Looking for Long Lived particles at the LHC

Based on

Discrimination between prompt and long-lived particles using convolutional neural network

BB, Swagata Mukherjee and Rhitaja Sengupta.

[e-Print: arXiv:1904.04811]

Novel signature for long-lived particles at the LHC

Shankha Banerjee, Geneviève Bélanger, **BB**, Fawzi Boudjema, Rohini Godbole and Swagata Mukherjee [e-Print: arXiv:1706.07407]

Biplob Bhattacherjee

Centre for High Energy Physics

Indian Institute of Science, Bengaluru, India

Kavli IPMU APEC Seminar, 30th October 2019

Large Hadron Collider: History and Current Status

1976: story began in 1976 European particle physics community started discussing about the Large Electron Positron (LEP) collider at CERN.

1977: Building of LEP tunnel, with a possibility of another ring of superconducting magnets to enable the acceleration of protons.

1994: Approval by CERN Council (1993: SCC cancelled)

2009-2010: LHC restarted (actual start : September, 2008)

2019-2020: Long Shutdown, preparing for run 3.
(Data collected so far ~ 160 ifb (Run2) + 30 ifb(Run1))

2021-2024: Run 3(6.5 TeV or 7 TeV ?) Total int luminosity~ 300-400ifb

2026: HL-LHC will start

2037- : beyond LHC .. new proposals

LHC : Two Major Goals

Search For SM Higgs Boson

Very specific in nature

Decay modes and branching ratios are completely known in SM

Discovered in 2012

Open question: Is it really the SM Higgs boson?

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Physics beyond the Standard Model

Many BSM models: SUSY , Extra dimensions···,

A large number of possible signatures, parameter dependence, assumptions on the interpretations of the available results

Everything looks consistent With standard model

Where is BSM physics hiding ?

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Three possible scenarios

Possibility I

BSM particles are much heavier than LHC reach /
(no TeV Scale SUSY …)

LHC will only reverify the correctness of
Standard Model

Nightmare scenario !!

Possibility II

BSM particles are just above LHC current bound

LHC will discover BSM particles soon

Best case scenario

Possibility III

BSM particles are light however LHC search channels are not very sensitive

Are we missing something ?

Discovery possible ??

Paradigm Shift

Current search methods: Mostly theory driven

We assume a particular model, assume some specific decay modes and try to find it.

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We expect new physics at the TeV scale

Nature of the new physics completely unknown

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- not yet searched for?
- experimentally challenging?

<u>We should also think of search strategies based on signatures</u>

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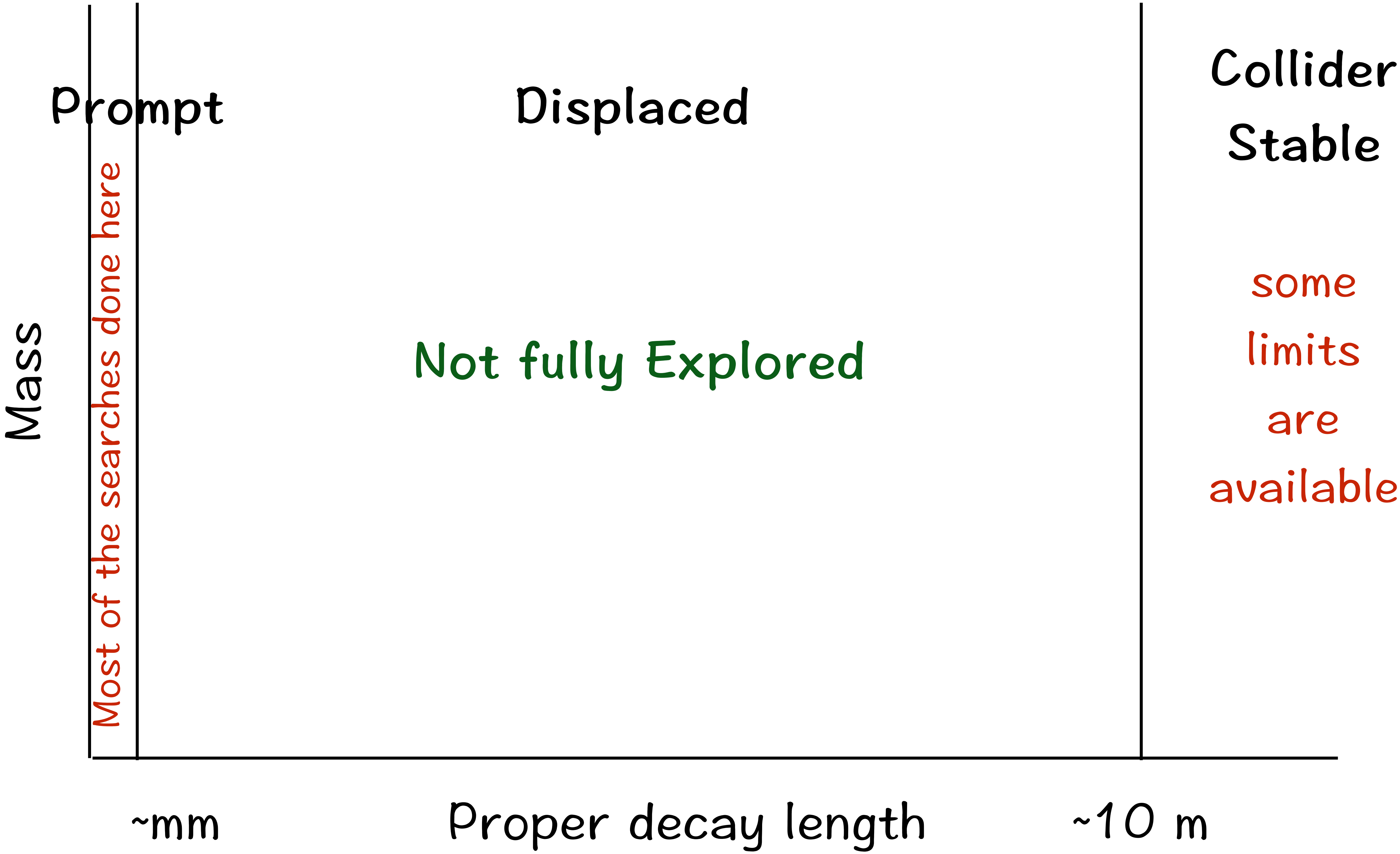
One such possibility: Long lived Particles at the LHC

LHC: PROMPT vs DISPLACED



Long lived particles

Long lived particles(LLP) are present in the Standard Model
(charged pion, neutron, ..)

Two possible reasons :

Small coupling

approximate symmetry,
higher dimensional operator
Example : RPV decay modes

Suppression in the phase space

decay of pure charged wino

LLP models

Many well motivated models predict LLPs.

SUSY :

charged wino/Higgsino NLSP

Neutralino in GMSB

Stealth SUSY

R-parity violation

Dark Matter :

Co-annihilation

Assymmetric dark matter

Freeze-in

+ Dark photon model, Hidden valley, neutrino mass models

… …

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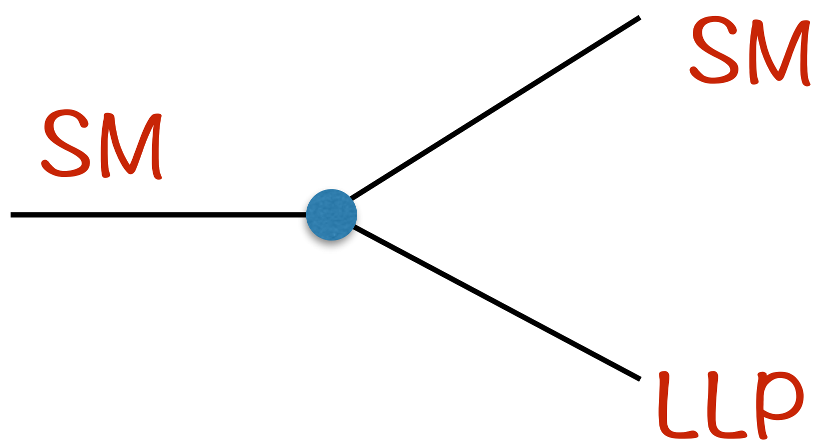
How do we produce LLP at the LHC ?

Production of LLP

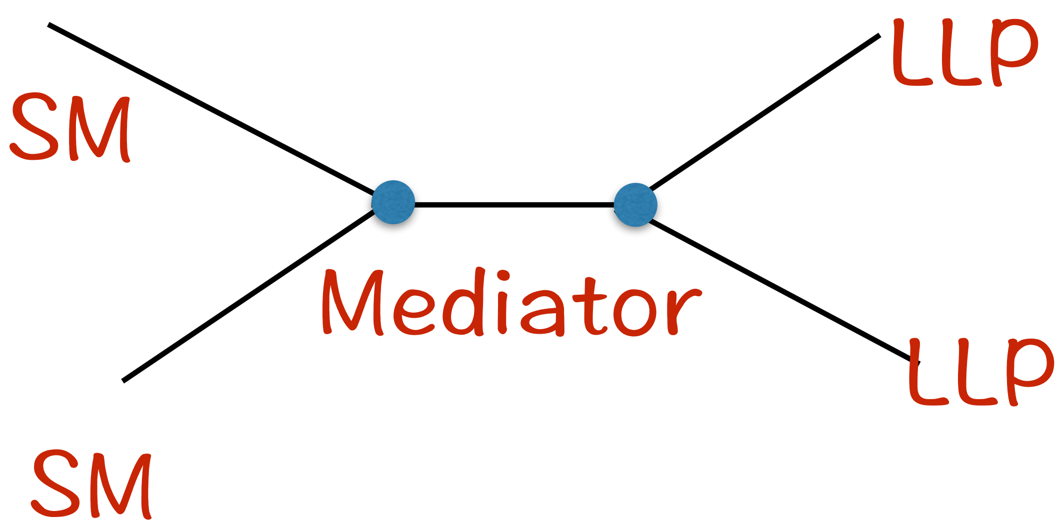


Should be suppressed

otherwise LLP-> SM SM will be prompt

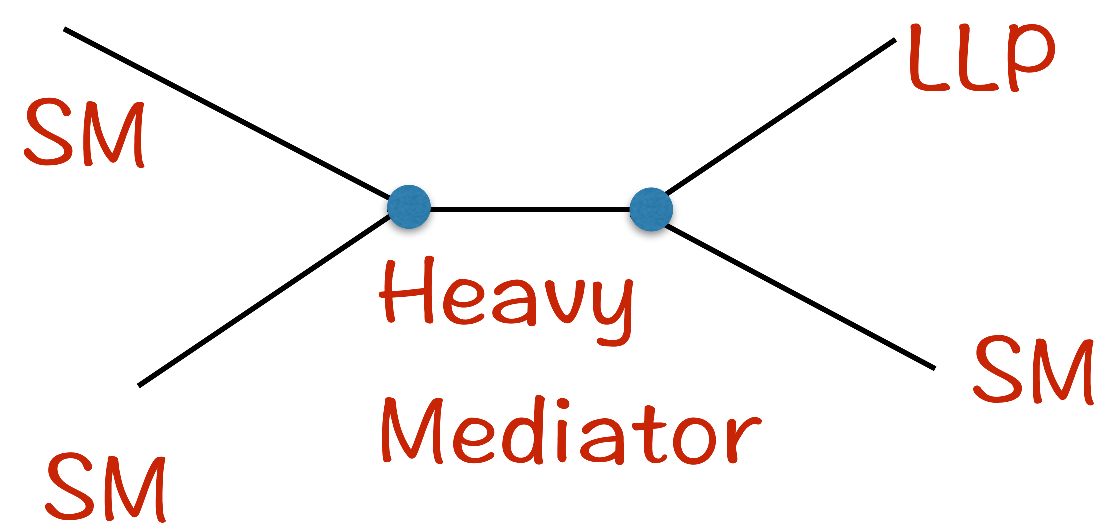
Single production cross section of LLP through only SM particles will be small

Mostly pair production of LLP considered



Mediator can be SM particles like Higgs, Z, etc
or new particles that couples to both the SM and LLP

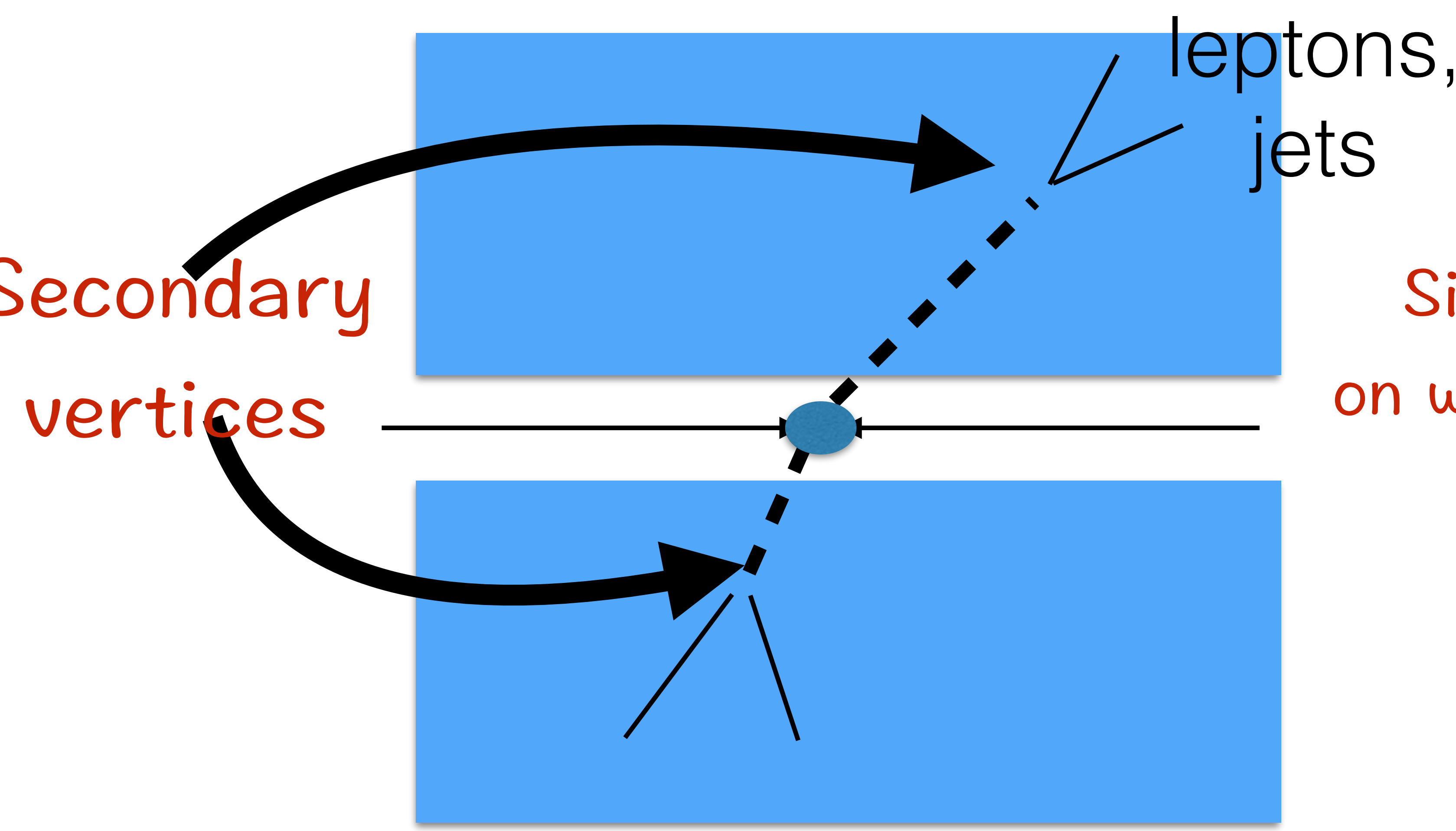
single production also possible with heavy BSM mediators



A. Search for displaced vertex

Pair production of neutral LLP

LLP -> standard model particles



Signature crucially depends on where LLP decays within the detector

Two ways to search for LLPs:

A. Use standard Trigger made for prompt analysis and identify LLP offline
B. Dedicated Triggers for LLP

ATLAS LLP —> almost prompt Di-jets

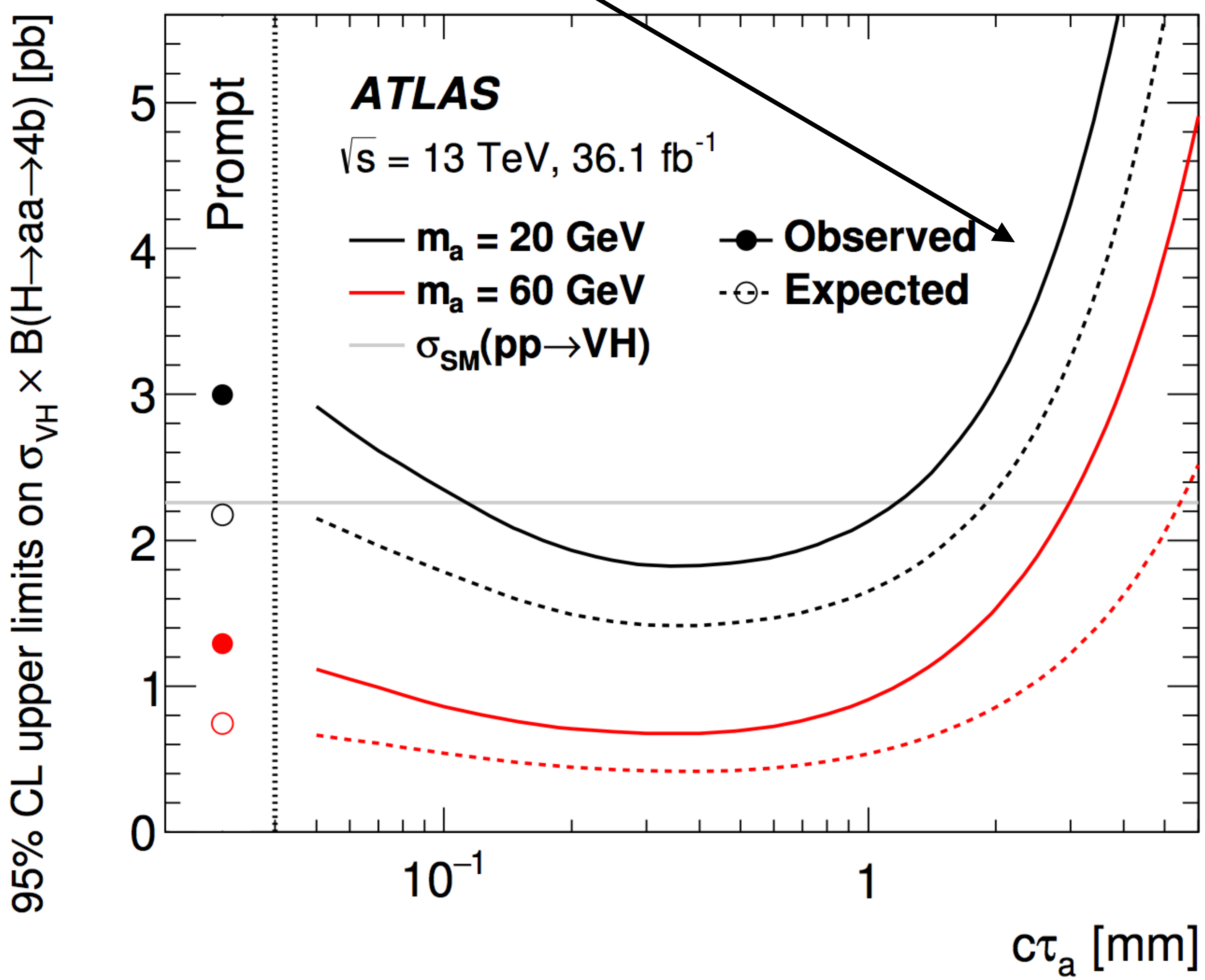
1806.07355

quickly losing sensitivity in the lifetime range >3-4mm

pp -> W/Z + H , H -> LLP LLP ,
LLP -> b b

Prompt search somewhat sensitive for the decay length of a ~ mm

The b-tagging algorithm is efficient in identifying jets containing b-hadrons with efficiency largest for proper lifetimes of $c\tau$ ~0.5 mm and decreases for longer lifetimes.



