

LHC Physics – BSM searches Claudia Seitz

DESY Summer Student Lectures, 16.08-17.08.2022



Shortcomings of the Standard Model

> Hierarchy problem

- Higgs mass should be at the Planck scale due to loop corrections from fermions to its mass
- ► Gravity is not included in the Standard Model
- No explanation for Dark Matter or Dark Energy
- ► Neutrinos
 - Assumed to be massless
 - Neutrino oscillations were discovered indicating a non-zero mass





Landscape of proposed New Physics scenarios is vast!



- ► Two ways of approaching this issue
 - ► Model driven
 - start from a specific theory prediction \Rightarrow design and optimize for that specific signal
 - Signature driven
 - Iook for deviation from the SM anywhere \Rightarrow look at specific final states (dijet, high MET)
 - ► Both strategies are followed at the LHC
 - Crucial: excellent understanding of Standard Model backgrounds is needed!



Resonance searches

> Many models predict the existence of additional, so-far undiscovered particles \Rightarrow would likely find them through their decay products





Resonance searches

> Many models predict the existence of additional, so-far undiscovered particles ⇒ would likely find them through their decay products



Z mass $\sim 90 \text{ GeV}$

 \blacktriangleright LHC strength: high CM energy => sensitivity to so far un-probed high masses!



Heavy partners of the known bosons $Z' \rightarrow ll$

Now probing masses up to 4 TeV



Di-jet resonances

- Several new physics models predict heavy resonances that decay into dijets (qq, qg or gg)
- Result presented as model independent limits on $\sigma \times BR \times A$
- Limit differs depending on the final state qq, qg or gg Model because of dependence String Scalar diquark of resonance shape Axigluon/coloron Excited quark on parton content W' SM-like

 10^{-3} 10^{-4} (Data-Prediction)

Z' SM-like

dơ/dm_{jj} [pb/



Supersymmetry

- Supersymmetry as possible extension of the Standard Model
- Assigns every SM particle a SUSY partner (sparticles)
 - ► R-parity to distinguish between SM and SUSY (B=Baryon number, L=Lepton number, s=Spin)

$$R = (-1)^{(2s+3B+L)} = \begin{cases} +1 \\ -1 \end{cases}$$

- ► R-parity conservation (RPC)
 - ► Always pairs of sparticles
 - Lightest supersymmetric particle (LSP) is stable and escapes detection
 - ► Final state decay has at least one LSP

- for SM particles
- -1 for SUSY particles
 - ► R-parity violation (RPV)
 - ► Either lepton or baryon number violation
 - Sparticles can decay exclusively to SM particles
 - ► Low missing energy in the final state



Supersymmetry

- SUSY predicts a plethora of new particles
- Potential parameter space is huge MSSM : ~ 100, pMSSM: 19, cMSSM: 4 + 1



MSSM = Minimal Supersymmetric Standard Model



A natural SUSY spectrum?

- ► Naturalness: one of the driving paradigms for SUSY searches at the LHC
 - However not entirely well defined: ratios between free parameters of a theory are "of order 1"
 - How much fine tuning can you live with?
- ► Implications
 - ► Tree-level: $m_Z^2 = -2(m_{H_u}^2 + |\mu|^2) + ...$

Light higgsinos

- ► One-loop:
 - ► Light stops (few hundred GeV) to stabilize the Higgs mass
- ► Two-loops
 - Not too heavy gluinos (TeV scale)
 - Loop corrections to the stop mass

[*N. Craig arXiv:1309.0528*]

$$\Delta[a_i] = \frac{\partial \ln m_Z^2}{\partial \ln a_i^2}, \Delta \equiv \max_i \Delta[a_i] \quad \cdots$$

 Δ as a parameter for tuning ~ 10 \rightarrow few % fine tuning







Simplified models in SUSY searches



Decoupled mass spectrum

RPC or RPV

Few parameters $\Delta M = \Delta M$ (Sparticle,LSP)

