Collider Physics

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Many excellent references

Books

Modern Particle Physics: Mark Thomson

Introduction to Elementary Particles: Griffiths

Quantum Field Theory and the Standard Model : Schwartz

QCD and Collider Physics : Ellis, Stirling and Webber

Online

CMS and ATLAS physics webpages

COLLIDER PHENOMENOLOGY : Tao Han(hep-ph:0508097)

Particle data Group https://pdg.lbl.gov/2021/reviews/rpp2020-rev-passage-particles-matter.pdf

Particle data Group https://pdg.lbl.gov/2023/AtomicNuclearProperties/adndt.pdf

CMS and ATLAS physics webpages

CMS L1 TDR 2020

Towards Jetography : G Salam

Pileup Mitigation by G. Soyez 1801.09721

SUSY search: Multi-jet + MET

ATLAS-CONF-2017-022

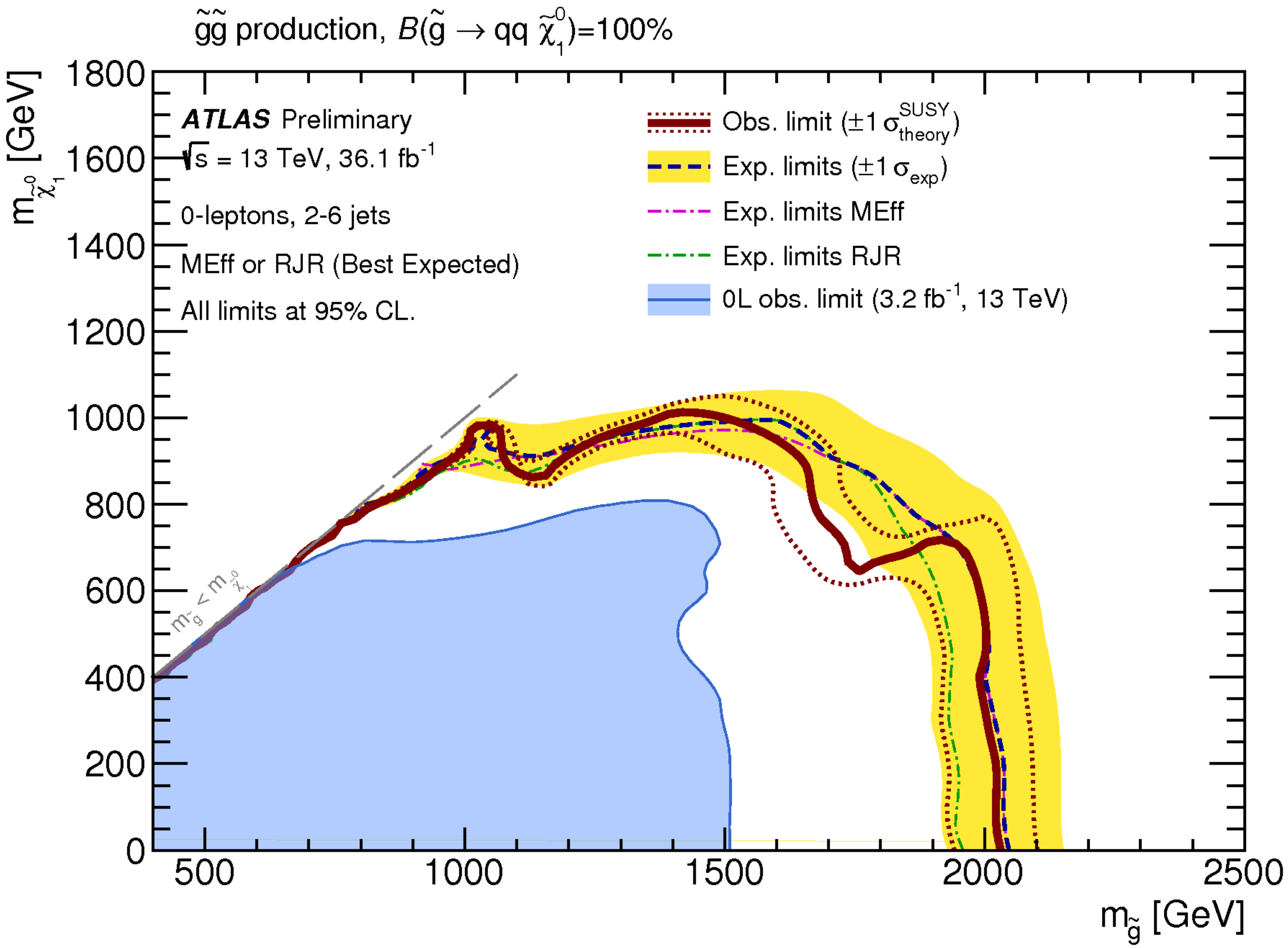
Not the most updated one

Targeted signal	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$						
Requirement	Signal Region [**Meff-**]						
	4j-1000	**4j-1400**	**4j-1800**	**4j-2200**	**4j-2600**	**4j-3000**	**5j-1700**
E_T^{miss} [GeV] >	250						
$p_T(j_1)$ [GeV] >	200						700
$p_T(j_4)$ [GeV] >	100				150		50
$p_T(j_5)$ [GeV] >	–						50
$\|\eta(j_{1,2,3,4})\|$ <	1.2	2.0					–
$\Delta\phi(\text{jet}_{1,2,(3)}, \vec{E}_T^{miss})_{min}$ >	0.4						
$\Delta\phi(\text{jet}_{i>3}, \vec{E}_T^{miss})_{min}$ >	0.4						0.2
$E_T^{miss}/m_{eff}(N_j)$ >	0.3	0.25			0.2		0.3
Aplanarity >	0.04						–
m_{eff}(incl.) [GeV] >	1000	1400	1800	2200	2600	3000	1700

also see http://slac.stanford.edu/pubs/slacreports/reports19/slac-r-504.pdf

SUSY search: Multi-jet + MET

ATLAS-CONF-2017-022



$$pp \rightarrow \tilde{g}\tilde{g}$$

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

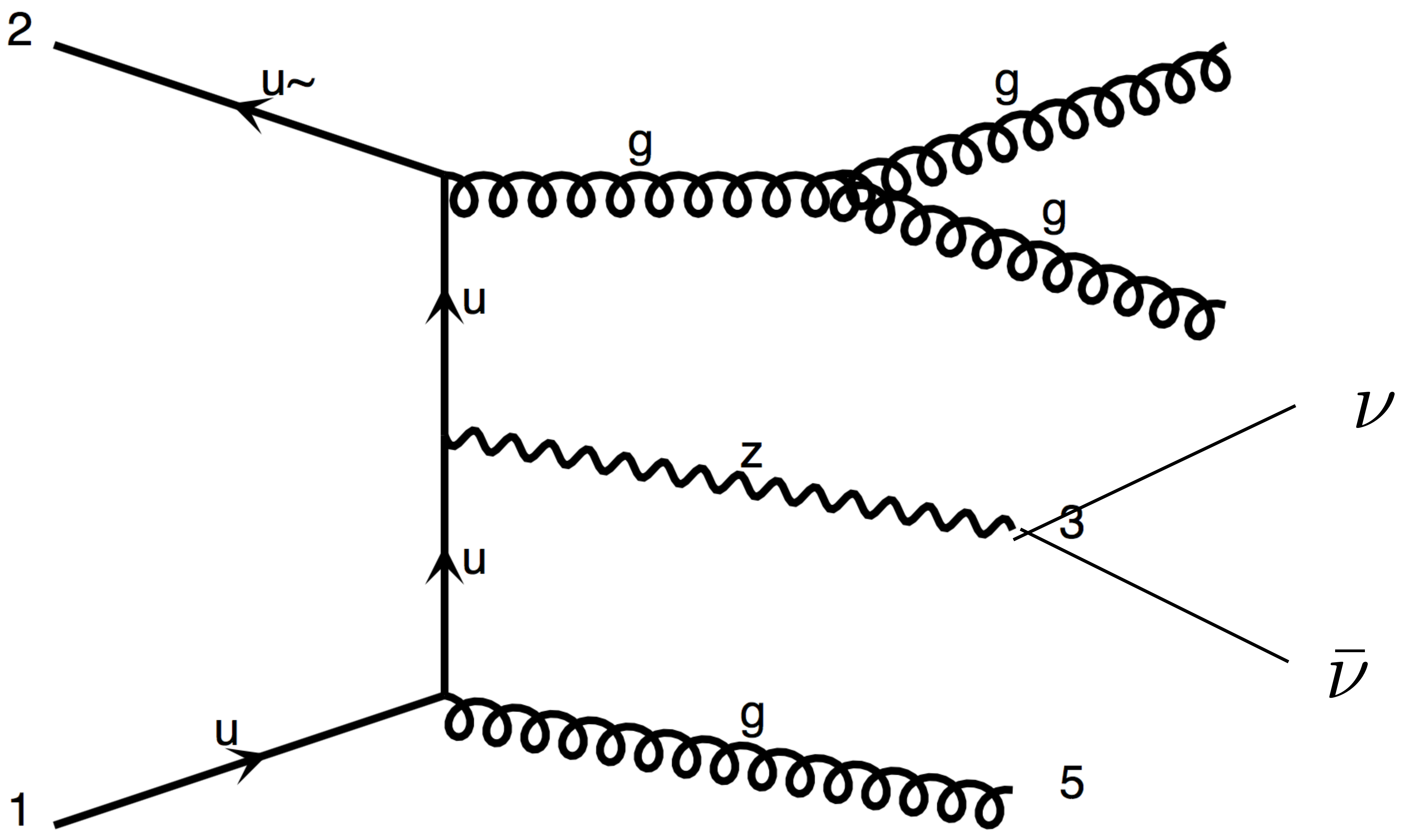
$$pp \rightarrow \tilde{q}\tilde{q}$$

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

Final state : $Multiple\ jets\ +\ MET$

SM backgrounds

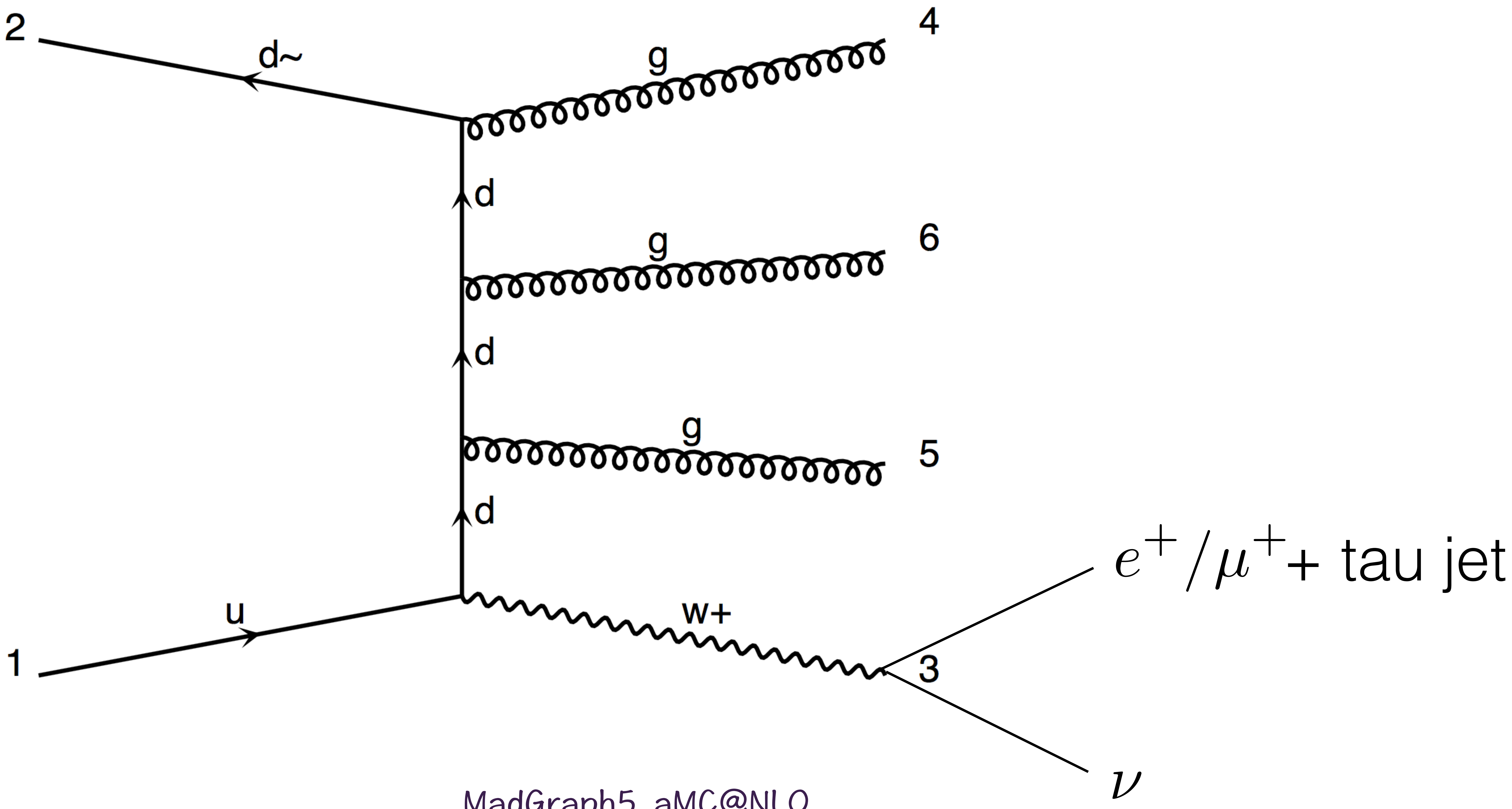
Z + jets



MadGraph5_aMC@NLO

SM backgrounds

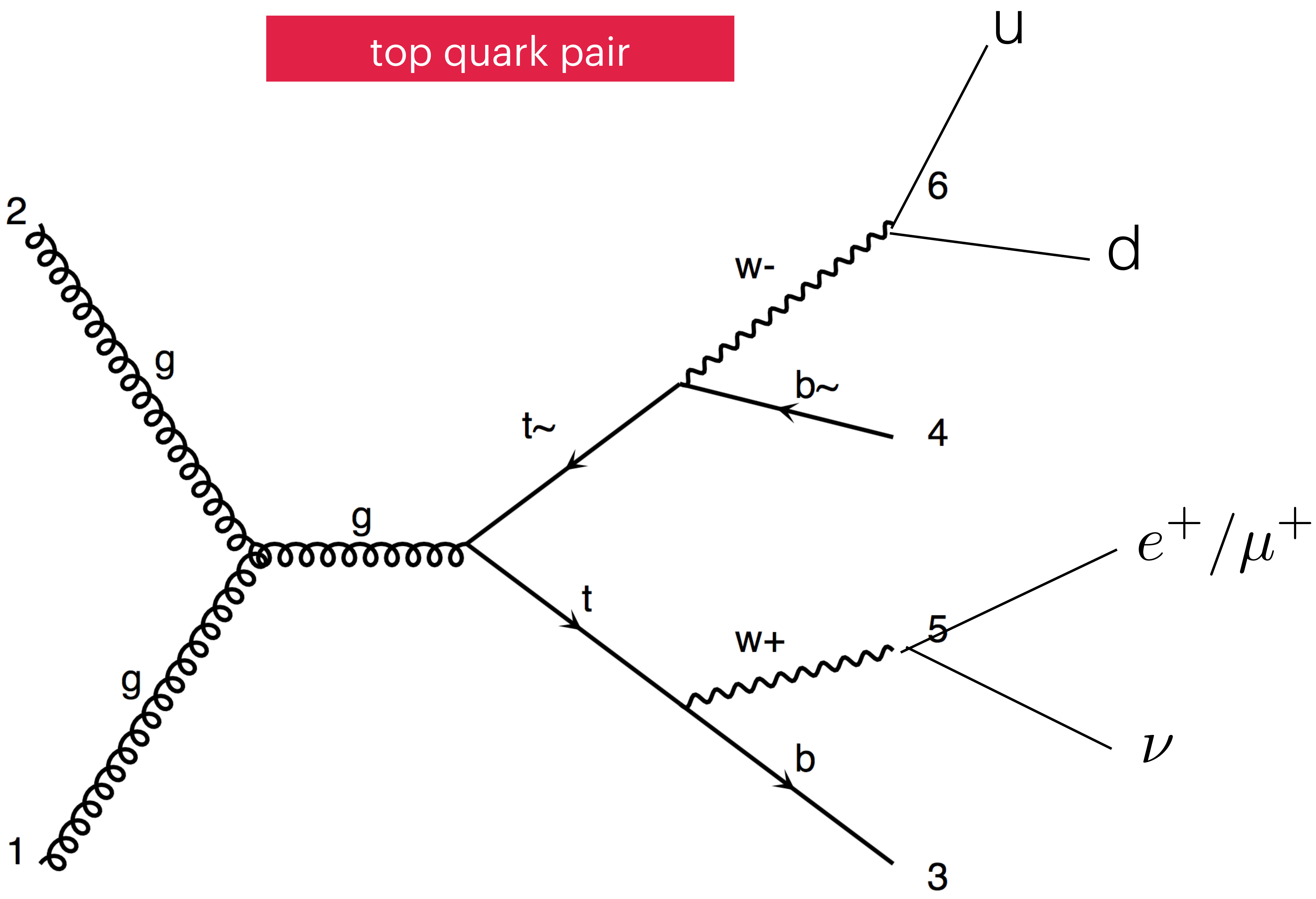
W + jets



MadGraph5_aMC@NLO

SM backgrounds

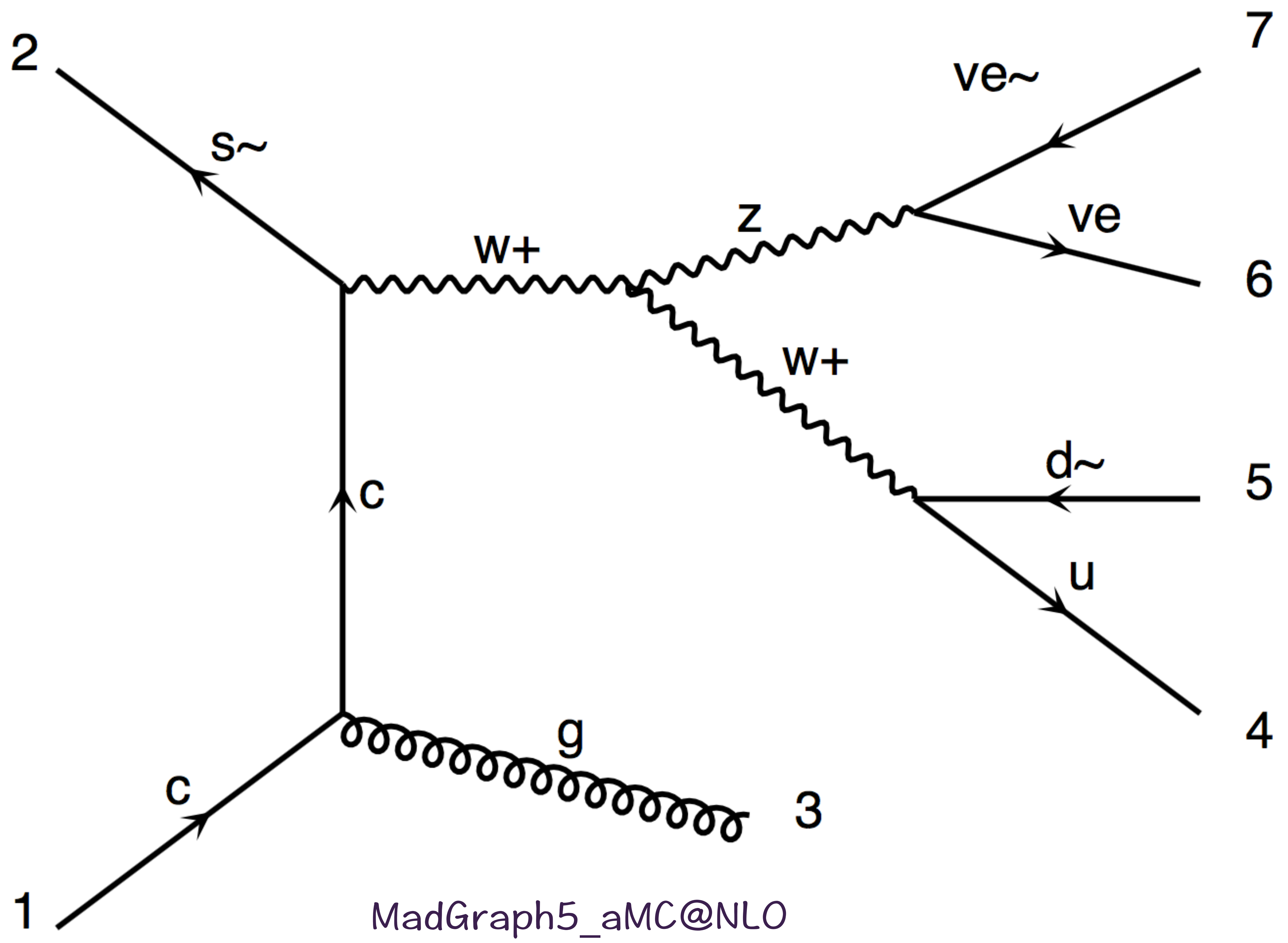
top quark pair



MadGraph5_aMC@NLO

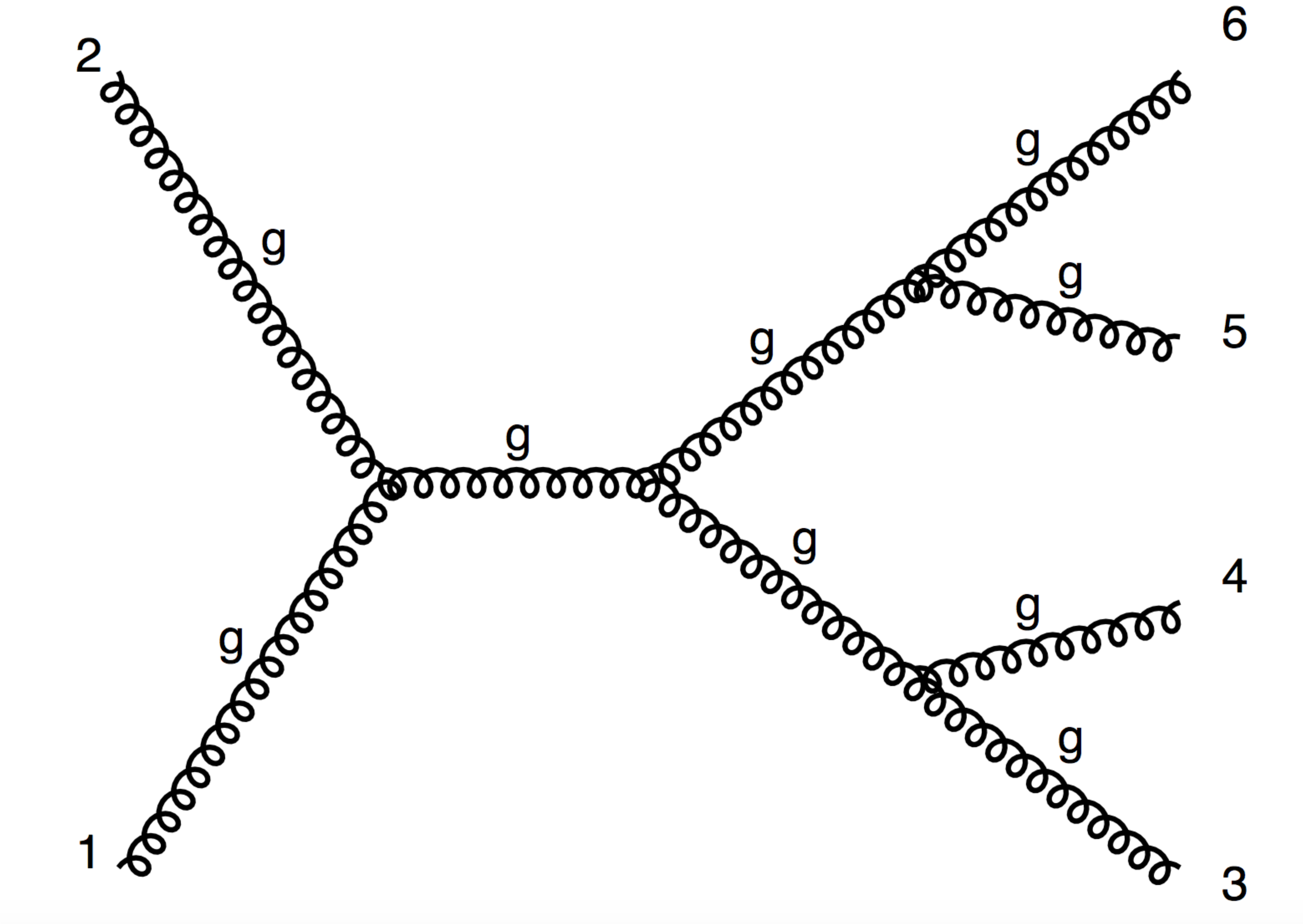
SM backgrounds

Other subdominant backgrounds VV + jets , single top



SM backgrounds

QCD Multi-jet background



MadGraph5_aMC@NLO

Simple Illustration

$$pp \rightarrow \tilde{q}\tilde{q}$$

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

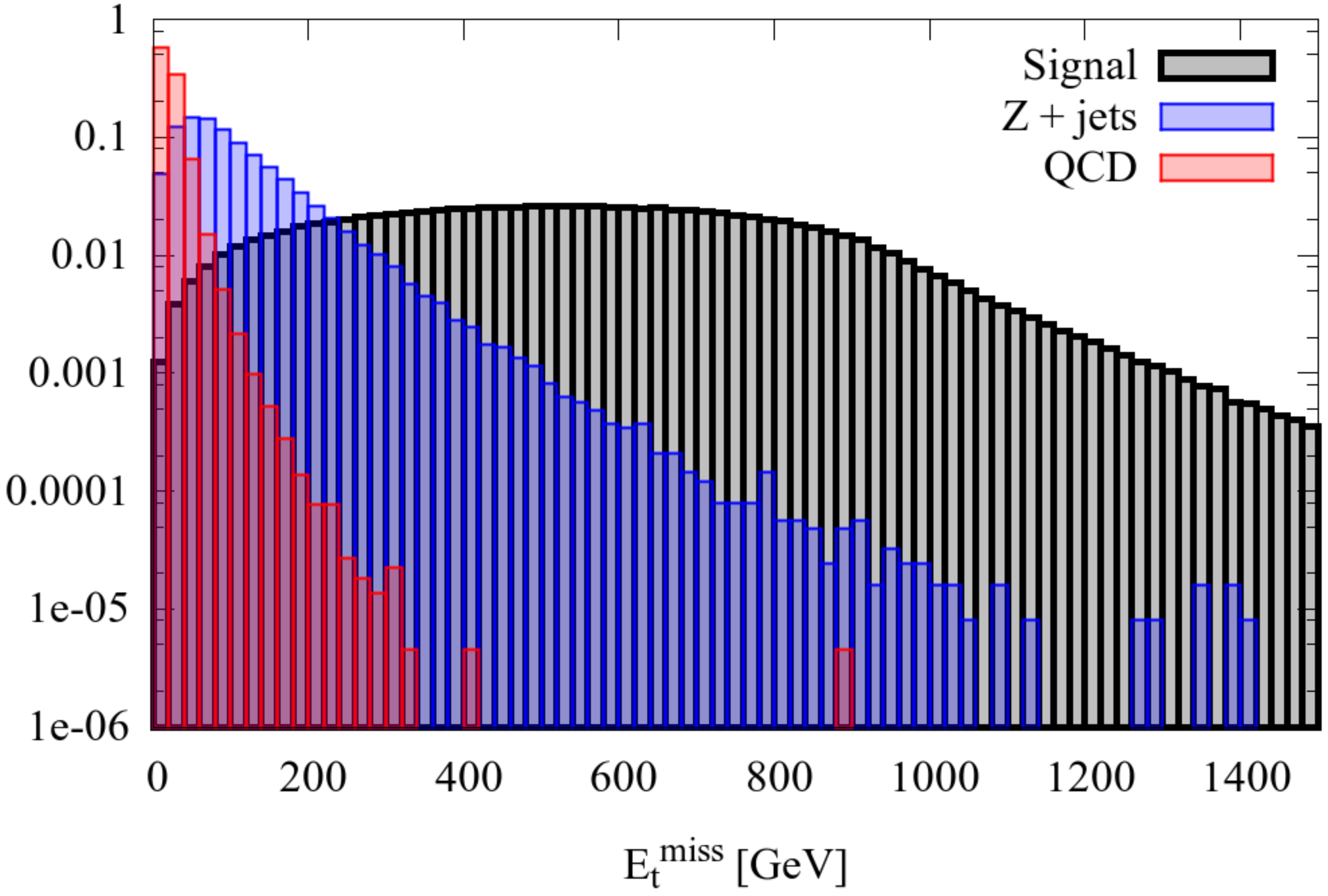
squark pair production (Mass = 1 TeV) using Pythia-6
squark to quark + neutralino (mass = 100 GeV)
Delphes 3 simulation
backgrounds: Z+ 2 jets , QCD dijet
(This is only for illustration)

