Hide-and-Seek with Light Scalars at the LHC

Jonathan Kozaczuk (TRIUMF)

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JK, Martin, JHEP 1501 (2015) 144
Blinov, **JK**, Morrissey, de la Puente, arXiv: 1510.today

Light Scalar Blind Spots

Many theories beyond the SM predict new, relatively light scalars weakly coupled to the SM

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Some well-motivated models will not be covered by combination of past + current + planned collider searches

How might we test such scenarios?

Light Scalar Blind Spots

Two examples:

1. Light psuedoscalar mediators for dark matter annihilation without missing energy signatures

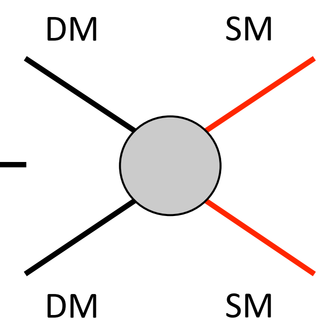
2. Compressed inert scalars

1. Light pseudoscalar mediators

Why a pseudoscalar mediator?

Weakly interacting massive particles (WIMPs) are a compelling thermal dark matter candidate

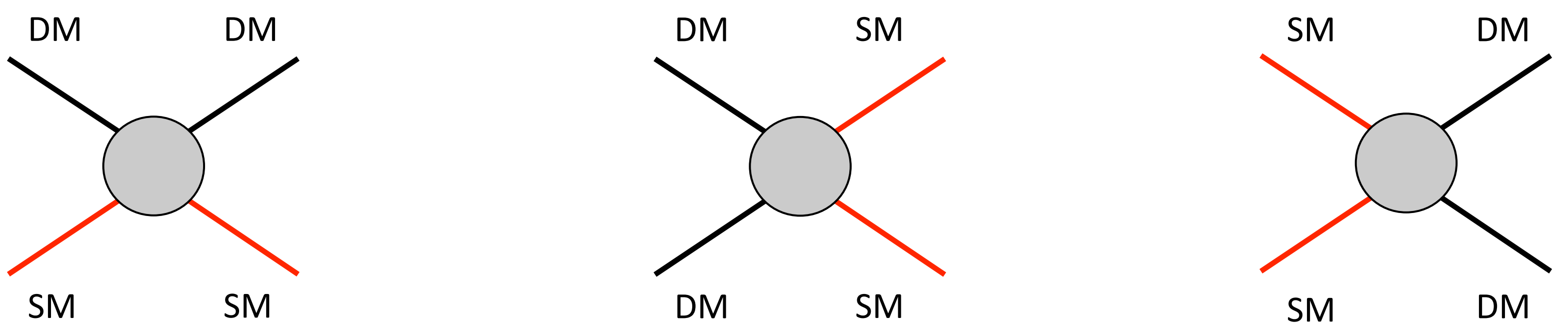
$$\Omega_\chi h^2 \simeq 0.2 \times \frac{3 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}}{\langle \sigma v \rangle}$$



Simplest incarnation relies on weak scale DM – SM interactions

Why a pseudoscalar mediator?

Present-day experiments are sensitive to new weak scale physics coupling to the Standard Model



Direct Detection

Indirect Detection

Colliders

But no conclusive evidence at colliders or DM experiments (yet)

Why a pseudoscalar mediator?

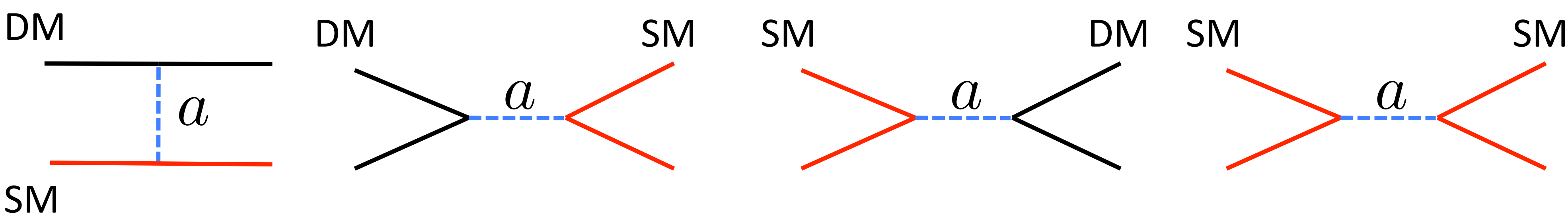
A possible explanation: pseudoscalar couplings of DM to SM fermions

$$\mathcal{O}_{\mathrm{DD}} = \left(\overline{\chi}\gamma^5\chi\right)\left(\overline{f}\gamma^5 f\right) \longrightarrow$$

No tree-level spin-independent direct detection cross-section

$\frac{q^4}{m_\chi^2 m_N^2}$ suppression for spin-dependent scattering

UV completion: pseudoscalar mediator



Why a pseudoscalar mediator?

If pseudoscalar – SM couplings proportional to Yukawa Couplings (MFV) → weakened collider constraints, even for low masses

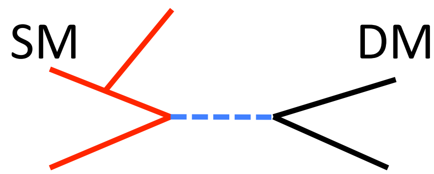
Scenario dubbed "coy" (Boehm et al, 1401.6458) or "pseudoscalar portal" (Berlin et al, 1502.06000) dark Matter

How can we probe these scenarios at the LHC?

Probing Light (Pseudoscalar) Mediators

2 generic possibilities:

$m_a > 2m_{\mathrm{DM}}$, large BR(a→ invisible)



Look for hard SM partons + missing energy (traditional DM search)

Boehm et al, 1401.6458,
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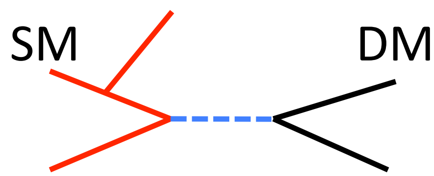

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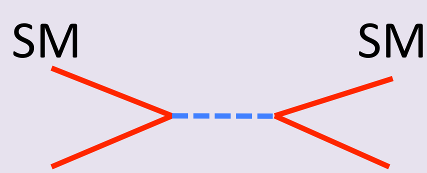

Look for SM decay products. Similar to Higgs searches, but **difficult for light states**

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No existing direct constraints for $15 \text{ GeV} \lesssim m_a \lesssim 90 \text{ GeV}$

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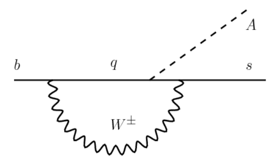
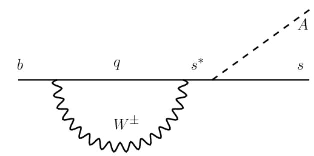
$g_d \lesssim \frac{3m_a}{10\ \mathrm{GeV}}$ (from $B_s \to \mu^+\mu^-$:





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See e.g. Dolan et al, 1412.5174

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  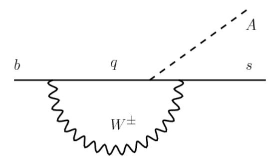

  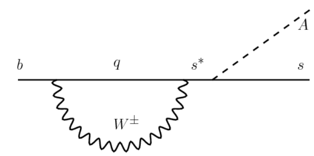

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- Higgs decays ($h \to aa$) can be avoided by cancellations or simply taking $m_a > m_h/2$

See e.g. JK and Profumo, 1308.5075, Cheung et al, 1406.6372

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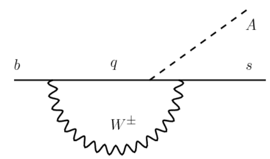
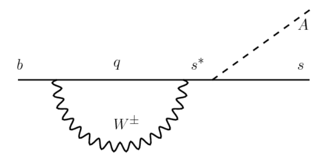
  $g_d \lesssim \frac{3m_a}{10 \text{ GeV}}$ (from $B_s \to \mu^+\mu^-$: 

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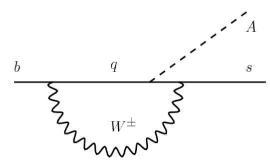

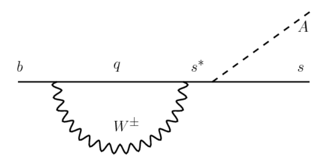

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- Tevatron, LHC $a \to \tau^+\tau^-$ searches constrain $m_a \gtrsim 90 \text{ GeV}$

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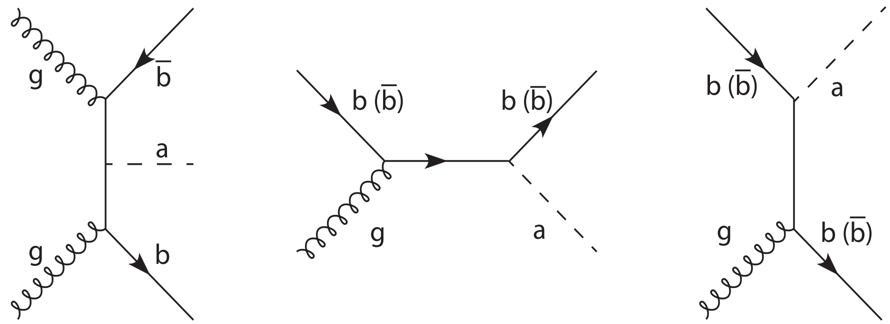
Can we close the gap in coverage with the 13 TeV LHC?

