La Thuile 2024

Search for dark mesons decaying to top and bottom quarks with the ATLAS detector

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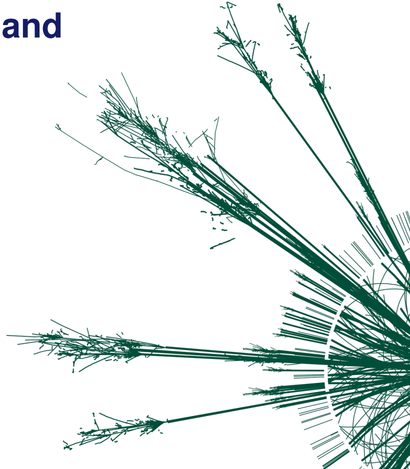
08 March, 2024

See ATLAS-CONF-2023-021

UNIVERSITY OF OREGON

ATLAS EXPERIMENT

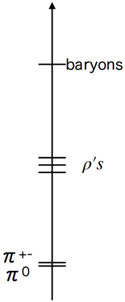


Imagine...

... a new strongly-coupled "dark" sector of vector-like fermions
... which transform under both the new dark group and the EW part of the SM group
... and also permits Higgs interactions

Mesons in QCD

- $SU(3)_{\text{colour}}$
- Exact $SU(2)$ isospin symmetry
- Fermions allowed to transform under EW and QCD
- Triplet of pions (π^-, π^0, π^+),...



"Dark" mesons

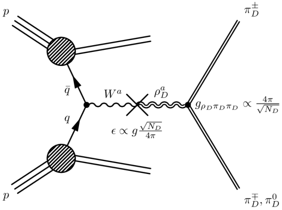
- $SU(N_{\text{dark}})$ (Here: $N_{\text{dark}} = 4$)
- Exact $SU(2)$ custodial symmetry
- Fermions allowed to transform under EW and "dark colour"
- Triplet of dark pions $(\pi_D^-, \pi_D^0, \pi_D^+)$,...

In arXiv:1809.10183 and arXiv:1809.10184 models containing a strongly-coupled, $SU(2)$ dark flavour symmetry preserving dark sector is developed and explored ⇒ Stealth Dark Matter [arXiv:1503.04203]

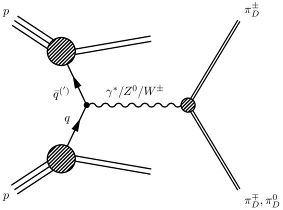
Production of Dark Pions

- Dark pions are always pair-produced and decay to pure SM states
- The dark sector is free of constraints from precision EW observables and Higgs coupling measurements

Resonant production via ρ_D



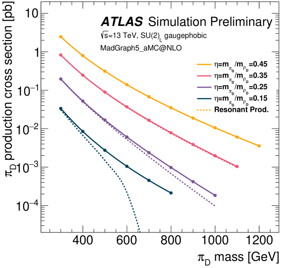
Drell-Yan-type production



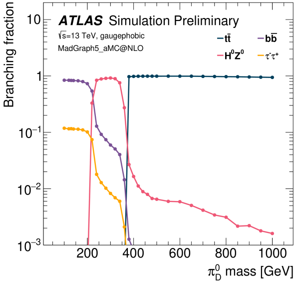
- Dark pion production trivially depends on $m_{\pi_D}/m_{\rho_D} = \eta$ (important parameter!)
- In this work focus on gaugephobic dark pion decay behaviour