CMS LLP —> Displaced Di-jets

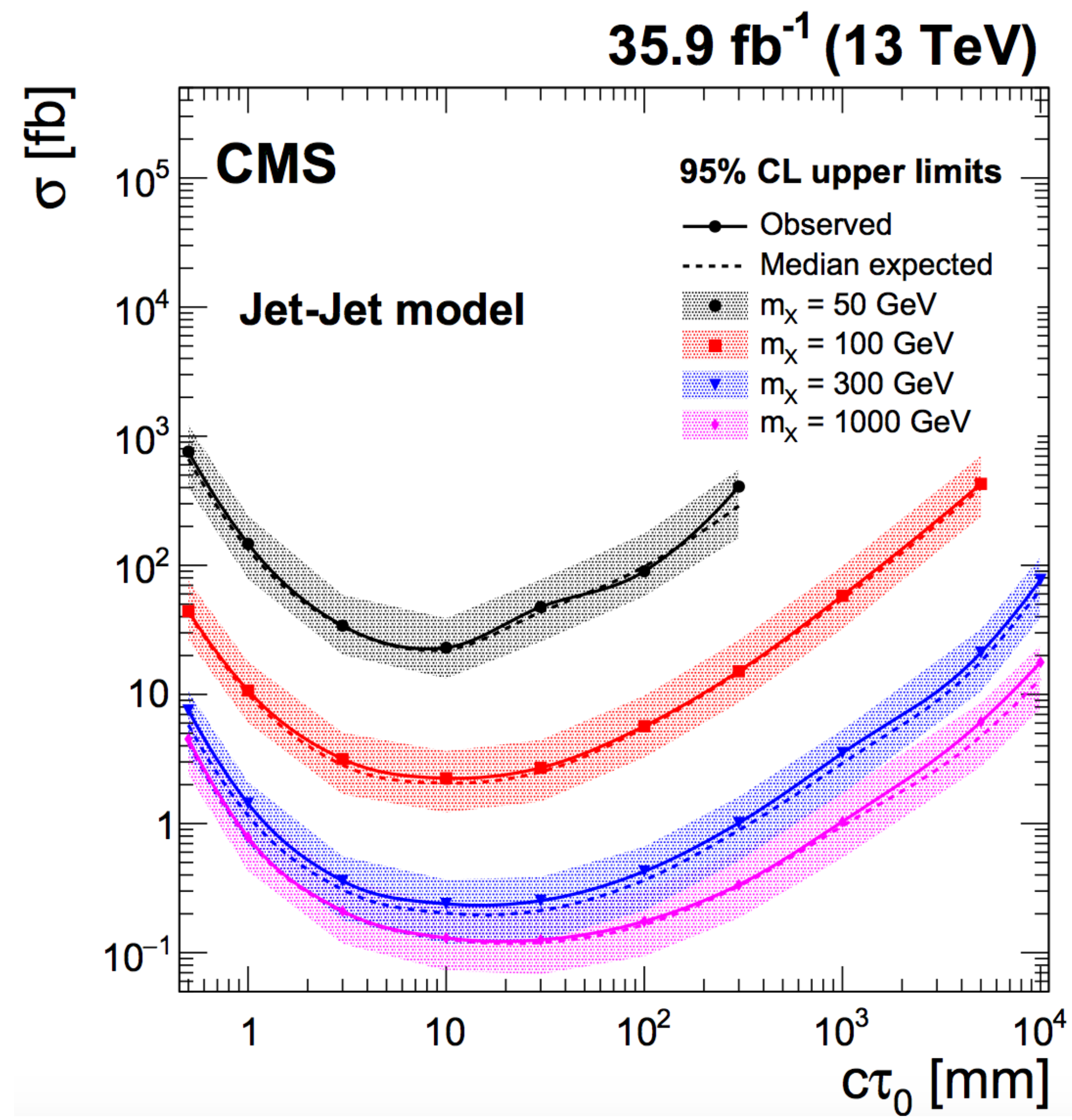
1811.07991

Dedicated Trigger developed for LLP identification

pp -> Z*-> LLP LLP

Displaced Jet trigger :

H_T > 350 GeV (H_T scalar sum of the transverse momenta of all jets satisfying pT > 40 GeV and $|\eta| < 2.5$)



Unusual jets:

at most two associated prompt tracks having a transverse impact parameter (with respect to the leading primary vertex) smaller than 1.0 mm

at least one associated displaced track, defined as a track with a transverse impact parameter (with respect to the leading primary vertex) larger than 0.5 mm,

vertex up to 55 cm in the transverse plane is identified
Sensitive even for 50 GeV LLP

ATLAS LLP —> Displaced Di-jets

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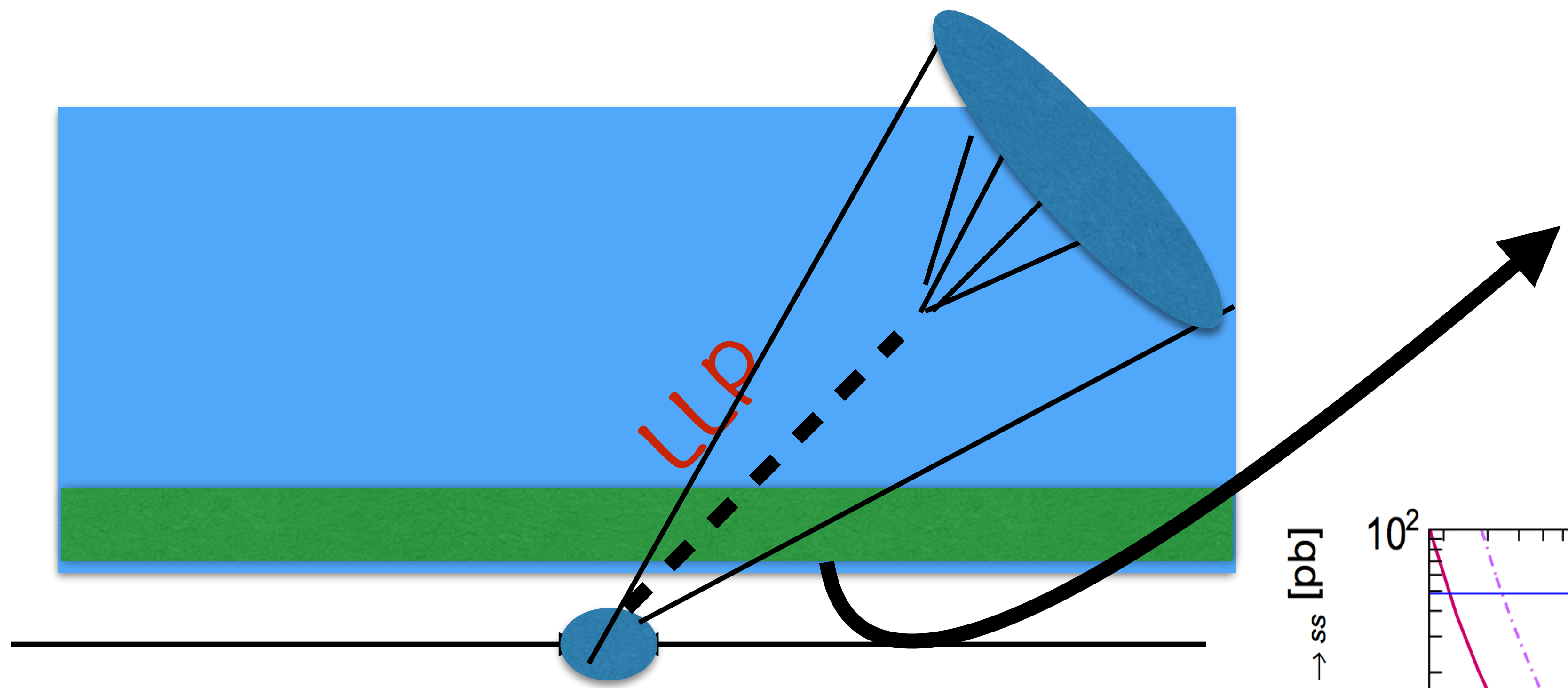
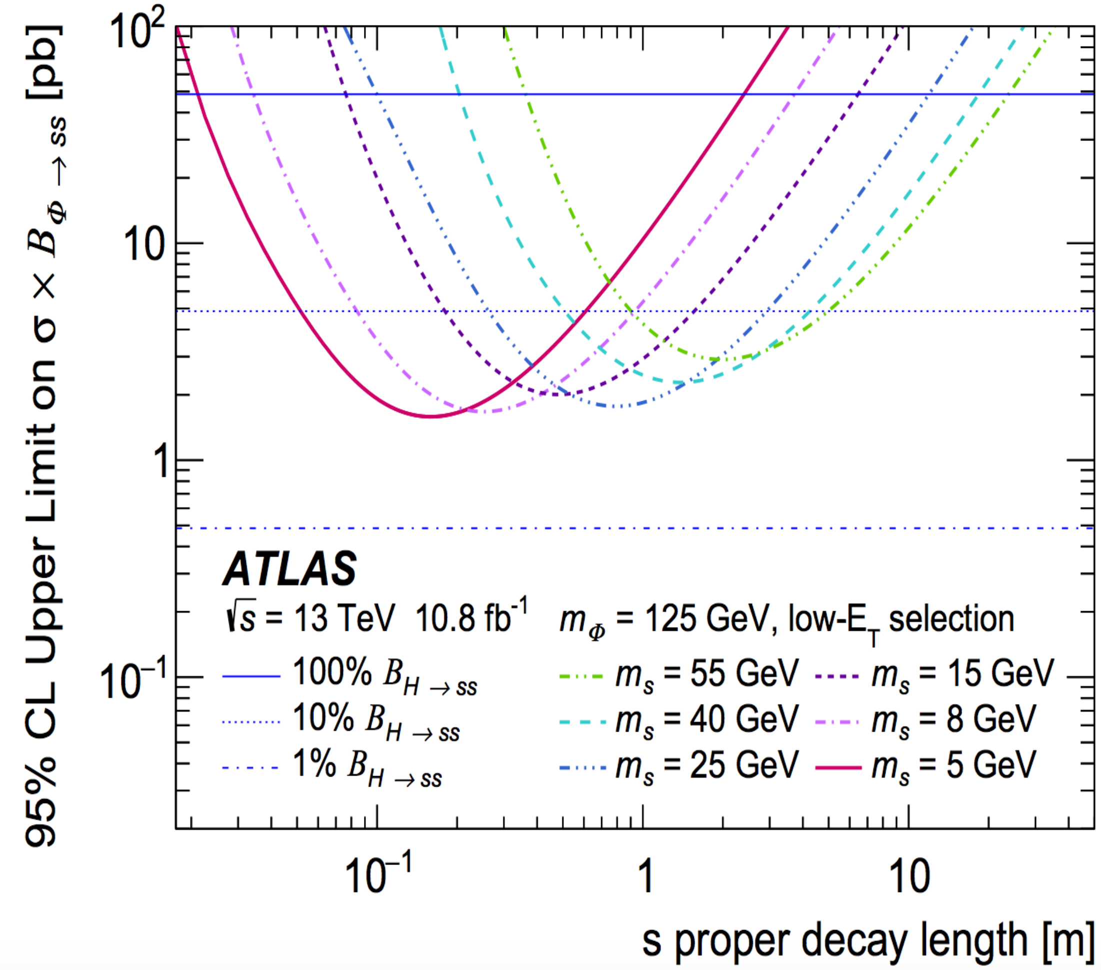
Dedicated Trigger developed for LLP decaying inside HCAL





Unusual jets

typically have no associated activity in the tracking system.

often have a high ratio of energy deposited in the HCal (EH) to energy deposited in the ECal (EM).

This ratio, EH/EM, is referred to as the CalRatio

ATLAS LLP —> Displaced Di-jets

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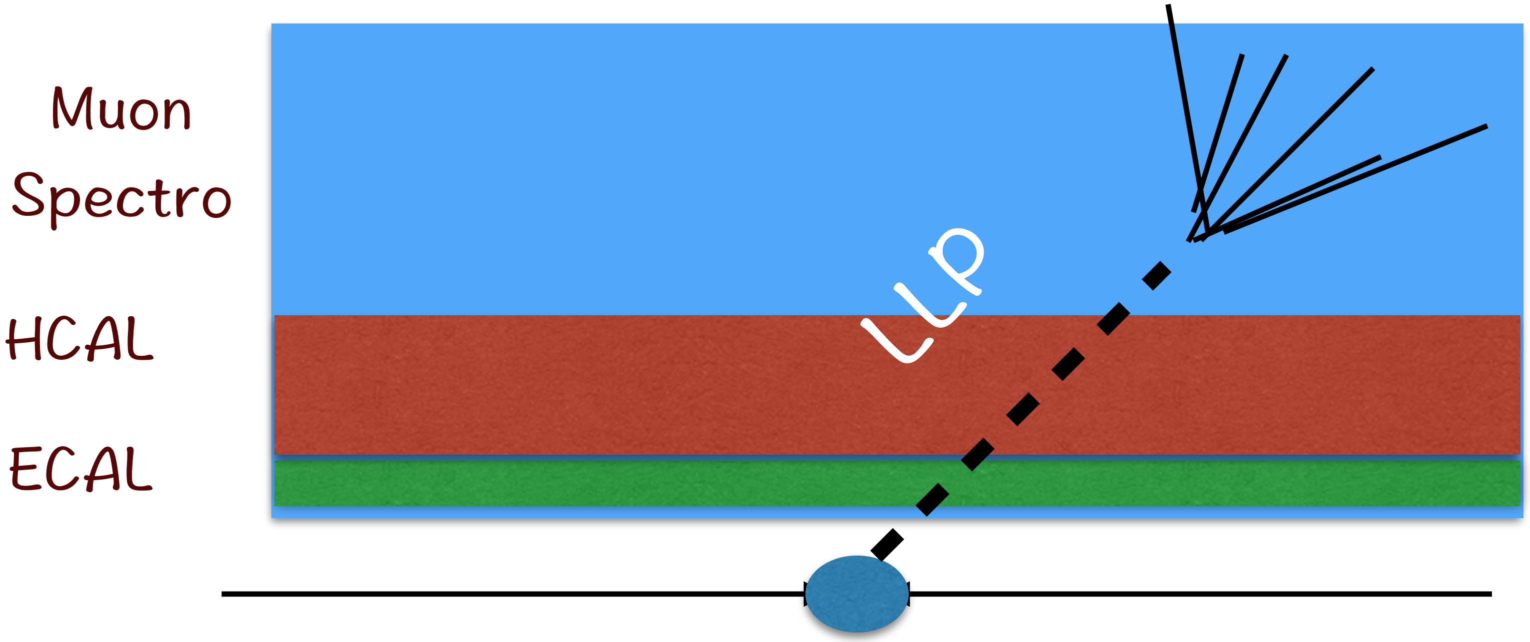
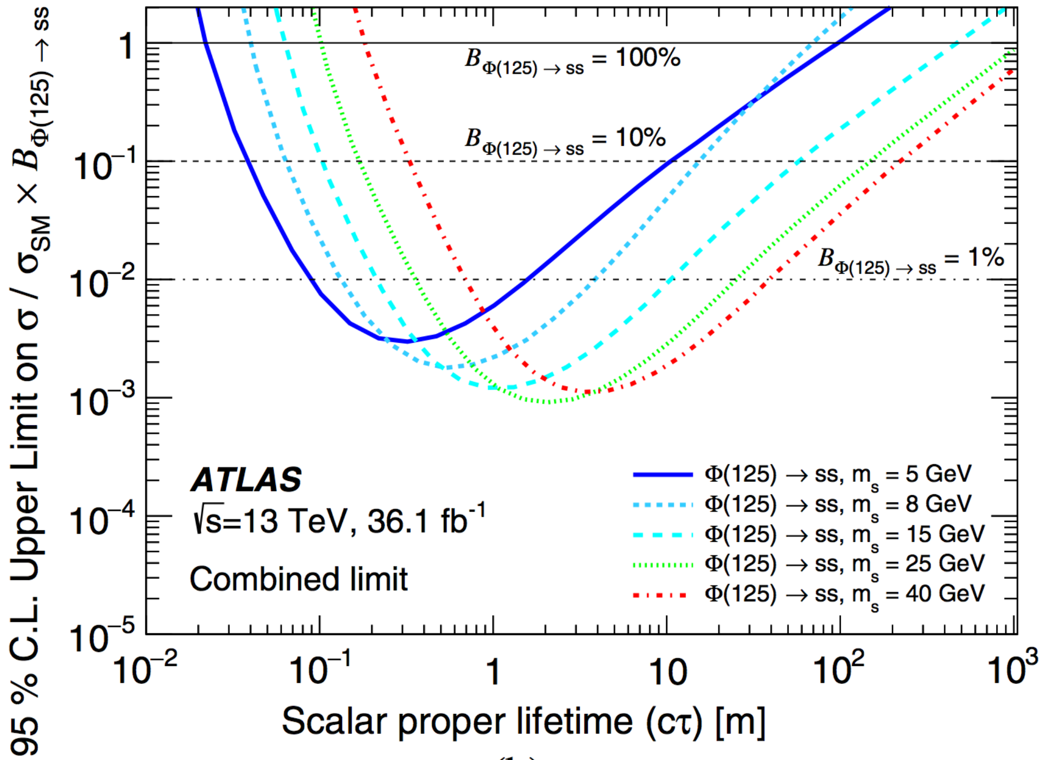
Dedicated Trigger developed for LLP decaying Muon Spectrometer





(b)

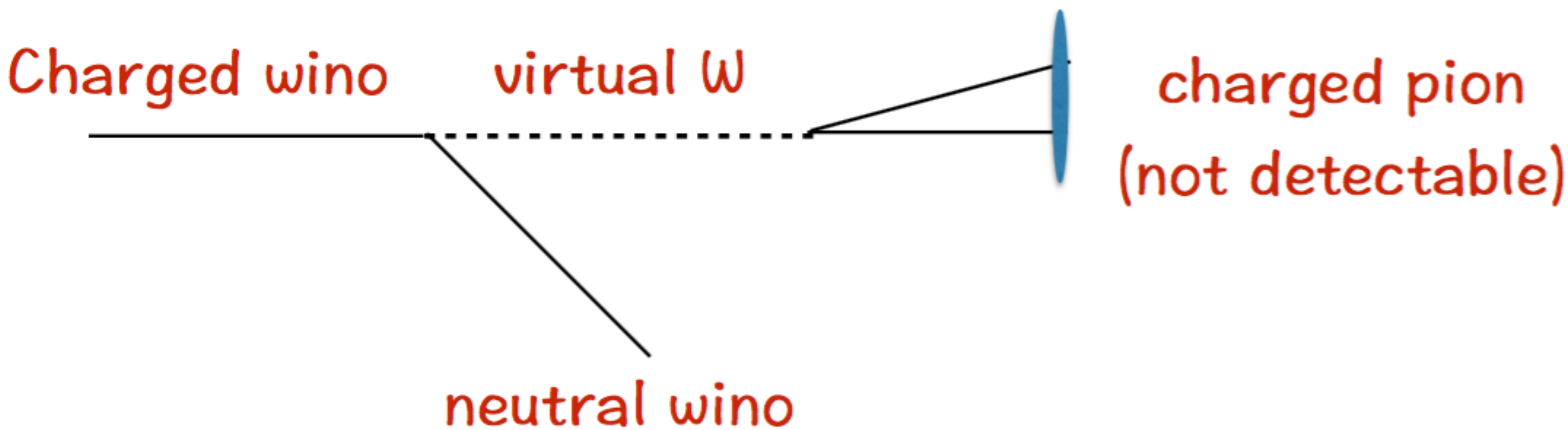
TABLE I. Topologies considered in this paper, corresponding basic event selection and benchmark models.

Strategy	Basic event selection	Benchmarks
2MSVx	at least 2 MS vertices	scalar portal, Higgs portal baryogenesis, stealth SUSY
1MSVx+Jets	exactly 1 MS vertex at least 2 jets with $E_T > 150$ GeV	stealth SUSY
1MSVx + E_T^{miss}	exactly 1 MS vertex $E_T^{miss} > 30$ GeV	scalar portal with $m_\Phi = 125$ GeV, Higgs portal baryogenesis

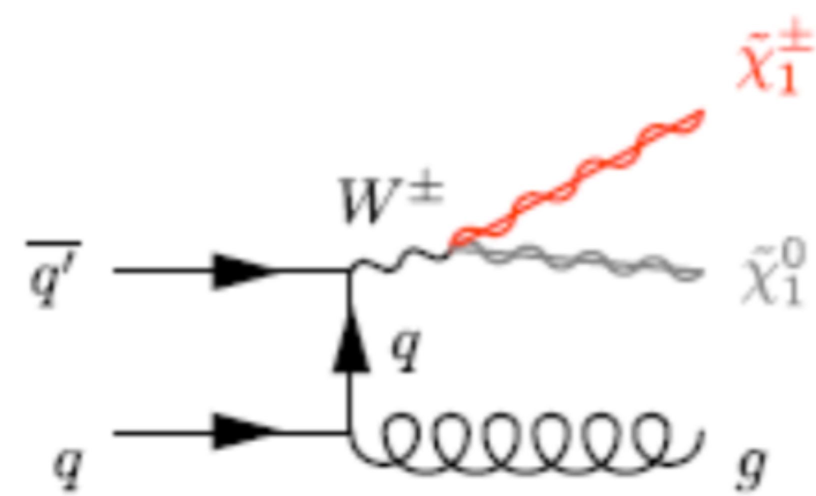
B. Disappearing Charged Track

decay of Charged wino to neutral wino

Mass difference ~ 165 MeV



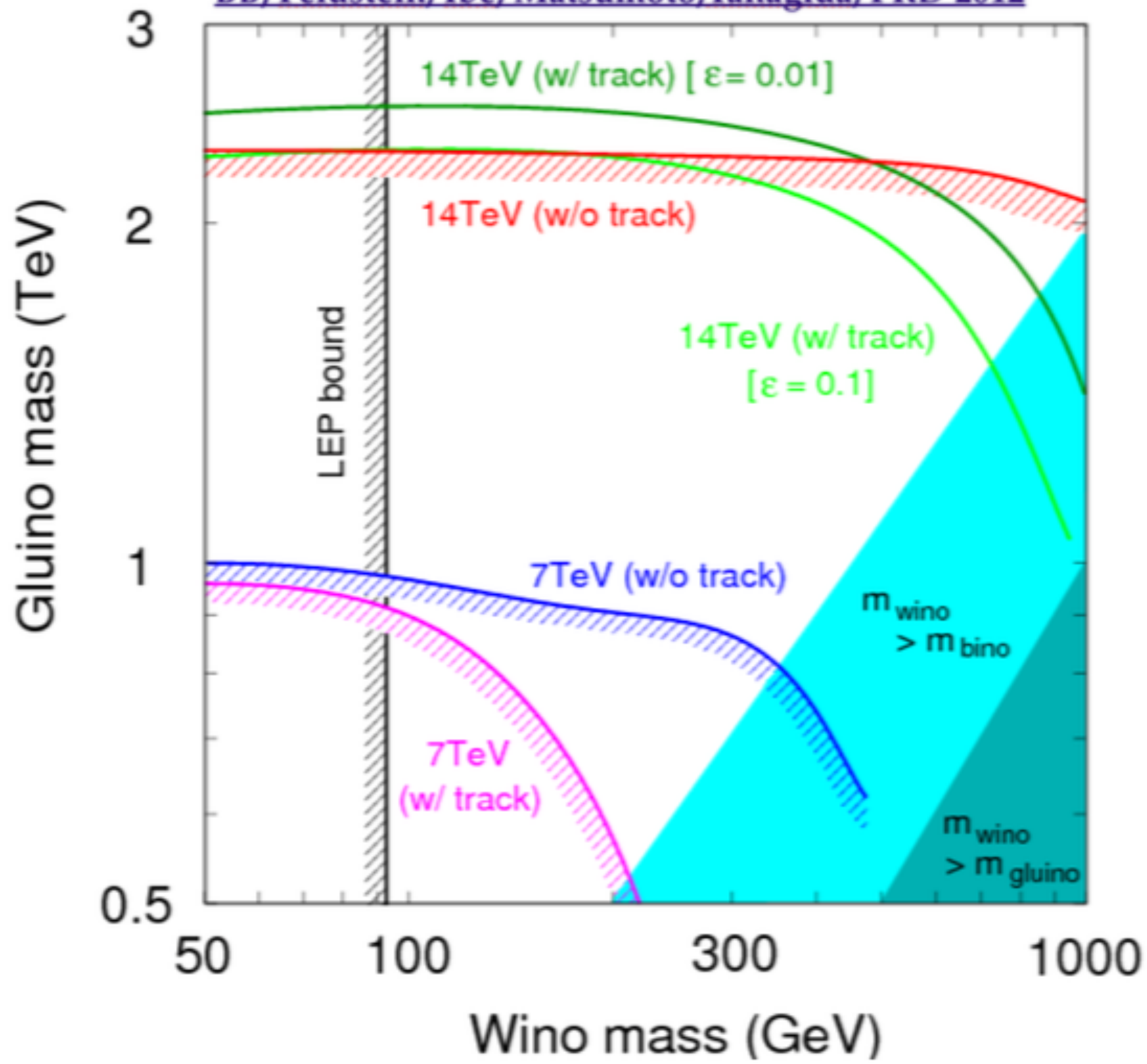
Charged wino pair + ISR jet



B. Disappearing Charged Track

Selection efficiency is very low for heavy wino: better to take tracks which travel up to SCT

BB, Feldstein, Ibe, Matsumoto,Yanagida, PRD 2012



Our Proposal

- The selected track must disappear between 142 mm and 520 mm, i.e. between the inner pixel detectors and the semiconductor detector (SCT).

