HARVARD
UNIVERSITY

2026 Phenomenology Symposium
May 11-13, 2026

Leptonically Rich Confining Dark Sectors from Dark Hadronization: recasting an ATLAS four-lepton analysis

Junyi Cheng (Harvard University)

[26XX.XXXXX JC & Rabia Husain & Lingfeng Li & Matthew Strassler]

Contents

Introduction: Hidden Valley / Dark Sector (HV/DS) theory [Strassler & Zurek 2006]

- Gauge group: $SU(3)_C \times SU(2)_L \times U(1)_Y \times$ dark sector
- Focus on QCD-like $SU(N)$ theory with confinement & dark showering
- Higgs-like scalar S with $gg \to S \to g_D g_D$
- Dark hadron spectrum: spin-0 π_D-like & spin-1 ρ_D-like
- Treat all π_D as stable
- $m_{\pi_D} = 0.6 m_{\rho_D}$, so $\rho_D \to \pi_D \pi_D$ is forbidden (different from QCD)
- $N_c = 3$, $N_f = 2$ with equal mass

$$m_q < \Lambda_{HV} < \frac{1}{2} m_{\rho_D} < m_{\pi_D}$$

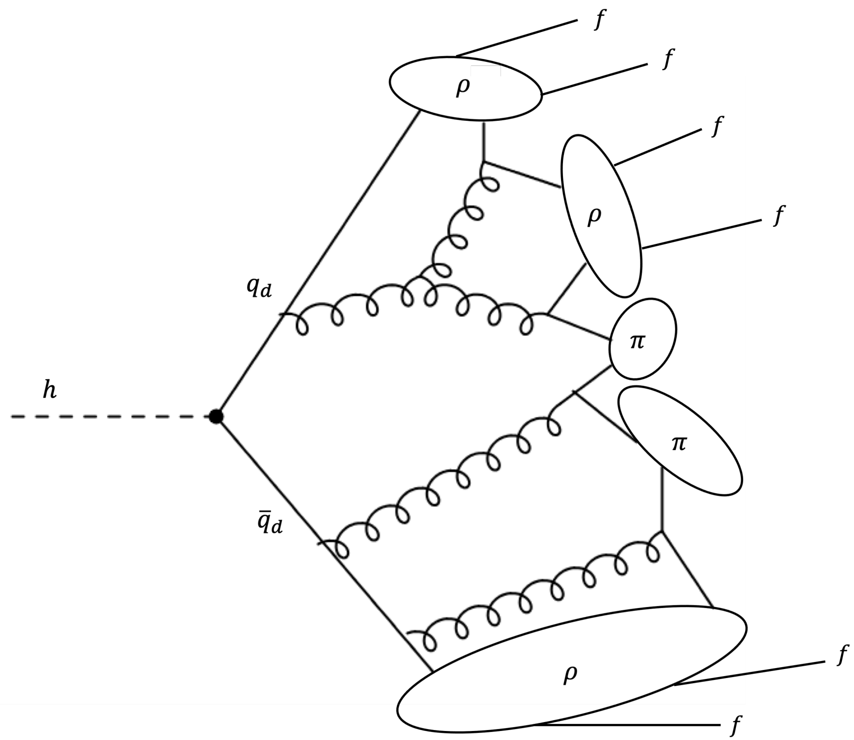
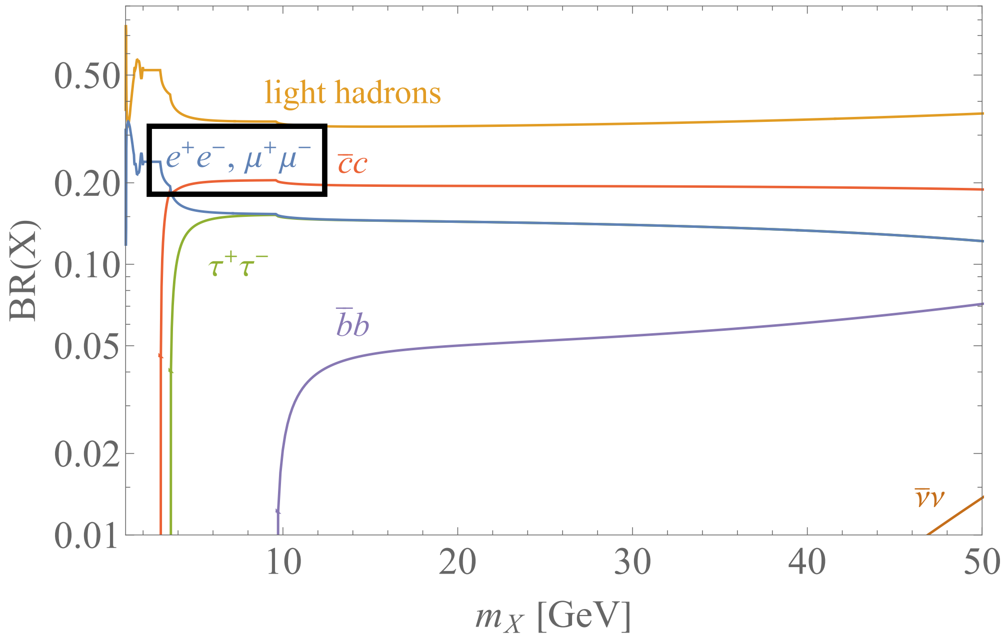


Figure from [Bernreuther & Kahlhoefer & Křamer & Tunney 1907.04346]

Introduction: benchmark models

- Assume ρ_D mix with heavy vector Z'_D which couples to SM, so effectively $\rho_D \to {Z'_D}^{(*)}/\gamma^{(*)}/Z^{(*)} \to f\bar{f}$
- Use dark photon-like lepton BR($\rho_D \to l\bar{l}$) $\sim 15\ \%$ as a benchmark



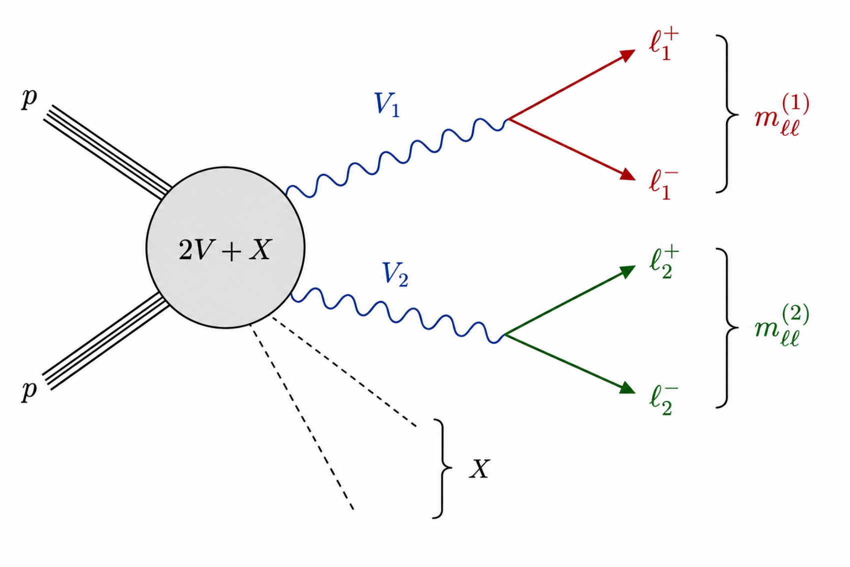
Introduction: benchmark models

- 4 vectors in total: ρ_D triplet + ω_D singlet
- All (B-like models) / only flavor-diagonal (A-like models) ρ_D can decay promptly to SM fermion pairs
- Models IJ are for comparison only

Name	m_S [GeV]	Decaying vectors	Stable vectors
A	125	2	2
B	125	4	0
C	200	2	2
D	200	4	0
E	400	2	2
F	400	4	0
G	1000	2	2
H	1000	4	0
I	1500	2	2
J	1500	4	0

Introduction: choice of signal

- signal:
  - ≥ 2 vector leptonic decays
  - ≥ 2 SFOC lepton pairs
  - equal $m_{ll} \lesssim 40$ GeV
- leptonic final states:
  - small backgrounds
  - easier to reconstruct
  - sizeable BRs
- good model-agnostic signature
  - fundamental / composite vector
  - vector / axial details



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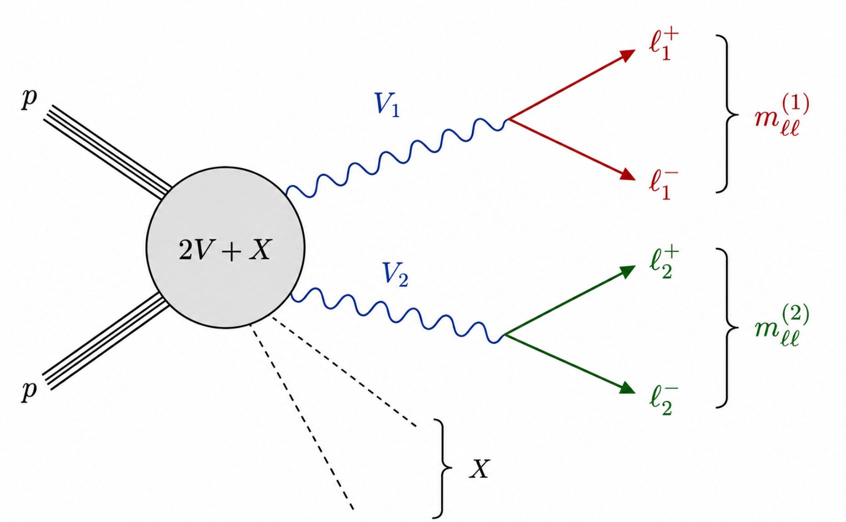
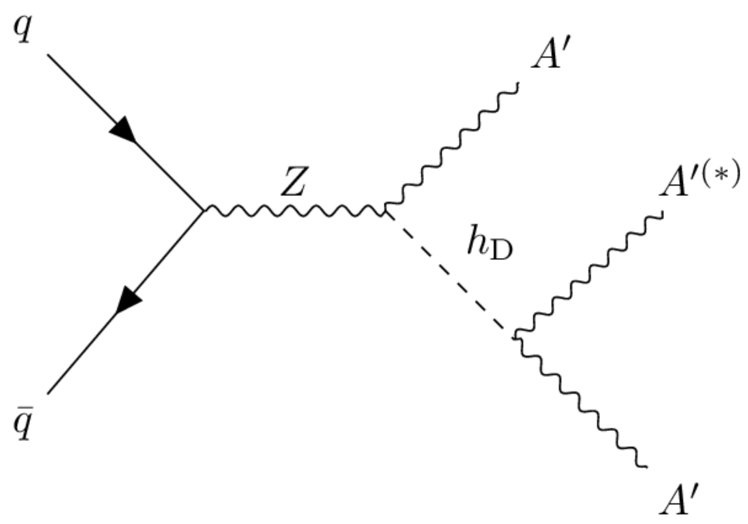


Leptons are clean!

