Light Dark matter @ LHC

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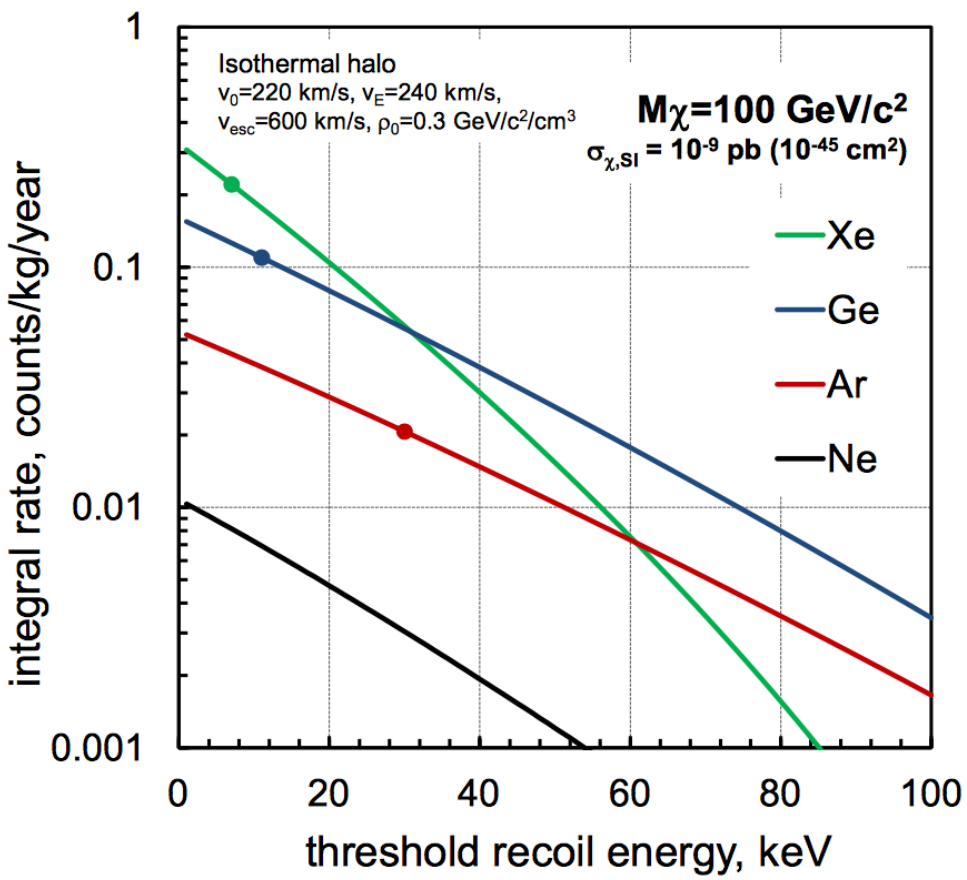
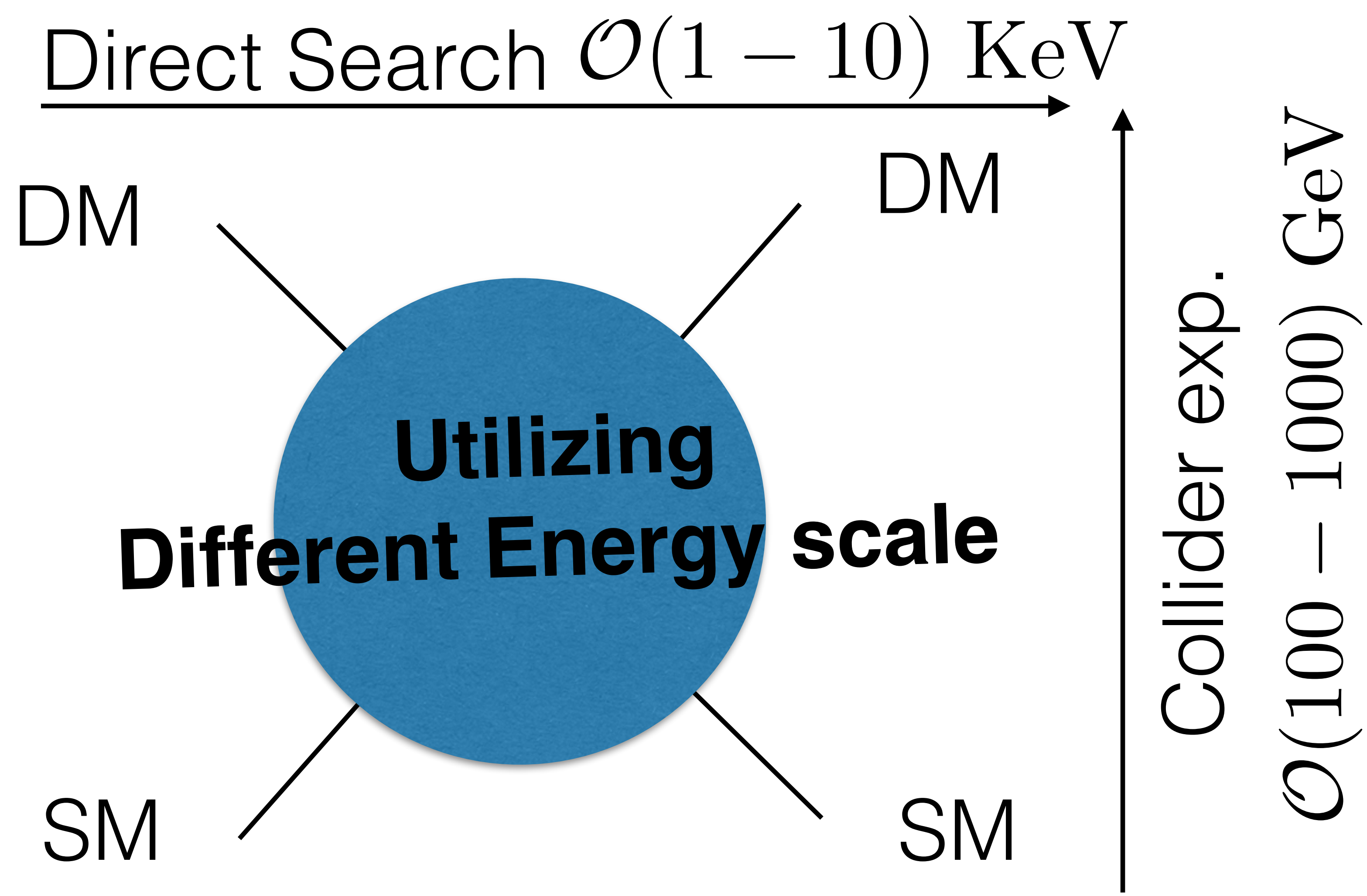
Two orthogonal EXPs