B. Disappearing Charged Track

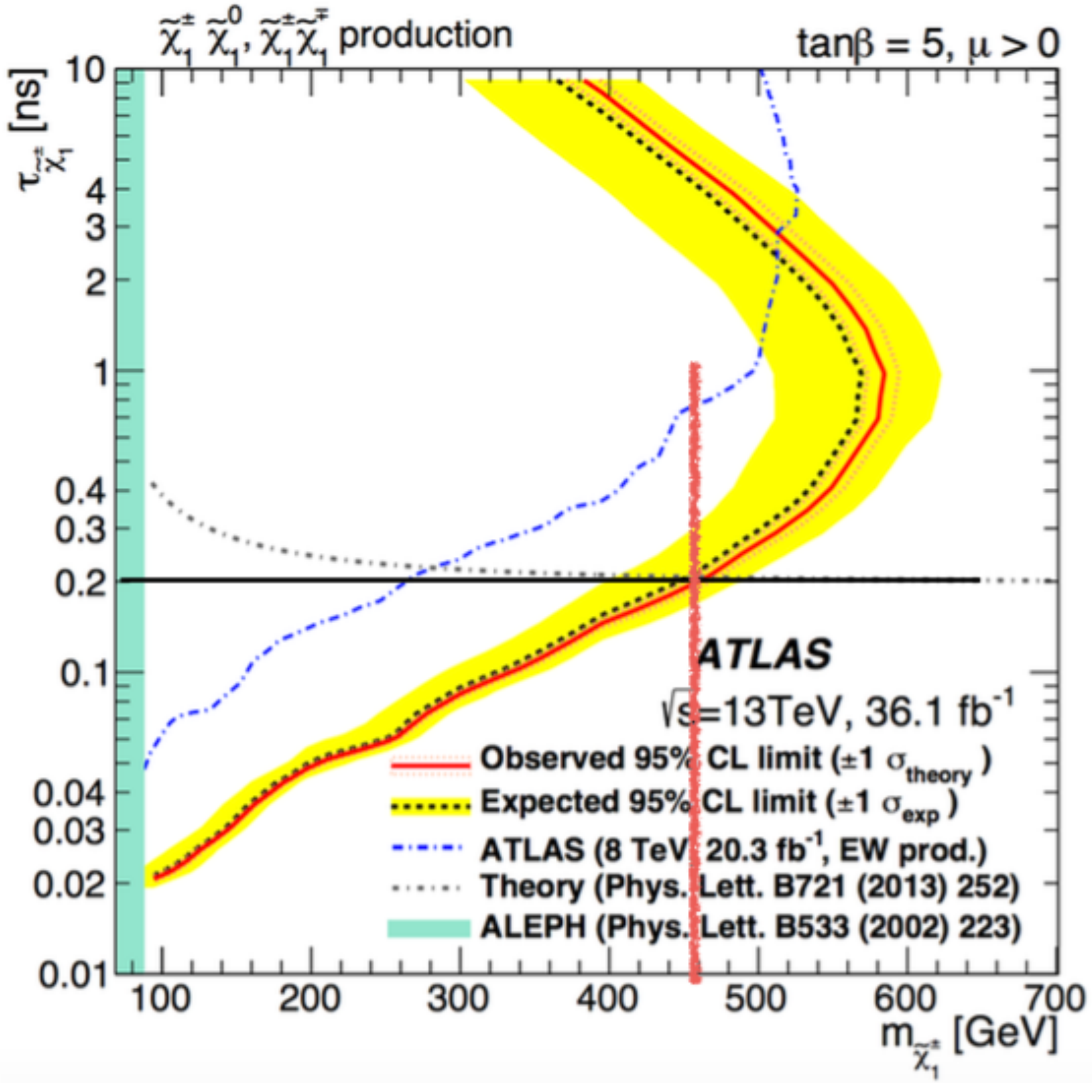
1712.02118

New study by ATLAS

TRACK ——> TRACKLET

Look for "tracklet" with hits in ATLAS pixel layers (R < 12 cm)but none in silicon strips (R > 30 cm)

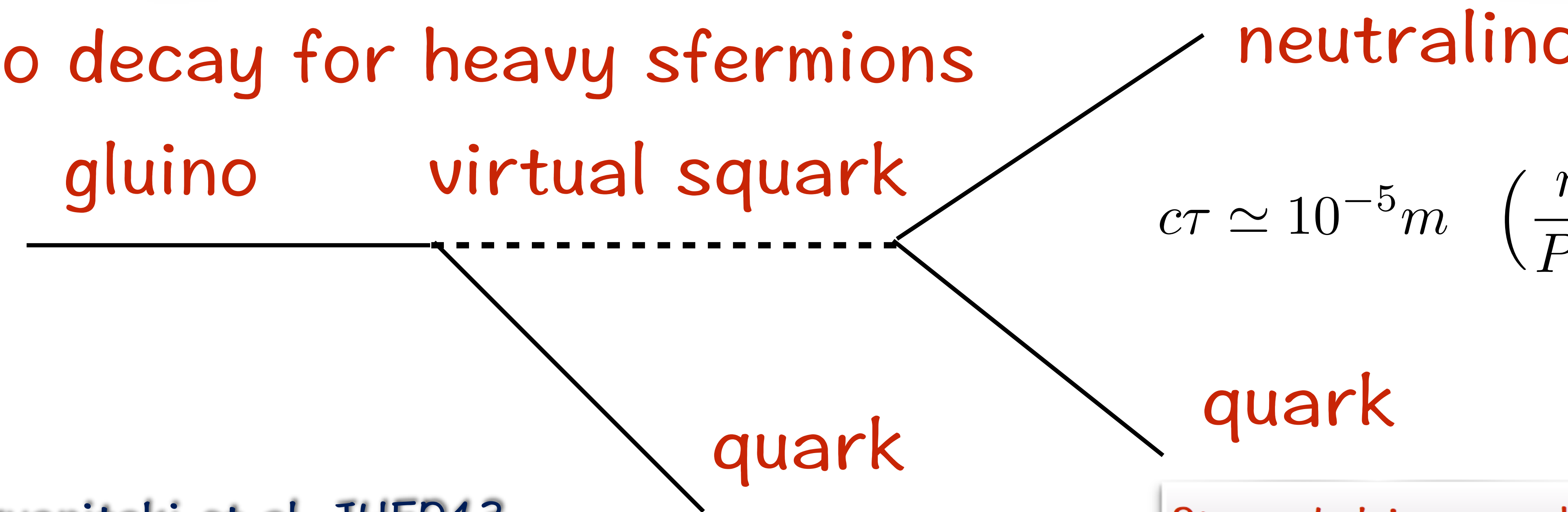
Possible because of new innermost pixel layer



limit for wino ~ 460 GeV

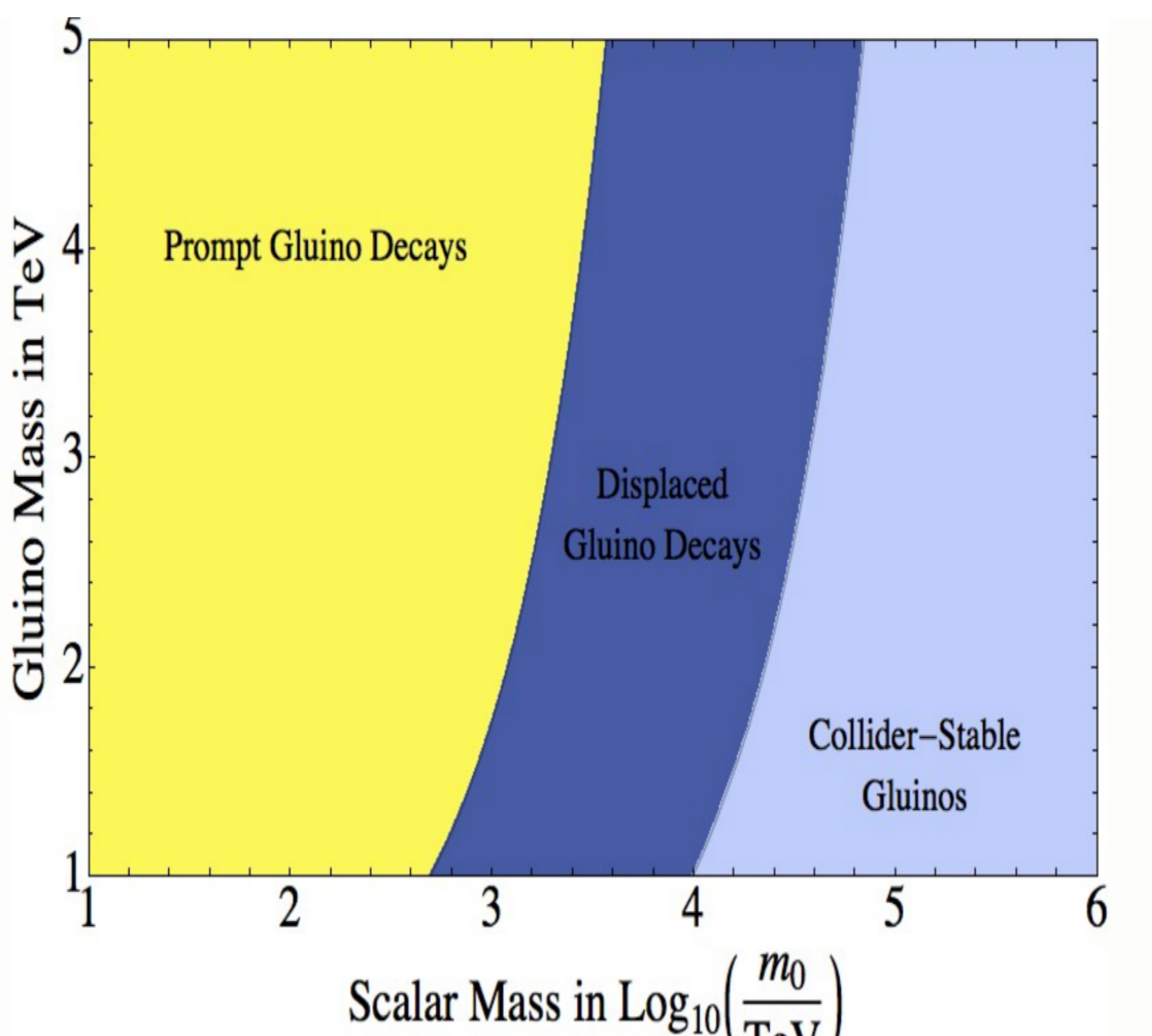
C. Stopped Particle : Out of time decay

gluino decay for heavy sfermions

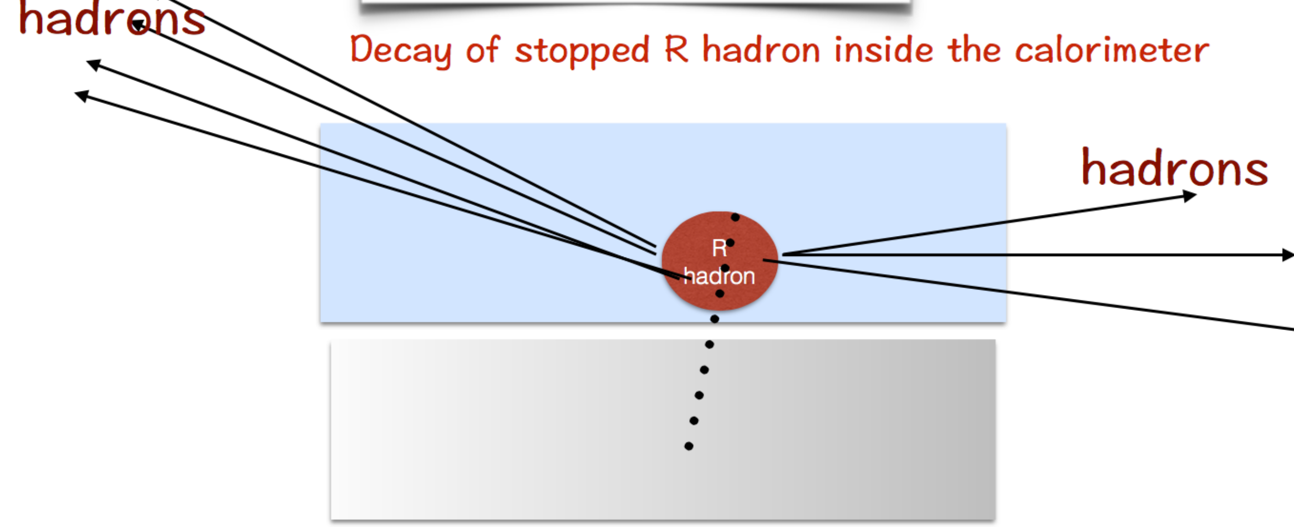


$$c\tau \simeq 10^{-5} m \left(\frac{m_{\tilde{q}}}{PeV}\right)^4 \left(\frac{TeV}{m_{\tilde{g}}}\right)^5$$

Arvanitaki et al. JHEP13



Stopped gluino search



signature : randomly-timed, relatively large energy response

most easily observed at times between pp collisions.

During these times the detector should be mostly quiet

(possible activity : :cosmic rays, beam-related backgrounds, and instrumental noise)

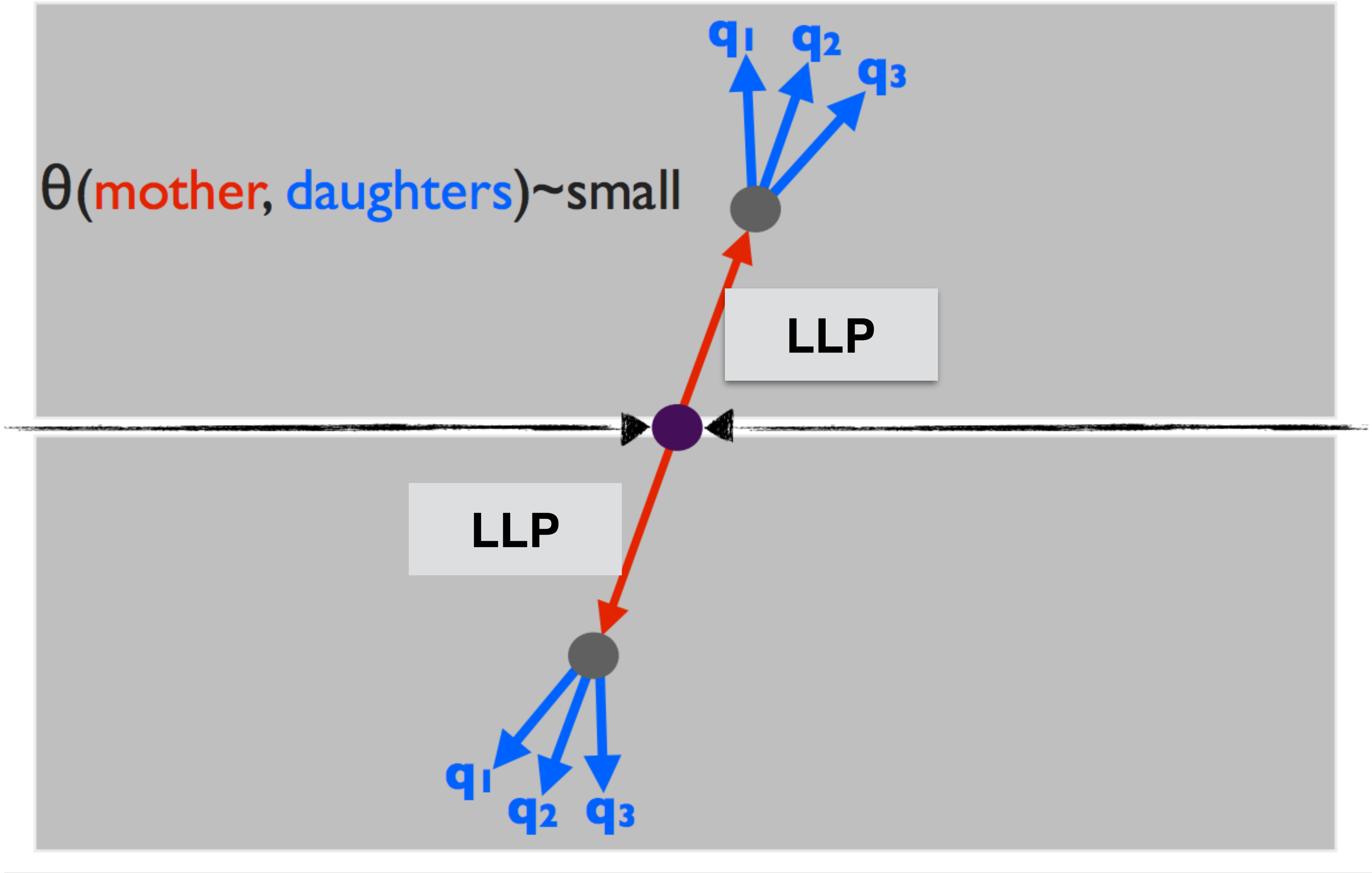
searched by DO of Tevatron , ATLAS, CMS : limits also depend on lifetime

hep-ex: 1501.05603, https://inspirehep.net/record/1599661/files/EXO-16-004-pas.pdf

