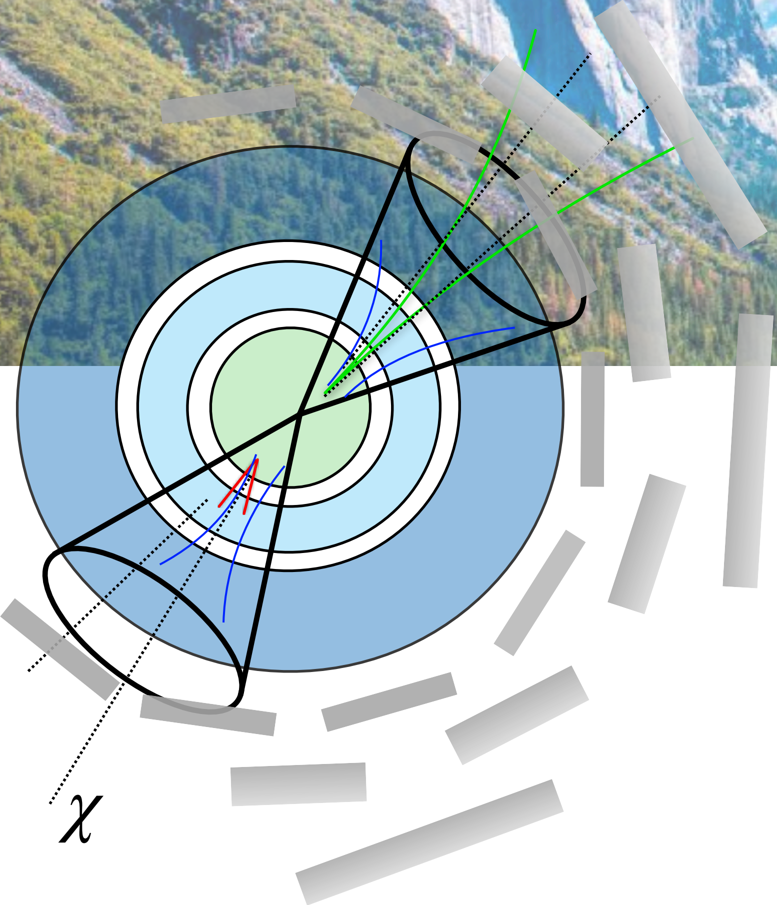
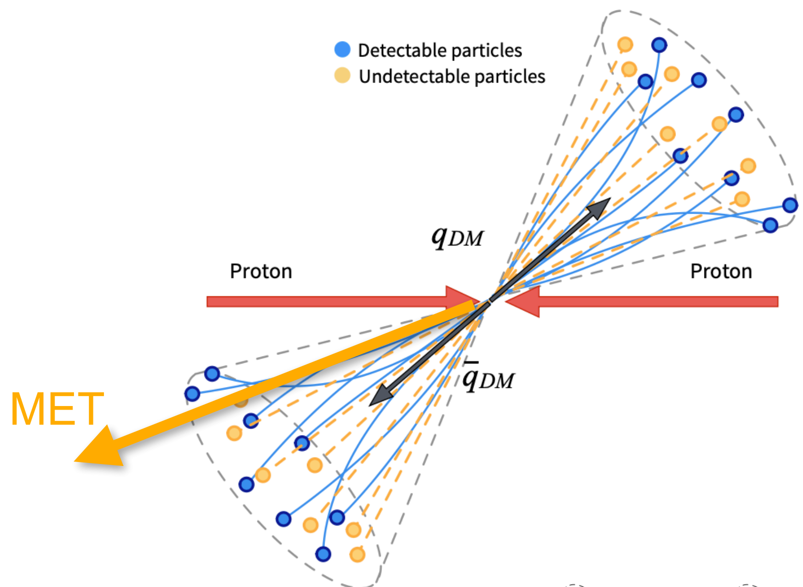


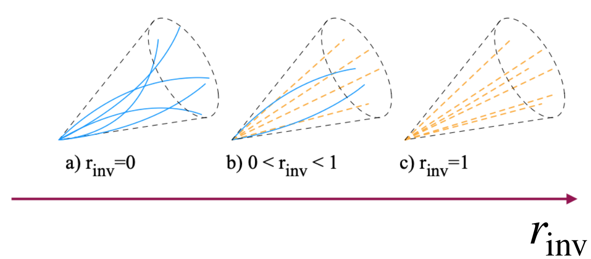
Probing New Signatures For Semi-Visible Jets At The LHC

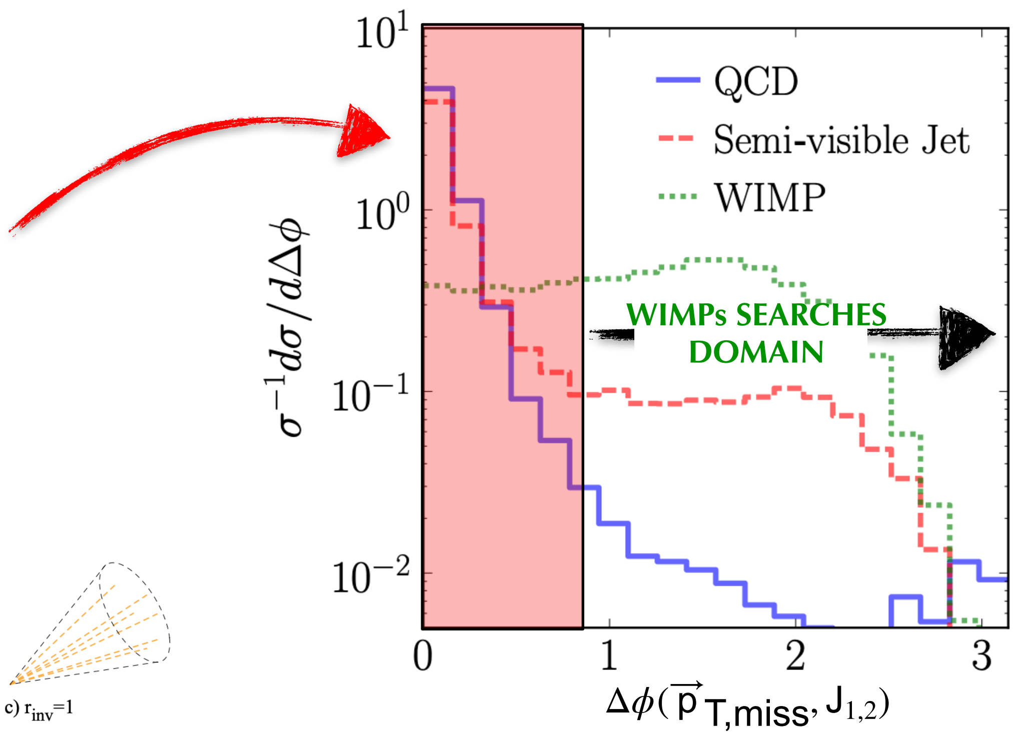
Cesare Cazzaniga (ETH Zurich)

UNCONVENTIONAL SIGNATURES: SEMI-VISIBLE JETS



$$r_{inv} = \left\langle \frac{\textbf{\textit{N stable dark hadrons}}}{\textbf{\textit{N dark hadrons}}} \right\rangle$$

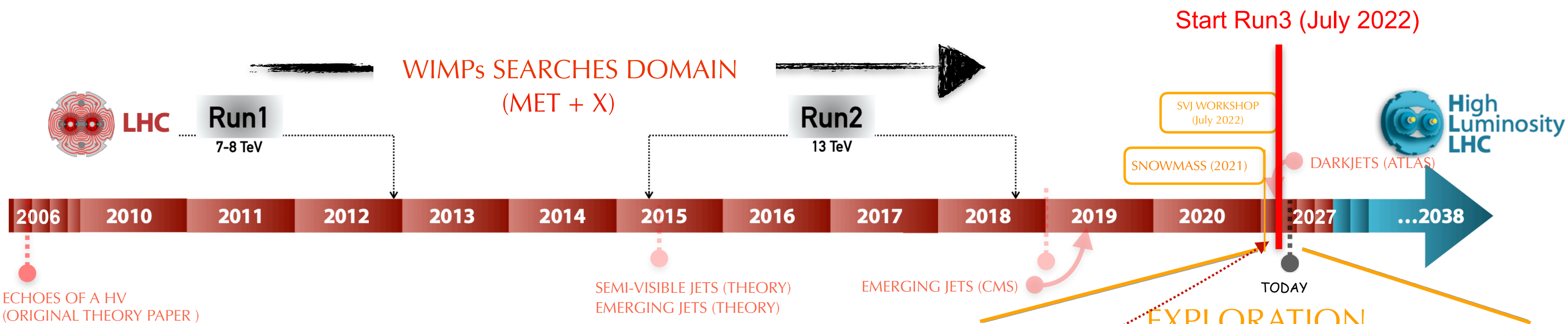




Phys. Rev. Lett. **115**, 171804

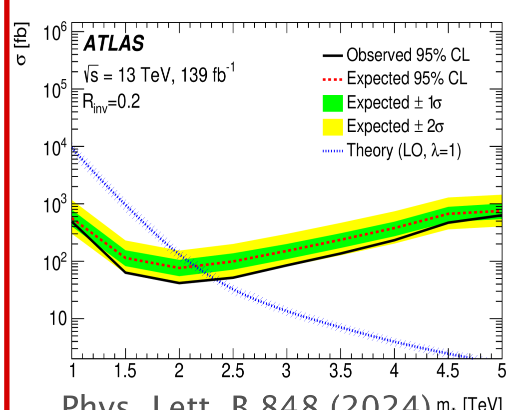
SVJ lays in between di-jet and WIMPs searches: broader resonances (if present) and dominated by QCD background (detector effects) : challenging signature !

QCD-LIKE DARK SECTORS @ THE LHC



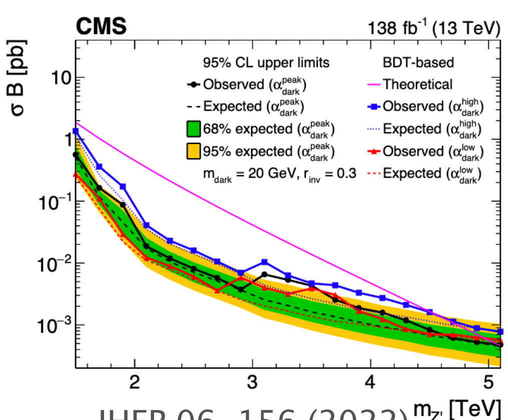
SEMI-VISIBLE JETS (SVJ)

t-channel



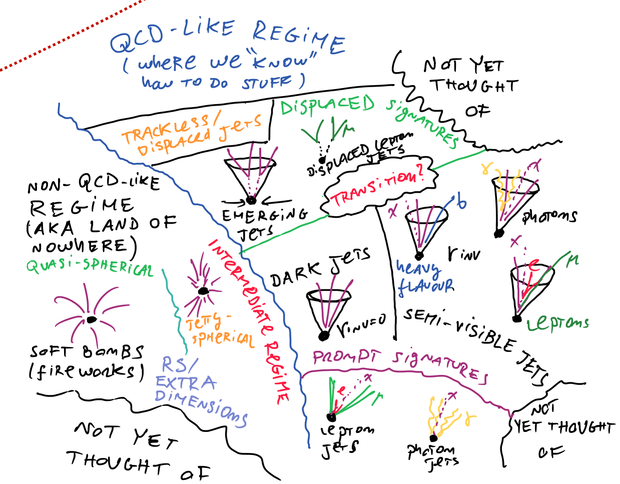
Phys. Lett. B 848 (2024)

s-channel

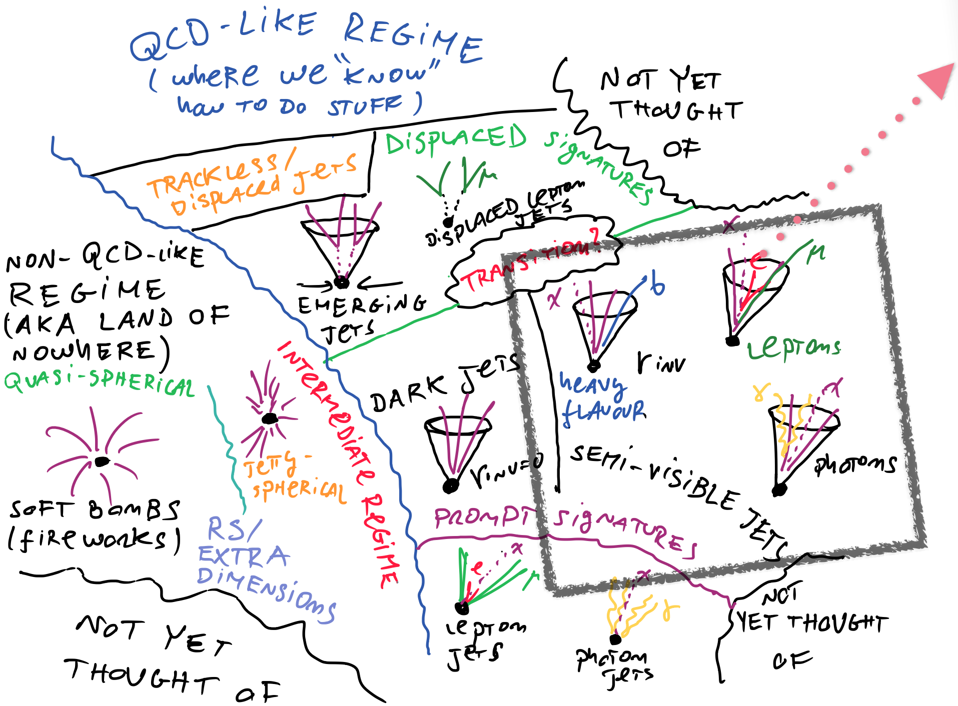


JHEP 06, 156 (2022)

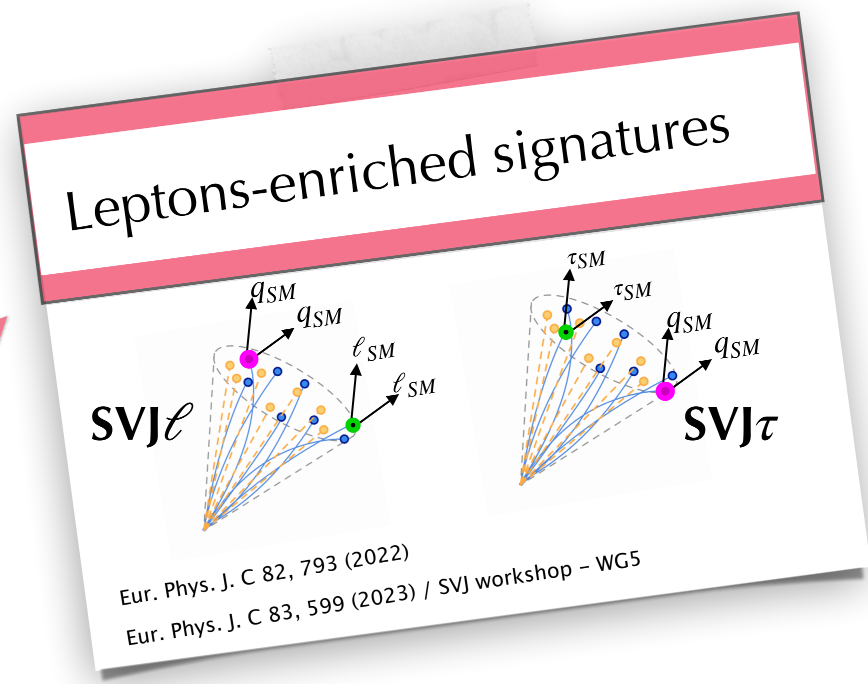
EXPLORATION



Vast landscape of models being investigated,
many others waiting in the drawer,
and lots of others still not being thought of …



BIG PICTURE OF HIDDEN VALLEYS



Contributors:

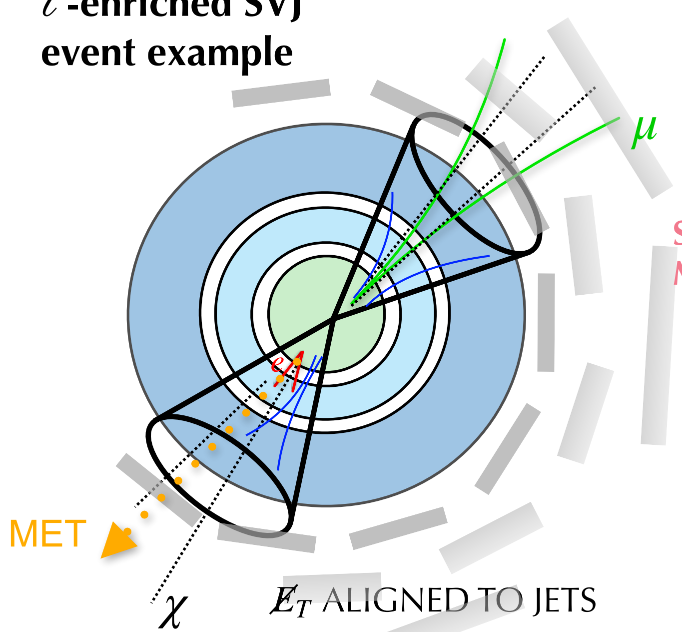
Eur. Phys. J. C 82, 793 (2022): C. Cazzaniga, A. de Cosa

Eur. Phys. J. C 83, 599 (2023): H. Beauchesne, C. Cazzaniga, A. de Cosa, C. Doglioni, T. Fitschen, G. Grilli di Cortona, Z. Zhou

LEPTONS-ENRICHED SIGNATURES FOR SVJS

EXTEND SVJ SIGNATURE: ALLOW DS DECAYS TO LEPTONS AND EXPLOIT NEW EXPERIMENTAL HANDLES

ℓ-enriched SVJ event example



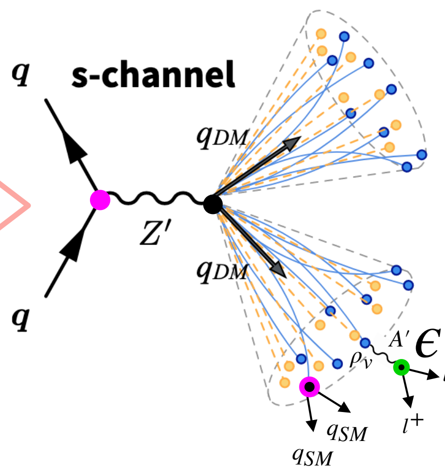
$\not{E}_T$ ALIGNED TO JETS

+ **PROMPT NON-ISOLATED LEPTON PAIRS** WITHIN HADRONIC JETS

Simplified Model

SVJℓ signature

di-lepton resonant

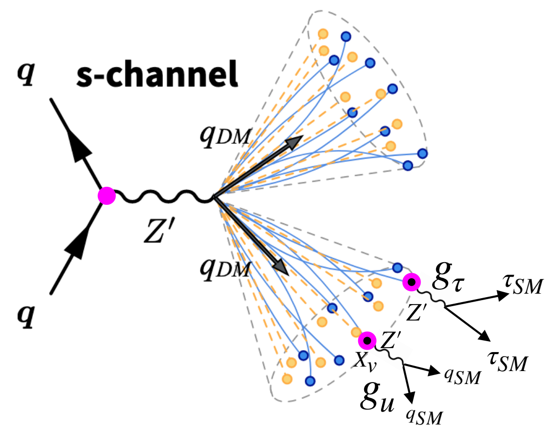


SVJ ℓ-ENRICHED

Eur. Phys. J. C 82, 793 (2022)

SVJτ signature

Neutrinos from τ decays



SVJ τ-ENRICHED

Eur. Phys. J. C 83, 599 (2023)

NOT ALLOWED IN ORIGINAL SVJ MODELS (leptophobic Z' portal)

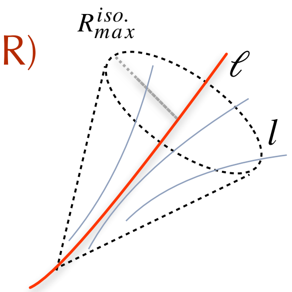
Current searches (including CMS SVJ searches) have limited sensitivity to this signal !

EXPERIMENTAL HANDLES: INTER-ISOLATION AND DI-LEPTON MASS

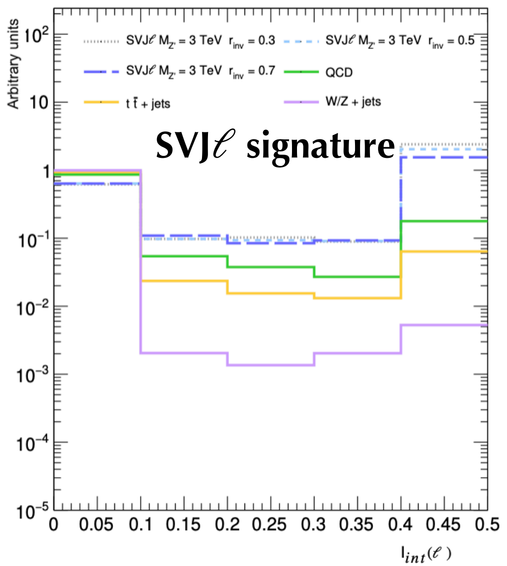
RELATIVE INTER-ISOLATION (FIXED R)

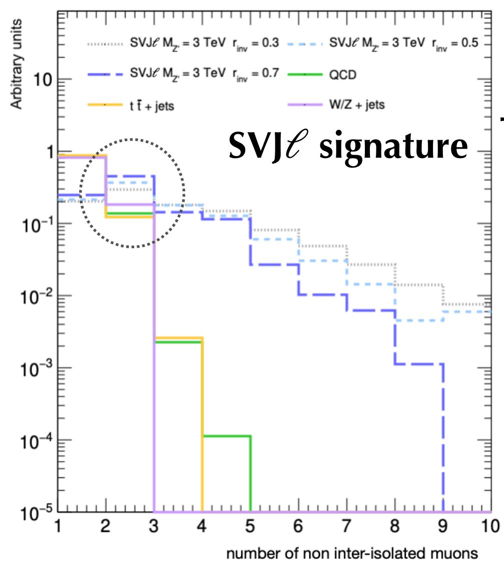
Eur. Phys. J. C 82, 793 (2022)

$$I_{int}(\ell) = \frac{1}{p_{T,\ell}} \sum_{l \neq \ell}^{\Delta R < R^{iso.}_{max}} p_T(l)$$



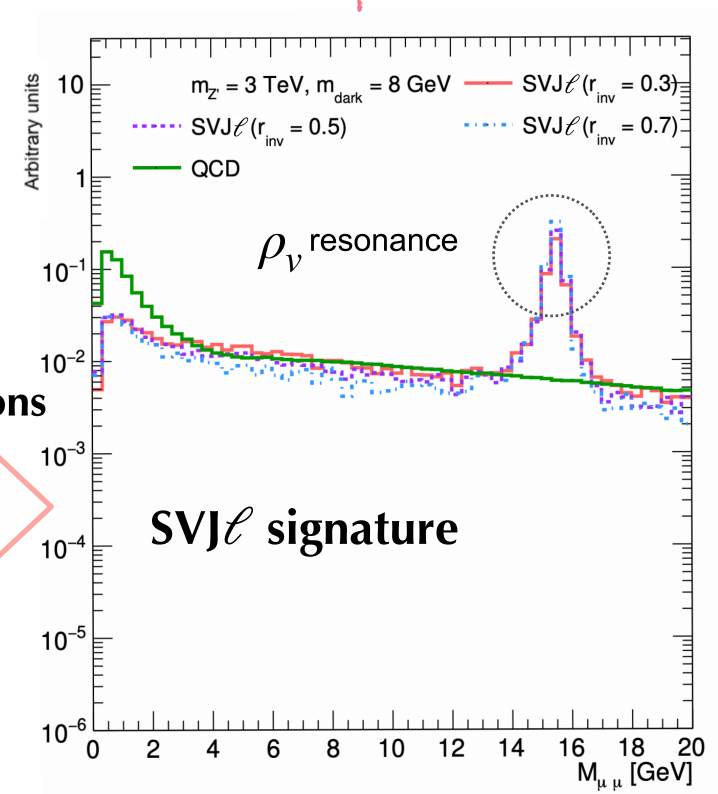
Exploit expected large number of nearby leptons in signal jets !