Mostly 100% BR

Not a complete story, but a useful tool

RPV gluino cascade decays



RPC slepton with ISR jet



RPC chargino neutralino



Interpretation: 2D limit plots

$\Delta M = \Delta M$ (Sparticle,LSP) vs M(sparticle)



M(Sparticle) vs M(LSP) **CMS** *Preliminary* 35.9 fb⁻¹ (13 TeV) [Ge /] 1000 pp $\rightarrow \tilde{g} \tilde{g}, \tilde{g} \rightarrow t \bar{t} \tilde{\chi}_1^0$ NLO+NLL exclusion section [pb] $\blacksquare Observed \pm 1\sigma_{theory}$ آ1600ي_ي س **Expected** $\pm 1\sigma_{\text{experiment}}$ 1400 not excluded Cross 1200 ⁻¹ 10⁻¹ 1000 upper limit on 800 600 10^{-2} excluded 400 95% CL 200 0 600 800 1000 1200 1400 1600 1800 2000 2200 10⁻³ m_{g̃} [GeV] Z-axis = upper limit on cross section

.

How are we trying to find SUSY?

- Many SUSY searches in CMS and ATLAS are signature based
 - (b)Jets + MET + Leptons + photons + dedicated search variables

$$m_{\rm T}^{\rm lep} = \sqrt{2p_{\rm T}^{\ell} E_{\rm T}^{\rm miss} \left(1 - \cos\Delta\phi(\vec{p}_{\rm T}^{\ell}, \vec{p}_{\rm T}^{\rm miss})\right)} \qquad \qquad M_{\rm T2} = \frac{1}{\vec{p}_{\rm T}^{\rm miss}}$$







Endpoint around W mass for background

Extension of transverse mass m_T for decay chains with 2 invisible particles

$$\min_{1^{1}+\vec{p}_{\mathrm{T}}^{\mathrm{miss}\,\mathrm{X}(2)}=\vec{p}_{\mathrm{T}}^{\mathrm{miss}}}\left[\max\left(M_{\mathrm{T}}^{(1)},M_{\mathrm{T}}^{(2)}\right)\right]$$

$$m_{eff} = \sum p_T + E_T^{miss}$$



Squark and Gluino searches

Assuming pair production of squarks and gluinos, decays to LSP + various SM quarks (light and heavy flavor) \rightarrow highes production cross sections



Let's go through one analysis example in some more detail: the "inclusive" approach

$$\tilde{t} \to t \; \tilde{\chi}_1^0$$

$$\tilde{q} \to q \; \tilde{\chi}_1^0$$

$$\tilde{b} \to b \ \tilde{\chi}_1^0$$



Example: all-hadronic CMS search

- > = 0 leptons in the final state
- Multijet bkg reduced through cut on $\Delta \phi$ (jets, MET/MHT) > 0.3 - 0.5
- Many search regions covering a wide variety of models
 - $M_{T2} + n(b)Jets + H_T$ Example "Binning" in
- Many different bkg sources

Data driven background estimates from CR by inverting event selection criteria:



- •W+jets, tt+jets (lost lepton, hadronic tau): Isolated e/μ , with low $M_T(l,MET)$
- **Z**-vv: Use χ +jets or Z-ll events as proxy
- Multijet: Estimate $r_{\phi} = \frac{\Delta \phi(jets, MET) > x}{\Delta \phi(jets, MET) < x}$ multijet enriched control region

Results: Unrolled search regions or bins

Many bins, but where does the sensitivity come from?





Which regions are sensitive to what?