Dark Pion Decays and Analysis Signature

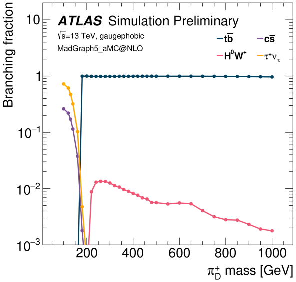
Production cross-section



Neutral π_D



Charged π_D



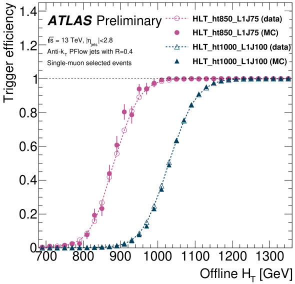
- Dark pions decay promptly back to SM states
- Branching fractions only depend on "gaugephobic-nes" and the mass of the dark pion
- Decays to t's and b's dominate once kinematically open ⇒ Consider ttbb and tttb final states
- Conduct search in the all-hadronic channel (search in 1-lepton channel is forthcoming)

Premise and Online Event Selection

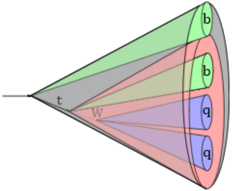
- This work is the first direct collider search for this type of model
- Existing limits from reinterpretation of ATLAS and CMS results are fairly weak
- Scanning 2-dimensional parameter space depending on η and m_{π_D}

- High jet-multiplicity + dark pions from heavy ρ_D decay
  $\Rightarrow$ Use lowest unprescaled H_T triggers
- H_T triggers reach full efficiency for large m_{π_D}
- Good agreement between simulated onset and real onset
  $\Rightarrow$ Onset has minimal impact on systematics

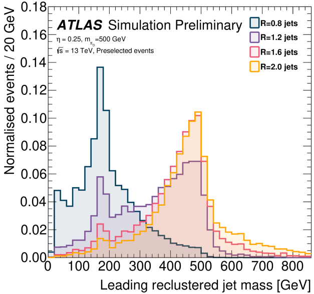
- All-hadronic channel sensitive to models with low η and low to medium dark pion masses
- 1-lepton channel more sensitive to higher η values

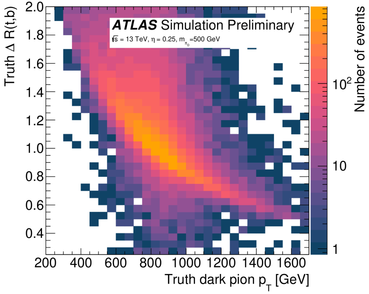


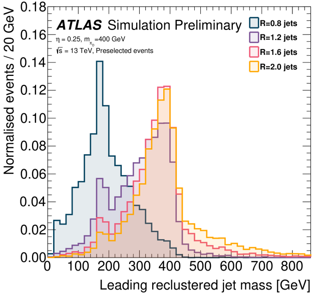
Dark Pion Reconstruction



- Dark pion reconstruction using reclustering of anti-k_t $R = 0.4$ PFlow jets
- R-parameter needs to strike balance between π_D reconstruction and QCD susceptibility
- $R = 1.2$ has best overall performance for targeted signal points







Preselection

- Event quality cuts that ensure operational detector
- Veto events containing any loose electrons or muons
- Require $H_T > 1150$ GeV
- At least six jets with $p_T > 25$ GeV to suppress QCD
- At least 3 b-tagged jets
- At least two reclustered jets with mass > 190 GeV

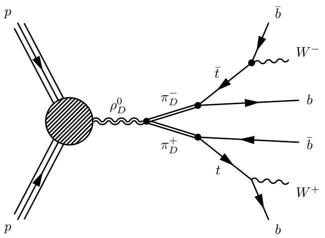
Sample	Yield	Percent SM MC sum
$t\bar{t}$	8756.9	78.0
V + jets	1688.3	15.0
$t\bar{t}$ + X	405.6	3.6
SingleTop	375.0	3.3
Multiboson	0.8	< 1
SM sum	11226.5	100
SU2L-45-400	804.7	
SU2L-35-500	867.3	
SU2L-25-500	549.5	
Data	67339	