Unusual signatures of LLP

Consider a process P P -> LLP pair, LLP -> j j j

Usual 'displaced vertices' , 'displaced jets' signature



Courtesy: Swagata Mukherjee

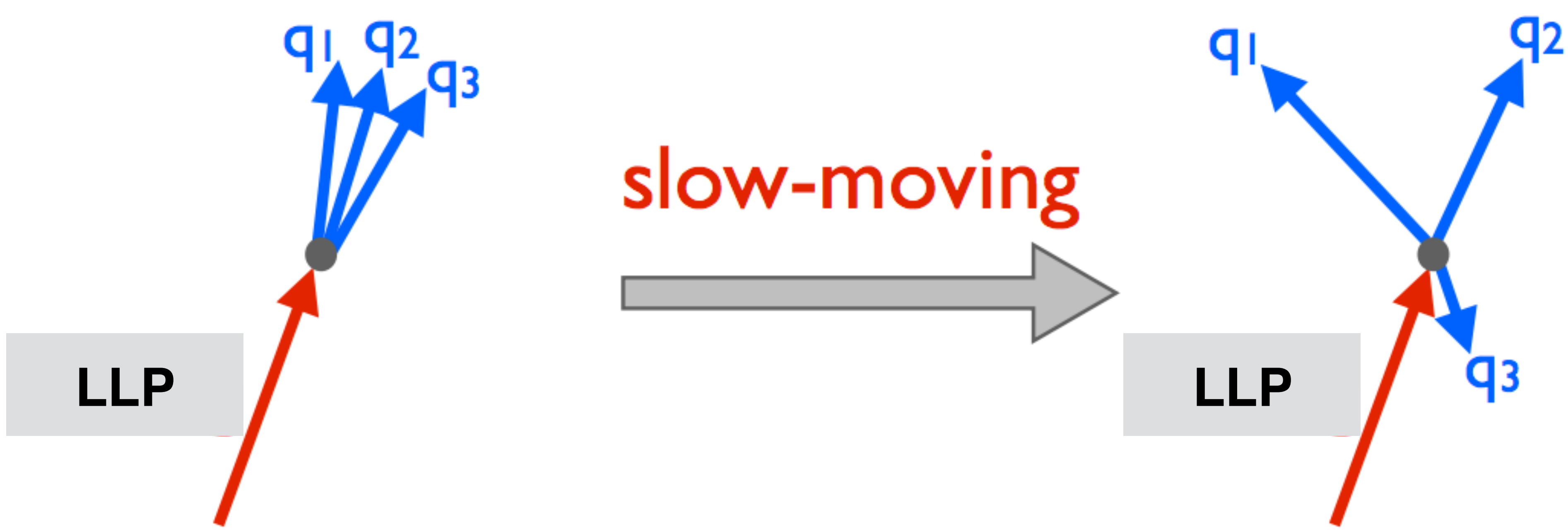
Unusual signatures of LLP

Heavy LLP —> Slow Moving

$$\beta(=p/E) < 1$$

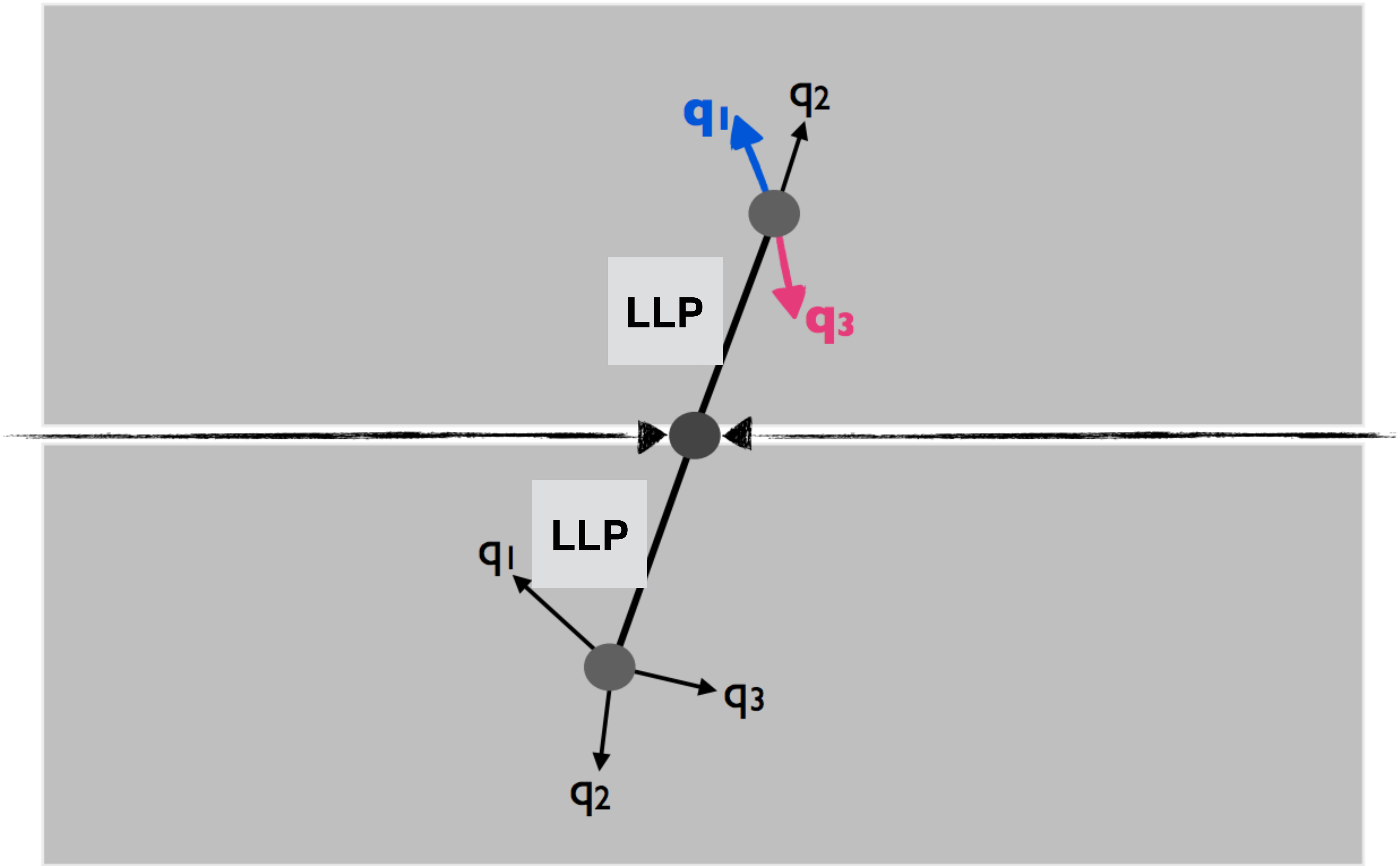
Decay products not collimated anymore

θ(mother, daughters) can be **big**



Unusual signatures of LLP

Non-pointing or even **backward-moving** particles

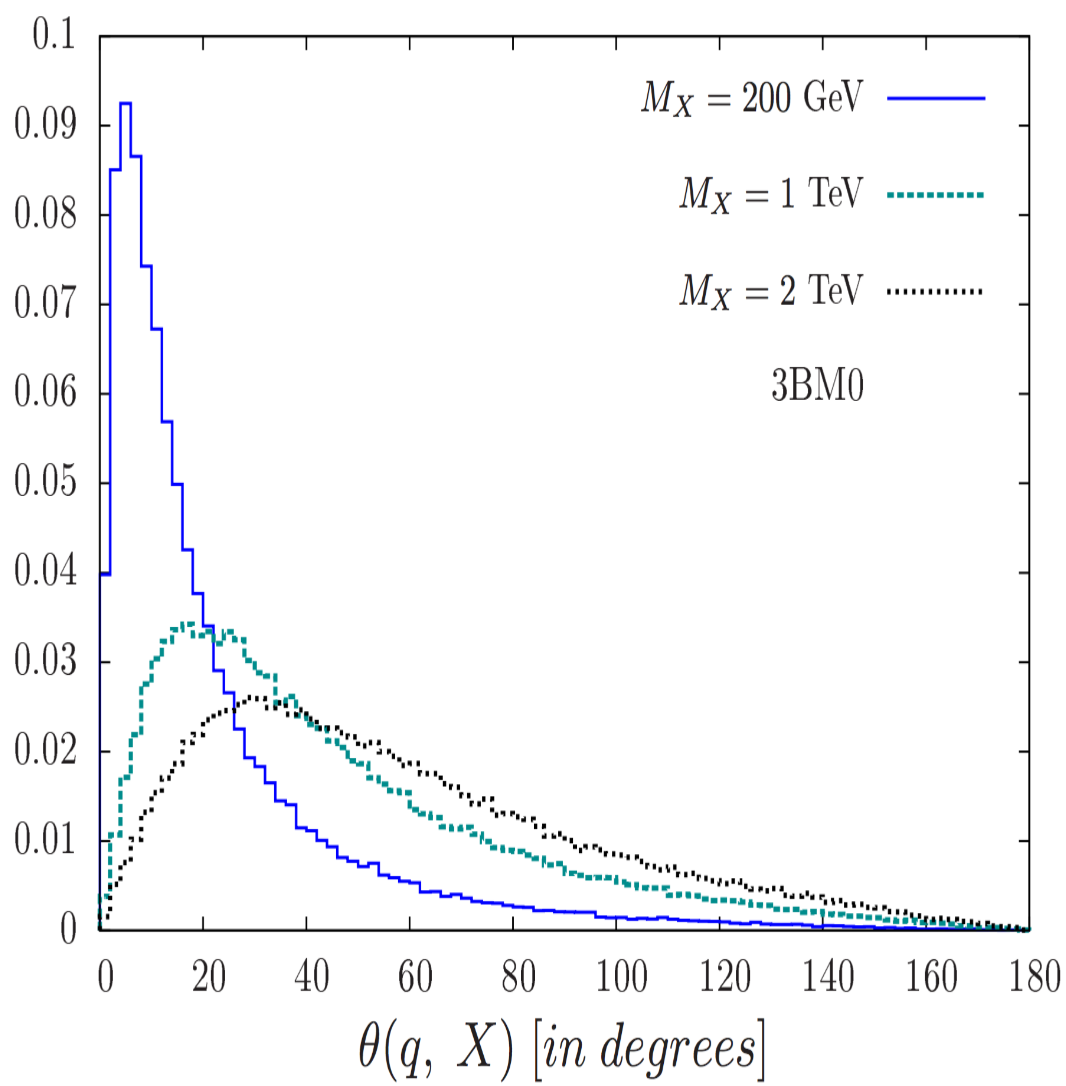


Backward Moving Particles

1706.07407

S Banerjee, G Bélanger, **BB**,
F Boudjema, R Godbole
and S Mukherjee

How often at-least one daughter is non-pointing / backward-moving ?



Case	M_X [TeV]	M_{DM} [TeV]	β (mean, RMS)	$\theta > 22.5°$	$\theta > 45°$	$\theta > 90°$	$\theta > 135°$
2BM0	0.2	-	0.75, 0.23	0.85	0.62	0.25	0.05
			0.87, 0.13	*0.78*	*0.46*	*0.13*	*0.03*
	0.5	-	0.66, 0.24	0.96	0.78	0.33	0.07
			0.81, 0.14	*0.94*	*0.65*	*0.19*	*0.04*
	1	-	0.58, 0.23	0.99	0.90	0.42	0.09
			0.72, 0.15	*0.99*	*0.83*	*0.28*	*0.06*
	2	-	0.46, 0.20	1.00	0.98	0.54	0.13
			0.60, 0.14	*1.00*	*0.97*	*0.40*	*0.08*
3BM0	0.2	-	0.76, 0.23	0.89	0.69	0.32	0.07
			0.94, 0.09	*0.65*	*0.34*	*0.09*	*0.02*
	0.5	-	0.67, 0.23	0.98	0.84	0.43	0.10
			0.86, 0.13	*0.92*	*0.61*	*0.20*	*0.04*
	1	-	0.58, 0.23	0.99	0.94	0.54	0.14
			0.76, 0.15	*0.99*	*0.84*	*0.33*	*0.07*
	2	-	0.46, 0.20	1.00	0.99	0.68	0.18
			0.62, 0.15	*1.00*	*0.98*	*0.52*	*0.12*

parton level analysis

Major Non-pointing fraction, non-negligible backward moving

Energy fractions in the backward direction

Reversing into the tracker

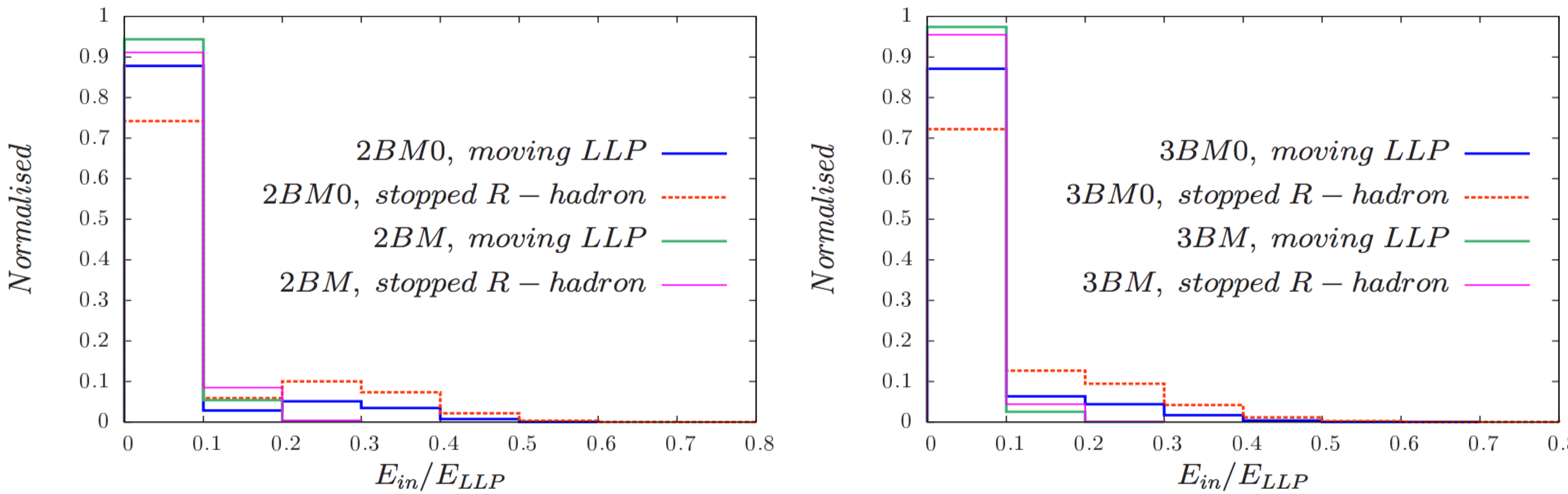
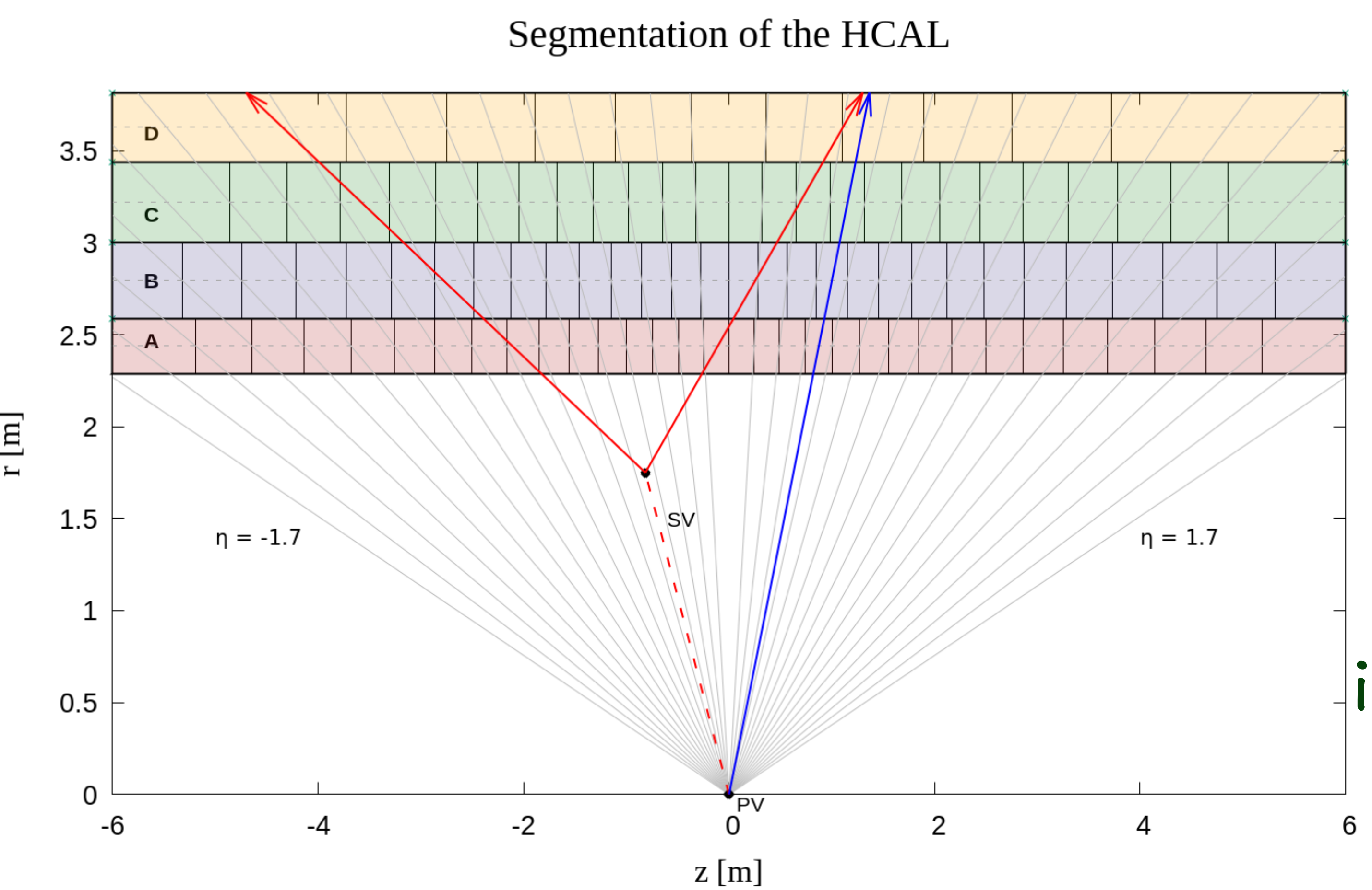


Figure 3. Normalised distribution of $E_{\rm in}/E_{\rm LLP}$, the energy fraction of visible daughter particles to the mother LLP shown for $M_{LLP} = 2$ TeV and $M_{\rm DM} = 0.75 \times M_{\rm LLP} = 1.5$ TeV. For the definition of the 2BM/3BM decays, see the text. In the first bin ($E_{\rm in}/E_{\rm LLP} < 0.1$) $E_{\rm in} = 0$. It should be interpreted as the case where no *BMO* has registered.

How to find backward moving particles?

Shower shapes for the ECAL/HCAL, Timing in the muon chamber and upgrades for the tracker, Secondary vertex reconstruction, unusual tracks

Jets from LLP : energy deposition pattern



mismatch of particle's eta-phi with calorimeter

(similar feature is used for the identification of non-pointing photon)

Jets consist of many particles:
effect more prominent or washed out ?

Another problem : HCAL has coarser resolution than ECAL

Fast detector simulation

Standard analysis?

- Standard displaced jets analysis of ATLAS and CMS loses sensitivity with increasing distance of the secondary vertex — different energy deposition patterns in the HCAL compared to the standard pattern of prompt jets make reconstruction of displaced jets challenging.

Fast Detector Simulator?

- Actual segmentation of the calorimeter needed for observing features associated with displacement of a particle. Fast detector simulation (e.g., `Delphes`) has $\eta - \phi$ segmentation of the calorimeters but no layered calorimeter structure and no segmentation in the physical z direction.

Models

1904.04811

BB, Swagata Mukherjee and Rhitaja Sengupta

- Scenario I: Jets coming from displaced Z

$$X(LLP) \to Z(SM) + Y(Invisible), \quad Z \to j\,j, \quad [m_X = 800 \text{ GeV}]$$

- Scenario II: Jets coming directly from decay of LLP

$$X(LLP) \to j\,j\,j, \quad [m_X = 100 \text{ GeV}]$$

Energy range: $(400, 500)$ GeV for both cases.
Both scenarios boosted enough to bring the displaced jets closer in the $\eta - \phi$ plane.

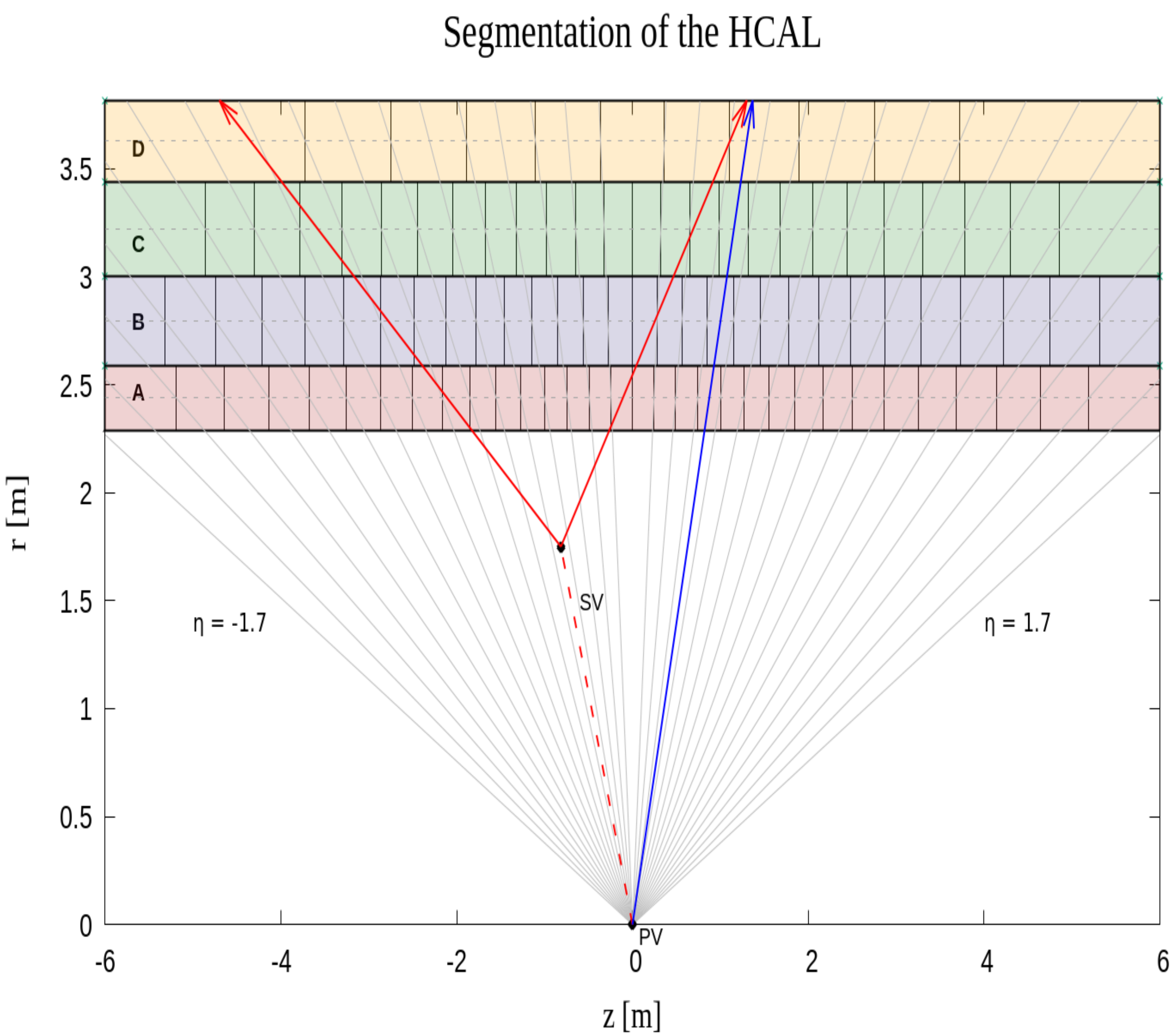
Also considered stopped particles decaying to quarks

Image generation: Any tower of the HCAL having energy deposit < 1 GeV is ignored.

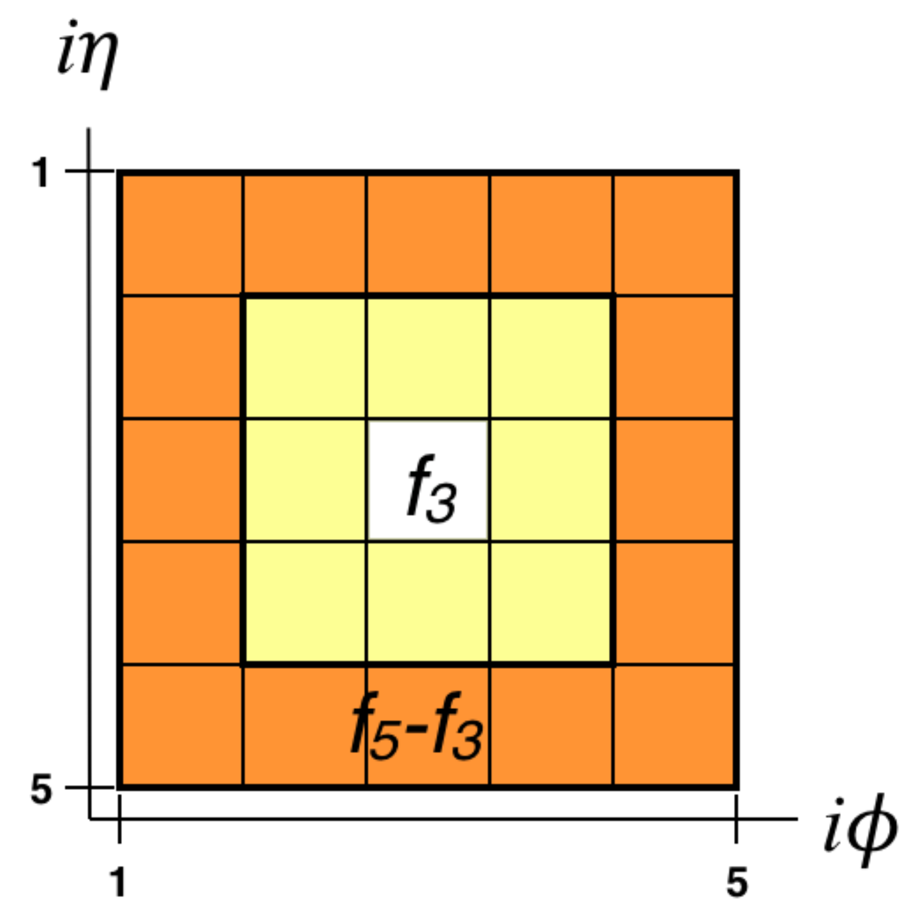
Normalise the energy in each tower of an event using the maximum energy deposited in the HCAL.