$$p_T^{j_1} \geq 100 \ GeV \quad p_T^{j_2} \geq 100 \ GeV$$

MET distribution

squark pair production (Mass = 1 TeV) using Pythia-6
squark to quark + neutralino (mass = 100 GeV)
Delphes 3 simulation

$p_T^{j_1} \geq 100\ GeV \quad p_T^{j_2} \geq 100\ GeV$



SM cross sections (background)

QCD(pt>100 GeV) ~ 2000000 pb

W + jets ~ 20000 pb (W decays to electron)

top pair ~ 900 pb

SUSY cross sections (signal)

Gluino pair (mass = 1 TeV) ~ 450 fb

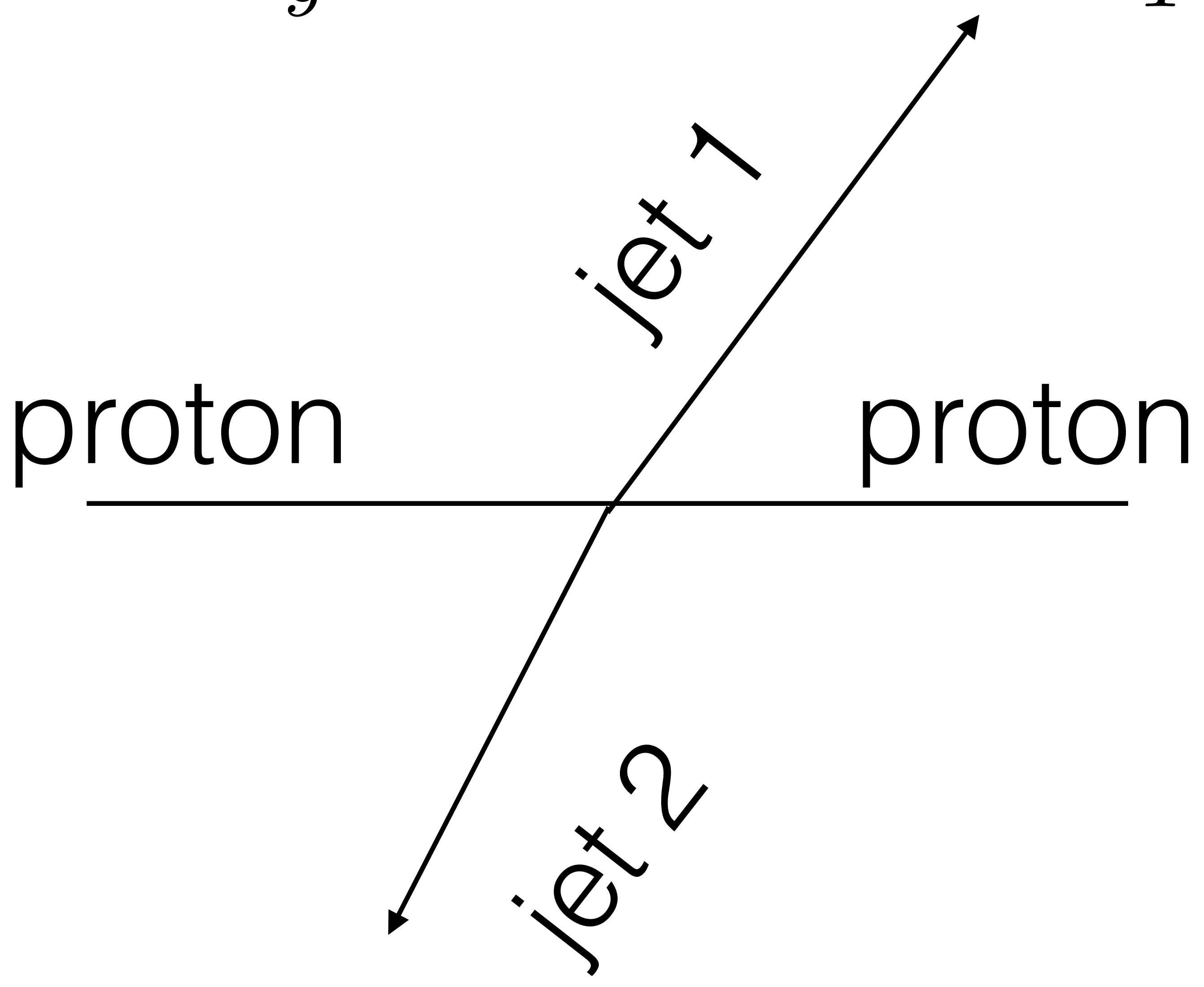
stop pair(mass = 1TeV) ~ 10 fb

Plot Credit : Rahool Kumar Barman

MET from QCD

ideal situation

$p_x^{j_1}$ =562 GeV, $p_y^{j_1}$ =195 GeV, $p_T^{j_1}$ ~595 GeV



$p_x^{j_2}$ =-564 GeV, $p_y^{j_2}$ =-193 GeV, $p_T^{j_2}$ ~596 GeV

$$p_x^{visible} = p_x^{j_1} + p_x^{j_2} = 562 - 564 = -2 \ \text{GeV}$$

$$p_y^{visible} = p_y^{j_1} + p_y^{j_2} = 195 - 193 = -2 \ \text{GeV}$$

$$p_y^{missing} = - \ p_y^{visible}$$

$$p_x^{missing} = - \ p_x^{visible}$$

$$p_T^{missing} = \sqrt{(p_x^{missing})^2 + ({p^{missing}}_y)^2} \sim 3 \ \text{GeV}$$

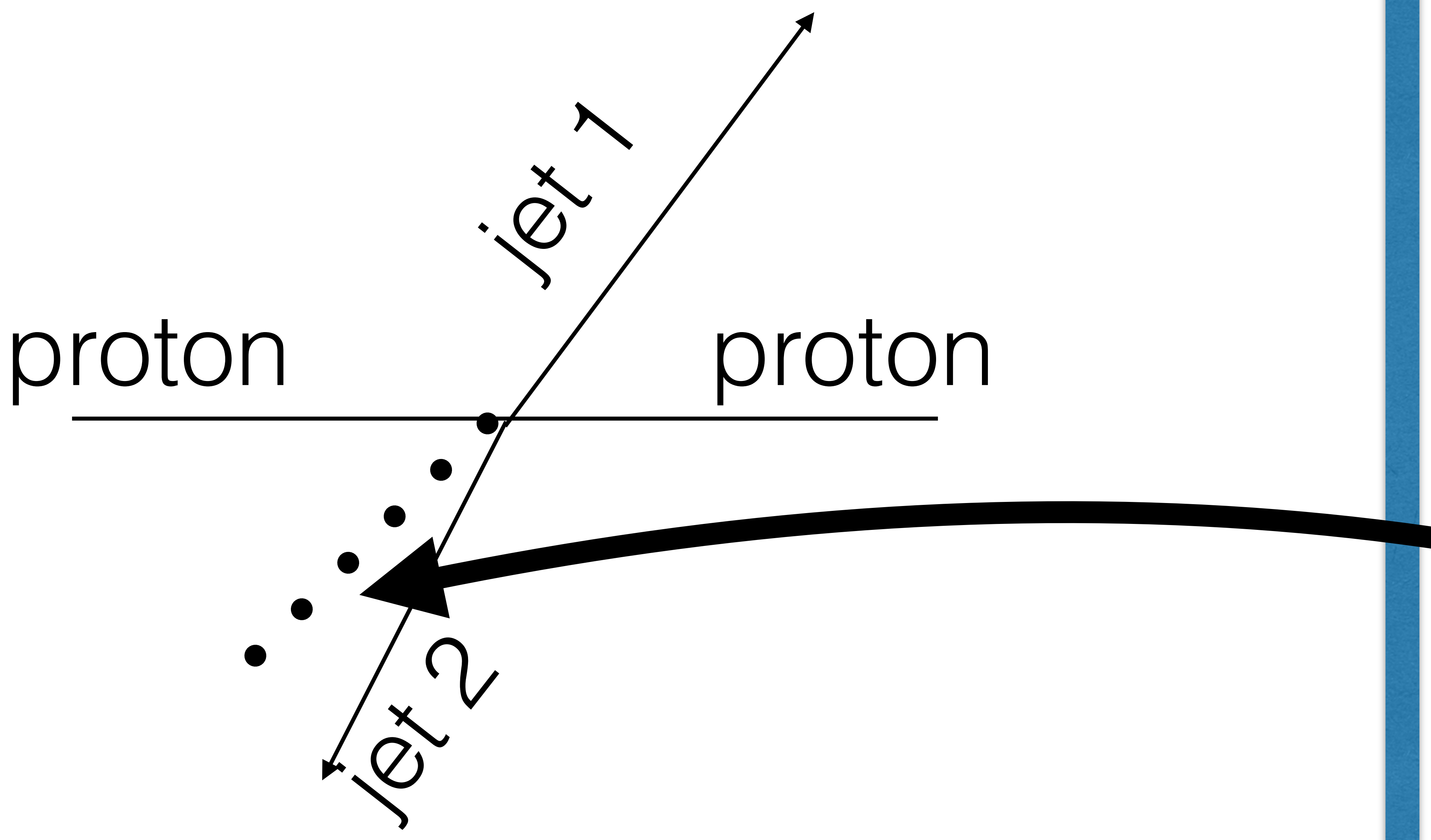
perfectly balanced di-jet

MET~ 0 GeV

MET from QCD

real example

$p_x^{j_1} = 562 \;\; \text{GeV}, \quad p_y^{j_1} = 195 \;\; \text{GeV}, \quad p_T^{j_1} \sim 595 \text{ GeV}$



$p_x^{j_2} = \text{-}350 \;\; \text{GeV}, \; p_y^{j_2} = \text{-}250 \;\; \text{GeV}$

$p_y^{missing} = \text{-} \;\; p_y^{visible}$

$p_x^{missing} = \text{-} \;\; p_x^{visible}$

$p_x^{missing} = \text{-}212 \text{ GeV}$

$p_y^{missing} = 55 \text{ GeV}$

$p_T^{missing} = 219 \text{ GeV}$

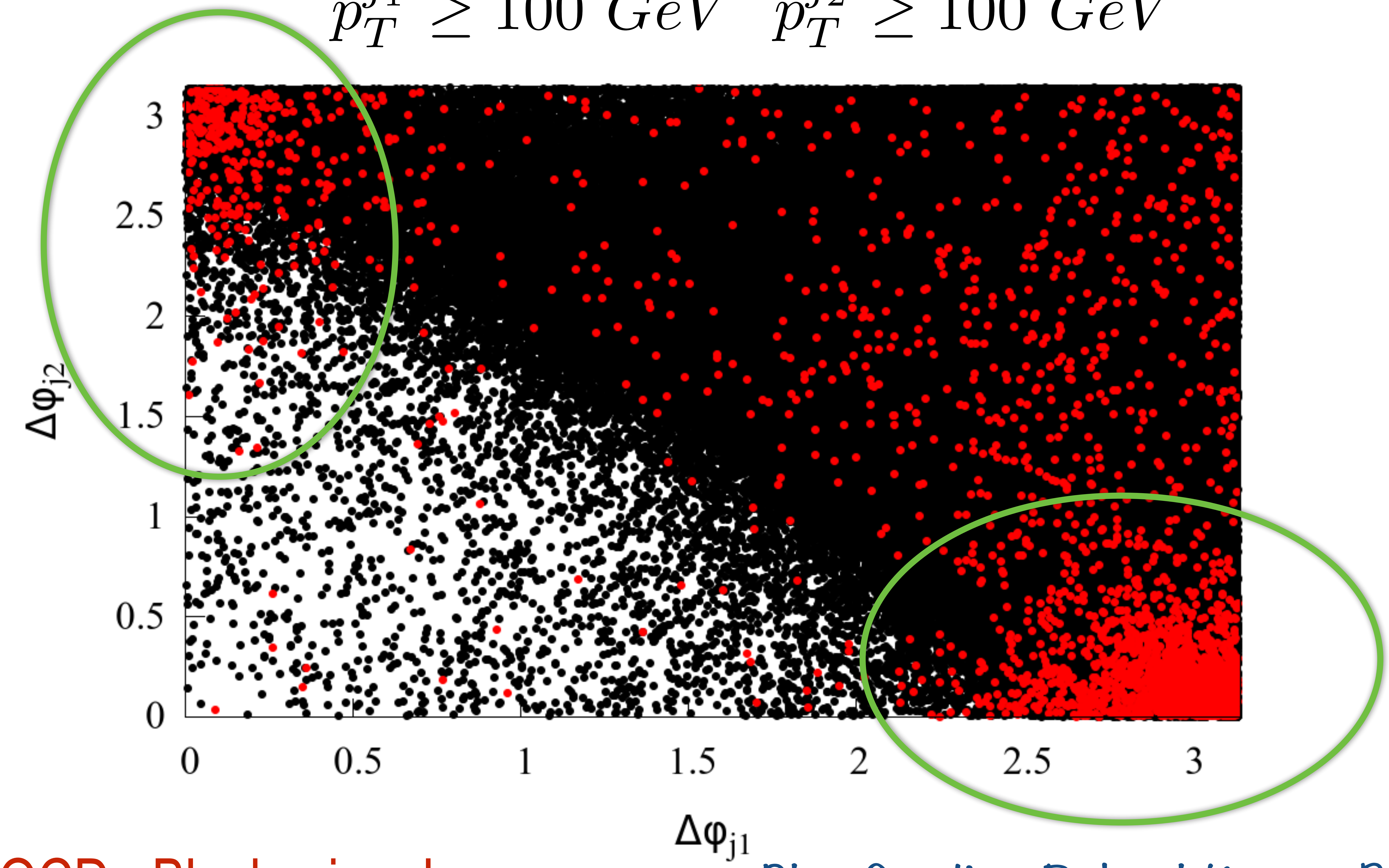
jet 2 is badly mis-measured

mis-measured di-jet (multi-jet)
large MET is not impossible

Δφ Cut

squark pair production (Mass = 1 TeV) using Pythia-6
squark to quark + neutralino (mass = 100 GeV)
Delphes 3 simulation

$$p_T^{j_1} \geq 100\ GeV \quad p_T^{j_2} \geq 100\ GeV$$

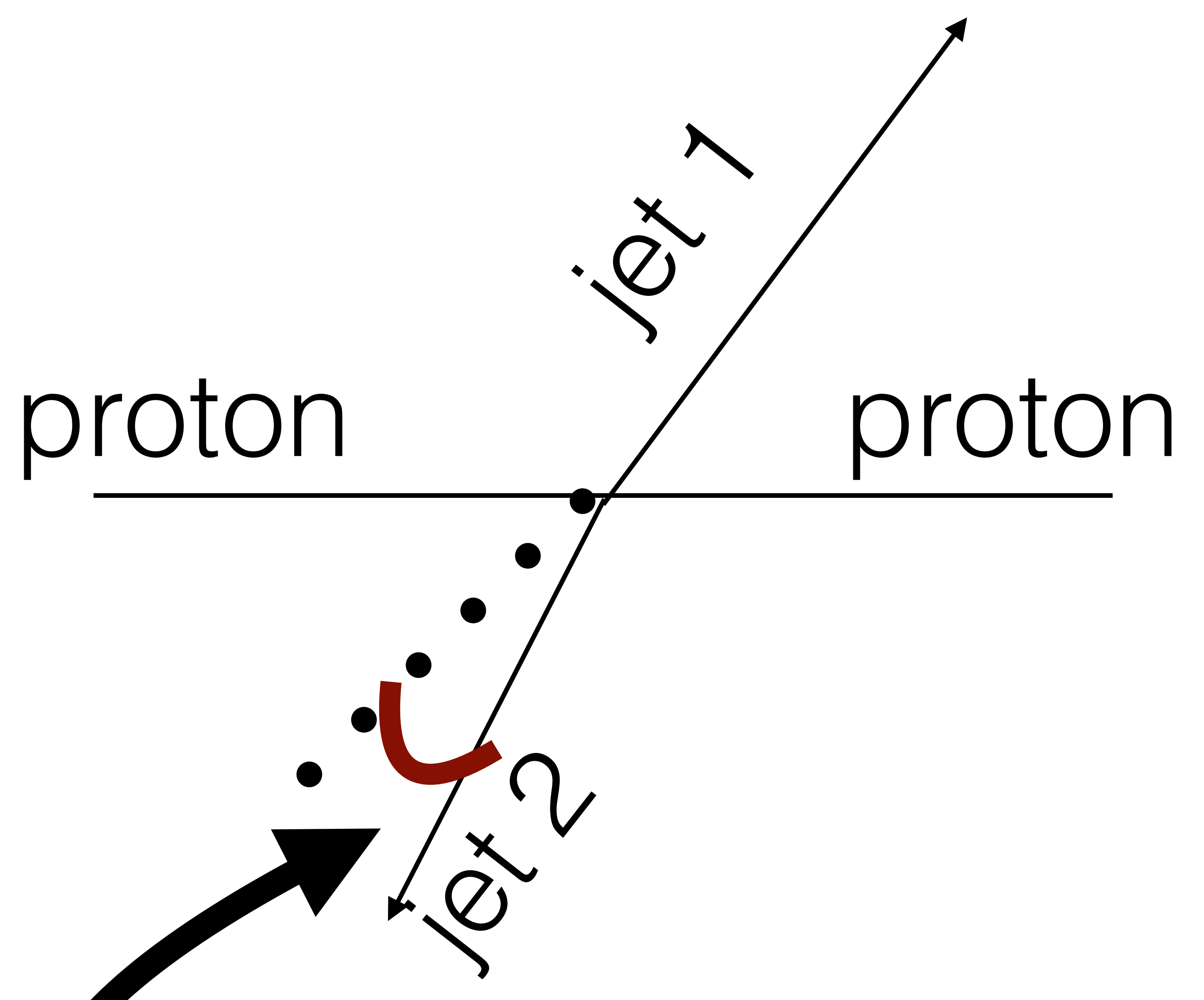


Red : QCD , Black: signal

Plot Credit : Rahool Kumar Barman

MET from QCD

$p_x^{j_1}$ =562 GeV, $p_y^{j_1}$ =195 GeV, $p_T^{j_1} \sim$595 GeV



$p_x^{j_2}$ = -350 GeV, $p_y^{j_2}$ = -250 GeV

jet 2 is badly mis-measured

$p_y^{missing} = - \; p_y^{visible}$

$p_x^{missing} = - \; p_x^{visible}$

$p_x^{missing} =$ -212 GeV

$p_y^{missing} =$ 55 GeV

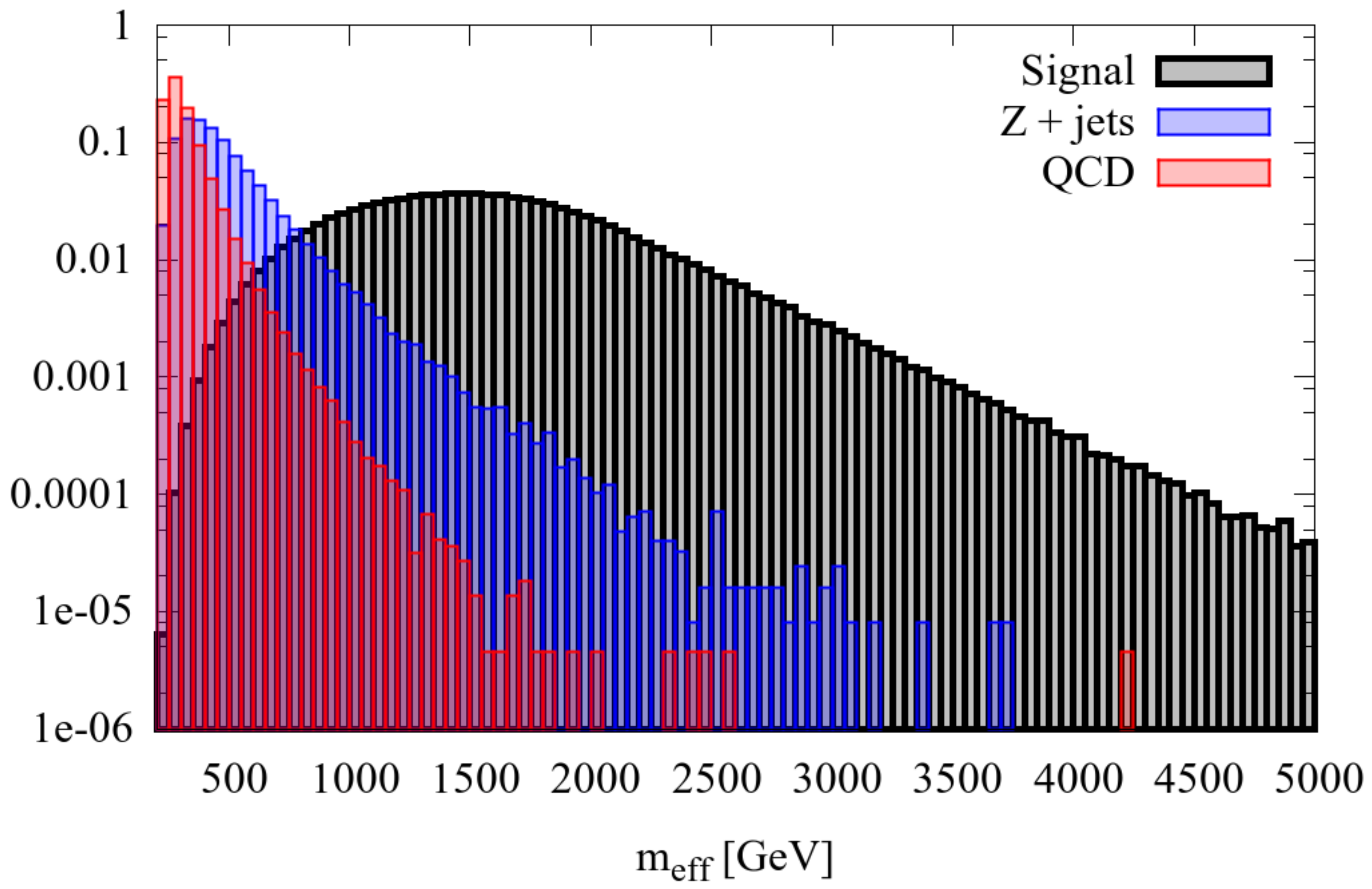
$p_T^{missing} =$ 219 GeV

(the angle between jet 2 and MET is small)

