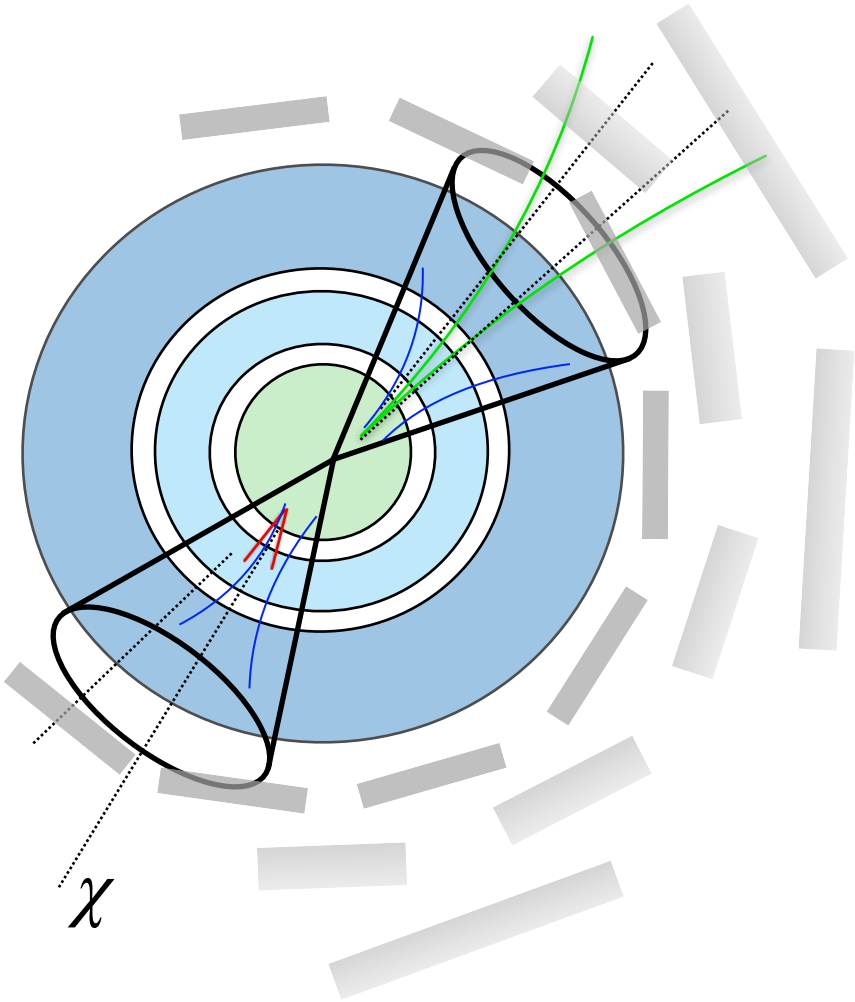
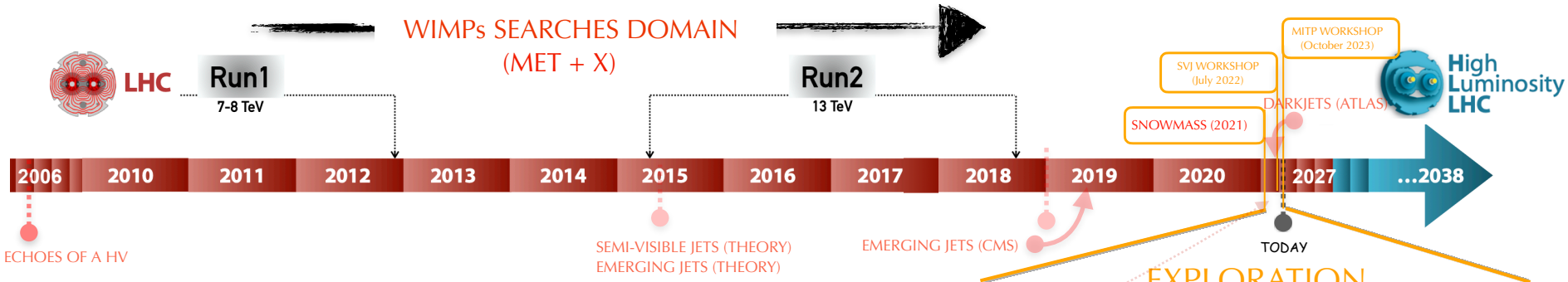


Leptons Lurking In Semi-Visible Jets At The LHC

Cesare Cazzaniga & Annapaola De Cosa

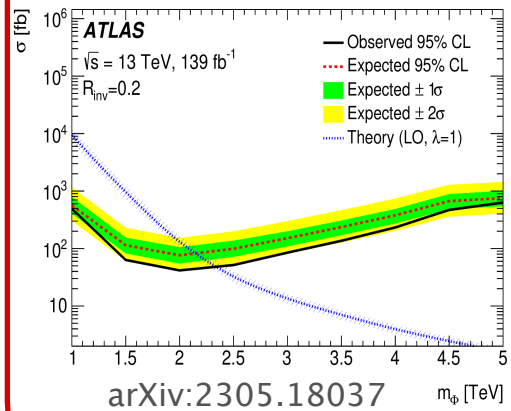
(ETH Zurich)

QCD-LIKE DARK SECTORS @ THE LHC



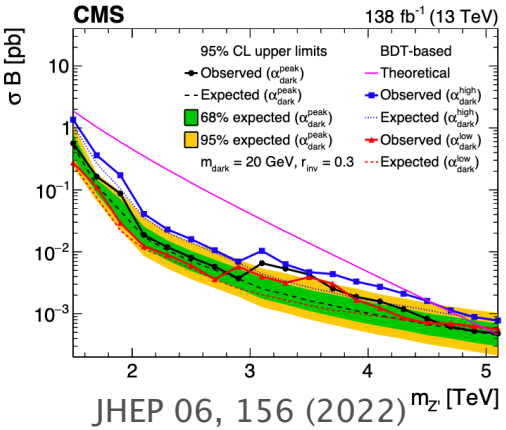
SEMI-VISIBLE JETS (SVJ)

t-channel



arXiv:2305.18037

s-channel



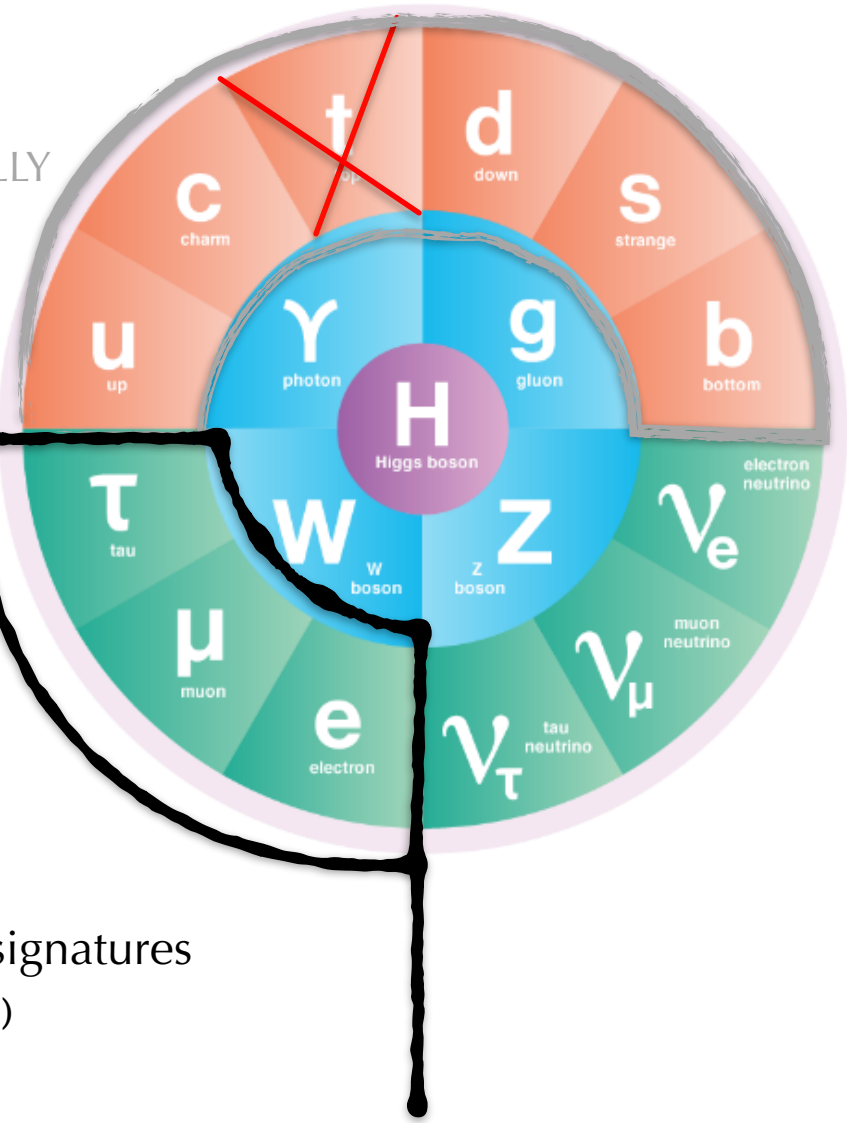
JHEP 06, 156 (2022)