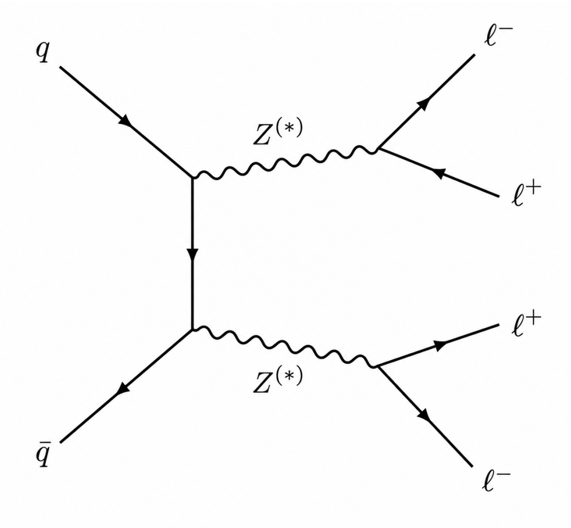
$Z \to 6f$ model [2306.07413 ATLAS]

- $pp \to Z \to A'h_D, h_D \to A'A', A' \to l^+l^-\ (l = e, \mu)$
- only require 4 leptons, the third A' can decay hadronically



$Z \to 6f$ model: ATLAS analysis

- dominant physics background is $q\bar{q} \to 4l$



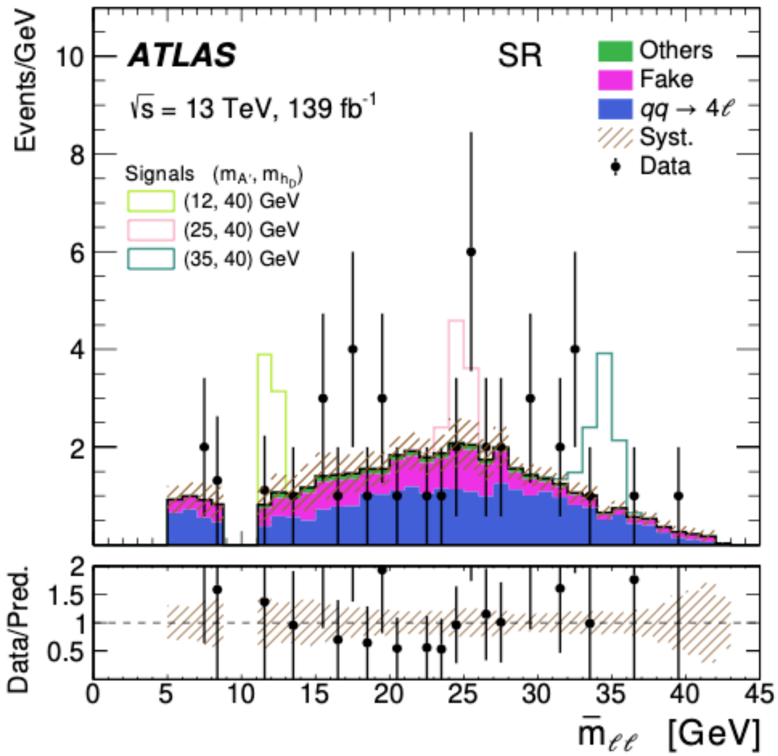


Figure from [2306.07413 ATLAS]

$Z \to 6f$ model: ATLAS analysis

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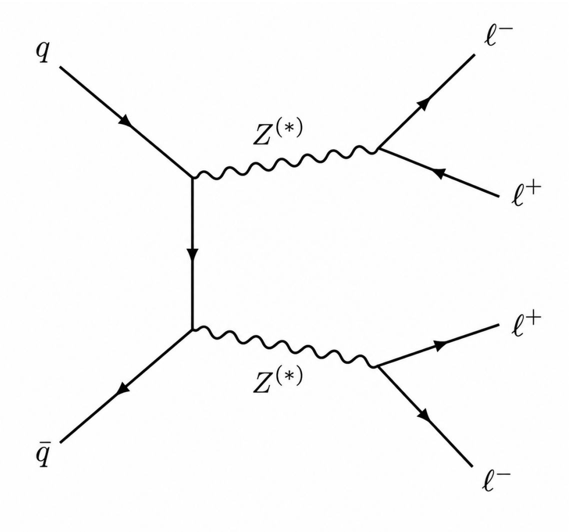
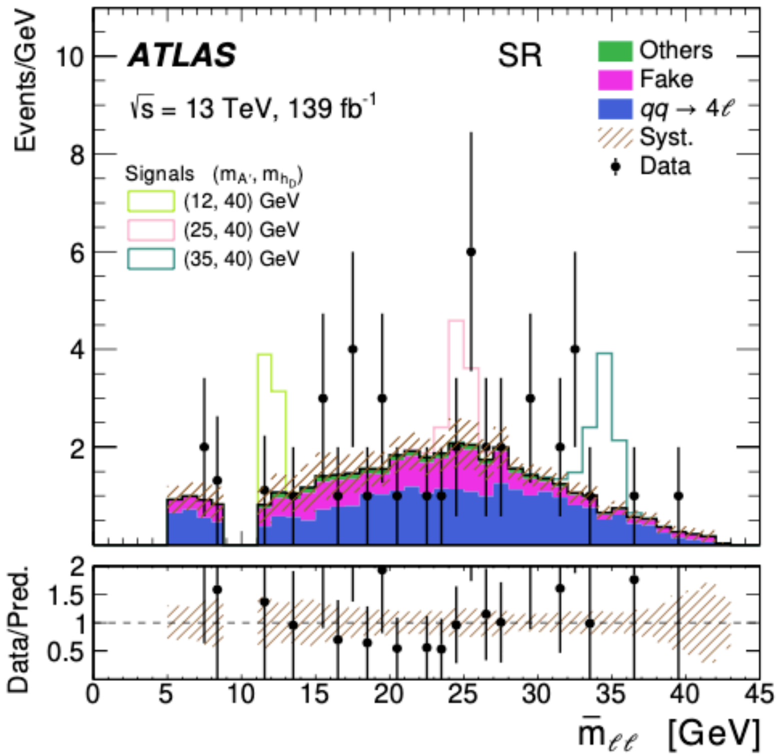


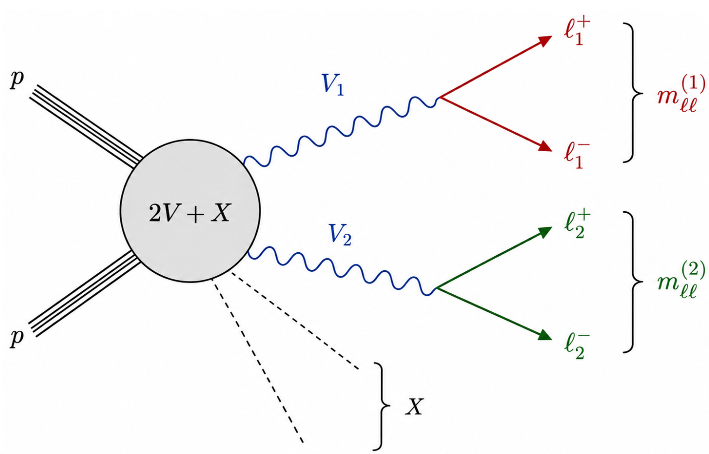


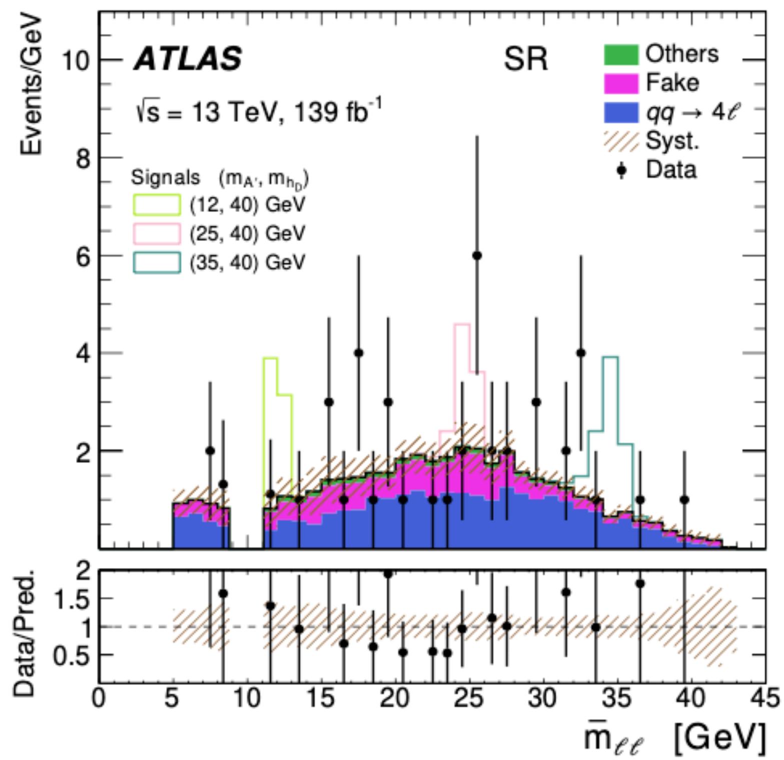
Tiny background!

Figure from [2306.07413 ATLAS]

$Z \to 6f$ model: ATLAS analysis

- event selection cuts:
  - ≥ 4 loosely isolated leptons with $p_T^e > 4.5$ GeV, $p_T^\mu > 3$ GeV
  - ≥ 2 SFOC lepton pairs
  - $0.85 < m_{34}/m_{12} < 1$
  - $m_{4l} < m_Z - 5$ GeV
  - reject $m_{ll} \in [0,5] \cup [8,12]$ GeV

