_{i1}^*\, R_{j(k+3)}^{d*} + \frac{m_{d_k}\, c_W\, N_{i4}^*\, R_{jk}^{d*}}{2\, m_W\, \sin\beta}
\end{aligned}
$$

$$
C_{d_i d_j \widetilde{u}_l} = \lambda''_{ijk} R^u_{l(k+3)} \quad \text{and} \quad C_{u_i d_j \widetilde{d}_l} = \lambda''_{ijk} R^d_{l(k+3)}
$$

With

$$
\widetilde{\chi}_i^0 = N_{ij} \psi_j^0 \quad \text{with} \quad i = 1, 2, 3, 4
$$

Tool chain

- **SLHA2 input file:** [Allanach et al.]
  - Model and parameters specification

$\Downarrow$

- **SUSY-spectrum:** `SPheno-3.2.1`: [Porod, Staub]
  - Compute **RGEs** at the **two loop level**

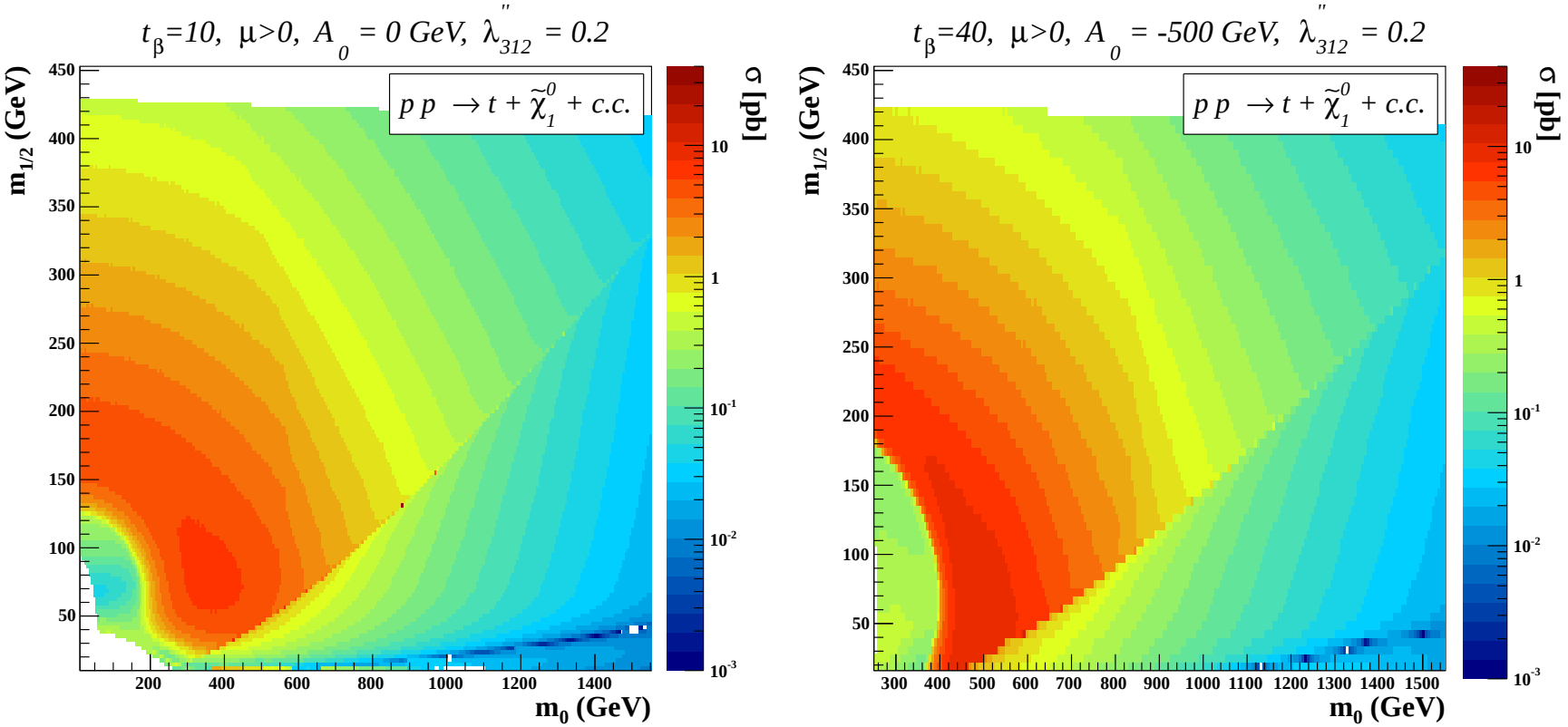
$\Downarrow$

- **Decay Width an Branching Ratios:** `SUSY-HIT-1.3` [Djouadi, Mullheitner,Spira]
  - **Width** and **BRs** of the **MSSM Higgs bosons**: `HDECAY`
  - **Width** and **BRs** of the **SUSY particles**: `SDECAY`

$\Downarrow$

- **Cross section & scans:** `XSUSY-1.9.23` (**Private code**)
  - Original `C++` **code** developed by **B. Fuks** & **B. Herrmann**
  - **Numerical integration** performed using `VEGAS`

Numerical results



- **Demanding from the computational point of view**
- **Is there a way to simplify the computations?**

The Narrow Width Approximation

- **The Narrow Width Approximation (NWA):**
  - **Reduction** of the **complexity of scattering amplitudes**
  - **Assumes peaked resonance** with a **Breit-Wigner lineshape**
  - **For small** Γ, **off-shell effects are suppressed**
    - ➟ **Intermediate resonance** can be **approximated** to be **on-shell**
  - **Production** and **decay** of **unstable particles** $\Rightarrow$ **factorized**
  - **Non-resonant contributions** are **neglected**
  - **Introduction** of an **error** of $\mathcal{O}(\Gamma/M)$ for each **Breit-Wigner**