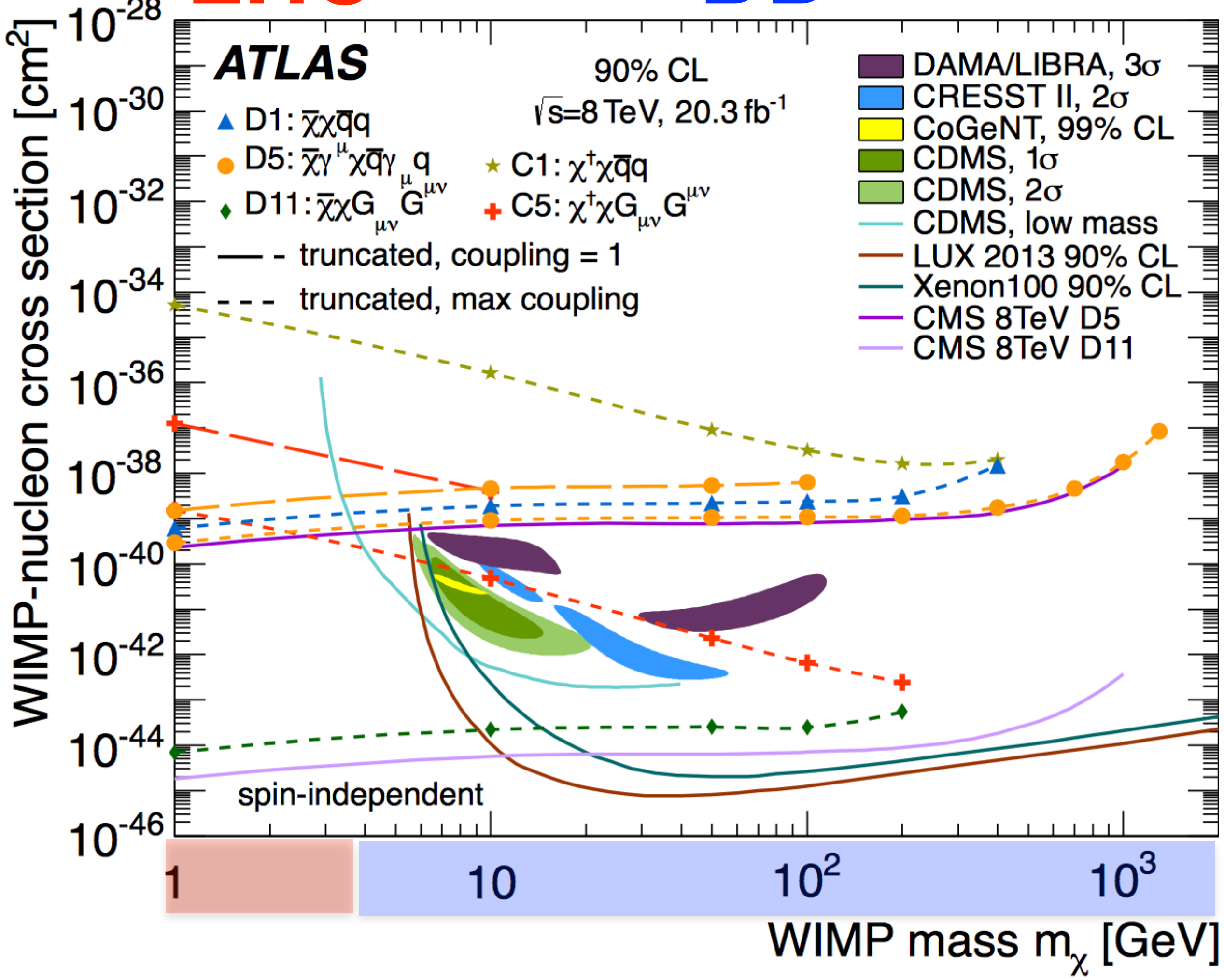


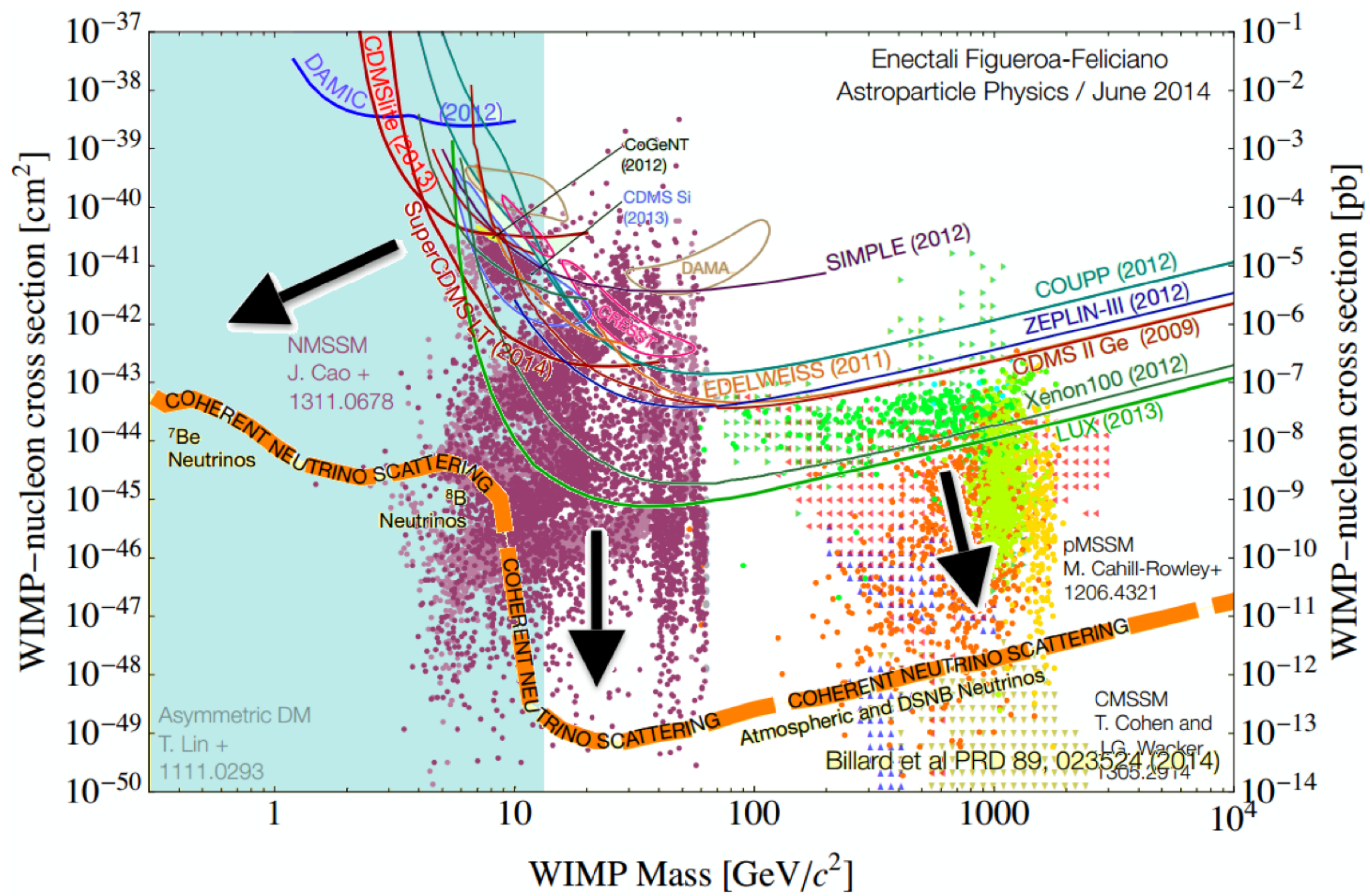
Snowmass summary
1310.8327 P. Cushman et.al



Interplay between DD and LHC

LHC **DD**

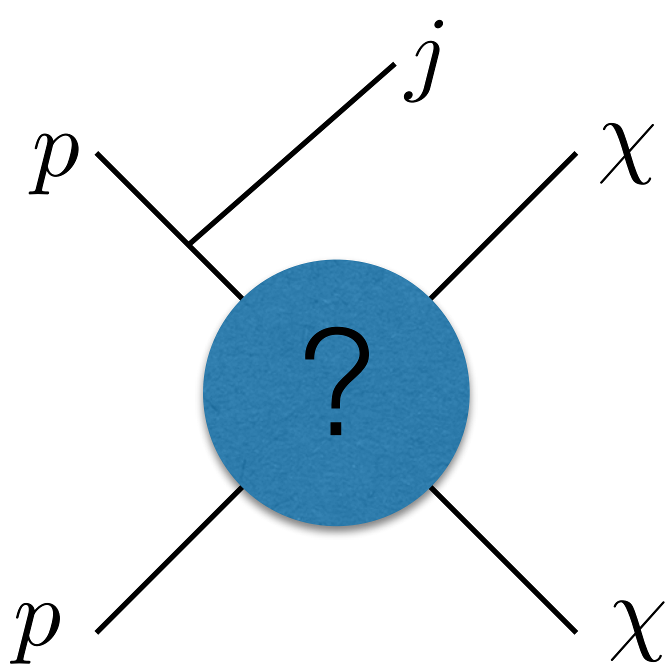




- Different experiments can cover different DM mass scale!

A strategy when we know NOTHING

- Very minimal set-up (search channel) for DM @LHC
  - Jet from Initial State Radiation (ISR) to **tag** Missing Transverse Energy events



Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu} q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta} q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

Name	Operator	Coefficient
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

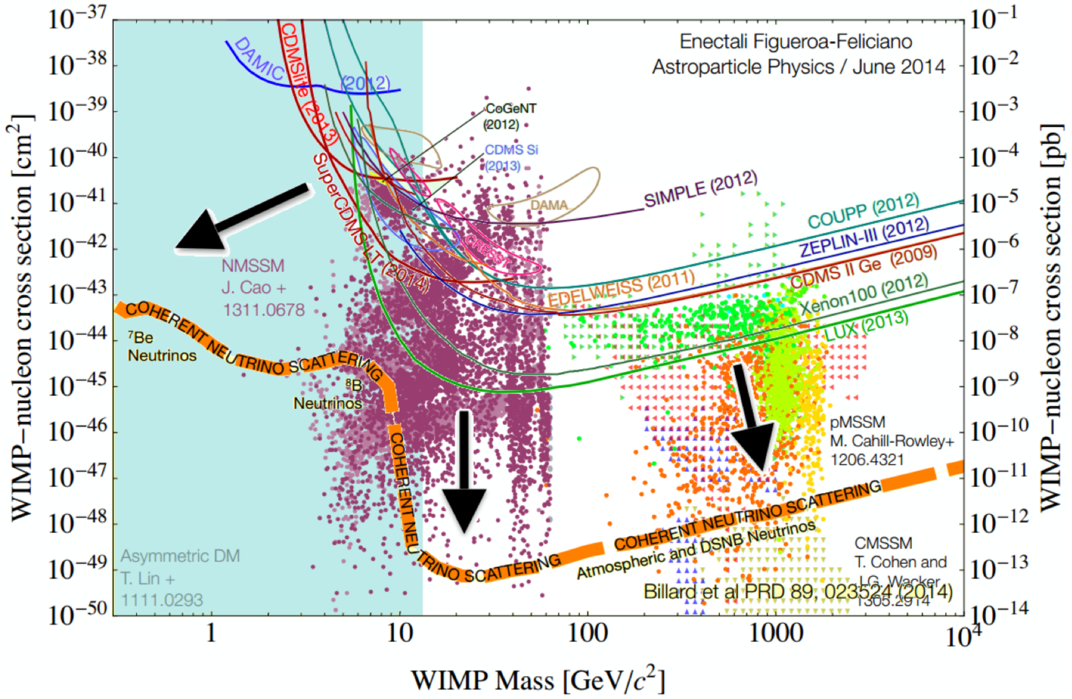
Tim Tait. et.al.
Phys.Rev. D82 (2010) 116010

Additional object for a Light DM

- A very light DM with a mediator around 2 M(dark) can enhance the DM annihilation process via a <u>resonance-enhancement</u>

- We can capture the light mediator @ LHC

Next-to-Minimal SUSY



- Light Dark Matter with a light mediator
- Light Dark Matter, charged under dark gauge

