(Light) Dark Matter @ LHC

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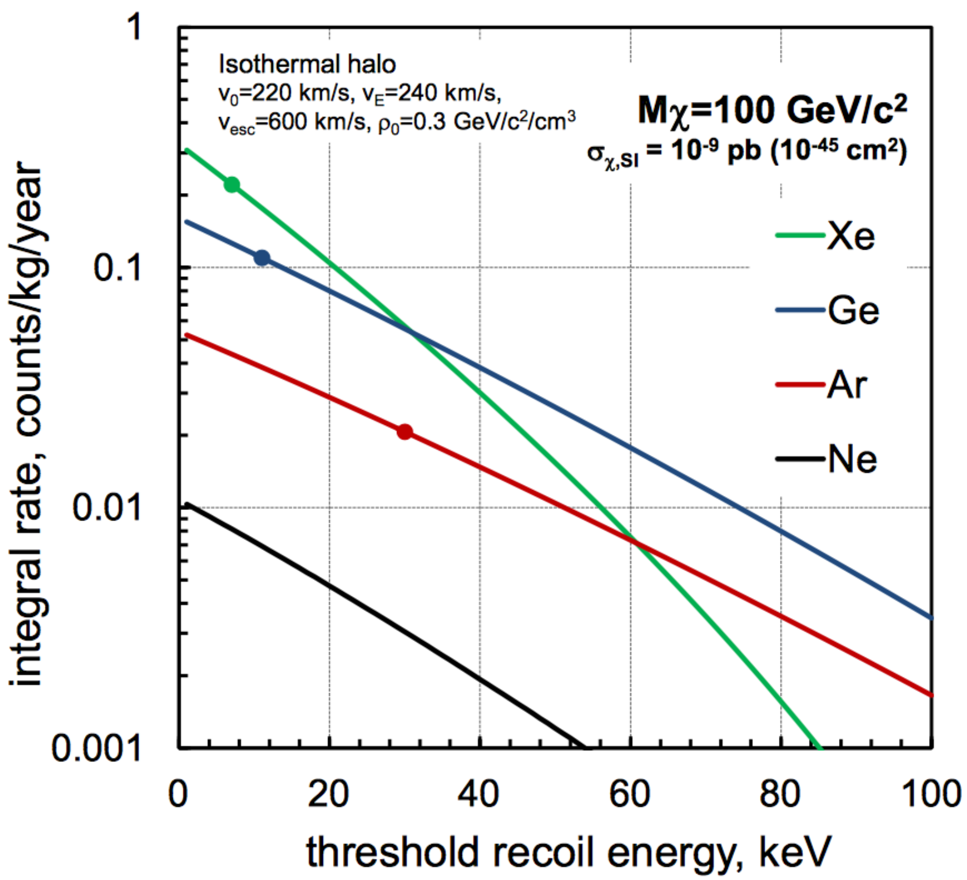
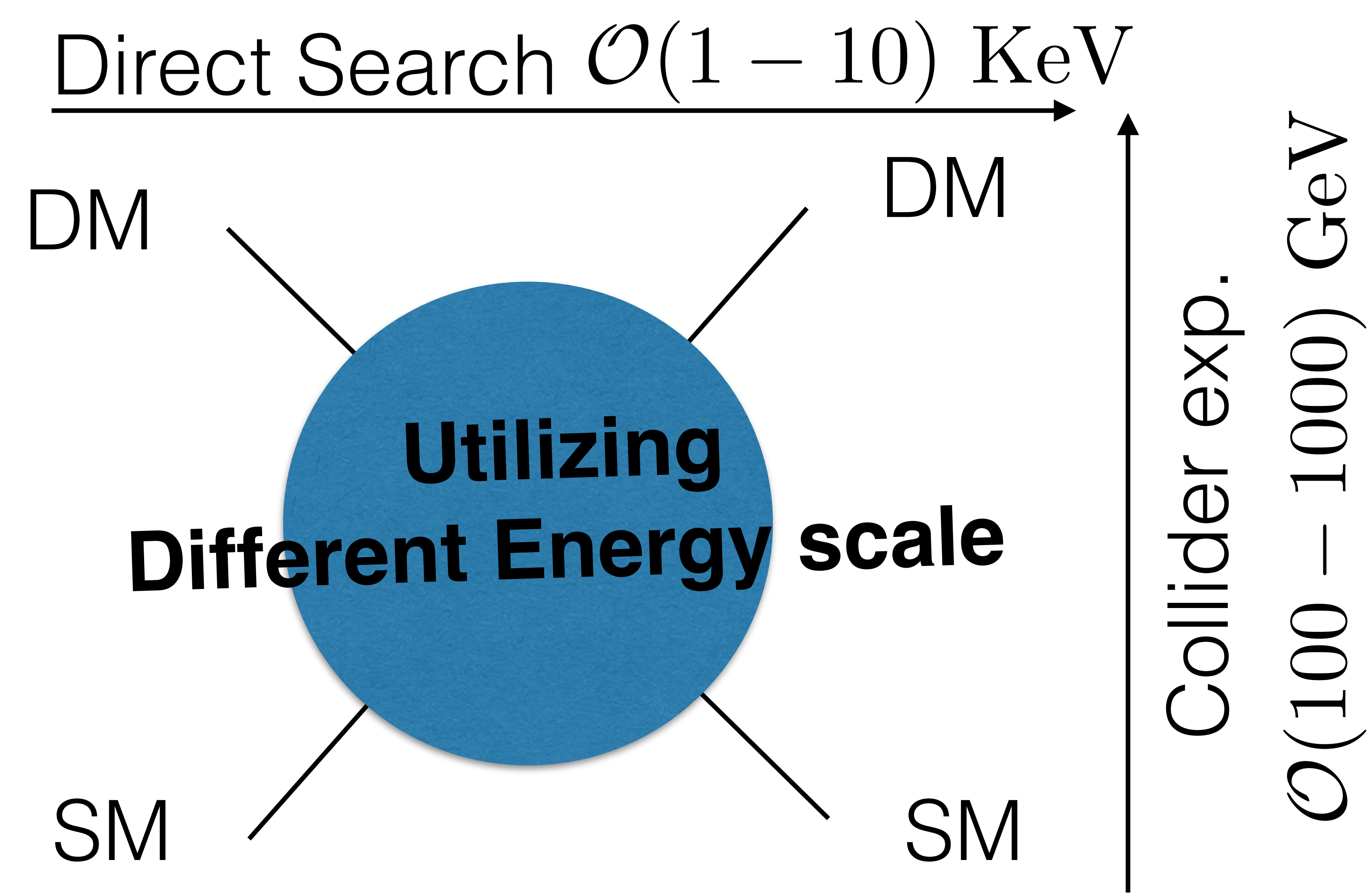
Dark Matter from aeV to ZeV

Two orthogonal EXPs

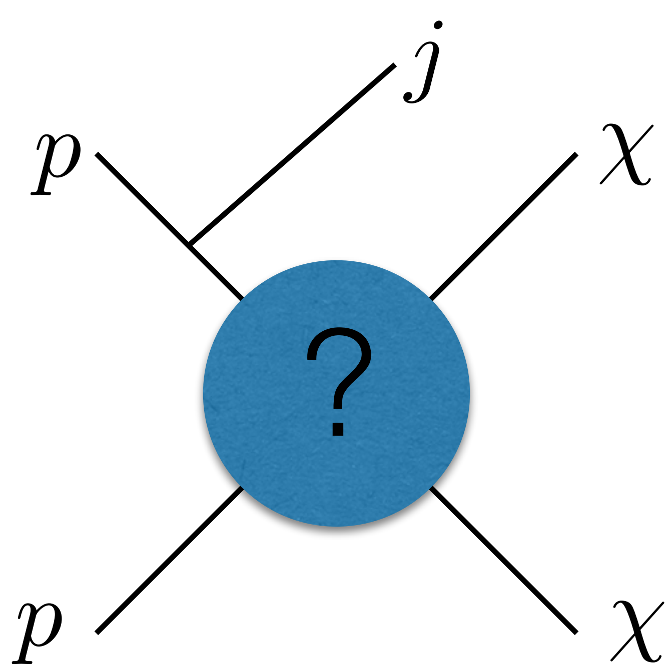


Snowmass summary
1310.8327 P. Cushman et.al



A strategy when we know NOTHING

- Very minimal set-up (search channel) for DM @LHC



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	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

