Long-lived particles: Current Status and Challenges
(From the point of view of a theorist)

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Saha Institute of Nuclear Physics, Kolkata
14th December 2023

Physics beyond the standard model

The next goal of the LHC after the Higgs discovery is to find new physics beyond the standard model(BSM).

Many possibilities: extended symmetry, new particles, new interactions..

.. and a large number of possible signatures.

Broad Signature based Classification

Resonance searches: peak in the di-photon, di-lepton, di-jet, multi-jet invariant mass distribution, merged objects etc.

Dark matter: mono jet/V + MET + resonance searches of mediator

SUSY/Extra Dimensions: multij-et+ multi-lepton + photon with or without MET etc.

Null results from different experiments put stringent limits on the BSM parameter space

Physics beyond the standard model

Many BSM models and a large number of possible signatures

No hint of BSM physics so far ..

Where is BSM physics hiding ?

Physics beyond the standard model

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Where is BSM physics hiding ?

<u>Three Possibilities:</u>

- BSM particles are very heavy ➔ Not accessible at the LHC
- BSM particles are just above the current limit ➔ LHC will discover soon
- New particles are within the reach of LHC ➔ search methods are not very sensitive

Are we missing something ??

Long-lived Particle (LLP)

Nature of the new physics is completely unknown
Probably very unconventional, exotic final states

Not yet searched for ?
Experimentally challenging ?

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One such interesting possibility : Long-lived particles(LLPs)

Presence of LLP is not unnatural

Many long-lived particles are present in our world

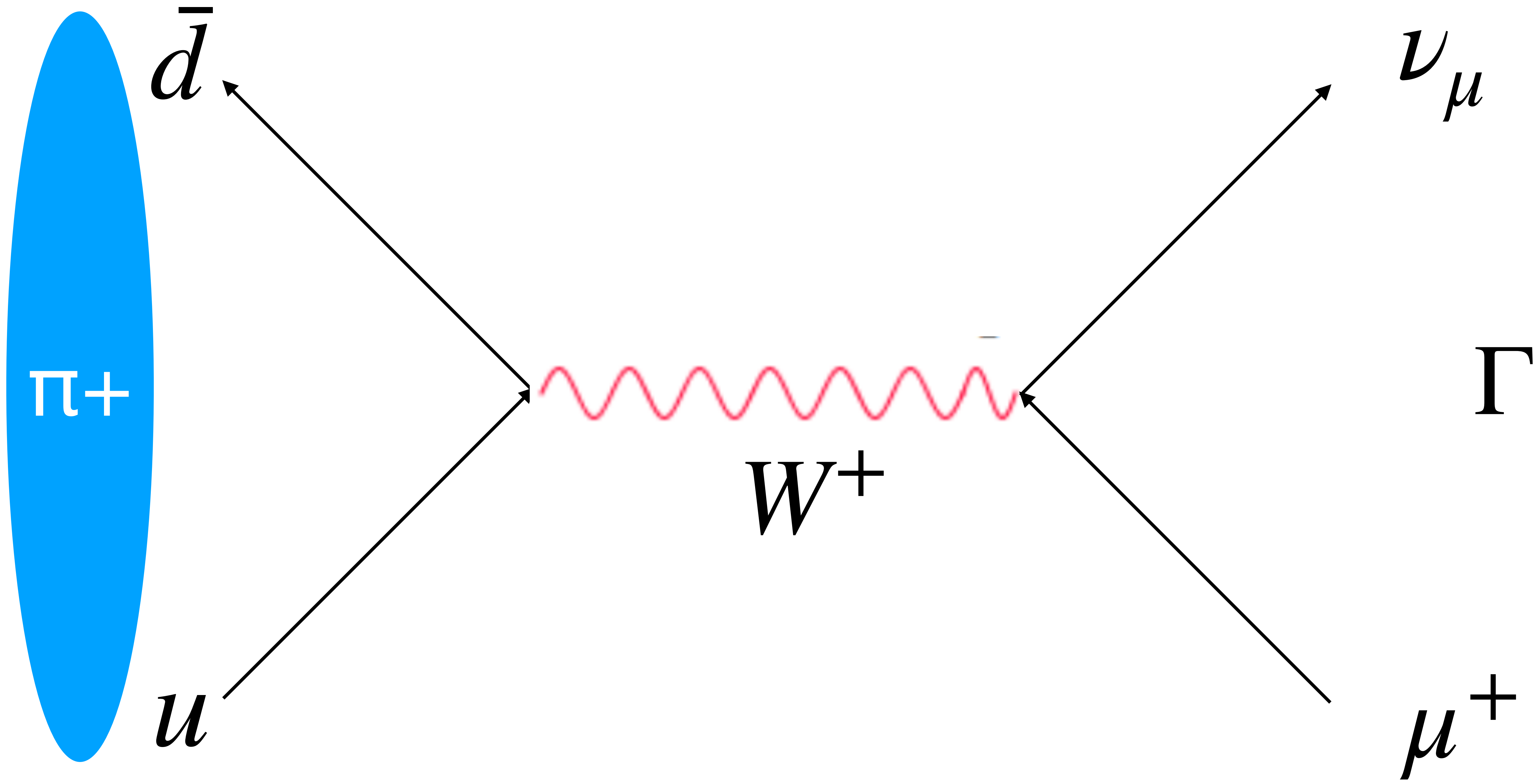
Particle	Lifetime
Muon	2.2 picosecond
Proton	> 10^{30} year
Neutron	878 second
B+	1600 femtosecond
π+	26 nanosecond

LLPs in the SM

Why are they long-lived?

Reason 1 : Heavy particle propagator

Pion decay in the SM



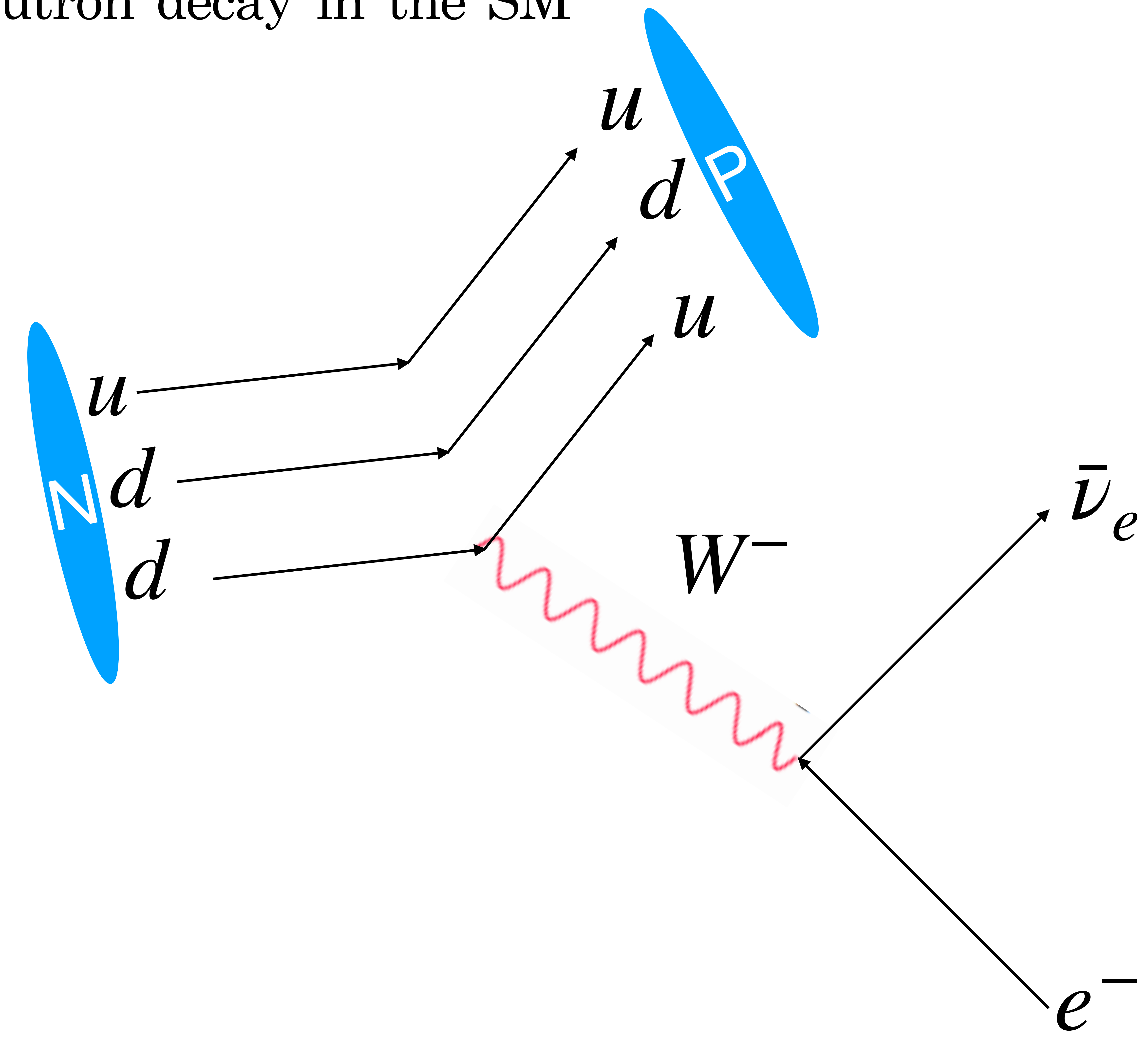
$$\Gamma \sim \frac{m_\pi^5}{m_W^4}$$

Huge suppression from the W boson propagator !

Why are they long-lived?

Reason 2 : Phase space suppression

Neutron decay in the SM



LLPs in SM

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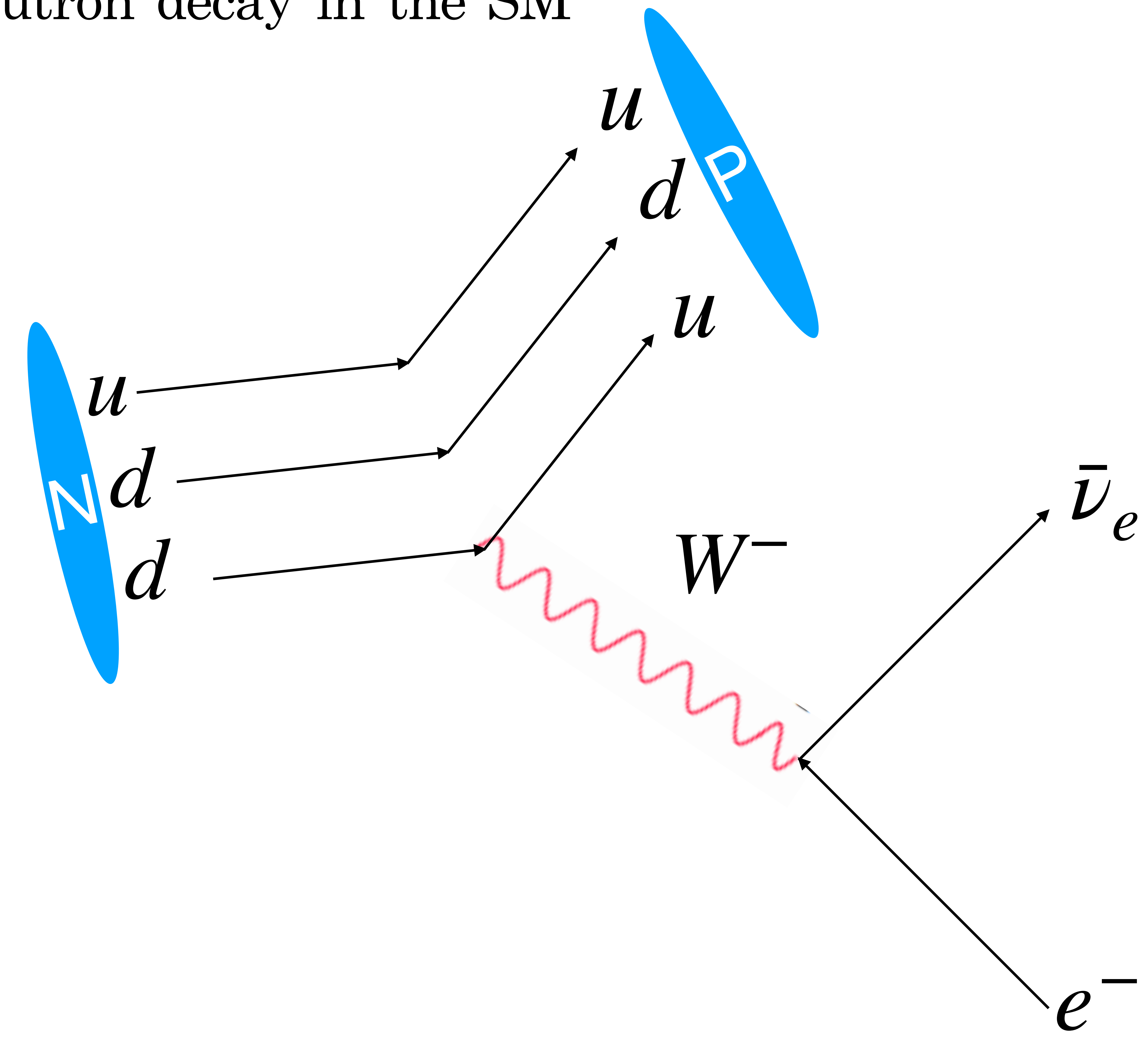


$$\Delta = M_n - M_p \sim 1.3 \text{ MeV}$$

Decay is highly phase space suppressed

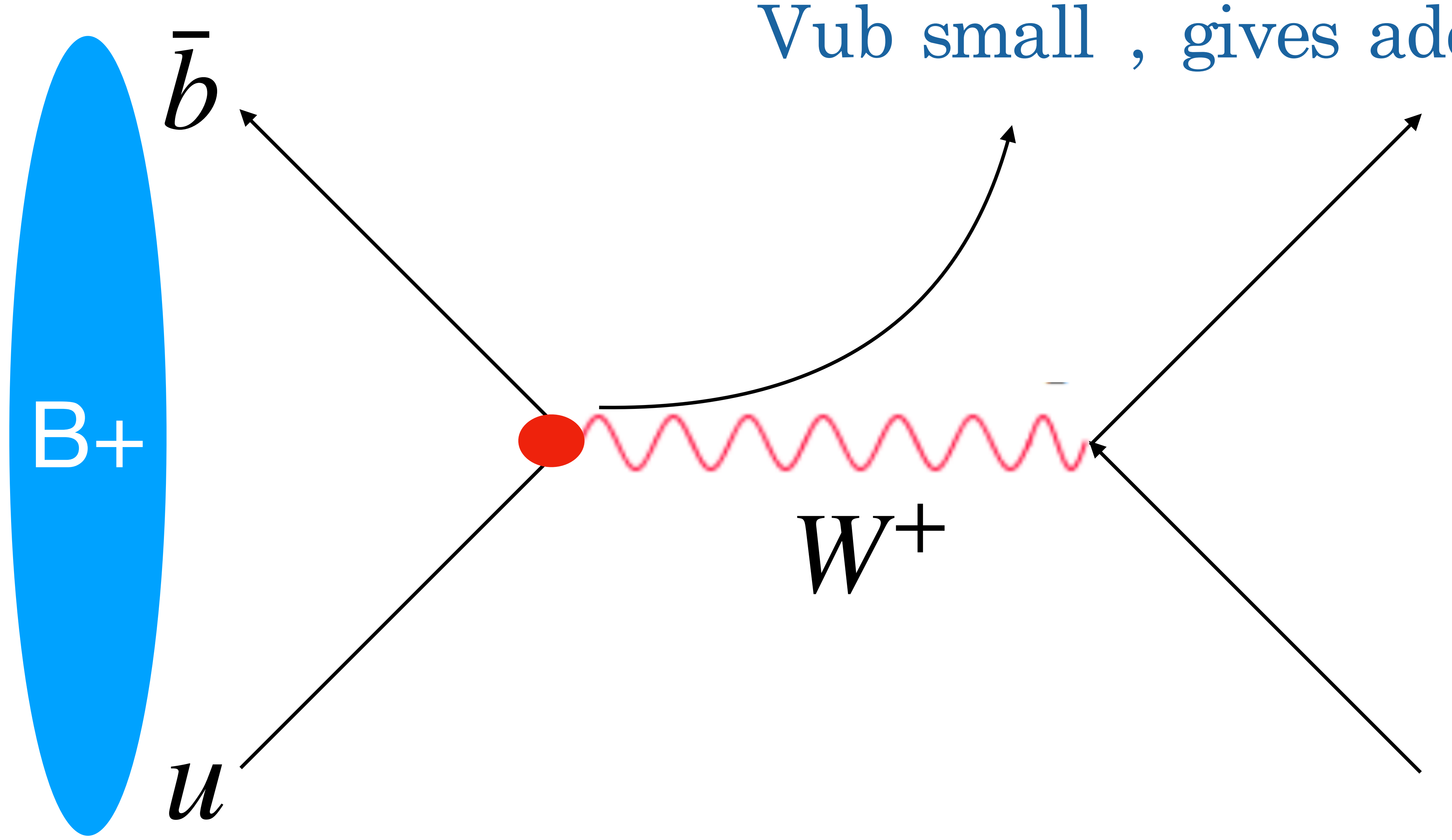
LLPs in SM

Why are they long-lived?

Reason 3 : Small coupling

B+ decay in the SM

Vub small , gives additional suppression



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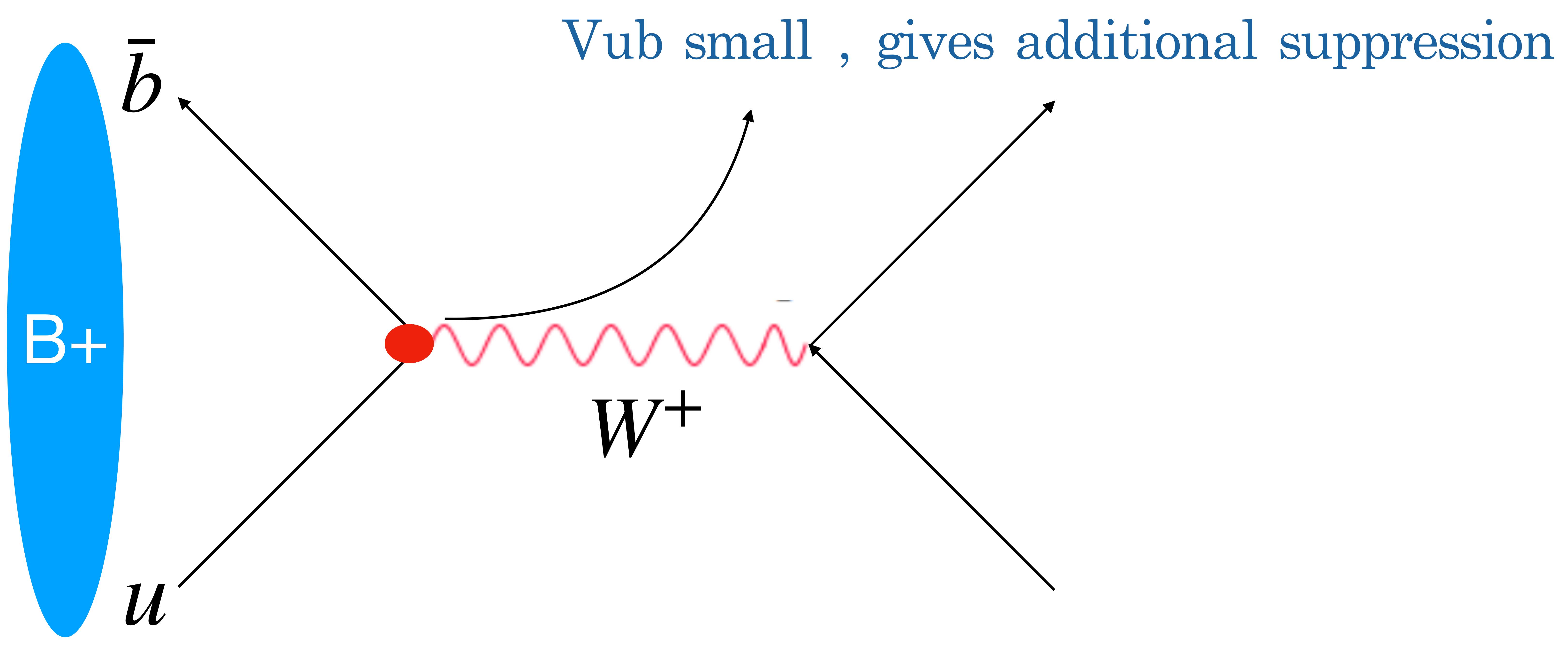
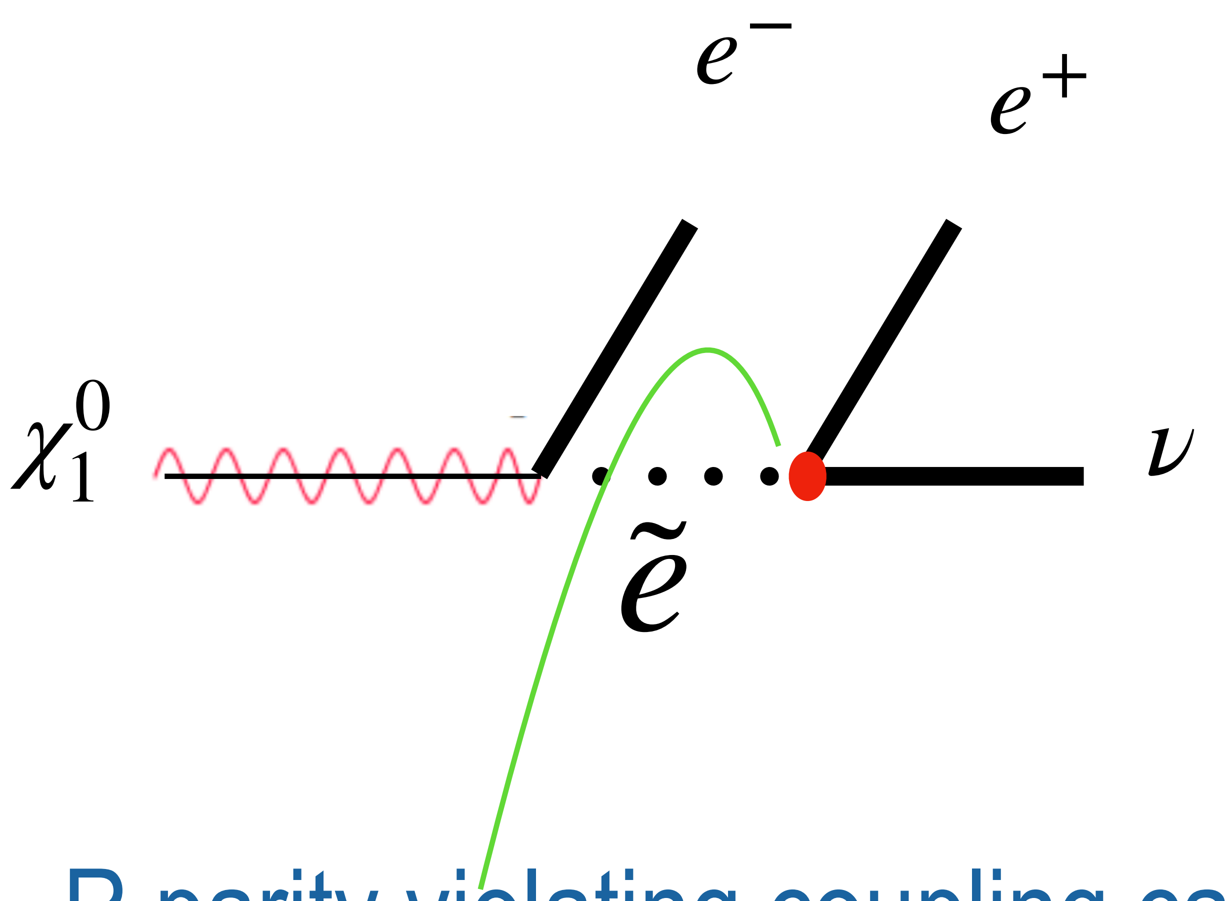


LLPs in BSM

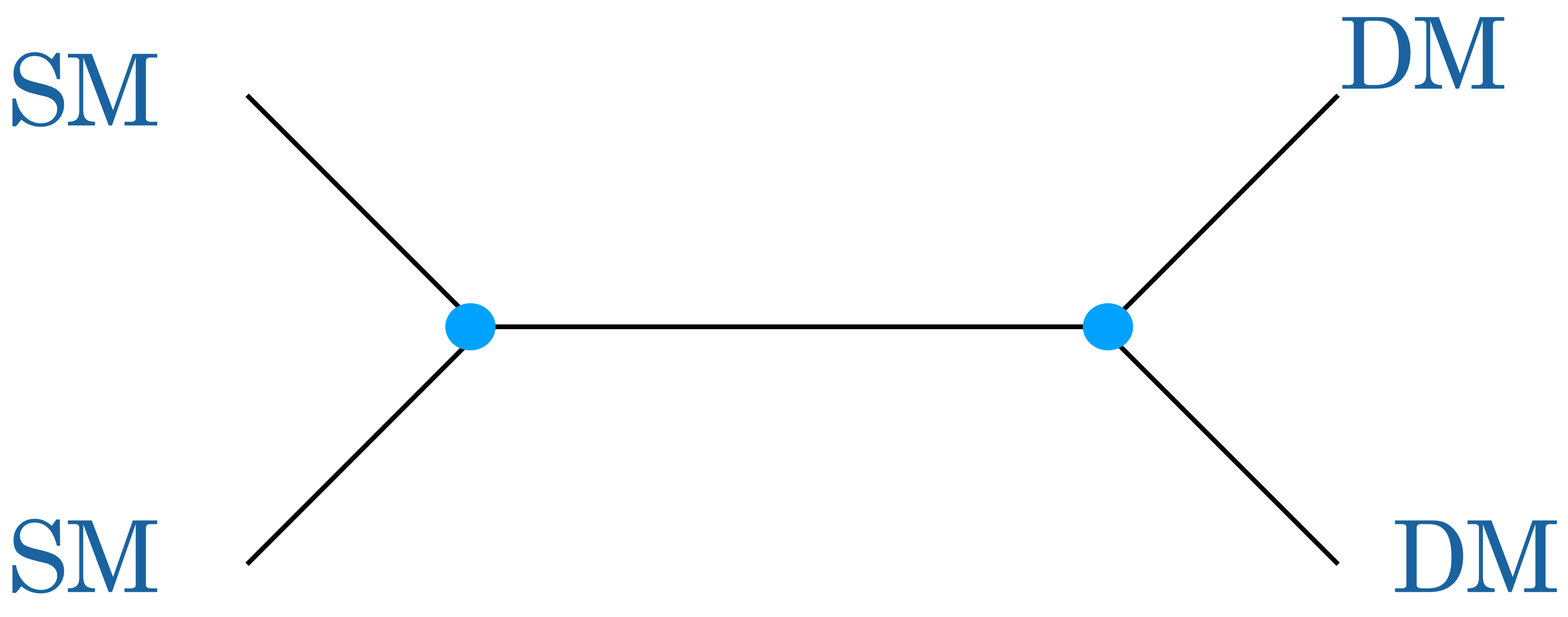
Case 1: Small Coupling

$$\chi_1^0 \rightarrow e^- e^+ \nu$$



R parity violating coupling can be
Arbitrarily small

Freeze-in Dark Matter



Typical Coupling strength ~ 10^{-12} or less

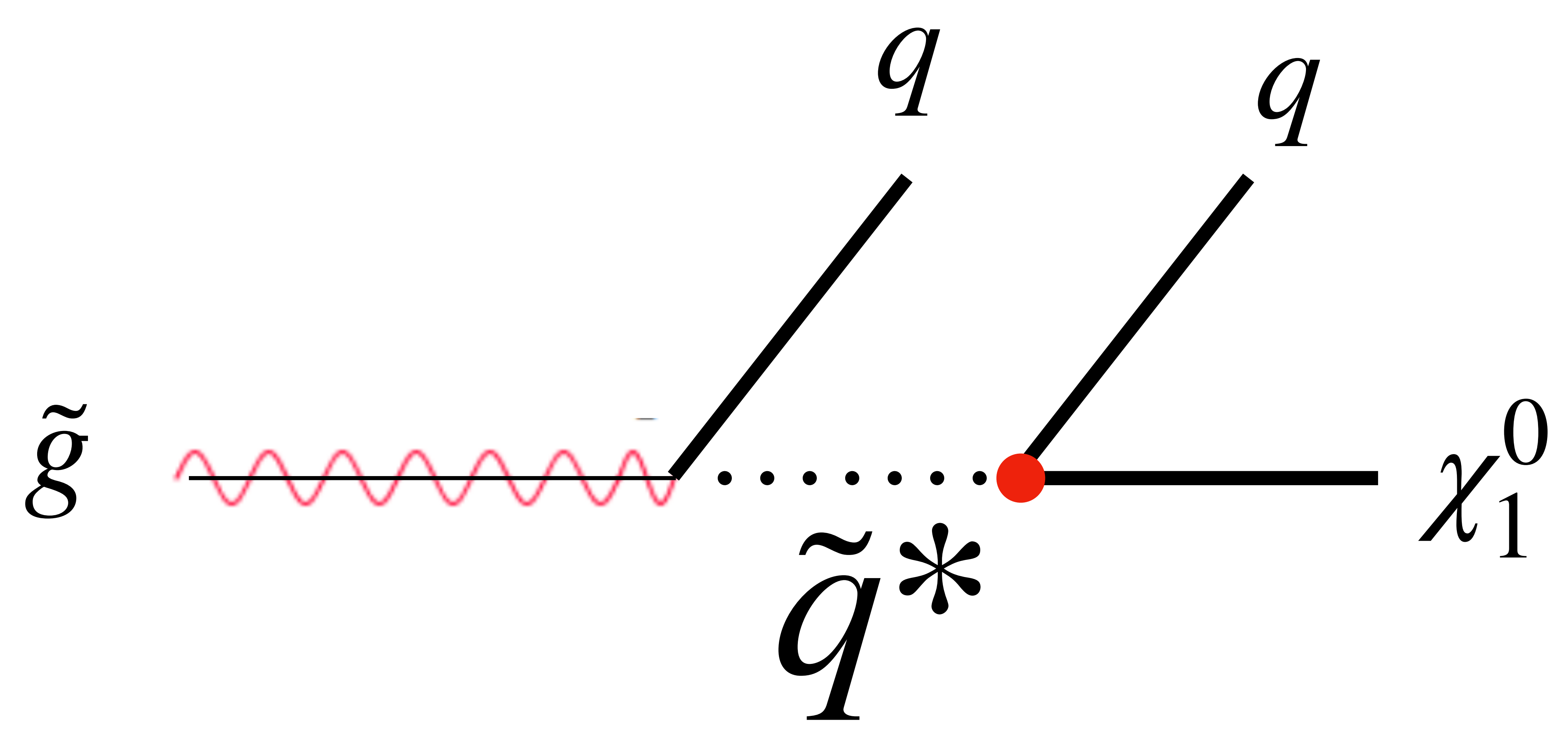
Many final states are possible depending on the spectrum and the type of coupling

$\tilde{g} \rightarrow jjj$ [Gluino LSP, λ'' coupling] $\chi_0^1 \rightarrow \gamma/Z+$Gravitino $[GMSB]$

And many other possibilities

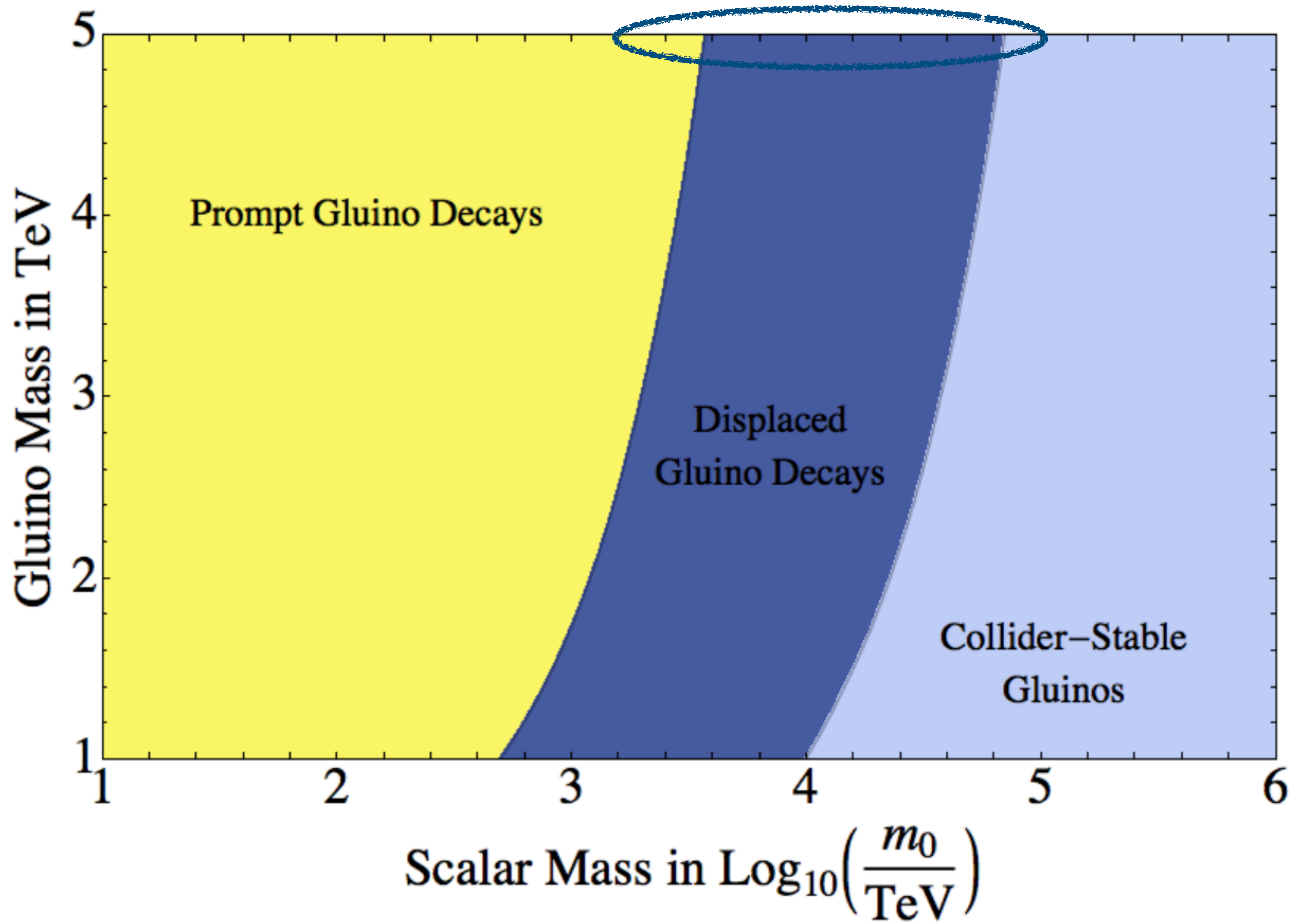
Case 2: Heavy propagator suppression

$$\tilde{g} \rightarrow q\bar{q}\chi_1^0$$



$$\Gamma \sim \frac{m_{\tilde{g}}^5}{m_{\tilde{q}}^4}$$

Decay length 100 μm to 10 m



MINI-SPLIT
A.Arvanitaki, N. Craig, S. Dimopoulos,G. Villadoro
1210.0555(hep-ph)

If the Decay width of the gluing exceeds Λ_{QCD} , it will form R-hadron (M. Chanowitz, S. Sharpe Physics Letters B 1983)

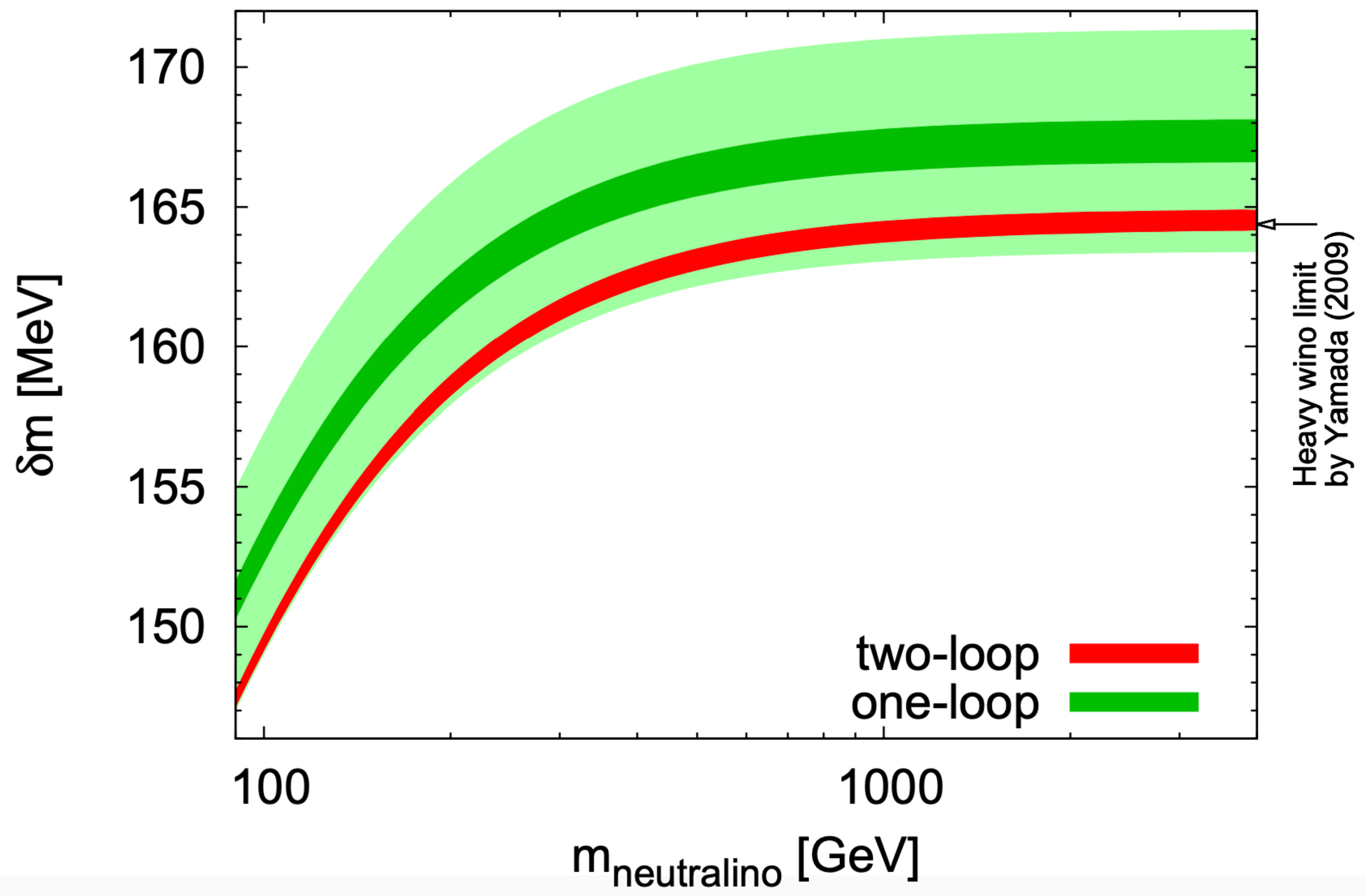
ATLAS Public note: ATL-PHYS-PUB-2019-019

Case 3: Phase space suppression

MSSM with neutral wino as the lightest supersymmetric particle

Charged wino becomes heavier than the neutral wino because of electroweak radiative corrections

For pure wino case



$$\Delta M = M_{\tilde{W}^{\pm}} - M_{\tilde{W}^{0}} \sim 160 \textbf{ MeV}$$

Mass splitting between charged and neutral winos at two-loop level
M. IBe, R. Sato, S. Matsumoto 1212.5989(hep-ph)

The decay modes are

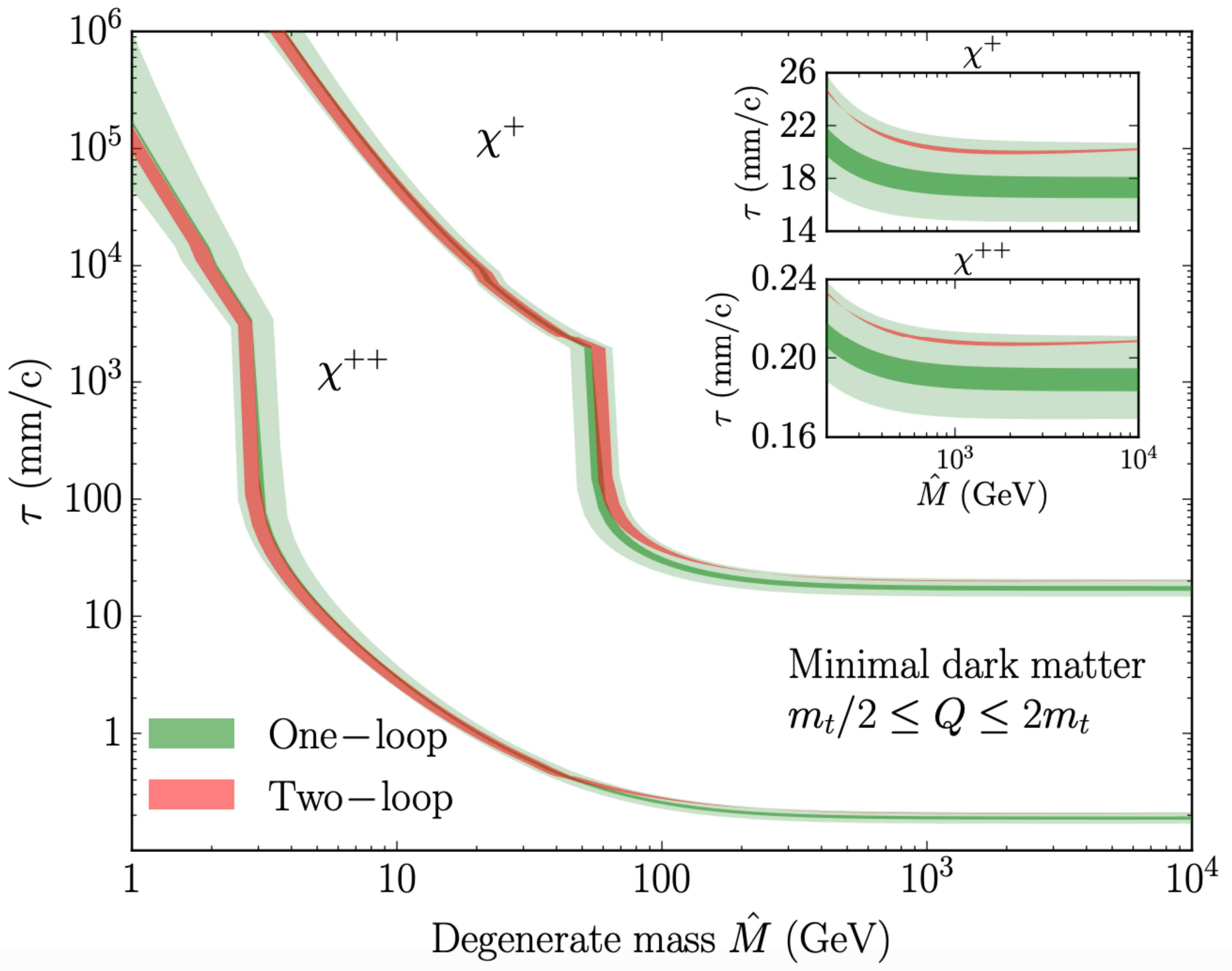
$$\chi^{\pm} \rightarrow \chi^{0} + \pi^{\pm}$$

$$\chi^{\pm} \rightarrow \chi^{0} + l^{\pm} + \bar{\nu}_{l}$$

One loop correction to the decay width is not very significant(2-4%)

Precise Estimate of Charged Wino Decay Rate M. IBe, M. Mishima, Y. Nakayama and S. Shirai arXiv: 2210.16035

Minimal dark matter M. Cirelli, N. Fornengo, A. Strumia hep-ph: 0512090



For pure wino , the
Decay length can be ~ a few cm

For higgsino, mass difference can be
higher => The length of the track is smaller

$$\Delta M = M_{\tilde{W}^\pm} - M_{\tilde{W}^0} \sim 160 \text{ MeV}$$

Two-loop mass splittings in electroweak multiplets: winos and minimal dark matter James McKay and Pat Scott 1712.00968(hep-ph)

Dark Sectors

Standard Model

Dark Sector

Dark Sectors

The dark sector particles are singlet under SM gauge groups

Dark sector particles talk to the SM particles through a portal

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The dark sector particles are singlet under SM gauge groups
Dark sector particles talk to the SM particles through a portal

Lowest dimensional operator

Vector Portal: $\epsilon B^{\mu\nu} X_{\mu\nu}$

Scalar Portals: $\kappa(H^\dagger H)S + \lambda(H^\dagger H)S^2$

Neutrino Portal: $yHLN$

Higher dimensional operator also possible

ALP: $\epsilon a F^{\mu\nu} \tilde{F}_{\mu\nu}$

The new couplings can be very small in principle

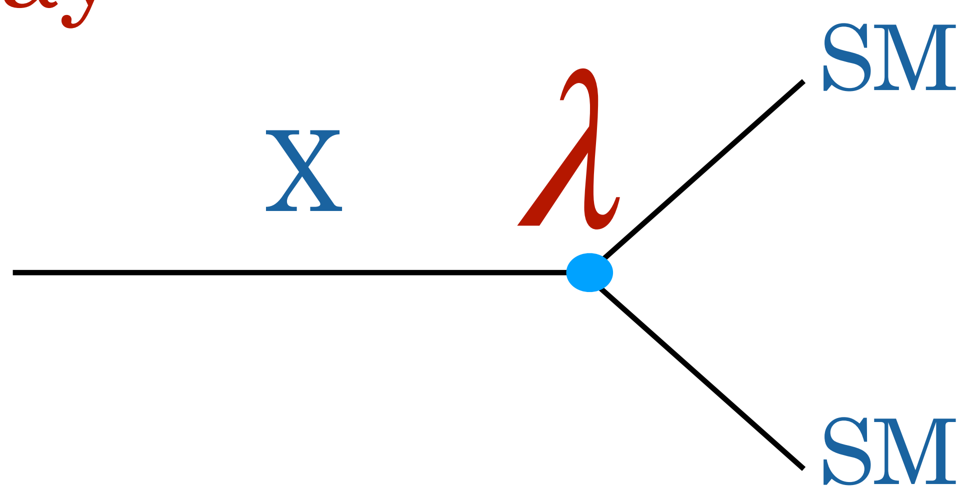
Possibility of Small Decay width

LLPs!!