A light DM in NMSSM

- Resolving mu-problem through the “Yukawa” interaction with S

$$W_{\rm NMSSM} = \text{MSSM Yukawa terms} + \lambda \widehat{S} \widehat{H}_u \widehat{H}_d + \frac{\kappa}{3} \widehat{S}^3$$

can lead interesting phenomena for DM

$$\mu_{\rm eff} \equiv \lambda s \ll \min[M_1, M_2]$$

MSSM + S

$$\mathcal{M}_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -m_W \tan\theta_W \cos\beta & m_W \tan\theta_W \sin\beta & 0 \\ 0 & M_2 & m_W \cos\beta & -m_W \sin\beta & 0 \\ -m_W \tan\theta_W \cos\beta & m_W \cos\beta & 0 & -\mu_{\rm eff} & -\lambda v_u \\ m_W \tan\theta_W \sin\beta & -m_W \sin\beta & -\mu_{\rm eff} & 0 & -\lambda v_d \\ 0 & 0 & -\lambda v_u & -\lambda v_d & 2\kappa s \end{pmatrix}$$

$[\mathcal{M}_{\tilde{\chi}_0}]_{55} = 2\kappa s = \frac{2\,\kappa\,\mu_{\rm eff}}{\lambda}$:a DM is singlino-dominated for $2\kappa/\lambda < 1$

A light DM in NMSSM with a light scalar

- From the soft-SUSY breaking term

$$V_{\text{soft}} = m_{H_u}^2|H_u|^2 + m_{H_d}^2|H_d|^2 + m_S^2|S|^2 + \left(\lambda A_\lambda S H_u H_d + \frac{1}{3}\kappa A_\kappa S^3 + \text{h.c.}\right)$$

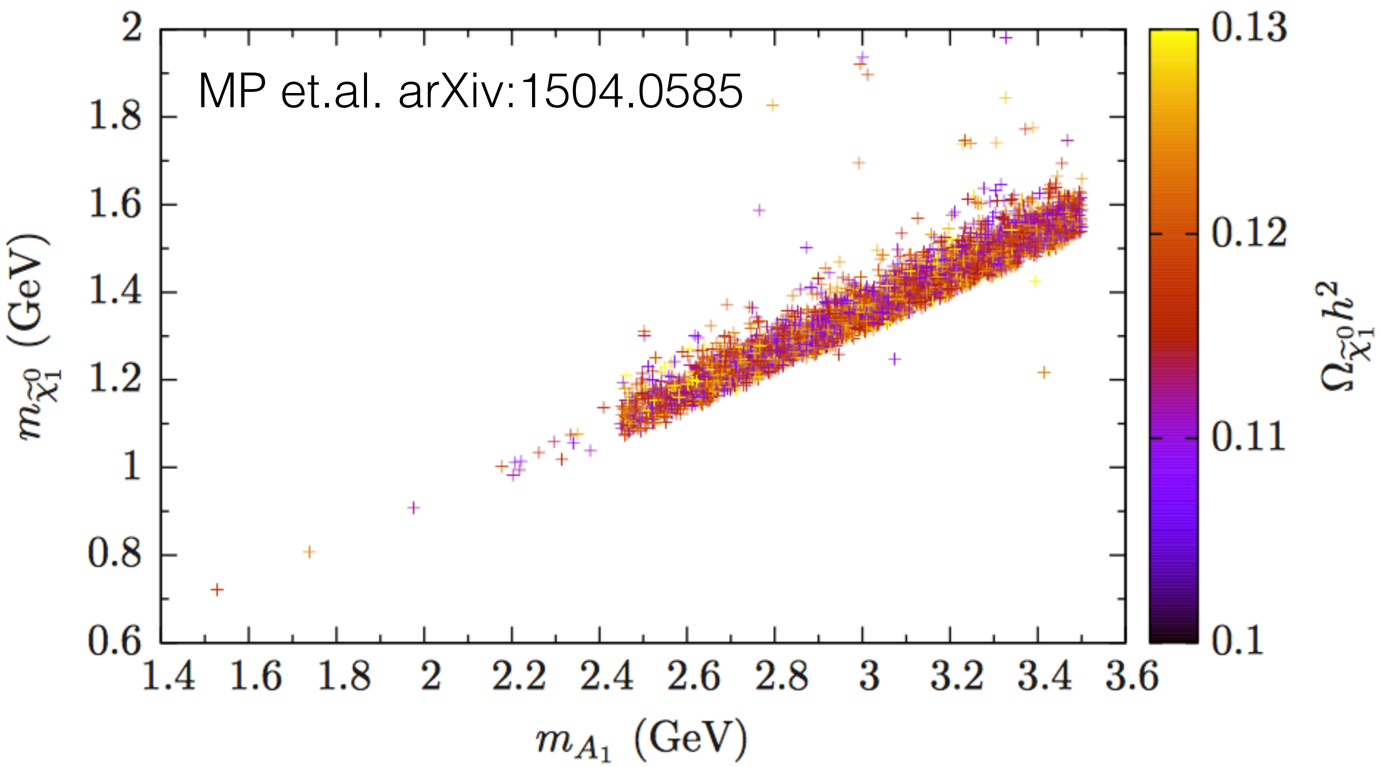
the mass of singlet-like pseudo scalar

$$m_{A_1}^2 \simeq \lambda(A_\lambda + 4\kappa s)\frac{v^2 \sin 2\beta}{2s} - 3\kappa s A_\kappa$$

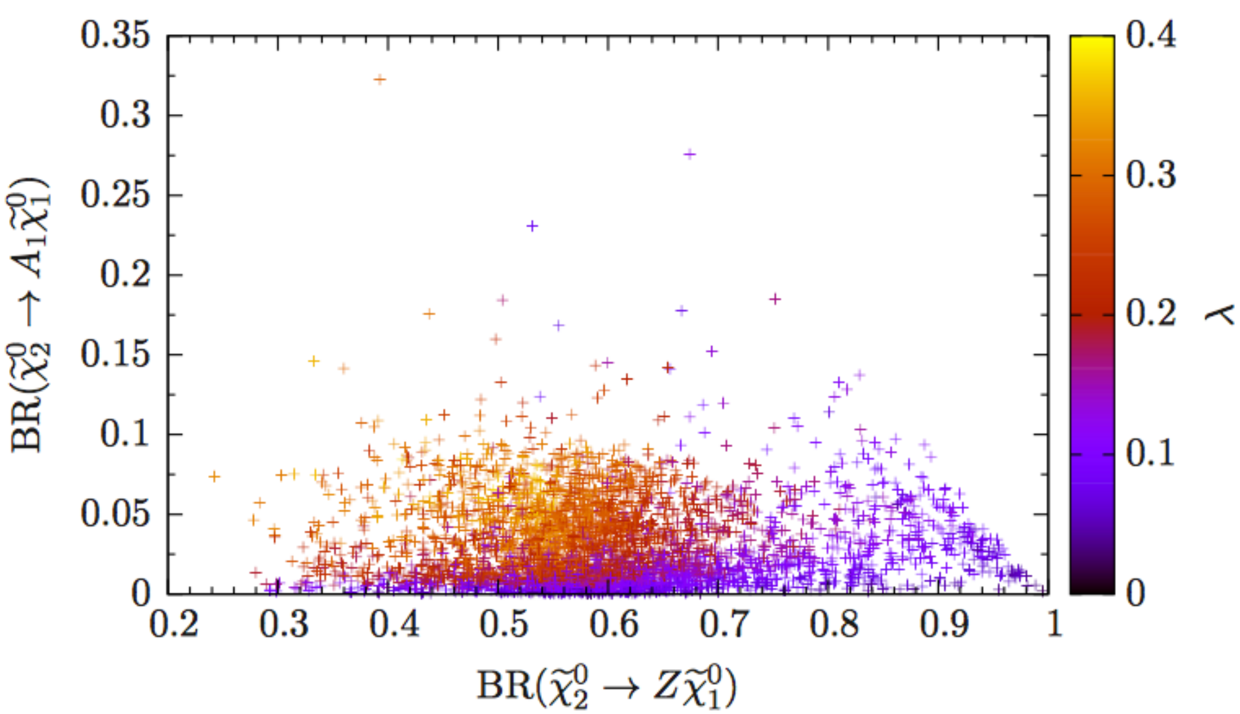
Singlino-dominated LSP (DM) [Small κ]

