Current Status of BSM Physics and Future Directions

Biplob Bhattacherjee

Centre for High Energy Physics
Indian Institute of Science
Bengaluru, India

From Big Bang to Now: A Theory-Experiment Dialogue
SRM University AP
24th January 2025

Standard Model of Particle Physics

Standard Model of particle physics provides an excellent description of various experiments so far

The Higgs boson: The last piece of Standard Model (SM) was discovered in 2012.

(One of the major goals of the LHC)

CMS and ATLAS experiments have measured various properties of the observed Higgs boson.

Standard Model of Particle Physics

Standard Model of particle physics provides an excellent description of various experiments so far

The Higgs boson: The last piece of Standard Model (SM) was discovered in 2012.

(One of the major goals of the LHC)

CMS and ATLAS experiments have measured various properties of the observed Higgs boson.

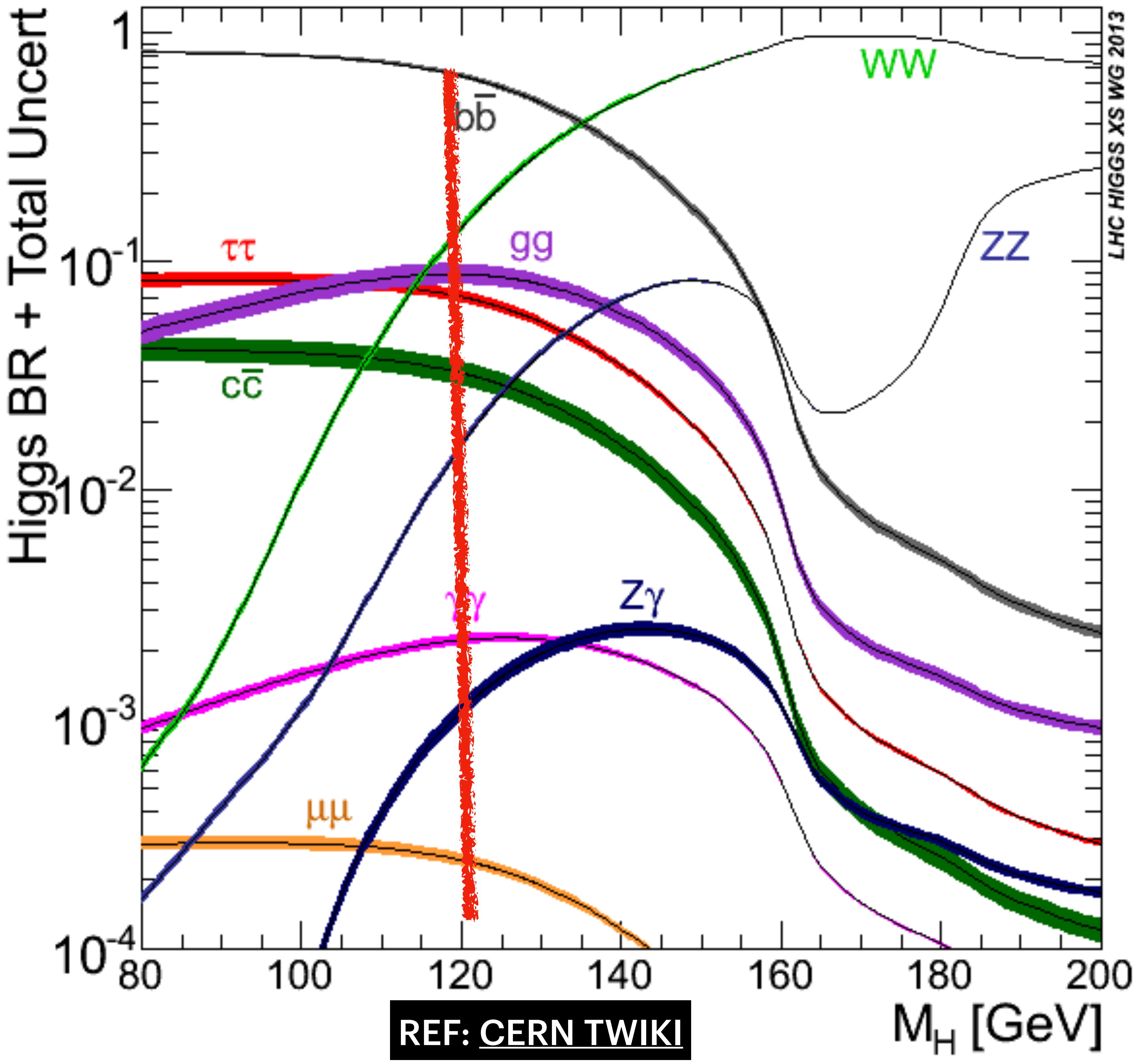
What do we know about the Higgs boson ?

Mass of the Higgs boson ~ 125 GeV

For MH~ 100 GeV => W and Z boson decays suppressed

For MH~ 200 GeV => only W and Z decays are important

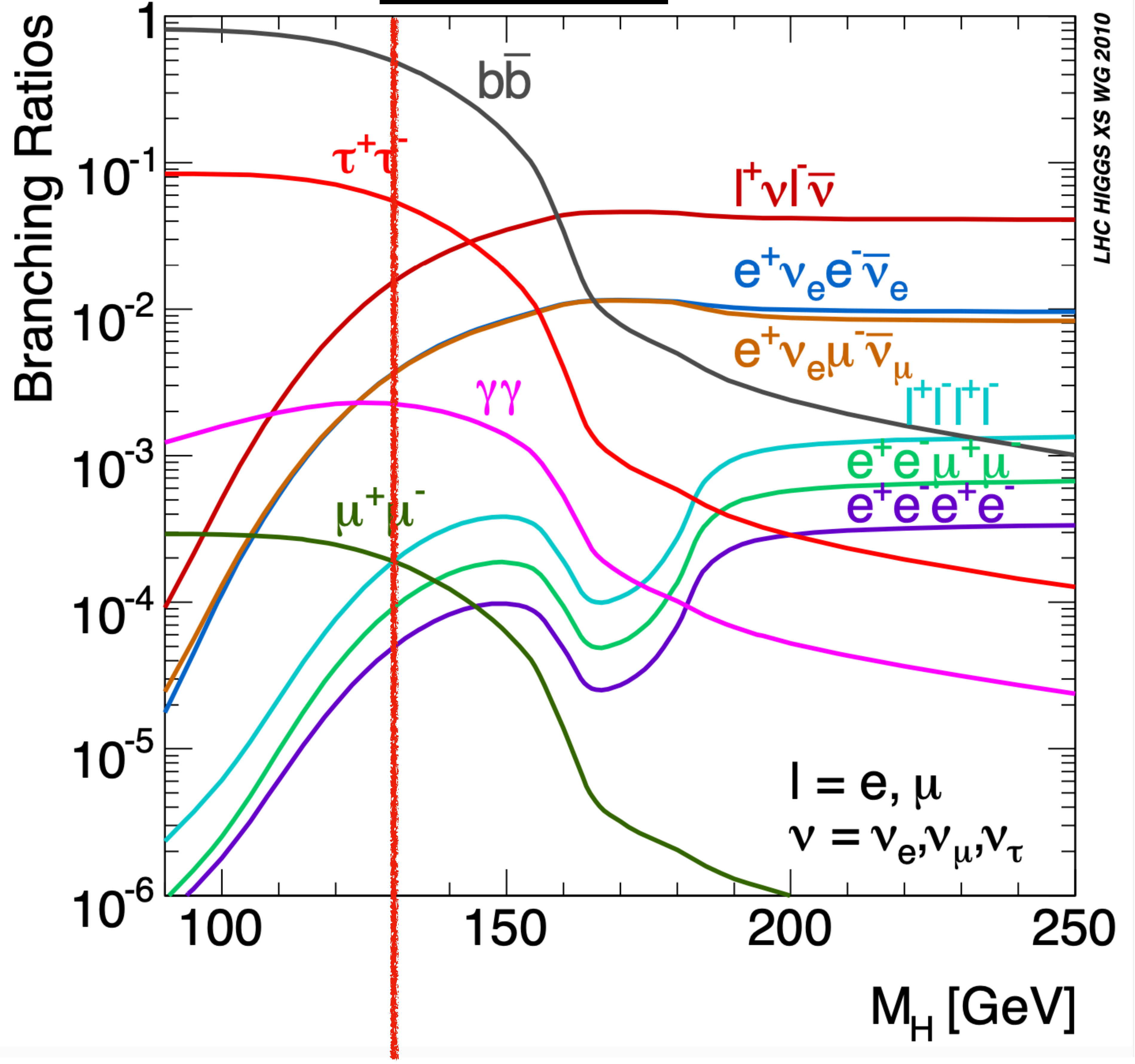
This gives us unique opportunity for several measurements



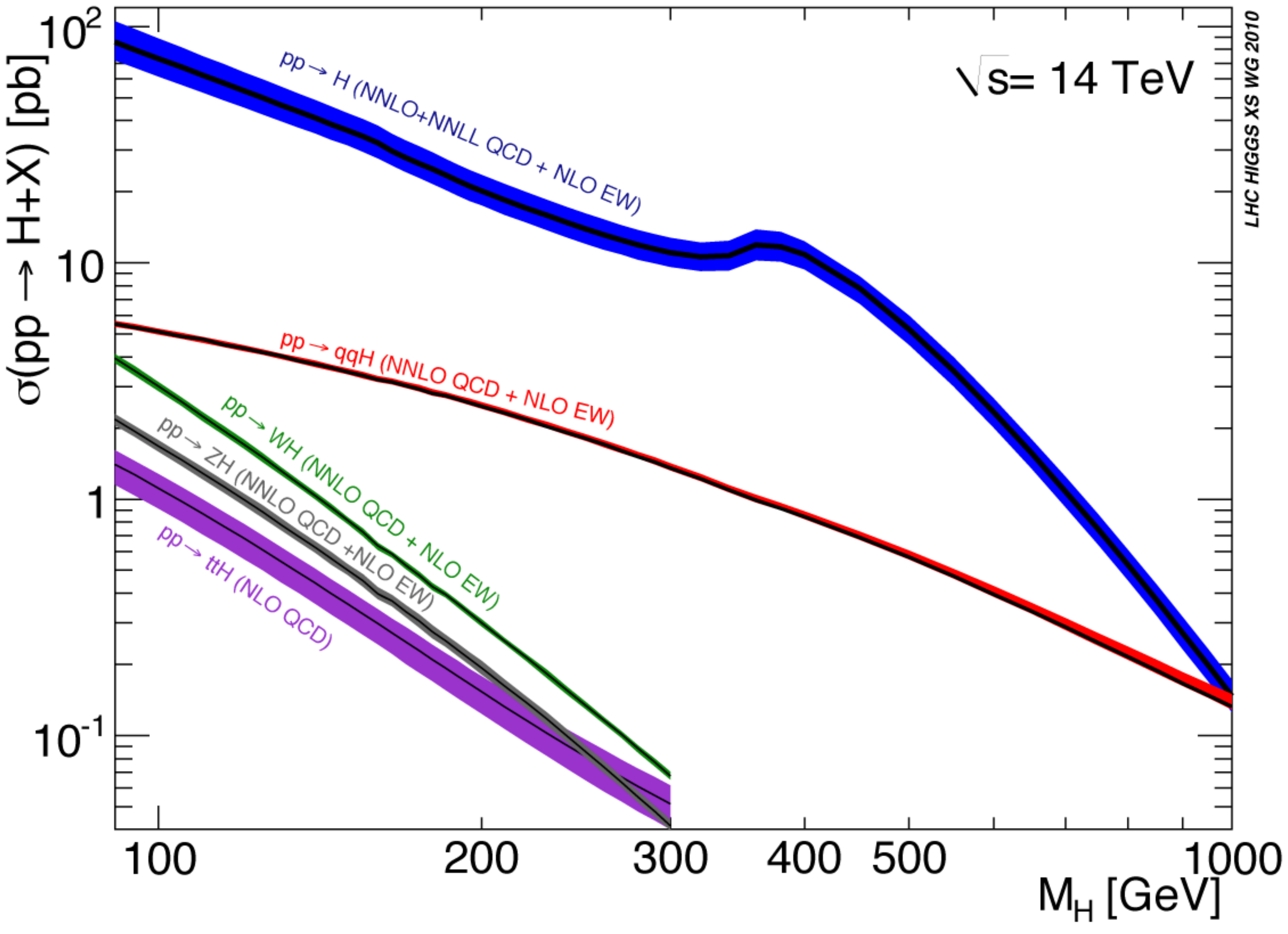
REF: CERN TWIKI

Decay and Production of Higgs boson@LHC

REF : CERN TWIKI



REF : CERN TWIKI



The dominant decay mode of H_{125} to $b\bar{b}$ ~ 57 %
although Higgs $b\bar{b}$ Yukawa coupling is small

This makes loop or 3-body decay modes sizeable

CMS and ATLAS observed Higgs boson in several production and decay channels

Current Status of Higgs physics@LHC

Consider a process $gg \to H_{125} \to \gamma\gamma$

Signal Strength: μ

$$\mu_{ggF}^{\gamma\gamma} = \frac{\sigma(gg \to H_{125})\ Br(H_{125} \to \gamma\gamma)}{\sigma(gg \to H_{125}^{SM})\ Br(H_{125}^{SM} \to \gamma\gamma)}$$

μ~1 if the observed Higgs boson is indeed the Higgs boson of the Standard Model

Measured signal strength $\mu_{total} = 1.05 \pm 0.06$

REF: 2404.05498

ggF process ~10 % accuracy , other channels ~ 10-20%

Decays ~ 10-50% accuracy

Beyond the Standard Model Physics

SM is a model: Many reasons to extend the SM
(Colloquium today by Prof. Sreerup Raychaudhuri)

Need to extend the Standard Model => beyond the standard model (BSM) Physics

BSM=> New particles and new interactions

Beyond the Standard Model Physics

SM is a model: Many reasons to extend the SM

(Colloquium today by Prof. Sreerup Raychaudhuri)

Need to extend the Standard Model => beyond the standard model (BSM) Physics

BSM=> New particles and new interactions

BSM Search Strategies

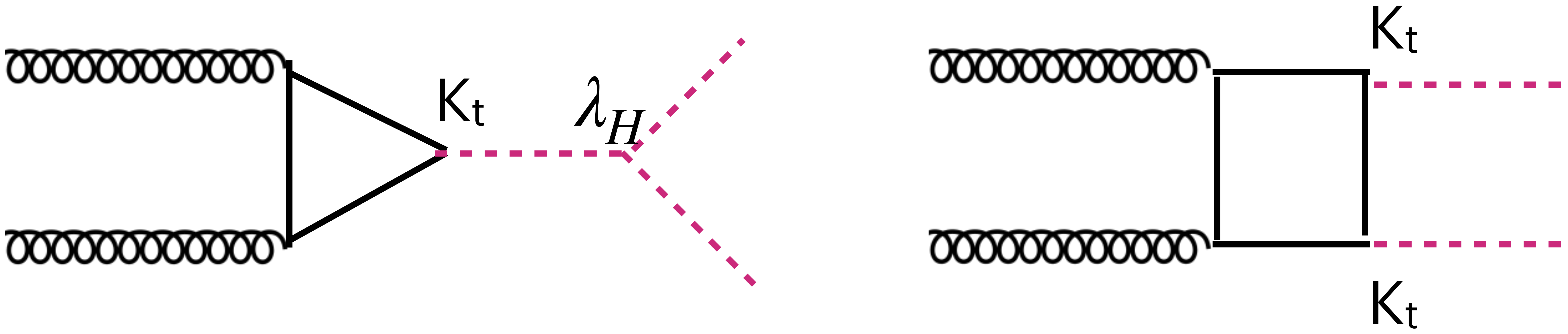
Indirect search:
Identify the effect of new physics from Standard Model measurements

Direct search:
Produce the new particles in experiment and measure the properties

Indirect search: BSM particles are heavier than LHC reach

SM Di-Higgs production at the LHC

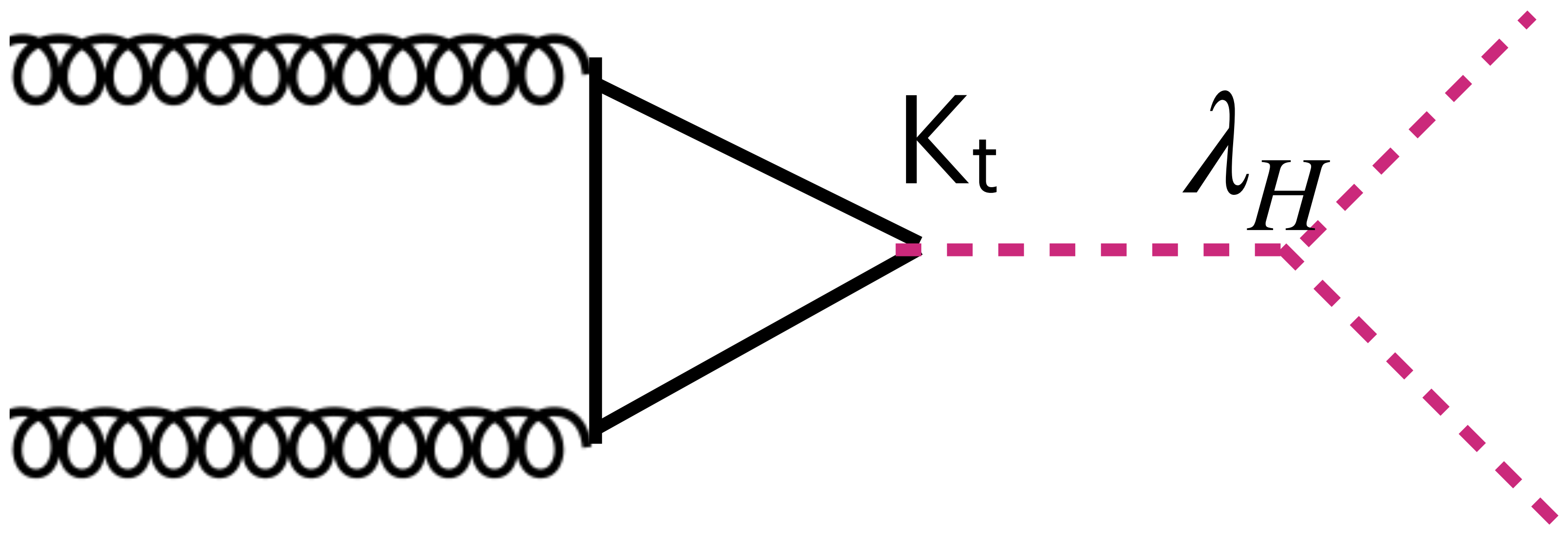
SM Di-Higgs production cross section ~ 40 fb (1000 times smaller than single Higgs production)

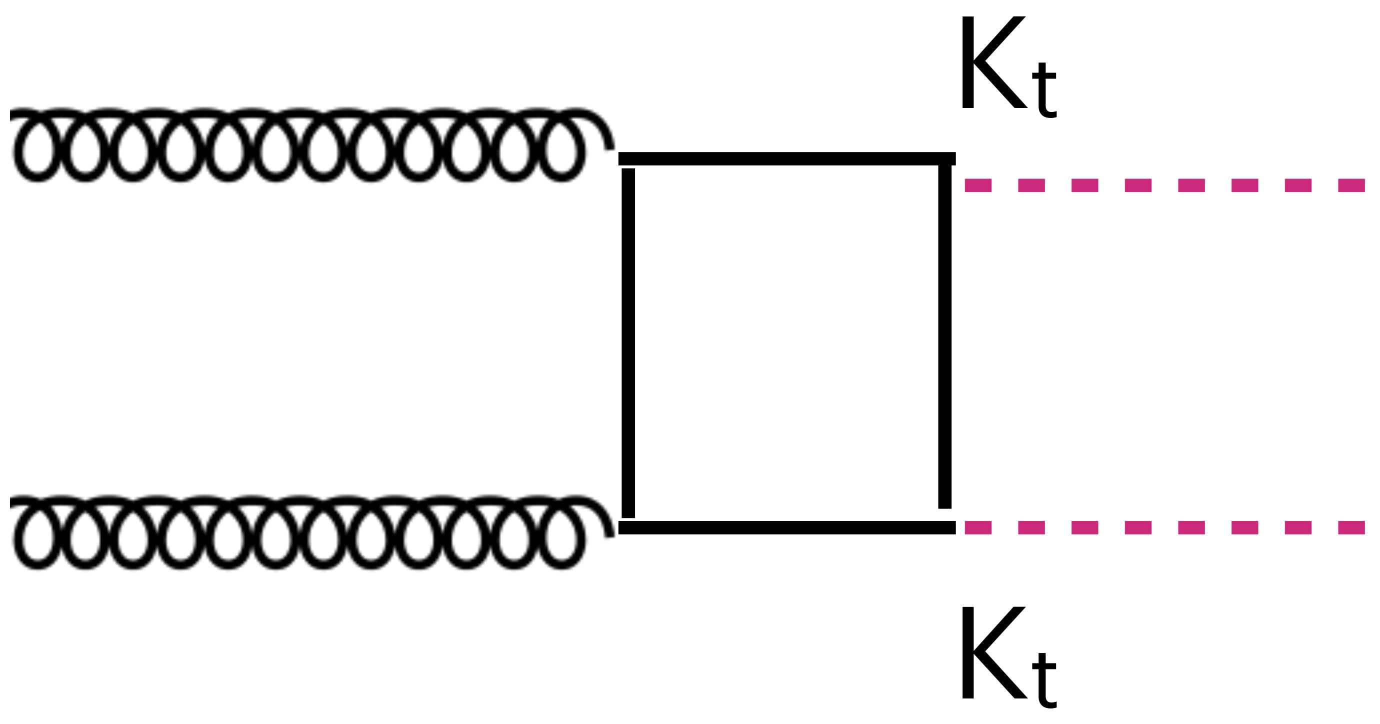


Indirect search: BSM particles are heavier than LHC reach

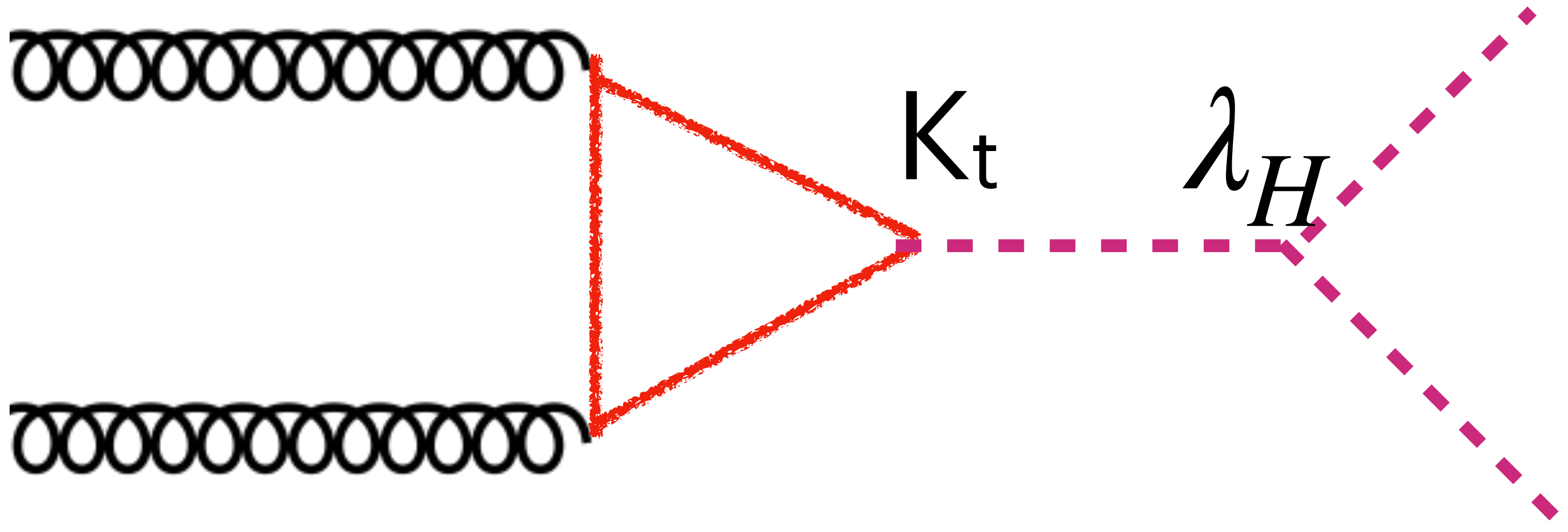
SM Di-Higgs production at the LHC

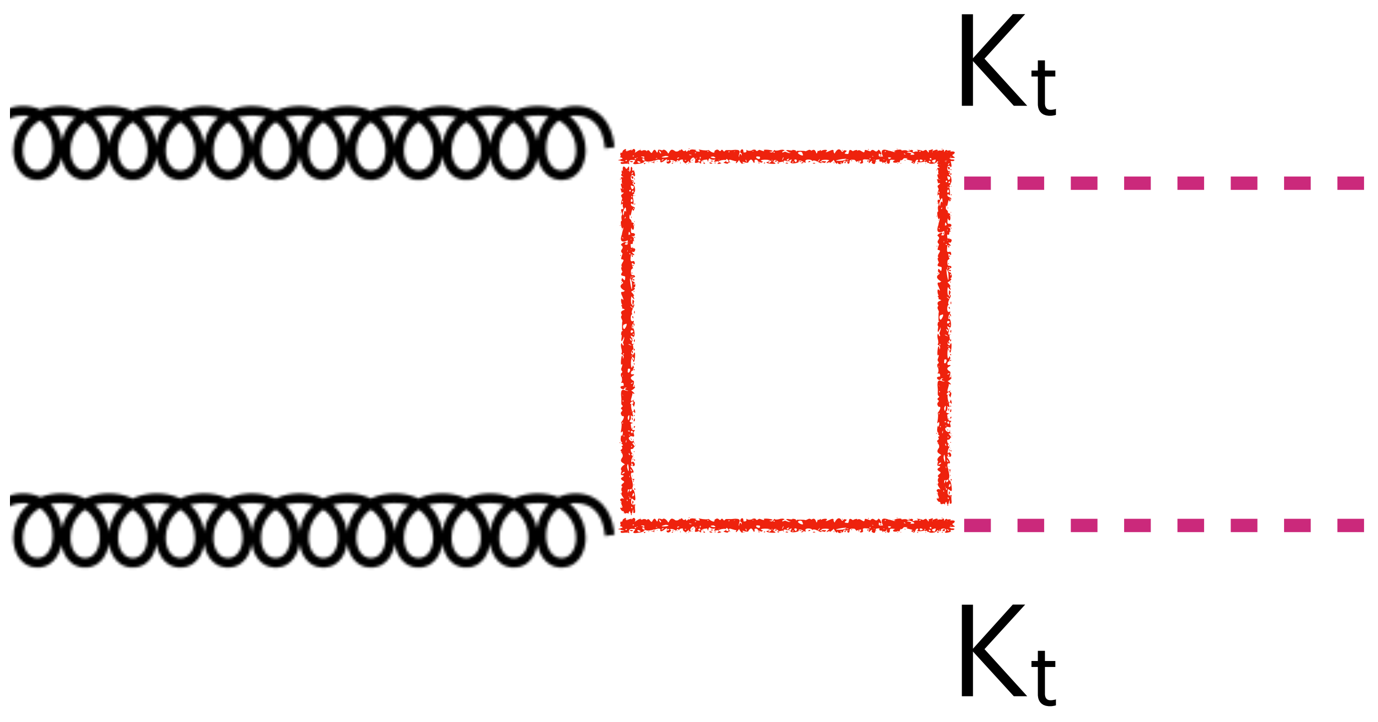
SM Di-Higgs production cross section ~ 40 fb (1000 times smaller than single Higgs production)





This process may be affected by heavy new particles => new particle in the loop





Effective field theory approach => Talk by Prof. Shankha Banerjee

Recipe for Direct search at the LHC

Goal: Find a new particle X

STEP I : Production

a). Single production $pp \rightarrow X$

b). Pair production $pp \rightarrow XX$

c). From decay $pp \rightarrow Y_{SM/BSM} \rightarrow XX$

STEP II : Decay

Various Decay modes possible : X to 2,3,4 body

decays to SM particles and also BSM particles

The Large Hadron Collider(LHC)

- LHC has four general purpose detectors : CMS, ATLAS, ALICE and LHCb
- There are other smaller experiments like TOTEM, LHCf, MoEDAL, ..
- LHC has collected and analysed about 5%-7% of the full data expected

LHC statistics :

Run 1 : 2010-2011	$\sqrt{s} = 7$ TeV	Integrated Luminosity ~ 5 fb^{-1}
2012	$\sqrt{s} = 8$ TeV	Integrated Luminosity ~ 20 fb^{-1}
Run 2: 2015-2018	$\sqrt{s} = 13$ TeV	Integrated Luminosity ~ 140 fb^{-1}
Run 3: 2022 -	$\sqrt{s} = 13.6$ TeV	Integrated Luminosity ~ 200fb^{-1} ?
Run 4: 2026- ?	$\sqrt{s} = 13.6/14??$ TeV	Integrated Luminosity ~ 3000 fb^{-1}

The Large Hadron Collider(LHC)

- LHC has four general purpose detectors : CMS, ATLAS, ALICE and LHCb
- There are other smaller experiments like TOTEM, LHCf, MoEDAL, ..
- LHC has collected and analysed about 5% of the full data expected

LHC statistics :

Run 1 :	2010-2011	$\sqrt{s} = 7$ TeV	Integrated Luminosity ~ 5 fb^{-1}
	2012	$\sqrt{s} = 8$ TeV	Integrated Luminosity ~ 20 fb^{-1}
Run 2:	2015-2018	$\sqrt{s} = 13$ TeV	Integrated Luminosity ~ 140 fb^{-1}
Run 3:	2022 -	$\sqrt{s} = 13.6$ TeV	Integrated Luminosity ~ 200fb^{-1} ?
Run 4:	2026- ?	$\sqrt{s} = 13.6/14??$ TeV	Integrated Luminosity ~ 3000 fb^{-1}

Various components of CMS and ATLAS detector and particle detection

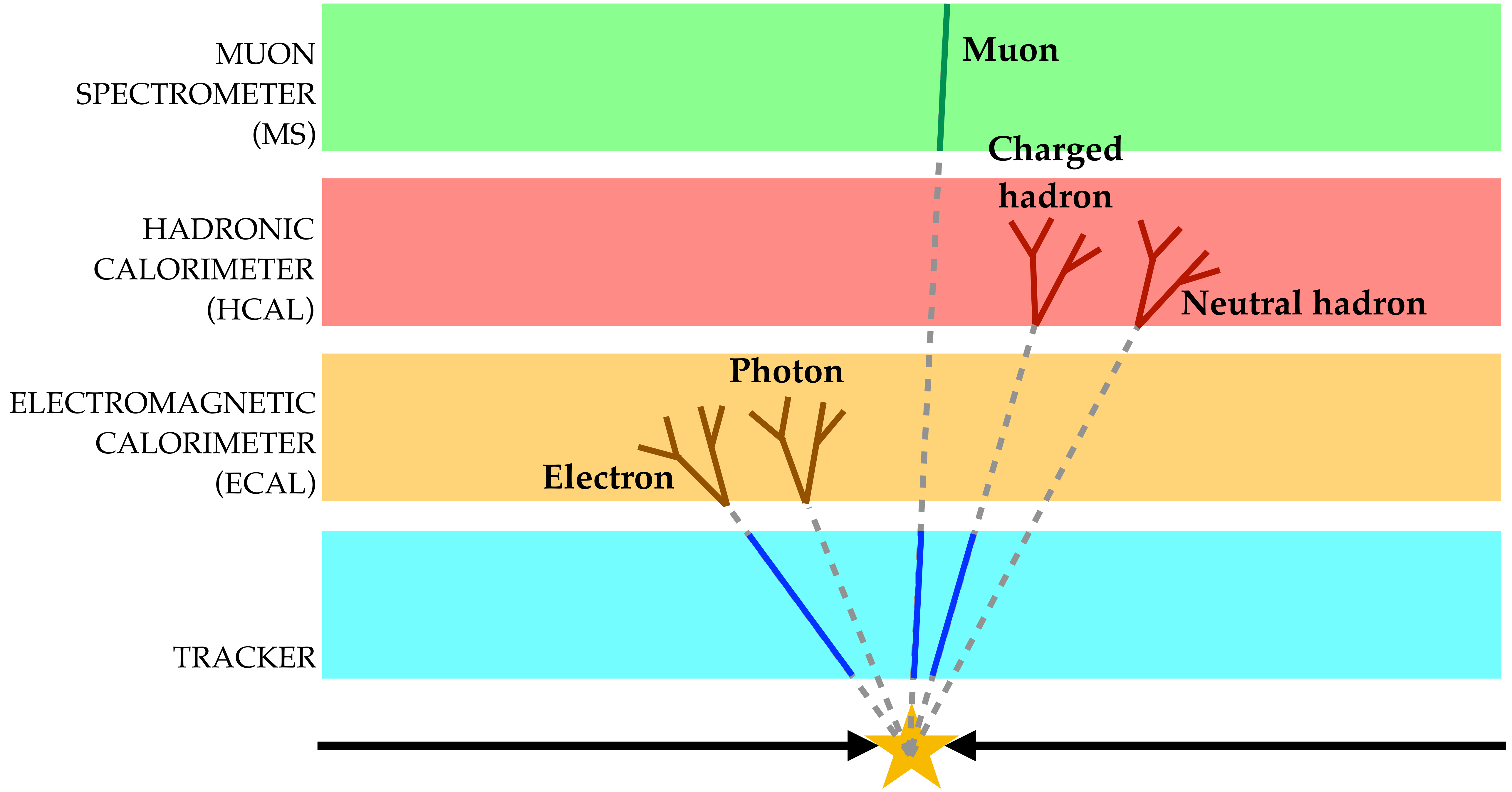


Fig: Taken from Rhitaja Sengupta's thesis

Electron=> track in the tracker and energy deposition in the ECAL

Muon=> track in the tracker and in the Muon Spectrometer and no or a little energy deposition in the ECAL/HCAL

Recipe for conventional search at the LHC

Goal: Find a new particle X

STEP I : Production

a). Single production $pp \to X$

b). Pair production $pp \to XX$

c). From decay $pp \to Y_{SM/BSM} \to XX$

STEP II : Decay

Various Decay modes possible : X to 2,3,4 body decays to SM particles and also BSM particles

STEP III : Final State

At the LHC we can identify electron, muon, photon, jets(from quarks and gluons)

Indirect identification of invisible particles like neutrinos, dark matter etc. possible (in terms of MET)

Classify the signatures based on the production mechanisms and decay modes

Example : di-muon final state, multiple jets + missing transverse energy, photons + leptons etc.

Analysis techniques

Define variable(s) which can separate signal process from the SM backgrounds.

Use sophisticated statistical techniques, ML etc.

Recipe for conventional search at the LHC

Analysis techniques

Define variable(s) which can separate signal process from the SM backgrounds.

Use sophisticated statistical techniques, ML etc.

Machine Learning: active field of research in High Energy Physics
Talk by Prof. Partha Konar

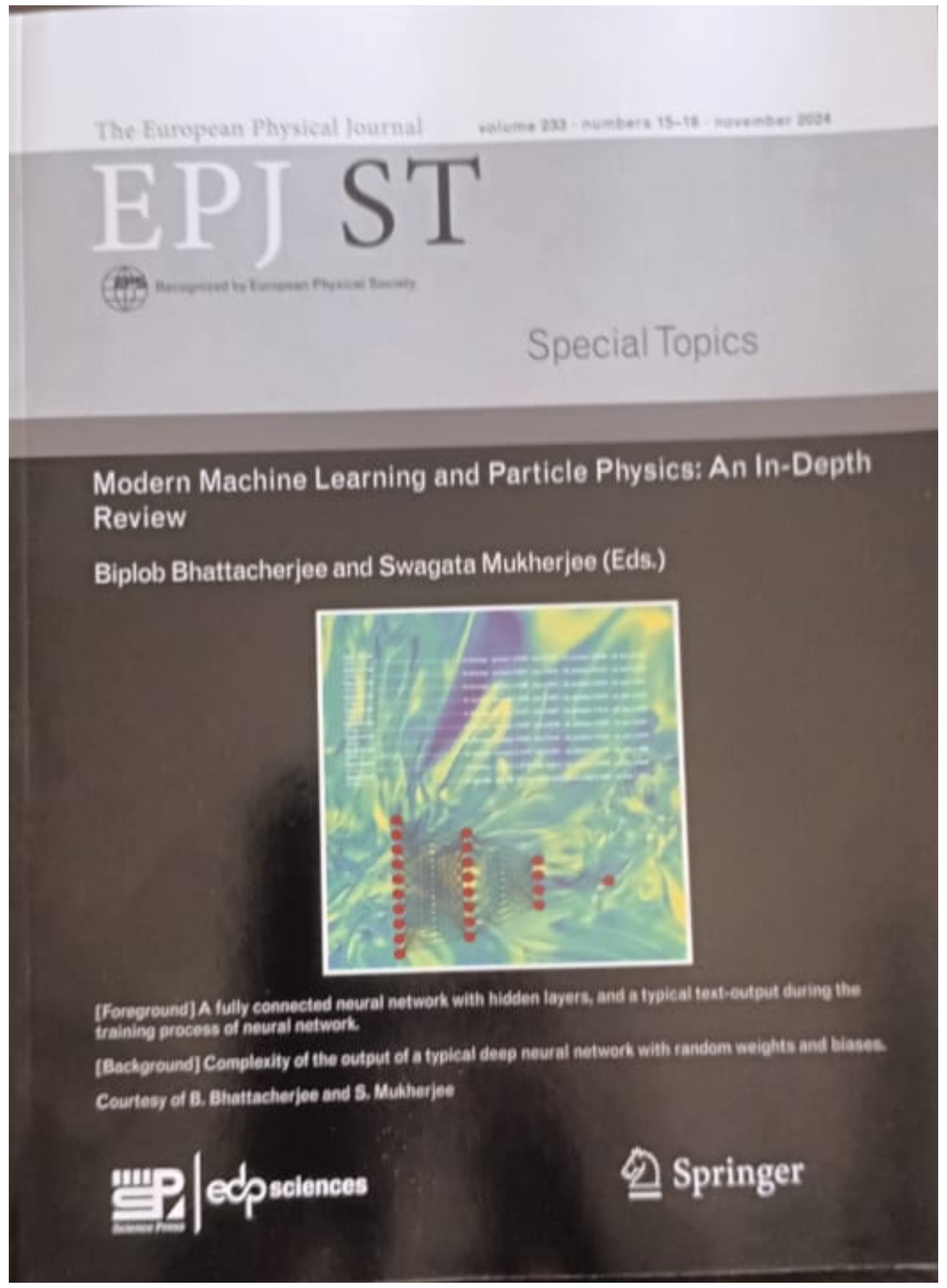
SRM HEP Group is actively involved in ML

See a recent review:

Interplay of traditional methods and machine learning algorithms for tagging boosted objects

Camellia Bose, Amit Chakraborty, Shreecheta Chowdhury, Saunak Dutta.