Process	Generator	PDF	Showering	Tune	Cross section
$t\bar{t}$	PowhegBox v2	NNPDF3.0nlo	Pythia8	A14	NNLO+NNLL
$t\bar{t}$+HF	Powheg Box Res	NNPDF3.0nlo	Pythia8	A14	NNLO
V + jets	Sherpa v2.2.11	NNPDF3.0nnlo	Sherpa	Def.	NLO
Single top	PowhegBox v2	NNPDF3.0nlo	Pythia8	A14	NLO+NNLL
$t\bar{t}t\bar{t}$	MadGraph5_aMC@NLO v2.4.3	NNPDF3.1nlo	Pythia8	A14	NLO
$t\bar{t}V$	MadGraph5_aMC@NLO v2.3.3	NNPDF3.0nlo	Pythia8	A14	NLO
$t\bar{t}H$	PowhegBox v2	NNPDF3.0nlo	Pythia8	A14	NLO
Other $t\bar{t}$ + X	MadGraph5_aMC@NLO	NNPDF2.3lo	Pythia8	A14	NLO
Multiboson	Sherpa v2.2.1/v2.2.2	NNPDF3.0nnlo	Sherpa	Def.	NLO

- Dominant background from QCD

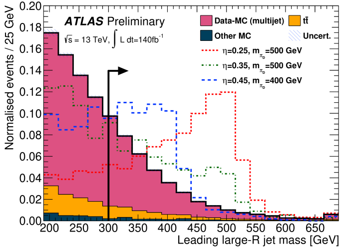
  ⇒ Data-driven background estimate using ABCD method

Define kinematic variables

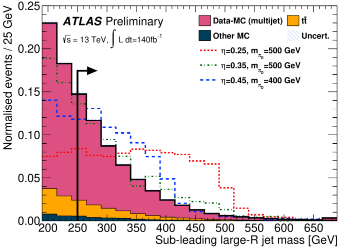


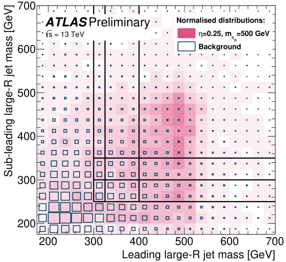
- Define a set of variables motivated by signal kinematics
  - $\Delta R(j, b_2)$: Distance between a RC jet and the second closest b-jet
  - $m_{bb}/p_{T,bb}$: For the closest b-jet pair to an RC jet to suppress QCD
  - $m_{\text{jet,R=1.2}}$: Mass of the RC jet, main discriminant
- Select ABCD regions based on $m_{bb}/p_{T,bb}$ and $m_{\text{jet,R=1.2}}$
- Subdivided into nine bins based on jet masses

Leading RC jet



Sub-leading RC jet





QCD Multijet Estimation

- Use a 4-variable generalisation of the ABCD method developed and used in arXiv:1801.02052
- Two tags and their slashed "anti-tags" are introduced:
  - bb_i-tag: i-th $R = 1.2$ jet has 2 b-tagged jets within $R = 1.0$
  - $\pi_{D,i}$-tag: i-th $R = 1.2$ jet has a mass within a certain window
- Permutations of all 4 tag states define 16 regions

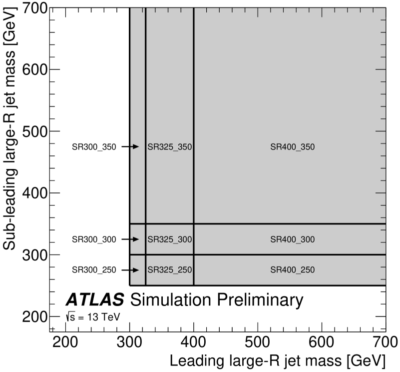
Leading large-R jet

Sub-leading large-R jet	$\not\pi_{D,1}\,\not{b}\not{b}_1$	$\pi_{D,1}\,\not{b}\not{b}_1$	$\not\pi_{D,1}\,bb_1$	$\pi_{D,1}\,bb_1$
$\pi_{D,2}\,bb_2$	J	K	L	S
$\not\pi_{D,2}\,bb_2$	B	D	H	N
$\pi_{D,2}\,\not{b}\not{b}_2$	E	F	G	M
$\not\pi_{D,2}\,\not{b}\not{b}_2$	A	C	I	O