Recent survey: Exploring Dark Sector Portals with High Intensity Experiments
B. Batell, N. Blinov, C. Hearty, R. McGehee arXiv:2207.06905

LLP production

Decay

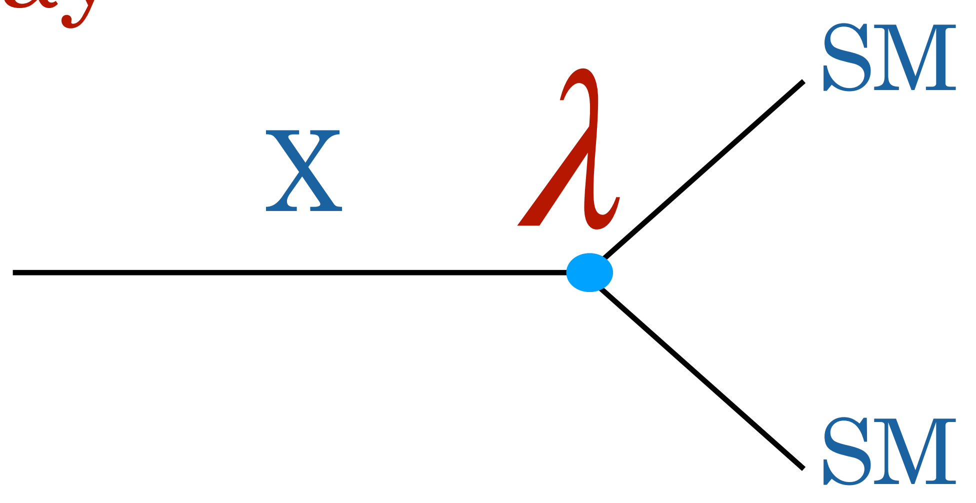


Suppose the coupling λ is small: X is LLP

Easy to make X an LLP

LLP production

Decay



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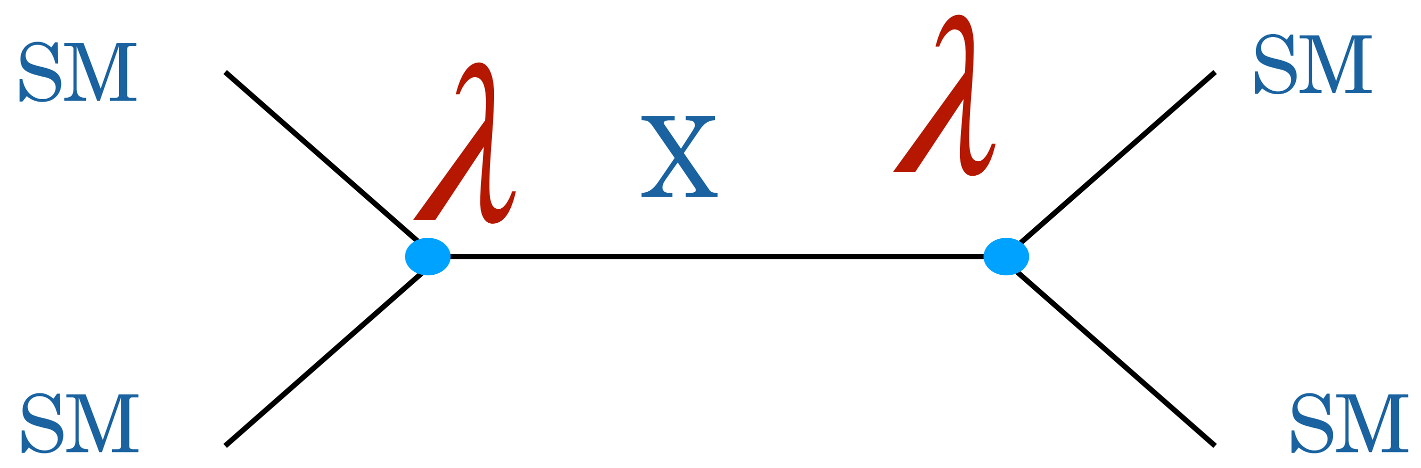
Production mode



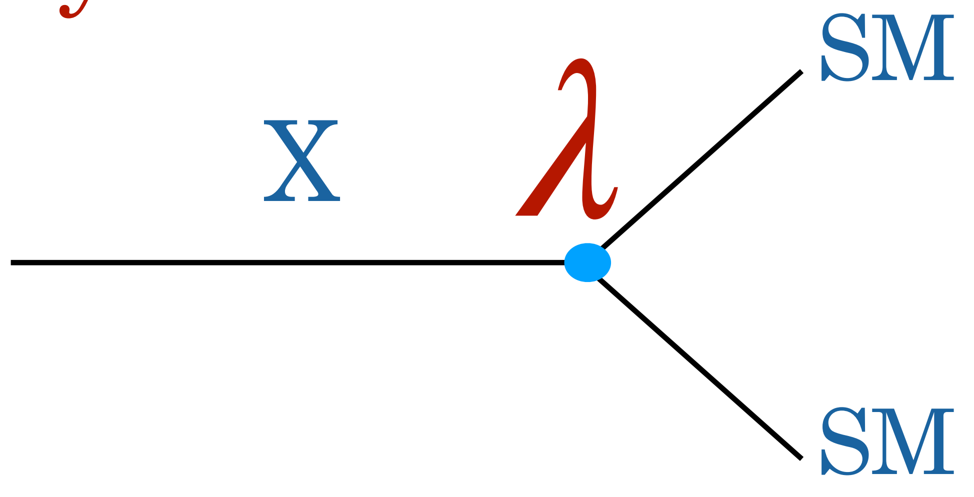
Single production cross section $\propto \lambda^4$

For very small coupling X will have high decay length and small cross section

"High" and "small" will depend on the process and the detector

LLP production

Decay



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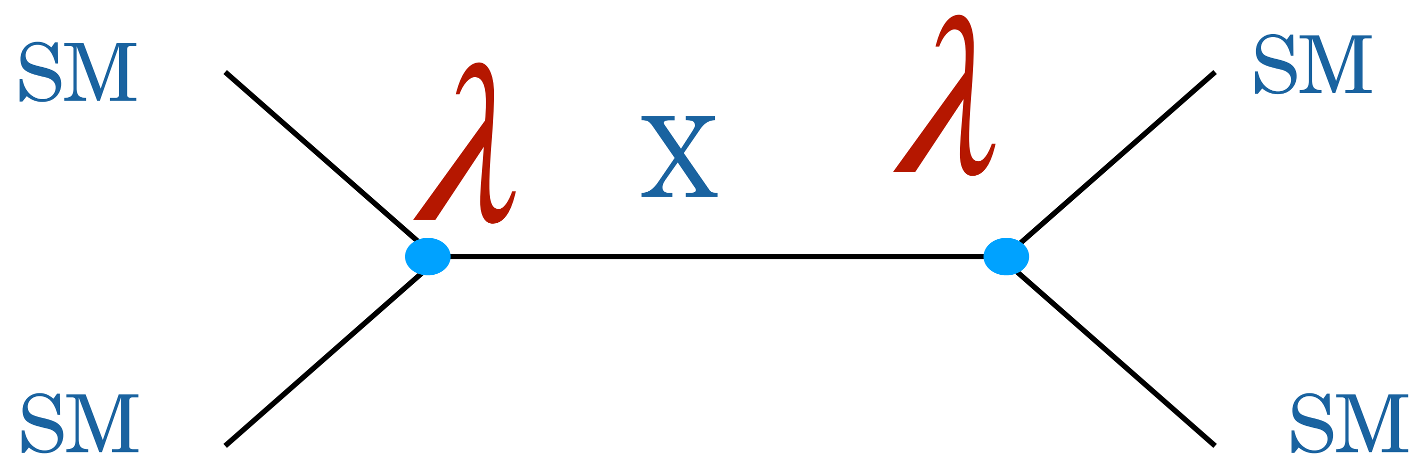

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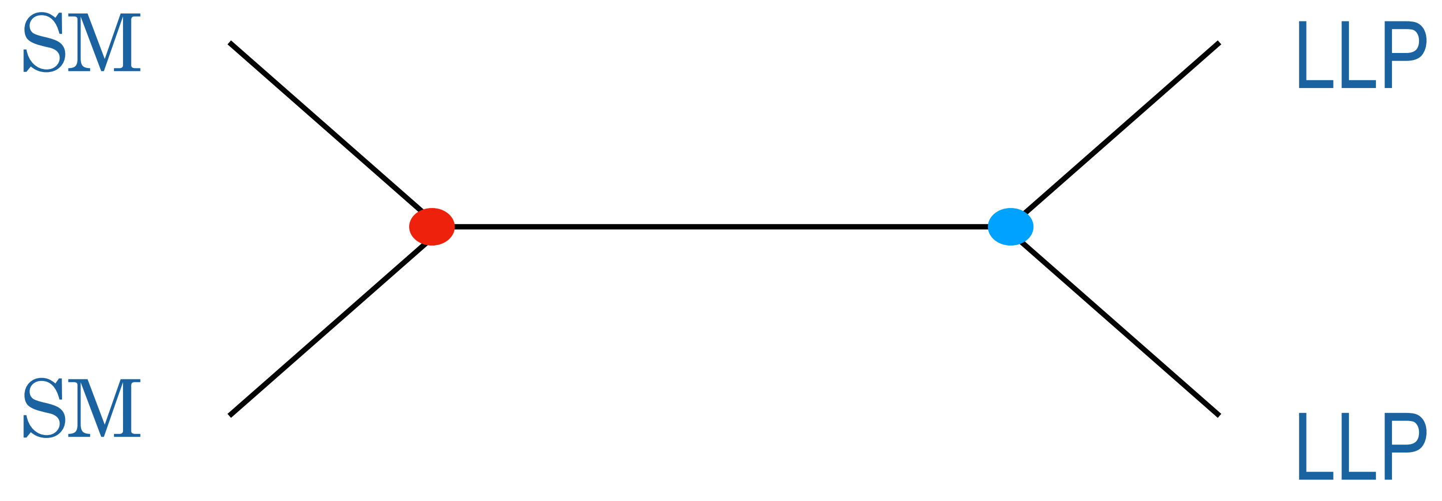
Other possibilities

LLP may come from the decay of SM or other BSM particles, we are using two different couplings



Single production of LLP is suppressed but not the pair production

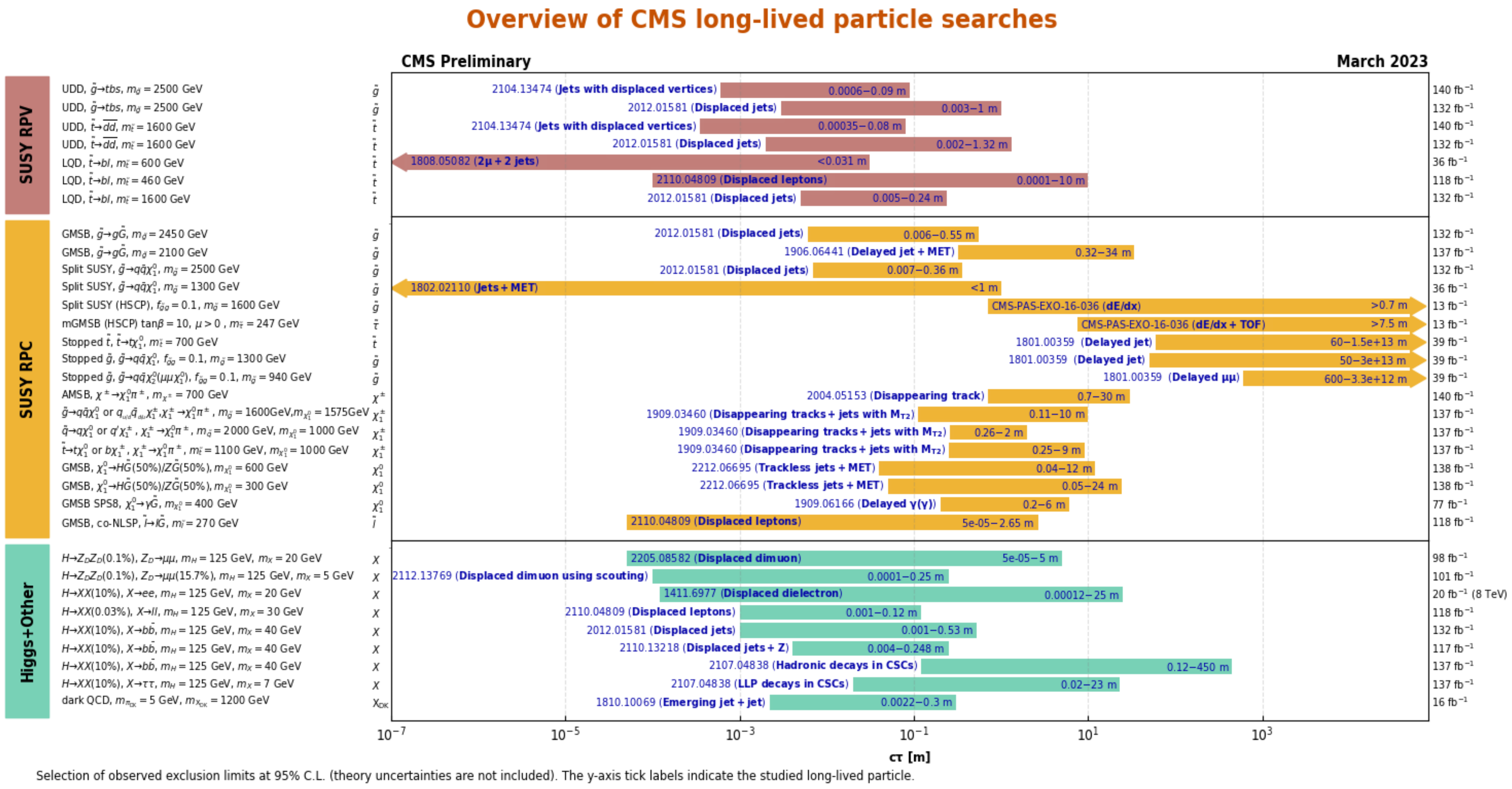
$$\chi^{\pm} \to \chi^{0} + \pi^{\pm}$$

No suppression in the coupling, LLP decay length is small because of the phase space suppression

In most of the models, mass and lifetime of the LLP is not fully bounded !

LLP searches in Experiments

Similar efforts from ATLAS, LHCb.. LLP white paper, dedicated conference on LLPs



CMS Summary plot

LLP simulation and interpretation is not straightforward for theorists

Simple example

Example 1 : Displaced vertex

$$pp \to XX,\ X_{LLP} \to e^{+}e^{-}$$

X is the long-lived particle

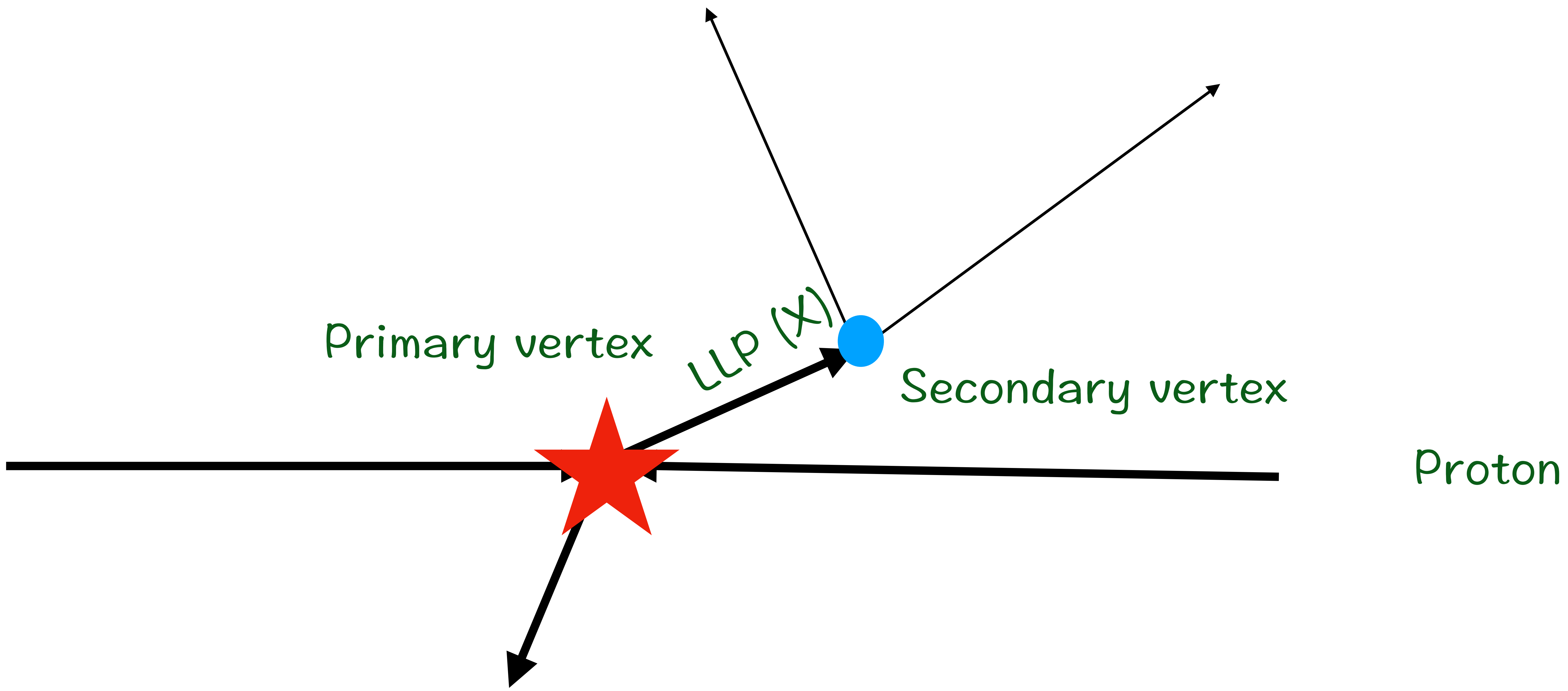
Simple example

Example 1 : Displaced vertex

$$pp \to XX,\ X_{LLP} \to e^{+}e^{-}$$

X is the long-lived particle

Identify displaced electrons and find out the secondary vertex



Looks easy to identify !!
Zero background ??

Displaced jets

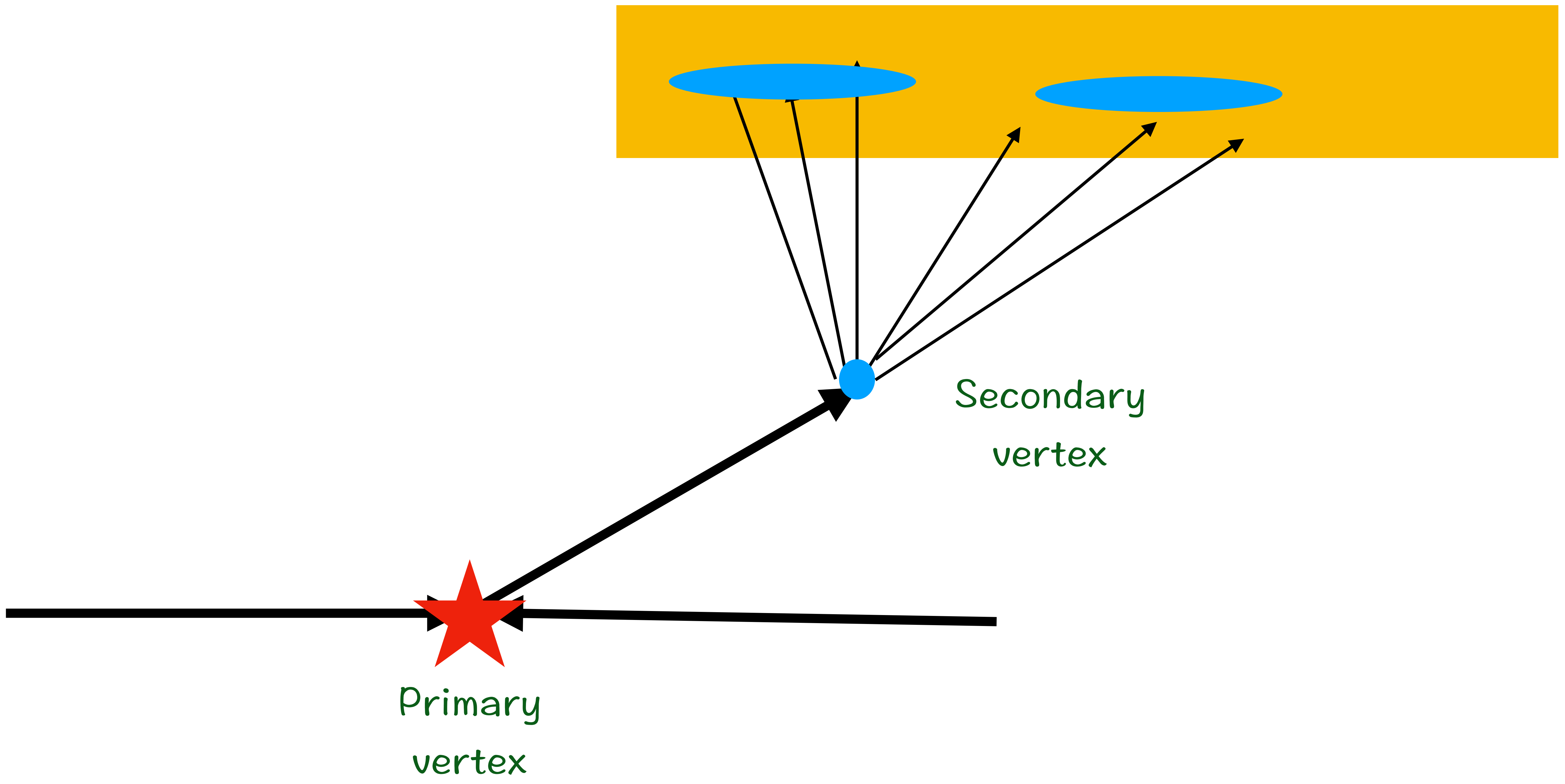
$$pp \to X_{LLP}X_{LLP},\ X_{LLP} \to q + \bar{q}$$ **(jets)**

Nice features

- Displaced multiple tracks
- Secondary vertices
- Calorimeter energy deposits are not associated with tracks from primary vertex=> trackless jet

Displaced jets

Energy deposit in the calorimeter, no associated tracks from the primary vertex



Displaced jets

$$pp \to XX,\, X \to q + \bar{q} \quad \textbf{(jets)}$$

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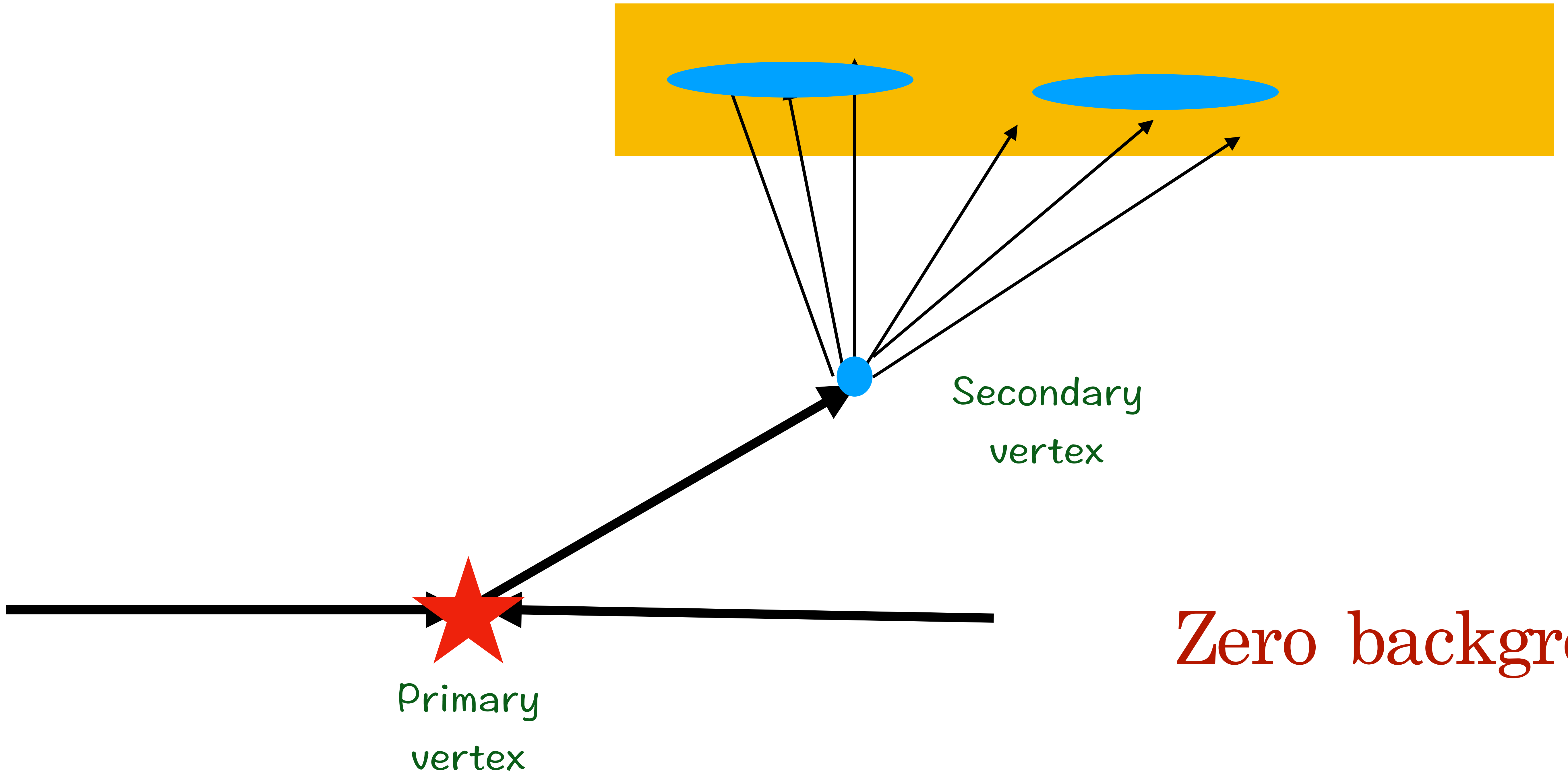
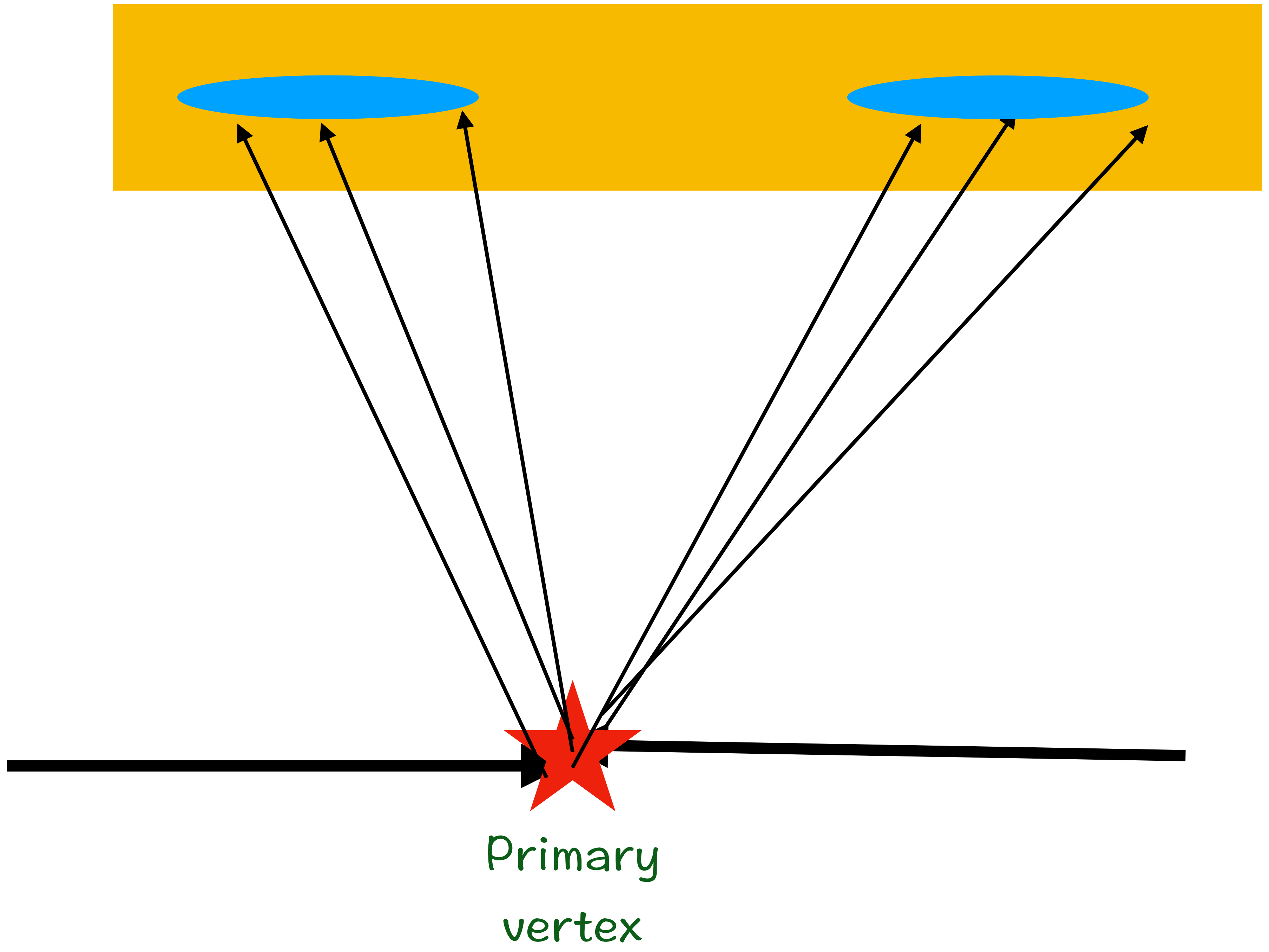
Displaced jets

Energy deposit in the calorimeter, no associated tracks from the primary vertex



Prompt QCD jets

Energy deposit in the calorimeter, associated tracks from the primary vertex



Zero background ??

Challenge 1

SM backgrounds

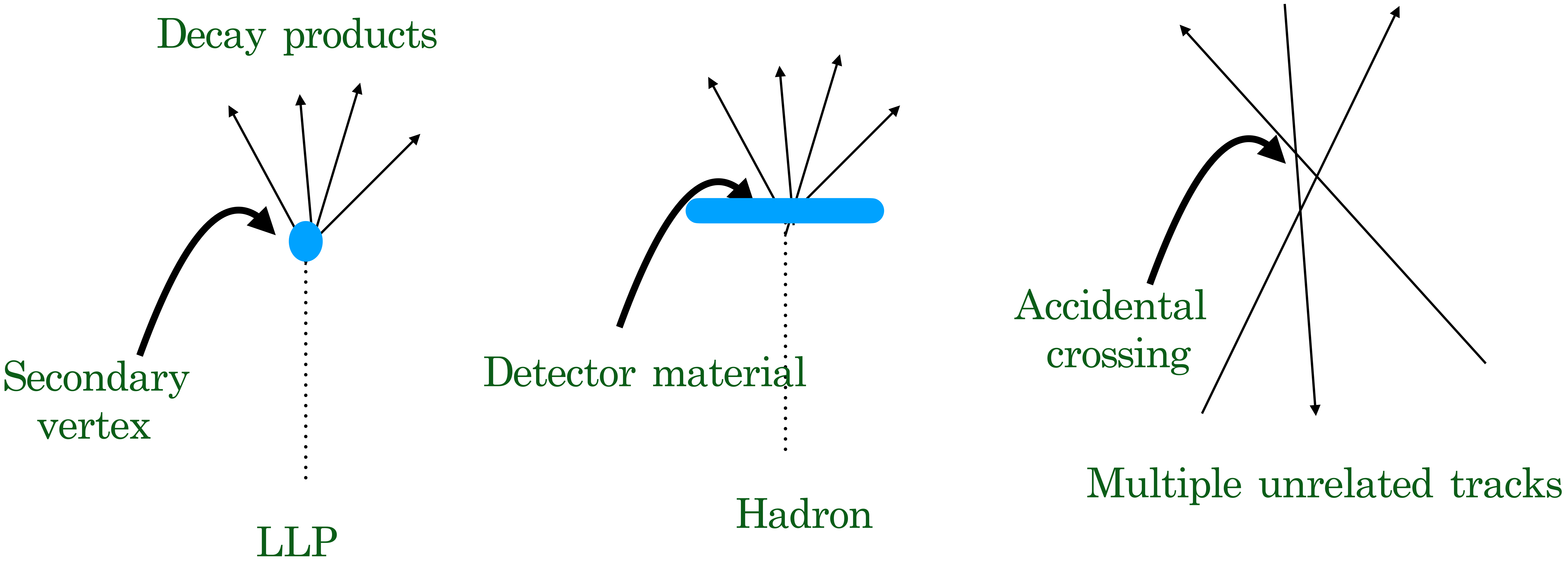
- There are a few SM hadrons which can also give rise to displaced vertex signature
    - their lifetimes and masses are known => better handle

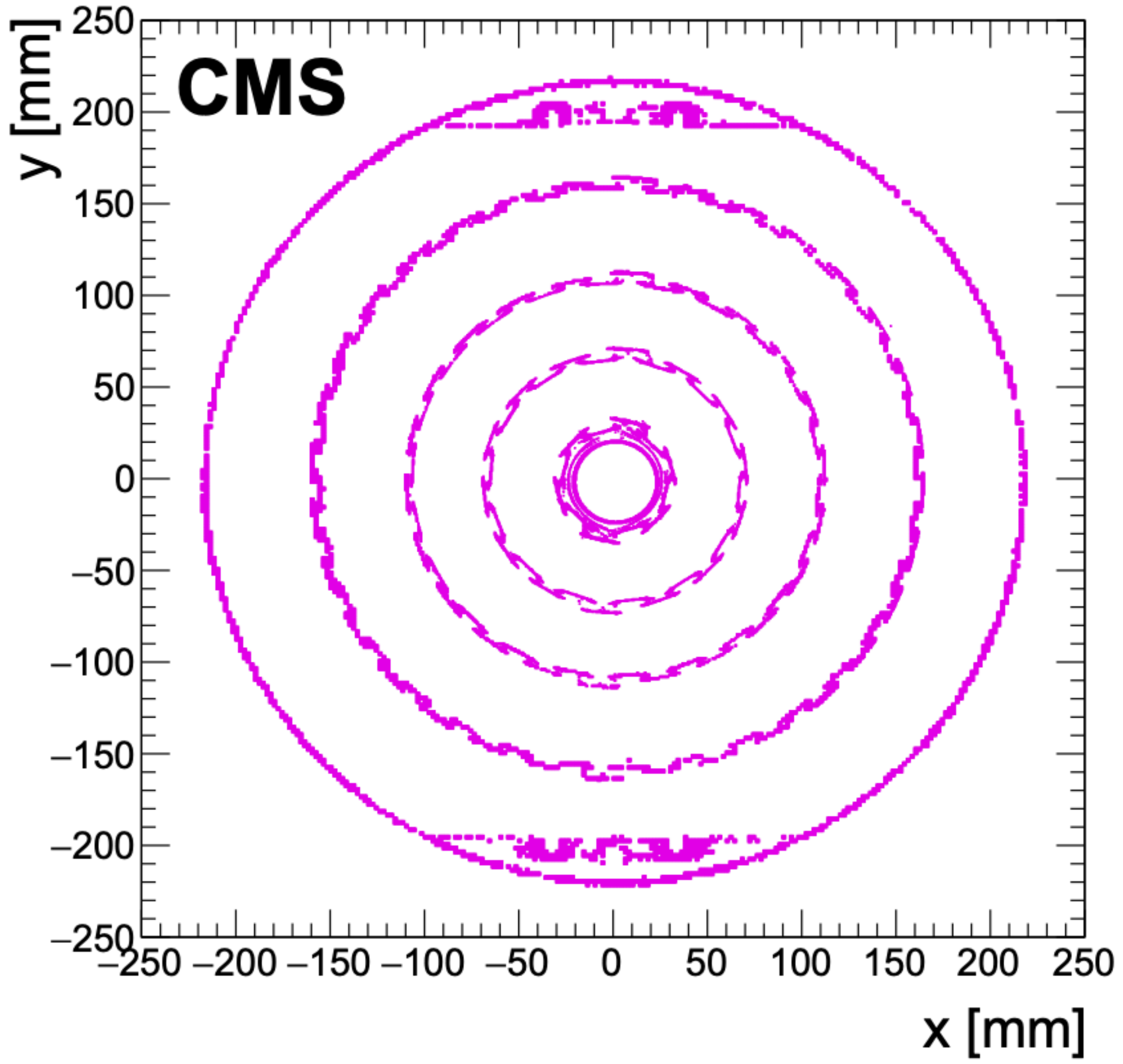
SM backgrounds

- There are a few SM hadrons which can also give rise to displaced vertex signature
  - their lifetimes and masses are known => better handle

- Highly energetic hadrons can interact with the material of the detector

- Accidental crossing of tracks and merged vertices



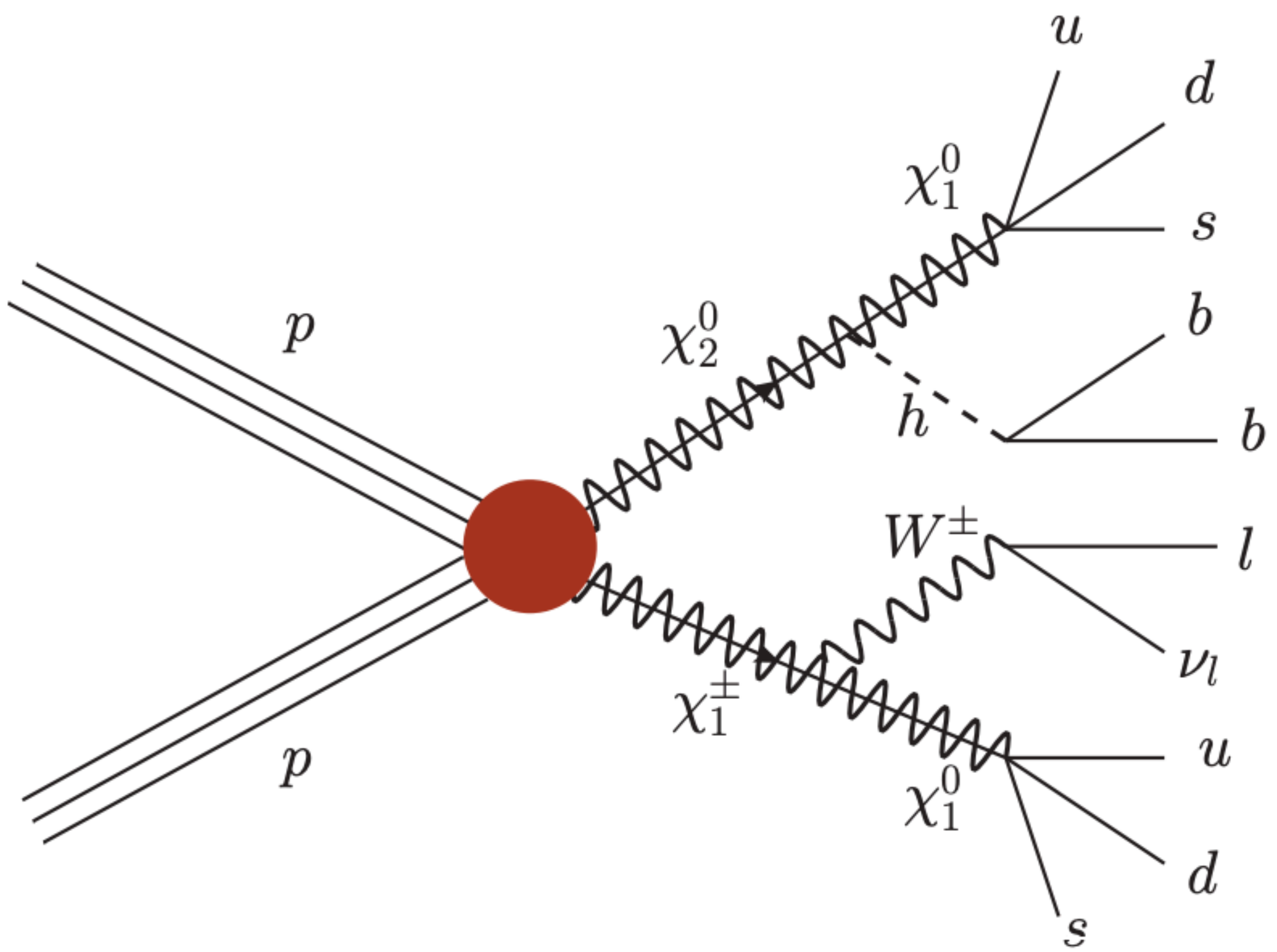


Material veto map (CMS)
2012.01581

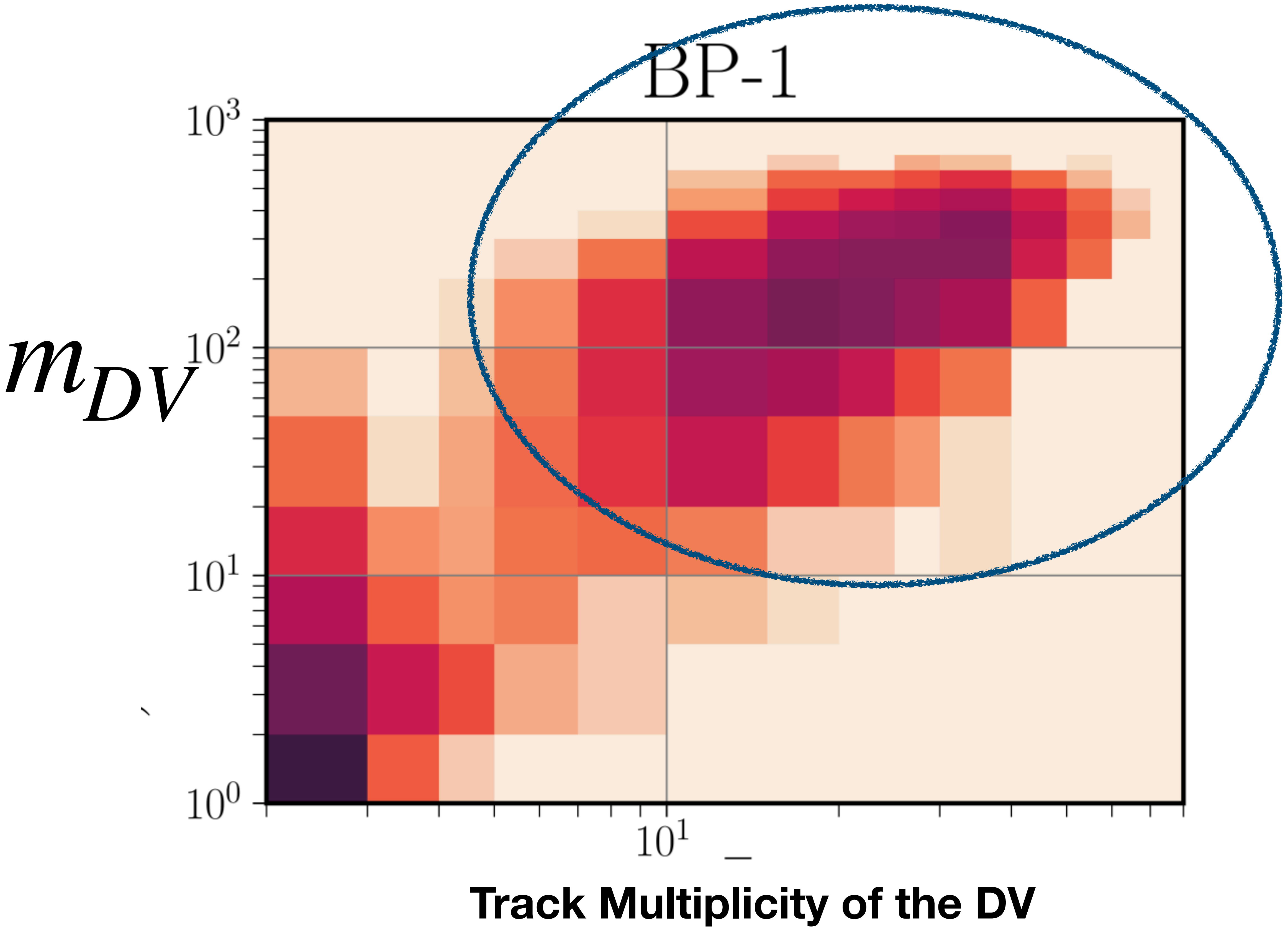
SM backgrounds

- Use material map veto : reject displaced vertices if it falls on the veto region(dense region)
  => residual backgrounds come from less dense region, LLP hadrons and accidental crossing
  => mostly peaks in the low invariant mass low multiplicity region

See ATLAS paper 2301.13866 for example



BB and Prabhat Solanki
arXiv:2308.05804, JHEP 23/24



Identification of light LLPs with low multiplicity may be difficult !!

Challenge 2
(Not a real one !!)

Simulation challenges faced by theorists

Consider a process : p p -> X Y

X-> quarks + invisible particle , Y -> quarks + leptons + invisible particles

(Generate parton level process: Madgraph, Calchep,...)

↓

Shower and Hadronization

(Pythia, Herwig,..)

↓

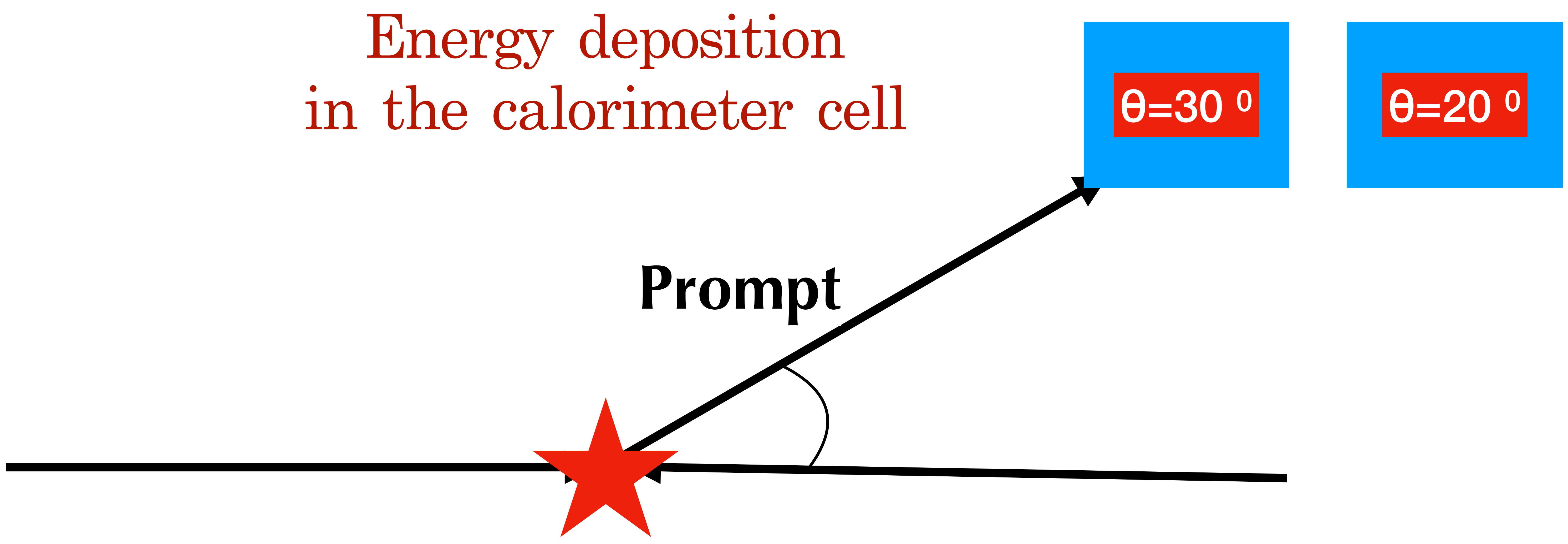
Apply detector response

Fast simulation: Delphes

Parametrised detector response applied on reconstructed objects

Question: Can we directly use fast detector simulation for LLPs ?

Prompt vs LLP (Non-pointing nature)

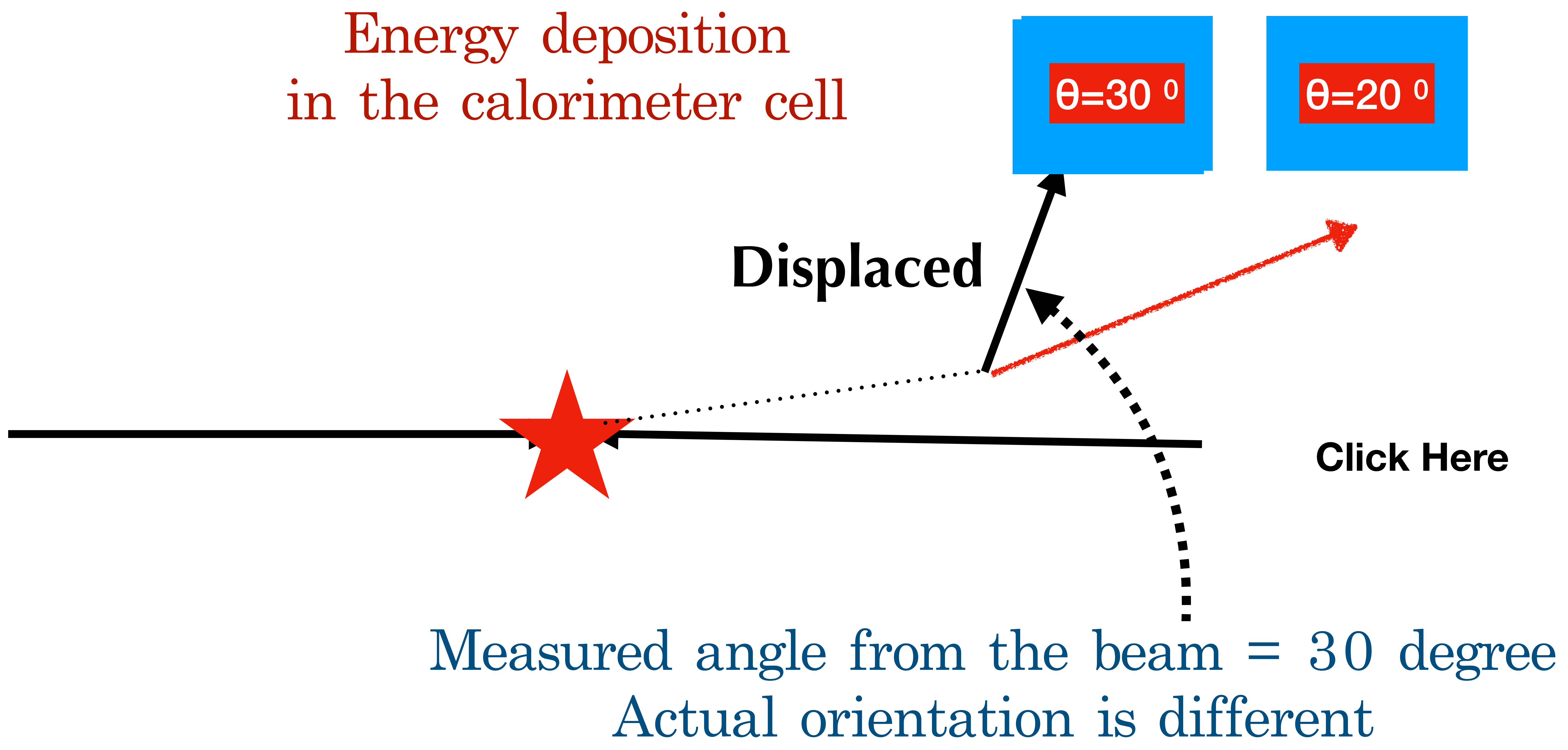


Orientation from the beam axis of the particle = 30 degree

Prompt vs LLP (Non-pointing nature)

In experiment, particle's η-ϕ corresponds to the η-ϕ of the detector cell where it deposits its energy

Mismatch of displaced particle's η-ϕ direction with η-ϕ segmentation of the detector



layered structure/depth segmentation needed to visualise the effect

Fast detector simulations do not have such layered structure (e.g. Delphes)

See non-pointing photon search by CMS collaboration

Energy deposition: prompt vs displaced

$X(\mathrm{LLP}) \to Z + \mathrm{inv}$

Energy ~400 -500 GeV

Physical area taken by the decay products become small with distance and they mostly get contained within fewer $\eta - \varphi$ towers.