We store the energy deposition of an event as a 28 × 28 image with the energy depositions in each tower as intensity values of each pixel of the image with the highest intensity (energy) pixel at the centre of the $i\eta - i\phi$ plane.

simplified segmentation of HCAL



simulated a simplified version of the segmentation following Tile Calorimeter of ATLAS.



$$f_i = \frac{\text{Energy deposited in } i \times i \text{ block of the image}}{\text{Energy deposited in the full } 28 \times 28 \text{ image}}$$

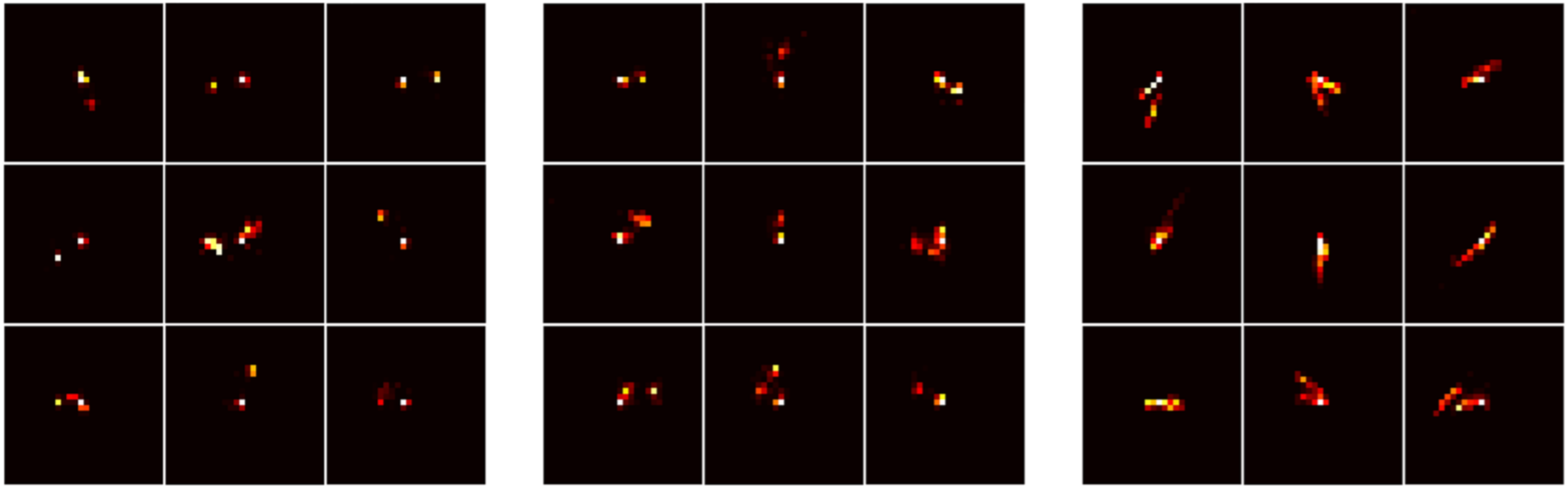
$$f_i, \quad i = 3, 5, 9, 11$$

Energy deposits: Individual Event

1904.04811

Scenario I: Jets coming from displaced Z

Typical energy deposition images of 9 events from



Z with no displacement — 50-70 cm displaced Z — 200-220 cm displaced Z

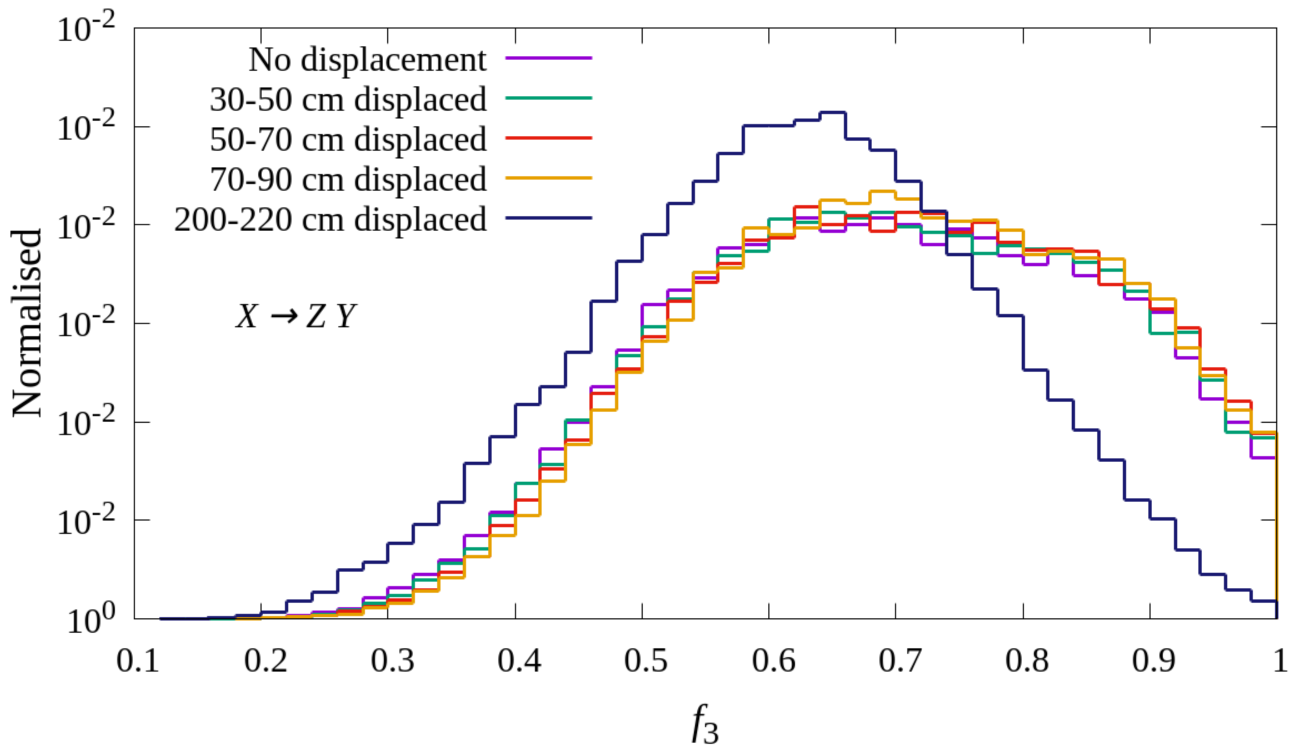
Although statistically different, discriminating individual images not an easy task — employing image-recognition technique