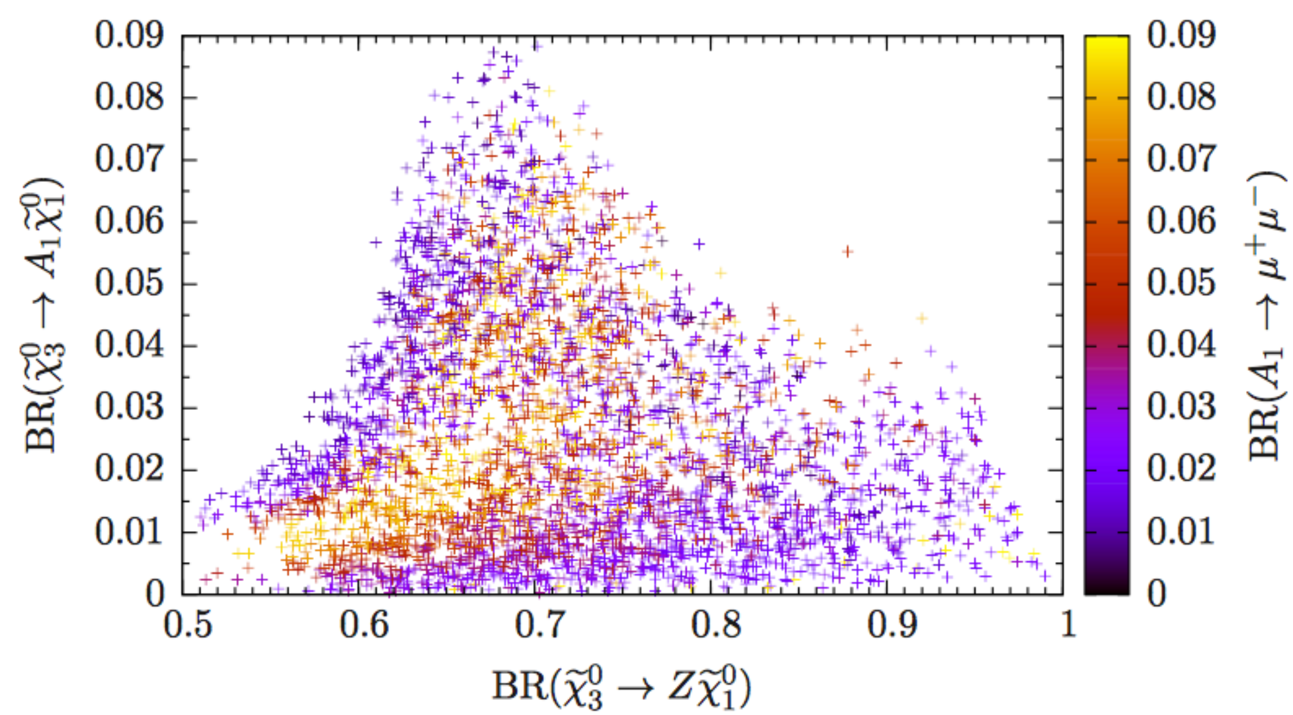
can be naturally accompanied by a light pseudo scalar

- DM relic via a resonance A_1 channel



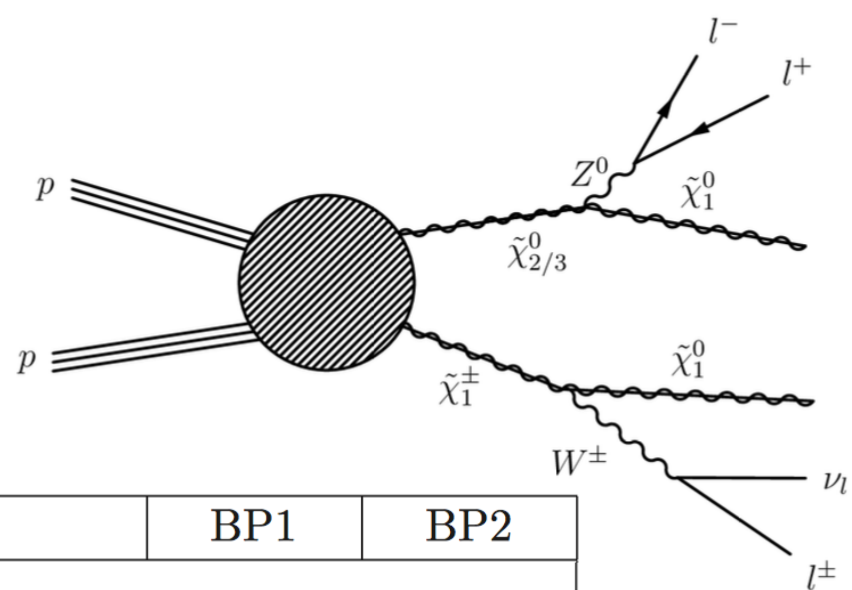
- Small μ_{eff} makes the 2nd and 3rd Neutralino -> higgino-like

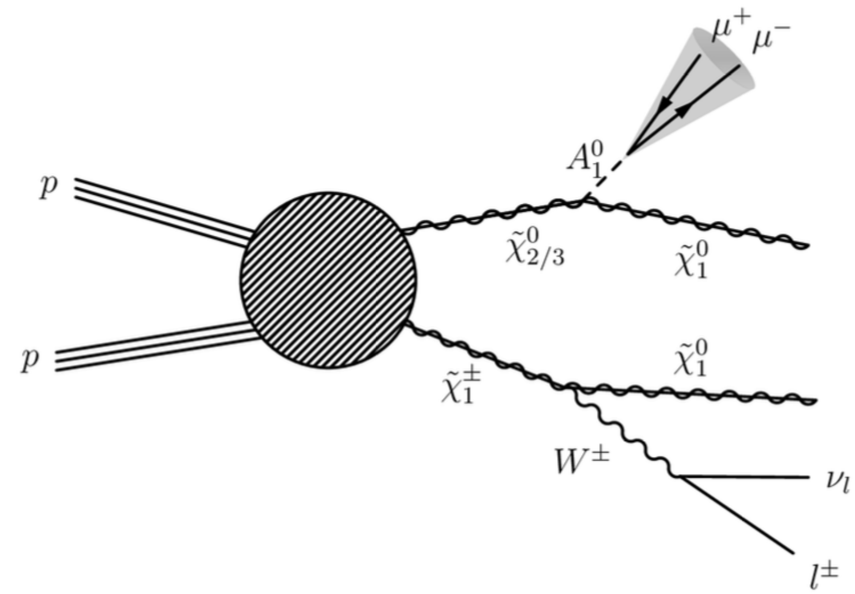




The chance of the LHC

- Conventional search (three leptons) v.s. Muon-jet





	BP1	BP2
Masses		
$m_{\tilde{\chi}_1^0}$ (GeV)	1.0025	1.4081
$m_{\tilde{\chi}_2^0}$ (GeV)	189.09	170.13
$m_{\tilde{\chi}_3^0}$ (GeV)	−201.67	−182.27
$m_{\tilde{\chi}_1^\pm}$ (GeV)	194.97	167.72
m_{A_1} (GeV)	2.1776	2.9856
m_{H_2} (GeV)	124.12	125.79
Branching Ratios		
$BR(\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0)$	0.634	0.603
$BR(\tilde{\chi}_2^0 \to A_1\tilde{\chi}_1^0)$	0.004	0.089
$BR(\tilde{\chi}_3^0 \to Z\tilde{\chi}_1^0)$	0.736	0.704
$BR(\tilde{\chi}_3^0 \to A_1\tilde{\chi}_1^0)$	0.004	0.081
$BR(A_1 \to \mu^+\mu^-)$	0.039	0.087

14TeV LHC for $\mathcal{L} = 300\text{fb}^{-1}$

Point	S/B in analysis		$\mathcal{Z}$ (σ) in analysis	
	3ℓ (SRZc region)	μ_{col}	3ℓ (SRZc region)	μ_{col}
BP1	0.591	0.42	2.7	1.2
BP2	0.436	15	2.0	27

MP et.al. arXiv:1504.0585

DM
with dark gauge boson(s)

- A light dark matter, accompanied by a dark gauge boson;
  - has a self-interaction under a hidden gauge
  - acquires milli-charge under the SM gauge bosons
  (e.g. by kinetic mixing $\epsilon F_{\mu\nu}^{(\mathrm{SM})} F^{\mu\nu}_{\mathrm{Dark}}$)

$$\mathcal{L} \ni \bar{\chi}\left(i\partial\!\!\!/ - m_\chi + ig' A\!\!\!/'\right)\chi - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu - \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu}$$

- What's the mechanism behind the mass of DM and Dark Gauge field?

DM, dark gauge boson and a Dark Higgs

A'_μ	Φ	χ_L	χ_R	ψ_L	ψ_R
	Q'_Φ	Q'_{χ_L}	Q'_{χ_R}	Q'_{ψ_L}	Q'_{ψ_R}

$$Q'_\Phi = Q'_{\chi_R} - Q'_{\chi_L} = -(Q'_{\Psi_R} - Q'_{\Psi_L})$$

$$\mathcal{L}_{\rm vector+scalar} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{\varepsilon}{2}F_{\mu\nu}F'^{\mu\nu} + |D_\mu\Phi|^2$$

$$\begin{aligned}\mathcal{L}_{\rm matter} &= \bar\chi_L i\gamma^\mu D_\mu\chi_L + \bar\chi_R i\gamma^\mu D_\mu\chi_R + \bar\psi_L i\gamma^\mu D_\mu\psi_L \\ &+ \bar\psi_R i\gamma^\mu D_\mu\psi_R - y_\chi\bar\chi_L\Phi^*\chi_R - y_\chi\bar\chi_R\Phi\chi_L \\ &- y_\psi\bar\psi_L\Phi\psi_R - y_\psi\bar\psi_R\Phi^*\psi_L\end{aligned}$$

DM, dark gauge boson and a Dark Higgs

A'_μ	Φ	χ_L	χ_R	ψ_L	ψ_R
	Q'_Φ	Q'_{χ_L}	Q'_{χ_R}	Q'_{ψ_L}	Q'_{ψ_R}

$$\mathcal{L} \ni -g_\chi Q'_V A'_\mu \bar{\chi}\gamma^\mu \chi - g_\chi Q'_A A'_\mu \bar{\chi}\gamma^\mu \chi$$

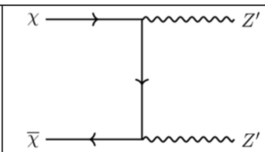
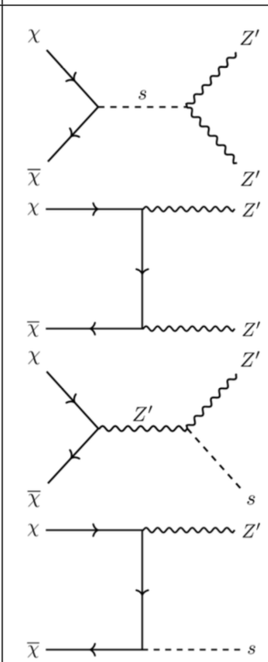
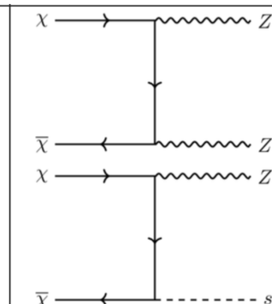
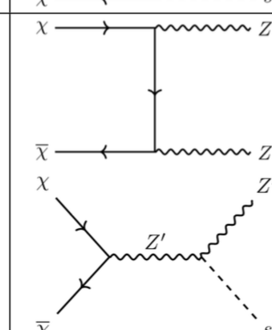
$$Q'_A = \frac{1}{2}(Q'_{\chi_R} - Q'_{\chi_L}) = \frac{Q'_\Phi}{2}$$

$$Q'_V = \frac{1}{2}(Q'_{\chi_R} + Q'_{\chi_L}) = \frac{Q'_\Phi}{2} + Q'_{\chi_L}$$

- Thus we always have the axial coupling between DM and a Dark photon

The origin of the mass of a DM and a dark photon

- One may ask the phenomenology according to the mass mechanism behind them (dark matter and dark photon).