CNN can discriminate displaced vs prompt energy deposition

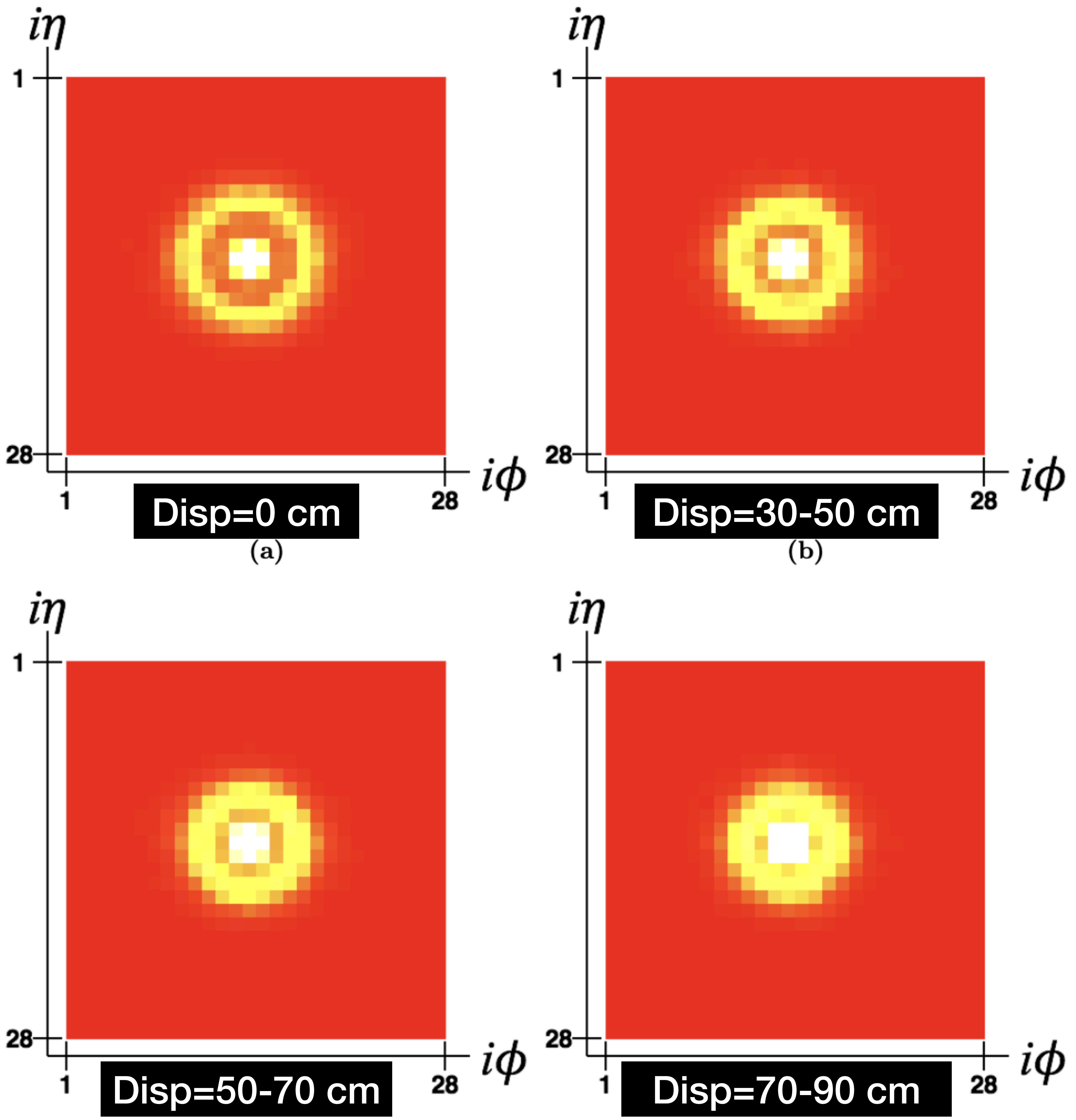
Discrimination between prompt and long-lived particles using convolutional neural network

BB, Swagata Mukherjee and Rhitaja Sengupta arXiv:1904.04811, JHEP 2019

S. Banerjee, G. Bélanger, BB, F. Boudjema, R. Godbole and S. Mukherjee Phys.Rev.D 98 (2018) 11, 115026

Fast convolutional neural networks for identifying long-lived particles in a high-granularity calorimeter
J. Alimena, Y. Iiyama and J. Kieseler 2004.10744 [hep-ex]

average of images: prompt vs displaced

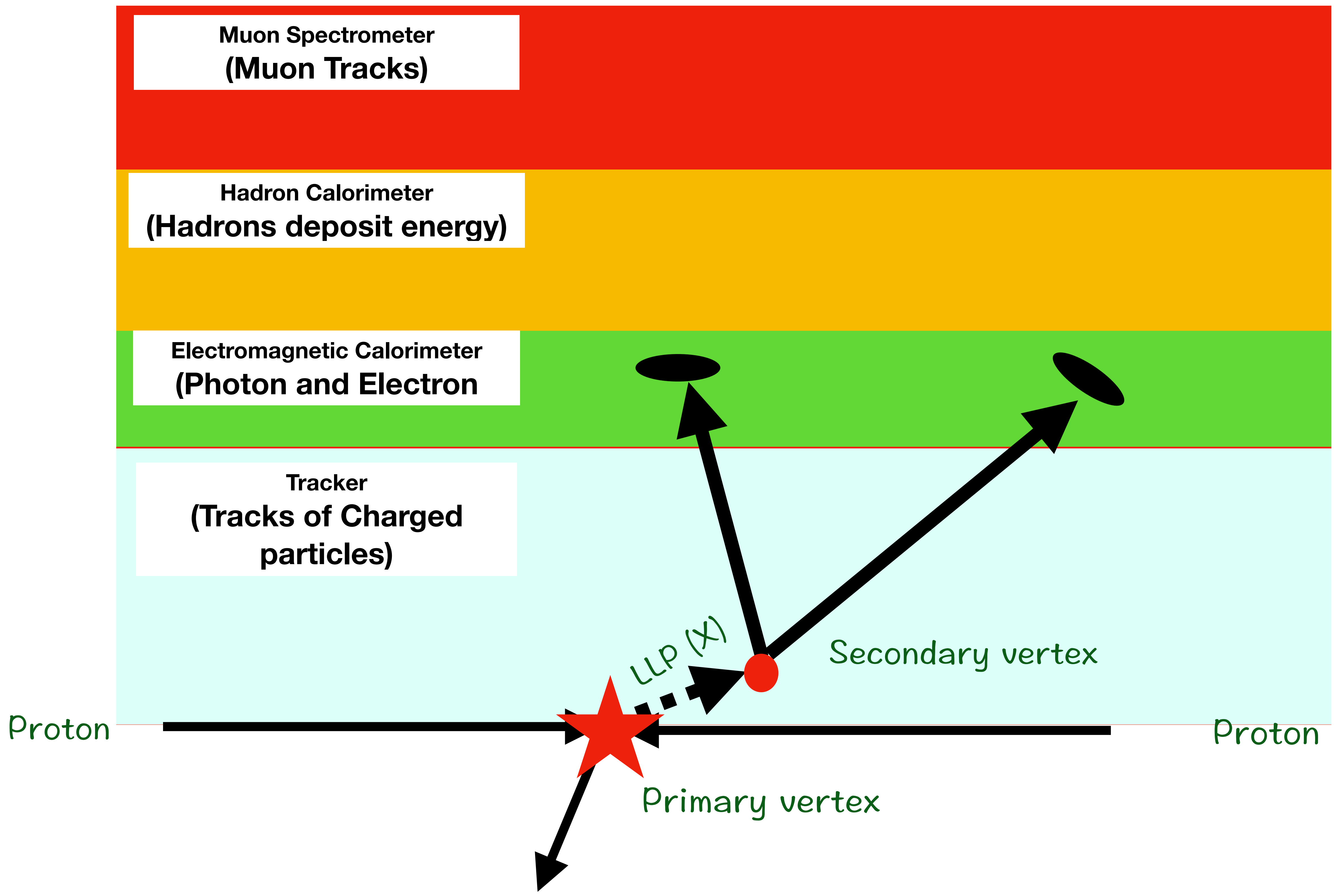


Click Here

Challenge 3

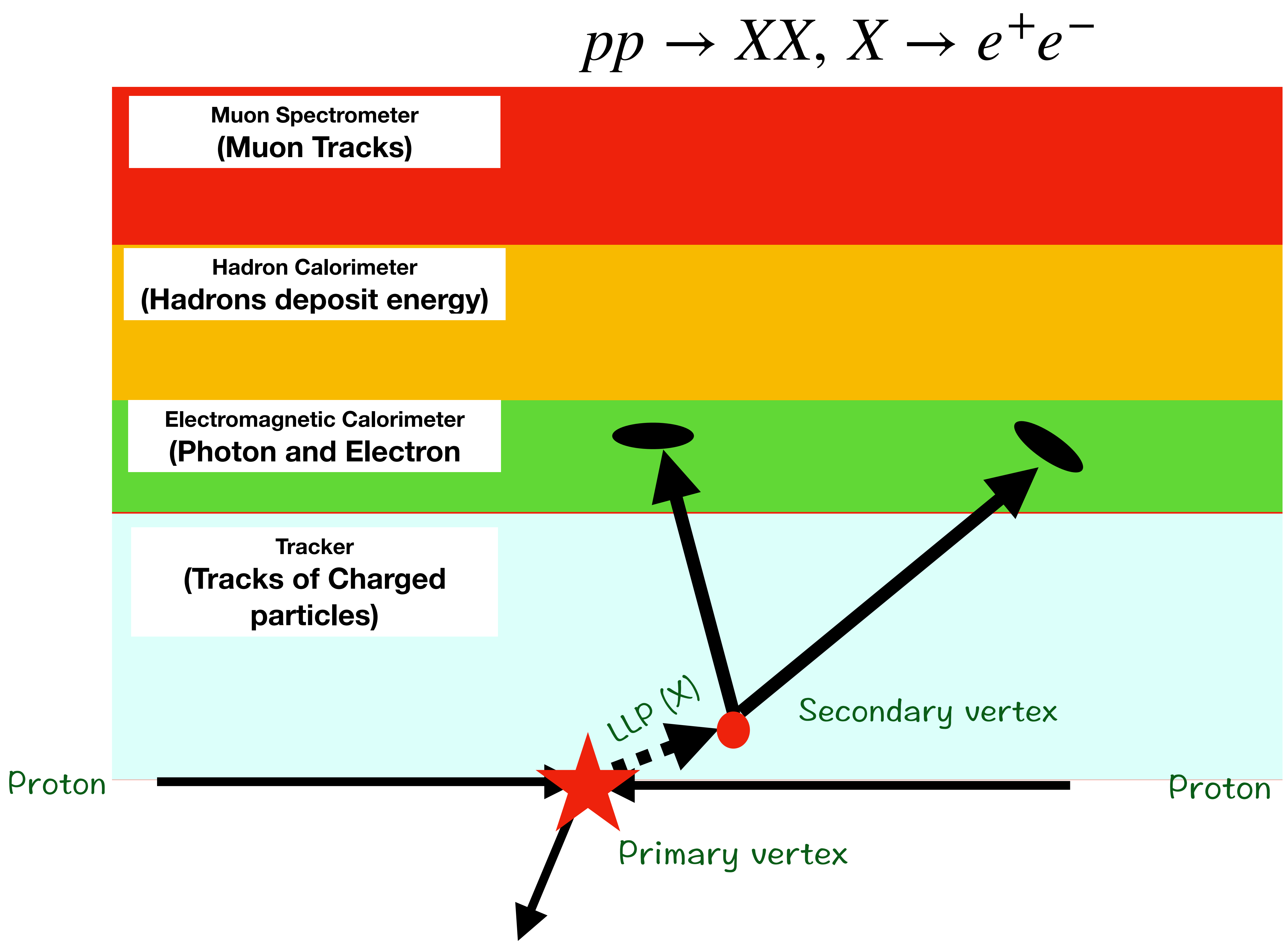
Where LLP decays ?

$$pp \to XX,\ X \to e^+e^-$$

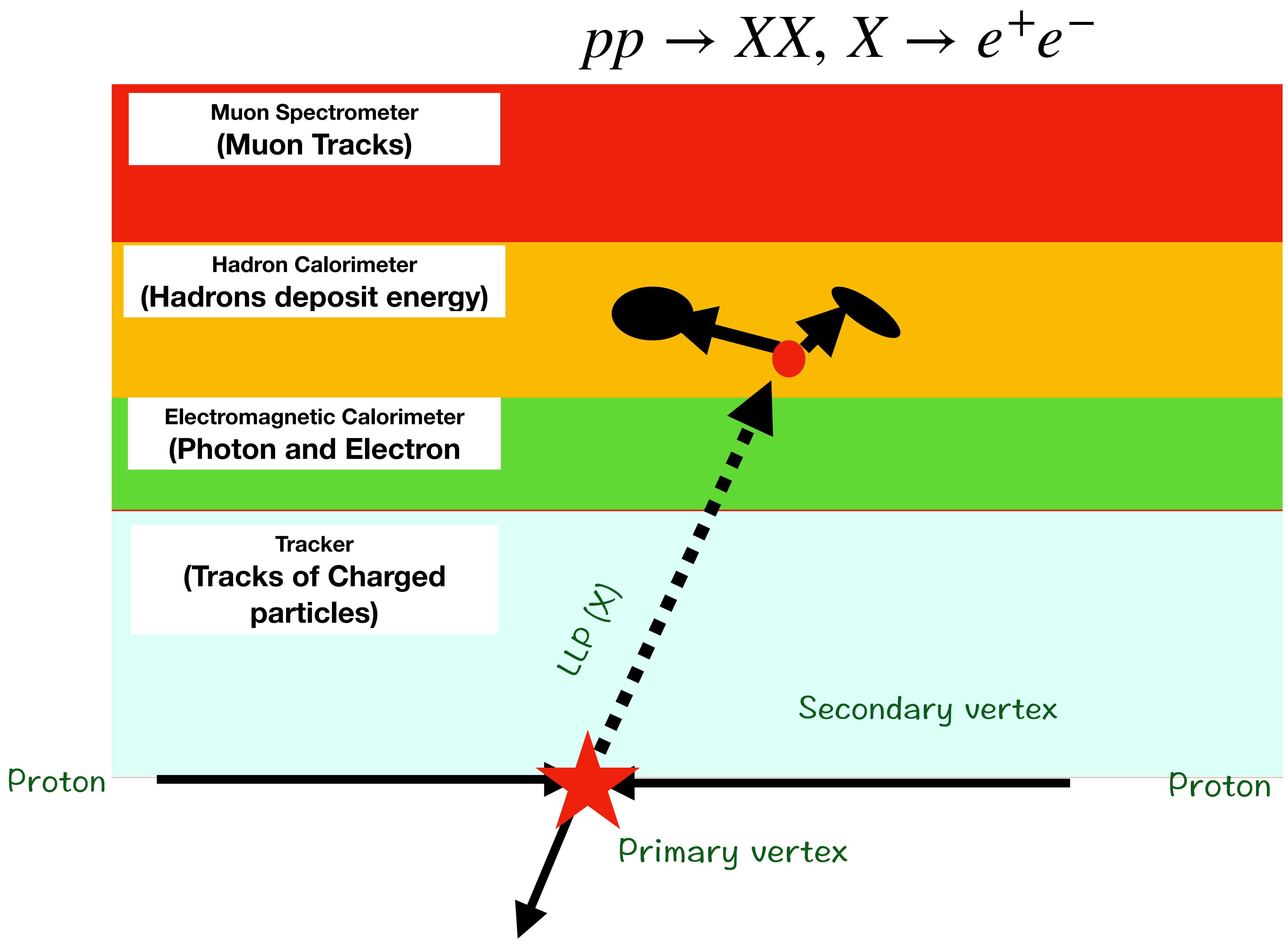


LLP decays inside the tracker

Where LLP decays ?



LLP decays inside the tracker



LLP decays inside the hadronic calorimeter

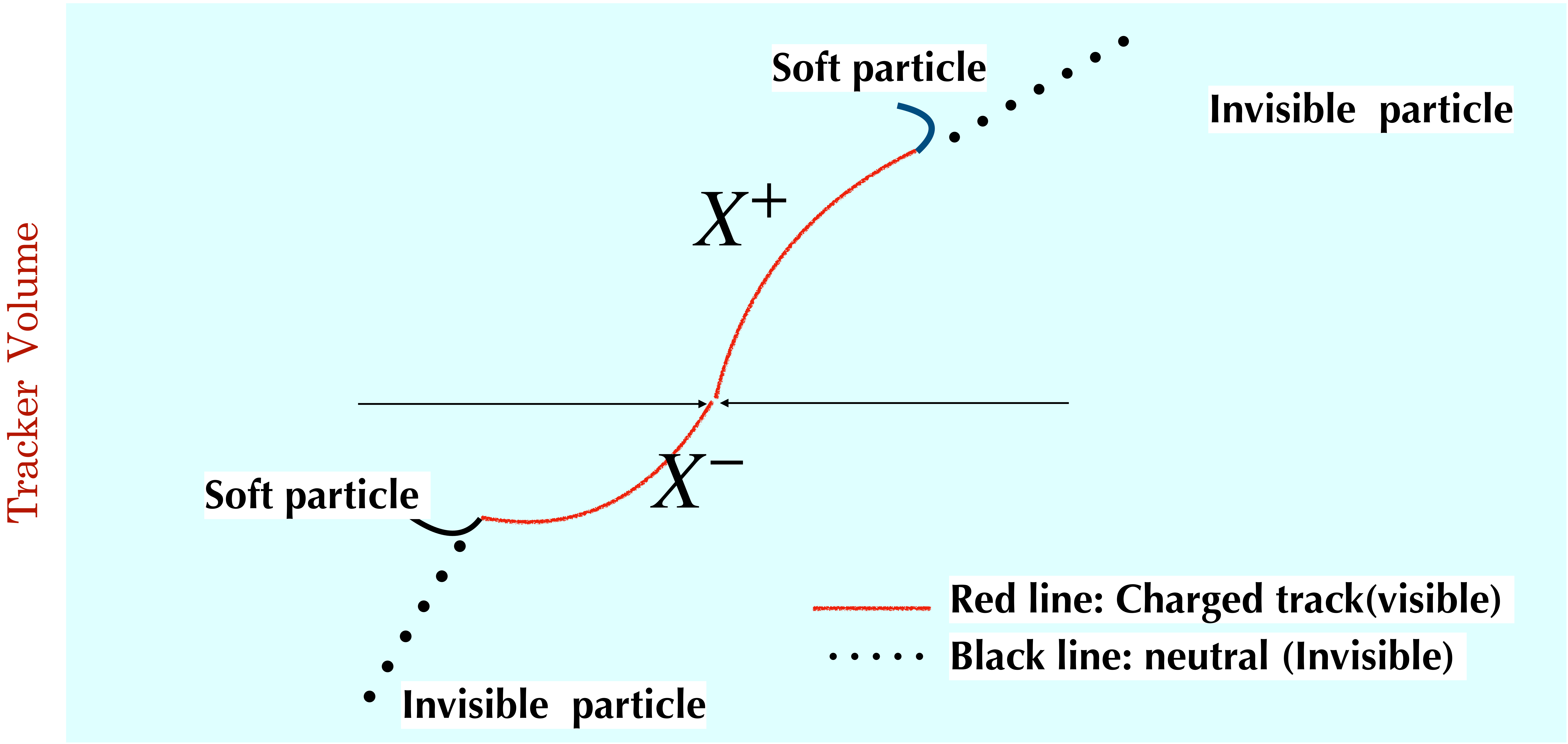
Signatures will be completely different in these two cases

Challenge 4

Signature of LLPs

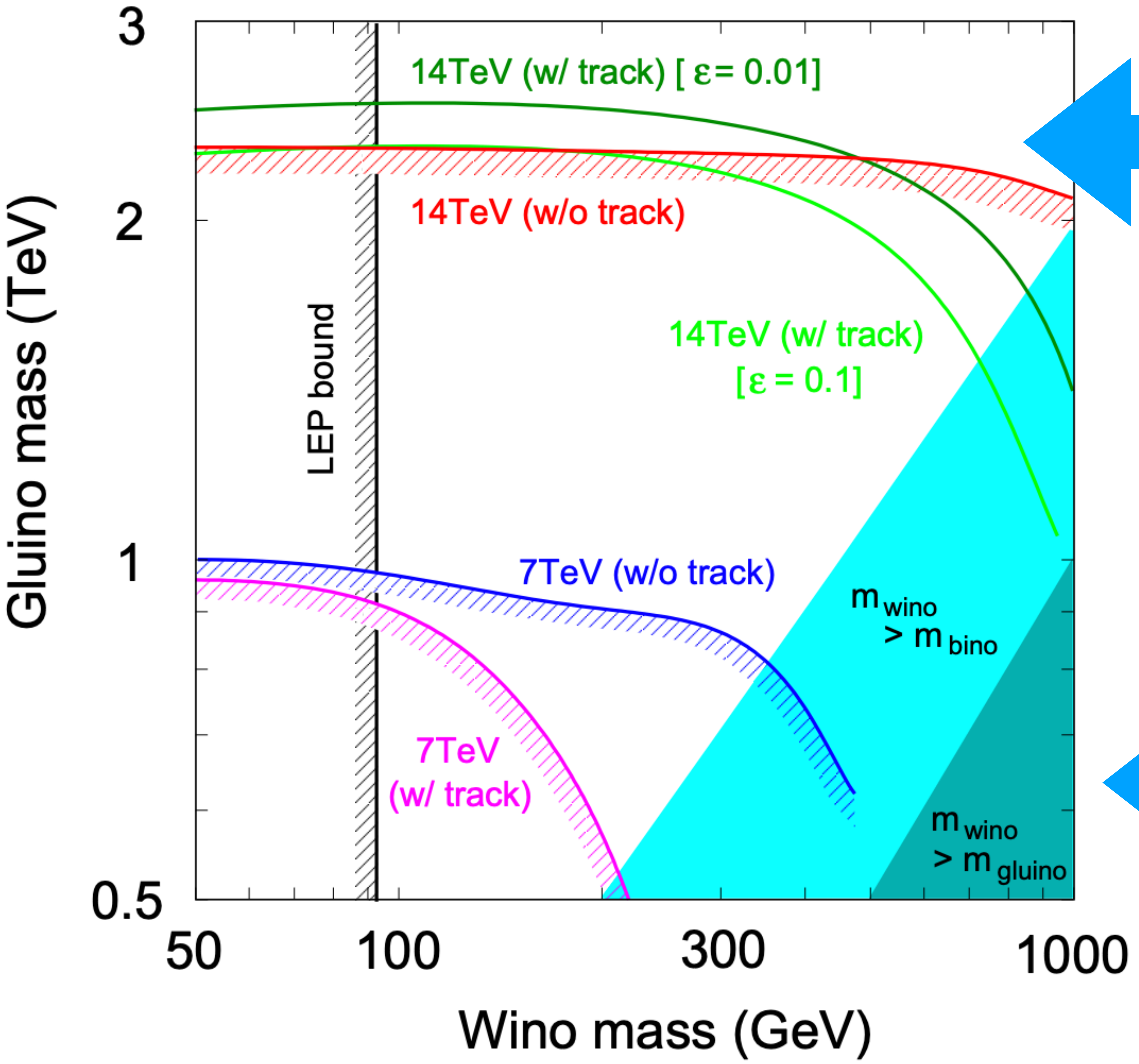
Disappearing Charged track

$$pp \to X^+X^-,\ X^\pm \to Y_{invisible} + \text{soft particles},$$



Significant improvements in the analysis techniques

$$\tilde{g} \to qq'\chi_1^{\pm}$$



BB, Brian Feldstein, Masahiro Ibe, Shigeki Matsumoto, Tsutomu T. Yanagida
arXiv:1207.5453, PRD 2013

Our Proposal : shorter tracks

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

7 TeV searches: Longer tracks

- The selected track must disappear between 514 mm and 863 mm, i.e. within the first and second layers of the transition radiation tracker (TRT).

ATLAS-CONF-2012-034

Current Situation (Huge improvement in the analysis)

Pixel tracklet searches By ATLAS 2201.02472

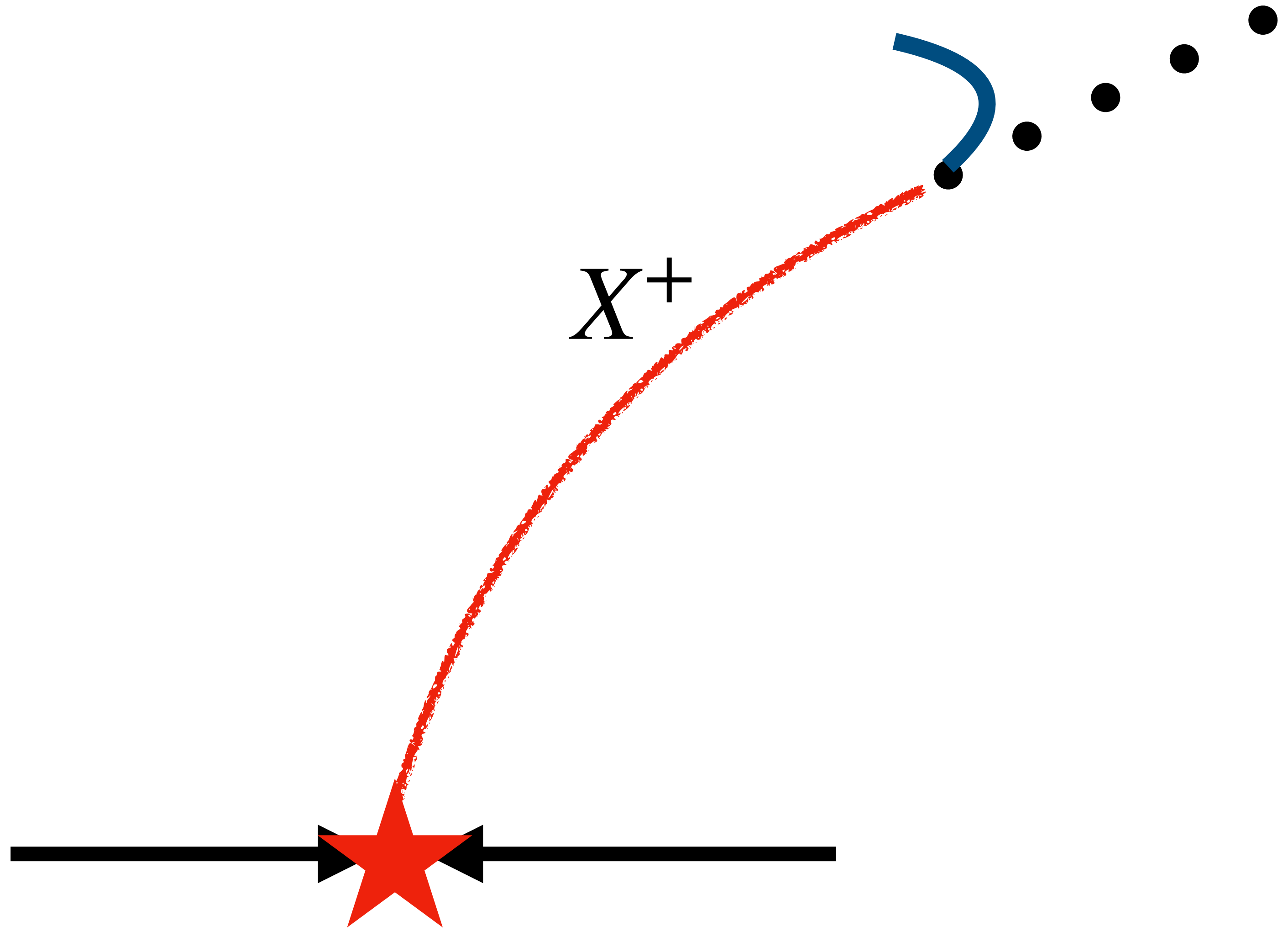
Also by CMS collaboration

Challenge 5

How do we identify LLP events ?

Soft particle

disappearing tracks =>
easy for identification?

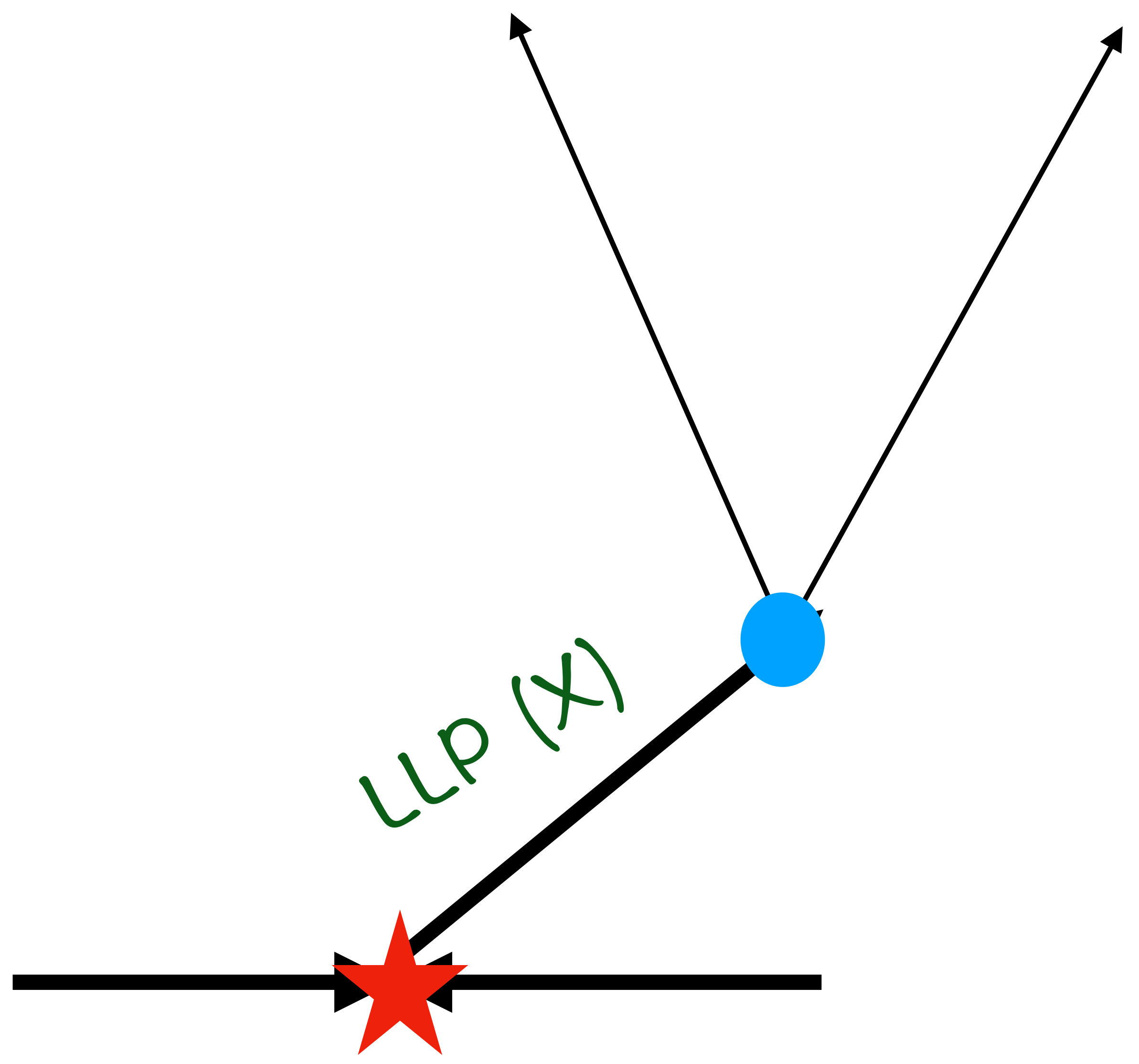


Tracking not available at Level 1
Use jet or Missing Transverse energy(MET) trigger to store the events and reconstruct the disappearing track in the offline analysis

MET >110 GeV

ATLAS analysis 2201.02472

Displaced electron

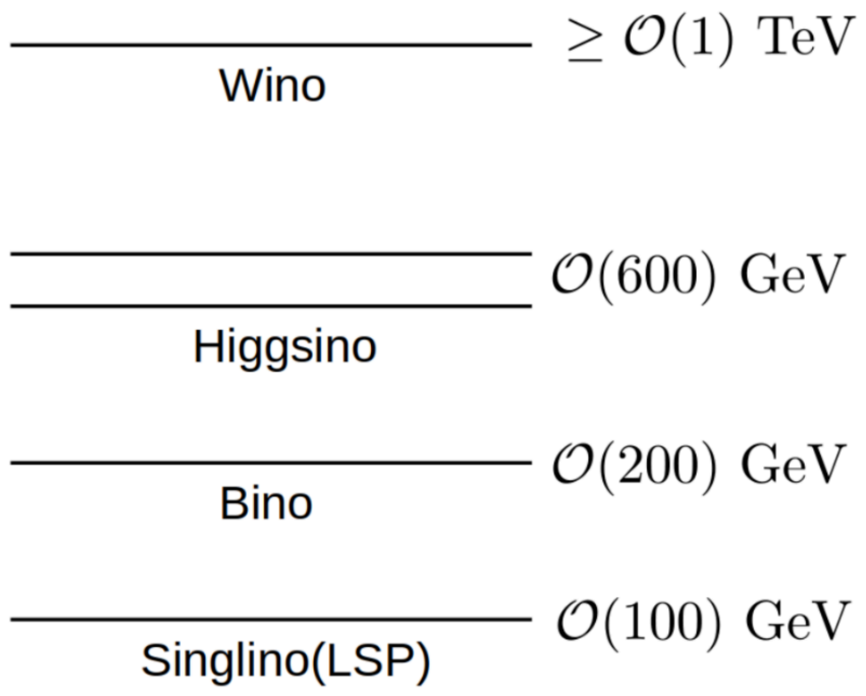


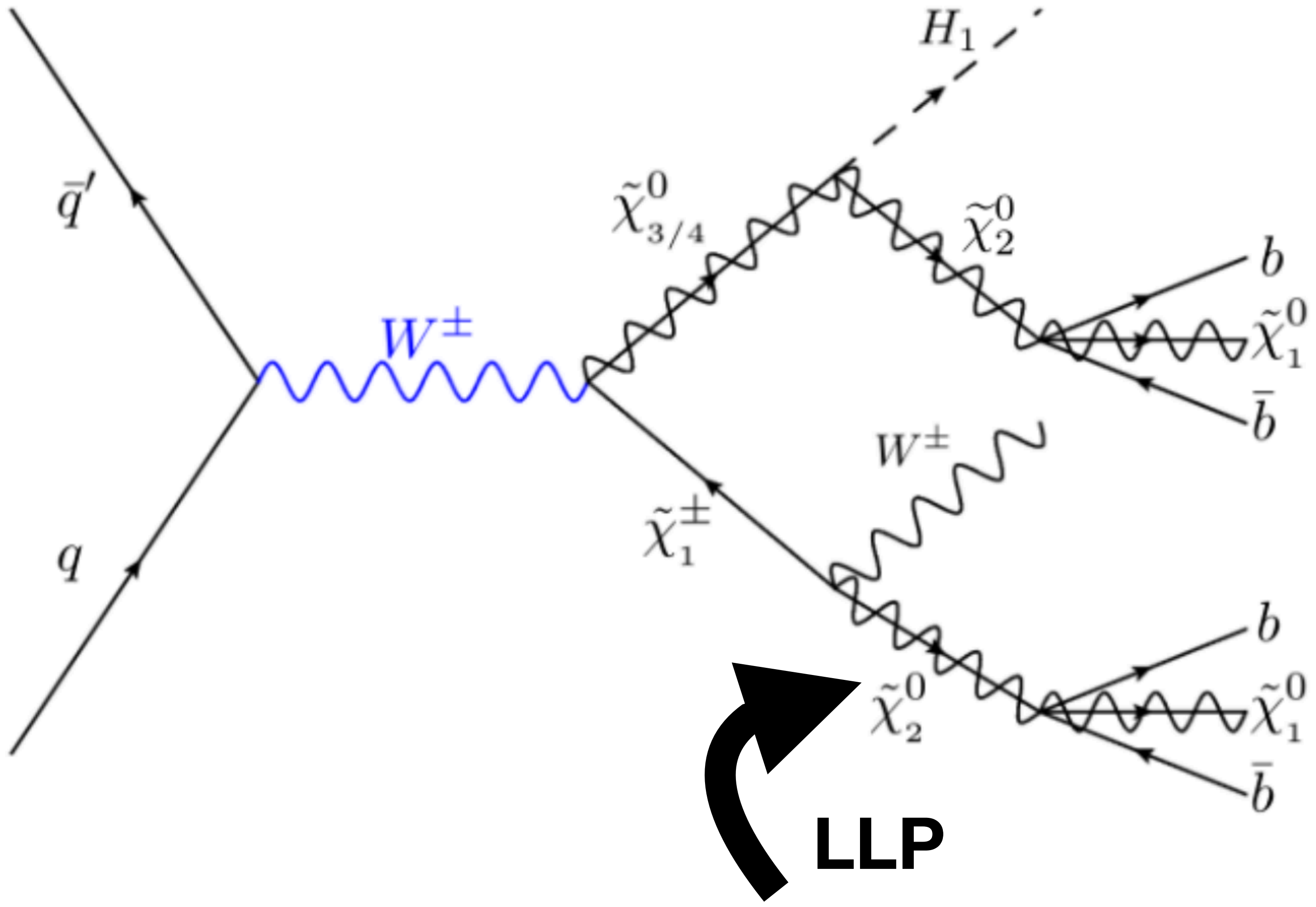
Use single or double photon trigger to store the event
Single photon p_T >140 GeV
Double photon p_T > 50 GeV

ATLAS analysis 1907.10037

LLP:R-parity conserving NMSSM

Simple idea: trigger the event with prompt leptons, identify secondary vertex offline.



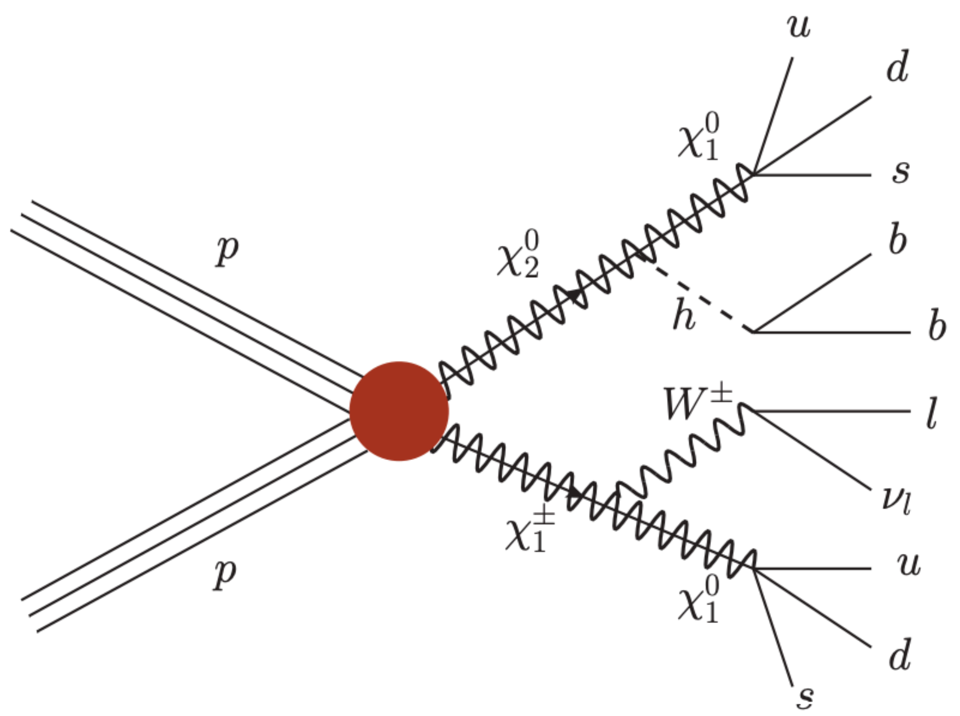


Apply cuts on the number of tracks and invariant mass of the secondary vertex to kill Instrumental background

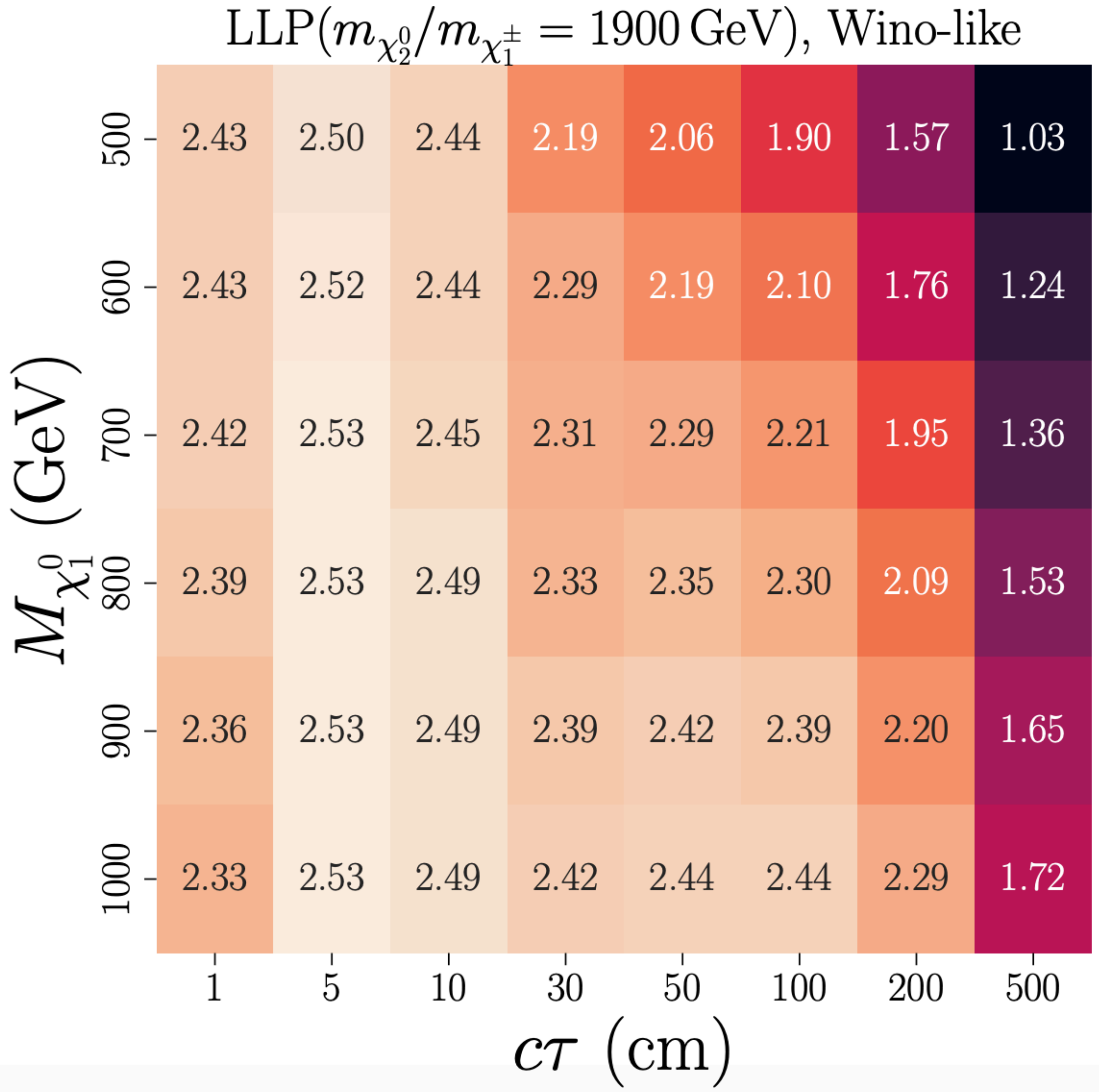
Amit Adhikary, Rahool Kumar Barman, BB, Amandip De, Rohini M. Godbole, Suchita Kulkarni
e-Print: 2207.00600, PRD 2023

LLP:R-parity violating MSSM

Combining displaced tracking, timing and prompt lepton trigger



Significance grid at the HL-LHC



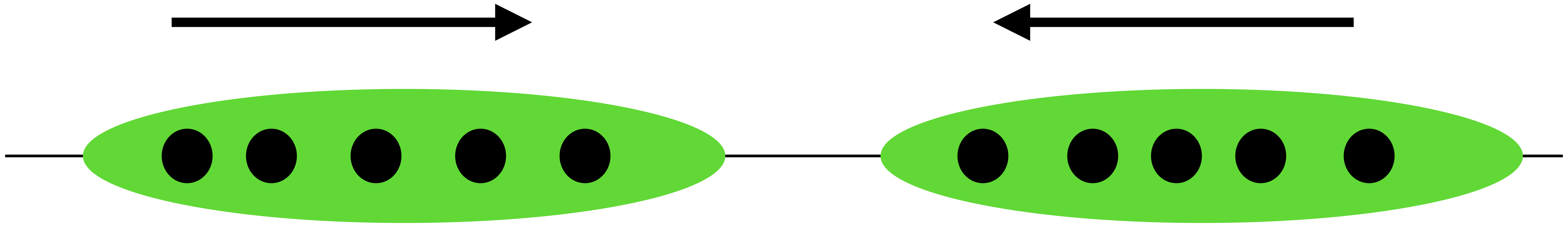
BB and Prabhat Solanki
arXiv:2308.05804, JHEP 23/24

Challenge 6

Pile up

Not a collision between two protons

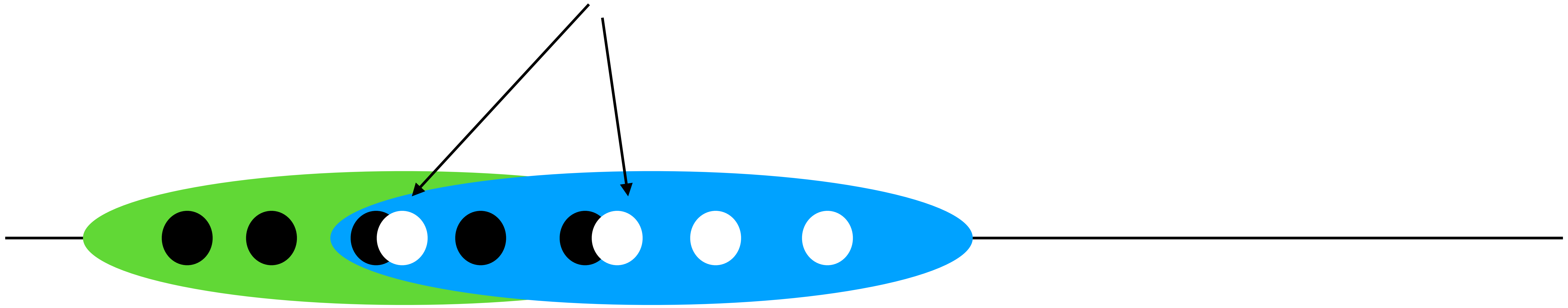
Collision between proton bunches



Proton bunch 1

Proton bunch 2

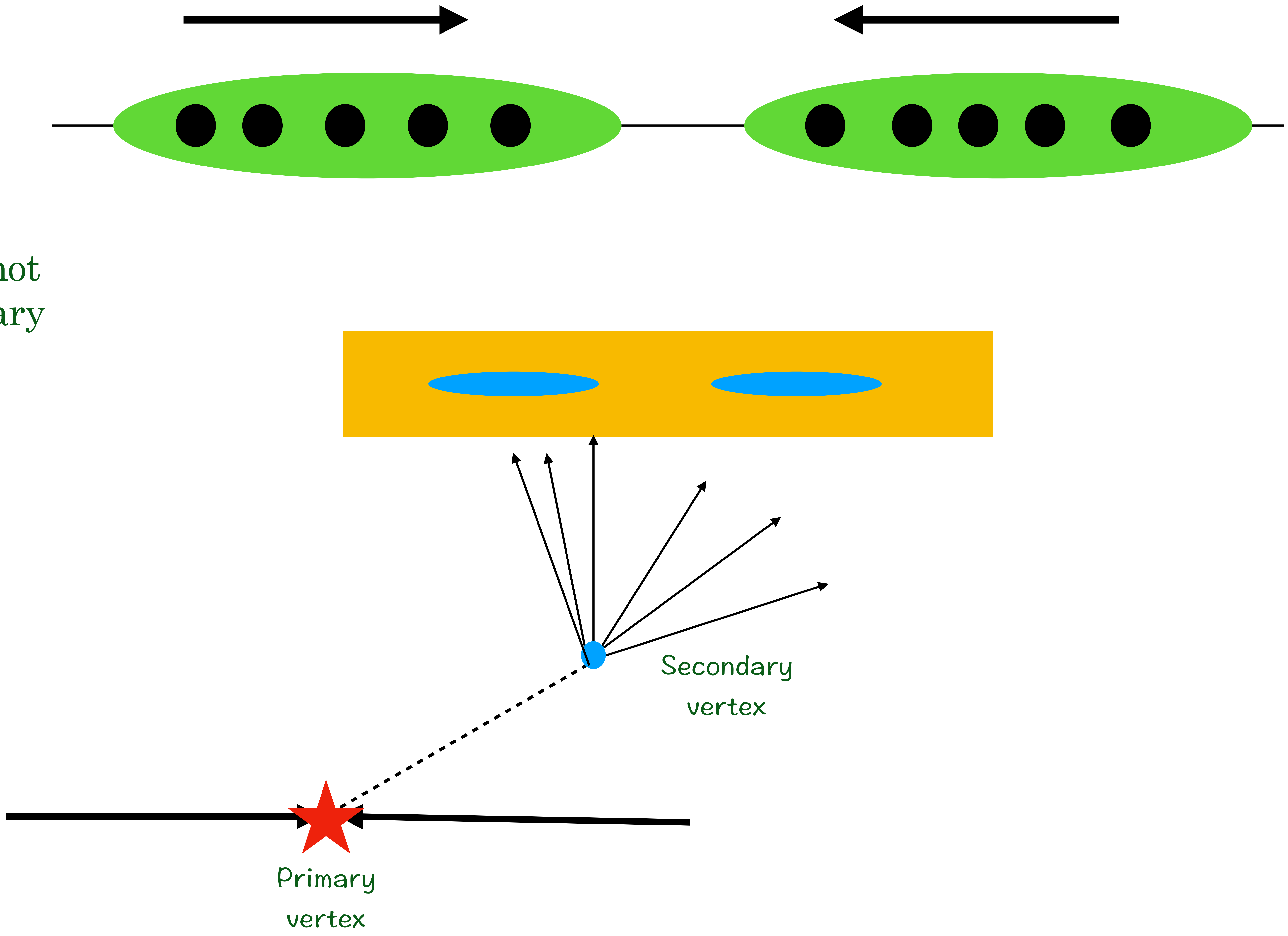
Multiple collision vertices : Pileup vertices