EXPLORATION

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

OUTLINE

EXPLORED THEORETICALLY
& EXPERIMENTALLY



OUR FOCUS

Leptons-enriched signatures for SVJs

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

➡ τ leptons-enriched SVJs signatures

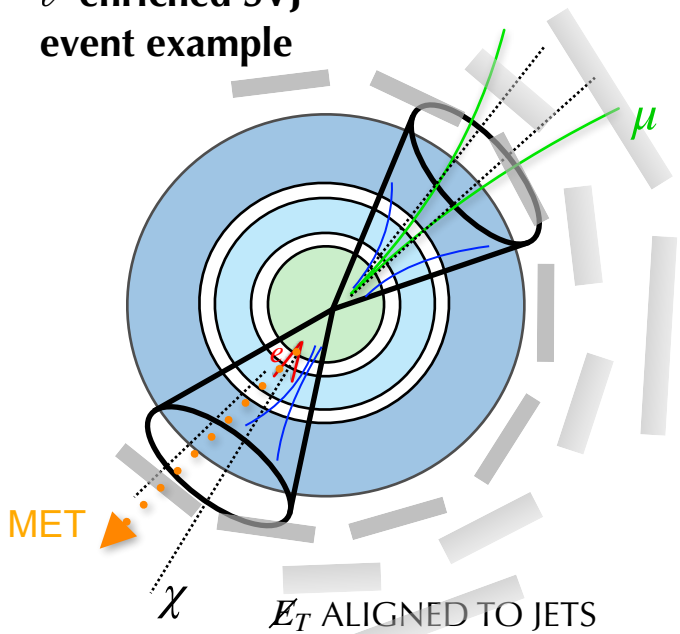
Eur. Phys. J. C 83, 599 (2023)

see T. Fitschen's talk

SIGNATURE-DRIVEN MODEL BUILDING

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

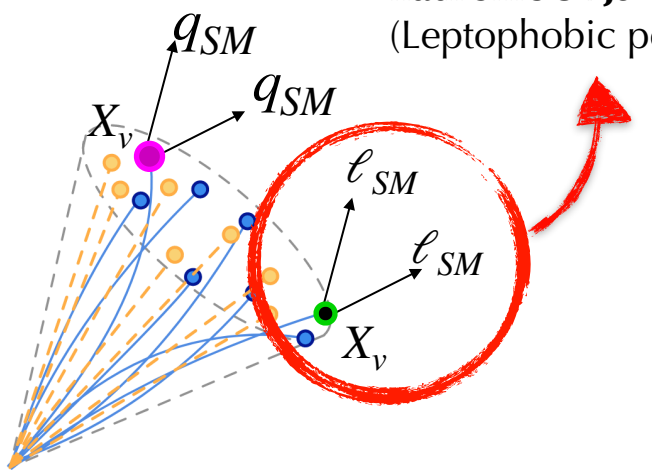
ℓ-enriched SVJ event example



$\not{E}_T$ ALIGNED TO JETS

+ PROMPT LEPTON PAIRS PRODUCED INSIDE HADRONIC JETS

Not allowed in fully hadronic SVJs
(Leptophobic portal)



ℓ-ENRICHED SVJ

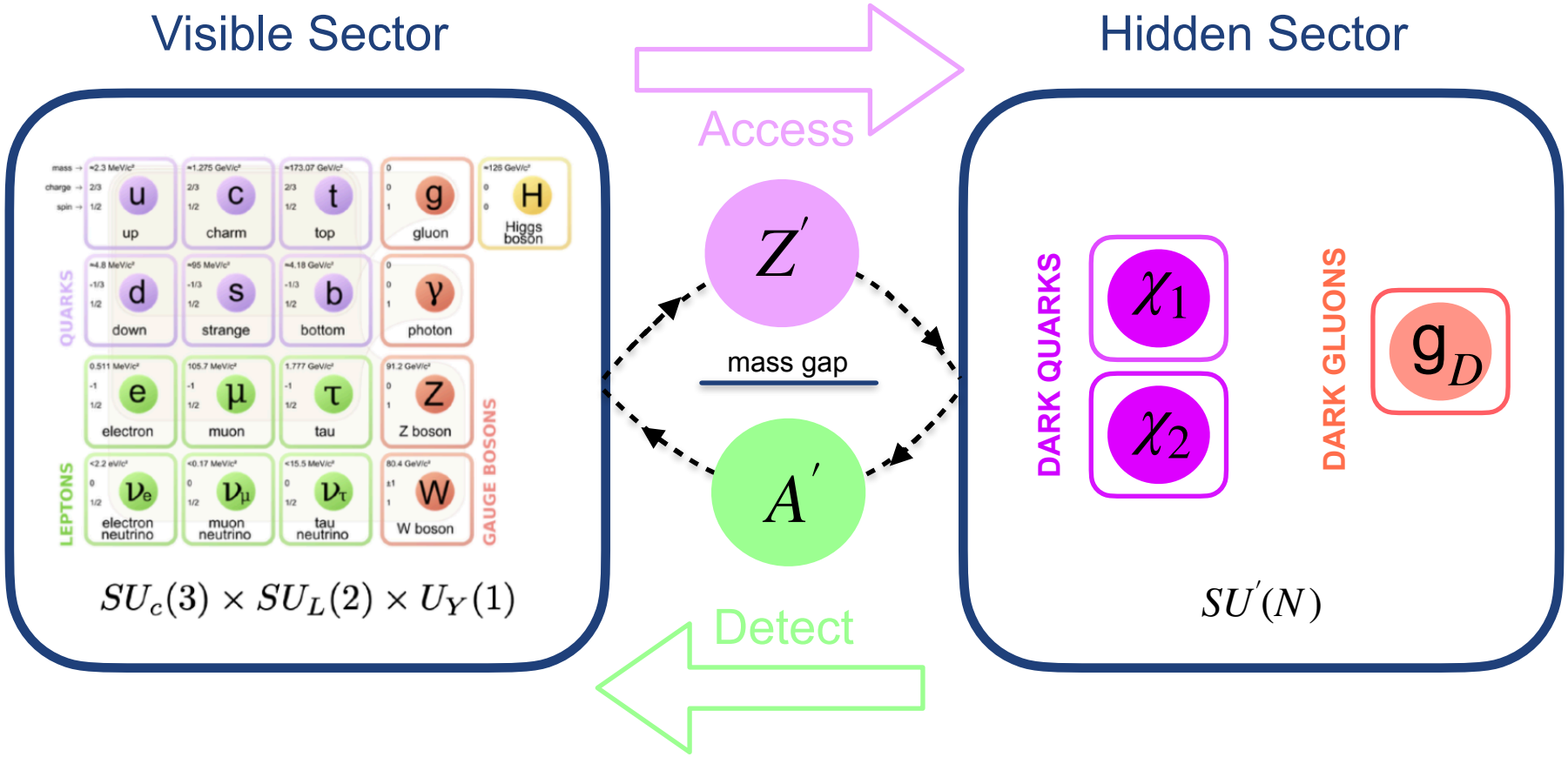
Eur. Phys. J. C 82, 793 (2022)

SIMPLIFIED MODEL(S) ?

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

PHYSICAL REVIEW D 103, 115013 (2021)

MODEL: TWO MESSENGER FIELDS

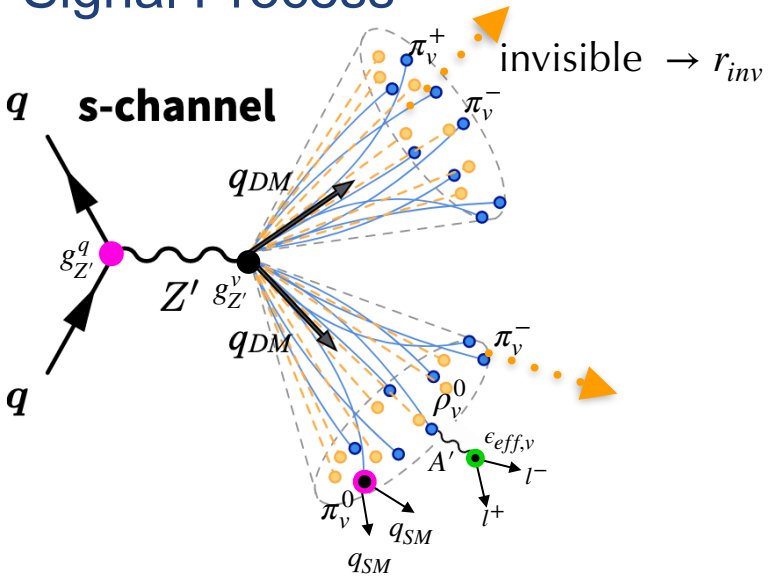


FAVOURED DARK BOUND STATES DECAYS TO BOTH LEPTONS AND QUARKS VIA A′ : OFF-SHELL Z′

SUPPRESSED ~ $1/M_{Z'}^4$

SIGNAL AND BACKGROUND PROCESSES

Signal Process

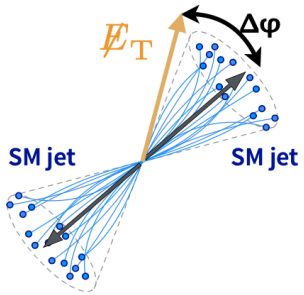


~ 15% democratic decay of unstable ρ to <u>all lepton flavours</u>

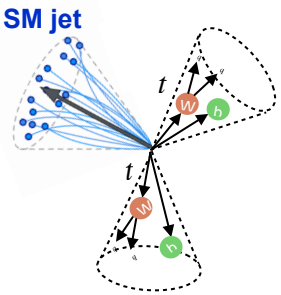
- Signals and backgrounds generated via MadGraph5_aMC@NLO + Pythia8 + Delphes3 (*)
- Signals process: scan over invisible fraction r_{inv} and $M_{Z'}$. Other parameters fixed according to constraints ($g^q_{Z'}, g^\nu_{Z'}, \epsilon_{eff,\nu}$) and theoretical assumptions ($m_{\pi_d}, m_{\rho_d}, \Lambda_d$) (*)

Background Process

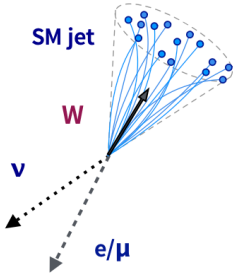
QCD - DIJET



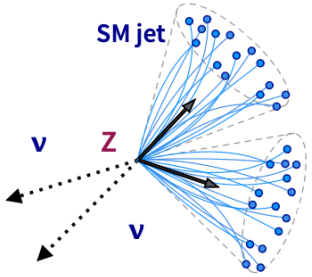
$t\bar{t}$ + jets



W + JETS



Z + JETS



(*) more details in backup

RESONANT HADRONIC SVJ INCLUSIVE ANALYSIS

GOOD OBJECTS

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

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 mini-isolated leptons (*) **LIMITATION !**

VARIABLES LEGEND

M_T : di-jet transverse mass

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

IS IT EFFICIENT FOR OUR SIGNATURES ?