Eur.Phys.J.ST 233 (2024) 15-16, 2531-2558



Modern Machine Learning and Particle Physics: An In-Depth Review

Edited by BB (IISc) and Swagata Mukherjee(IIT Kanpur)

Conventional Signature: Strong production cross section

Goal: Search for gluino ($\tilde{g}$) of MSSM

STEP I : Production

Pair production $pp \to \tilde{g}\tilde{g}$

STEP II : Decay

$\tilde{g} \to q\bar{q}\tilde{\chi}$

Gluino can decay to quarks and dark matter (LSP in MSSM)

STEP III : Final State

Final State : Multiple jets + Missing transverse energy

Analysis techniques

Missing transverse energy, effective mass , H_T etc

Use different techniques to separate signal and backgrounds

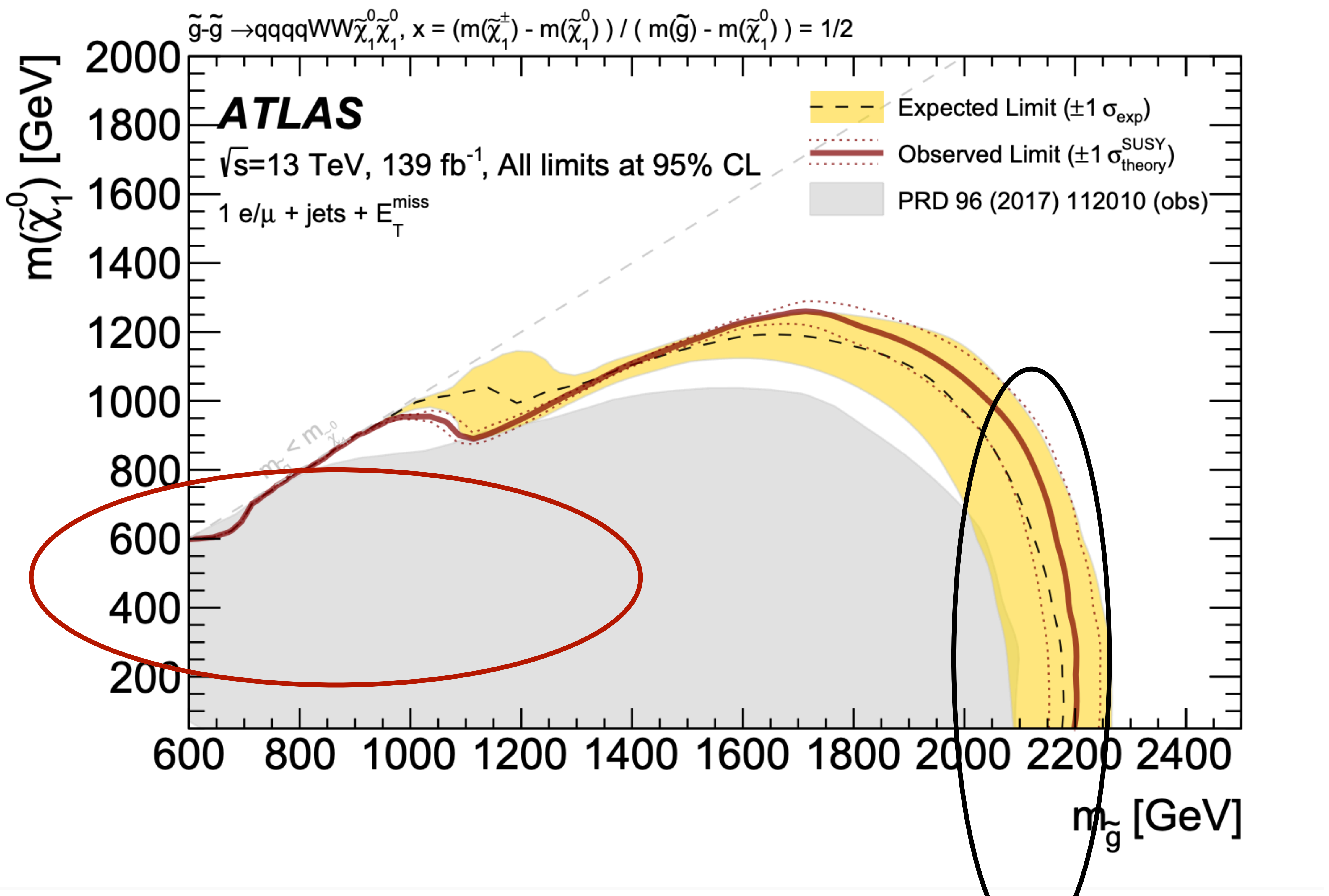
Null results from different experiments put stringent limits on the conventional BSM scenarios

Conventional signature: Strong production cross section

Strong Exclusion limits

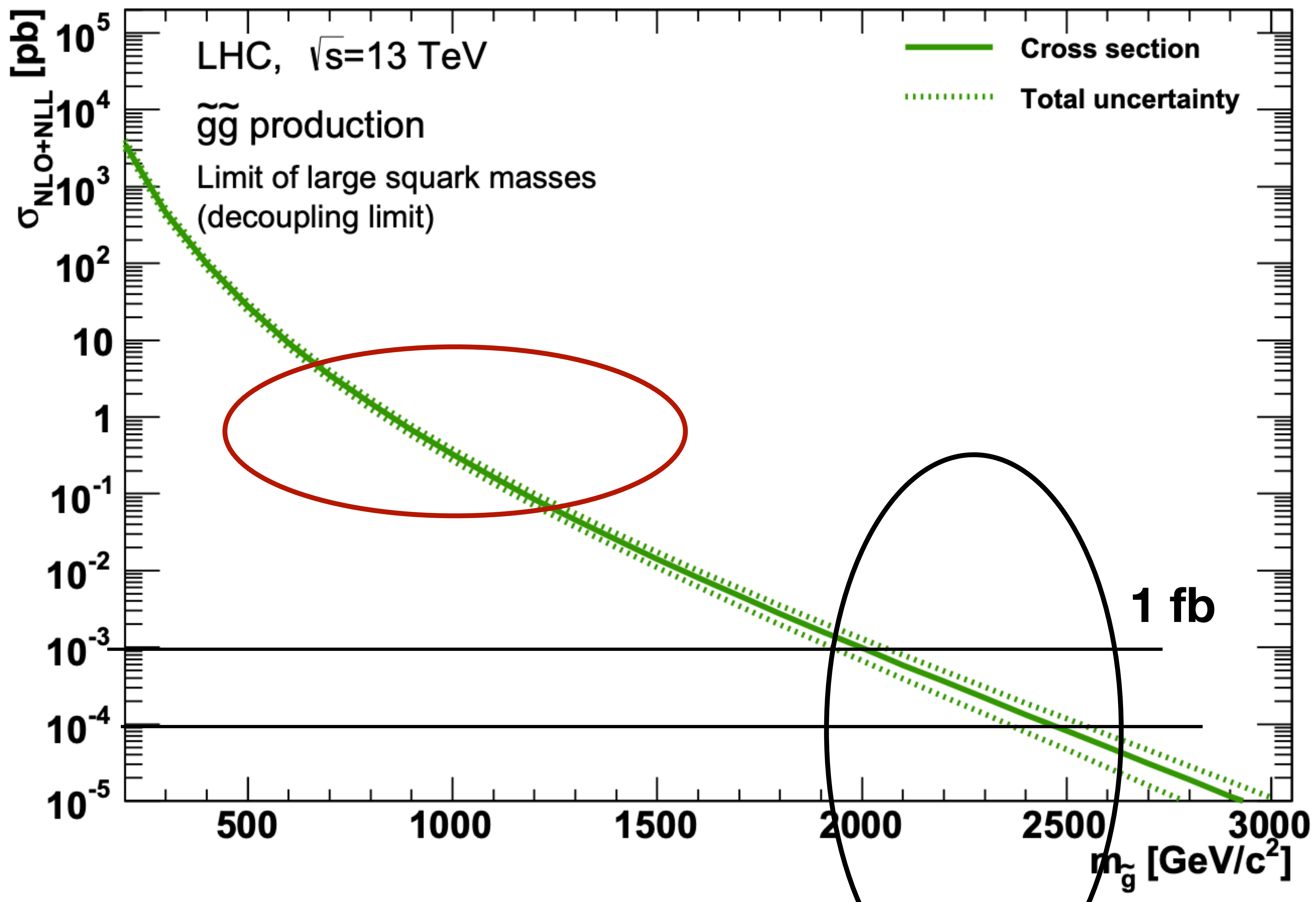
Pair production of gluino (simplified model)

Leptonic channel hep-ex: 2101.01629



hep-ph: 1407.5066

Cross section using NLL-fast



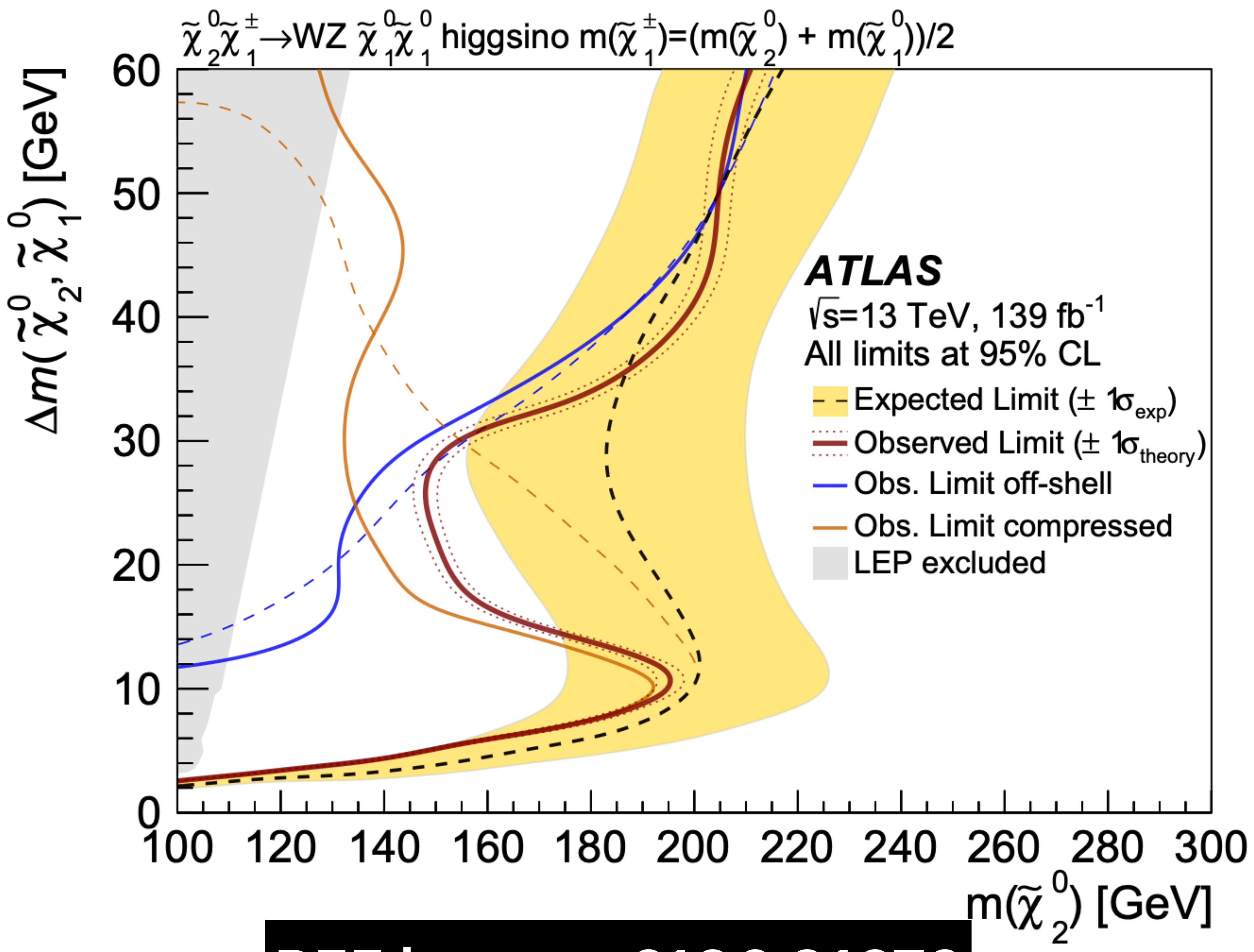
Summary : Degenerate gluino ~ 1TeV , high mass gap limit ~ 2-2.2/2.3 TeV

Conventional signature: Heavy vs light BSM particle

Decay products of heavy particles => generally more energetic compared to particles from SM processes
Easier to detect => already highly constrained
Limits are almost saturated ==> increase in luminosity will not help improve the limit drastically

Light particle searches ==> high SM backgrounds

Higgsino pair production



REF:hep-ex: 2106.01676

Mass limit below 200 GeV

$pp \to h_{125} \to \phi\phi,\ \phi \to \tau\tau$

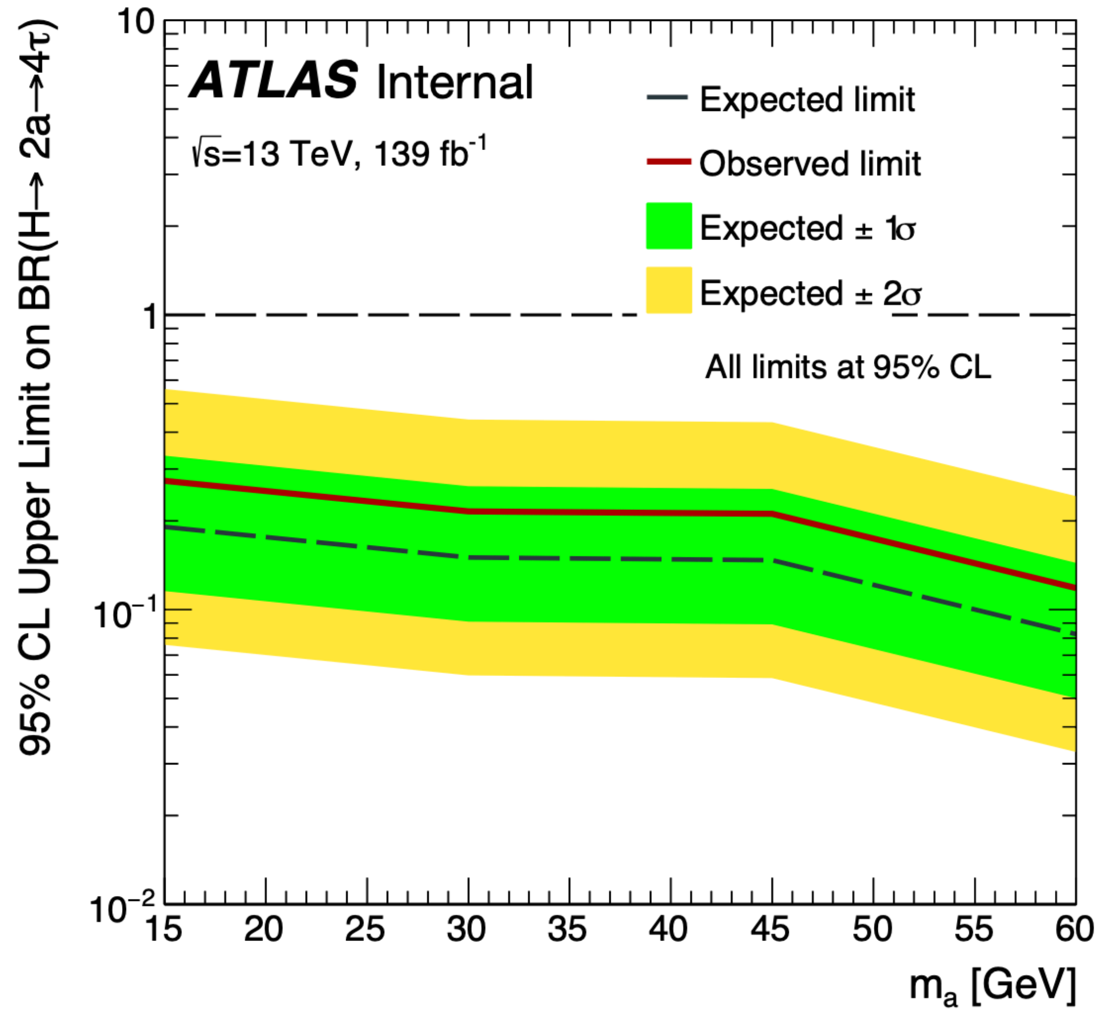


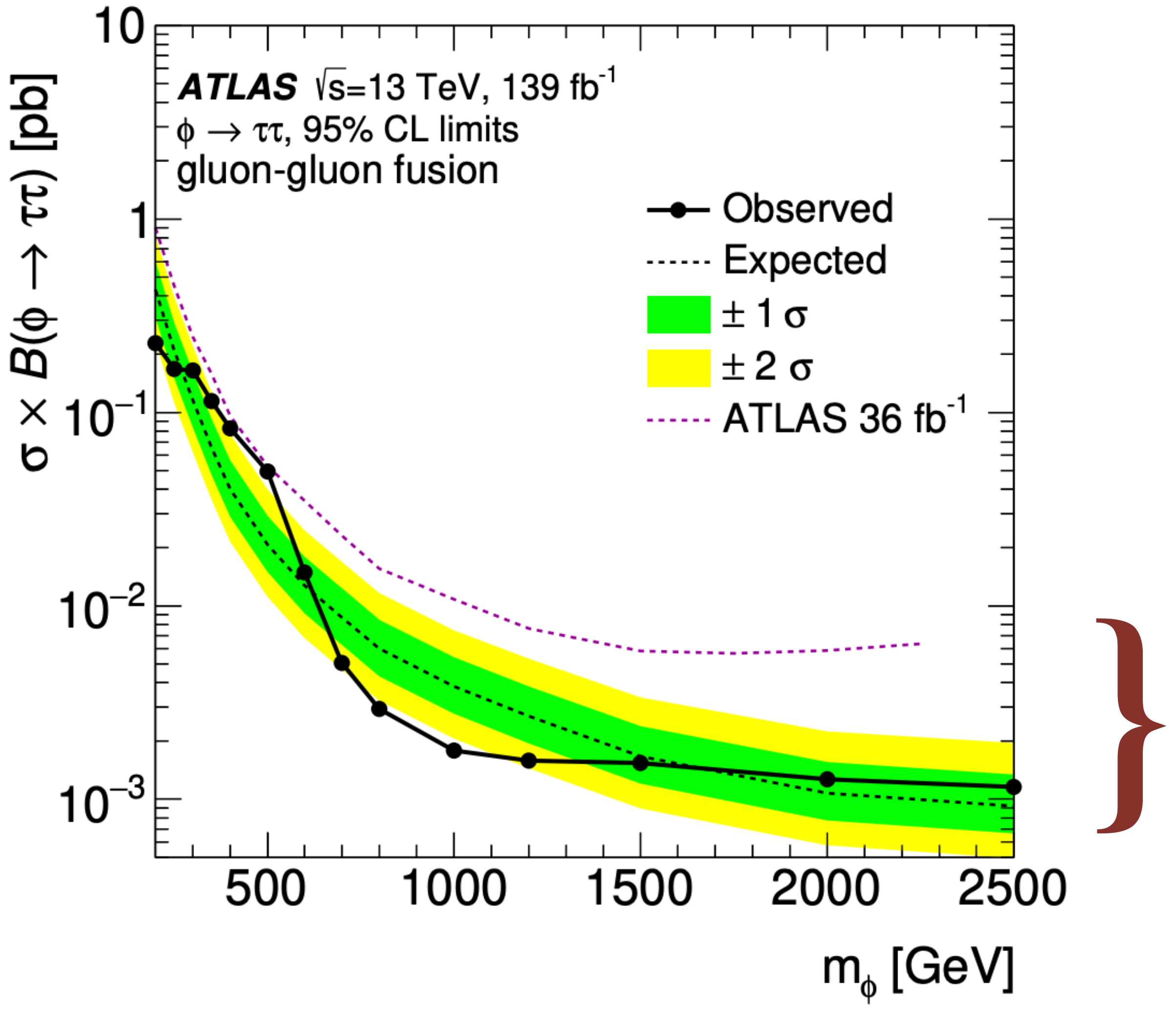
Figure 7.16: The 95% CL upper limit on the branching ratio of $Br(H \to 2a \to 4\tau)$ in the $\mu\mu$ channel. The expected limit is shown in dashed line and the observed limit is in red solid line.

REF: Thesis of HUACHENG CAI. Link

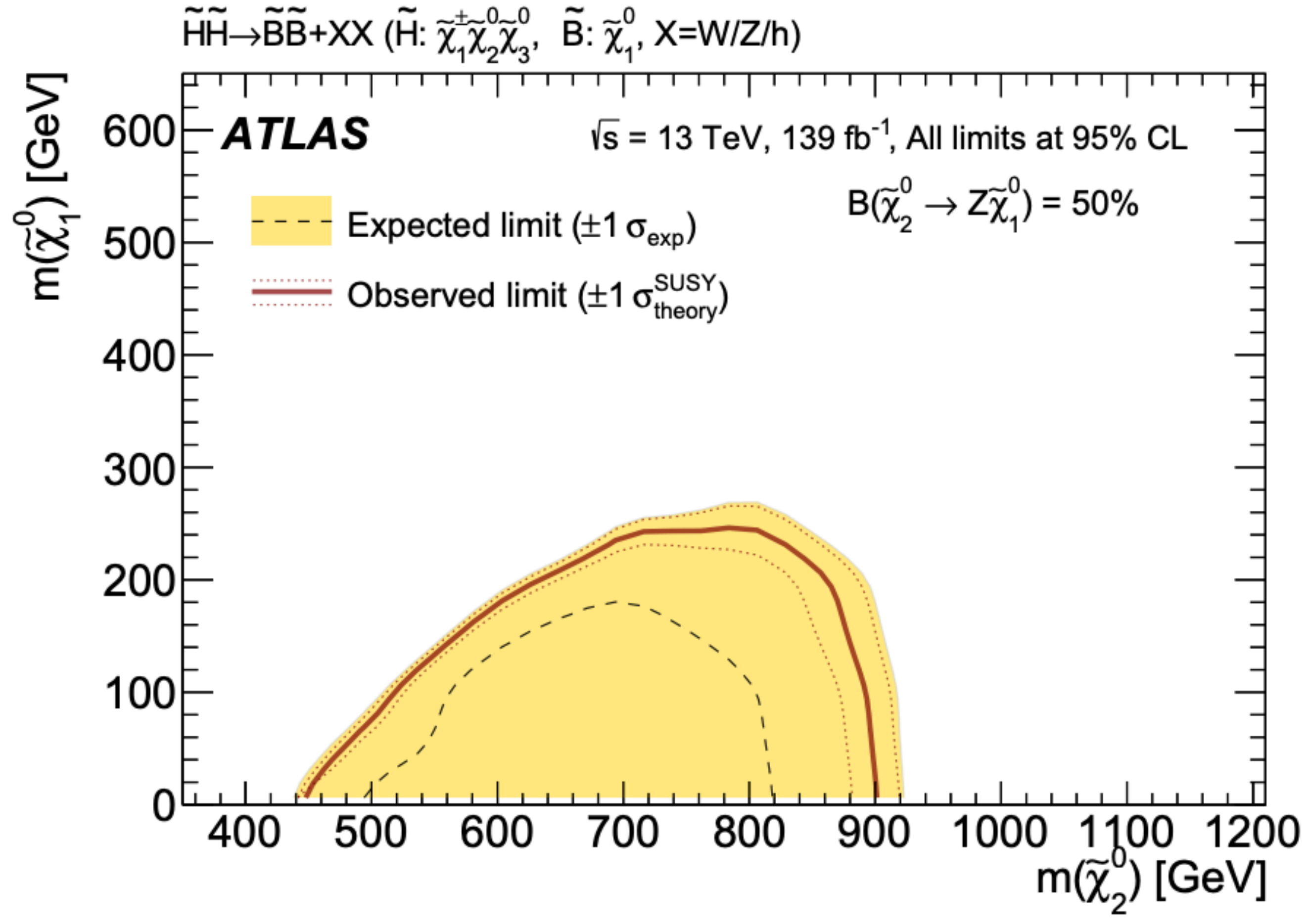
Branching above 10% Ruled out

Complementarity between collider and other DM experiments

Better background modelling	Better exclusion using New channels	Complementarity
HEP-EX: 2002.12223	HEP-EX: 2108.07586	HEP-EX: 2207.03764

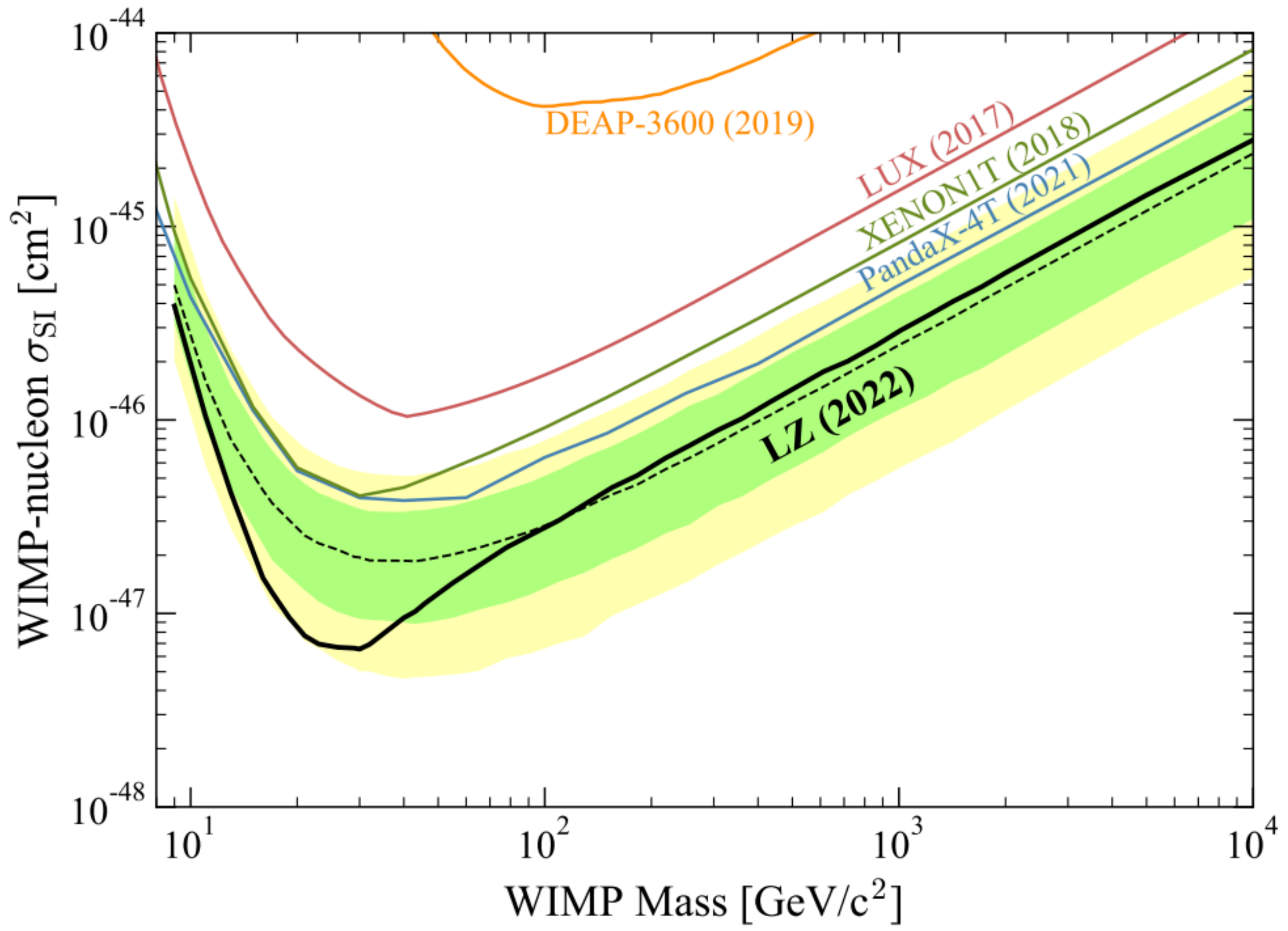


Heavy Higgs in tau channel



(d) $(\widetilde{H}, \widetilde{B})$ with $\mathcal{B}(\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0) = 50\%$

higgsino limit hadronic channel



Direct detection limit by LZ collaboration

+ Higgs signal strengths + Flavour data + CMS + ATLAS + Xenon1T

Light neutralino dark matter with mass below $M_H/2$ is severely constrained

REF: PRD 2025 and PRL 2023 by Rahool Kumar Barman, Genevieve Belanger, BB, Rohini Godbole, Rhitaja Sengupta

New physics searches: Current status

Many BSM models and a large number of possible signatures

No hint of BSM physics so far …..

Where is BSM physics hiding ?

New physics searches: Current status

Many BSM models and a large number of possible signatures

No hint of BSM physics so far …..

Where is BSM physics hiding ?

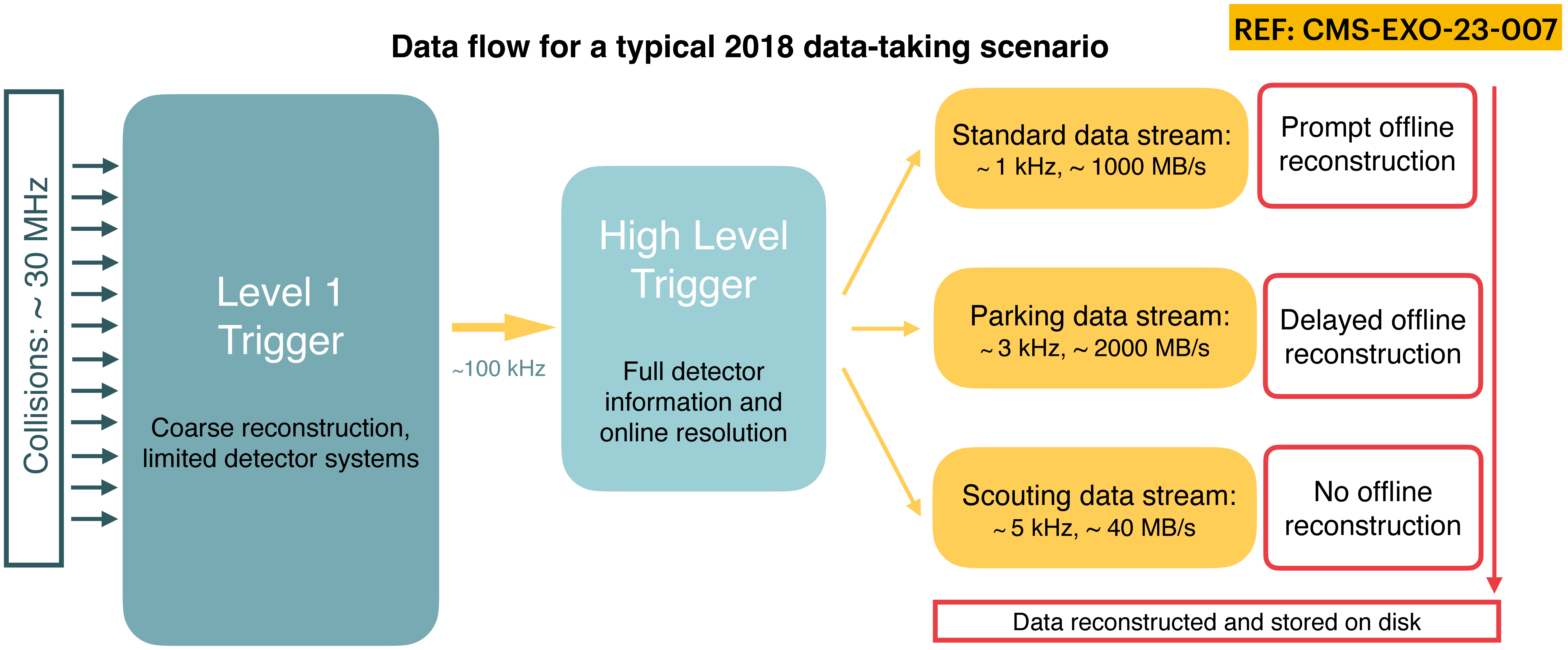
Three Possibilities:

- 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
- BSM particles are very heavy -> Not accessible at the LHC

Search methods are not very sensitive

Example A

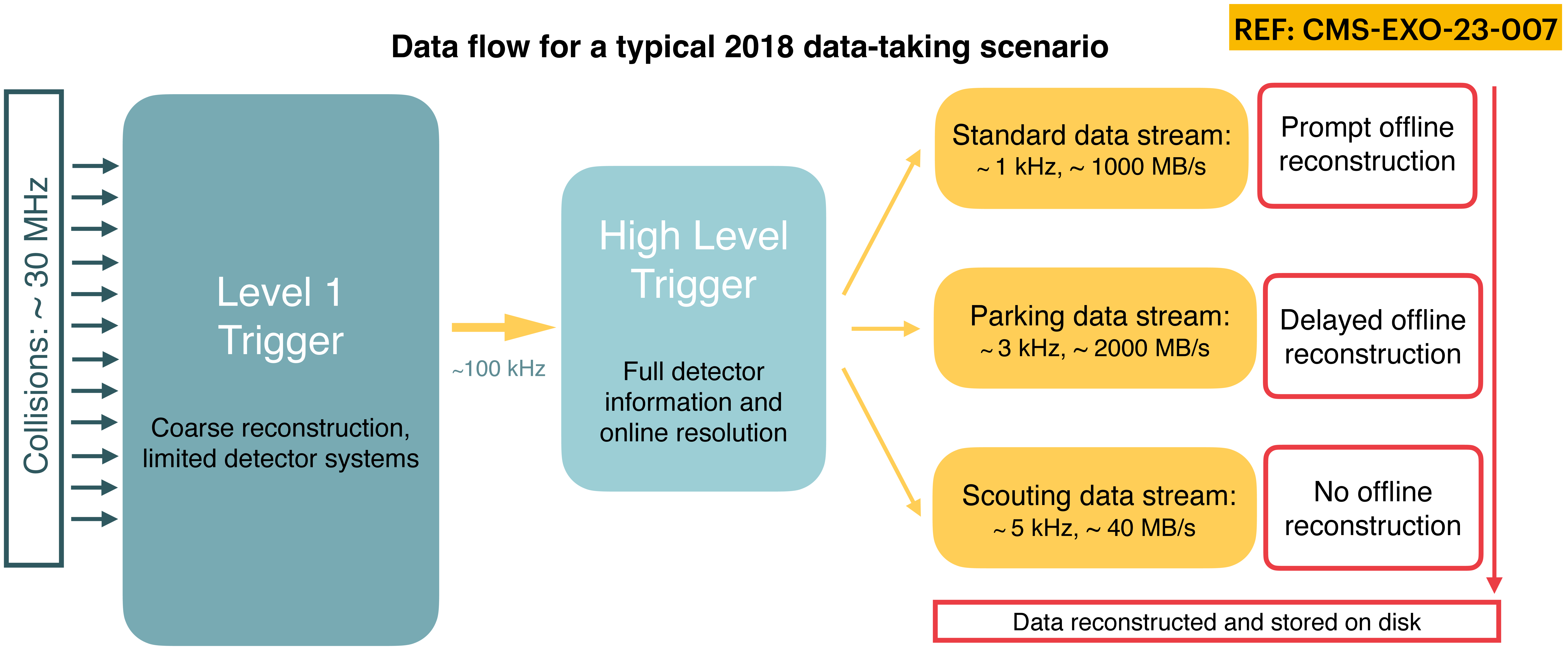
LHC Trigger system : CMS Experiment



Standard Trigger path

Initial rate : 30 MHz. ==> Data for offline analysis: 1KHz

LHC Trigger system : CMS Experiment



Standard Trigger path

Initial rate : 30 MHz. ==> Data for offline analysis: 1KHz (Huge suppression !!)

=> new physics signals may not be stored if not selected by the Trigger system

Dark Sector

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

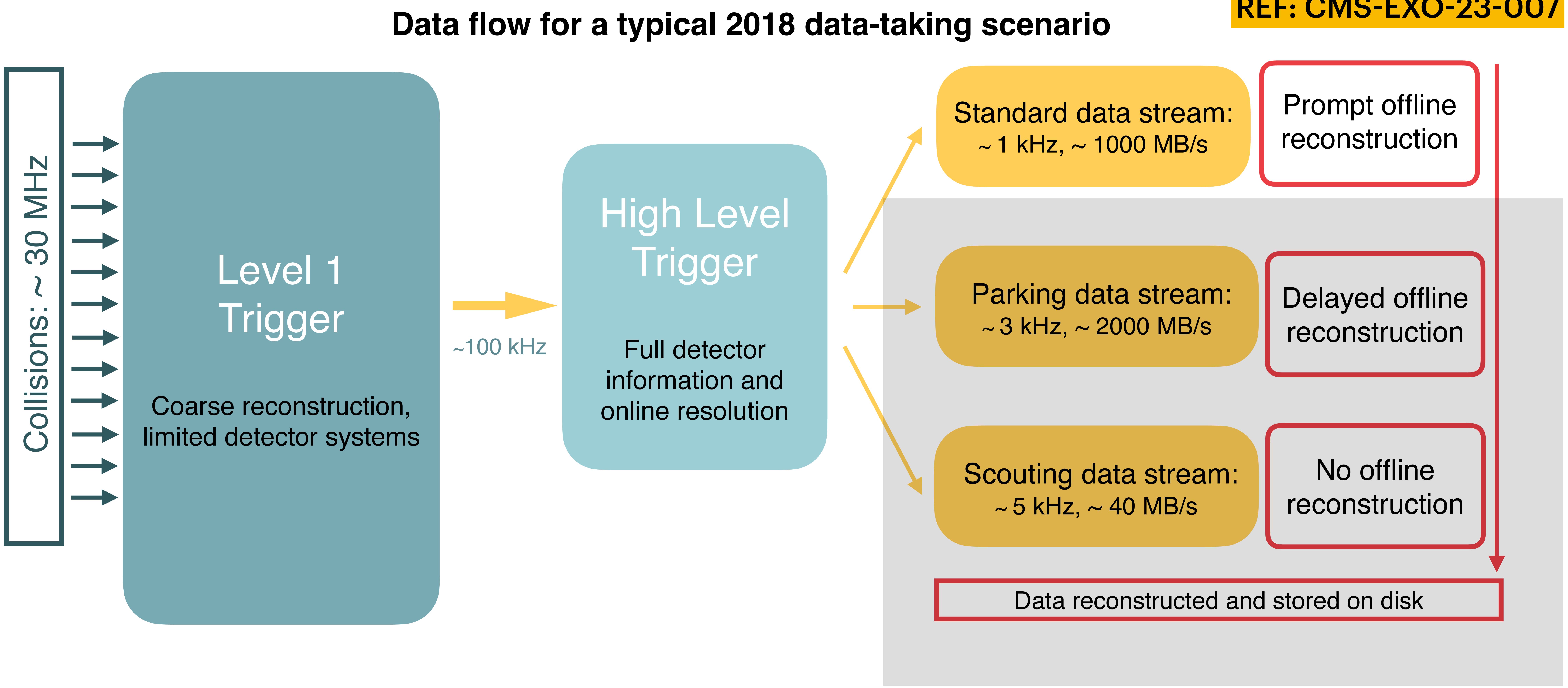
These particles can be very light

In many cases signals are below Trigger threshold

Recent survey: Exploring Dark Sector Portals with High Intensity Experiments [arXiv:2207.06905]

LHC Trigger system : Dedicated paths (Scouting and Parking)

REF: CMS-EXO-23-007



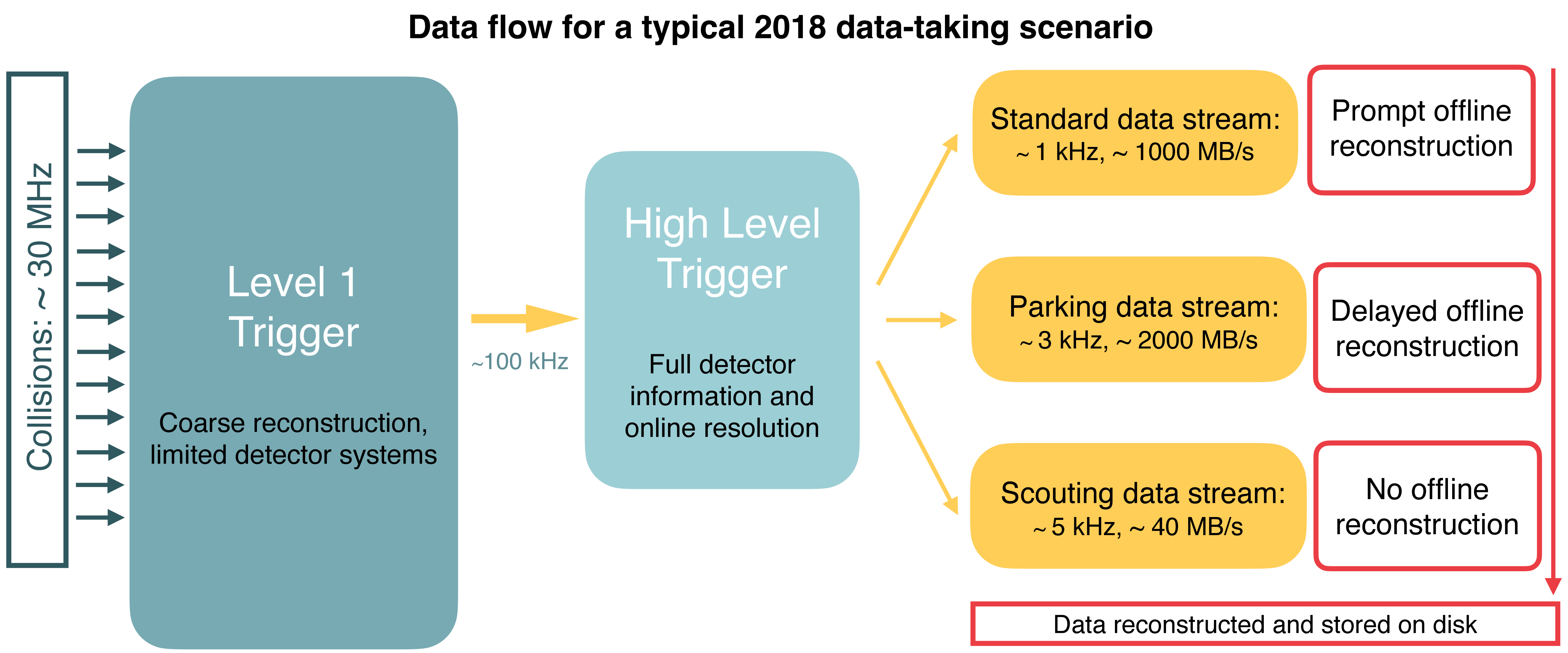
B-parking@CMS

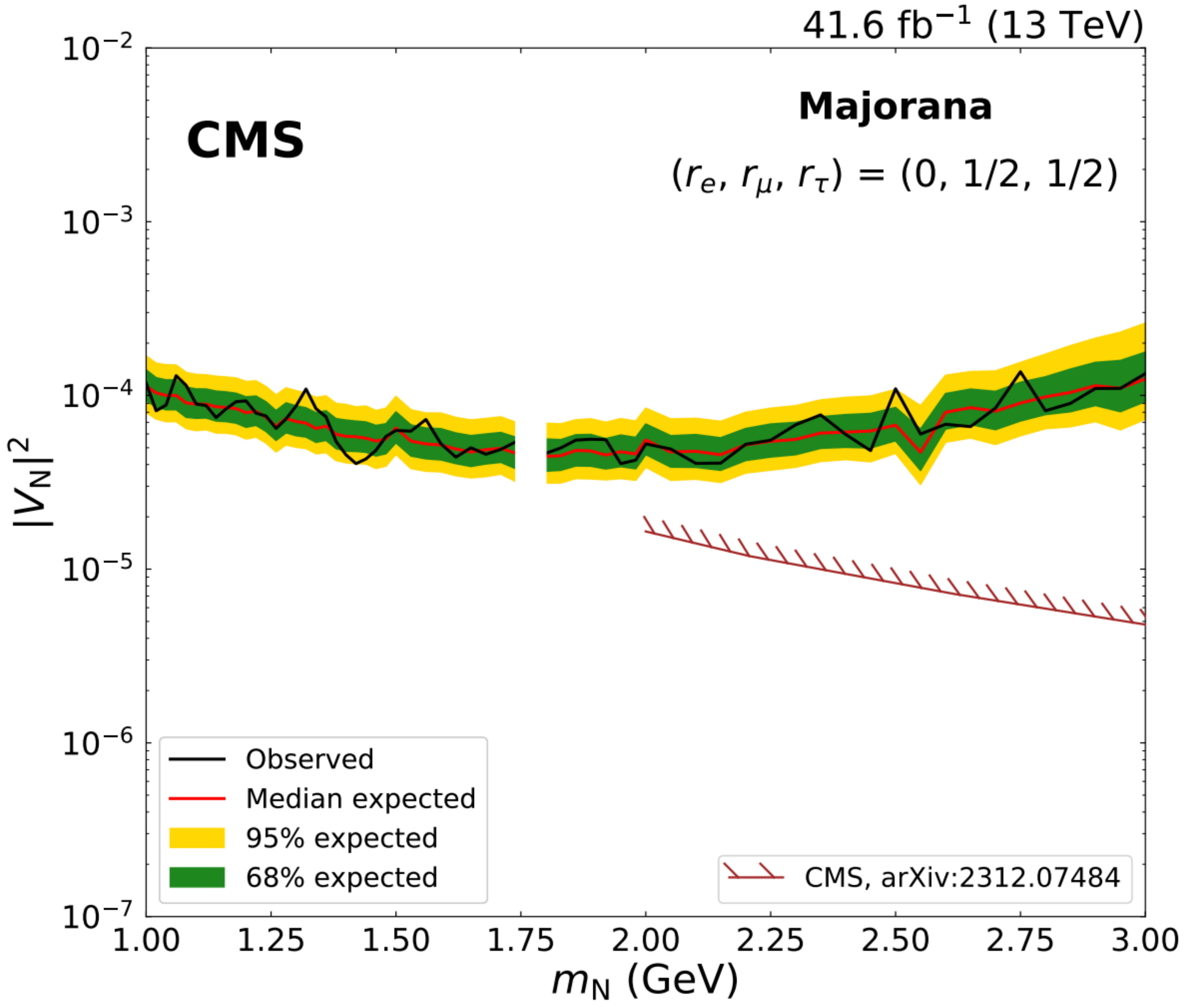
2018: CMS collected 10^{10} $b\bar{b}$ events using a dedicated data stream

Events with muons with pT > 7 to 12 GeV recorded

Raw data stored and later processed

New limit in the low mass region !!