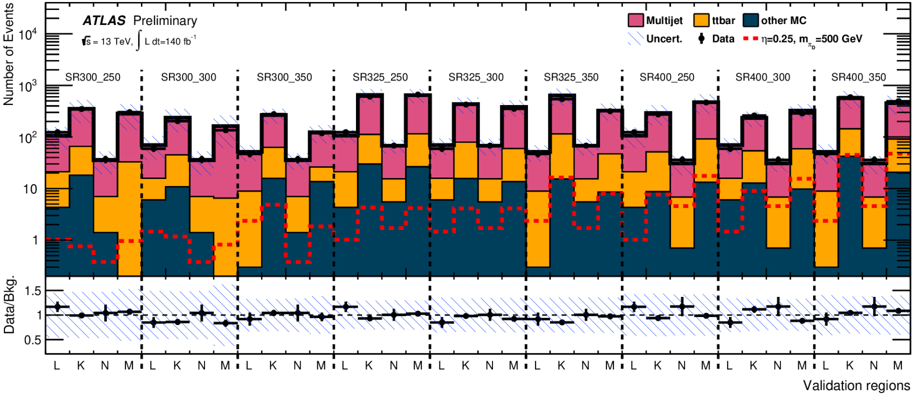
- Extrapolate from orange regions and use 2-tag correction factors for 1-tag correlations
- Signal region S (red) has all four tags applied
- 3-tag regions K, L, M and N (pink) are validation regions
- Perform independent estimates for each SR bin

Tag selections

	Tag	Variable	Tag selection	Anti-tag selection
Both large-R jets		$m_{bb}/p_{\mathrm{T},bb}$	> 0.25	
Leading large-R jet	bb_1	$\Delta R\,(j, b_2)$	< 1.0	≥ 1.0
Sub-leading large-R jet	bb_2	$\Delta R\,(j, b_2)$	< 1.0	≥ 1.0
Leading large-R jet	$\pi_{D,1}$	$m_{\mathrm{jet,R=1.2}}$	$[300 - 325\,GeV,$ $325 - 400\,GeV,$ $> 400\,GeV]$	$\leq 300\,GeV$
Sub-leading large-R jet	$\pi_{D,2}$	$m_{\mathrm{jet,R=1.2}}$	$[250 - 300\,GeV,$ $300 - 350\,GeV,$ $> 350\,GeV]$	$\leq 250\,GeV$



Validation of Multijet Estimate



- Have good agreement in all 36 VRs

  ⇒ Method works very well with no uncontrolled correlations

Systematic Uncertainties

- Main source of systematic uncertainty is the data-driven multijet estimation
- Study closure in all VR bins independently via k-factors $k_{VR} = (\text{data-MC})/\text{QCD}$
- Also consider statistical uncertainty on k-factors σ_k

Systematic: $\sigma_{ABCD} = \sqrt{(1 - \prod_{VR} k_{VR})^2 + \sum_{VR} \sigma^2_{k_{VR}}}$

	SR300_250	SR300_300	SR300_350
Non-closure uncertainty	40%	45%	1.4%
Stat. uncert. on k-factors	37%	35%	39%
Total Multijet Uncertainty	55%	57%	39%

	SR325_250	SR325_300	SR325_350
Non-closure uncertainty	16%	28%	28%
Stat. uncert. on k-factors	29%	29%	29%
Total Multijet Uncertainty	33%	40%	41%

	SR400_250	SR400_300	SR400_350
Non-closure uncertainty	34%	3.2%	29%
Stat. uncert. on k-factors	37%	38%	38%
Total Multijet Uncertainty	51%	38%	48%