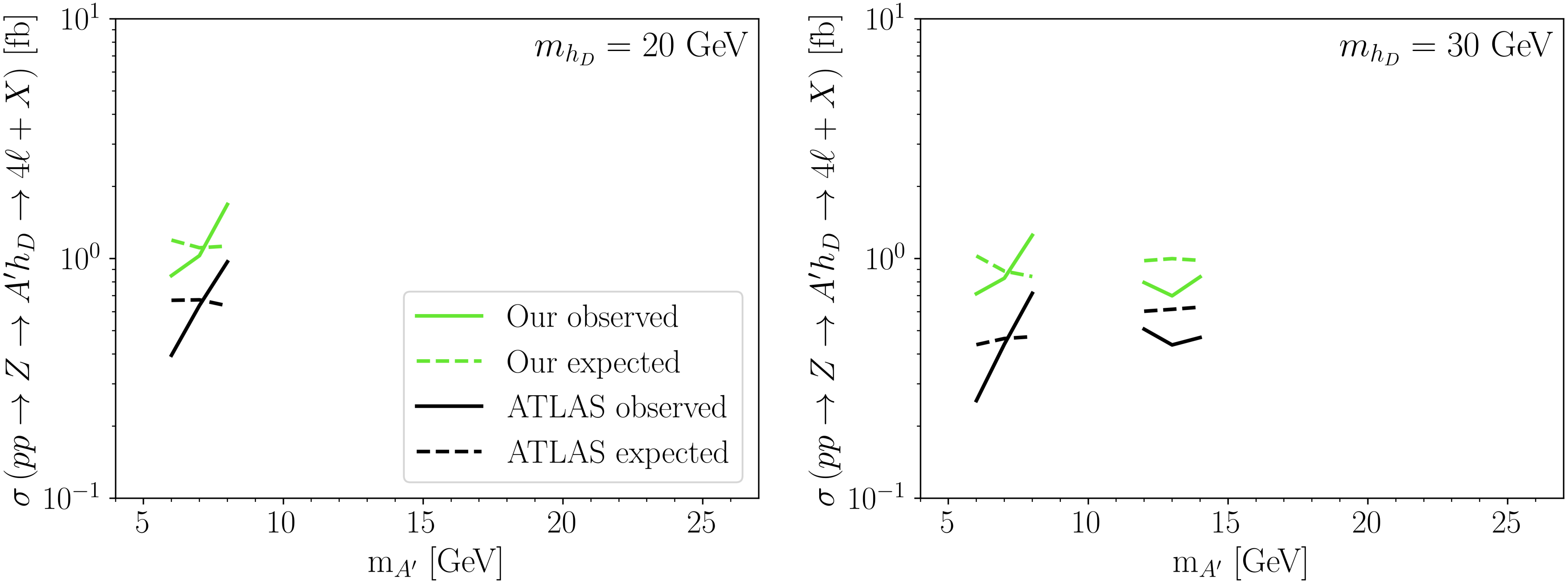


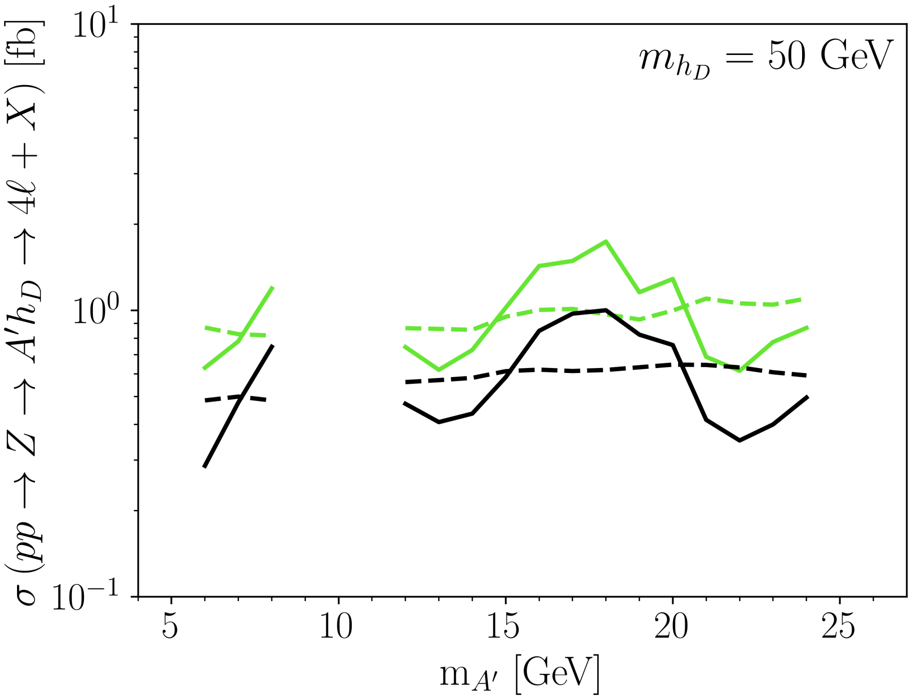


$Z \to 6f$ model: our reproduction

[2412.14452 JC & Husain & Li & Strassler]

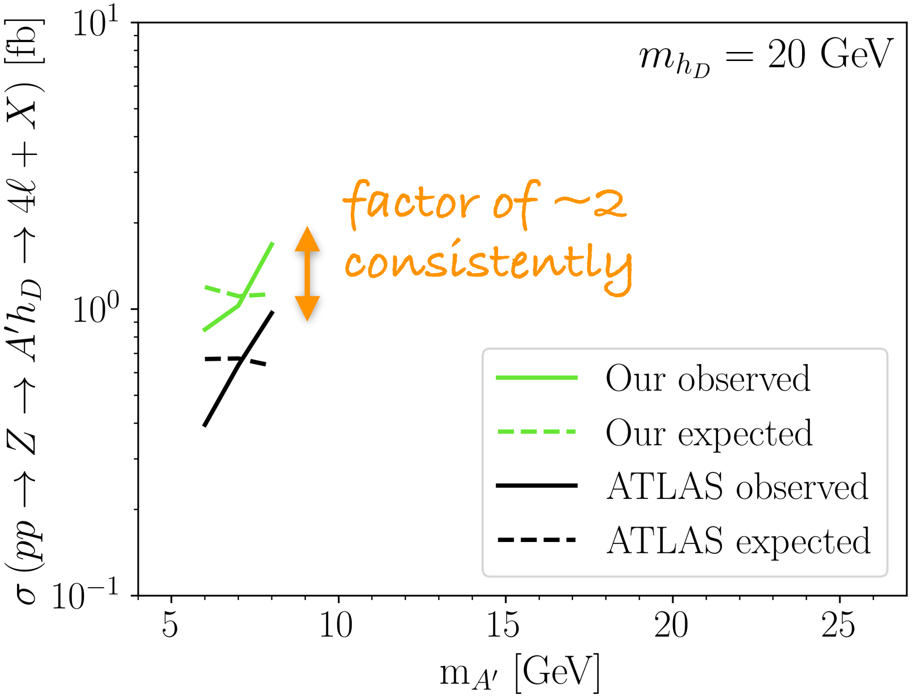
- simulate signal and use the backgrounds in the ATLAS analysis
- same trigger & cuts as in ATLAS analysis
- recalibration factors:
  - $r_{\text{lep}} = 0.78 \pm 0.11$: detector effects for soft & fake leptons
  - $r_{\text{trig}} = 0.81 \pm 0.10$
- use ATLAS MC study to check these recalibration factors can reproduce single step efficiencies

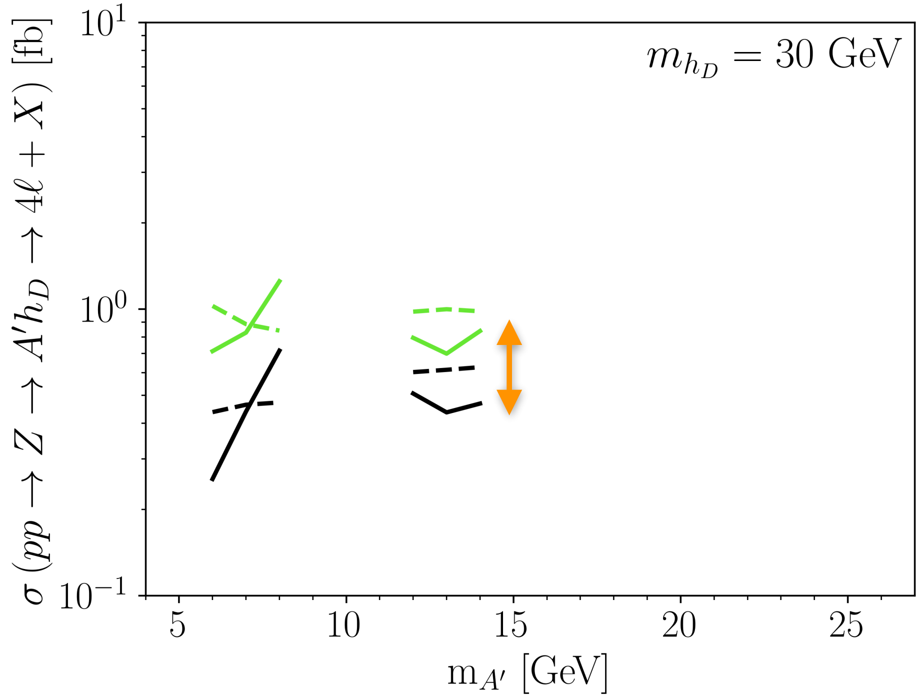


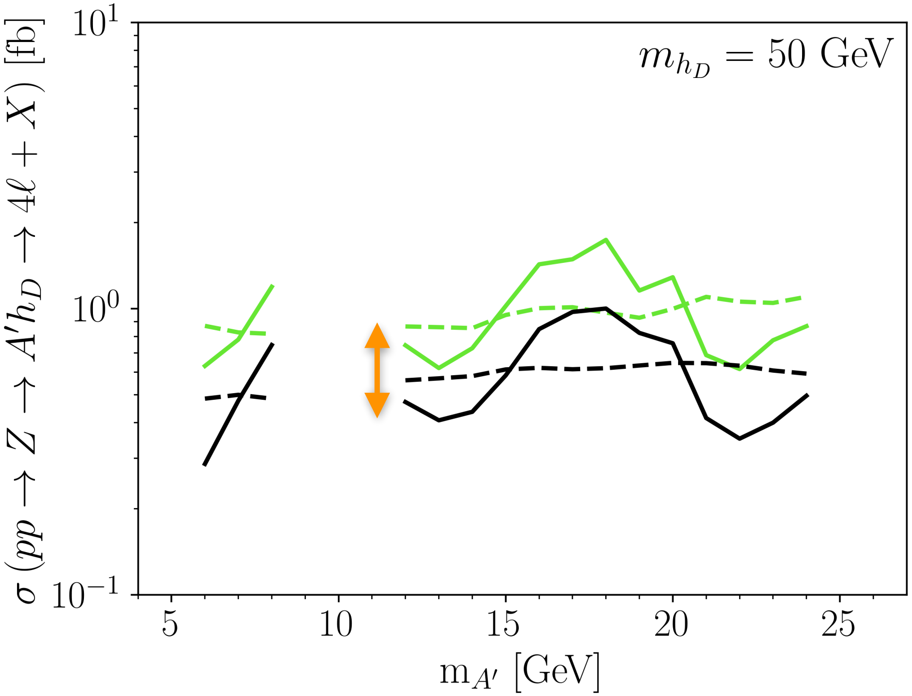


- Total uncertainty $\sim 60\,\%$
- CL_S method for limits on $\sigma(pp \to Z \to A'h_D \to 4l + X)$

Figure from [2412.14452 JC & Husain & Li & Strassler]