I	Bare mass term	Stueckelberg mechanism	Vector		Z'_T
II	Yukawa coupling to Dark Higgs	Dark Higgs mechanism	Vector & axial-vector or pure axial-vector. The $U(1)$ charge assignments of χ_L and χ_R determine the relative size of the V and A couplings. **The axial-vector coupling must be non-zero.**		Z'_T & Z'_L
III	Yukawa coupling to Dark Higgs	Stueckelberg mechanism	Vector		Z'_T
IV	Bare mass term	Dark Higgs mechanism	Vector		Z'_T

Nicole F. Bell et.al. arXiv:1610.03063

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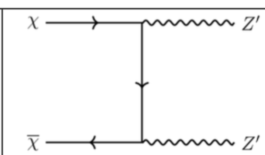
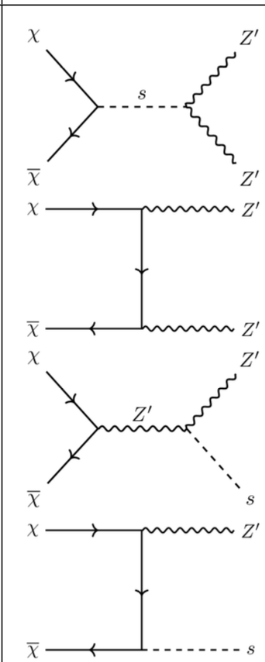
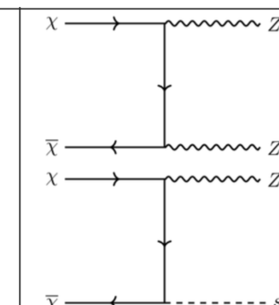
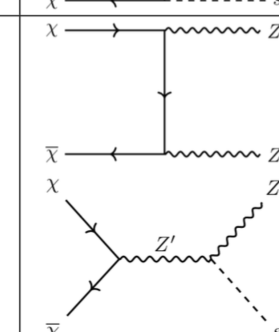
I	Bare mass term	Stueckelberg mechanism	Vector		Z'_T
II	Yukawa coupling to Dark Higgs	Dark Higgs mechanism	Vector & axial-vector or pure axial-vector. The $U(1)$ charge assignments of χ_L and χ_R determine the relative size of the V and A couplings. **The axial-vector coupling must be non-zero.**		Z'_T & Z'_L

III	Yukawa coupling to Dark Higgs	Stueckelberg mechanism	Vector		Z'_T
IV	Bare mass term	Dark Higgs mechanism	Vector		Z'_T

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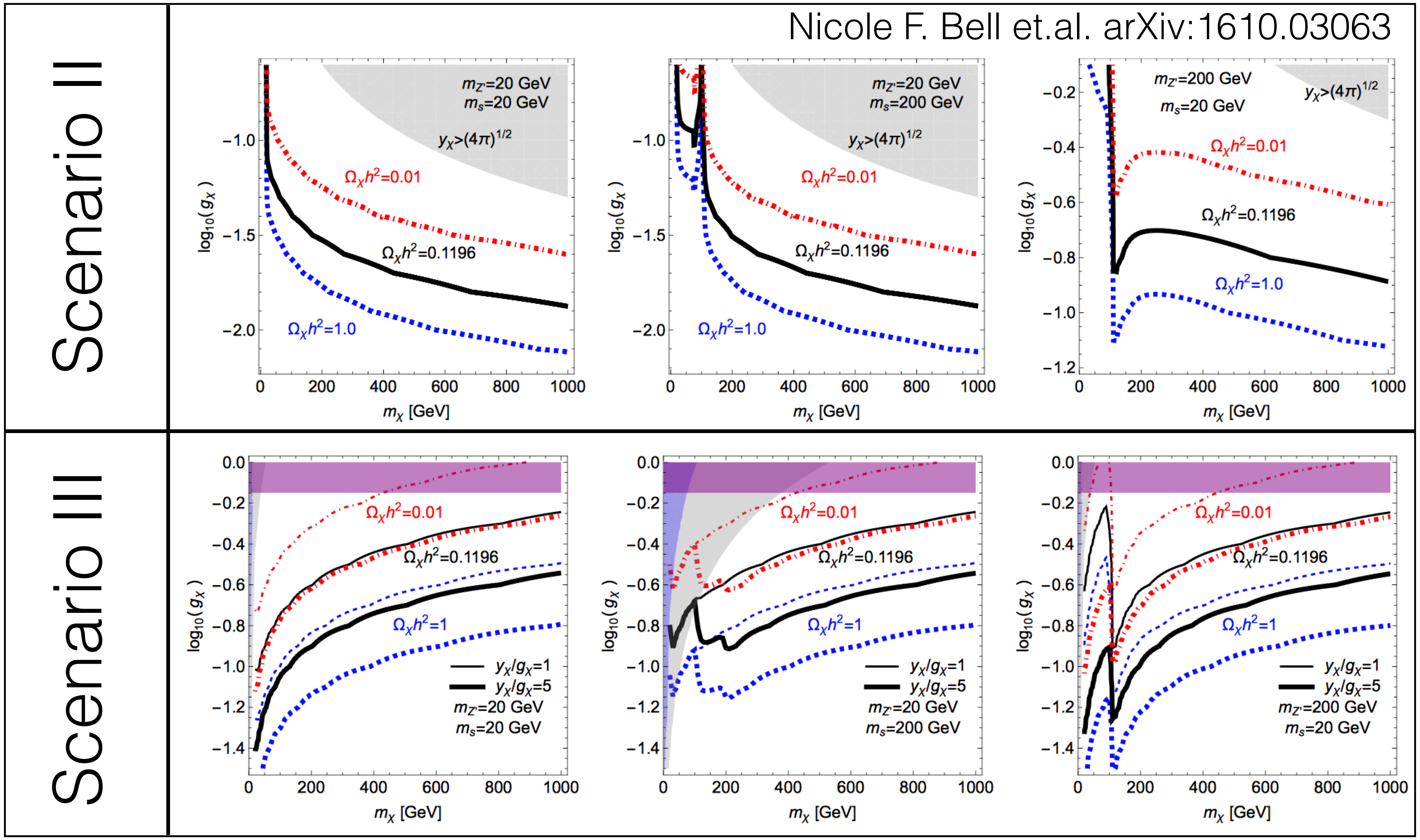
Cosmological aspect

- One may ask the phenomenology according to the mass mechanism behind them (dark matter and dark photon).