Displaced jets

Expected features

- Displaced multiple tracks
- Secondary vertices
- Calorimeter energy deposits are not associated with tracks from primary vertex=> trackless jet

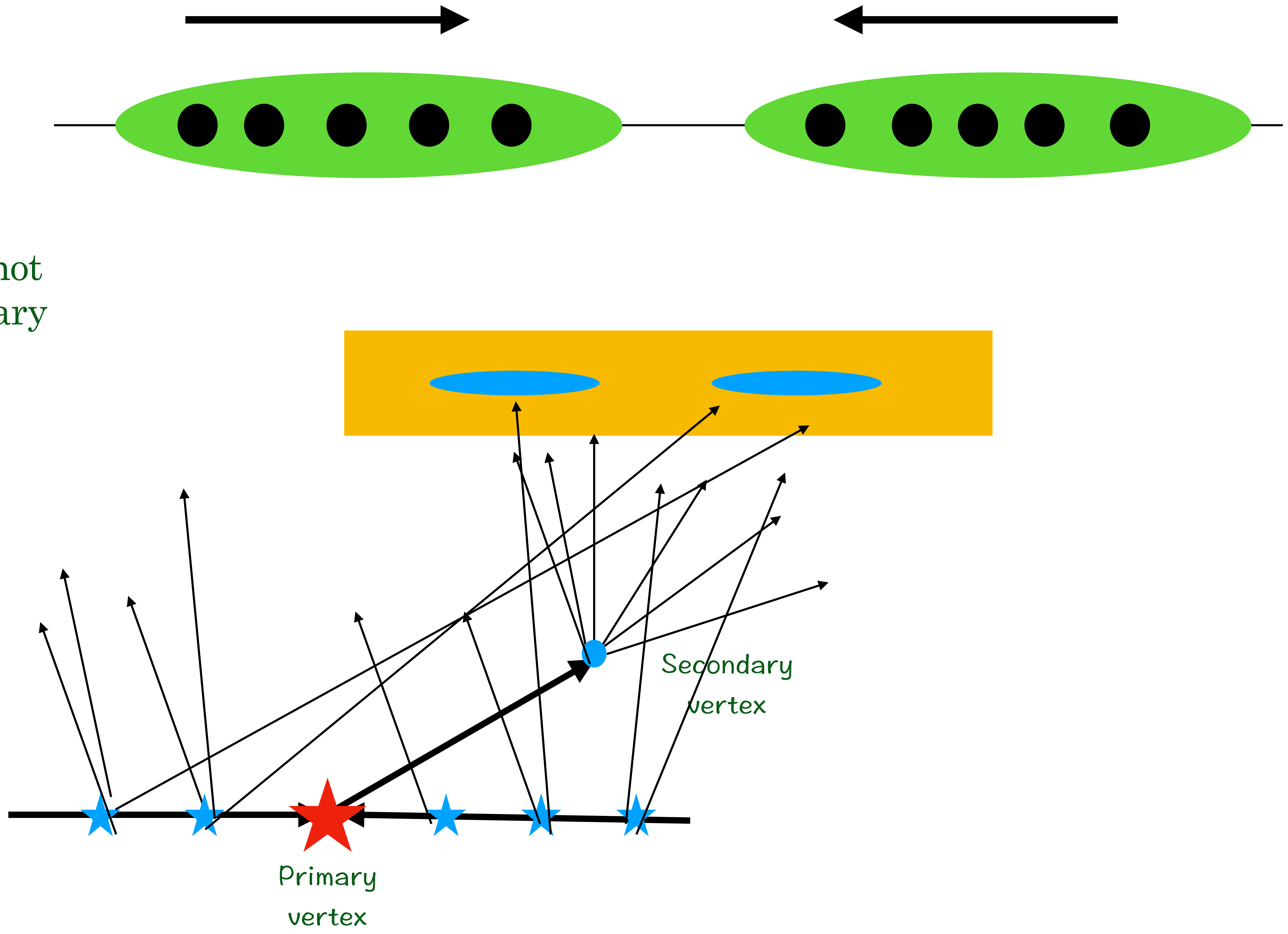


Displaced jets

Expected features

- Displaced multiple tracks
- Secondary vertices
- Calorimeter energy deposits are not associated with tracks from primary vertex=> trackless jet

Pile up vertex ★

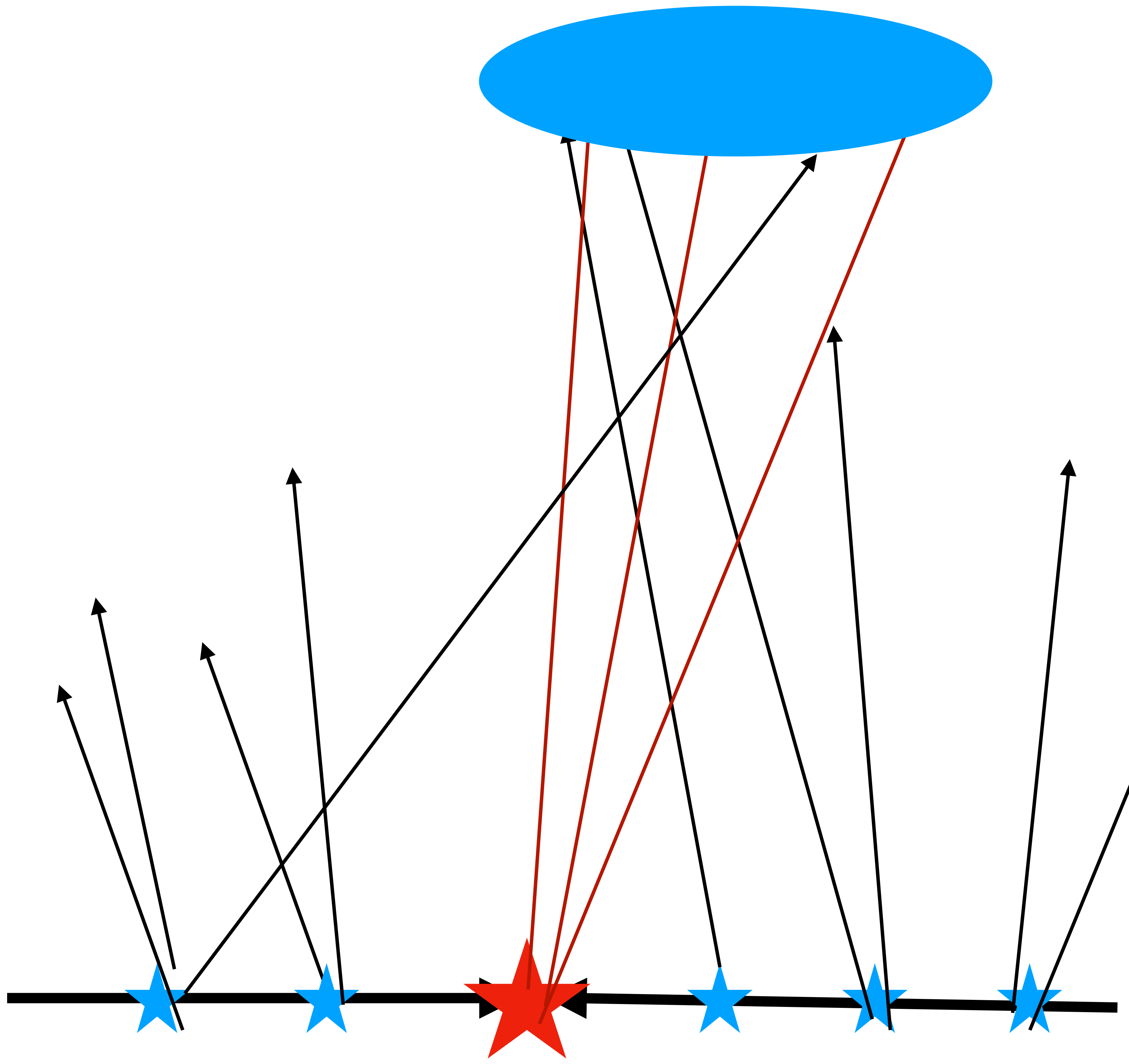


Current Run of LHC: average number of pileup ~50

HL-LHC : effect of Pileup

Average number of pileup for HL-LHC = 140 to 200

Too many particles, multiple tracks can be associated with the the energy deposits => average energy of jets will increase

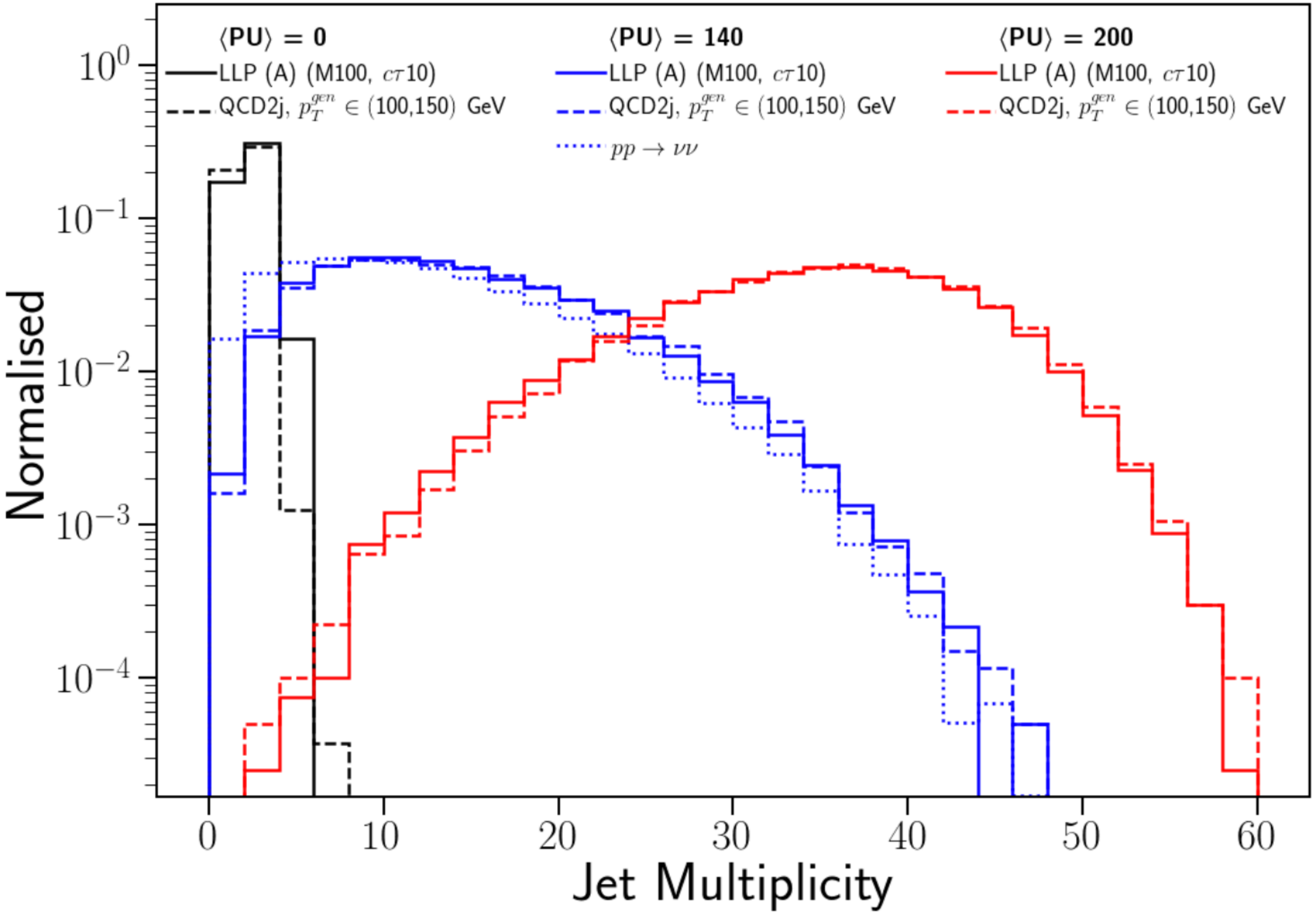


HL-LHC: Triggering challenge more severe because of high pileup

Jets at HL-LHC

LLP Model: $pp \to XX, X \to q\bar{q}$

BB, Swagata Mukherjee, Rhitaja Sengupta, Prabhat Solanki
e-Print: 2003.03943, JHEP 2020



Jet info

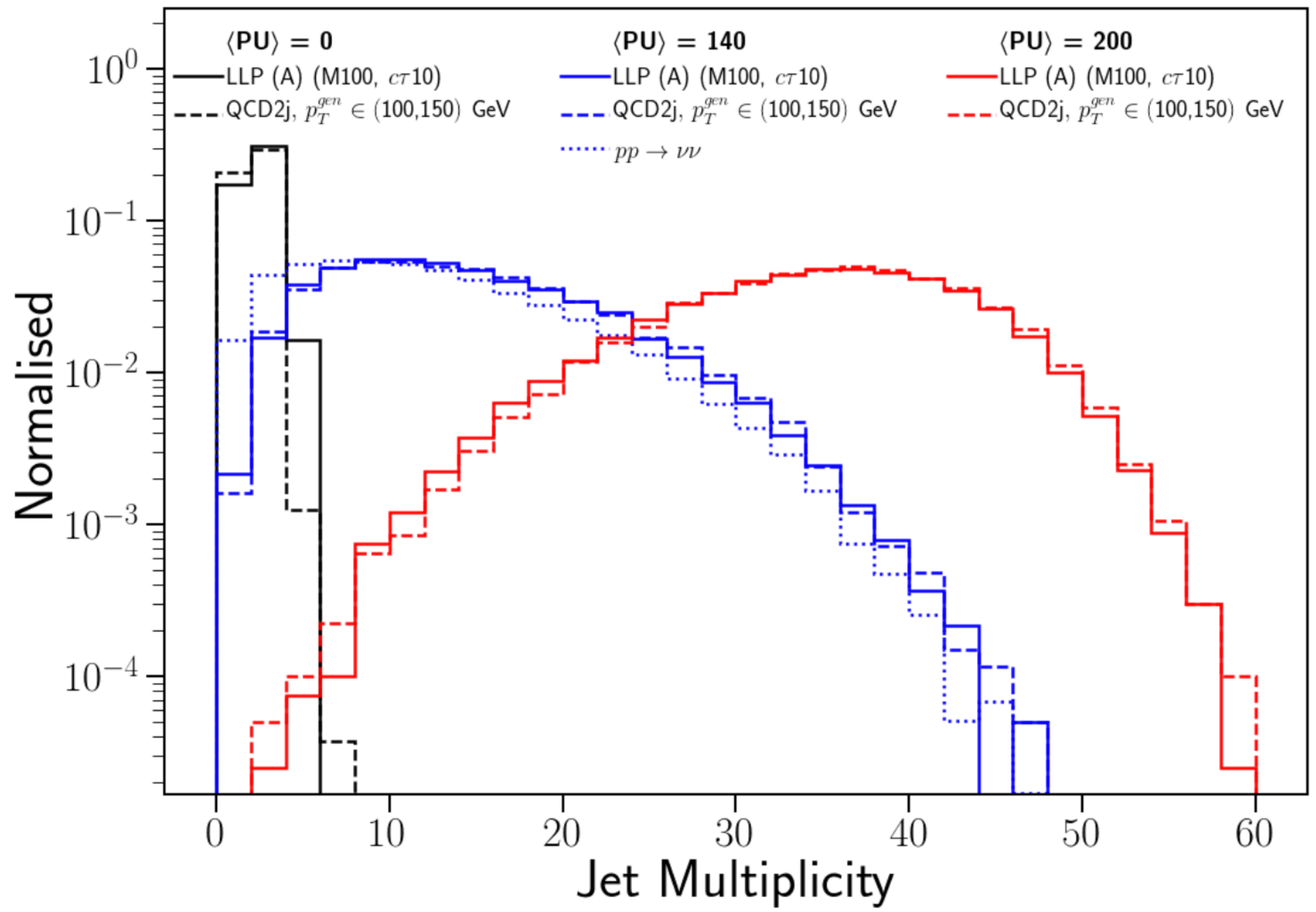
Jet parameter = 0.4
p_T >60 GeV
$|\eta|$ <2.5

Calorimeter jet multiplicity dominated by PU jets

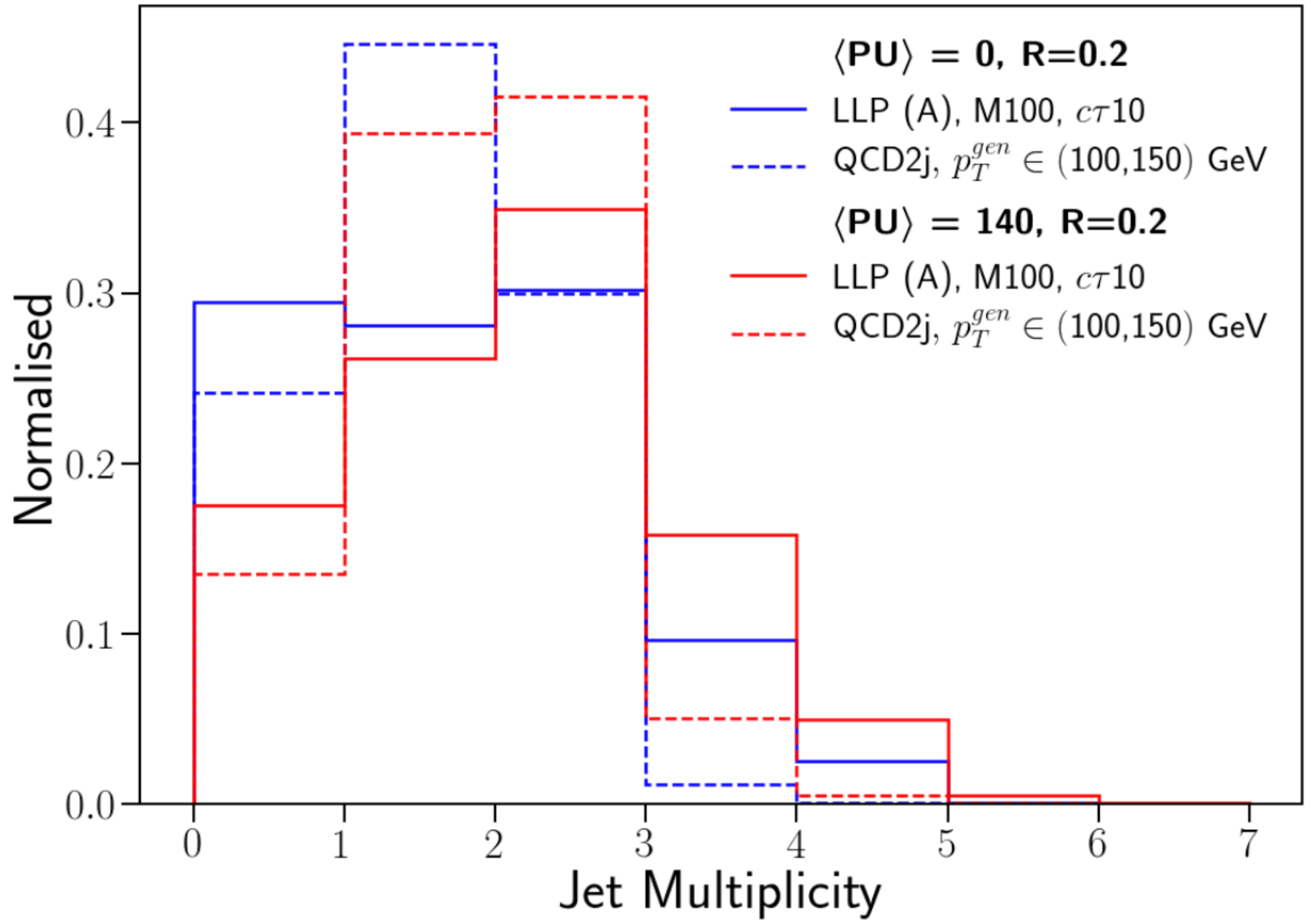
Narrow jets for LLP

BB, Swagata Mukherjee, Rhitaja Sengupta, Prabhat Solanki
e-Print: 2003.03943, JHEP 2020

LLP Model: $pp \to XX, X \to q\bar{q}$



Narrow jets !!



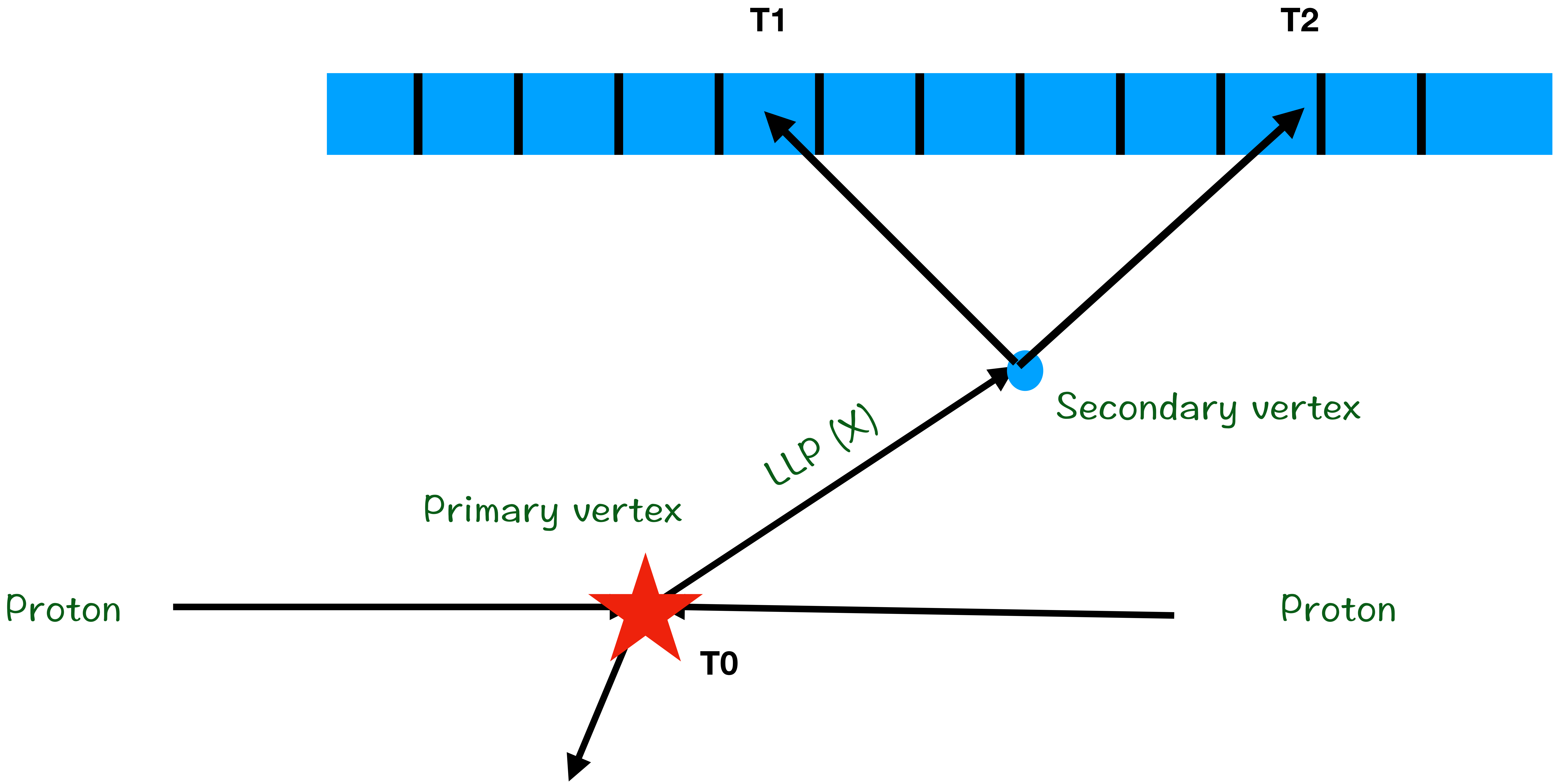
Only narrow jet will not be sufficient to suppress background
Many Variables can be constructed
Single narrow jet trigger with pT >60 GeV with strict cuts on tracking variables may be used.

Example 2 : Timing Information

$$pp \to XX,\ X \to e^+e^-$$

Decay products of heavy LLPs will reach late compared to the prompt particles

T1 -T0 can be used as a discriminant



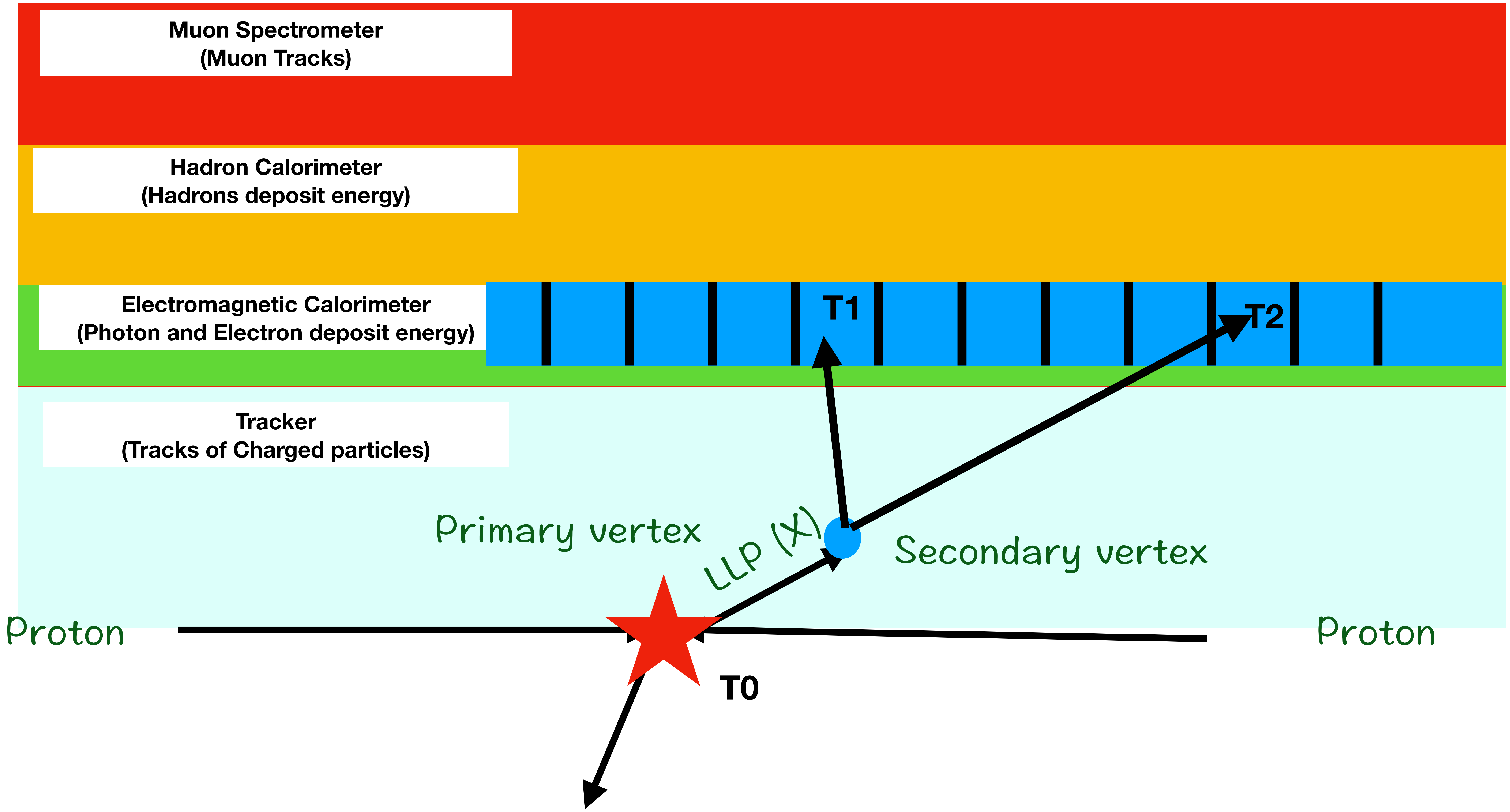
Signature of LLPs

Example 2 : Timing Information

$$pp \to XX,\ X \to e^+e^-$$

Decay products of heavy LLPs will reach late compared to the prompt particles

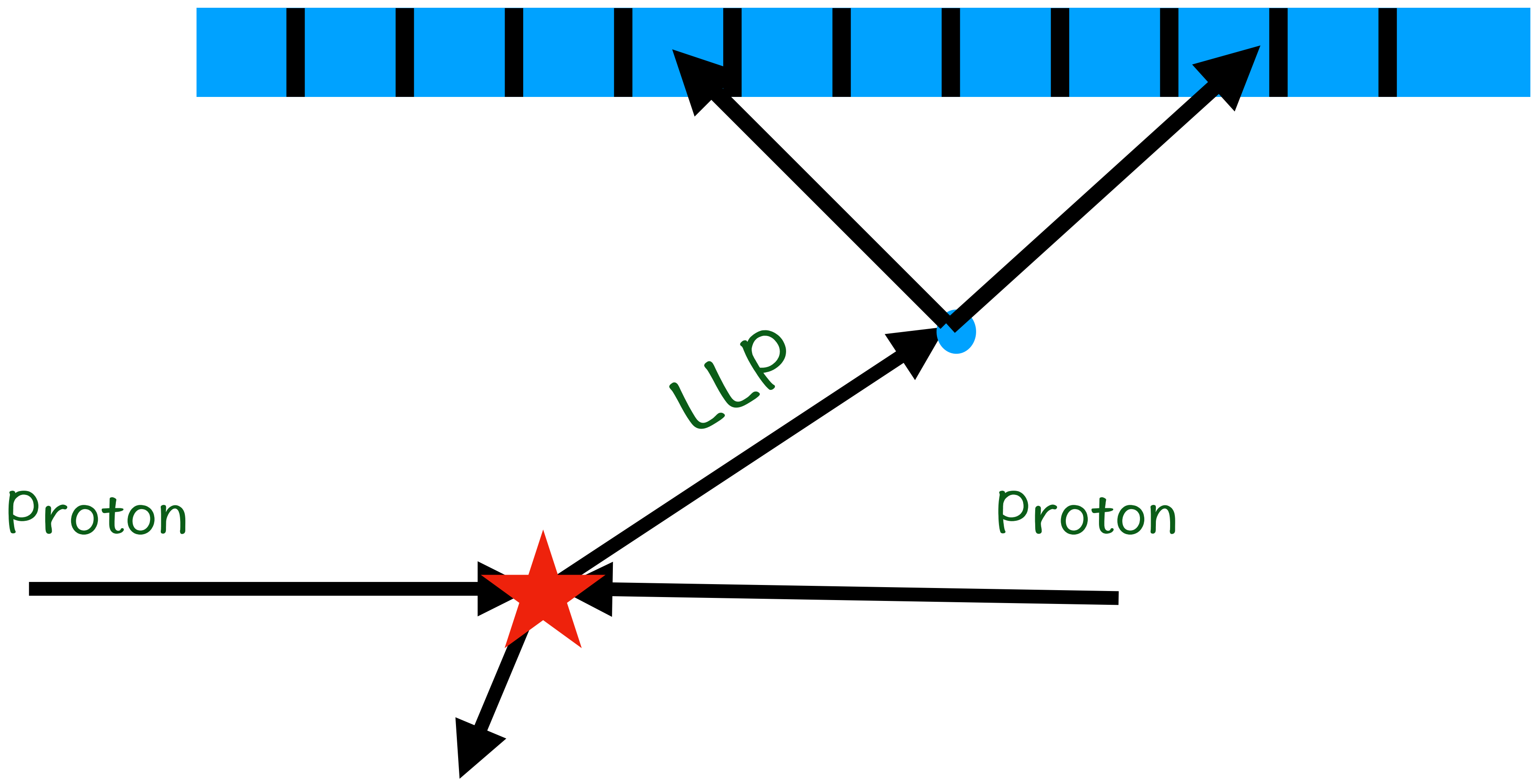
T1 -T0 can be used as a discriminant

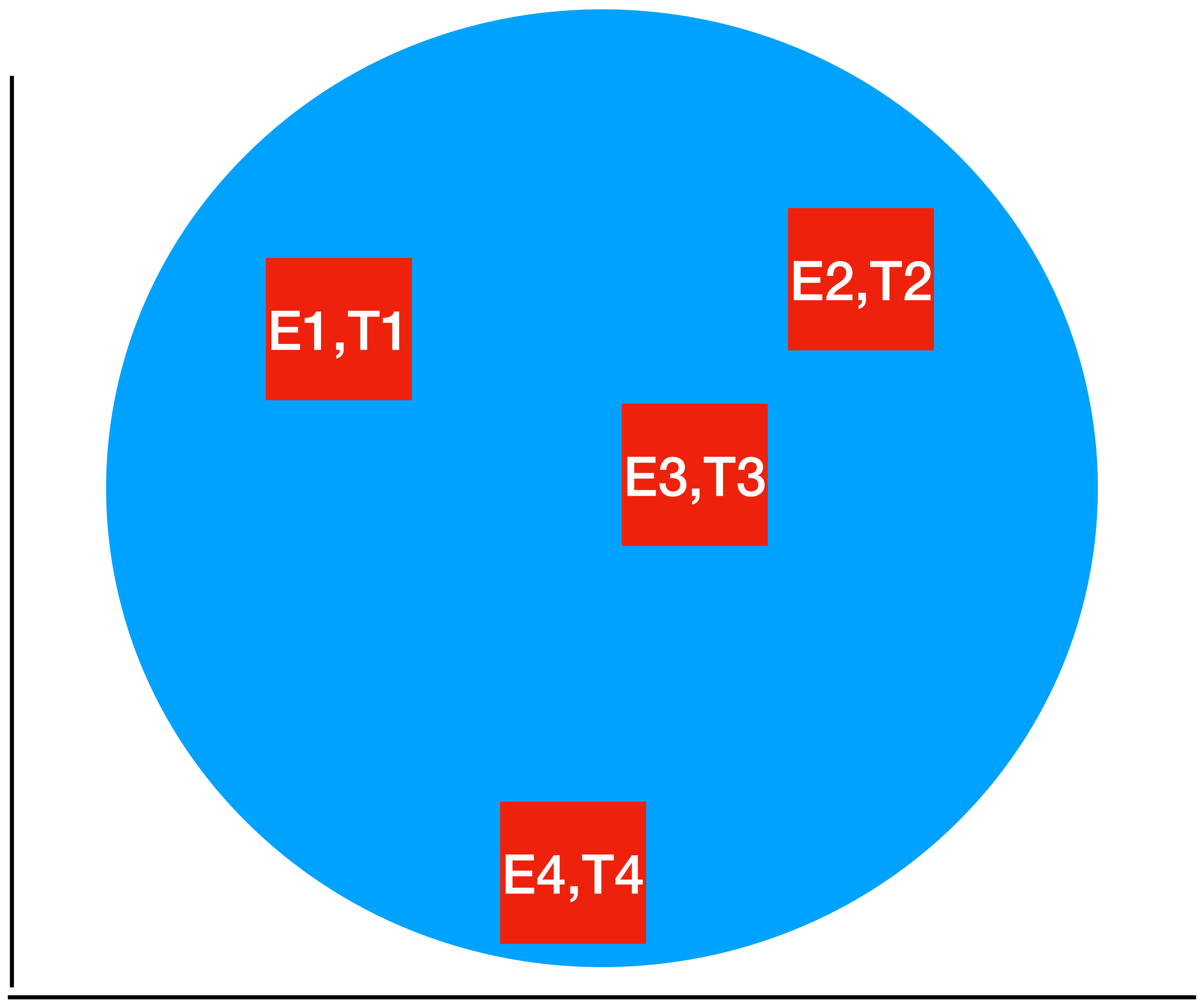


ECAL timing

ECAL barrel detector will also provide precise timing information

30ps timing resolution for 20 GeV energy deposition at the beginning of HL-LHC





Energy weighted mean time

$$\Delta T^{Ewt}_{mean} = \frac{(T_1 - T_0) * E_1 + (T_2 - T_0) * E_2 + (T_3 - T_0) * E_3 + (T_4 - T_0) * E_4}{E_1 + E_2 + E_3 + E_4}$$

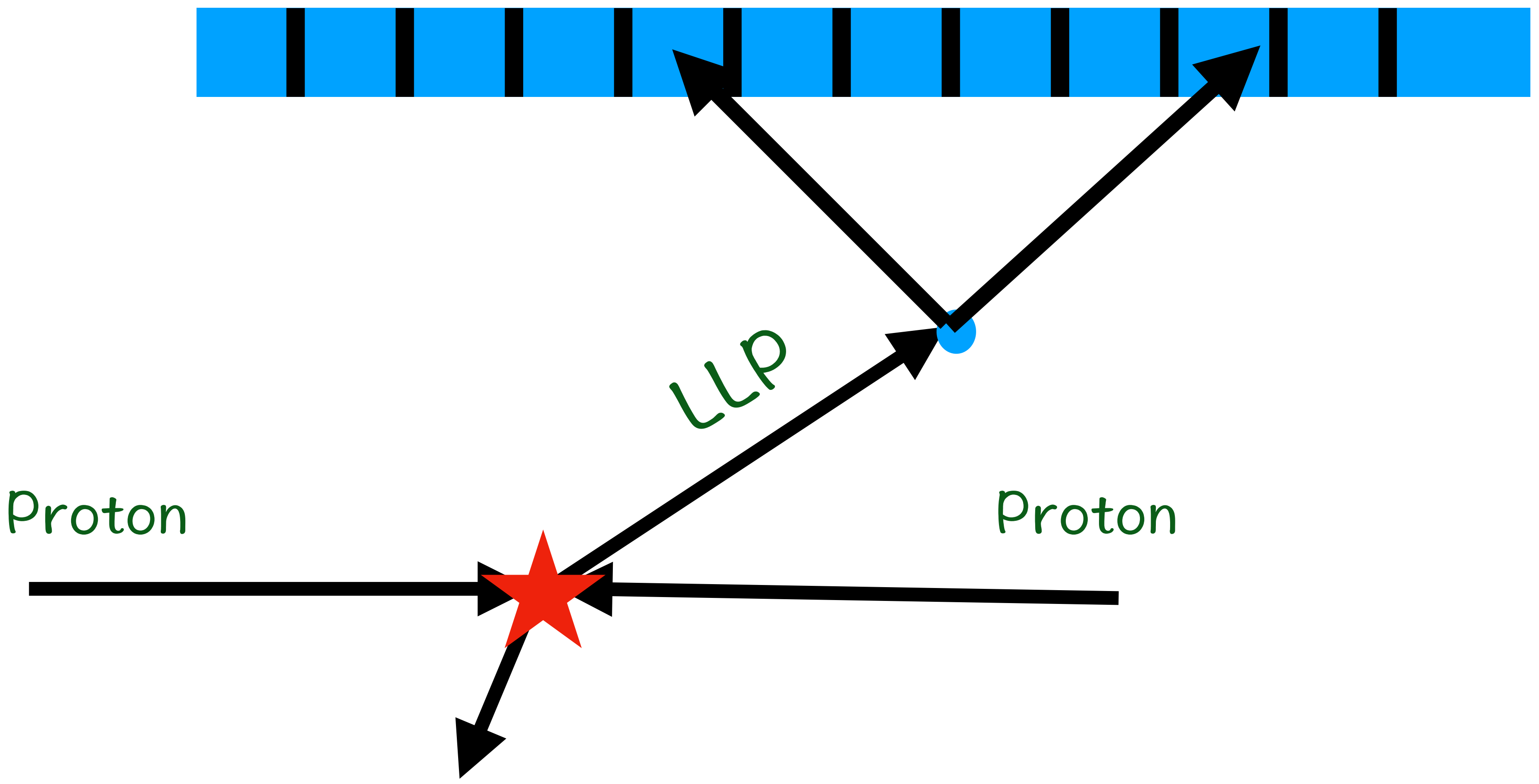
T0 = time required by a photon to reach the crystal from the origin

Electromagnetic energy deposits inside a jet

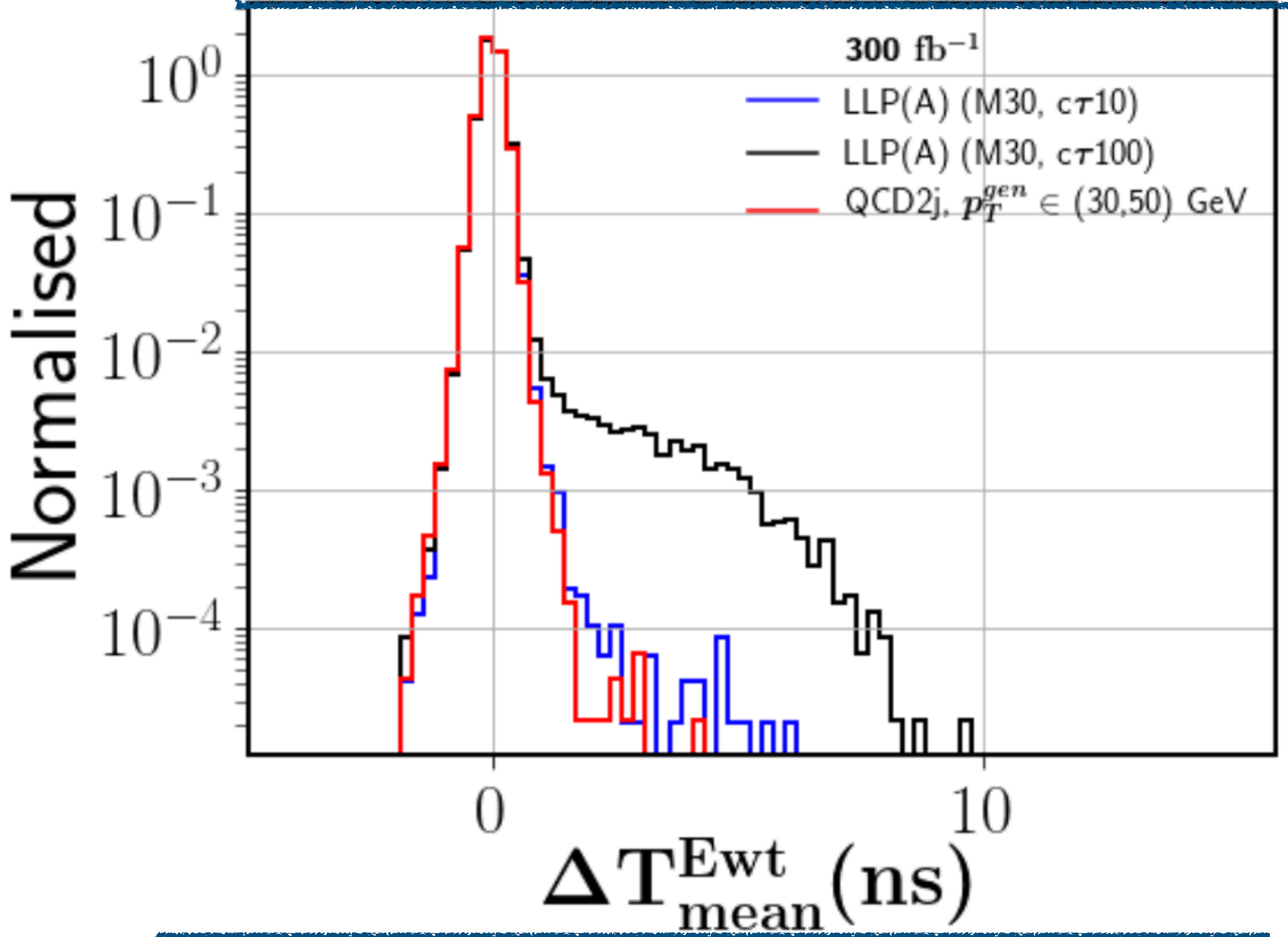
ECAL timing

ECAL barrel detector will also provide precise timing information

30ps timing resolution for 20 GeV energy deposition at the beginning of HL-LHC



LLP Model: $pp \to h \to XX, X \to q\bar{q}$



$$\Delta T^{Ewt}_{mean} = \frac{\sum \Delta T_i \times E_i}{\sum E_i}, \quad i \equiv \text{crystals inside the jet}$$

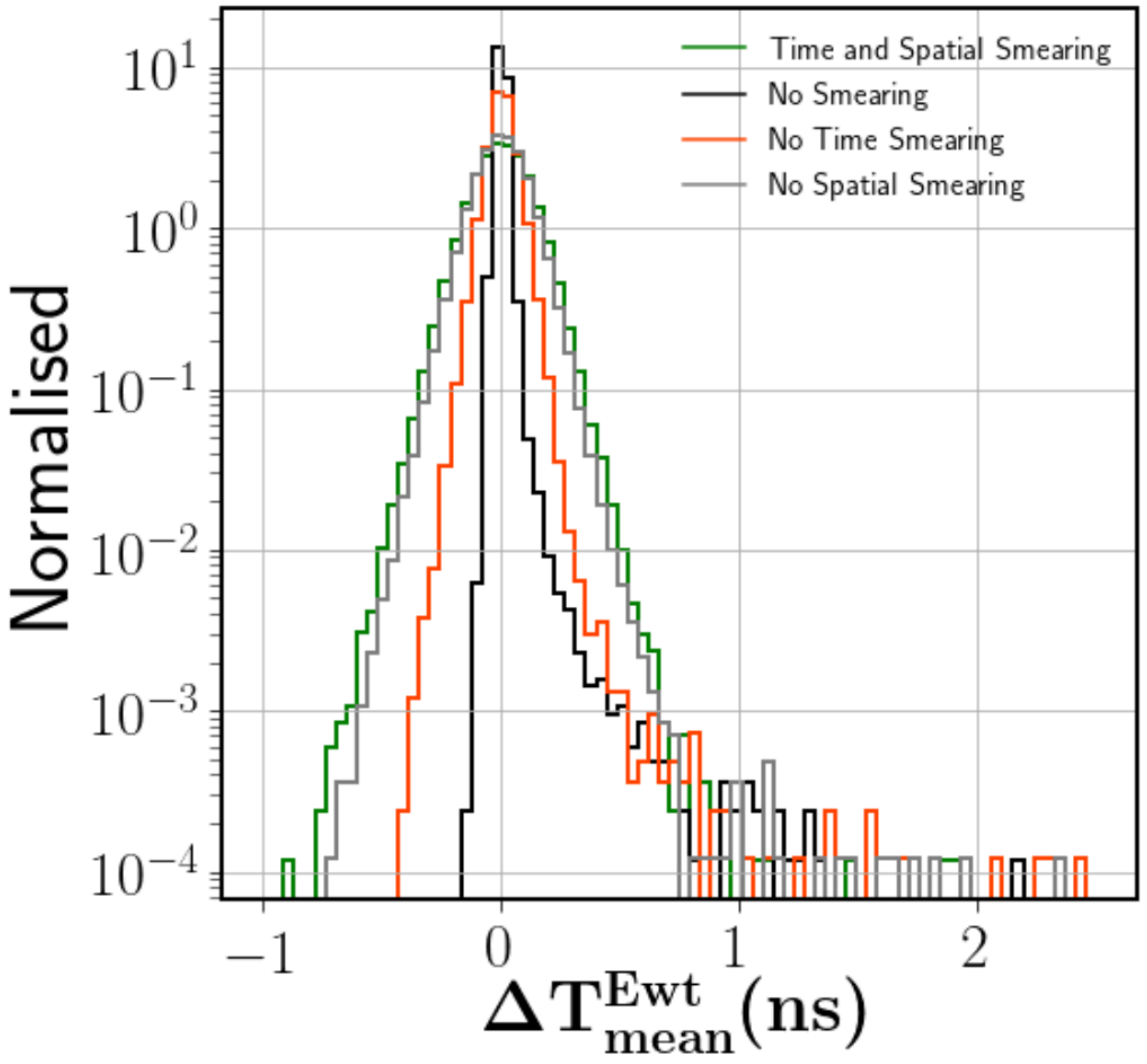
distribution is different for high decay length

QCD jets can also have a long tail

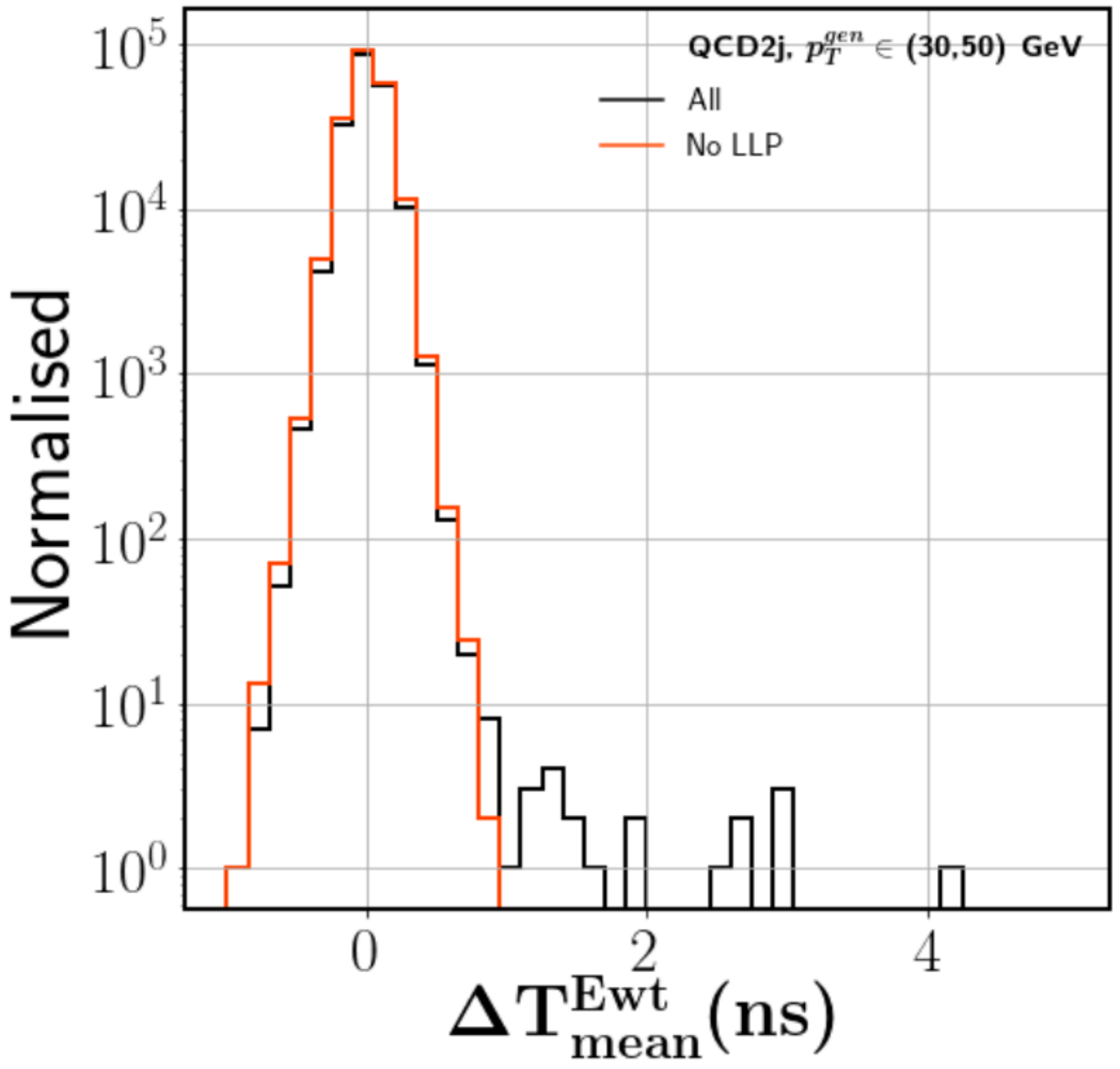
BB, Tapasi Ghosh , Rhitaja Sengupta , Prabhat Solanki
e-Print: 2112.04518, JHEP 2022

Why do prompt QCD jets having high time delays?