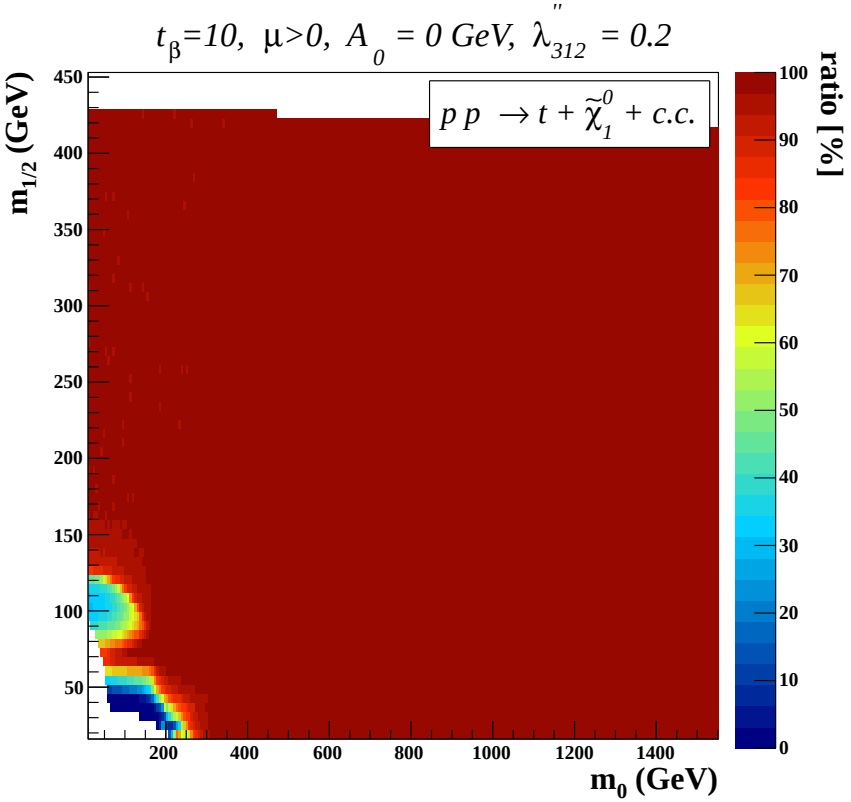
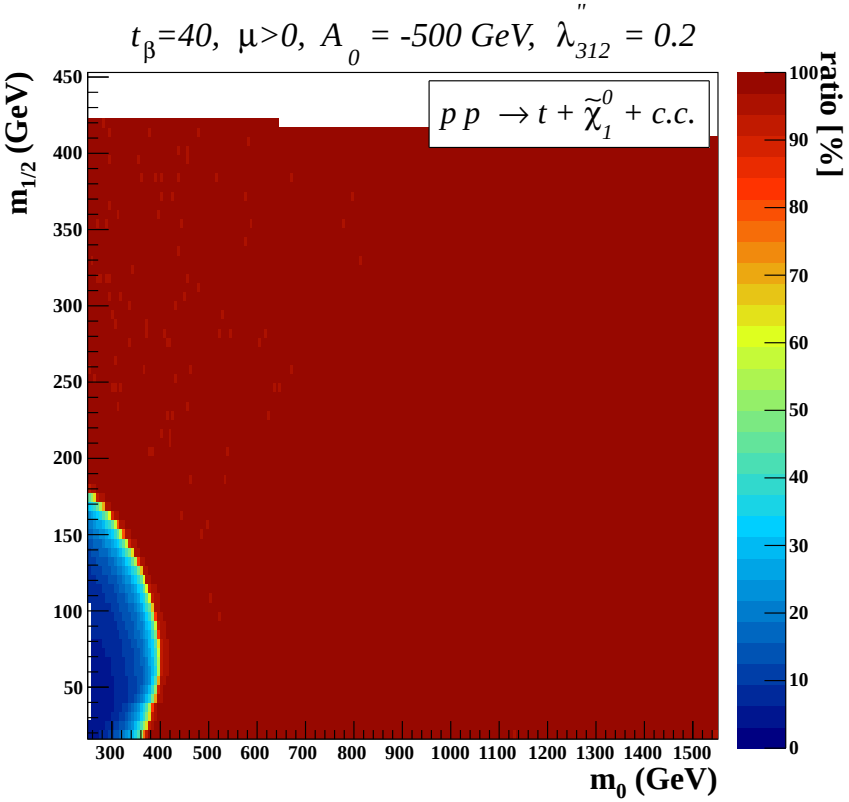
Requirements for the NWA

1. **Total width** of the particle way **smaller** than its **mass**: $\Gamma \ll M$
2. **Propagator separable** from the **matrix element**
3. **No significant interferences** from **non-resonnant processes**
4. **Scattering energy larger** than mass of the **resonance**: $\sqrt{s} \gg M$
5. Mass of **resonance larger** than masses of the **daughter** particles

Narrow Width Approximation & New Physics

[Kauer, Rainwater, Berdine arXiv:0703058]

- **Narrow Width Approximation features:**
  - **Drastically simplifies calculations** $\Rightarrow$ $\sigma_p \times \mathrm{BR}$
  - **Reduce CPU time** required **for computations**
  - **Works pretty well** in the **case** of the **SM**
  - **Extensively used** for **BSM searches**

- **Is the NWA reliable in the context of BSM searches?**
  - **NWA assumes Breit-Wigner resonance**
    - In the vicinity of kinematical bounds like $\sqrt{s} \sim M$
    - For near-degenerate parent-daughter masses $m \sim M$
  - **Breit-Wigner lineshape** is **distorted** by threshold factors
    - phase space factors e.g. $\beta = \sqrt{1-(m/M)^2}$

Validity of the NWA