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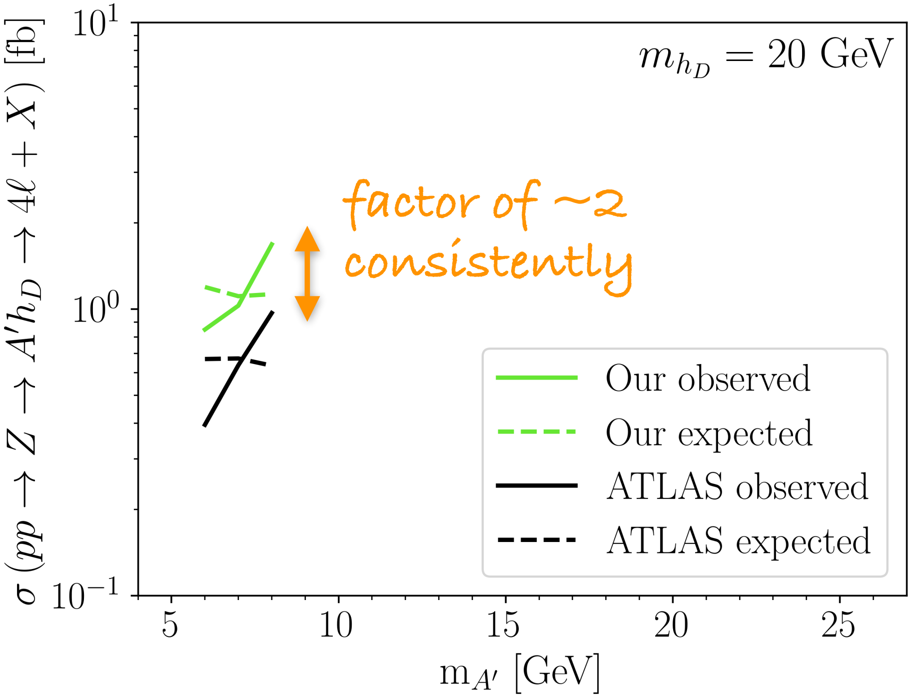

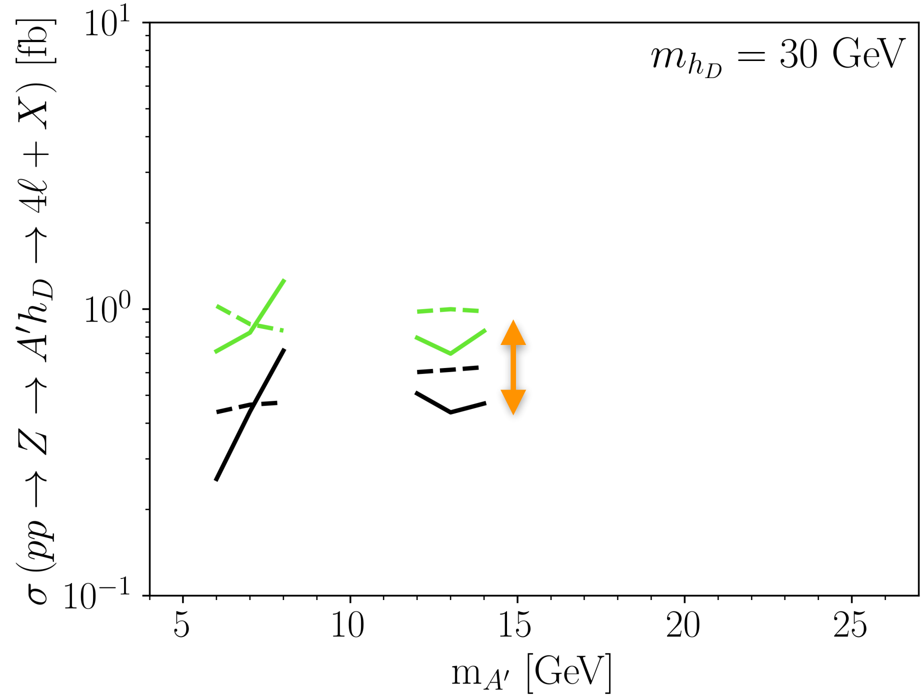

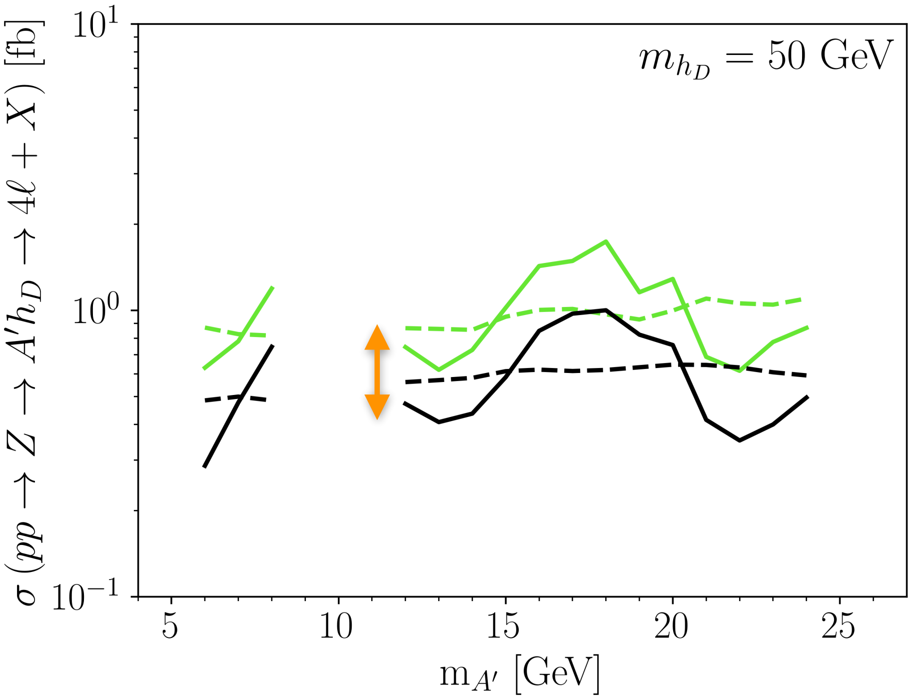

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Figure from [2412.14452 JC & Husain & Li & Strassler]

Ready to recast!

HV/DS models: estimate of uncertainties

- Total uncertainty $\sim$ recast uncertainty $+ \delta$hadron $+ \delta n$

- δhadron: uncertainty from Pythia HV/Lund model parameter choice
- Lattice & experiment inspired central value & range of variation
- Dominated by p_V (probability to produce ρ_D instead of π_D) & (a, b) (how dark shower energy is distributed among dark hadrons)

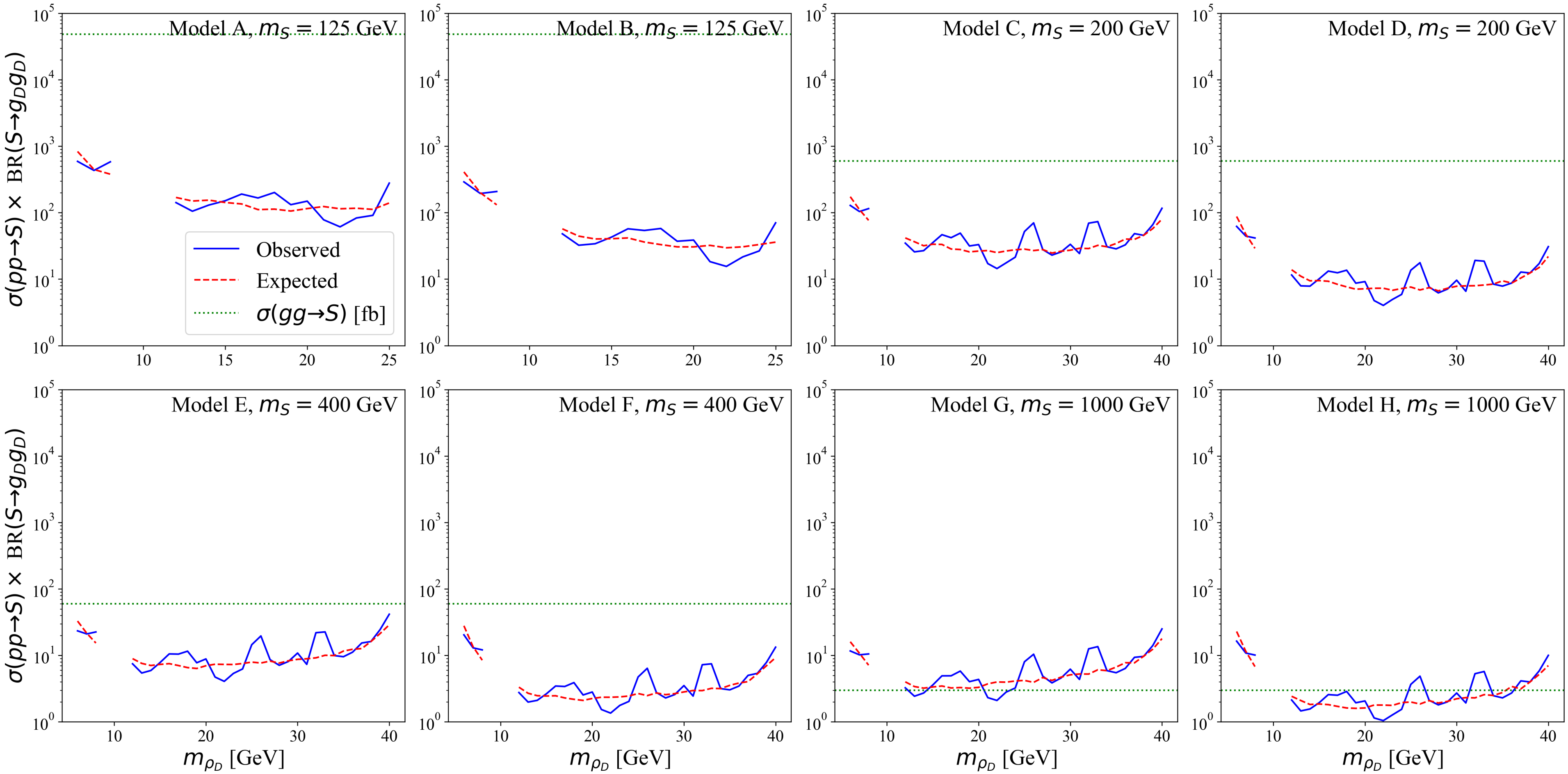
- δn: intrinsic uncertainty of Pythia Lund model
- e.g. dark hadron multiplicity

HV/DS models: estimate of uncertainties

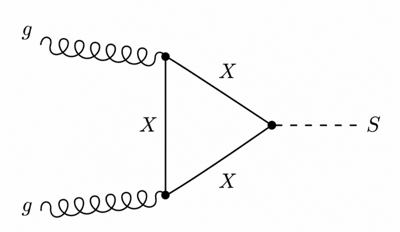
- Total uncertainty dominated by recast uncertainty $\sim 60\,\%$
- We do not put limits on models AB for $m_{\rho_D} > 25$ GeV