REF: CMS-EXO-23-007

REF:2403.04584

Search methods are not very sensitive

Example B

Unconventional signature:

Goal: Search for long-lived gluino ($\tilde{g}$) of MSSM

STEP I : Production

Pair production $pp \to \tilde{g}\tilde{g}$

STEP II : Decay

$\tilde{g} \to q\bar{q}\tilde{\chi}$ decay width is suppressed

$\tilde{g}$ will be produced at the collision point but not decay

instantaneously => Long-lived gluino !!!

Unconventional signature: Long-lived Gluino

Goal: Search for long-lived gluino ($\tilde{g}$) of MSSM

STEP I : Production

Pair production $pp \to \tilde{g}\tilde{g}$

STEP II : Decay

$\tilde{g} \to q\bar{q}\tilde{\chi}$ decay width is suppressed => long lived gluino

STEP III : Final State

Gluino may not decay to quarks and dark matter (LSP in MSSM)

Gluino will hadronize and form heavy hadron

Gluino is now semi-stable and will travel through the detector

Analysis techniques

The signature is no longer multi-jet + MET

Questions : Is it possible to make gluino long-lived ?
Is such a possibility rare ? Or too much fine-tuned ?

LLPs in the Standard Model

Presence of LLP is not unnatural

Many long-lived particles are present in our world

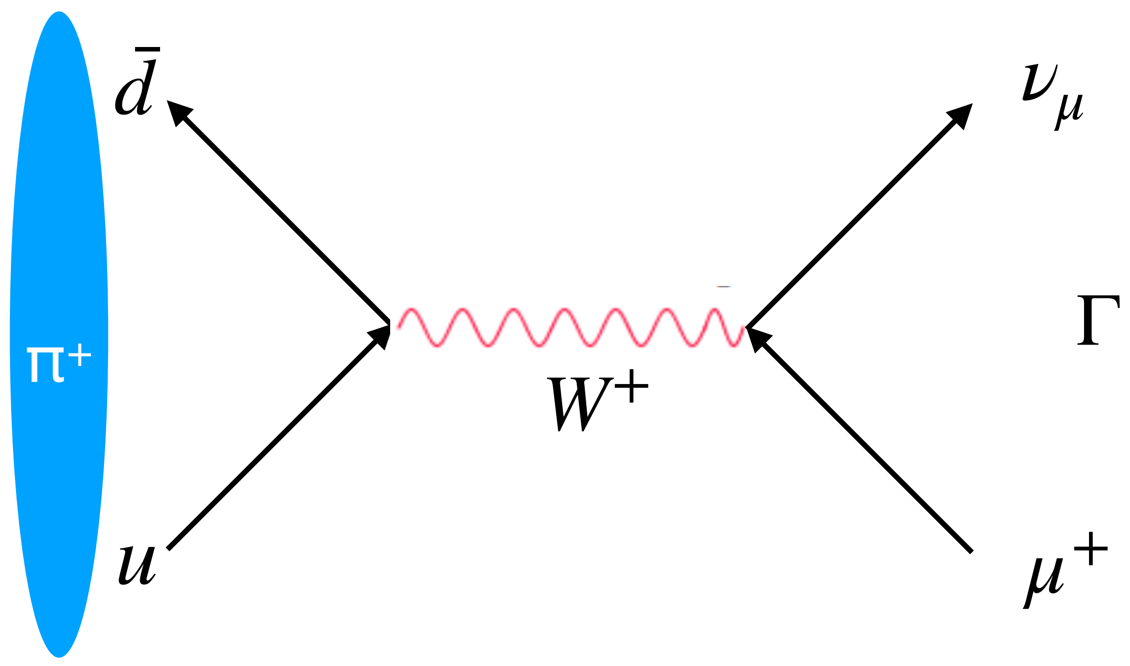
Particle	Lifetime
Muon	2.2 picosecond
Proton	$> 10^{30}$ year
Neutron	878 second
B^+	1600 femtosecond
π^+	26 nanosecond

LLPs in the Standard Model

Particle	Lifetime
Neutron	878 second
B^+	1600 femtosecond
π^+	26 nanosecond

Case I

Pion decay in the SM

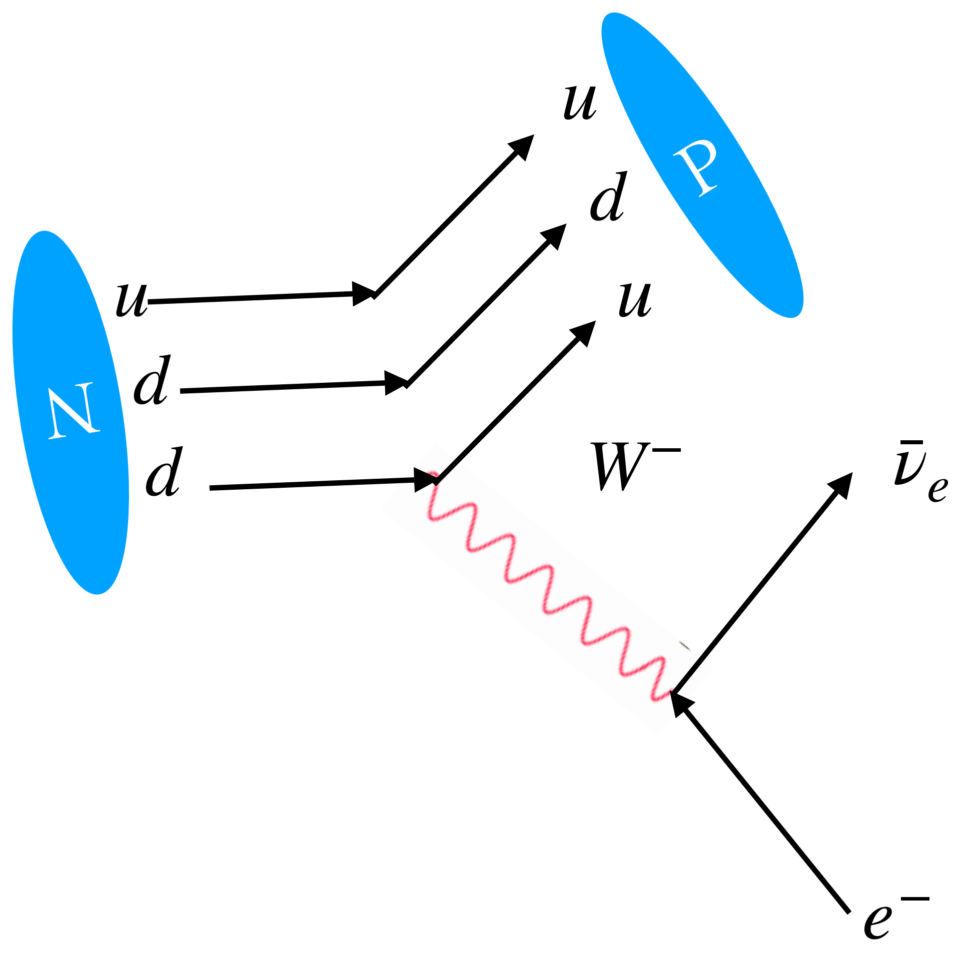


$$\Gamma \sim \frac{m_\pi^5}{m_W^4}$$

Huge suppression from the W boson propagator

Case II

Neutron decay in the SM

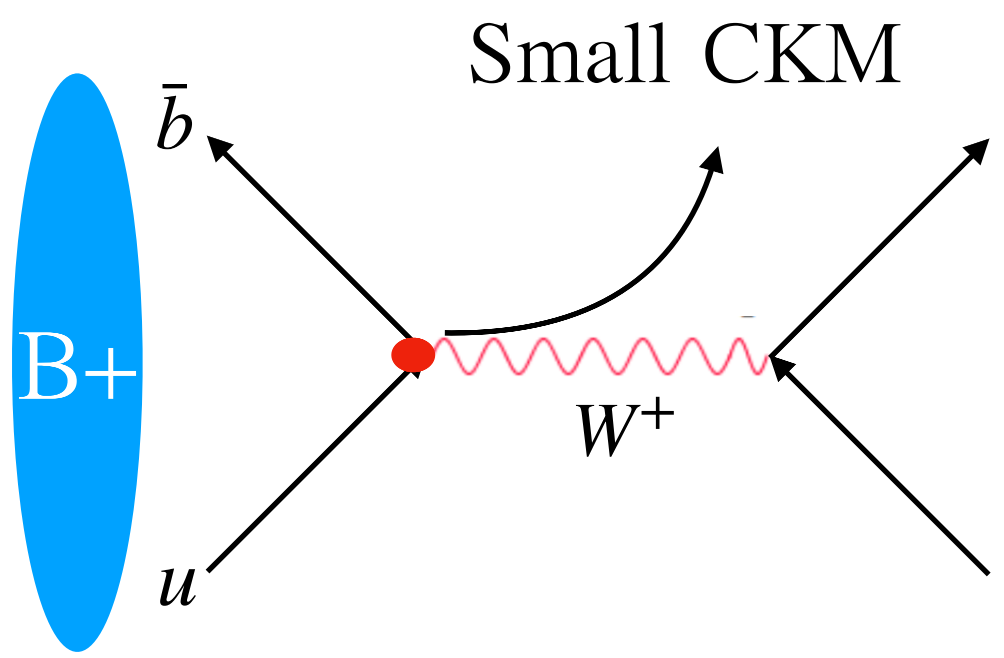


$\Delta = M_n - M_p \sim 1.3$ **MeV**

Decay is highly phase space suppressed

Case III

B^+ decay in the SM

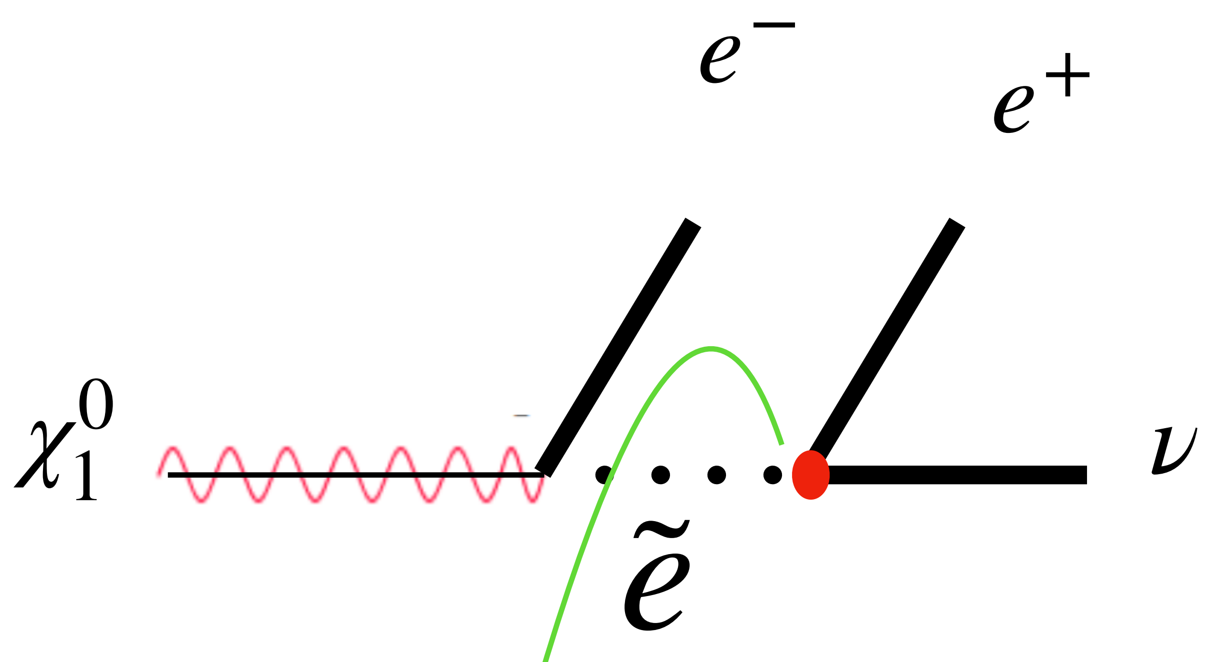


V_{ub} small, gives additional suppression

Long-lived BSM particles

Case 1: Small Coupling

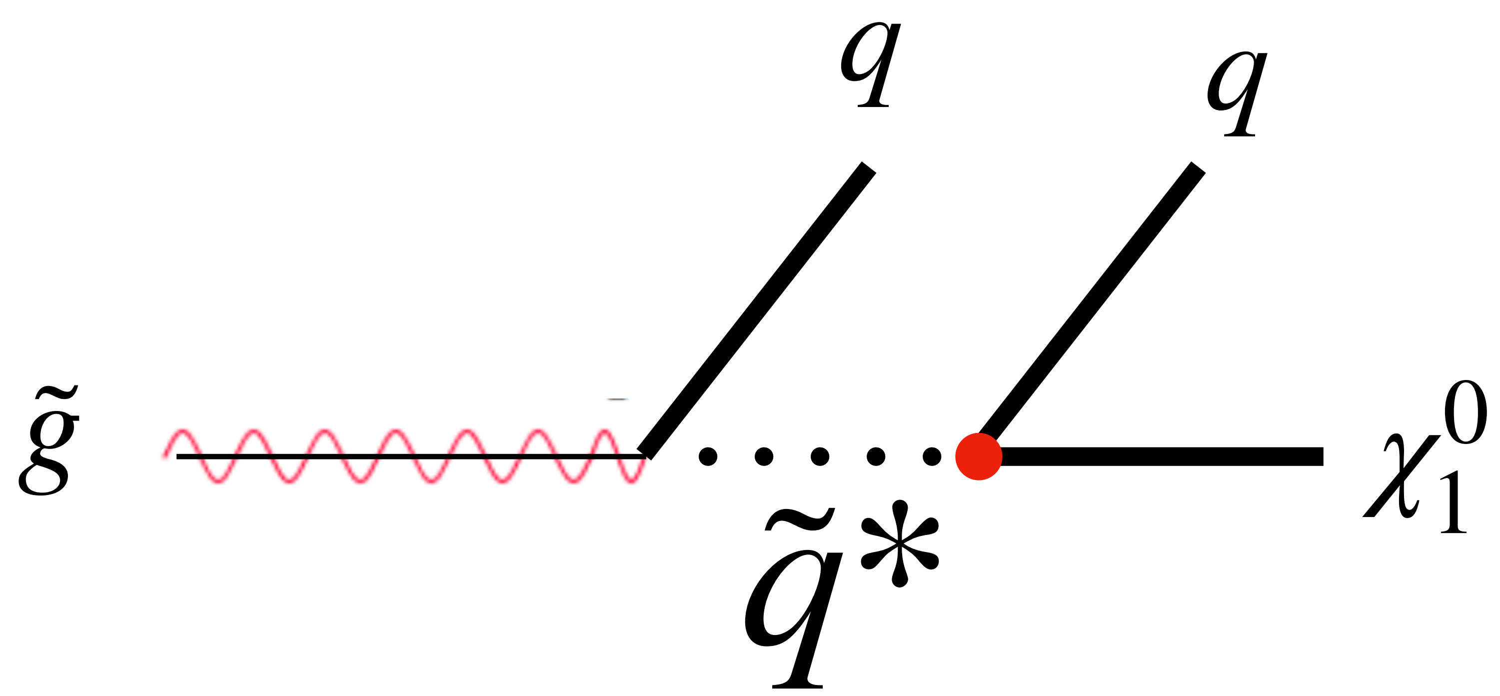
$$\chi_1^0 \rightarrow e^- e^+ \nu$$



R parity violating coupling can be Arbitrarily small

Case 2: Heavy Propagator

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



Mass of the squark very high

Case 3: Small mass difference

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

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

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

MSSM with neutral wino as the lightest supersymmetric particle

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

Dark Sector

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

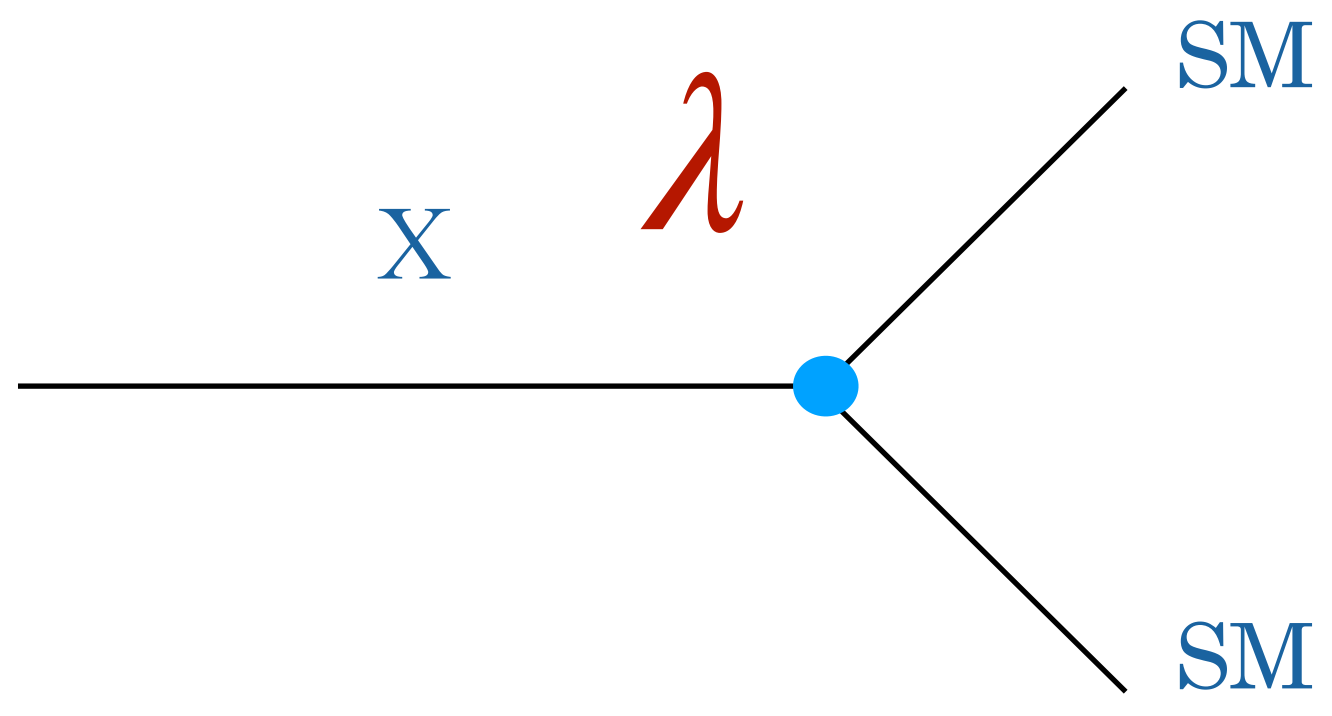
The new couplings can be very small in principle

Possibility of small decay width => LLP !!

Talk by Prof. Sabyasachi Chakraborty

Minimal model of LLPs: small coupling

Decay

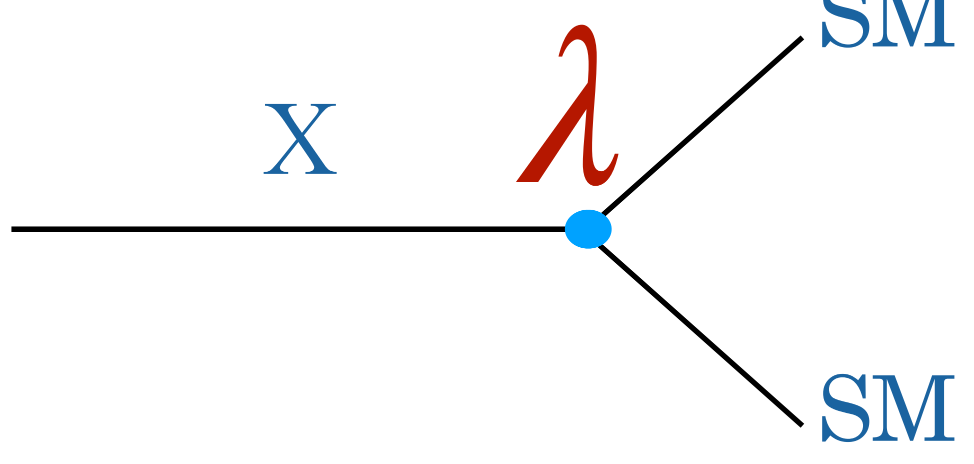


Suppose the coupling λ is small: X is LLP

Easy to make X an LLP

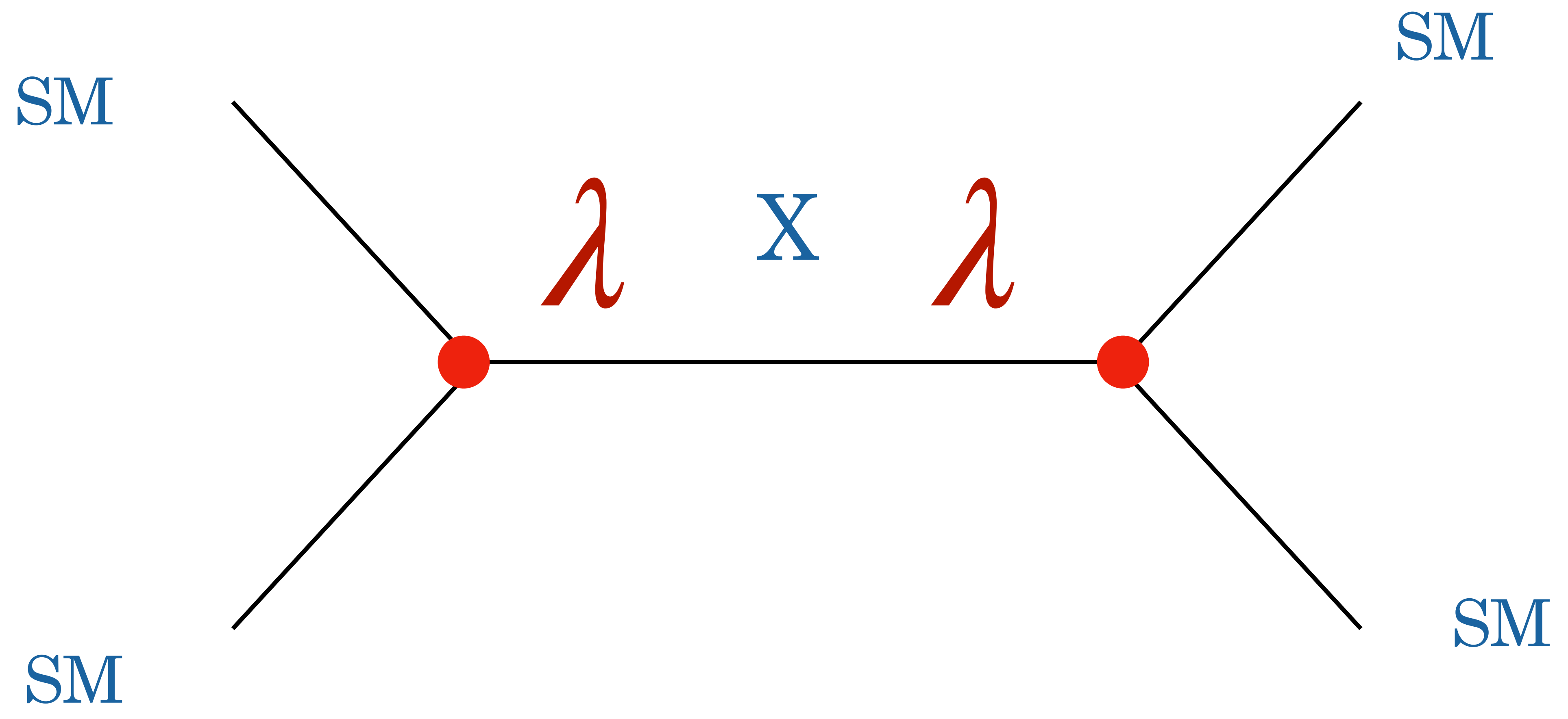
Minimal model of LLPs: small coupling

Decay



Suppose the coupling λ is small: X is LLP
Easy to make X an LLP

Production mode



Minimal model : decay and production determined by the same coupling

Single production cross section $\propto \lambda^2$
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

More 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

Non-minimal model : decay width and production cross section determined by the different couplings

Decay of phase space suppressed LLPs $\chi^{\pm} \to \chi^{0} + \pi^{\pm}$

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

=> production cross section can be large

Unusual features of LLPs

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

X is the long-lived particle

Unusual features of LLPs

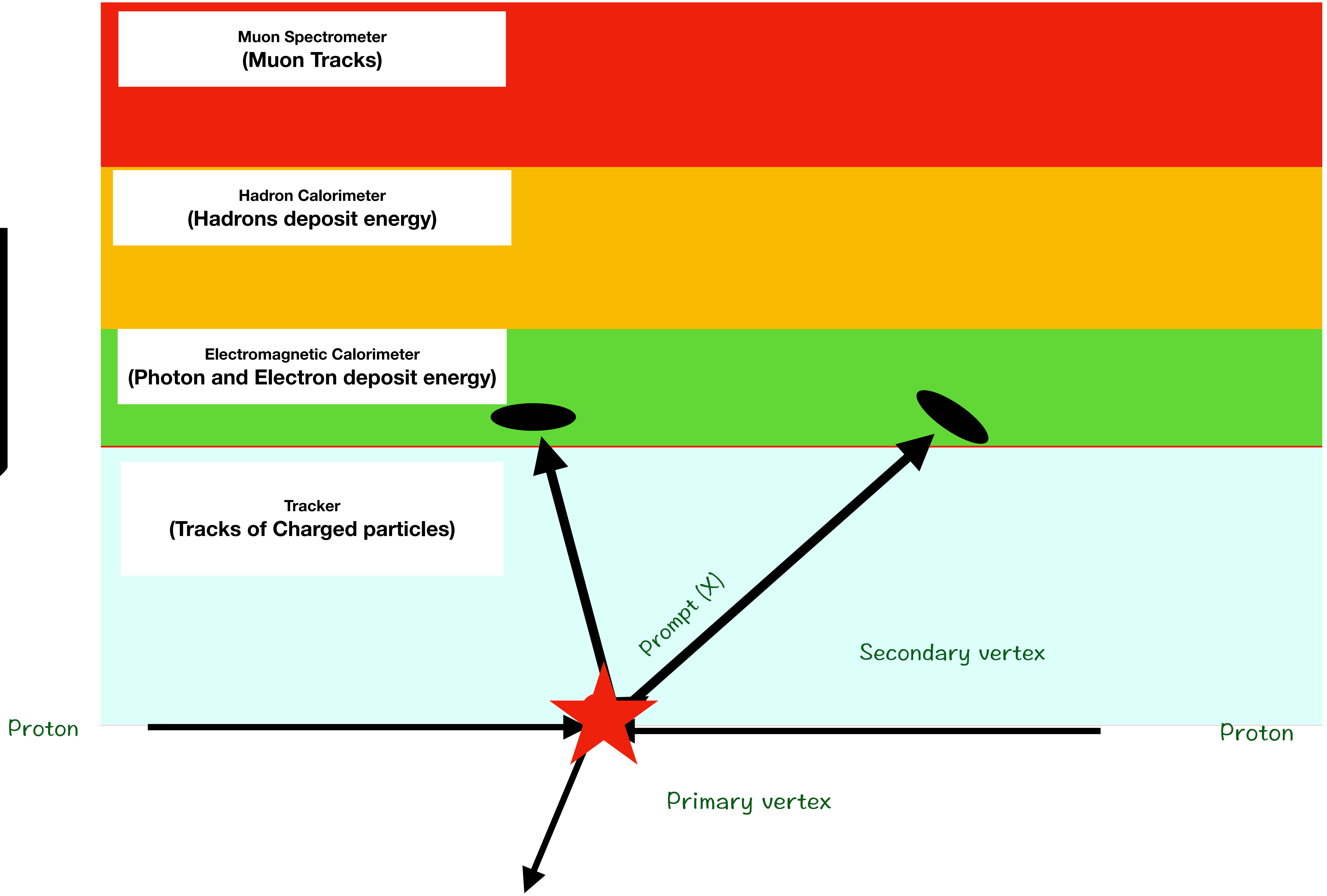
X decays promptly

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

Suppose X decays promptly

Electron Identification :

Tracker: Track
ECAL: energy deposits
HCAL : No energy deposition



Unusual features of LLPs

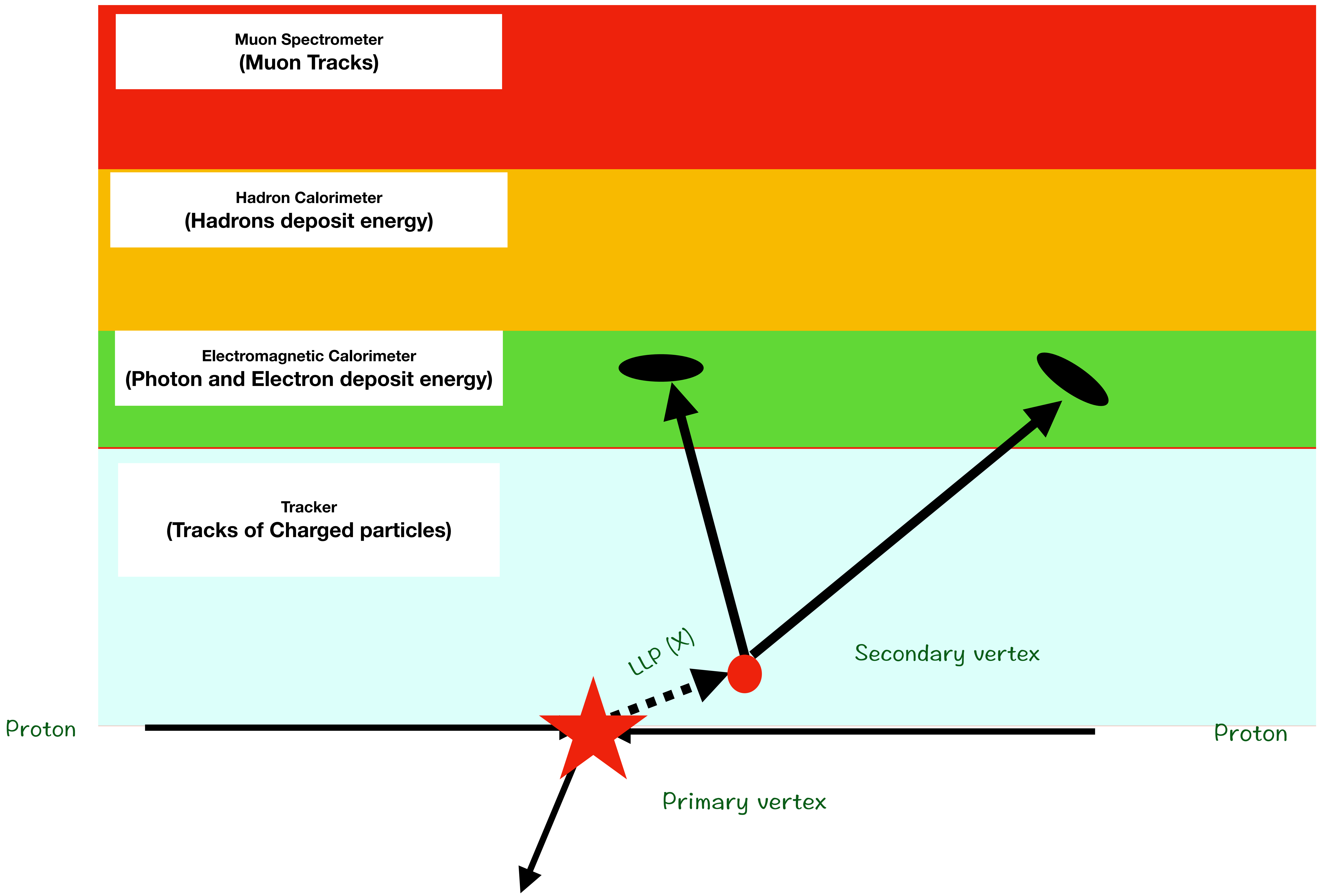
LLP decays inside the tracker

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

Electron Identification :

Tracker: May not be any reconstructed tracks
ECAL: energy deposits
HCAL : No energy deposition

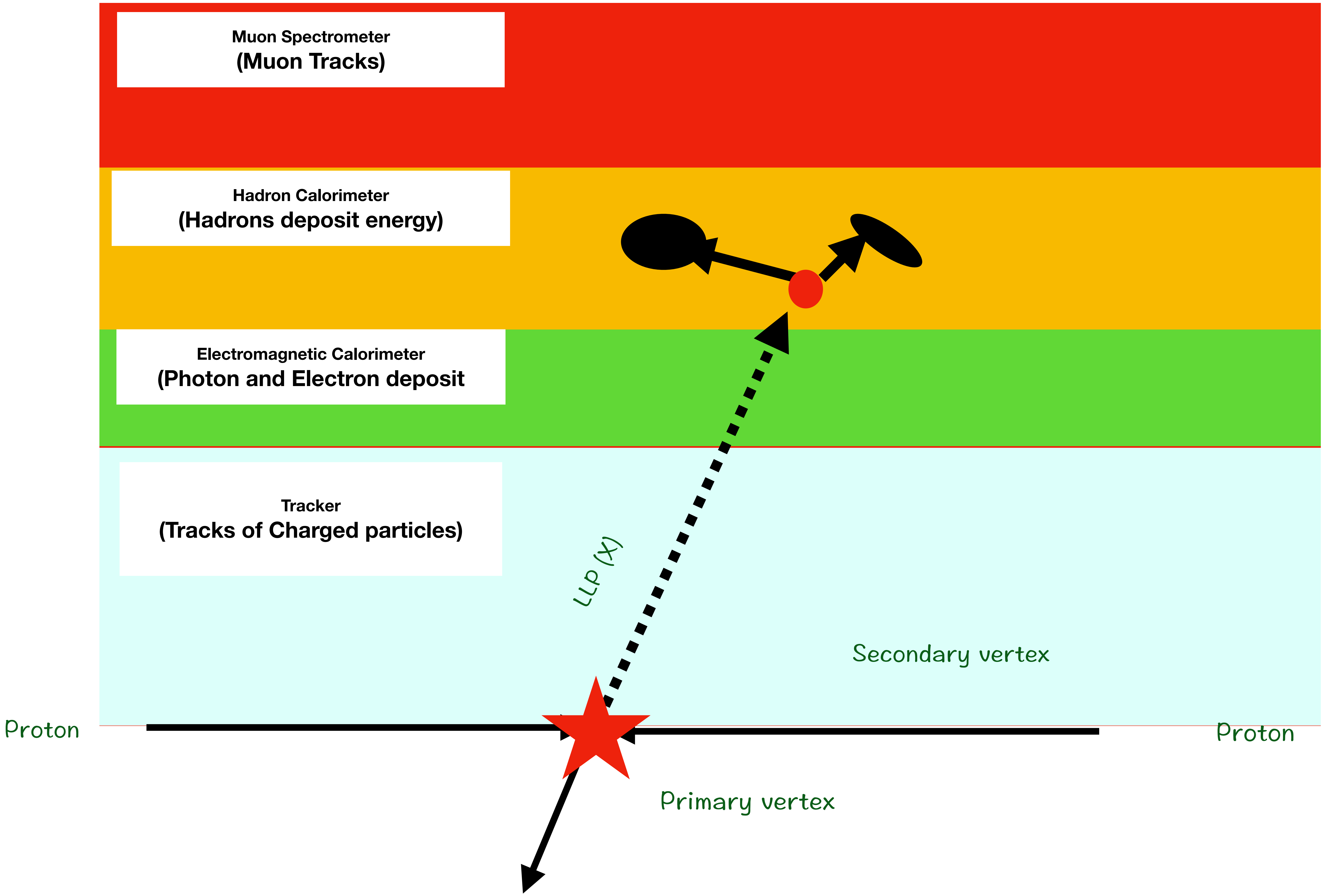
Looks like a photon !!!



Unusual features of LLPs

LLP decays inside the hadronic calorimeter

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



Electron Identification :

Tracker: No track
ECAL: No energy deposit
HCAL : energy deposition

Looks like a neutral hadron !!!