Effective Mass

squark pair production (Mass = 1 TeV) using Pythia-6
squark to quark + neutralino (mass = 100 GeV)
Delphes 3 simulation

$$p_T^{j_1} \geq 100\ GeV \quad p_T^{j_2} \geq 100\ GeV$$



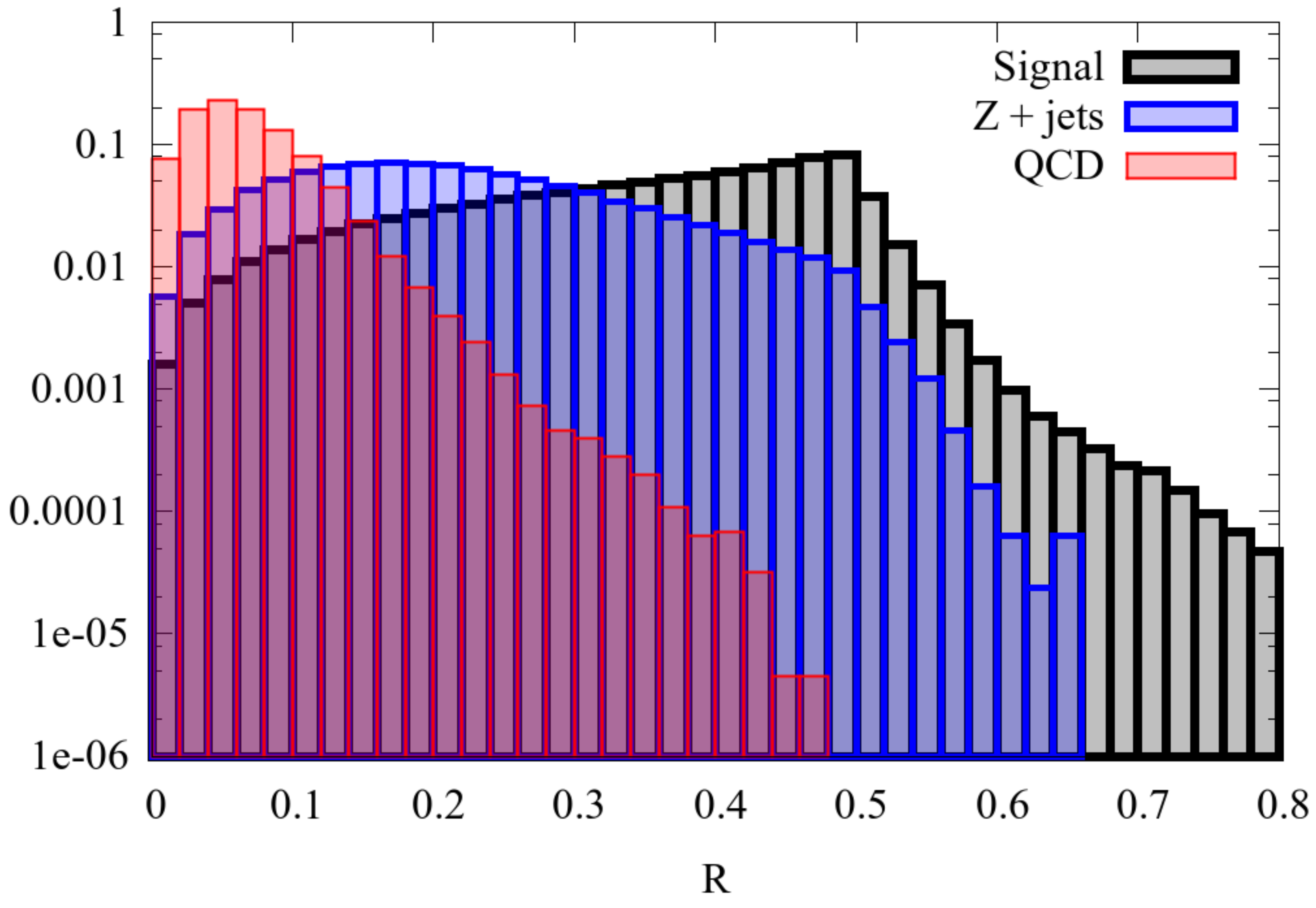
$$m_{eff} = \sum p_T^{jets} + p_T^{mis}$$

Plot Credit : Rahool Kumar Barman

MET/ Effective Mass Cut

squark pair production (Mass = 1 TeV) using Pythia-6
squark to quark + neutralino (mass = 100 GeV)
Delphes 3 simulation

$$p_T^{j_1} \geq 100\ GeV \quad p_T^{j_2} \geq 100\ GeV$$



Plot Credit : Rahool Kumar Barman

Results

Signal Region [Meff-]	2j-1200	2j-1600	2j-2000	2j-2400	2j-2800
MC expected events					
Diboson	28.17	14.37	7.02	3.09	0.86
Z/γ^*+jets	346.37	140.61	54.13	24.23	10.22
W+jets	142.39	47.49	18.33	8.23	3.37
$t\bar{t}$(+EW) + single top	21.40	5.84	2.54	1.13	0.32
Fitted background events					
Diboson	28 ± 4	14.4 ± 2.3	7.0 ± 1.1	3.1 ± 0.5	0.86 ± 0.17
Z/γ^*+jets	337 ± 19	141 ± 10	61 ± 8	26.8 ± 3.1	11.4 ± 1.4
W+jets	136 ± 24	57 ± 16	19 ± 5	9.4 ± 2.6	3.1 ± 1.1
$t\bar{t}$(+EW) + single top	15 ± 4	3.1 ± 1.7	1.34 ± 1.0	0.4 ± 0.4	0.18 ± 0.15
Multi-jet	1.8 ± 1.8	0.34 ± 0.34	–	–	–
Total bkg	517 ± 31	216 ± 18	88 ± 9	40 ± 4	15.5 ± 1.9
Observed	582	204	70	33	17
$\langle\epsilon\sigma\rangle_{\rm obs}^{95}$ [fb]	3.6	1.00	0.42	0.30	0.32
$S_{\rm obs}^{95}$	131	36	15	11	11
$S_{\rm exp}^{95}$	78^{+33}_{-21}	43^{+17}_{-12}	24^{+10}_{-6}	15^{+7}_{-4}	10^{+4}_{-3}
p_0 (Z)	0.06 (1.53)	0.50 (0.00)	0.50 (0.00)	0.50 (0.00)	0.33 (0.43)

ATLAS-CONF-2017-022

Transverse Mass

$$A \rightarrow B + \ X \ (inv)$$

$$M_A^2 = M_B^2 + M_X^2 + 2(E_T^B E_T^X \cosh(\Delta\eta_{BX}) - \mathbf{p}_T^B \cdot \mathbf{p}_T^X)$$

$$cosh(x) \geq 1 \qquad\qquad E_T = \sqrt{p_T^2 + m^2}$$

$$M_T^2 = M_B^2 + M_X^2 + 2(E_T^B E_T^X \ - \mathbf{p}_T^B \cdot \mathbf{p}_T^X)$$

Transverse Mass

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$$M_T^2 = M_B^2 + M_X^2 + 2(E_T^B E_T^X - \mathbf{p}_T^B \cdot \mathbf{p}_T^X) \qquad M_A^2 \geq M_T^2$$

Suppose B and X are massless

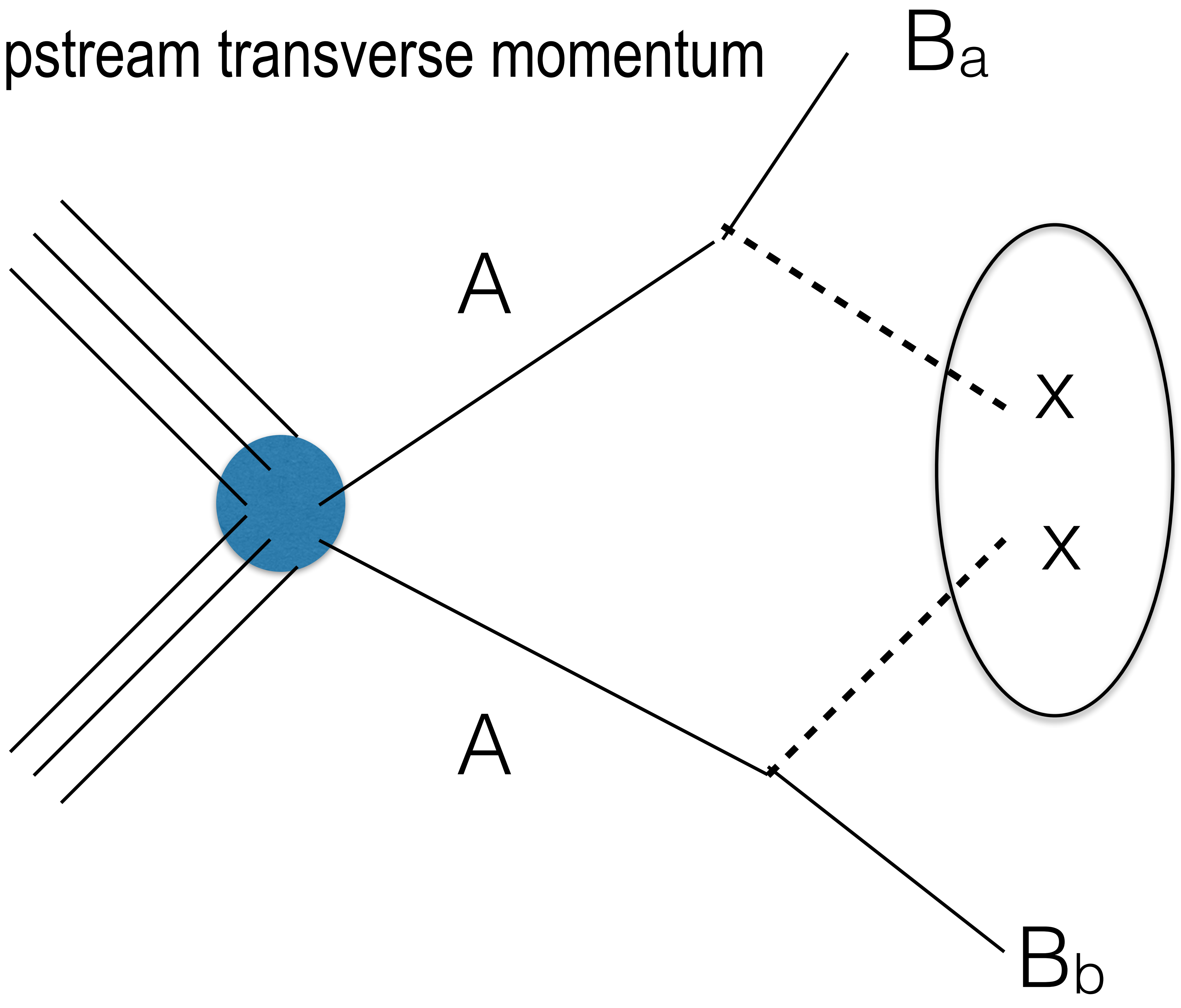
Suppose B and X are massless

$$M_T^2 = 2E_T^B E_T^X (1 - \cos\phi)$$

Discovery of W boson in lepton + MET channel : Transverse Mass variable used

Stransverse Mass

No ISR and upstream transverse momentum



Two invisible particles
x particle coming from A => x_a
x particle coming from B => x_b

The vector sum will give MET

Split the missing transverse energy into two parts

$$p_T^{mis} = p_T^{x_a} + p_T^{x_b}$$

Assume the mass of the invisible particle and calculate

$$M_T(x_a, B_a) \ and \ M_T(x_b, B_b)$$

Take the Max of $M_T(x_a, B_a) \ and \ M_T(x_b, B_b)$

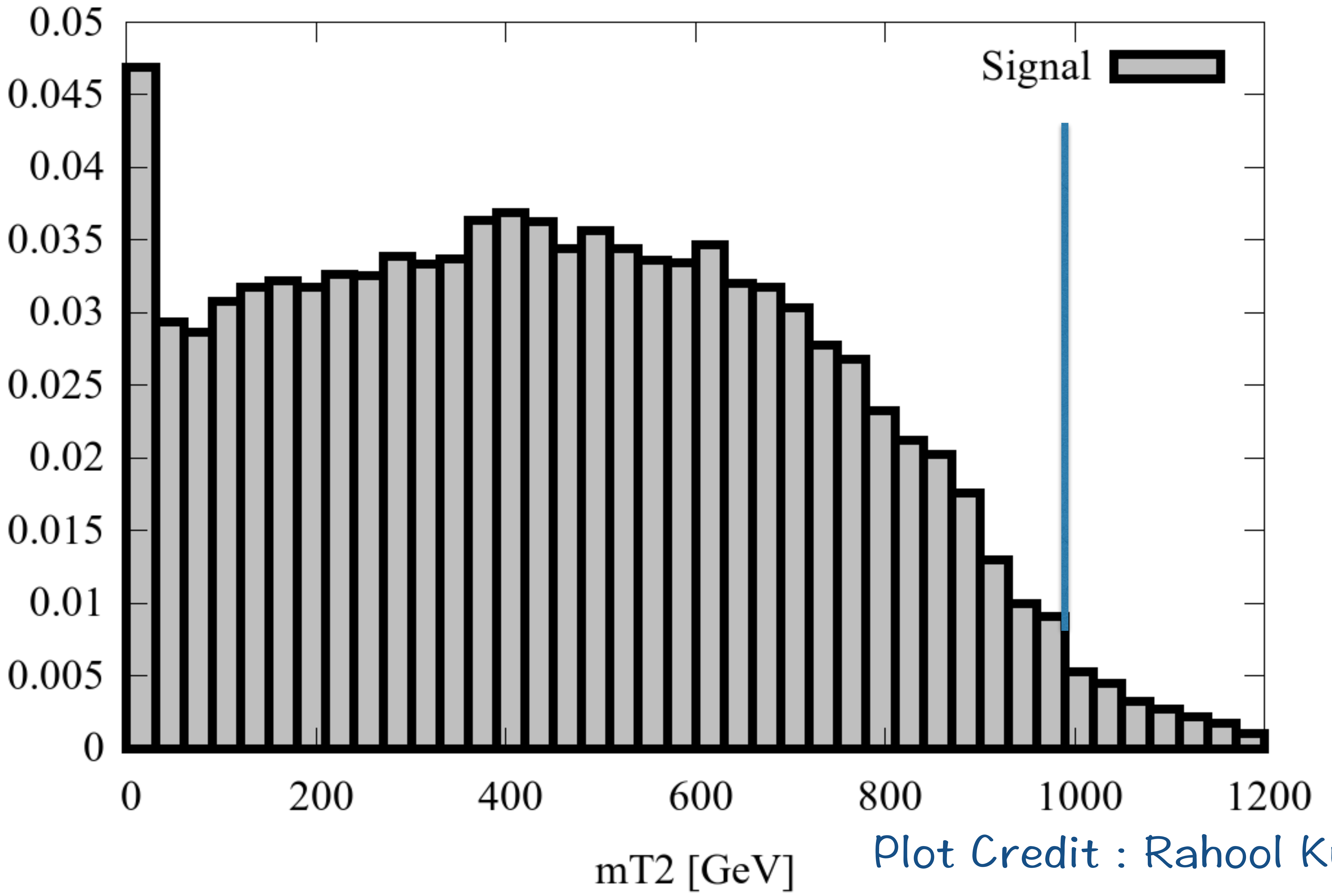
Now vary the MET splitting* which minimises the Max($M_T(x_a, B_a) M_T(x_b, B_b)$)

$$M_{T2} = \min_{p_T^{mis} = p_T^{x_a} + p_T^{x_b}} \left[\mathrm{Max}(M_T(x_a, B_a), M_T(x_b, B_b))\right]$$

REF: Lester and Summers https://arxiv.org/abs/hep-ph/9906349

MT_2 Variable

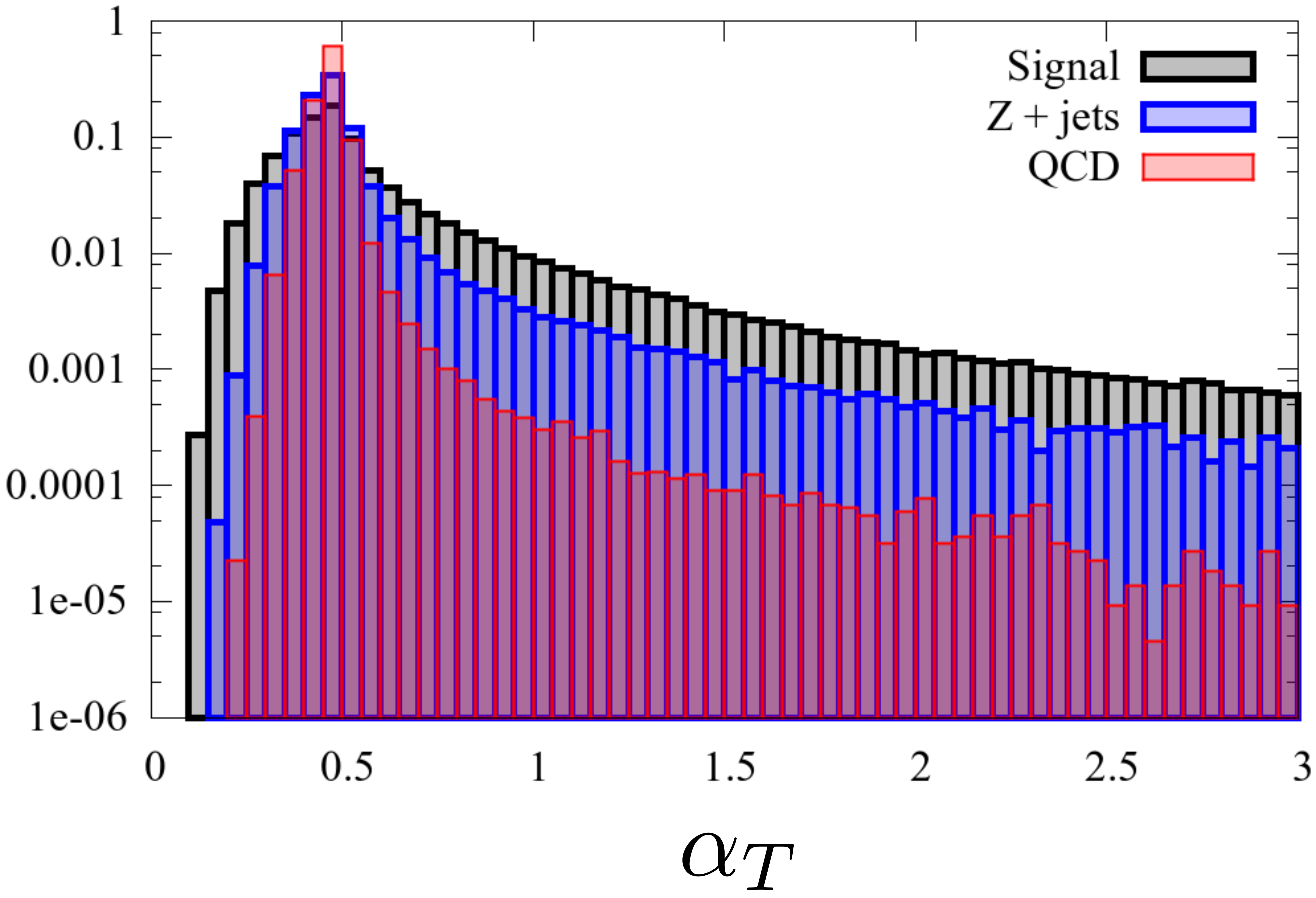
squark pair production (Mass = 1 TeV) using Pythia-6
squark to quark + neutralino (mass = 100 GeV)
Delphes 3 simulation
(naively written code for MT2, slight discrepancy in result when compared with the public code)



Plot Credit : Rahool Kumar Barman

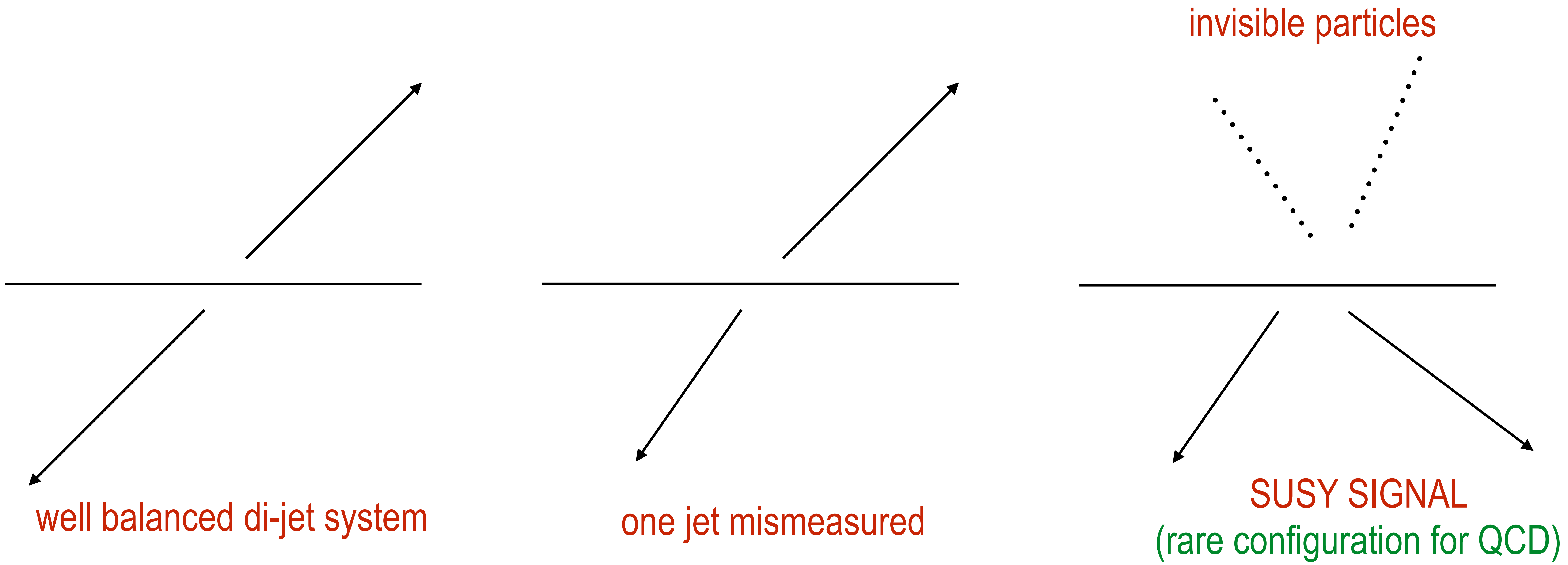
α_T Variable

$$\alpha_T = \frac{p_T^{j_2}}{M_T^{j_1 j_2}}$$



α_T Variable

$$\alpha_T = \frac{p_T^{j_2}}{M_T^{j_1 j_2}} = \sqrt{\frac{p_T^{j_2}}{p_T^{j_1}}} \frac{1}{\sqrt{2(1-\cos\Delta\phi)}}$$



$$\Delta\phi = \pi$$

$$p_T^{j_2} = p_T^{j_1}$$

$$\alpha_T = 0.5$$

$$\alpha_T < 0.5$$

$$\alpha_T > 0.5$$

Pile up

Luminosity

REF:https://cds.cern.ch/record/941318/files/p361.pdf

Colliding beams

The number of events per second $= \frac{dR}{dt} \propto \sigma$

$$\frac{dR}{dt} = \mathscr{L}\sigma$$

$$\mathcal{L} = \text{luminosity } (cm^{-2} second^{-1})$$

$$1 \text{ cm}^{-2} \text{ s}^{-1} = 10^{-33} \text{ nb}^{-1} \text{ s}^{-1}$$

The proportionality constant is called Luminosity

Luminosity

REF:https://cds.cern.ch/record/941318/files/p361.pdf

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The proportionality constant is called Luminosity

Consider two gaussian bunches (spread in the x-y plane) containing N_1 and N_2 particles respectively
These bunches collide with frequency f and N_b is the number of bunches in one beam then

$$\mathscr{L} = \frac{N_1 N_2 f N_B}{4\pi\sigma_x\sigma_y}$$

where σ_x and σ_y are the Gaussian horizontal and vertical widths, respectively.