SELECTIONS BASED ON: JHEP 06, 156 (2022)

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

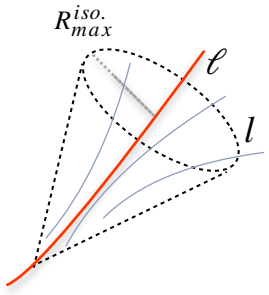
(*) more details in backup

BEYOND CLASSICAL ISOLATION: INTER-ISOLATION

RELATIVE INTER-ISOLATION (FIXED R)

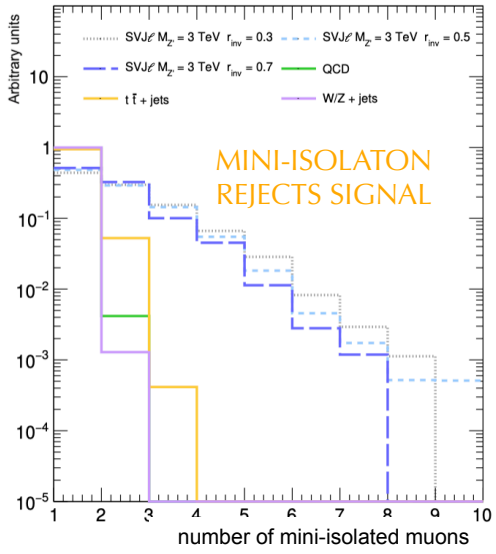
Eur. Phys. J. C 82, 793 (2022)

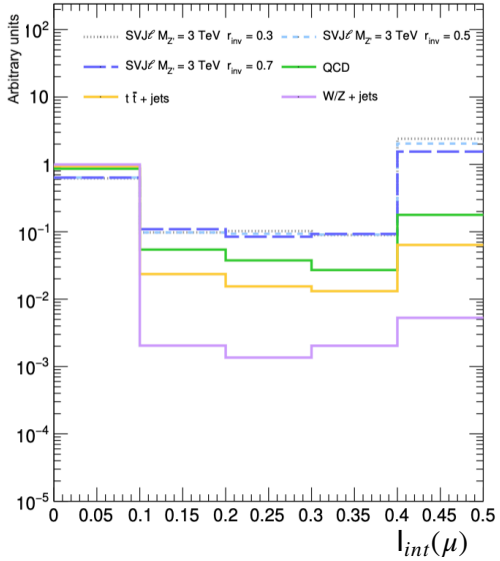
$$I_{int}(\ell) = \frac{1}{p_{T,\ell}} \sum_{l \neq \ell}^{\Delta R < R^{iso.}_{max}} p_t(l)$$

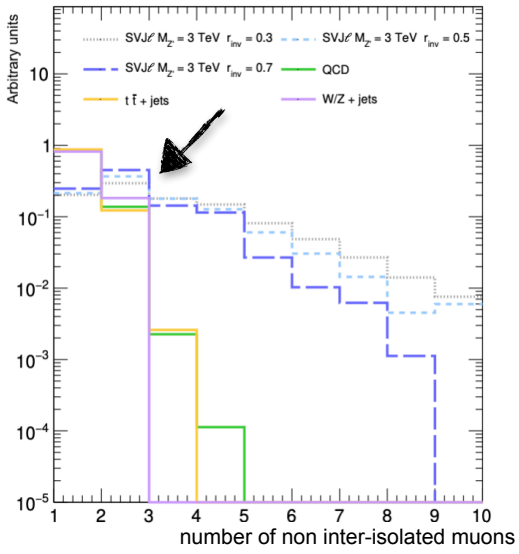


- CAPTURES NEARBY NON-ISOLATED LEPTONS INSIDE JETS (LEPTONIC ACTIVITY)
- BACKGROUNDS ARE EXPECTED TO BE MORE INTER-ISOLATED

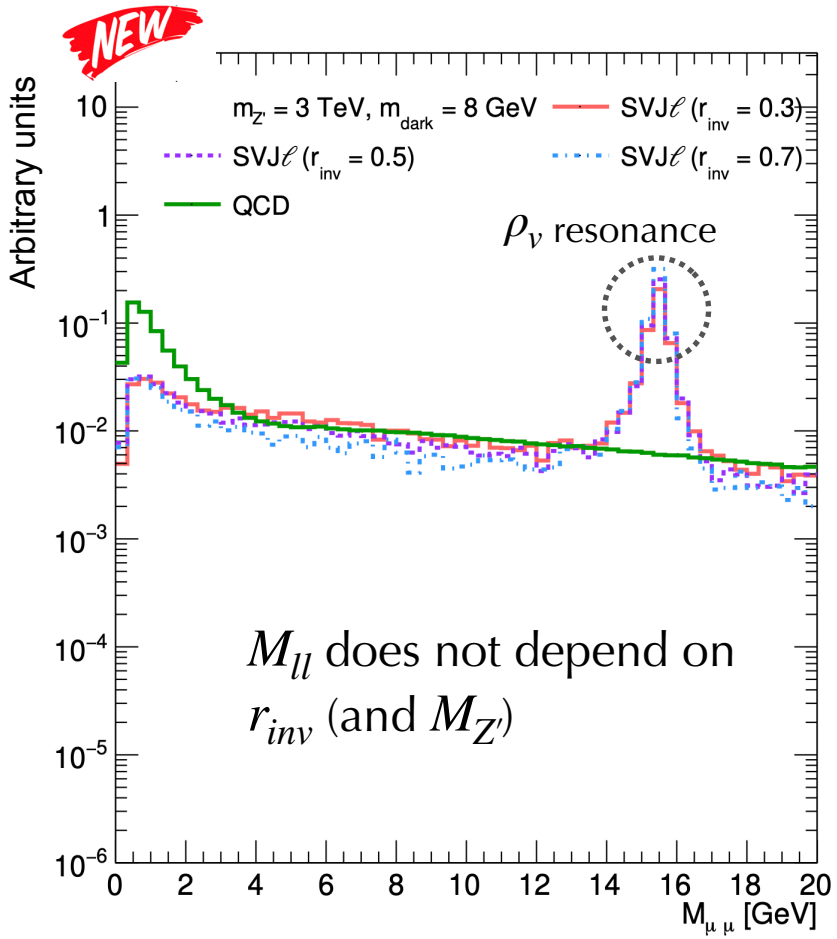
➡ Remove mini-isolated leptons veto and **select opposite sign non inter-isolated leptons pairs**







EXPLOITING DI-LEPTON RESONANCE

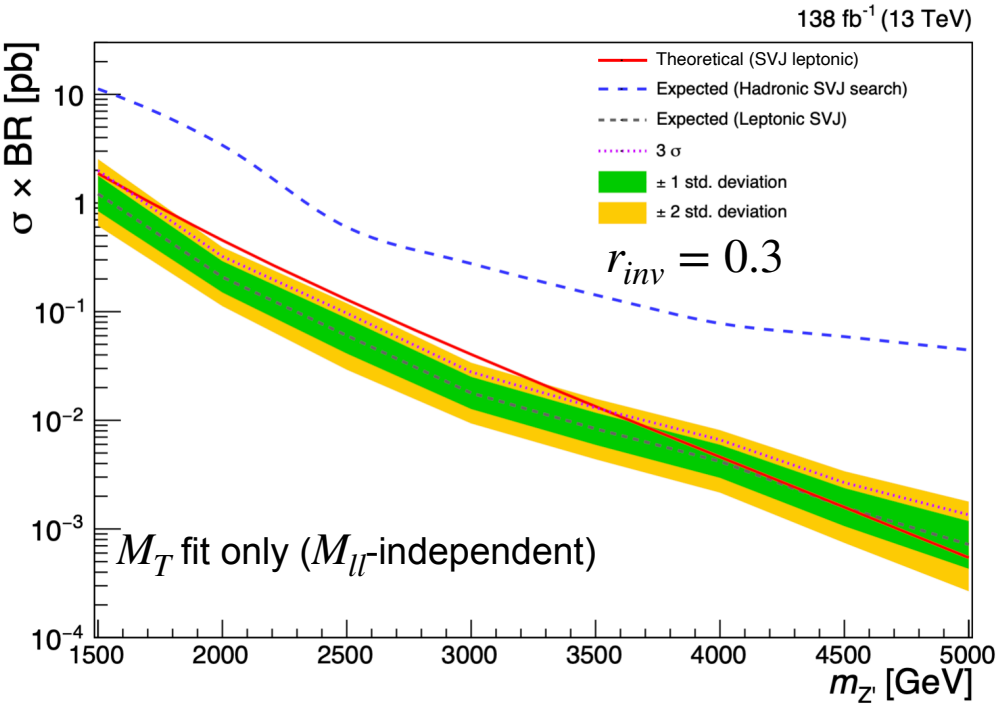


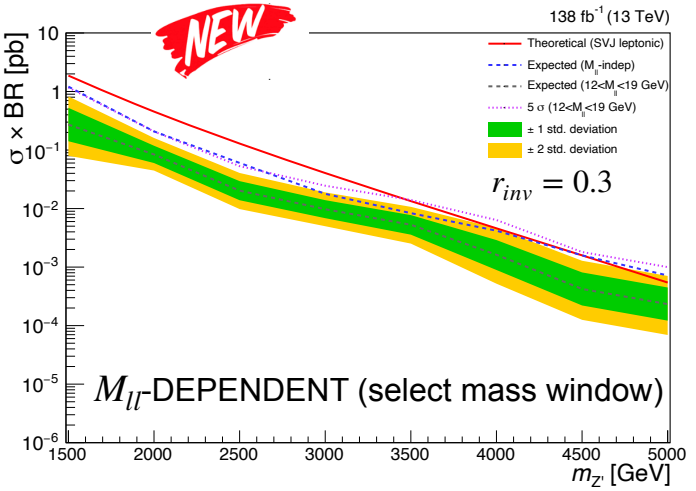
POSSIBLE STRATEGIES

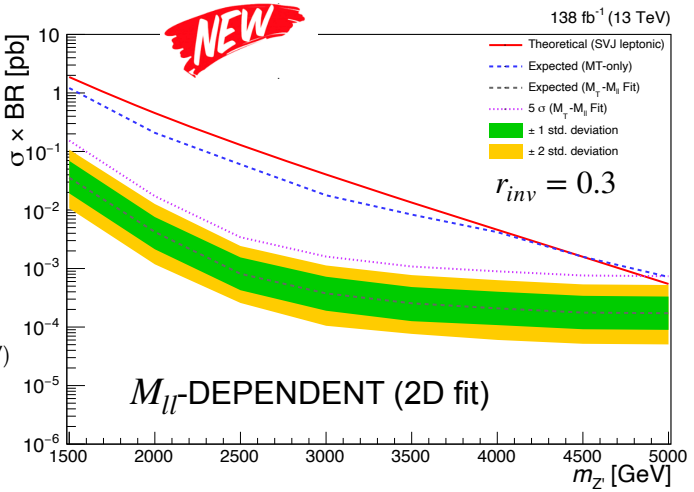
- Can select a mass window in M_{ll} and fit M_T
- Can perform 2D fit $M_{ll} - M_T$
- Can look independently for low mass resonance(s) in the non-isolated di-lepton spectrum