Unusual features of LLPs

LLP decays outside the detector

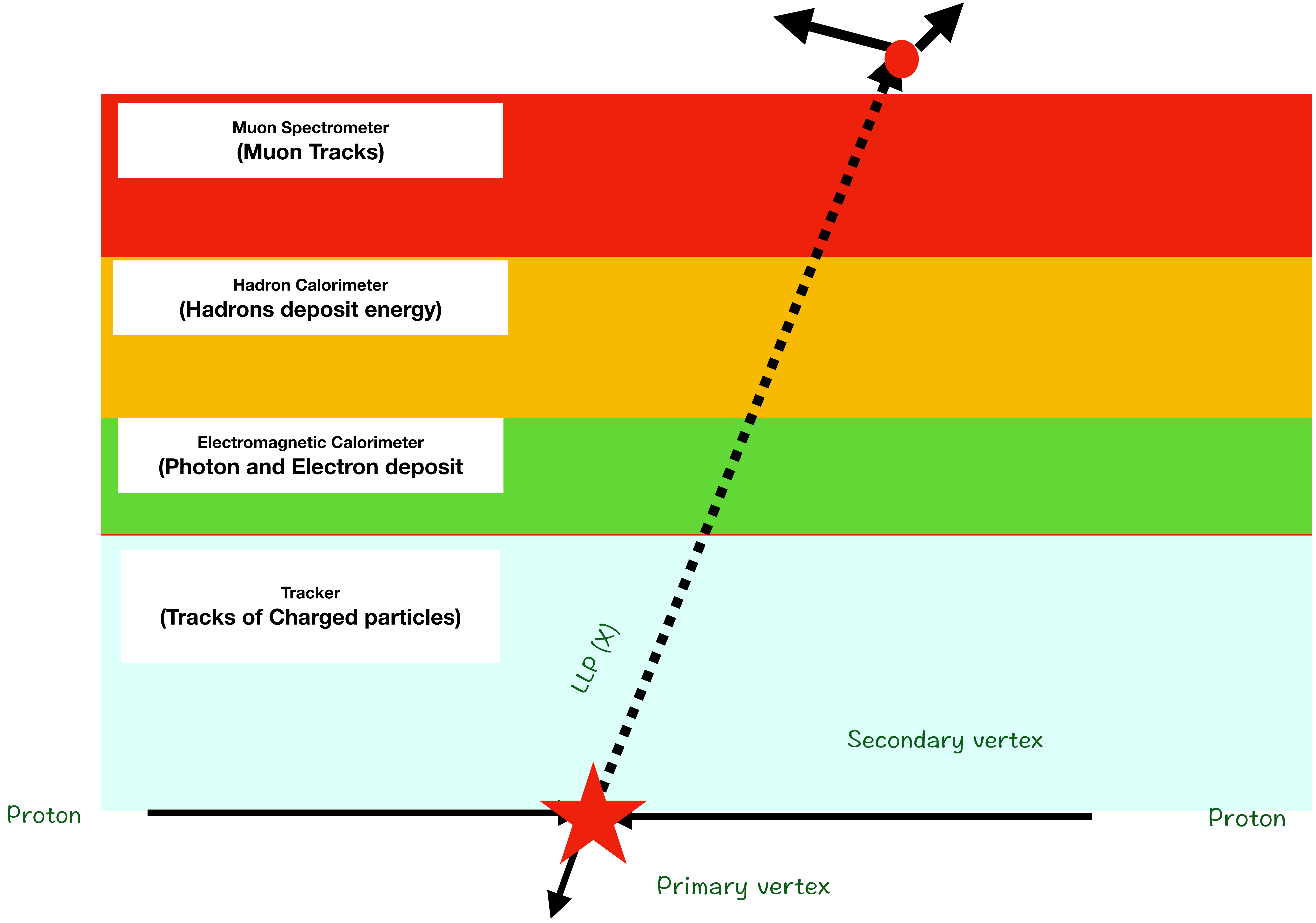
$$pp \rightarrow XX,\ X \rightarrow e^+e^-$$

Electron Identification :

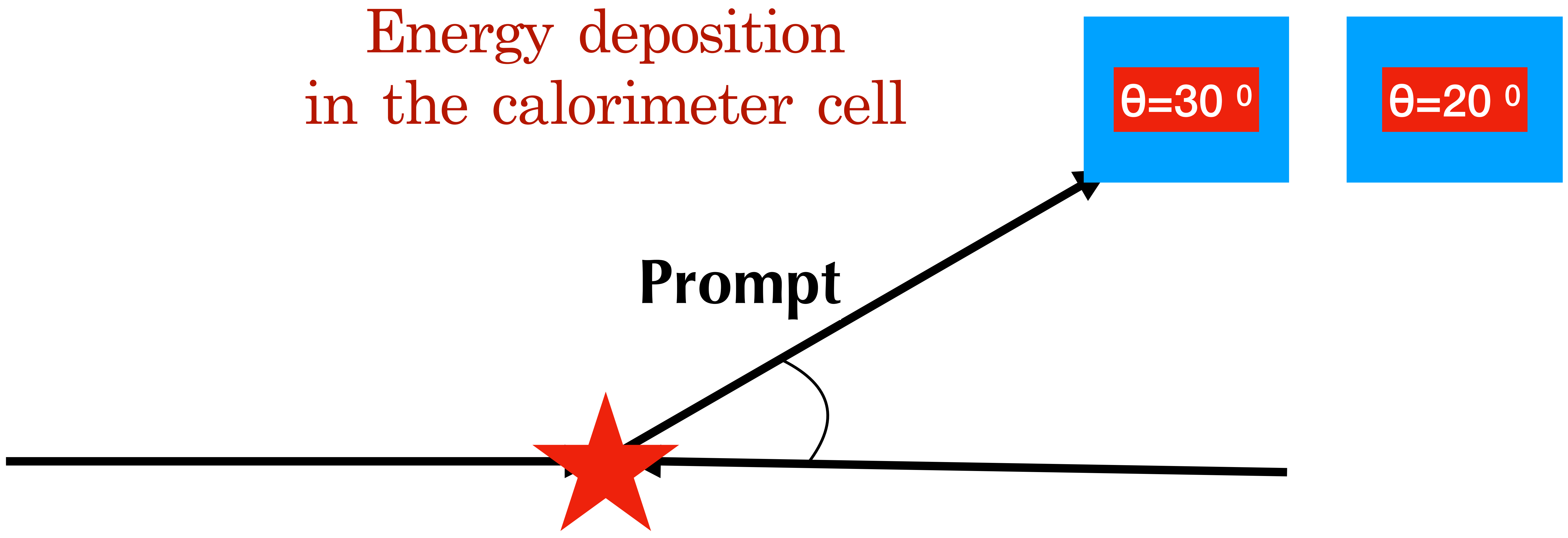
Tracker: No track
ECAL: No energy deposits
HCAL : No energy deposits

Looks like an invisible particle !!!

Observation: signature depends where LLP decays Lifetime dependent search required



Unusual features of LLPs : Non-pointing nature



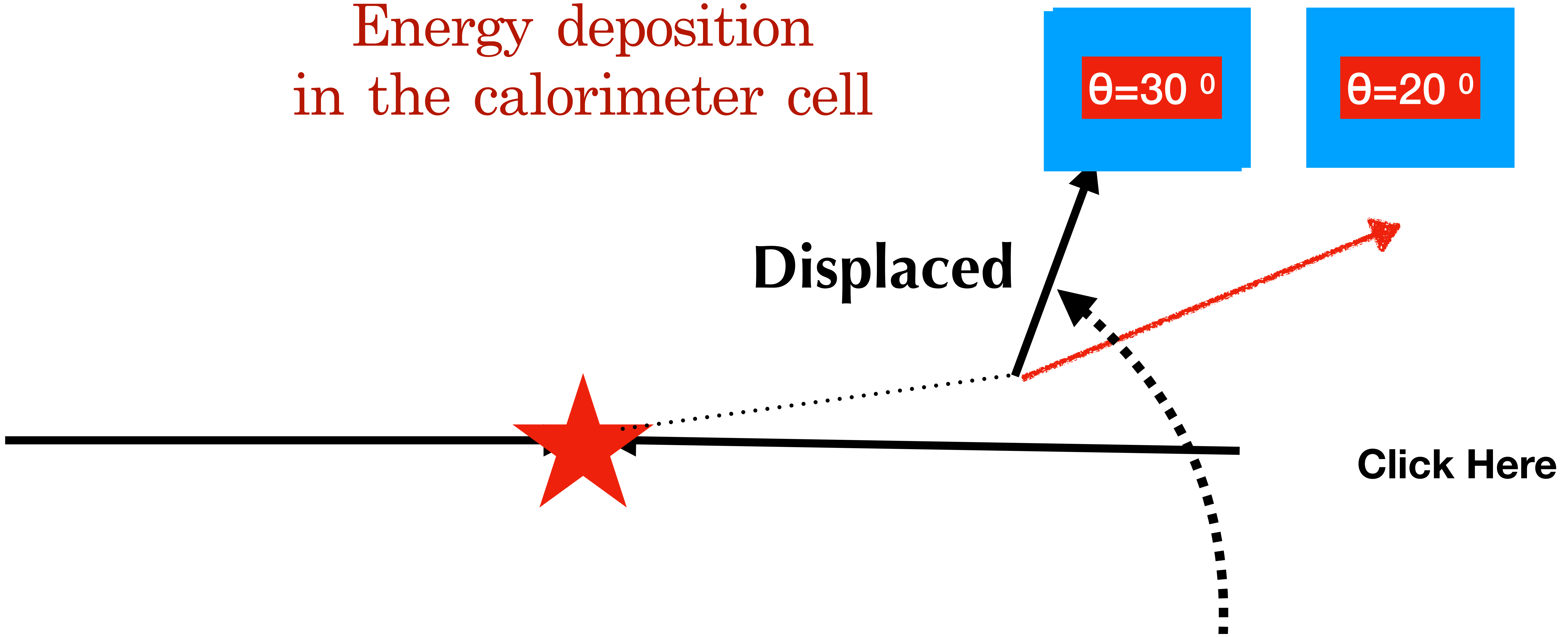
Orientation from the beam axis of the particle = 30 degree

Unusual features of LLPs : 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

Energy deposition
in the calorimeter cell



Measured angle from the beam = 30 degree
Actual orientation is different

layered structure/depth segmentation needed to visualise the effect

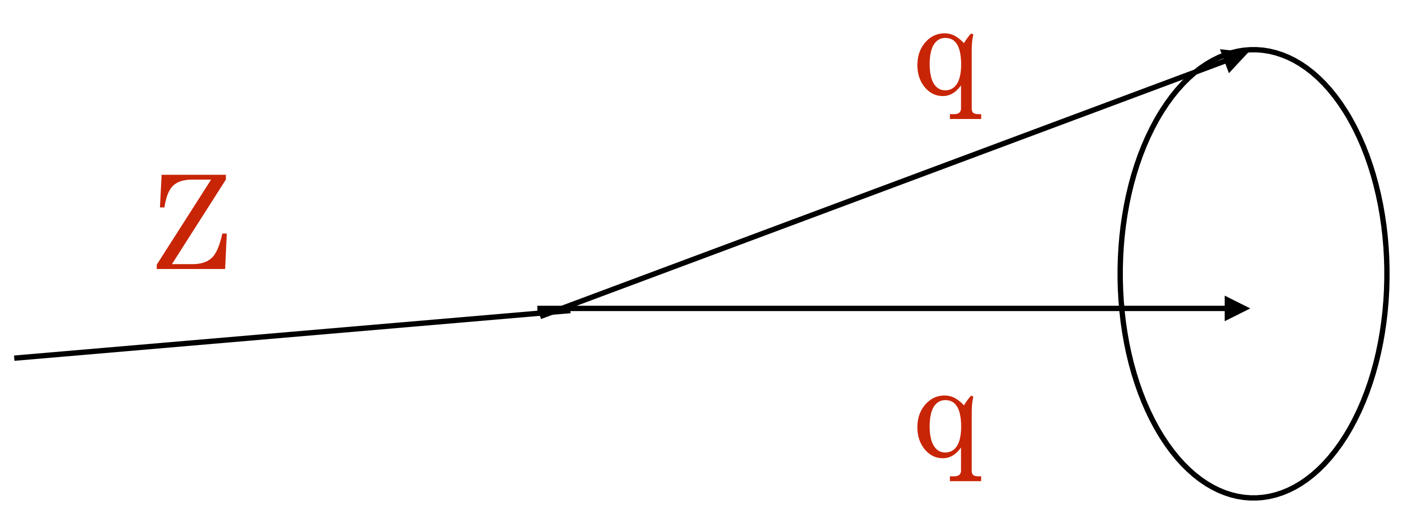
Fast detector simulations do not have such layered structure (e.g. Delphes)

See non-pointing photon search by CMS collaboration

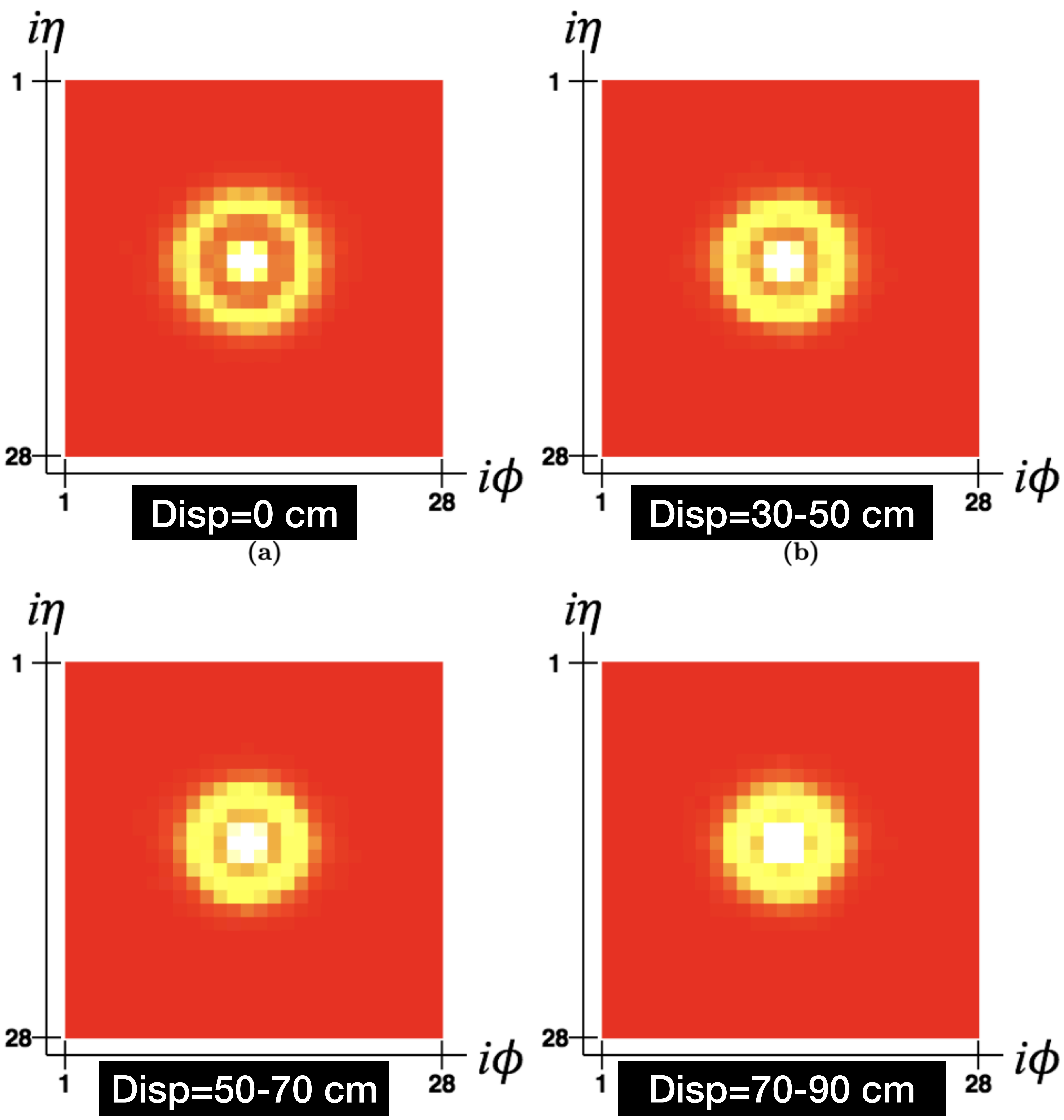
Unusual features of LLPs : Non-pointing nature

$X(\text{LLP}) \rightarrow Z + \text{inv}$

Energy ~400 -500 GeV



average of images: prompt vs displaced

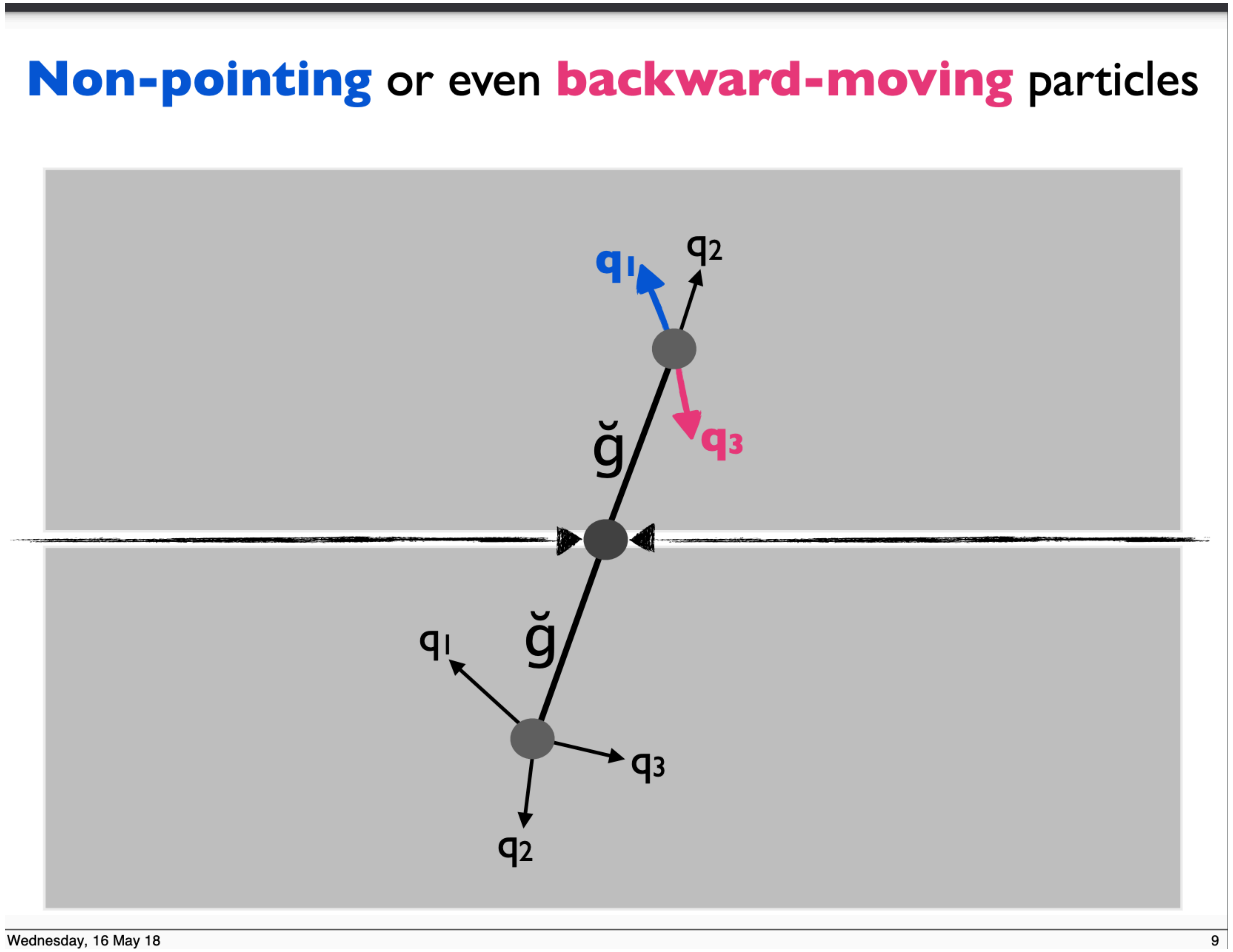


CNN can discriminate displaced vs prompt energy deposition

Physical area taken by the decay products become small with distance and they mostly get contained within fewer η – φ towers.

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

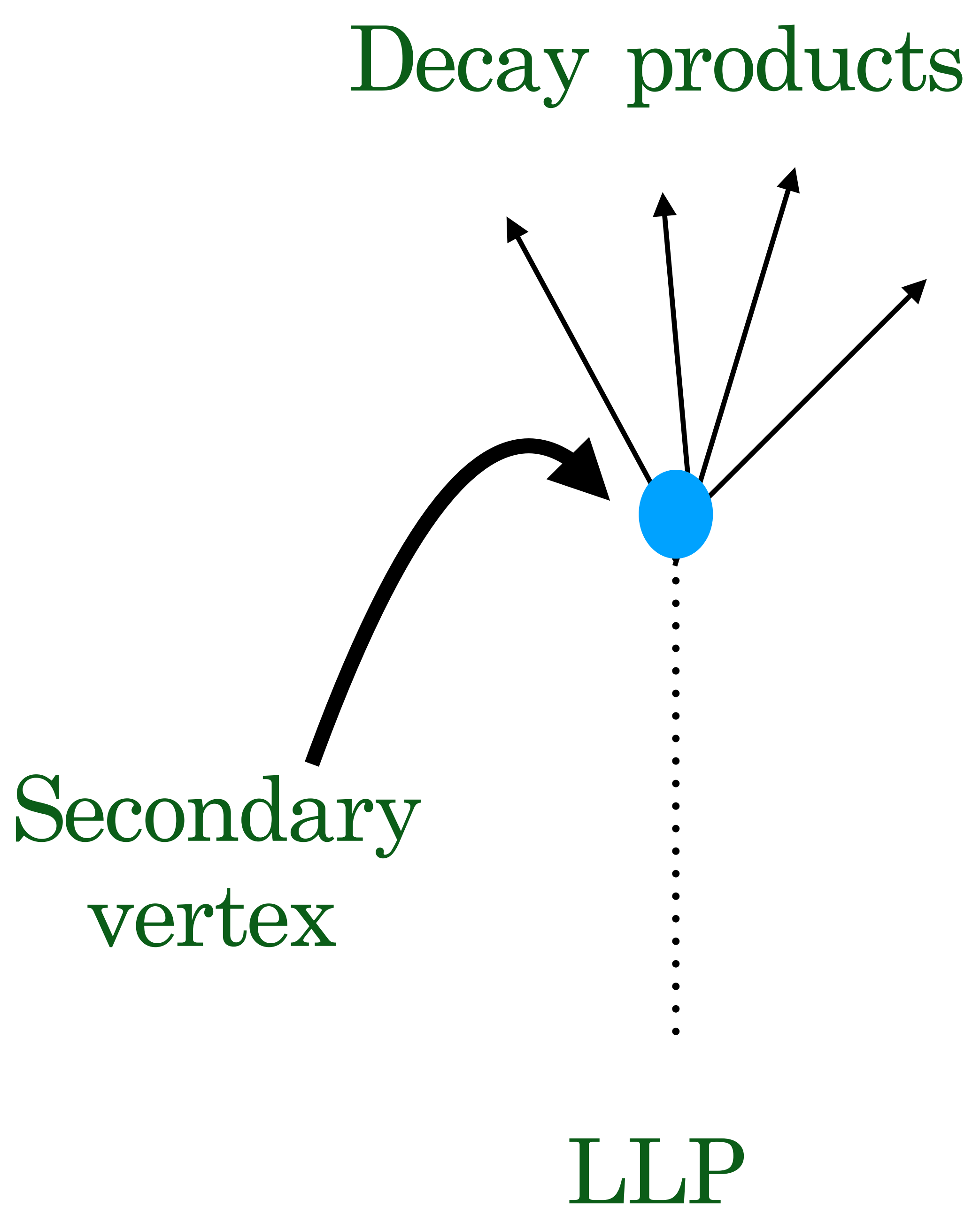
Unusual features of LLPs : backward moving particle



Talk by Swagata Mukherjee
LHC LLP Workshop 16-18 May, 2018 CERN

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

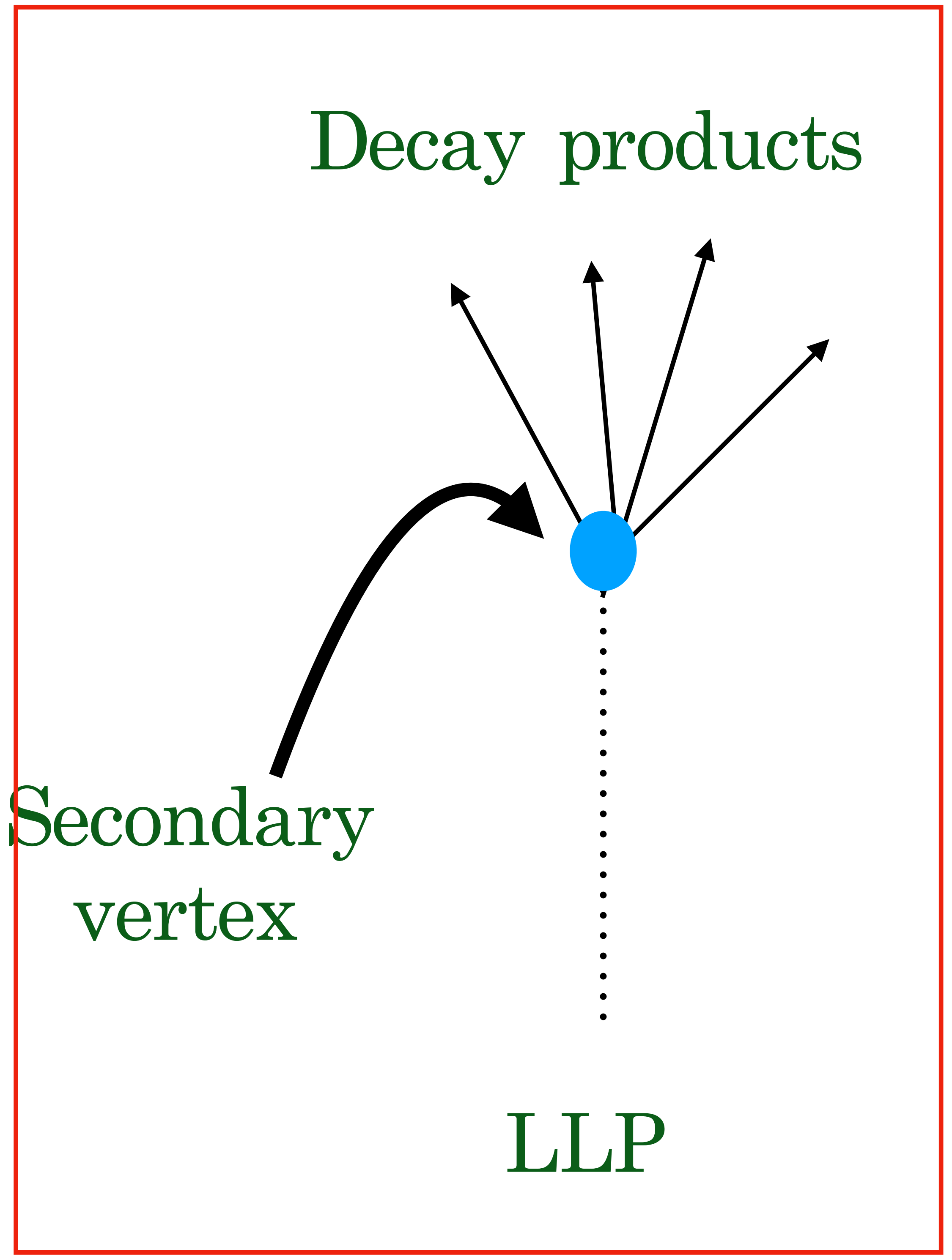
Displaced Vertex search

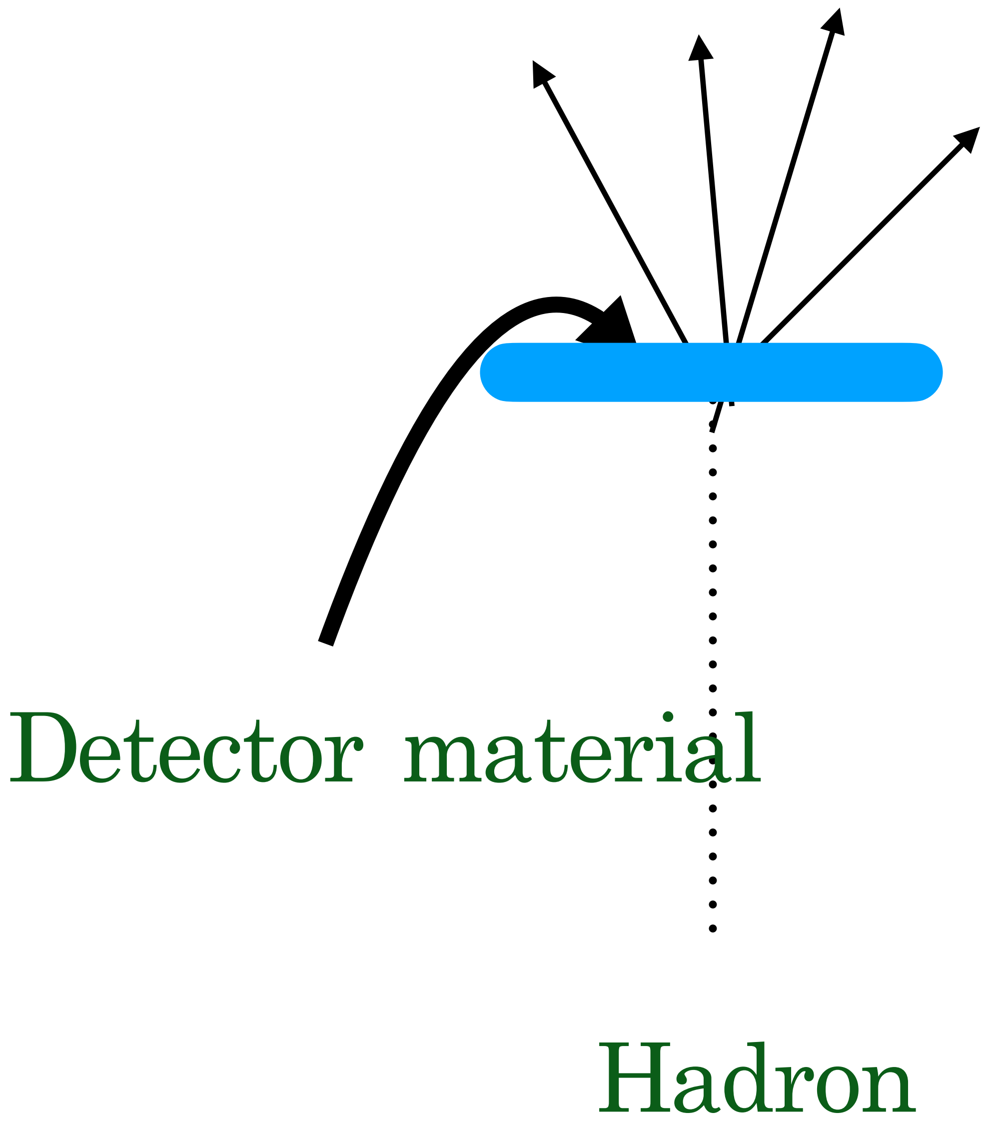


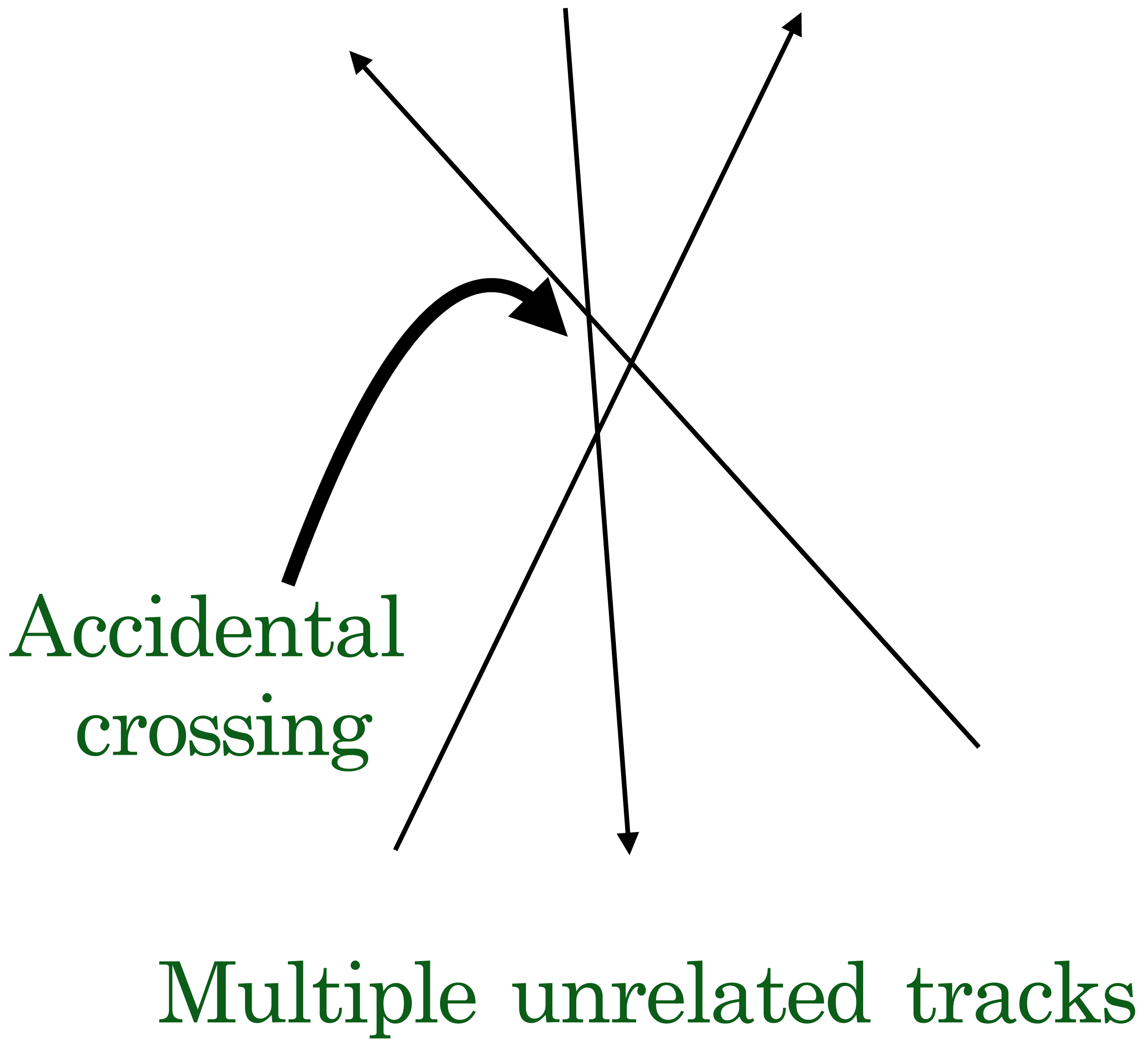
Looks background free ??

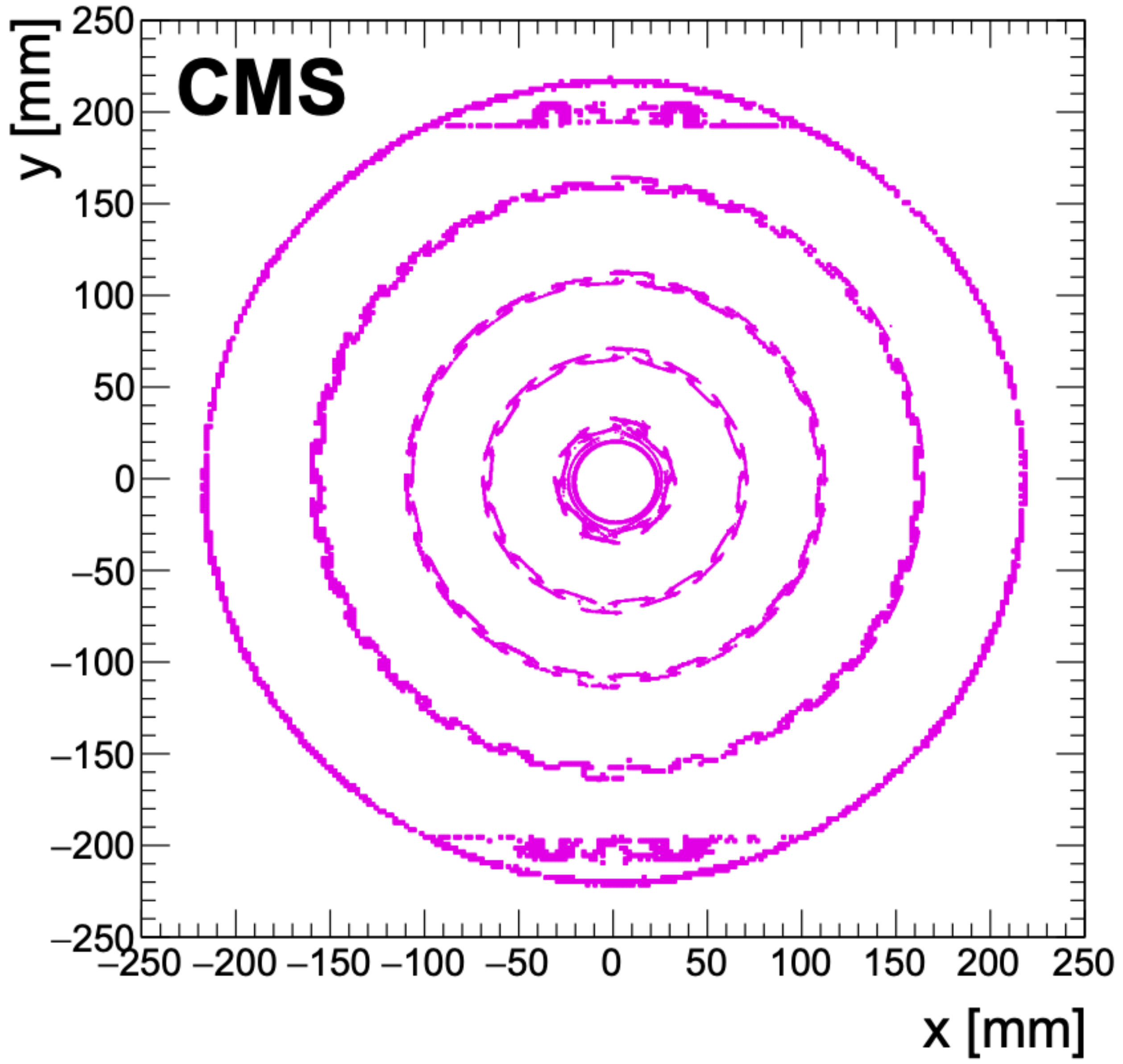
Displaced Vertex search

- 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







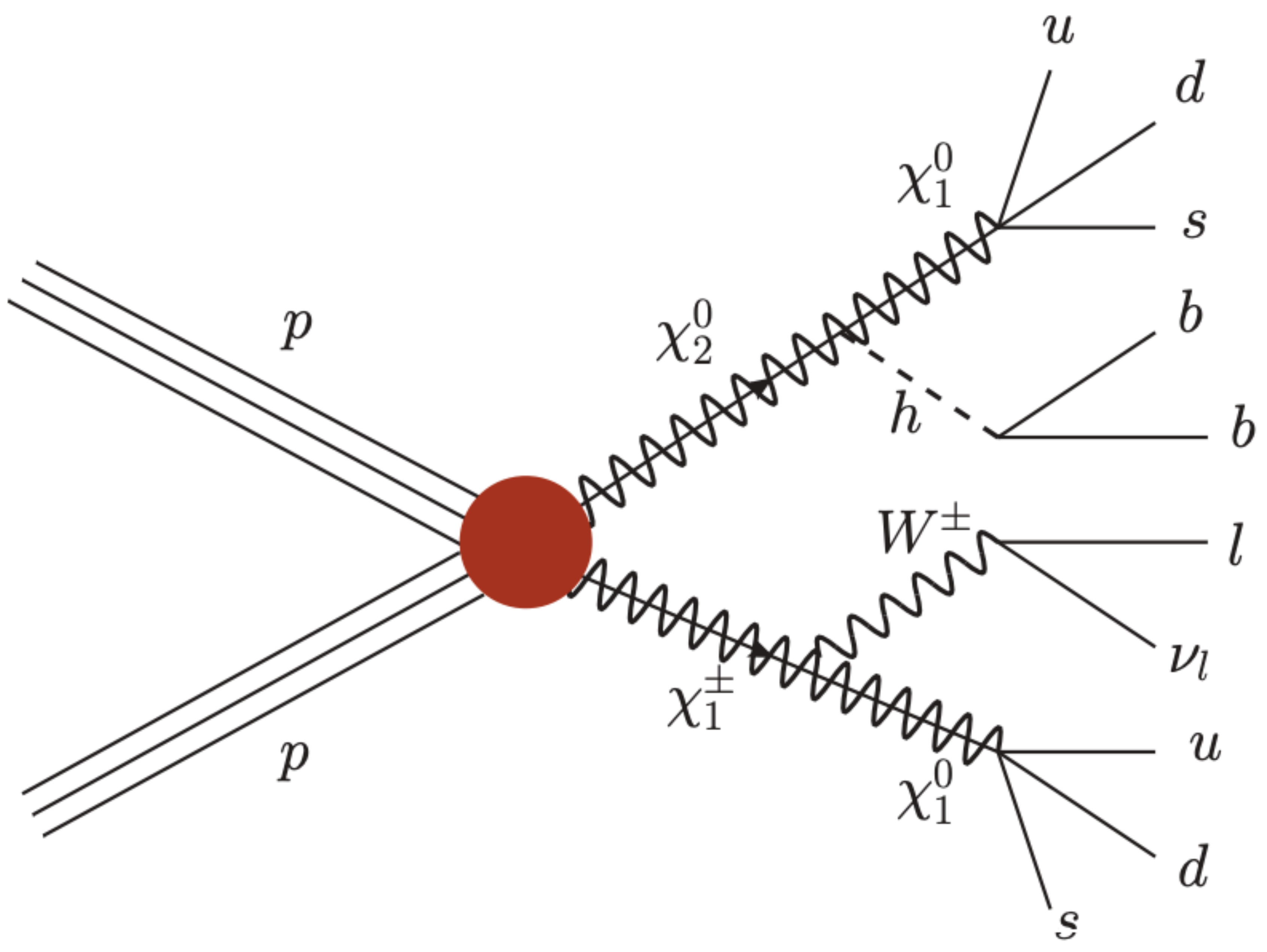


Material veto map (CMS)
2012.01581

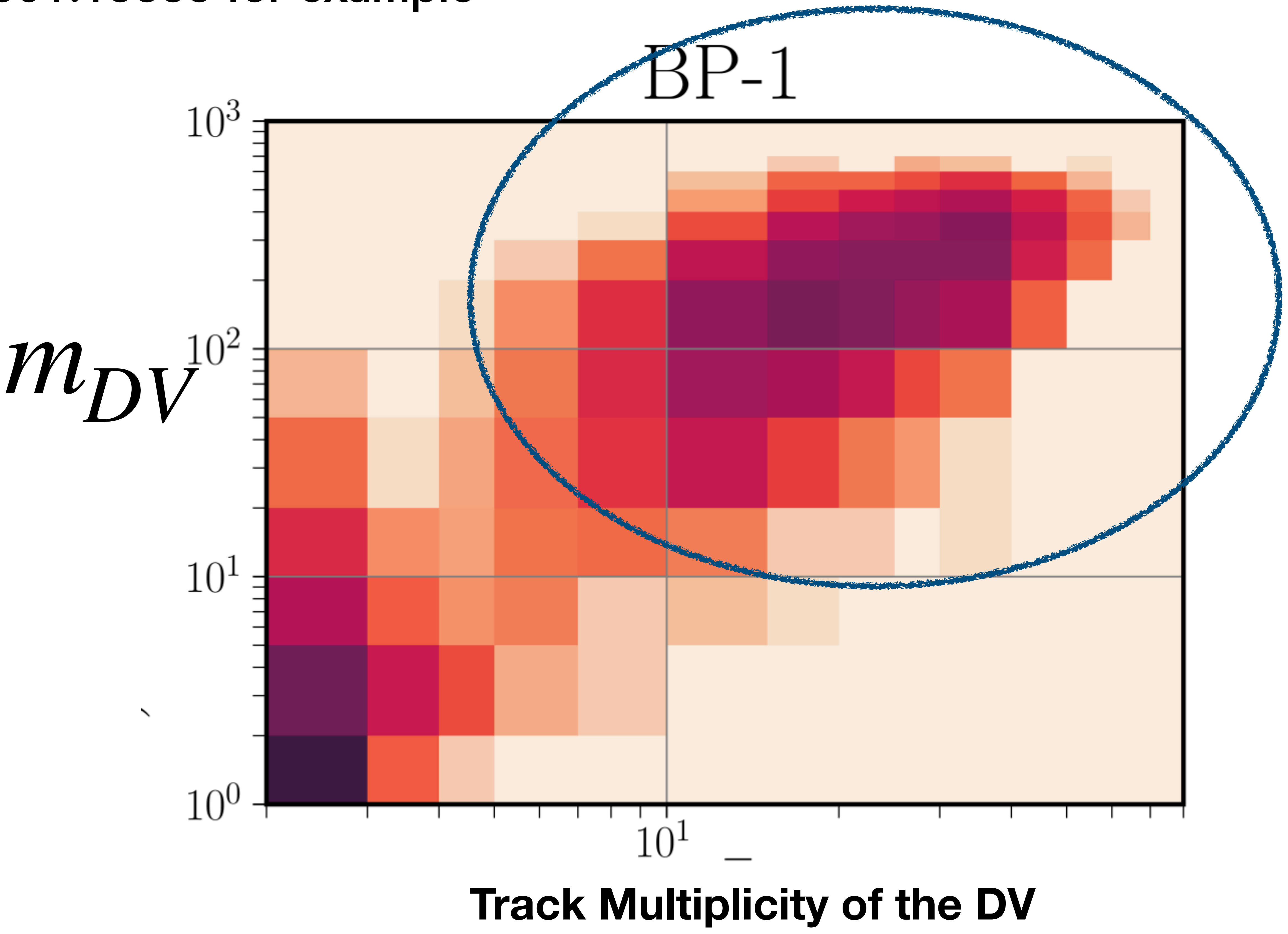
Displaced Vertex search

- 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



Identification of light LLPs with low multiplicity final states may be difficult !!
(Exception : Muon final state)