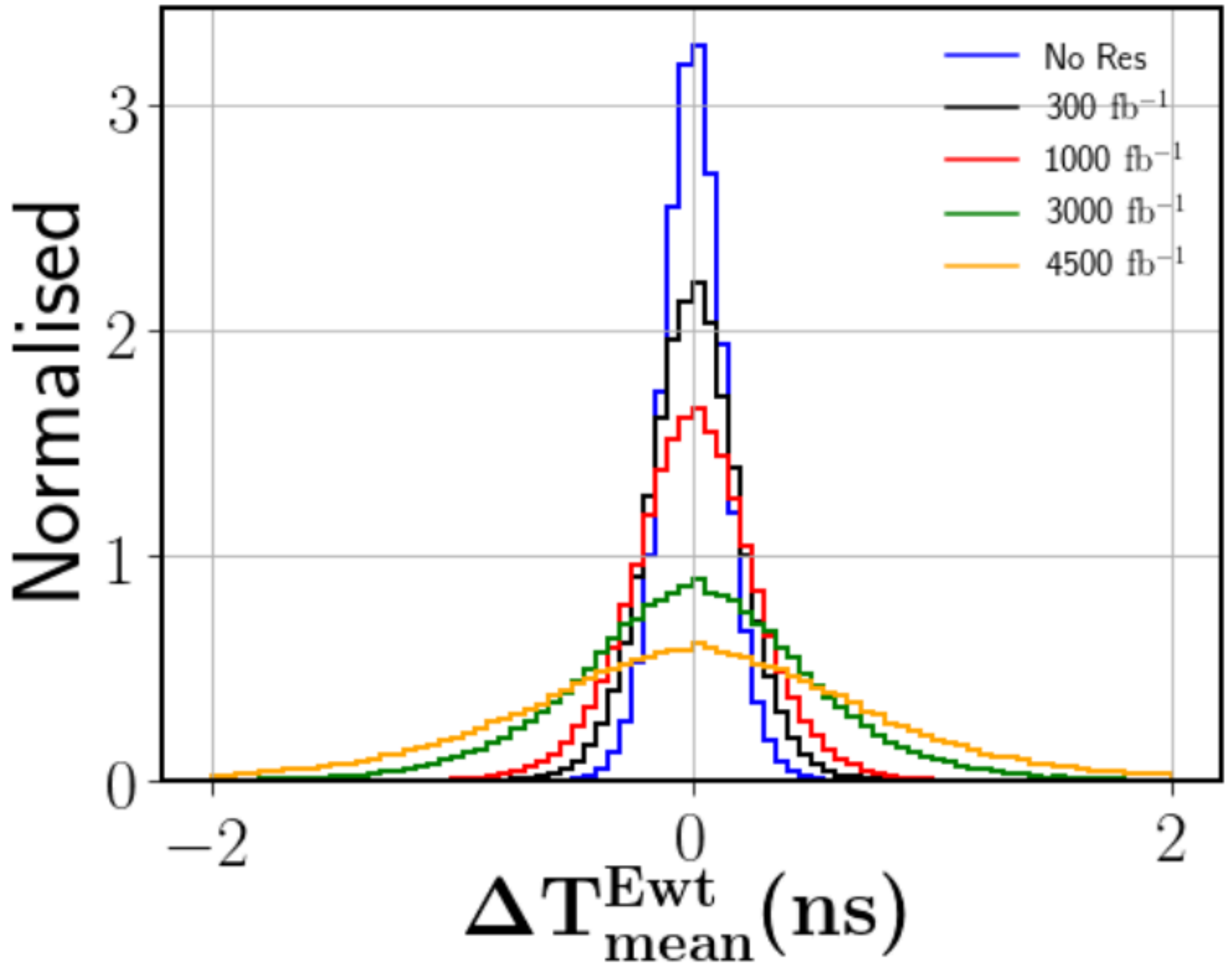
BB, Tapasi Ghosh , Rhitaja Sengupta , Prabhat Solanki
e-Print: 2112.04518, JHEP 2022



Smearing effect



LLPs in SM



ECAL resolution

Intrinsic spread of the beam-spot in both the temporal and longitudinal direction

Particles like KS, Λ , Ω etc. are long lived in the detector

ECAL resolution changes with time

Scalar Mediator : Production and decays

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu \Phi)^2 - A_{\Phi H}\Phi|H|^2 - \frac{\lambda_{\Phi H}}{2}\Phi^2|H|^2 - \mu_1^3\Phi - \frac{\mu_\Phi^2}{2}\Phi^2 - \frac{\mu_3}{3!}\Phi^3 - \frac{\lambda_\Phi}{4!}\Phi^4 + \mathcal{L}_{\rm DS},$$

Minimal model of scalar mediator with a mixing
With the SM Higgs boson

$\Phi|H|^2 \rightarrow$ Induces mixing between Φ and H -> Mass eigenstates : φ and h
Single production of φ possible,
Mixing highly constrained (For current bounds see 1811.03292)

$\Phi^2|H|^2 \rightarrow$ Not severely constrained so far, as it must be accompanied by an on-shell Higgs boson to probe it sensitively.

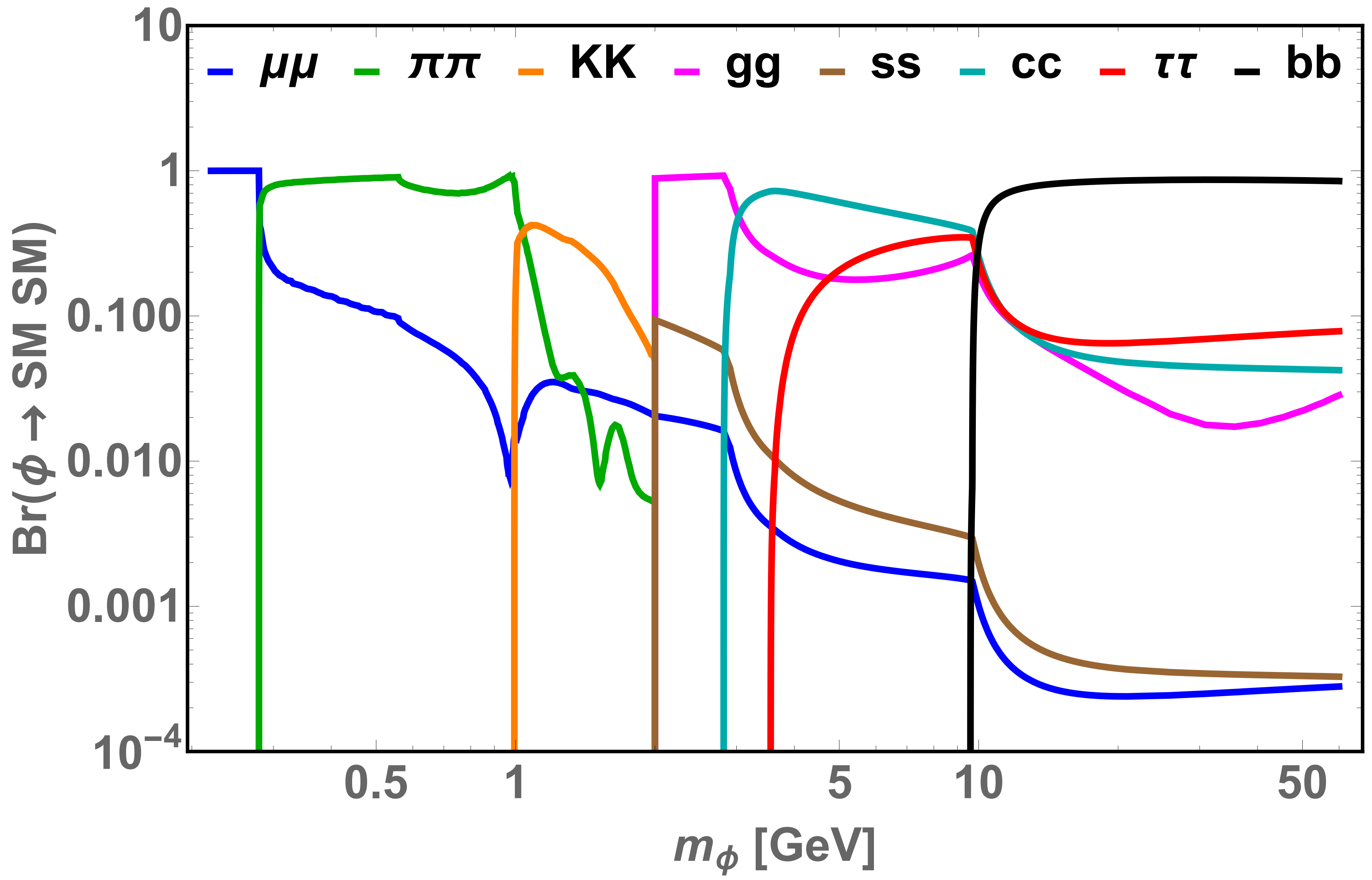
If $m_\varphi < m_h/2$ the interaction induces the Higgs boson to decay into a pair of mediator particles, i.e. $h \rightarrow \varphi\varphi$

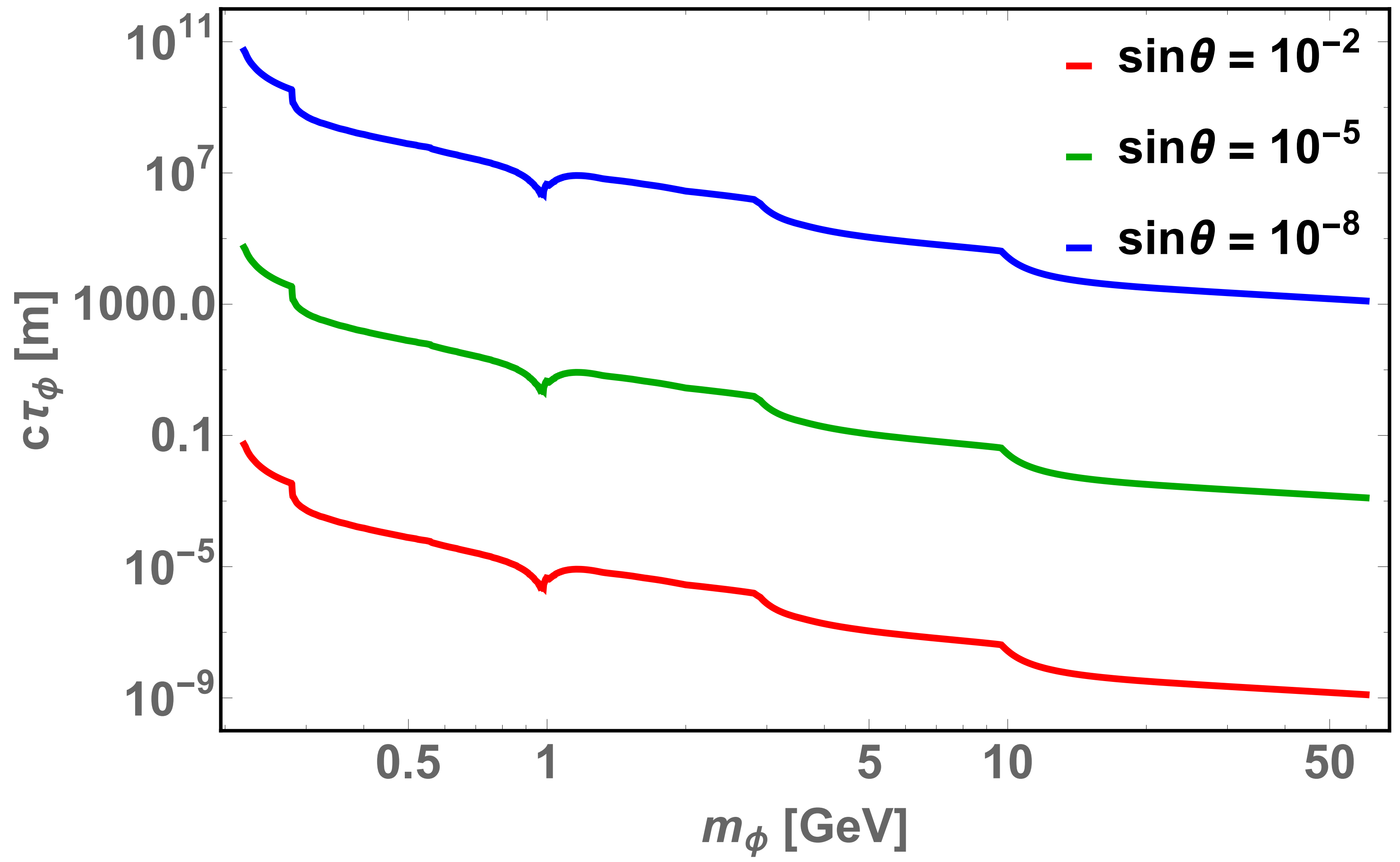
$$g_{SM\,SM\,\phi} \propto \sin\theta$$

Mixing angle θ determines the strength of the φ with SM particles

For heavy dark sector, φ will behave like SM Higgs boson with suppressed Decay width (suppression factor = $\sin^2\theta$)

For very small θ , φ can be long-lived





m_φ > a few GeV , φ will dominantly decay to jets

Signature : Displaced jets

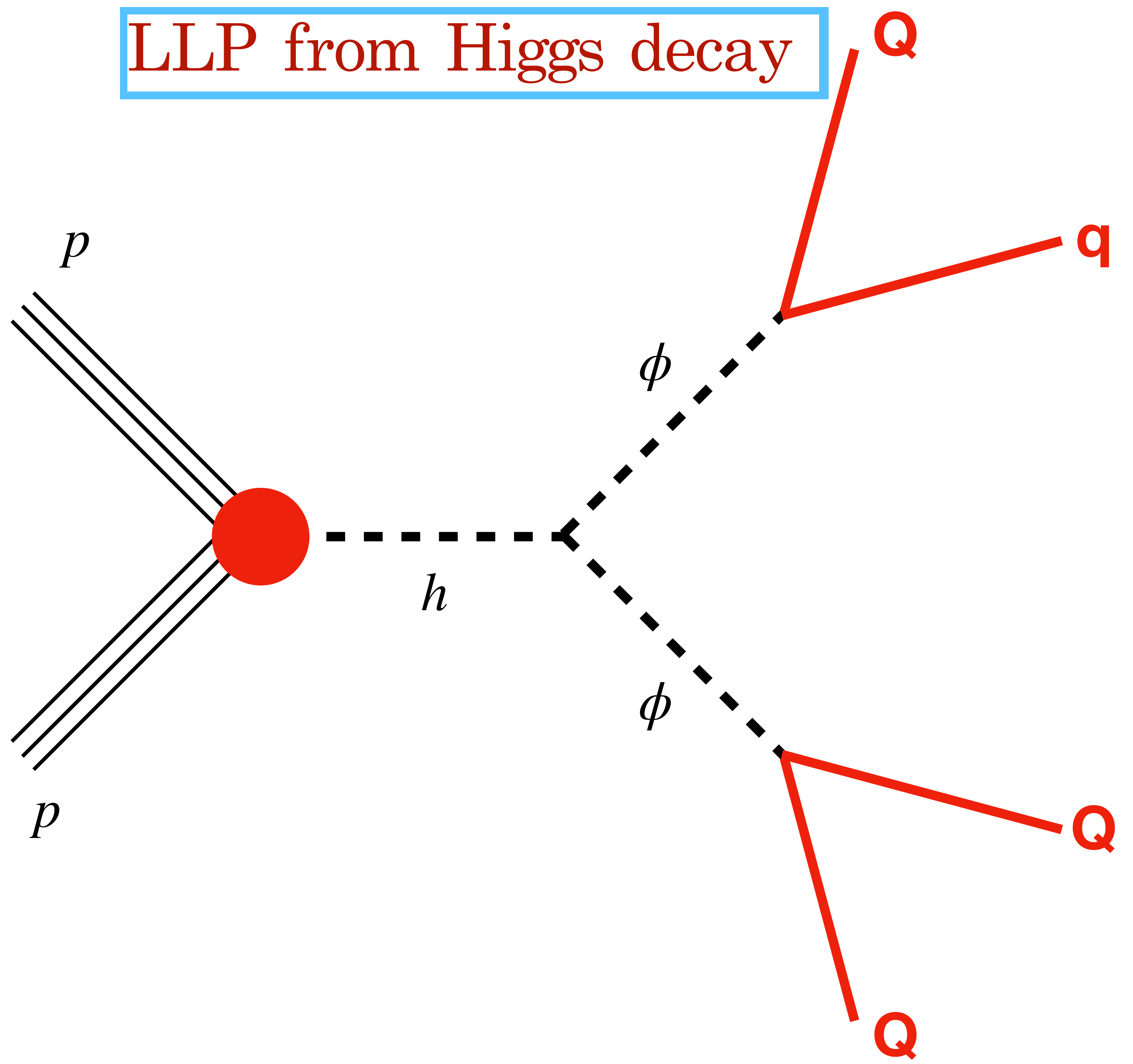
Displaced jets

Review on Exotic Higgs decays : Exotic Decays of the 125 GeV Higgs Boson

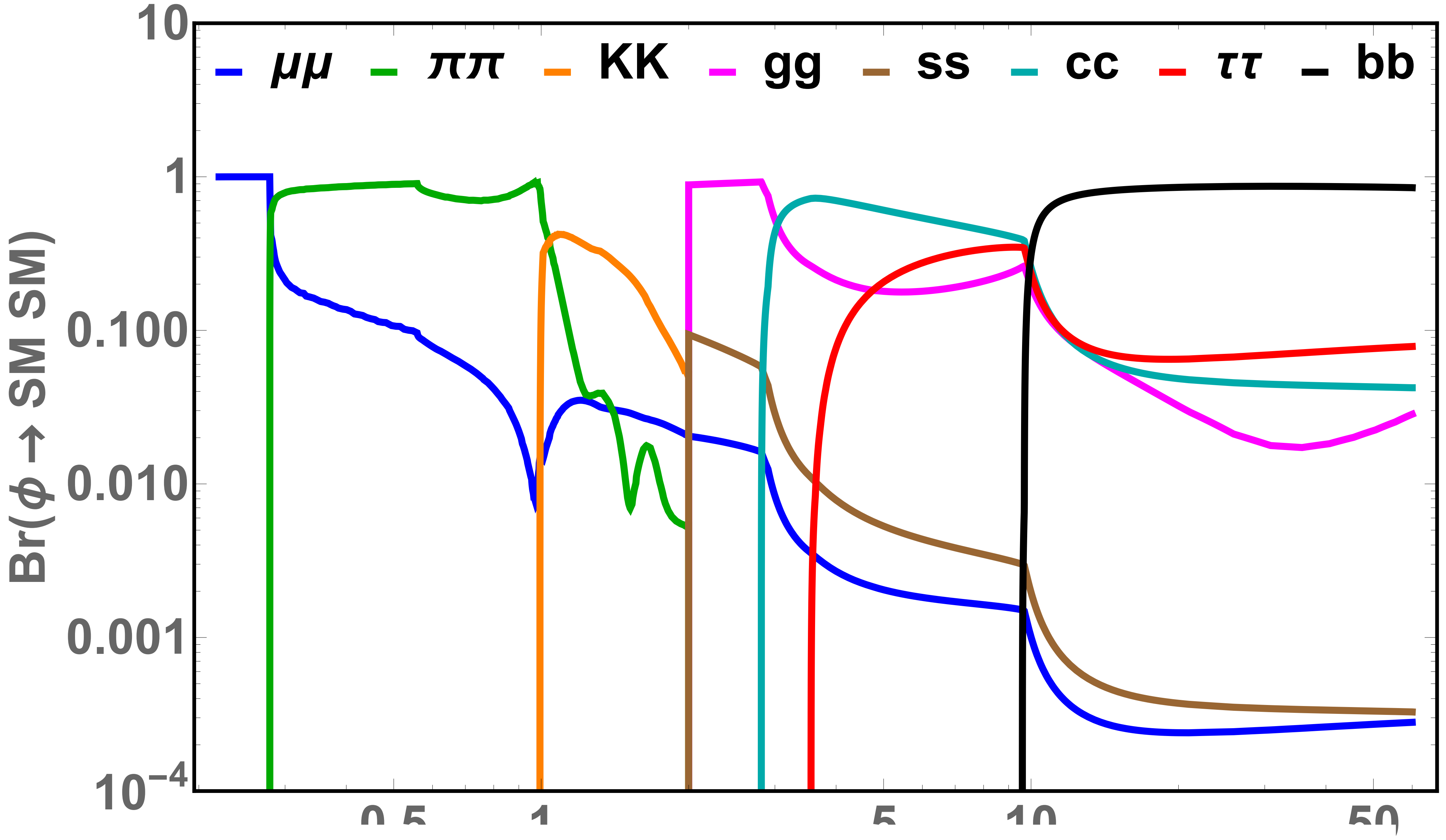
David Curtin et.al., arXiv: 1312.4992

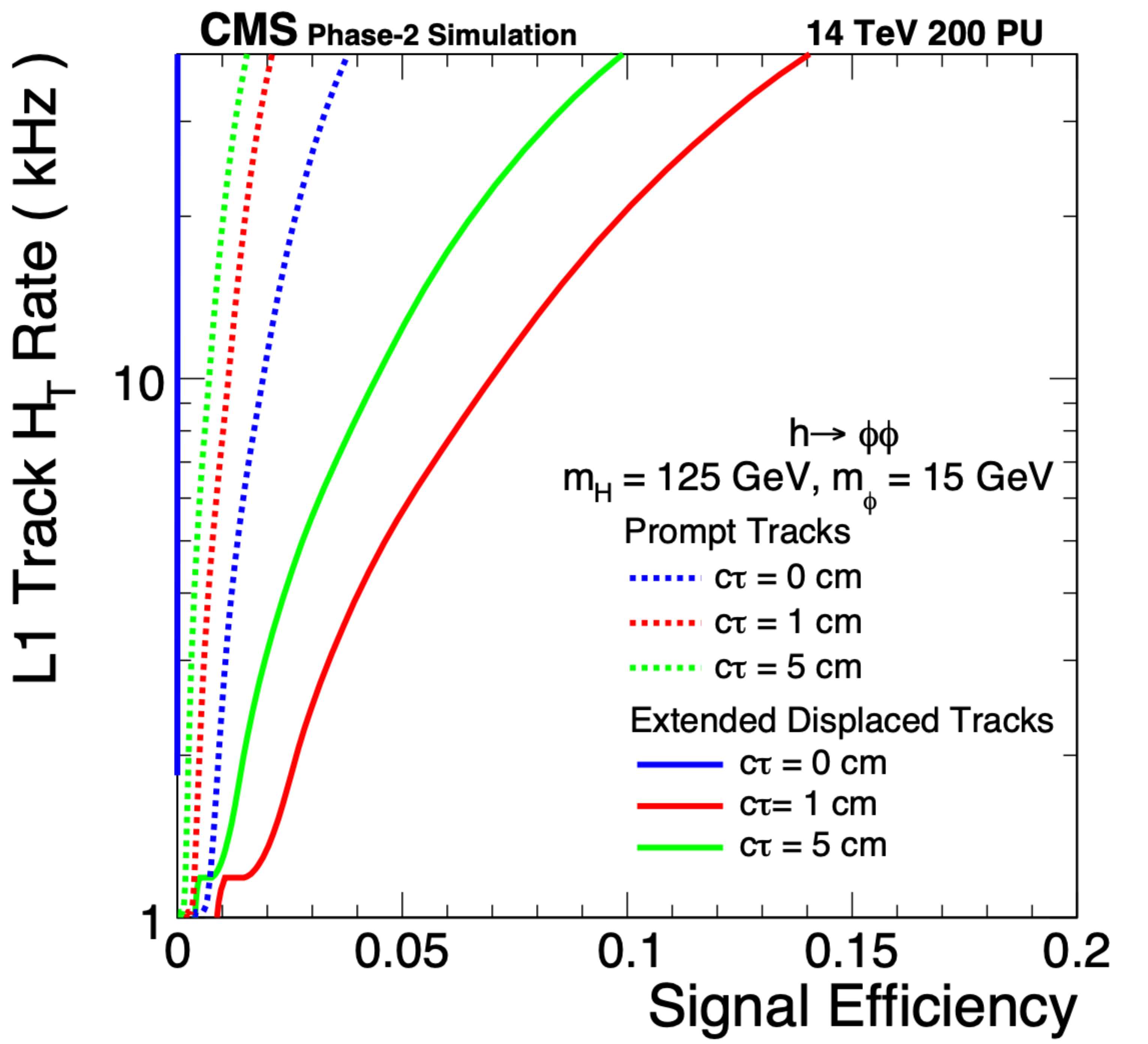
ϕ: Long-lived mediator

LLP from Higgs decay



$$\phi \to q\bar{q}$$





CMS Efficiency plot using Displaced tracks

The Phase-2 Upgrade of the CMS Level-1 Trigger, CERN-LHCC-2020-004

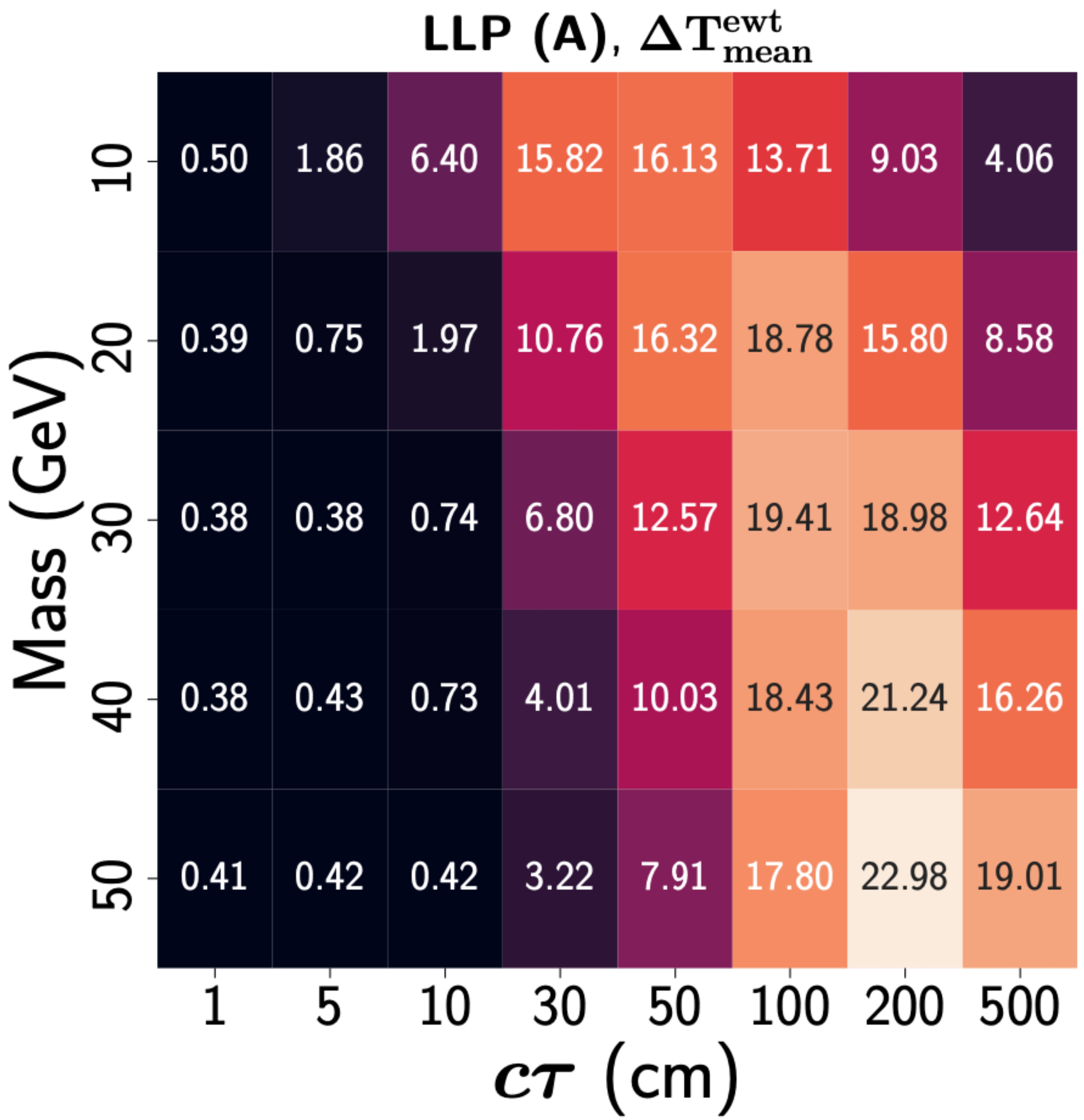
Signature : Displaced jets

ECAL timing

$$pp \to h_{125} \to \phi\phi, \phi \to b\bar{b}$$

BB, Tapasi Ghosh , Rhitaja Sengupta , Prabhat Solanki
e-Print: 2112.04518, JHEP 2022

$\Delta T^{Ewt}_{mean} > 1.1\text{ns}$ and $p_T^{jet} > 35\text{GeV}$



Other variables can be constructed.

Future sensitivity

(50 events at L1)

- $\text{Br}(h \to XX) \lesssim 6.2 \times 10^{-6}$ for $M_X = 10\,\text{GeV}$, $c\tau = 50\,\text{cm}$
- $\text{Br}(h \to XX) \lesssim 5.1 \times 10^{-6}$ for $M_X = 30\,\text{GeV}$, $c\tau = 100\,\text{cm}$
- $\text{Br}(h \to XX) \lesssim 4.3 \times 10^{-6}$ for $M_X = 50\,\text{GeV}$, $c\tau = 200\,\text{cm}$

Tracker vs CMS Muon spectrometer

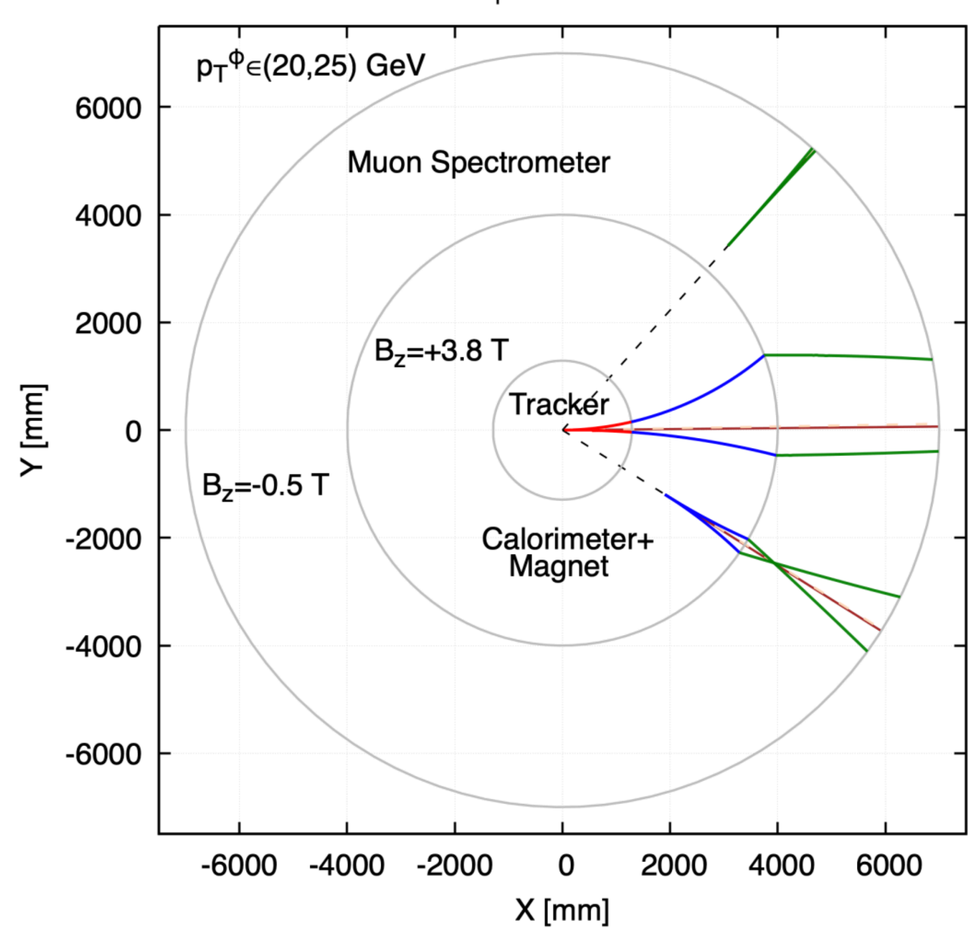
The ratio increases with the decay length

$\frac{\epsilon_{MS}}{\epsilon_{Tracker}}$ The ratio of efficiencies for the LLP (the mediator particle) which decays inside the muon spectrometer and the tracker of the CMS detector

$c\tau_\phi$ \ m_ϕ	0.5 GeV	5 GeV	50 GeV
0.01 m	0.09	0.00	0.00
0.1 m	1.10	0.09	0.00
1.0 m	1.68	1.07	0.07
10.0 m	2.04	1.67	0.85
100.0 m	-	1.59	1.53
1000.0 m	-	-	1.52

MS volume : d_T > 4m or $|d_Z|$ > 7m, and, d_T < 7m and $|d_Z|$ < 10m
tracker volume : (d_T < 1.29m and $|d_Z|$ < 3m)

LLP Model: $pp \rightarrow h \rightarrow \phi\phi$



Why Muon spectrometer

- Muon spectrometer is least affected by the increased PU rate (farthest from the IP)
- Large decay volume, suitable for LLPs
- MS has the capability to detect various final states from the mediator decay other than muons
- There exists a range of decay lengths where this ratio is equal to or greater than one

Activity in the Muon Spectrometer

LLP searches using MS by CMS/ATLAS collaborations:
1811.07370, 1911.12575, CMS PAS EXO-20-015, 2107.04833

Particles except muons will look different in the CMS MS due to their interactions with the iron yokes, i.e., they shower and give rise to a cluster of hits.

Experimental Questions : how they exactly look in the MS ? whether these hits can be reconstructed ? whether the position of the dSV can be identified with such clusters of hits

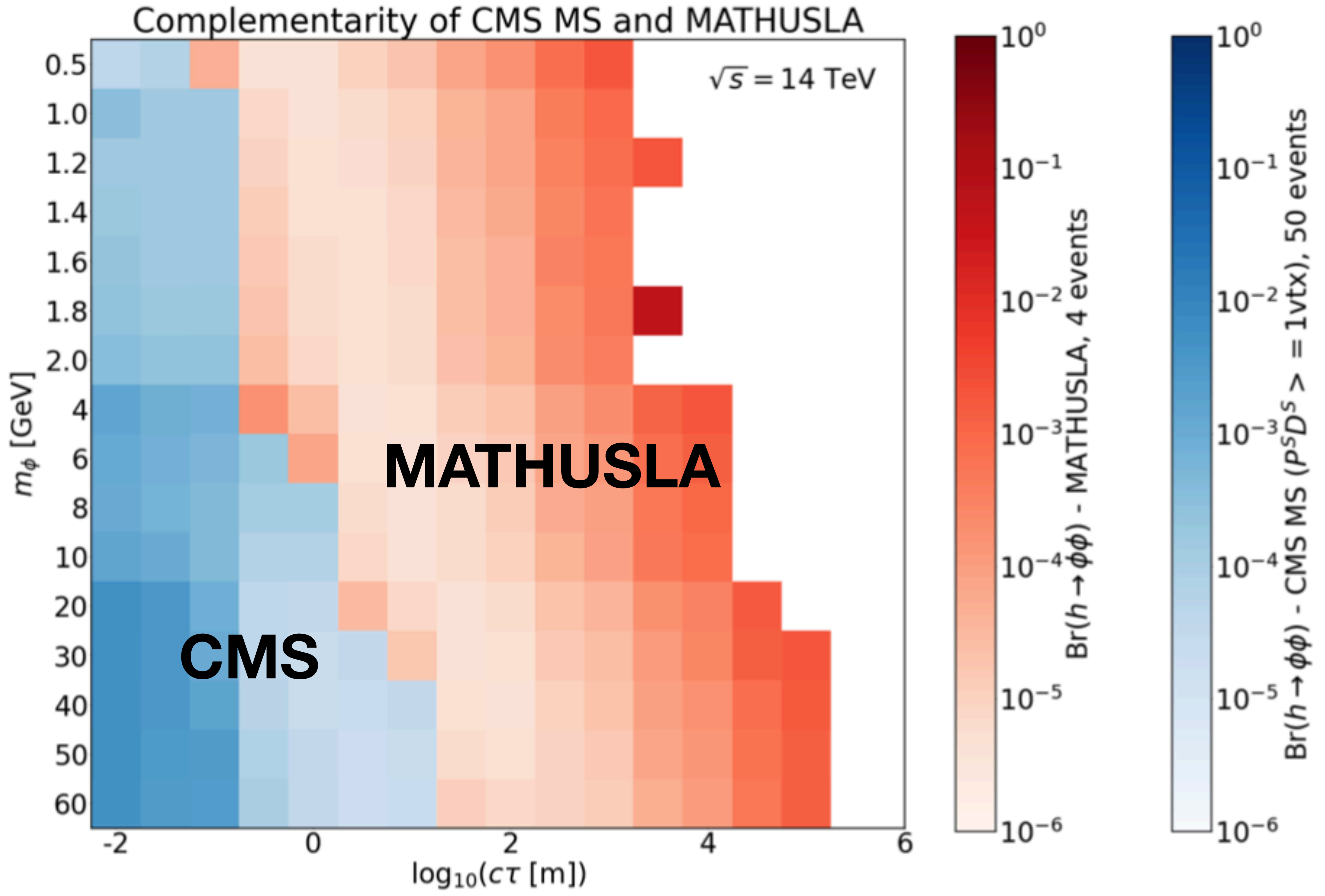
Combination of results of CMS and dedicated LLP detectors

BB, Shigeki Matsumoto, Rhitaja Sengupta
e-Print: 2111.02437, PRD 2022

LLP Model: $pp \to h \to \phi\phi$

$25 \times 100 \times 100\,\mathrm{m}^3$

$$60 < x < 85\,\mathrm{m}$$
$$-50 < y < 50\,\mathrm{m}$$
$$68 < z < 168\ \ \mathrm{m},$$



Complementarity of the CMS analyses using the muon spectrometer and the MATHUSLA LLP detector at 14 TeV with an integrated luminosity of 3000 fb^{-1}

- The dedicated detectors placed far away from the IP might be sensitive to a range of lifetimes which is complementary to the CMS MS.
- These proposed detectors will be placed a few tens of meters away from the IP of the pp collision.
- Enough shielding of rock or concrete as well as active veto to guarantee very little or almost no backgrounds.
- Therefore, observation of even a few events (∽ 4) can be claimed as a discovery of displaced decays of particles.

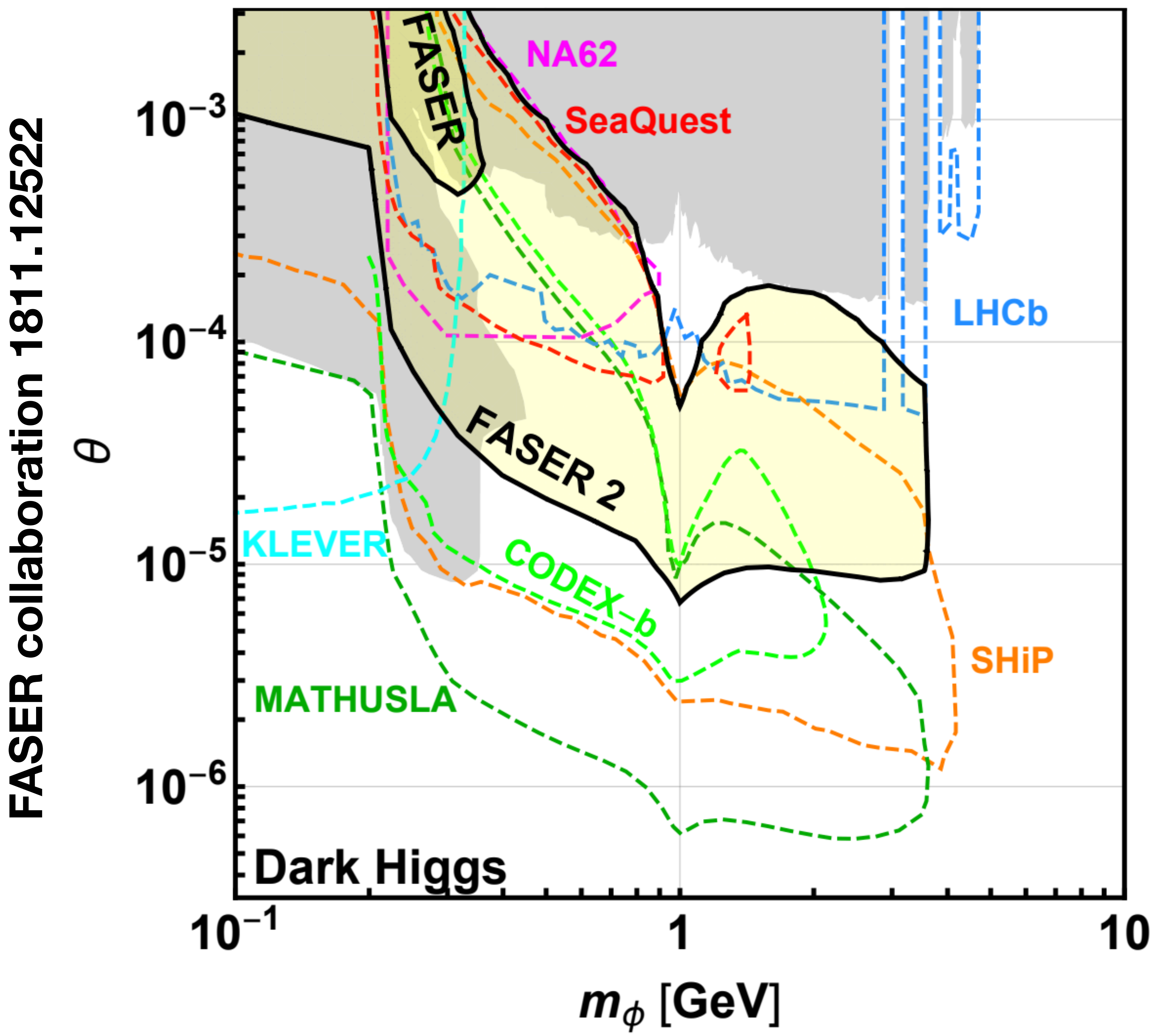
Dedicated Forward Detector : FASER

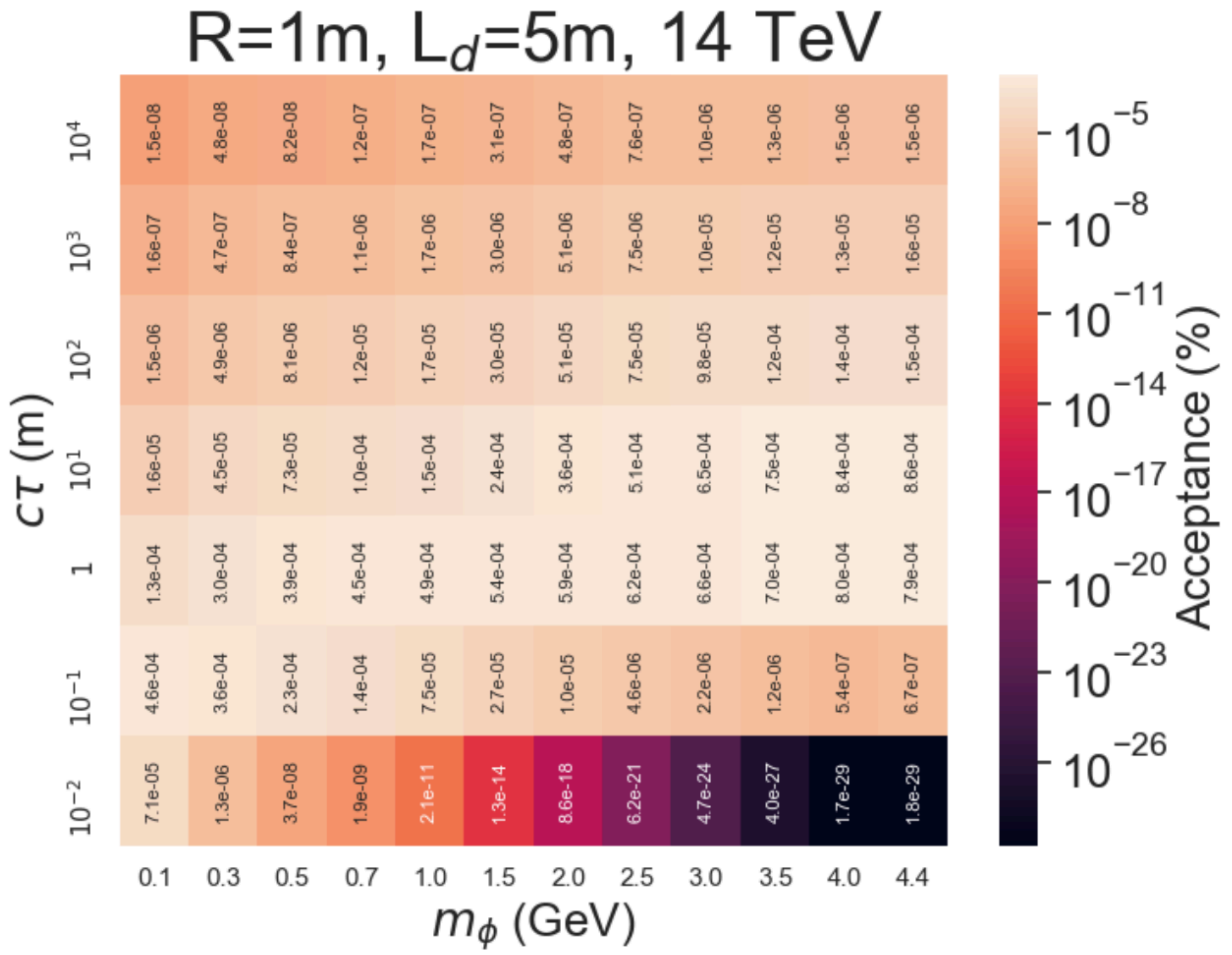
BB, Herbi Dreiner, Nivedita Ghosh, Shigeki Matsumoto,, Rhitaja Sengupta , Prabhat Solanki
e-Print: 2306.11803

Light Dark Higgs can also be produced from the decay of hadrons.

$$B^{\pm} \rightarrow \phi K^{\pm}$$

$$Br(B^{+} \rightarrow \phi + K^{+}) \sim 5.7 \sin^2 \theta$$





Various dump experiments, LHCb, MATHUSLA are sensitive

FASER: ForwArd Search ExpeRiment at the LHC J. L. Feng, I. Galon, F. Kling, and S. Trojanowski arXiv: 1708.09389
Long-Lived Particles at the Energy Frontier: The MATHUSLA Physics Case, Curtin et. Al., 1806.07396
Search for Higgs-like bosons decaying into long-lived exotic particles LHCb collaboration , arXiv: 1609.03124

FCC-hh

International FCC collaboration has been working on the design for PP collider at the CoM energy 100 TeV

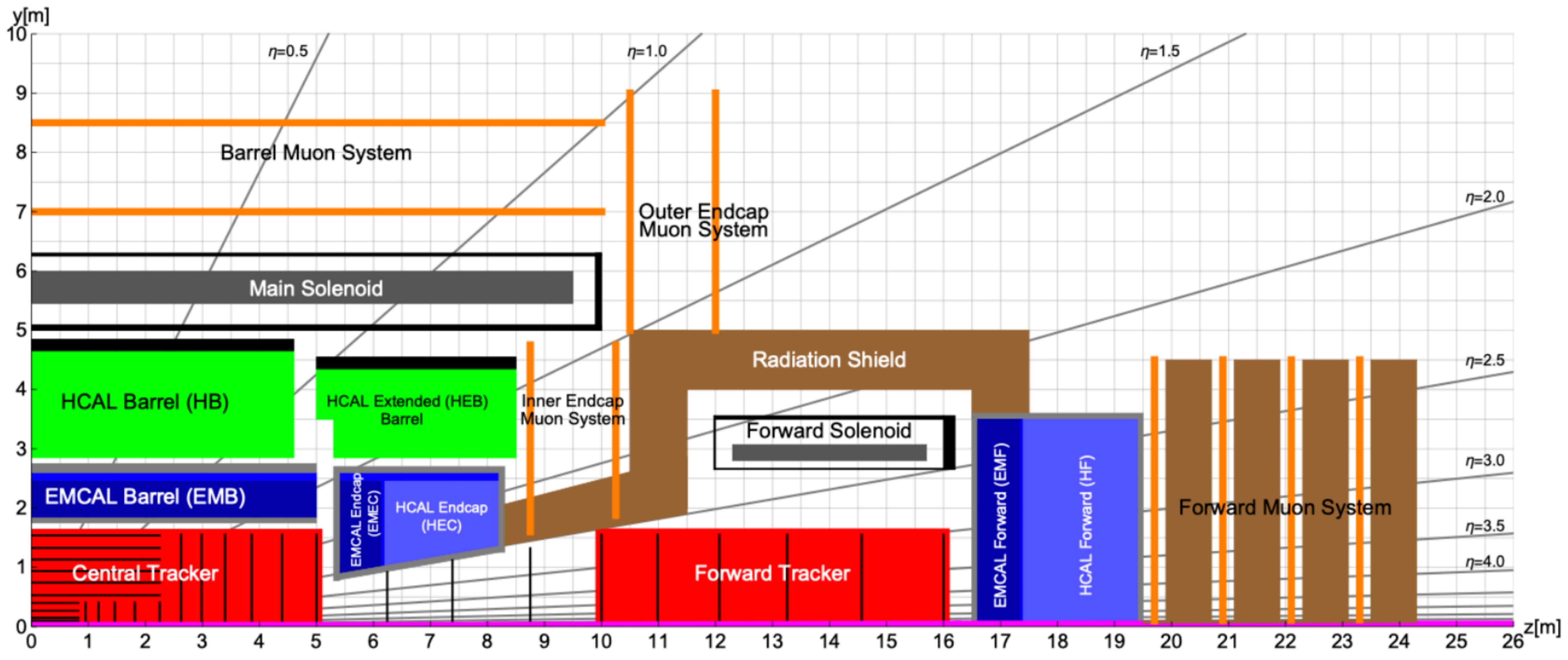
- Conceptual Design Report (CDR) published in 2019
- 25 years of run can accumulate 20k-30k ifb of data
- 2 main detectors will be placed (combination of results possible)
- For 125 GeV Higgs boson gain ~150 in the ggF channel and ~ 400 in the di-Higgs, ~ 500 in the ttH

$\sqrt{s}$ [TeV]	Process	Cross section [pb]
14	ggF	50.35
	VBF	4.172
	Vh	2.387 (Wh:1.504, Zh:0.8830)
100	ggF	740.3
	VBF	82.00
	Vh	27.16 (Wh:15.90, Zh:11.26)

$$\begin{aligned} \textbf{Tracker:} \quad & R \leq 1.5\,\text{m}, \quad |Z| \leq 5\,\text{m}, \\ \textbf{Barrel + Endcap MS:} \quad & 6\,\text{m} \leq R \leq 9\,\text{m}, \quad 9\,\text{m} \leq |Z| \leq 12\,\text{m}, \quad \eta \leq 2.5, \\ \textbf{Forward MS:} \quad & 12\,\text{m} \leq |Z| \leq 23\,\text{m}, \quad 2.5 \leq \eta \leq 5.0. \end{aligned} \tag{4.1}$$

FCC-hh Reference Detector

50m long, 20m diameter
Cavern length 66m
L* of FCC 40m.