Tag leptons

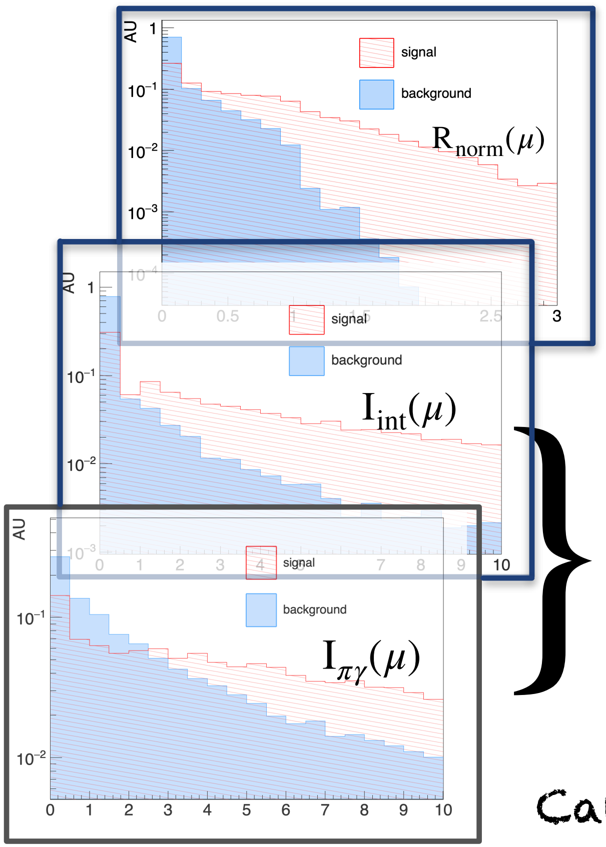
Narrow dilepton resonance



(*) Simulated events with MG+PY8+Delphes (backup)

LEPTON FLAVOUR-BASED JET TAGGER FOR SVJτ

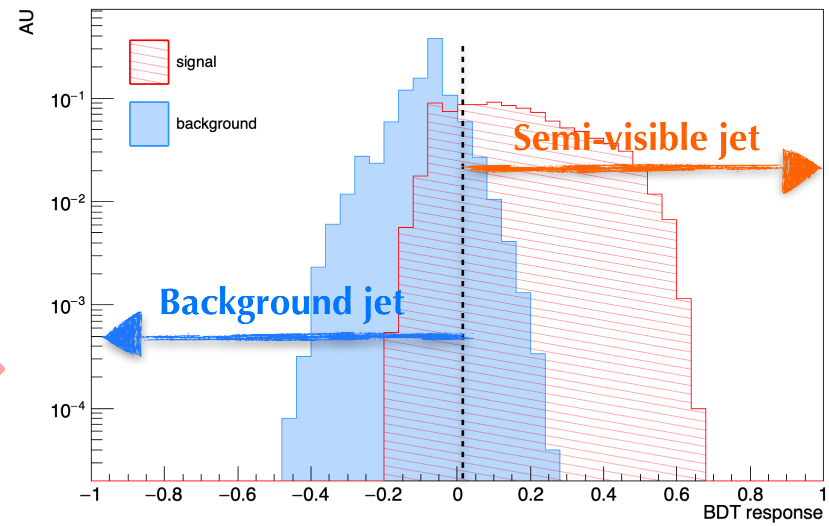
LEPTON-BASED SUBSTRUCTURE
(most discriminative)



spatial/energy flow

custom isolations

BDT Tagger Score



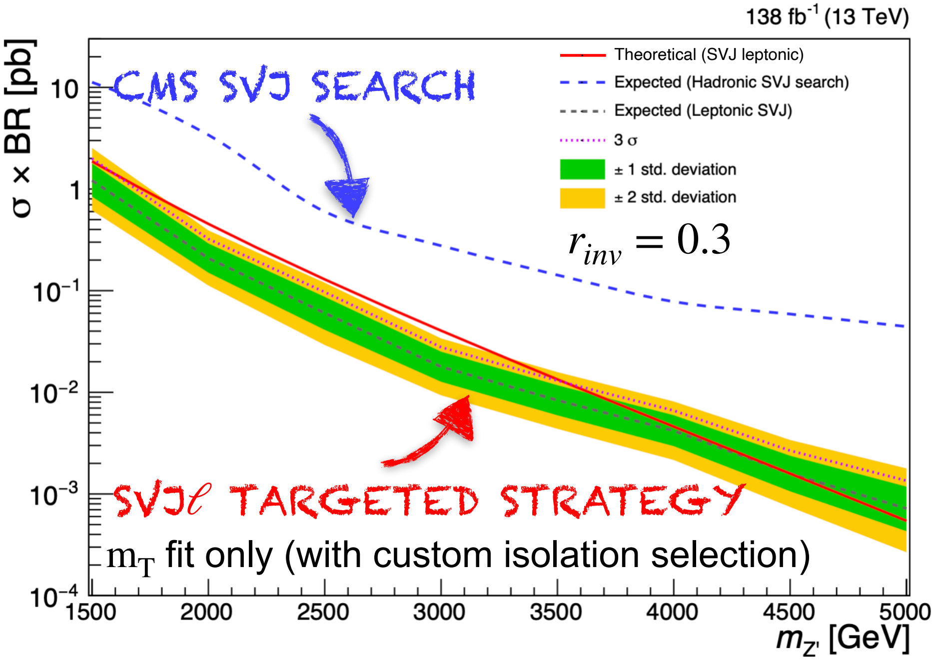
➡ Laverage anomalous leptonic content in jets from τ coming from unstable hidden sector bound states

Can tag jets based on leptons substructure !

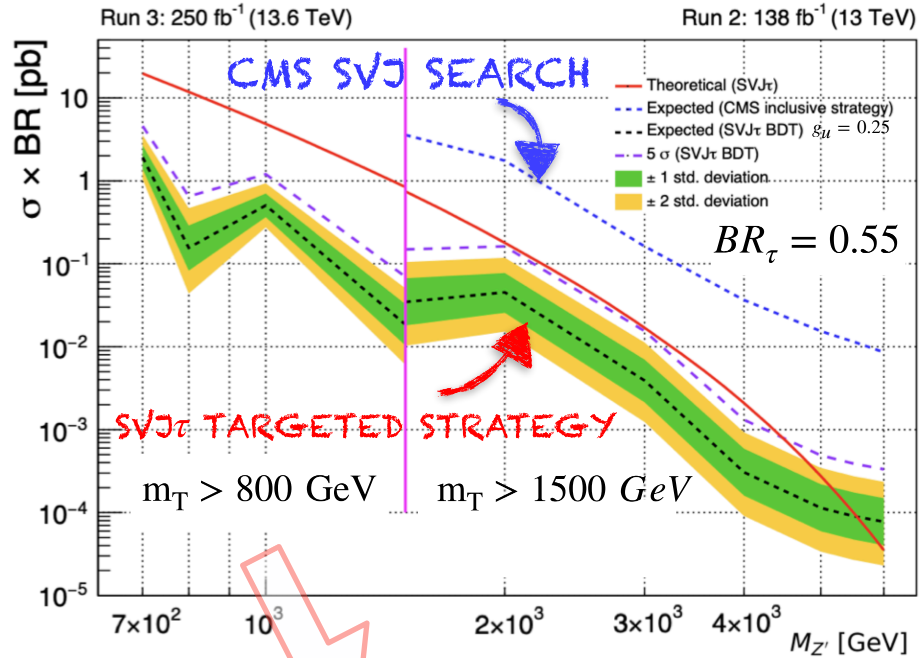
Leptons-enriched signatures

SIGNALS HIDING IN LHC RUN2 AND RUN3 DATA

EXPECTED SENSITIVITY SVJℓ SIGNATURE



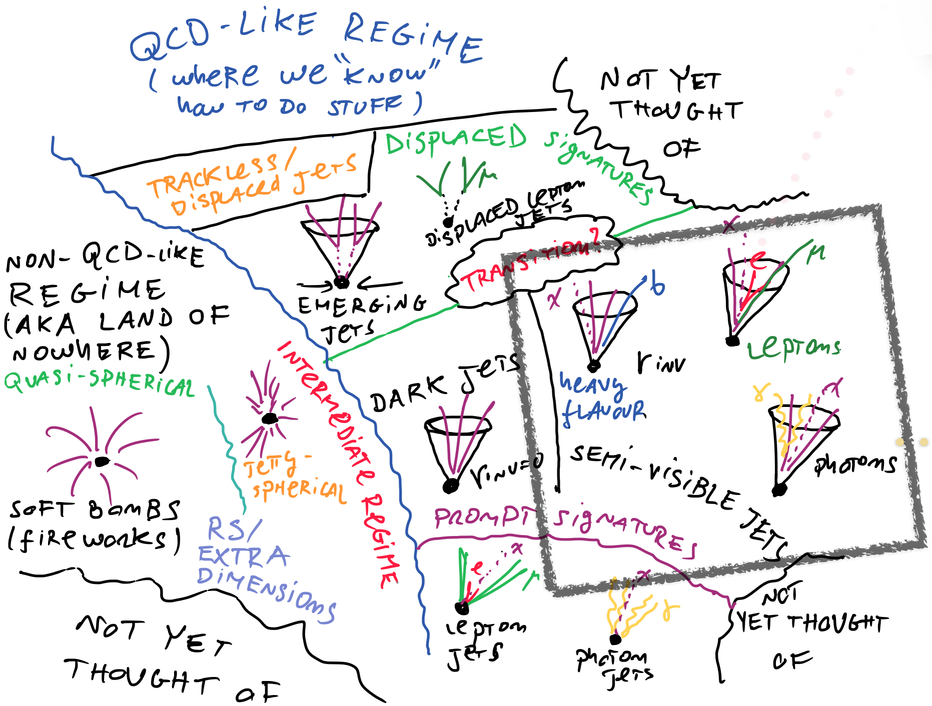
EXPECTED SENSITIVITY SVJτ SIGNATURE



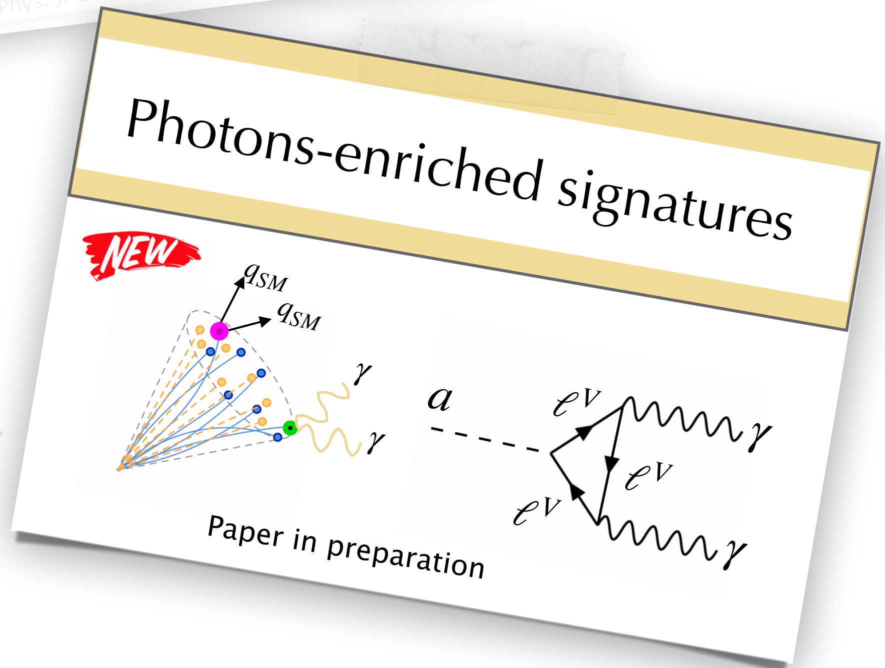
THESE SIGNALS MIGHT STILL BE LURKING IN THE LHC RUN2 DATA !

Scouting/TLA strategies: occasion to access lower masses !

(*) Limits produced on FastSim MC events



BIG PICTURE OF HIDDEN VALLEYS



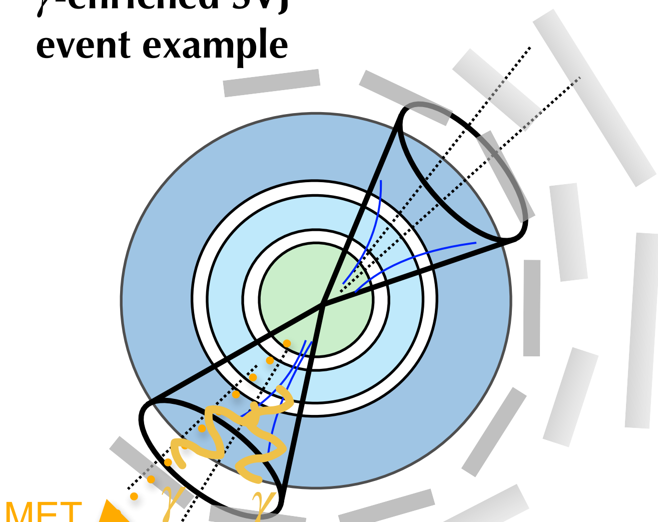
Contributors:

C. Cazzaniga, A. de Cosa, A. Russo, E. Sitti

PHOTONS-ENRICHED SIGNATURES FOR SVJS (SVJγ)

EXTEND SVJ SIGNATURE: ALLOW DS DECAYS TO PHOTONS AND EXPLOIT NEW EXPERIMENTAL HANDLES

γ-enriched SVJ event example

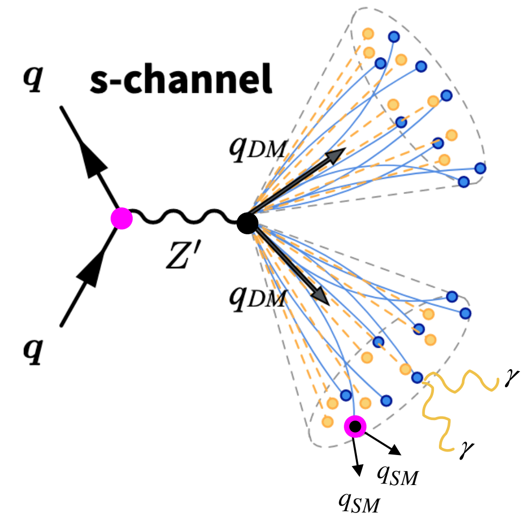


$\not{E}_T$ ALIGNED TO JETS

+ **PROMPT NON-ISOLATED PHOTON PAIRS** PRODUCED INSIDE HADRONIC JETS

Simplified Model

SVJγ signature (resonant production)



SVJ γ-ENRICHED

Paper in preparation

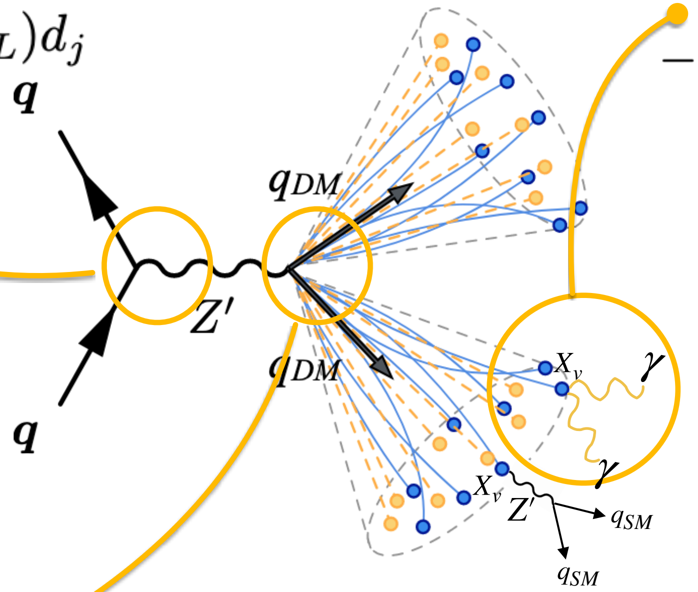
SVJγ MODEL IN A NUTSHELL: Z' + VLL + ALP

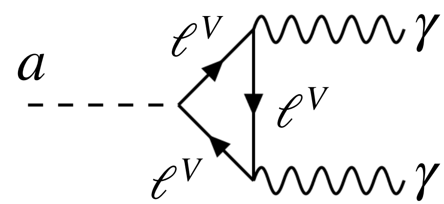
A portal for pp colliders

$$-Z'_\mu \bar{u}_i \gamma^\mu (g_{ij}^{u_R} P_R + g_{ij}^{u_L} P_L) u_j$$
$$-Z'_\mu \bar{d}_i \gamma^\mu (g_{ij}^{d_R} P_R + g_{ij}^{d_L} P_L) d_j$$

A decay mode to photons

$$-\frac{\alpha}{4\pi}\frac{y_Q N_Q}{M_Q} a F\tilde{F} - i y_\psi a \bar{q}_v \gamma_5 q_v$$





Axion + VLL portal

MODEL BASED ON:

Phys. Rev. D 84, 115006 (2011)

Phys. Rev. D 89, 095033 (2014)

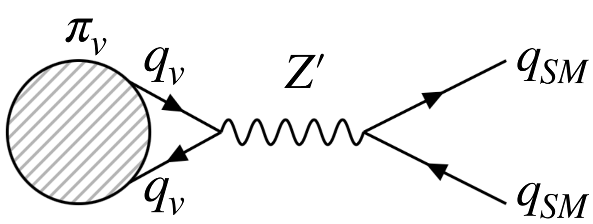
Phys. Rev. D 103, 115013 (2021)

A coupling to the dark sector

$$-Z'_\mu \bar{q}_{vi} \gamma^\mu (g_{ij}^{q_v R} P_R + g_{ij}^{q_v L} P_L) q_{vj}$$

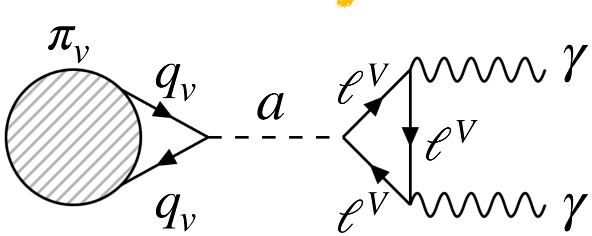
MODEL PARAMETRIZATION AND BRANCHING RATIOS

Hadronic decay channel



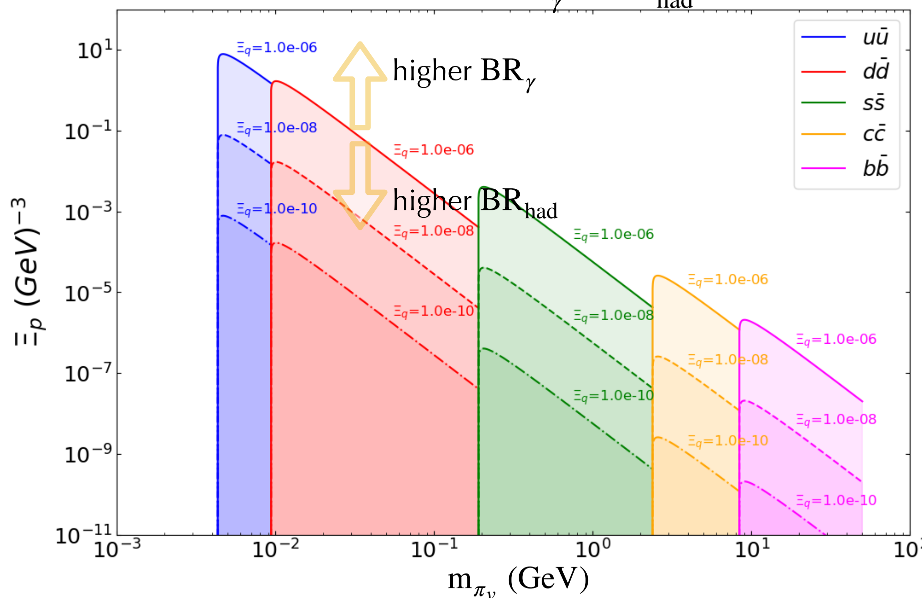
$$\Gamma_p = \frac{\alpha^2}{64\pi^2} m_{\pi_v}^7 \Xi_p^2$$

Photons decay channel



$$\Gamma_q = \frac{3}{32\pi} m_{f_i}^2 m_{\pi_v} \sqrt{1 - \frac{4m_{f_i}^2}{m_{\pi_v}^2}} \Xi_q^2$$

ISOCURVES FOR $BR_\gamma = BR_{had} = 0.5$



Effective parameters

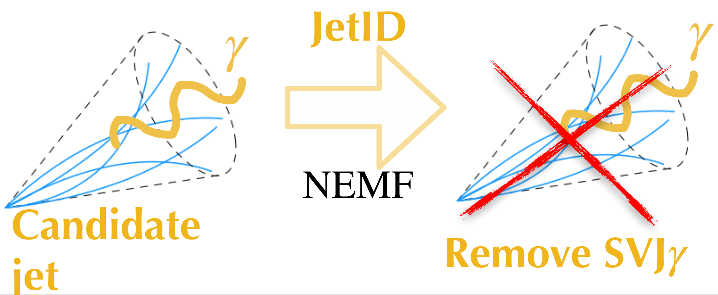
$$\Xi_q := \frac{(\Delta_{ii}^f \Delta_a^{q_v})}{M_{Z'}^2} \qquad \Xi_p := \frac{y_Q y_\psi}{m_a^2 M_Q}$$