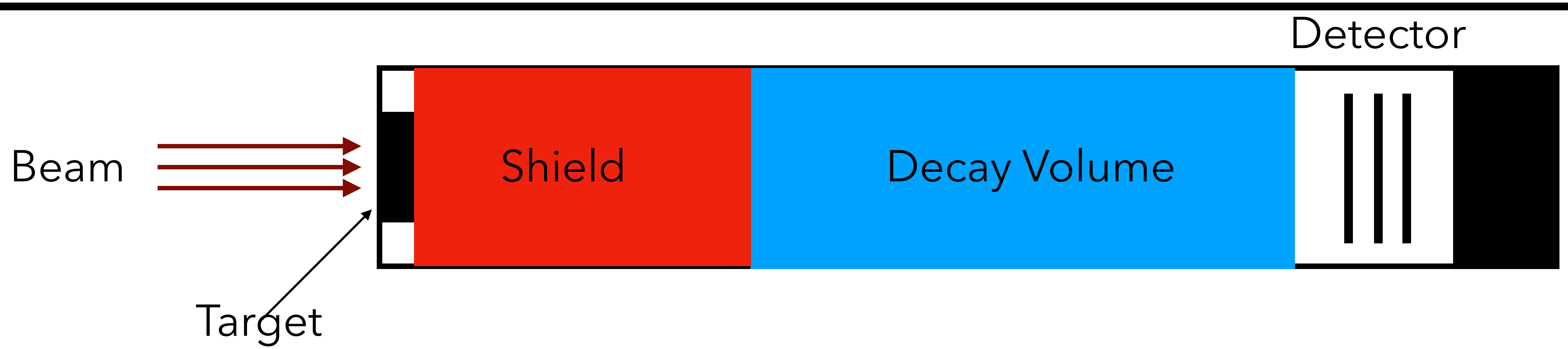
Search methods are not very sensitive

Example C

Fixed Target/ Beam Dump Experiment

Fixed target experiment: a beam is dumped mostly on a heavy target(absorb the hadronic cascade quickly)

Produce light LLPs from rare meson decay, bremsstrahlung etc.(MeV to a few GeV)



Disadvantage :COM energy is small compared to collider experiment

Advantage: High Intensity beam, long decay volume => particularly effective for light LLPs

Various past/existing/proposed Fixed target/Beam dump experiments :

Past : E137,E141, KEK, Orsay ..

Existing : NA64e, NA64mu,NA62-BD Proposed : NA64h, Ship, HIKE, SHADOW

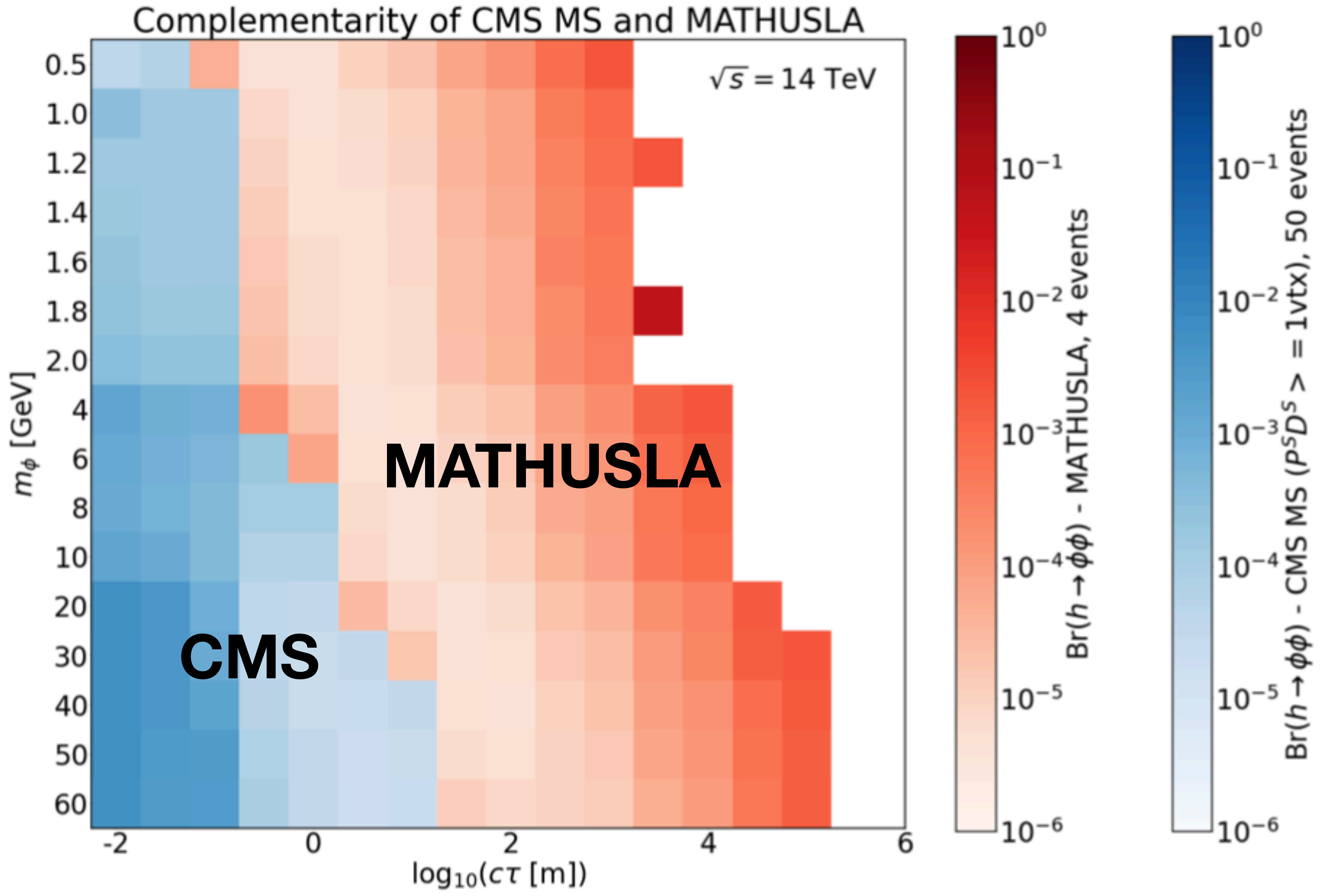
Future : ILC beam dump : 2105.13768

CMS vs Transverse detector MATHUSLA

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}

Complementarity of LHC main detector and proposed transverse detector

- 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.

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

Summary so far

There is always a chance to find the new physics in the near future

=> probably unconventional, exotic, or just need more data

Summary so far

There is always a chance to find the new physics in the near future

=> probably unconventional, exotic, or just need more data

Why do we need new high energy collider in future?

Consider three speculative scenarios supporting High Energy collider

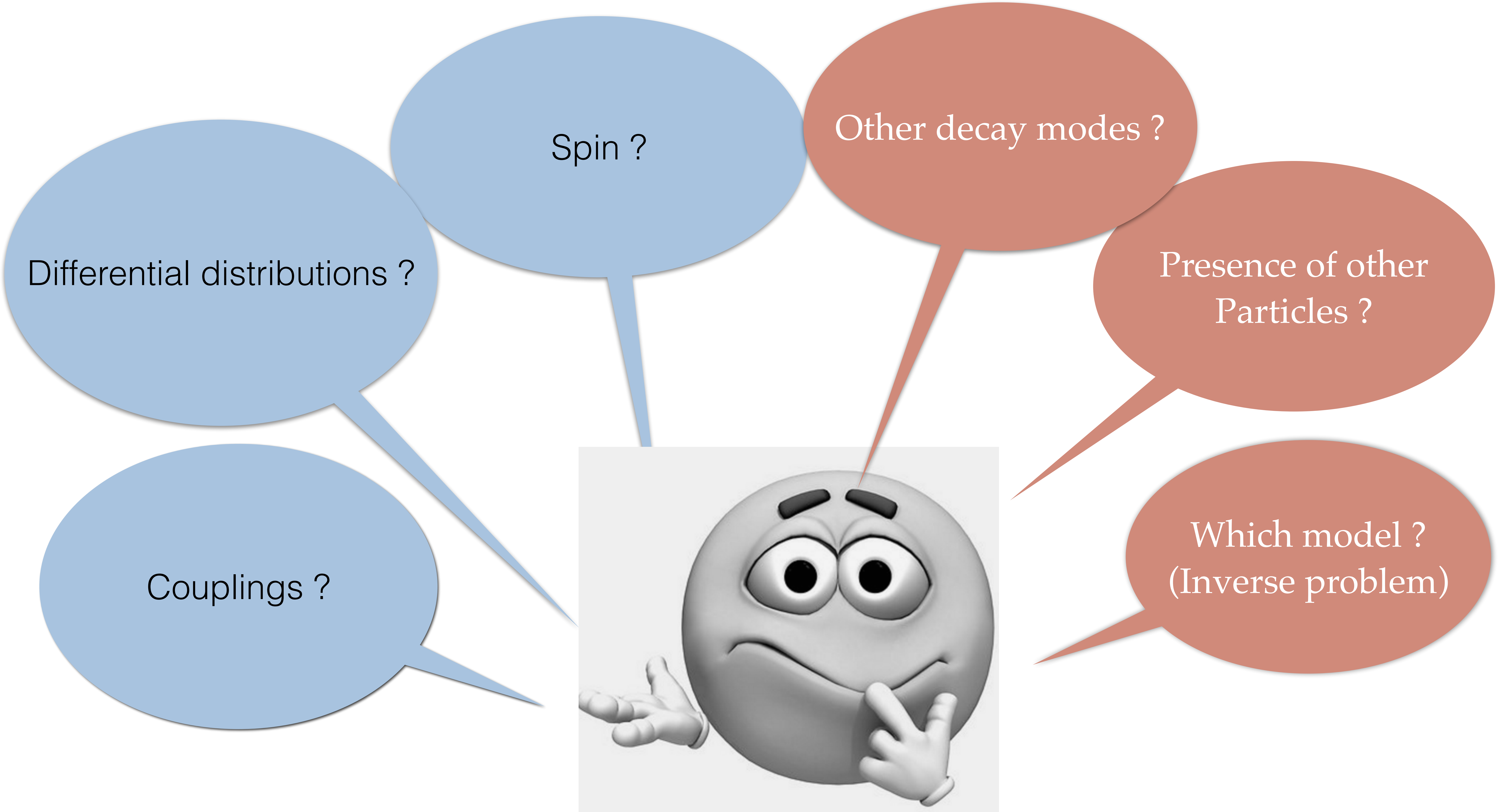
Scenario A: Most optimistic

Late discovery of some new heavy particle(X) at the kinematic edge of LHC

Example : Discovery of higgsino-like particle at the HL-LHC, no trace of other SUSY particles

Scenario A: Most optimistic

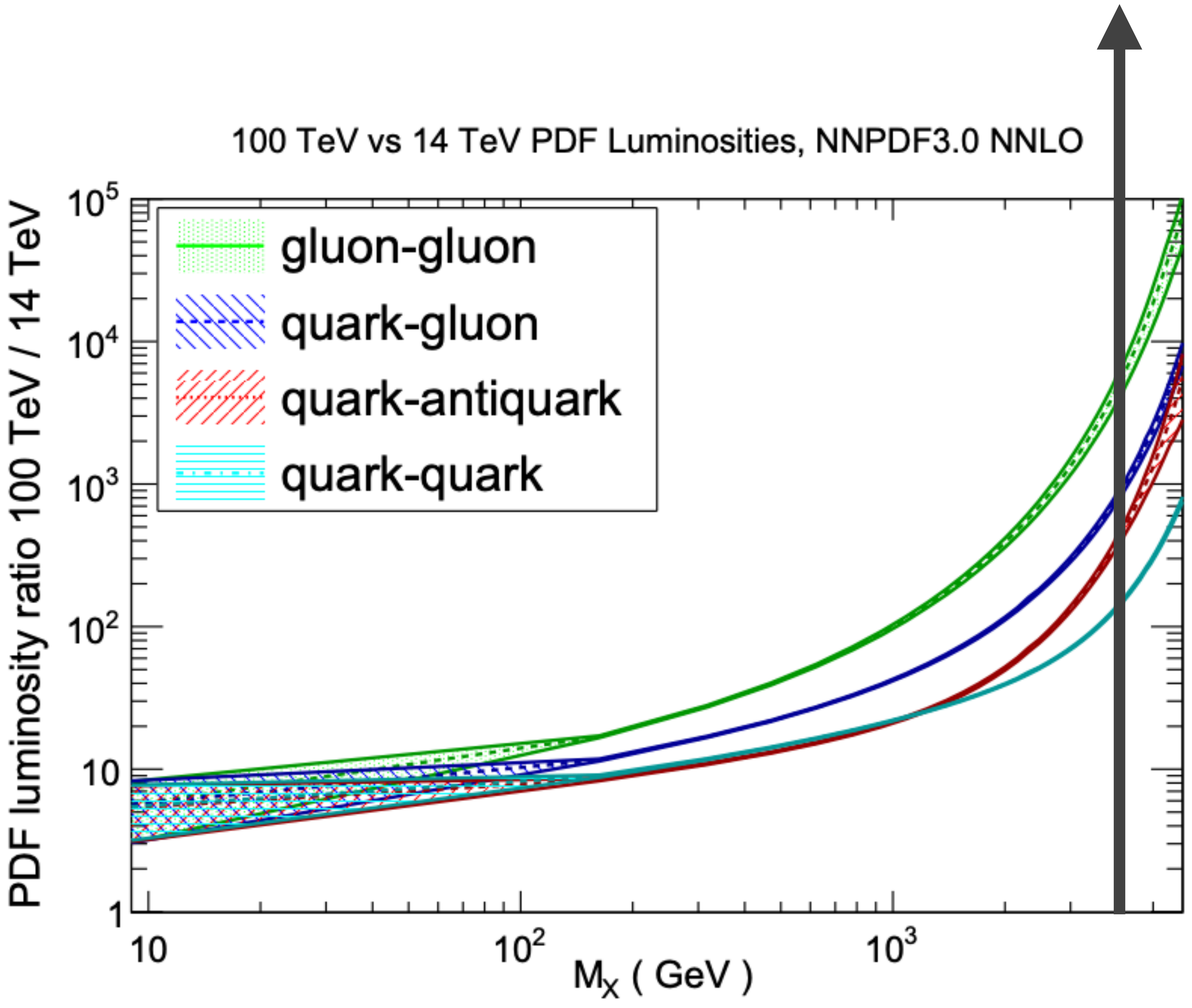
Example : Discovery of higgsino-like particle at the HL-LHC, no trace of other SUSY particles



Future Circular Collider(FCC-hh)

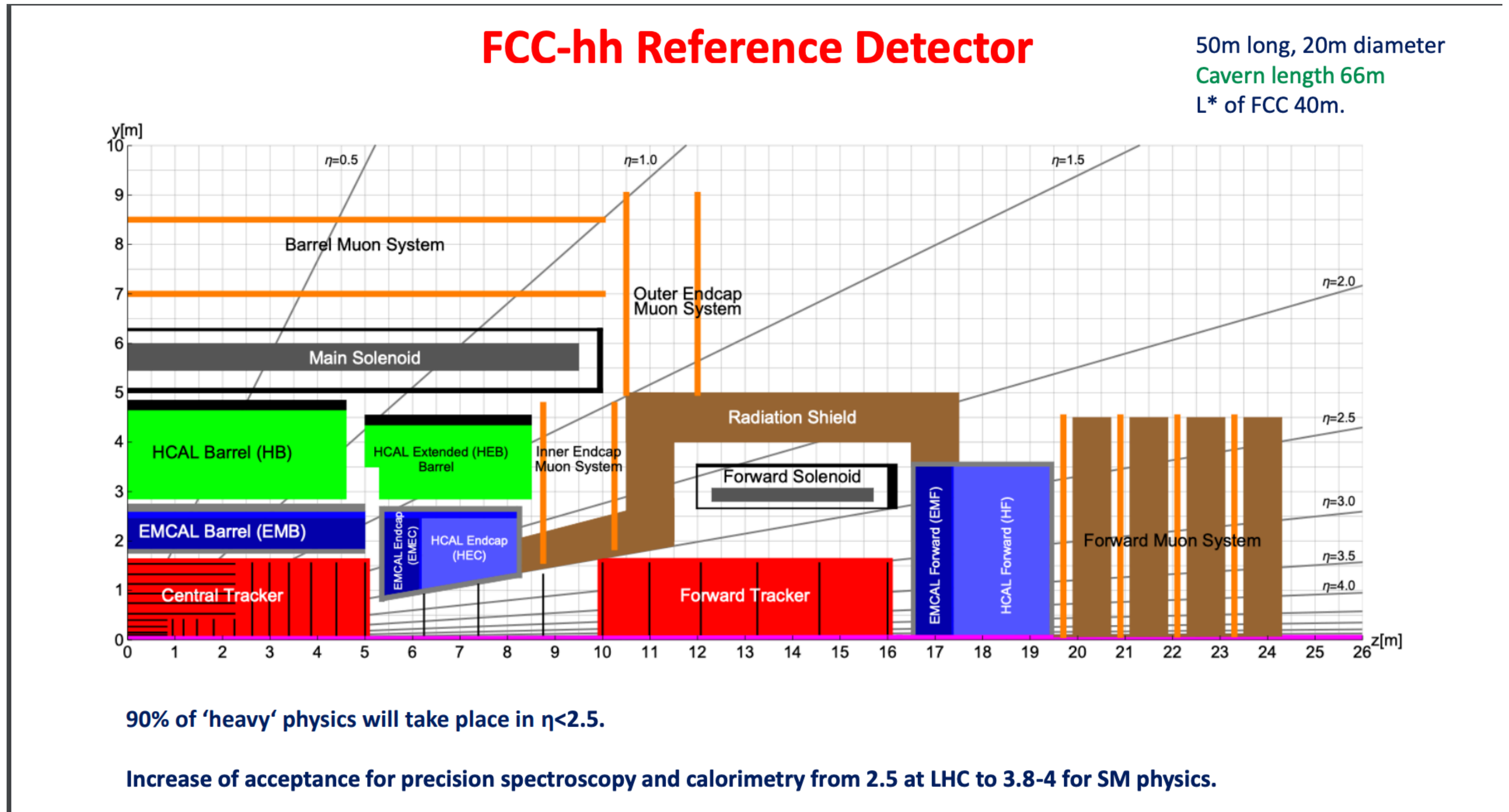
International FCC collaboration has been working on the design for PP collider at the CoM energy 100 TeV

- Conceptual Design Report (CDR) published in 2019
- 25 years of run can accumulate 20k-30k fb^{-1} 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



Huge gain in the cross section for heavy particle

HEP-PH:1607.01831



LINK HERE

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

SUSY@Future Hadron Collider

Strong sector : squarks and gluinos(33/100 TeV)

HEP-PH: 1606.00947

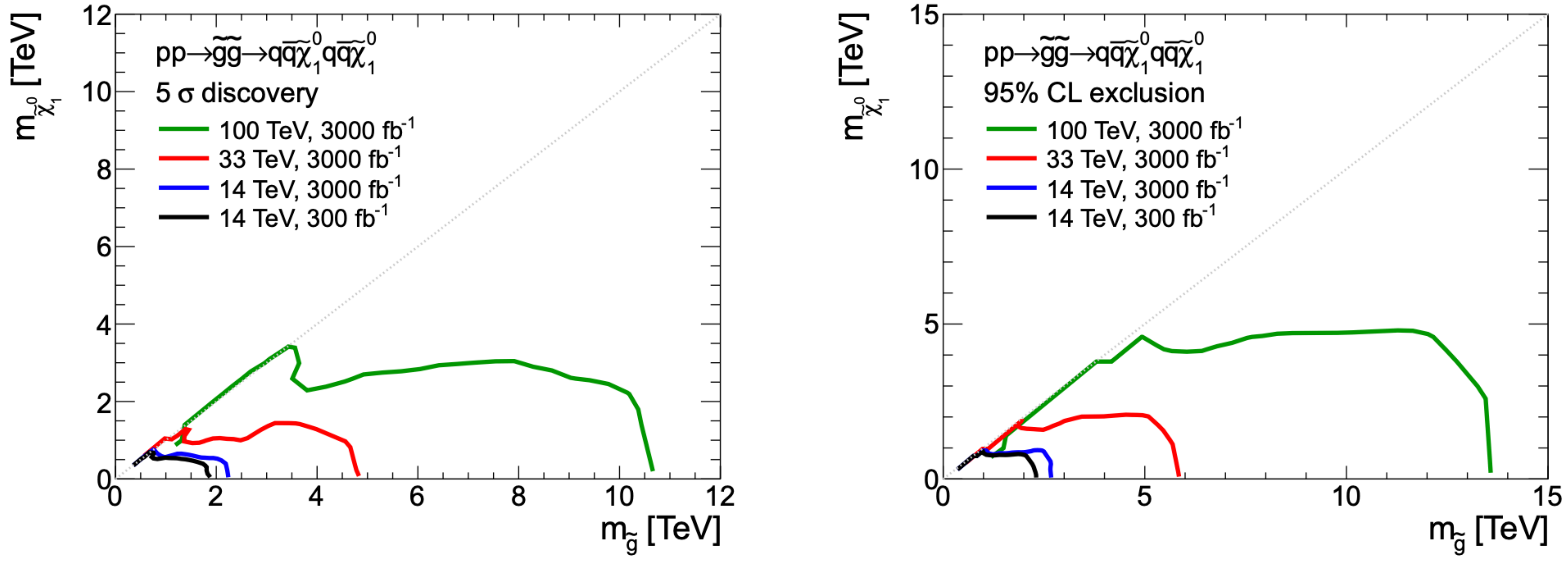


Fig. 13: Results for the gluino-neutralino model with light flavor decays. The left [right] panel shows the $5\,\sigma$ discovery reach [95% CL exclusion] for the four collider scenarios studied here. A 20% systematic uncertainty is assumed and pile-up is not included.

HEP-PH: 1407.5066

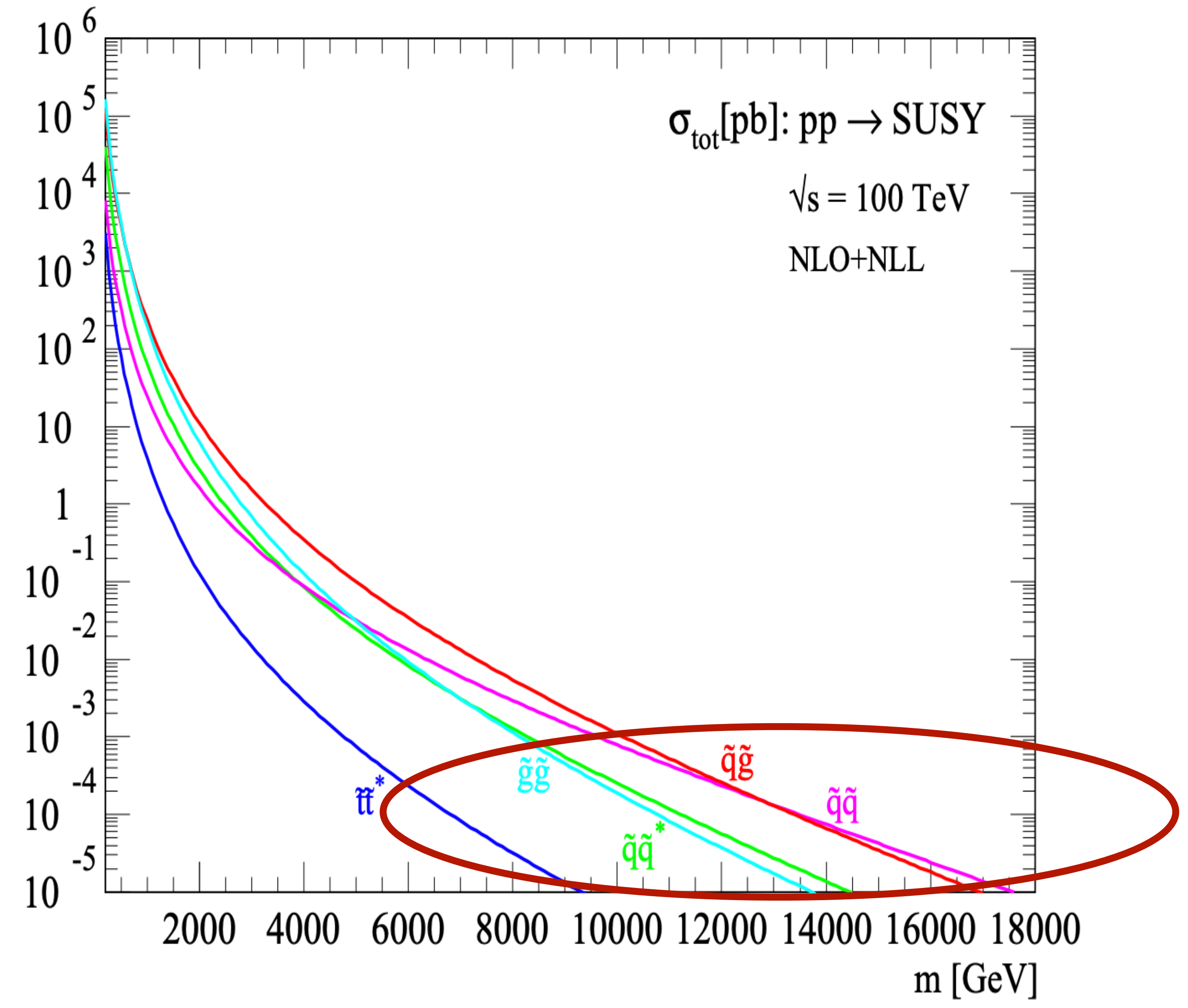


Figure 4: NLO+NLL production cross sections for the case of equal degenerate squark and gluino masses as a function of mass at $\sqrt{s} = 100$ TeV.

20 percent systematic uncertainty, Integrated Luminosity= 3000 fb^{-1}

100 TeV Collider	33 TeV Collider
Discovery reach ~ 10 TeV	Discovery reach ~ 5 TeV
Exclusion reach ~ 14 TeV	Exclusion reach ~ 6 TeV

Scenario B: optimistic

No discovery at the LHC, However breakthrough comes from other experiments (Dark matter, Flavour physics , …)

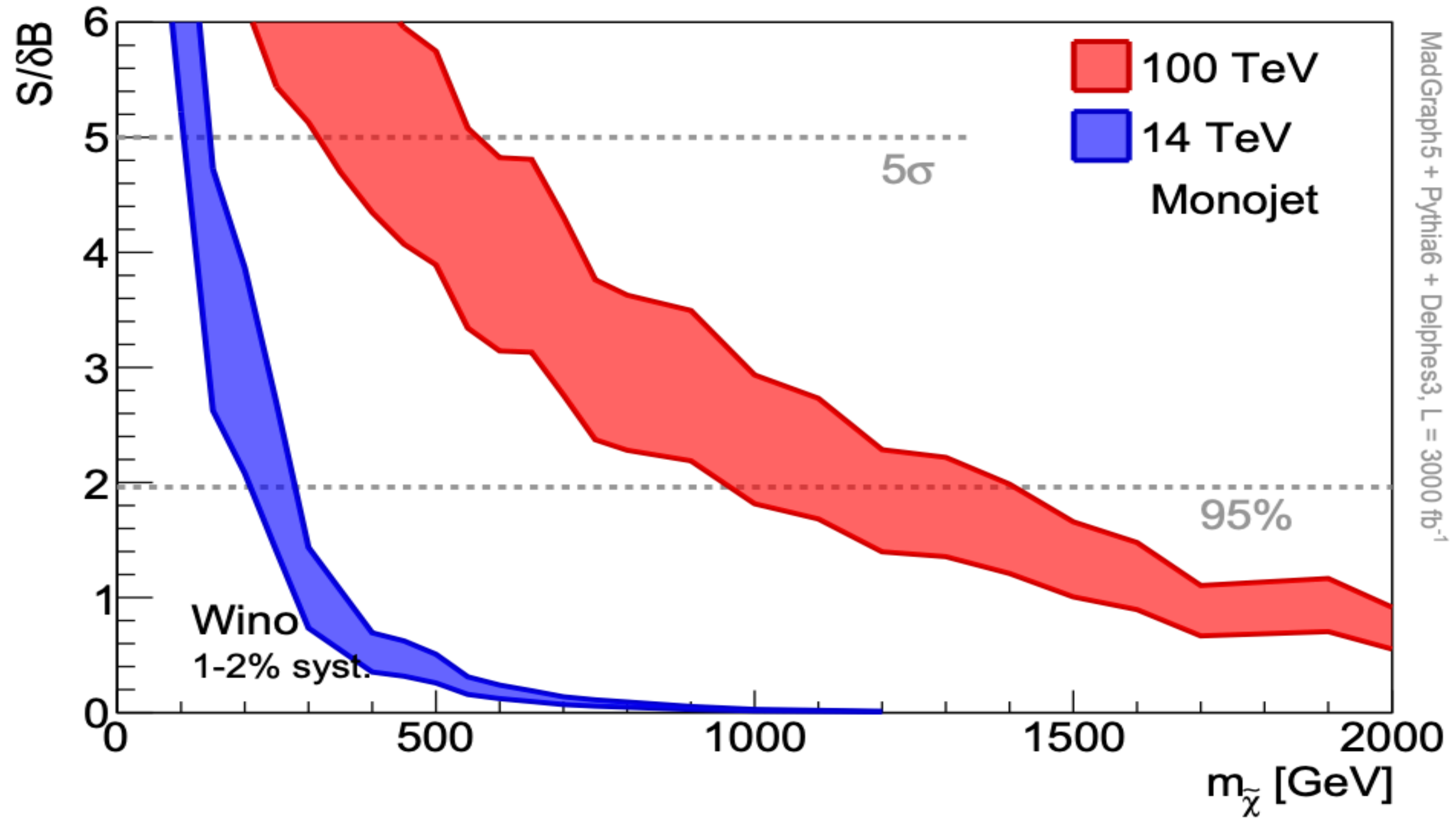
Examples :
A. Dark matter signal in indirect detection / Direct detection
B. Flavour physics anomaly confirmed , or unified picture emerges from multiple anomalies

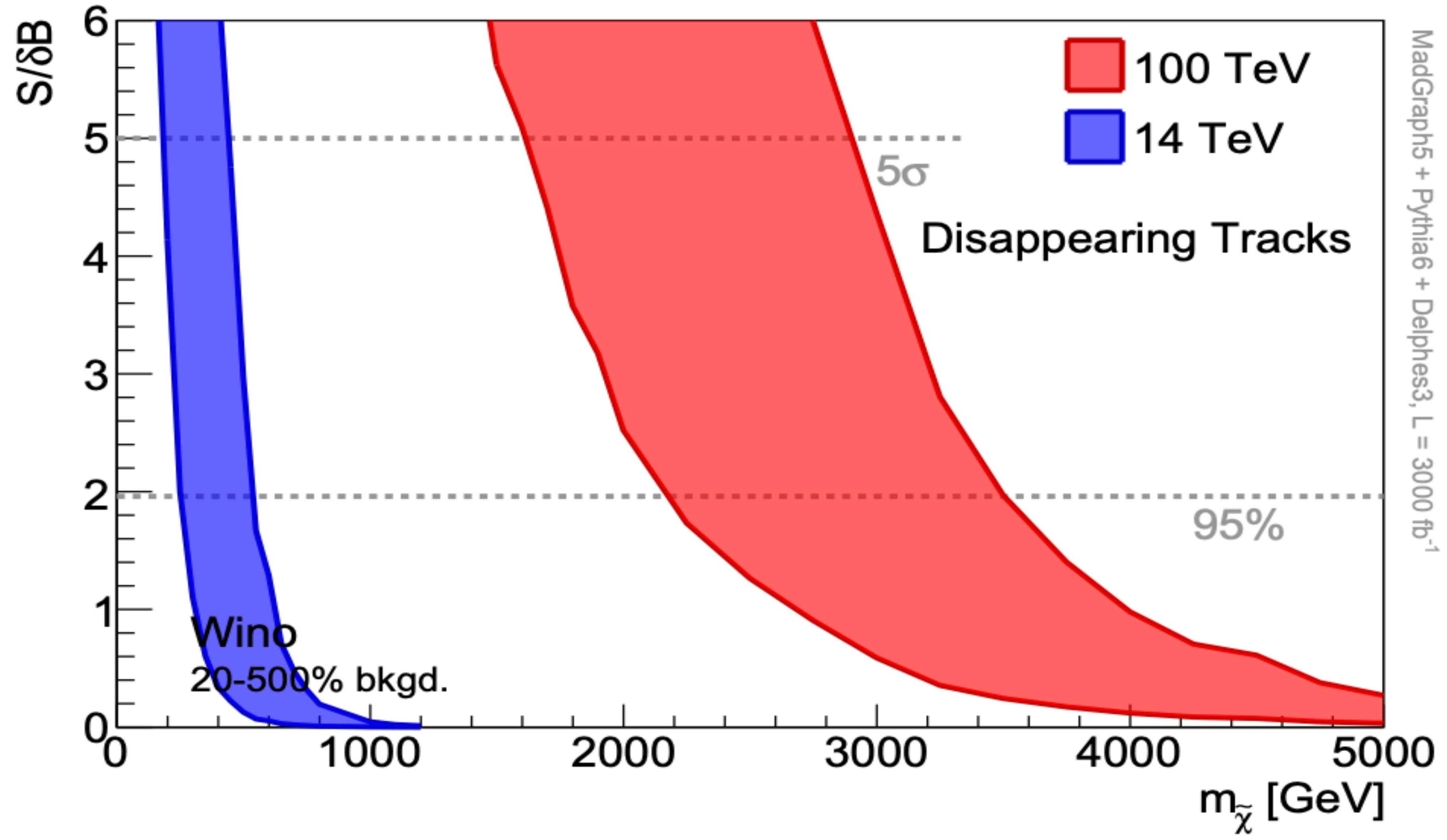
New physics scale may be bounded by the data

Similar story: Hint of W/Z particle from Gargamelle experiment

Dark Matter@ 100 TeV

- FCC-hh will be able to probe huge dark matter parameter space in Mono-X + MET channel.
- Mediator searches will also be improved drastically
- Light DM-Higgs portal models : The Higgs to invisible Branching ratio will probed ~ 10^{-4} (CERN-ACC-2018-0045).
- Disappearing track search will be sensitive to the full mass range of thermal relic parameter space.





Low and Wang, hep-ph: 1404.0682

Also see Han, Mukhopadhyay and Wang hep-ph: 1805.00015

Scenario C: Nightmare Scenario ??

No hint of new physics at the LHC, dark matter, flavour ….

No idea about the scale of the new physics:

Even in this case future hadron collider will be the best option for new physics searches.