Example : $\sigma_x = \sigma_y = 20\mu m\ N_B = 2800\ f = 40MHz\ N_1 = N_2 = 10^{11}$ $\mathscr{L} \sim 10^{34} cm^{-2} s^{-1}$

Pile up

Each proton bunch contains billions of protons

Consider Instantaneous luminosity $10^{34} cm^{-2} s^{-1} = 10^7 mb^{-1} Hz$

Proton proton cross section ~ 100 mb (dominated by inelastic processes)

Event rate = $10^7 mb^{-1} Hz \times 100 mb = 10 \times 10^8 \ Hz$

Pile up

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Proton proton cross section ~ 100 mb (dominated by inelastic processes)

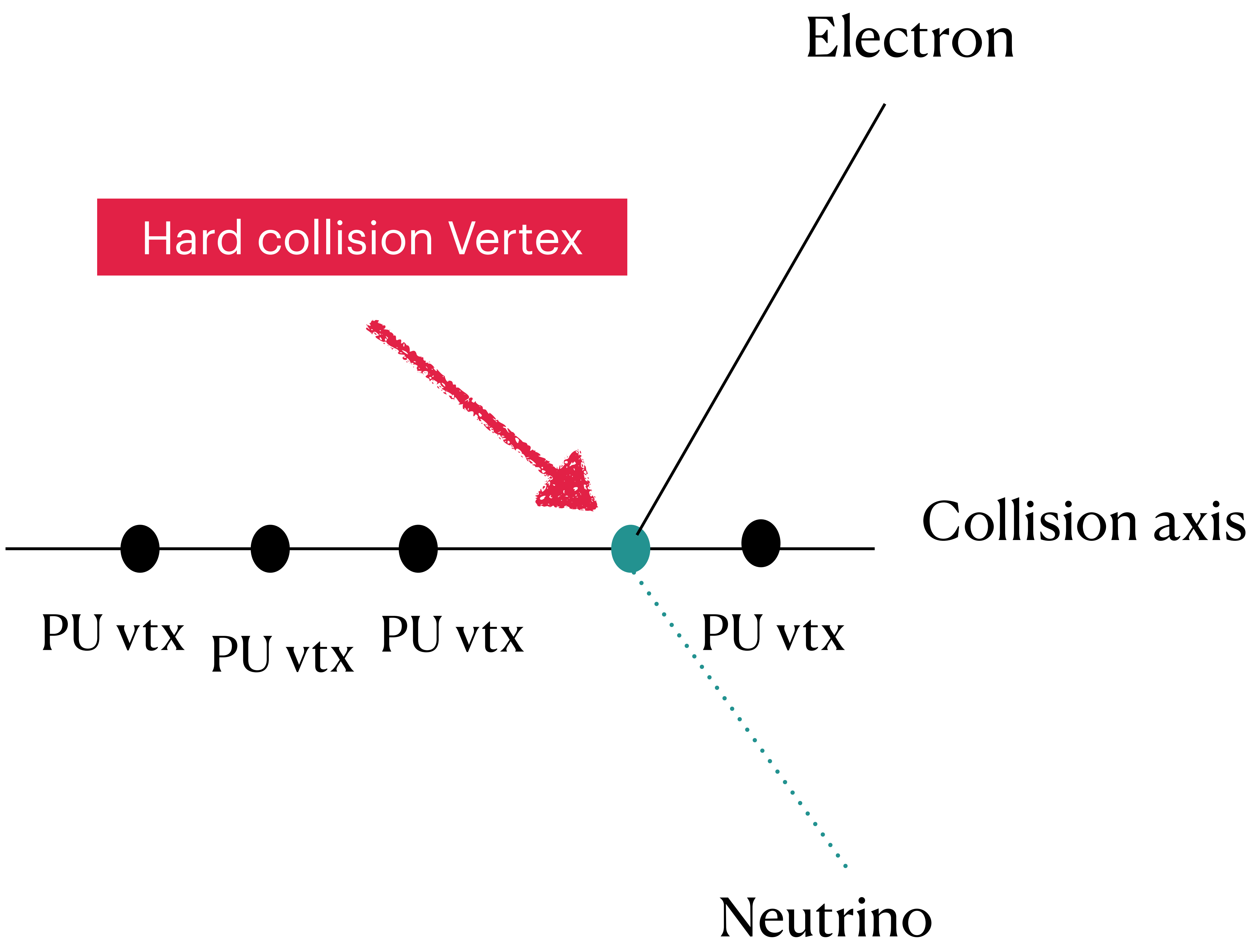
Event rate = $10^7 mb^{-1} Hz \times 100 mb = 10 \times 10^8 \ Hz$

Time gap between two bunch crossing =25ns $= 25 \times 10^{-9} Hz^{-1}$

Expected number of event per 25 ns = 25 events

In any bunch crossing we expect about 25 events superimposed on interesting process like Higgs production, top quark , new physics etc. => Pileup

Pile up



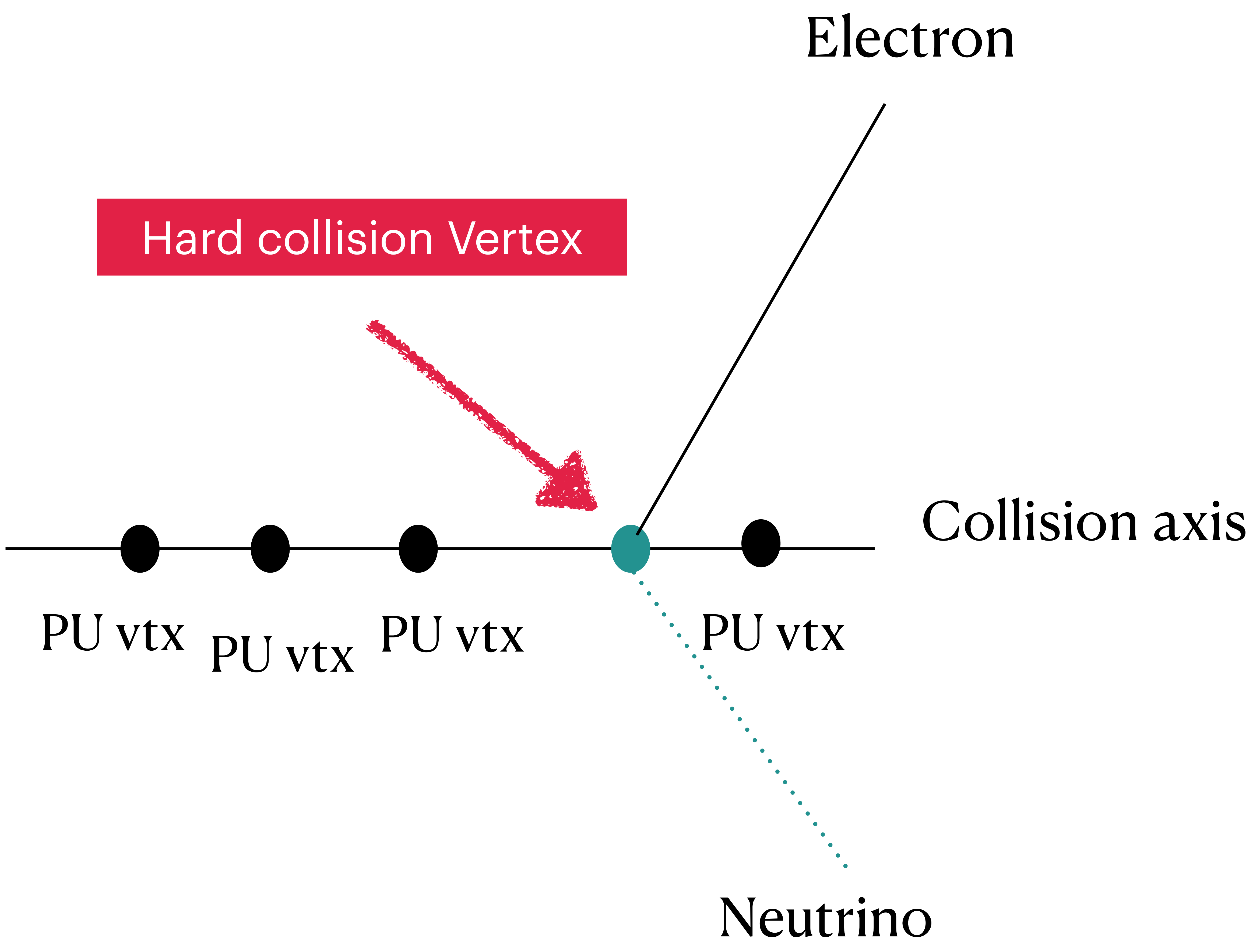
Average number of PU vertices at Tevatron ~ 5

Average number of PU vertices at the HL-LHC ~ 140-200

Actual number in a given bunch crossing fluctuates

follows Poisson distribution around its mean value

Pile up



Average number of PU vertices at Tevatron ~ 5

Average number of PU vertices at the HL-LHC ~ 140-200

Actual number in a given bunch crossing fluctuates

follows Poisson distribution around its mean value

Each PU vertex generally produce a few tens of soft hadrons

The detected final state particles will be the superposition

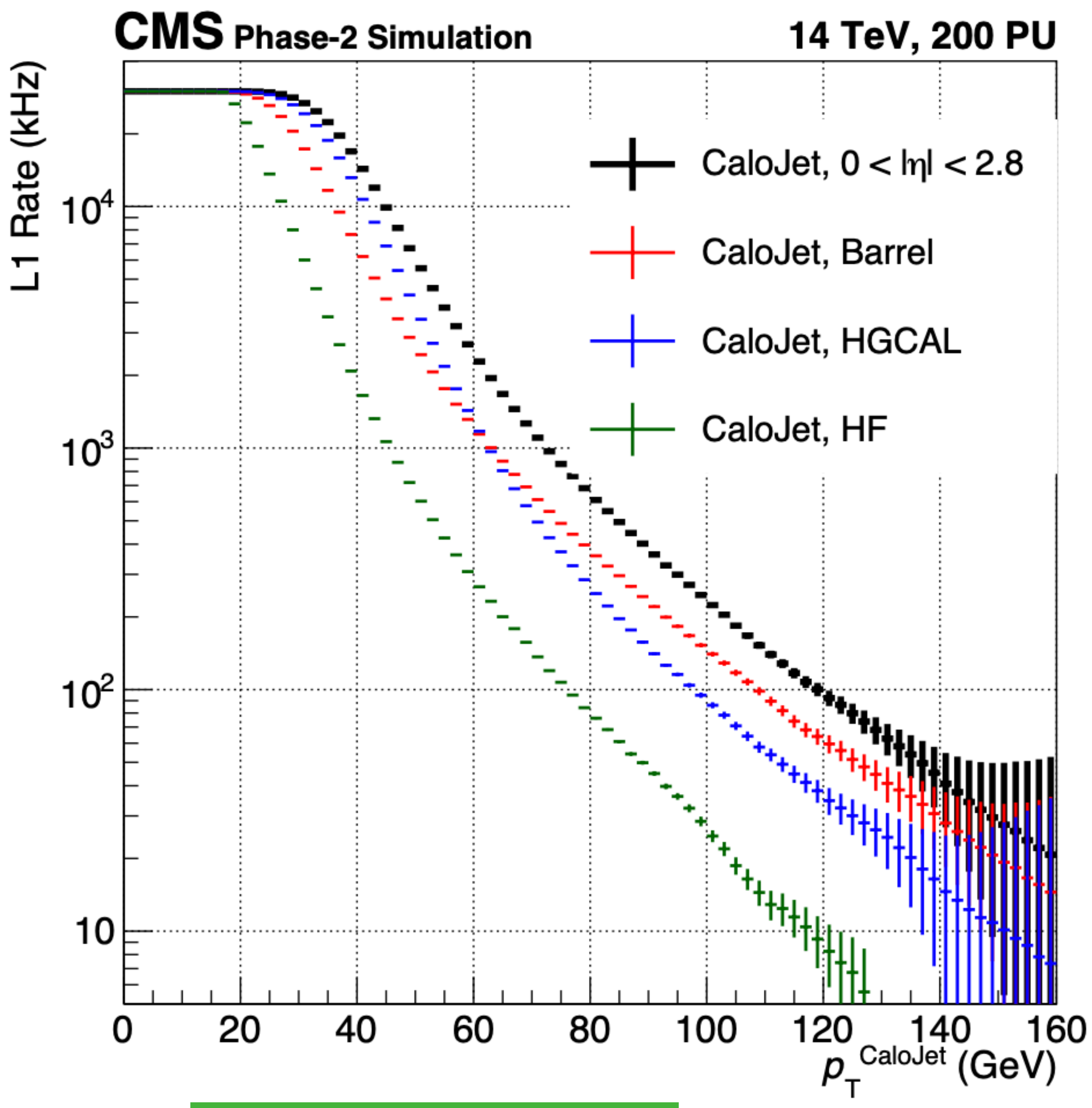
Of particles coming from hard process and soft particles

Coming from PU vertices (soft Hadrons)

1 Event takes 1-2 MB of storage : storage required for 10^9. Events per second = 1000 TB/s !!

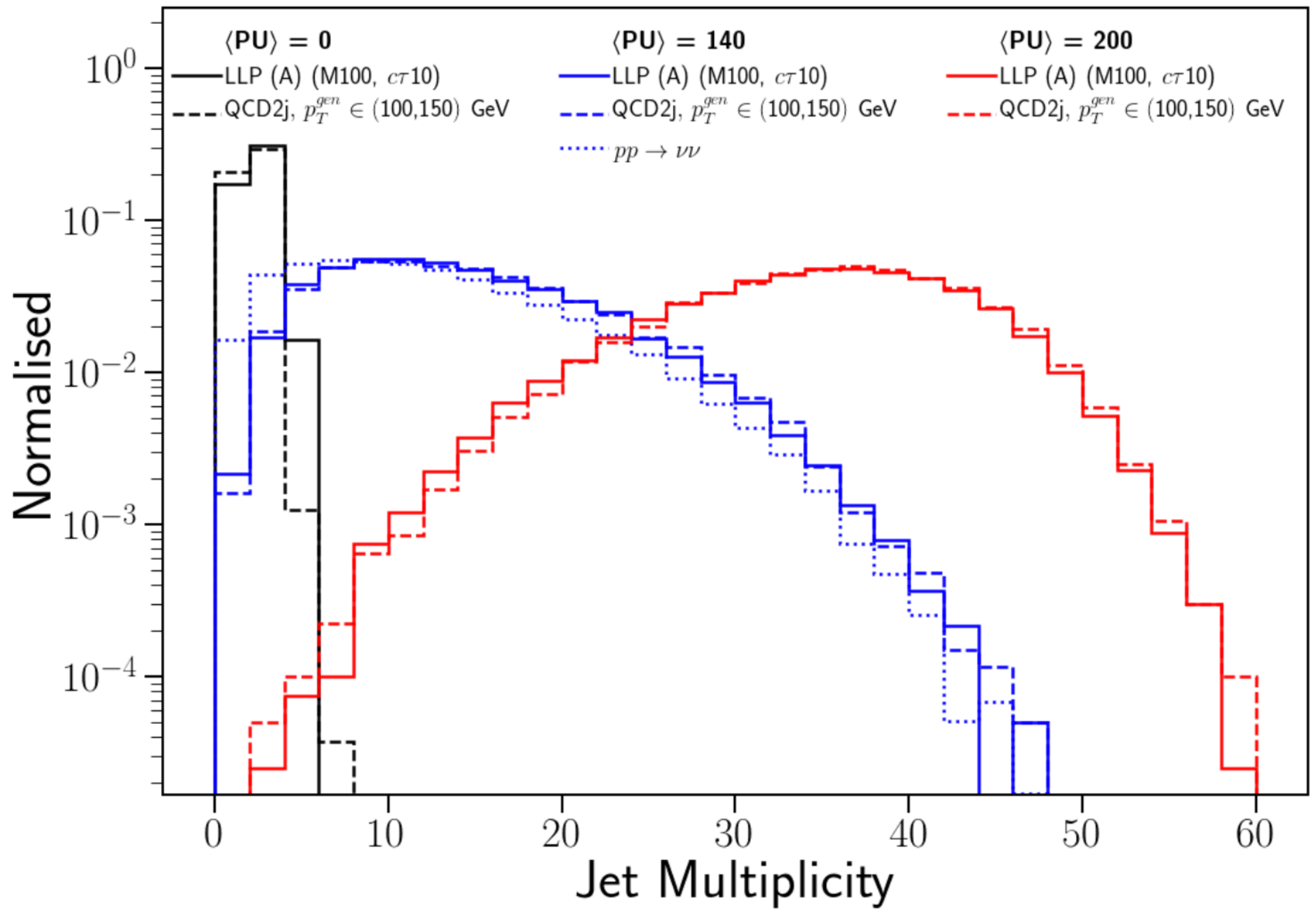
Jets@HL-LHC

Number of jets increases with PU



REF:CMS L1 TDR 2020

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



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

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

Event rates

Inelastic events : 10^9 Hz (cross section100 mb)

W Events : (Cross section)

Top quark Events: (Cross section ~1000 pb)

Higgs Events : (cross section ~ 50 pb)

New Physics Rate : (Cross section 1 fb)

Event selection should be sensitive at 1: 10^{11} level

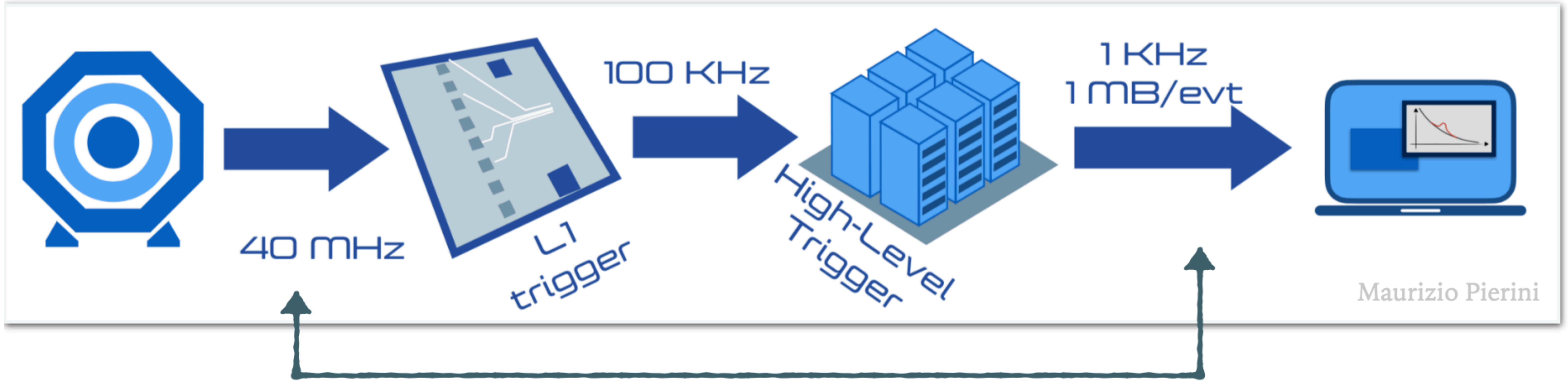
Dedicated selection conditions required to select a few interesting events => Trigger

Trigger system in CMS

Level I (L1) Trigger : Coarse Granularity, Hardware based, fast decision (3 micro second), Output 100 KHz

High Level Trigger (HLT) : Full Granularity, Software based, avg time req:300 milli second, Output 1 KHz

Low or zero sensitivity to new physics with low-mass.



Taken from Swagata Mukherjee's talk
https://indico.cern.ch/event/1182683/attachments/2518736/4330705/7August.pdf

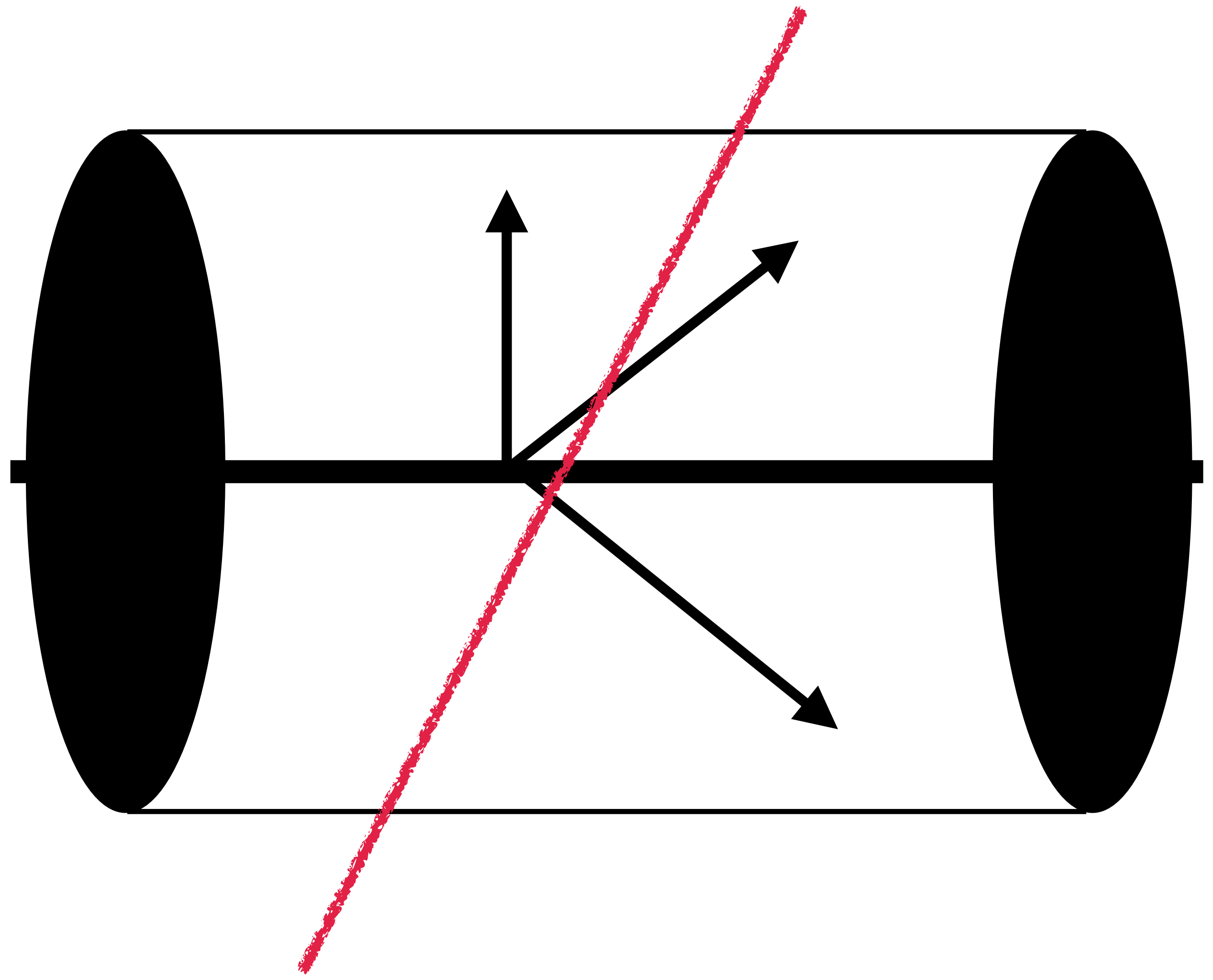
Trigger Menu@ HL-LHC(PU=200)

L1 Trigger seeds	Offline Threshold(s) at 90% or 95% (50%) [GeV]	Rate $\langle PU \rangle = 200$ [kHz]	Additional Requirement(s) [cm, GeV]	Objects plateau efficiency [%]
Single/Double/Triple Lepton (electron, muon) seeds				
Single TkMuon	22	12	$\|\eta\| < 2.4$	95
Double TkMuon	15,7	1	$\|\eta\| < 2.4, \Delta z < 1$	95
Triple TkMuon	5,3,3	16	$\|\eta\| < 2.4, \Delta z < 1$	95
Single TkElectron	36	24	$\|\eta\| < 2.4$	93
Single TkIsoElectron	28	28	$\|\eta\| < 2.4$	93
TkIsoElectron-StaEG	22, 12	36	$\|\eta\| < 2.4$	93, 99
Double TkElectron	25, 12	4	$\|\eta\| < 2.4$	93
Single StaEG	51	25	$\|\eta\| < 2.4$	99
Double StaEG	37,24	5	$\|\eta\| < 2.4$	99
Photon seeds				
Single TkIsoPhoton	36	43	$\|\eta\| < 2.4$	97
Double TkIsoPhoton	22, 12	50	$\|\eta\| < 2.4$	97
Taus seeds				
Single CaloTau	150(119)	21	$\|\eta\| < 2.1$	99
Double CaloTau	90,90(69,69)	25	$\|\eta\| < 2.1, \Delta R > 0.5$	99
Double PuppiTau	52,52(36,36)	7	$\|\eta\| < 2.1, \Delta R > 0.5$	90
Hadronic seeds (jets,H_T)				
Single PuppiJet	180	70	$\|\eta\| < 2.4$	100
Double PuppiJet	112,112	71	$\|\eta\| < 2.4, \Delta\eta < 1.6$	100
PuppiH_T	450(377)	11	jets: $\|\eta\| < 2.4, p_T > 30$	100
QuadPuppiJets-PuppiH_T	70,55,40,40,400(328)	9	jets: $\|\eta\| < 2.4, p_T > 30$	100,100
E_T^{miss} seeds				
PuppiE_T^{miss}	200(128)	18		100

REF: CMS L1 TDR 2020

More and More backgrounds

Non Collisional: Some trigger fired and a cosmic muon can pass the detector at the same time



If it passes through the both hemisphere of the detector it will be identified as two back to back muons

Removal: impact parameter cut, timing cut and angular cut between two muons

Beam halo: Collision of proton beam with some part of the LHC part, mostly collimator (required to clean stray particles)

Beam Gas: Collision of proton beam with gas molecule inside the beam pipe (both elastic and inelastic)

Detector induced: Some parts of the detector may not work or misfire => change the 4 momentum measurements

Of the particles or generate missing energy signal

Dedicated efforts are required to understand to mitigate such backgrounds

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 ?