Coy Pseudoscalars at the LHC

Case study: focus on associated production with *b* quarks



$\mathrm{SR1}: \ 1e1\mu$
$\mathrm{SR2}: \ 1\ell 1\tau_h$
$\mathrm{SR3}: \ 2\mu$

$$\mathcal{L}_{\rm int} \supset -i\frac{g_{\rm DM}}{\sqrt{2}} a\bar{\chi}\gamma^5\chi - i\sum_{i=u,c,t}\frac{g_u y_i}{\sqrt{2}} a\bar{f}_i\gamma^5 f_i - i\sum_{\substack{i=d,s,b,\\ e,\mu,\tau}}\frac{g_d y_i}{\sqrt{2}} a\bar{f}_i\gamma^5 f_i$$

Require 1-2 b jet tags and no light jets (p_T>40 GeV)

Consider leptonic final states (cleaner signal)

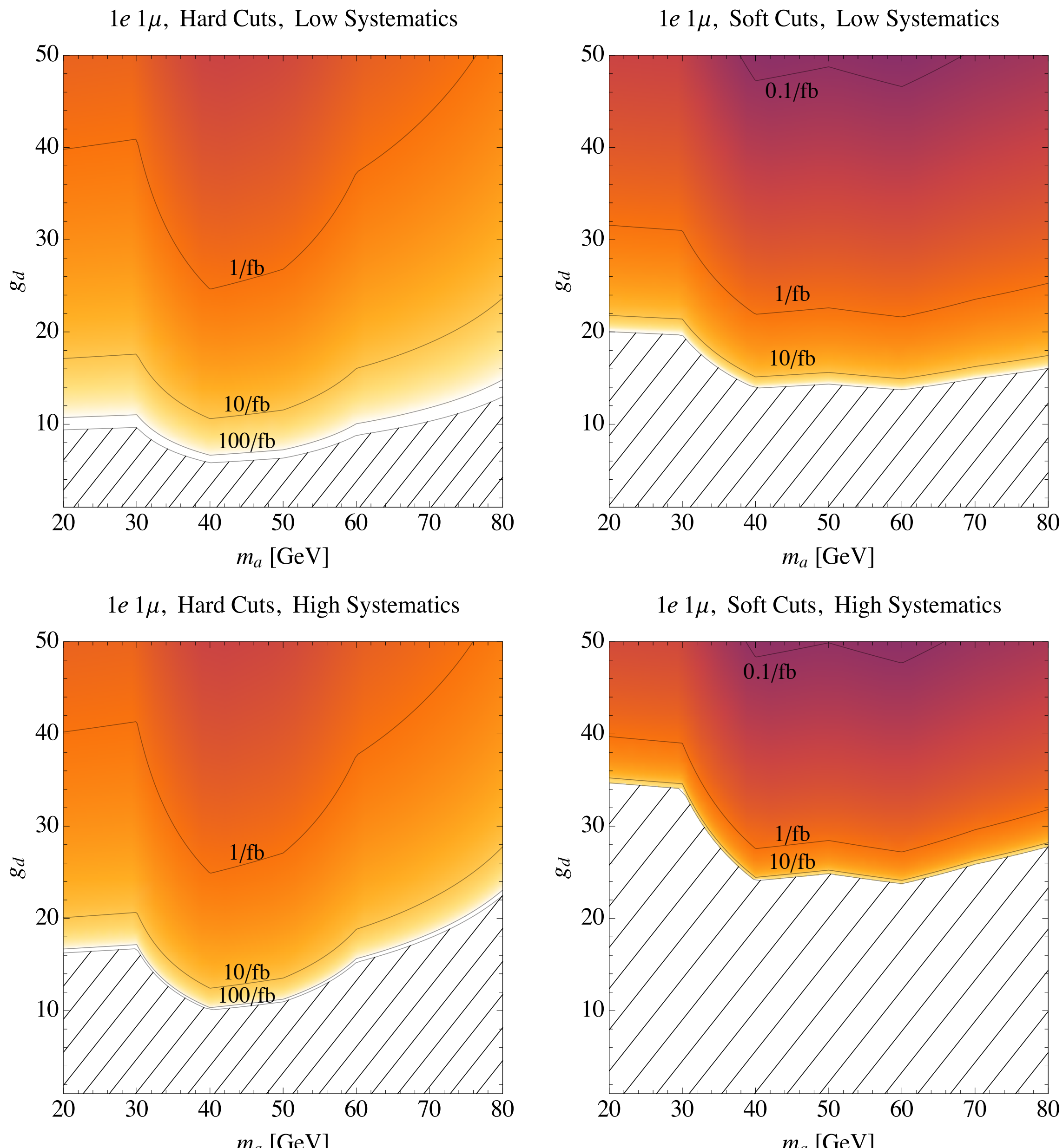
Primary irreducible backgrounds: $t\bar{t}$ and inclusive γ^*/Z production

Coy Pseudoscalars at the LHC

Results (SR1):

Two scenarios for systematics:
$\epsilon_{\rm sys} = 0.1,\ 0.3$

Significant reach even at low integrated luminosity

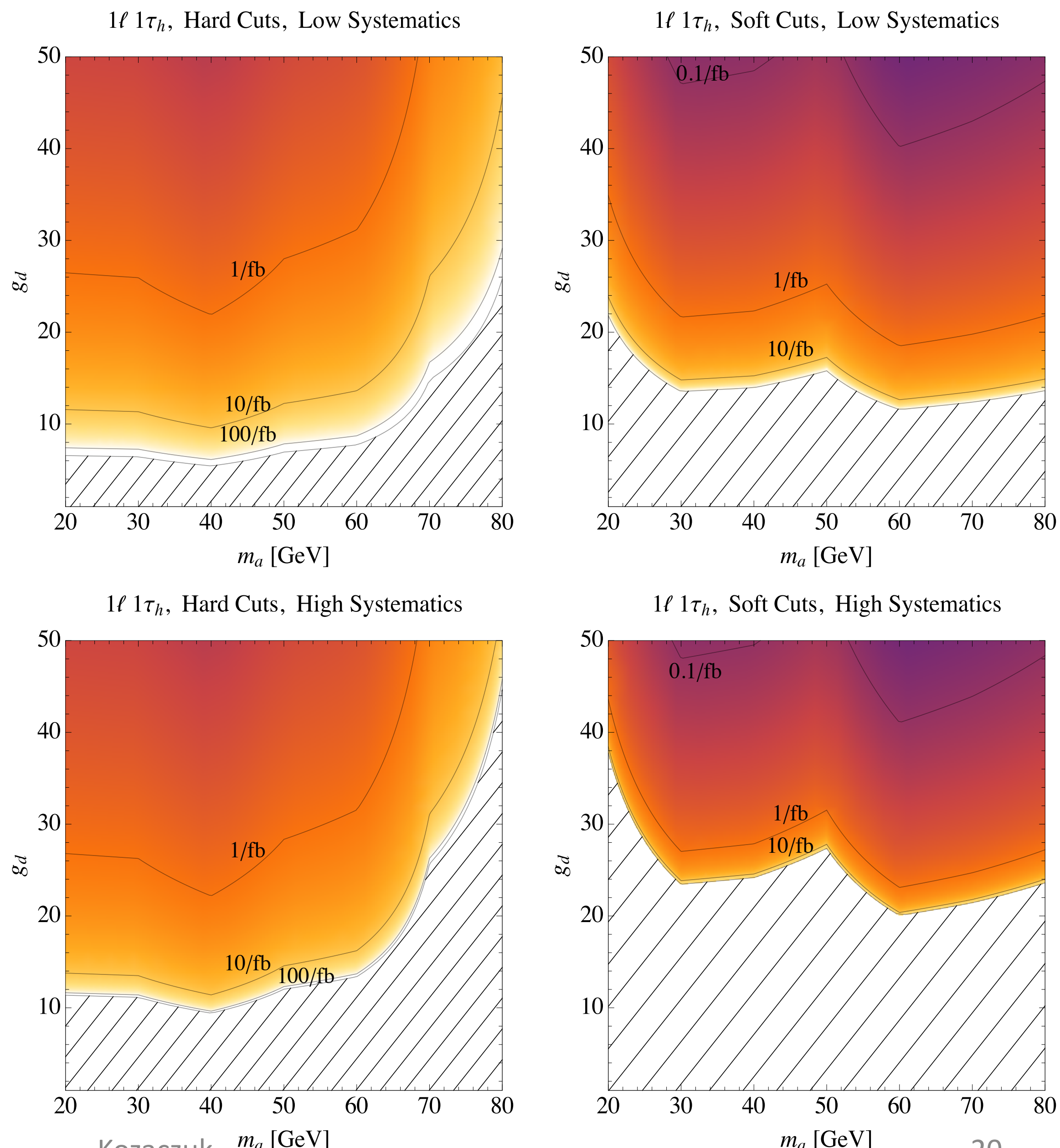


Coy Pseudoscalars at the LHC

Results (SR2):