Fcc-hh : will gain both in the energy side and in the luminosity side

Definite goal : Higgs precision, Understand Higgs potential

Not so specific: goals discussed in Scenario A and B

Higgs Physics @ fcc-hh

	$gg \to H$ (Sect 3.1)	VBF (Sect 3.5)	$HW^{\pm}$ (Sect 3.4)	HZ (Sect 3.4)	$t\bar{t}H$ (Sect 3.6)
σ(pb)	802	69	15.7	11.2	32.1
σ(100 TeV)/σ(14 TeV)	16.5	16.1	10.4	11.4	52.3

1606.09408

Huge improvement in statistics
2.4 10 [10.] Higgs from gluon fusion (factor of ~ 180)

FCC-hh

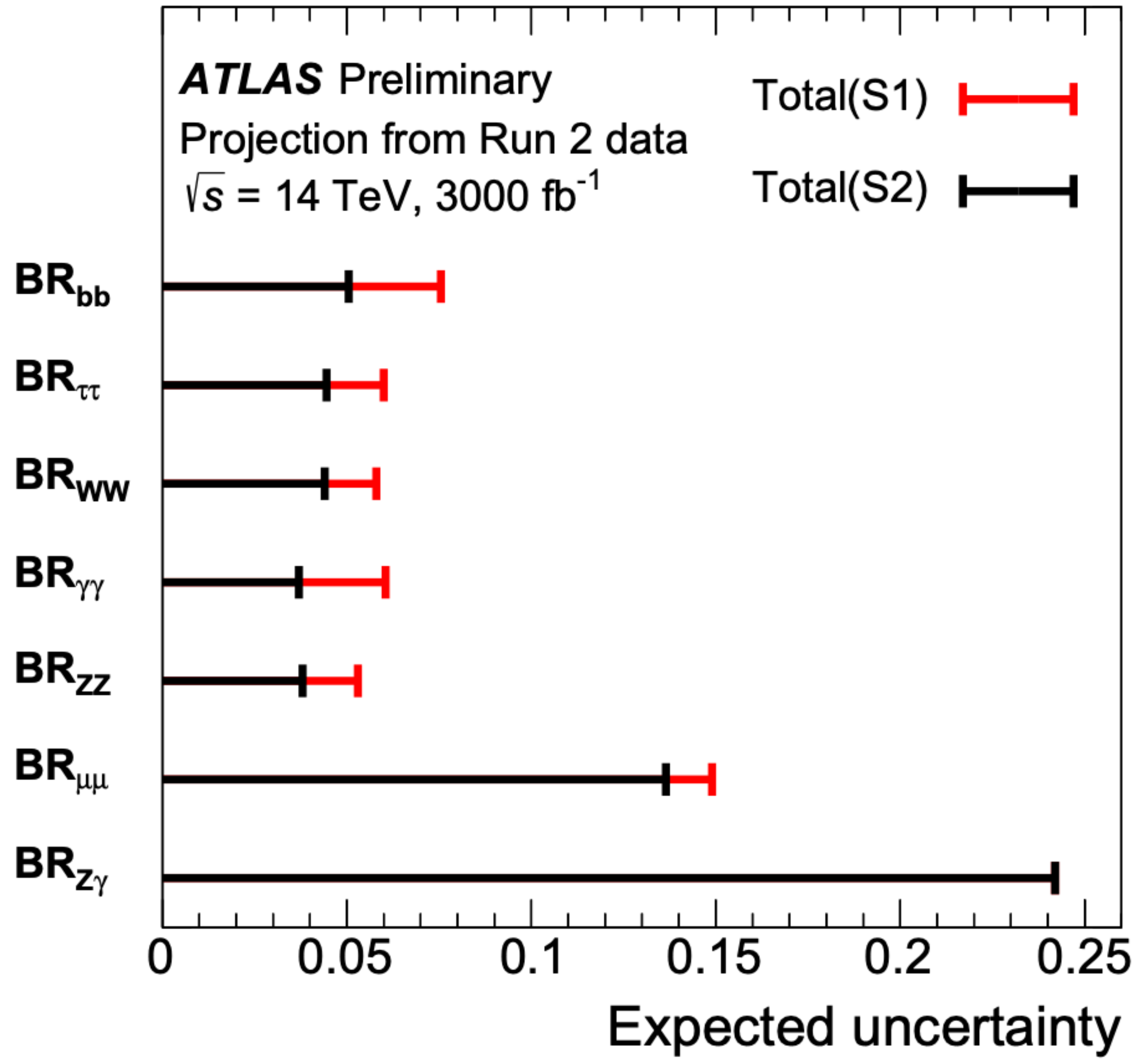
HL-LHC

Table 1.2. Target precision for the parameters relative to the measurement of various Higgs decays, ratios thereof, and of the Higgs self-coupling λ.

Observable	Parameter	Precision (stat)	Precision (stat+syst+lumi)
$\mu = \sigma(\mathrm{H}) \times \mathrm{B}(\mathrm{H} \to \gamma\gamma)$	$\delta\mu/\mu$	0.1%	1.45%
$\mu = \sigma(\mathrm{H}) \times \mathrm{B}(\mathrm{H} \to \mu\mu)$	$\delta\mu/\mu$	0.28%	1.22%
$\mu = \sigma(\mathrm{H}) \times \mathrm{B}(\mathrm{H} \to 4\mu)$	$\delta\mu/\mu$	0.18%	1.85%
$\mu = \sigma(\mathrm{H}) \times \mathrm{B}(\mathrm{H} \to \gamma\mu\mu)$	$\delta\mu/\mu$	0.55%	1.61%
$\mu = \sigma(\mathrm{HH}) \times \mathrm{B}(\mathrm{H} \to \gamma\gamma)\mathrm{B}(\mathrm{H} \to \mathrm{b\bar{b}})$	$\delta\lambda/\lambda$	5%	7.0%
$R = \mathrm{B}(\mathrm{H} \to \mu\mu)/\mathrm{B}(\mathrm{H} \to 4\mu)$	$\delta R/R$	0.33%	1.3%
$R = \mathrm{B}(\mathrm{H} \to \gamma\gamma)/\mathrm{B}(\mathrm{H} \to 2e2\mu)$	$\delta R/R$	0.17%	0.8%
$R = \mathrm{B}(\mathrm{H} \to \gamma\gamma)/\mathrm{B}(\mathrm{H} \to 2\mu)$	$\delta R/R$	0.29%	1.38%
$R = \mathrm{B}(\mathrm{H} \to \mu\mu\gamma)/\mathrm{B}(\mathrm{H} \to \mu\mu)$	$\delta R/R$	0.58%	1.82%
$R = \sigma(\mathrm{t\bar{t}H}) \times \mathrm{B}(\mathrm{H} \to \mathrm{b\bar{b}})/\sigma(\mathrm{t\bar{t}Z}) \times \mathrm{B}(\mathrm{Z} \to \mathrm{b\bar{b}})$	$\delta R/R$	1.05%	1.9%
$B(\mathrm{H} \to \text{invisible})$	B@95%CL	1×10^{-4}	2.5×10^{-4}

Notes. Notice that Lagrangian couplings have a precision that is typically half that of what

HTTPS://CDS.CERN.CH/RECORD/2651300/FILES/CERN-ACC-2018-0058.PDF



ATL-PHYS-PUB-2018-054

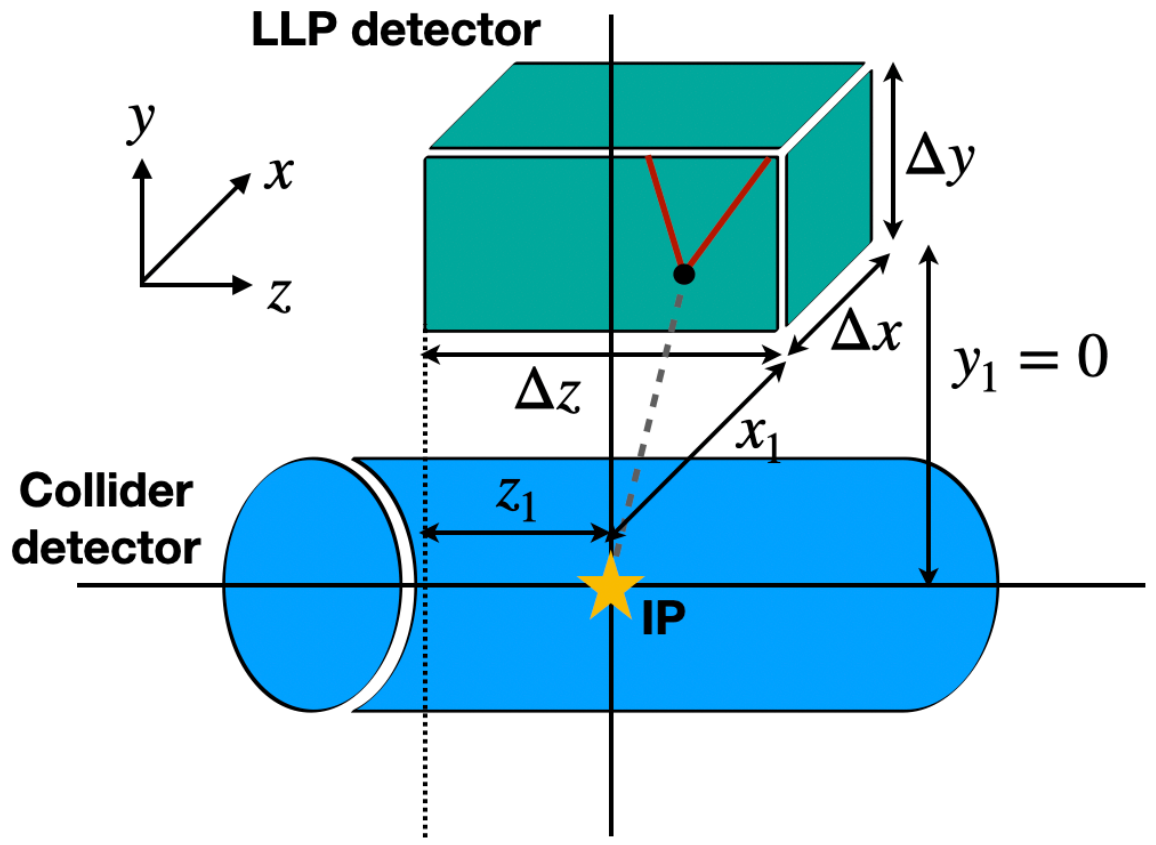
Advantage for FCC-hh

A dedicated Transverse Detector fror FCC-hh for LLPs

BB, Shigeki Matsumoto
and 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 (Detector for long-lived particles at high energy of 100 TeV),
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.

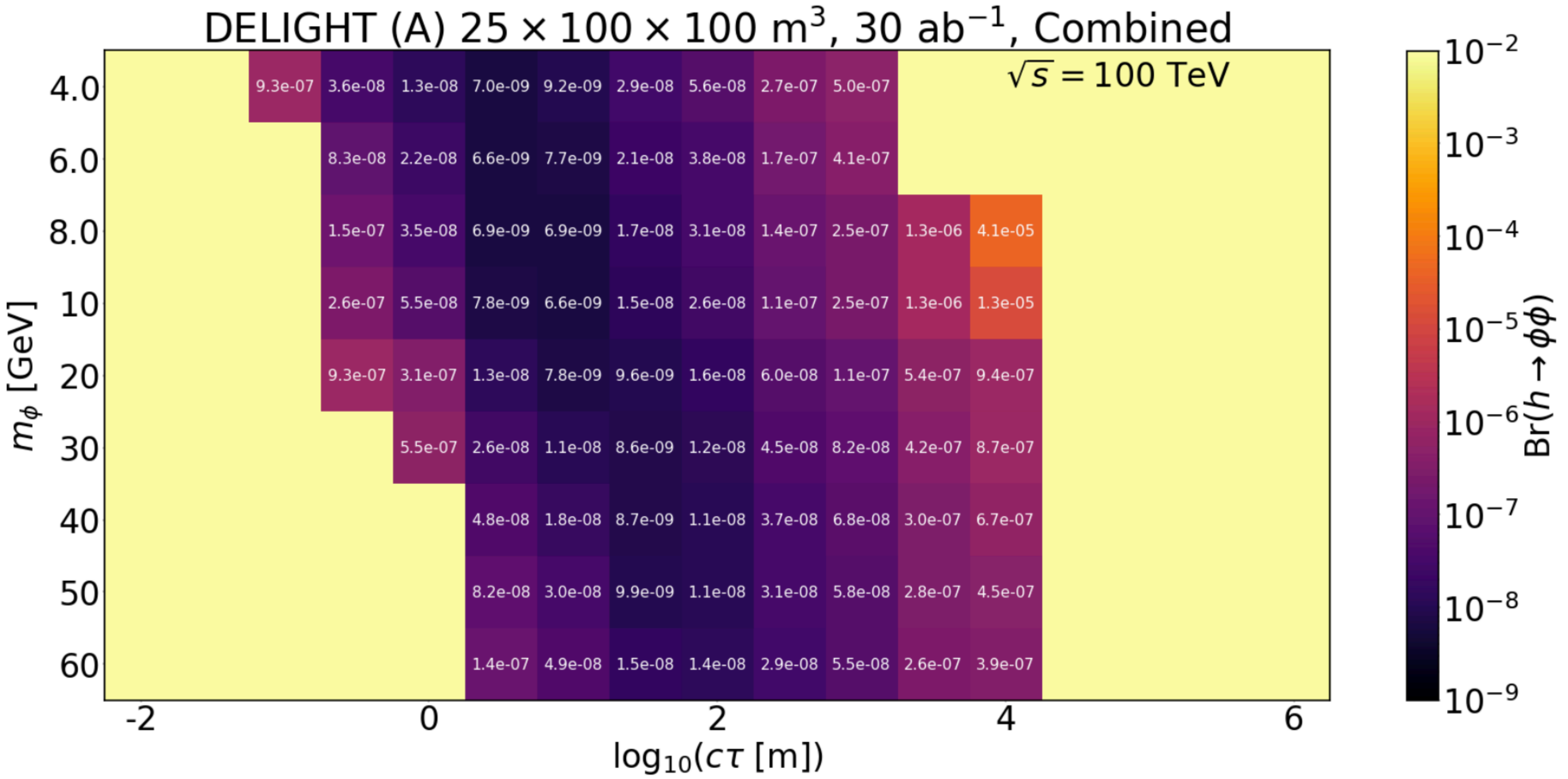
LLP detectors for FCC-ee is proposed here : 2011.01005

DELIGHT-A

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

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

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.

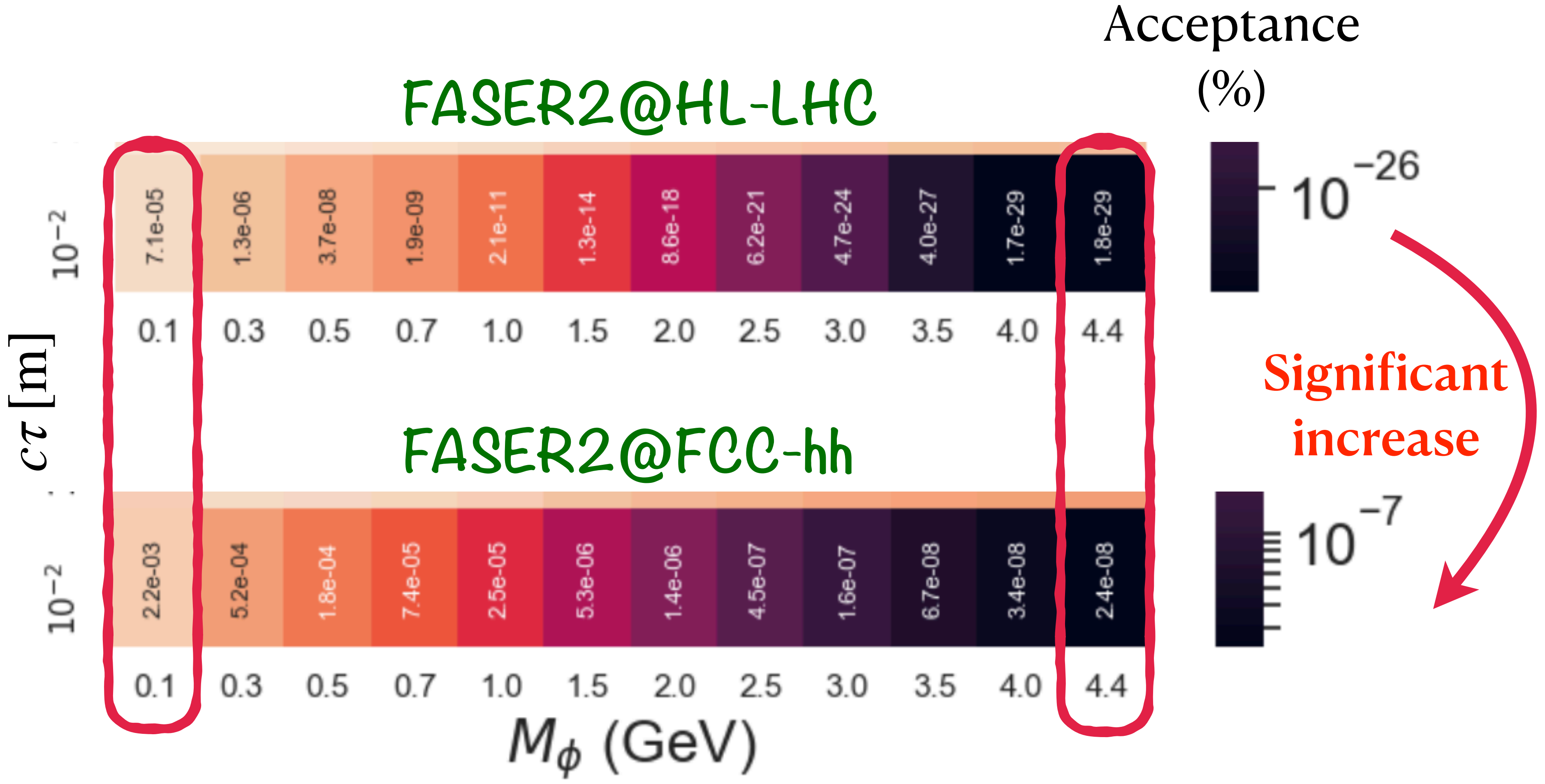
Central position of the detector can benefit light LLPs.

Proposal for a dedicated forward detector@FCC-hh

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

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

FASER2 $L_s = 480$ m, $R = 1$ m, $L_d = 5$ m, $p_\phi > 100$ GeV



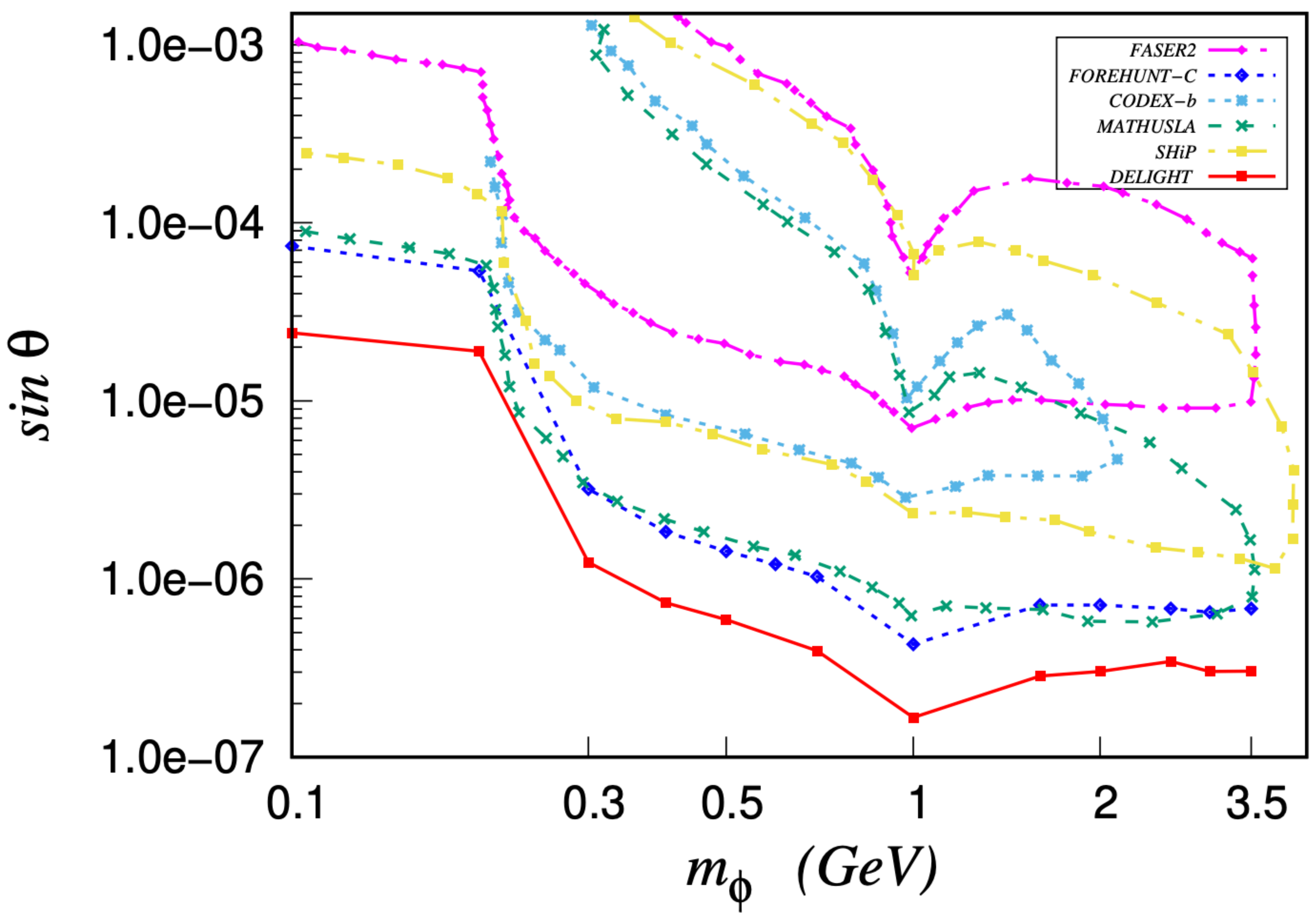
B-mesons more energetic at 100 TeV collider

The LLP coming from B-meson decay has larger boost

Increased efficiency for smaller decay lengths and heavier masses

Taken from Rhitaja Sengupta's Talk

Dark Scalar



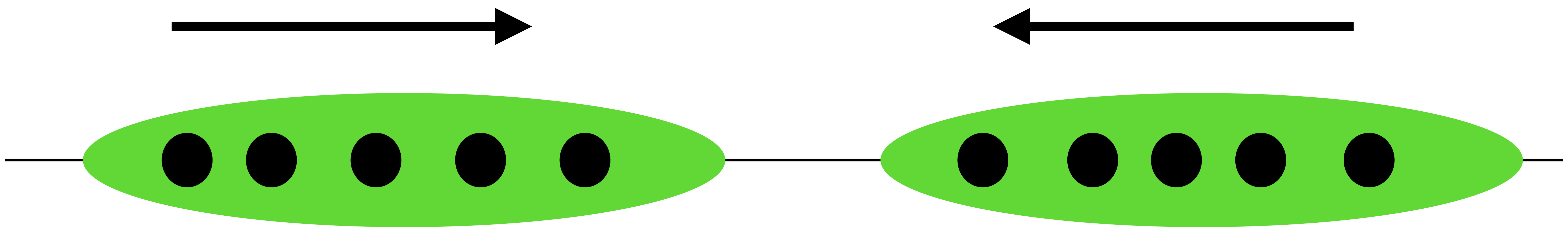
BB, Herbi Dreiner, Nivedita Ghosh, Shigeki Matsumoto, Rhitaja Sengupta, Prabhat Solanki PRD 2024

Challenges for FCC-hh

Pile up

Not a collision between two protons

Collision between proton bunches

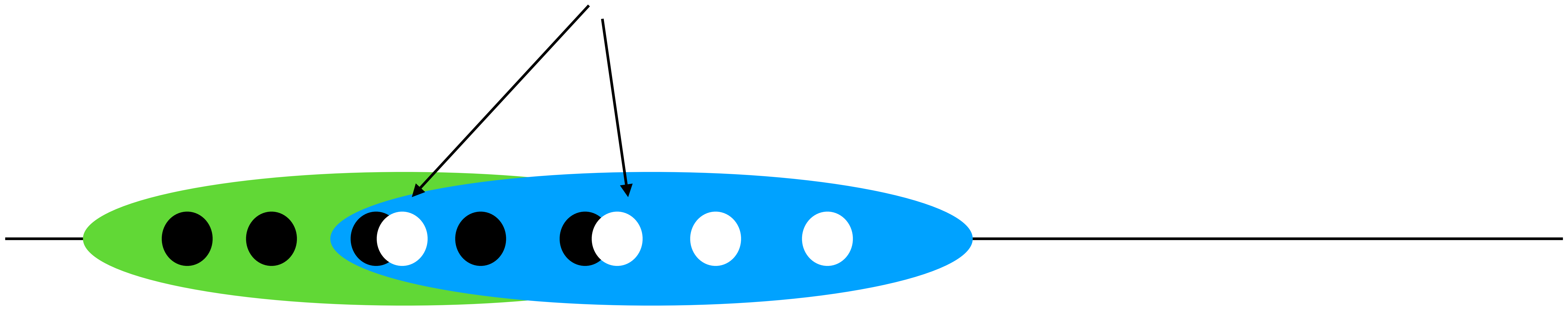


Proton bunch 1

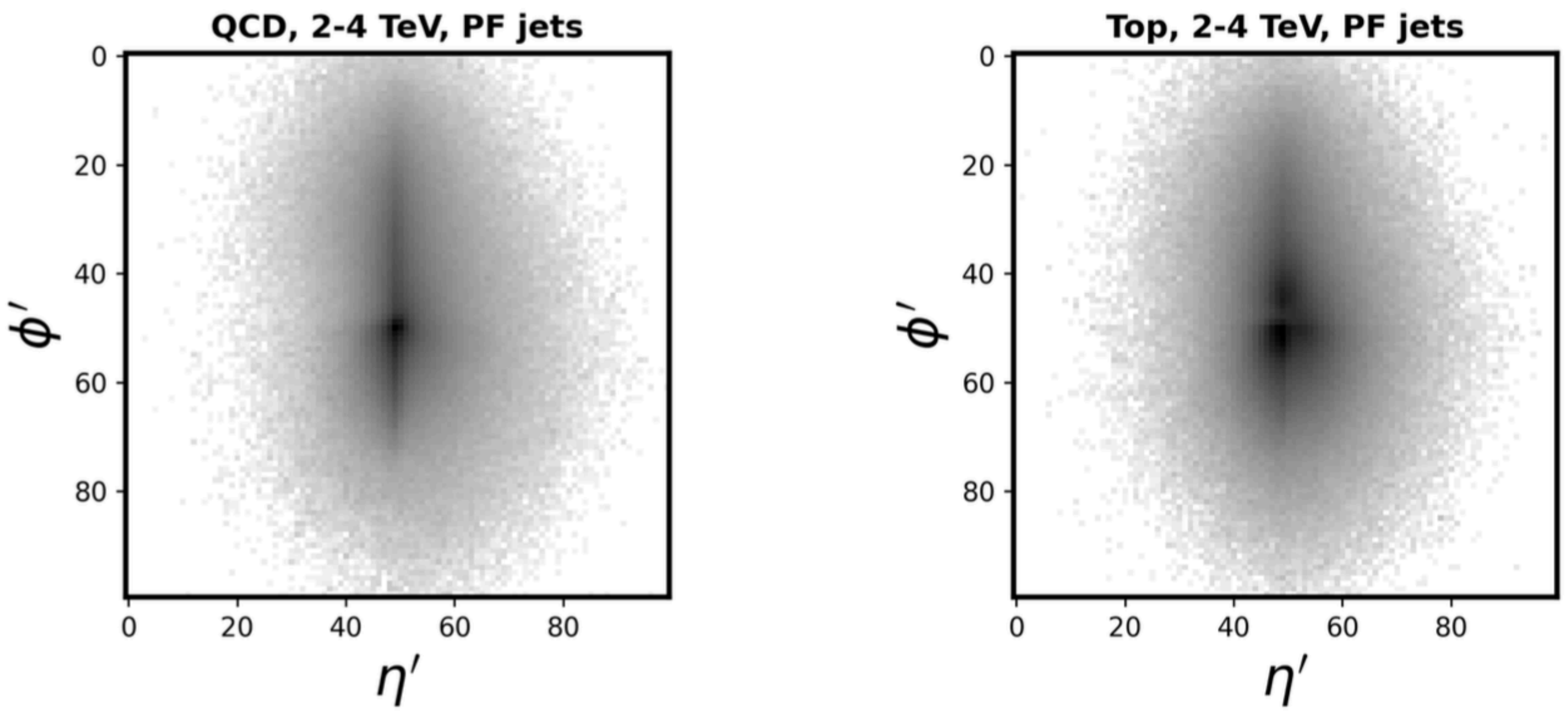
Proton bunch 2

- Average Pile up HL-LHC: 140-200
- Average Pile up for FCC-hh: ~500-1000 !

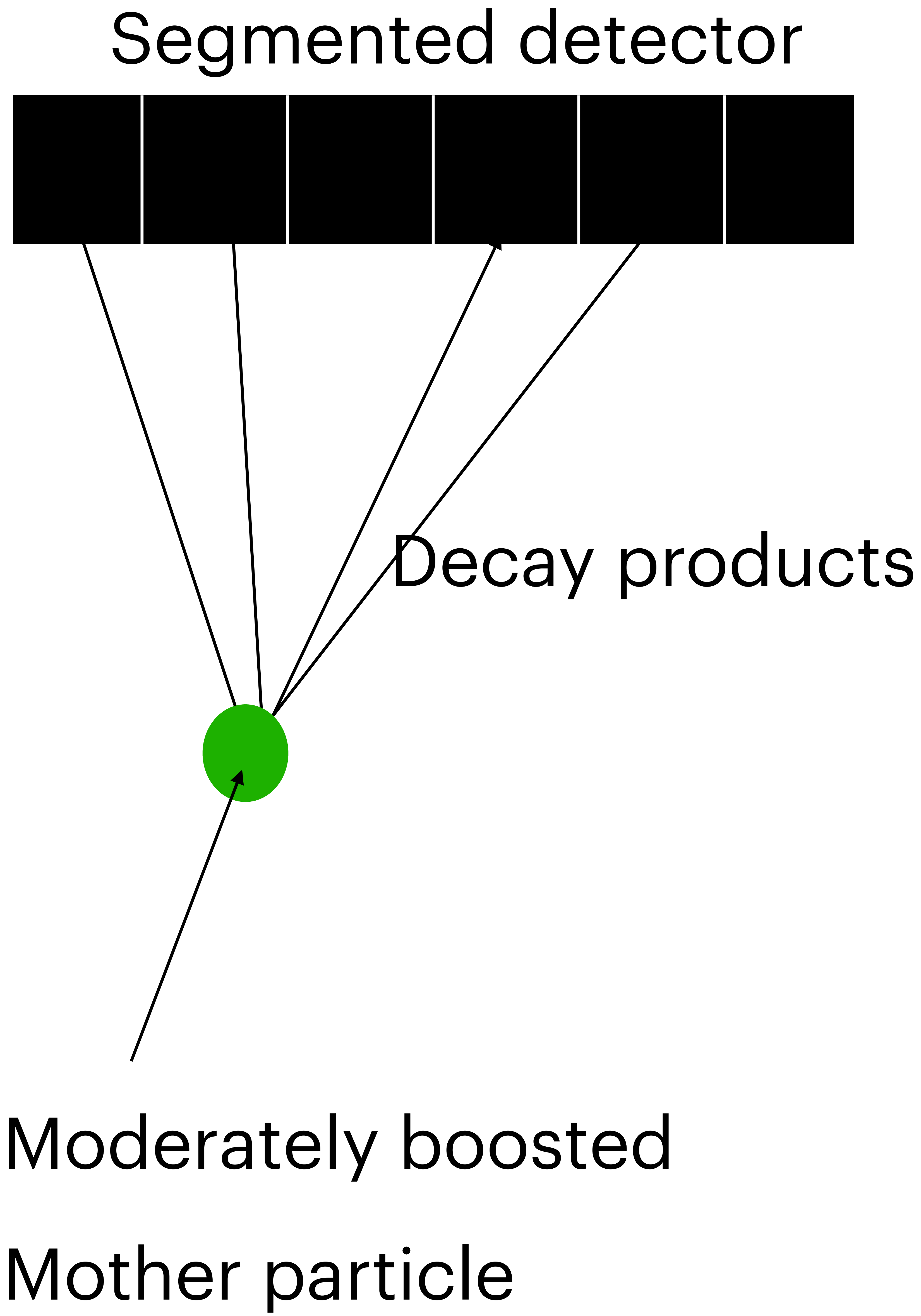
Multiple collision vertices : Pileup vertices



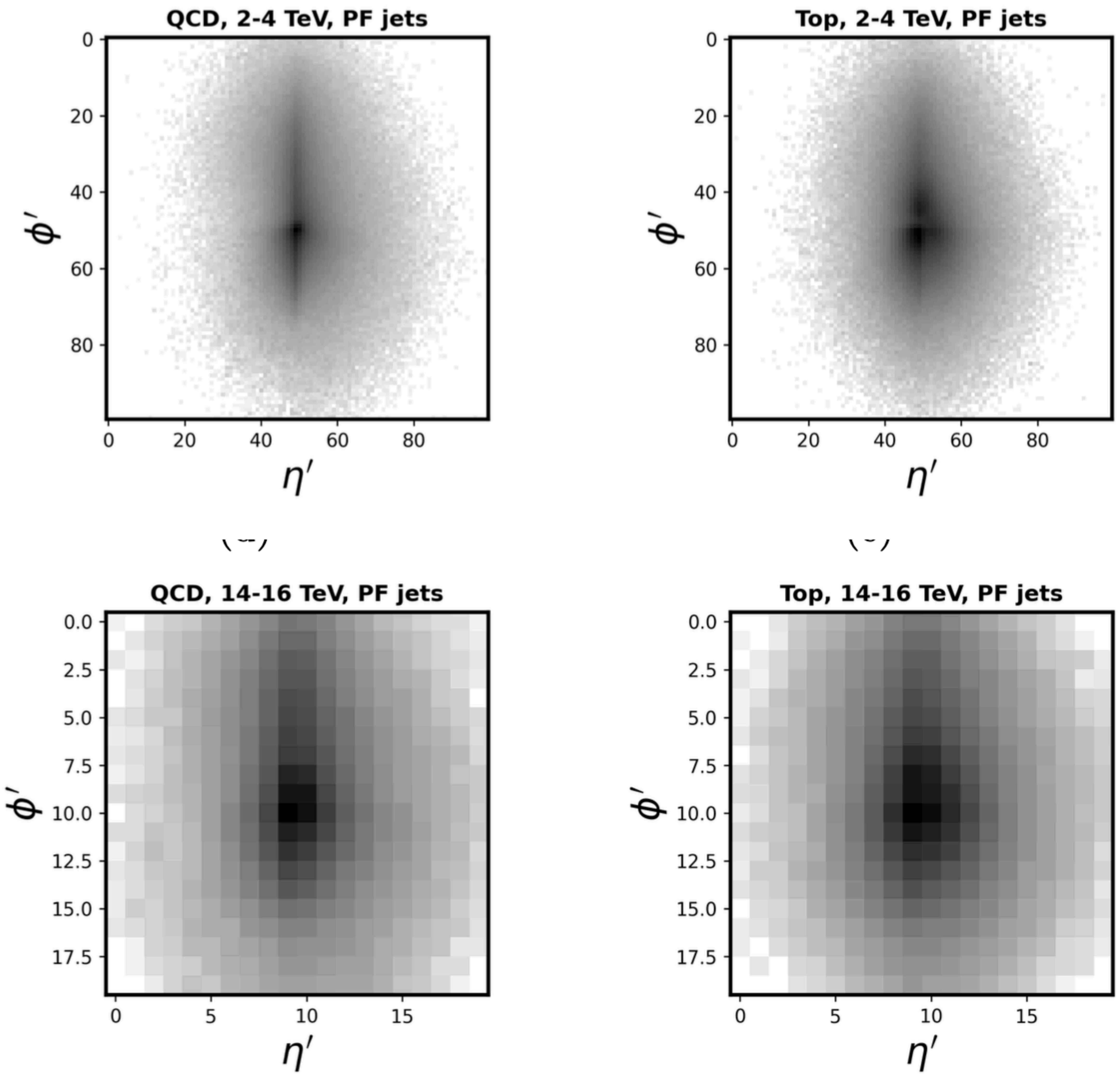
Multi-TeV Resonance searches @FCC-hh

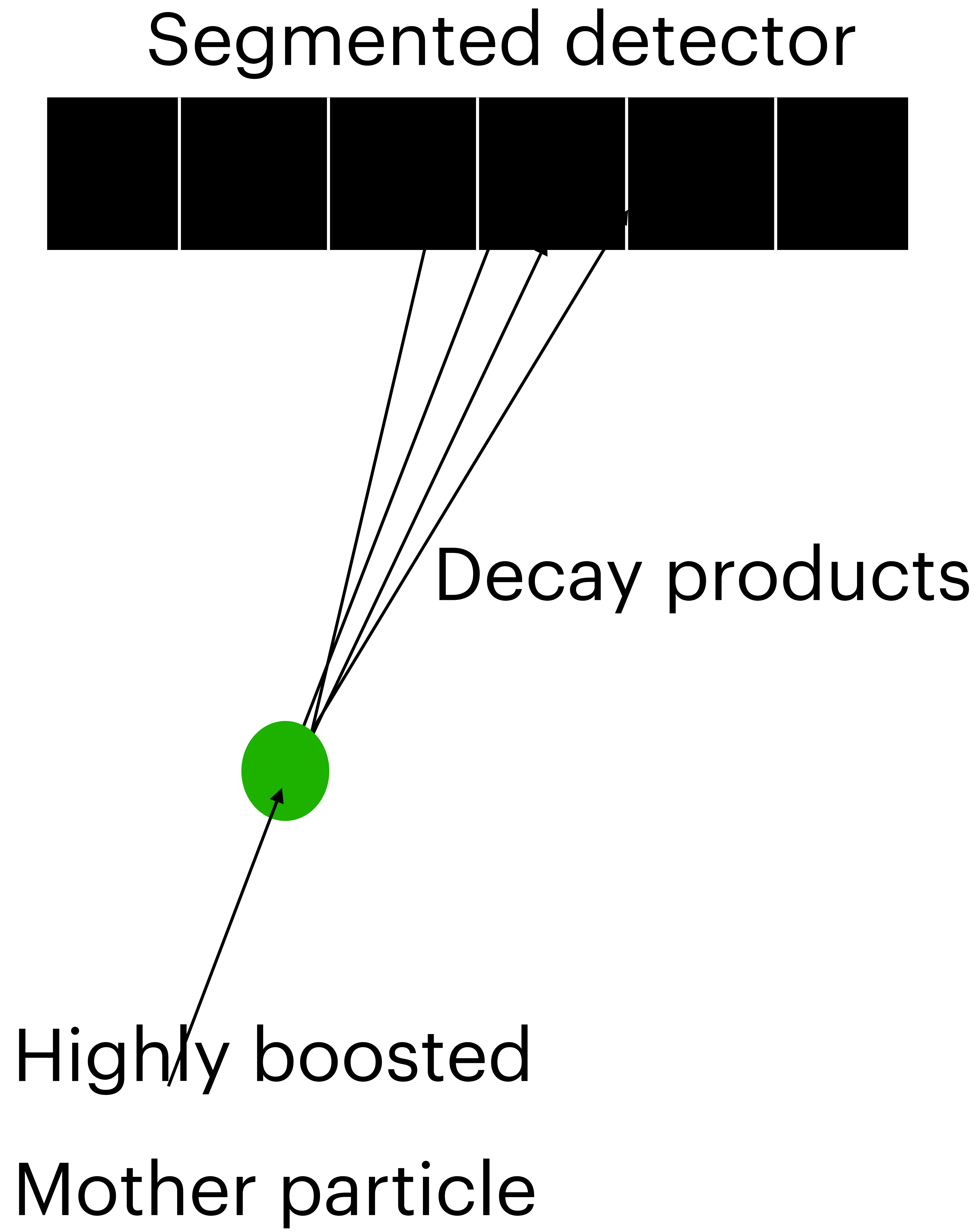


Average image of QCD and top is reasonably Different



Multi-TeV Resonance searches @FCC-hh





ML techniques , Imagage recognition required to Suppress QCD background

Average image of QCD and top is smaller and not so different

Multi-TeV Resonance searches @FCC-hh

arXiv: 2501.06702

Tagging ultra-boosted jets at FCC-hh using machine learning techniques

Biplob Bhattacherjee,[a] **Sanchari Bhattacharyya,**[a] **Camellia Bose,**[a] **Debtosh Chowdhury,**[b] **Swagata Mukherjee**[b]

[a] *Centre for High Energy Physics, Indian Institute of Science, Bangalore 560012, India*
[b] *Department of Physics, Indian Institute of Technology, Kanpur 208016, India*
E-mail: biplob@iisc.ac.in, sancharibhat@iisc.ac.in, camelliabose@iisc.ac.in, debtoshc@iitk.ac.in, swagata@iitk.ac.in

- Top tagging at very high energy (Multi-TeV)
- Various challenges : Detector resolution, QCD contamination, granularity of the detector
- Variable jet radius used
- Various model have been considered: Vector-like quarks, Z prime, Hevy Higgs etc.
- ML based tagger developed which can be used to identify QCD jets, top quark and W boson with energy from 2 to 16 TeV

Thanks to my Collaborators (HL-LHC and Future collider) :

1. Dr. Rhitaja Sengupta (Graduated in 2023, now at Bonn Univ.)
2. Dr. Prabhat Solanki (Graduated in 2024, Now in INFN Pisa, CMS experiment)
3. Dr. Nivedita Ghosh (Postdoc @IISc)
4. Dr. Swagata Mukherjee (IIT Kanpur)
5. Prof. Shigeki Matsumoto(Kavli IPMU)
6. Camellia Bose(IISc)
7. Dr. Sanchari Bhattacharyya(IISc)

Directions :

1. Trigger developments for LLPs
2. ECAL and MTD Timing
3. ML for LLPs
4. Dedicated detector for FCC-hh
5. Parameter estimation for LLPs
6. Boosted object tagging

Summary

- There is always a chance to discover new particles in the near future
- We need to close the gaps in the search algorithms => look for unusual signatures
- Different complimentary experiments will be required to pin-down the nature of the new physics
- 100 TeV energy will be achievable if 16T magnet can be developed
- Pile up will be increased from 140-200 to ~500-1000 !
- We proposed dedicated detector for Long-lived particles for FCC-hh => huge improvement possible
- Advanced detectors and algorithm will be required to keep the resolutions (Example : Di-photon invariant mass resolution for Higgs identification), and efficiencies (b/tau tagging, ultra relativistic top tagging etc.) , at par with the LHC
- Future Collider: Electron collider - Muon collider - Hadron collider ? => European strategy group will decide soon

Thank you

Extra slides

Higgs pair Production at future hadron collider

- BSM effects could affect the measurement of Higgs self-coupling λ
- HL-LHC will not be able to measure λ very precisely (statistically limited sample)
- Future hh collider will provide the unique opportunity

- **27 TeV studies in different channels (XGBOOST)**
- **Adhikary, BB and Barman JHEP 12 (2020) 179**

Channel	Statistical Significance
$b\bar{b}\gamma\gamma$	9.5-12.5
$b\bar{b}\tau\tau$	~5
$b\bar{b}WW^*$	~2.75
$\gamma\gamma WW^*$	~2
$b\bar{b}ZZ^*$	1+1

- Many dedicated studies available for FCC-hh (30 times enhancement in cross section)
- **Yao(1308.6302); Fuks,Kim and Lee, PRD 93 (2016) 3; Papaefstathiou, PRD 91 (2015) 11; Barr et.al., JHEP 02 (2015) 016; Banerjee et.al, Eur.Phys.J.C 78 (2018) 4, 322; Borgonovi et.al., CERN-ACC-2018-0045; Blas et.al., JHEP 139(2020); Mangano, Ortona,Selvaggi 2004.03505 + many more ...**
- λ can be measured with a few percent precision (significance dominated by bb$\gamma\gamma$ channel)

SHiP Experiment

The Search for Hidden Particles Collaboration

Proposed general purpose beam dump experiment at CERN SPS

SPS is capable of delivering 4 x 10^{19} protons with energy 400 GeV (per year)

The detector consists of heavy target, hadron stopper, active muon shield followed by Scattering and Neutrino detector and Hidden sector spectrometer (Total length ~ 120 m).