- Allow to tune branching to hadrons (BR_{had}) and photons (BR_γ)
- Able to define a **parametric model** that can be mapped to the simplified one

EXPERIMENTAL CONSTRAINTS AND CHALLENGES

Jet-based searches

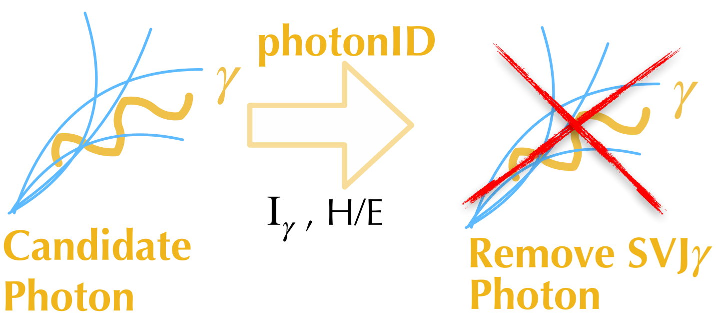
SVJ & dijet searches



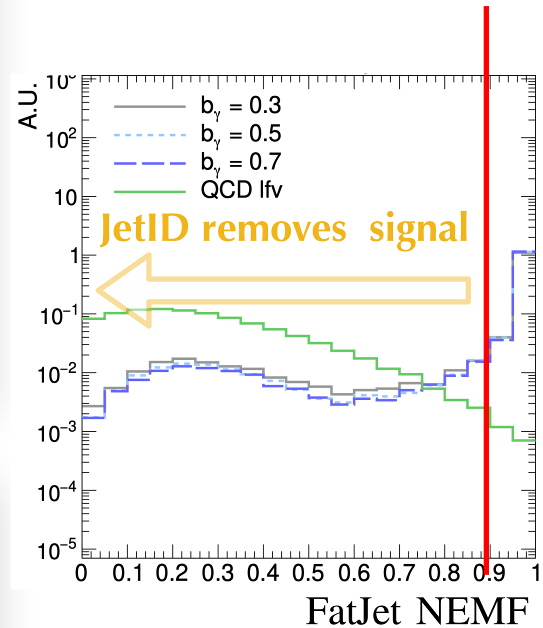
NEMF = Neutral ElectroMagnetic Fraction

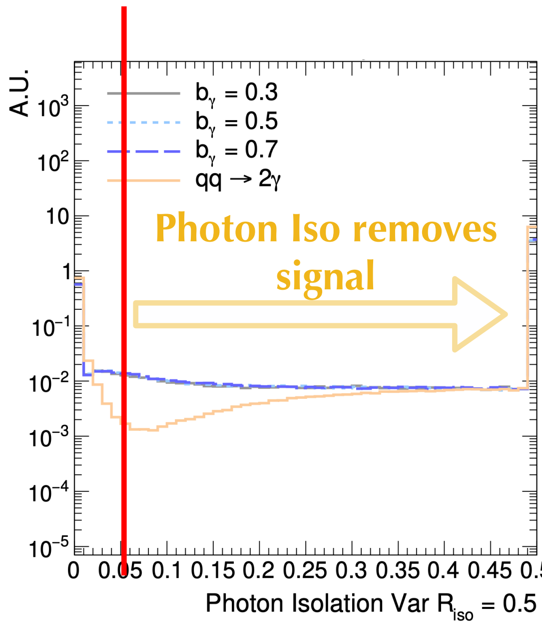
Photons-based searches

Low & high mass di-photon resonances

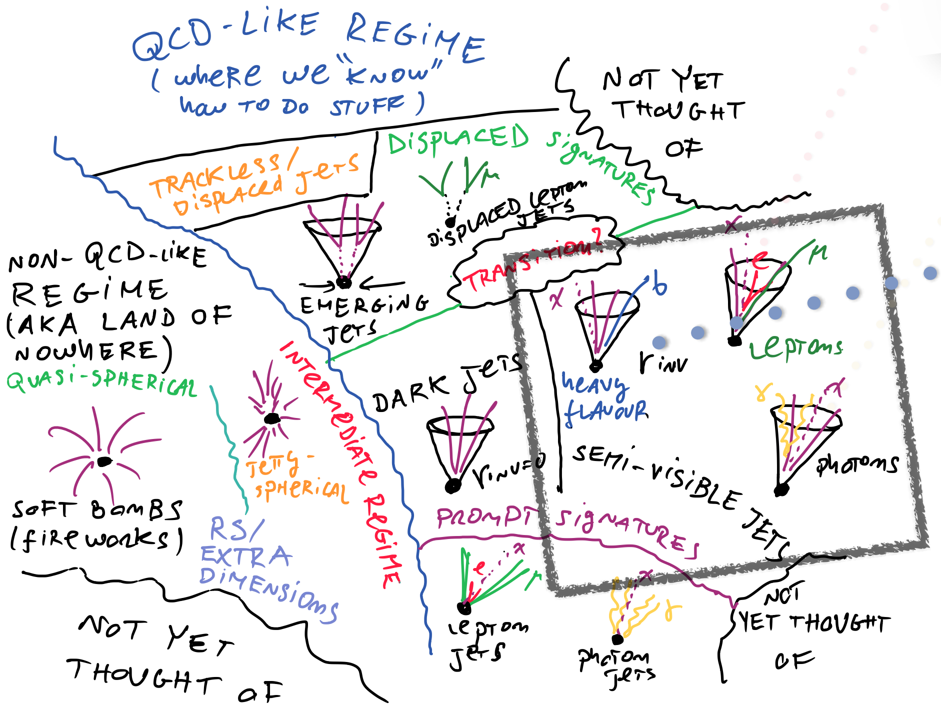


I_γ = photons isolation, H/E = hadronic vs electromagnetic Calo tower energy

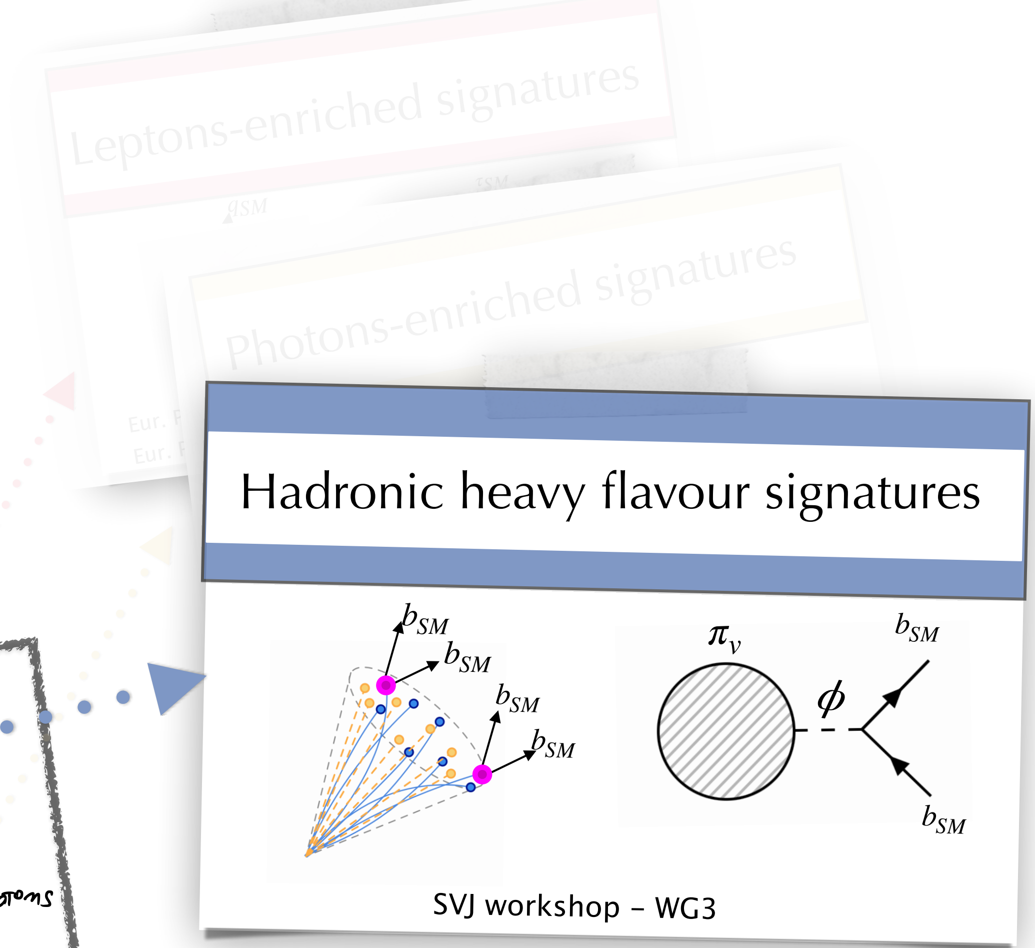




Need new identification criteria for SVJγ !



BIG PICTURE OF HIDDEN VALLEYS



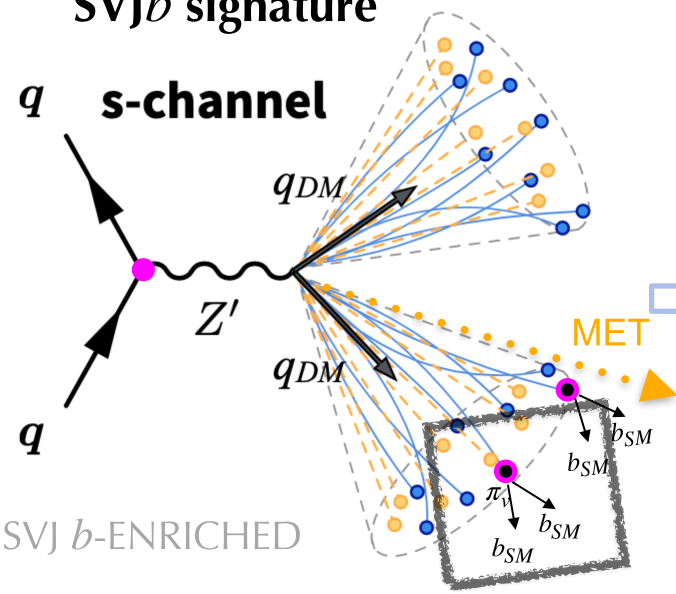
Contributors:

C. Cazzaniga, A. de Cosa, A. Ellaboudy, F. Eble, S. Knapen, B. Liu, D. Stolarski

Look also: SVJ workshop WG3

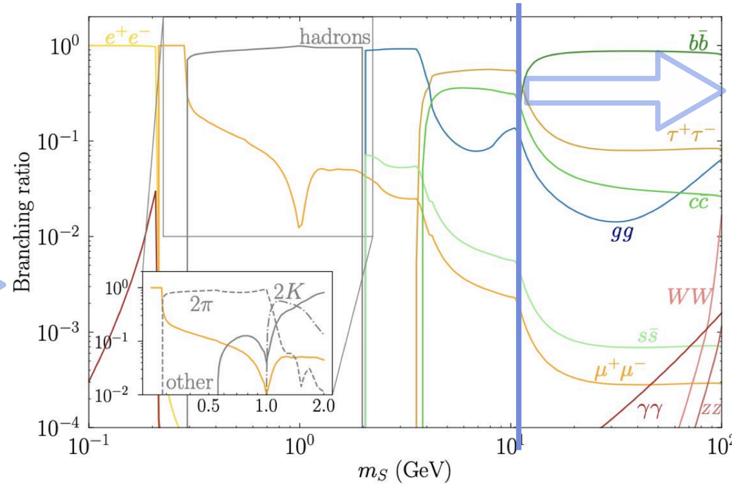
HEAVY-FLAVOURED SIGNATURES FOR SVJS (SVJb)

SVJb signature

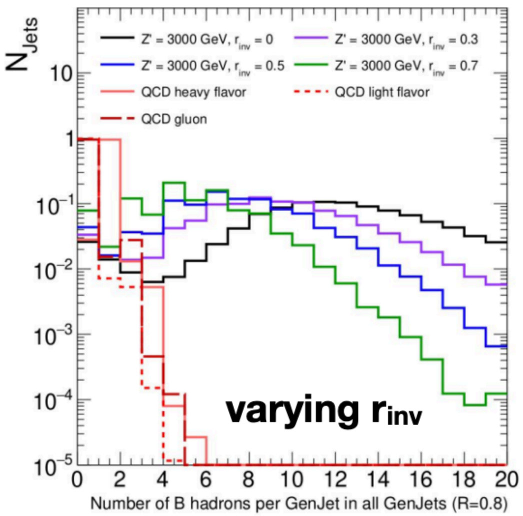


SVJ b-ENRICHED

BRANCHING RATIO SCALAR MESON



Enhanced decays to b



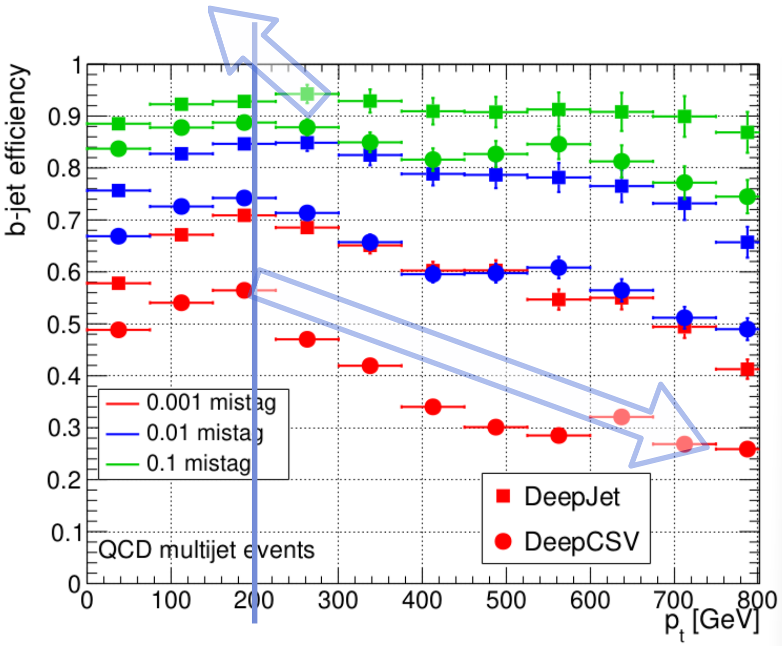
Large number of B-hadrons per-jet ($N_{\mathrm{btag}} \geq 2$)

Experimental features

- High **displaced vertex** multiplicity
- High **displaced tracks** multiplicities
- High **lepton multiplicities**
- Expected soft-drop mass peak

B-TAGGING CHALLENGES

loose WP, high mistag rates



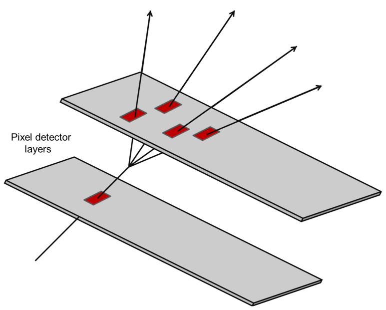
JINST 15 (2020) P12012

Observed also for TTJ and boosted Z′ to bb

Why expected inefficiencies ?

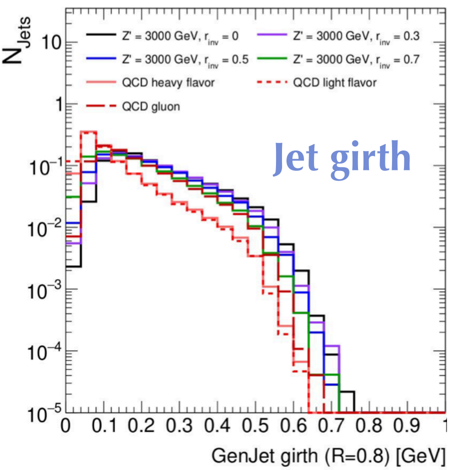
higher jet pT ⇨ Boosted/merged objects

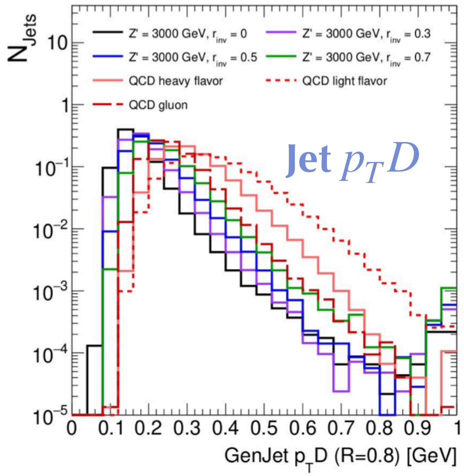
- **Reduced track reco efficiencies** : higher hits density (ambiguous hit-track association or merging)
- Increasing fraction of missing hits in inner layers, **impact Param degradation**
- **Many SVs**, but more **difficult to reconstruct them** !

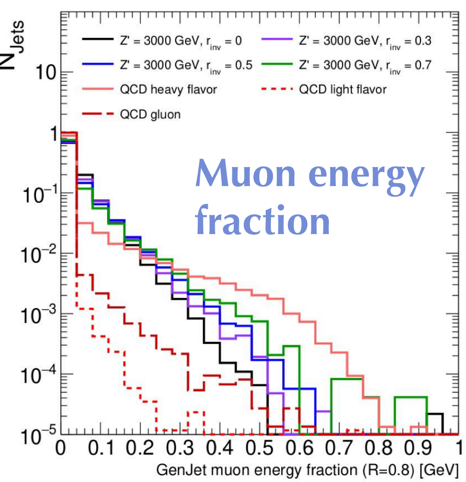


Other references: JINST 13 (2018) P05011

HANDLES FOR SVJ*b* TAGGING

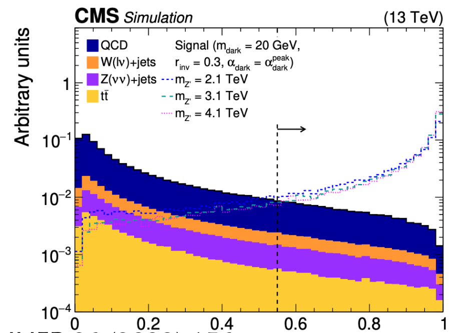






- SVJ*b*: energy fractions powerful features against gluon and heavy flavour QCD
- SVJ*b*: JSS similar to gluon-QCD

A dedicated tagger ?



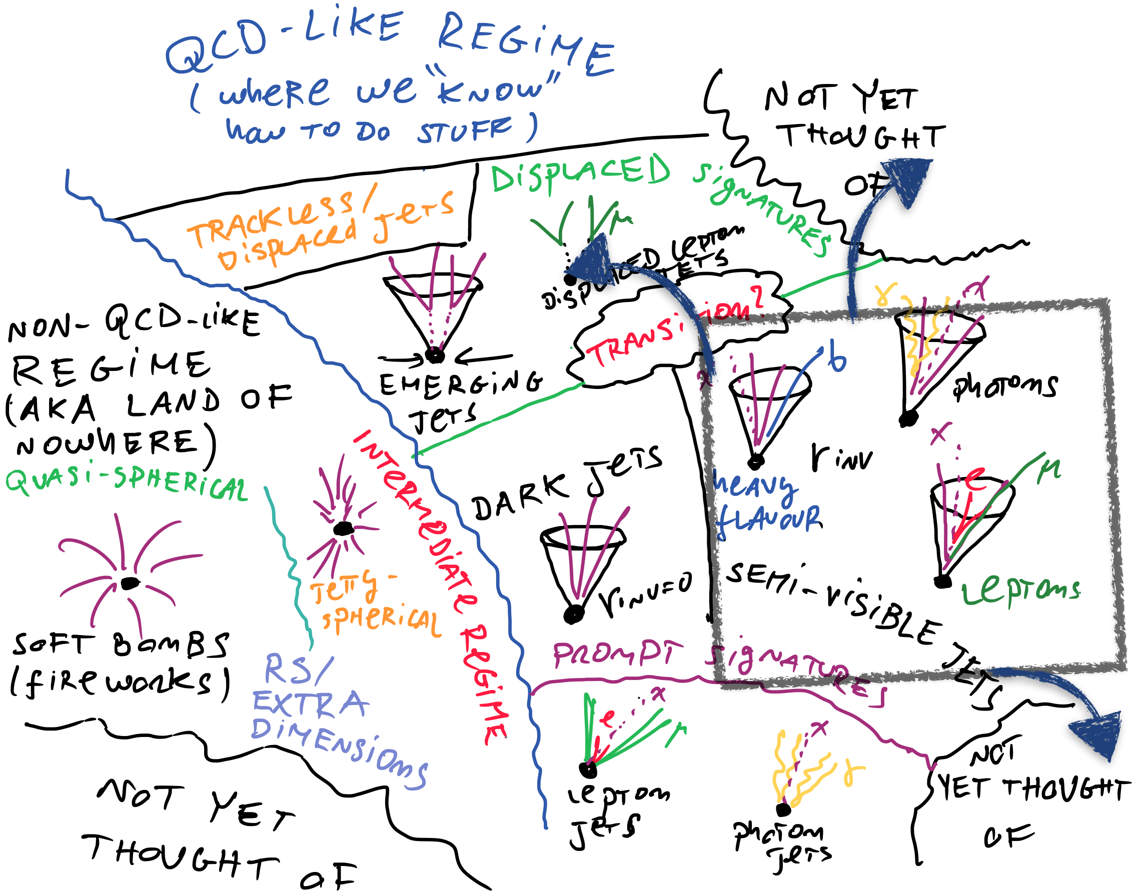
JHEP 06 (2022) 156

CMS tagger

Trained with signal models with **~65% branching to b-quarks**

Must assess impact of CMS tagger when enhancing branching to b-quarks to extreme case