DI-LEPTON MASS SPECTRUM IS MODEL-DEPENDENT AND MULTIPLE RESONANCES ARE POSSIBLE (DARK QUARKS FLAVOURS & POSSIBLE MASS SPLITTING …)

SVJℓ-TARGETED INCLUSIVE ANALYSIS SENSITIVITY







- ✦ CMS INCLUSIVE HADRONIC STRATEGY: NO SENSITIVITY
- ✦ SVJℓ-INCLUSIVE STRATEGY : EXCLUSION REACH (EVIDENCE) UP TO ~ 4.5 TeV (~ 3.5 TeV)
- ✦ IMPROVEMENT EXPLOITING DI-LEPTON RESONANCE - METHOD-DEPENDENT (MODEL-DEPENDENT)

(*) more on limits varying r_{inv} in backup

CONCLUSIONS AND OUTLOOKS

LEPTONS-ENRICHED SIGNATURES: NEW PROMISING SEARCHES FOR CONFINING DARK SECTORS

→ Investigated models allowing dark bound states leptonic decays

→ Provided possible search strategies based on: new lepton-based variables (Inter-isolation)

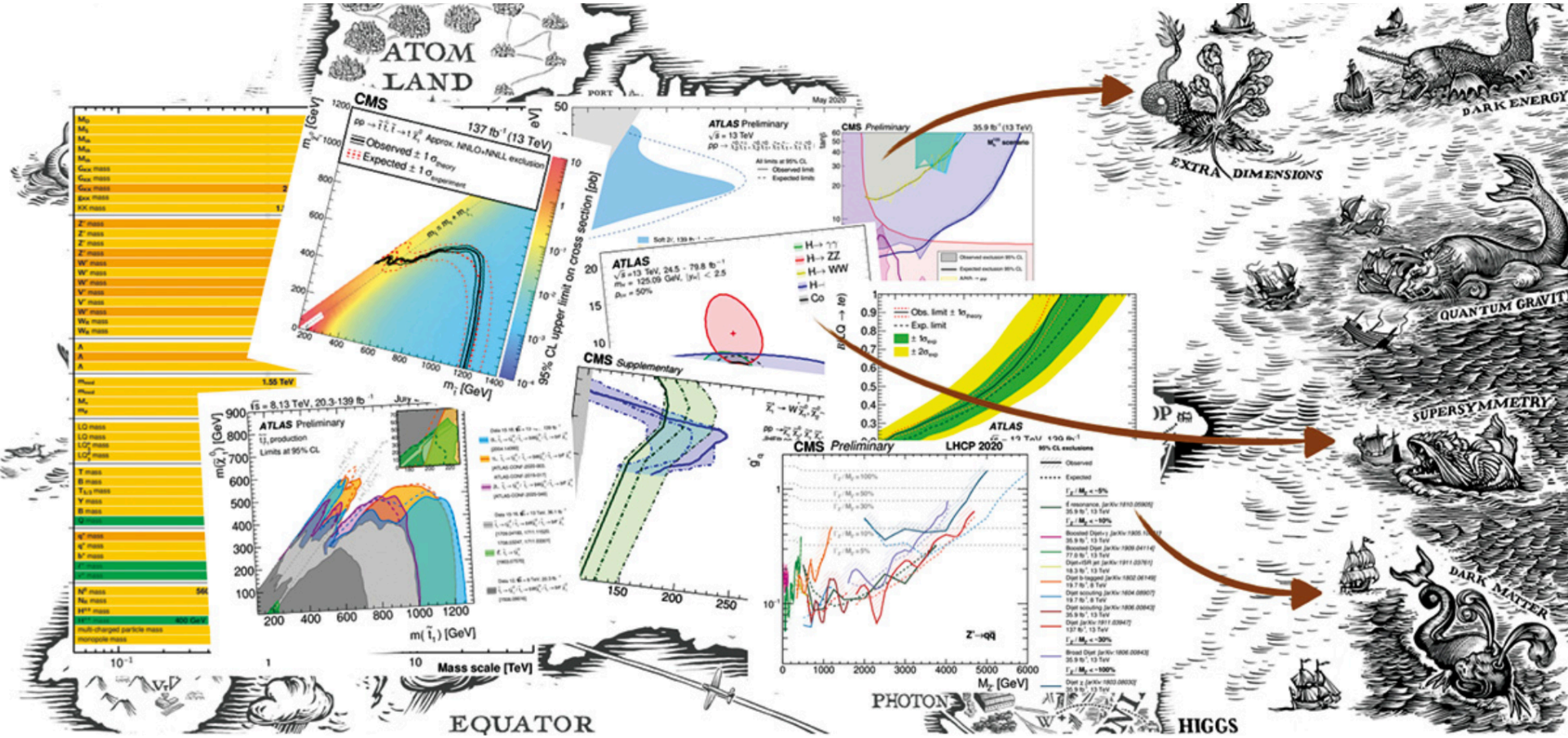
→ These signatures are currently mildly constrained and offer Hidden Valleys discovery opportunities

…. WHAT IS NEXT ?

→ Analysis of both signatures (SVJℓ and SVJτ) with full Run 2, and Run 3 data

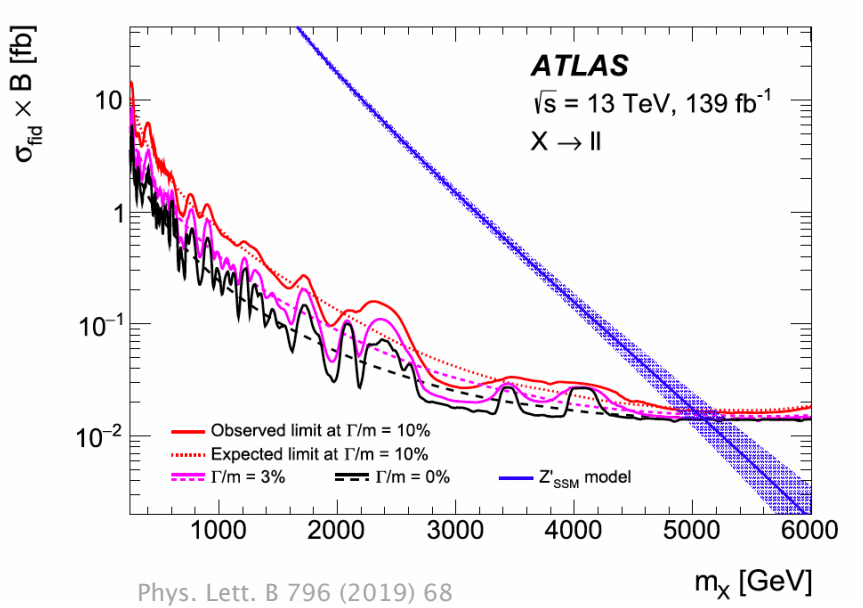
→ Not excluded further pheno studies on uncharted territories