Three Possibilities:

- 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

A. Huge background (top corridor , Compressed spectrum)

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

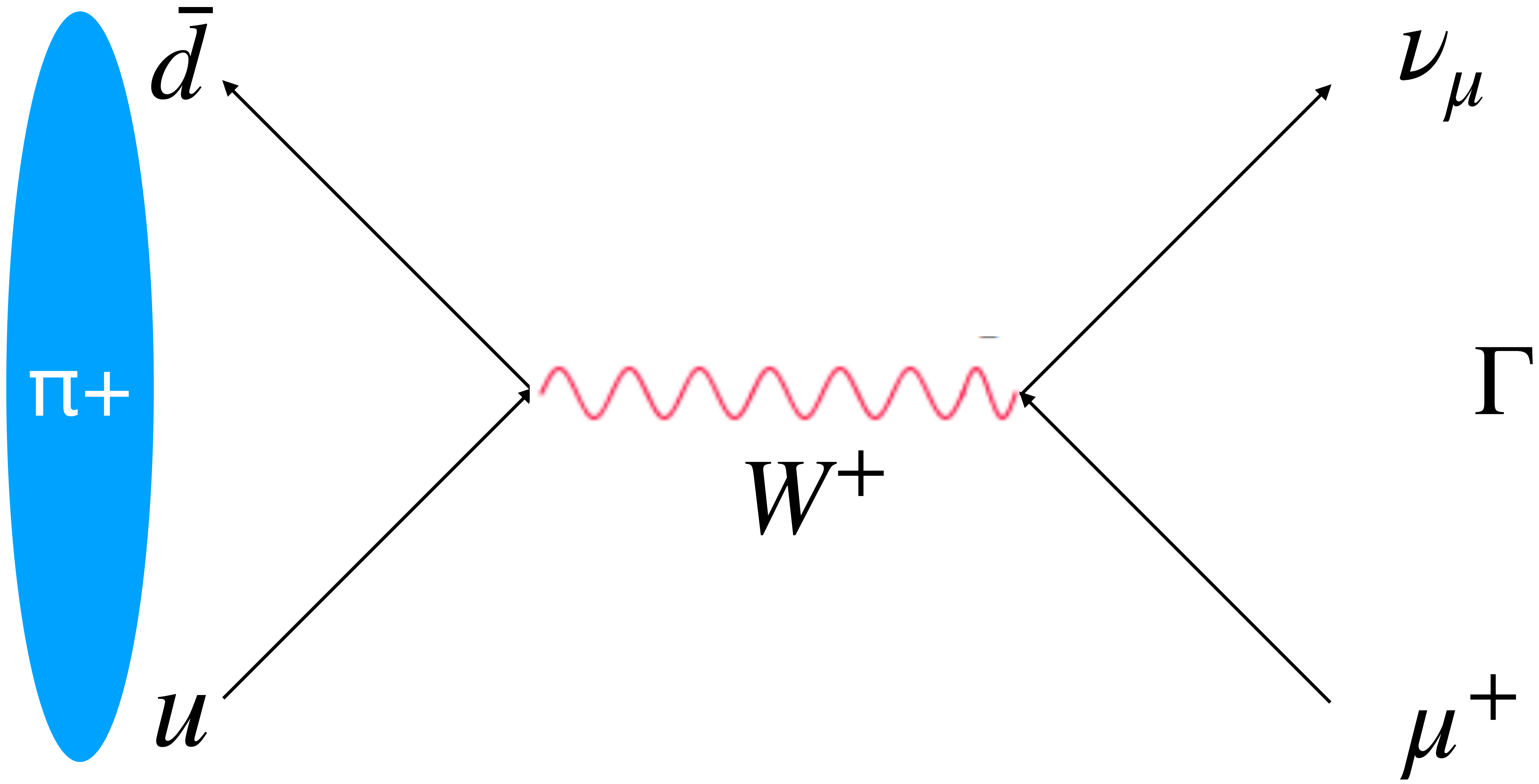
Many long-lived particles are present in our world

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

Why are they long-lived?

Reason 1 : Heavy particle propagator

Pion decay in the SM



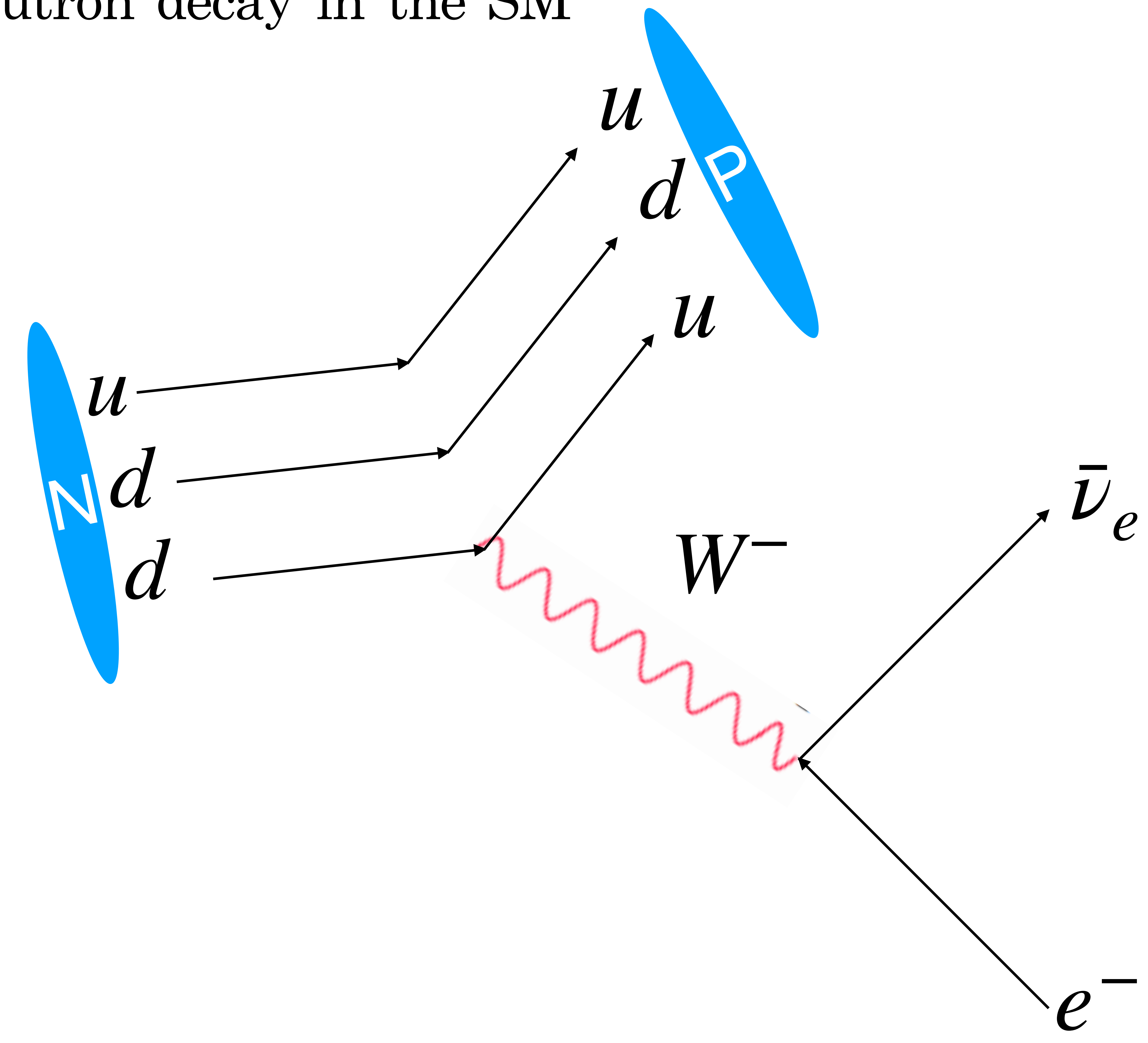
$$\Gamma \sim \frac{m_\pi^5}{m_W^4}$$

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

Why are they long-lived?

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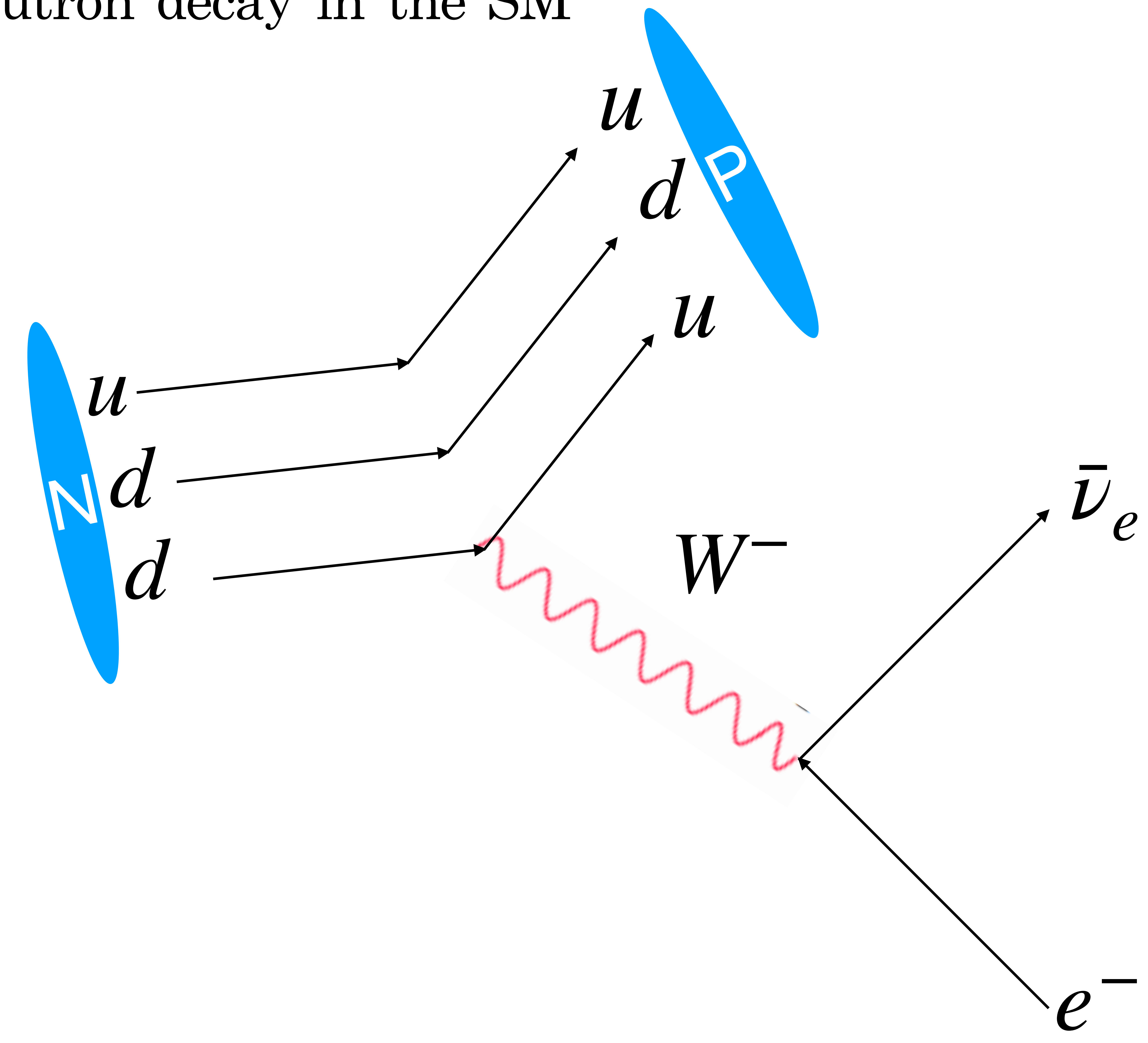
Neutron decay in the SM



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

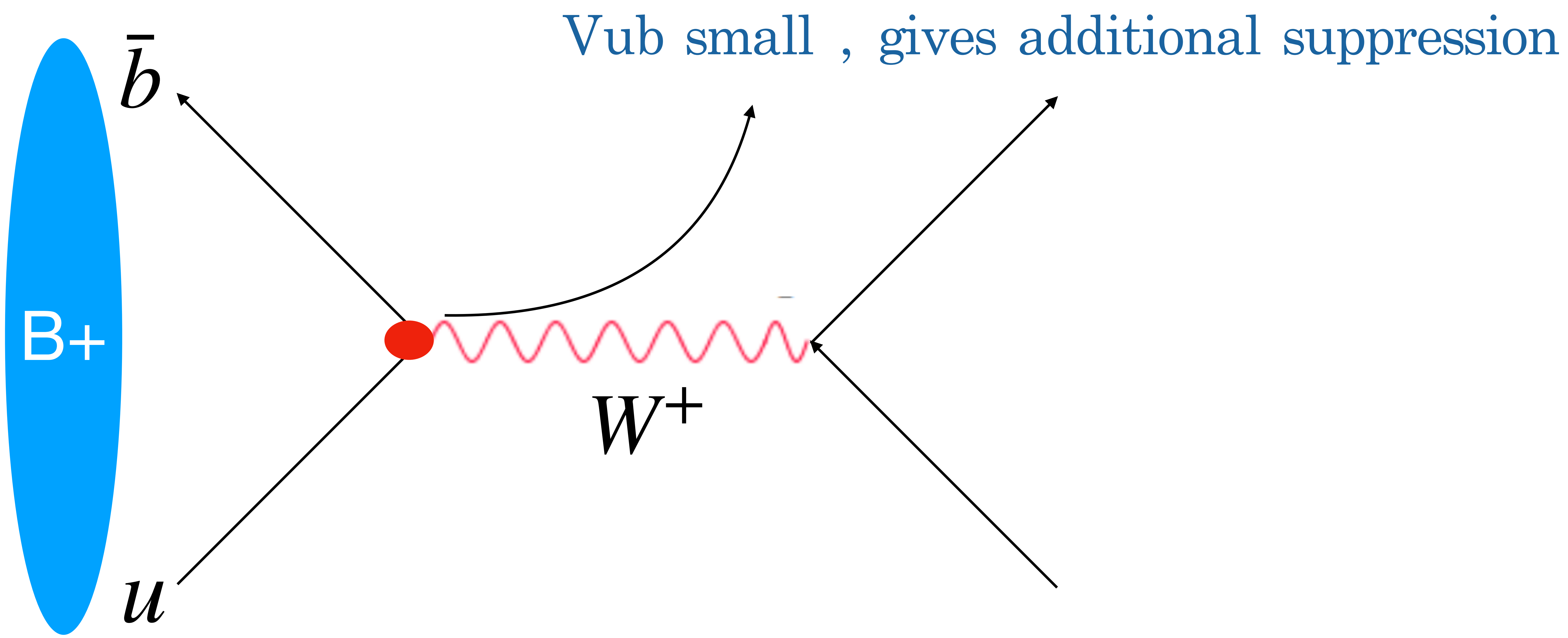
Decay is highly phase space suppressed

LLPs in SM

Why are they long-lived?

Reason 3 : Small coupling

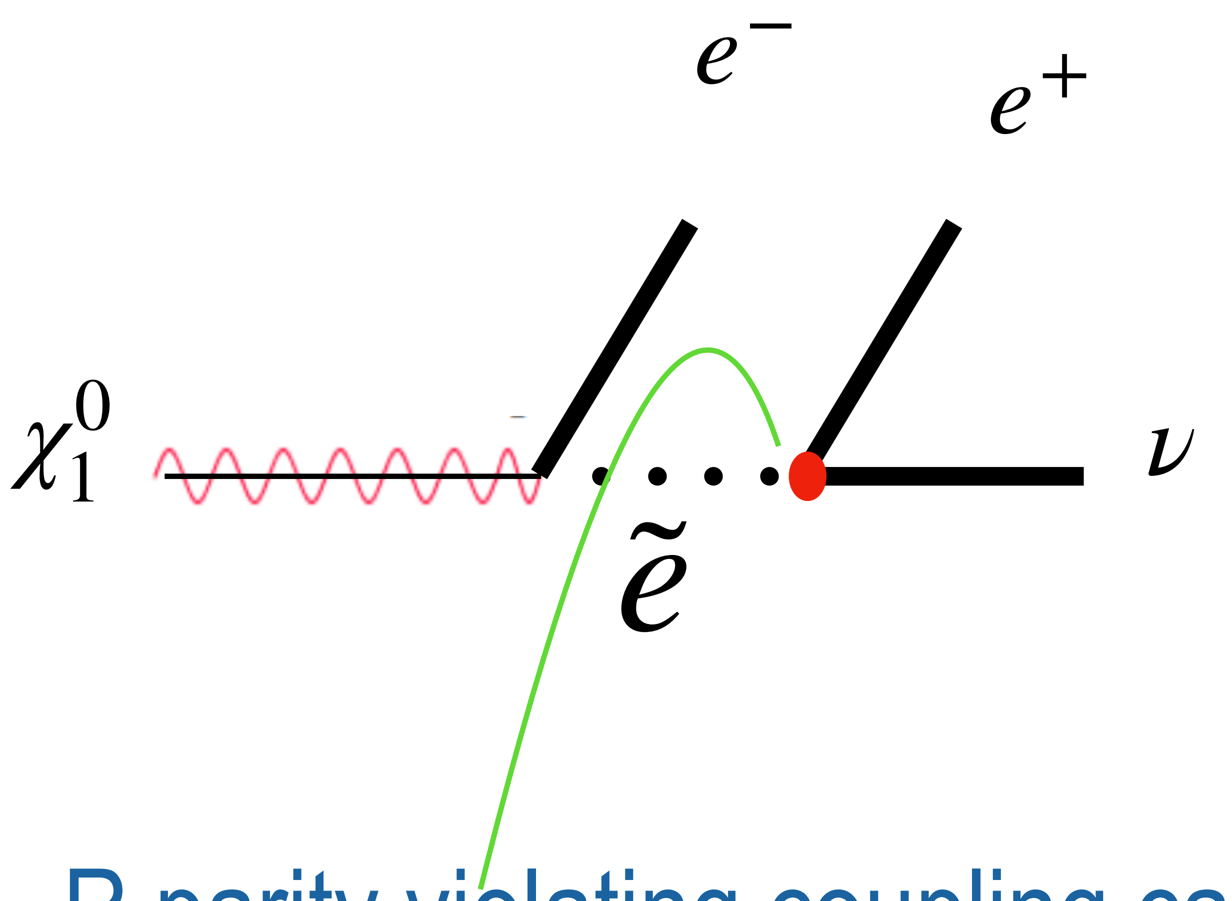
B+ decay in the SM



LLPs in BSM

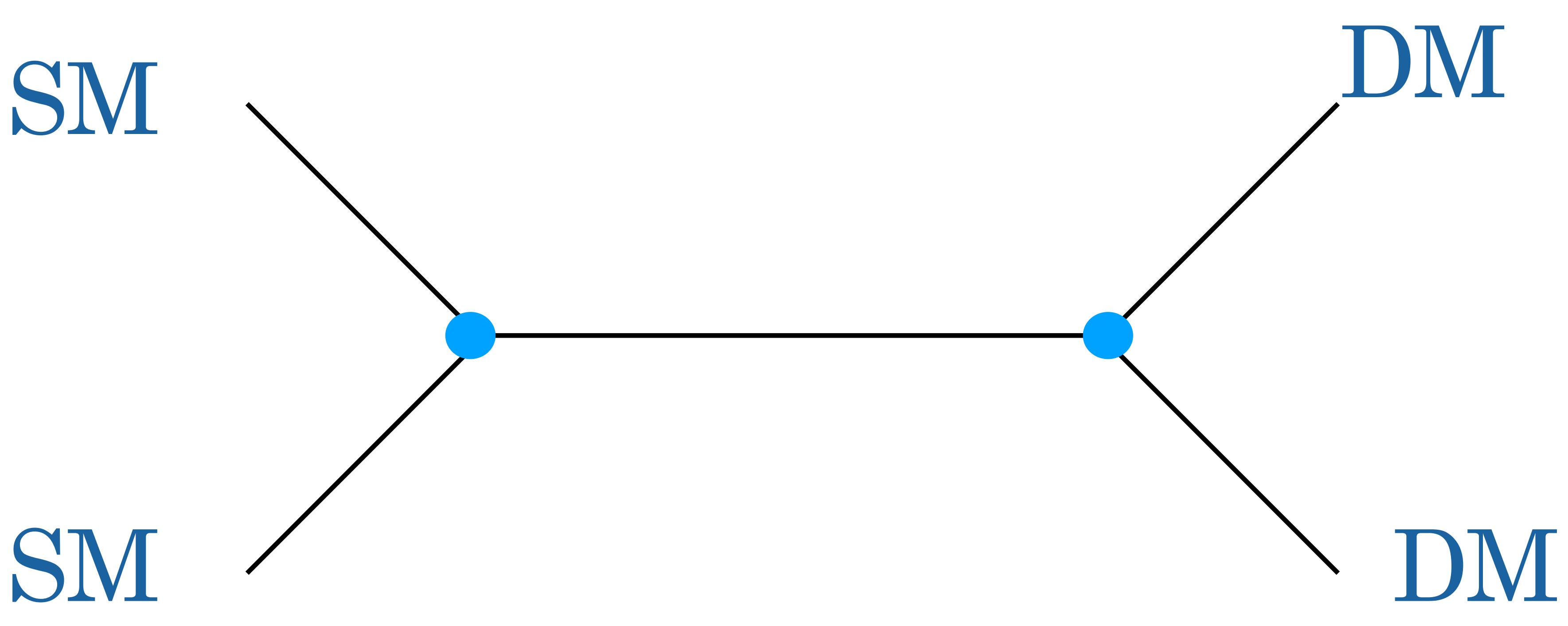
Case 1: Small Coupling

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



R parity violating coupling can be Arbitrarily small

Freeze-in Dark Matter



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

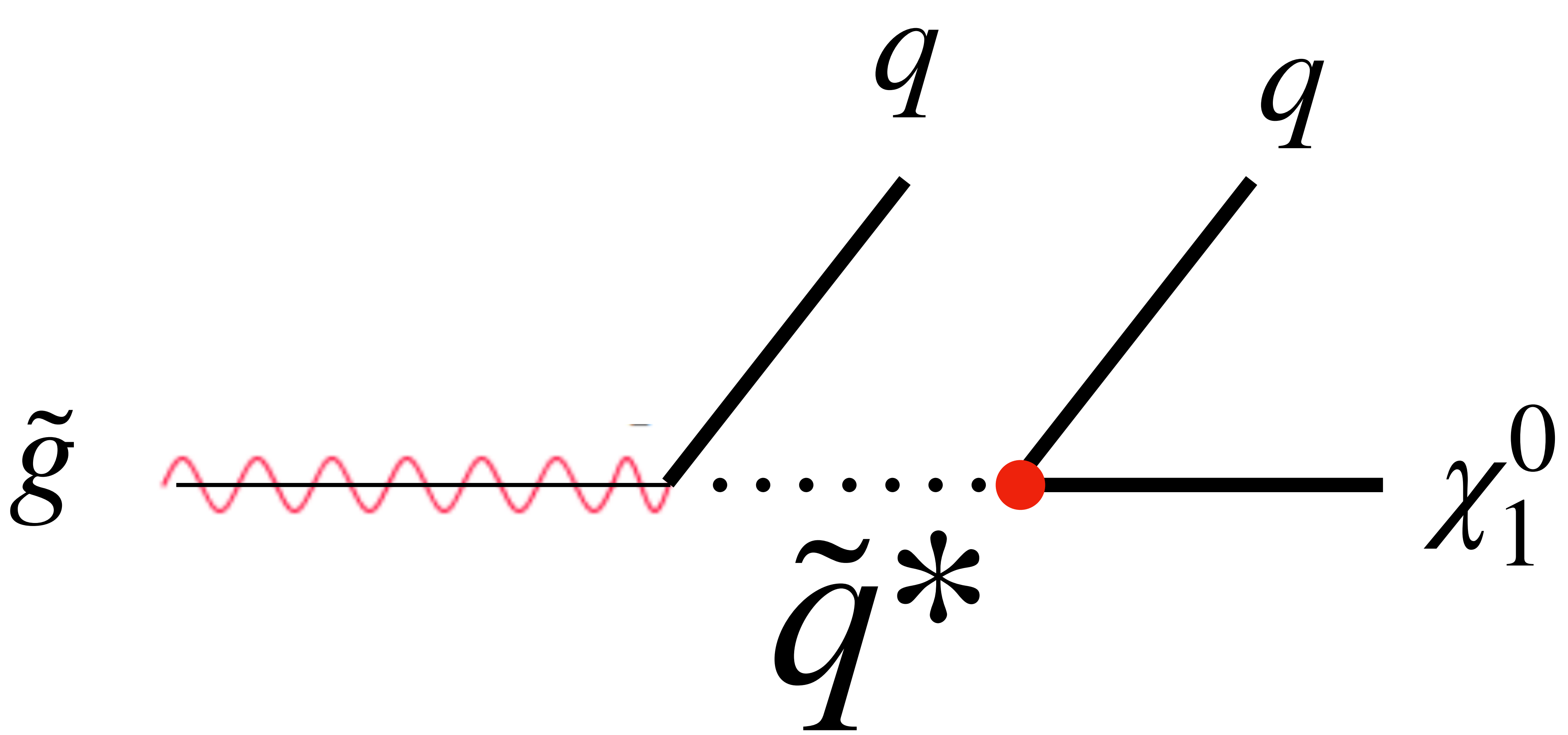
Many final states are possible depending on the spectrum and the type of coupling