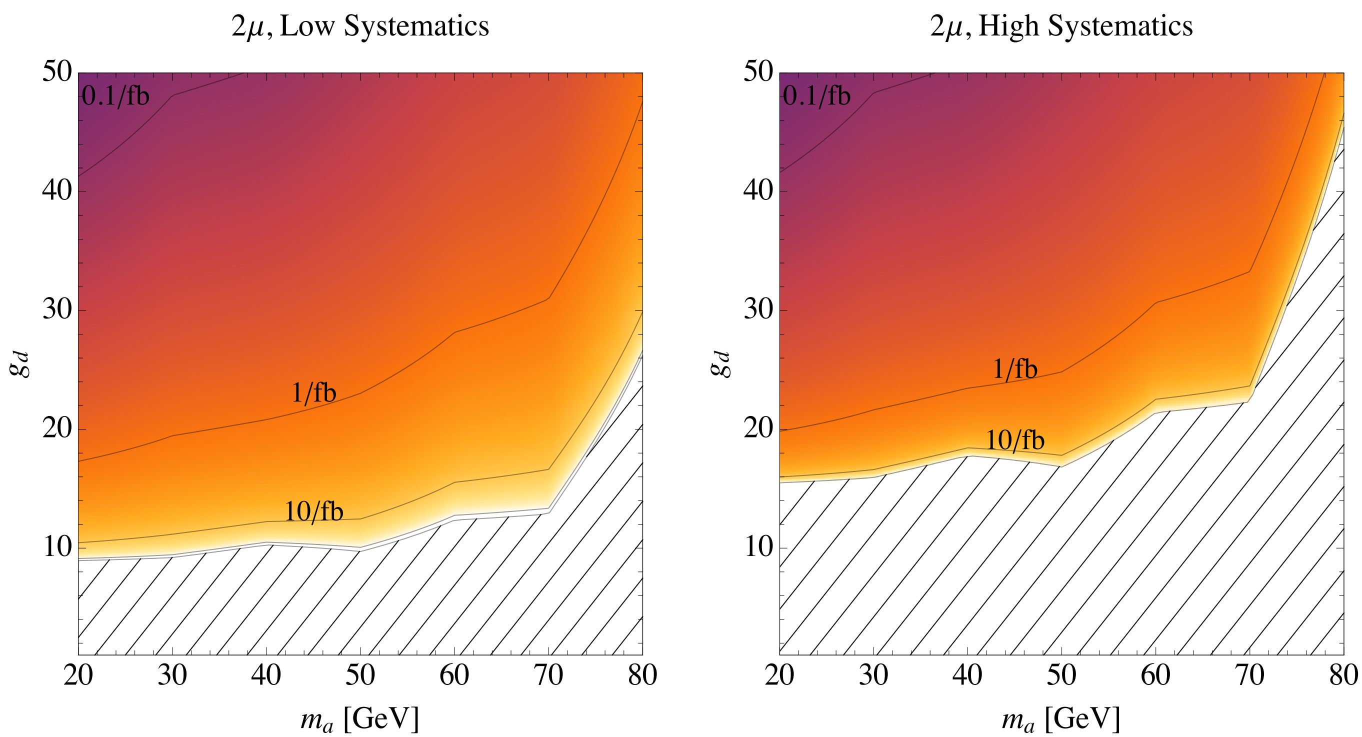
Two scenarios for systematics:
$\epsilon_{\rm sys} = 0.1,\ 0.3$

Significant reach even at low integrated luminosity



Coy Pseudoscalars at the LHC

Results (SR3):



Good reach with only 10/fb!

Expect lower systematics (bump hunting)

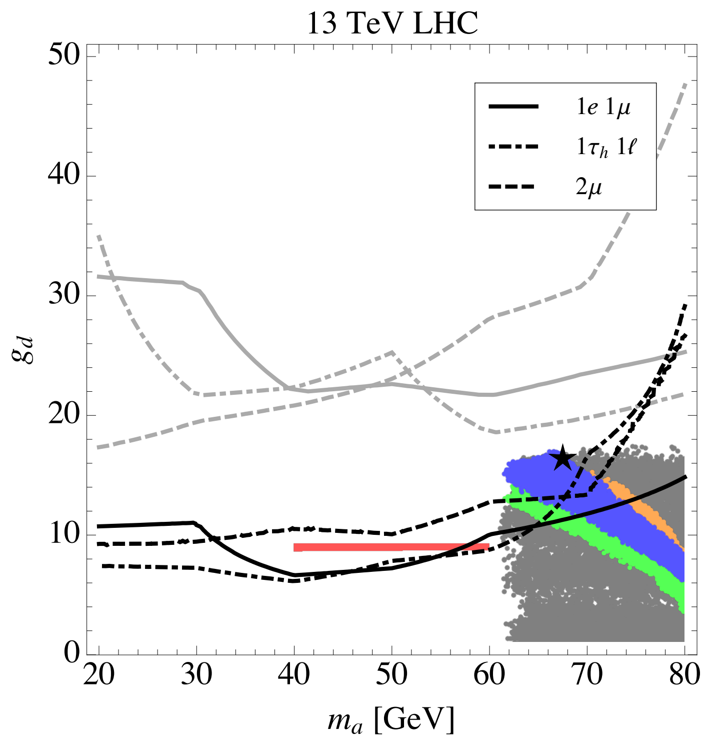
Coy Pseudoscalars at the LHC

Application: **the NMSSM**

$$W = W_{\mathrm{MSSM}}\big|_{\mu=0} + \lambda \widehat{S}\widehat{H}_u \cdot \widehat{H}_d + \frac{\kappa}{3}\widehat{S}^3$$

$$a = A\cos\theta + a_s \sin\theta$$

$$g_u = \cos\theta\cot\beta, \quad g_d = \cos\theta\tan\beta.$$

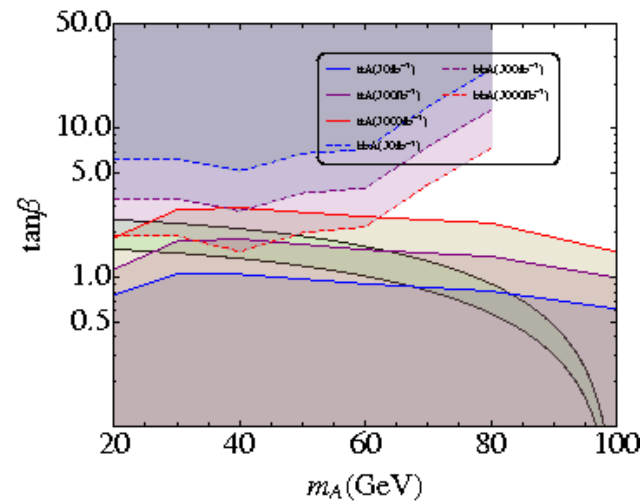


These searches can provide new tests of currently unexplored parameter space even at relatively low integrated luminosity

Recent Developments

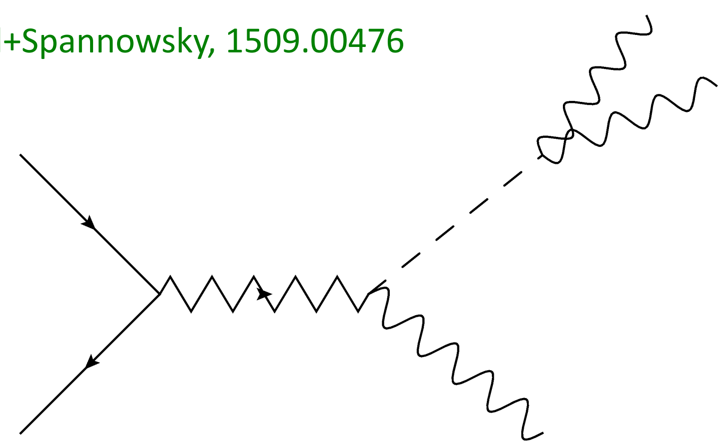
Associated production w/tops can also be promising in some cases