BACKUP


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

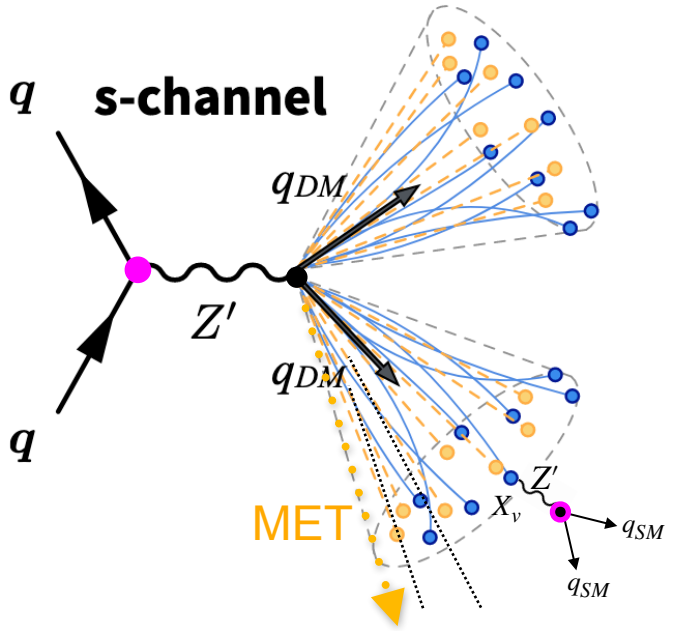
RESTRICTIONS OF THE CURRENT SVJ MODEL

HIGH MASS DI-LEPTON SEARCH



Phys. Lett. B 796 (2019) 68

SIMPLIFIED MODEL

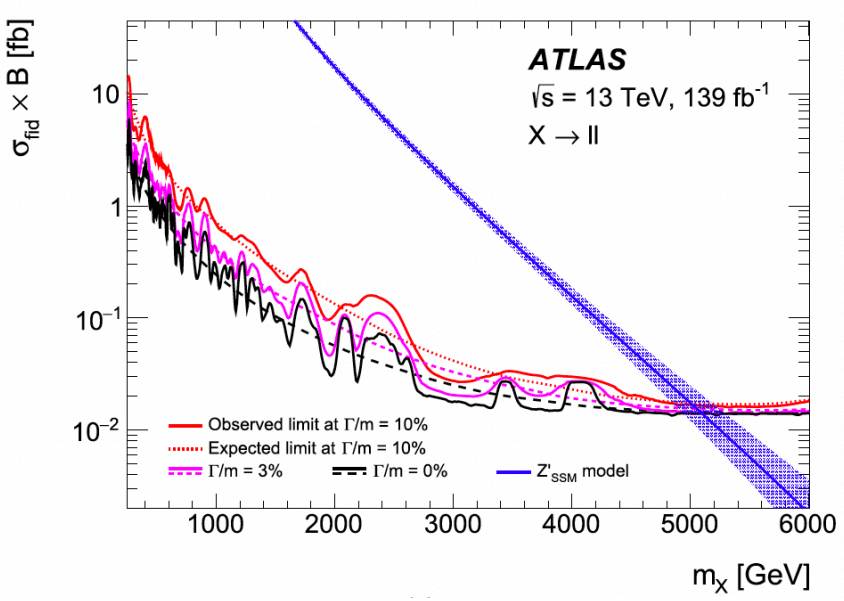


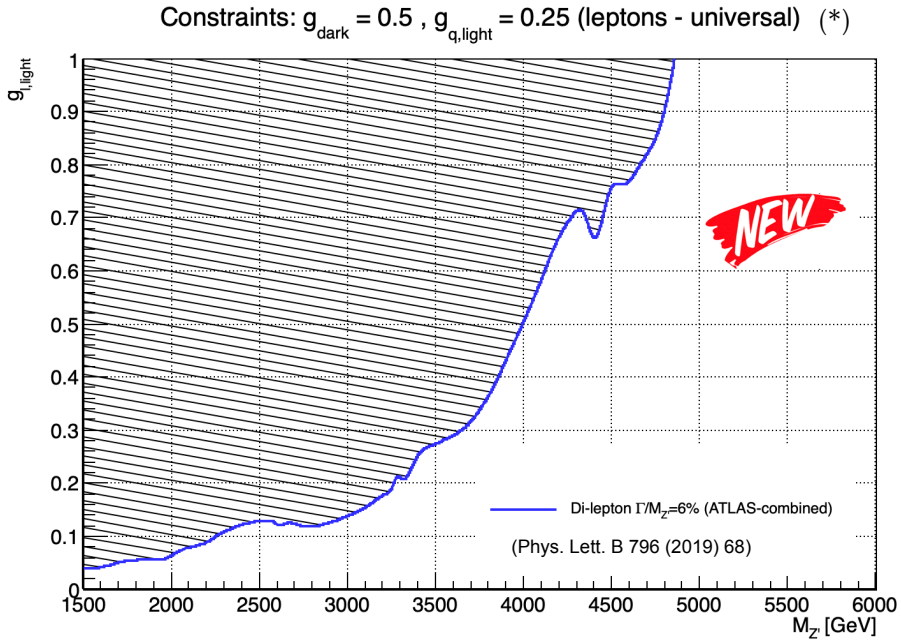
FULLY HADRONIC SVJ (MULTI-JET + $\not{E}_T$)

LEPTOPHOBIC (*) Z′ AS MEDIATOR TO EVADE HIGH MASS DI-LEPTON SEARCHES
CONSTRAINTS: FULLY HADRONIC DARK BOUND STATES DECAYS (OFF-SHELL Z′)

(*) constraints on Z′ coupling to leptons (backup)

CONSTRAINTS ON Z′ COUPLING TO LEPTONS



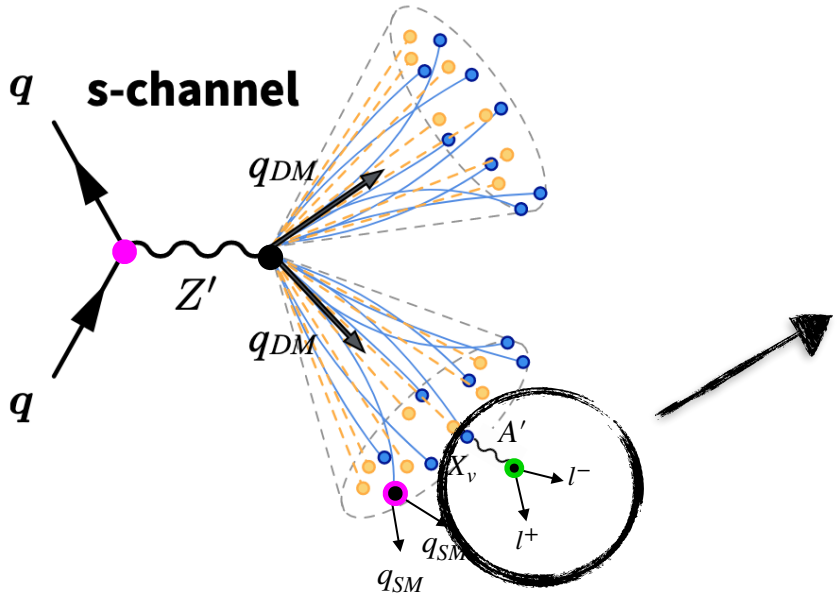


ALLOWING IN THE CURRENT SVJ MODEL FOR Z′ COUPLING TO LEPTONS WOULD INTRODUCE IMPORTANT CONSTRAINTS FROM HIGH MASS DI-LEPTON SEARCHES

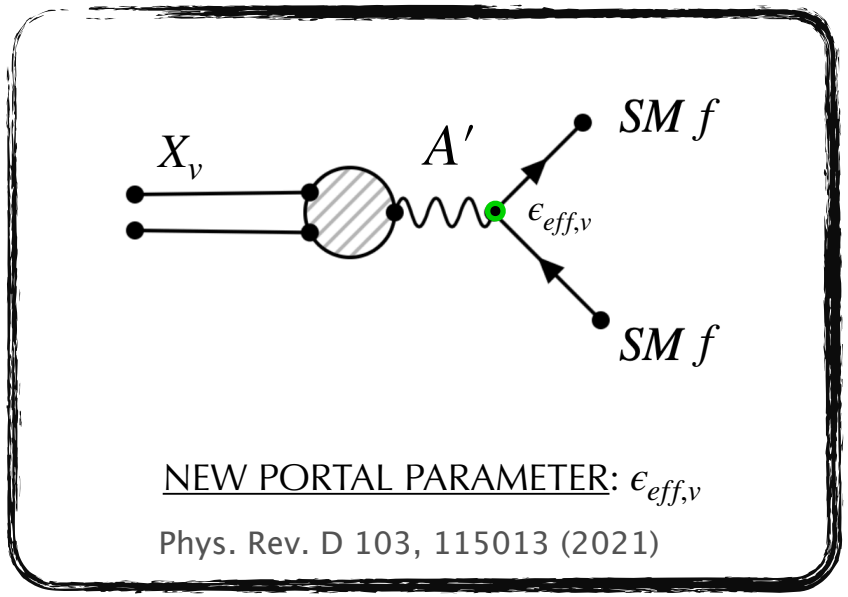
(*) parameters are set consistently with CMS Z′ model

MODEL: LEPTONIC DECAYS IN SVJ VIA A′

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



HADRONS + LEPTONS SVJ

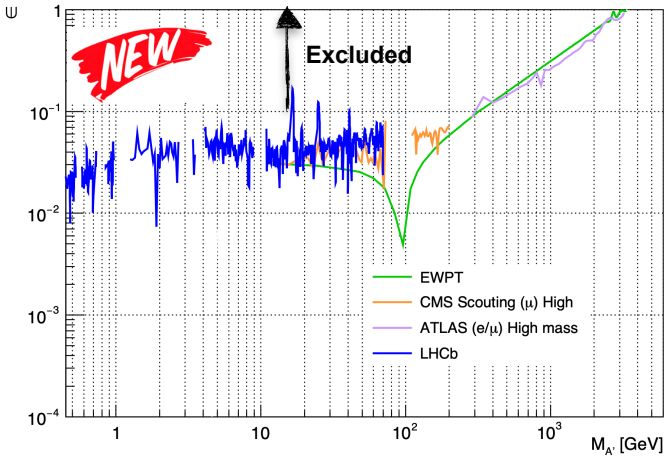


LOWER MASS MEDIATOR: OFF-SHELL Z′ SUPPRESSED IN DARK BOUND STATES DECAYS ~ $1/M_{Z'}^4$

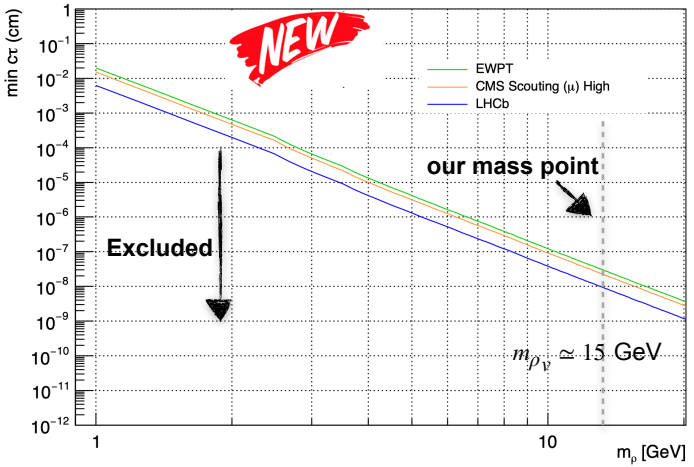
Eur. Phys. J. C 82, 793 (2022)

MODEL : 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



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



- **~ 15% democratic decay** of unstable ρ to <u>all lepton flavours</u>
- **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

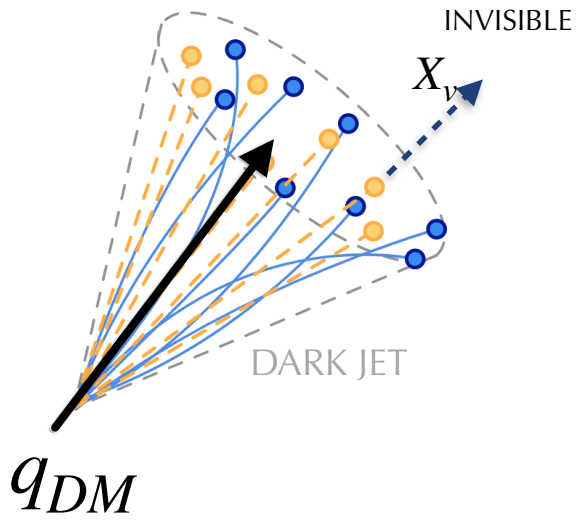
** dark hadron masses set using Lattice QCD fits (Nf = 2, Nc = 3):

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

(*) samples generation flow (backup)