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

And many other possibilities

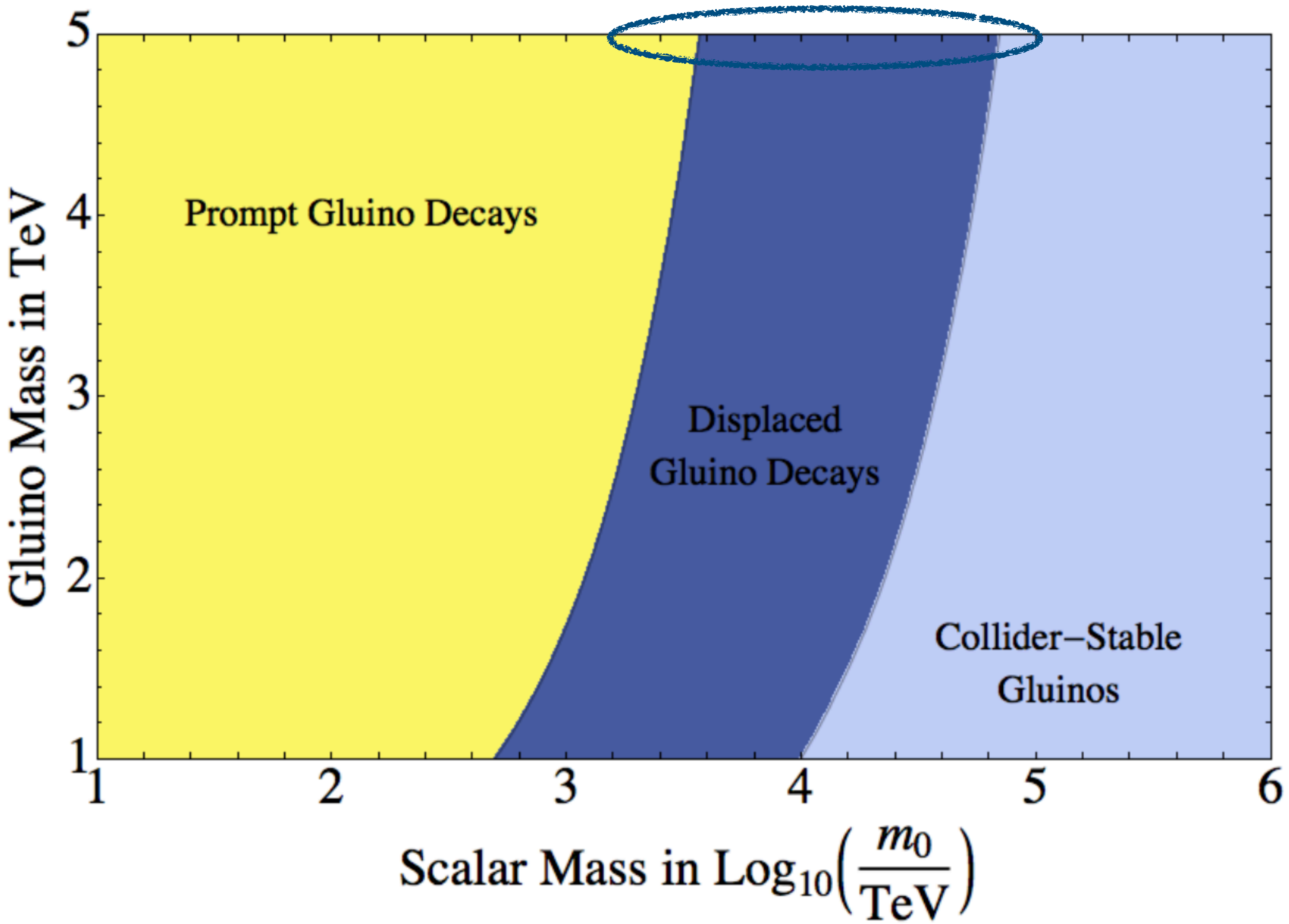
Case 2: Heavy propagator suppression

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



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

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)

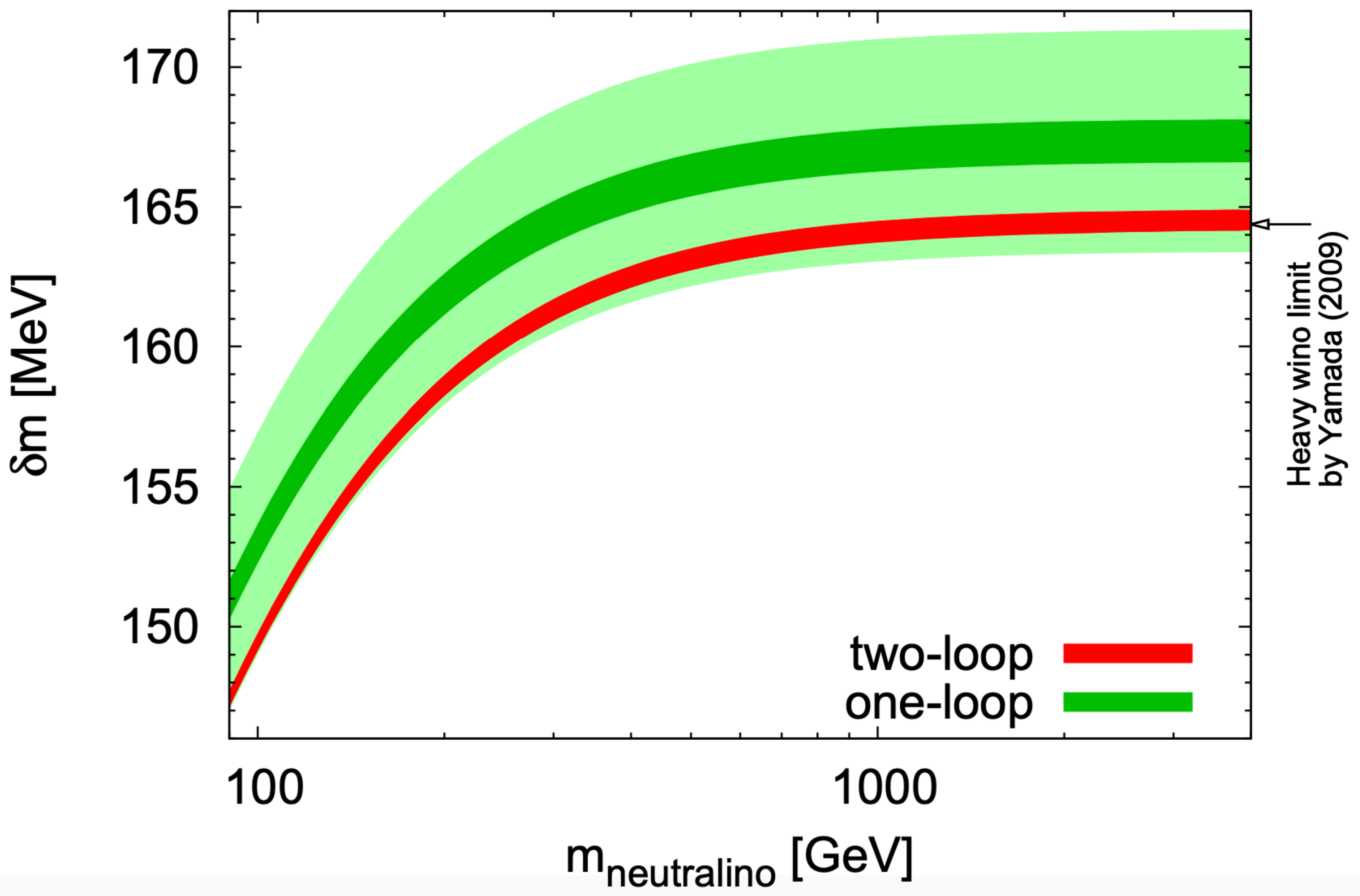
ATLAS Public note: ATL-PHYS-PUB-2019-019

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



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

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

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

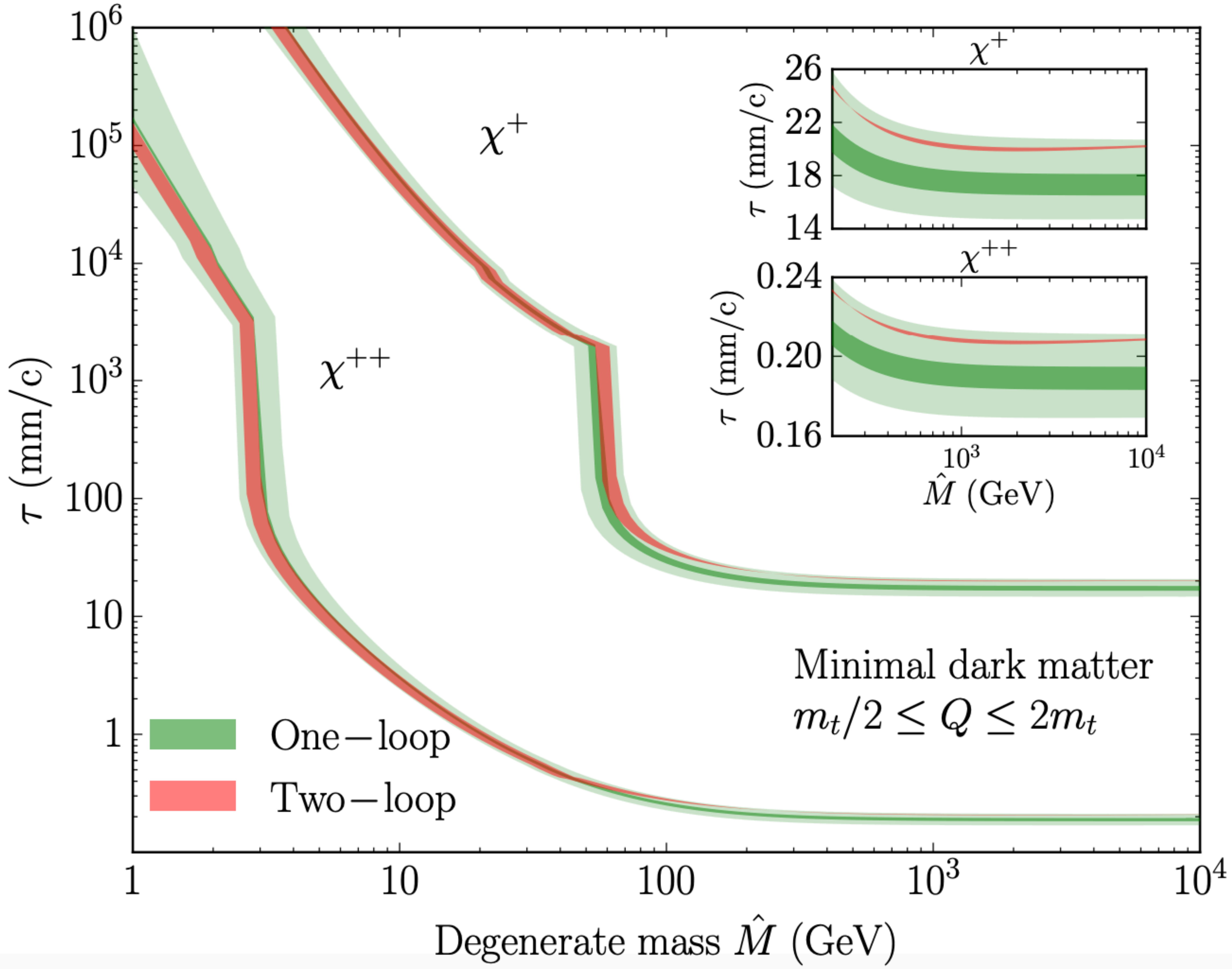
$$\chi^{\pm} \rightarrow \chi^{0} + l^{\pm} + \bar{\nu}_{l}$$

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

LLPs in BSM

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



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

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

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

Dark Sectors

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

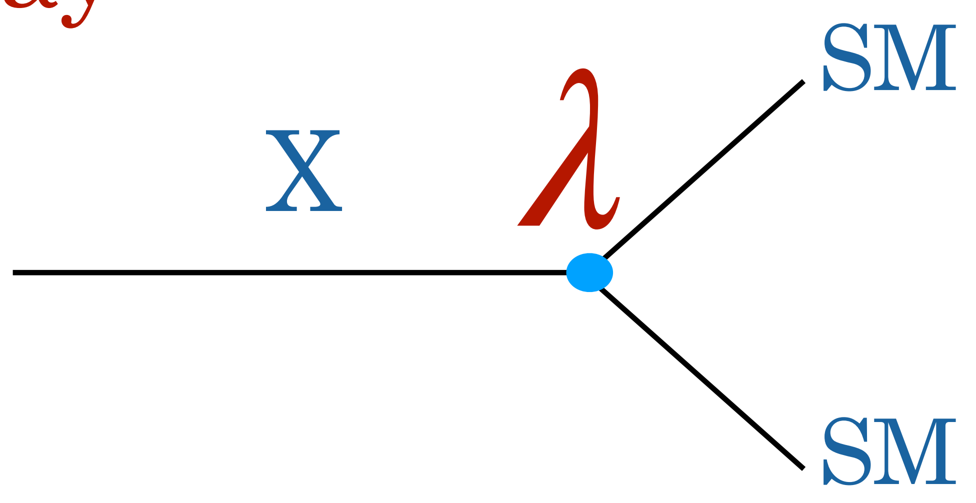
Possibility of Small Decay width

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

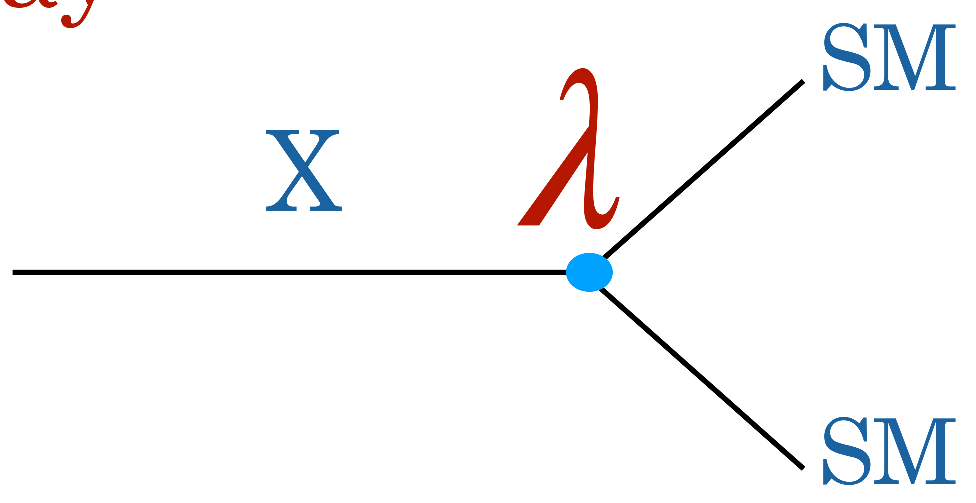


Suppose the coupling λ is small: X is LLP

Easy to make X an LLP

LLP production

Decay



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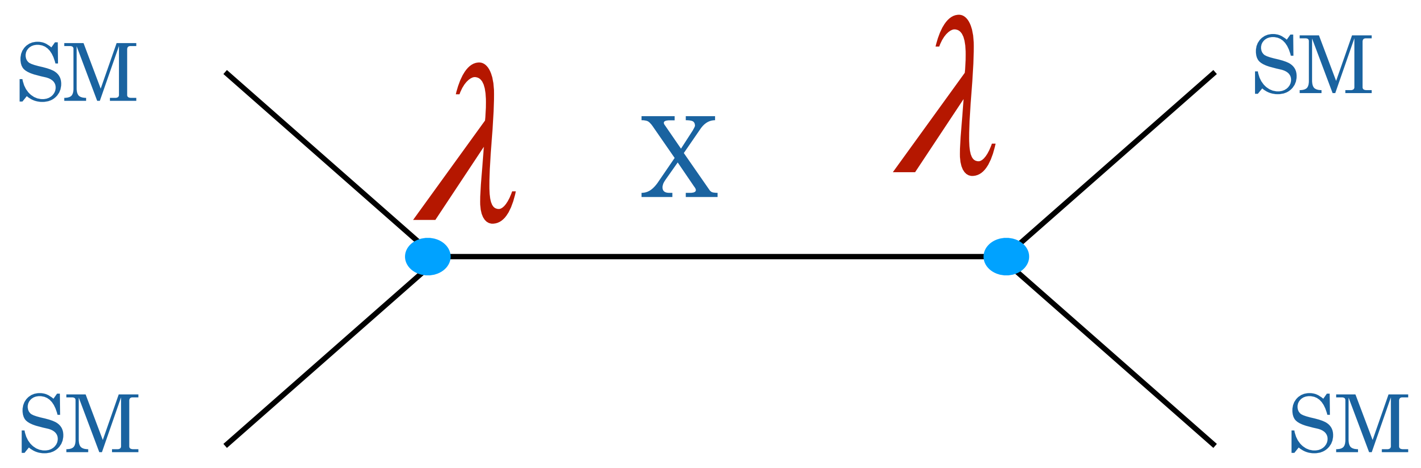
Production mode



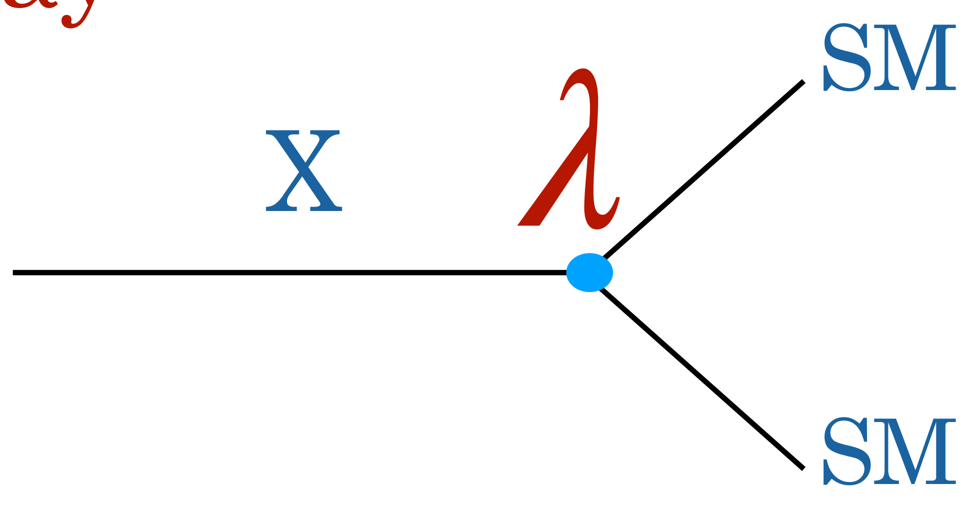
Single production cross section $\propto \lambda^4$

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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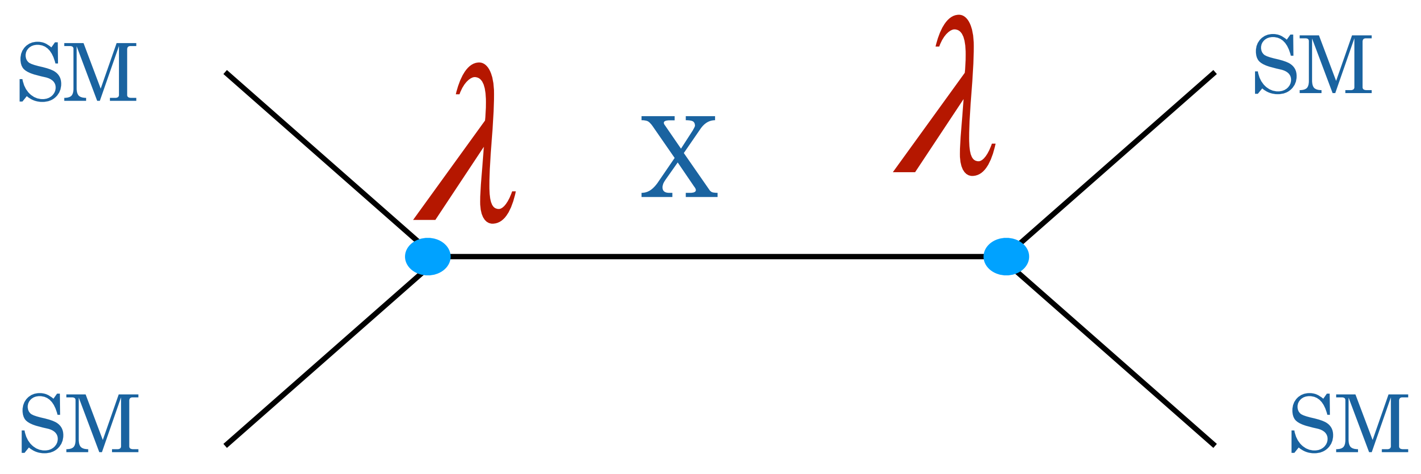

Single production cross section $\propto \lambda^4$
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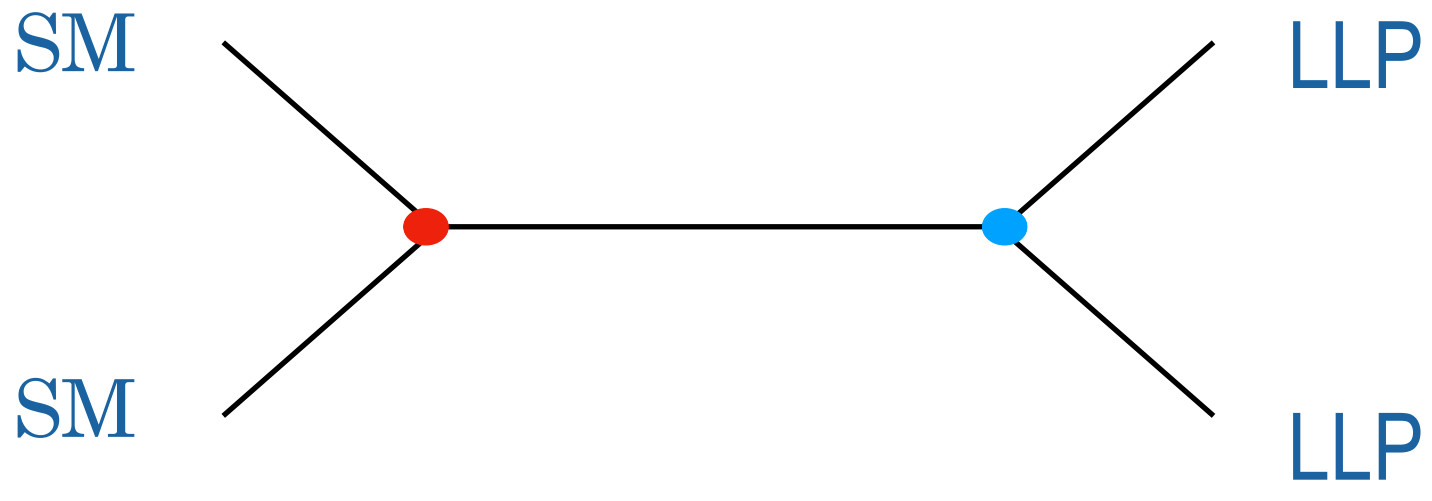
"High" and "small" will depend on the process and the detector

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

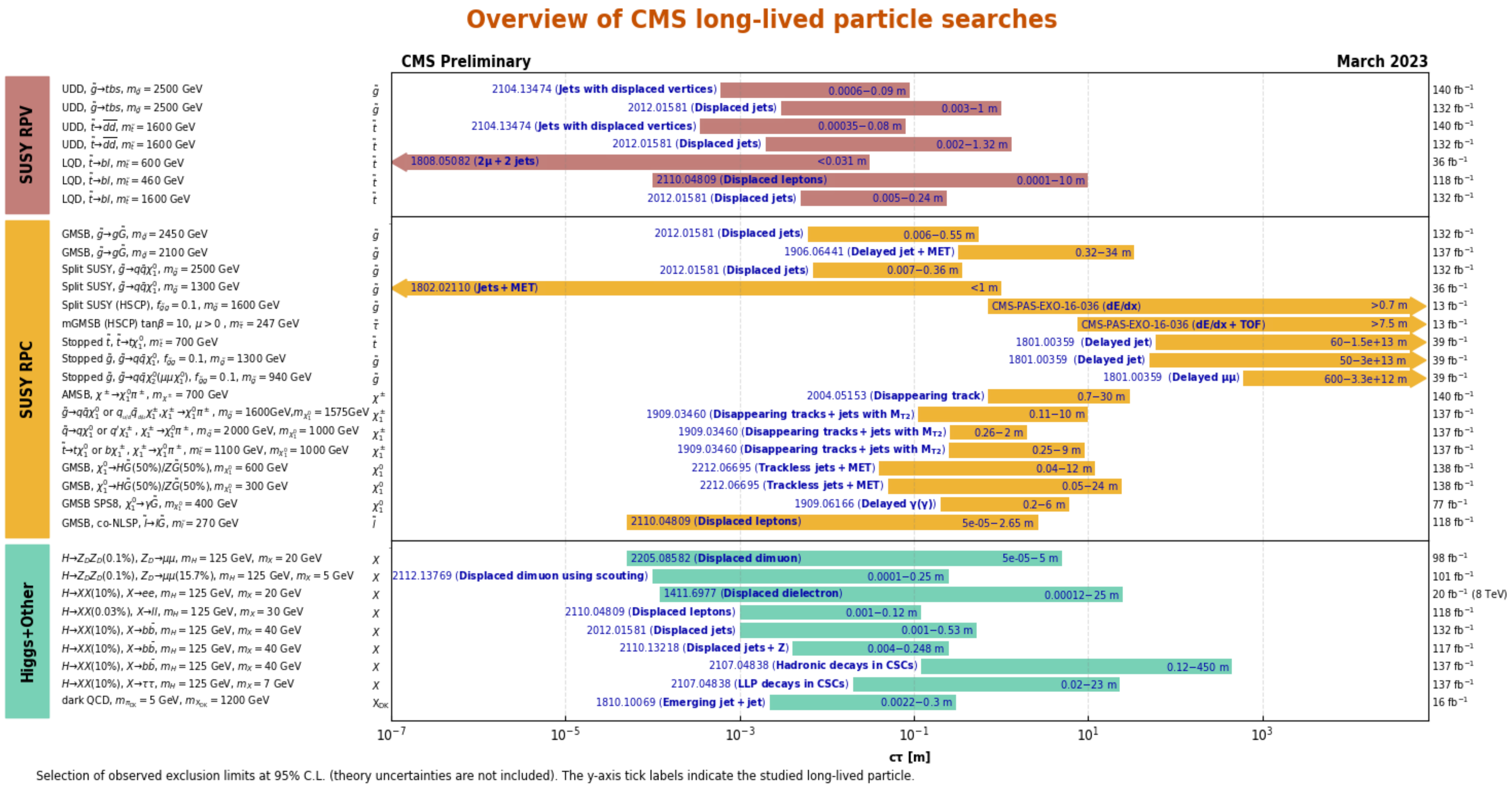
$$\chi^{\pm} \rightarrow \chi^{0} + \pi^{\pm}$$