90% of 'heavy' physics will take place in η<2.5.

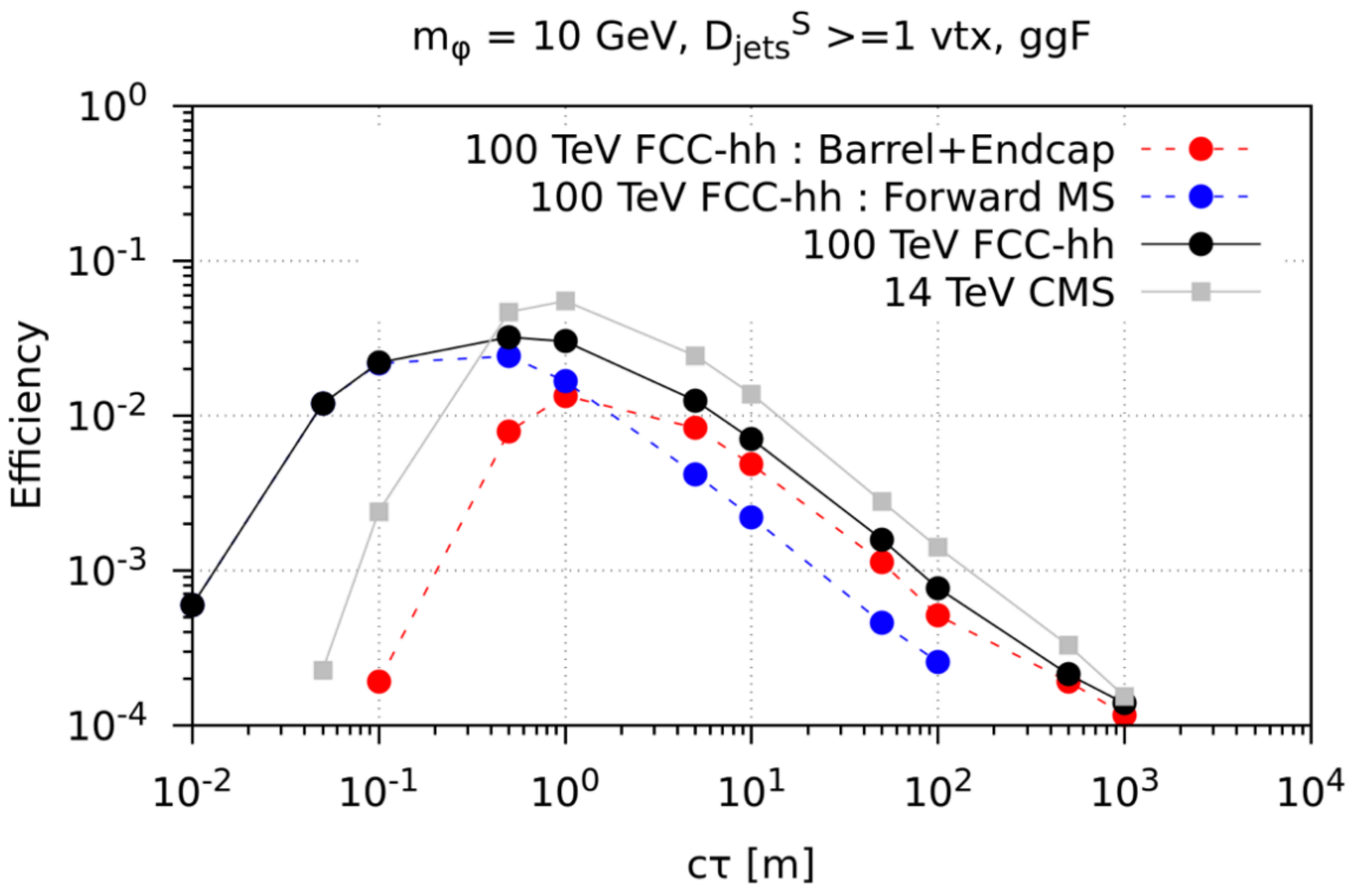
Increase of acceptance for precision spectroscopy and calorimetry from 2.5 at LHC to 3.8-4 for SM physics.

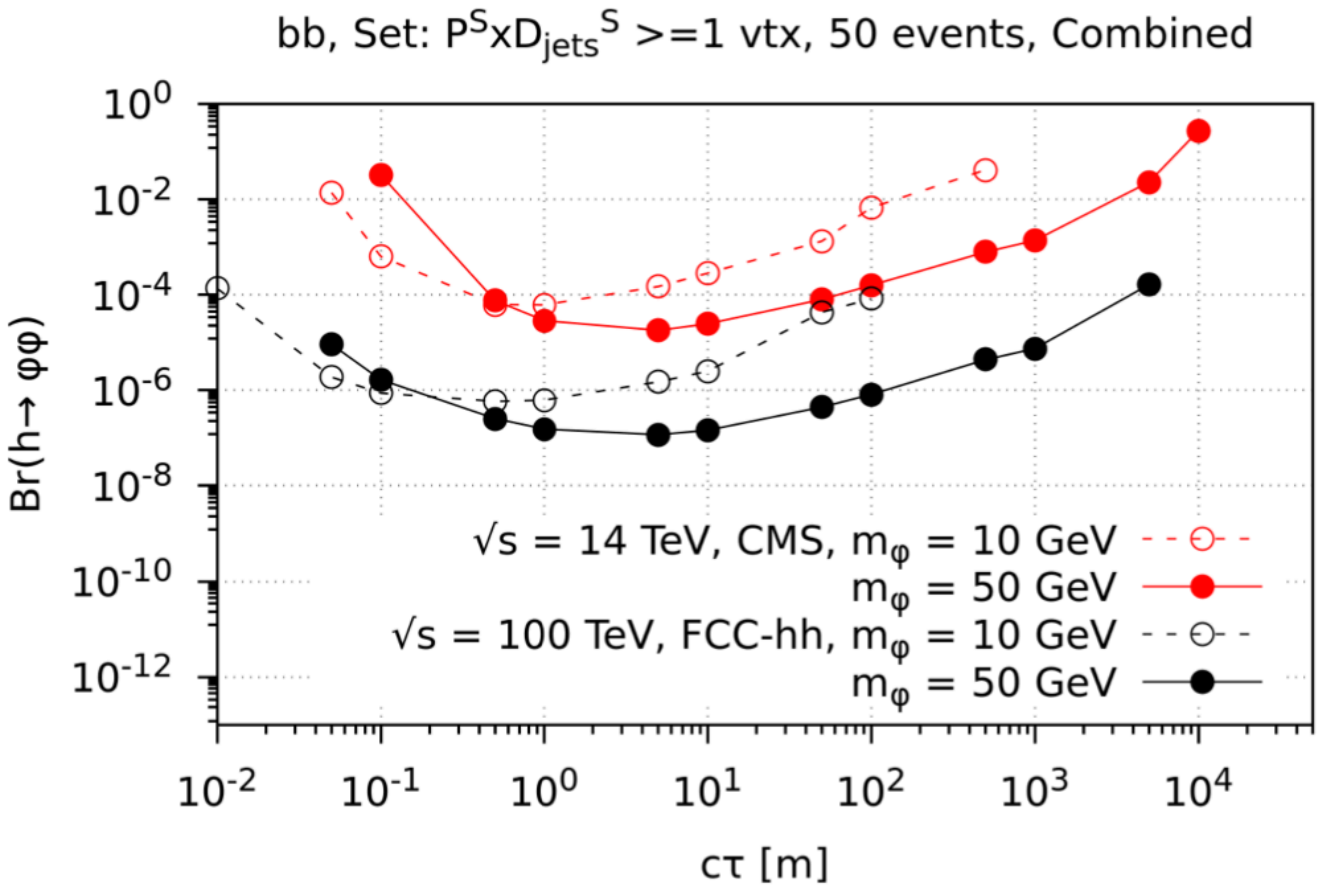
https://indico.cern.ch/event/789349/contributions/3298692/attachments/1805766/2946875/fcc_hh_detector_cdr_presentation_feb_2019.pdf

FCC-hh : Future projections

LLP Model: $pp \to h \to \phi\phi$

BB, Shigeki Matsumoto, Rhitaja Sengupta
e-Print: 2111.02437, PRD 2022





(Comparison of the efficiencies as a function of decay lengths)

- We use the same cuts as we used for the CMS analysis
- Combined 100 TeV efficiency is larger than that achieved in 14TeV by a factor of ∽ 1.4.
- Addition of forward MS with that in the barrel and endcap MS of FCC-hh, improves the limits by around 15-20%.
- The enhancement due to the forward MS is more for lower decay lengths

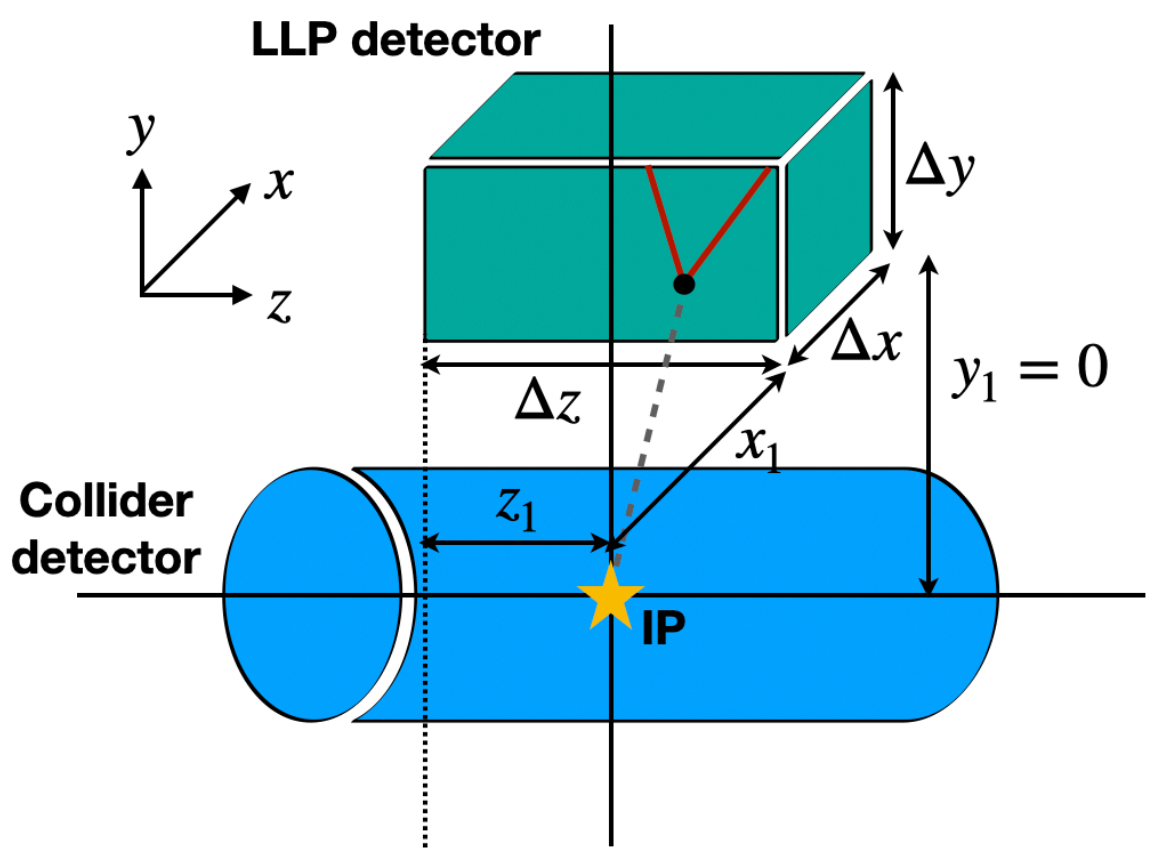
.

Dedicated LLP detector for FCC-hh

BB, Shigeki Matsumoto, Rhitaja Sengupta
e-Print: 2111.02437, PRD 2022

Advantage: The collider, as well as the detectors, are not yet constructed, possible to optimise the position as well as the size of the detector to maximise its sensitivity, rather than finding empty spaces near the various IPs to place and fit the LLP detectors for the HL-LHC experiment.

We here propose three designs of a dedicated LLP detector DELIGHT (**De**tector for **l**ong-l**i**ved particles at hi**gh** energy of 100 **T**eV), a box-type detector in the periphery of the FCC-hh collider



DELIGHT (A): The same as the dimensions of the MATHUSLA detector, i.e. $\Delta x \times \Delta y \times \Delta z = 25 \times 100 \times 100\,\mathrm{m}^3$.

DELIGHT (B): Four times bigger than the MATHUSLA detector, i.e. $\Delta x \times \Delta y \times \Delta z = 100 \times 100 \times 100\,\mathrm{m}^3$.

DELIGHT (C): The same decay volume as the MATHUSLA detector with different dimensions, i.e. $\Delta x \times \Delta y \times \Delta z = 200 \times 50 \times 50\,\mathrm{m}^3$.

A position starting at around 25 m in the x-direction around η = 0 region can be kept empty for placing a dedicated LLP detector.

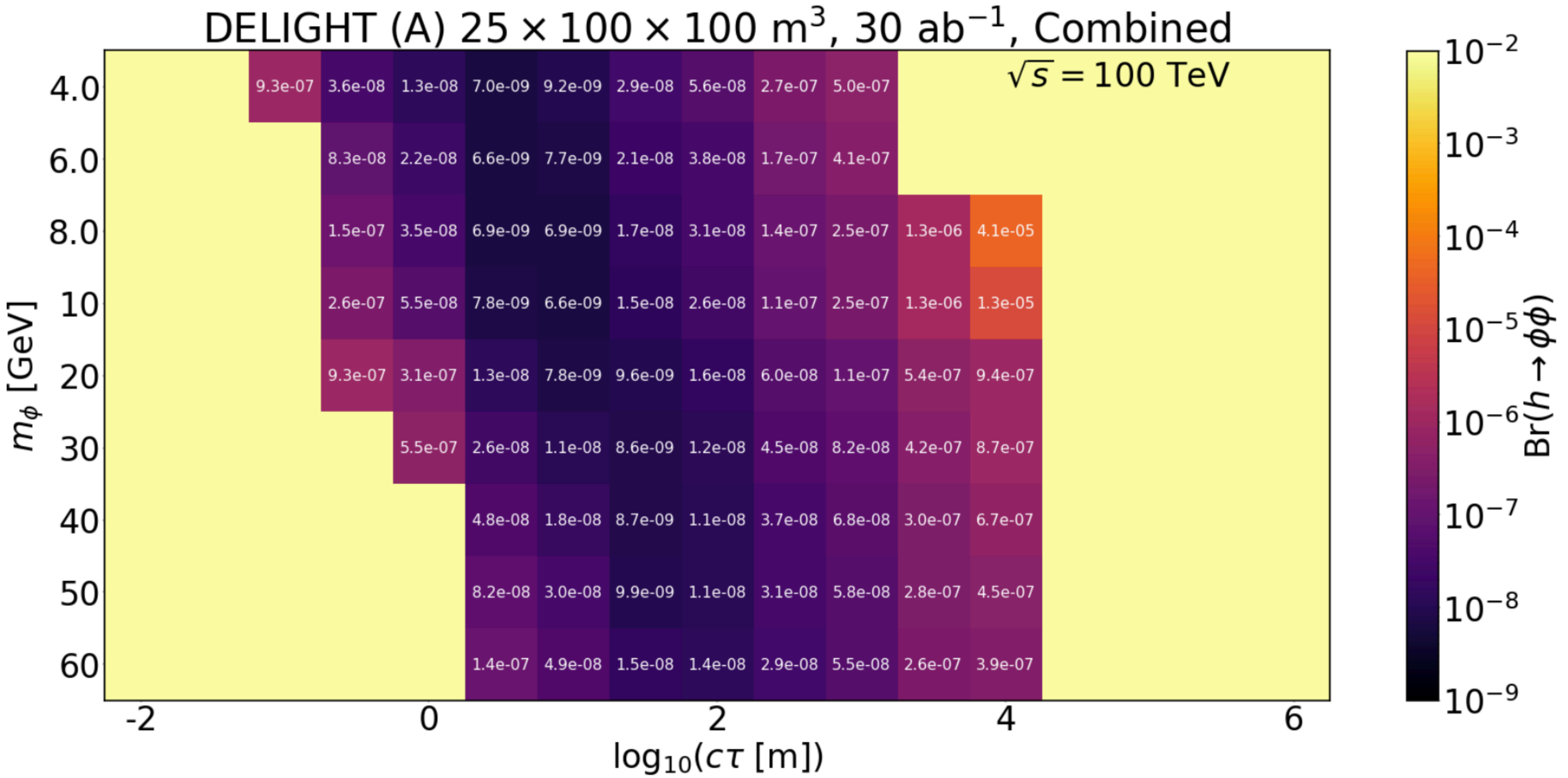
LLP detectors for FCC-ee is proposed here : 2011.01005

DELIGHT (A)

DELIGHT (A): The same as the dimensions of the MATHUSLA detector, i.e. $\Delta x \times \Delta y \times \Delta z = 25 \times 100 \times 100\,\text{m}^3$.

BB, Shigeki Matsumoto, Rhitaja Sengupta
e-Print: 2111.02437, PRD 2022

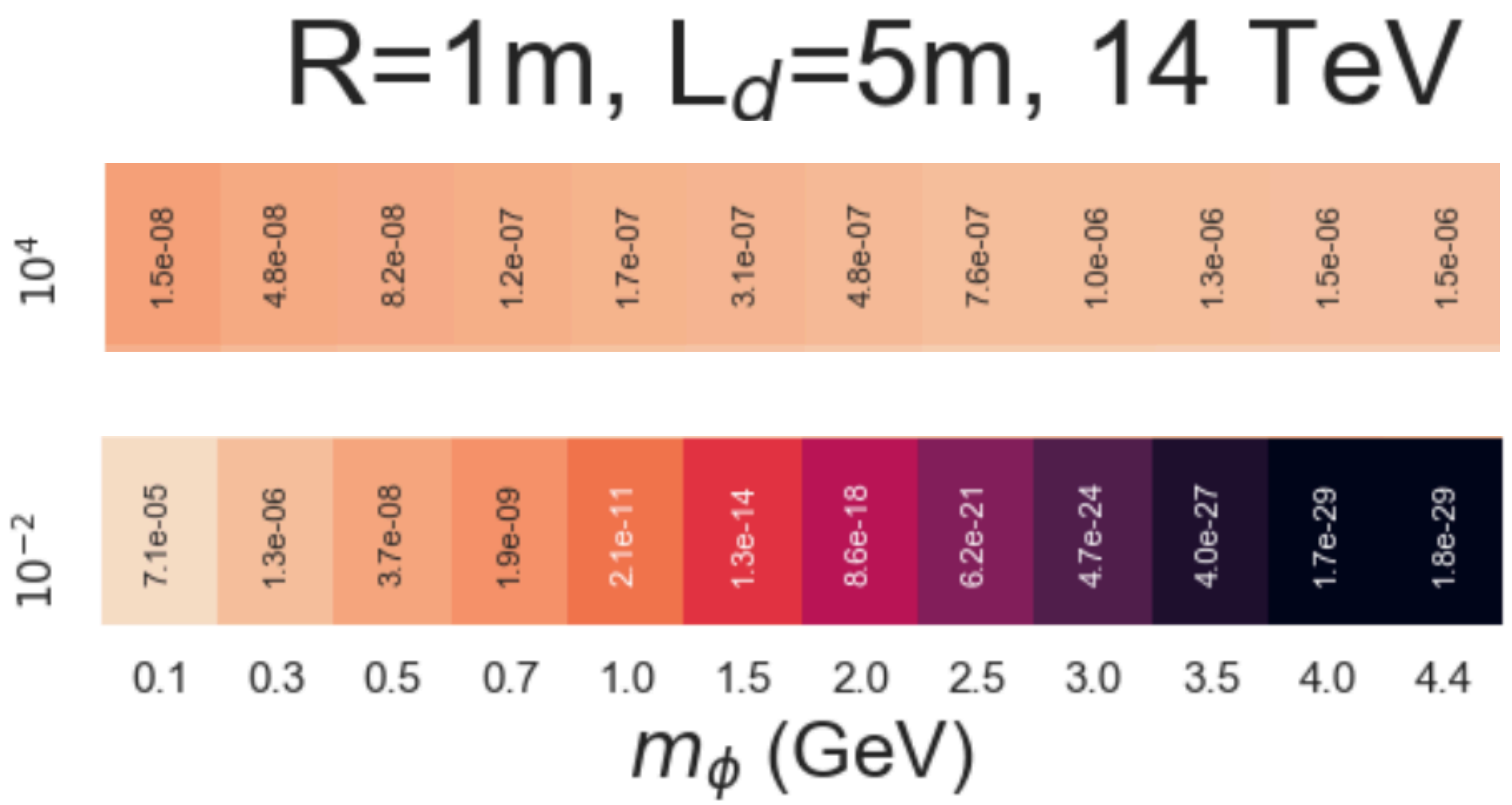
LLP Model: $pp \to h \to \phi\phi$

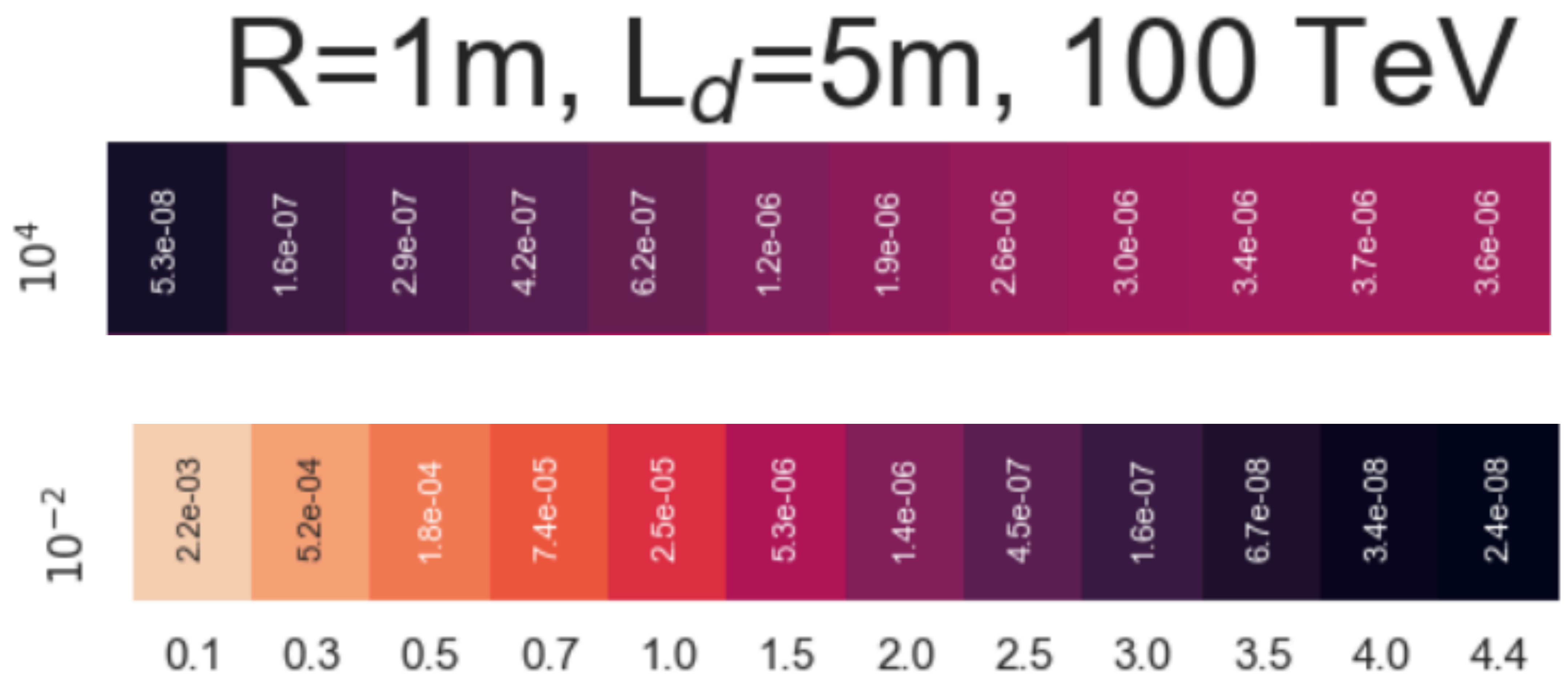


DELIGHT(A) vs MATHUSLA: an improvement by a factor of ~ 540,
around ~ 150 from increased cross-section and integrated luminosity,
another factor of ~ 3–4 is gained by moving the detector close to the IP.
Central position of the detector can benefit light LLPs.

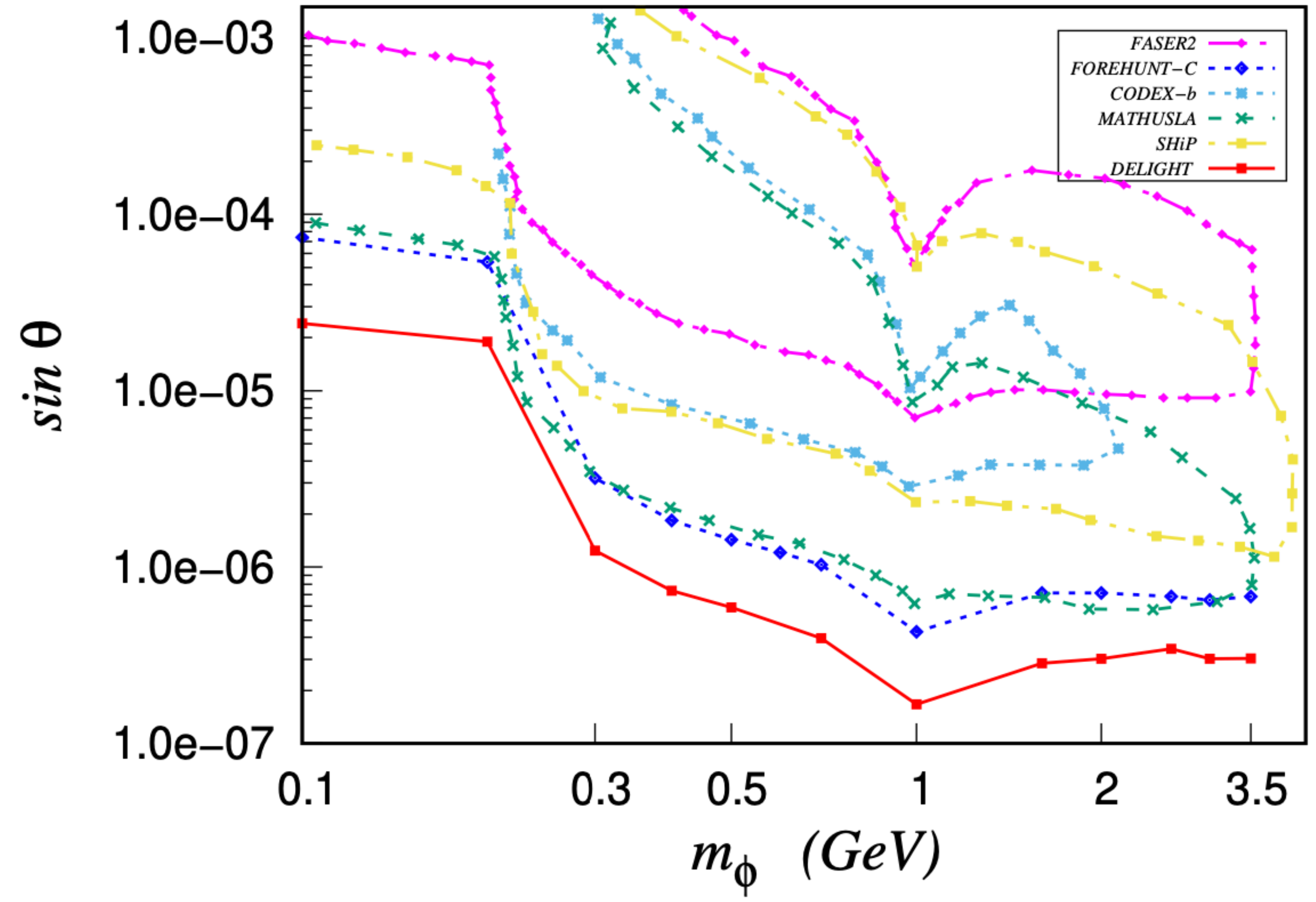
Proposal for Forward detector at Fcc-hh

BB, Herbi Dreiner, Nivedita Ghosh, Shigeki Matsumoto,, Rhitaja Sengupta , Prabhat Solanki
e-Print: 2306.11803





Proposal for a dedicated forward detector, **FOREHUNT (FORward Experiment for HUNdred TeV),** for 100 TeV FCC-hh



Many interesting ideas not covered in my talk

LLP ML

Fast Neural Network Inference on FPGAs for Triggering on Long-Lived Particles at Colliders,
A. Coccaro , F. Armando Di Bello, S. Giagu, L. Rambelli and N. Stocchetti (arXiv: 2307.05152)

LLPNet: Graph Autoencoder for Triggering Light Long-Lived Particles at HL-LHC
BB, Partha Konar, Vishal Singh Ngairangbam, Prabhat Solanki (arXiv: 2308.13611)

LLP Trigger

CMS Hardware Track Trigger: New Opportunities for Long-Lived Particle Searches at the HL-LHC Yuri Gershtein (arXiv:1705.04321)

Optimizing trigger-level track reconstruction for sensitivity to exotic signatures
K.F. Di Petrillo, J.N. Farr, C. Guo, T.R. Holmes, J. Nelson et al. 2211.05720 [hep-ex]

Triggering on Emerging Jets
Dylan Linthorne and Daniel Stolarski, 2103.08620

LLP Reinterpretation

Energetic long-lived particles in the CMS muon chambers
A. Mitridate, M. Papucci, Christina W. Wang, Cristián Peña, Si Xie e-Print: 2304.06109 [hep-ph]

LLP @100 TeV

Discovery reach for wino and higgsino dark matter with a disappearing track signature at a 100 TeV pp collider
M. Saito, R. Sawadaa, K. Terashib, S. Asai (1901.02987)

And many more …….

Summary

- Long-lived particles are well-motivated in BSM theories
- Signature of LLP not only depends on the decay products also depend where it decays
- Various unusual signatures are possible : understanding of detector is required for estimation of backgrounds
- General purpose detectors like CMS/ATLAS are capable to identify the presence of LLPs in many cases
- Dedicated detectors will be required to probe light LLPs
- FCC-hh will be able to improve the search sensitivity as expected
- Optimization of the location and size of the dedicated detectors will be possible for the future collider unlike LHC
- Two proposals for dedicated detectors : FOREHUNT and DELIGHT are made by our group. => More studies are ongoing

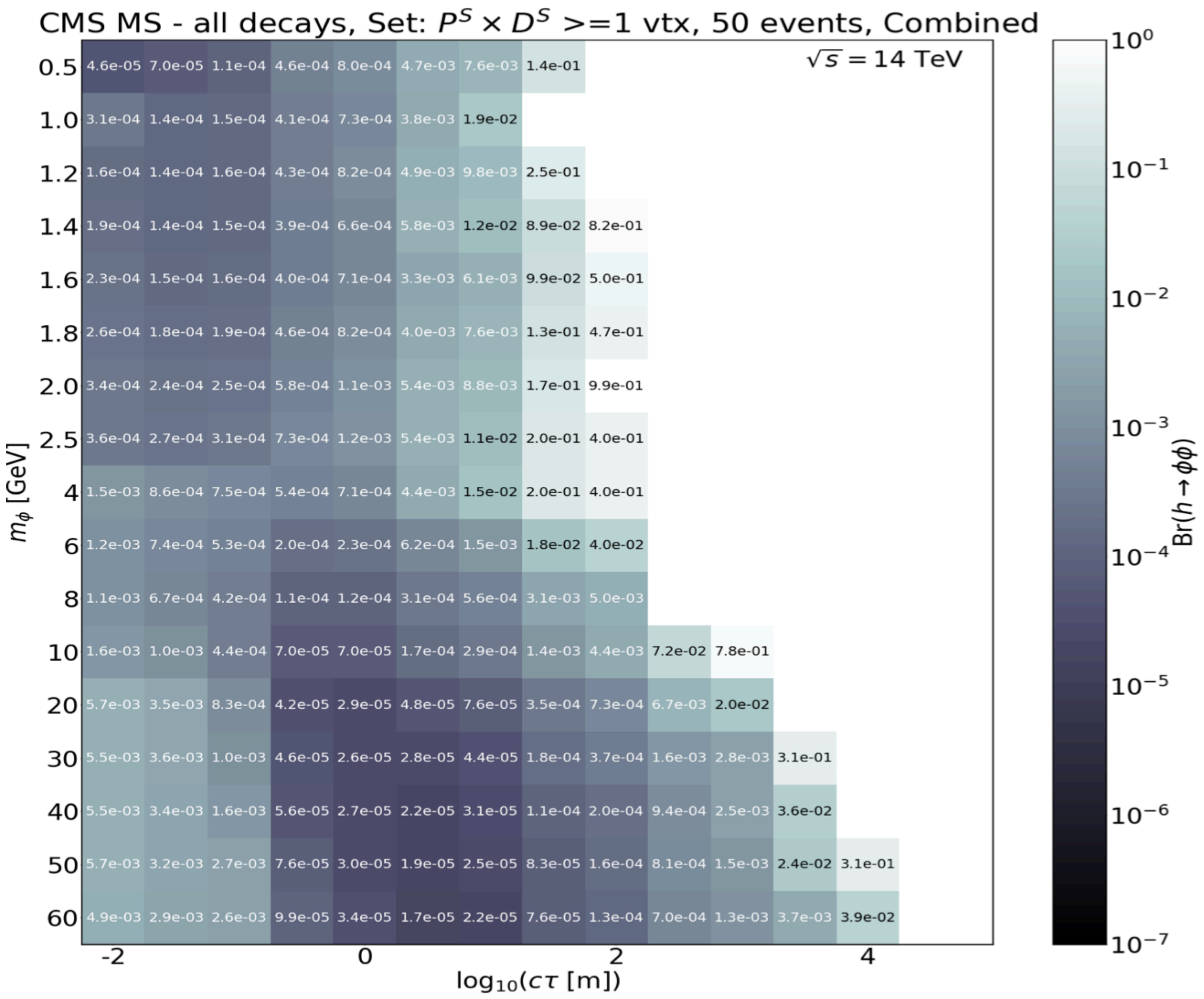
Thank you

Extra Slides

Tracker vs CMS Muon spectrometer

LLP Model: $pp \to h \to \phi\phi$

We cannot address properly in a phenomenological study such as the one in this paper. —> However CMS and ATLAS collaborations have developed algorithms to identify such clusters. We just devise our cuts to ensure that a cluster with a high multiplicity of hits can be detected in the MS for various final states other than muons.



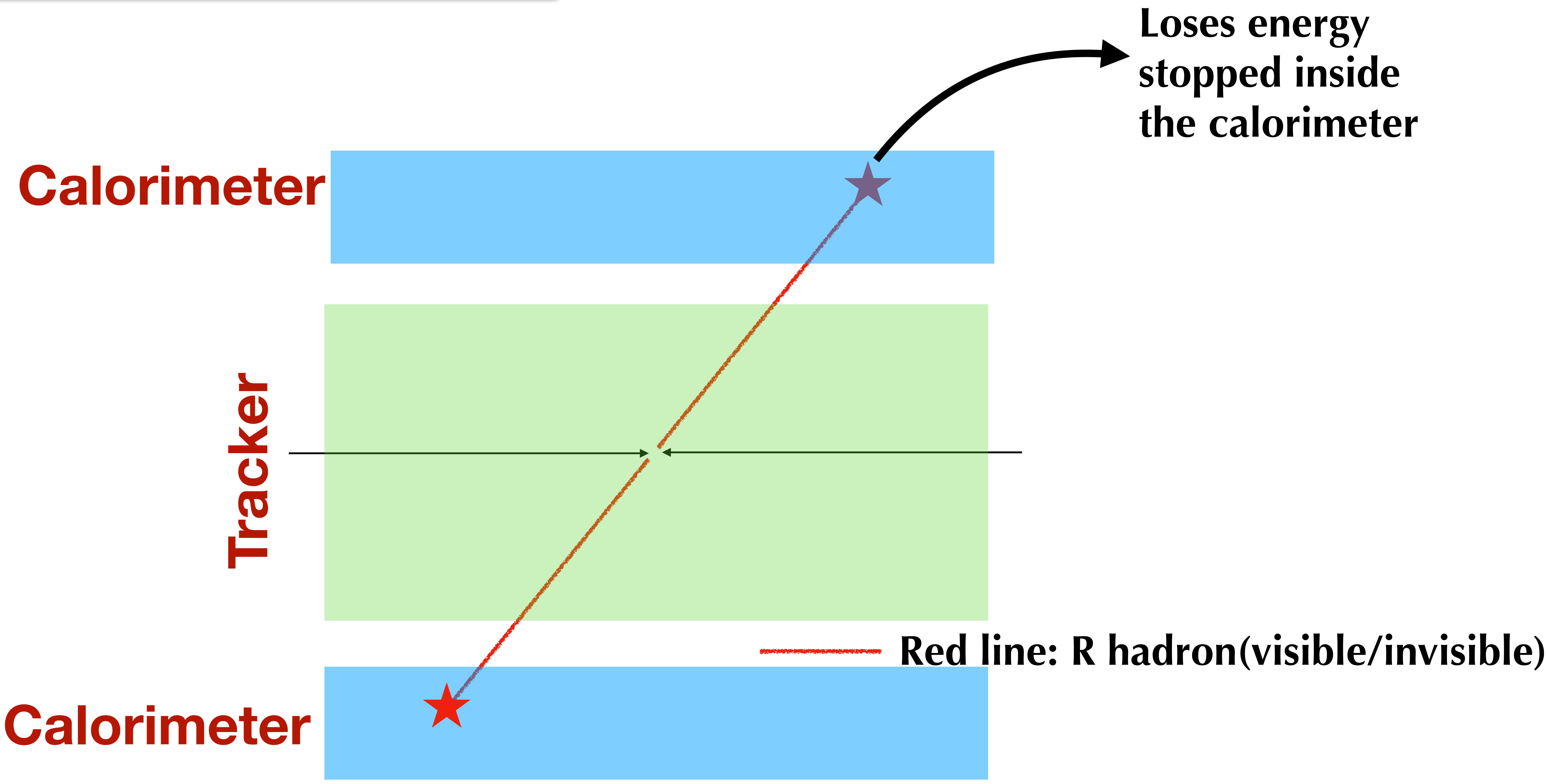
BB, Shigeki Matsumoto, Rhitaja Sengupta
e-Print: 2111.02437, PRD 2022

Results

Combined ggF, VBF, VH and several decay modes

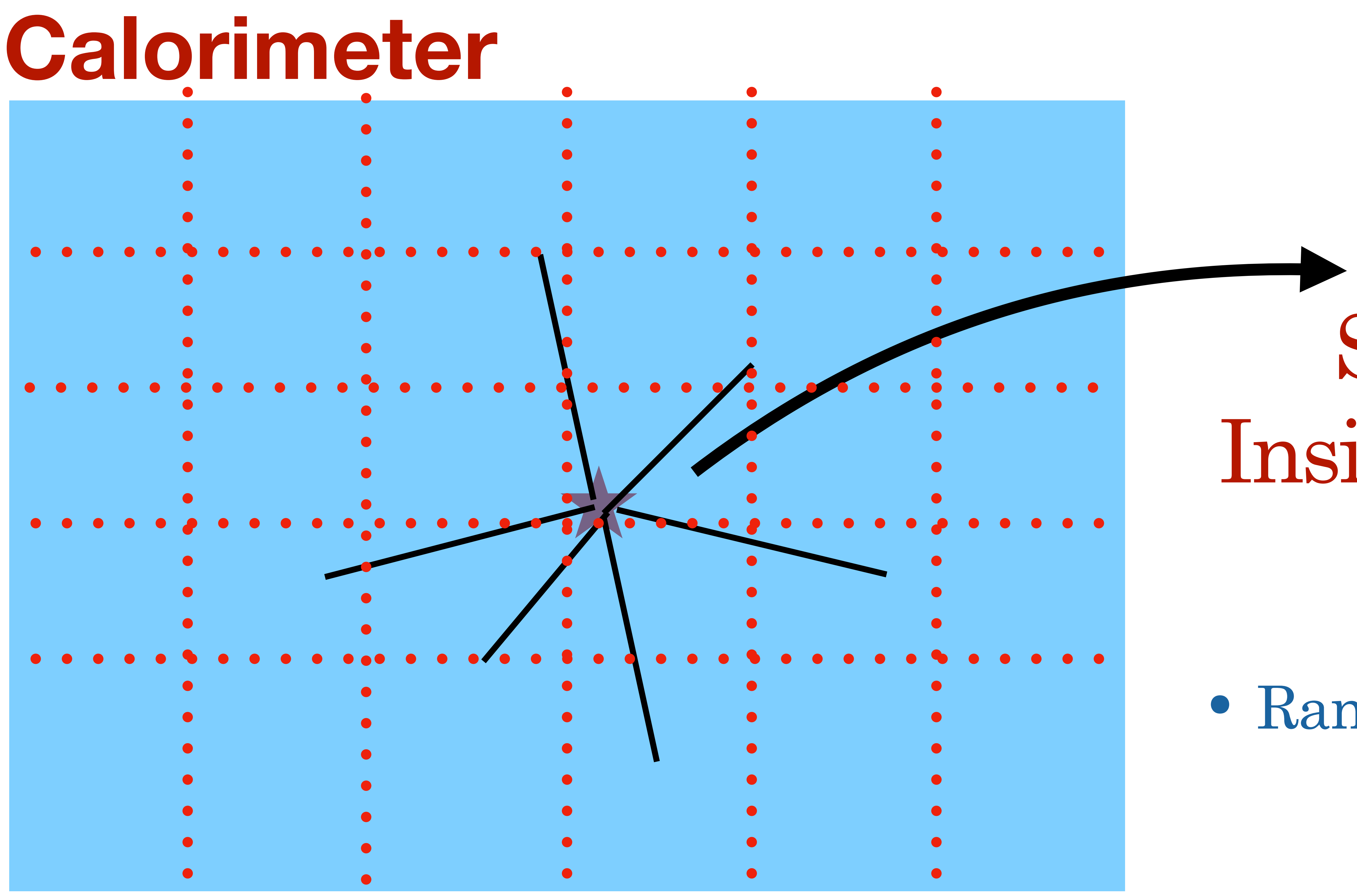
- We combine all these decay modes taking into account the branching ratios predicted in the minimal model (m_Φ = 0.5-60 GeV)
- We can probe Br(h -> $\Phi\Phi$) = 3 x 10^{-5} (decay length=1m) for m_Φ = 50 GeV for P^S X D^S_{jet} $\geq$ 1 vertex.
- combination of various production modes of Higgs boson as well as the decay modes of the mediator contribute non-trivially to the limits

Stopped particles in the Calorimeter



Stopped particles in the Calorimeter

ATLAS result: 2104.03050



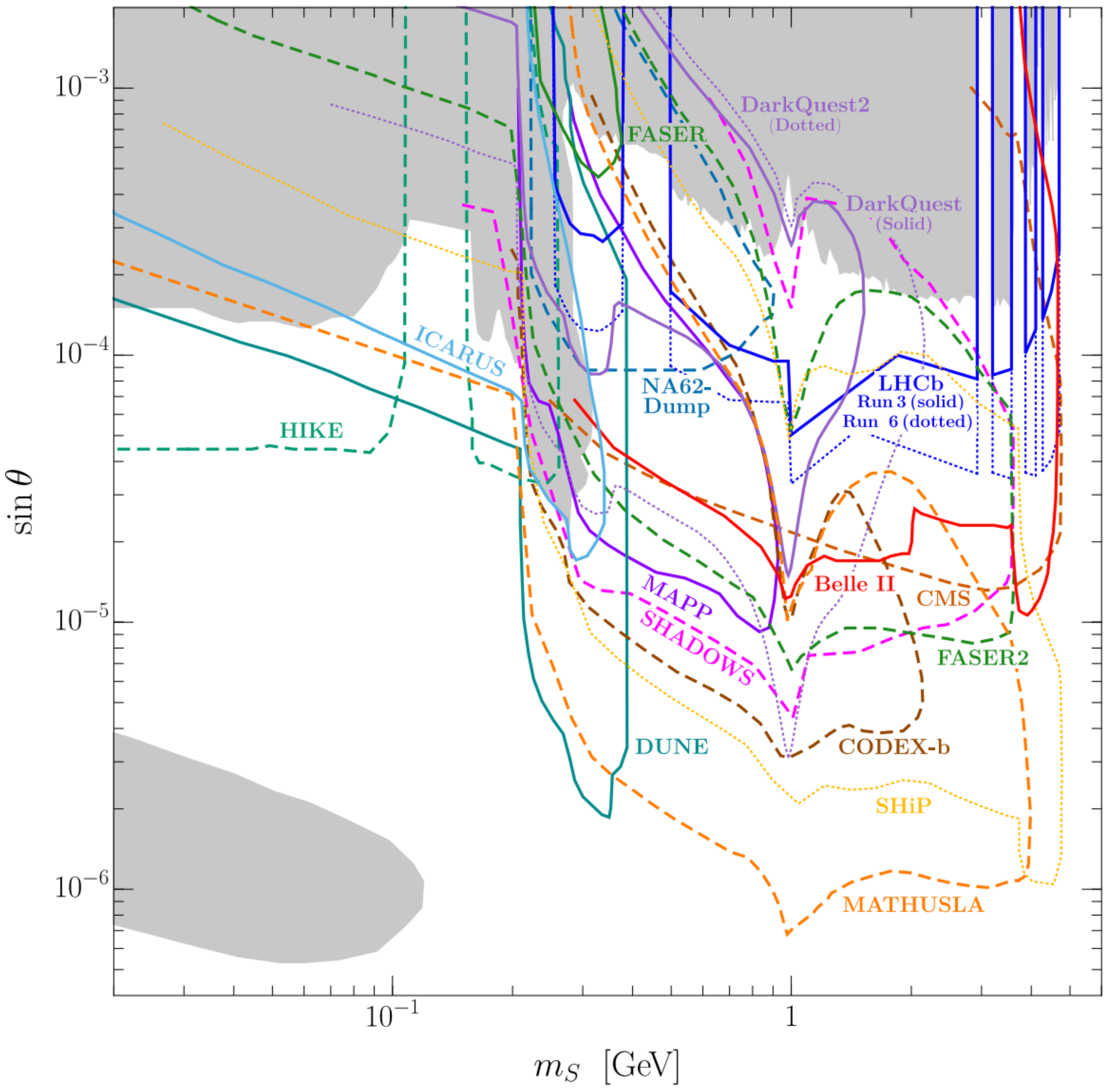
Sudden decay
Of the
Stopped particle
Inside the calorimeter

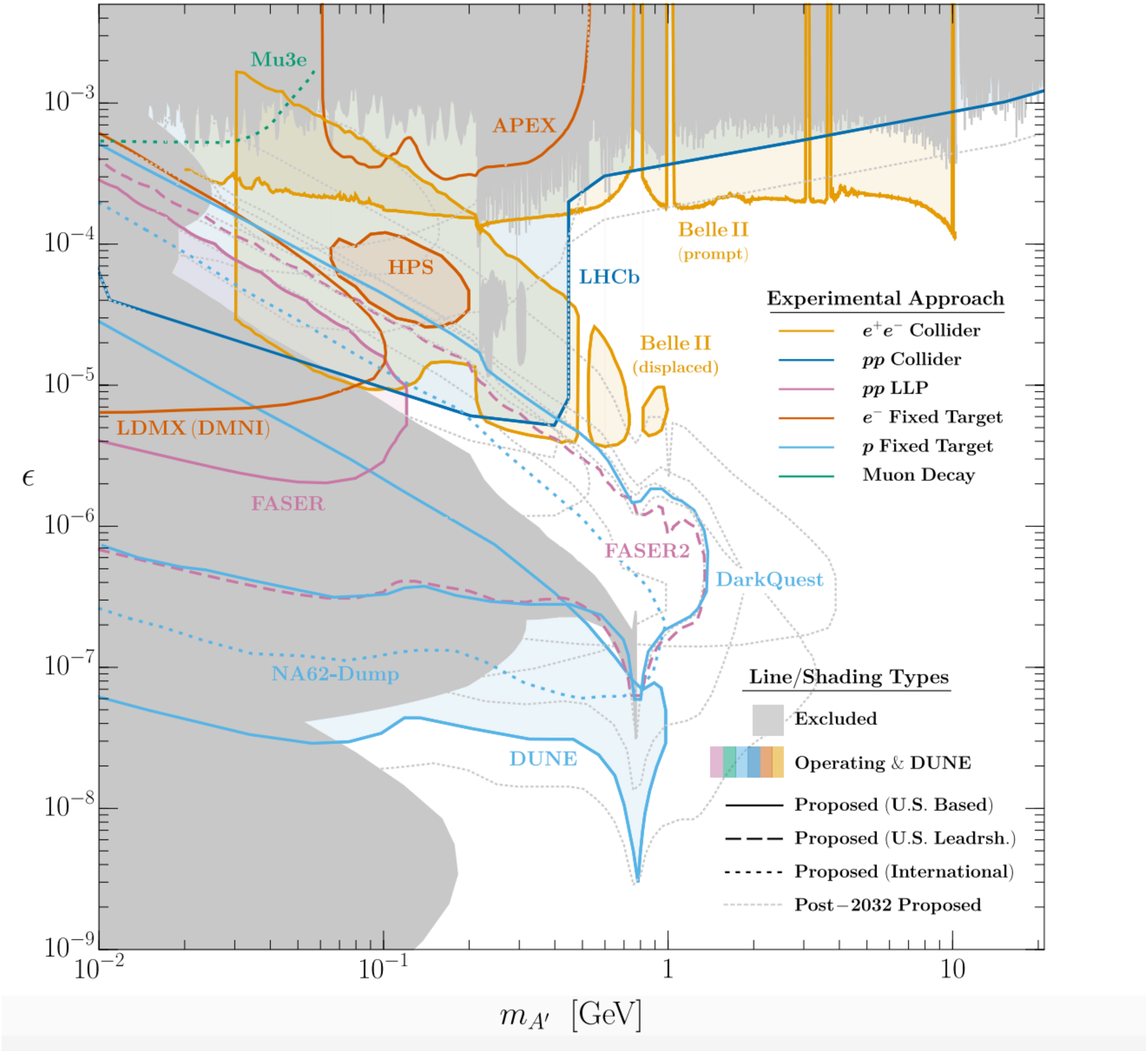
- Randomly timed large energy response

For very long-lived particles (say lifetime of 1000 year), beam pipe or detector parts can be taken out and scanned
(First piece of the CMS beam pipe tested in 2012) Eur. Phys. J. C 72 2212.