INVISIBLE FRACTION

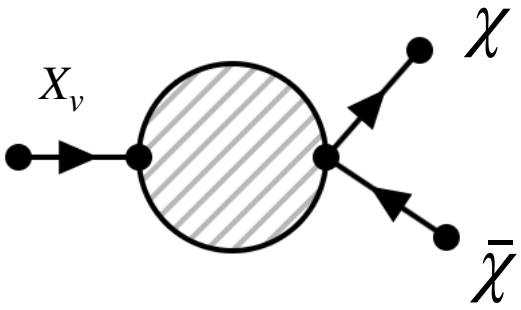
NUMBER OF INVISIBLE DM STATES IMPLEMENTED AS A BRANCHING RATIO



EFFECTIVE INVISIBLE FRACTION

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

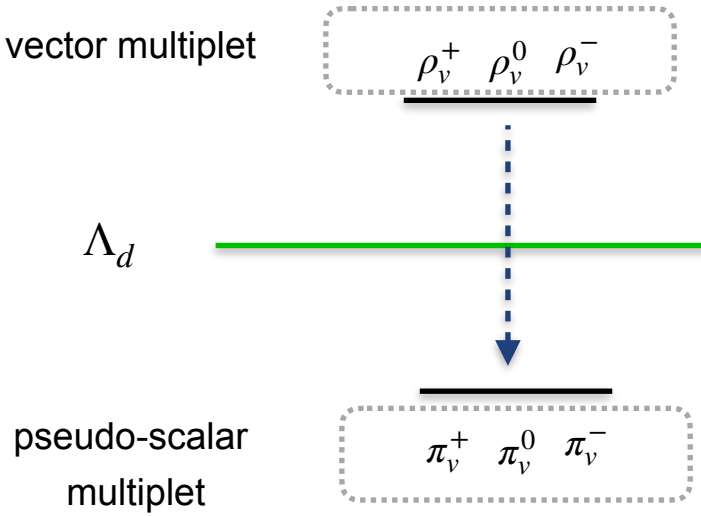
BR_{inv} :



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

SIMPLIFIED HIDDEN VALLEY SPECTRUM

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



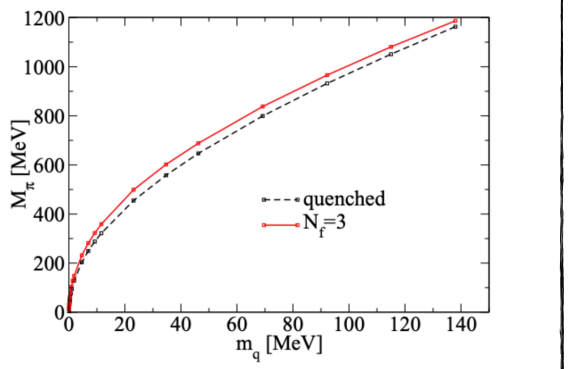
HOW TO FIX THE MASSES ?

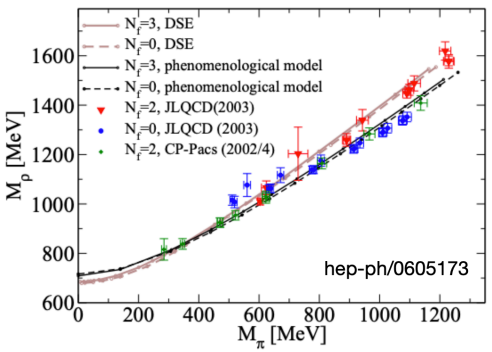
FULL HADRONIC SEARCH ASSUMES ONE DARK HADRON MASS SCALE

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

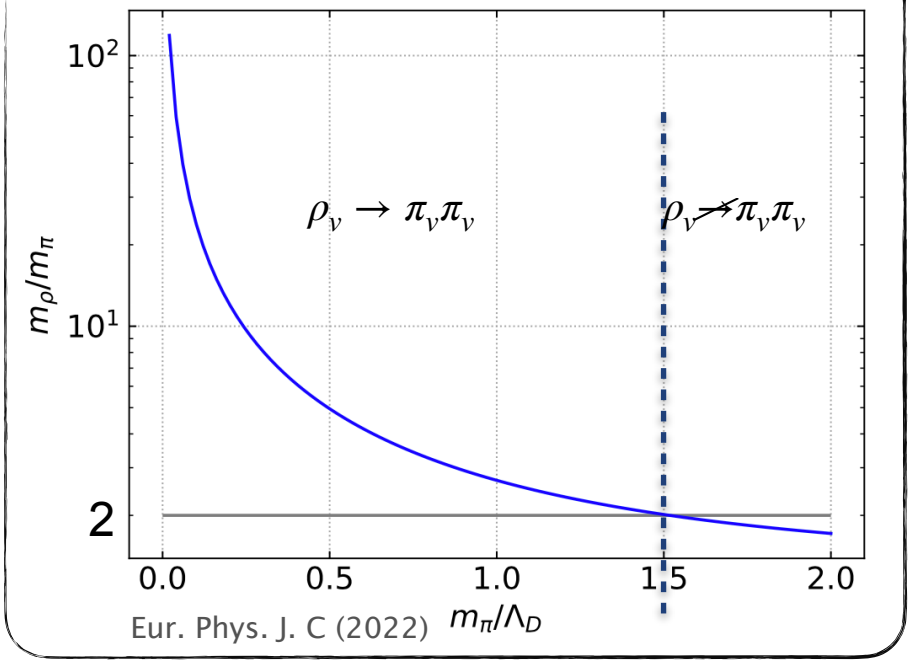
DARK SECTOR HADRON MASSES

LATTICE CALC





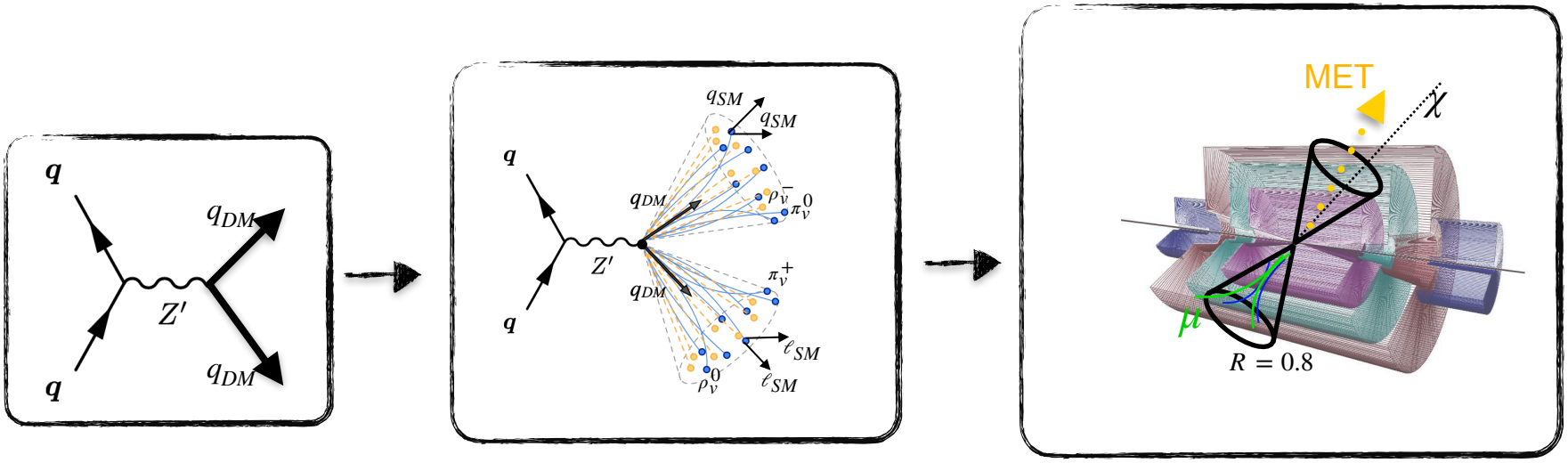
DM SPECTRUM PREDICTION



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

SIGNAL MODELS GENERATION CHAIN



Madgraph5

- ✦ Generation of matrix element
- ✦ Cross-section computation
- ✦ Inputs: couplings, $M_{Z'}$ mass

PYTHIA8

- ✦ HV MODULE : dark sector parton shower, hadronization, dark hadrons decays to SM
- ✦ Inputs: dark sector parameters and dark hadrons decay modes

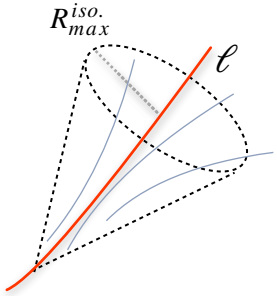
FASTJET/DELPHES3

- ✦ Clustering AK8 jets with $p_T > 200$ GeV
- ✦ Filter out from AK8 invisible final states (DM, neutrinos)
- ✦ Fast detector simulation: parametric response

LIMITATIONS: CLASSICAL LEPTONS ISOLATIONS

RELATIVE STANDARD ISOLATION (FIXED R)