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

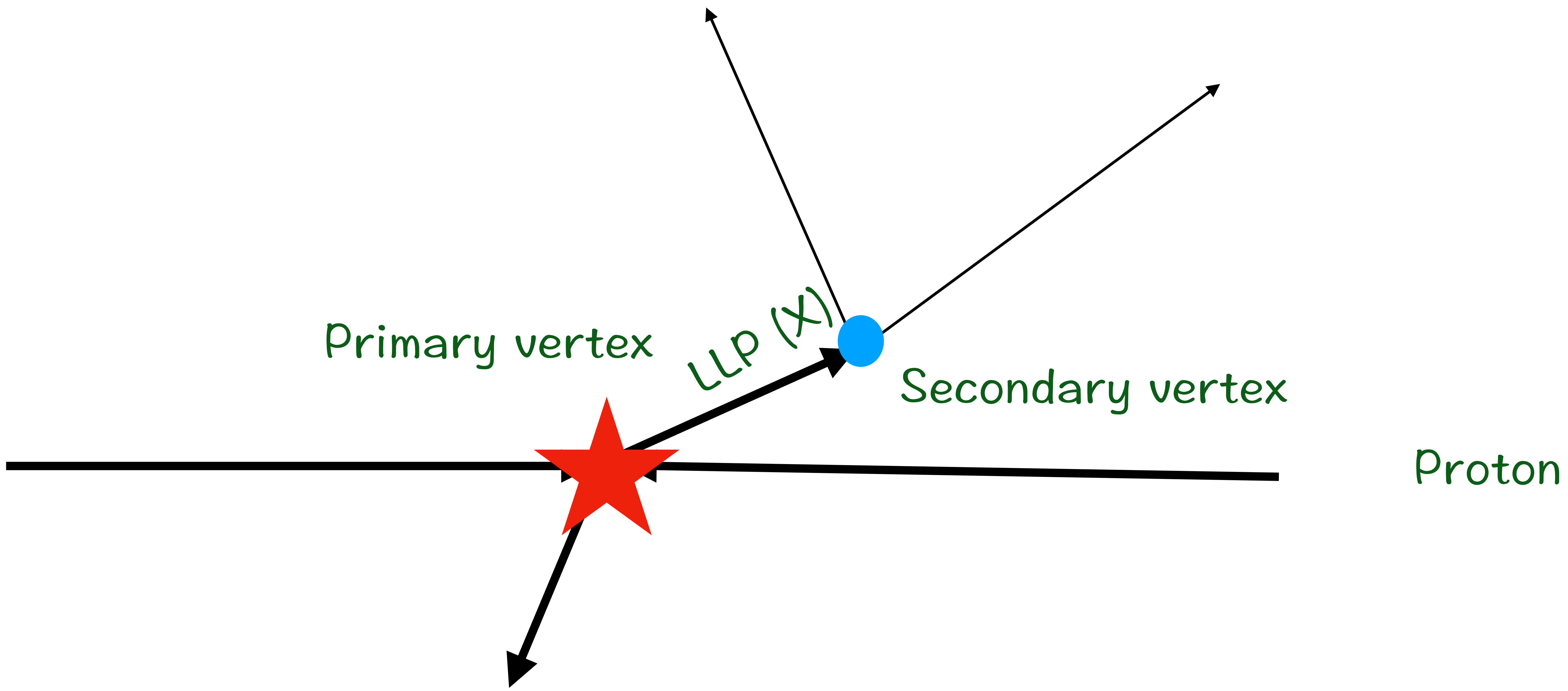
Simple example

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

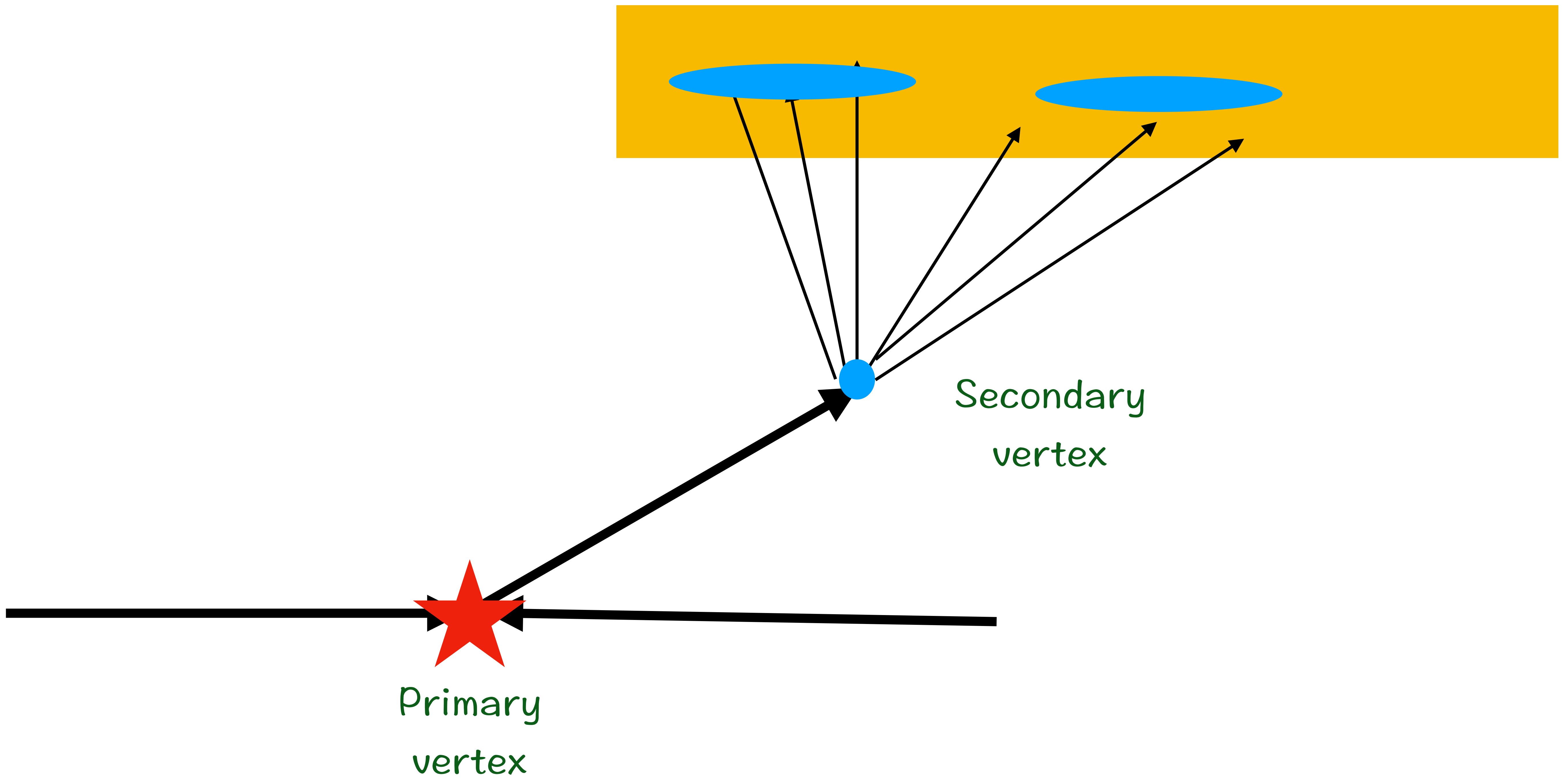
$$pp \to X_{LLP}X_{LLP},\ X_{LLP} \to q + \bar{q}$$ **(jets)**

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

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

Nice features

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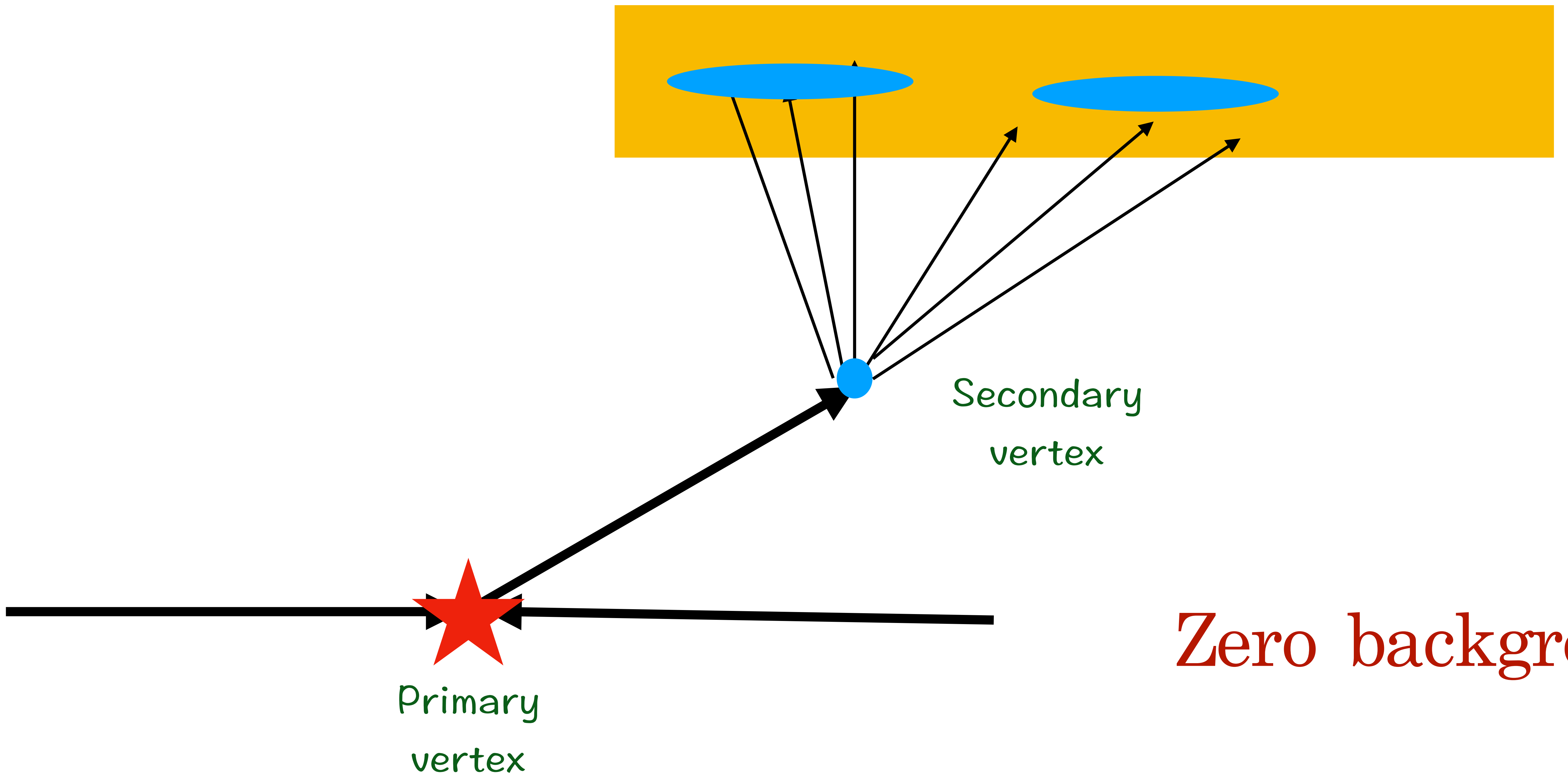
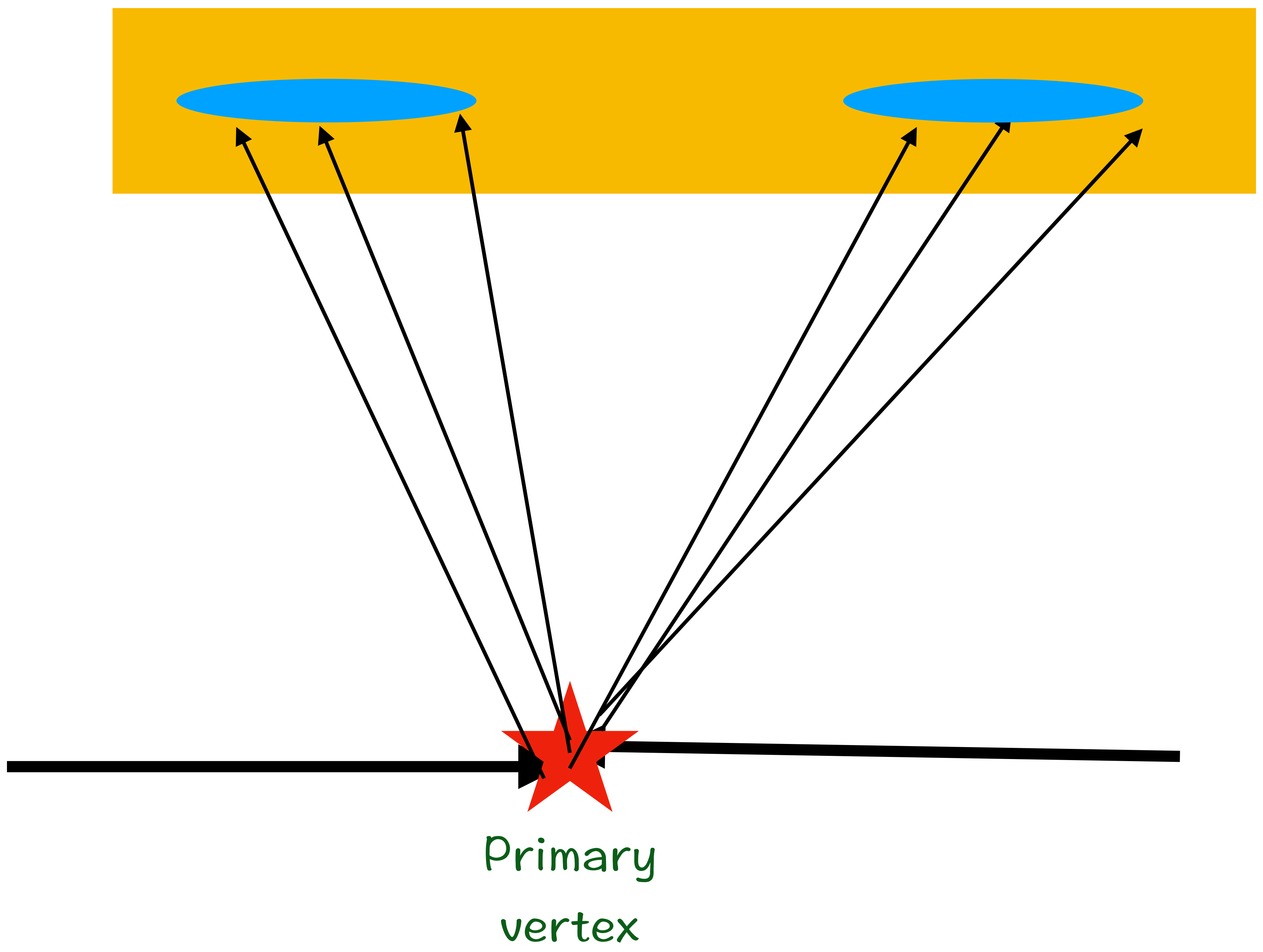
Displaced jets

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



Prompt QCD jets

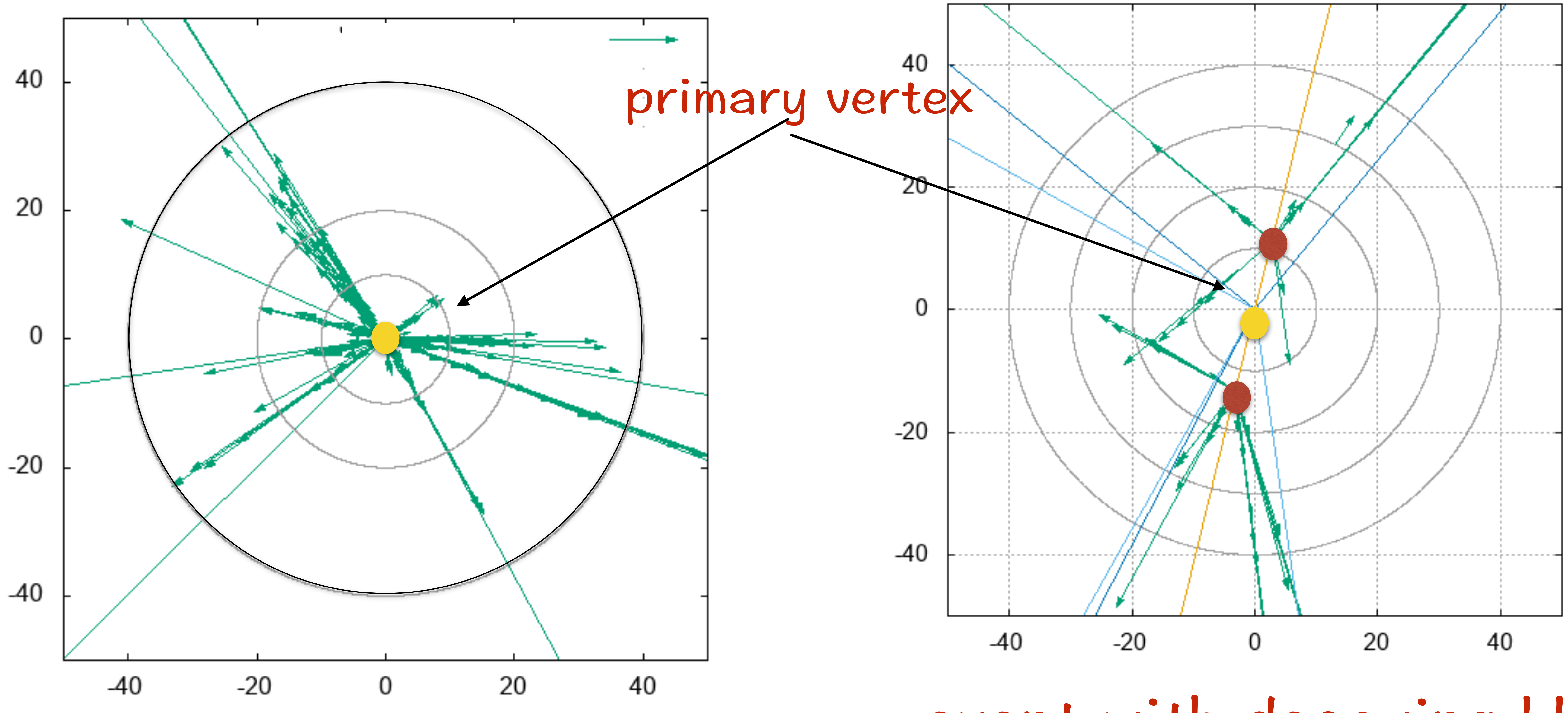
Energy deposit in the calorimeter, associated tracks from the primary vertex



Zero background ??

R parity violation

View along the beam axis



a generic event

event with decaying LLP

Challenge 1

SM backgrounds

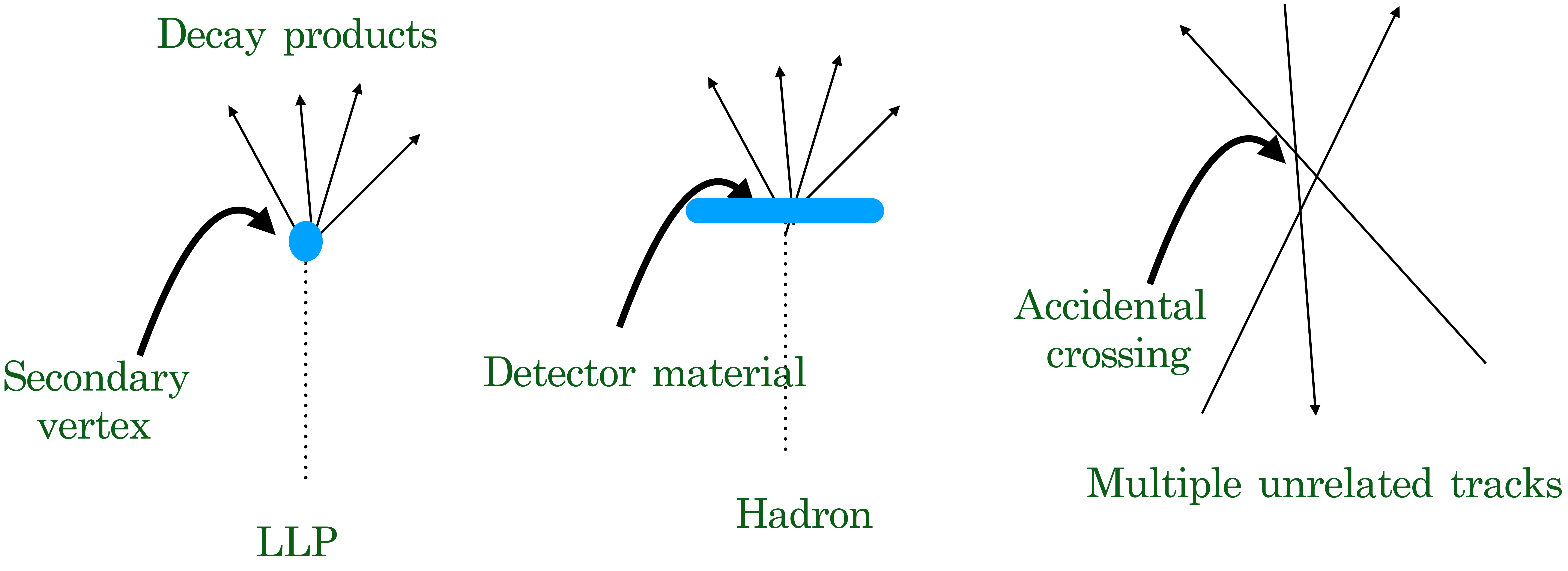
- There are a few SM hadrons which can also give rise to displaced vertex signature
    - their lifetimes and masses are known => better handle