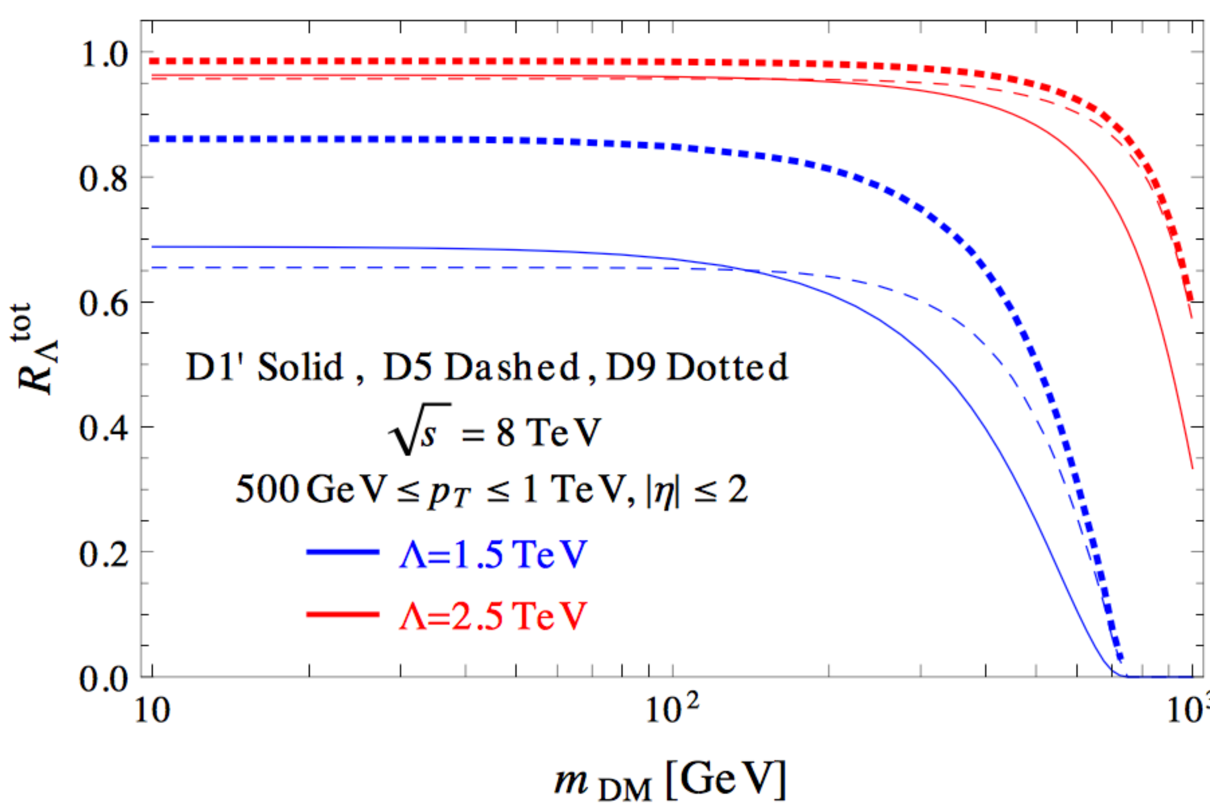
Tim Tait. et.al.
Phys.Rev. D82 (2010) 116010

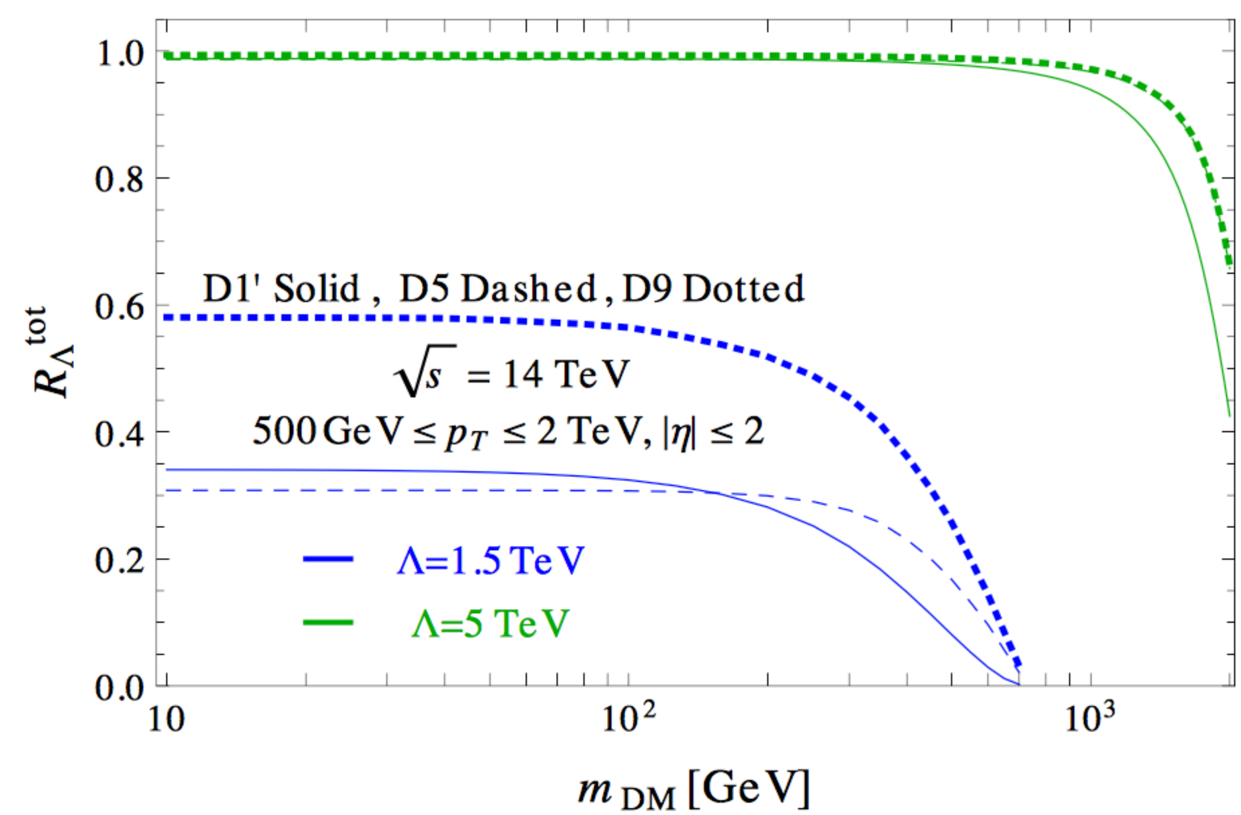
Difference between DD and LHC

Busoni et.al. arxiv:1402.1275

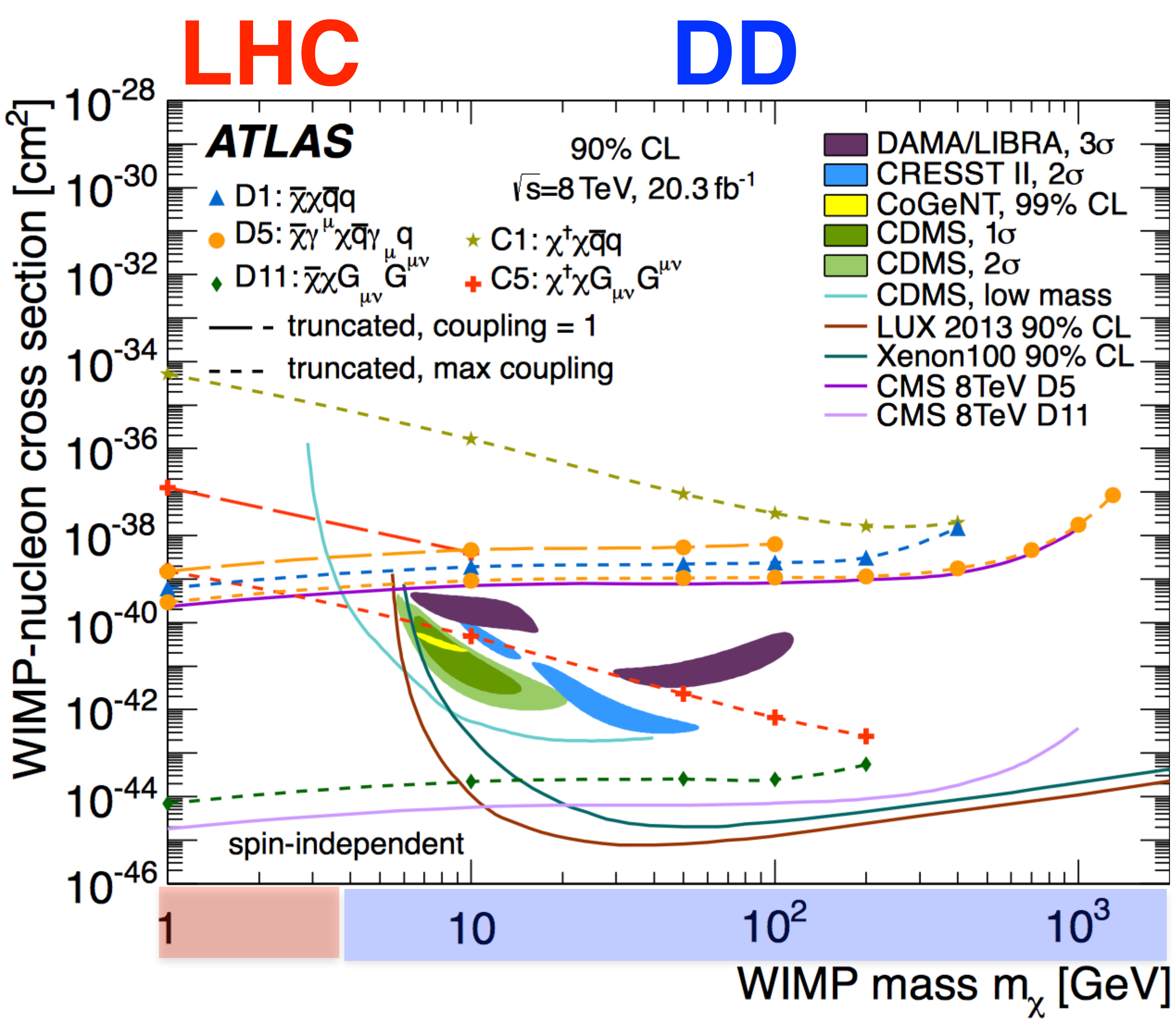
- At LHC, we need count events only , which follow EFF, $Q_{\rm tr} < \Lambda$