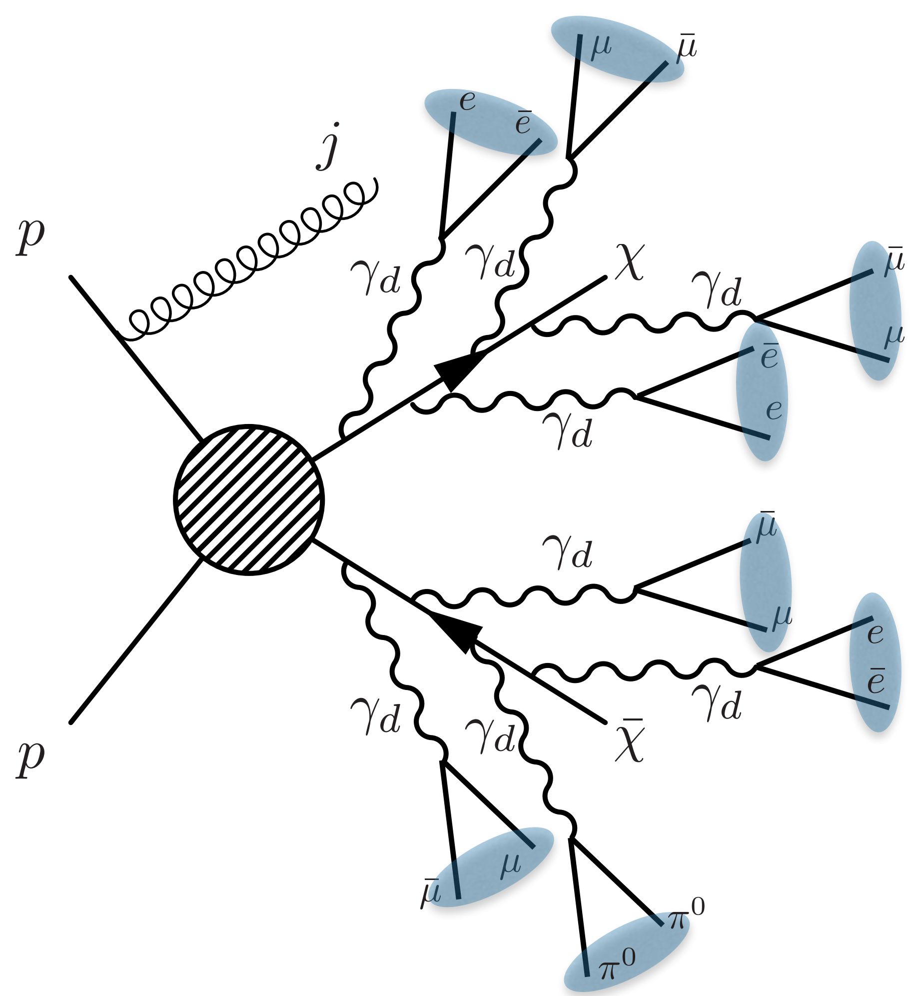


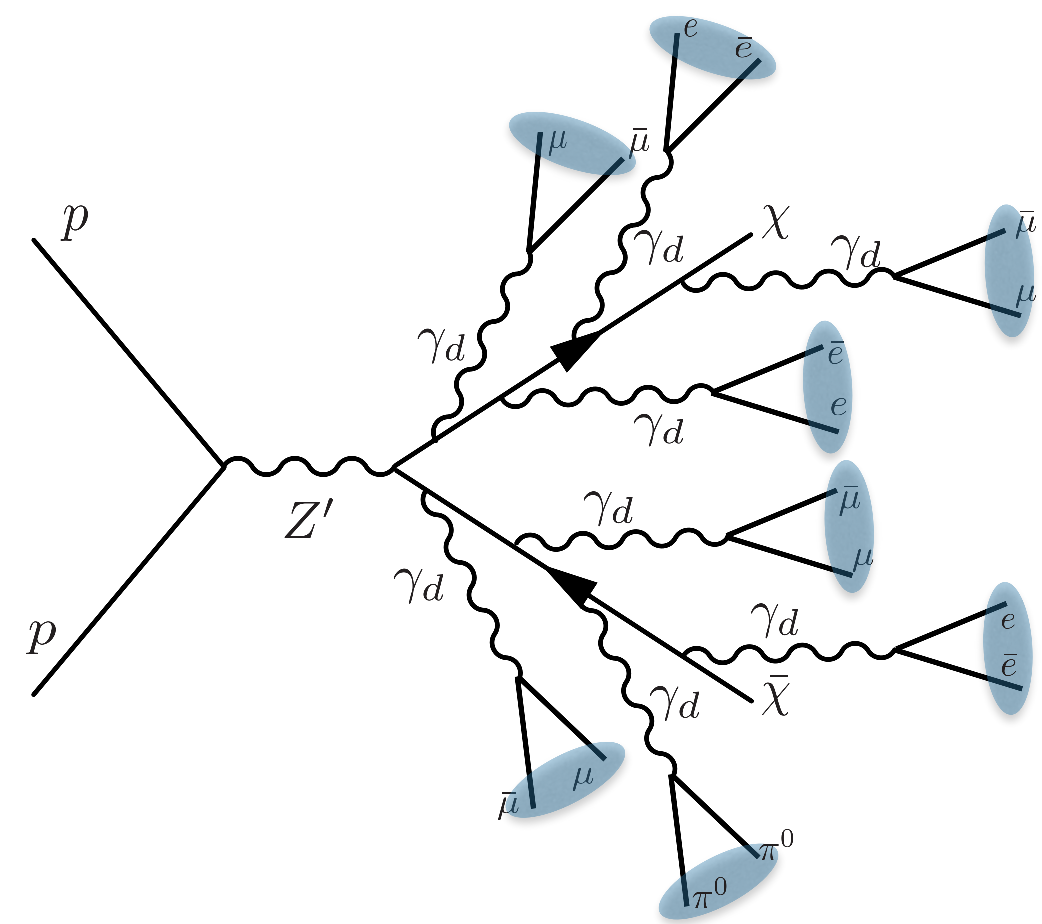
Collider aspect

- "Charged" Dark Matter showers off the dark photons
  -> Dark photons decay back to SM particles: Collider Obs

Mengchao Zhang,[1] Minho Kim,[1,2] Hye-Sung Lee,[1] and Myeonghun Park[1]

arXiv:THIS.WEEK





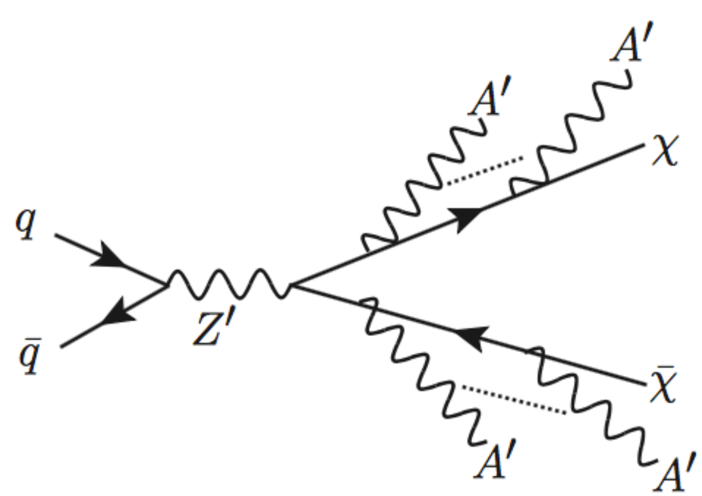
Collider aspect

M. Buschmann et.al arXiv:1505.07459

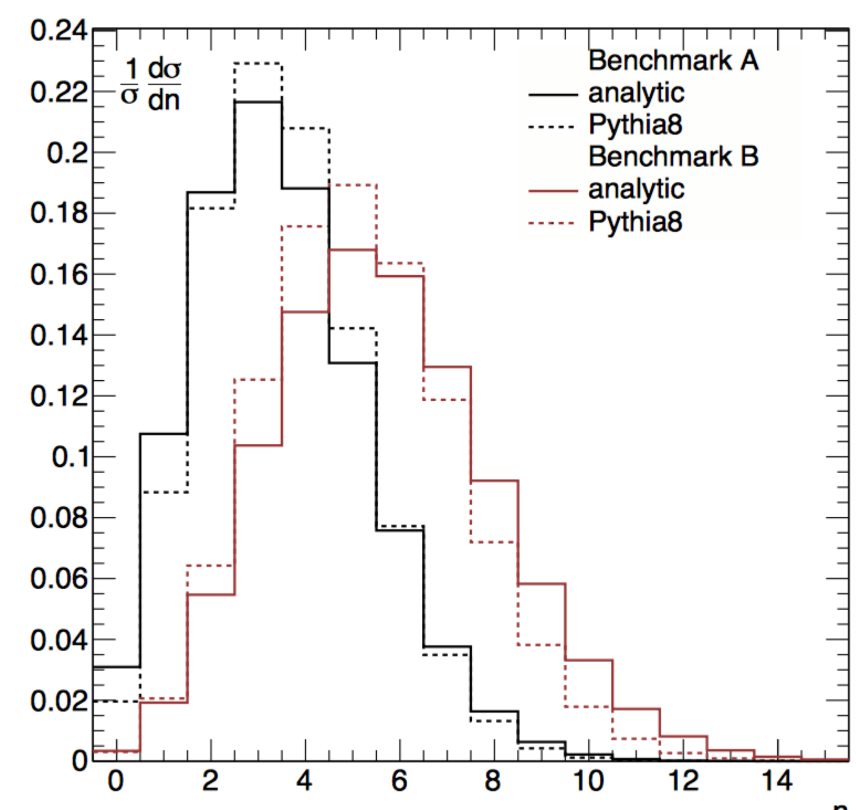
- A light dark matter, accompanied by a dark gauge boson.

$$\mathcal{L}_{\rm dark} \equiv \bar{\chi}(i\partial\!\!\!/ - m_\chi + i g_{A'} A\!\!\!/') \chi - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} - \frac{1}{2} m_{A'}^2 A'_\mu A'^\nu - \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu}$$

- The highly boosted “dark charged” DM will shower dark photons



	$m_{Z'}$ [TeV]	g_q	g_χ	m_χ [GeV]	$m_{A'}$ [GeV]	$\alpha_{A'}$	$c\tau$ [mm]	ϵ [10^{-6}]	$\sigma_7(Z')$ [pb]	$\sigma_8(Z')$ [pb]	$\sigma_{13}(Z')$ [pb]	$\Gamma_{Z'}$ [GeV]	BR($Z' \to \chi\bar{\chi}$)	$2\langle n_{A'}\rangle_8$	$2\langle n_{A'}\rangle_{13}$
A	1	0.1	1	4	1.5	0.2	10	2.8	0.58	0.85	2.7	31.3	84.8%	3.50	3.51
B	1	0.03	0.3	0.4	0.4	0.2	1	24	0.052	0.076	0.244	2.82	84.8%	5.15	5.17



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- The highly boosted "dark cha… will shower dark photons