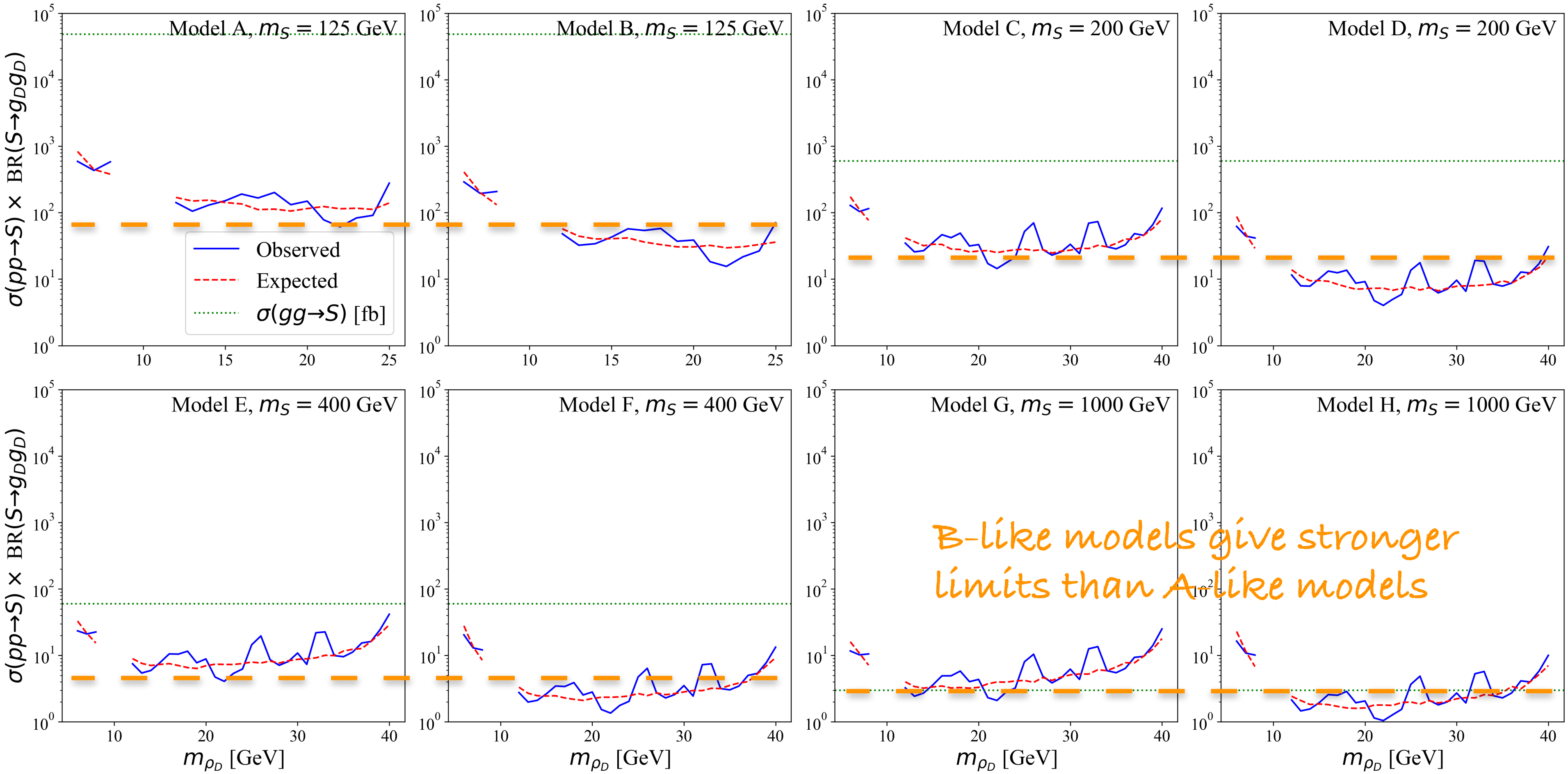
total uncertainty

m_S [GeV]	Model	m_{ρ_D} [GeV]			
		8	15	25	40
125	Model A	64.4%	70.2%	98.1%	–
	Model B	65.5%	69.7%	98.6%	–
200	Model C	64.8%	65.3%	66.7%	69.7%
	Model D	63.7%	64.8%	66.1%	67.1%
400	Model E	61.0%	62.0%	62.7%	62.7%
	Model F	60.8%	61.4%	62.0%	62.1%
1000	Model G	61.6%	62.1%	62.3%	61.9%
	Model H	61.7%	61.5%	61.2%	60.8%



- Models AB: use $\sigma(gg \to h) \sim 48600$ fb
- Models C-H: use $\sigma(gg \to S)$ in benchmark model $\longrightarrow$





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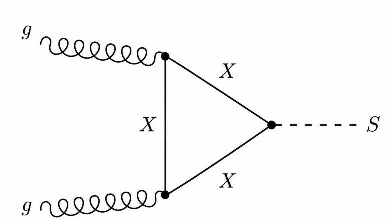

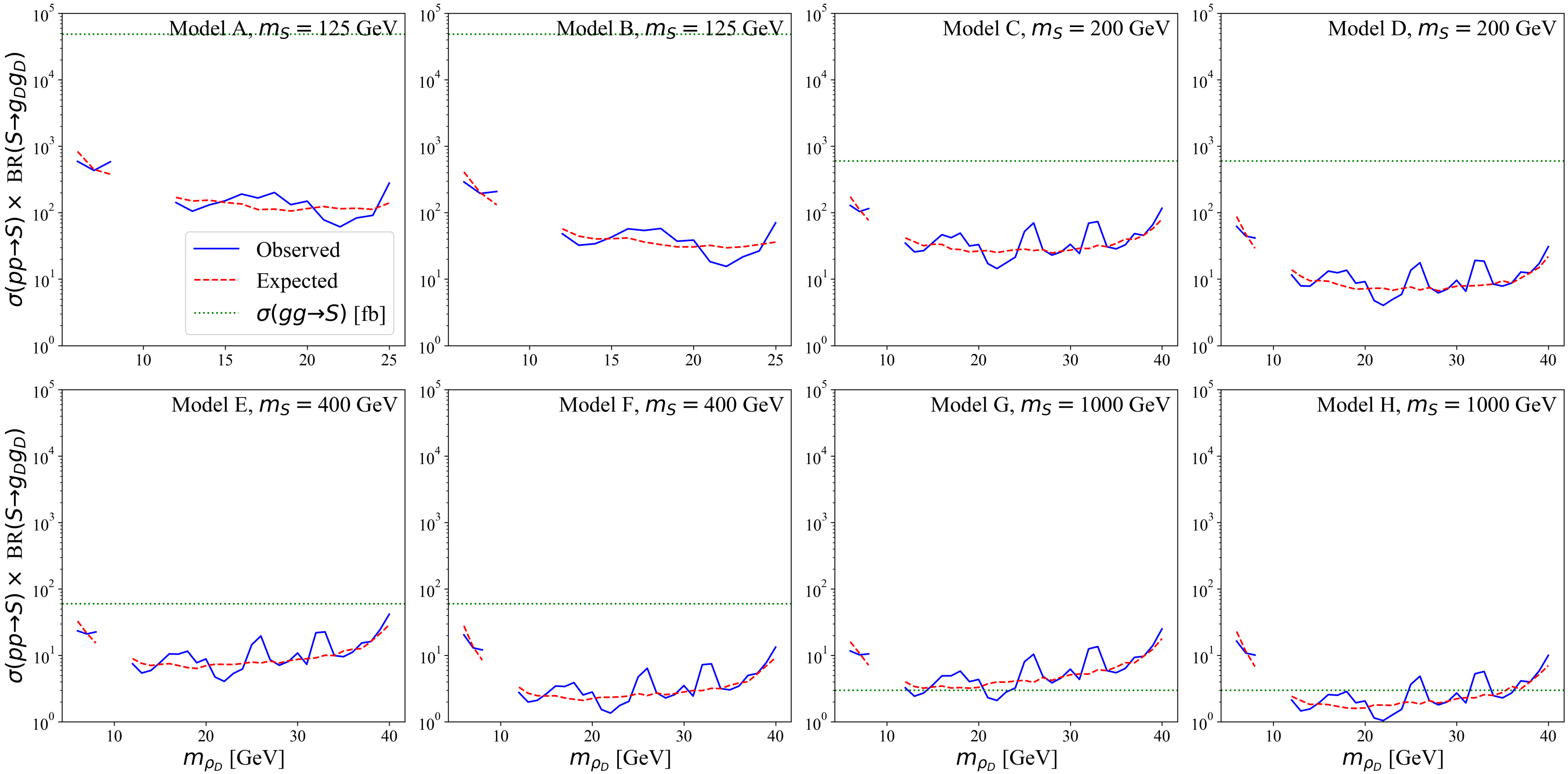

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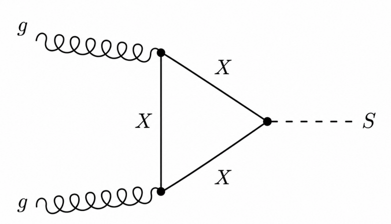