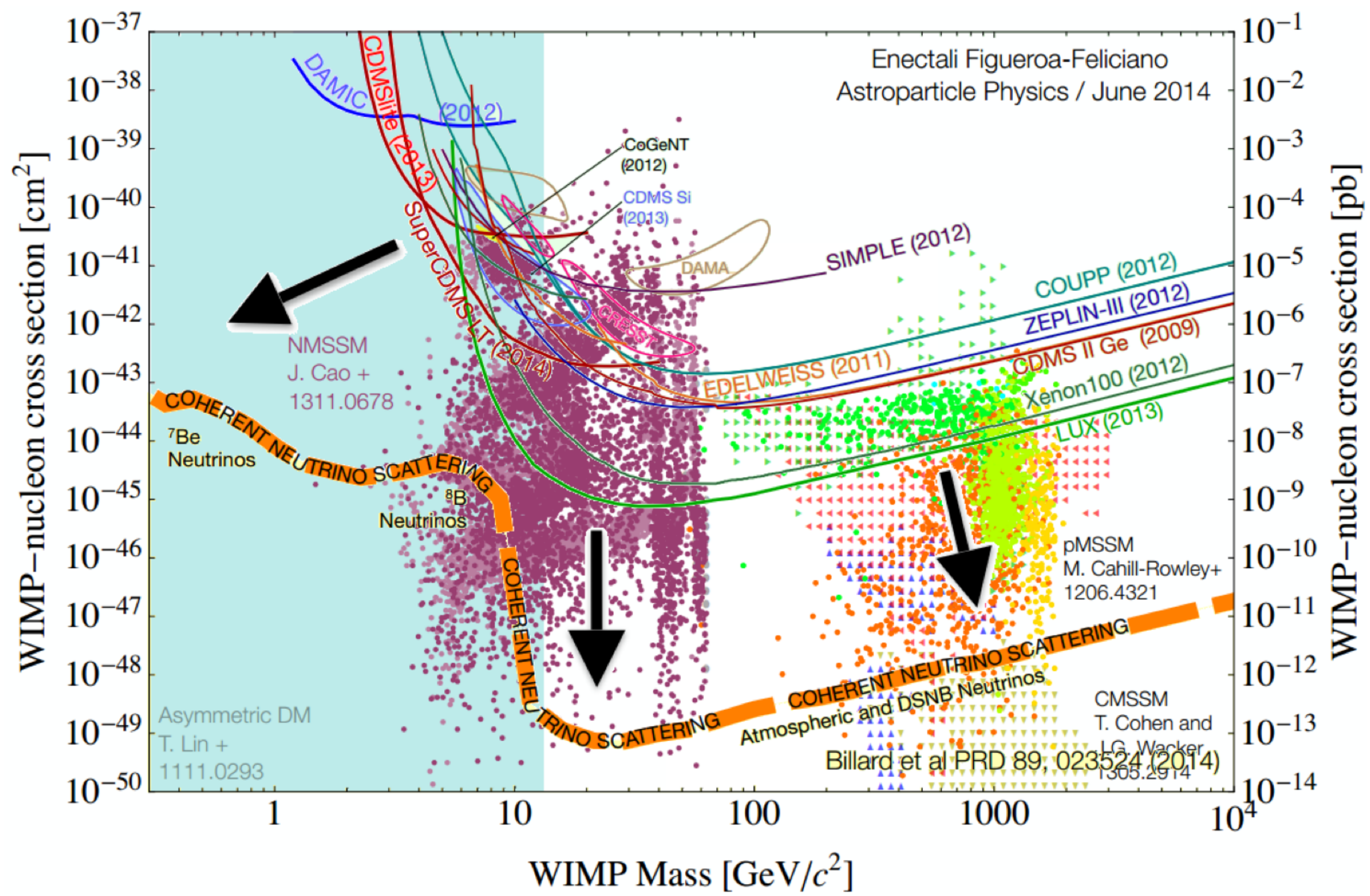
$$R_\Lambda^{\rm tot} \equiv \frac{\sigma|_{Q_{\rm tr}<\Lambda}}{\sigma} = \frac{\int_{p_{\rm T}^{\rm min}}^{p_{\rm T}^{\rm max}} {\rm d}p_{\rm T} \int_{-2}^{2} {\rm d}\eta \left.\frac{{\rm d}^2\sigma}{{\rm d}p_{\rm T}{\rm d}\eta}\right|_{Q_{\rm tr}<\Lambda}}{\int_{p_{\rm T}^{\rm min}}^{p_{\rm T}^{\rm max}} {\rm d}p_{\rm T} \int_{-2}^{2} {\rm d}\eta \frac{{\rm d}^2\sigma}{{\rm d}p_{\rm T}{\rm d}\eta}}$$





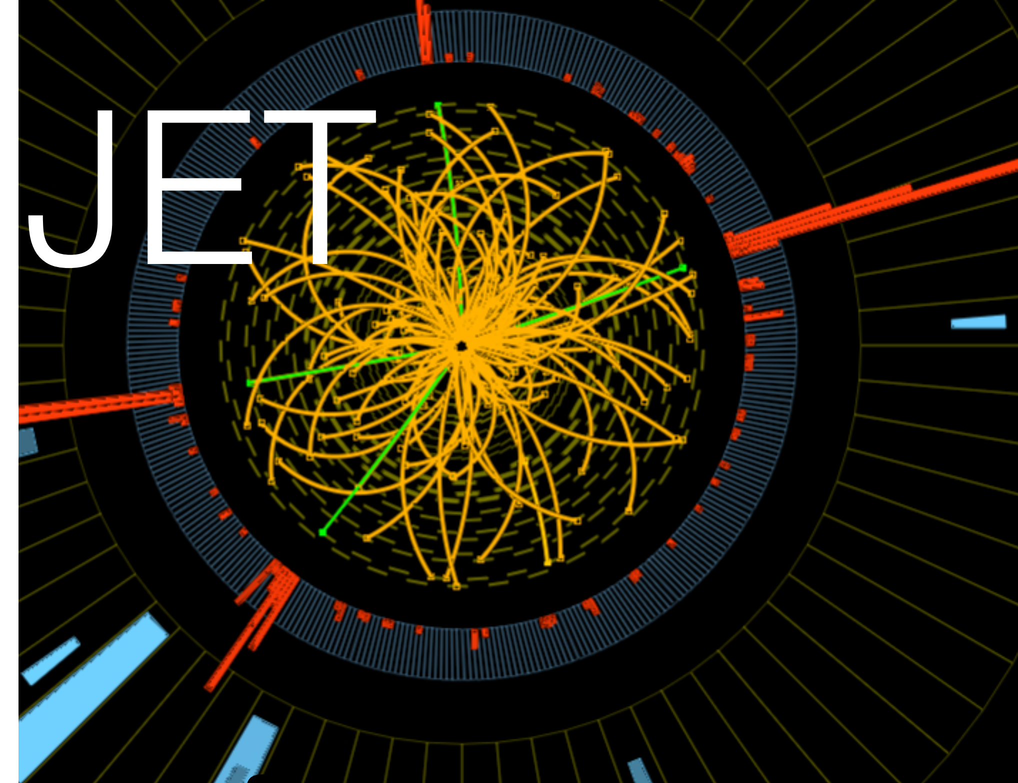
Interplay between DD and LHC





- Different experiments can cover different DM mass scale!
- We can improve (go beyound) simple Mono-jet+MET