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

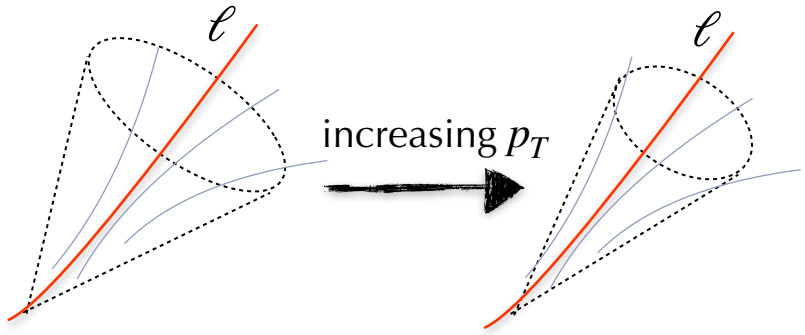


ISOLATION VETO: LIMITATION FOR ELECTRONS AND MUONS PRODUCED INSIDE JETS

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

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

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

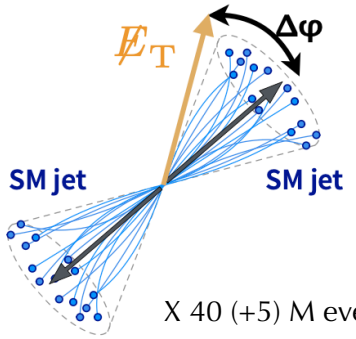


USED IN CMS SVJ AS A VETO

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

BACKGROUNDS SAMPLES DETAILS

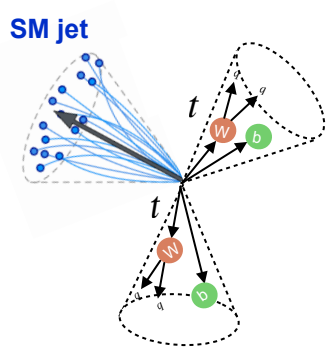
QCD - DIJET



- 2 HARD PARTONS IN ME
- GEN PT CUT: 500 GeV

X 40 (+5) M events

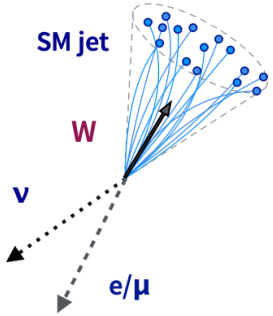
$t\bar{t}$ + jets



- MAXIMUM 2 ADDITIONAL PARTONS IN ME

X 50 M events

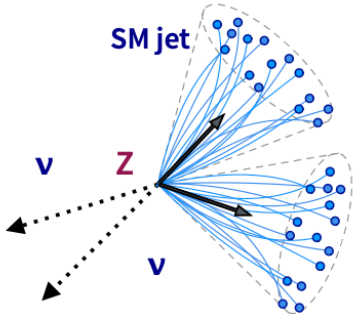
W + JETS



- MAXIMUM 3 ADDITIONAL PARTONS IN ME
- GEN HT CUT: 100 GEV

X 25 M events

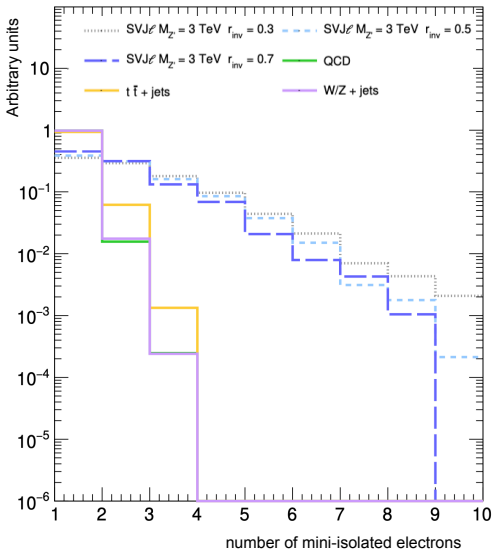
Z + JETS

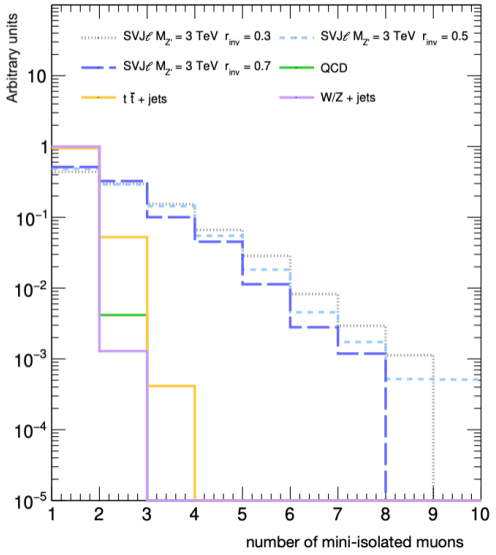


- MAXIMUM 3 ADDITIONAL PARTONS IN ME
- GEN HT CUT: 100 GEV

X 25 M events

MINI-ISOLATION VETO





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 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.

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

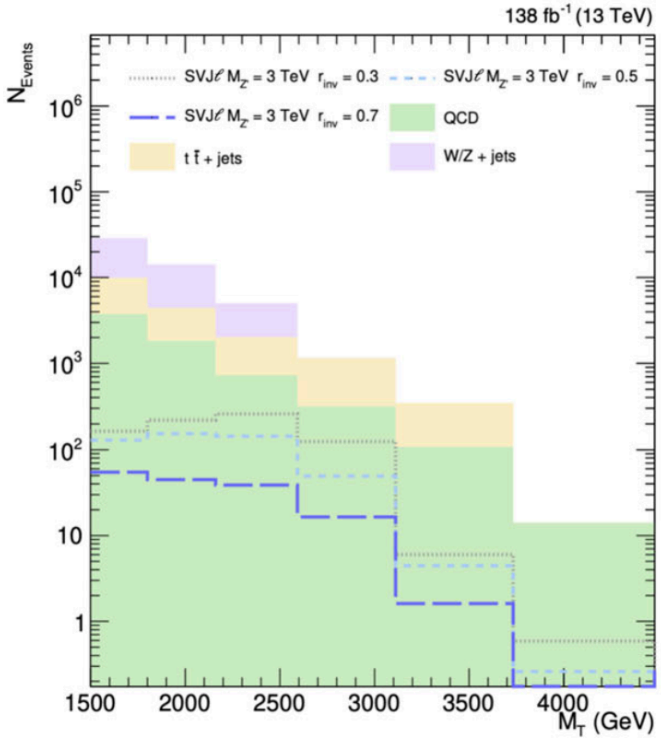
BACKGROUNDS

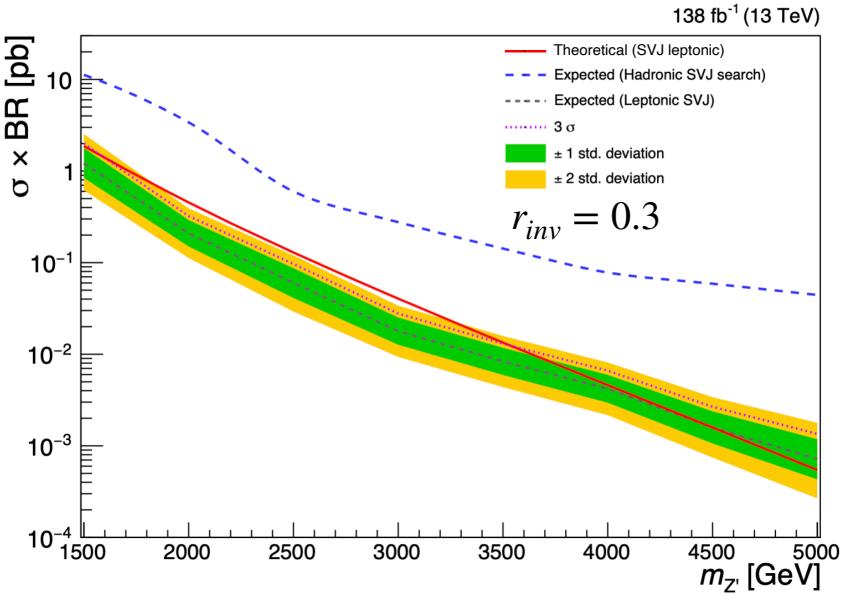
Variable	Selection	$\epsilon_{QCD}\%$	$\epsilon_{t\bar{t}}\%$	$\epsilon_{Zj}\%$	$\epsilon_{Wj}\%$
$n(good\ AK8)$	≥ 2	98.16813	7.18502	1.02670	1.58200
$\Delta\eta_{j0,j1}$ $(AK8)$	≤ 1.5	66.54385	5.31659	0.66615	1.09866
M_T $(AK8)$	≥ 1500	15.00132	0.15060	0.03025	0.0227
R_T $(AK8)$	≥ 0.15	0.70012	0.03026	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

SENSITIVITY ESTIMATION



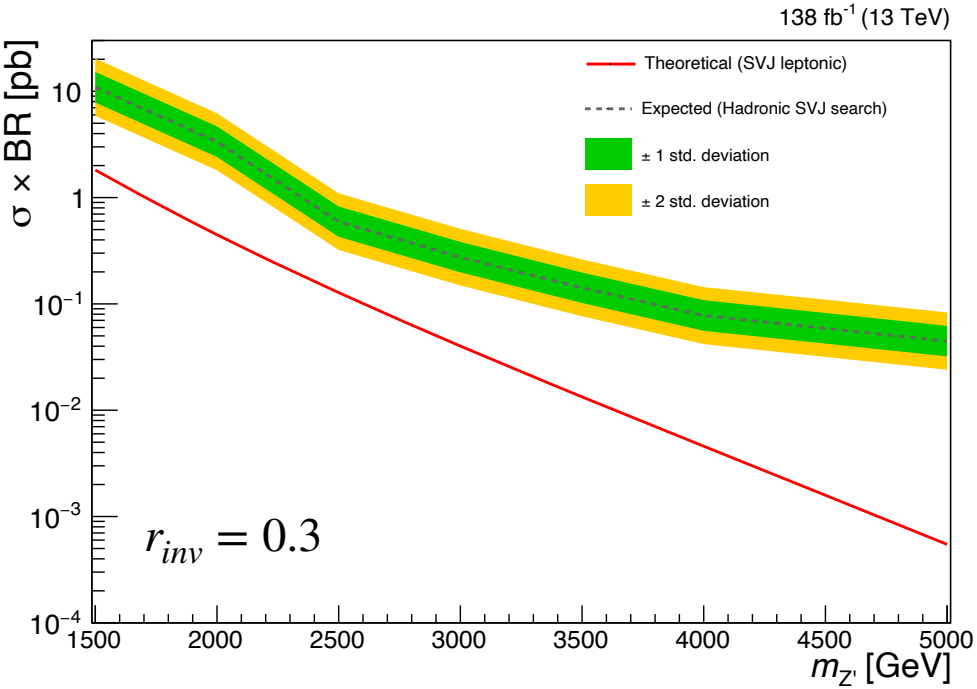


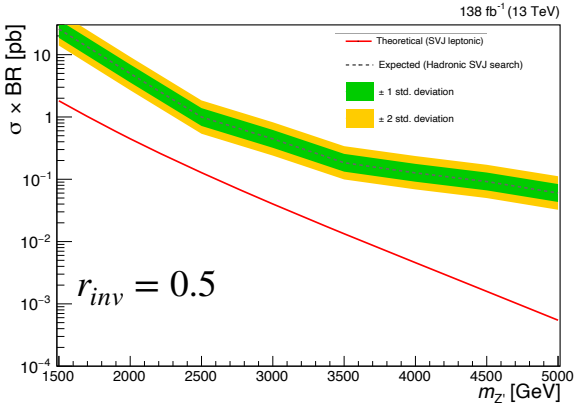
BUMP HUNT ON A FALLING BACKGROUND IN M_T SPECTRUM : 1.5 - 5 TeV (HIGH MASS SEARCH)