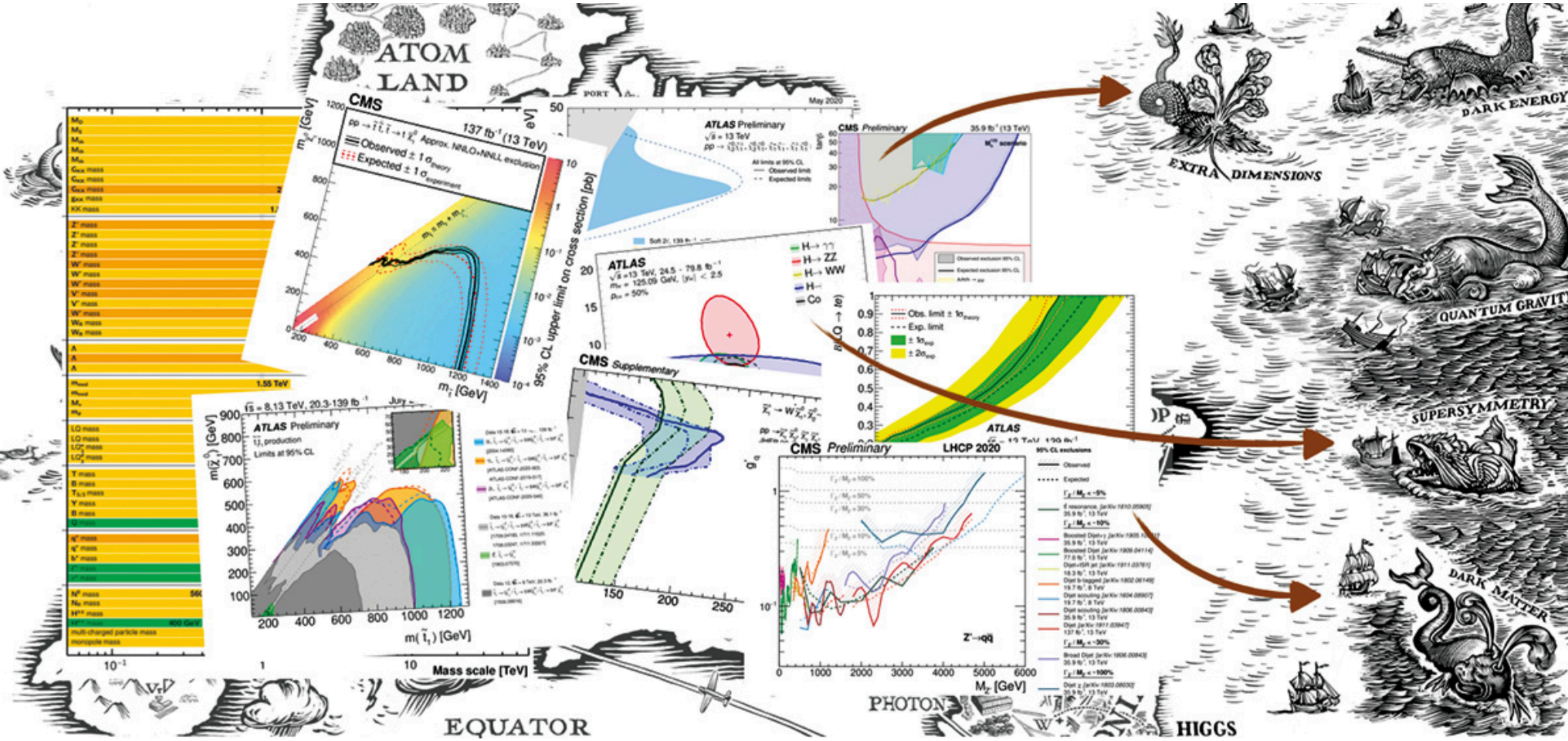
MAPPING STRONGLY COUPLED DARK SECTORS



BIG PICTURE OF HIDDEN VALLEYS

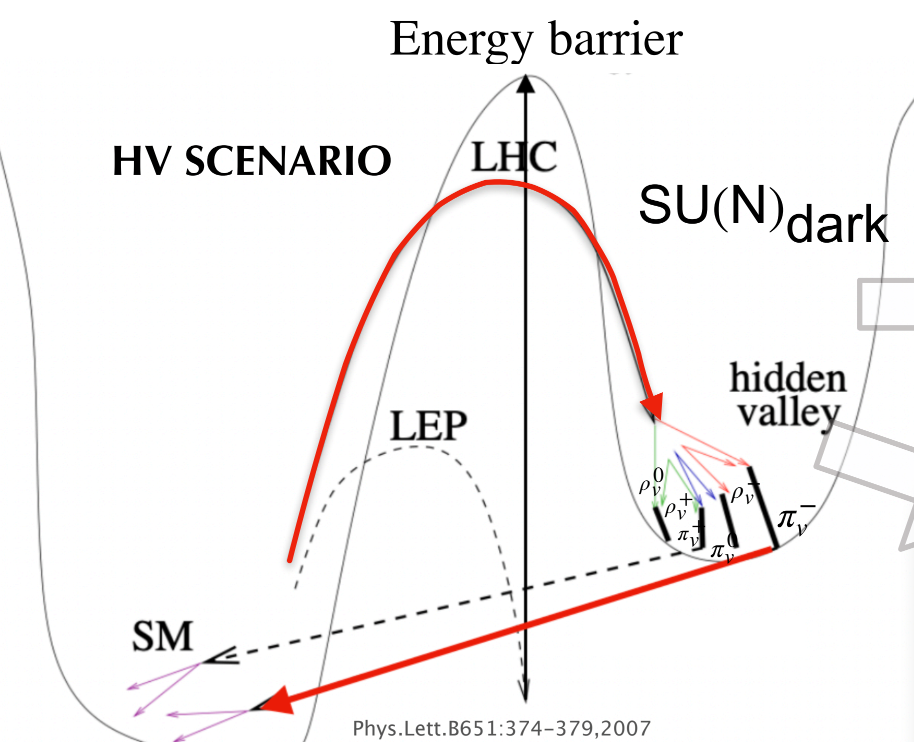
GROWING FIELD & UNCHARTED TERRITORIES STILL TO BE EXPLORED !

BACKUP

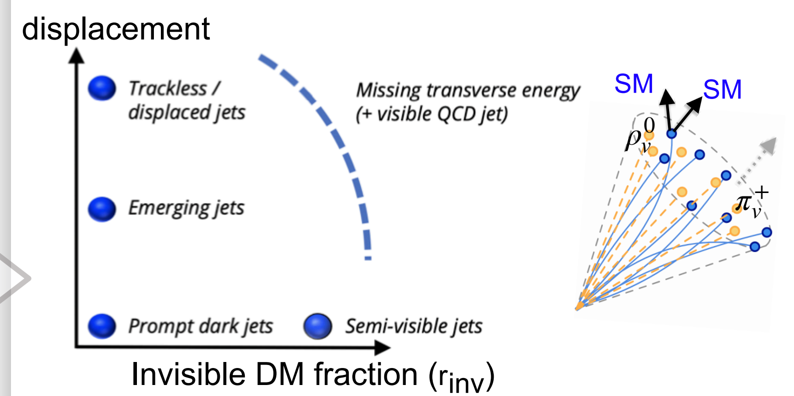

ATOM LAND
EXTRA DIMENSIONS
DARK ENERGY
QUANTUM GRAVITY
SUPERSYMMETRY
DARK MATTER
EQUATOR
PHOTON
HIGGS
CMS
ATLAS Preliminary
CMS Preliminary
CMS Supplementary
LHCP 2020
Mass scale [TeV]

A HIDDEN VALLEY OF UNCONVENTIONAL SIGNATURES

HV SCENARIO

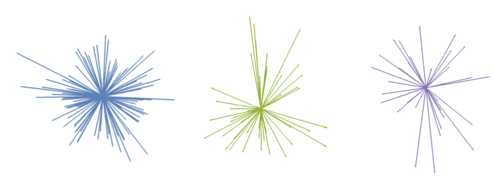


QCD-LIKE SIGNATURES

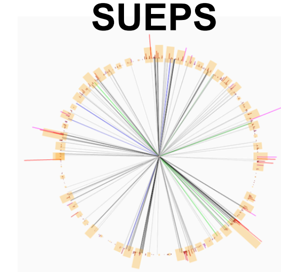


QUASI-SPHERICAL SIGNATURES

Jetty-spherical

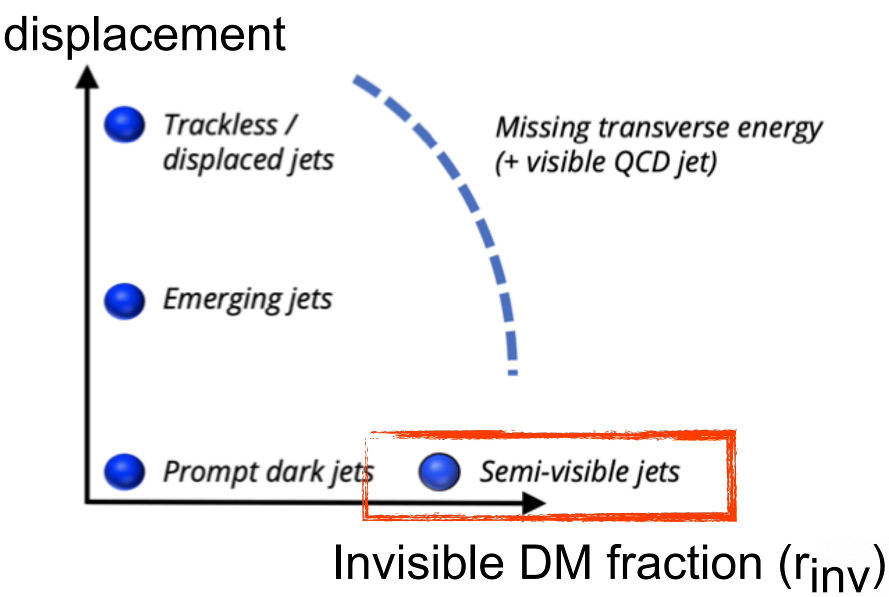


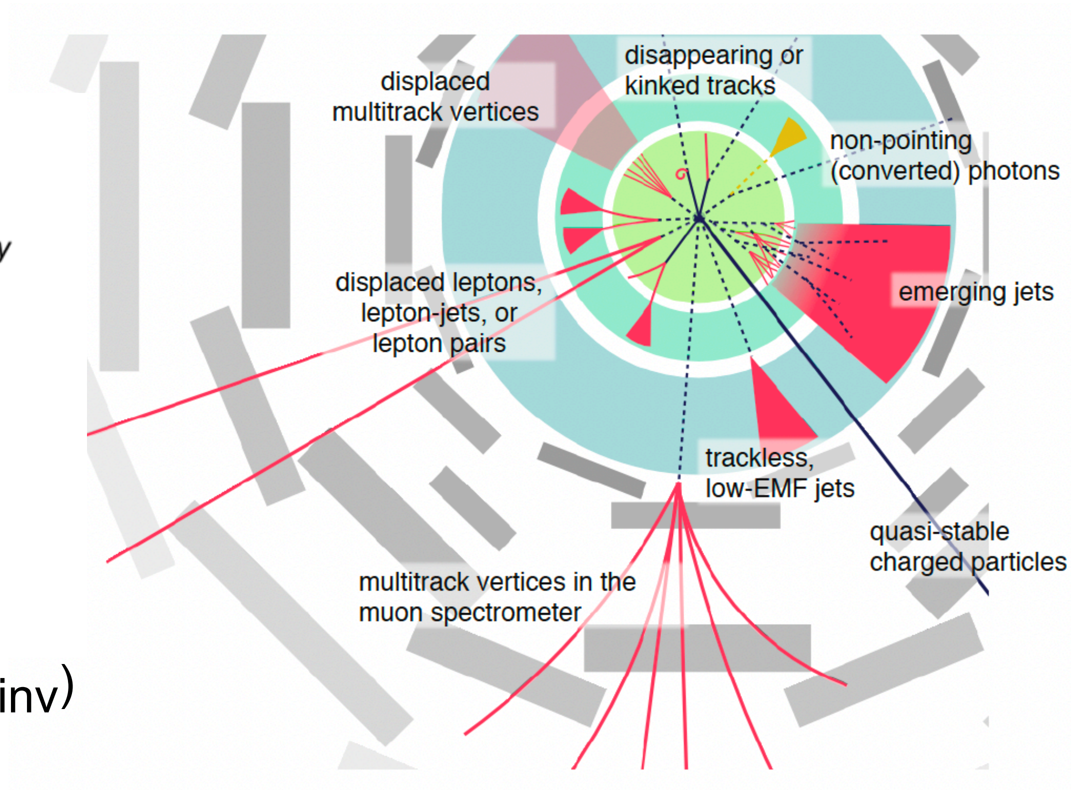
SUEPS



BEYOND CONVENTIONAL SIGNATURES

JETTY SIGNATURES (QCD-LIKE HIDDEN SECTORS)



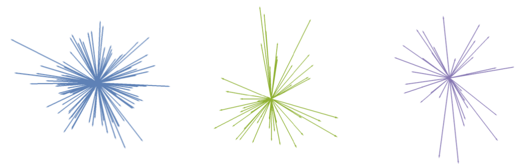


HIDDEN VALLEYS PROVIDE NEW UNEXPLORED SIGNATURES DEPENDING ON BOUND STATES LIFE-TIMES AND DECAY MODES

CONFINING HIDDEN SECTORS REGIMES

"Safe" regime

INTERMEDIATE REGIME



arXiv:2011.06599 arXiv:2009.08981

- **Pheno interpolation** between showers regimes
- Intermediate signals **between jetty and spherical**

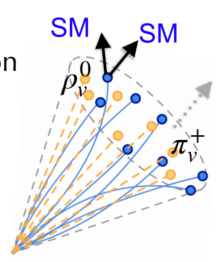
't Hooft coupling

($N_C^{dark} g^2_{dark}$)

1

QCD-LIKE REGIME

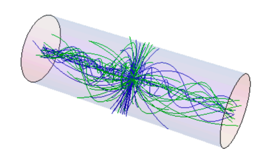
- Dark partons evolution (soft and collinear): **parton showers**
- **Dark jets** signatures



... Highly speculative

QUASI-SPHERICAL REGIME

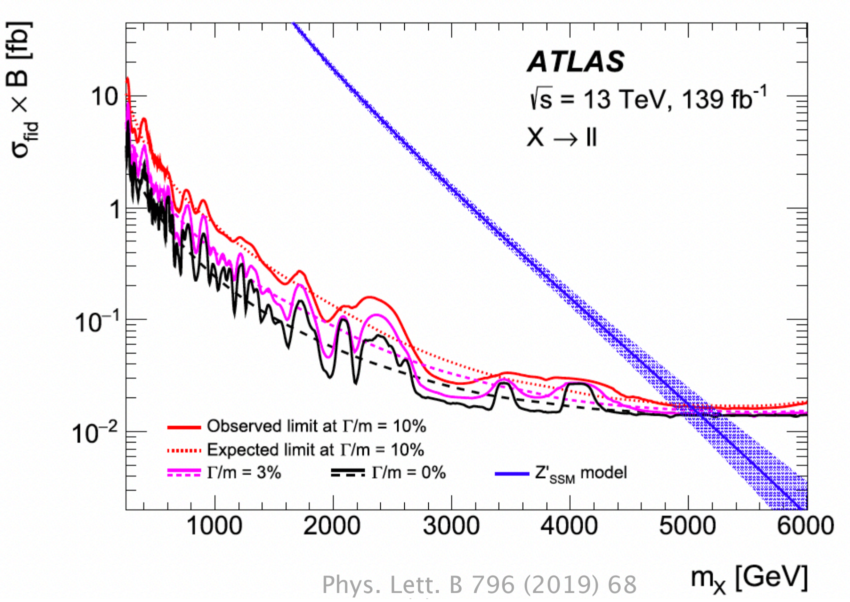
- AdS-CFT insights
- Soft unclustered energy patterns (**SUEPS**)



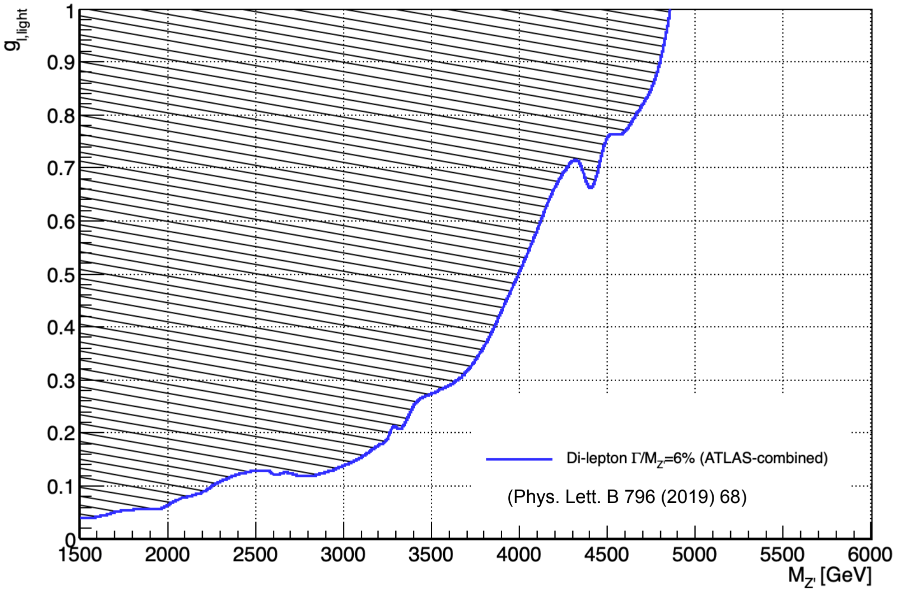
arXiv:1612.00850

arXiv:0801.0629

CONSTRAINTS ON Z′ COUPLING TO LEPTONS



Constraints: $g_{dark} = 0.5$, $g_{q,light} = 0.25$ (leptons - universal) (*)

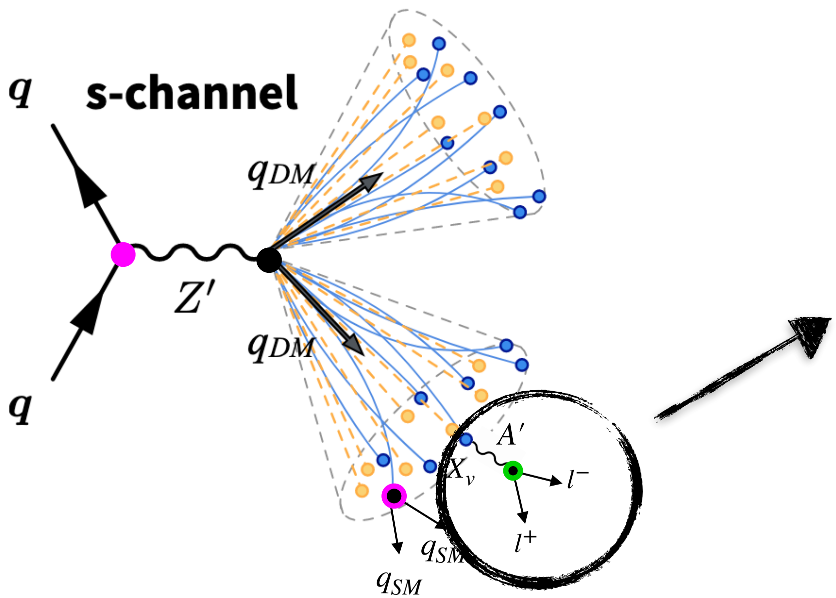


ALLOWING IN THE CURRENT SVJ MODEL FOR Z′ COUPLING TO LEPTONS WOULD INTRODUCE IMPORTANT CONSTRAINTS FROM HIGH MASS DI-LEPTON SEARCHES

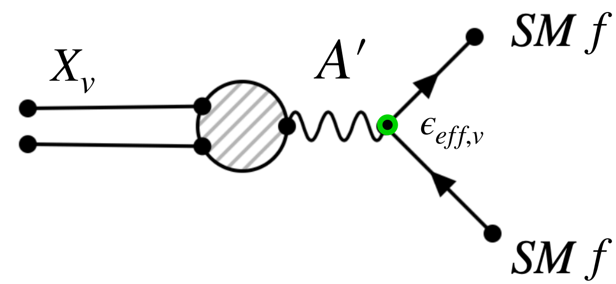
(*) parameters are set consistently with CMS Z′ model

SVJℓ MODEL: LEPTONIC DECAYS IN SVJ VIA A′

PROMPT LEPTONIC DECAYS OF DARK BOUND STATES ALLOWED BY LOWER MASS MEDIATOR A′



HADRONS + LEPTONS SVJ



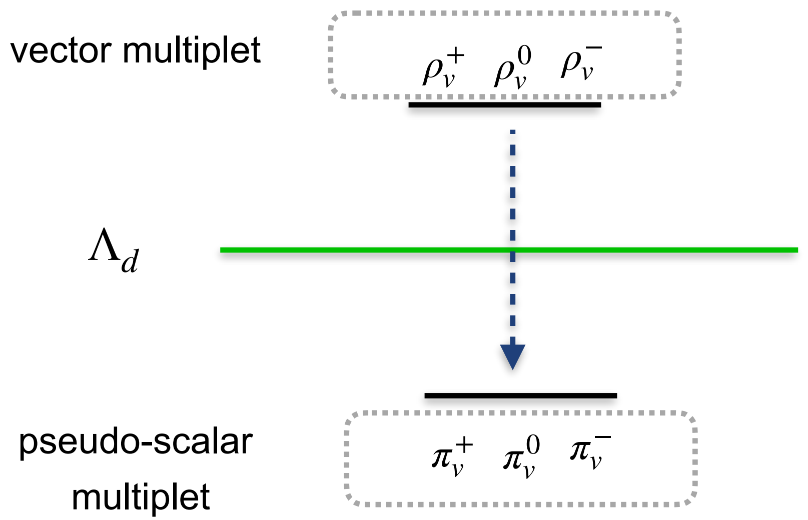
NEW PORTAL PARAMETER: $\epsilon_{eff,v}$

Phys. Rev. D 103, 115013 (2021)

LOWER MASS MEDIATOR: OFF-SHELL Z′ SUPPRESSED IN DARK BOUND STATES DECAYS ~ $1/M_{Z'}^4$

SIMPLIFIED HIDDEN VALLEY SPECTRUM

SIMPLE Nf = 2 HV SPECTRUM
(mass degenerate dark quarks)



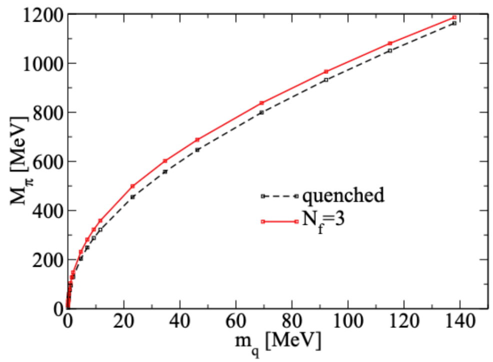
HOW TO FIX THE MASSES ?