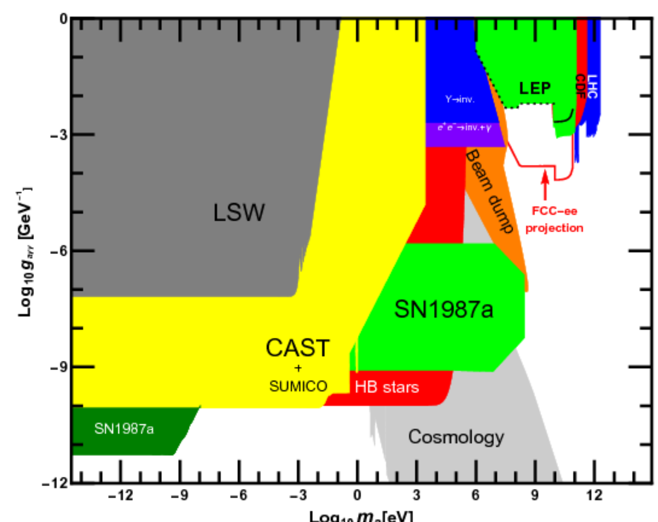
Casolino et al, 1507.07004



Also processes involving γ/Z

Jaeckel+Spannowsky, 1509.00476





Takeaways (Part 1)

* Pseudoscalar mediators for DM annihilation are phenomenologically and theoretically well-motivated

* There is currently a blind spot for moderately light mediators at the LHC

* LHC searches we propose can effectively probe scenarios that do not predict large missing energy signatures, even with low integrated luminosity

2. Compressed Scalars

The Compressed Inert Doublet Model

Inert Doublet Model extends the SM with an additional Y=1/2 $SU(2)_L$ doublet charged under a new Z_2 and without a VEV

Attractive features:

- Provides a dark matter candidate
- Can yield a strong first order phase transition for electroweak baryogenesis
- Useful pheno tool; many models with new electroweakly-charged scalars map directly onto the IDM in certain limits

The Compressed Inert Doublet Model

Most general potential:

$$\begin{aligned} V &= \mu_1^2 |H_1|^2 + \mu_2^2 |H_2|^2 + \lambda_1 |H_1|^4 + \lambda_2 |H_2|^4 \\ &\quad + \lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 |H_1^\dagger H_2|^2 + \frac{\lambda_5}{2}\left[(H_1^\dagger H_2)^2 + \text{ h.c.}\right] \end{aligned}$$

Scalar mass spectrum:

$$\begin{aligned} m_h^2 &= -2\mu_1^2 \;=\; 4\lambda_1 v^2 \\ m_H^2 &= \mu_2^2 + (\lambda_3 + \lambda_4 + \lambda_5) v^2 \\ m_A^2 &= \mu_2^2 + (\lambda_3 + \lambda_4 - \lambda_5) v^2 \\ m_{H^\pm}^2 &= \mu_2^2 + \lambda_3 v^2 \ . \end{aligned}$$

The Compressed Inert Doublet Model

Additional symmetries compress the spectrum

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E.g. *$U(1)_2$*

$$
\begin{aligned}
V &= \mu_1^2|H_1|^2 + \mu_2^2|H_2|^2 + \lambda_1|H_1|^4 + \lambda_2|H_2|^4 \\
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The Compressed Inert Doublet Model

Additional symmetries compress the spectrum

E.g. *SU(2)$_2$* or extended custodial symmetry

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The Compressed Inert Doublet Model

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U(1)$_2$ can be exact, while *SU(2)*$_2$ or extended custodial symmetry broken by gauging *SU(2)*$_L$ x *U(1)*$_Y$

$$\Delta^0 = (m_A - m_H) \sim 100\,\mathrm{keV} - 5\ \mathrm{GeV} \ll \Delta^{\pm}$$

$$\Delta^{\pm} = (m_{H^\pm} - m_H) \sim 1 - 30\ \mathrm{GeV}\ \text{with}\ m_H > m_Z/2.$$

"Compressed IDM" is a technically natural limit of the theory and a **blind spot** for light scalar searches

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Few constraints for $m_H > m_Z/2$ in the compressed limit

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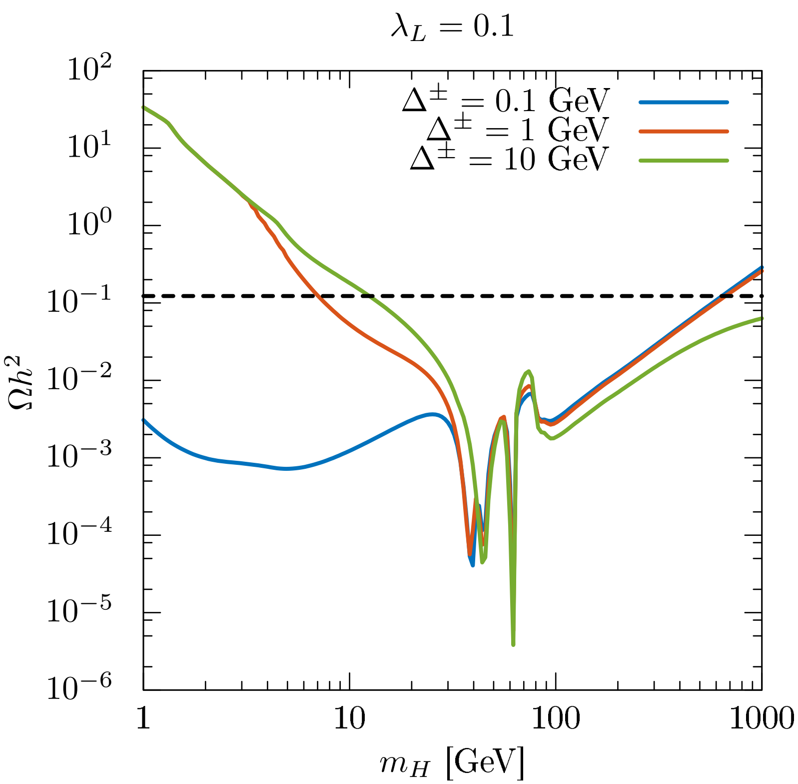

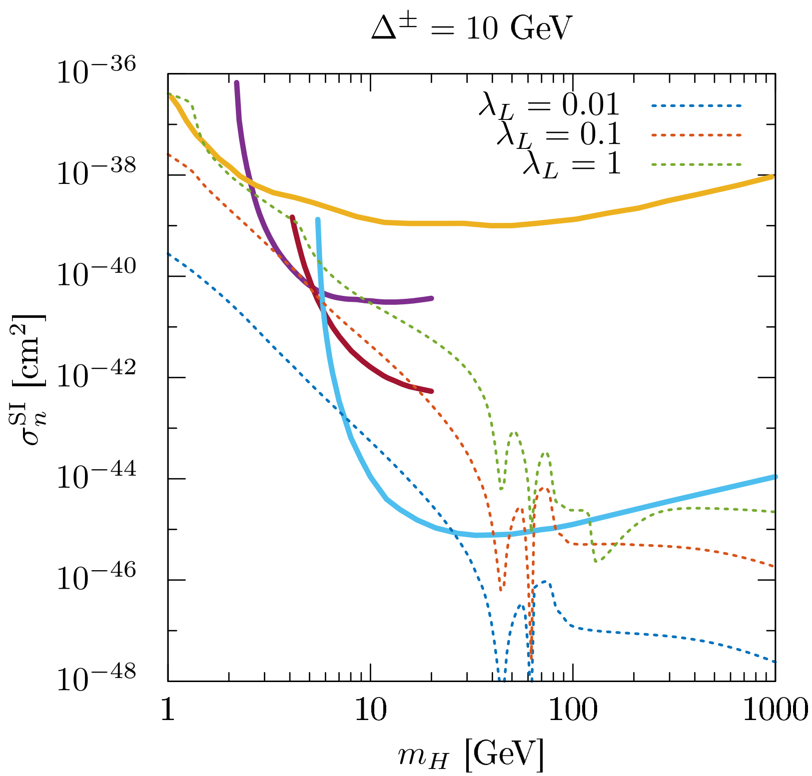

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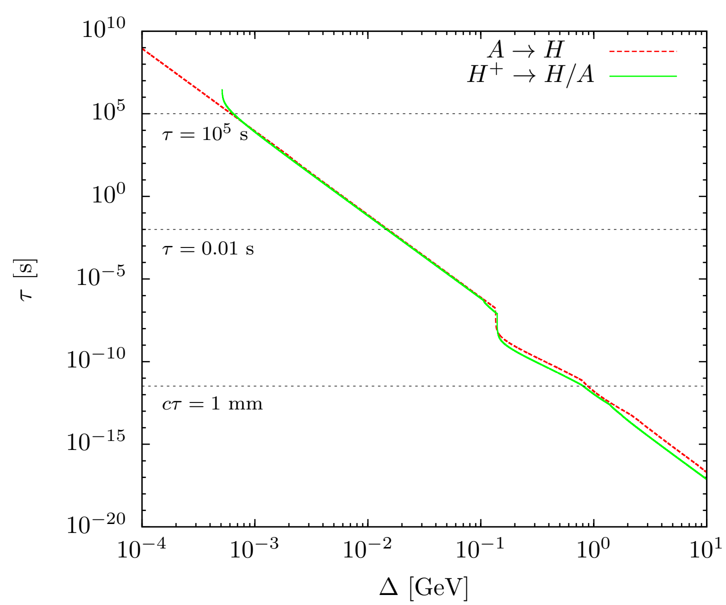

See e.g. Jedamzik, astro-ph/0402344, Kawasaki et al, astro-ph/0408426, Kanzaki et al, 0705.1200

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$$\Delta T \simeq \frac{1}{24\pi^2 \alpha v^2}(m_{H^\pm} - m_A)(m_{H^\pm} - m_H)$$

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What about LEP? LHC?