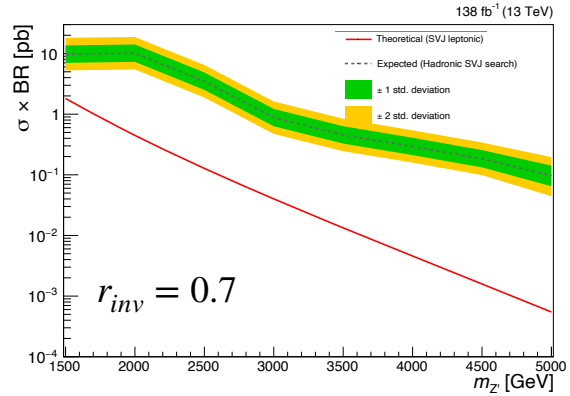
ASYMPTOTIC CLs (J.Phys.G 28 (2002) 2693–2704 , Eur. Phys. J. C (2011) **71**: 1554)

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

HADRONIC SVJ ANALYSIS SENSITIVITY ON SVJℓ

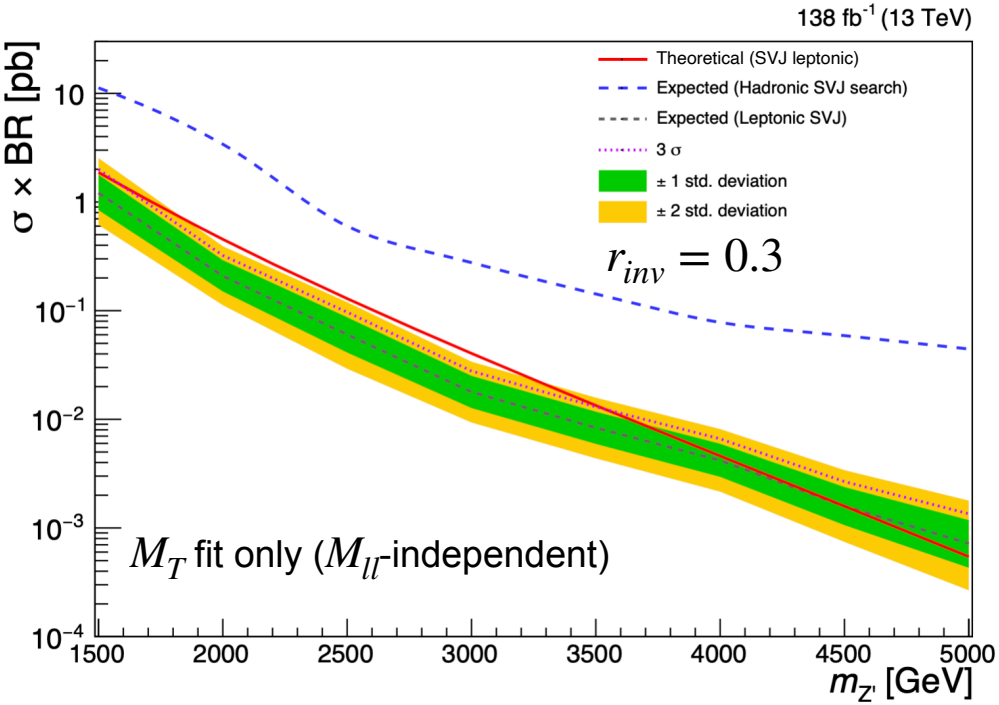


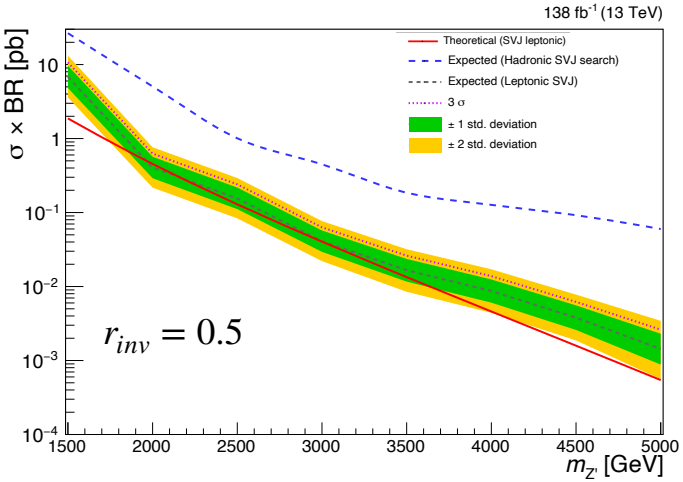


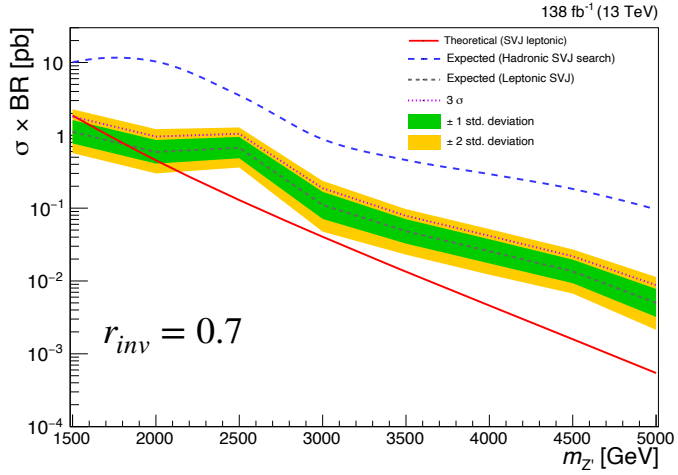


NO EXCLUSION REACH FROM FULL HADRONIC ON SVJℓ (NOR DISCOVERY) IN THE FULL MASS RANGE AND ALL TESTED VALUES OF INVISIBLE FRACTION

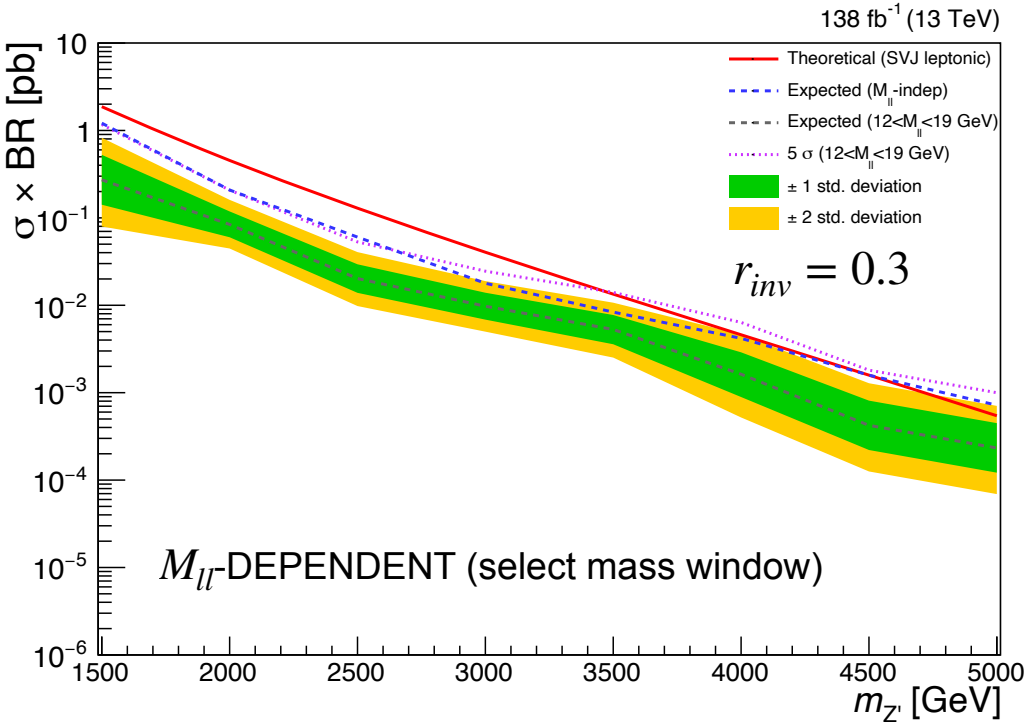
SVJℓ-TARGETED ANALYSIS SENSITIVITY (m_{ll}-INDEPENDENT)

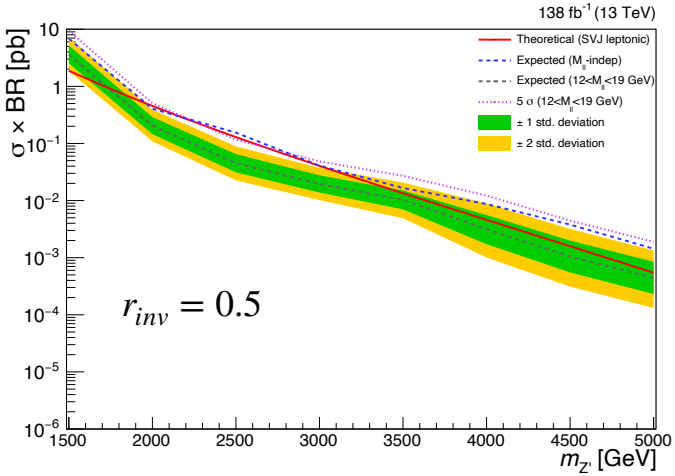


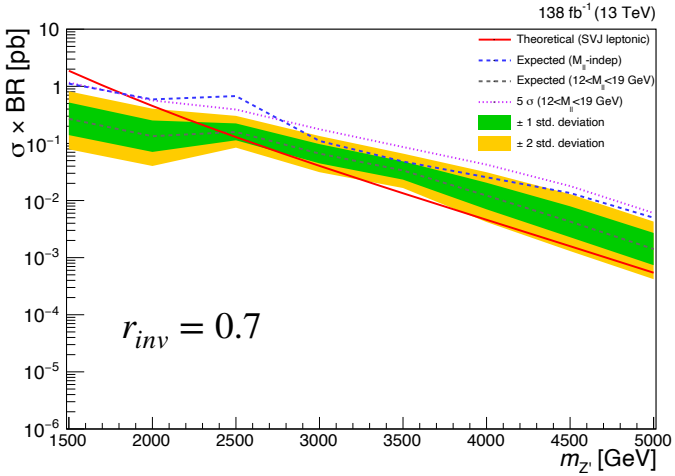




SVJℓ-TARGETED ANALYSIS SENSITIVITY (M_{ll}-CUT)







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SVJℓ-TARGETED ANALYSIS (M_T vs M_{ll} 2D FIT)