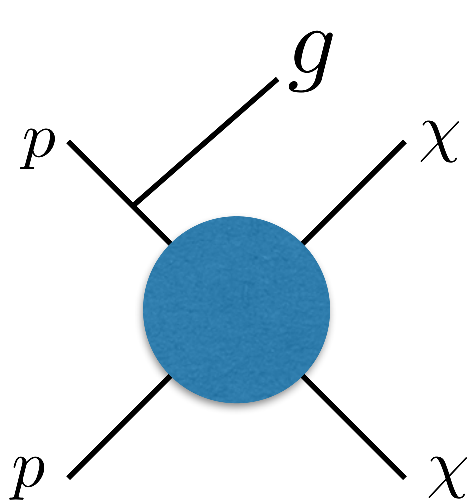
Tagging a JET

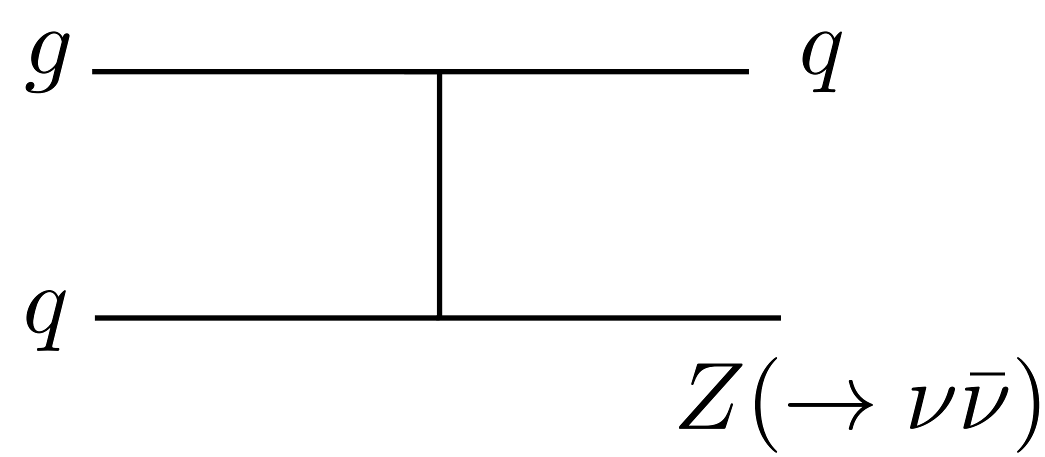


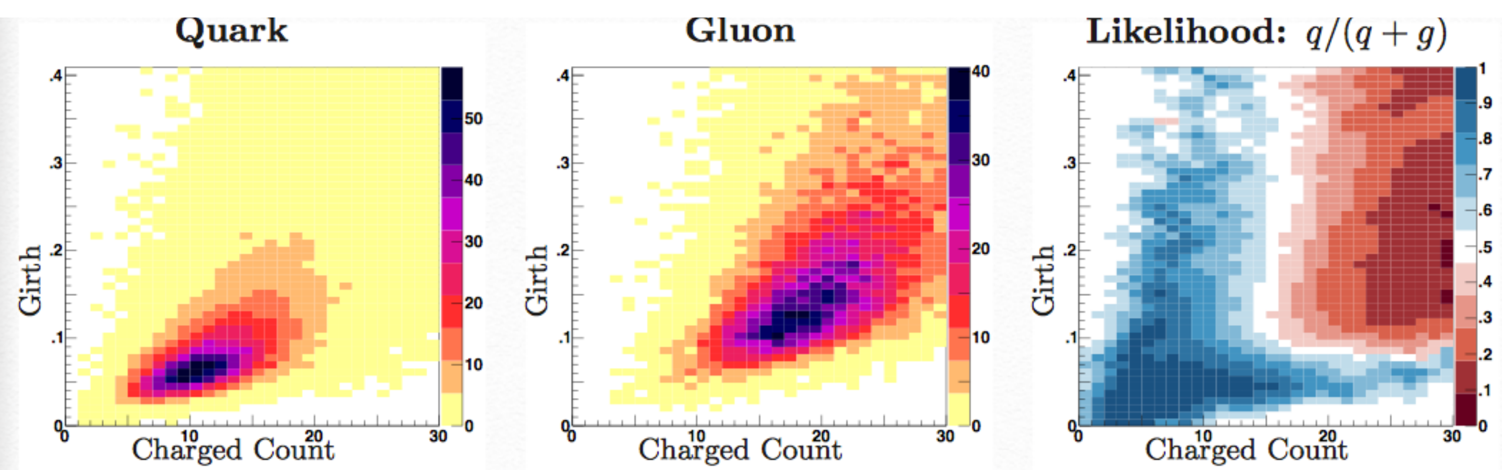
- Tagging ISR jets + MET

  - signals from SUSY decay become **soft**
  - PT of ISR gets **harder** with the mass scale of SUSY
  - Major BKG will be Z(to neutrinos)+jets

  - Possibility to discriminate
    ISR jet (initially gluon) v. s. quark jets (in Z+jets)

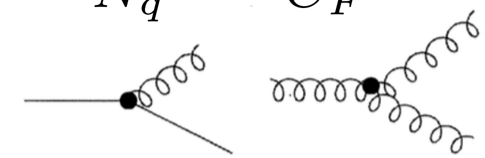






Schwarz et.al. PRL. 2011

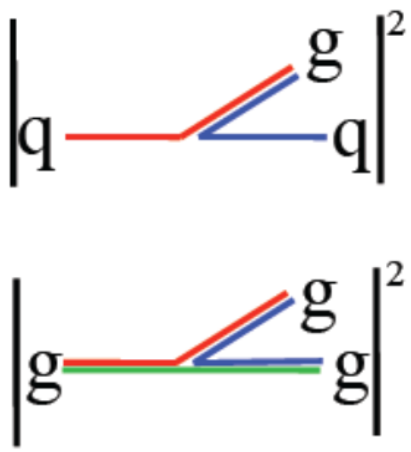
$$\frac{N_g}{N_q} = \frac{C_A}{C_F}$$



Gluon radiation $q \to qg$ $\boxed{C_F = \frac{4}{3}}$

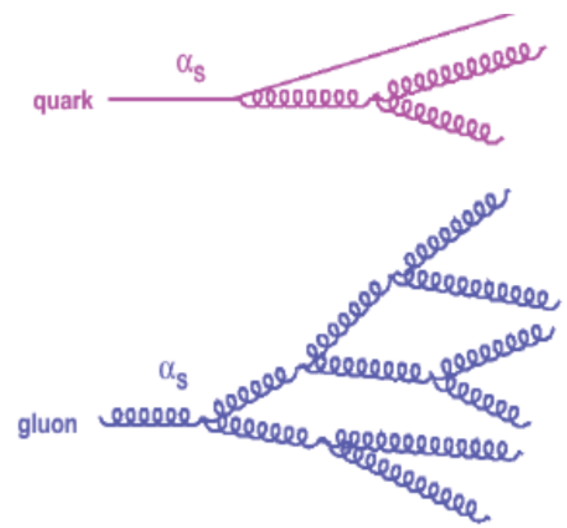
Triple gluon vertex $g \to gg$ $\boxed{C_A = 3}$