Results for squarks and gluinos



Limits on Gluino mass pushing 2200 GeV in simplified models



Dedicated searches for stops

- Stops play important role in stabilizing the Higgs mass
- Dedicated search strategies are also employed



"Optimize" dedicated regions to make sure difficult corners of phase space aren't missed



Dedicated searches for stops

- \succ 0, 1, and 2 lepton channels \rightarrow remember ttbar decay modes + extra MET
- ► Strategy:
 - Design dedicated signal regions for specific signal topologies:

► low MET, medium MET

- Estimate SM backgrounds from simulation and data control regions
- Extrapolate and Test in validation regions





CR1

observable 1

HistFitter: arXiv:1410.1280

VR3

- CR3-







Results on stop



Limits on Stop quark mass pushing 1200 GeV in simplified models



Electroweak searches

Production cross section much lower for Higgsinos, winos and sleptons, than for squarks and gluinos



Rare SM processes become main backgrounds

 $\tilde{\chi}_1^{\mp}$



[JHEP 07 (2021) 167]

[Eur. Phys. J. C 81 (2021) 1118]

4 lepton, bkg: ZZ, ttZ, VVV

3 lepton bkg: WZ, ZZ





Where do we stand after Run2?

ATLAS SUSY Searches* - 95% CL Lower Limits								ATLAS Preliminary
	Model	Signatu	ure .	∫ <i>L dt</i> [fb ⁻	Mass limit			Reference
Inclusive Searches	$ ilde{q} ilde{q}, ilde{q}{ ightarrow}q ilde{\chi}_1^0$	0 e, μ 2-6 jet mono-jet 1-3 jet	s E_T^{miss} s E_T^{miss}	139 139	\tilde{q} [1×, 8× Degen.] \tilde{q} [8× Degen.]	1.0 0.9	1.85 $m(\tilde{\chi}_1^0) < 400 \text{ GeV}$ $m(\tilde{a}) = m(\tilde{\chi}_1^0) = 5 \text{ GeV}$	2010.14293 2102.10874
	$\tilde{g}\tilde{g}, \tilde{g} {\rightarrow} q \bar{q} \tilde{\chi}_1^0$	0 <i>e</i> , <i>µ</i> 2-6 jet	s E_T^{miss}	139	ξ ğ	Forbidden	2.3 $m(\tilde{\chi}_1^0)=0 \text{ GeV}$ 1.15-1.95 $m(\tilde{\chi}_1^0)=1000 \text{ GeV}$	2010.14293 2010.14293
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}W\tilde{\chi}_1^0$	1 <i>e</i> , <i>µ</i> 2-6 jet	S	139	ĝ		2.2 $m(\tilde{\chi}_1^0) < 600 \text{ GeV}$	2101.01629
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	$ee, \mu\mu$ 2 jets	E_T^{miss}	139	õg z		2.2 $m(\tilde{\chi}_1^0) < 700 \text{ GeV}$	CERN-EP-2022-014
	$gg, g \rightarrow qqWZ\chi_1$	$SS e, \mu$ 6 jets	E_T	139	g ğ	1.15	1.97 $m(\chi_1) < 600 \text{ GeV} \\ m(\tilde{g}) - m(\tilde{\chi}_1) = 200 \text{ GeV}$	1909.08457
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$	$\begin{array}{ccc} \text{0-1} \ e,\mu & \text{3} \ b\\ \text{SS} \ e,\mu & \text{6} \ \text{jets} \end{array}$	$E_T^{ m miss}$	79.8 139	ĩg ĩg	1.25	2.25 $m(\tilde{\chi}_1^0) < 200 \text{ GeV}$ $m(\tilde{g}) - m(\tilde{\chi}_1^0) = 300 \text{ GeV}$	ATLAS-CONF-2018-041 1909.08457
3 rd gen. squarks direct production	$ ilde{b}_1 ilde{b}_1$	0 <i>e</i> , <i>µ</i> 2 <i>b</i>	$E_T^{ m miss}$	139	$ ilde{b}_1 ilde{b}_1$	0.68	$m(ilde{\chi}_1^0){<}400GeV$ 10 $GeV{<}\Deltam(ilde{b}_1 ilde{\chi}_1^0){<}20GeV$	2101.12527 2101.12527