Courtesy: Rhitaja Sengupta

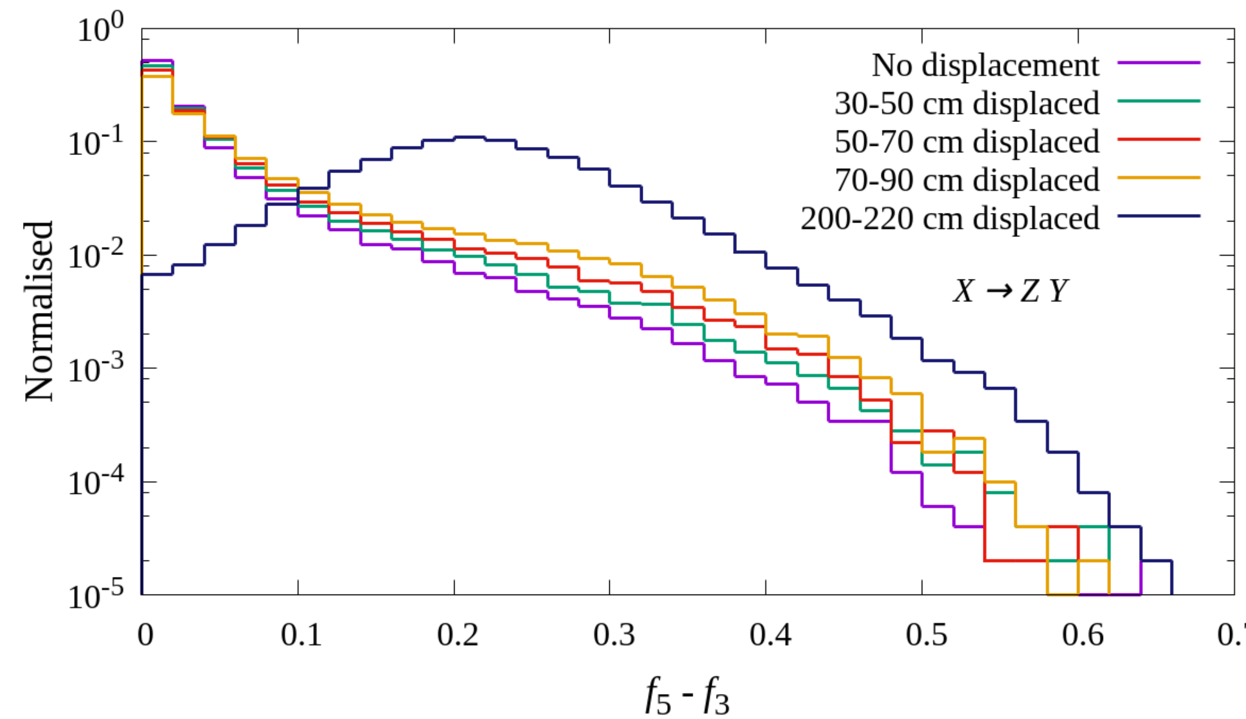
Scenario I : Energy deposition pattern

X(LLP)→Z(SM)+Y(Invisible), Z →j j

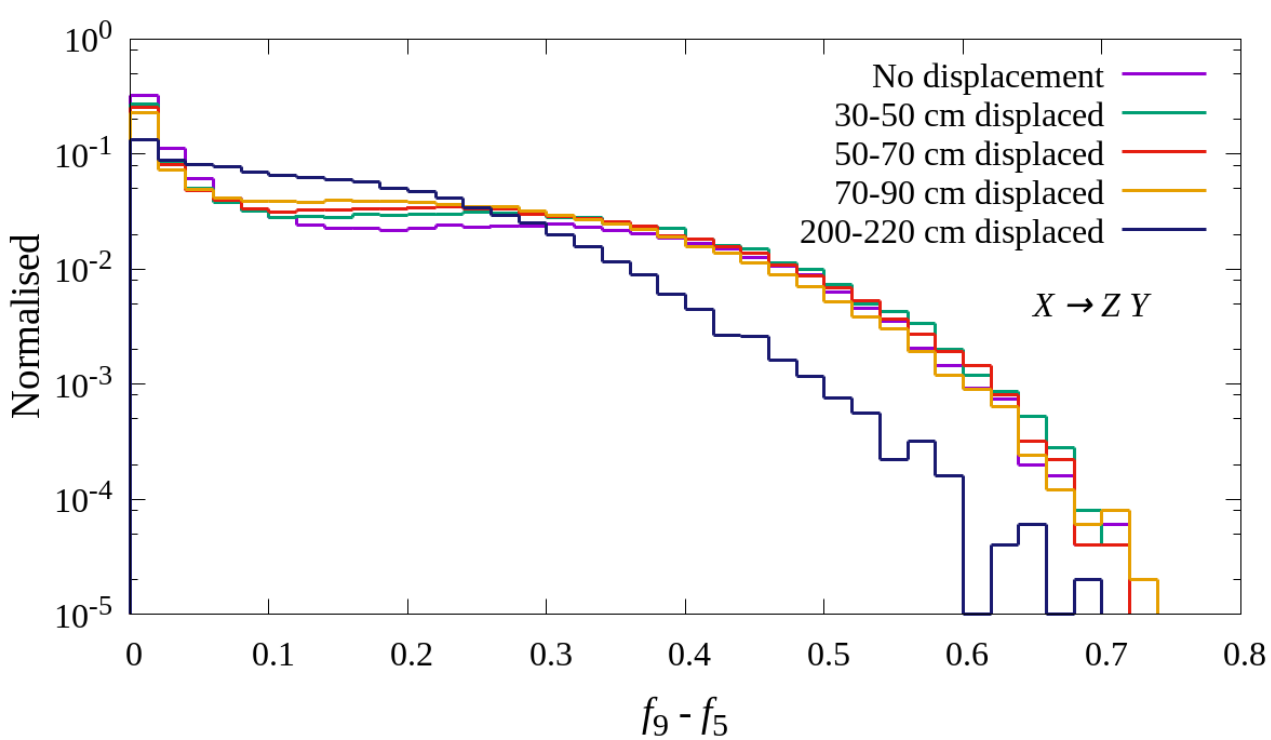
Fraction of energy in 3x3



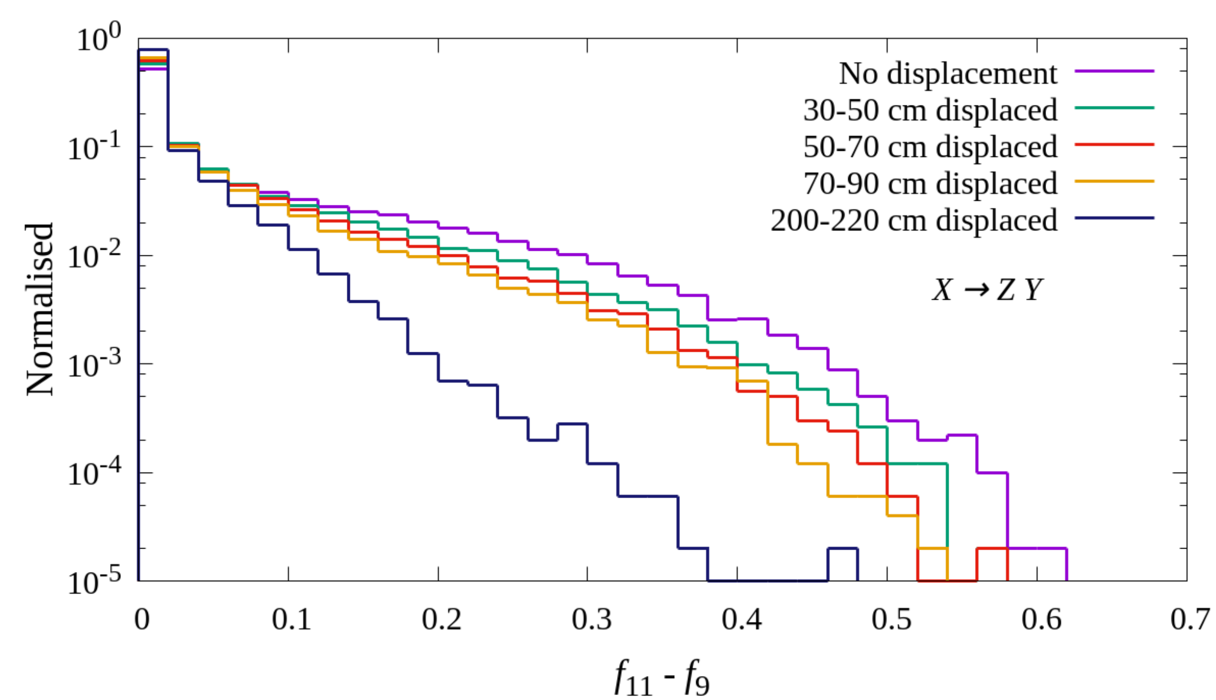
Fraction of energy in 5x5



Fraction of energy in 9x9

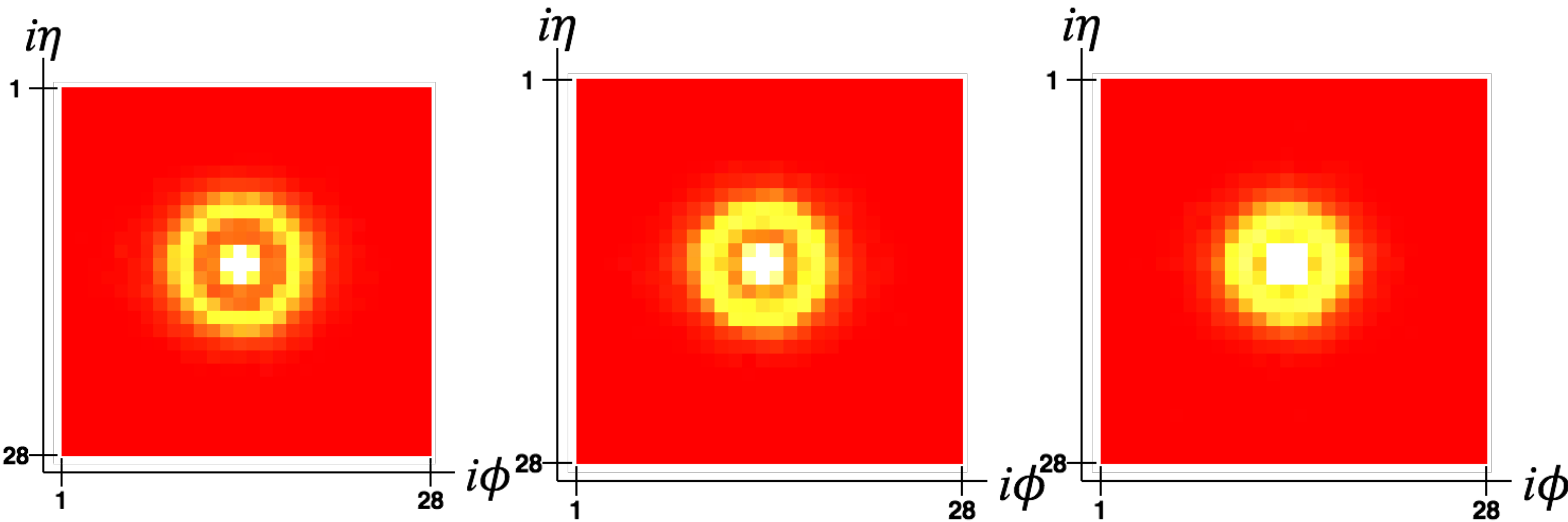


Fraction of energy in 11x11



Displaced Z -> q $\bar{q}$

Average over 50K images



Z with no displacement

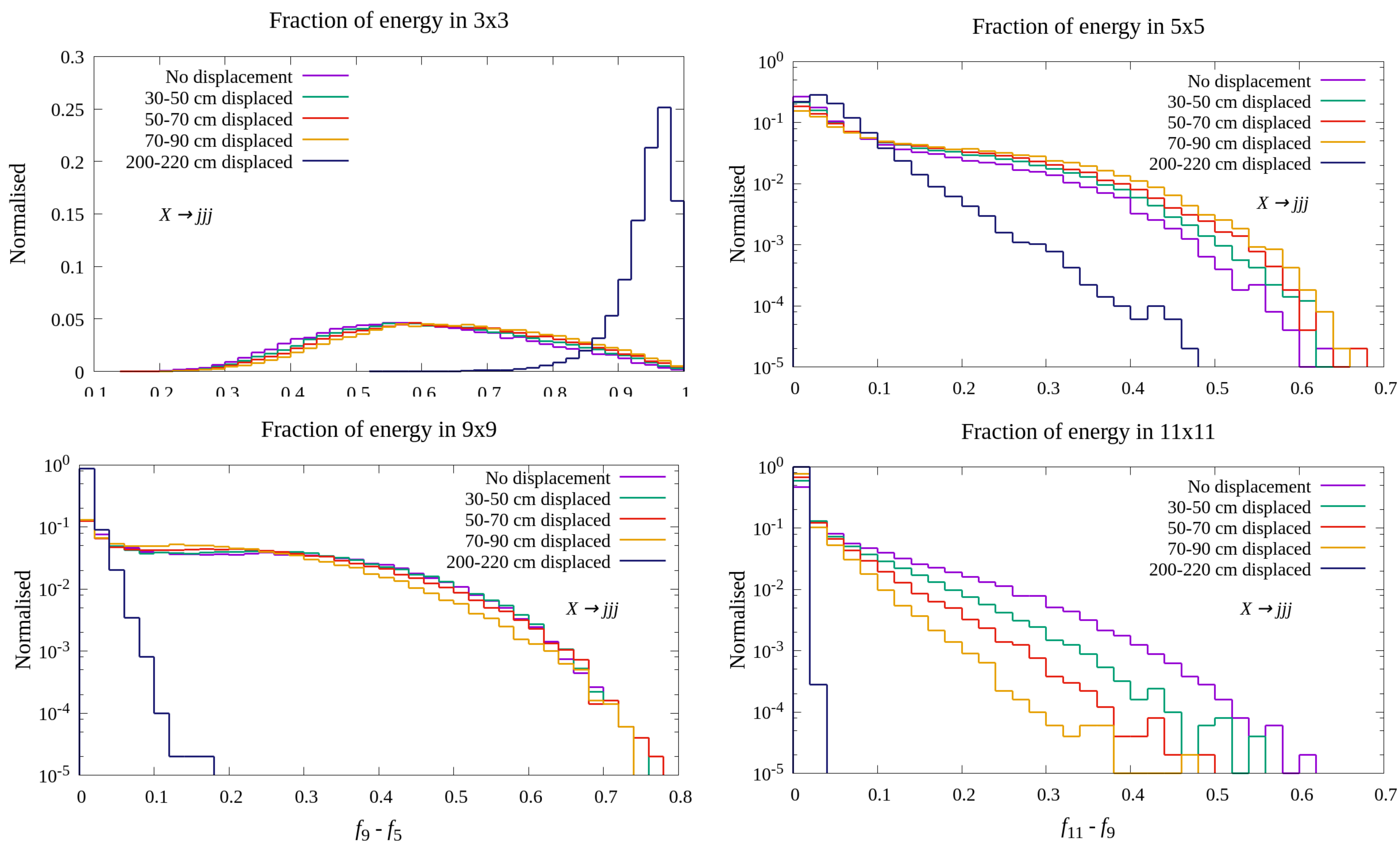
displaced Z $30<d_T<50$ cm

displaced Z $70<d_T<90$ cm

displacement in the transverse plane -> d_T

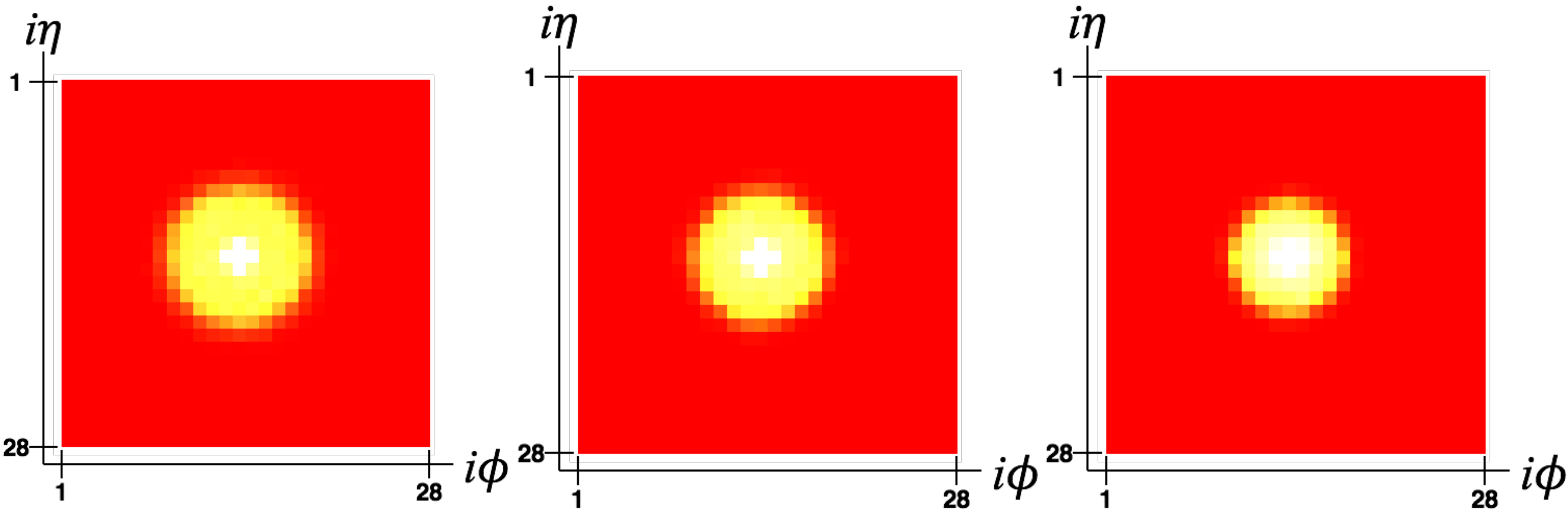
Scenario II: Energy deposition pattern

X(LLP)→j j j



Displaced X -> q q q

Average over 50K images



X with no displacement	displaced X $30<d_T<50$ cm	displaced X $70<d_T<90$ cm

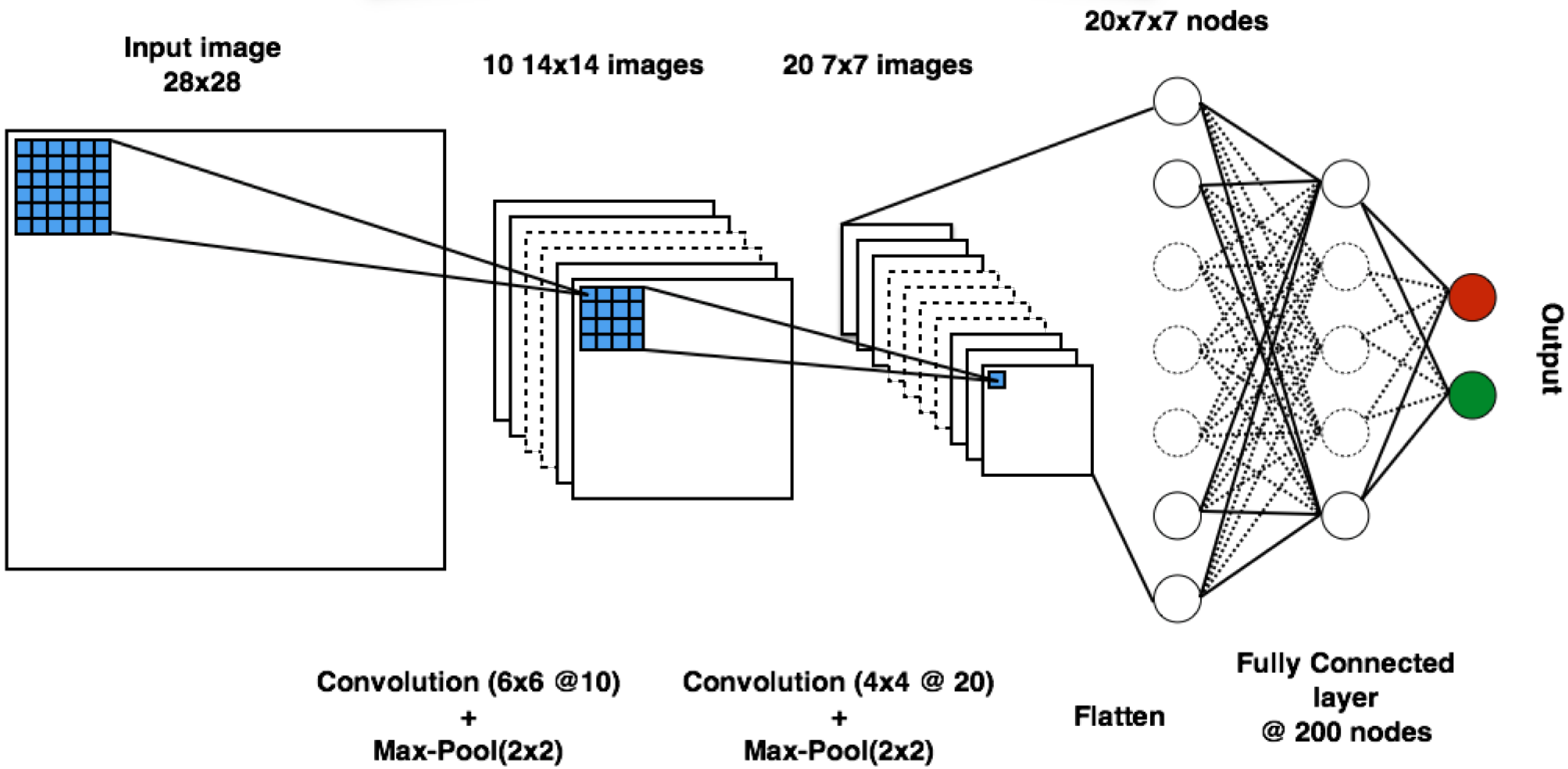
displacement in the transverse plane = > d_T

Observations

- **Elongated energy deposition in the HCAL**
  Mismatch of displaced particles' $\eta - \phi$ direction with standard calorimeter $\eta - \phi$ towers – energy deposition of displaced jets have more elongated patterns different from standard patterns of prompt jets

- **Total energy deposit more contained in the $i\eta - i\phi$ region**
  Physical segmentation of the detector (in z direction) increases with increasing radial distance – displaced jets from X have smaller energy deposit even if ΔR between them is same as in prompt decay

Neural network architecture

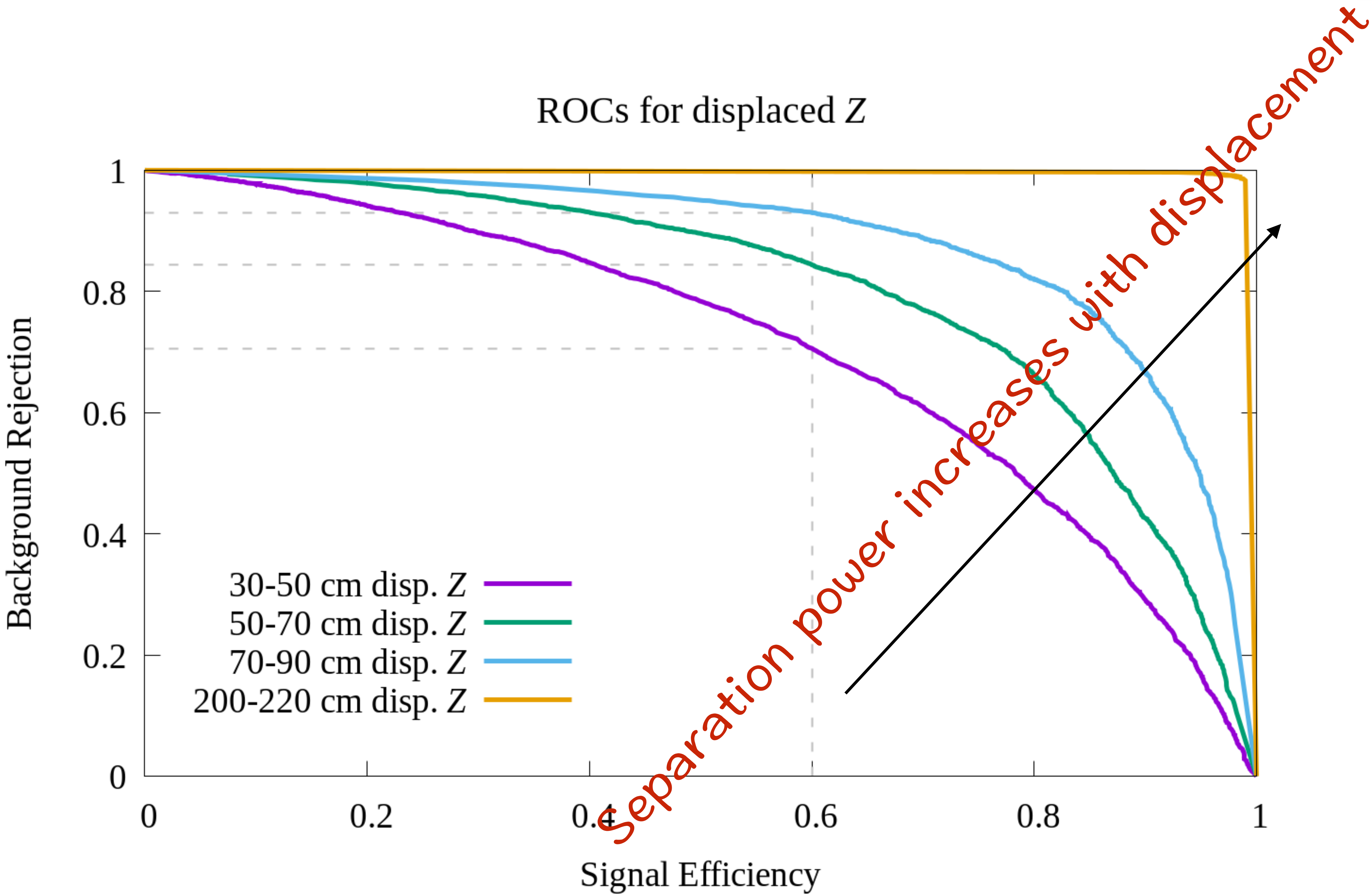


Adam Optimizer with a learning rate of 0.001 Batch size: 200, Dropout: 50%

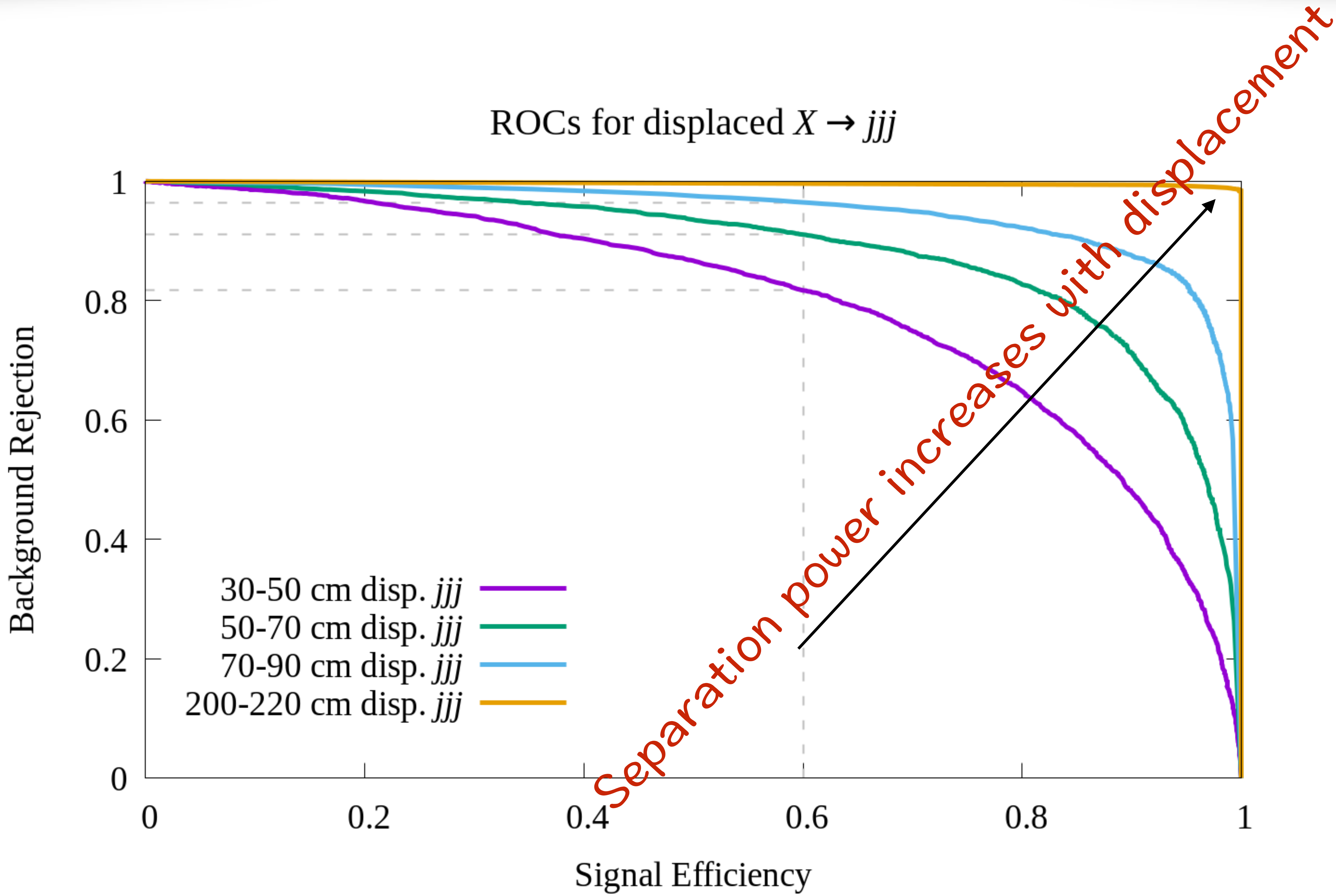
60,000 images for training, 20,000 for validation and another 20,000 for testing the network.

Training was stopped at the epoch with minimum validation loss.

Scenario I : discrimination between displaced vs non- displaced

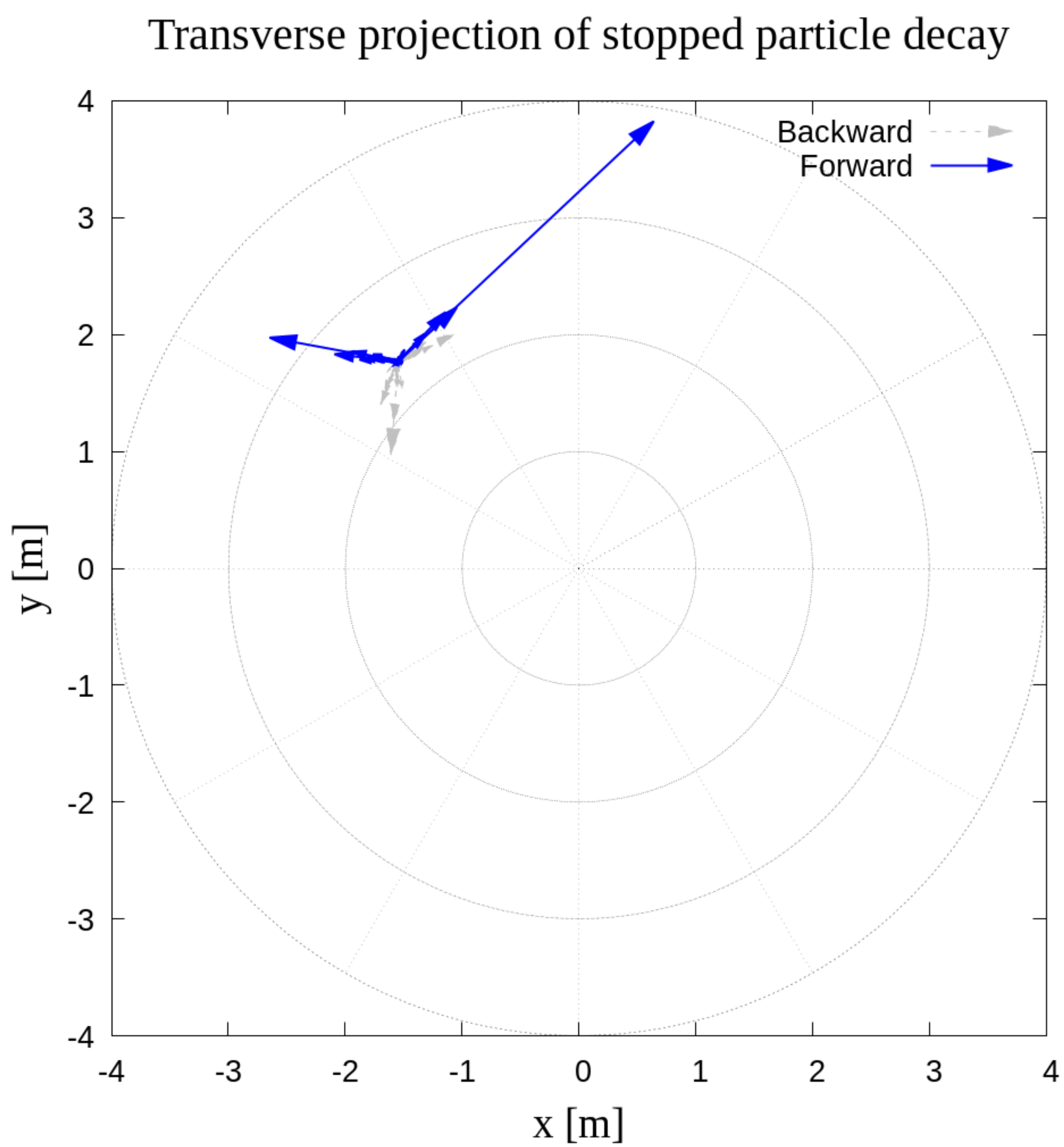


Scenario II : discrimination between displaced vs non- displaced



Decay of stopped particle inside the HCAL

A typical event display : X -> j j j (M_X= 1TeV)

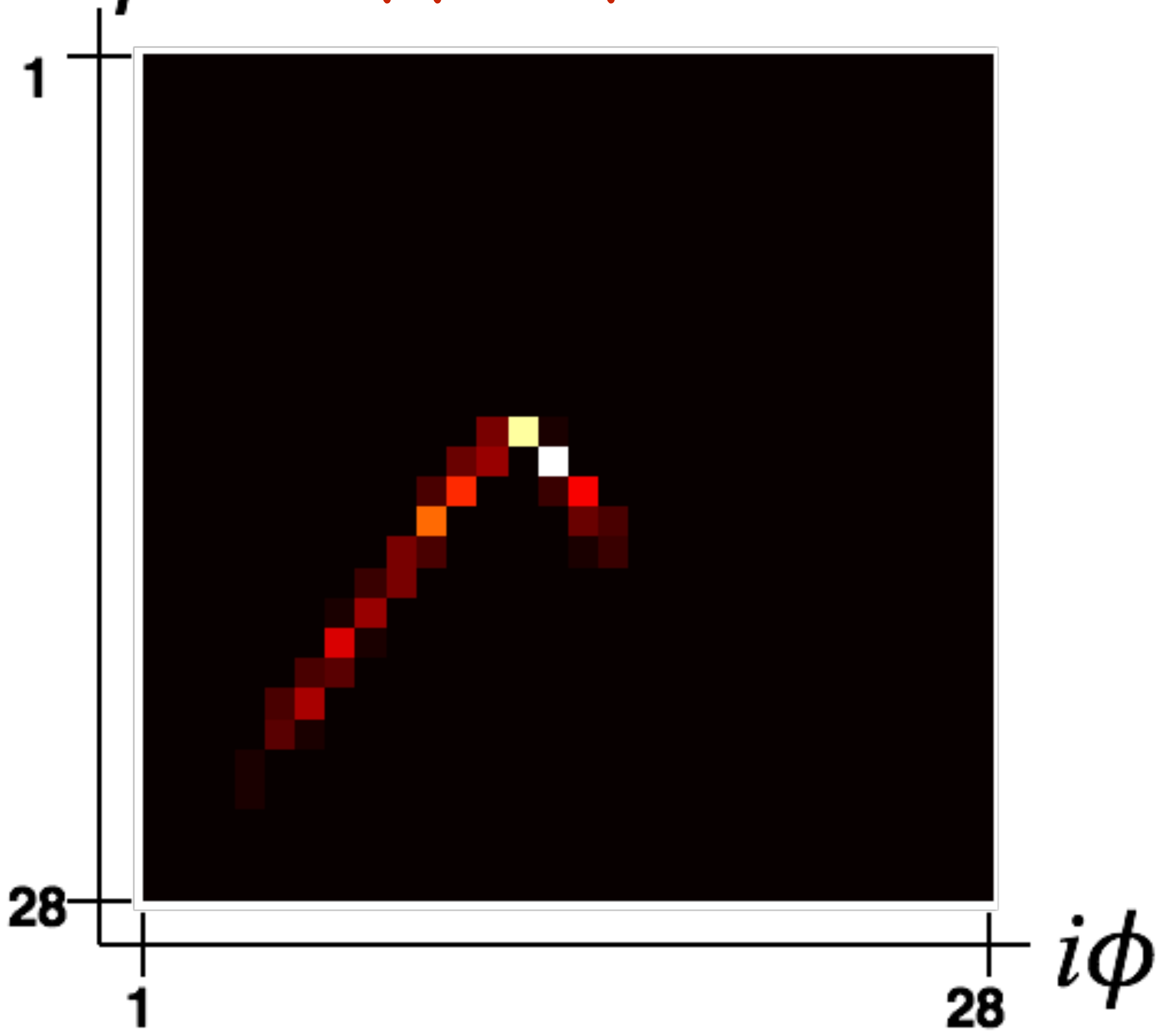


dotted lines: backward moving particles (not covered here)

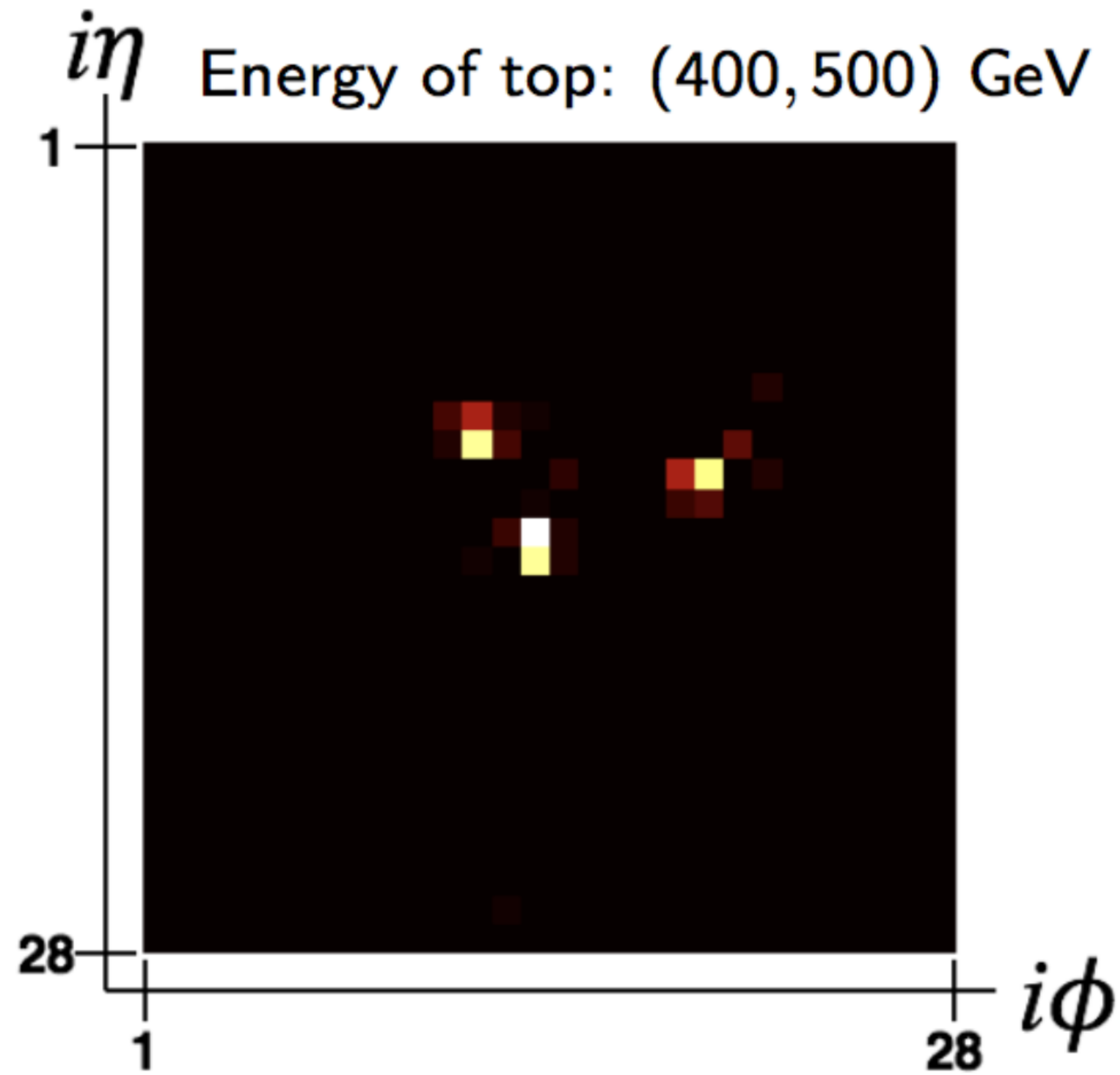
Decay of stopped particle inside the HCAL