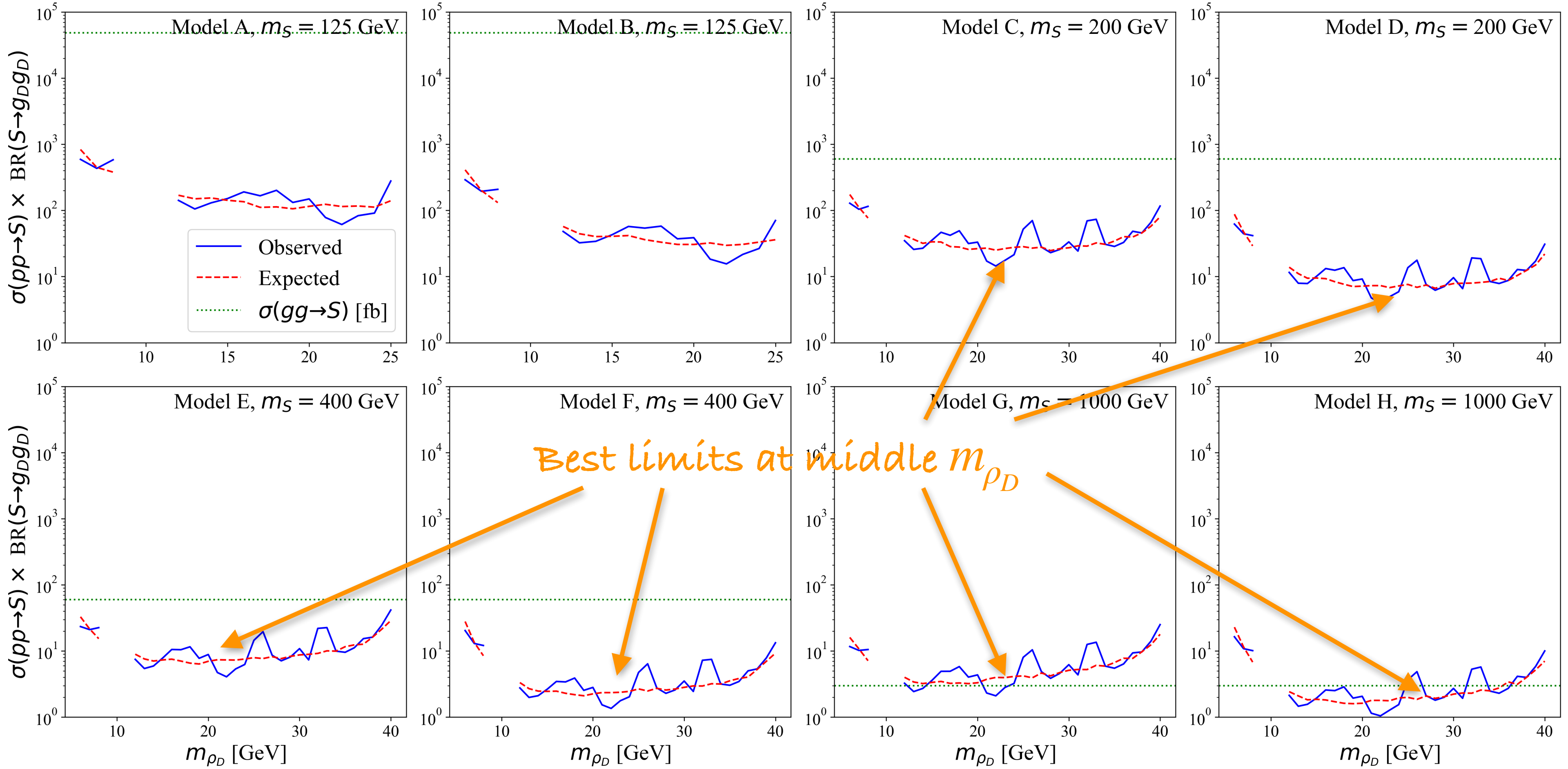

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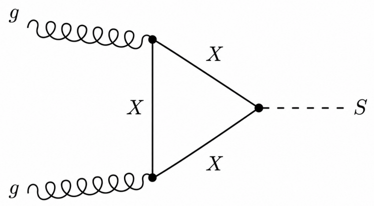
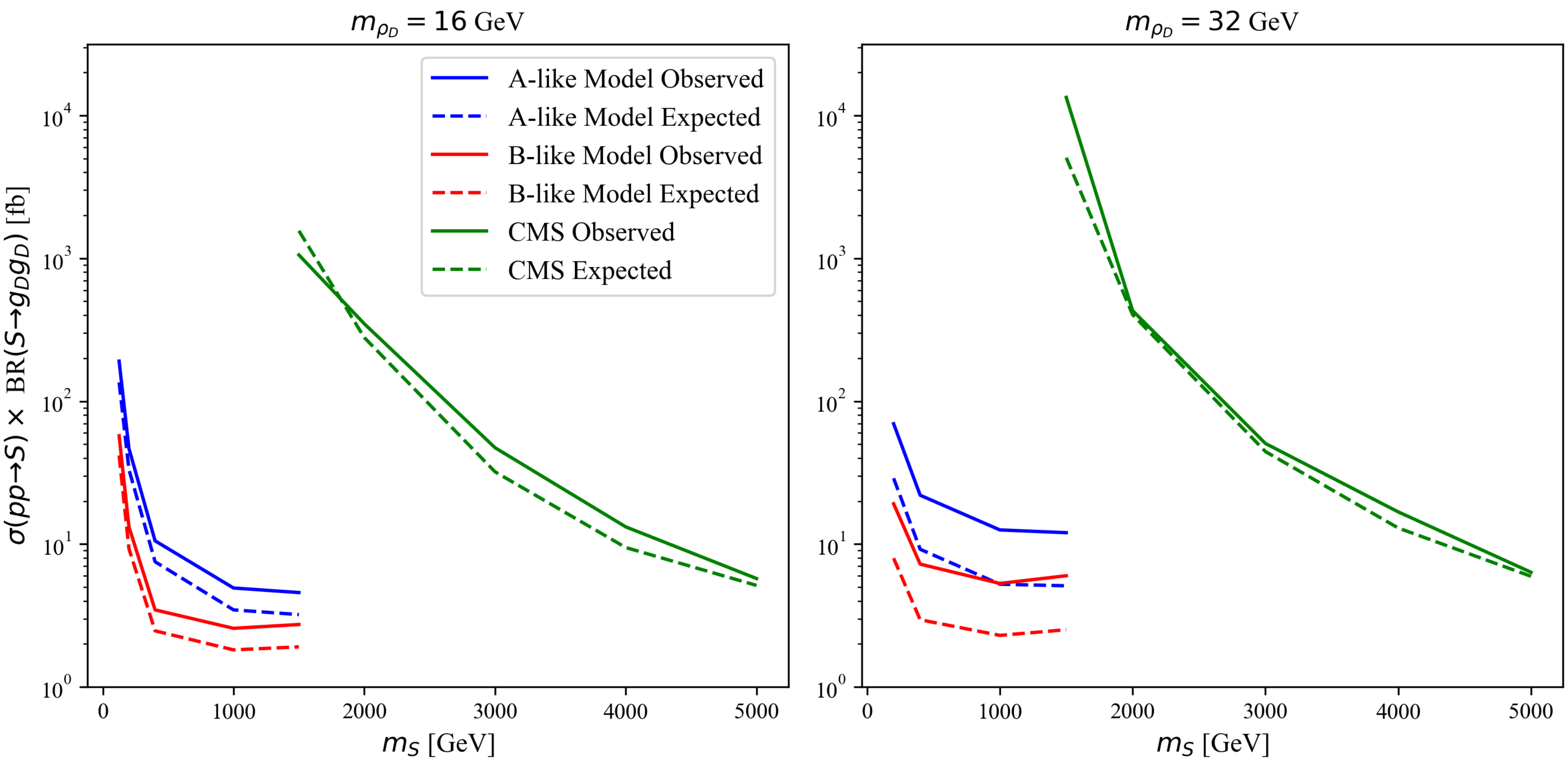


HV/DS models: compare with semivisible jet search [CMS EXO-24-029, 2025]

- CMS signal: $Z' \to q_D \bar{q}_D \to 2$ lepton-enriched semivisible jets
- Why our limits are stronger: reconstructing leptons is easier than reconstructing jets & we have tiny backgrounds & clean resonances



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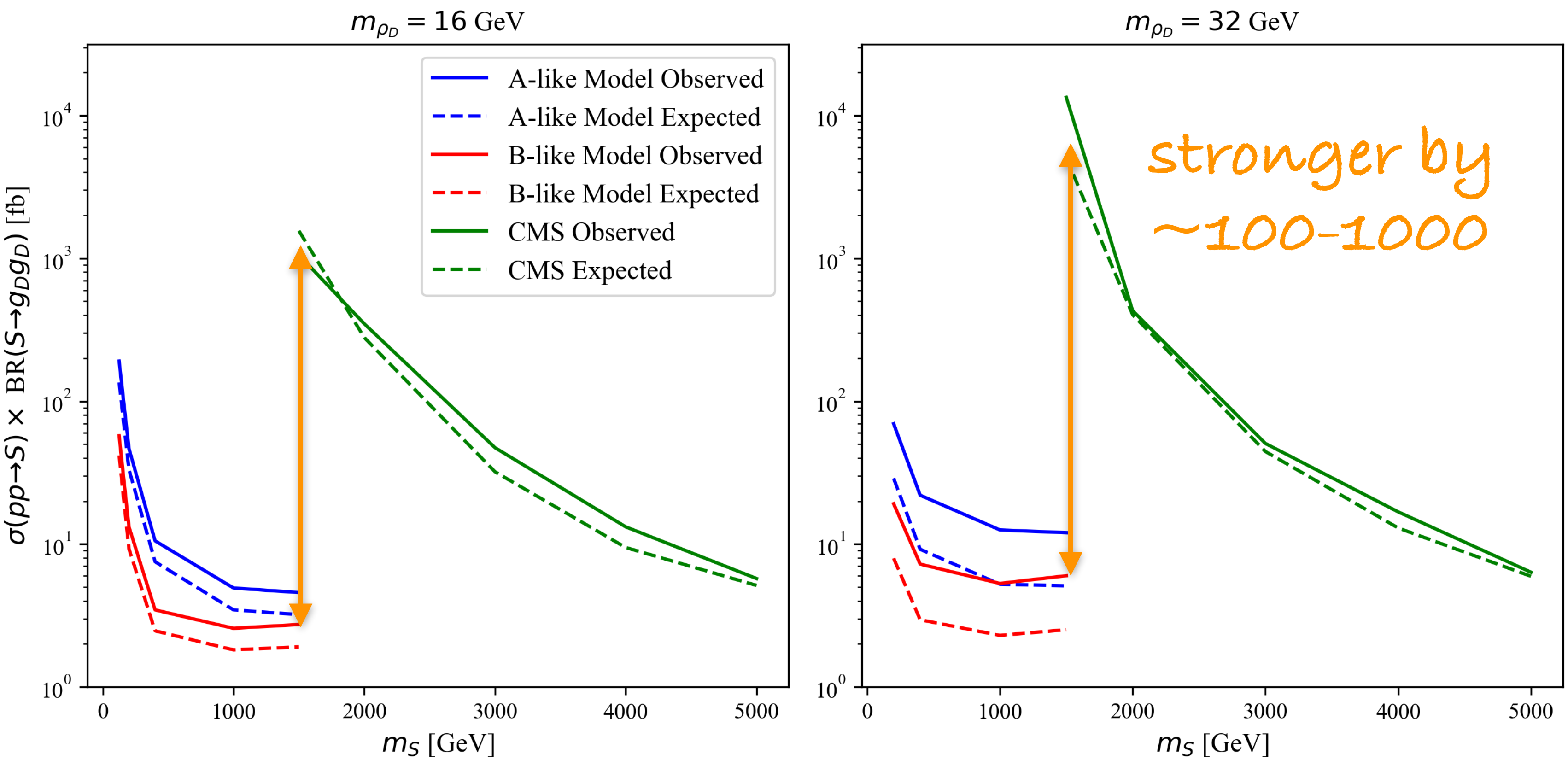

Conclusions

- ATLAS four-lepton search provides powerful, model-agnostic sensitivity to confining dark sectors where dark vectors ρ_D decay promptly to leptons.
- Reinterpreting the ATLAS $Z \to 6f$ analysis demonstrates that existing multi-lepton data can effectively constrain scalar-mediated Hidden Valley models.
- Despite large uncertainties from dark hadronization, the recast yields meaningful and robust exclusion limits.
- Using di-lepton mass reconstruction in lepton final states offers better sensitivity over traditional semivisible jet searches due to significantly lower backgrounds.

Conclusions

Thank you for your attention!