	$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \!\rightarrow\! b \tilde{\chi}_2^0 \rightarrow b h \tilde{\chi}_1^0$	$\begin{array}{ccc} 0 \ e, \mu & 6 \ b \\ 2 \ \tau & 2 \ b \end{array}$	$E_T^{ m miss} \ E_T^{ m miss}$	139 139	$ $	0.23-1.35 0.13-0.85	$\Delta m(\tilde{\chi}_{2}^{0}, \tilde{\chi}_{1}^{0}) = 130 \text{ GeV}, m(\tilde{\chi}_{1}^{0}) = 100 \text{ GeV}$ $\Delta m(\tilde{\chi}_{2}^{0}, \tilde{\chi}_{1}^{0}) = 130 \text{ GeV}, m(\tilde{\chi}_{1}^{0}) = 0 \text{ GeV}$	1908.03122 2103.08189
	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$	0-1 $e, \mu \ge 1$ je	t E_T^{miss}	139	\tilde{t}_1	1.25	$m(\tilde{\chi}_1^0)=1 \text{ GeV}$	2004.14060,2012.03799
	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \to W b \tilde{\chi}_1^0$ $\tilde{t}_1 \tilde{t}_1 \to \tilde{t}_1 \to \tilde{t}_1 \to \tilde{t}_1 \to \tilde{t}_1$	1 e, μ 3 jets/1	$b E_T^{\text{miss}}$ $b E^{\text{miss}}$	139	ĩ Forbidden	0.65	$m(\tilde{\chi}_{1}^{0})=500 \text{ GeV}$	2012.03799
	$t_1 t_1, t_1 \rightarrow \tau_1 b v, \tau_1 \rightarrow \tau G$ $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow c \tilde{\chi}_1^0 / \tilde{c} \tilde{c}, \tilde{c} \rightarrow c \tilde{\chi}_1^0$	$0 e, \mu$ $2 c$	$ D E_T E_T E_T $	36.1	\tilde{c}	0.85	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$ $m(\tilde{\chi}_1^0)=0 \text{ GeV}$	1805.01649
		$0 e, \mu$ mono-j	et E_T^{fmiss}	139	<i>τ</i> ₁ 0.55		$m(\tilde{t}_1,\tilde{c})-m(\tilde{\chi}_1^0)=5 GeV$	2102.10874
	$ \tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow t \tilde{\chi}_2^0, \tilde{\chi}_2^0 \rightarrow Z/h \tilde{\chi}_1^0 $ $ \tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z $	$1-2 e, \mu$ $1-4 b$ $3 e, \mu$ $1 h$	E_T^{miss} E_T^{miss}	139 139	t ₁ Ĩ ₂ Forbidden	0.067-1.18	$m(\tilde{\chi}_{2}^{0}) = 500 \text{ GeV}$ $m(\tilde{\chi}_{1}^{0}) = 360 \text{ GeV}$ $m(\tilde{\chi}_{1}) - m(\tilde{\chi}_{1}^{0}) = 40 \text{ GeV}$	2006.05880 2006.05880
EW direct	$ ilde{\chi}_1^{\pm} ilde{\chi}_2^0$ via WZ	$\begin{array}{ll} \text{Multiple }\ell/\text{jets}\\ ee,\mu\mu &\geq 1 \text{ jet} \end{array}$	t E_T^{miss}	139 139	$\tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{0}^{0}$ $\tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{0}^{2}$ 0.205	0.96	$m(\tilde{\chi}_1^{\pm})=0$, wino-bino $m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^{0})=5$ GeV, wino-bino	2106.01676, 2108.07586 1911.12606
	$ ilde{\chi}_1^{\pm} ilde{\chi}_1^{\mp}$ via WW	2 <i>e</i> , <i>µ</i>	E_T^{miss}	139	$\tilde{\chi}_1^{\pm}$ 0.42		$m(\tilde{\chi}_1^0)=0$, wino-bino	1908.08215
	$\tilde{\chi}_1^{\pm} \tilde{\chi}_2^0$ via <i>Wh</i>	Multiple <i>ℓ</i> /jets	E_T^{miss}	139	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ Forbidden	1.06	m($\tilde{\chi}_1^0$)=70 GeV, wino-bino	2004.10894, 2108.07586
	$\chi_1^+\chi_1^+$ via $\ell_L/\tilde{\nu}$	$2 e, \mu$	E_T^{miss} E^{miss}	139 139	χ_1^- $\tilde{\tau}$ [$\tilde{\tau}_1, \tilde{\tau}_{\rm P,I}$] 0.16-0.3 0.12-0.39	1.0	$m(\ell,\tilde{\nu})=0.5(m(\tilde{\chi}_{\perp}^{\pm})+m(\tilde{\chi}_{\perp}^{0}))$ $m(\tilde{\nu}^{0})=0$	1908.08215