LO basics



$\sim C_F = 4/3$

$\sim C_A = 3$

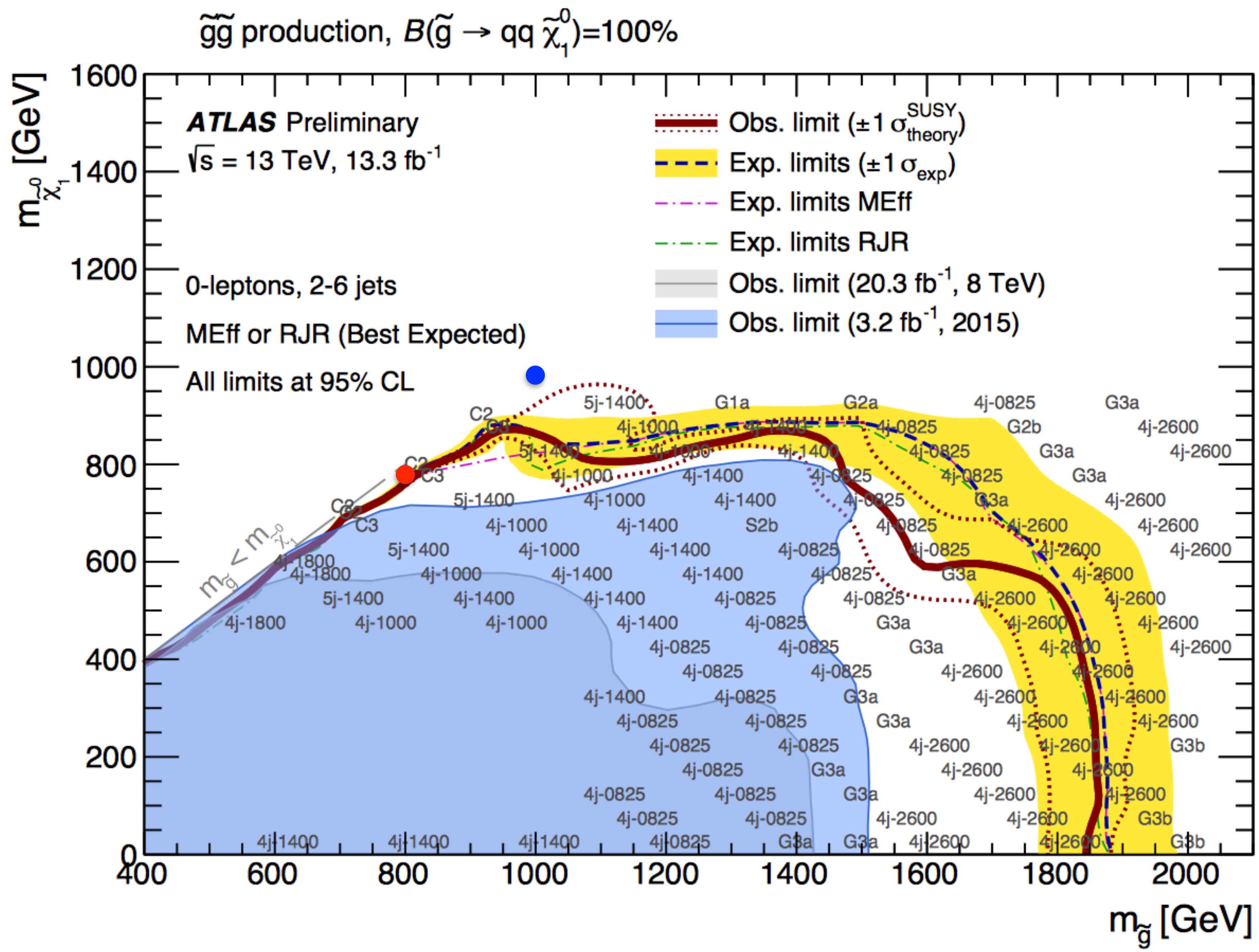


quark jets

gluon jets

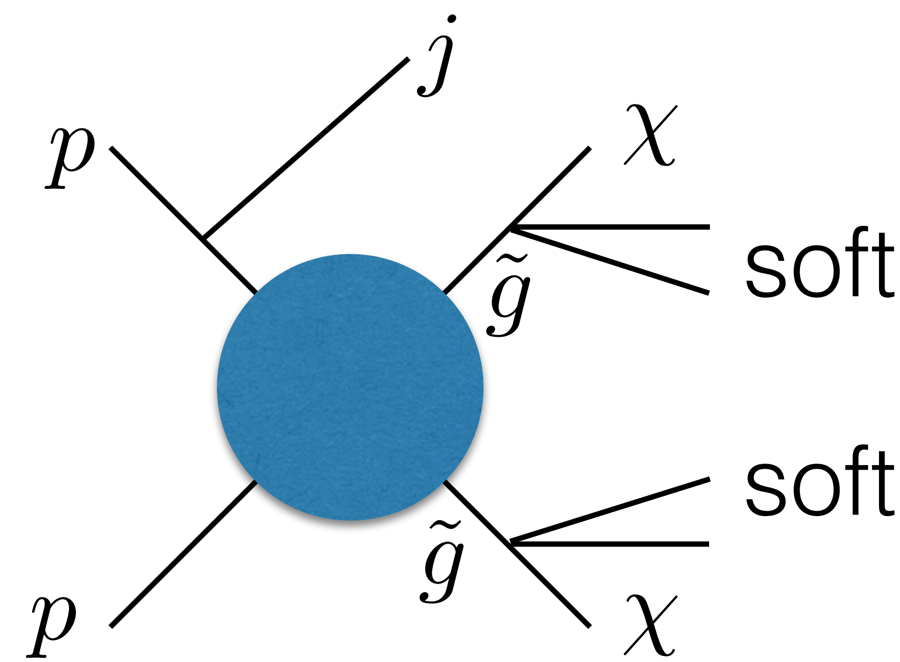
g-initiated jet is “wider” compared to q-initiated jet