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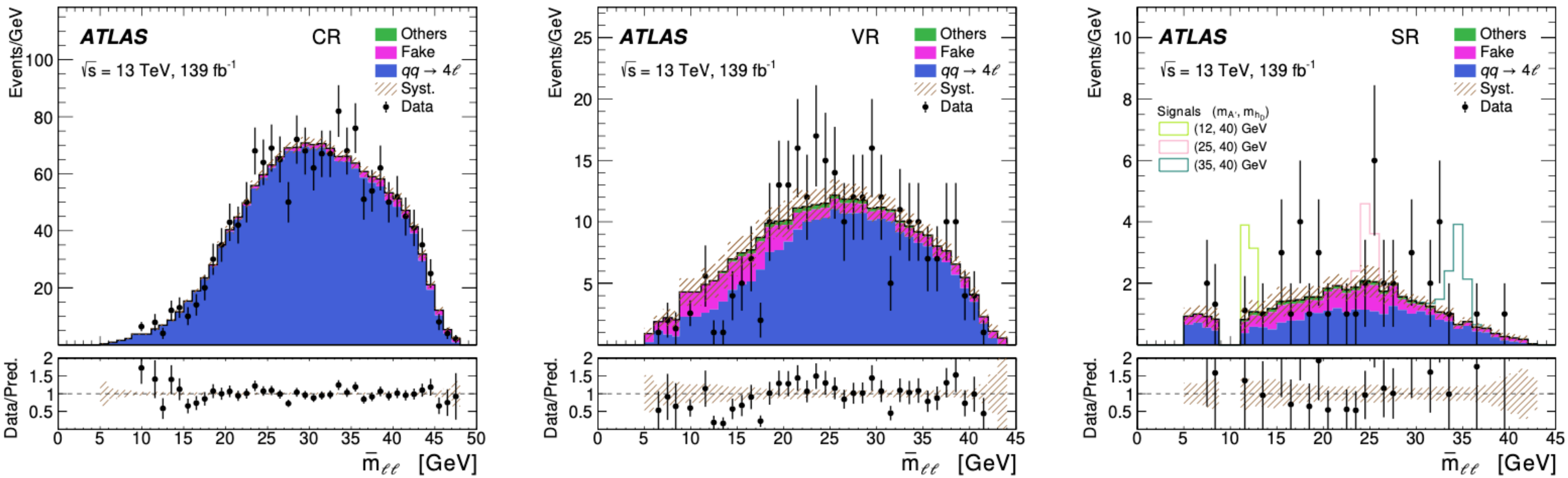
BACKUP SLIDES



SM backgrounds	SR	CR	VR
$qq \to 4\ell$	26.0 ± 2.4	1555 ± 48	239 ± 15
Fake	13.2 ± 5.6	43 ± 25	47 ± 26
Others	2.2 ± 0.7	5.8 ± 1.9	6.8 ± 2.0
Total background	41.3 ± 5.3	1604 ± 40	293 ± 28
Data	44	1602	286
Signal $(m_{A'}, m_{h_D})$ = (12, 30) GeV	5.9 ± 0.9	-	-
Signal $(m_{A'}, m_{h_D})$ = (25, 60) GeV	3.5 ± 0.6	-	-

Figure and table from [2306.07413 ATLAS]

Trigger

- p_T requirements:
  - single electron (26 GeV)
  - single muon (26 GeV)
  - dielectron symmetric (17 GeV)
  - dimuon symmetric (14 GeV)
  - dimuon asymmetric (22 GeV and 8 GeV)
  - electron (17 GeV) and muon (14 GeV)
  - two electron (12 GeV) and muon (10 GeV)
  - electron (12 GeV) and two muon (10 GeV)
- $|\eta_e| < 2.47$ for electrons, $|\eta_\mu| < 2.7$ for muons

Event selection cuts

- Number of identified leptons satisfying the following cuts ≥ 4:
  - $p_T^e > 4.5$ GeV, $p_T^\mu > 3$ GeV
  - $|\eta_e| < 2.47,\ |\eta_\mu| < 2.7$
  - $|z_0 \sin\theta| < 0.5$. z_0 is the longitudinal impact parameter relative to the primary vertex.
  - Isolation: $E^e_{\text{cone}20} < 0.2p_T^e$ & $(p_T)^e_{\text{varcone}20} < 0.15p_T^e$ for electrons. $E^e_{\text{cone}20}$ is the energy of all particles within a cone of $\Delta R = 0.2$ surrounding the electron. $(p_T)^e_{\text{varcone}20}$ is the scalar p_T sum of all charged particles (with $p_T > 1$ GeV and $|\eta| < 2.5$) that lie within a cone of radius $\Delta R = \min(10\text{ GeV}/p_T^e,\ 0.2)$ around the electron.
  - Isolation: $(p_T)^\mu_{\text{varcone}30} + 0.4E^\mu_{\text{neflow}20} < 0.16p_T^\mu$ for muons. $E^\mu_{\text{neflow}20}$ is the transverse energy of all neutral particle flow candidates within a cone of $\Delta R = 0.2$ surrounding the muon. $(p_T)^\mu_{\text{varcone}30}$ is the scalar p_T sum of all charged particles (with $p_T > 0.5$ GeV and $|\eta| < 2.5$) that lie within a cone of radius $\Delta R = \min(10\text{ GeV}/p_T^\mu,\ 0.3)$ around the muon.
- All possible 2 SFOC pairs need to satisfy $m_{4l} < m_Z - 5$ GeV. Pass if there are no 2 SFOC pairs.
- Number of SFOC pairs ≥ 2. Select the quadruplet with the smallest $m_{12} - m_{34}$, where $m_{12} > m_{34}$ are the SFOC 2-lepton invariant masses. Also need all possible combinations in the 4 selected leptons to satisfy $\Delta R > 0.1$ for 2 same flavor leptons and $\Delta R > 0.2$ for 2 different flavor leptons.
- $m_{34}/m_{12} > 0.85$
- All possible SFOC 2-lepton invariant masses need to satisfy $m_{ll} \notin [0,5] \cup [8.761,11.105]$ GeV

$Z \to 6f$ model: estimate of uncertainties

- $$\sigma_{\text{eff,reco}} = \sqrt{\left(4\frac{\Delta r_{\text{lep}}}{r_{\text{lep}}}\right)^2 + \left(\frac{\Delta r_{\text{trig}}}{r_{\text{trig}}}\right)^2 + \delta\text{theory}^2} \approx 0.6$$
- $\Delta r_{\text{lep}} = 0.11$, $r_{\text{lep}} = 0.78$
- $\Delta r_{\text{trig}} = 0.10$, $r_{\text{trig}} = 0.81$
- $\delta\text{theory} = 0.14$: theoretical uncertainty from perturbative calculations, hadronization, and parton distribution functions, same as in [2306.07413 ATLAS]

HV/DS models: estimate of uncertainties

- $\sigma_{\text{eff,reco}} = \sqrt{\left(4\frac{\Delta r_{\text{lep}}}{r_{\text{lep}}}\right)^2 + \left(\frac{\Delta r_{\text{trig}}}{r_{\text{trig}}}\right)^2 + \delta\text{theory}^2 + \delta\text{hadron}^2 + \frac{\delta n^2}{3}}$
- Combined theoretical uncertainty subdominant compared to recast uncertainty
- Add isolation correction factor trigY/trigN<1 to efficiency without uncertainty

- $\Delta r_{\text{lep}} = 0.11$, $r_{\text{lep}} = 0.78$
- $\Delta r_{\text{trig}} = 0.10$, $r_{\text{trig}} = 0.81$
- $\delta\text{theory} = 0.15$: theoretical uncertainty from $S\ p_T$ distribution

[Chen & Gehrmann & Glover & Huss & Li & Neill et al 2019]

We do not put limits on models AB for $m_{\rho_D} > 25$ GeV

δhadron

m_{ρ_D} [GeV]	7	12	15	25	35
Model A	0.196	0.204	0.206	0.234	0.273
Model B	0.225	0.188	0.188	0.227	0.257
Model C	0.217	0.197	0.190	0.197	0.211
Model D	0.181	0.167	0.185	0.191	0.190
Model E	0.116	0.156	0.171	0.187	0.184
Model F	0.101	0.135	0.149	0.158	0.159
Model G	0.138	0.158	0.161	0.173	0.169
Model H	0.145	0.138	0.138	0.129	0.118

δn

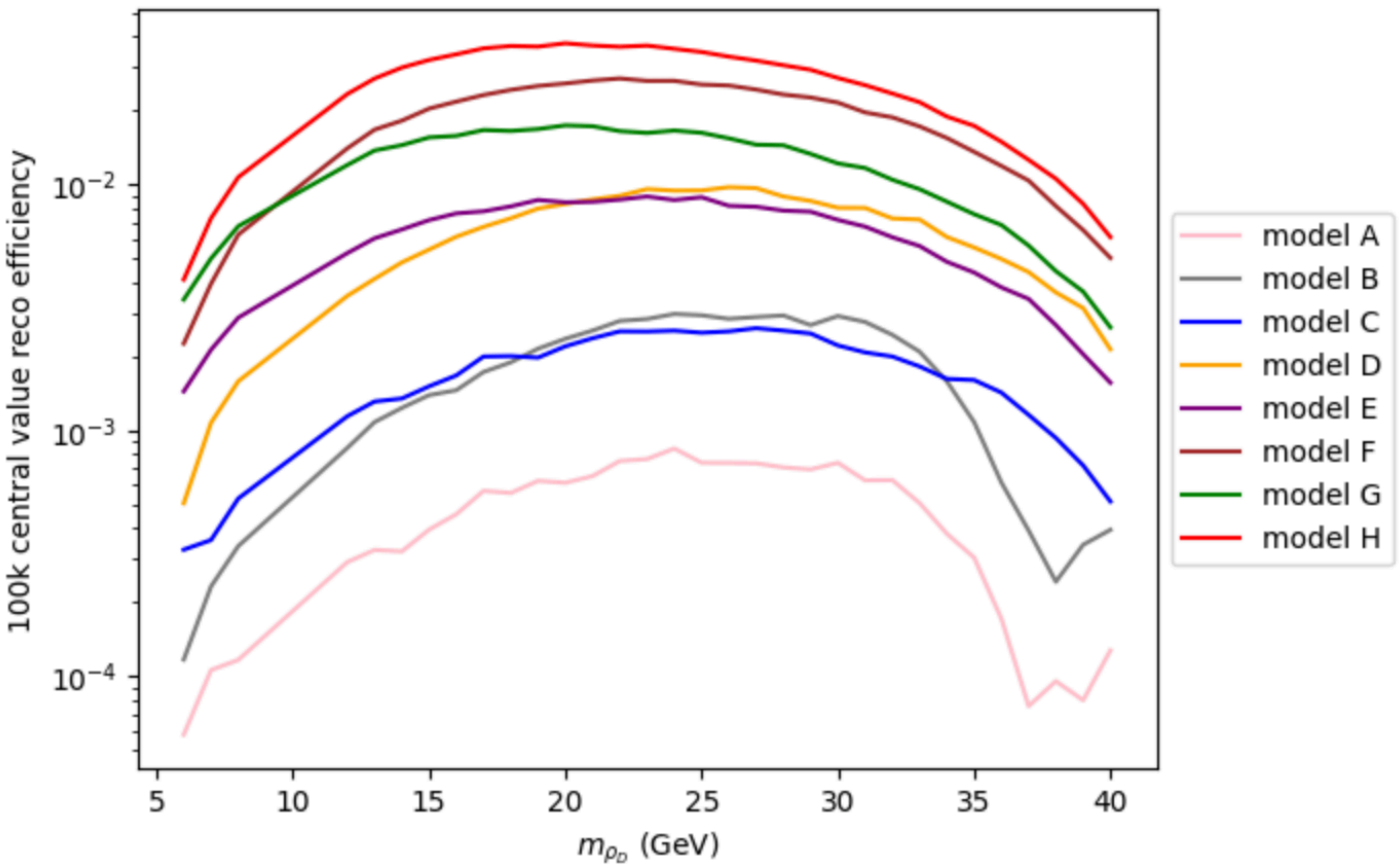
m_{ρ_D} [GeV]	7	12	15	25	35
Model A	0.215	0.401	0.518	1.287	0.147
Model B	0.267	0.426	0.515	1.303	1.164
Model C	0.234	0.285	0.313	0.394	0.455
Model D	0.226	0.278	0.305	0.373	0.407
Model E	0.015	0.005	0.004	0.035	0.114
Model F	0.083	0.058	0.049	0.056	0.119
Model G	0.099	0.096	0.094	0.087	0.080
Model H	0.110	0.103	0.099	0.084	0.070