HS spectrometer will be able to detect the decay products of the long-lived mediator which decays inside the 50m long decay volume between SND and HS.

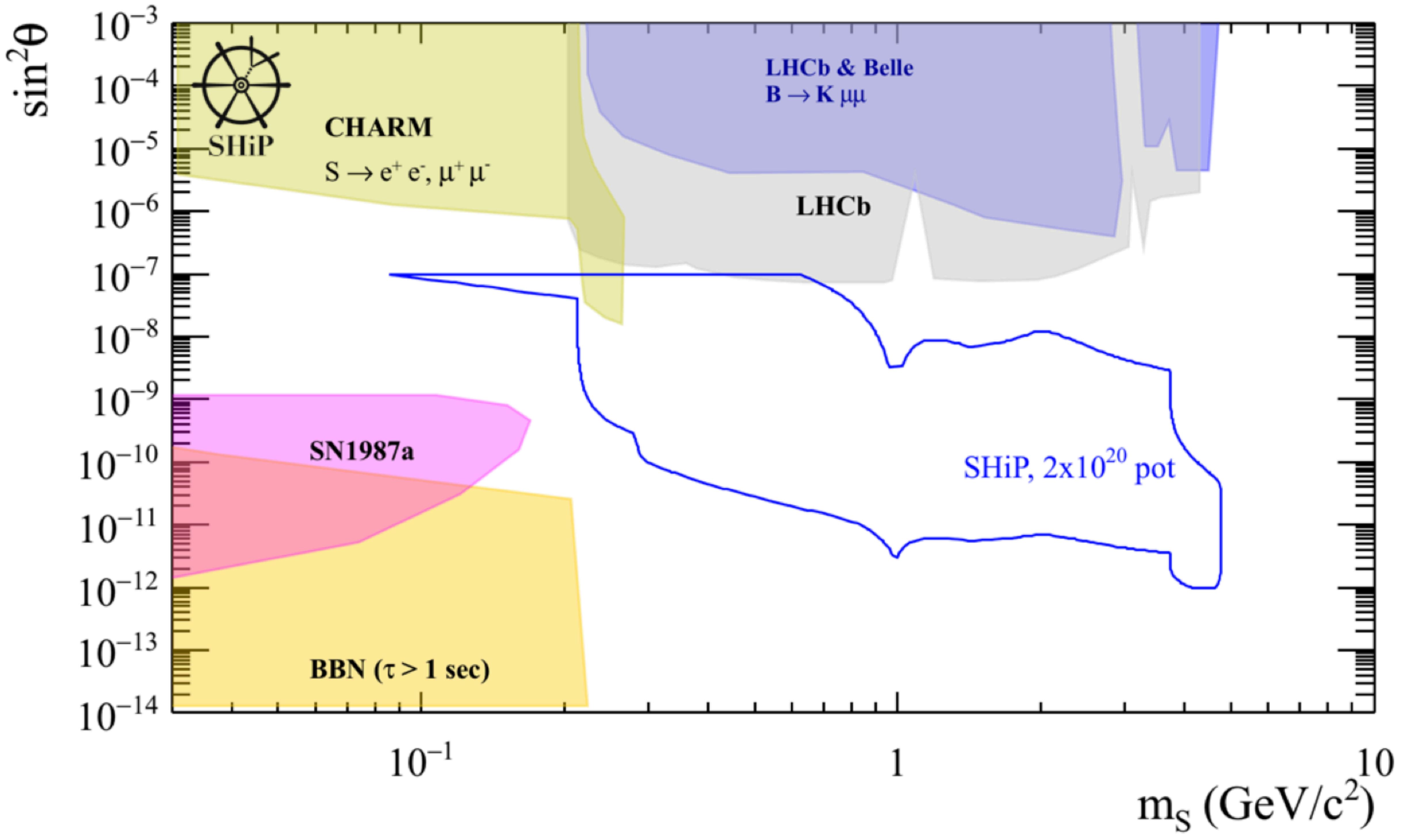
SHiP Experiment

The decay spectrometer will have tracker, muon detector and calorimeter=> possible to identify various decay products of the mediator and also for background suppression

Various backgrounds can be reduced below 1 event

K -> X , B -> X

DARK SCALAR



SHiP is sensitive to wide range of models

	Physics model	Final state
HSDS	HNL, SUSY neutralino	$\ell^\pm\pi^\mp$, $\ell^\pm K^\mp$, $\ell^\pm\rho^\mp(\rho^\mp \to \pi^\mp\pi^0)$
	DP, DS, ALP (fermion coupling), SUSY sgoldstino	$\ell^+\ell^-$
	DP, DS, ALP (gluon coupling), SUSY sgoldstino	$\pi^+\pi^-$, K^+K^-
	HNL, SUSY neutralino, axino	$\ell^+\ell^-\nu$
	ALP (photon coupling), SUSY sgoldstino	$\gamma\gamma$
	SUSY sgoldstino	$\pi^0\pi^0$

2112.01487

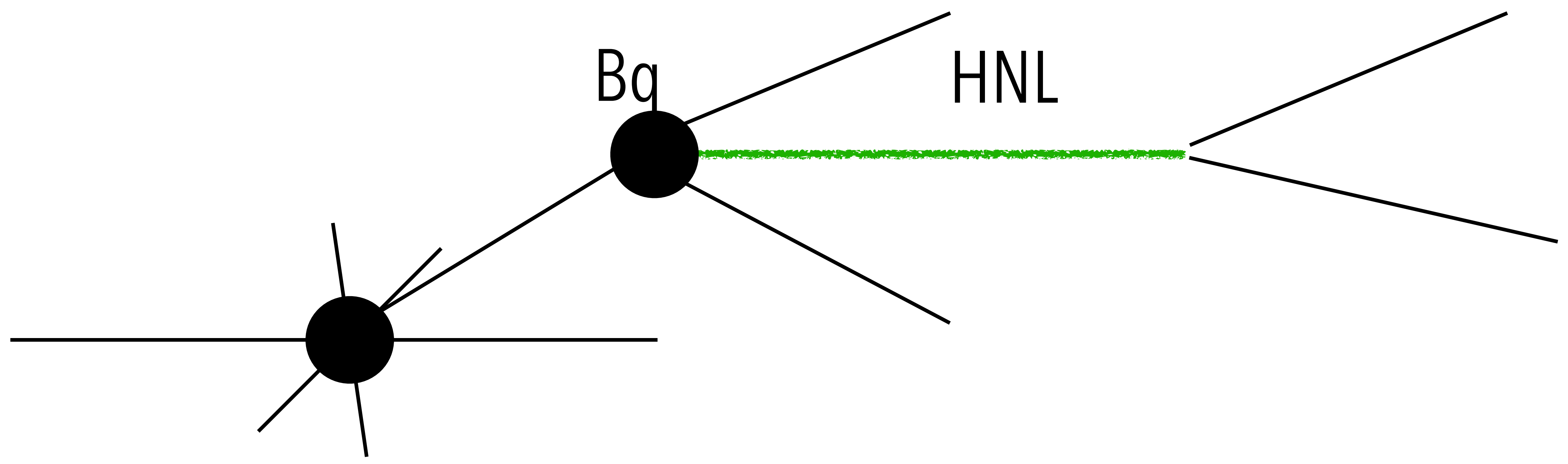
Projected sensitivity for dark photon and HNL are also available here SPSC-SR-248

SHiP Progress report SPSC-SR-248

LHCb

It uses the high production rate in the forward direction.

Detection of low p_T event possible



Standard analysis : $pp \to W \to lN \to lljj$ also possible

Light scalar : $B \to \phi K, \phi \to \mu\mu$

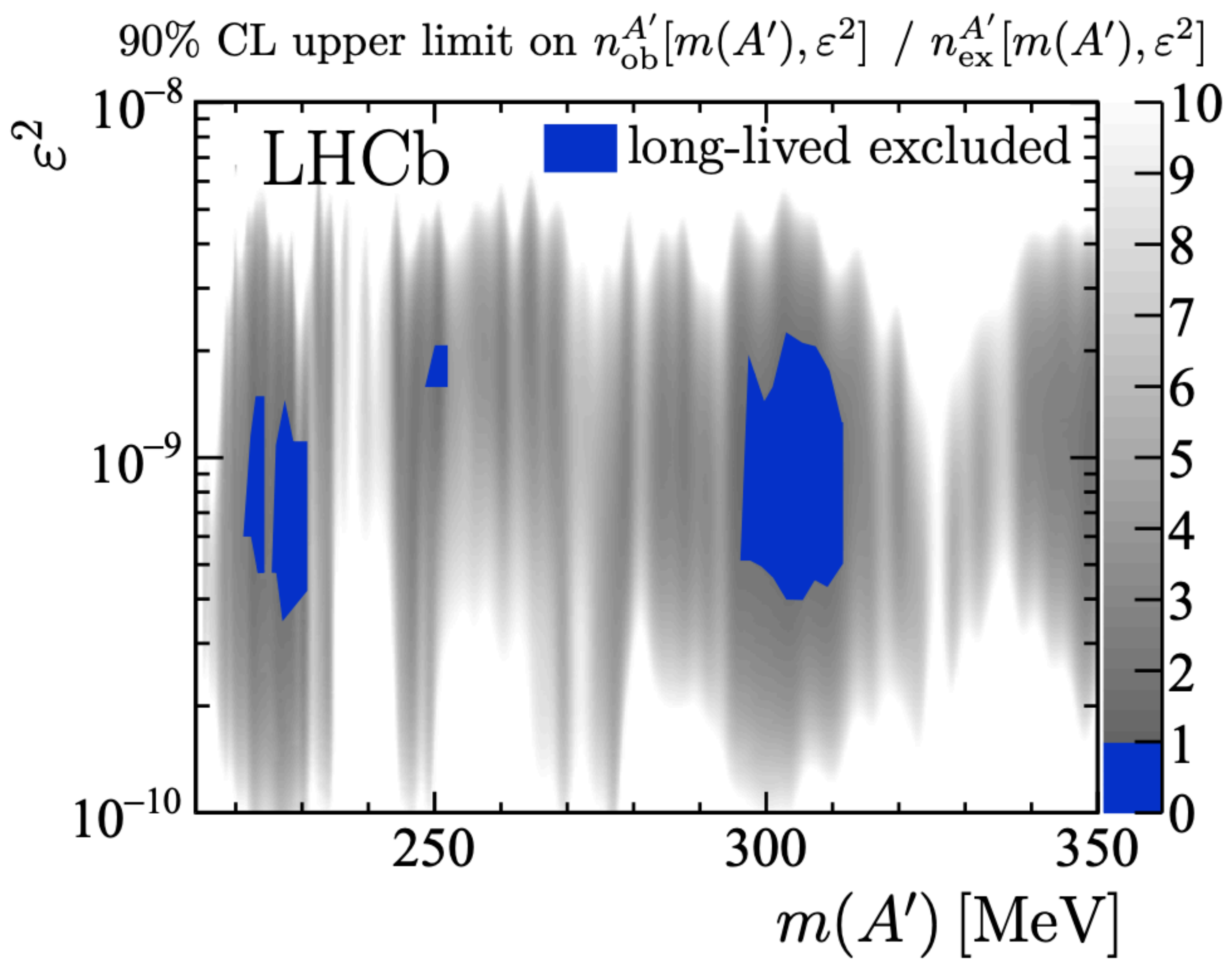
From Run 3, LHCb is using full software trigger

LHCb future sensitivity without VELO 2312.14016

1710.02867

Dark Photon search in the di-muon channel => Peak search above SM continuum bkg. PT of muon >1 GeV Resonance regions excluded

Some patches for LL dark photon also excluded



Light dark photon below 200 MeV can be studied in future from pion decay $\pi \to Z_D + \gamma$

Flavour Physics and Dark Matter detection

BELLE-II :

Collected ~ 400 fb^{-1} data, expected to collect 50 ab^{-1}. Should be able to reach 5 ab^{-1} in 10 years , Uncertainties in BELLE on RK and RK* is ~ 25-30% (will be reduced to 10% using 5 ab^{-1}) ,

BELLE-II will also require a few ab^{-1} data to tell us whether RD* anomaly comes from systematic error or statistical

(PTEP 2019 , 12 , 123C01)

A. Dark matter detection :

LZ, XENONnt, PANDAX-4T …

B. Dark matter indirect detection:

- Many experiments: Fermi, IceCube, HESS, VERITAS, AMS-02 …..
- Future Experiments : CTA, SWGO, IceCube-Gen2 , AMS-100 ?

DETAILED DISCUSSIONS IN THE SNOWMASS REPORT :

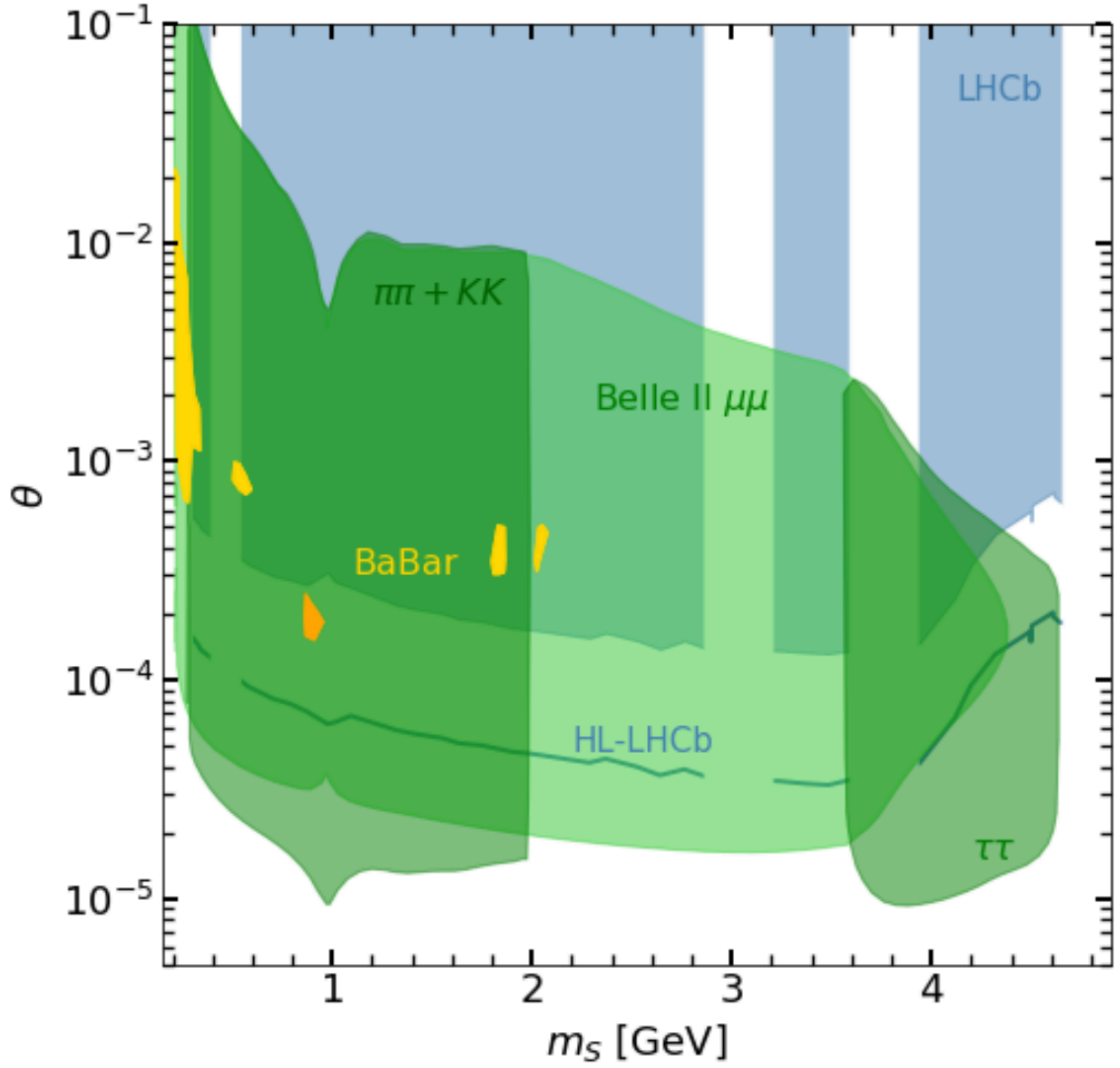
2209.07426

Future projection@BELLE-II

10 GeV electron-positron collider at the SuperKEKB (KEK) Capable of collecting 50 ab-1 of data in future

Smaller background compared to LHC experiments (no Pileup)

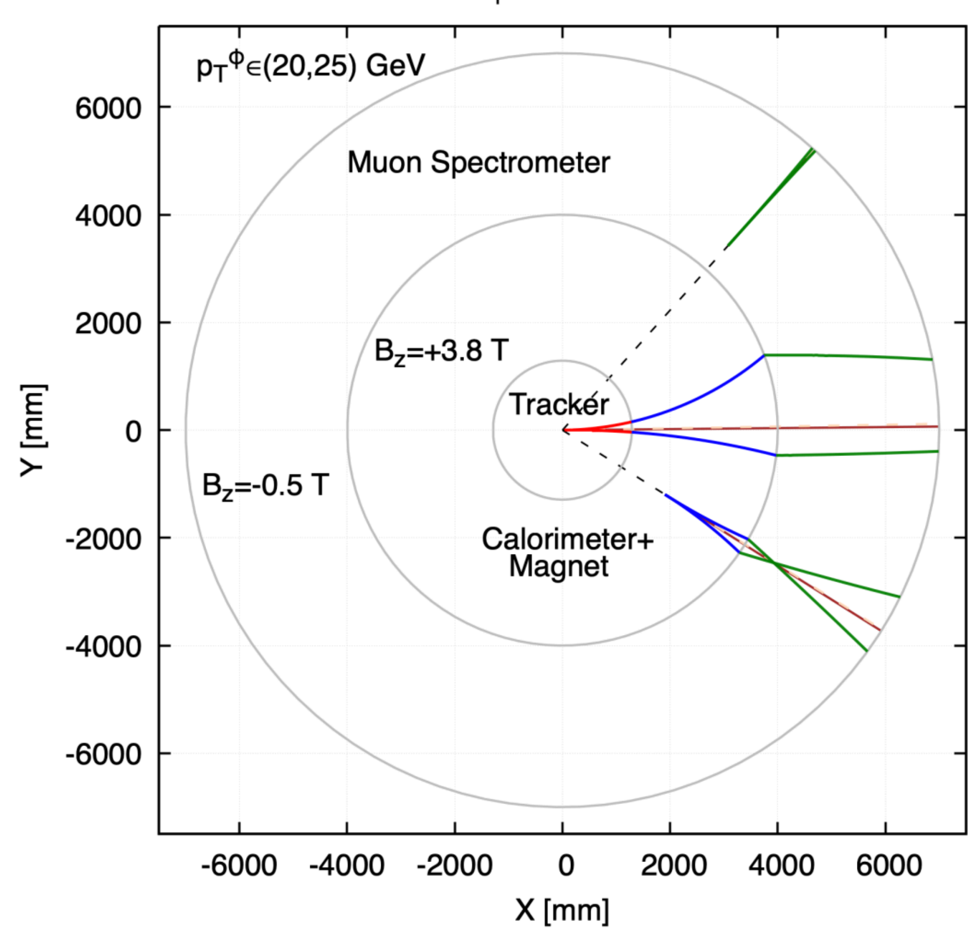
Reconstruction of charged and neutral hadrons possible



1911.03490

Future projection for dark scalars from BELLE-II(Green) : B + → K+ Phi
Phi -> pion, Kaon, Mu and tau

Tracker vs 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 : $d_T > 4$m or $|d_z| > 7$m, and, $d_T < 7$m and $|d_z| < 10$m

tracker volume : ($d_T < 1.29$m and $|d_z| < 3$m)

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

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**

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

Activity in the Muon Spectrometer

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

Displaced Jets

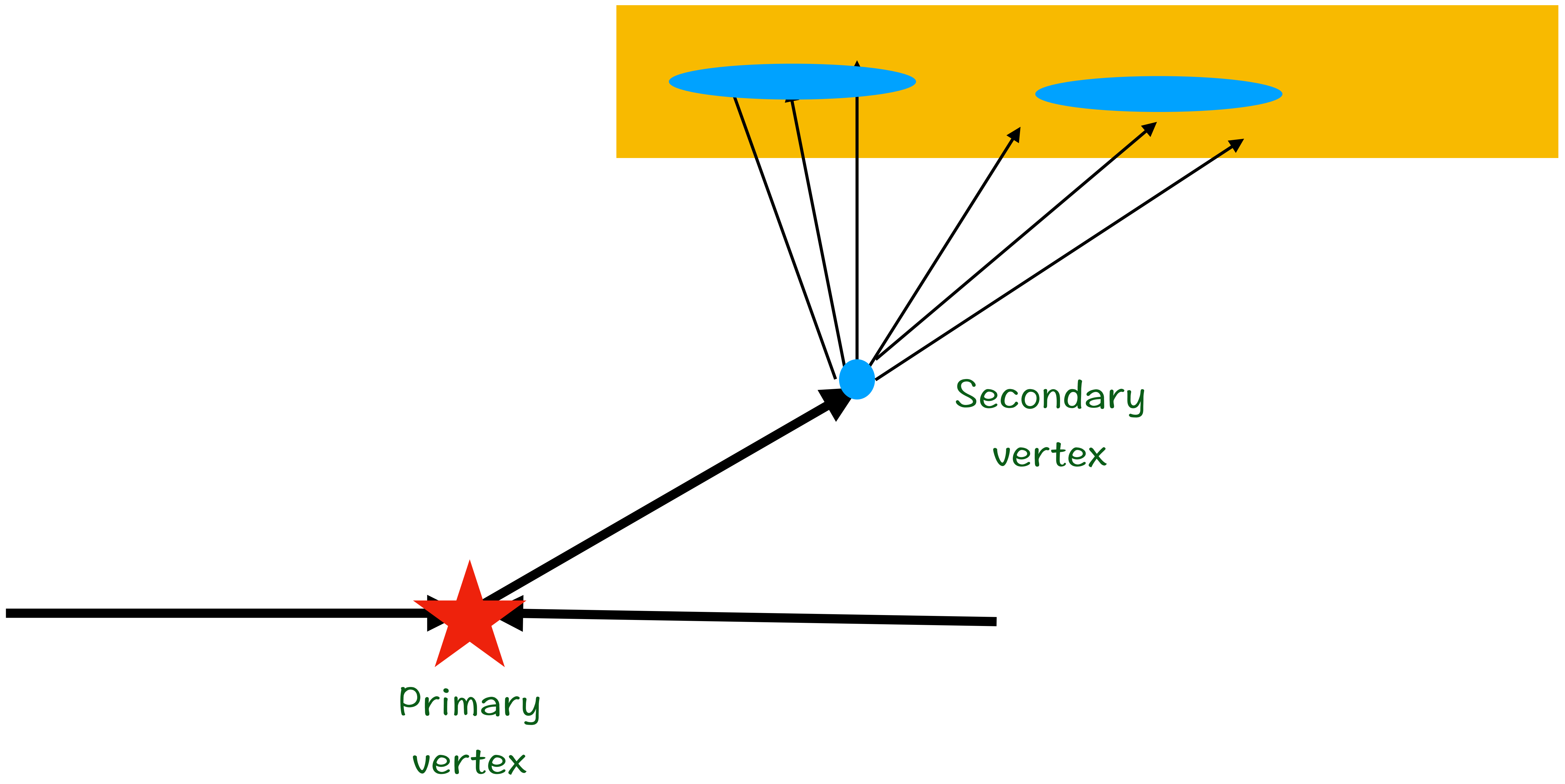
$$pp \to X_{LLP}X_{LLP},\ X_{LLP} \to q + \bar{q}$$ **(jets)**

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

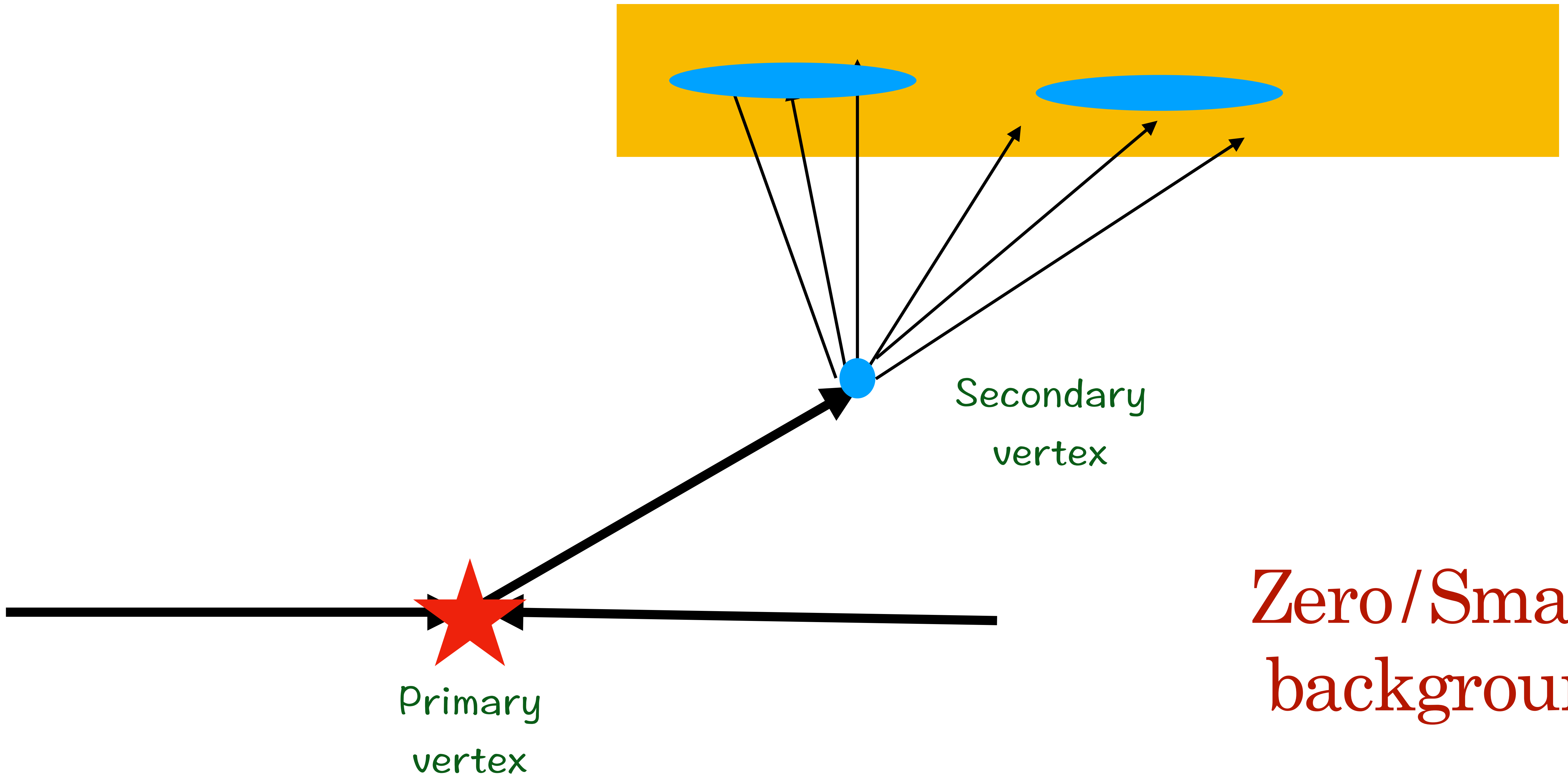
$$pp \to X_{LLP}X_{LLP},\ X_{LLP} \to q + \bar{q}$$ **(jets)**

Nice features

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

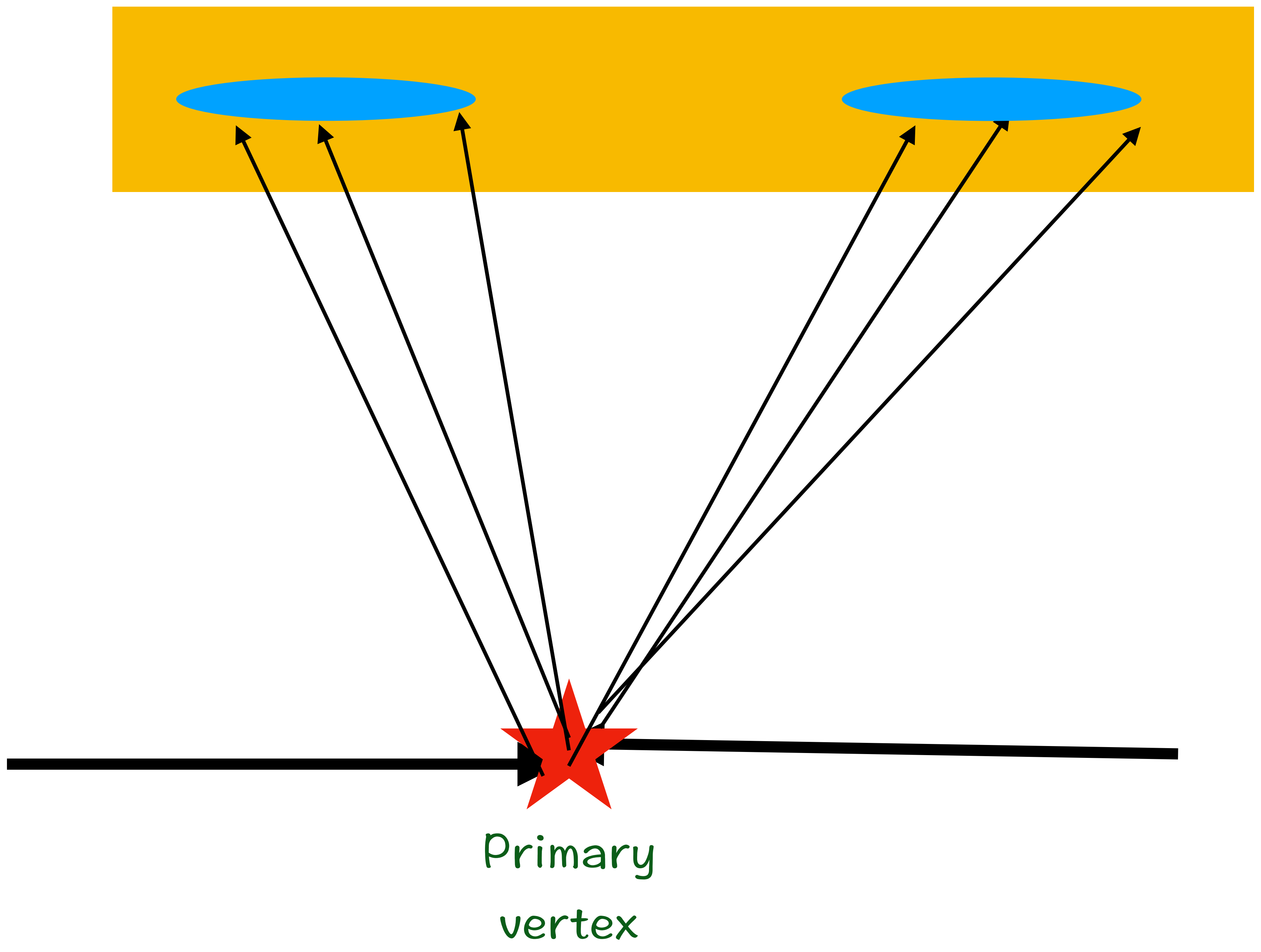
Displaced jets

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



Prompt QCD jets

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



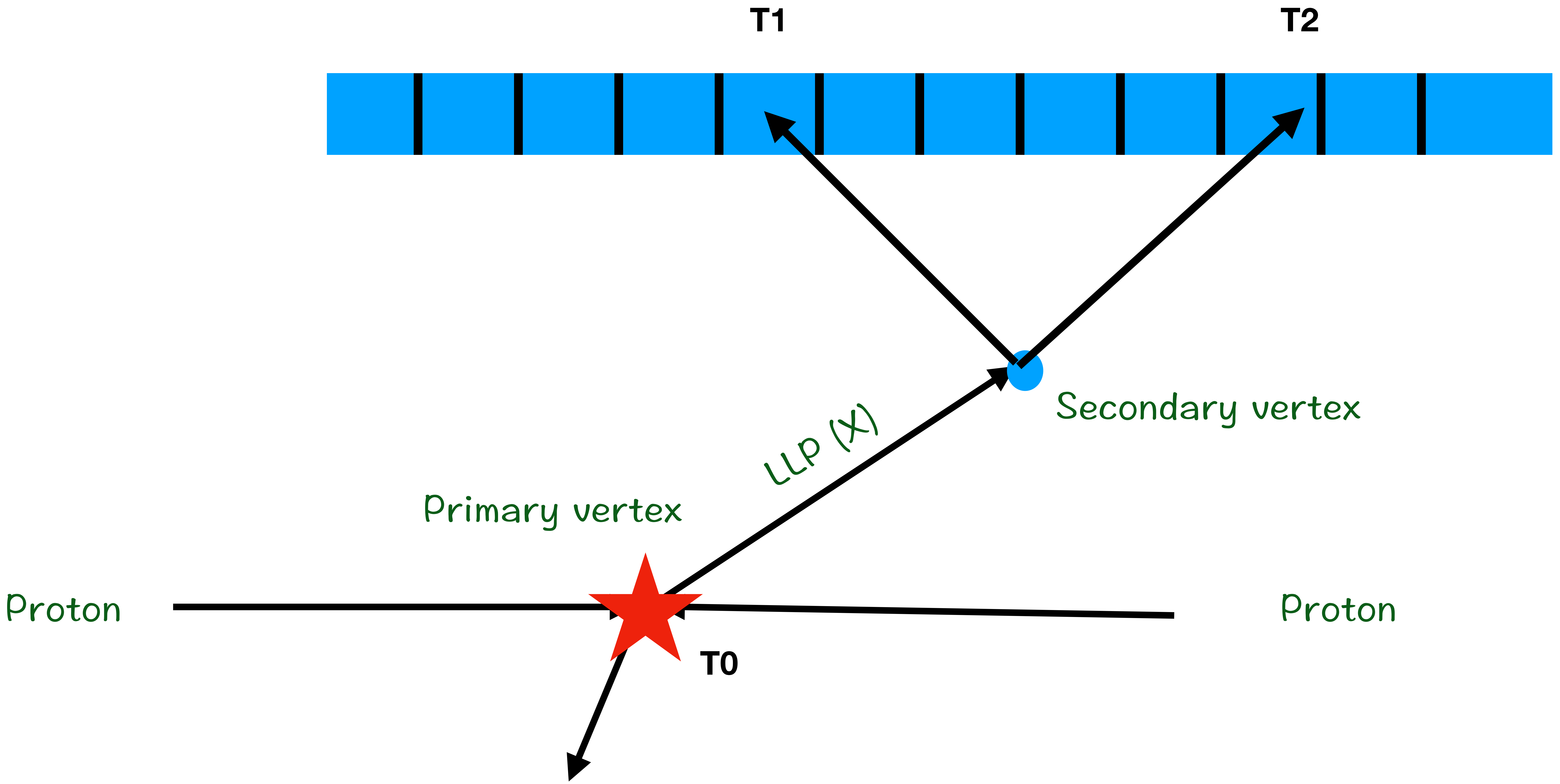
Zero/Small SM background ??