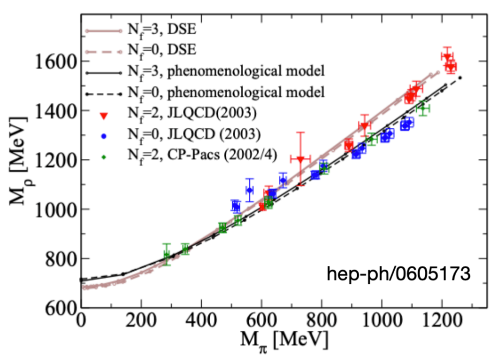
FULL HADRONIC SEARCH ASSUMES ONE DARK HADRON MASS SCALE

→ DEVELOPMENTS IN SNOWMASS 2021-2022 Eur. Phys. J. C (2022)

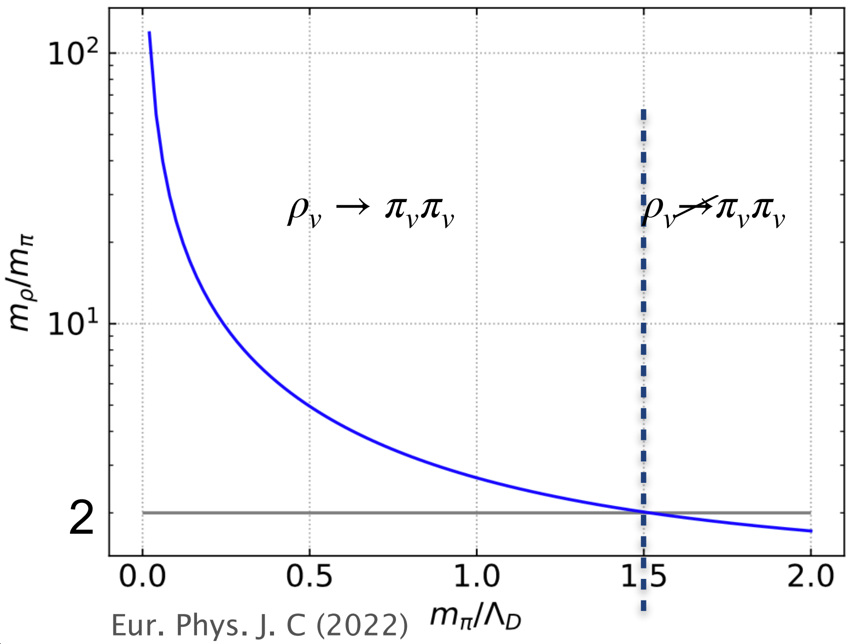
DARK SECTOR HADRON MASSES

LATTICE CALC





DM SPECTRUM PREDICTION

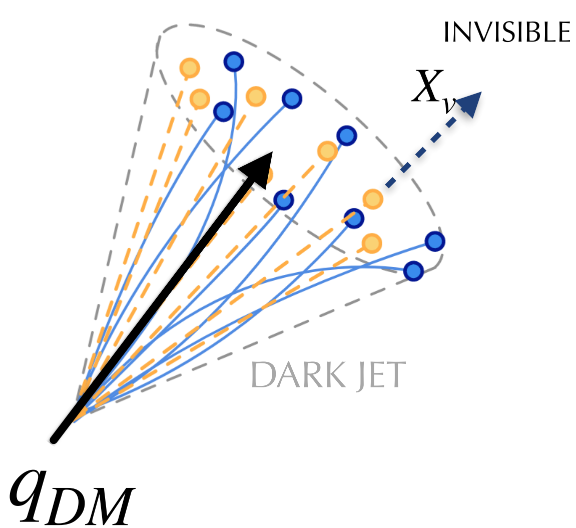


LATTICE CALCULATION: INPUT DARK CURRENT QUARK MASS AND GET DARK HADRON MASSES (BOTH DIVIDED BY OVERALL SCALE Λ_d)

(*) Predictions DM spectrum independent from Nc and Nf

INVISIBLE FRACTION

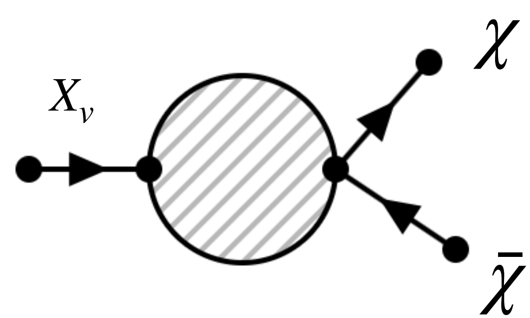
NUMBER OF INVISIBLE DM STATES IMPLEMENTED AS A BRANCHING RATIO



EFFECTIVE INVISIBLE FRACTION

$$r_{\rm inv} \equiv \left\langle \frac{\#\text{ of stable hadrons}}{\#\text{ of hadrons}} \right\rangle$$

$\mathrm{BR_{inv}}$:

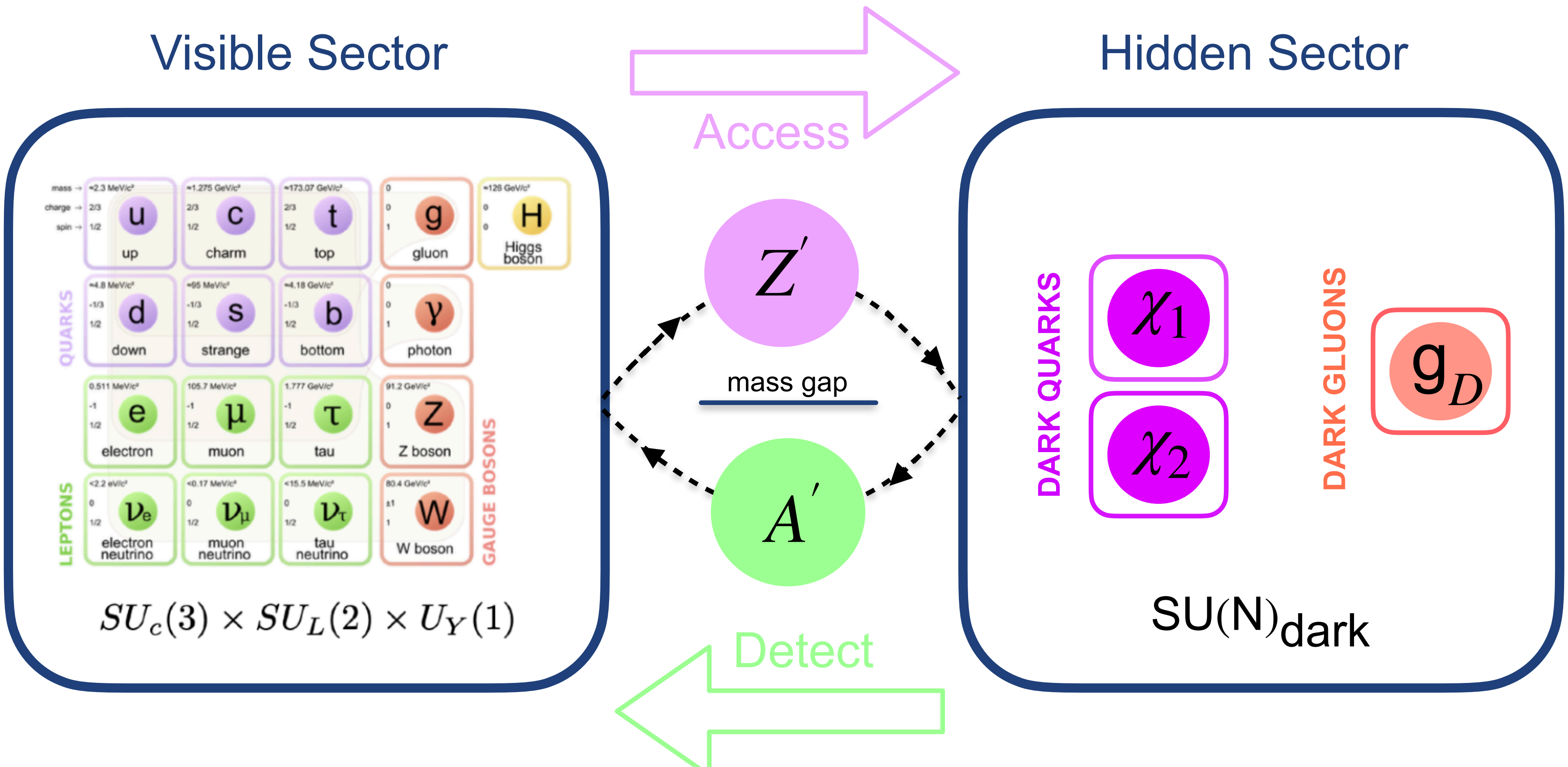


CAPTURES VARIATION IN NUMBER OF DARK FLAVOURS (N_f), NUMBER OF DARK COLORS (N_c) & DARK QUARKS MASS SPLITTING (LUND STRING)

Eur. Phys. J. C 82, 793 (2022)

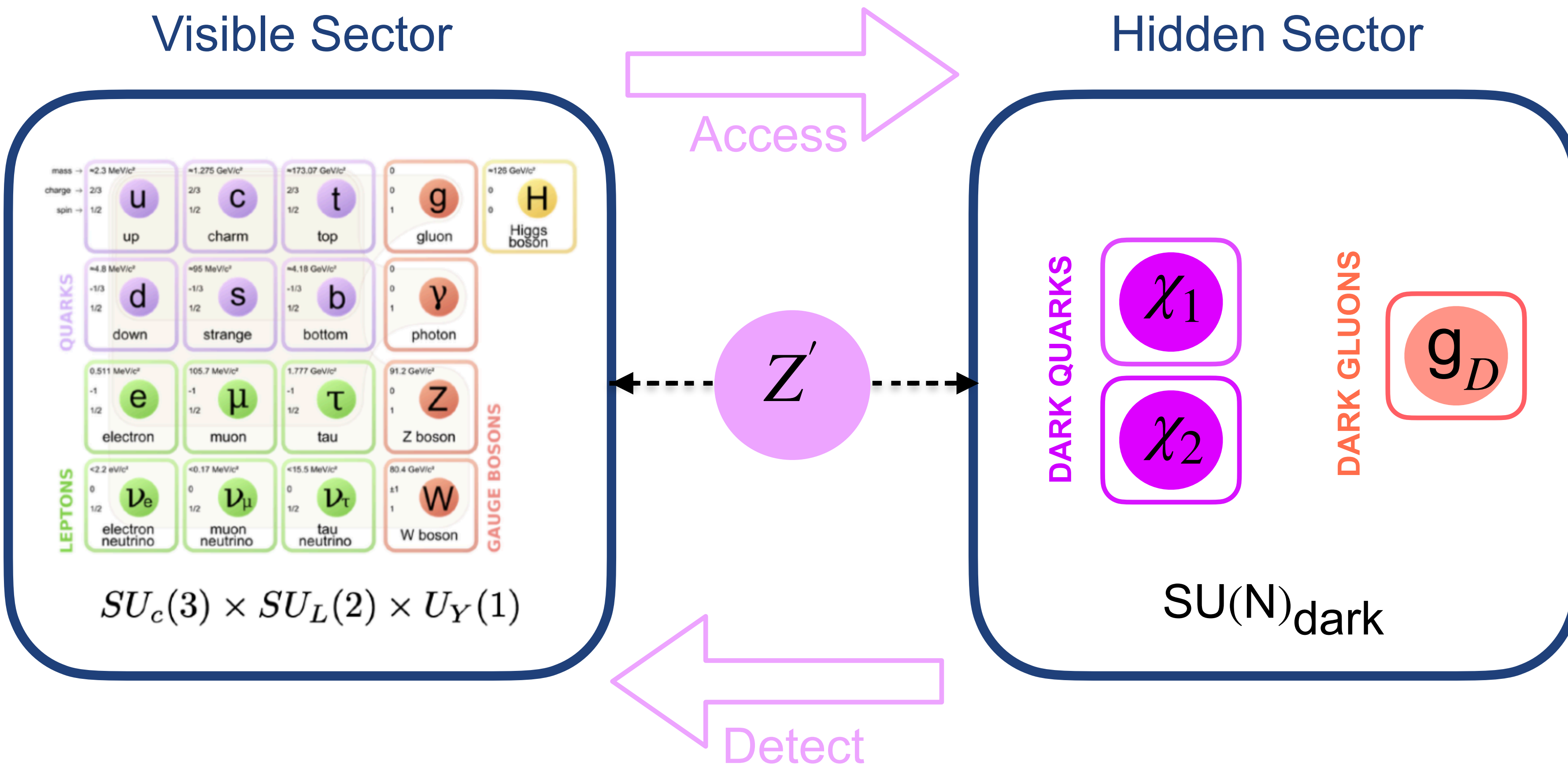
PRD 103, 115013 (2021)

SVJℓ MODEL: TWO MESSENGER FIELDS



Eur. Phys. J. C 83, 599 (2023)

SVJτ MODEL : SINGLE MESSENGER FIELD



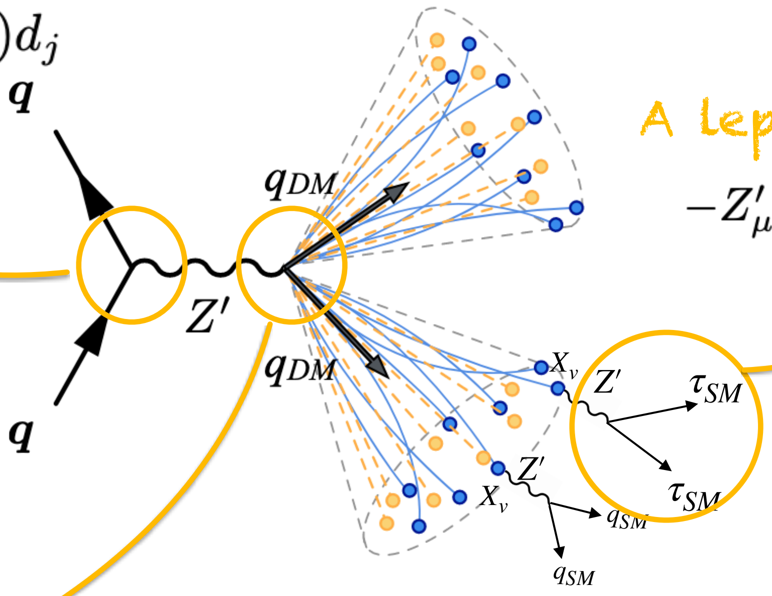
Eur. Phys. J. C 83, 599 (2023)

SVJτ MODEL: SINGLE MESSENGER FIELD

A portal for pp colliders

$$-Z'_\mu \bar{u}_i \gamma^\mu (g_{ij}^{u_R} P_R + g_{ij}^{u_L} P_L) u_j$$

$$-Z'_\mu \bar{d}_i \gamma^\mu (g_{ij}^{d_R} P_R + g_{ij}^{d_L} P_L) d_j$$



A leptonic decay mode

$$-Z'_\mu \bar{e}_i \gamma^\mu (g_{ij}^{e_R} P_R + g_{ij}^{e_L} P_L) e_j$$

A coupling to the dark sector

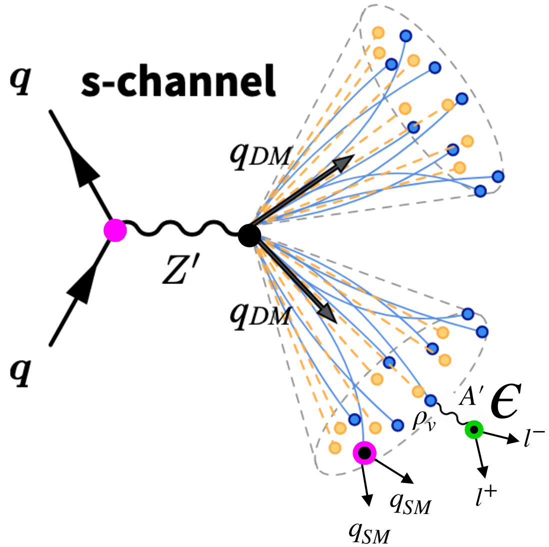
$$-Z'_\mu \bar{q}_{vi} \gamma^\mu (g_{ij}^{q_v R} P_R + g_{ij}^{q_v L} P_L) q_{vj}$$

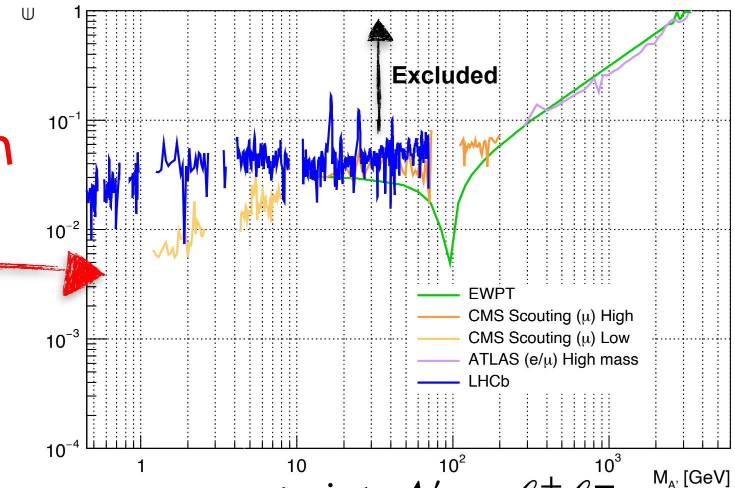
MODEL BASED ON:

Phys. Rev. D 84, 115006 (2011)

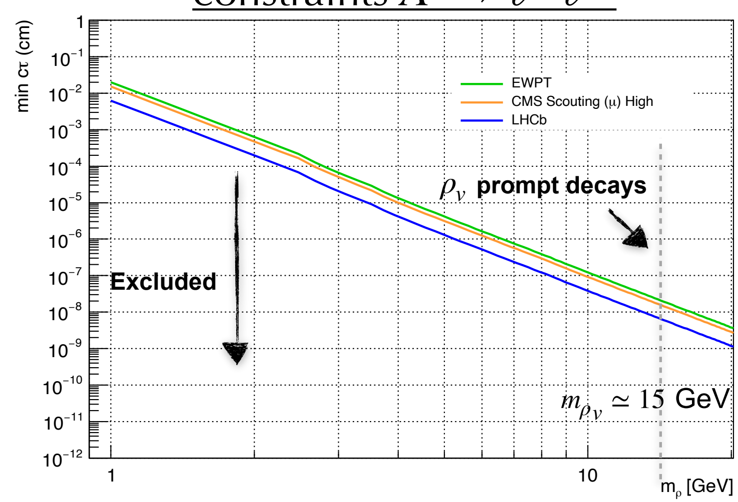
Phys. Rev. D 89, 095033 (2014)

SVJℓ MODEL : PARAMETERS & CONSTRAINTS



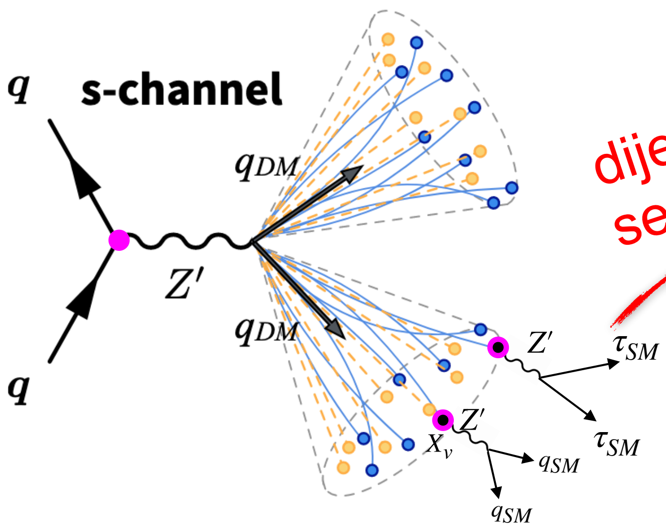


constraints $A' \to \ell^+\ell^-$

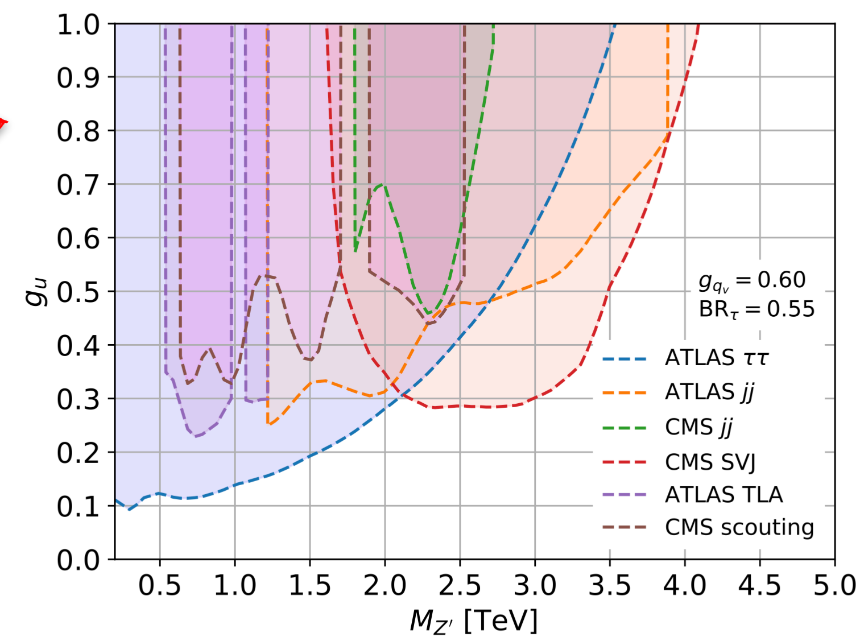


- ➡ **Portal mixing parameter** ϵ between Hidden Valley photon A′ and SM photon
- ➡ Dark ρ mesons inherit A′ decay modes **~ 15% democratic decay** of unstable ρ_v to <u>all lepton flavours</u> (from Chiral EFT)
- ➡ **Prompt signatures** allowed above few GeV for dark bound states