Future Sensitivity plot

Exploring Dark Sector Portals with High Intensity Experiments
Brian Batell, Nikita Blinov, Christopher Hearty, and Robert McGehee 2207.06905





DELIGHT (B)

DELIGHT (B): Four times bigger than the MATHUSLA detector,
i.e. $\Delta x \times \Delta y \times \Delta z = 100 \times 100 \times 100\,\mathrm{m}^3$.

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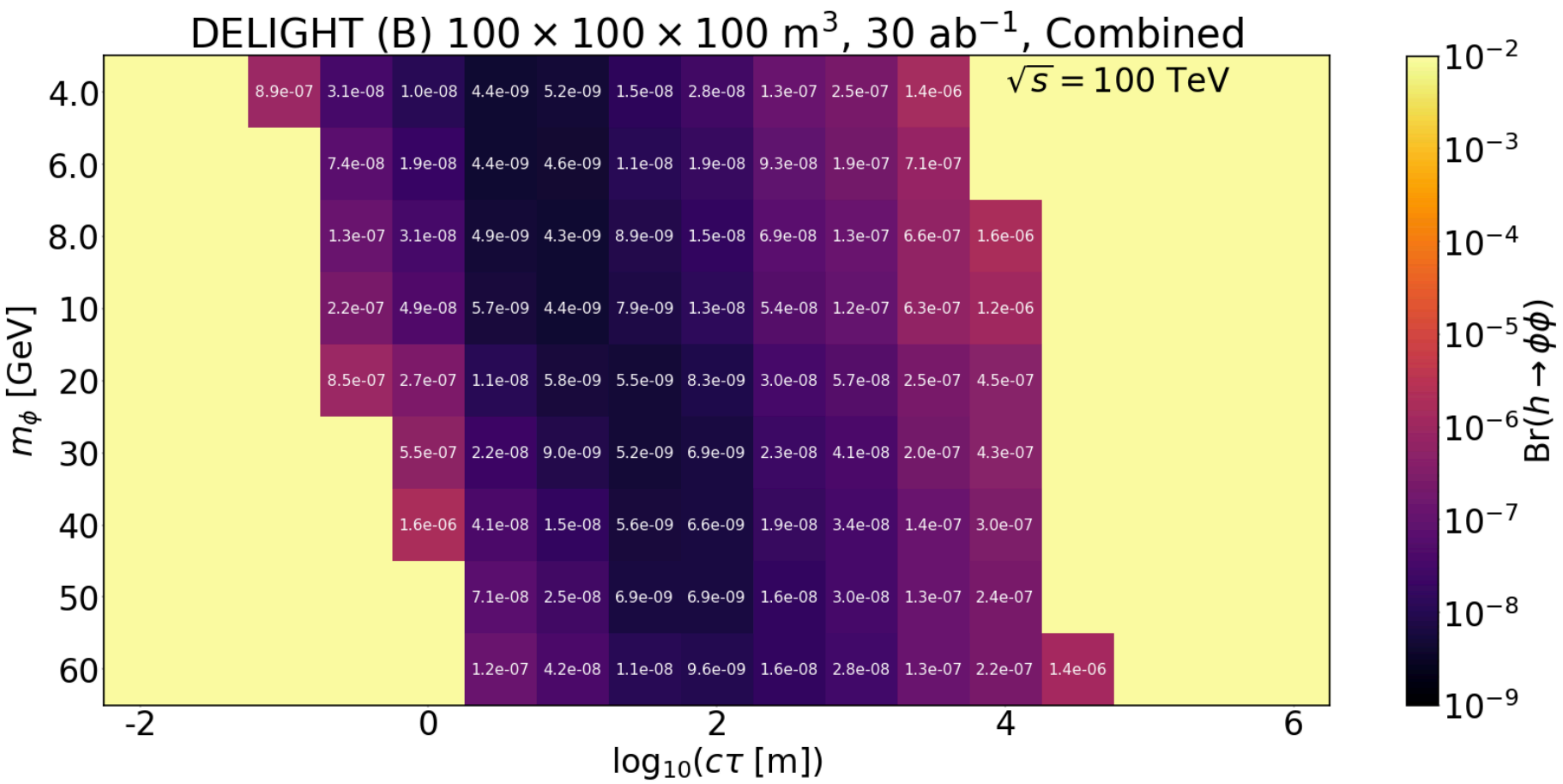
LLP Model: $pp \to h \to \phi\phi$



DELIGHT(B): The best limits come from DELIGHT(B), highest decay volume among the three (about four times bigger than the decay volume of MATHUSLA), and the performance is better by ~ 2 compared to DELIGHT (A).

DELIGHT (C)

DELIGHT (C): The same decay volume as the MATHUSLA detector with different dimensions, i.e. $\Delta x \times \Delta y \times \Delta z = 200 \times 50 \times 50\,\mathrm{m}^3$.

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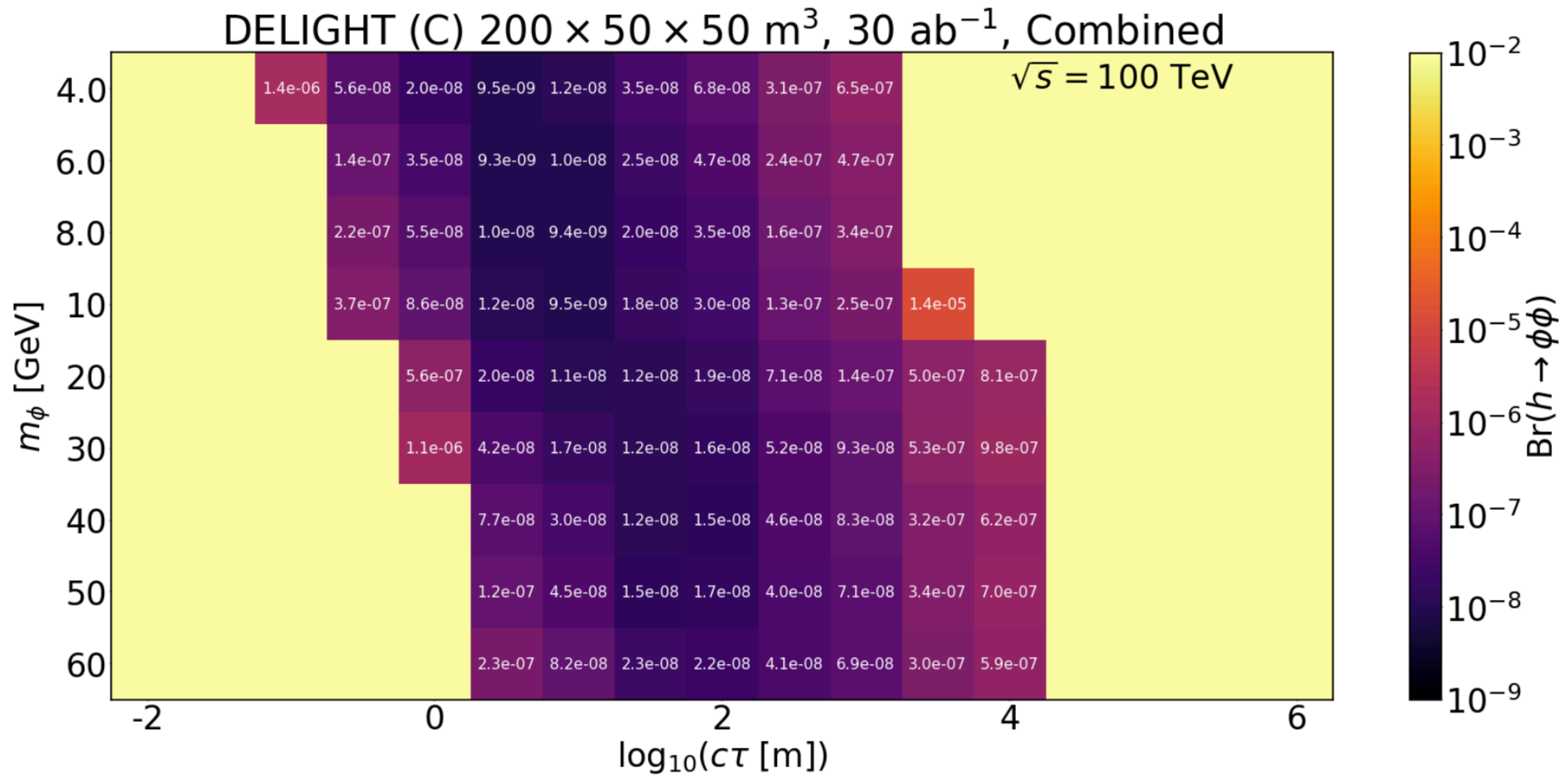
e-Print: 2111.02437, PRD 2022

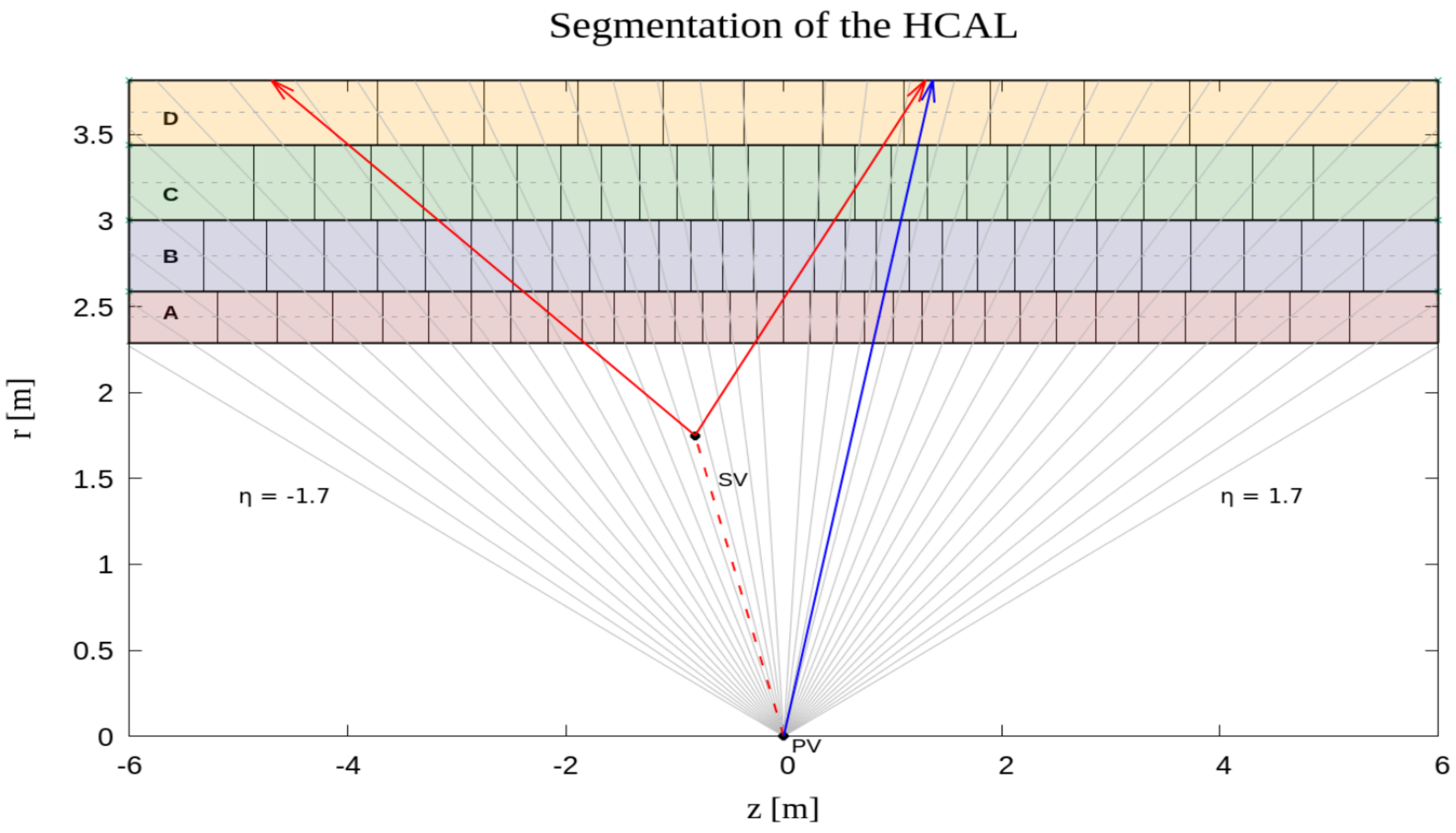
LLP Model: $pp \to h \to \phi\phi$



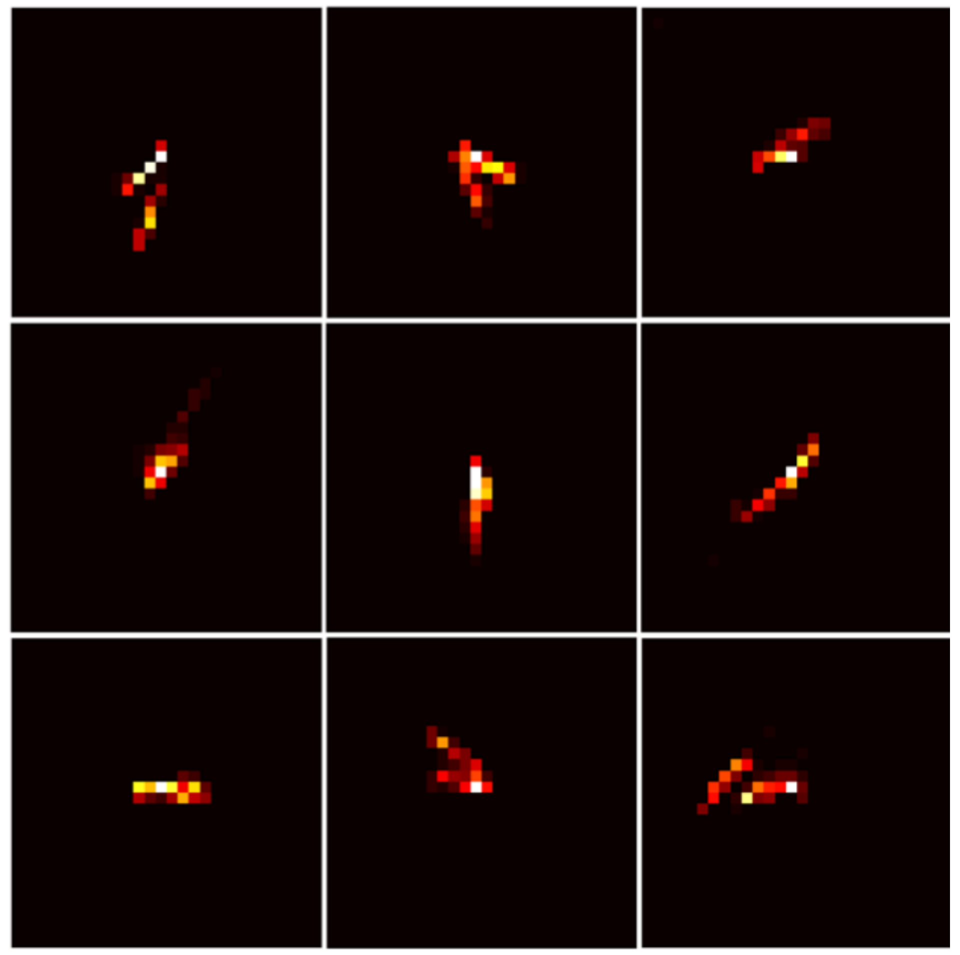
DELIGHT (A) vs DELIGHT(C): have the same decay volumes, lower Δη×Δϕ coverage, limits slightly weaker (factor of around 0.8 – 0.9), may have better shielding from cosmic rays, tunnel like structure might be useful for other LLP models (needs more detailed analysis) (A).

HCAL Segmentation and Images

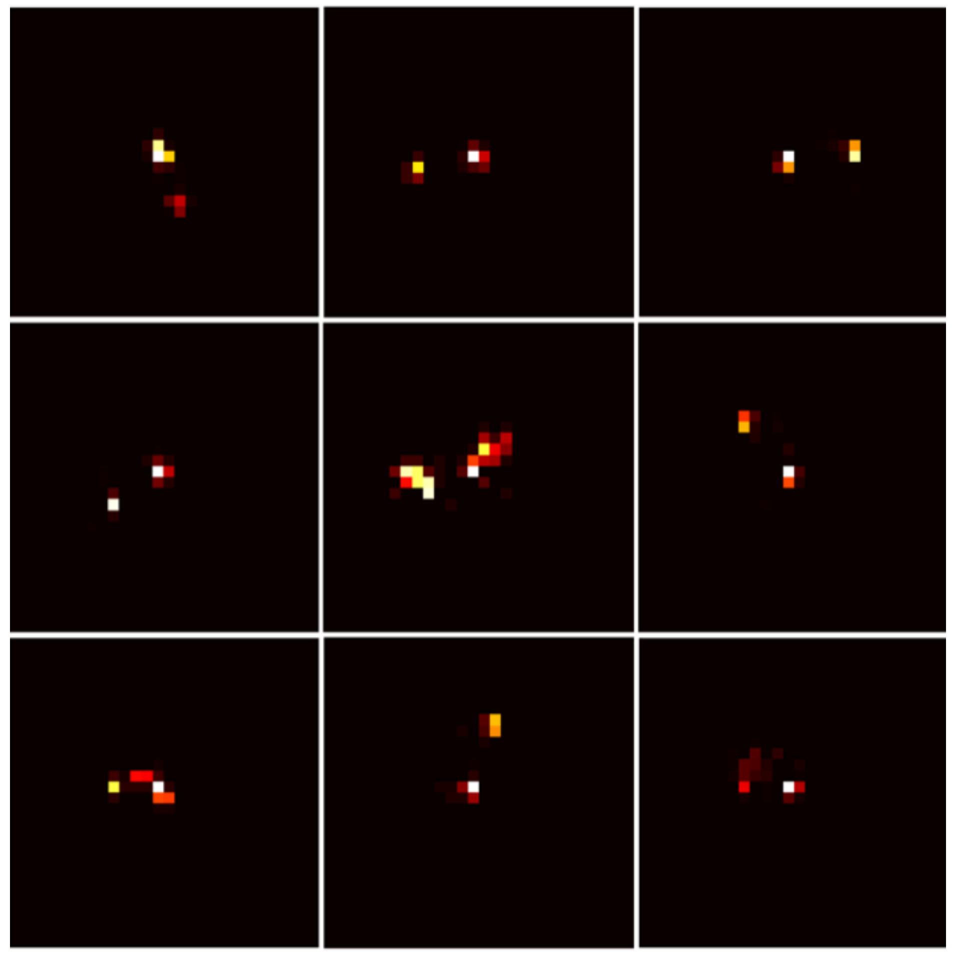
BB, Swagata Mukherjee and Rhitaja Sengupta
arXiv:1904.04811, JHEP 2019



Click Here



- Prompt Z



- Displaced Z

CNN architecture and ROC

BB, Swagata Mukherjee and Rhitaja Sengupta
arXiv:1904.04811, JHEP 2019

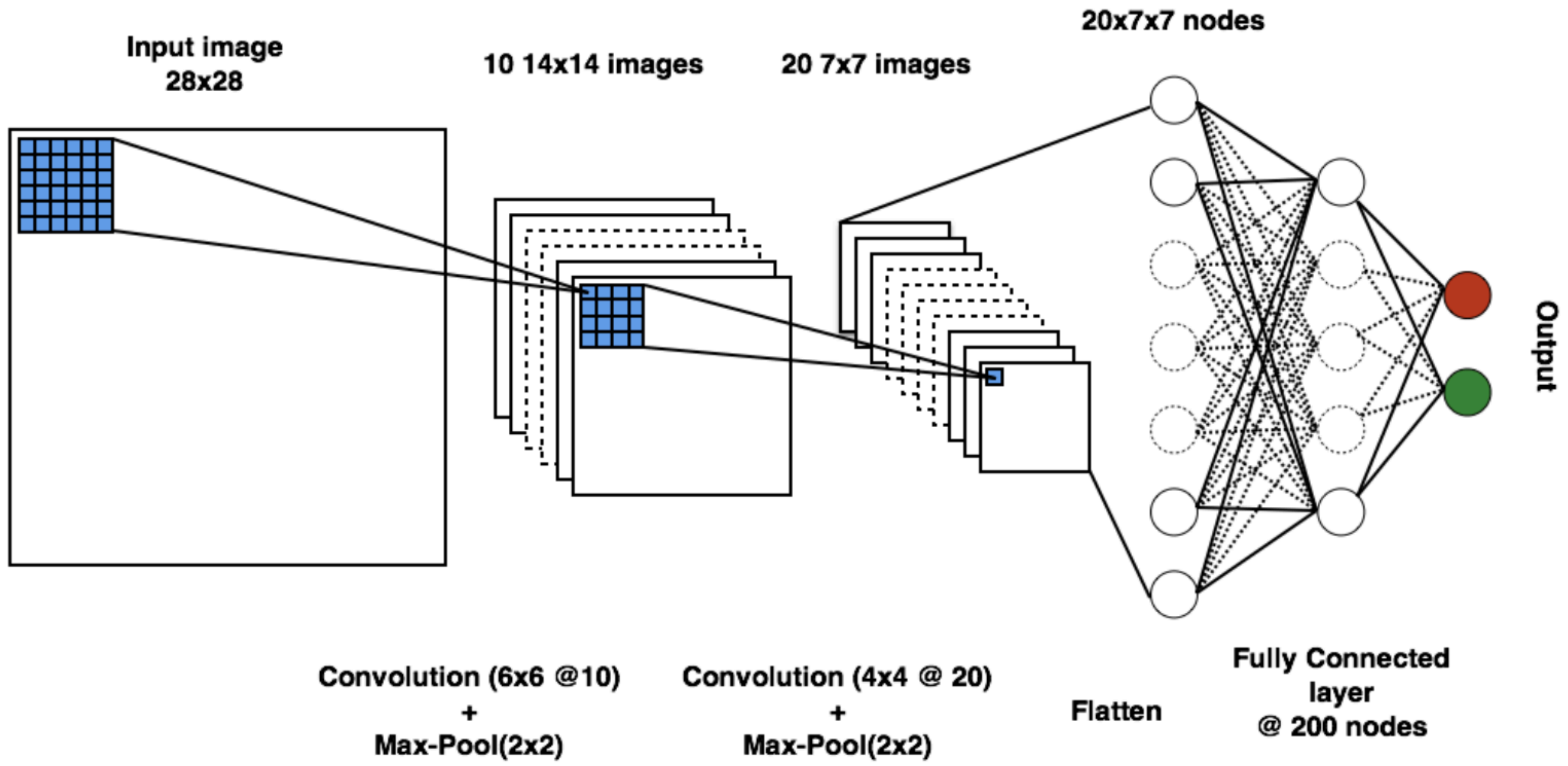


Figure 8: The CNN architecture used.

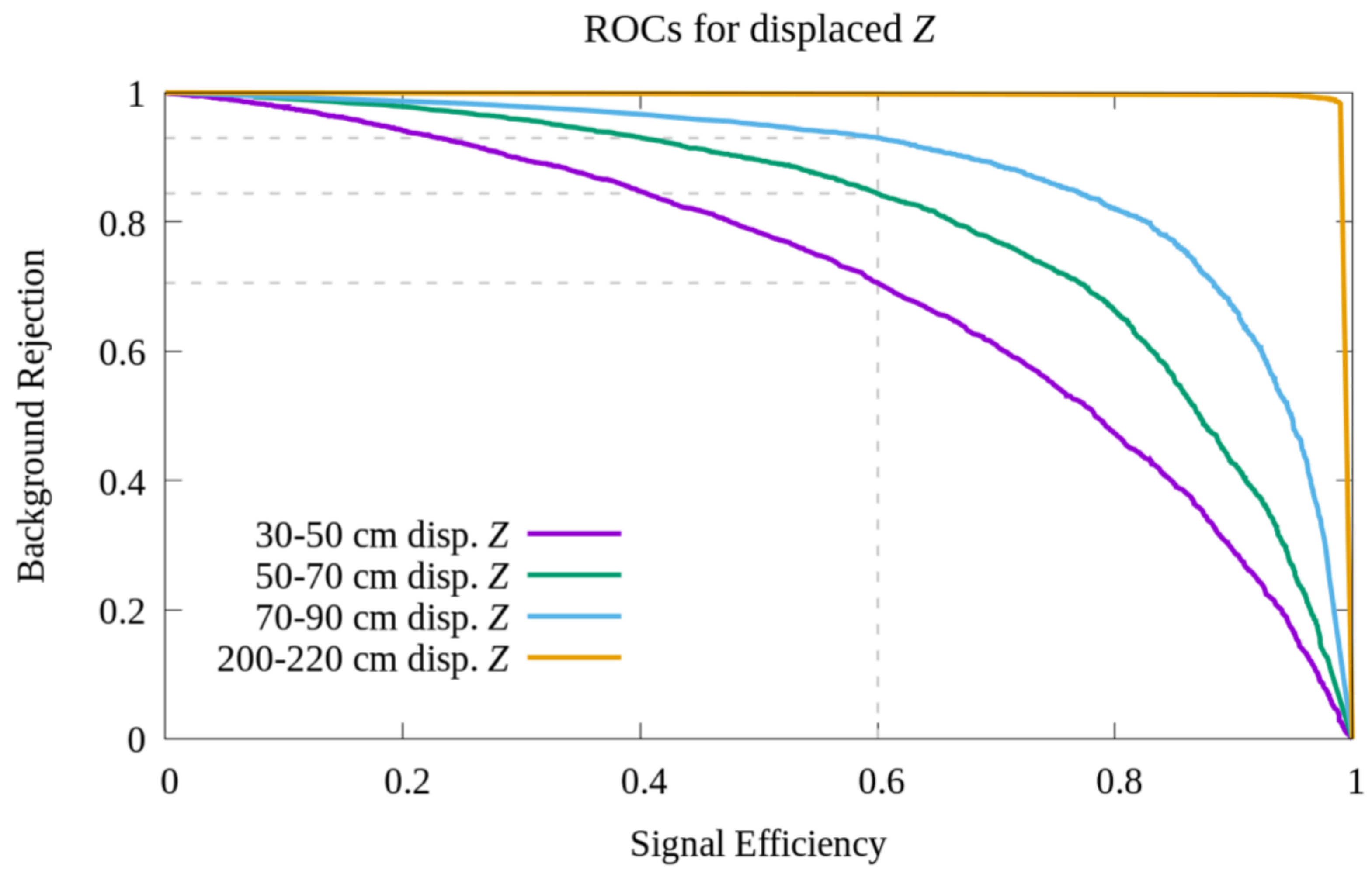
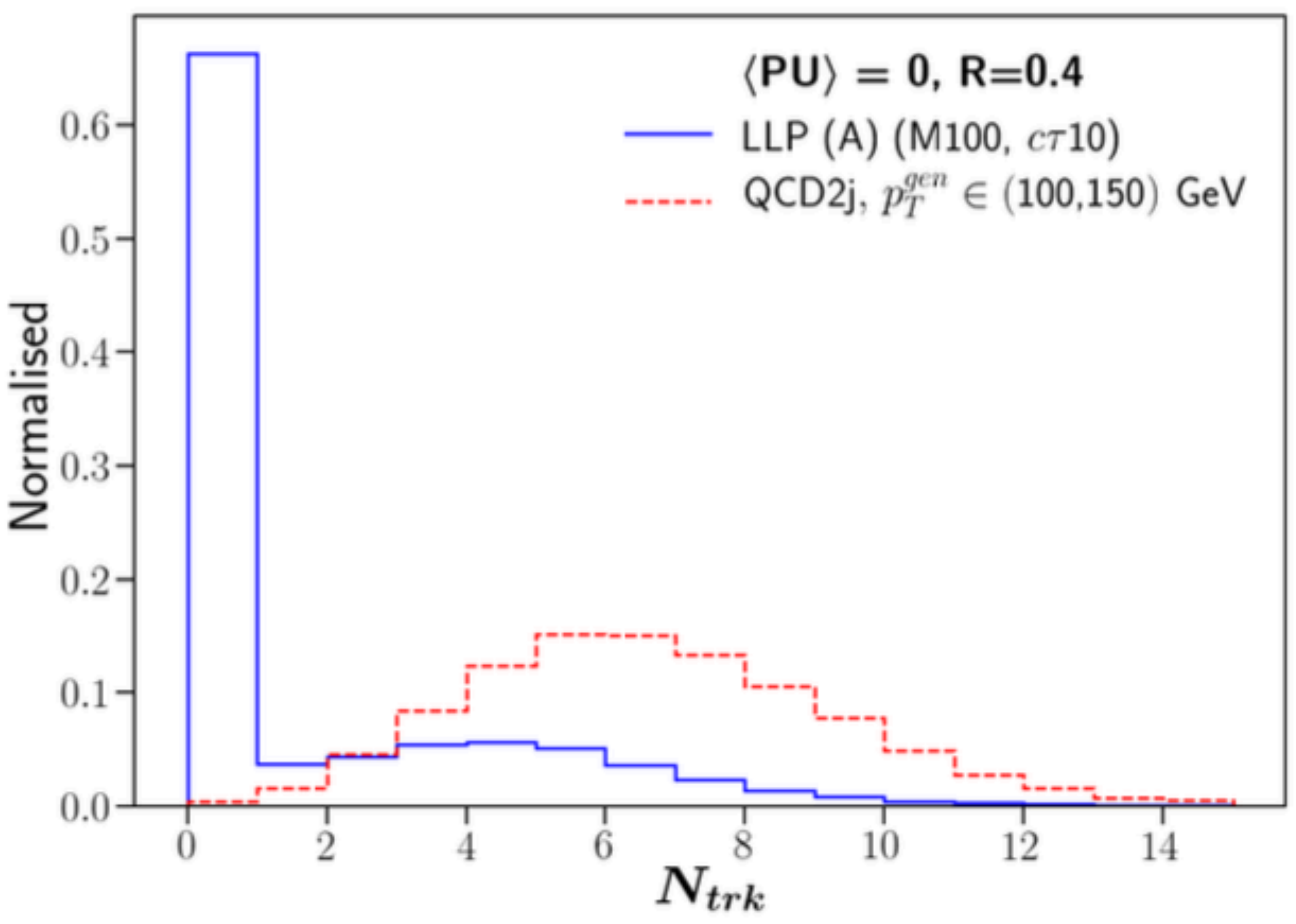


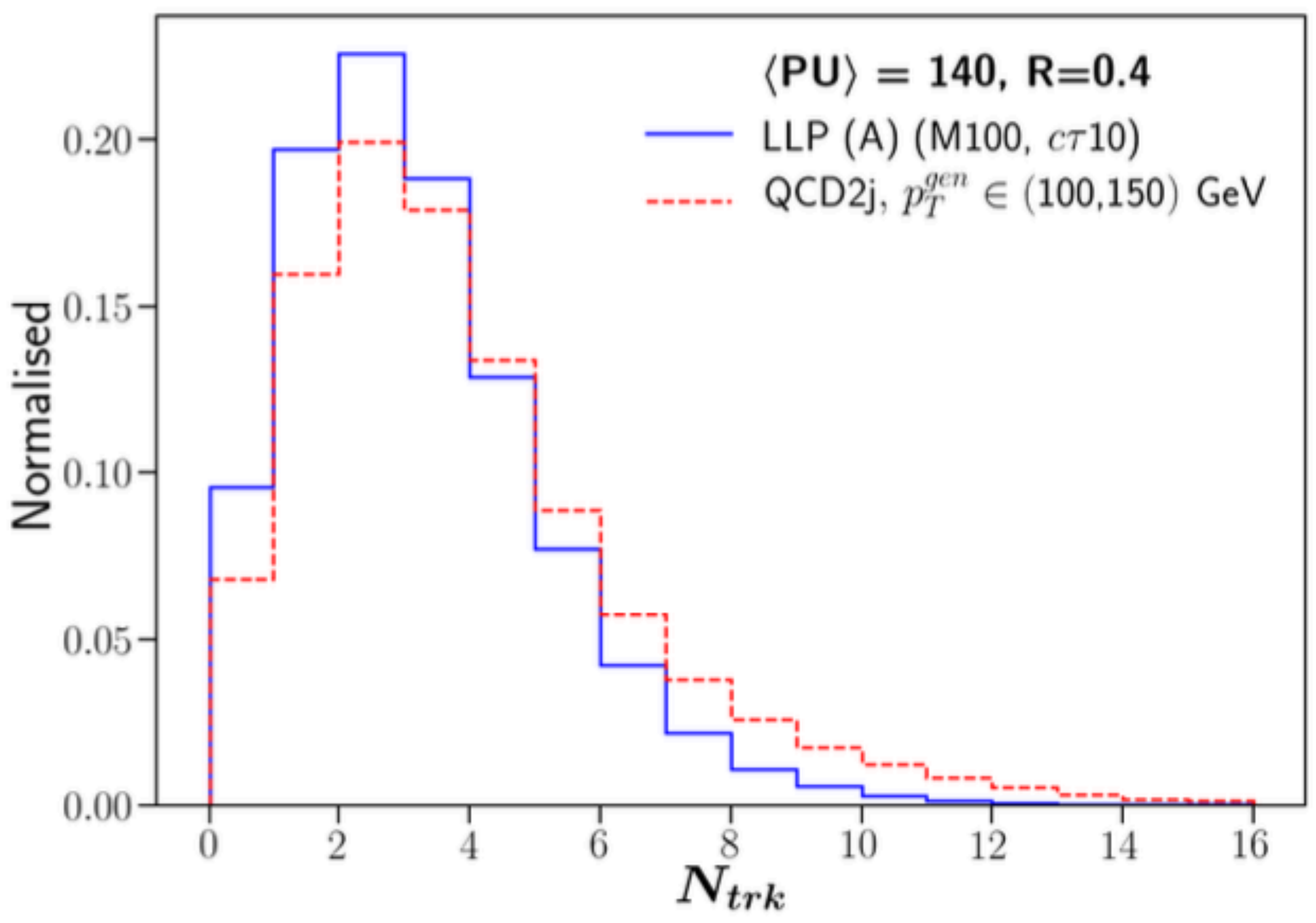
Figure 9: ROCs of the CNN performance to separate non-displaced Z from different classes of displaced Z.

Number of tracks inside the jets

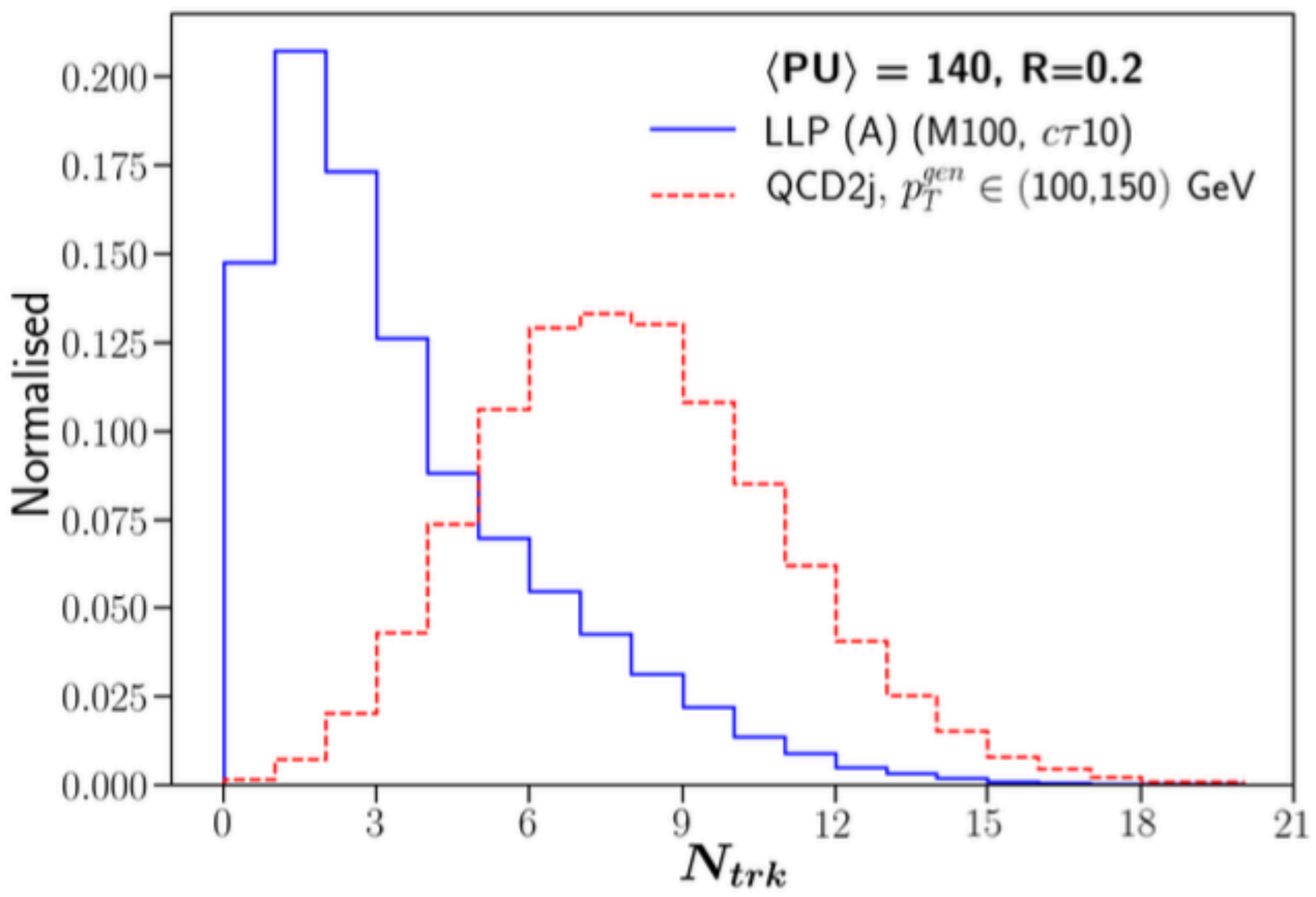
BB, Swagata Mukherjee, Rhitaja Sengupta, Prabhat Solanki
e-Print: 2003.03943, JHEP 2020



Pile up =0
Jet parameter =0.4
Many trackless jets for LLPs
(As expected)



Pile up =140
Jet parameter =0.4
No difference between
prompt and LLP jets !!



Pile up =140
Jet parameter =0.2
Some difference between
prompt and LLP jets !!

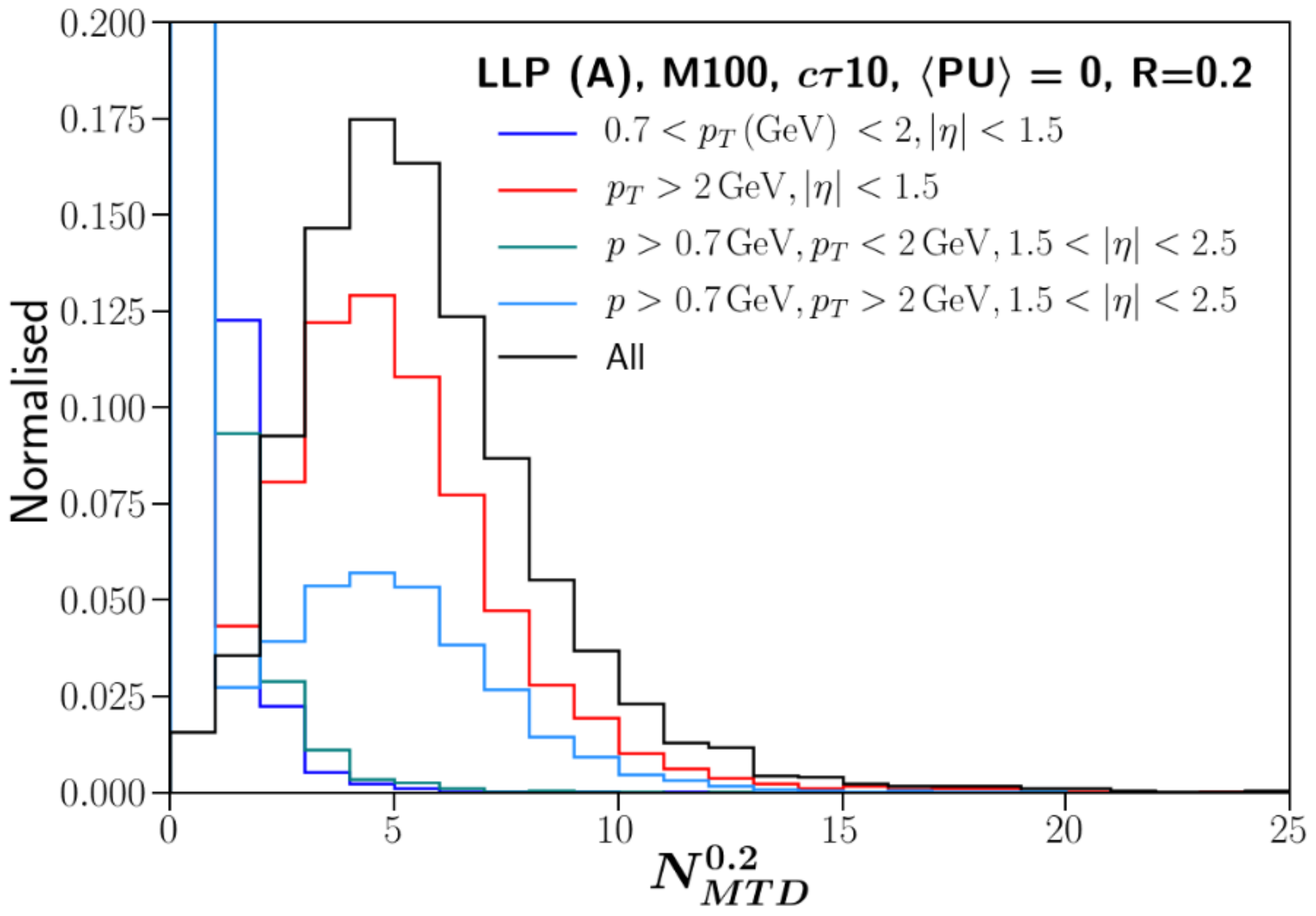
More variables construction possible
Single narrow jet trigger with pT >60 GeV with strict cuts on tracking variables may be used.