Timing Information

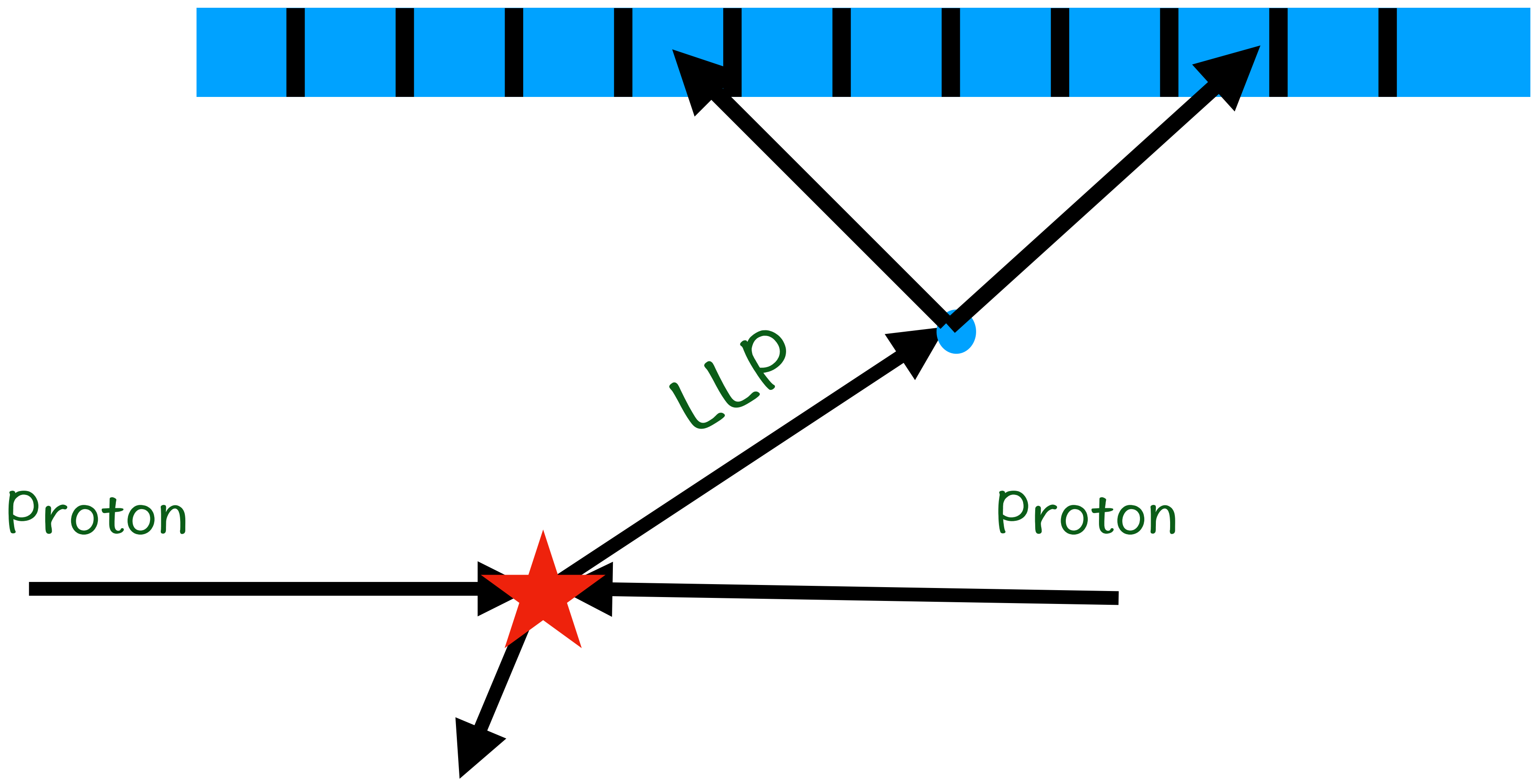
$$pp \to \phi\phi,\ \phi \to e^+e^-$$

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

T1 -T0 can be used as a discriminant



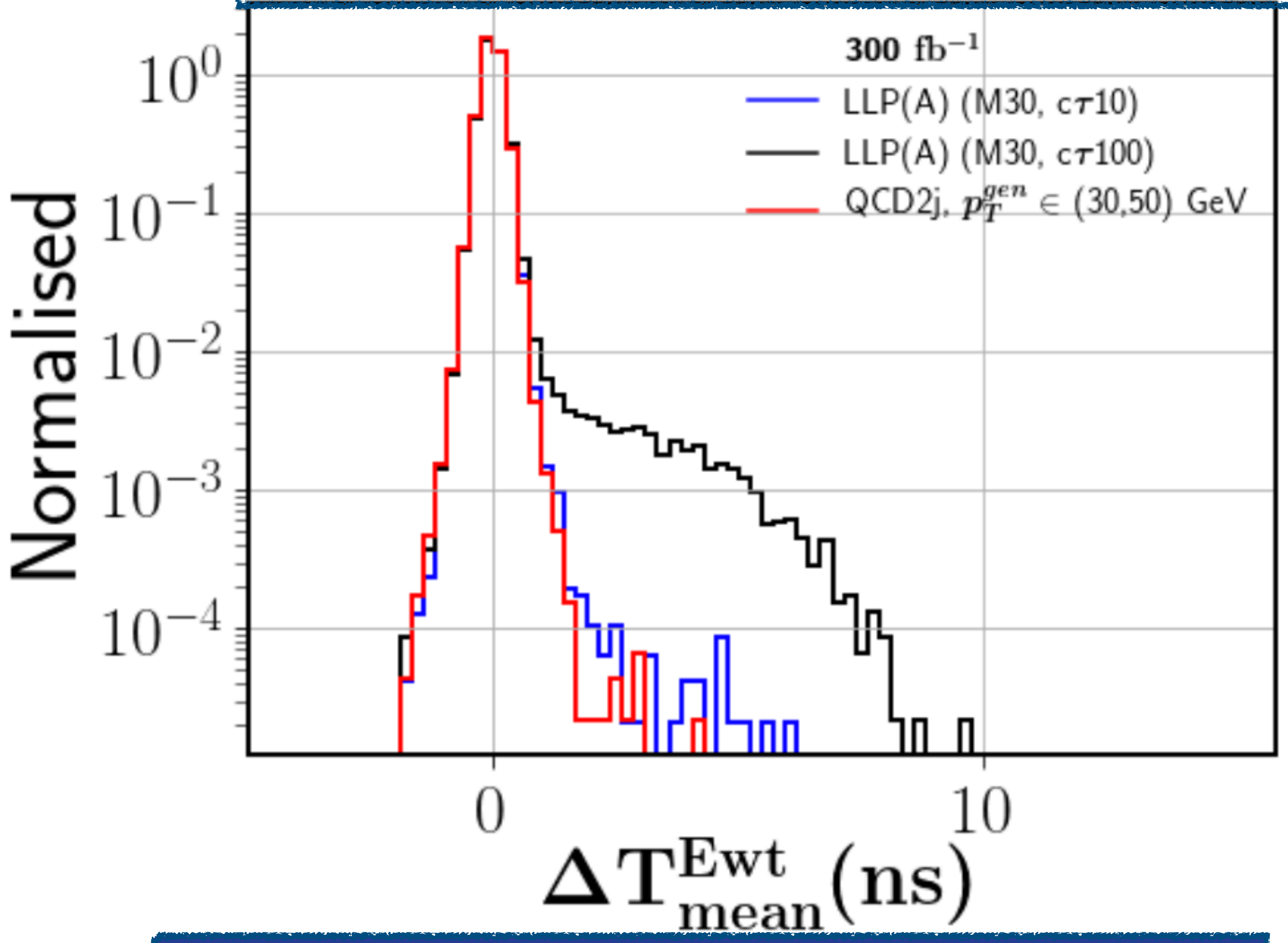
Jet timing



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



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

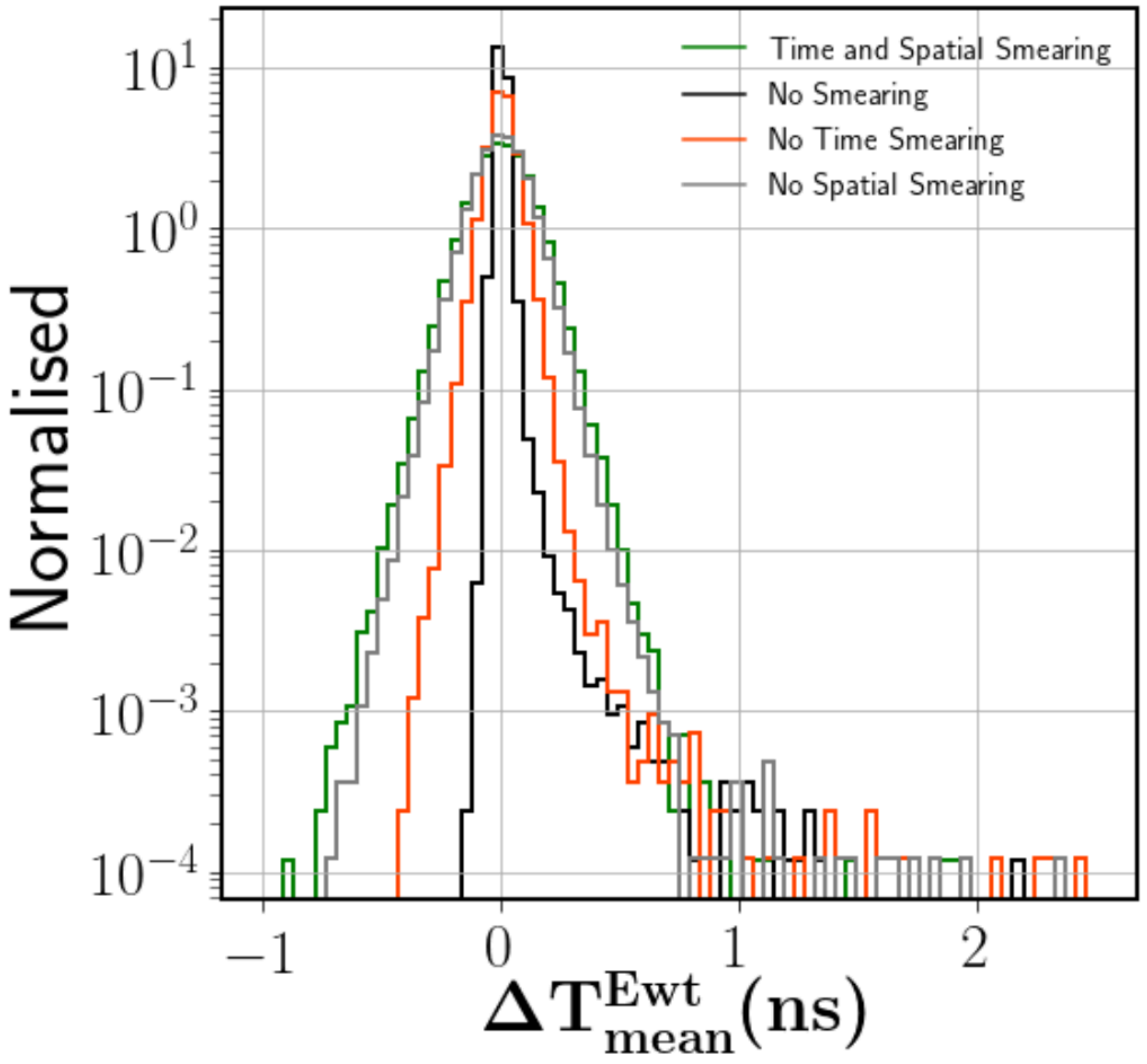
distribution is different for high decay length

QCD jets can also have a long tail

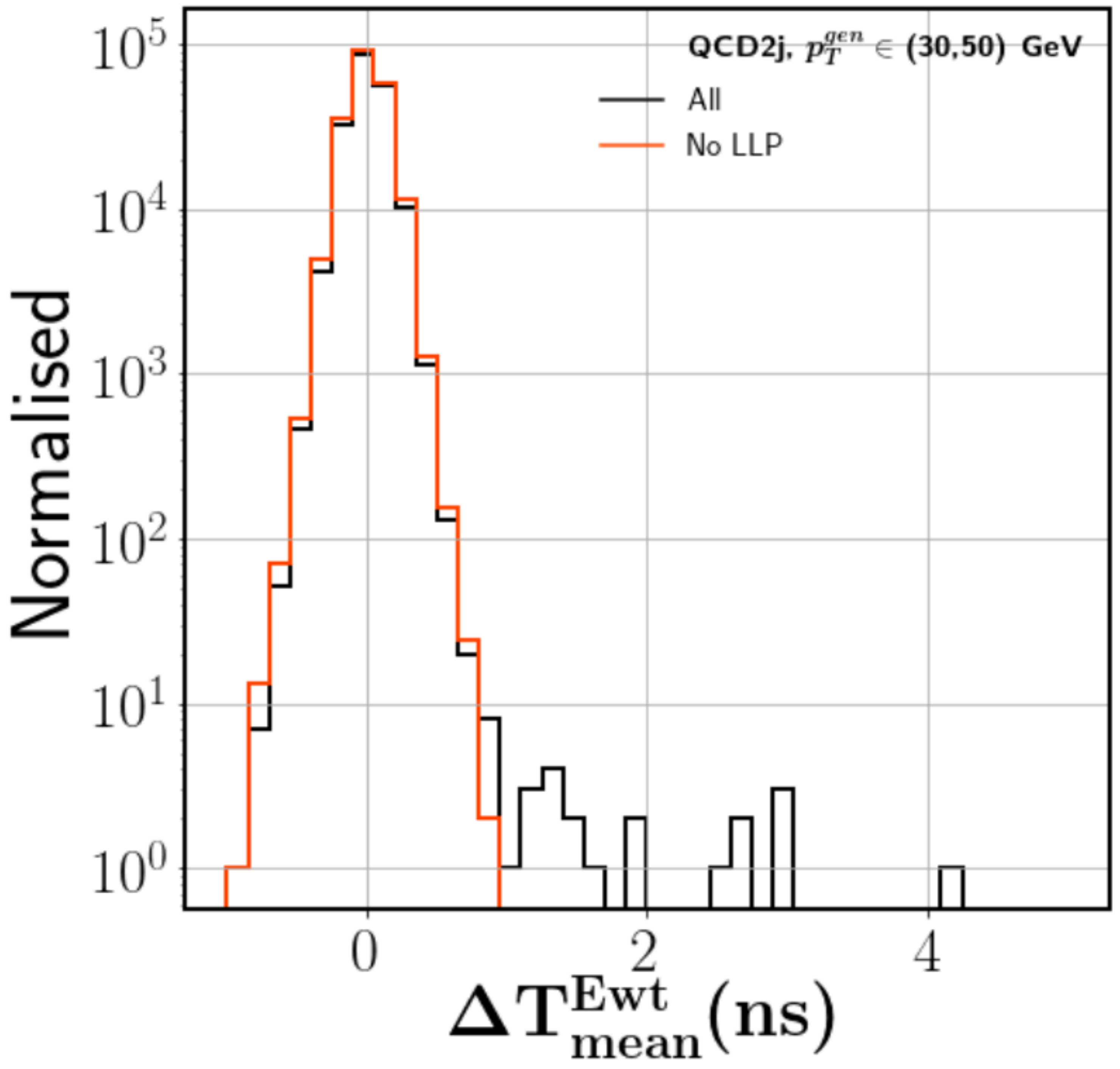
BB, Tapasi Ghosh , Rhitaja Sengupta , Prabhat Solanki
e-Print: 2112.04518, JHEP 2022

Time-delayed QCD jets

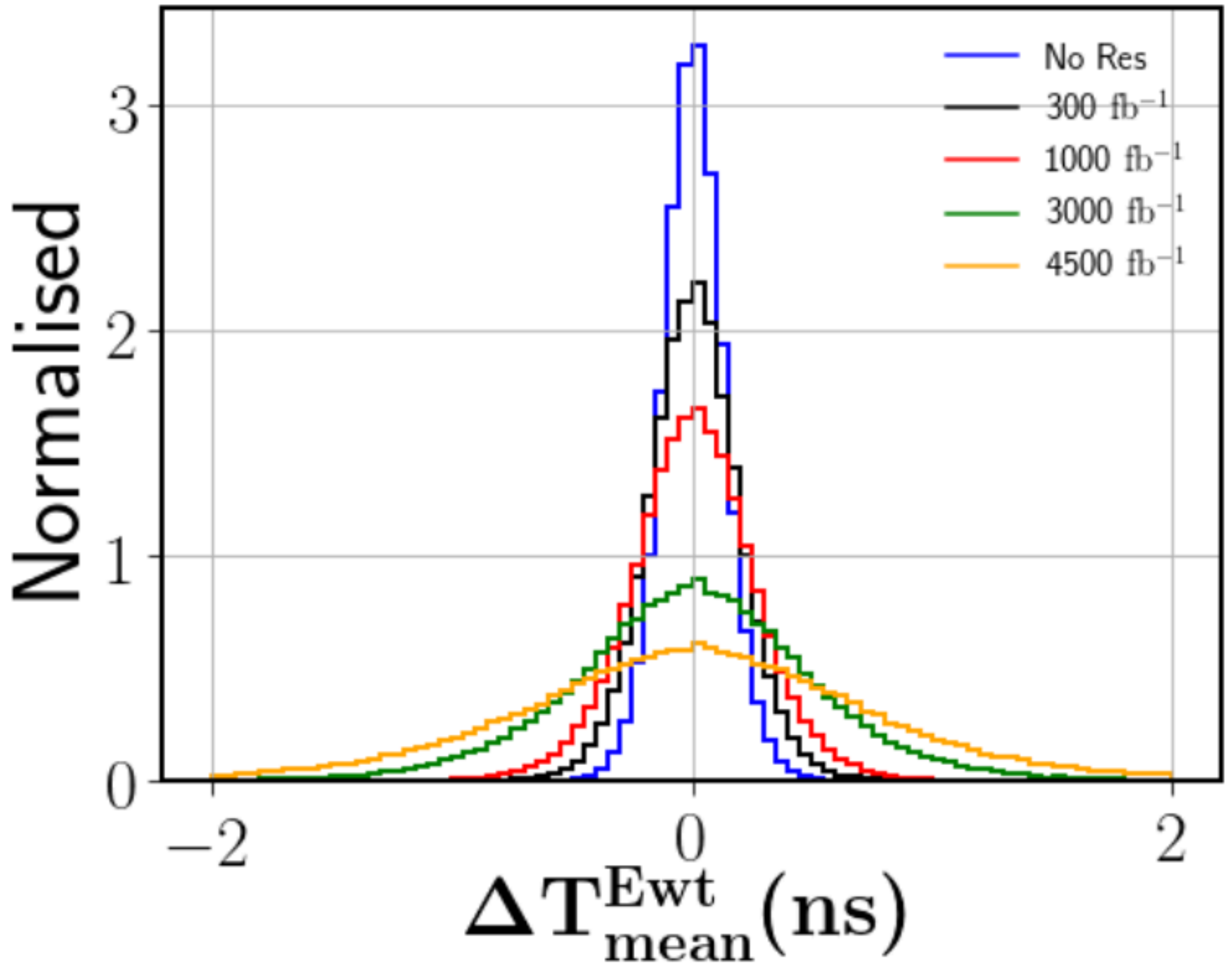
BB, Tapasi Ghosh , Rhitaja Sengupta , Prabhat Solanki
e-Print: 2112.04518, JHEP 2022



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

NA62 Experiment

Fixed-target experiment at CERN SPS

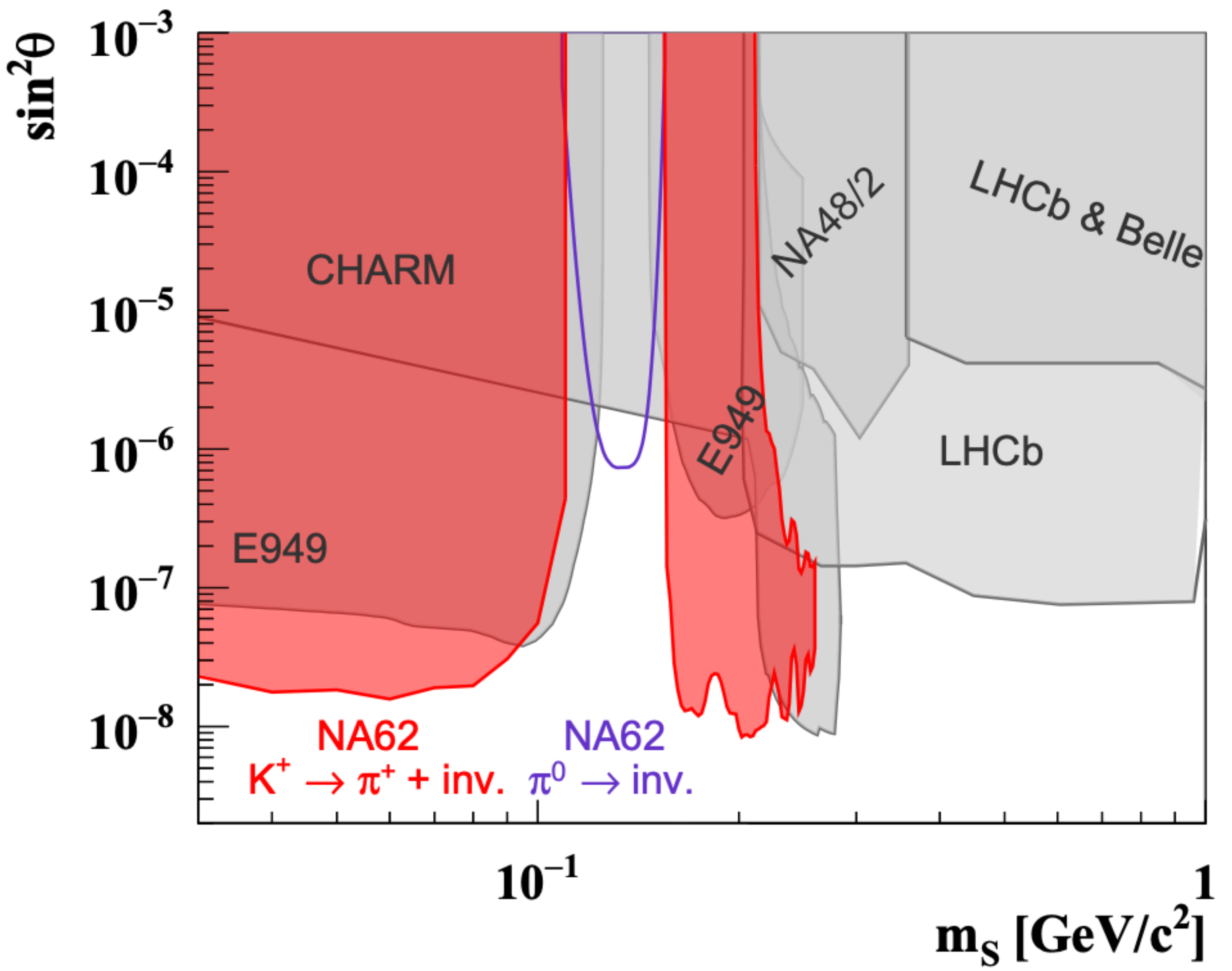
Goal : measure $K^+ \to \pi^+ \nu \bar{\nu}$

NA62: 2103.15389

400 GeV proton on Beryllium target=> 75 GeV K+ is selected

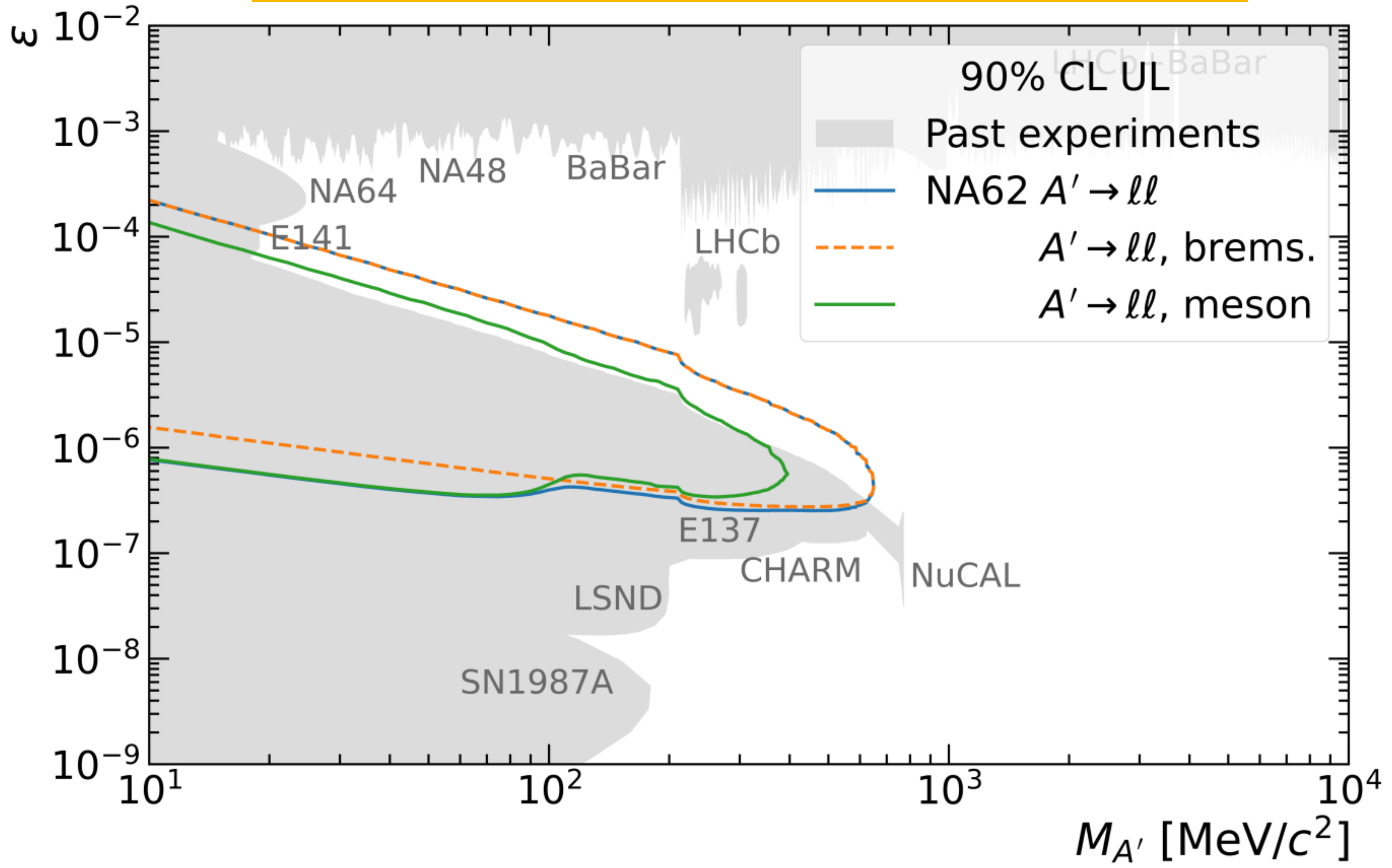
Kaon is tagged by KTAG, momentum measured by GTK => decay volume is 60 m

Decay products are measured by several detectors (and veto on photons)



The result can be translated to $K^+ \to \pi^+ X_{LLP}$

https://pos.sissa.it/445/073/pdf



It can also run in a beam-dump mode:

Limit on dark-photon model

Dedicated Forward detector: FASER Experiment

The flux of light hadrons produced at the interaction points of ATLAS/CMS in the forward direction is very high.

Mediators produced from the decay of such hadrons will have significant boost.

If the mediator are long-lived, it can travel ~O(100 m) before it decays.

=> Need for a forward detector
the ForwArd Search ExpeRiment(FASER)

REF: The FASER Detector: 2207.11427

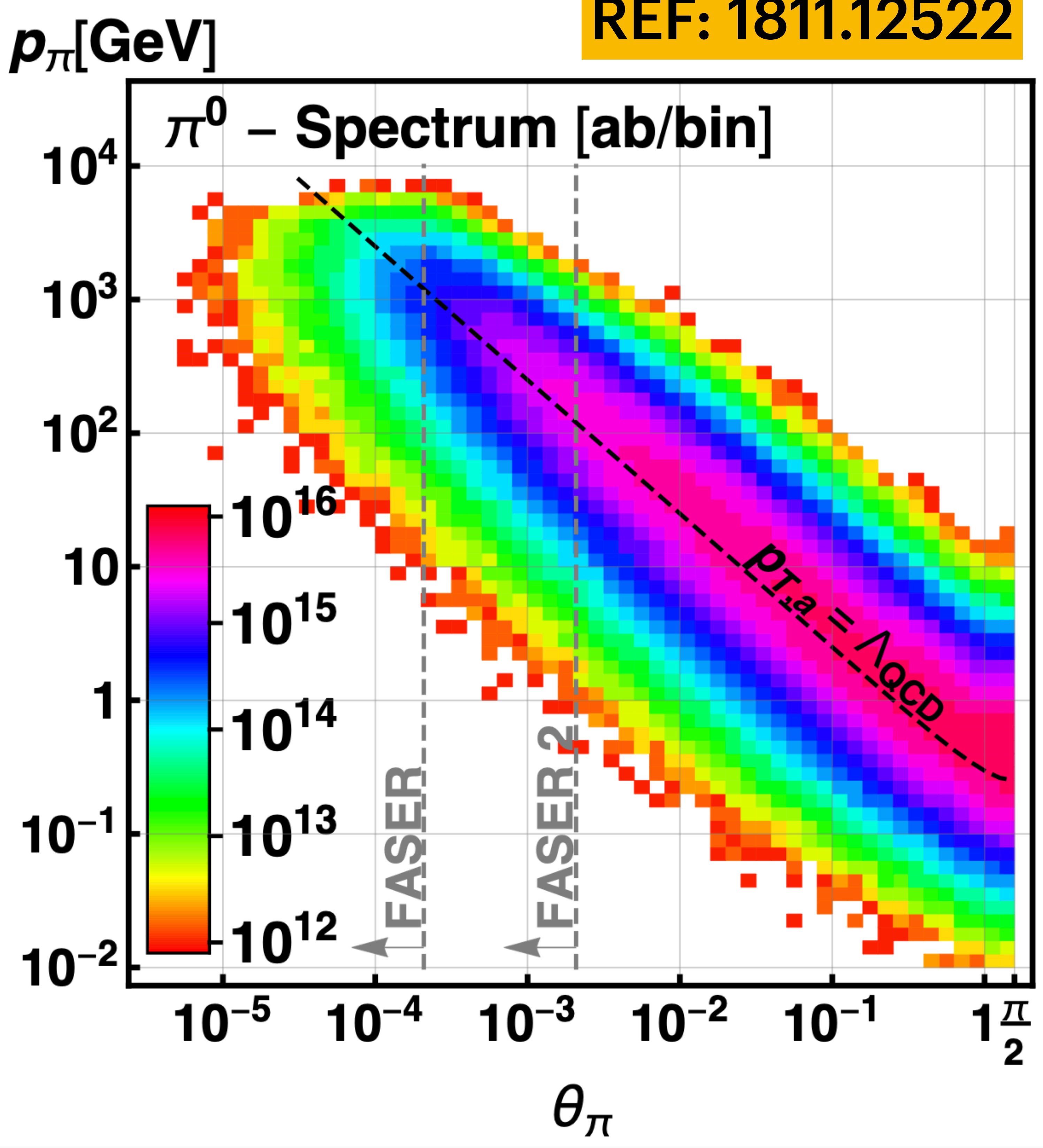
The FASER detector is located at ~480 m from the ATLAS detector.

It has about 1.5 m long decay volume followed by tracking stations and calorimeter.

Four Scintillator stations: in front of FASERnu(veto), decay volume, tracking station and Calorimeter

Decay volume and tracking stations are surrounded by 0.57 T Magnetic field.

REF: 1811.12522



FASER Experiment : Backgrounds

Trigger: Signals form Scintillators or Calorimeter

Dark photon search strategy: $Z_D \to e^+e^-$

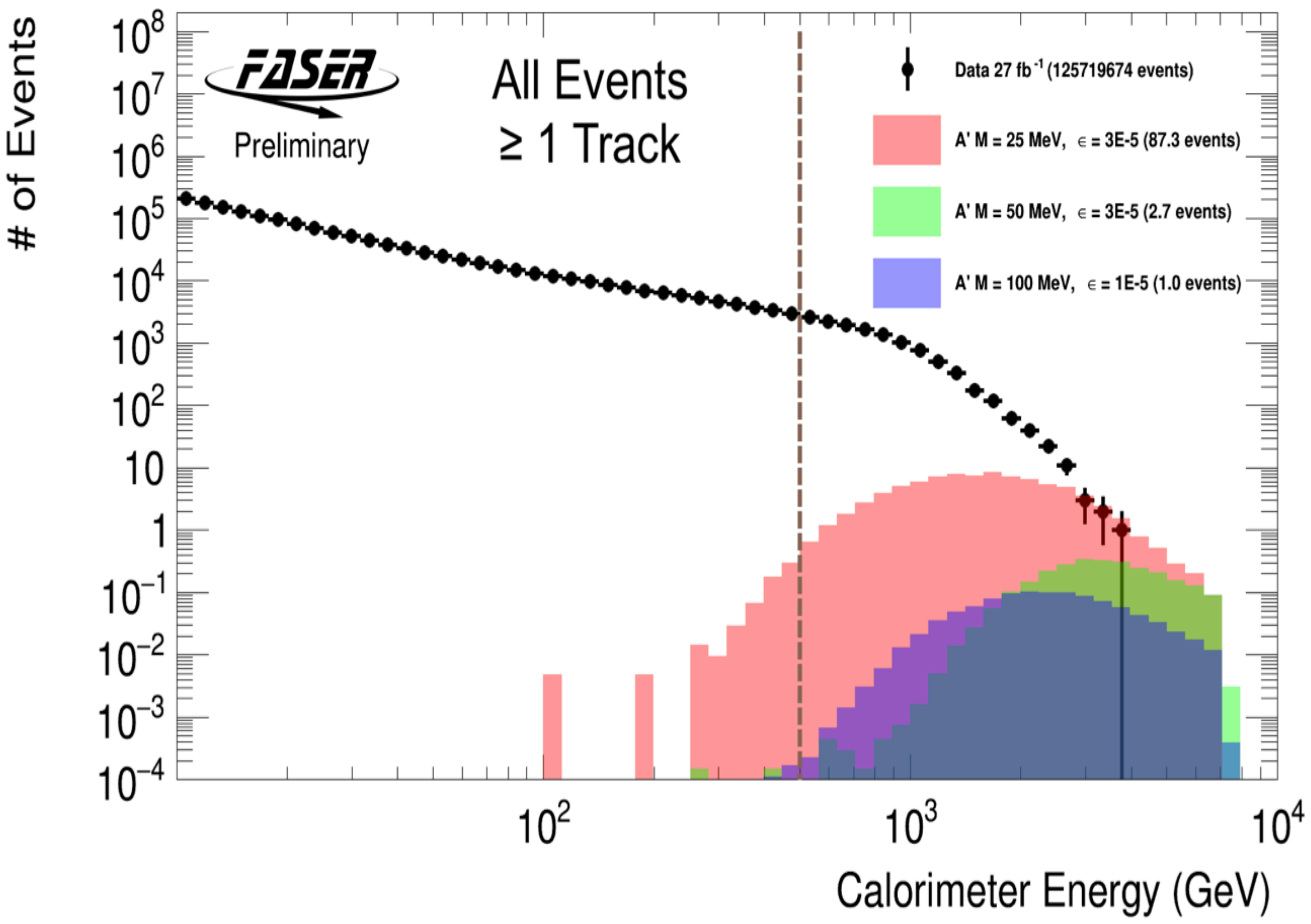
two collimated charged tracks in the tracker, large energy deposit in the calorimeter

Trigger Rate : ~ 1KHz mostly from muons

Other backgrounds : Neutral hadrons from muon in the rock, cosmic muon and neutrino

no signal in the scintillator, Each Scintillator efficiency > 99.99% => 4 scintillators can effectively suppress muon background, two good quality reconstructed tracks and more than 500 GeV energy in the calorimeter

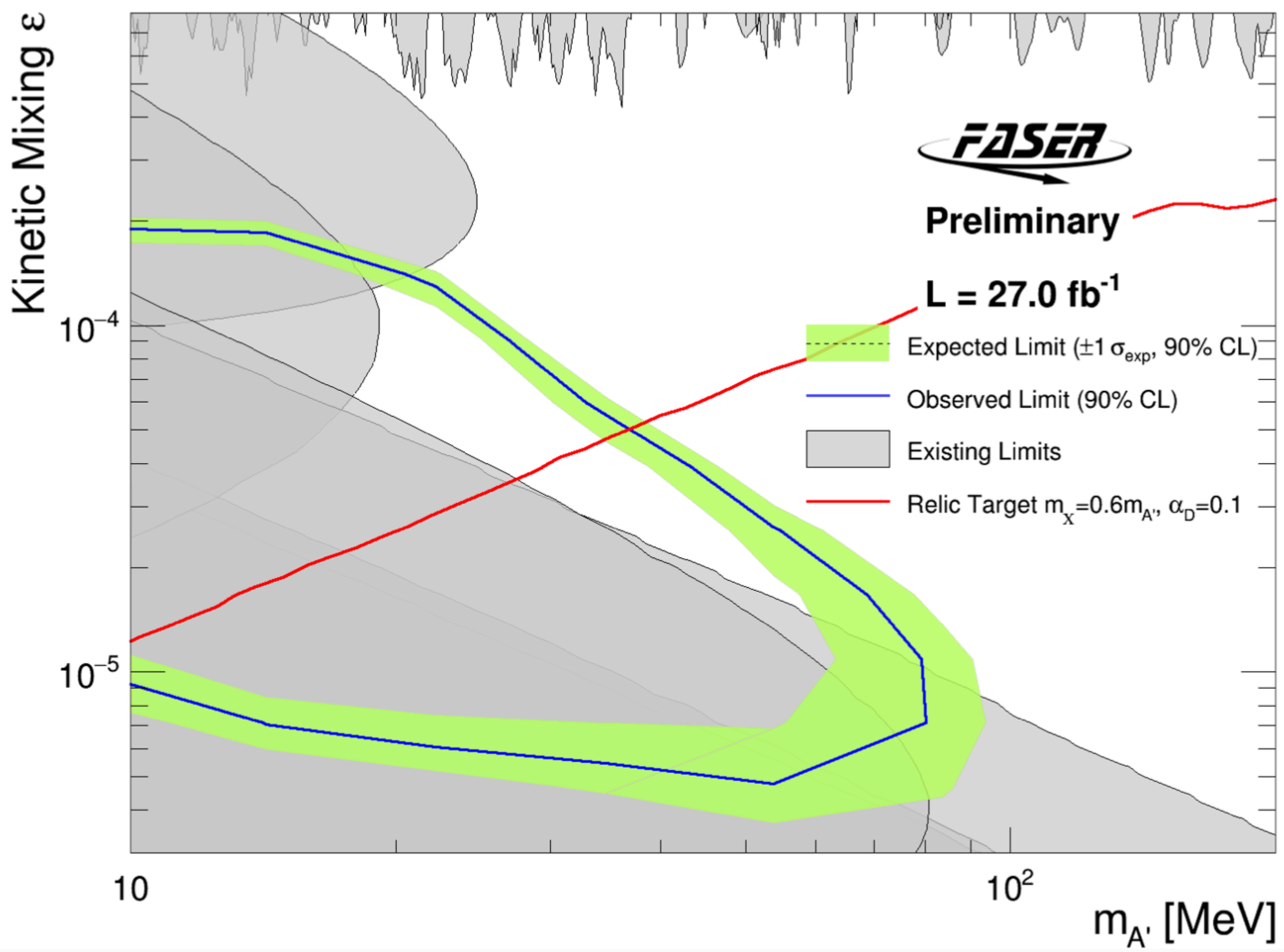
Total estimated background less than 1 (~2 X 10^-3)



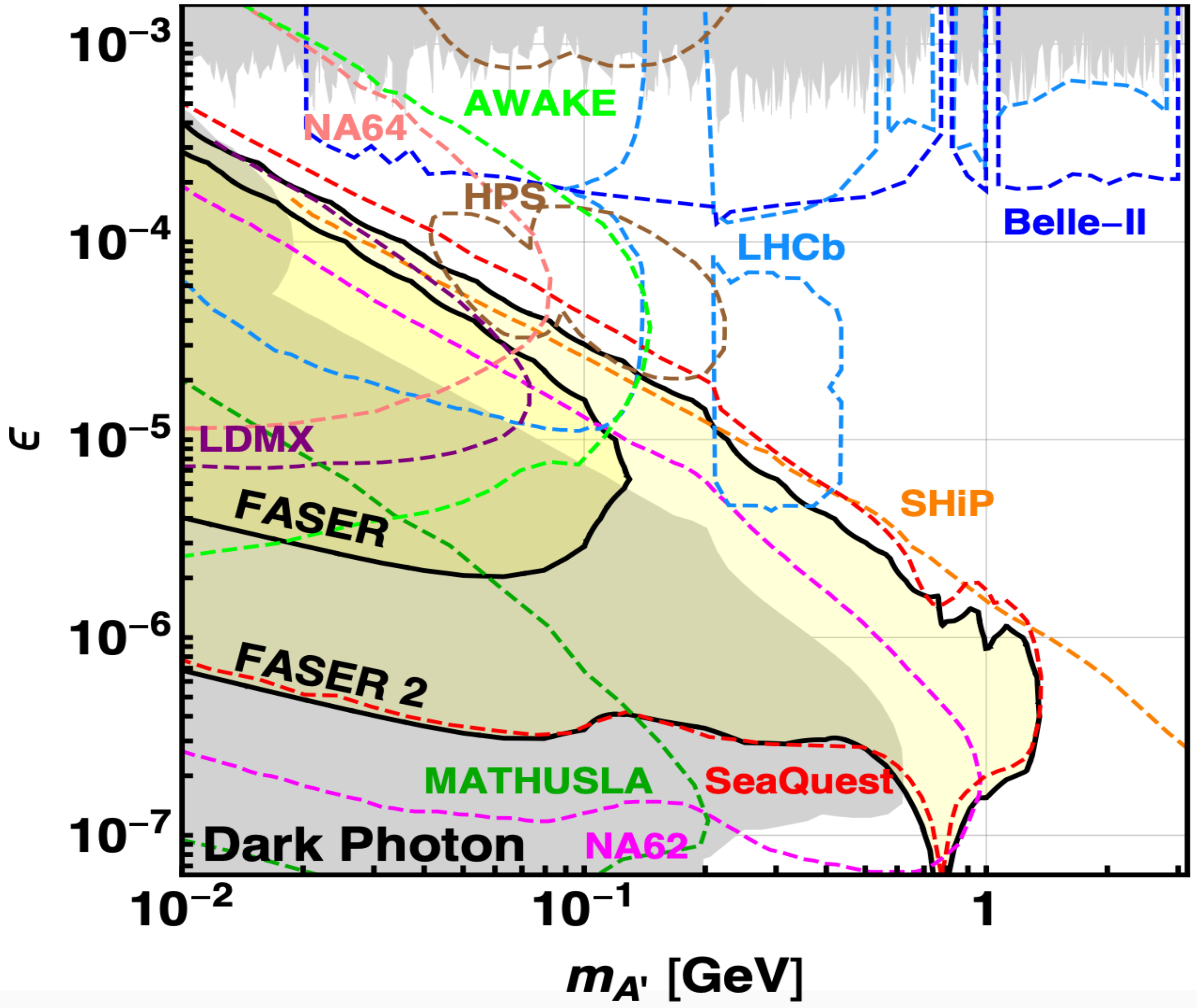
Background@FASER
COM 13.6 TeV , LHC Run 3
REF: CERN-FASER-CONF-2023-001

FASER: Limits and Future Projections:

$$pp \to Z_D + X$$
$$\pi \to Z_D \gamma$$



First result on dark photon
COM 13.6 TeV , LHC Run 3
CERN-FASER-CONF-2023-001



Future projection
1811.12522