LEP Constraints

Dominant decays: $A \to HZ^*$ and $H^\pm \to HW^{\pm *}$

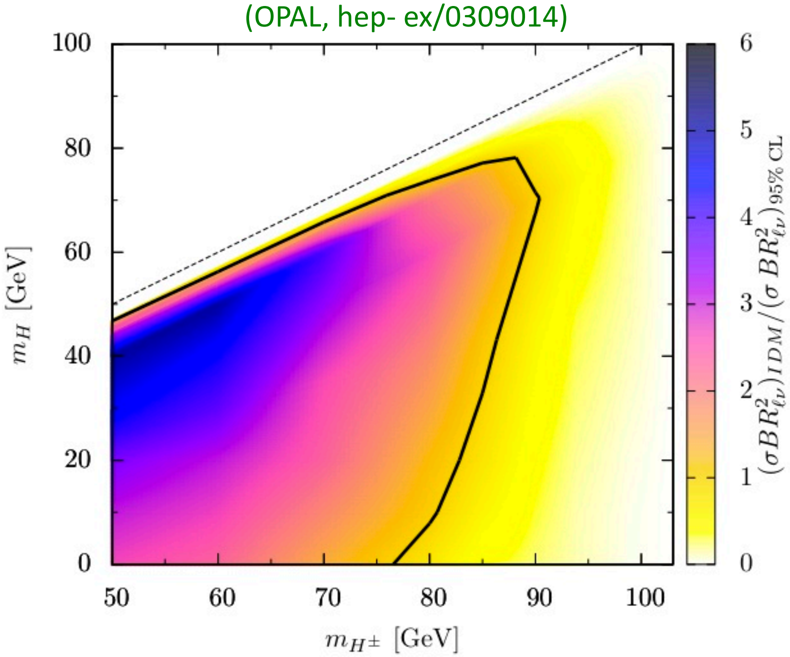
LEP Constraints

LEP chargino searches constrain $m_H \lesssim 90\,\mathrm{GeV}$ for large enough splitting. No limit for $\Delta^{\pm} \lesssim 5\,\mathrm{GeV}$.

Dominant decays: $A \to HZ^*$ and $H^{\pm} \to HW^{\pm *}$

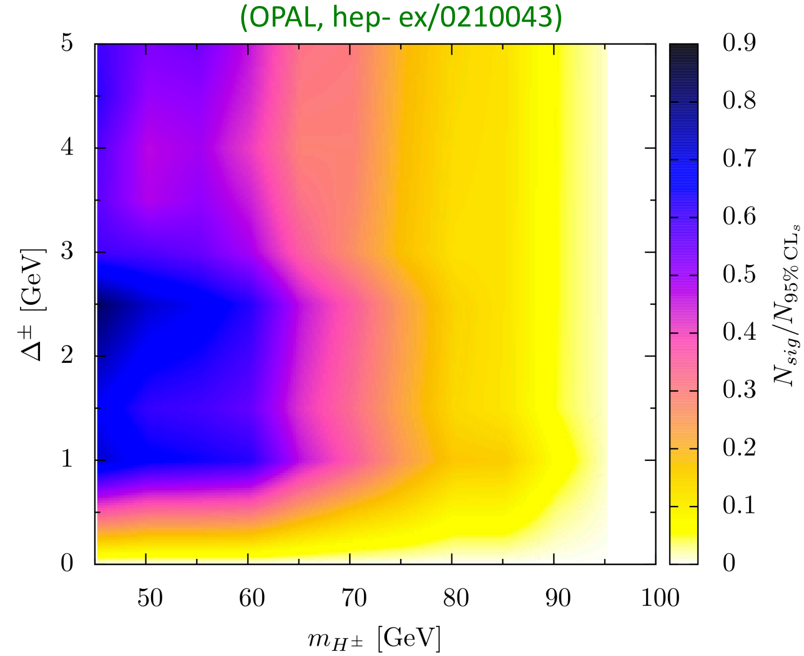
Dilepton + MET

(OPAL, hep- ex/0309014)



Mono-photon + Soft tracks

(OPAL, hep- ex/0210043)

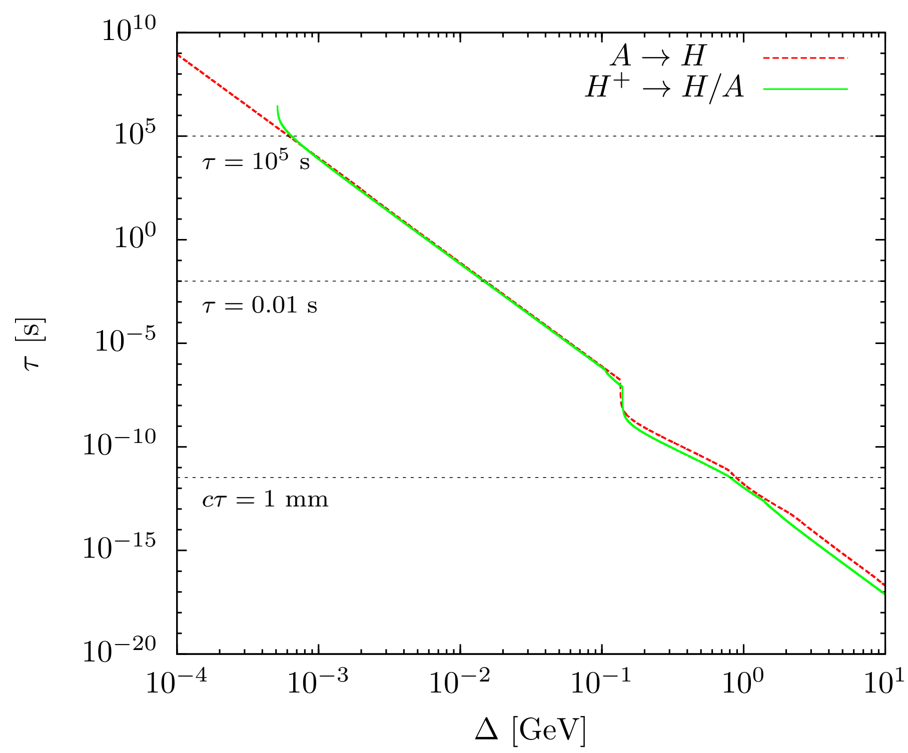


LEP Constraints

Other LEP searches do not provide additional sensitivity

Charged state typically not long-lived enough for charged track searches

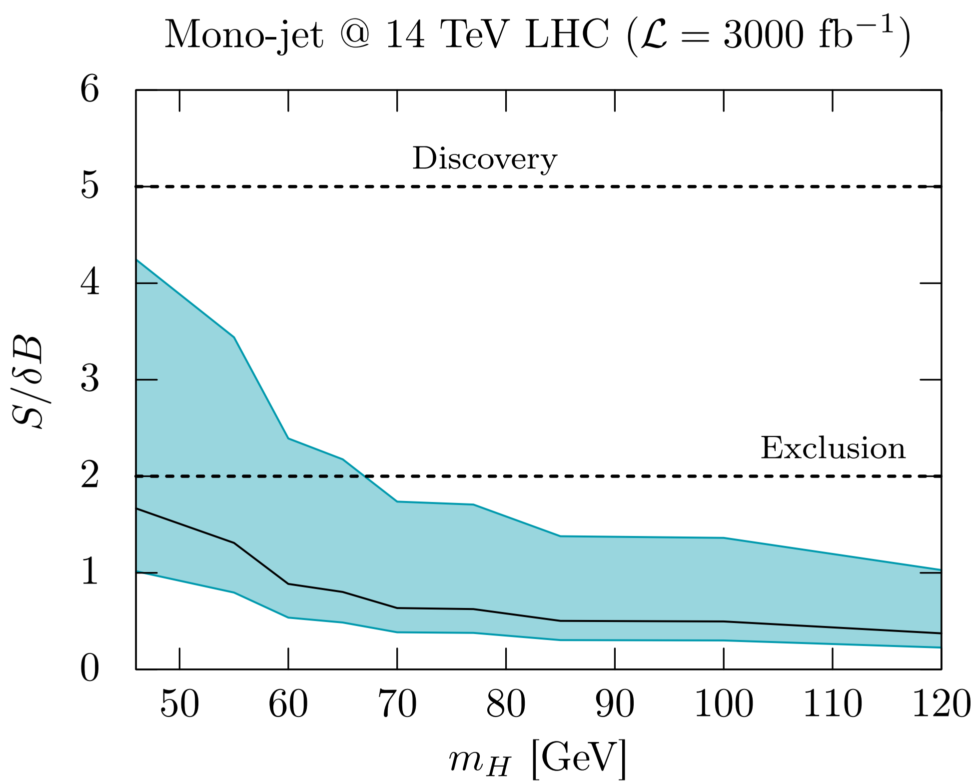
Pure mono-photon not as sensitive



Can the LHC close the blind spot?