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell \tilde{\chi}_1^0$	$2 e, \mu$ 0 jets	E_T^{miss}	139	<i>ℓ</i>	0.7	$m(\tilde{\chi}_1^0) = 0$	1908.08215
	~~~~~	$ee, \mu\mu \ge 1$ je	t $E_T^{\text{miss}}$	139	<i>ĩ</i> 0.256		$m(\tilde{\ell})$ - $m(\tilde{\chi}_1^0)$ =10 GeV	1911.12606
	$HH, H \rightarrow hG/ZG$	$\begin{array}{ccc} 0 \ e, \mu & \geq 3 \ b \\ 4 \ e, \mu & 0 \ \text{jets} \end{array}$	$E_T^{\text{miss}}$ $E_T^{\text{miss}}$	36.1 139	$\hat{H}$ 0.13-0.23 $\tilde{H}$ 0.55	0.29-0.88	$BR(\widetilde{\mathcal{X}}_1^0  o h\widetilde{G}) = 1$ $BR(\widetilde{\mathcal{X}}_1^0  o Z\widetilde{G}) = 1$	1806.04030 2103.11684
		$0 \ e, \mu \ge 2 \text{ large}$	jets $E_T^{\text{fmiss}}$	139	Ĥ	0.45-0.93	$BR(\tilde{\chi}^0_1 \to Z\tilde{G})=1$	2108.07586
Long-lived particles	Direct $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk 1 jet	$E_T^{ m miss}$	139	$ \tilde{\chi}_1^{\pm} $ $ \tilde{\chi}_1^{\pm} $ 0.21	0.66	Pure Wino Pure higgsino	2201.02472 2201.02472
	Stable $\tilde{g}$ R-hadron	pixel dE/dx	$E_T^{\rm miss}$	139	Ĩġ		2.05	CERN-EP-2022-029
	Metastable $\tilde{g}$ R-hadron, $\tilde{g} \rightarrow qq \tilde{\chi}_1^0$	pixel dE/dx Displ. lep	$E_T^{\text{miss}}$	139	$\tilde{g} = [\tau(\tilde{g}) = 10 \text{ ns}]$	0.7	<b>2.2</b> $m(\tilde{\chi}_1^0) = 100 \text{ GeV}$	CERN-EP-2022-029
	$\iota\iota,\iota \rightarrow \iota O$		$L_T$	139	$\tilde{\tau}$ 0.34	0.7	$\tau(t) = 0.1 \text{ ns}$ $\tau(\tilde{t}) = 0.1 \text{ ns}$	2011.07812 2011.07812
		pixel dE/dx	$E_T^{\rm mass}$	139	$ ilde{ au}$ 0.36		$ au(\ell) = 10 \text{ ns}$	CERN-EP-2022-029
RPV	$\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp} / \tilde{\chi}_1^0$ , $\tilde{\chi}_1^{\pm} \rightarrow Z \ell \rightarrow \ell \ell \ell$	3 <i>e</i> , μ	mice	139	$\tilde{\chi}_{1}^{\mp}/\tilde{\chi}_{1}^{0}$ [BR( $Z\tau$ )=1, BR( $Ze$ )=1] <b>0</b> .	.625 1.05	Pure Wino	2011.10543
	$\begin{array}{ccc} \hat{\chi}_{1}^{+}\chi_{1}^{+}/\chi_{2}^{0} \rightarrow WW/Z\ell\ell\ell\ell\nu\nu\\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow gg\tilde{\chi}_{0}^{0}, \tilde{\chi}_{0}^{0} \rightarrow ggg\\ \end{array}$	4 <i>e</i> ,μ 0 jets 4-5 large	$E_T^{\text{minss}}$	139 36 1	$\tilde{\boldsymbol{\chi}}_{1}^{*}/\boldsymbol{\chi}_{2}^{*}  [\lambda_{i33} \neq \boldsymbol{0}, \lambda_{12k} \neq \boldsymbol{0}]$ $\tilde{\boldsymbol{\chi}}_{1}^{*}  [\boldsymbol{m}(\tilde{\boldsymbol{\chi}}^{0}) = 200 \text{ GeV}   1100 \text{ GeV}   100 $	0.95 1.3	<b>19</b> $m(\chi_1^o) = 200 \text{ GeV}$	2103.11684
	$\widetilde{t}\widetilde{t}, \ \widetilde{t} \to t\widetilde{\chi}_1^0, \ \widetilde{\chi}_1^0 \to tbs$	Multipl	e	36.1	$\tilde{t} = [\lambda'_{323} = 2e-4, 1e-2]$ 0.55	1.05	$m(\tilde{\chi}_1^0)=200 \text{ GeV, bino-like}$	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}, \tilde{t} \rightarrow b\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^{\pm} \rightarrow bbs$	$\geq 4b$	<b>.</b> .	139	ĩ Forbidden	0.95	$m({ ilde {\cal X}}_1^\pm)$ =500 GeV	2010.01015