Vector-like DM

	$m_{Z'}$ [TeV]	g_q	g_χ	m_χ [GeV]	$m_{A'}$ [GeV]	$\alpha_{A'}$	[mm]	ϵ [10^{-6}]	$\sigma_7(Z')$ [pb]	$\sigma_8(Z')$ [pb]	$\sigma_{13}(Z')$ [pb]	$\Gamma_{Z'}$ [GeV]	BR($Z' \to \chi\bar{\chi}$)	$2\langle n_{A'}\rangle_8$	$2\langle n_{A'}\rangle_{13}$
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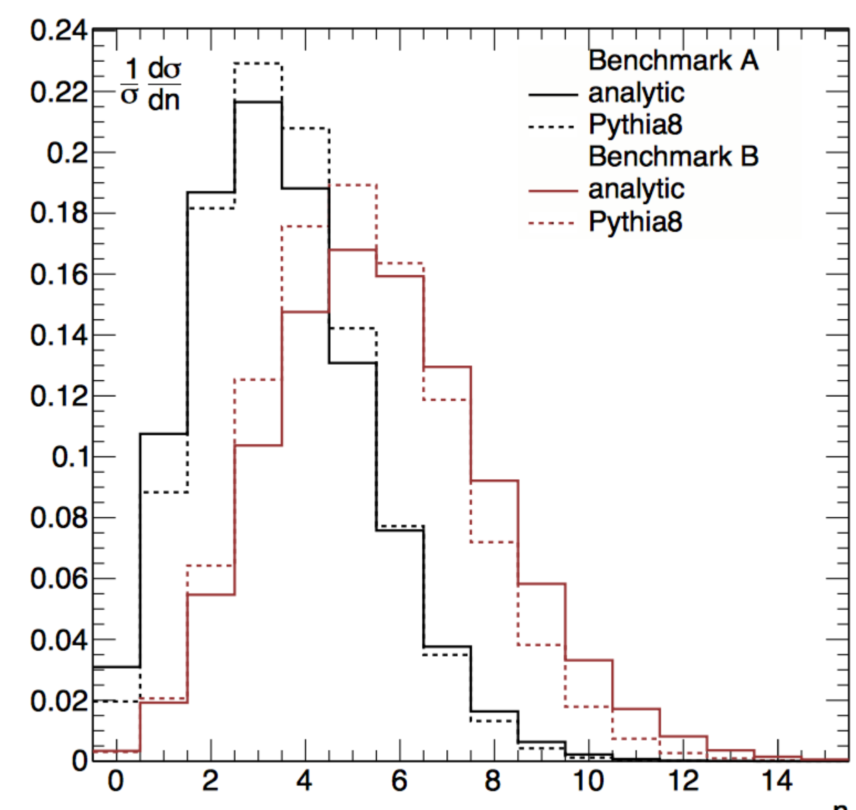
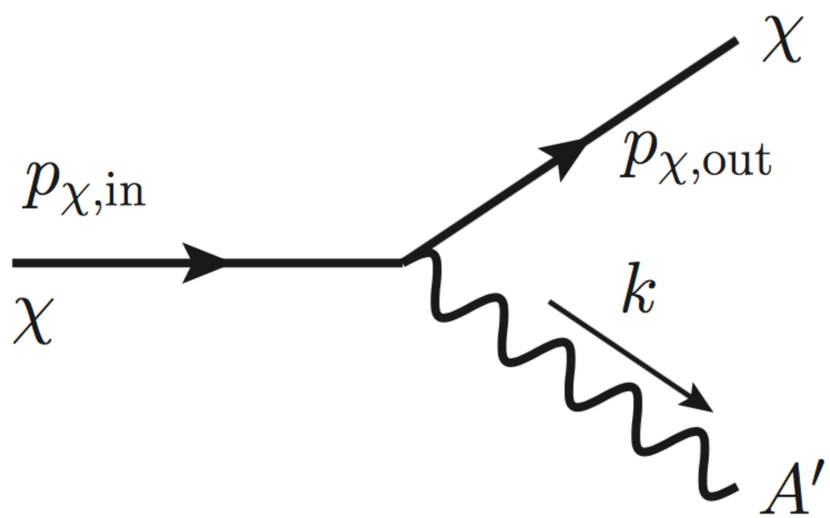


Collider aspect



M. Buschmann et.al arXiv:1505.07459

Splitting function

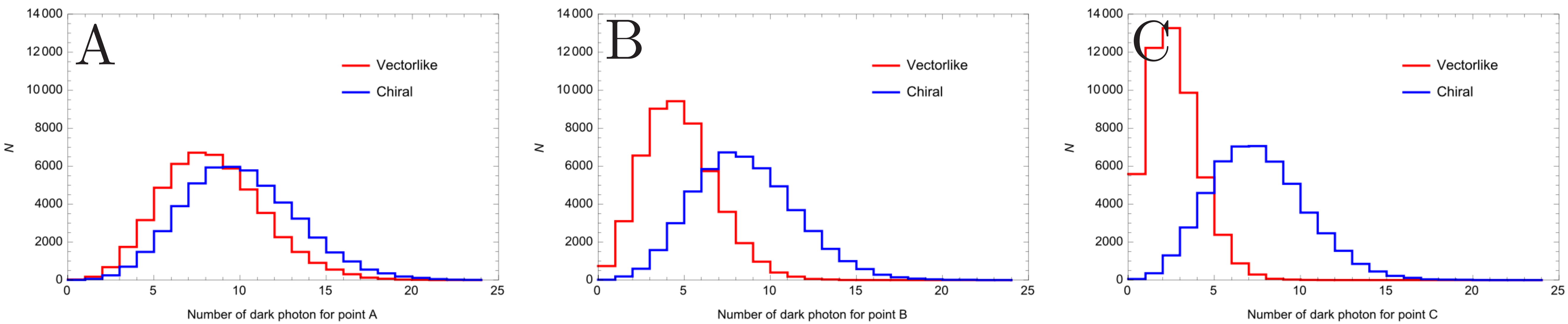
$$P_{\chi\to\chi}(x,t) \simeq \frac{1}{2}\left(Q'^2_{\chi_L} + Q'^2_{\chi_L}\right)\frac{1+x^2}{1-x}$$

- In general case

$$P_{\chi\to\chi}(x,t) \simeq \frac{1}{2}\left(Q'^2_{\chi_L} + Q'^2_{\chi_L}\right)\frac{1+x^2}{1-x} + \frac{1}{2}\left(Q'_{\chi_L} - Q'_{\chi_R}\right)^2\frac{m_\chi^2}{m_{A'}^2}$$

Different showering@LHC

Vector : (Q'L, Q'R) = (1,1)
Chiral: (Q'L, Q'R) = (1,0)



	A	B	C
α'	0.3	0.15	0.075
$m_\chi(GeV)$	0.7	1.0	1.4
$m_{A'}(GeV)$	0.4	0.4	0.4

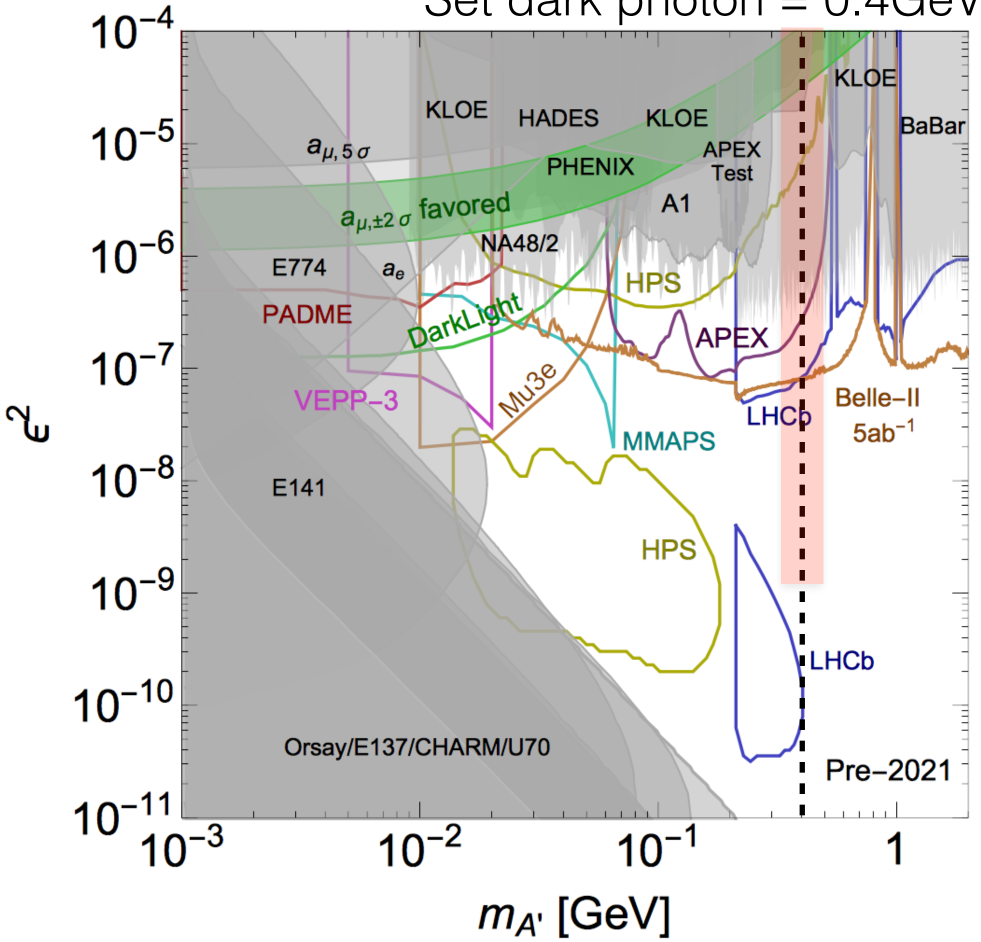
@LHC, we may see the difference among various mechanism behind the mass of dark matter & a dark-photon