Utilizing the “signal” ISR jet tagging can improve the search sensitivity



M.M. Nojiri et.al arxiv:1403.6028

- expected excl.
- expected excl. with 300fb-1

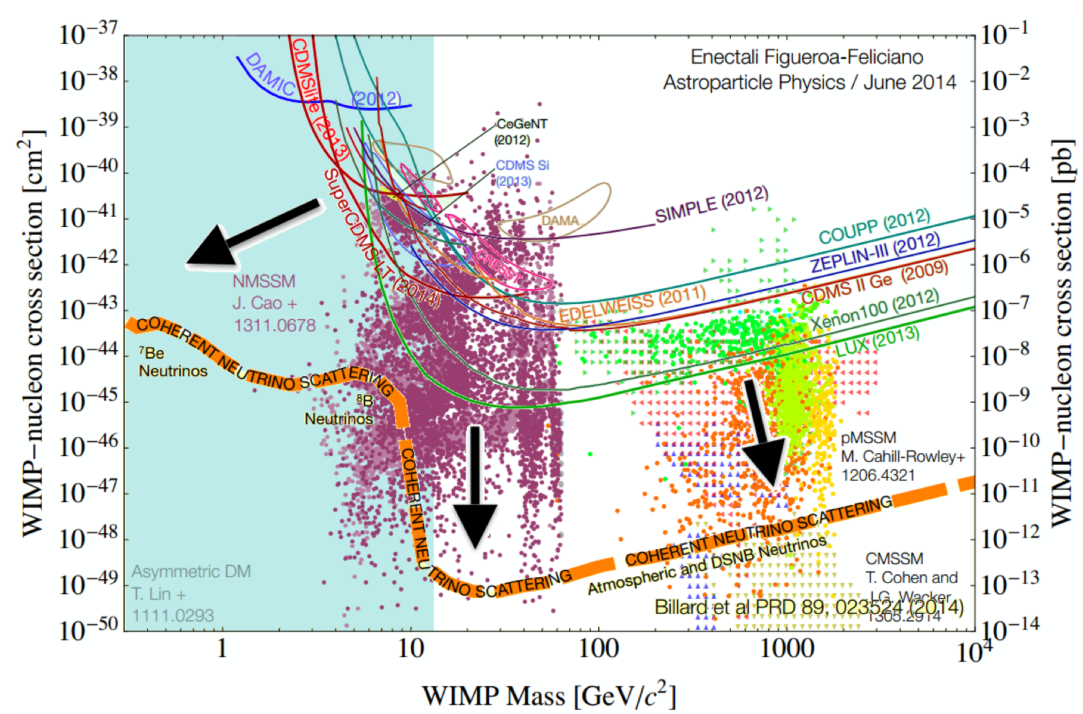


Additional object for a Light DM

- 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



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

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

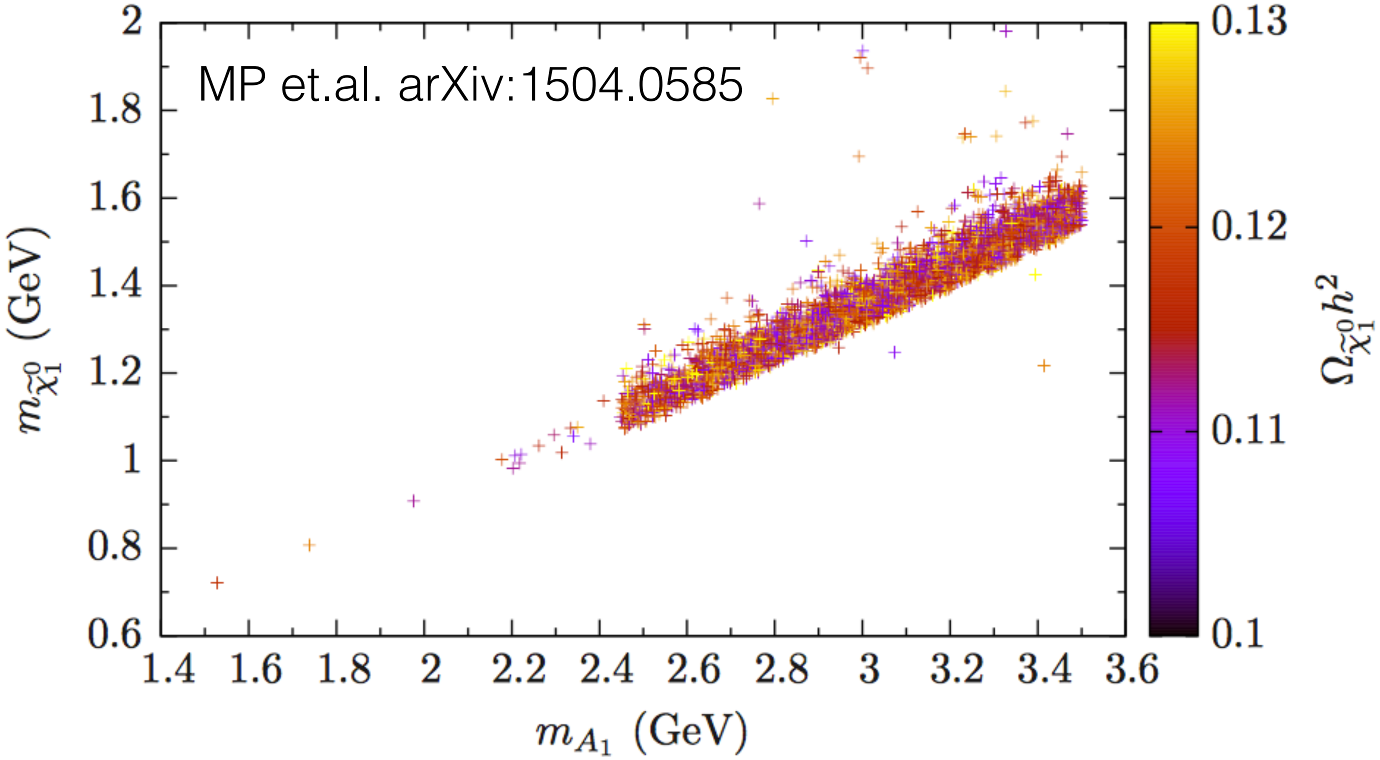
the mass of singlet-like pseudo scalar

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

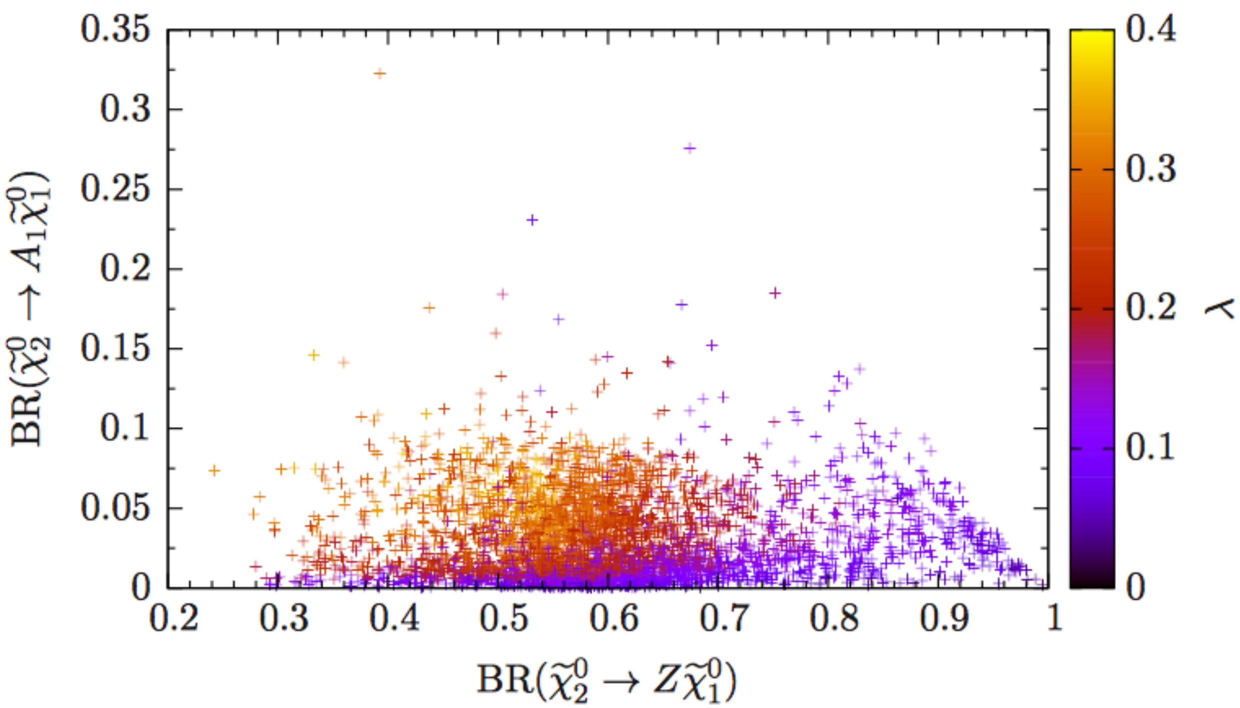
Singlino-dominated LSP (DM) [Small κ]

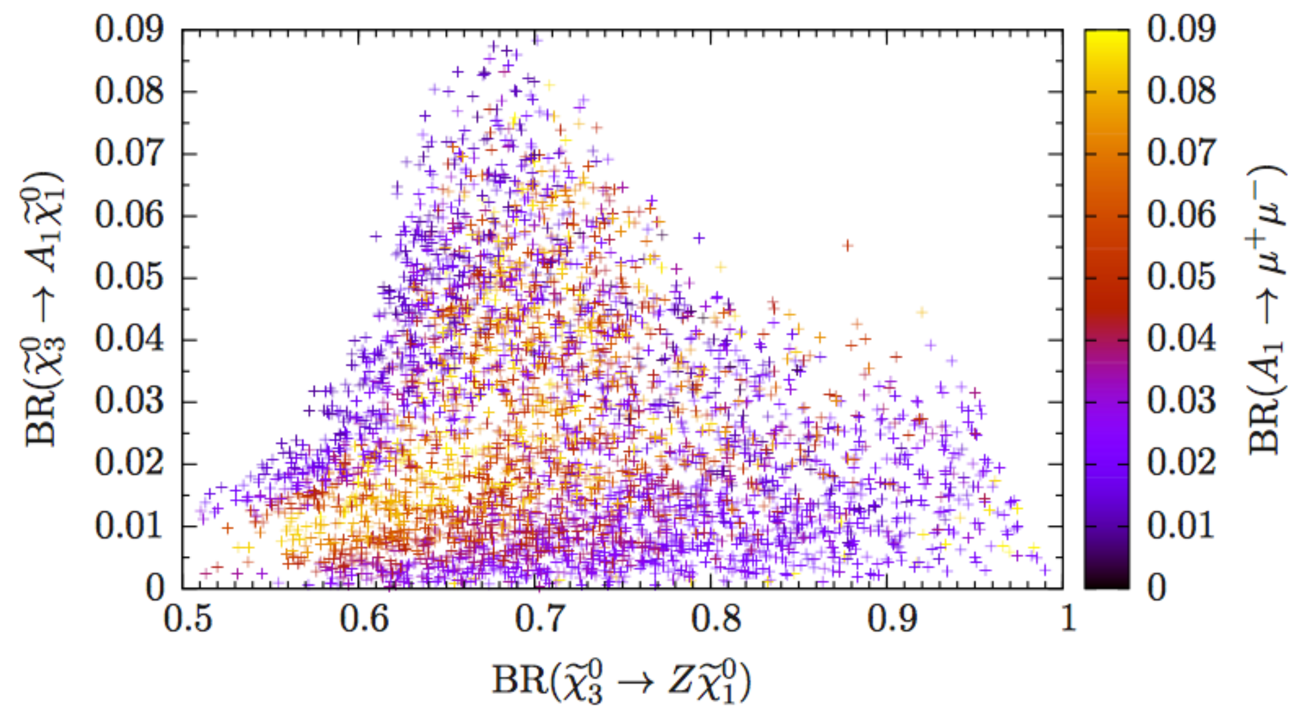
can be naturally accompanied by a light pseudo scalar

- DM relic via a resonance A_1 channel



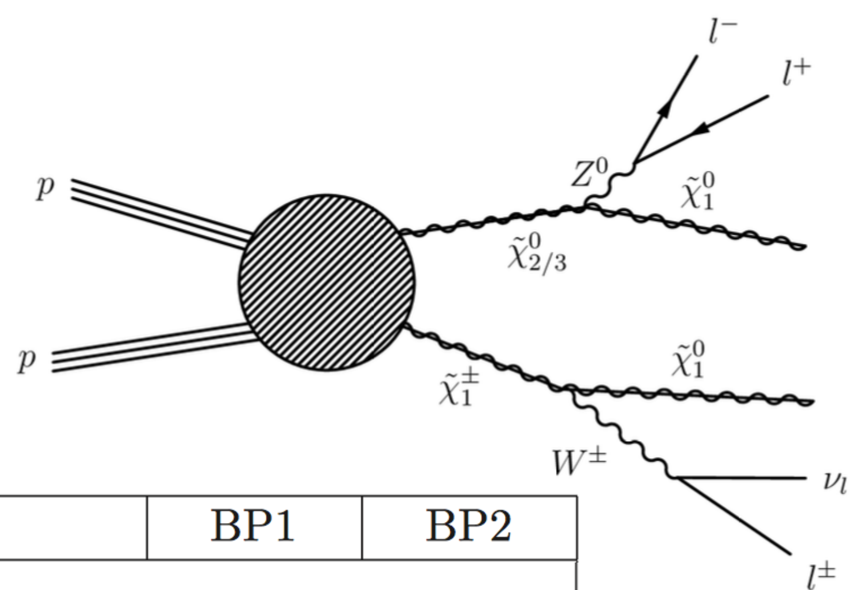
- Small μ_{eff} makes the 2nd and 3rd Neutralino -> higgino-like