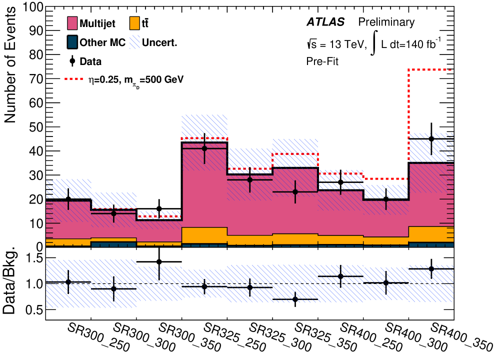
- All remaining systematic uncertainties propagated to multijet estimate
- With exception of ttbar modeling uncertainty (up to 6%) and some jet systematics (up to 4%), all systematics are small

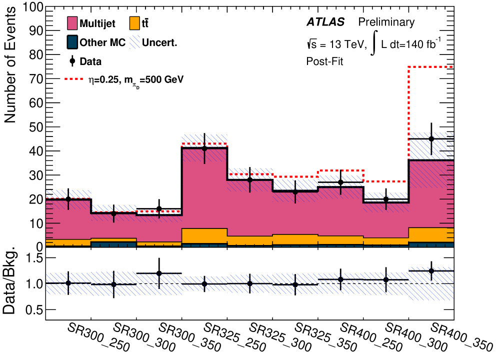
$\Rightarrow$ Expected since multijet estimate constrains to data

Statistical Analysis

- Perform a profile likelihood fit over all signal regions
- Nuisance parameters below 1% impact are pruned away

  ⇒ Excellent agreement of data and predicted background



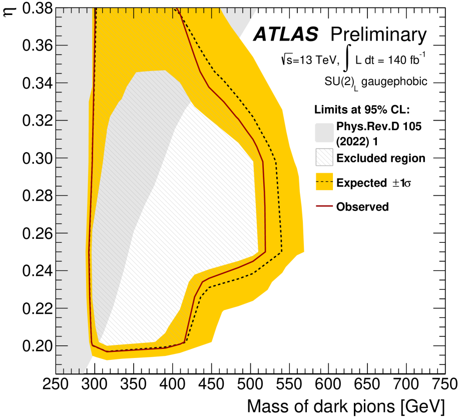


Results

- Setting limits on dark pion masses given predicted xsections

  $\Rightarrow$ Observed limits very similar to expected
- Huge gain in coverage over existing limits (grey area) based on reinterpretation
- First direct constraints to this type of model by a collider experiment
- See the full results here

- Expect 1-lepton channel to increase coverage extensively



Summary

- Searching for gaugephobic dark pion decays with signatures *ttbb or tttb* in the all-hadronic channel
- Reconstruction of dark pions from reclustered jets
- Cut-based selection with SR binned in large-R jet masses
- Data-driven estimate of QCD multijet background that passes validation tests
- Limits significantly extend existing coverage

- Link to publication

Postdoc contract ending in October this year!
Looking for a new member of your group?
⇒ linkedin.com/in/jochen-jens-heinrich

BACKUP MATERIAL

Link to publication

The Dark Meson Sector of Stealth Dark Matter [arXiv:1503.04203]

We can explore the phenomenology of such models which has never been done in ATLAS or CMS!