Differentiate algorithm @ LHC

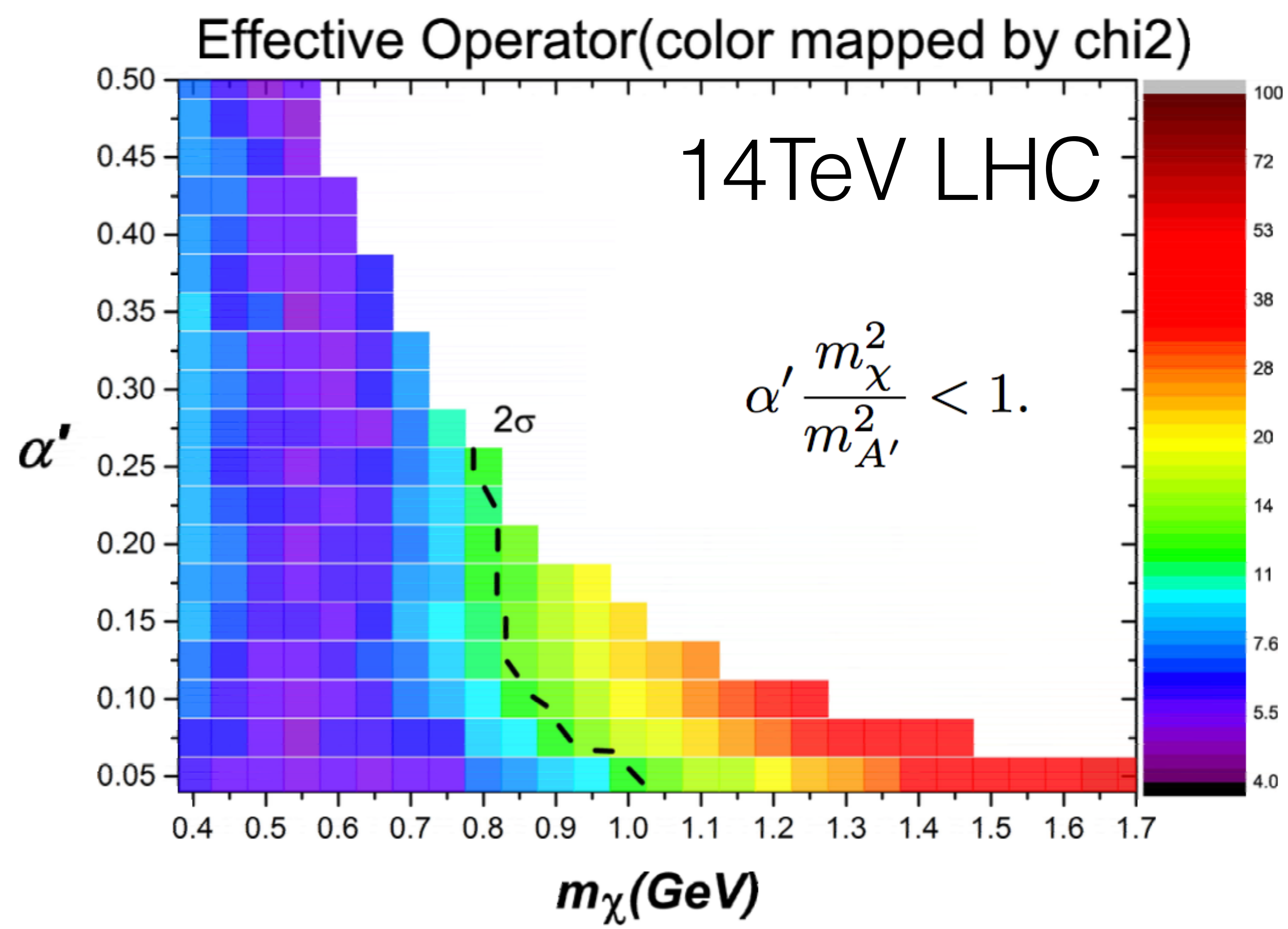
- How one can distinguish two mechanism@LHC

$$H_{T\,lepton} = \sum_{\mu,e} p_{T\,j}.$$

Set dark photon = 0.4GeV



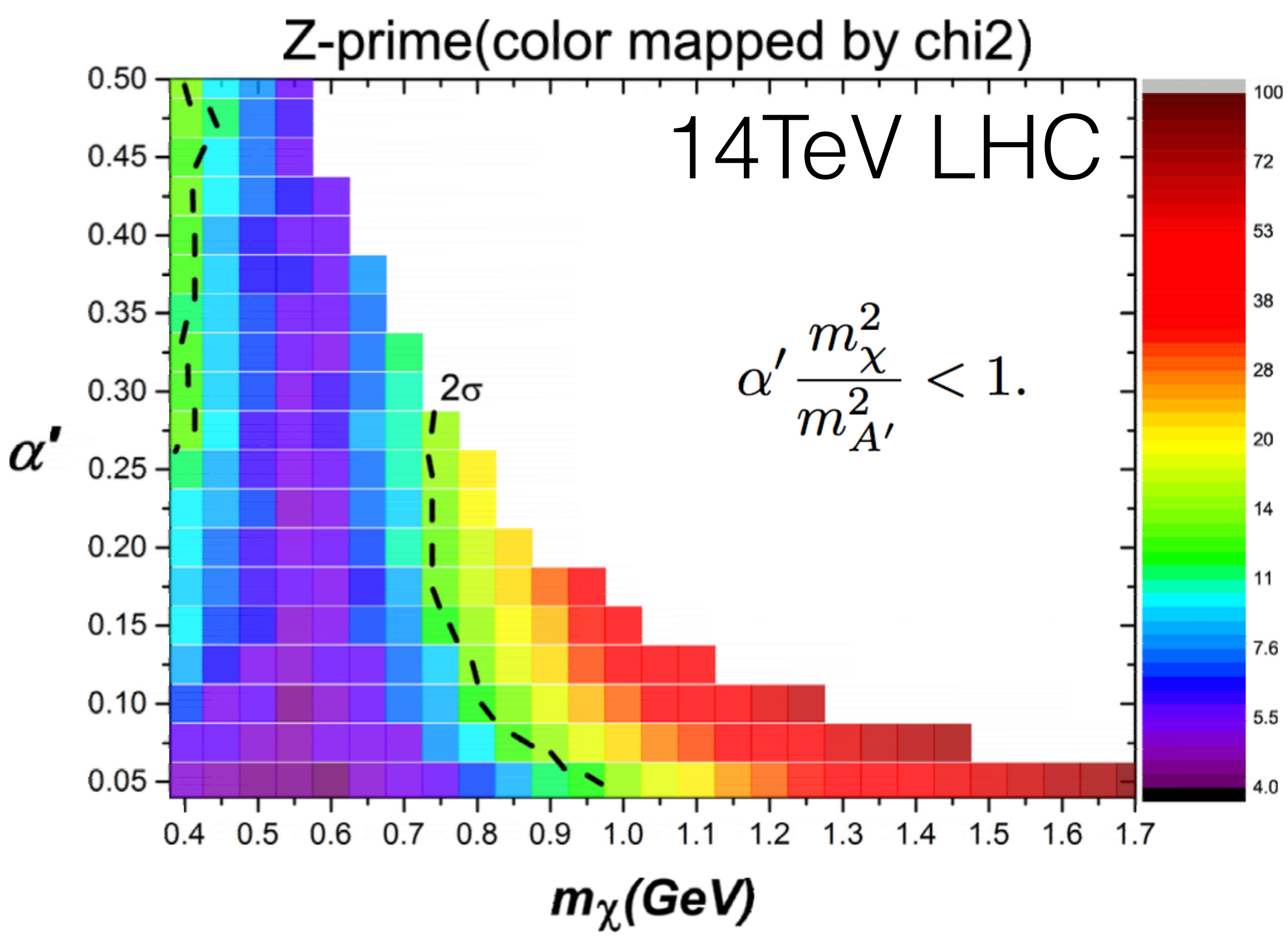
Dark Sectors 2016 Workshop
arXiv:1608.08632

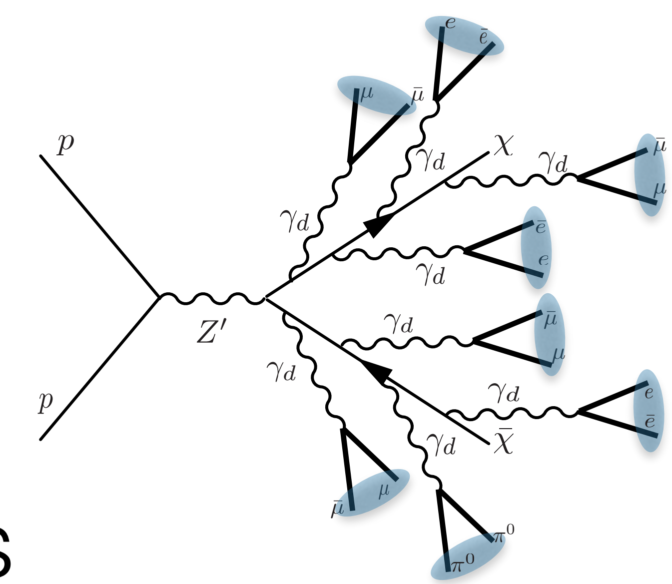


Number of events = 200

Differentiate algorithm @ LHC

- Case of DM production via a heavy Zprime





<n> / events

	Vectorlike	Chiral
$\alpha' = 0.16, m_\chi = 1GeV$	4.6	8.6
$\alpha' = 0.0016, m_\chi = 10GeV$	0.04	6.0
$\alpha' = 0.000016, m_\chi = 100GeV$	0.0004	3.6

Conclusion

- HL-LHC can become the precision machine as we can control / understand QCD activities.
- LHC proves the LIGHT Dark matter!
- By looking into the different shower pattern from "energetic" dark matter@LHC, we can tell more than "just discovery".