SVJτ MODEL: PARAMETERS & CONSTRAINTS



dijet & ditau searches

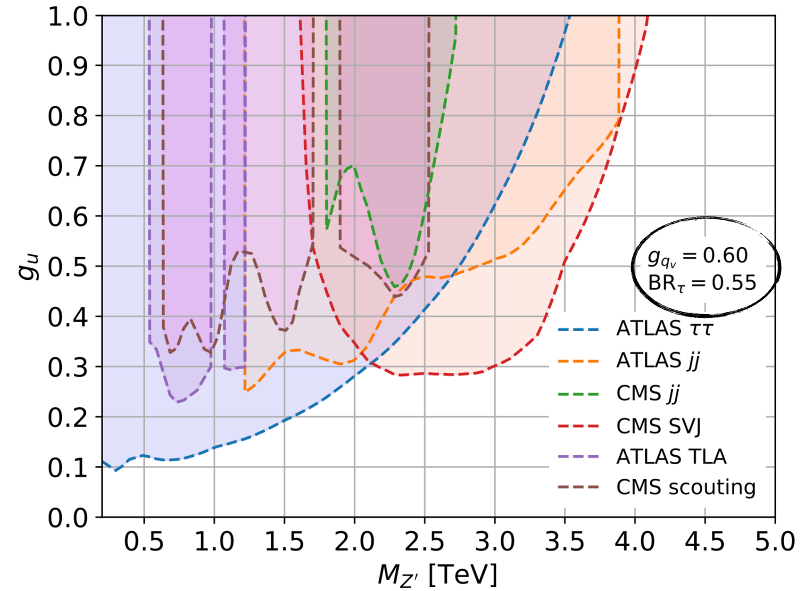


Eur. Phys. J. C 83, 599 (2023)

- ➡ Introduce an **effective branching fraction BR$_\tau$** of dark pions to τ leptons (controlled by ratio g_u/g_τ)
- ➡ Invisible fraction not only from stable dark bound states, enhancement from τ leptons decays to neutrinos

MODEL 1: PARAMETERS & CONSTRAINTS

Parameter	Description	Benchmark
$M_{Z'}$	Z' pole mass	0.5-5 TeV
r_{inv} (*)	invisible fraction	0.3
Λ_v	dark confinement scale	10 GeV
m_{π_v}/Λ_v (**)	pseudo-scalar mass ratio	0.8
BR_τ (***)	branching to τ leptons	0.15, 0.3 0.55, 0.7



* Neutrinos can be included adding a term $\propto \text{BR}_\tau \times (1 - r_{inv})$

** dark hadron masses set using Lattice QCD fits (Nf = 2, Nc = 3):

$m_{\pi_v} = 8$ GeV $\quad m_{\rho_v} \simeq 25$ GeV $\quad \rho \to \pi\pi$ open

see Eur. Phys. J. C (2022) , and backup

*** effective parameter controlled by the ratio: g_u/g_τ

COUPLINGS SETTINGS

Constrained by high mass di-lepton searches

$$g_{ij}^{d_R} = g_{ij}^{d_L} = g_{ij}^{u_L} = g_{ij}^{e_L} = 0, \quad g_{ij}^{u_R} = g_u \delta_{ij},$$

$$g_{ij}^{e_R} = g_\tau \delta_{i3}\delta_{j3}, \quad g_{ij}^{q_v R} = g_{ij}^{q_v L} = g_{q_v}\delta_{ij}.$$

Allow coupling to third generation leptons

respect NWA

[Phys. Dark Univ. 27, 100365 (2020)
JHEP 06, 156 (2022)]

MODEL 2: PARAMETERS & CONSTRAINTS

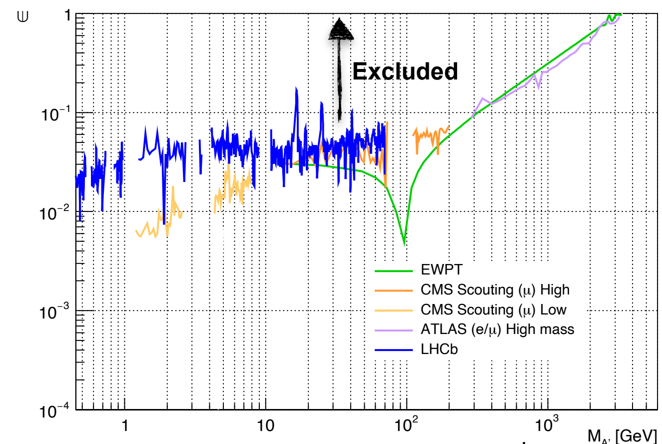
Parameter	Description	Benchmark
$M_{Z'}$	Z' pole mass	1.5–5 TeV
$\epsilon_{\text{eff,v}}$	Effective mixing	0.03
r_{inv}	Invisible fraction	0.3, 0.5, 0.7
Λ_v	Dark confinement scale	5 GeV
m_{π_v}/Λ_v (*)	Pseudo-scalar mass ratio	1.6

- ~ **15% democratic decay** of unstable ρ to all lepton flavours
- **Z′ COUPLINGS SETTINGS**: $g^v_{Z'} = 0.4$, $g^q_{Z'} = 0.25$
  [Phys. Dark Univ. 27, 100365 (2020)
  JHEP 06, 156 (2022)]

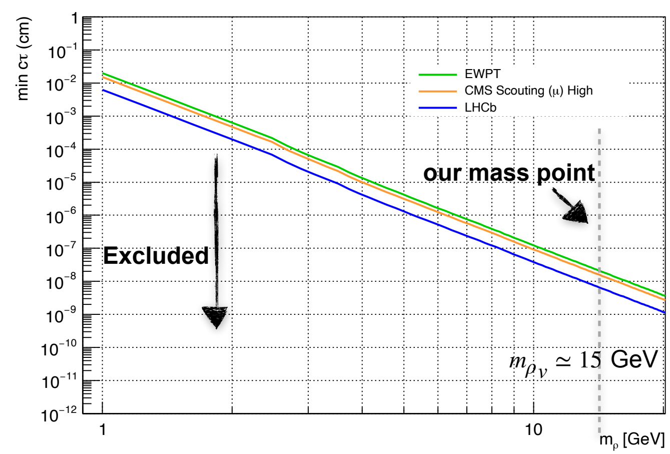
* effective mixing fixed saturating $A' \to \ell^+\ell^-$ bounds

** dark hadron masses set using Lattice QCD fits (Nf = 2, Nc = 3):

$m_{\pi_v} = 8$ GeV $m_{\rho_v} \simeq 15$ GeV $\rho \to \pi\pi$ closed

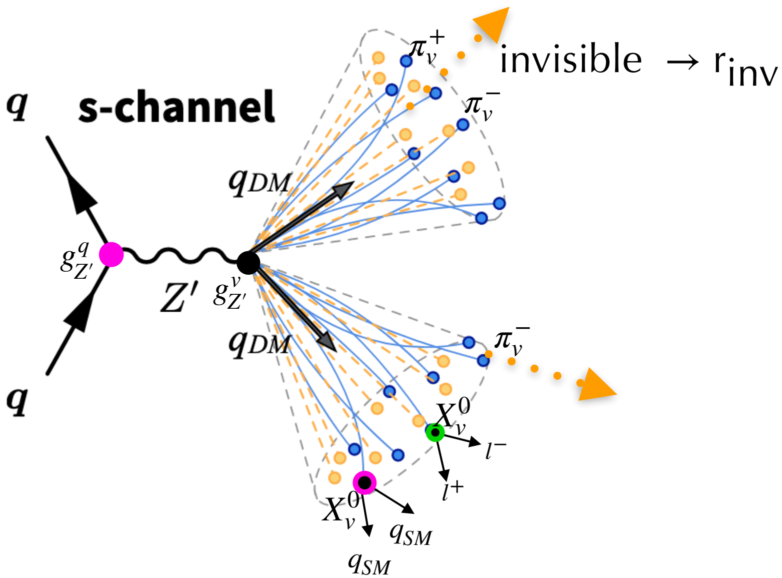


constraints $A' \to \ell^+\ell^-$



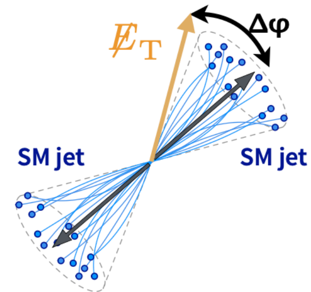
SIGNAL AND BACKGROUND PROCESSES

Signal Process

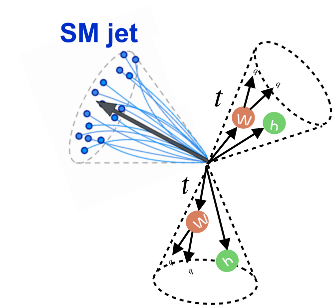


Background Process

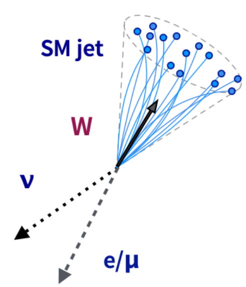
QCD - DIJET



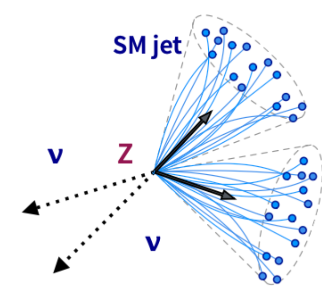
$t\bar{t}$ + jets



W + JETS



Z + JETS

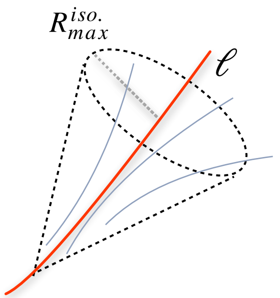


- ✦ Signal mainly characterised by hadronic jets with $\vec{p}_{T,miss}$ aligned and non-isolated leptons
- ➡ Large QCD background (fake $\vec{p}_{T,miss}$ and B hadrons), Boosted Top Jets with semi-leptonic W decays
- ➡ Z/W + Jets: minor since bulk at large $\Delta\phi(\vec{p}_{T,miss}, J_{1,2})$

LIMITATIONS: CLASSICAL LEPTONS ISOLATIONS

RELATIVE STANDARD ISOLATION (FIXED R)

$$I(\ell) = \frac{1}{p_{T,l}} \sum_{i \neq \ell}^{\Delta R < R_{\max}^{\text{iso.}}} p_T(i)$$

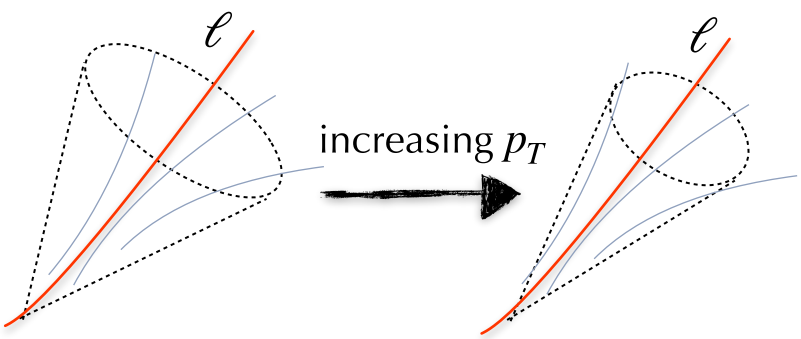


ISOLATION VETO: LIMITATION FOR ELECTRONS AND MUONS PRODUCED INSIDE JETS

RELATIVE MINI-ISOLATION (VARIABLE R) JHEP 1103:059,2011

$$I_{\text{mini}} = \frac{1}{p_{T,l}} \sum_{i \neq l}^{\Delta R < R_{\max}^{\text{mini iso.}}} p_T(i)$$

$$R_{\max}^{\text{mini iso.}} = \begin{cases} 0.2, & p_T^\ell \leq 50\,\text{GeV} \\ \frac{10\,\text{GeV}}{p_T^\ell}, & 50\,\text{GeV} < p_T^\ell < 200\,\text{GeV} \\ 0.05, & p_T^\ell \geq 200\,\text{GeV} \end{cases}$$



USED IN CMS SVJ AS A VETO

MINI-ISOLATION VETO: LIMITATION FOR e/μ FROM DIRECT DARK BOUND STATES DECAYS (RESONANT SIGNATURE)

HADRONIC SVJ INCLUSIVE ANALYSIS AS STANDARD CANDLE

Selections

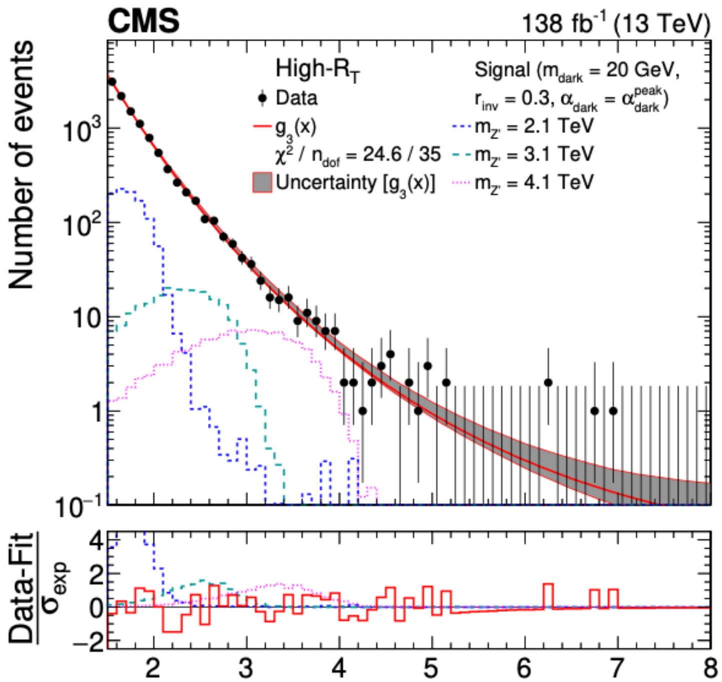
1. At least 2 good jets (R = 0.8)
2. Large missing momentum aligned to $J_{1,2}$
3. Maximum $\Delta\eta(J_1, J_2)$
4. Trigger plateau ($m_T > 1.5$ TeV)
5. Mini-isolated leptons veto

SELECTIONS BASED ON CMS ANALYSIS : JHEP 06, 156 (2022)

Dijet transverse mass

$$m_T^2 = [E_{T,JJ} + E_T^{miss}]^2 - [\vec{p}_{T,JJ} + \vec{p}_T^{miss}]^2$$
$$= m_{JJ}^2 + 2p_T^{miss}\left[\sqrt{m_{JJ}^2 + p_{T,JJ}^2} - p_{T,JJ}\cos(\phi_{JJ,miss})\right]$$

Look for a broad resonance



JHEP 06, 156 (2022)

IS IT EFFICIENT FOR OUR SIGNATURES ?

HADRONIC SVJ INCLUSIVE ANALYSIS AS STANDARD CANDLE

Preselection requirements

$p_T(J_{1,2}) > 200\,\text{GeV},\ \eta(J_{1,2}) < 2.4$

$R_T > 0.15$

$\Delta\eta(J_1, J_2) < 1.5$

$m_T > 1.5\,\text{TeV}$

$N_\mu = 0$

$N_e = 0$

(*) p_T^{miss} filters

(*) $\Delta R(j_{1,2}, c_{\text{nonfunctional}}) > 0.1$

Final selection requirements

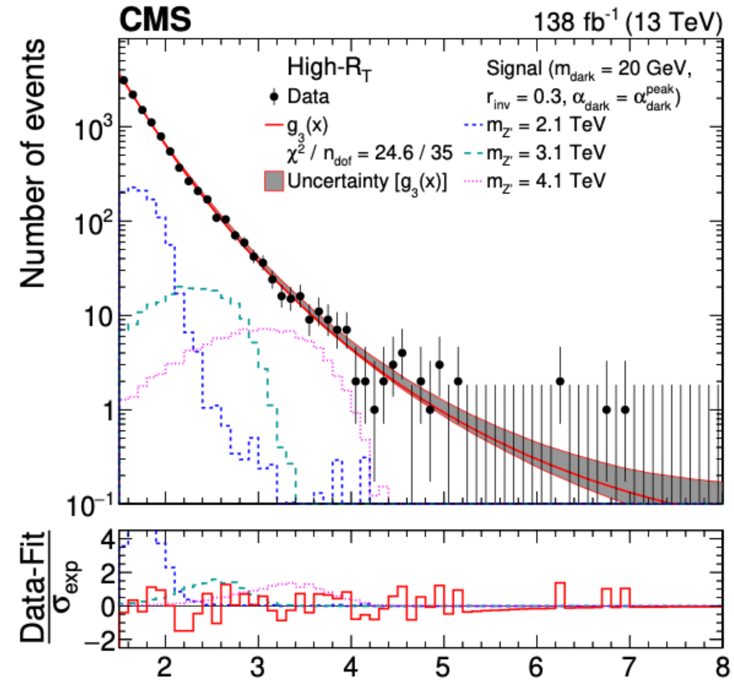
(*) veto $f_\gamma(j_1) > 0.7$ & $p_T(j_1) > 1.0\,\text{TeV}$

(*) veto $-3.05 < \eta_j < -1.35$ & $-1.62 < \phi_j < -0.82$ *

$\Delta\phi_{\min} < 0.8$

SELECTIONS FROM CMS ANALYSIS : JHEP 06, 156 (2022)

Look for a broad resonance



JHEP 06, 156 (2022)

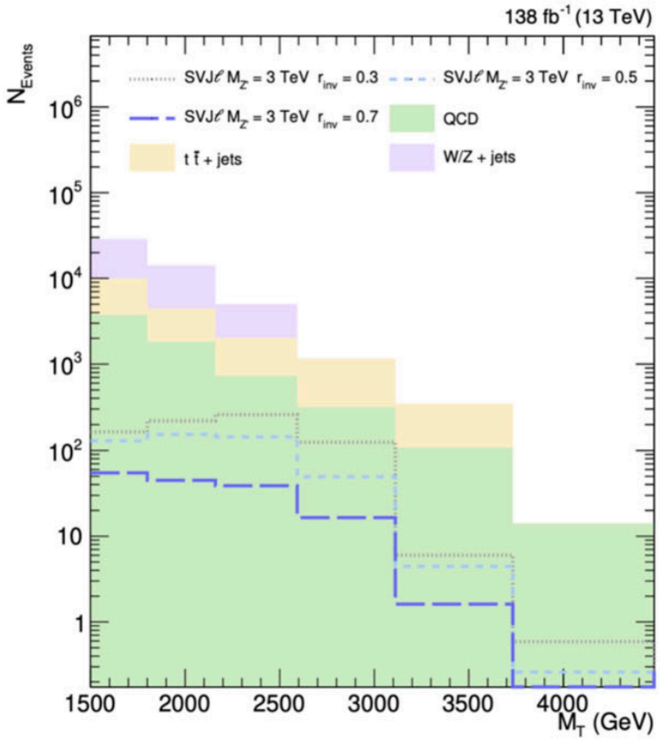
Variables Legend

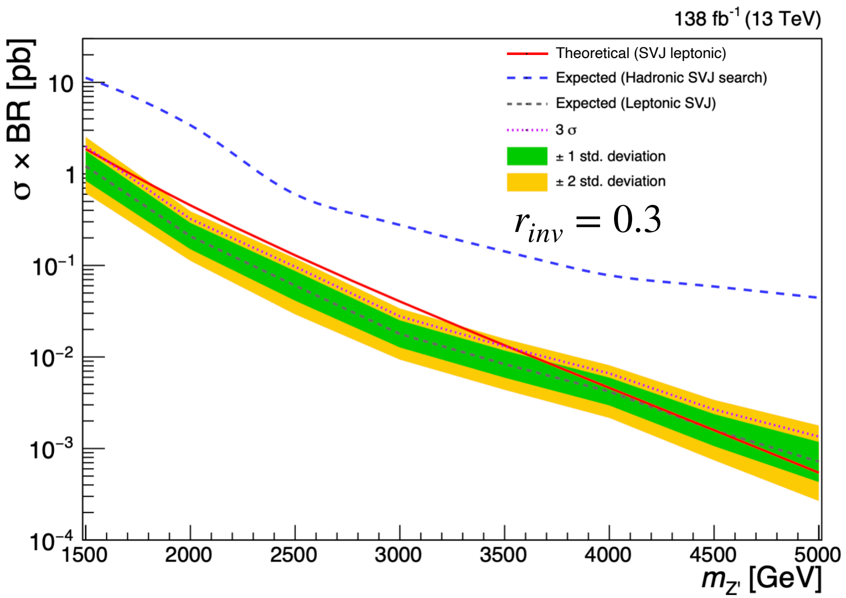
m_T : di-jet transverse mass

R_T : $\not{E}_T / m_T$

(*) negligible in phenomenological study

SENSITIVITY ESTIMATION



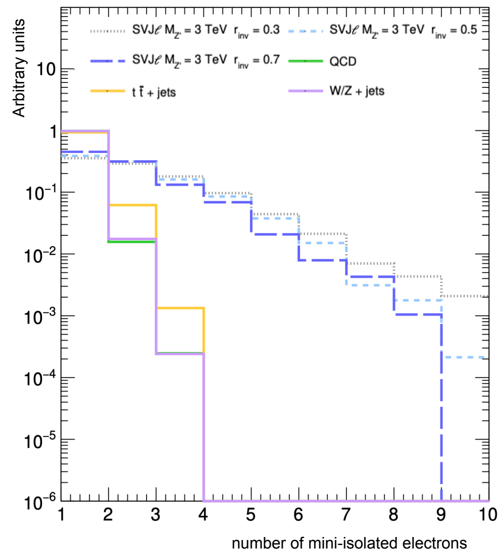


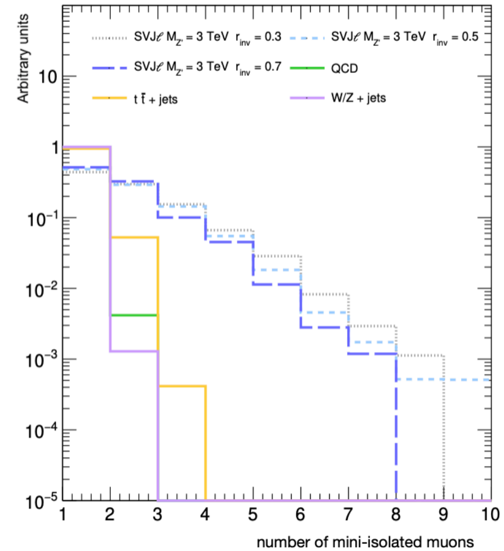
BUMP HUNT ON A FALLING BACKGROUND IN M_T SPECTRUM : 1.5 - 5 TeV (HIGH MASS SEARCH)

ASYMPTOTIC CLs (J.Phys.G 28 (2002) 2693-2704 , Eur. Phys. J. C (2011) **71**: 1554)

MINIMAL SYSTEMATICS (LOG-NORMAL): LUMINOISITY (2.6 %) & TRIGGER (2 %)

MINI-ISOLATION VETO





SIGNAL BENCHMARK : MZ′ = 3 TeV

Variable	Selection	$\epsilon_{sig}, r_{inv} : 0.3$	$\epsilon_{sig}, r_{inv} : 0.5$	$\epsilon_{sig}, r_{inv} : 0.7$
$n(good\ AK8)$	≥ 2	67.53	46.69	22.42
$\Delta\eta_{j0,j1}\ (AK8)$	≤ 1.5	45.25	32.80	16.53
$M_T\ (AK8)$	≥ 1500	31.01	18.11	7.45
$R_T\ (AK8)$	≥ 0.15	19.22	13.41	6.00
$\Delta\Phi_{\min}(\not{E}_T, Jets)$	≤ 0.8	17.61	11.58	4.51
n Good Mini Iso leptons	$N_\mu = N_e = 0$	2.84	2.42	1.37

MINI-ISOLATION LEPTONS VETO USED IN CMS SVJ ANALYSIS IS EXPECTED TO REJECT MOST OF THE SIGNAL
(STATEMENT VALID FOR DIFFERENT INVISIBLE FRACTIONS AND MEDIATOR MASSES)

SVJℓ TARGETED INCLUSIVE APPROACH

GOOD OBJECTS

- ≥ 2 AK8 Jets with $p_T > 200$ GeV & $|\eta| < 2.4$
- $p_T(e, \mu) > 10$ GeV & $|\eta(e, \mu)| < 2.4$

✦ $d_0(\mu, e) < 100\ \mu m$: prompt dark hadrons leptonic decays

SELECTIONS

- $R_T > 0.15$: $\not{E}_T$-like cut, no M_T sculpting
- $\Delta\eta(j_1, j_2) < 1.5$: removes t-channel QCD
- $M_T > 1500$ GeV : trigger requirement
- $\Delta\phi_{min}(j_{1,2}, \not{E}_T) < 0.8$: W/Z + jets suppression

✦ Veto events with at least 2 isolated leptons

✦ Opposite sign non inter-isolated ($I_{int} > 0.1$) leptons pairs

VARIABLES LEGEND

M_T : di-jet transverse mass

R_T : $\not{E}_T / M_T$

d_0 : transverse impact param.