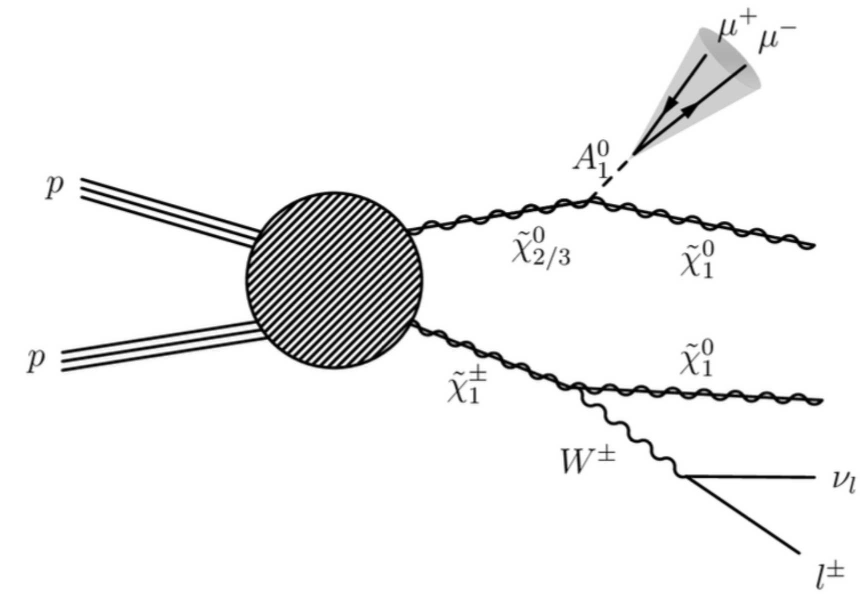




The chance of the LHC

- 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

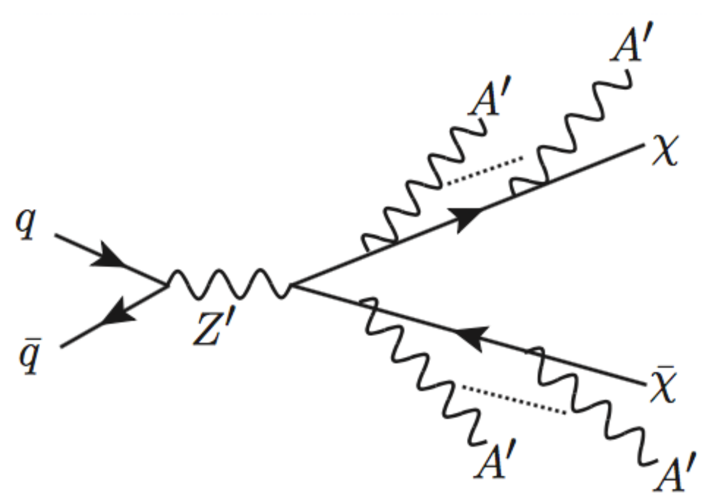
Light DM with a light dark photon

M. Buschmann et.al arXiv:1505.07459

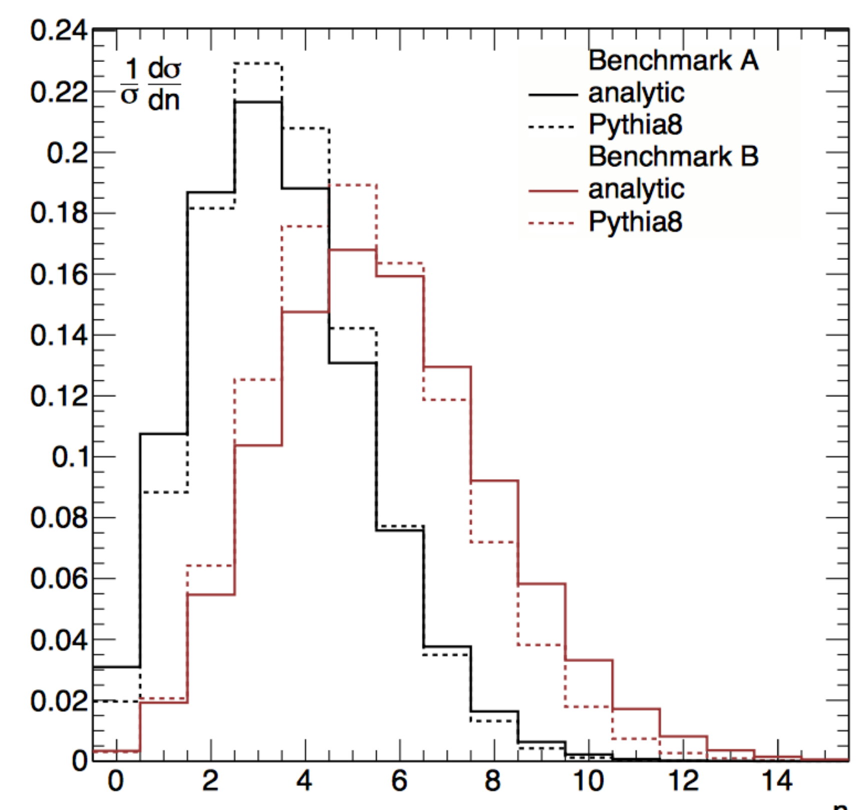
- A light dark matter, accompanied by a dark gauge boson.

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

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



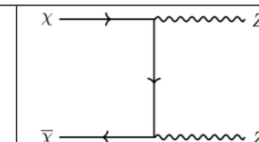
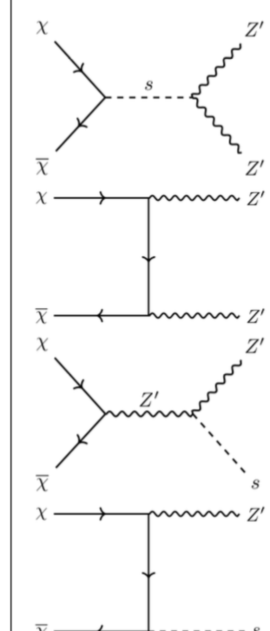
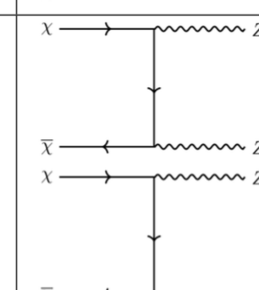
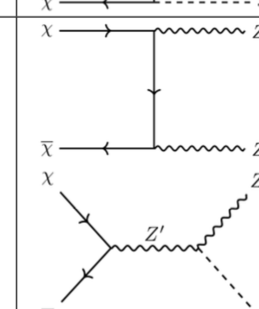
	$m_{Z'}$ [TeV]	g_q	g_χ	m_χ [GeV]	$m_{A'}$ [GeV]	$\alpha_{A'}$	$c\tau$ [mm]	ϵ [10^{-6}]	$\sigma_7(Z')$ [pb]	$\sigma_8(Z')$ [pb]	$\sigma_{13}(Z')$ [pb]	$\Gamma_{Z'}$ [GeV]	$\mathrm{BR}(Z' \to \chi\bar{\chi})$	$2\langle n_{A'}\rangle_8$	$2\langle n_{A'}\rangle_{13}$
A	1	0.1	1	4	1.5	0.2	10	2.8	0.58	0.85	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



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

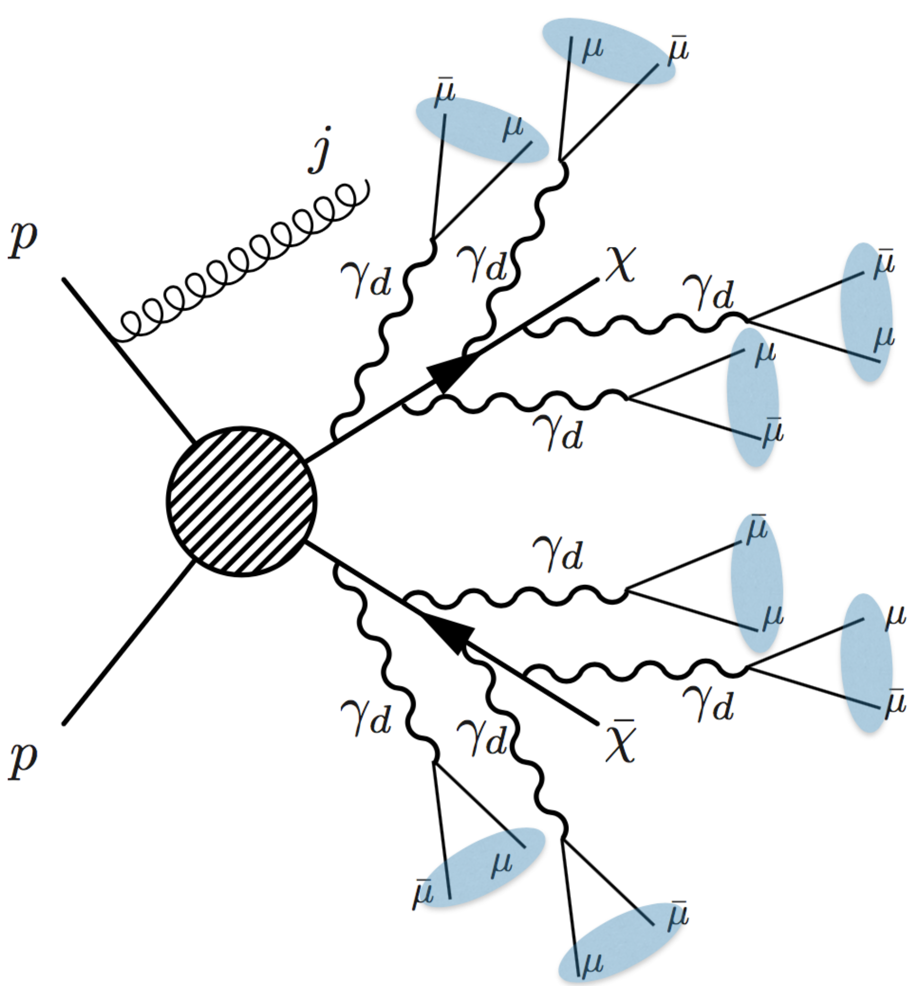
Nicole F. Bell et.al. arXiv:1610.03063

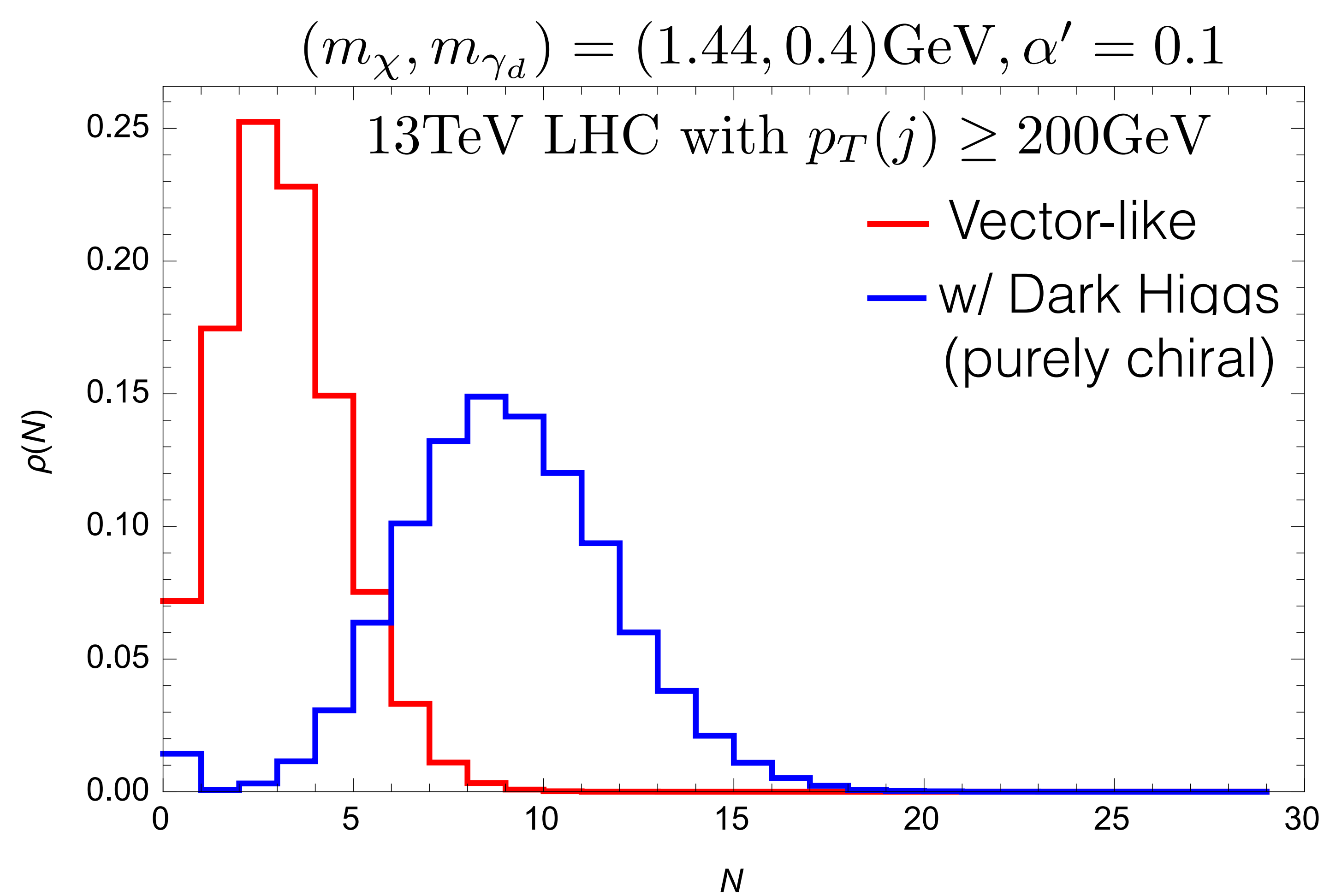
- One may ask the phenomenology according to the mass mechanism behind them.