	$ \tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow bs $ $ \tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow c \ell $	2 jets + 2	2 <i>b</i>	36.7	$\vec{t}_1  [qq, bs] \qquad \qquad 0.42 0$	0.61	$PP(\tilde{i} \to h_a/h_u) > 200/$	1710.07171
	$\iota_1\iota_1, \iota_1 \rightarrow q\iota$	$1 \mu$ DV		136	$t_1^{i_1}$ [1e-10< $\lambda'_{23k}$ <1e-8, 3e-10< $\lambda'_{23k}$ <3e-9]	1.0	<b>1.6</b> BR $(\tilde{i}_1 \rightarrow q\mu) = 100\%$ , $\cos\theta_i = 1$	2003.11956
	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0/\tilde{\chi}_1^0, \tilde{\chi}_{1,2}^0 \rightarrow tbs, \tilde{\chi}_1^+ \rightarrow bbs$	1-2 $e, \mu \ge 6$ jets	S	139	<i>x</i> ₁ ⁰ 0.2-0.32		Pure higgsino	2106.09609
*Only	a selection of the available ma	ass limits on new sta	ites or	1	<b>_</b>	1		L
phen	omena is shown. Many of the	limits are based on		'		•		

- ► The air is getting thin for natural SUSY
  - ► Gluinos ~ 2.2 TeV
  - ► Stops ~ 1.2 TeV
  - ► Elektroweakinos ~ 800 GeV
- ► However
  - Simplified models are only part of the story
  - always check assumptions in the model and how it fits with the bigger picture



### **Dark Matter**

 Astrophysical observations show that a new kind of matter exists, that interacts gravitationally



Strong gravitational lensing as observed by the <u>Hubble Space Telescope</u> in <u>Abell 1689</u>



#### Rotational curves of galaxies



#### Cosmic microwave background



### WIMP miracle

- ➤ In the early universe dark matter and SM particles were in a thermal equilibrium
  - > Constant production and annihilation of dark matter  $\chi \chi \rightleftharpoons ff$
- ► Freeze out:

≻

- ► universe cools
- > WIMP mass too high for production  $\chi \chi \rightarrow ff$
- particles don't meet anymore
- can obtain relic density from Boltzmann equation
- compare with observation (CMB)
- ► Corresponds to ~100 GeV particle interacting with the weak force





### Searching for Dark Matter





### Dark Matter searches at colliders

- DM can be produced in proton-proton collisions
  - > DM does not interact with the detector
  - $\Rightarrow$  mono-X (can also be several particles)





# Mono-X signature

► ATLAS and CMS cannot detect what they cannot see  $\rightarrow$  if DM is produced at the LHC need some X to trigger on



ISR **jet** with (axial-)vector Z exchanged in s-channel

Could also be: photon, W, Z

#### [*Phys. Rev. D* 103 (2021) 112006]





# **Comparing LHC results with direct detection**

Axial-vector mediator DM coupling  $g_{\chi} = 1$  quark coupling  $g_q = 0.1$ lepton coupling  $g_l = 0.1$ 



Can only compare results for a given model and set of parameters



# **Comparing LHC results with direct detection**

Axial-vector mediator  $DM \ coupling \ g_{\chi} = 1$   $quark \ coupling \ g_q = 0.25$  $lepton \ coupling \ g_l = 0$ 



Can only compare results for a given model and set of parameters



# **Comparing LHC results with direct detection**

Vector mediator DM coupling  $g_{\chi} = 1$ quark coupling  $g_q = 0.25$ lepton coupling  $g_l = 0$ 