• = SVJ topology ✦ = additional requirements

SVJℓ CUT EFFICIENCIES

SIGNAL BENCHMARK : MZ′ = 3 TeV

Variable	Selection	ϵ_{sig}, r_{inv} : 0.3	ϵ_{sig}, r_{inv} : 0.5	ϵ_{sig}, r_{inv} : 0.7
$n(good\ AK8)$	≥ 2	67.53	46.69	22.42
$\Delta\eta_{j0,j1}$ $(AK8)$	≤ 1.5	45.25	32.80	16.53
M_T $(AK8)$	≥ 1500	31.01	18.11	7.45
R_T $(AK8)$	≥ 0.15	19.22	13.41	6.00
$\Delta\Phi_{\min}(\not{E}_T, Jets)$	≤ 0.8	17.61	11.58	4.51
n non-interIso Good OS lepton pairs	> 0	14.01	8.70	2.83

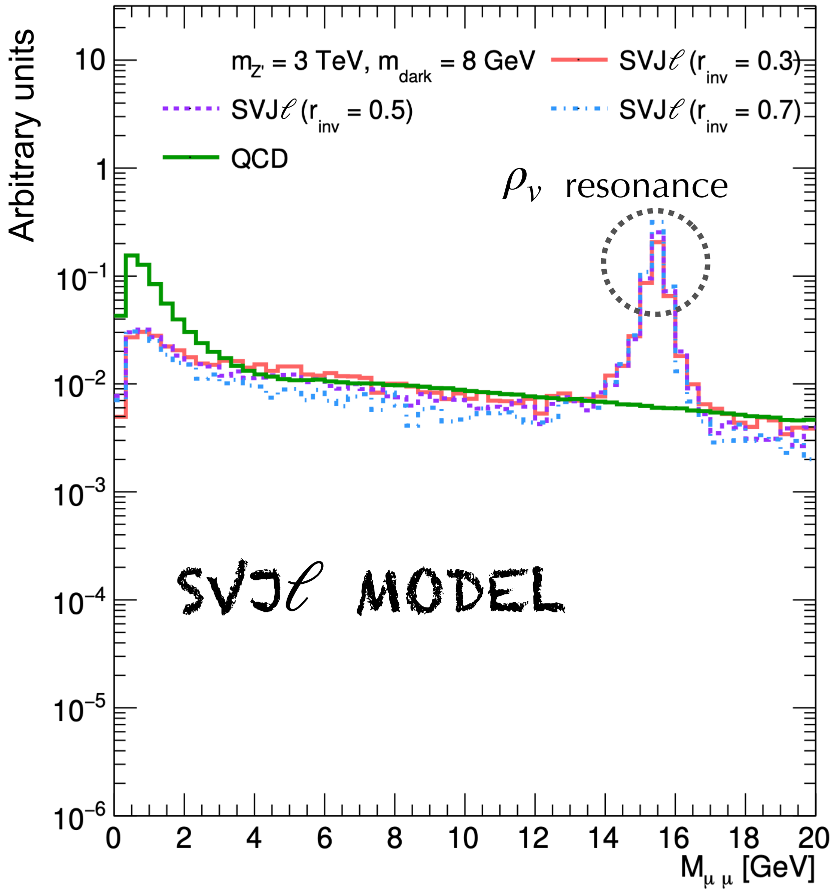
BACKGROUNDS

Variable	Selection	$\epsilon_{QCD}\%$	$\epsilon_{t\bar{t}}\%$	$\epsilon_{Zj}\%$	$\epsilon_{Wj}\%$
$n(good\ AK8)$	≥ 2	98.16813	7.18502	1.02670	1.58200
$\Delta\eta_{j0,j1}$ $(AK8)$	≤ 1.5	66.54385	5.31659	0.66615	1.09866
M_T $(AK8)$	≥ 1500	15.00132	0.15060	0.03025	0.0227
R_T $(AK8)$	≥ 0.15	0.70012	0.03026	0.01346	0.00692
$\Delta\Phi_{\min}(\not{E}_T, Jets)$	≤ 0.8	0.68872	0.02722	0.00753	0.00535
(*) n non-interIso Good OS lepton pairs	> 0	0.05426	0.00243	0.00030	0.00036

→ REMAINING MAJOR BACKGROUND: QCD (HADRONS PROMPT LEPTONIC DECAYS)

(*) all good lepton pairs are non-isolated

EXPLOITING DI-LEPTON RESONANCE



POSSIBLE STRATEGIES

✦ Can select a mass window in m_{ll} and fit m_T

✦ Can perform 2D fit $m_{ll} - m_T$

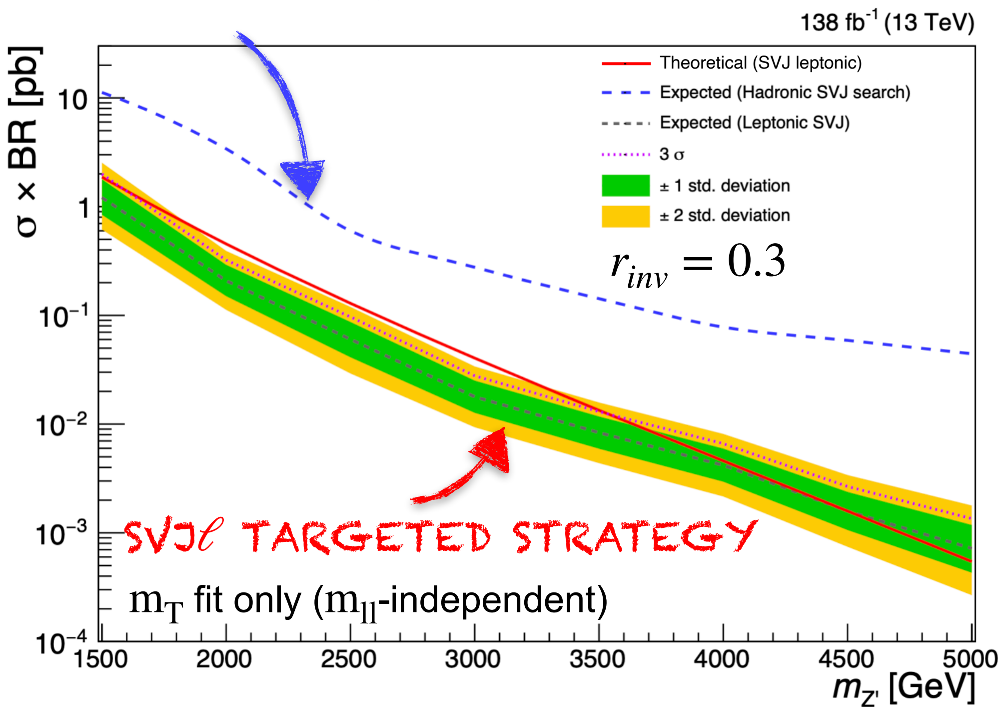
✦ Can look independently for low mass resonance(s) in the non-isolated di-lepton spectrum

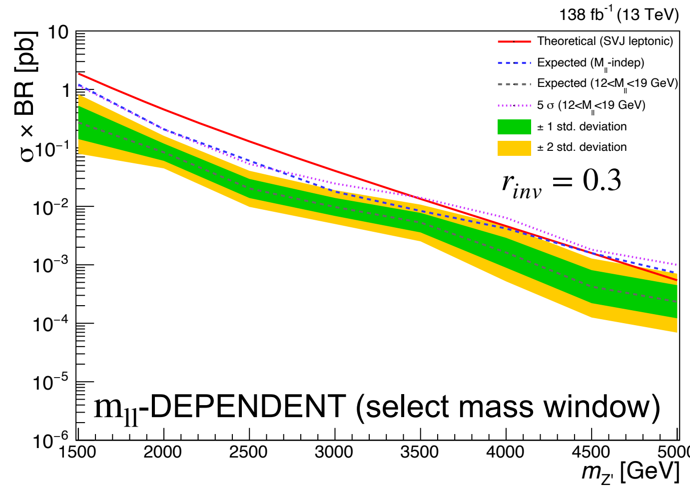
➡ Model dependent feature: number of resonances depends on dark sector details

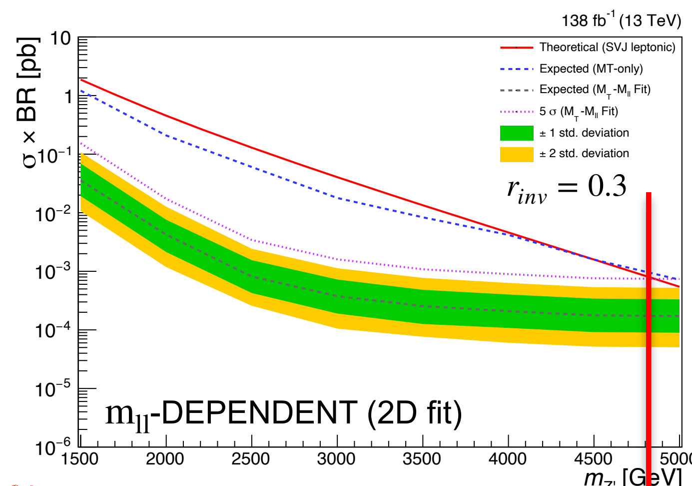
BACKUP

SVJℓ-TARGETED INCLUSIVE ANALYSIS SENSITIVITY

CMS SVJ SEARCH







THE SIGNAL MIGHT STILL BE LURKING IN LHC RUN 2 DATA !

Can claim 5σ with full Run2 up ~ 5 TeV !

LIMITATIONS OF CLASSICAL TRIGGERS

✦ Jet HT || pT triggers used by CMS: inherited from high mass di-jet search JHEP 06, 156 (2022)

✦ CMS fully efficient trigger requirement $m_T > 1.5$ TeV limits sensitivity for SVJτ (**effect of neutrinos from τ decays** shifts m_T to lower values)

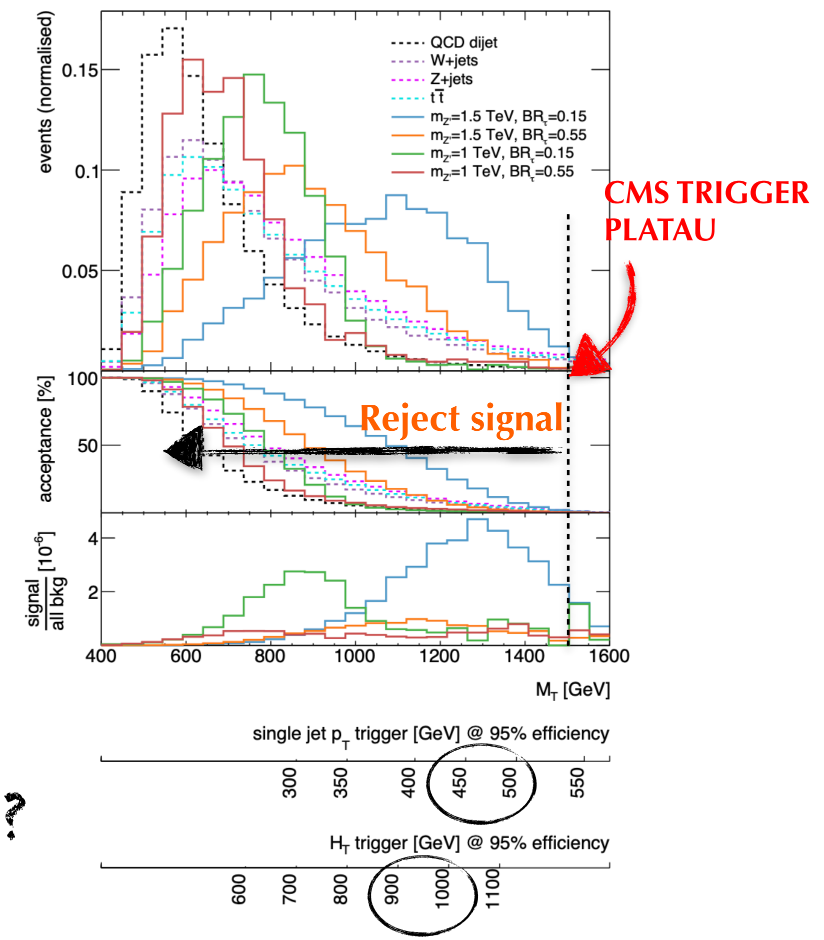
✦ Hadronic triggers below current thresholds $p_T(500)/H_T(1050)$ are prescaled (limited statistics)

✦ MET triggers: too high threshold for lowest unprescaled

✦ Tau triggers: limited by isolation criteria and soft τ leptons in signal

ARE THERE OTHER POSSIBILITIES ?

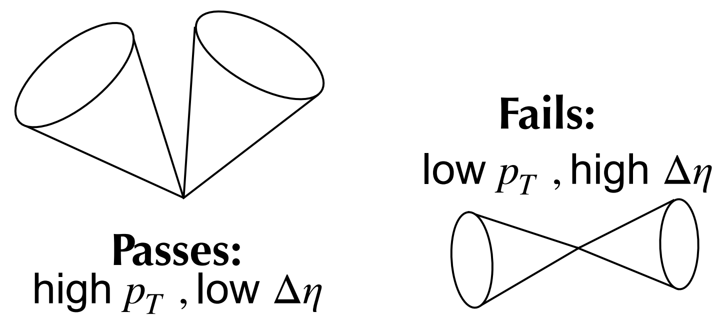
HADRONIC TRIGGERS



TOPOLOGICAL TRIGGERS AND BEYOND

TOPOLOGICAL TRIGGERS

- Exploit the s-channel topology at L1:
  ≥ 2 AK4 $p_T > 100$ GeV & $\Delta\eta(j_1, j_2) < 2$
  reduce hadronic rates prior to HLT
- Promising for lowering HT threshold
- Hypothetical target: HT > 600 GeV
  ($m_T > 800$ GeV) [need full sim]



TOPOLOGICAL TRIGGERS

acceptance [%]

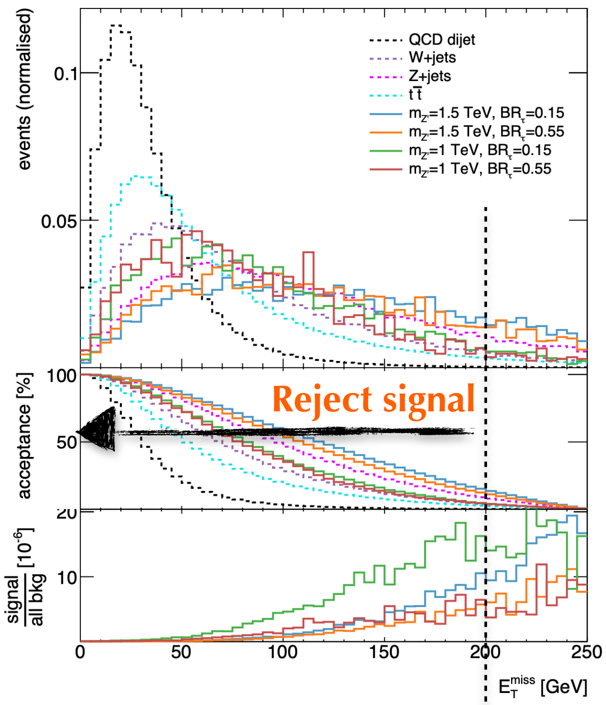
	H_T>0.6 TeV, no Δη	H_T>0.6 TeV, with Δη	H_T>0.8 TeV, no Δη	H_T>0.8 TeV, with Δη	H_T>1.0 TeV, no Δη	H_T>1.0 TeV, with Δη	p_T>0.3 TeV, no Δη	p_T>0.3 TeV, with Δη	p_T>0.4 TeV, no Δη	p_T>0.4 TeV, with Δη	p_T>0.5 TeV, no Δη	p_T>0.5 TeV, with Δη
$M_{Z'} = 3.0$ TeV, BR_τ=0.55	99	84	98	83	94	81	93	81	81	73	64	61
$M_{Z'} = 1.5$ TeV, BR_τ=0.55	95	90	81	77	65	62	72	70	35	35	13	12
$M_{Z'} = 1.0$ TeV, BR_τ=0.55	84	81	62	59	43	40	44	43	12	12	4	4
$M_{Z'} = 0.7$ TeV, BR_τ=0.55	80	74	61	56	44	40	35	32	17	16	10	9
ttbar	99	85	97	83	92	78	43	37	19	17	9	8
W+jets	80	66	65	52	49	40	47	39	19	16	8	7
Z+jets	92	73	77	62	61	48	53	43	23	19	10	9
QCD dijet	77	61	56	44	38	30	34	28	9	8	3	2

… AND BEYOND ?

- Alternative data-taking: Data Parking and Scouting
- Partial Event Building (PEB): can retain full jet substructure for tagging (but fully reconstructing only part of the event)

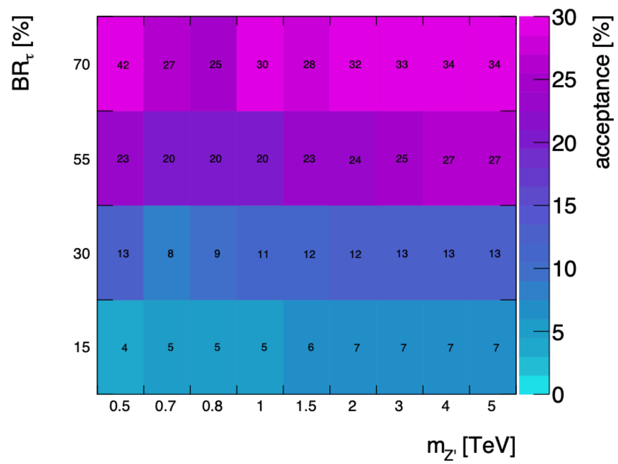
CLASSICAL MET AND TAU TRIGGERS

MET TRIGGERS

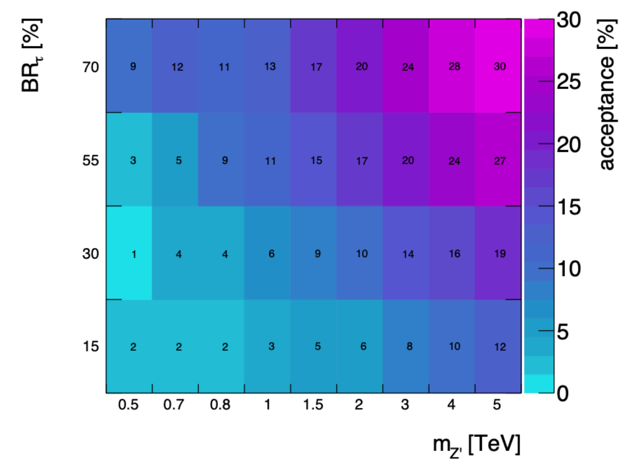


lowest unprescaled threshold $\mathcal{O}(200\ GeV)$

SINGLE TAU TRIGGER



DI-TAU TRIGGER



- ✦ MET triggers: too high threshold for lowest unprescaled
- ✦ Single tau triggers: limited by isolation criteria
- ✦ Di-tau triggers: isolation applied to τ candidates $p_T < 25$ GeV no significant improvement (relatively soft τ leptons in signal)

LEPTON FLAVOUR-BASED JET TAGGER FEATURES

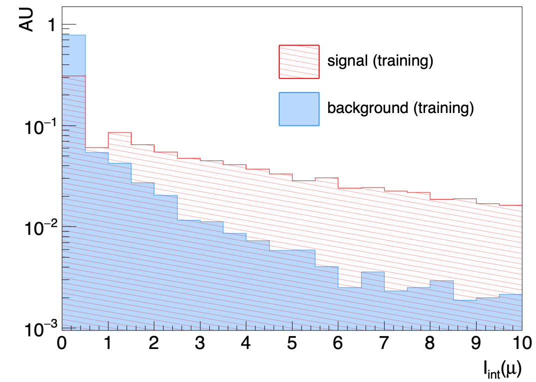
JET-TAGGER INPUT FEATURES

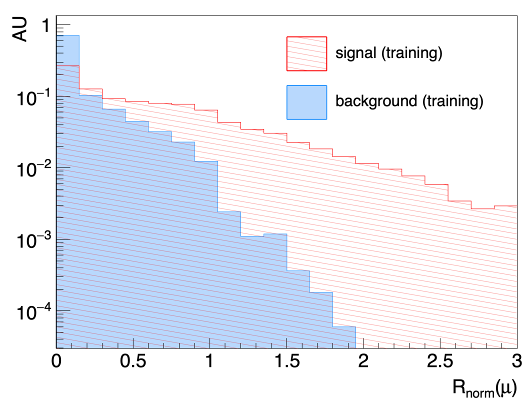
- Set of variables to exploit e/μ enriched jet content from leptonic τ decays (~ 35 %)