total uncertainty

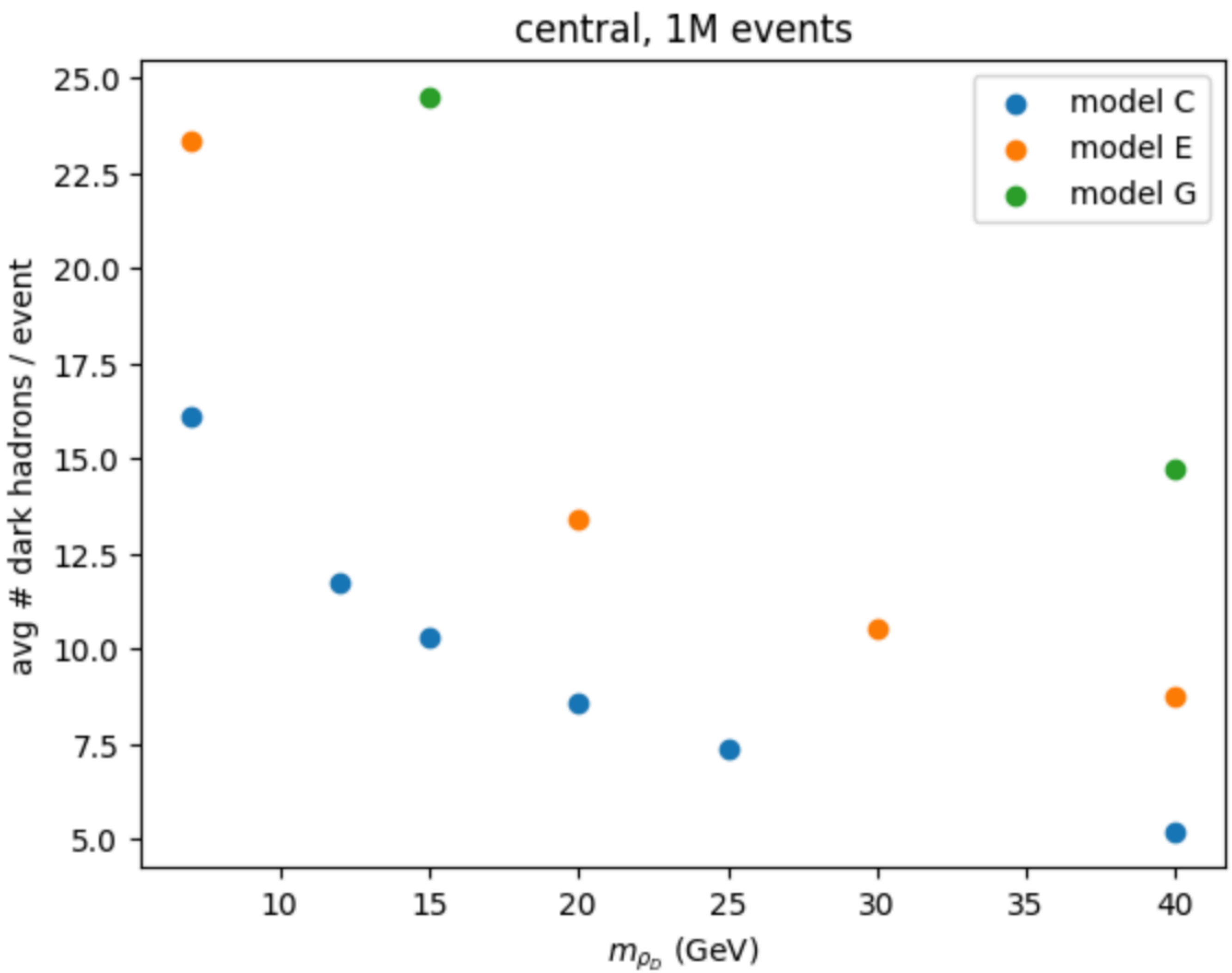
m_{ρ_D} [GeV]	8	15	25	40
Model A	64.4%	70.2%	98.1%	–
Model B	65.5%	69.7%	98.6%	–
Model C	64.8%	65.3%	66.7%	69.7%
Model D	63.7%	64.8%	66.1%	67.1%
Model E	61.0%	62.0%	62.7%	62.7%
Model F	60.8%	61.4%	62.0%	62.1%
Model G	61.6%	62.1%	62.3%	61.9%
Model H	61.7%	61.5%	61.2%	60.8%

isolation correction factor

m_{ρ_D} [GeV]	7	12	15	25	35
Model A	0.905	0.938	0.947	0.962	
Model B	0.935	0.958	0.959	0.959	
Model C	0.938	0.987	0.989	0.991	0.991
Model D	0.902	0.949	0.961	0.980	0.988
Model E	0.921	0.949	0.959	0.979	0.990
Model F	0.752	0.922	0.949	0.973	0.977
Model G	0.828	0.919	0.942	0.973	0.984
Model H	0.509	0.743	0.824	0.955	1.006



100k central value reco efficiency
10^{-2}
10^{-3}
10^{-4}
5
10
15
20
25
30
35
40
m_{ρ_D} (GeV)
model A
model B
model C
model D
model E
model F
model G
model H


central, 1M events
avg # dark hadrons / event
25.0
22.5
20.0
17.5
15.0
12.5
10.0
7.5
5.0
10
15
20
25
30
35
40
m_{ρ_D} (GeV)
model C
model E
model G

Sample	Varied parameter(s)	Central value(s)	Varied value(s)
central	–	$\sigma_{\text{Lund}} = 0.344\, m_{\rho_D}$ $a_{\text{Lund}} = 0.68$ $b_{\text{Lund}} = 0.0916\sigma^2_{\text{Lund}}$ $P_{\text{vec}} = 0.37$ $\Lambda_{\overline{\text{MS}}} = 0.317\, m_{\rho_D}$ $p^{\text{FSR}}_{T,\text{min}} = 1.5\,\Lambda_{\overline{\text{MS}}}$ $\alpha_{\text{order}} = 1$	same as central
sig1	σ_{Lund}	$\sigma_{\text{Lund}} = 0.344\, m_{\rho_D}$	$\sigma_{\text{Lund}} = (0.344 + 0.053)\, m_{\rho_D}$ $b_{\text{Lund}} = 0.0916\sigma^2_{\text{Lund}}$
sig2	σ_{Lund}	$\sigma_{\text{Lund}} = 0.344\, m_{\rho_D}$	$\sigma_{\text{Lund}} = (0.344 - 0.053)\, m_{\rho_D}$ $b_{\text{Lund}} = 0.0916\sigma^2_{\text{Lund}}$
ab1	$a_{\text{Lund}}, b_{\text{Lund}}$	$a_{\text{Lund}} = 0.68$ $b_{\text{Lund}} = 0.0916\sigma^2_{\text{Lund}}$	$a_{\text{Lund}} = 0.40$ $b_{\text{Lund}} = 0.060\sigma^2_{\text{Lund}}$
ab2	$a_{\text{Lund}}, b_{\text{Lund}}$	$a_{\text{Lund}} = 0.68$ $b_{\text{Lund}} = 0.0916\sigma^2_{\text{Lund}}$	$a_{\text{Lund}} = 0.96$ $b_{\text{Lund}} = 0.123\sigma^2_{\text{Lund}}$
ab3	$a_{\text{Lund}}, b_{\text{Lund}}$	$a_{\text{Lund}} = 0.68$ $b_{\text{Lund}} = 0.0916\sigma^2_{\text{Lund}}$	$a_{\text{Lund}} = 0.88$ $b_{\text{Lund}} = 0.073\sigma^2_{\text{Lund}}$
ab4	$a_{\text{Lund}}, b_{\text{Lund}}$	$a_{\text{Lund}} = 0.68$ $b_{\text{Lund}} = 0.0916\sigma^2_{\text{Lund}}$	$a_{\text{Lund}} = 0.48$ $b_{\text{Lund}} = 0.110\sigma^2_{\text{Lund}}$
pv1	P_{vec}	$P_{\text{vec}} = 0.37$	$P_{\text{vec}} = 0.37 + 0.07$
pv2	P_{vec}	$P_{\text{vec}} = 0.37$	$P_{\text{vec}} = 0.37 - 0.07$
L1	$\Lambda_{\overline{\text{MS}}}$	$\Lambda_{\overline{\text{MS}}} = 0.317\, m_{\rho_D}$	$\Lambda_{\overline{\text{MS}}} = (0.317 + 0.025)\, m_{\rho_D}$ $p^{\text{FSR}}_{T,\text{min}} = 1.5\,\Lambda_{\overline{\text{MS}}}$
L2	$\Lambda_{\overline{\text{MS}}}$	$\Lambda_{\overline{\text{MS}}} = 0.317\, m_{\rho_D}$	$\Lambda_{\overline{\text{MS}}} = (0.317 - 0.062)\, m_{\rho_D}$ $p^{\text{FSR}}_{T,\text{min}} = 1.5\,\Lambda_{\overline{\text{MS}}}$
pt1	$p^{\text{FSR}}_{T,\text{min}}$	$p^{\text{FSR}}_{T,\text{min}} = 1.5\,\Lambda_{\overline{\text{MS}}}$	$p^{\text{FSR}}_{T,\text{min}} = 1.9\,\Lambda_{\overline{\text{MS}}}$
pt2	$p^{\text{FSR}}_{T,\text{min}}$	$p^{\text{FSR}}_{T,\text{min}} = 1.5\,\Lambda_{\overline{\text{MS}}}$	$p^{\text{FSR}}_{T,\text{min}} = 1.1\,\Lambda_{\overline{\text{MS}}}$
loop	α_{order}	$\alpha_{\text{order}} = 1$	$\alpha_{\text{order}} = 2$

Model	m_{ρ_D} [GeV]	r_{inv}
A	16	0.84
	32	0.87
C	16	0.82
	32	0.84
E	16	0.80
	32	0.81
G	16	0.79
	32	0.80
B	16	0.64
	32	0.75
D	16	0.62
	32	0.69
F	16	0.58
	32	0.64
H	16	0.58
	32	0.61

$r_{\text{inv}} = \left\langle \frac{N_{\text{stable}}}{N_{\text{stable}} + N_{\text{unstable}}} \right\rangle$, we compare with $r_{\text{inv}} = 0.7$ in [CMS EXO-24-029, 2025]