LHC Constraints and Prospects

Current 8 TeV mono-jet searches unconstraining, but may have a shot at low masses with 14 TeV LHC



Compare to Higgsino case in Low + Wang, 1404.0682

LHC Constraints and Prospects

Other typically useful strategies unlikely to help much

- **Leptons too soft to trigger on in exclusive lepton searches** (see e.g. Cao et al, 0708.2939, Dolle et al, 0909.3094, Belanger et al, 1503.07367)

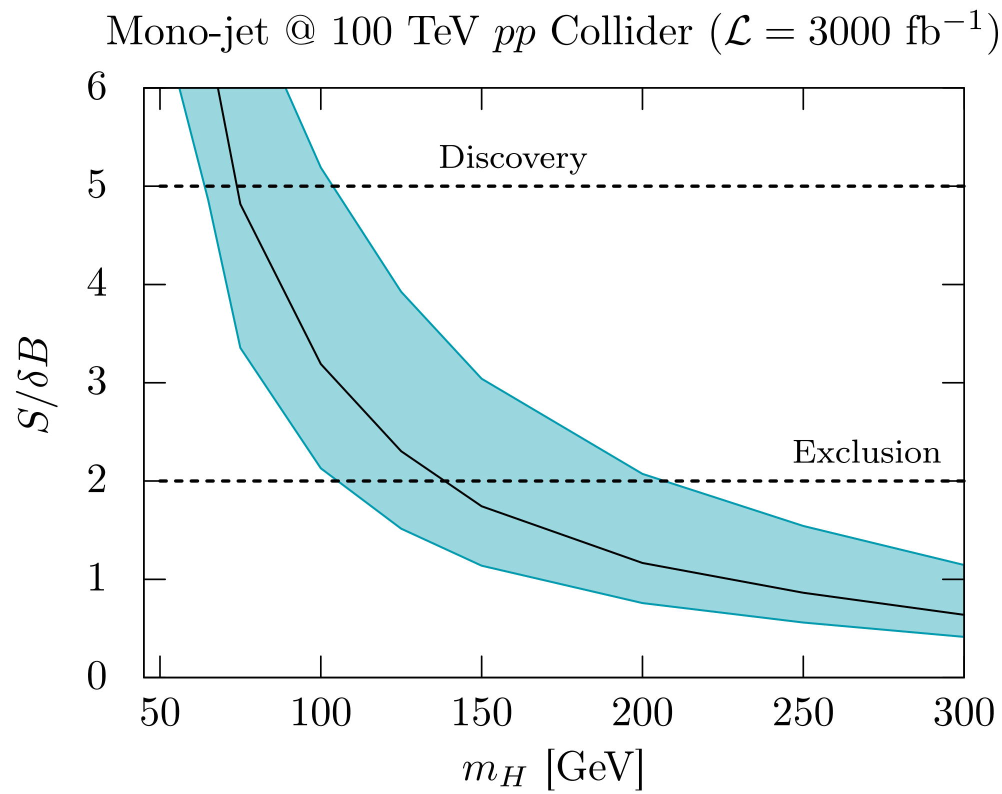
- **Mono-jet + soft leptons not as effective as in the Higgsino case** (see e.g. Low & Wang, 1404.0682, Han et al, 1401.1235, Han et al 1502.03734), since splittings are smaller and $\Delta^{\pm} \gg \Delta^{0}$ so lepton kinematics uncorrelated

- **Charged decay is typically too prompt for disappearing tracks** (Low & Wang, 1404.0682) **and Δ^{0} too small to identify leptons in searches for mono-jets + displaced vertices** (see e.g. Izaguirre et al, 1508.03050)

What about future colliders?

Prospects at Future Colliders

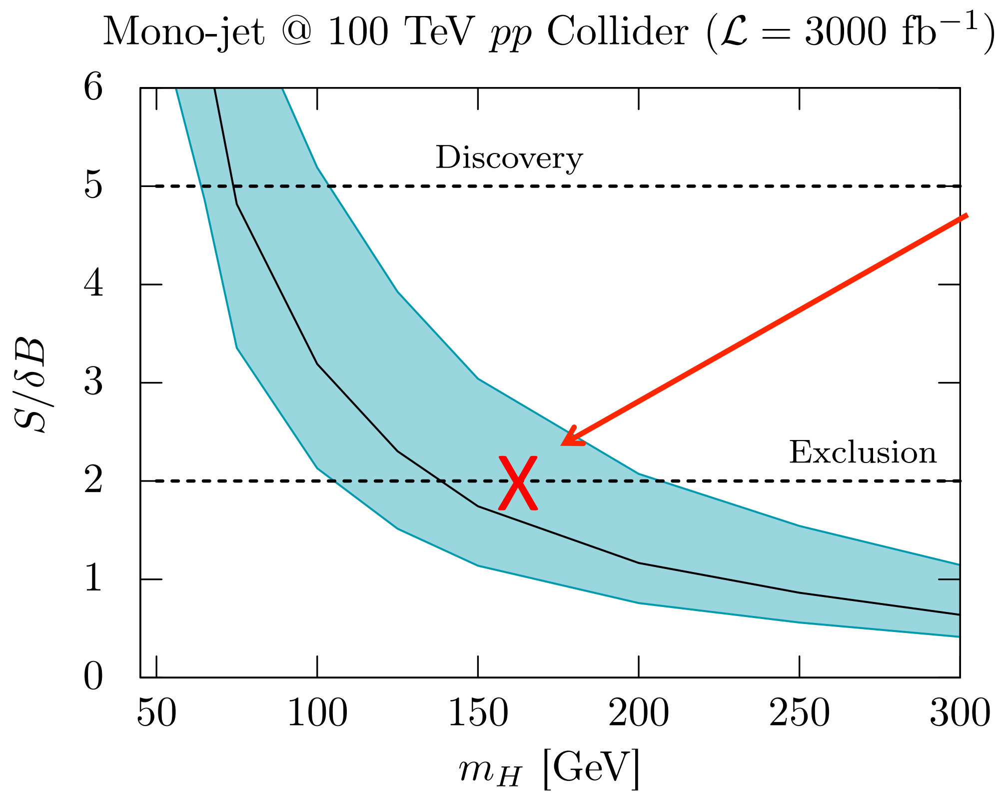
A 100 TeV *pp* collider will have better reach, although depends strongly on systematics



Significantly lower reach than for Higgsino case (see Low + Wang, 1404.0682)

Prospects at Future Colliders

An ILC-like e^+e^- collider would be well-suited to test the compressed IDM



ILC mono-photon exclusion (500 fb^{-1} @ 500 GeV w/ polarized beams)
[From Choi et al, 1503.08538]

Mono-jet + soft leptons will likely improve over this, provided low pT threshold

Still, region saturating DM relic abundance likely only to be tested via direct detection

Takeaways (Part 2)

* Compressed IDM arises in the presence of new approximate symmetries in a technically natural way
* Important differences from degenerate Higgsino scenarios
* LEP and DM constraints are currently strongest. Small splittings are still mostly unconstrained. Difficult for the LHC to improve on LEP
* Mono-X searches at a 100 TeV pp collider and ILC can probe low to intermediate masses. Direct detection needed for higher masses

Conclusions

Leave no stone unturned at Run 2

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Future colliders are important!

Thanks!

Backup

Coy Pseudoscalars at the LHC

Some details:

- Implemented model in Feynrules, generated events at LO in MadGraph5+aMC@NLO. Showered in Pythia 6.4, detector simulation in Delphes 3.0
- Exclusive *bba* events generated in 4 flavor scheme (required p_T>5 GeV to avoid double counting). To avoid large logarithms, used 5 Flavor Scheme for semi-inclusive *ba* events with dynamic renormalization scale
- Cross-check production cross-section with MCFM. Factor of <1.5 difference from LO to NLO
- Used default CMS tagging efficiencies as in Delphes 3.0

Coy Pseudoscalars at the LHC

-Two main issues: **trigger** and **backgrounds**

Primary triggers (motivated by CMS)