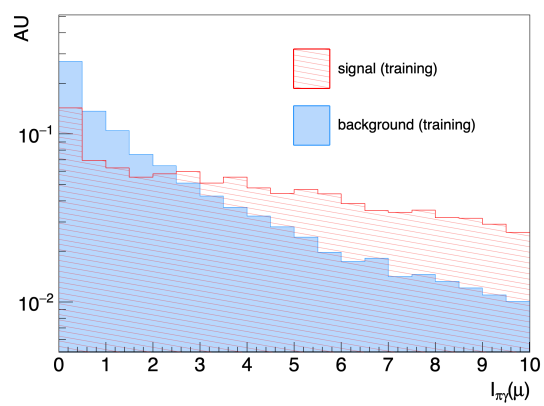
- 3 main classes of features (per e/μ):
  1. Energy/momentum flow,
  2. Spatial distributions,
  3. Specific isolations (capture leptonic and hadronic boosted di-τ decays)

- Adaptive BDT (TMVA) trained on a mixture of signal jets hypo (scan over Z' mass and BR_τ)

Rank	Variable	Separation
1	$I_{inter}(\mu)$	2.703×10^{-1}
2	$R_{Norm}(\mu)$	2.601×10^{-1}
3	$I_{\gamma\pi}(\mu)$	2.164×10^{-1}
4	$R_{Norm}(e)$	1.786×10^{-1}
5	$I_{inter}(e)$	1.632×10^{-1}
6	$Energyfraction(e)$	7.500×10^{-2}
7	$I_{\gamma\pi}(e)$	7.175×10^{-2}
8	$p_{T,Norm}(\mu)$	6.272×10^{-2}
9	$Energyfraction(\mu)$	6.220×10^{-2}

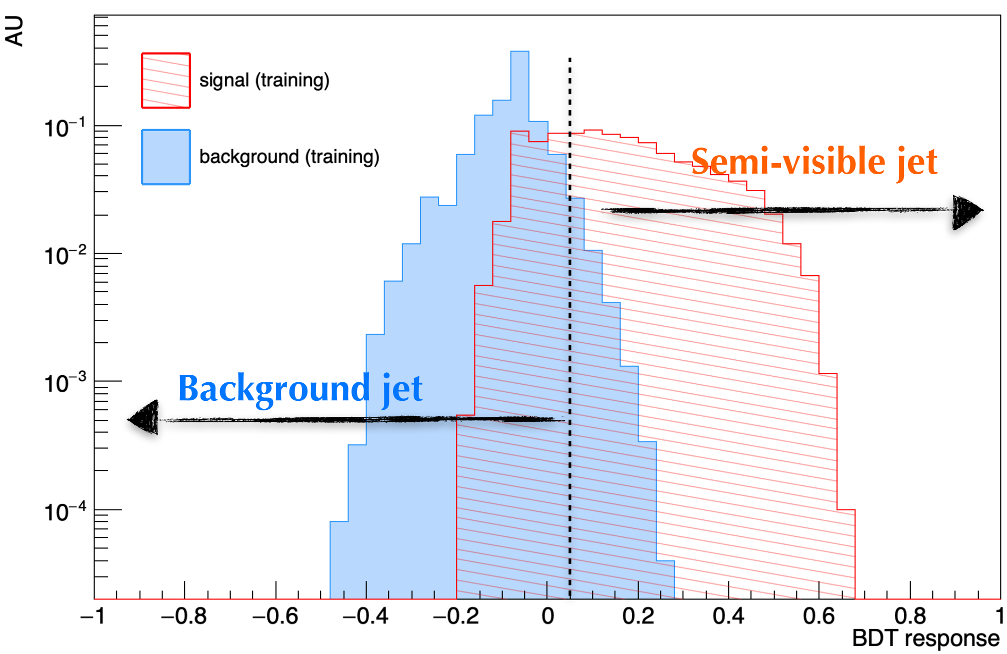


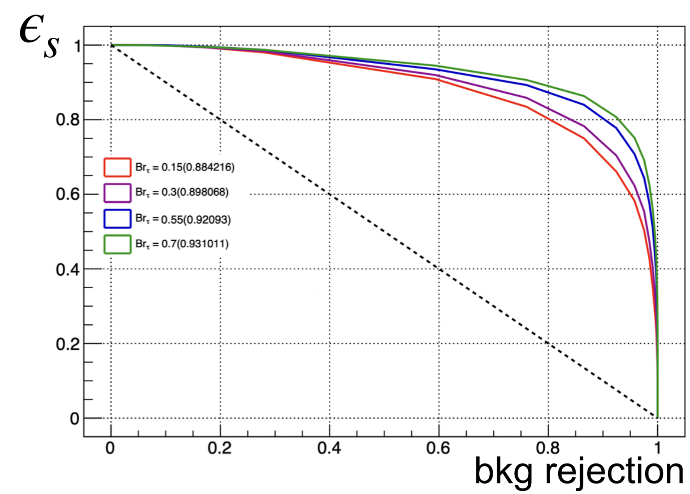


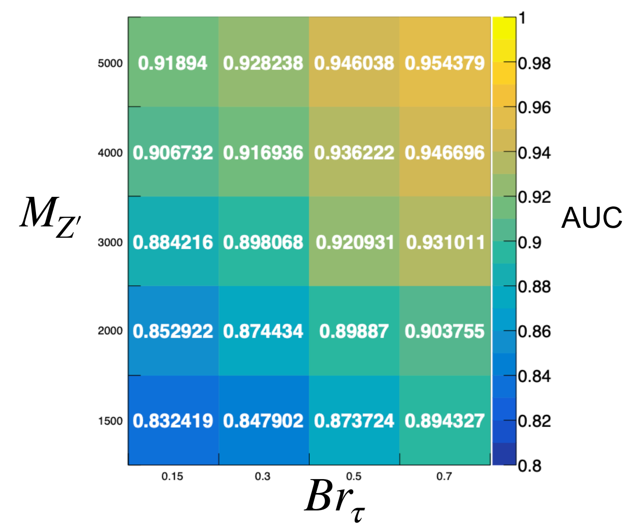


(*) all distributions shown are for training datasets

LEPTON FLAVOUR-BASED JET TAGGER PERFORMANCE

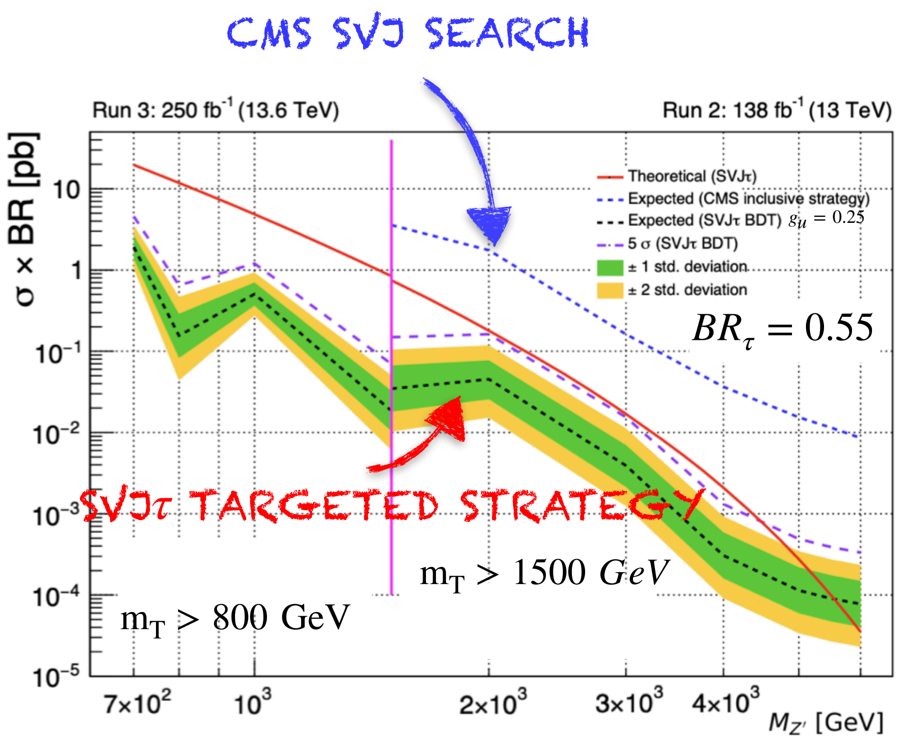


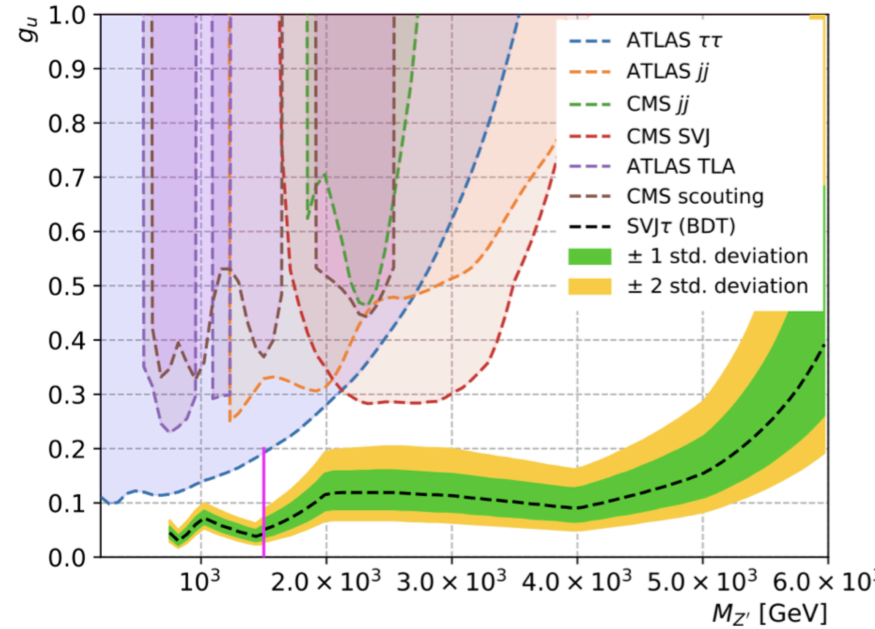




- ✦ BDT working point: maximise $s/\sqrt{s+b}$
- ✦ Rejects ~97% of background jets, tags: 80%, 84%, 90%, 93% signal jets ($BR_\tau = 0.15, 0.3, 0.55, 0.7$)

SVJτ-TARGETED ANALYSIS SENSITIVITY

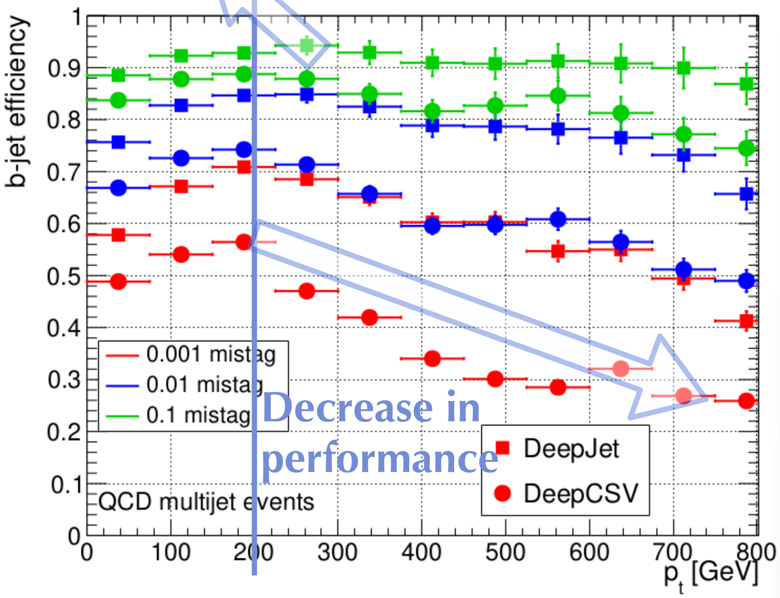




- ✦ NO SENSITIVITY FOR CMS INCLUSIVE HADRONIC STRATEGY: NEED TO EXPLOIT TAU CONTENT FEATURES
- ✦ EXPLOITING BDT JET-CLASSIFICATION : EXCLUSION REACH (DISCOVERY) UP TO ~ 5.5 TeV (~ 4.5 TeV)
- ✦ EXPECTED TO OUTPERFORM ANY EXISTING SEARCH: PROBE UNEXPLORED g_u COUPLING VALUES

POSSIBLE B-TAGGING INEFFICIENCIES

loose WP, high mistag rates



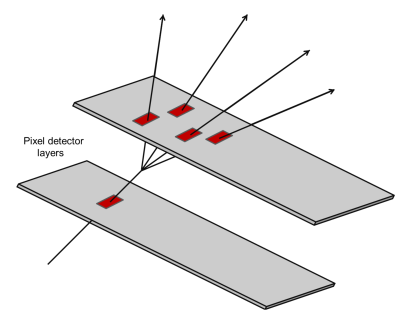
JINST 15 (2020) P12012

Observed also for TTJ and boosted Z′ to bb

Why expected inefficiencies ?

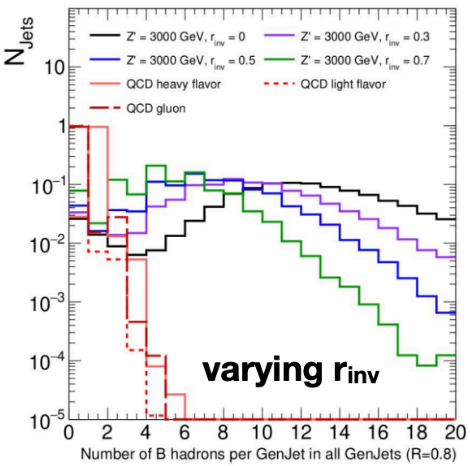
higher jet pT ⇨ Boosted/merged objects

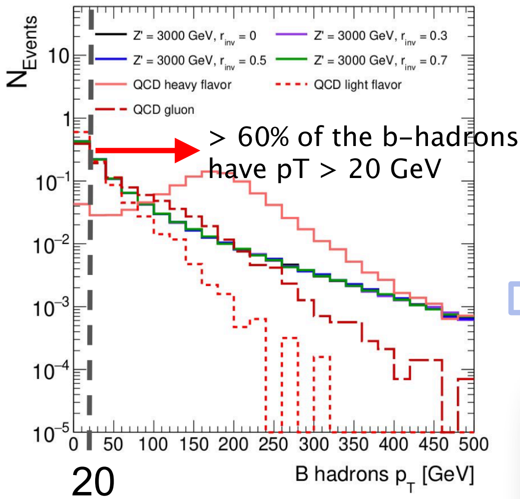
- **Reduced track reco efficiencies** : higher hits density (ambiguous hit-track association or merging)
- Increasing fraction of missing hits in inner layers, **impact Param degradation**
- **Many SVs**, but more **difficult to reconstruct them** !

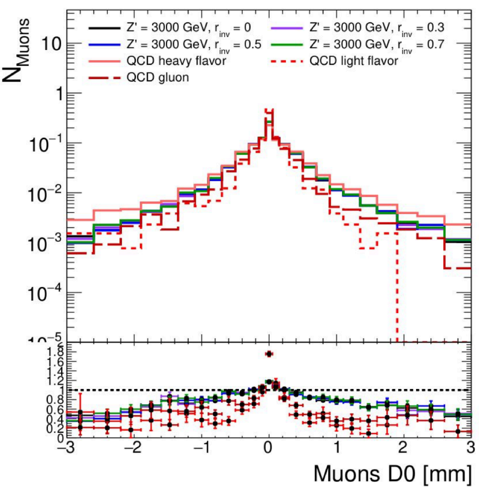


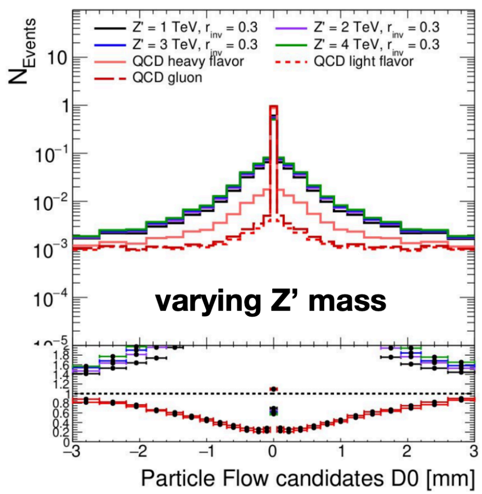
Other references: JINST 13 (2018) P05011

THE HEAVY-FLAVOURED SVJS FEATURES





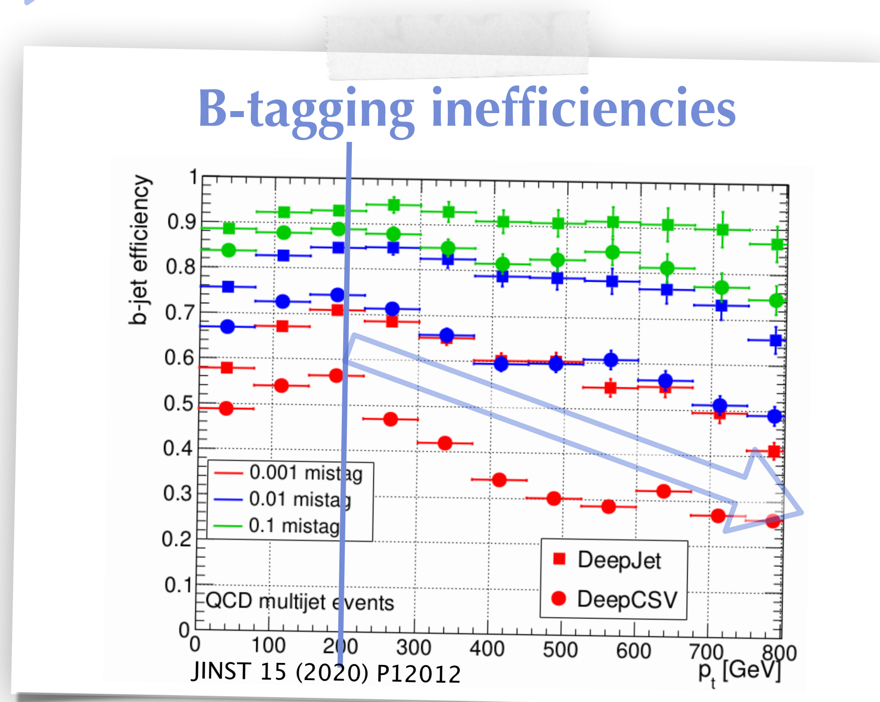




✔ Need **enough pT for B-hadrons** to originate **displaced vertices and tracks**

✘ High b-hadron multiplicity may impact **vertex performance**

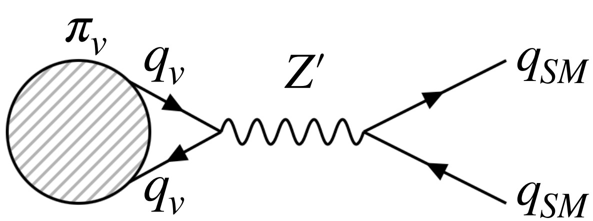
⇨ Might **impact performance of b-tagging algos**



(*) Plots to be taken with grain of salt: Delphes reco

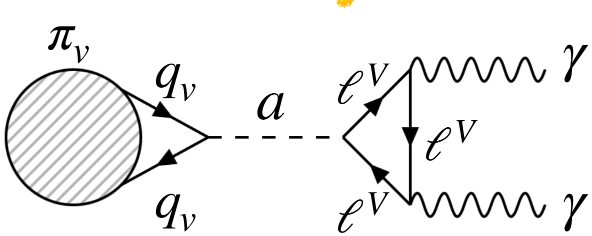
MODEL PARAMETRIZATION AND BRANCHING RATIOS

Hadronic decay channel



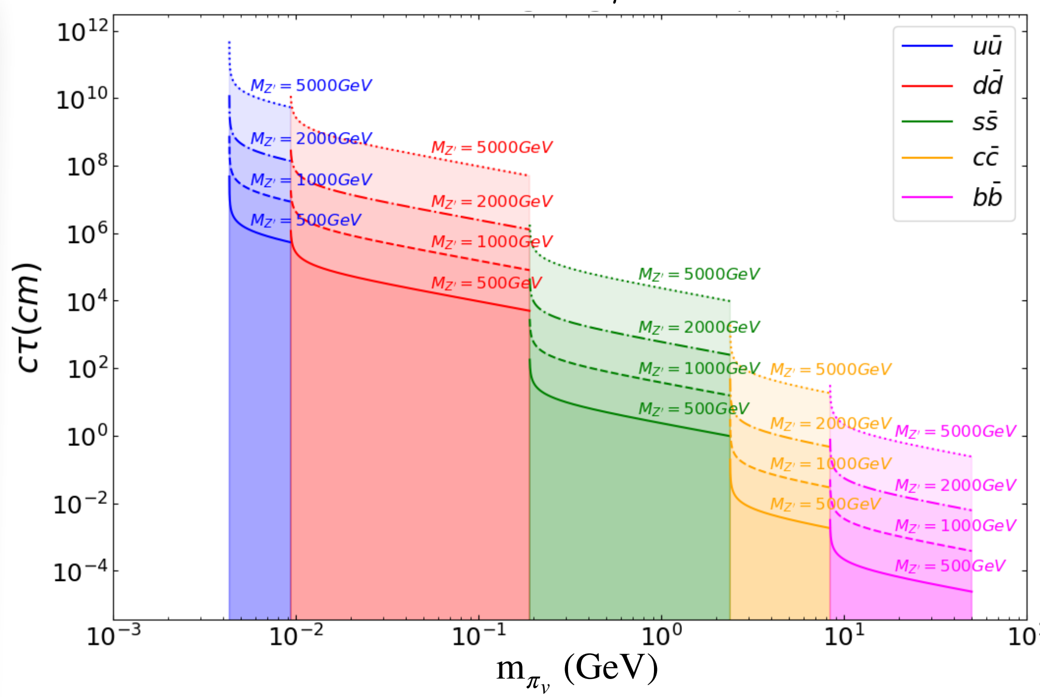
$$\Gamma_p = \frac{\alpha^2}{64\pi^2} m_{\pi_v}^7 \Xi_p^2$$

Photons decay channel



$$\Gamma_q = \frac{3}{32\pi} m_{f_i}^2 m_{\pi_v} \sqrt{1 - \frac{4m_{f_i}^2}{m_{\pi_v}^2}} \Xi_q^2$$

ISOCURVES FOR $BR_\gamma = BR_{had} = 0.5$



Effective parameters

$$\Xi_q := \frac{(\Delta_{ii}^f \Delta_a^{q_v})}{M_{Z'}^2} \qquad \Xi_p := \frac{y_Q y_\psi}{m_a^2 M_Q}$$