1904.04811

Typical stopped particle



Top quark



Energy deposition pattern is very different compared to SM processes (may not require empty bunch crossing to identify these events)

Future Directions

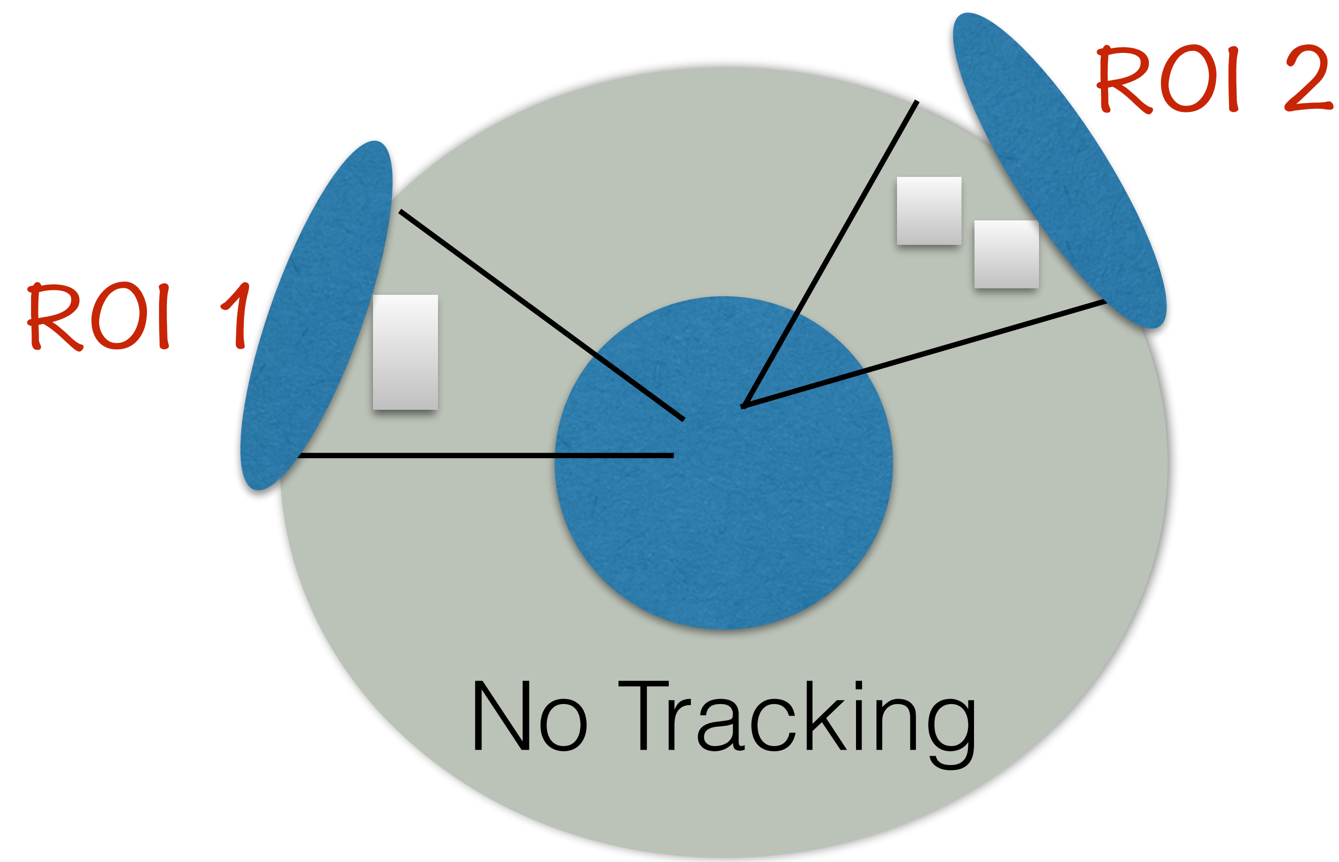
Run3 and HL-LHC

L1 Trigger: based calorimeter and Muon spectrometer

40 MHz is reduced to 100KHz at this stage

HLT: 100 KHz to 1KHz (Tracking performed in ROI)

HL-LHC: pile up 140-200



Example: LLP -> electrons

L1 trigger for electron ~ 20 GeV

L1 trigger for photon ~ 20 GeV

(No tracking so far, no difference between electron/photon)

HLT Trigger for electron ~ 50-60 GeV

HLT Trigger for photon ~150 GeV

For LLP we have to use photon trigger (limited by Trigger)

LHC Run3

FTK : The Fast Tracker for ATLAS

Full Tracking at the HLT for tracks with p_T >1 GeV |eta|< 2.5

Current ROI Tracking ~ 10 ms

Offline tracking ~ 1-10 s

For FTK time ~0.1 ms

FTK will ignore TRT, divide barrel into several segments (paralleize) , match pattern with pattern bank

There are proposals to add pattern bank for displaced particles

No sensitivity for LLPs which decays in TRT

New Ideas

1705.04321

Off-pointing track reconstruction at L1

$h \to \phi\phi \to 4q$ -> inaccessible with HT trigger

$Br[h \to \phi\phi \to 4q] = 10^{-5}$,

10-50 of events for decay length ~ cm

Tracking: Replacement of standard algorithm
by image based neural networks , graph network etc

More optimistic scenario for HL-LHC: full/partial Tracking at L1 ??

Timing Layer : CMS

CERN-LHCC-2017-027 ; LHCC-P-009

At HL-LHC, the number of pile up vertices will increase by a factor of 4-5. —> degradation of event reconstruction

New idea —> 4D vertex reconstruction (position + time)

MIP detector : good time resolution(30ps)

Reduction of actual pileup to level of the current LHC possible

Timing Layer can be used to study long lived particles which decay inside the tracker

LLP will reach late ->

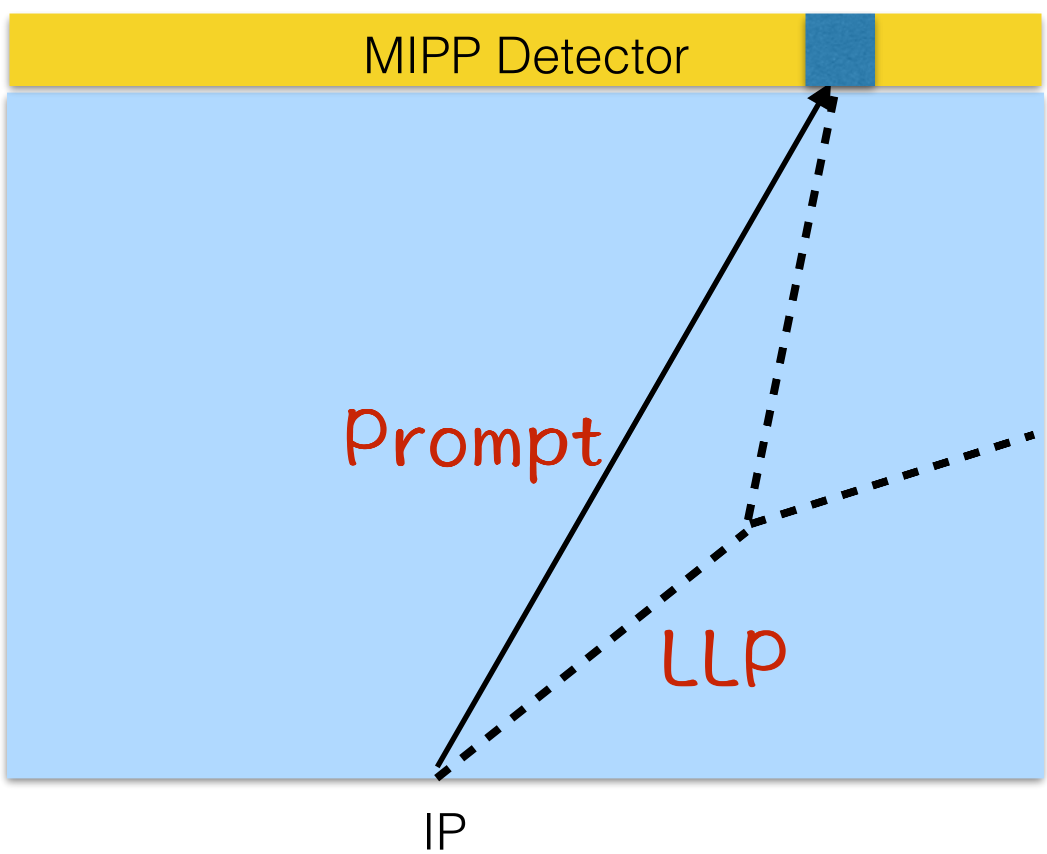
a cut on timing can

separate signal and bkg

Displaced leptons,

converted photons

displaced jets



FASER

LHC can identify particles with pT above a certain threshold → not fully optimal for very light LLP

sub-MeV/GeV LLPs can be produced from the decay of pion, kaon or B mesons

If the coupling of LLP with SM particles is very small

Br(meson) —> LLP will be extremely small

We need huge number of mesons to see LLP from the decay of mesons

Use pp inelastic scattering cross section ~ 100 mb ==> 10^{16}-10^{17} Events

about 10% of the produced pions are in the very forward region

($\delta \sim M_{meson}/E$, E ~ TeV, $\delta \sim$ 2mrad angle wrt beam axis)

Deviation ~ distance * δ ~ a few cm for distance 100 m

A small detector in the very forward direction may identify light LLPs provided the signal can be differentiated from the SM background.

FASER

Technical proposal of FASER: 1812.09139

FASER: ForwArd Search ExpeRiment at the LHC

It will be placed near the ATLAS detector (480m from IP)sensitive to particles that decay in a cylindrical volume with radius R = 10 cm and length L = 1.5 m

March 2019: FASER fully approved by CERN

2019-20: Install FASER will be installed in Long Shutdown 2

2021-23: Collect data in Run 3 with the potential to discover new particles

$pp \to LLP + X$, LLP travels ~ 480 m,
$LLP \to$ charged tracks + X (or $\gamma\gamma + X$)

two oppositely charged tracks (or two photons) with very high energy (~ TeV) from a common vertex inside the detector and combined momentum that points back to the IP

Mathusla

Letter of intent : 1811.00927

MATHUSLA : MAssive Timing Hodoscope for Ultra-Stable neutraL pArticles

HL-LHC will produce ~ 10^8 Higgs bosons

Consider H-> LLP LLP

Number of X decays within the detector volume ~ Nh * Br(h->LLP) * $\varepsilon_{geometric}$ * L/(b cτ)

$\varepsilon_{geometric}$ = geometric acceptance

L= length of the detection in the direction of LLP decay

b= boost factor ~ 2-3 for M_{LLP}=20 GeV

For N_{obs} ~ 3 LLP decay events at the MATHUSLA when cτ ~ 10^7 m, if

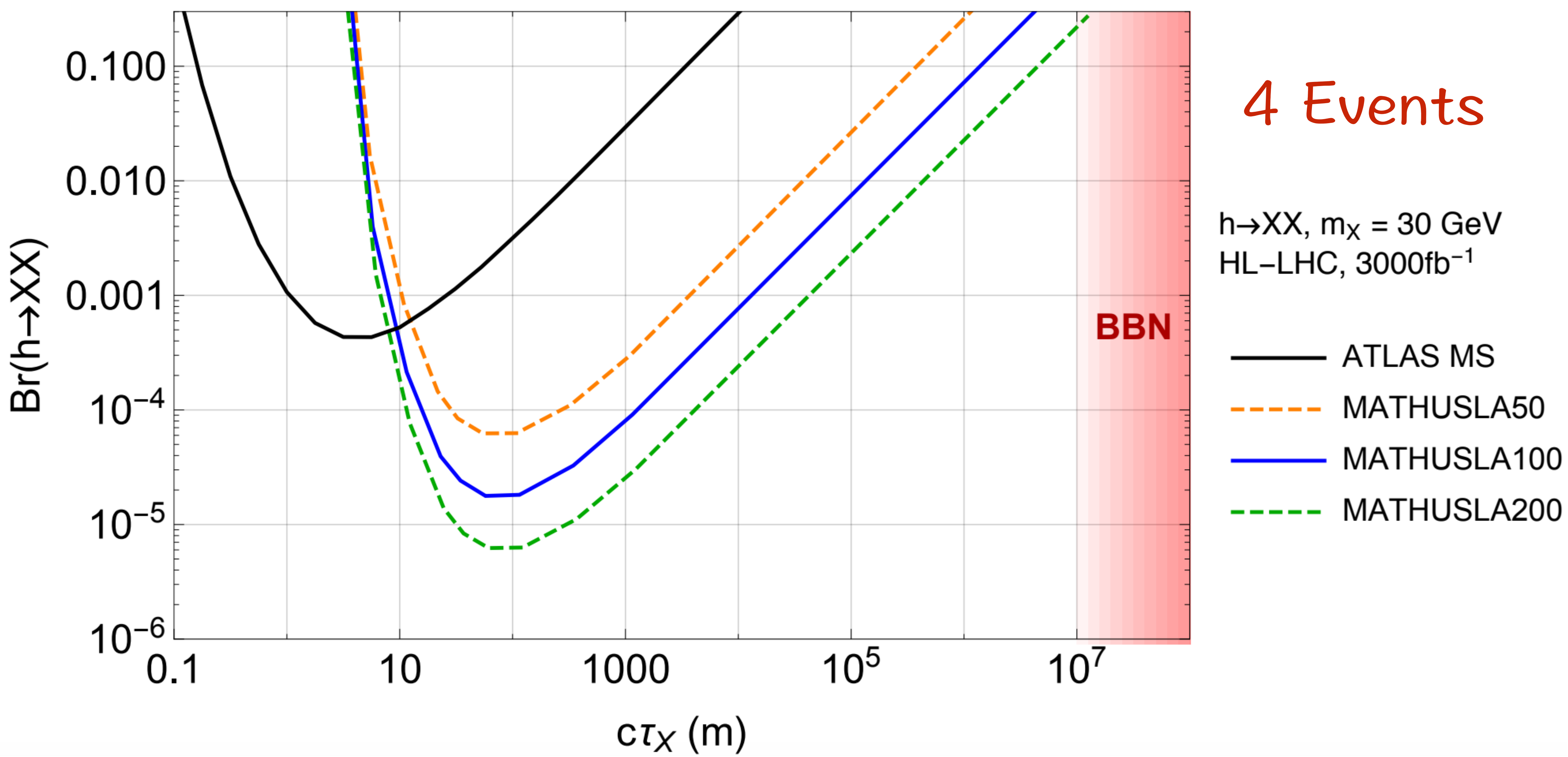
L ~ 20 m and $\varepsilon_{geometric}$ ~ 10%

in order to achieve $\varepsilon_{geometric}$ ~ 10% at at a distance ~ 100 m ,

we need ~ 100X100 m^2 detector

Mathusla

Letter of intent : 1811.00927



4 Events

proposed place near CMS detector (~68 m from IP)

studies on Optimal detector material undergoing

Many Other experiments sensitive to LLPs

NA62: fixed target kaon experiment at CERN with 400 GeV Proton beam

Kaon-> pi + pi0 , pi0-> gamma + dark photon(LLP)

65 m tunnel for decay, Peak searches in the missing mass spectrum

NA62++ upgrade

CODEX-B: near LHCB,

underground, 10 × 10 × 10 m box, around 25 m from LHCb.

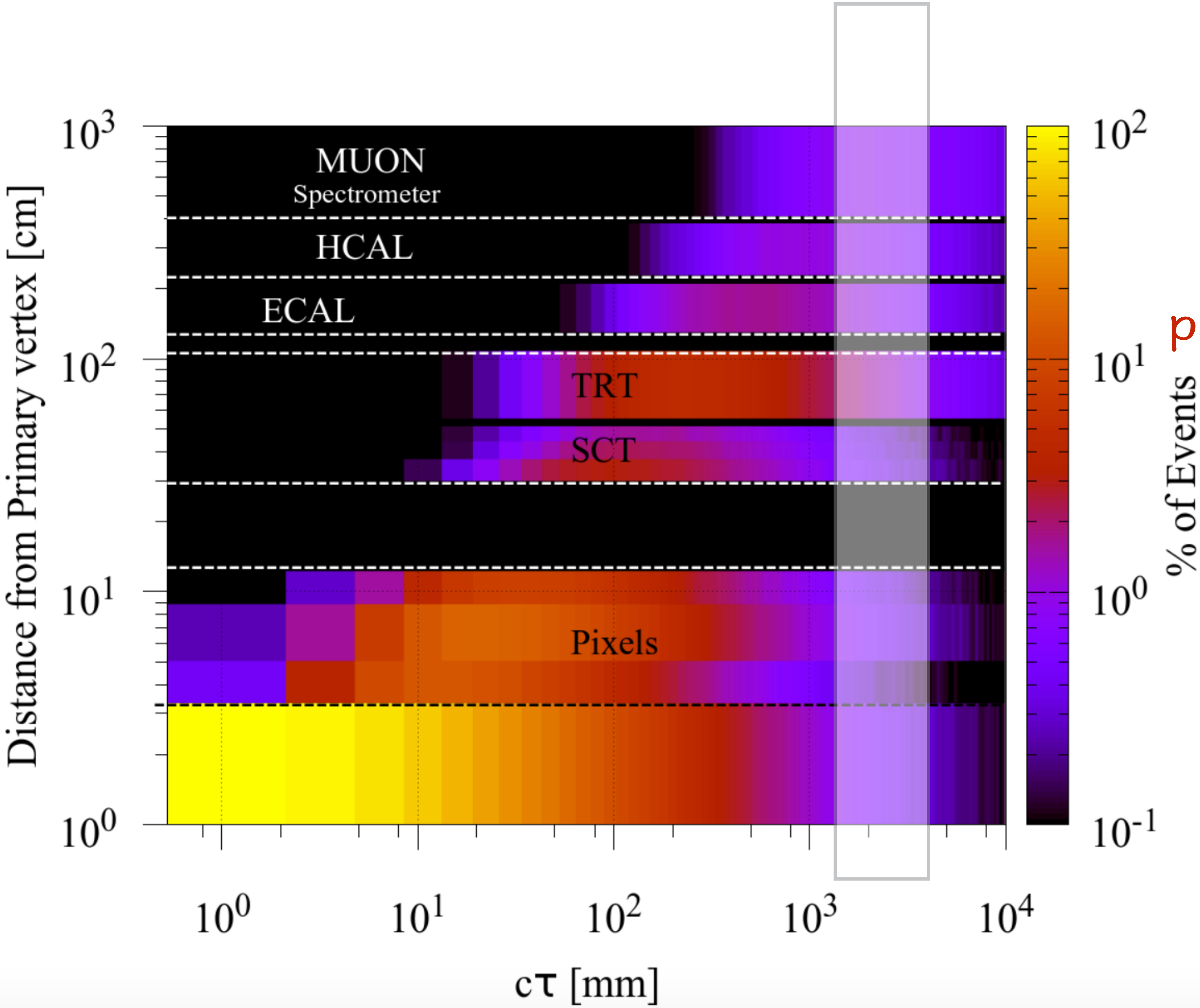
RPC tracking layers B-> K phi-> l+l- (complementary to LHCb)

Neutrino detectors, ShiP, ……

Combination of different signatures

1811.09195

PP -> H125 -> LLP LLP



We expect small number of events in each part of the detector for high lifetime

Combination of different search methods may give the most stringent limits

Conclusion

Long lived particles : Predicted in many well motivated BSM Models

Many unusual signatures: Challenging for LHC searches

Two striking features identified:

backward moving particles and Distortion in the energy deposits

Our first attempt to understand the energy deposition patten of LLP decaying to jets using image recognition techniques

Delphes simulation will not capture the effect

Several improvements and directions identified : work in progress

Dedicated methods are required for HL-LHC searches (including trigger developments)

Many dedicated approved (proposed) experiments for Long lived particles

STAY TUNED

BACKUP

Is everything consistent ?

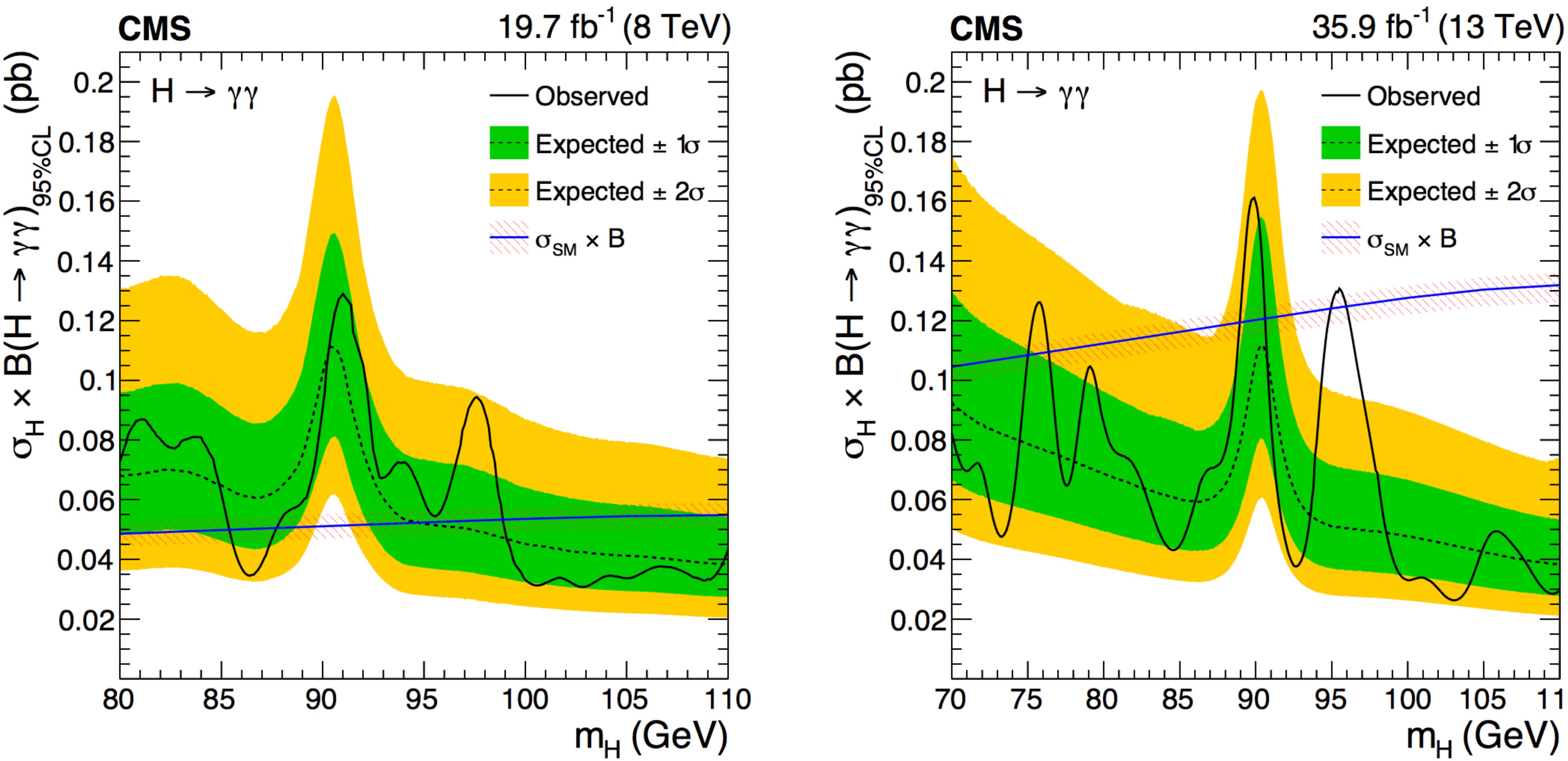
Some of the Collider anomalies
My watch list

Warning: may be just statistical fluctuations !!