Can only compare results for a given model and set of parameters

 $\rightarrow$  no enhancement



### Dark Matter + heavy flavor

- ► WIMP model for DM produced at colliders Phys. Rev. D91 015017, arXiv:1507.00966
- ► Minimal flavor violation
  - Same flavor structure as in the SM
  - > Yukawa couplings to spin-0 mediator
- > DM production via (pseudo)scalar most compelling for heavy flavor + DM > Parameters:  $m_{\varphi}$ ,  $m_{\chi}$ ,  $g_q$ ,  $g_{\chi}$  Benchmark:  $g_q = g_{\chi} = 1$
- Mediator decays into two dirac fermion dark matter particles  $\chi$ , which escape detection  $\rightarrow$  Missing energy is the main signature  $\rightarrow$  Amount depends on mediator and its mass





Very similar signature to stop searches



### Dark Matter + heavy flavor

- Sometimes existing results can be reinterpreted for new models
  - ATLAS SUSY stop searches contained a dedicated "Dark Matter" signal region
  - Search for a 2 Higgs doublet (2HDM+a) model with an additional pseudo scalar predicting tW+MET final states is also sensitive





[Eur. Phys. J. C 81 (2021) 860]





# **Unconventional signatures**

So far the models were BSM but the signatures contained "known" SM particles  $\rightarrow$  what if also the decay products are "BSM"?



BSM	
lepton	
🗖 quark	
photon	
anything	

Not pictured: stopped particles

- Often "long lived" new particles
- Backgrounds very different from other searches
  - Attailed the approaches to estimate them
- Often dedicated data reconstruction algorithms needed







# **Searches for new physics at the LHC**

- So far no smoking gun for signs of new physics
  - Flavor anomalies will be covered in b-physics lecture
- > Here and there local 2-3 sigma excesses  $\rightarrow$  important to follow up
  - However luminosity will now double only every couple of years
- ► NEW IDEAS?

  - detected with other experiments  $\rightarrow$  Proposals FASER, MATHUSLA etc.

 $\blacktriangleright$  Make sure we didn't miss something  $\rightarrow$  what we didn't trigger on is lost forever Maybe something super long lived is produced in ATLAS/CMS but can only be



# Where do we go next?

#### We will still collect 15 times more data



http://lhc-commissioning.web.cern.ch/schedule/LHC-long-term.htm

#### HL-LHC

- Major detector upgrades underway
  - $\blacktriangleright$  expected pile up of ~200 poses an immense challenge
- Precision measurements of the Higgs boson
  - Establish Higgs self coupling at the 5 sigma level
- Push the boundaries of SM precision measurements
  - Find deviations that could hint at new physics
  - Watch out for exciting LHCb results
- Pursue dedicated searches for new physics ► Your new crazy idea!





# Thank you very much for your attention!

Measure

Standard Model

parameters with high precision

Search for the

Higgs boson

and measure it's properties

#### Large Hadron Collider



New Physics

Beyond the Standard Model

#### **Questions?**