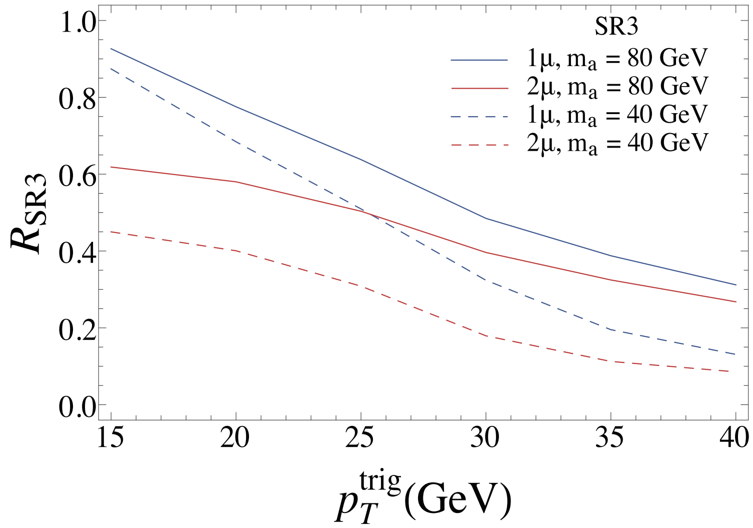
- $1e$: single electron with $p_T > 35$ GeV;
- 1μ: single muon with $p_T > 25$ GeV;
- 2μ: di-muon leading with $p_T > 17$ GeV, subleading $p_T > 10$ GeV;
- $e\tau_h$: electron + hadronic tau with $p_T^\tau > 45$ GeV, $p_T^e > 19$ GeV;
- $\mu\tau_h$: muon + hadronic tau with $p_T^\tau > 40$ GeV, $p_T^e > 15$ GeV;
- $e\mu$: leading electron + muon with $p_T^e > 23$ GeV, $p_T^\mu > 10$ GeV;
- μe: electron + leading muon with $p_T^e > 12$ GeV, $p_T^\mu > 23$ GeV;

Coy Pseudoscalars at the LHC

-Low acceptance for light mediators.

SRx	m_a (GeV)	$1e$	1μ	2μ	$e+\mu$	$\mu+e$	all
SR1	20	0.03	0.12	0.00	0.16	0.13	0.30
	40	0.05	0.21	0.00	0.22	0.15	0.39
	60	0.06	0.21	0.00	0.25	0.23	0.44
	80	0.14	0.31	0.00	0.36	0.33	0.59
SR2	20	0.01	0.06	0.00	0.00	0.00	0.07
	40	0.03	0.10	0.00	0.00	0.00	0.13
	60	0.05	0.12	0.00	0.00	0.00	0.17
	80	0.06	0.15	0.00	0.00	0.00	0.21
SR3	20	0.00	0.41	0.75	0.00	0.00	0.75
	40	0.00	0.51	0.78	0.00	0.00	0.78
	60	0.00	0.55	0.86	0.00	0.00	0.86
	80	0.00	0.64	0.86	0.00	0.00	0.86

$$R^{\mathrm{T_y}}_{SRx} = \frac{\sigma^{T_y}_{SRx}}{\sigma^{gen}_{SRx}}$$



Changing the thresholds can have significant effect on efficiencies.

Coy Pseudoscalars at the LHC

-Two main issues: **trigger** and **backgrounds**

Primary irreducible backgrounds: $t\bar{t}$ and inclusive γ^*/Z production

- $pp \to \gamma^*/Z + b\bar{b} + (0,1)j,\ \gamma^*/Z \to \ell^+\ell^-;$
- $pp \to \gamma^*/Z + b(\bar{b}) + (0,1,2)j,\ \gamma^*/Z \to \ell^+\ell^-;$
- $pp \to \gamma^*/Z + (0,1,2,3)j,\ \gamma^*/Z \to \ell^+\ell^-;$
- $pp \to W^\pm + b\bar{b} + (0,1)j,\ W^\pm \to \ell^\pm\nu_\ell(\bar{\nu}_\ell);$
- $pp \to W^\pm + b(\bar{b}) + (0,1,2)j,\ W^\pm \to \ell^\pm\nu_\ell(\bar{\nu}_\ell);$
- $pp \to W^\pm + (0,1,2,3)j,\ W^\pm \to \ell^\pm\nu_\ell(\bar{\nu}_\ell);$
- $pp \to W^+W^- + b\bar{b} + (0,1)j,\ W^+ \to \ell^+\nu_\ell,\ W^- \to \ell'^-\bar{\nu}_{\ell'};$
- $pp \to W^+W^- + b(\bar{b}) + (0,1,2)j,\ W^+ \to \ell^+\nu_\ell,\ W^- \to \ell'^-\bar{\nu}_{\ell'};$
- $pp \to W^+W^- + (0,1,2,3)j,\ W^+ \to \ell^+\nu_\ell,\ W^- \to \ell'^-\bar{\nu}_{\ell'};$
- $pp \to ZW^\pm + b\bar{b} + (0,1)j,\ W^\pm \to \ell^\pm\nu_\ell(\bar{\nu}_\ell),\ Z \to \ell'^+\ell'^-;$
- $pp \to ZW^\pm + b(\bar{b}) + (0,1,2)j,\ W^\pm \to \ell^\pm\nu_\ell(\bar{\nu}_\ell),\ Z \to \ell'^+\ell'^-;$
- $pp \to ZW^\pm + (0,1,2,3)j,\ W^\pm \to \ell^\pm\nu_\ell(\bar{\nu}_\ell),\ Z \to \ell'^+\ell'^-;$

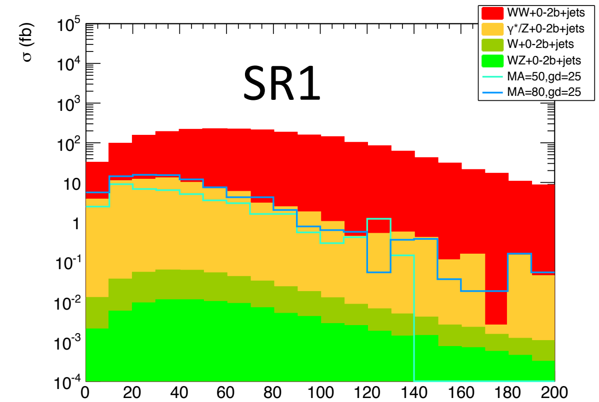
Coy Pseudoscalars at the LHC

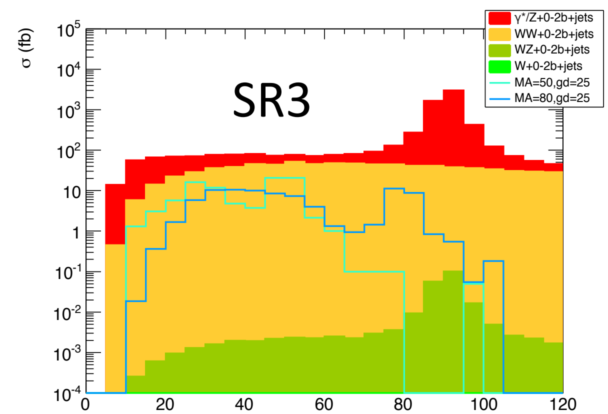
-Cut to reduce backgrounds

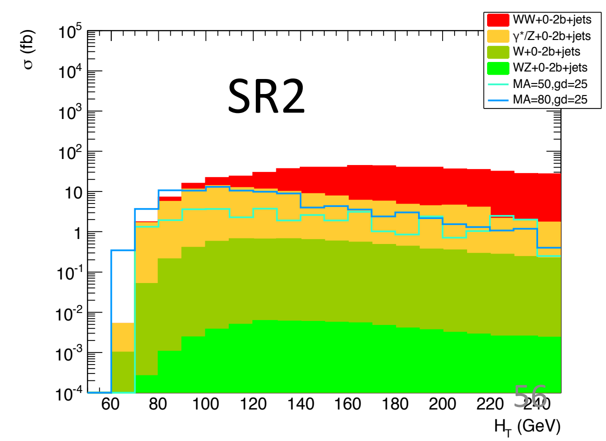
$t\bar{t}$ background reduced by MET and transverse mass cut

Backgrounds with Z resonance reduced by cut on dilepton invariant mass

Cut on scalar sum of p_T







Coy Pseudoscalars at the LHC

-Two scenarios: thresholds determined by maximizing

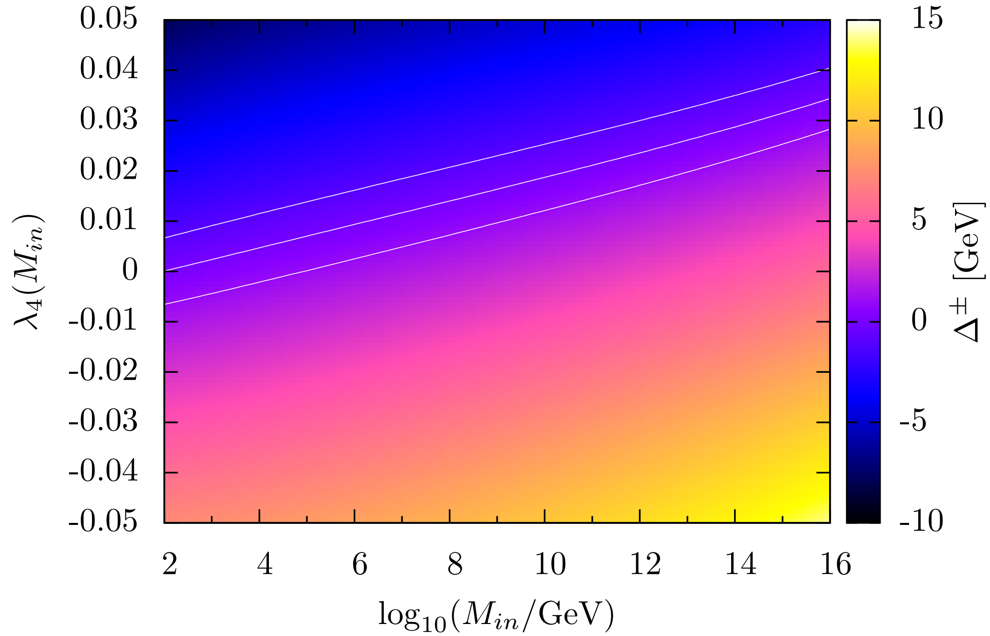
$$\sigma_{sig} * L / \sqrt{\sigma_{sig} * L + \sigma_{bkg} * L + \epsilon^2_{sys} \sigma^2_{bkg} * L^2}$$

while maintaining $\sigma^{\rm cut}_{\rm sig}/\sigma^{\rm tot}_{\rm sig} \gtrsim 0.5$ ("hard cuts")
or $\sigma^{\rm cut}_{\rm sig}/\sigma^{\rm tot}_{\rm sig} \gtrsim 0.8$ ("soft cuts") for $m_a > 40$ GeV