CMS low mass di-photon search below 110 GeV

1811.08459

$$pp \to \gamma\gamma$$



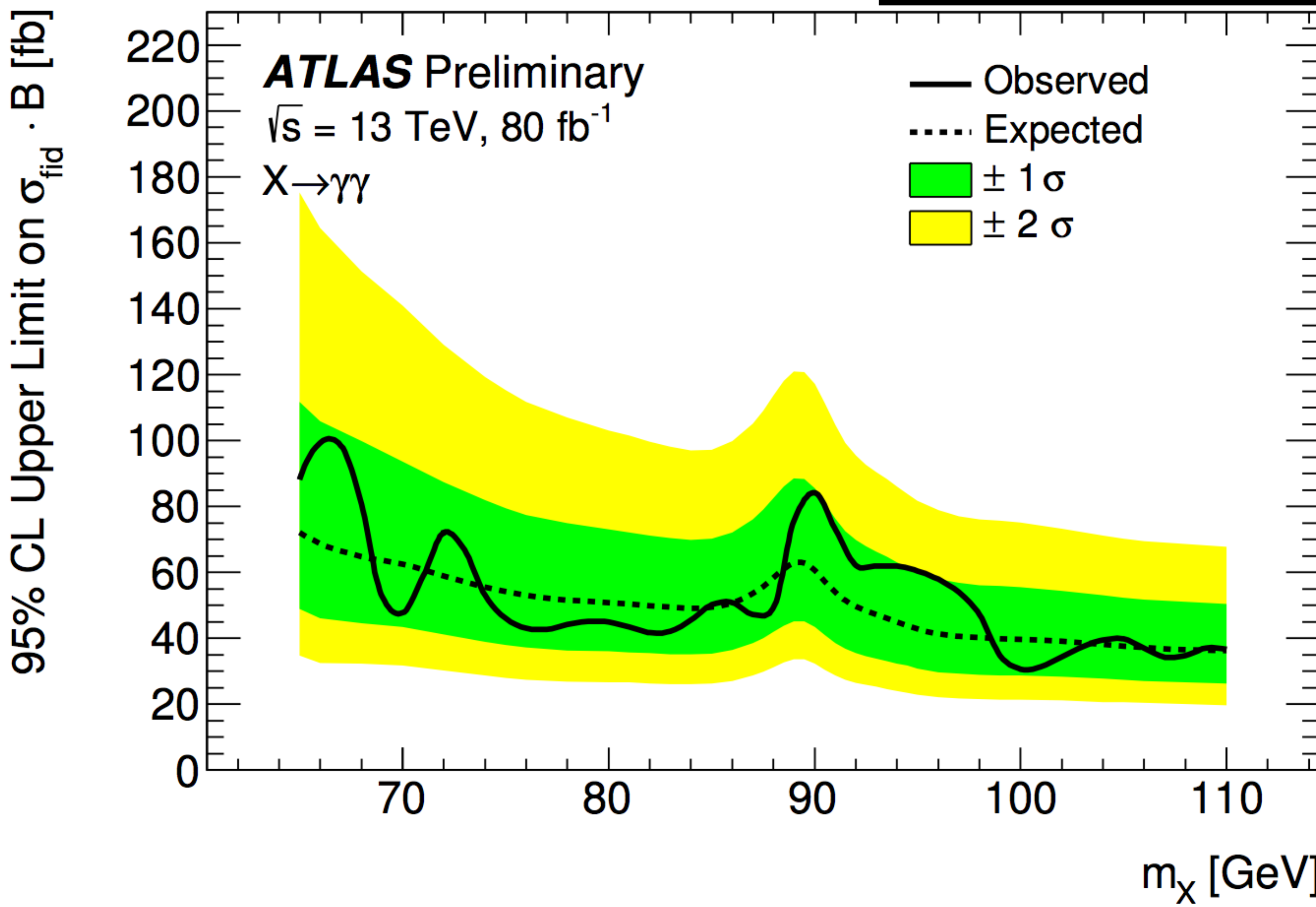
Run I : local excess ~ 2σ

Run II : local excess ~ 3σ

ATLAS di-photon search below 110 GeV

$$pp \to \gamma\gamma$$

ATLAS-CONF-2018-025



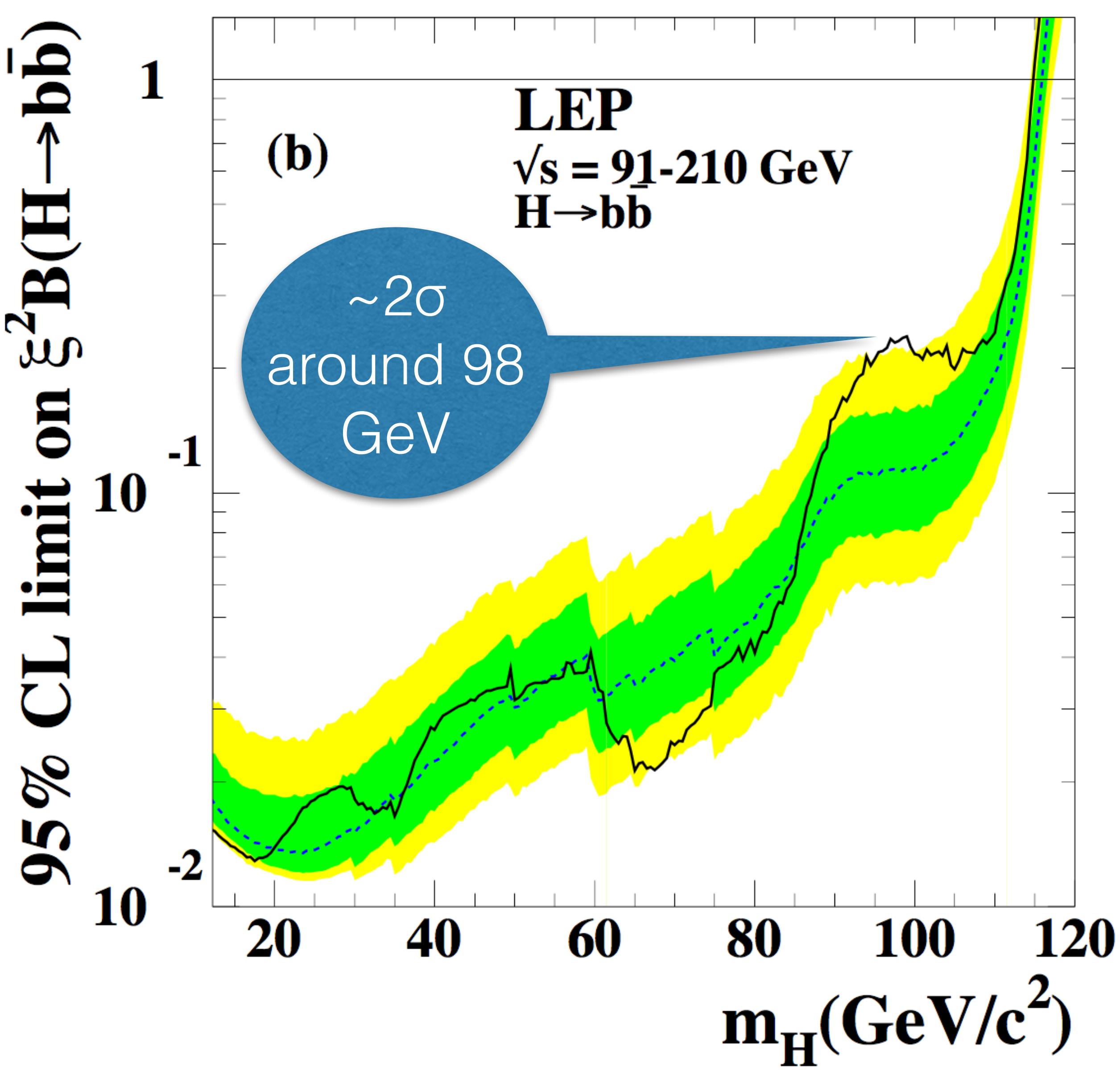
LEP anomaly around 100 GeV

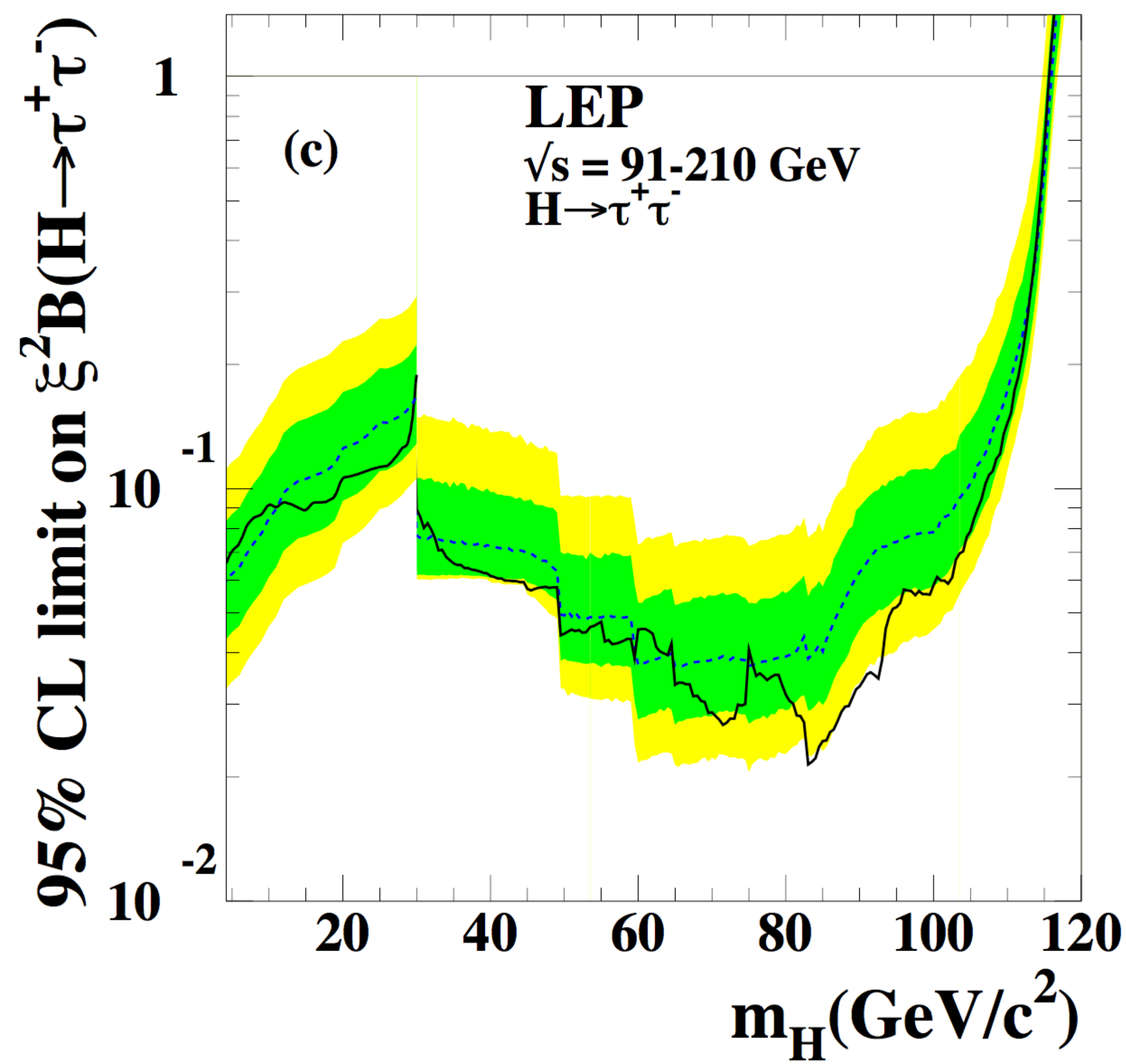
LEP Higgs working group

$$e^+e^- \to Zh$$

$$\xi^2 = (g_{\mathrm{HZZ}}/g_{\mathrm{HZZ}}^{\mathrm{SM}})^2$$

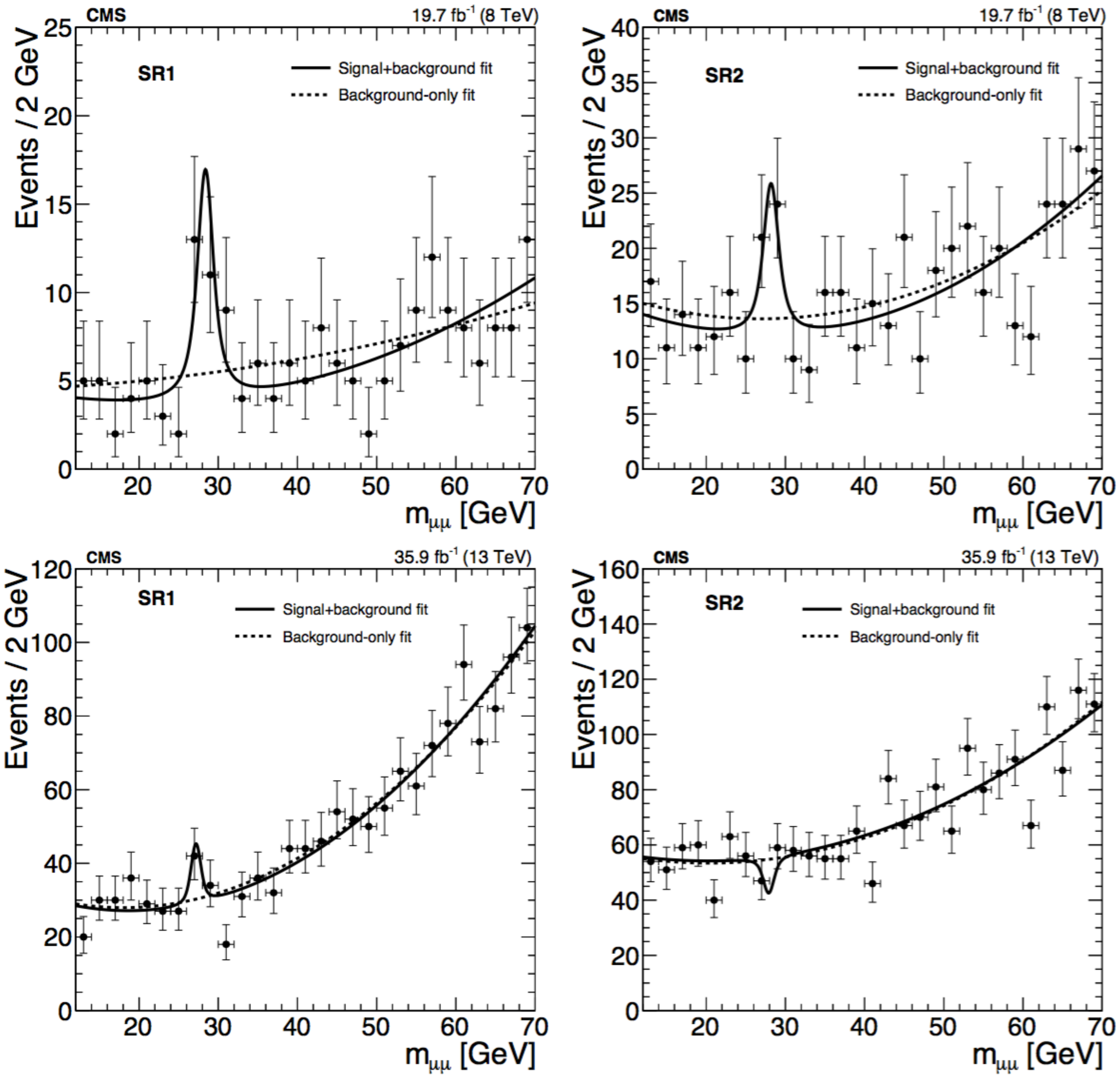
hep-ex: 0306033





CMS di-muon resonance search

1808.01890



An excess near a dimuon mass of 28 GeV in the 8 TeV data:

local significances of 4.2(category I) and 2.9 standard

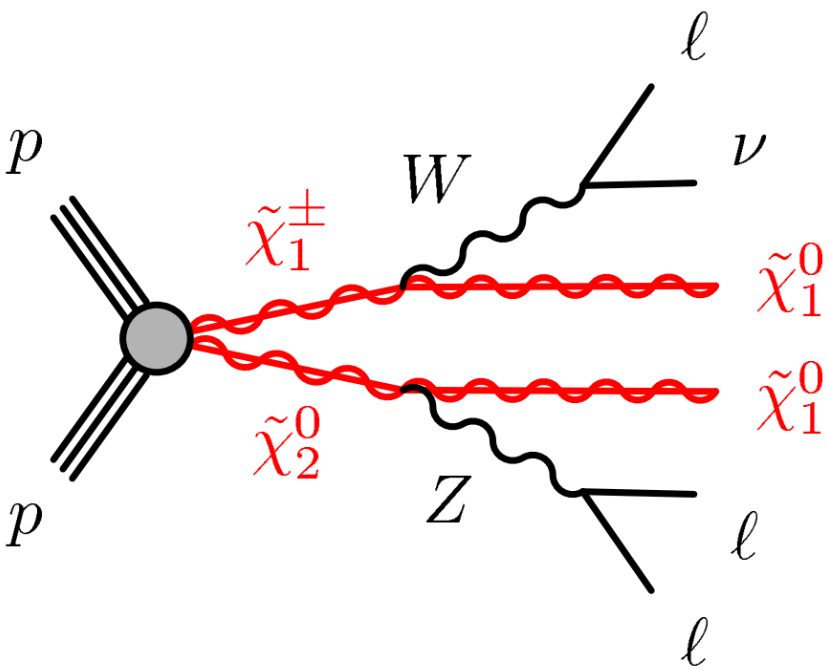
deviations for the category II

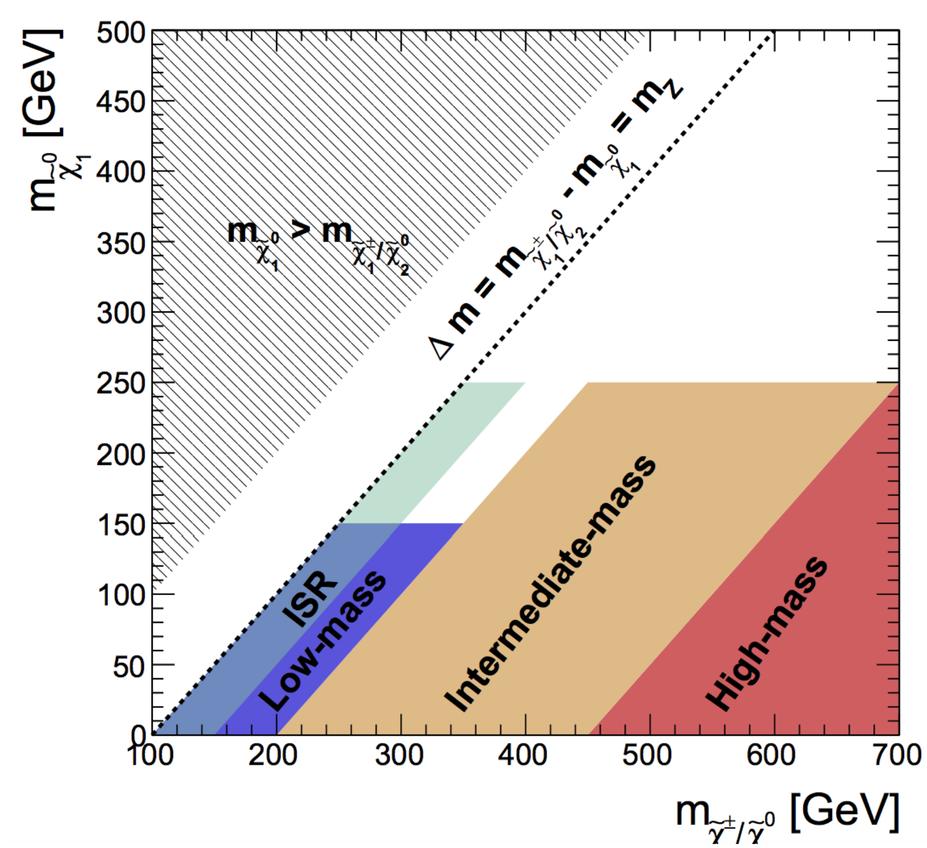
<u>13 TeV data :</u>

a mild excess in the category I (local significance of 2.0 standard deviations) second category results in a 1.4 standard deviation deficit.

ATLAS Electrowikino searches

1806.02293





An excess of events above the background estimate is observed in each of the four low-mass and ISR signal regions

Table 16: Expected and observed yields from the background-only fit for the 3ℓ SRs. The errors shown are the statistical plus systematic uncertainties. Uncertainties in the predicted background event yields are quoted as symmetric, except where the negative error reaches down to zero predicted events, in which case the negative error is truncated.

Signal region	SR3ℓ_High	SR3ℓ_In	SR3ℓ_Low	SR3ℓ_ISR
Total observed events	2	1	20	12
Total background events	1.1 ± 0.5	2.3 ± 0.5	10 ± 2	3.9 ± 1.0
Other	$0.03^{+0.07}_{-0.03}$	0.04 ± 0.02	$0.02^{+0.34}_{-0.02}$	$0.06^{+0.19}_{-0.06}$
Triboson	0.19 ± 0.07	0.32 ± 0.06	0.25 ± 0.03	0.08 ± 0.04
Fit output, *VV*	0.83 ± 0.39	1.9 ± 0.5	10 ± 2	3.8 ± 1.0
Fit input, *VV*	0.76	1.8	9.2	3.4