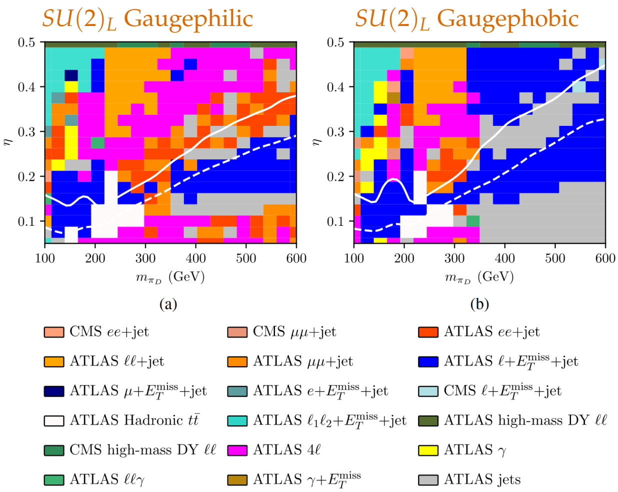
- Higgs interactions break the global (species) symmetries of the dark sector
  $\Rightarrow$ Allows dark pions to decay to SM
- The dark sector is free of constraints from precision EW observables and Higgs coupling measurements
  $\Rightarrow$ Very weak existing limits

Consider models with two flavours of dark fermions $\Rightarrow$ dark pions and one set of dark vector mesons

- Vector-like nature of dark sector permits two possibilities of gauging global flavour symmetry leading to two distinct models of kinetic mixing

$$SU(2) \text{ kinetic mixing:} \quad SU(2)_{\text{global flavour}} \leftrightarrow SU(2)_L$$
$$U(1) \text{ kinetic mixing:} \quad SU(2)_{\text{global flavour}} \leftrightarrow SU(2)_R$$

Existing constraints



- Phys. Rev. D **105**, 015008 (2022) tested the sensitivity of several ATLAS and CMS analyses
- Solid line is 95% CL exclusion, dashed corresponds to 68% CL
- Even weaker limits for $SU(2)_R$

  $\Rightarrow$ Vast parameter space still open!
- Other analyses fail to be sensitive because they are optimised for high target masses, expect single production or require large E_T^{miss}
- Strong constraints in models with $\eta > 0.5$ from dilepton searches

  $\Rightarrow$ Only consider models with $\eta < 0.5$ for analysis!

Object Definitions

Small-R Jets

Small-R Jets:

- $R = 0.4$ Anti-k_t EMPFlow Jets
- $p_T > 20$ GeV
- $|\eta| < 2.8$
- JVT working point: `tight`
- ForwardJVT working point: `tight`

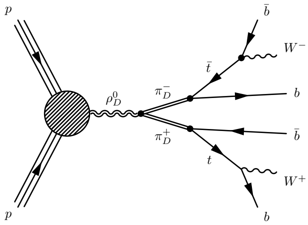
B-tagged Jets:

- $|\eta| < 2.5$
- Only for small-R jets
- DL1r tagger with 77% efficiency working point

Large-R Jets

Reclustered Jets:

- $R = 1.2$ and recluster
  $R = 0.4$ Anti-k_T EMPFlow Jets
- $m > 60$ GeV



Leptons

Baseline electron (for veto):

- ID: `MediumLH`
- Isolation: None
- $p_T > 10$ GeV
- $|\eta| < 1.37$ OR $1.52 < |\eta| < 2.47$

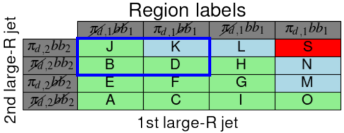
Baseline muon (for veto):

- ID: `Medium`
- Isolation: None
- $p_T > 10$ GeV
- $\eta < 2.7$

Details of the multijet estimate

- Consider estimate $\hat{K}$ in region K with standard ABCD

$$\hat{K} = \frac{J \cdot D}{B}$$



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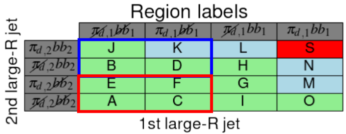

$$\hat{K} = \frac{J \cdot D}{B}$$

- This is correct if $\pi_{D,1}$ and $\pi_{D,2}$ uncorrelated, otherwise correct with $k_{\pi_{D,1},\pi_{D,2}} = \frac{F \cdot A}{C \cdot E}$

$$\hat{K} = \frac{J \cdot D}{B} \cdot \frac{F \cdot A}{C \cdot E} = \frac{J \cdot D}{B} \cdot k_{\pi_{D,1},\pi_{D,2}}$$