- SR1 hard: leading $p_T^\ell < 30$ GeV, $12 < m_{\ell\ell} < 35$ GeV, $H_T < 90$ GeV, $\not{H}_T^\ell < 80$ GeV.
- SR1 soft: leading $p_T^\ell < 40$ GeV, $12 < m_{\ell\ell} < 45$ GeV, $H_T < 140$ GeV, $m_T < 40$ GeV, $\not{H}_T^\ell < 120$ GeV.
- SR2 hard: leading $p_T^\ell < 40$ GeV, $12 < m_{\ell\ell} < 45$ GeV, $H_T < 130$ GeV, $\not{H}_T^\ell < 100$ GeV.
- SR2 soft: $12 < m_{\ell\ell} < 60$ GeV, $H_T < 190$ GeV, $m_T < 45$ GeV, $\not{H}_T^\ell < 140$ GeV.
- SR3: leading $p_T^\ell < 50$ GeV, $H_T < 120$ GeV, $\not{H}_T^\ell < 120$ GeV.

Mass Splittings in the Compressed IDM

Charged mass splitting typically ~10 GeV, while neutral splitting can be arbitrarily small



$$
\begin{aligned}
(4\pi)^2\frac{d\lambda_4}{dt} &= -3\lambda_4(3g^2+g'^2)+4\lambda_4(\lambda_1+\lambda_2+2\lambda_3+\lambda_4)+2\lambda_4(3y_t^2+3y_b^2+y_\tau^2) \\
&\quad + 3g^2g'^2 \;+\; 8\lambda_5^2 \\
(4\pi)^2\frac{d\lambda_5}{dt} &= -3\lambda_5(3g^2+g'^2)+4\lambda_5(\lambda_1+\lambda_2+2\lambda_3+3\lambda_4)+2\lambda_5(3y_t^2+3y_b^2+y_\tau^2)
\end{aligned}
$$

14 TeV LHC Mono-jet Search

Requirements:

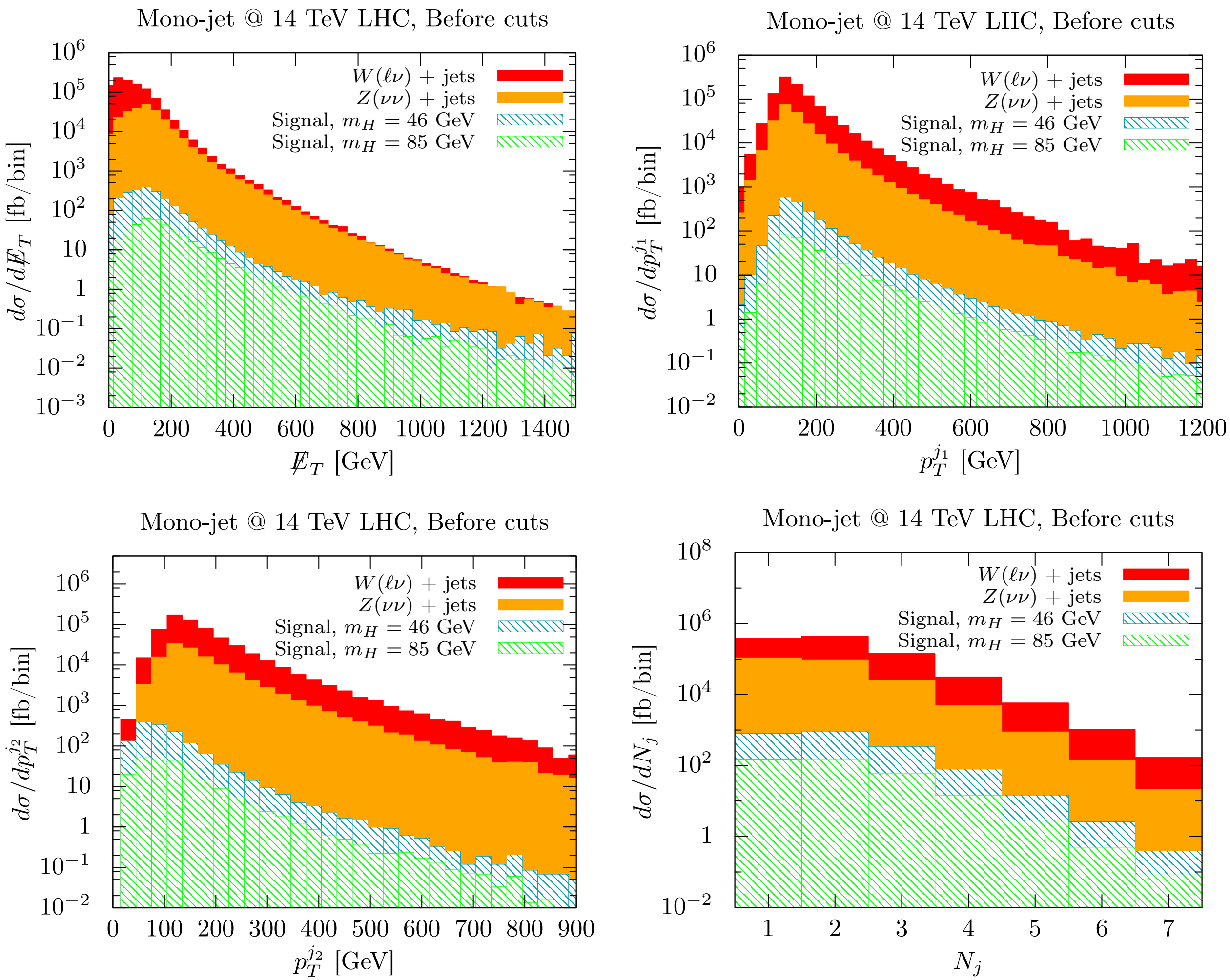
$$p_T^{j_1} > 300\,\text{GeV},\ \ |\eta_{j_1}| < 2.0,\ \ \not{E}_T > 1\,\text{TeV},$$
$$\Delta\phi(j_{1,2}, \not{E}_T) > 0.5,\ \ p_T^{j_2} < 100\,\text{GeV},\ N_j \leq 2$$

- Veto on e with $p_T(e) > 7$ GeV, $|\eta(e)| < 2.5$
- Veto on μ with $p_T(\mu) > 7$ GeV, $|\eta(\mu)| < 2.47$
- Veto on hadronic taus, with $p_T(\tau_h) > 20$ GeV, $|\eta(\tau_h)| < 2.3$

Significance: $$\frac{S}{\delta B} \equiv \frac{S}{\sqrt{B + \epsilon_{\text{bkg}}^2 B^2 + \epsilon_{\text{sig}}^2 S^2}}$$

14 TeV LHC Mono-jet Search

Largest backgrounds are Z (vv) + jets and W (lv) + jets



100 TeV Collider Mono-jet Search

Requirements:

$$p_T^{j_1} > 1.2\,\mathrm{TeV},\ \ |\eta_{j_1}| < 2.0,\ \ \not{E}_T > 5\,\mathrm{TeV},$$
$$\Delta\phi(j_{1,2}, \not{E}_T) > 0.5,\ \ N_j \leq 2$$

- Veto on e with $p_T(e) > 20$ GeV, $|\eta(e)| < 2.5$
- Veto on μ with $p_T(\mu) > 20$ GeV, $|\eta(\mu)| < 2.1$
- Veto on hadronic taus, with $p_T(\tau_h) > 40$ GeV, $|\eta(\tau_h)| < 2.3$

Significance: $$\frac{S}{\delta B} \equiv \frac{S}{\sqrt{B + \epsilon_{\mathrm{bkg}}^2 B^2 + \epsilon_{\mathrm{sig}}^2 S^2}}$$