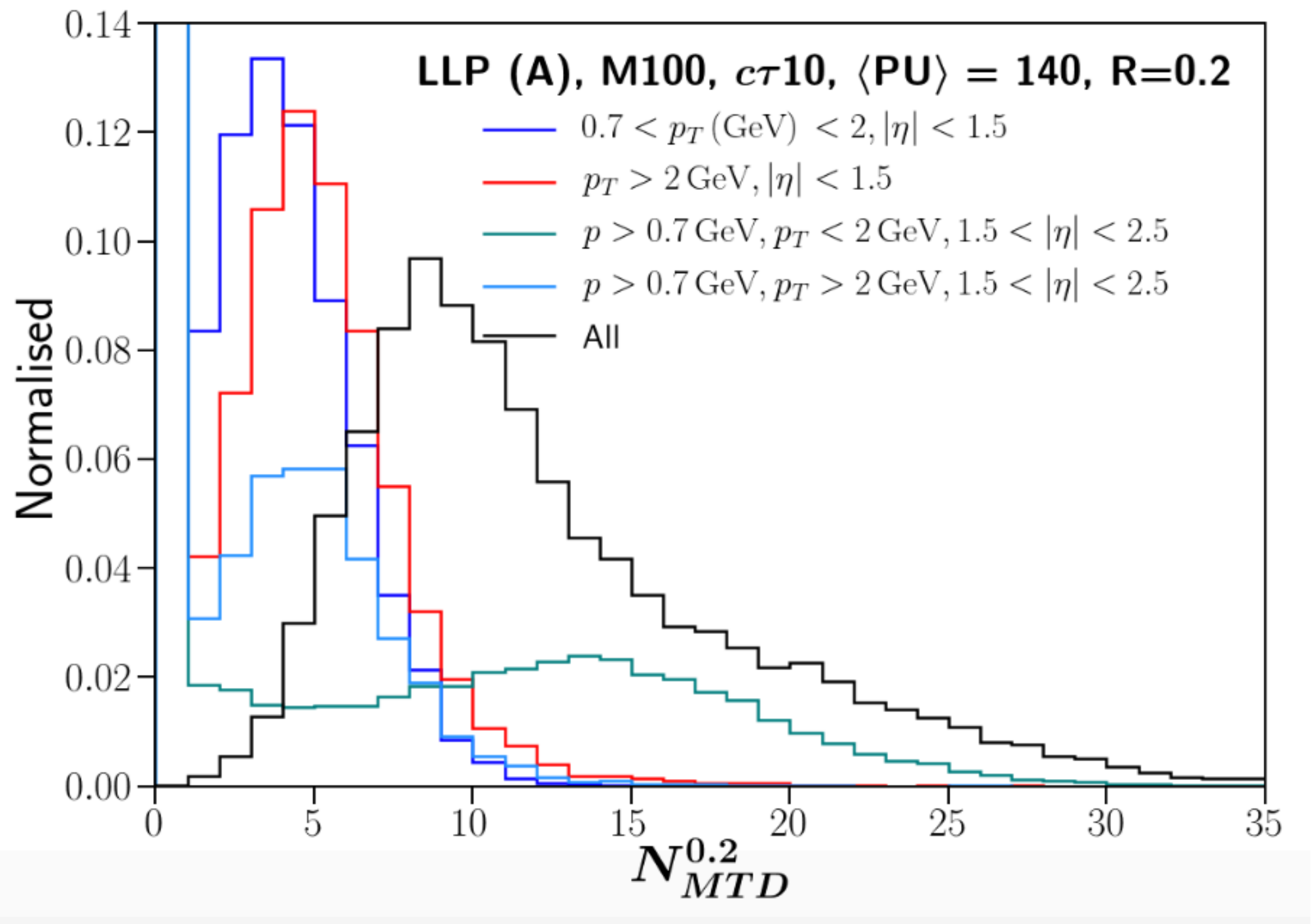
Timing Layer in CMS

BB, Swagata Mukherjee, Rhitaja Sengupta, Prabhat Solanki
e-Print: 2003.03943, JHEP 2020

MTD : capable of measuring timing of all electrically charged particles with timing precision of around 30 ps.

This timing layer will be positioned at 1.161 meters away from the beam pipe of CMS: in the small gap between the tracker and the ECAL with a half-length of 2.6 m.



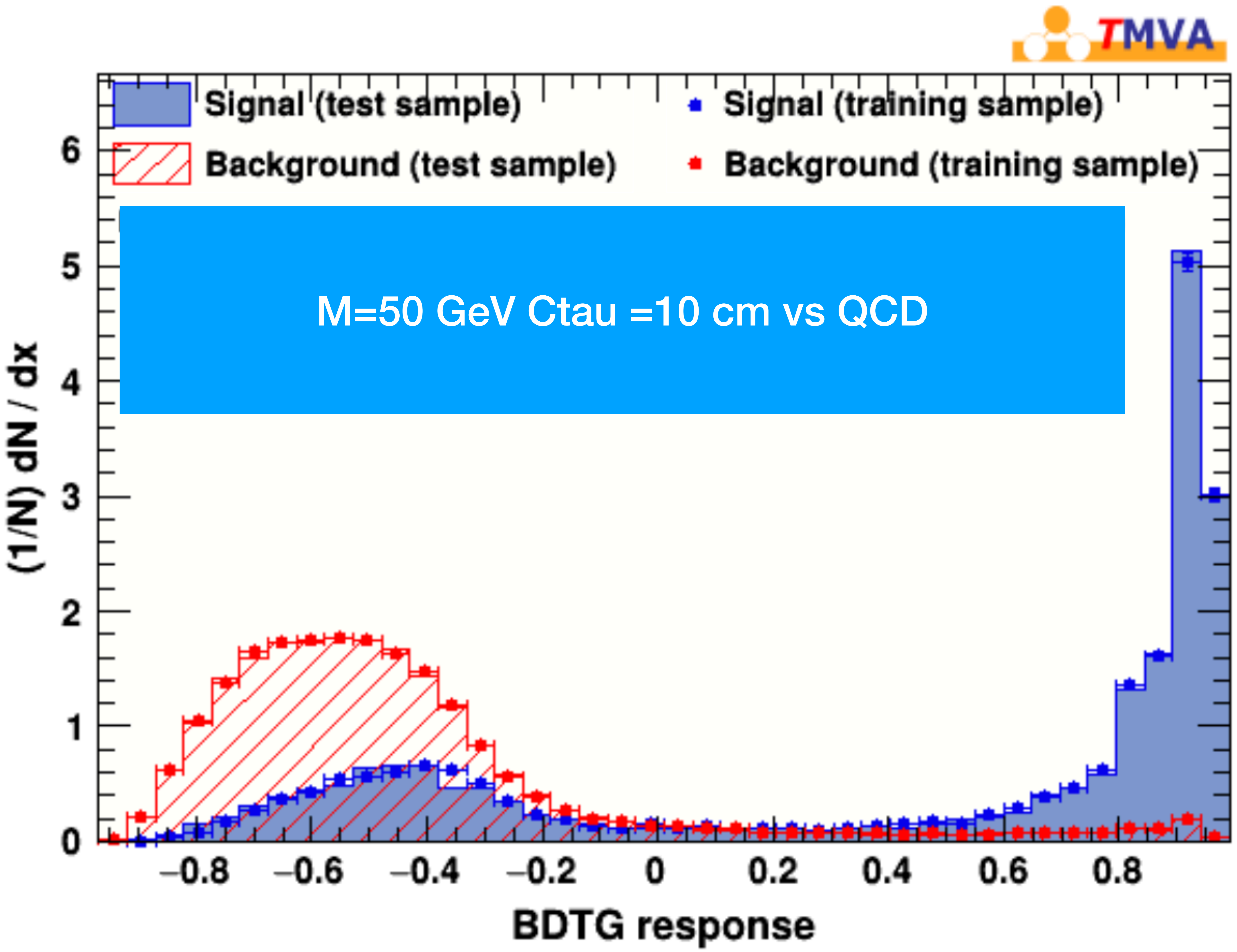


- 0.7 GeV $< p_T < 2$ GeV, $|\eta| < 1.5$
- $p_T > 2$ GeV, $|\eta| < 1.5$
- $p > 0.7$ GeV, $p_T < 2$ GeV, $1.5 < |\eta| < 2.5$
- $p > 0.7$ GeV, $p_T > 2$ GeV, $1.5 < |\eta| < 2.5$

MTD hits associated with a jet will have significant PU contribution and these large number of MTD hits coming from PU will contaminate both the QCD and LLP hard processes equally

The BDT performance is comparable to that when variables with tracking information are used, though the former is slightly weaker

Combination of tracking and timing variables can be used to reduce the rate


TMVA
Signal (test sample)
Signal (training sample)
Background (test sample)
Background (training sample)
M=50 GeV Ctau =10 cm vs QCD
(1/N) dN / dx
BDTG response
0
1
2
3
4
5
6
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8

Click here

Tracker and MTD based search using classifiers

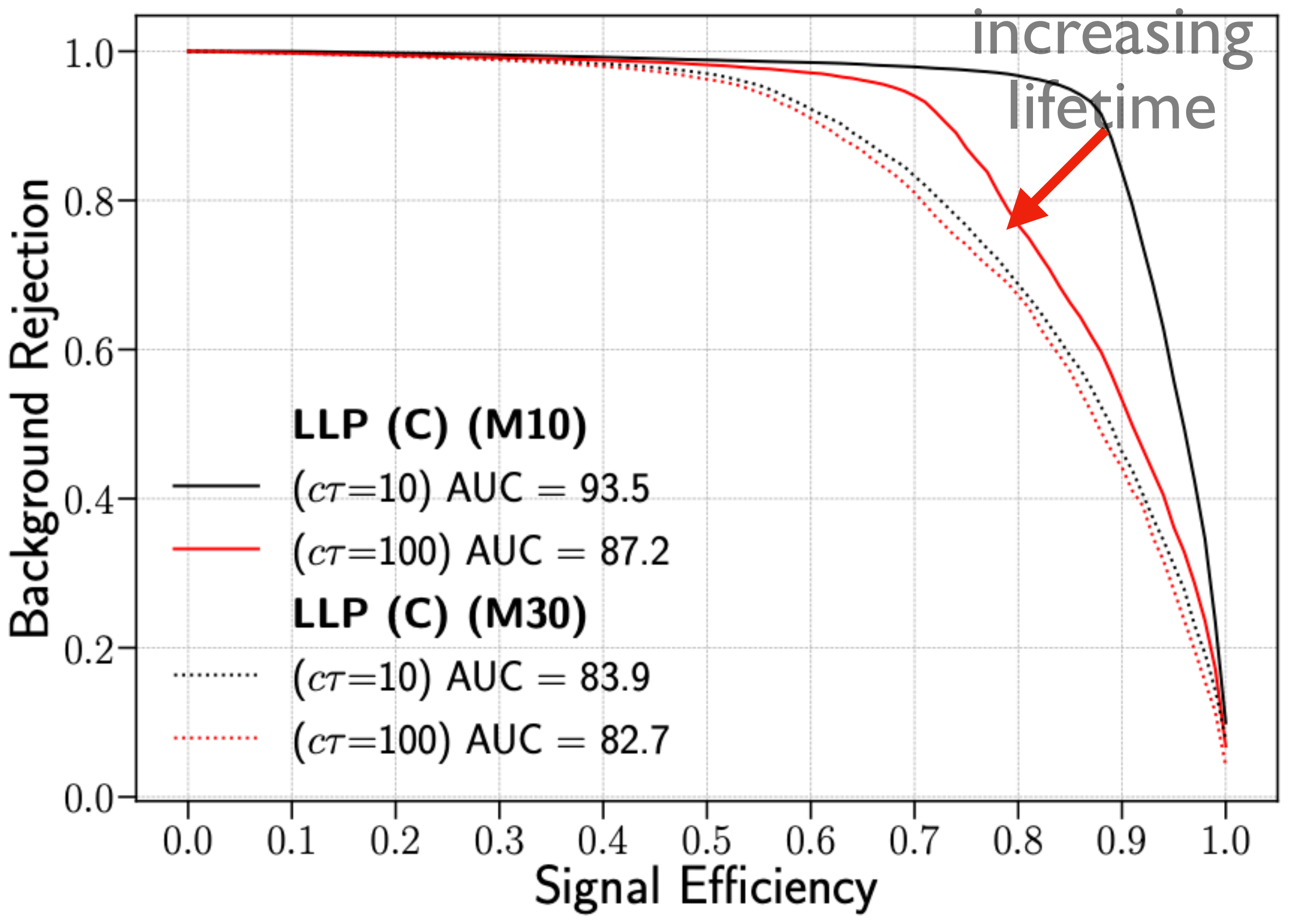
Tracking:

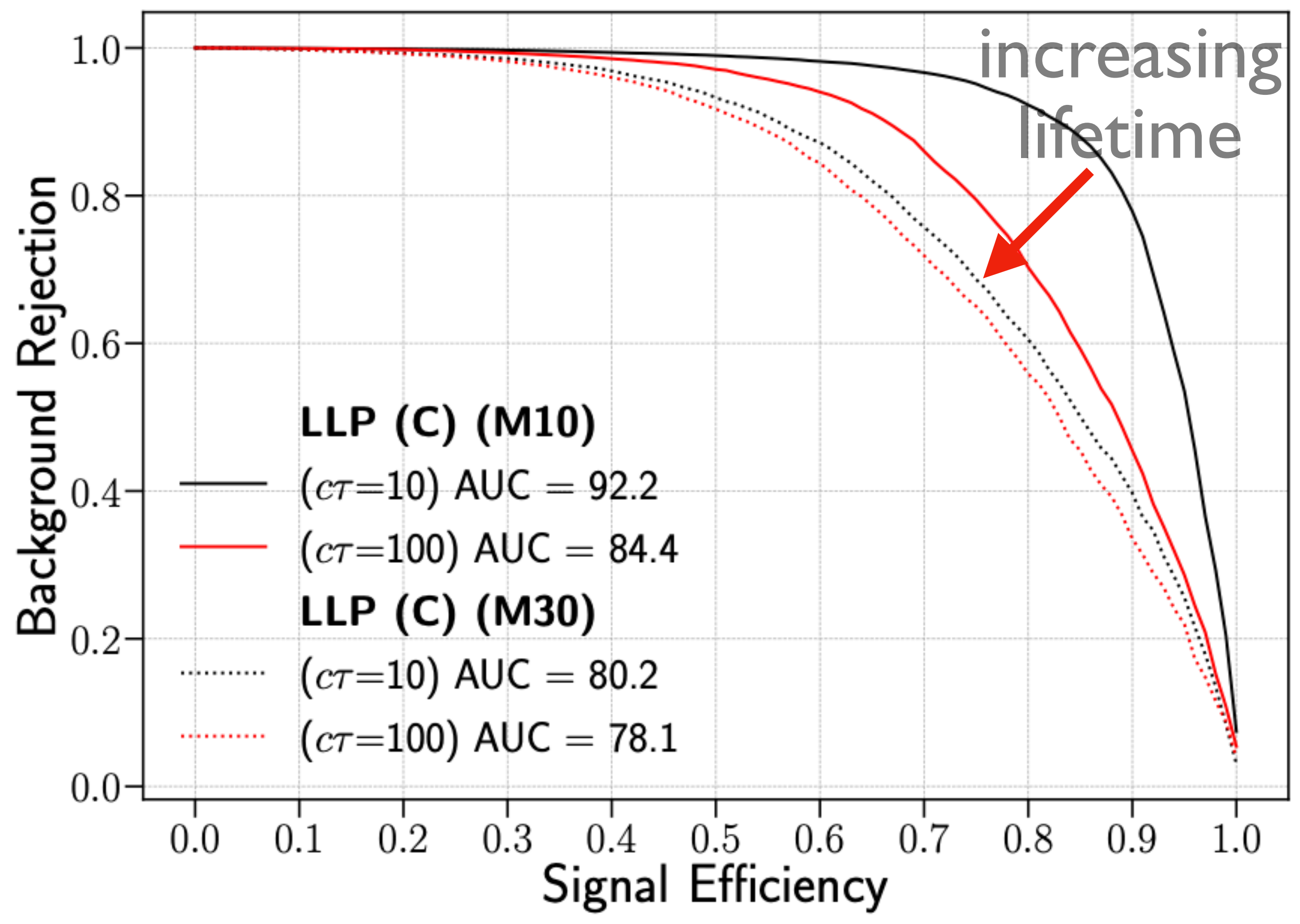
N_{trk} | $\sum p_T$ | z_{j_vtx} | Δz_{j_vtx} | $p_{T(vtx)}^{miss}$ | $n_{z_{trk\_max}}$ | Δz_{trk_max} | $\sum p_T^{z_{trk\_max}}$ | $\sum p_T^{z_a \neq z_{trk\_max}}$ | $\frac{\sum p_T^{z_{trk\_max}}}{\sum p_T}$ | $S(\frac{|z_i|}{\sum |z_i|})$ | $S(z_i + 301)$ | $S(\frac{z_i + 301}{\sum (z_i + 301)})$ | $S(p_{T,i})$ | $S(\frac{p_{T,i}}{\sum p_{T,i}})$ |

Same vars with trks within $\Delta R = 0.2$ | $\frac{N_{trk}}{N_{trk}^{(0.2)}}$ | $\frac{\sum p_T}{\sum p_T^{(0.2)}}$

Timing:

- p_T
- η
- $N_{MTD}^{(0.2)}$
- $T_{Med}^{(0.2)}$
- $\Delta T_{Med,PV}^{(0.2)}$
- $N_{MTD}^{(0.2),NT}$
- $\Delta T_{Med,PV}^{(0.2),NT}$



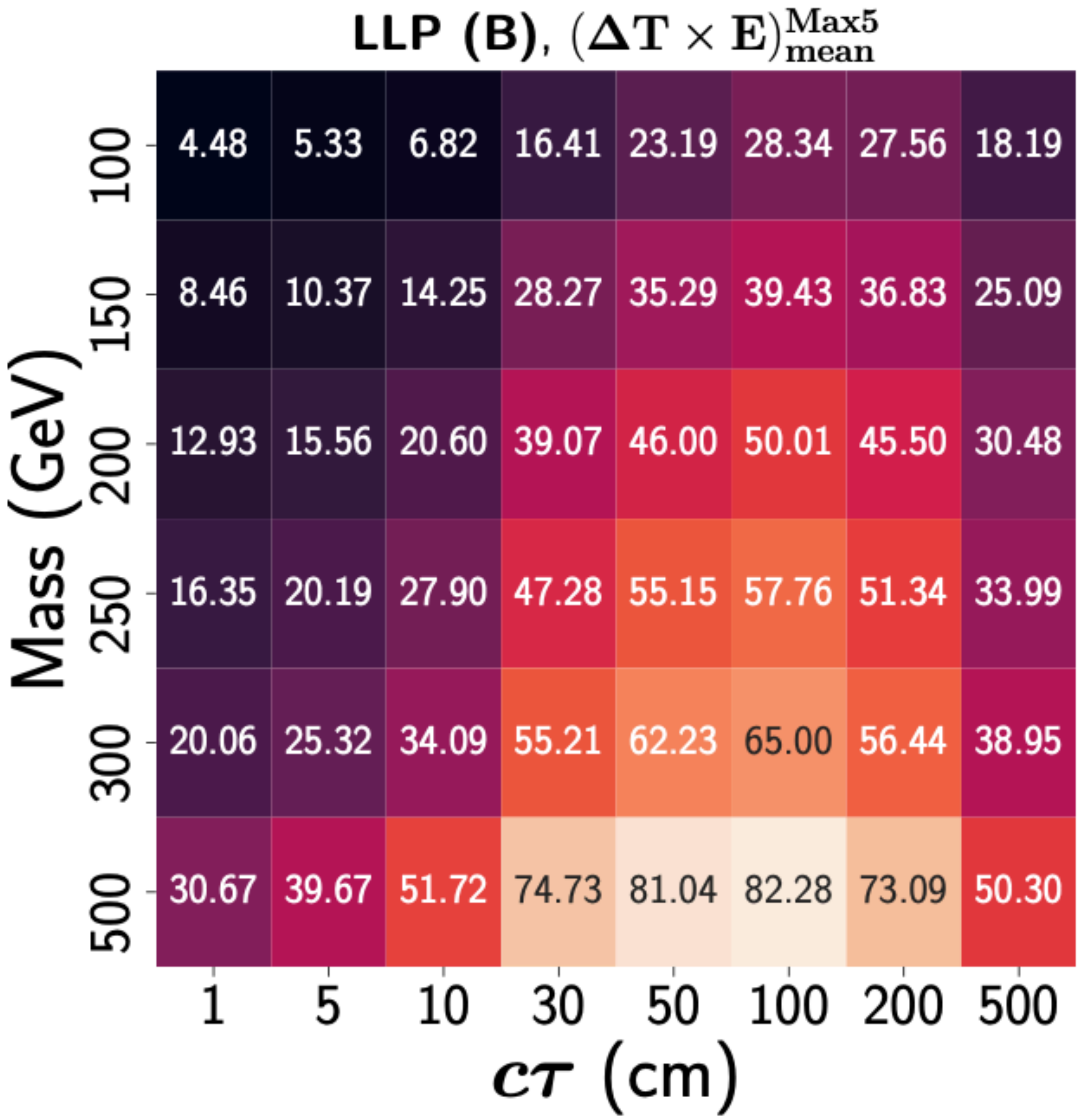


Click Here

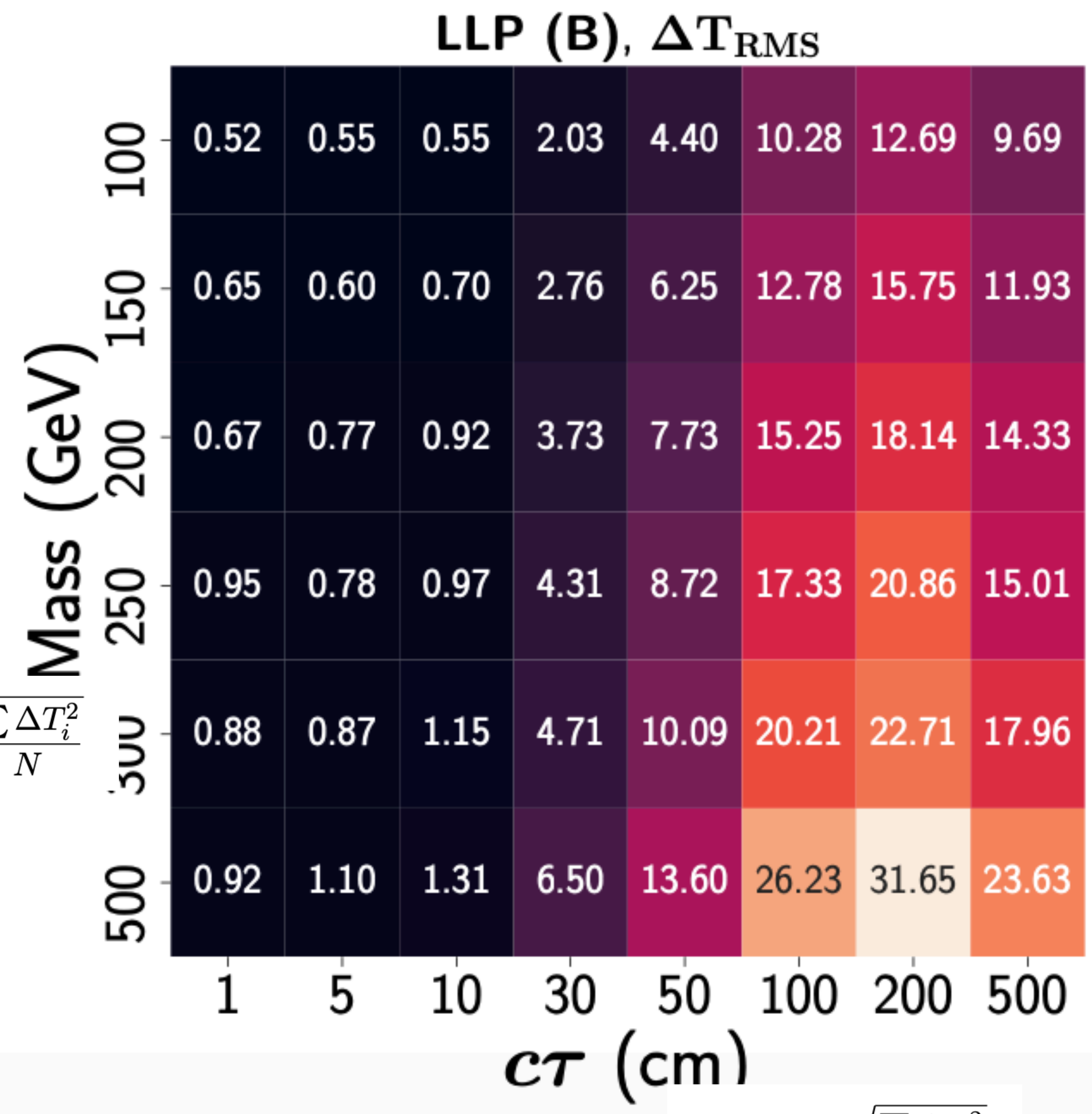
- **Reasonable performance can be achieved, degrades with the lifetime of the mediator**
- **Similar performance of tracking and timing variables.**
- **More improvement possible using the tracking of displaced tracks at L1 (CMS-TDR-021)**
- **For higher decay length, ECAL timing provides good sensitivity (most sensitive decay length is cτ=50 cm for m_Φ = 10 GeV)**

MIP timing detector (MTD): Timing of charged particles with $p_T > 0.7$ GeV up to $|\eta| = 1.5$; $p > 0.7$ GeV for $1.5 < |\eta| < 3.0$ with 30 ps resolution

ECAL timing



$$\Delta T_{RMS} = \sqrt{\frac{\sum \Delta T_i^2}{N}}$$



$(\mathbf{\Delta T \times E})^{\mathbf{Max5}}_{\mathbf{mean}}$: mean of the energy multiplied timing of the 5 ECAL crystals with largest energy multiplied timing in the jet, $\sum_{i=1}^{5} \Delta T_i \times E_i/5$, where i runs over the 5 crystals having the highest $\Delta T \times E$.

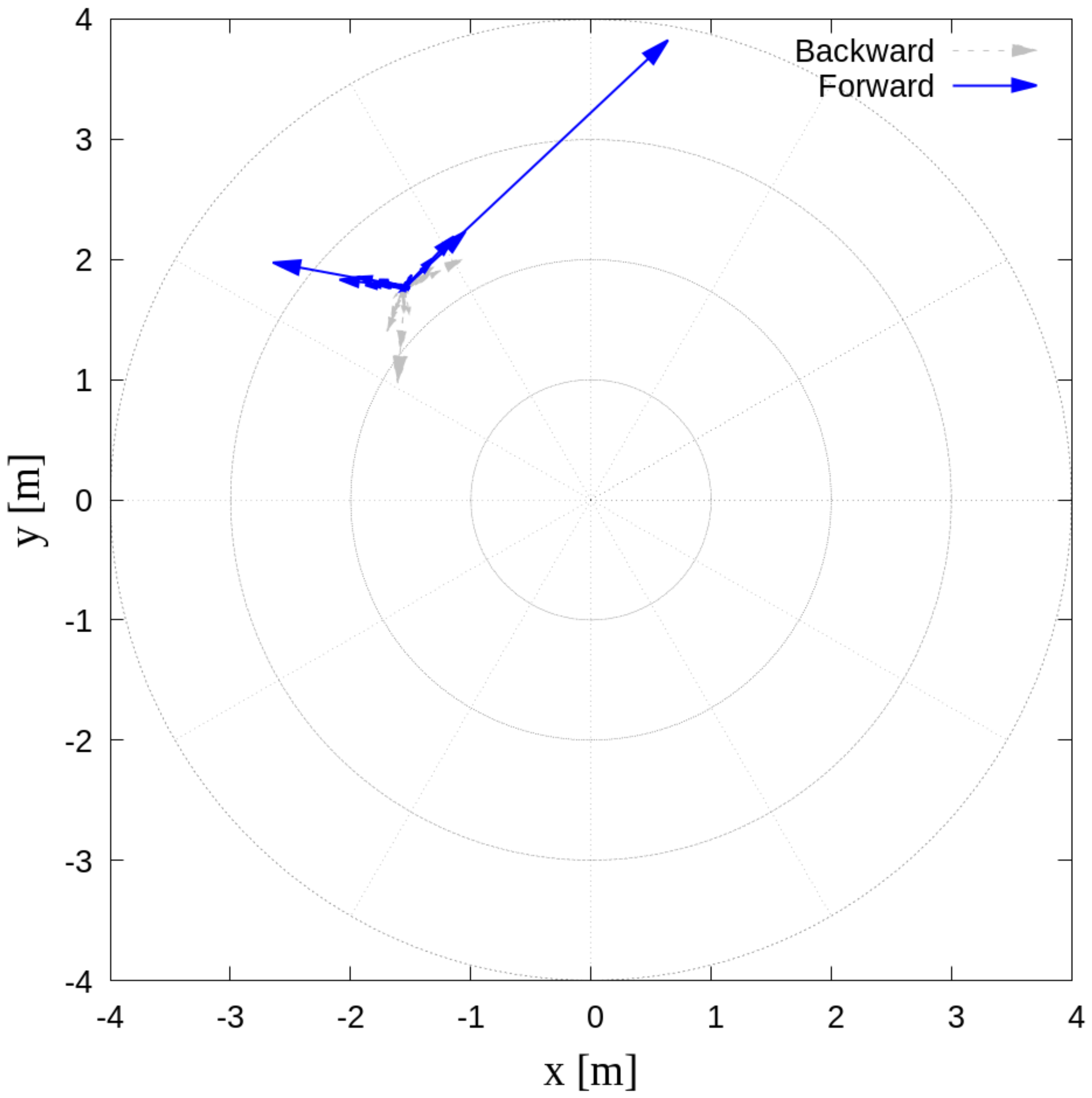
$$\Delta T_{RMS} = \sqrt{\frac{\sum \Delta T_i^2}{N}}$$

Timing variable	Time (ns)	Number of ECAL towers	p_T (GeV)
ΔT^{Ewt}_{mean}	> 1.1	≥ 3	> 35
$(\Delta T \times E)^{Max5}_{mean}$	> 5.5	–	
ΔT_{RMS}	> 1.9	≥ 4	

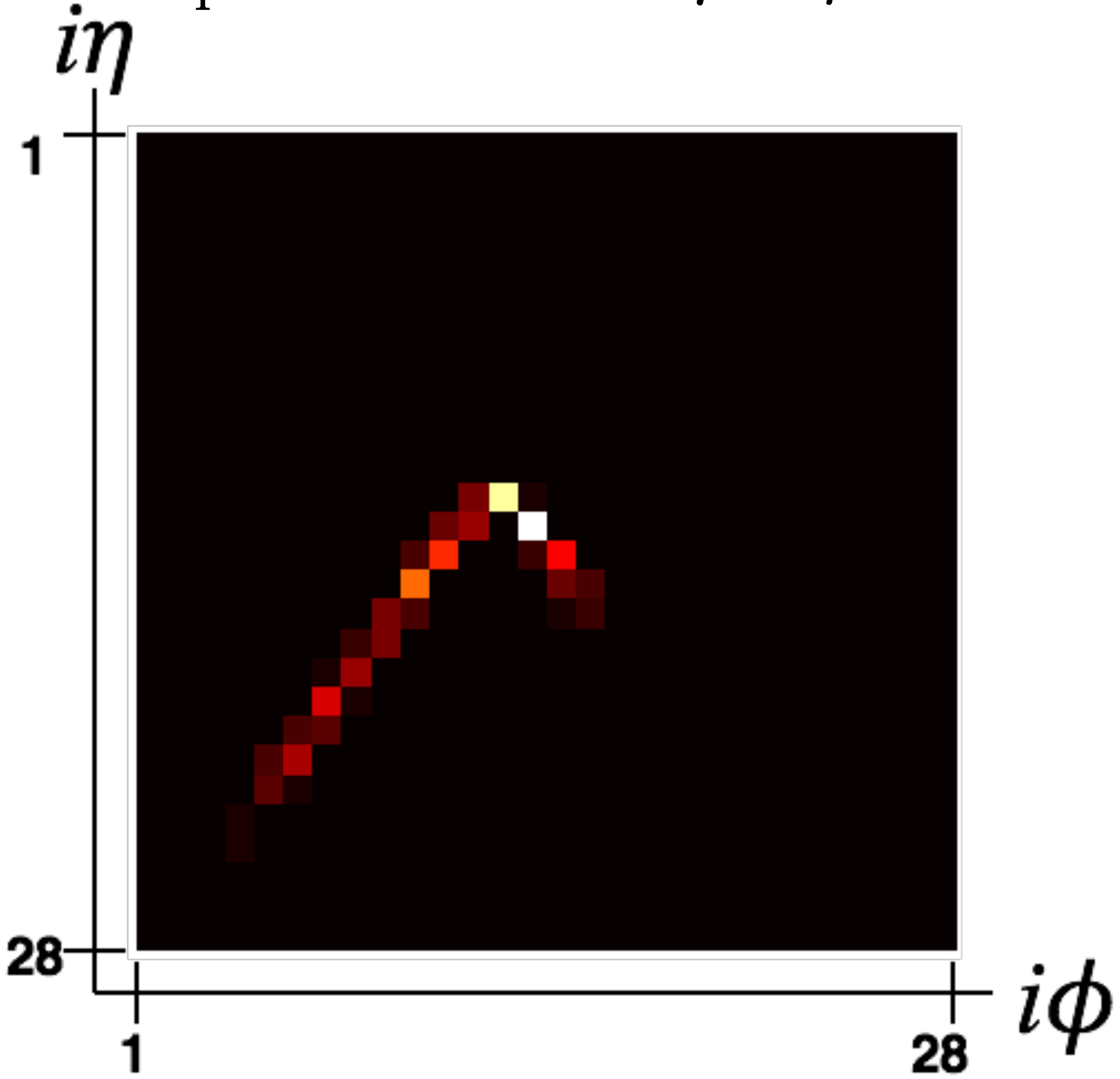
Click Here

Stopped particles in the Calorimeter

Transverse projection of stopped particle decay



spread over several $\eta - \varphi$ towers



Energy deposition of stopped particle

BB, Swagata Mukherjee and Rhitaja Sengupta
arXiv:1904.04811, JHEP 2019

For slow moving LLPs, some of the decay products can move in the backward direction !

S. Banerjee, G. Bélanger, BB, F. Boudjema, R. Godbole and S. Mukherjee Phys.Rev.D 98 (2018) 11, 115026

Mass [GeV], Decay Length [cm]	Reco as L1 tracks	Before MTD	Before ECAL	Before HCAL	Before MS	Inside MS	Outside detector
50, 10	13.20	80.51	1.26	1.85	1.72	1.19	0.26
50, 100	1.38	46.55	3.38	7.58	11.02	12.55	17.55
100, 10	10.59	86.81	0.70	0.91	0.68	0.28	0.02
100, 100	1.15	49.46	3.71	8.84	13.66	12.31	10.88
200, 10	10.83	88.42	0.27	0.31	0.14	0.02	0.002
200, 100	1.12	56.27	3.79	9.66	14.27	9.72	5.17
500, 10	11.94	87.99	0.04	0.04	0.04	0	0
500, 100	1.32	66.65	3.75	9.54	12.80	4.86	1.10

Table 1: Percentage of decays for different benchmark points from scenario (A) in various detector parts using the CMS detector dimensions.

Φ -> b b channel

BB, Shigeki Matsumoto, Rhitaja Sengupta
e-Print: 2111.02437, PRD 2022

Trigger

- We can trigger the event using the prompt associated objects like jets, leptons etc.
- We have applied a set of cuts on prompt objects motivated from CMS Level-1 trigger TDR to select events .
- It is possible to reduce the prompt threshold if we can consider activity in the MS.

Observations

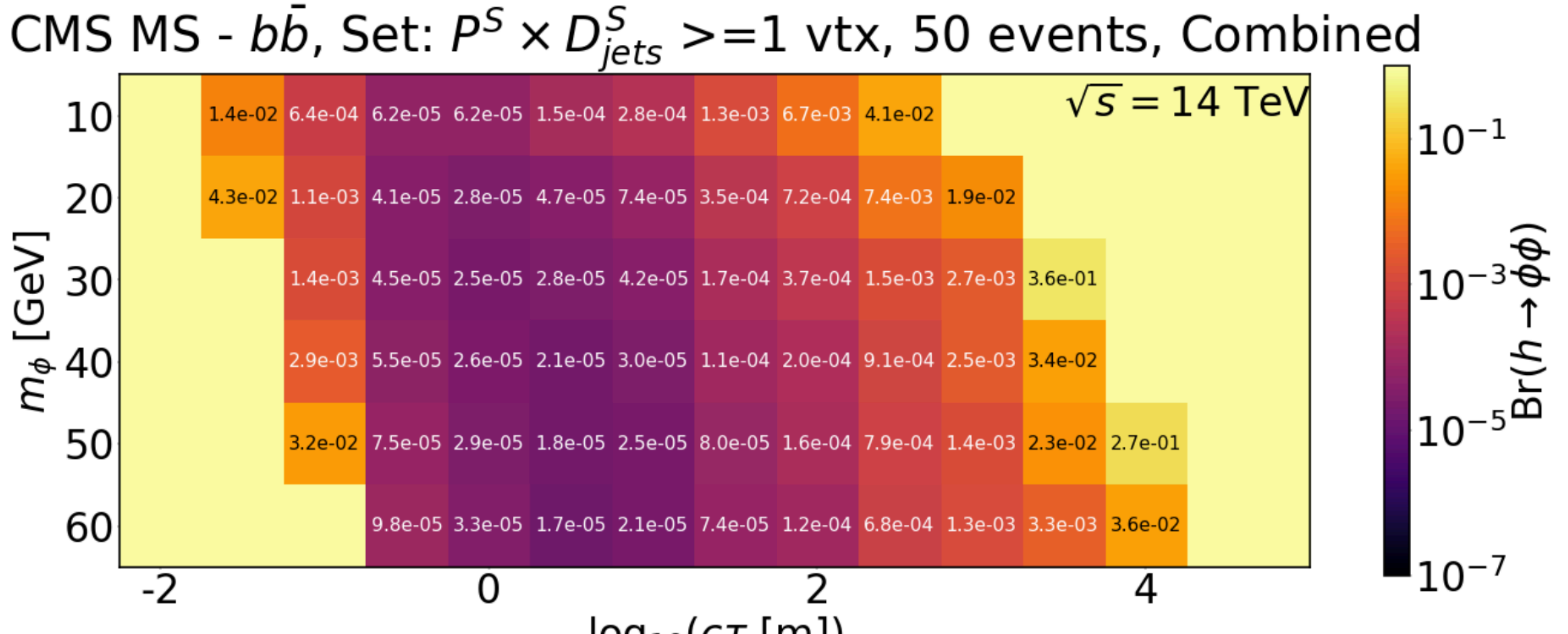
- Fraction of decays inside the fiducial volume ~ 10-15% at most
- Efficiency drops by about half if we apply $\Delta\varphi$ cut for m_ϕ = 10

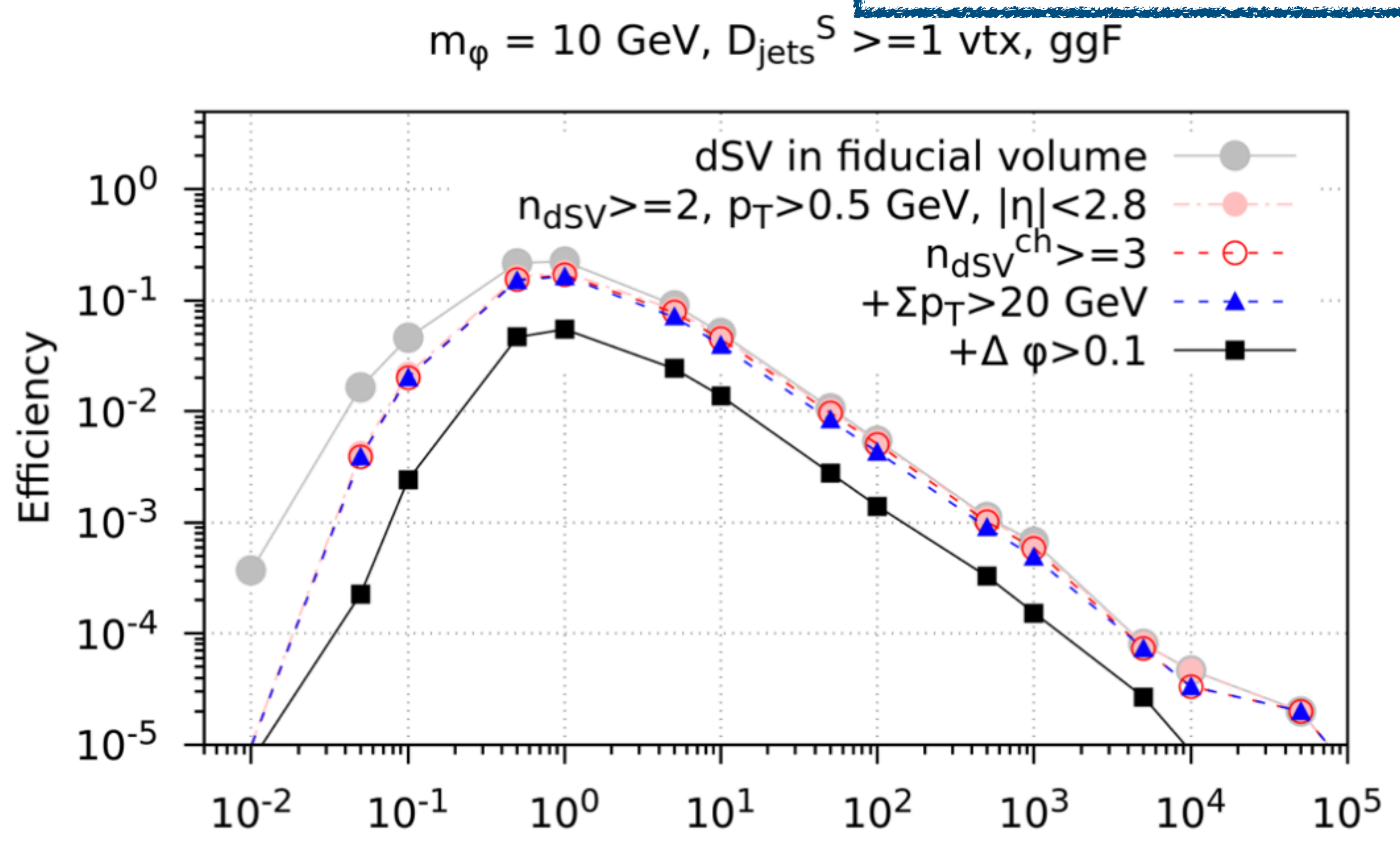
Trigger	In $P^H_{\rm Mode}$	In $P^S_{\rm Mode}$	Mode
Single jet	$p_T^j > 180\,\text{GeV}$, $\lvert\eta_j\rvert < 2.4$.	$p_T^j > 90\,\text{GeV}$, $\lvert\eta_j\rvert < 2.4$.	ggF, VBF, Vh-jet.
Di-jet	$p_T^j > 112\,\text{GeV}$, $\lvert\eta_j\rvert < 2.4$, $\Delta\eta < 1.6$.	$p_T^j > 90\,\text{GeV}$, $\lvert\eta_j\rvert < 2.4$, $\Delta\eta < 1.6$.	
VBF jet	$p_T > 70\,\text{GeV}$ for Leading jet, $p_T > 40\,\text{GeV}$ for Sub-leading jet, $\lvert\eta_j\rvert < 5$, $\eta_{j_1} \times \eta_{j_2} < 0$, $\Delta\eta > 4.0$, $\Delta\phi < 2.0$, $m_{jj} > 1000\,\text{GeV}$.	$p_T > 60\,\text{GeV}$ for Leading jet, $p_T > 30\,\text{GeV}$ for Sub-leading jet, $\lvert\eta_j\rvert < 5$, $\eta_{j_1} \times \eta_{j_2} < 0$, $\Delta\eta > 4.0$, $\Delta\phi < 2.0$, $m_{jj} > 500\,\text{GeV}$.	
Single electron	$p_T^e > 36\,\text{GeV}$, $\lvert\eta\rvert < 2.4$.	$p_T^e > 18\,\text{GeV}$, $\lvert\eta\rvert < 2.4$.	Vh-lep.
Double electron	$p_T^{e_1} > 25\,\text{GeV}$, $p_T^{e_2} > 12\,\text{GeV}$, $\lvert\eta\rvert < 2.4$.	$p_T^{e_1} > 12\,\text{GeV}$, $p_T^{e_2} > 12\,\text{GeV}$, $\lvert\eta\rvert < 2.4$.	
Single muon	$p_T^\mu > 22\,\text{GeV}$, $\lvert\eta\rvert < 2.4$.	$p_T^\mu > 11\,\text{GeV}$, $\lvert\eta\rvert < 2.4$.	
Double muon	$p_T^{\mu_1} > 15\,\text{GeV}$, $p_T^{\mu_2} > 7\,\text{GeV}$, $\lvert\eta\rvert < 2.4$.	$p_T^{\mu_1} > 7\,\text{GeV}$, $p_T^{\mu_2} > 7\,\text{GeV}$, $\lvert\eta\rvert < 2.4$.	

	D^H_{jets}	D^S_{jets}
Electrons, photons, hadrons	$p_T > 0.5\,\text{GeV}$	$p_T > 0.5\,\text{GeV}$
	$\lvert\eta\rvert < 2.8$	$\lvert\eta\rvert < 2.8$
MS cluster from same dSV (< 1 cm)	$d_T > 4\,\text{m}$ or $\lvert d_z\rvert > 7\,\text{m}$	$d_T > 4\,\text{m}$ or $\lvert d_z\rvert > 7\,\text{m}$
	$d_T < 6\,\text{m}$ and $\lvert d_z\rvert < 9\,\text{m}$	$d_T < 6\,\text{m}$ and $\lvert d_z\rvert < 9\,\text{m}$
	$n^{\rm ch}_{\rm dSV} \geq 5$	$n^{\rm ch}_{\rm dSV} \geq 3$
	$\sum p_{T,dSV} > 50\,\text{GeV}$	$\sum p_{T,dSV} > 20\,\text{GeV}$
	$\Delta\phi_{\max} > 0.2$	$\Delta\phi_{\max} > 0.1$
Event	$n_{\rm cluster} \geq 1$, $n_{\rm cluster}$ =2	$n_{\rm cluster} \geq 1$, $n_{\rm cluster} = 2$

P^H : a hard set of cuts P^S : a softer set of cuts

LLP Model: $pp \to h \to \phi\phi$

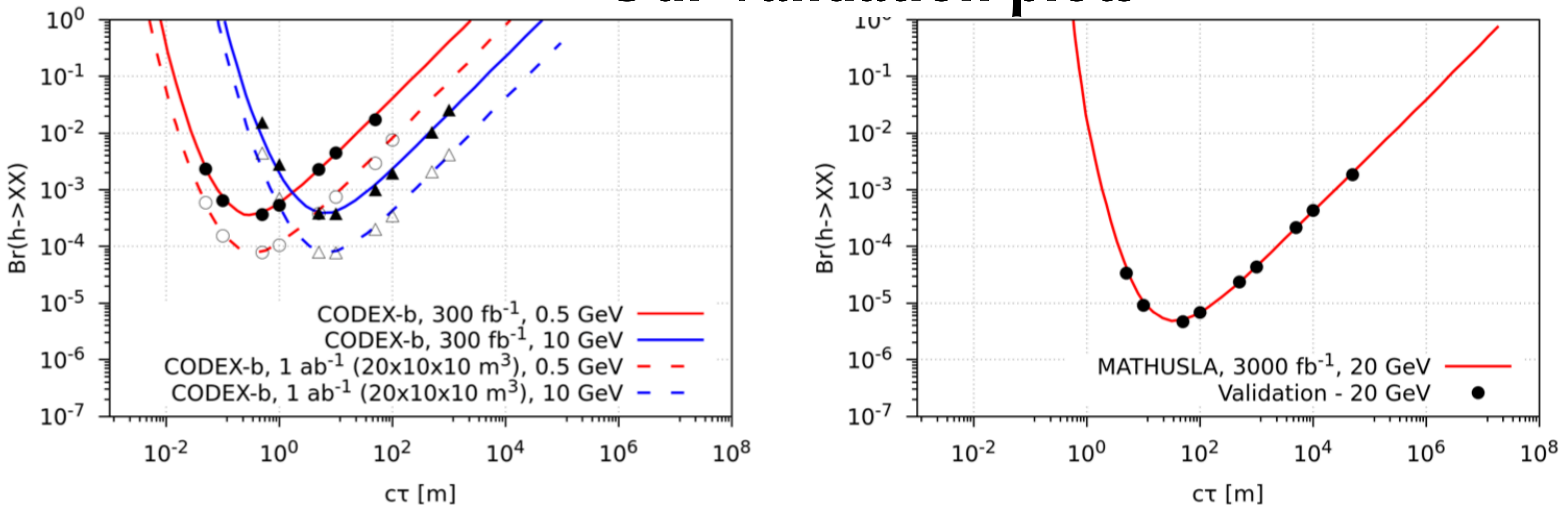




Dedicated LLP detectors : Mathusla and CODEX-b

- The dedicated detectors placed far away from the IP might be sensitive to a range of lifetimes which is complementary to the CMS MS.
- These proposed detectors will be placed a few tens of meters away from the IP of the pp collision.
- Enough shielding of rock or concrete as well as active veto to guarantee very little or almost no backgrounds.
- Therefore, observation of even a few events (∽ 4) can be claimed as a discovery of displaced decays of particles.
- We have computed the limits assuming CODEX-b and Mathusla LLP detectors for our minimal model.

Our Validation plots



LLP Model: $pp \to h \to \phi\phi$

Compared with these two references

C. Alpigiani, "Exploring the lifetime and cosmic frontier with the MATHUSLA detector," JINST 15 no. 09, (2020) C09048, arXiv:2006.00788 [physics.ins-det].

V. V. Gligorov, S. Knapen, M. Papucci, and D. J. Robinson, "Searching for Long-lived Particles: A Compact Detector for Exotics at LHCb," Phys. Rev. D 97 no. 1, (2018) 015023, arXiv:1708.09395 [hep-ph].