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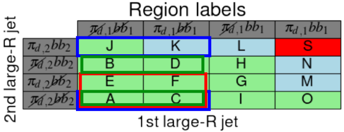

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$$\hat{K} = \frac{J \cdot D}{B} \cdot \frac{F \cdot A}{C \cdot E} = \frac{J \cdot D}{B} \cdot k_{\pi_{D,1},\pi_{D,2}}$$

- In a three-variable ABCD estimate with two correlation factors $\hat{K}$ would be computed via

$$\hat{K} = \frac{J \cdot C}{A} \cdot k_{\pi_{D,1},\pi_{D,2}} \cdot k_{\pi_{D,1},bb_2} = \frac{J \cdot C}{A} \cdot \frac{F \cdot A}{C \cdot E} \cdot \frac{D \cdot A}{B \cdot C} = \frac{J \cdot D \cdot F \cdot A}{B \cdot C \cdot E}$$

Details of the multijet estimate

Region labels

2nd large-R jet \ 1st large-R jet	$\not\pi_{d,1}\not{bb}_1$	$\pi_{d,1}\not{bb}_1$	$\not\pi_{d,1}bb_1$	$\pi_{d,1}bb_1$
$\pi_{d,2}bb_2$	J	K	L	S
$\not\pi_{d,2}bb_2$	B	D	H	N
$\pi_{d,2}\not{bb}_2$	E	F	G	M
$\not\pi_{d,2}\not{bb}_2$	A	C	I	O

- Consider estimate $\hat{K}$ in region K with standard ABCD

$$\hat{K} = \frac{J \cdot D}{B}$$

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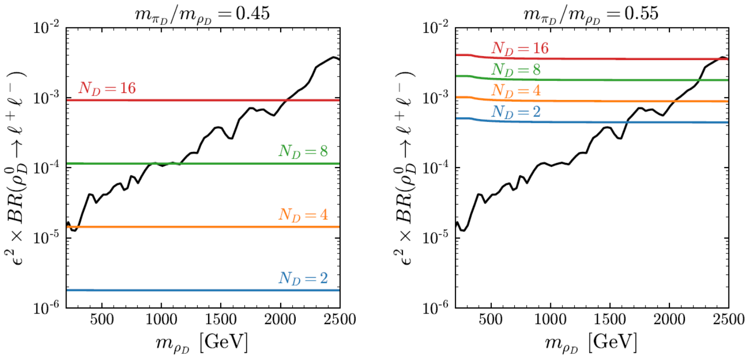
$$\hat{K} = \frac{J \cdot C}{A} \cdot k_{\pi_{D,1},\pi_{D,2}} \cdot k_{\pi_{D,1},bb_2} = \frac{J \cdot C}{A} \cdot \frac{F \cdot A}{C \cdot E} \cdot \frac{D \cdot A}{B \cdot C} = \frac{J \cdot D \cdot F \cdot A}{B \cdot C \cdot E}$$

- For a four-variable ABCD estimate $\hat{S}$ one needs to consider six correlation factors correcting the traditional estimate $\hat{S}'$

$$\hat{S} = \hat{S}' \cdot k_{\pi_{D,1},bb_1} \cdot k_{\pi_{D,2},bb_2} \cdot k_{\pi_{D,1},bb_2} \cdot k_{\pi_{D,2},bb_1} \cdot k_{\pi_{D,1},\pi_{D,2}} \cdot k_{bb_1,bb_2}$$

Constraints on ρ_D (see arXiv:1809.10184)



- Plot shows the constraints on the kinetic mixing between SM and ρ_D through absence of a dilepton reonance
- Coloured lines correspond to the $SU(2)_L$ model varying the number of colours N_D
- For $\eta < 0.5$, there is virtually no constraint on ρ_D when $N_D \leq 4$