Scenario	χ **mass**	Z' **mass**	**Required** $\chi - Z'$ **coupling type**	**Annihilation processes**	Z' **pol**
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

Different showering @LHC

- The very minimal set-up to focus on the dark showering;



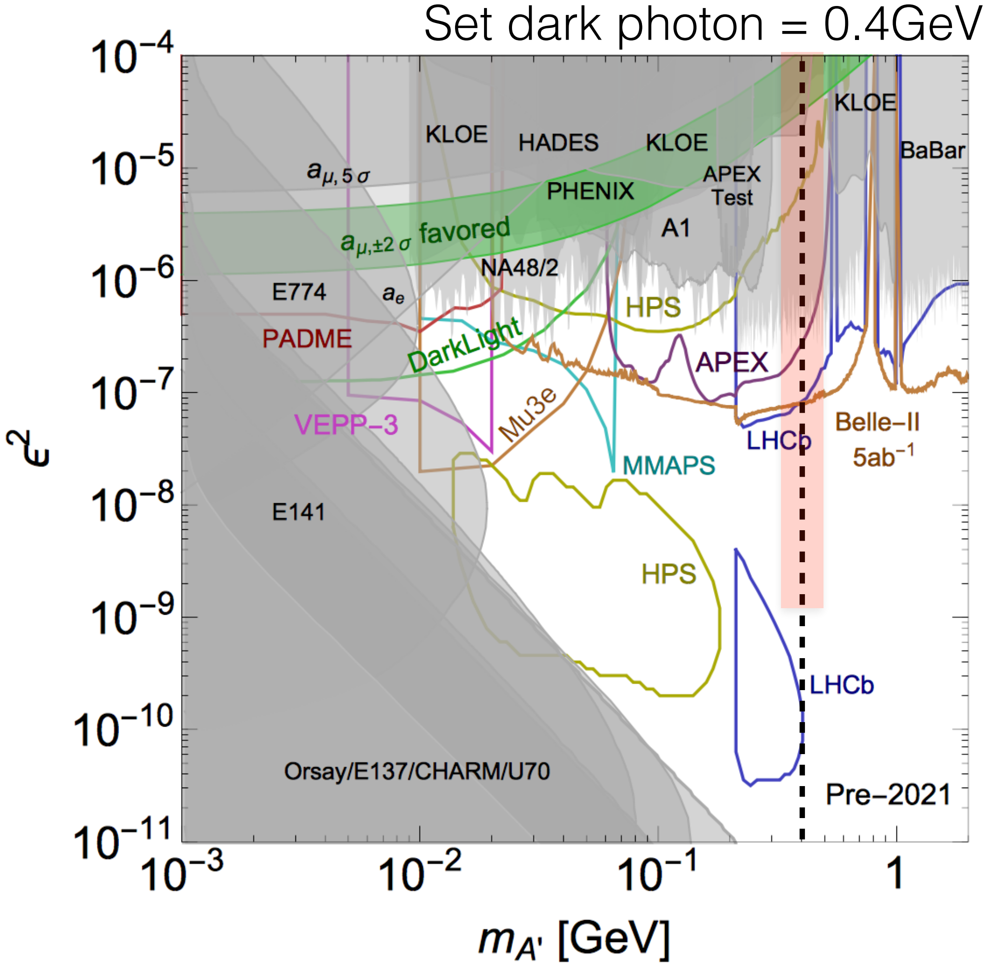


Mengchao Zhang, Minho Kim, Hye-Sung Lee, MP
arXiv:1612.SOONE

Differentiate algorithm @ LHC

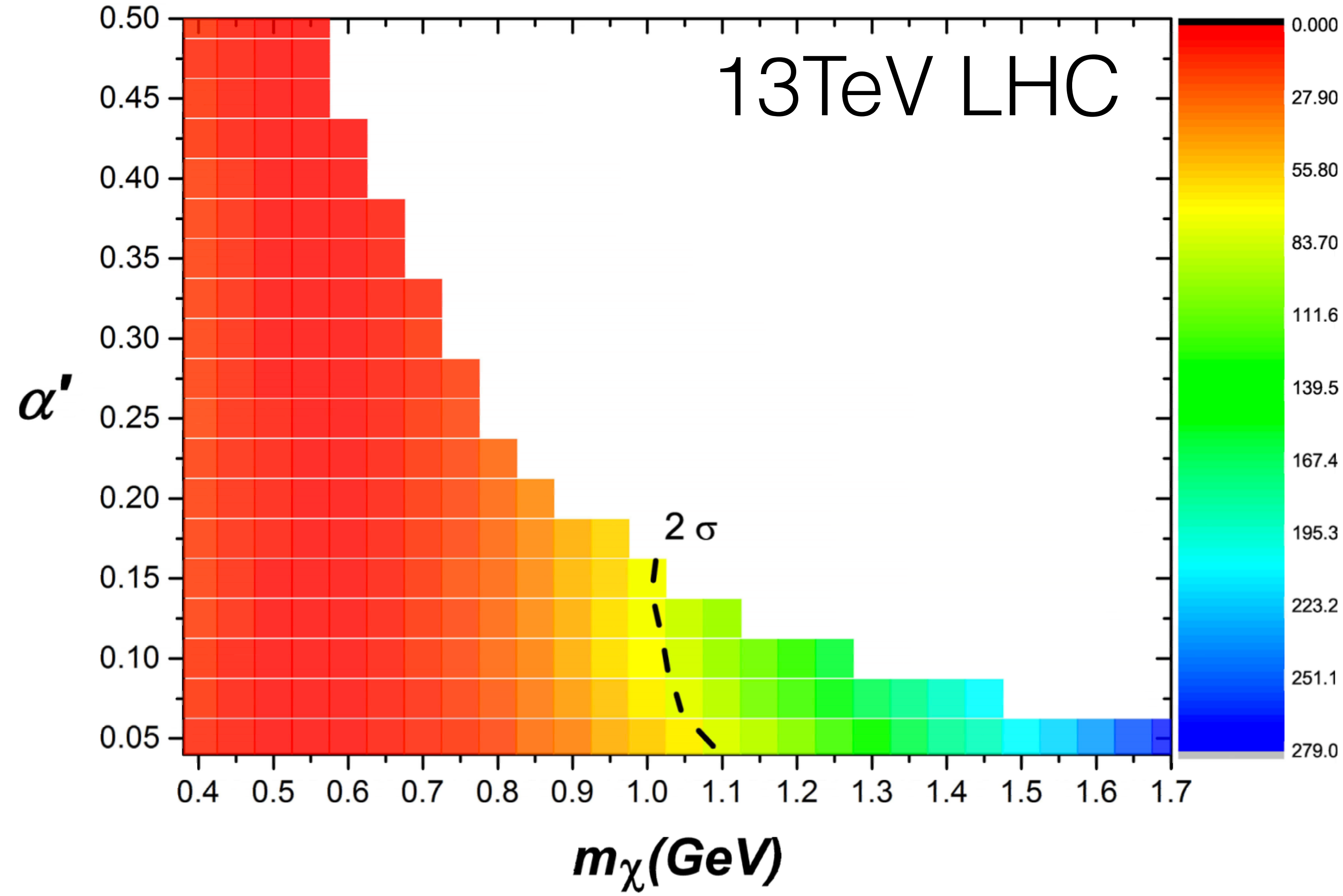
- How one can distinguish two mechanism with muon-jet

Set dark photon = 0.4GeV



Dark Sectors 2016 Workshop
arXiv:1608.08632

$$H_{T,\mu J} = \sum_{muon-jet} |\vec{p_T}|$$



- The collider experiments (including LHC) is the orthogonal tool in hunting DM.
- Especially, the collider can probe the light DM and check the properties of light DM.