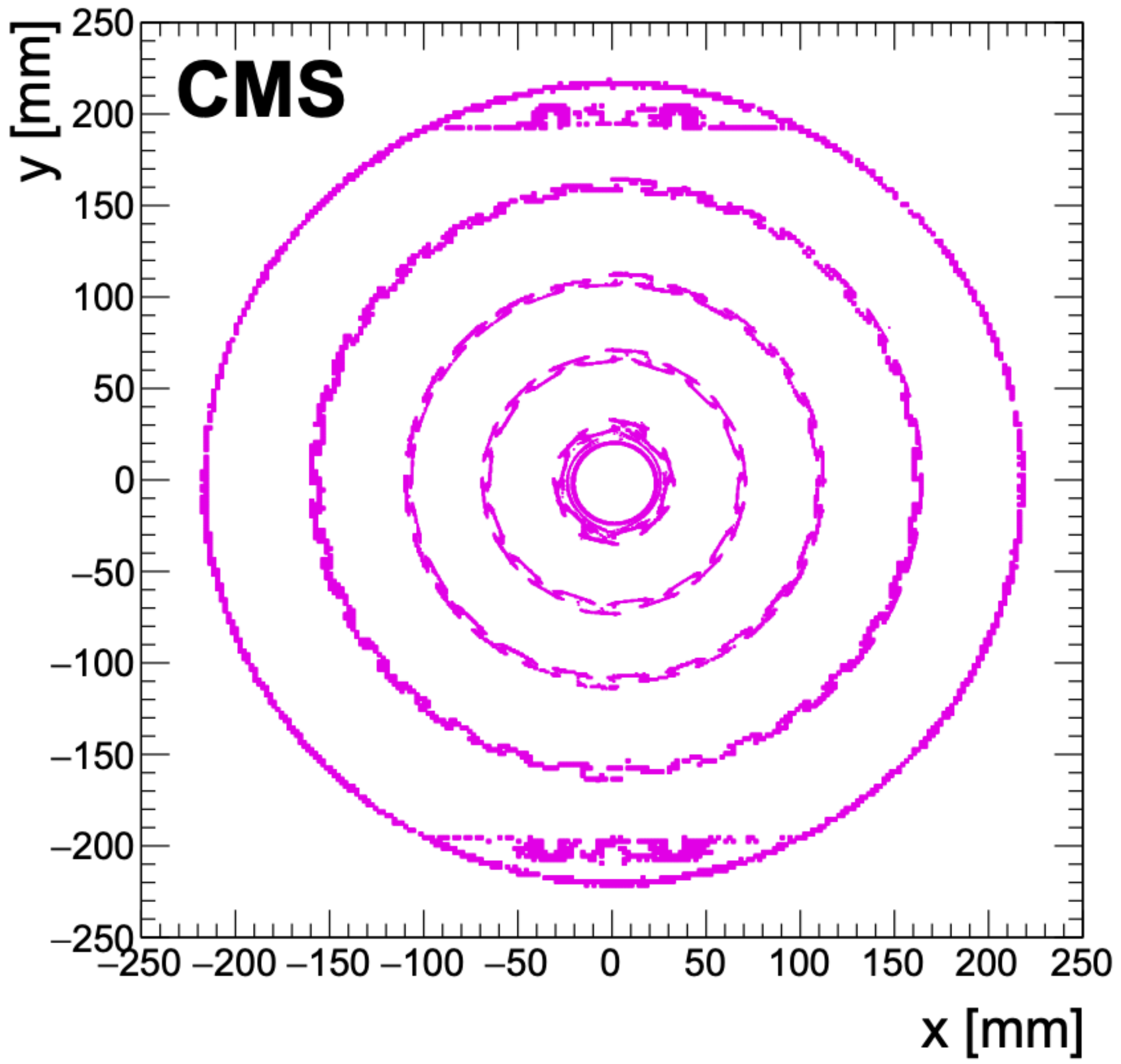
SM backgrounds

- 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



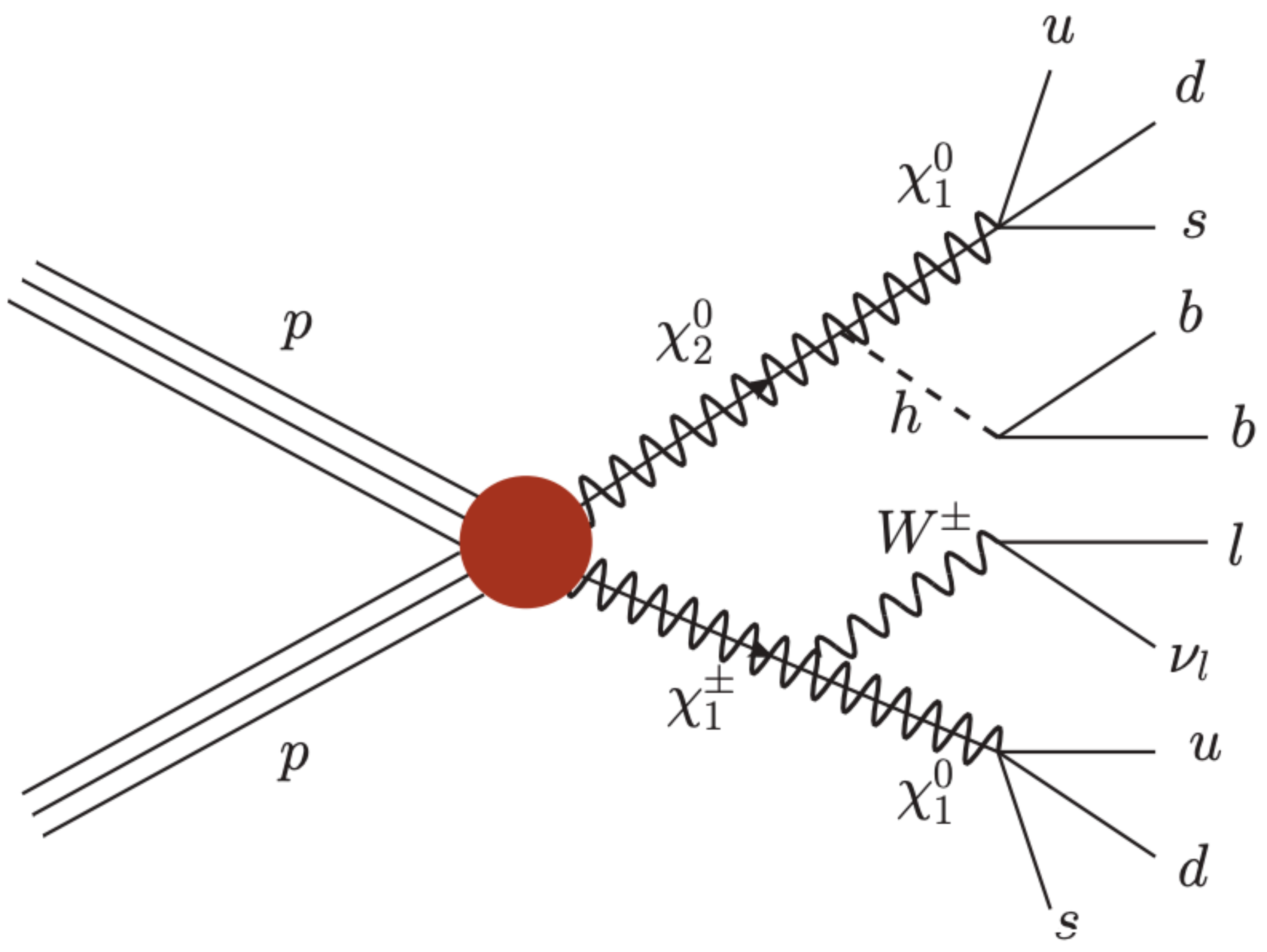


Material veto map (CMS)
2012.01581

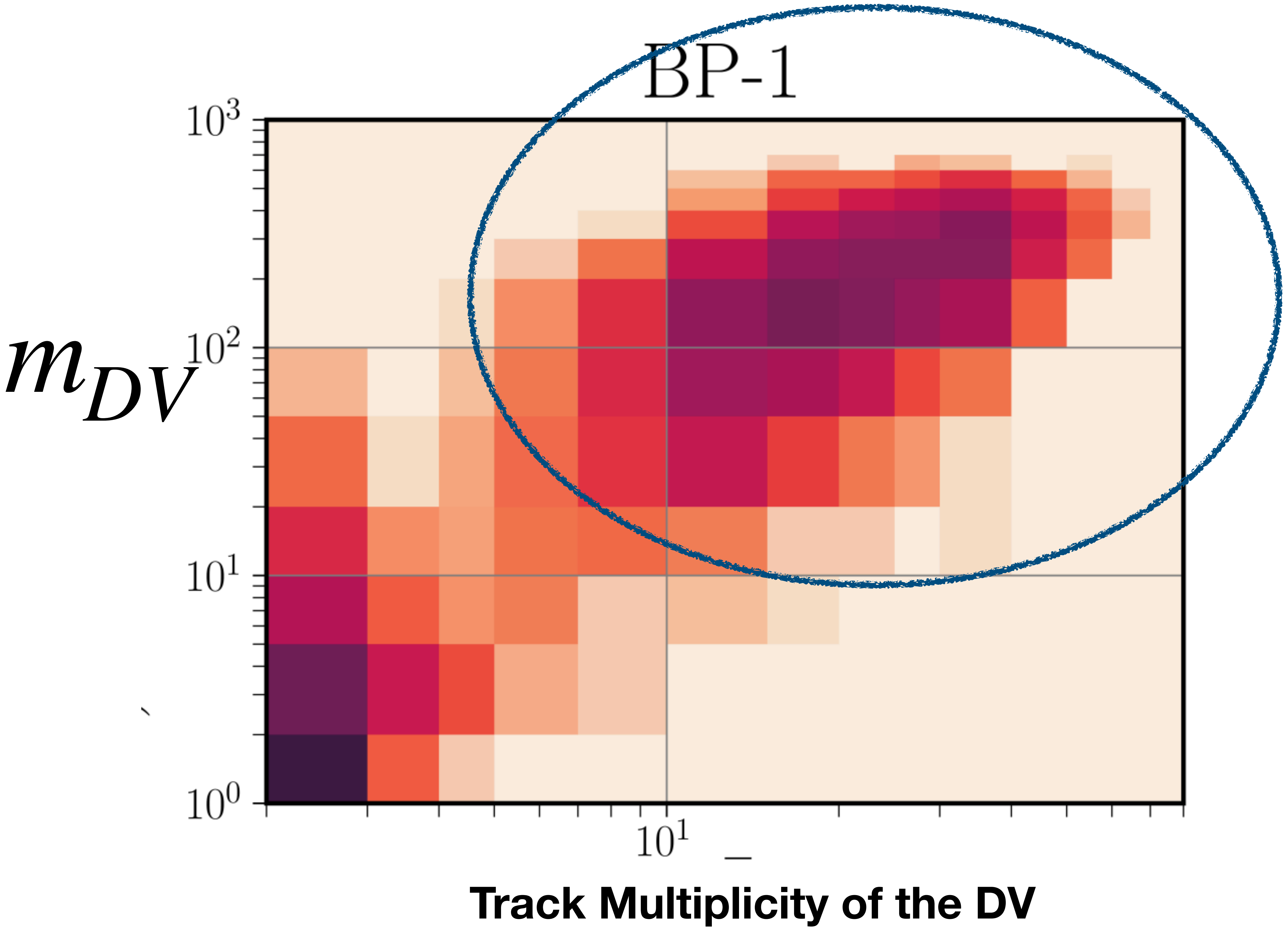
SM backgrounds

- 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,..)

↓

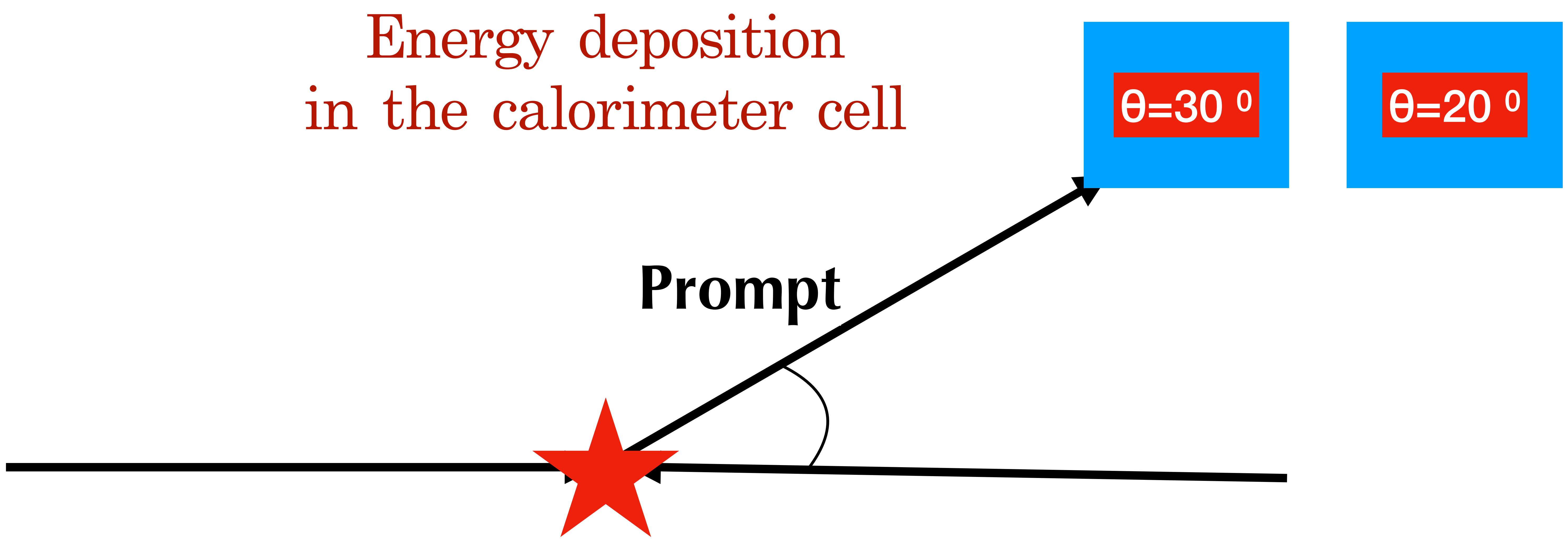
Apply detector response

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)

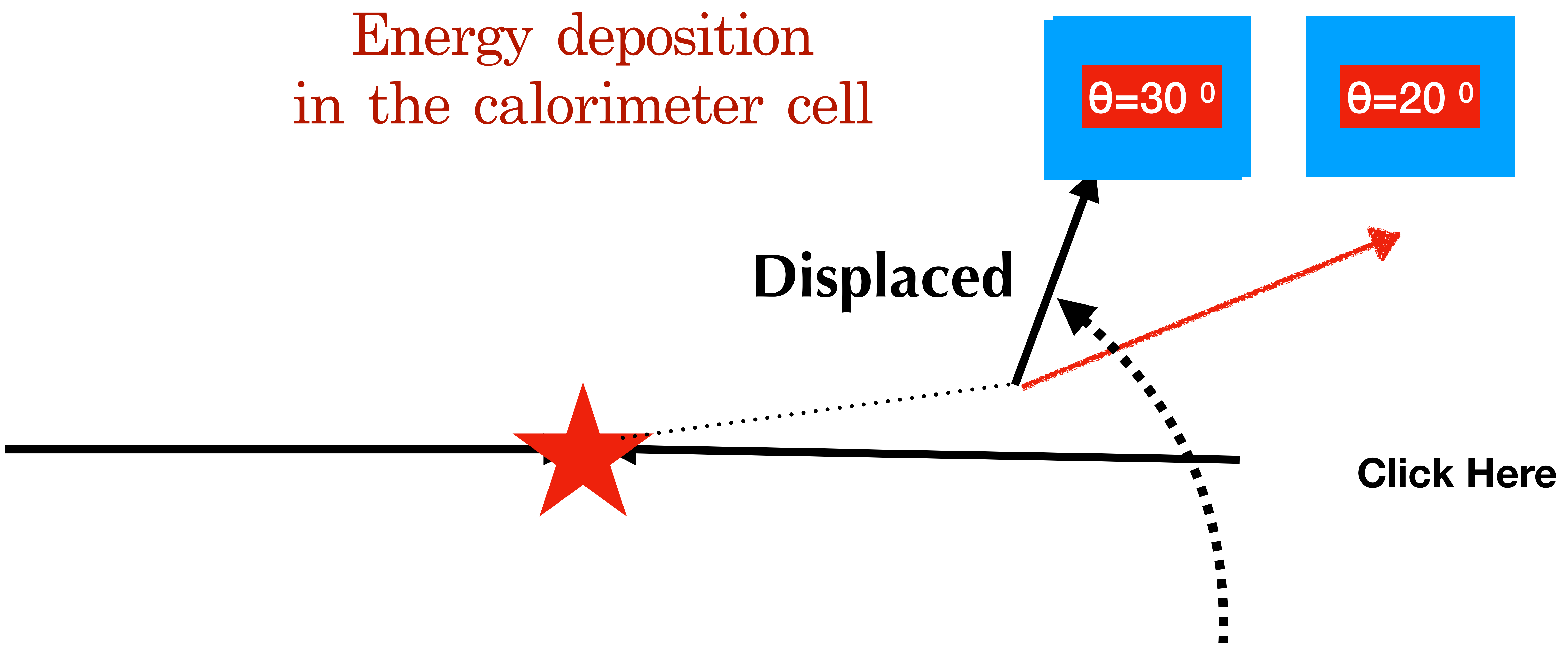


Orientation from the beam axis of the particle = 30 degree

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



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

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

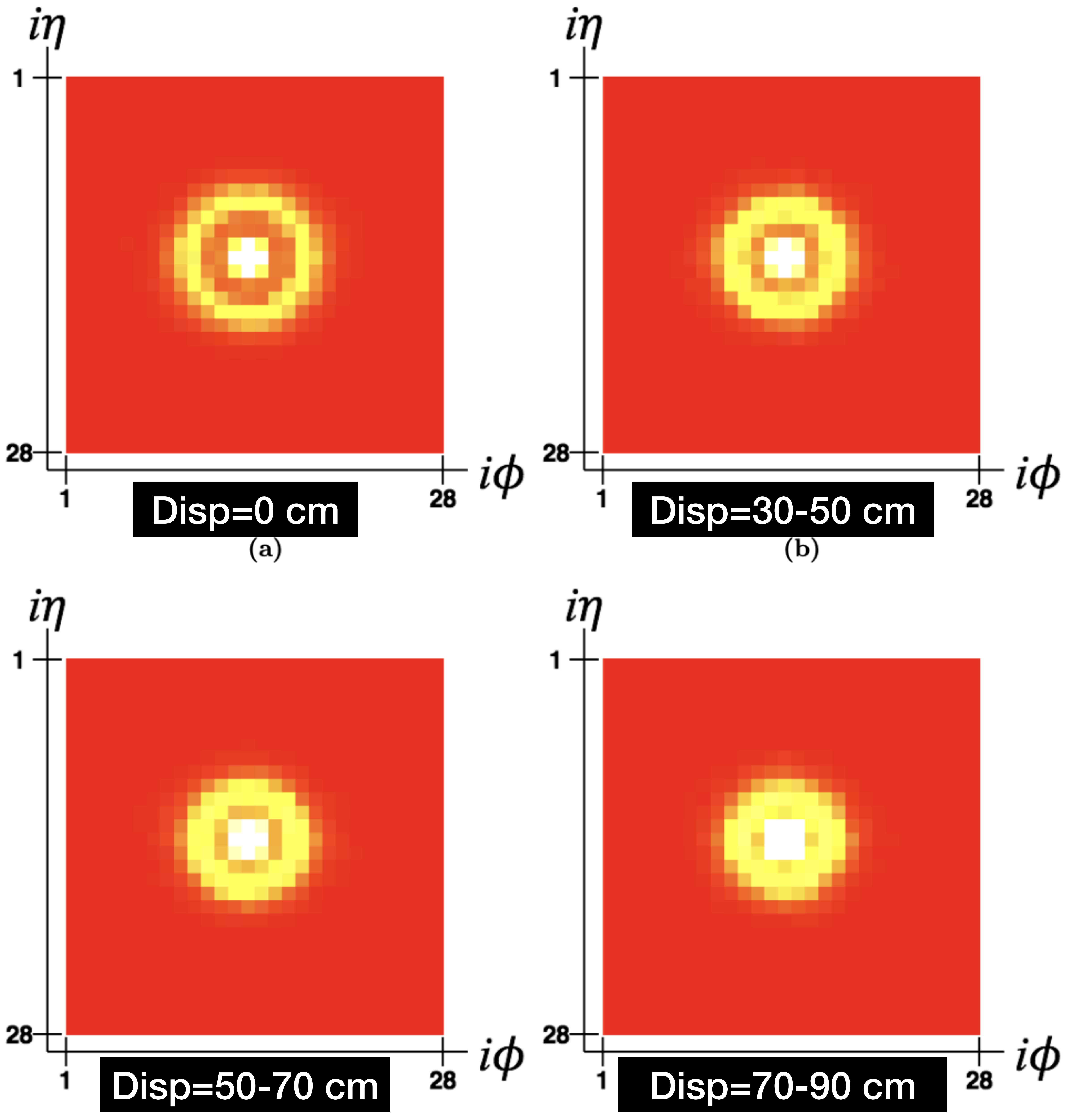
Discrimination between prompt and long-lived particles using convolutional neural network

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

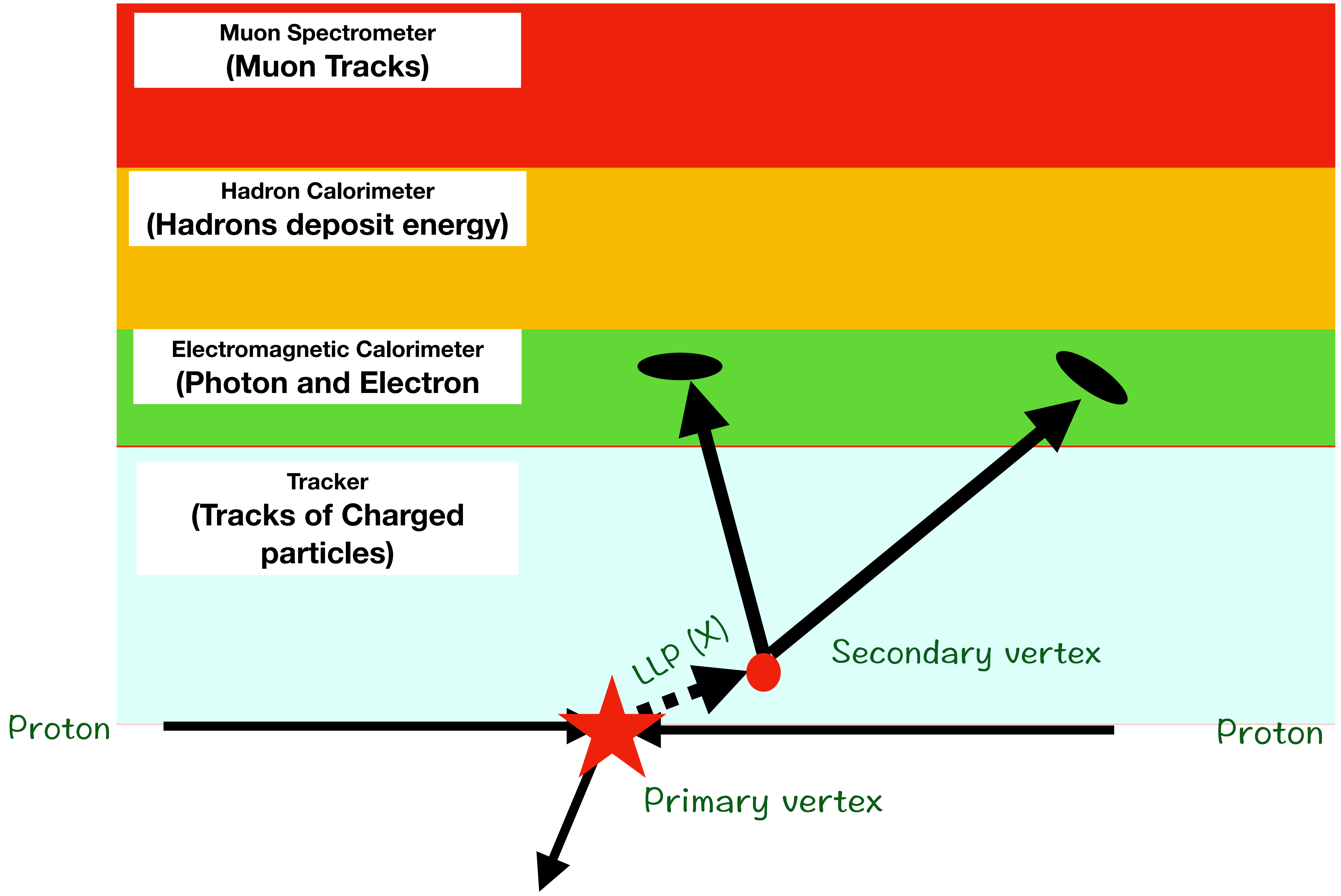


Click Here

Challenge 3

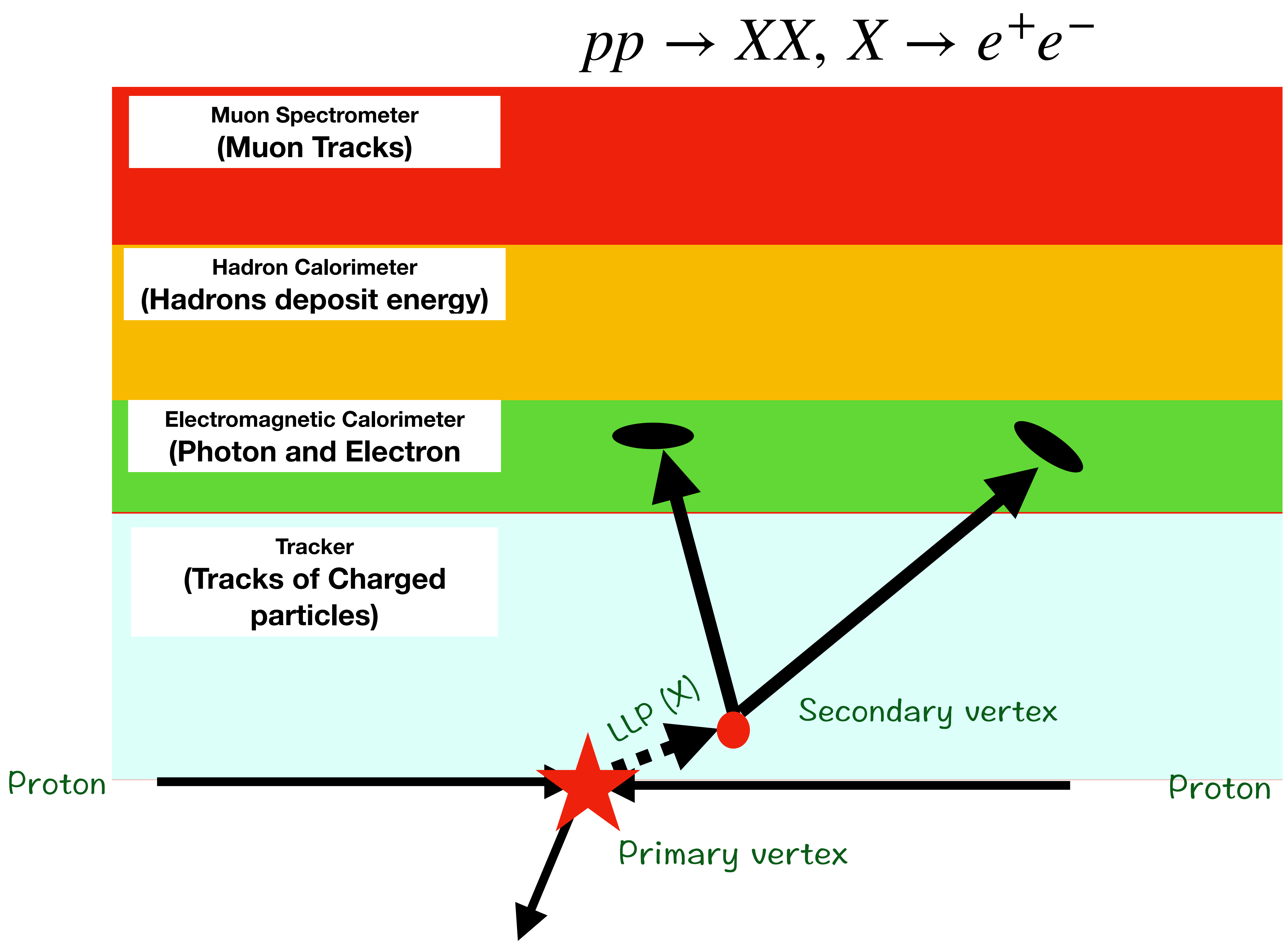
Where LLP decays ?

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

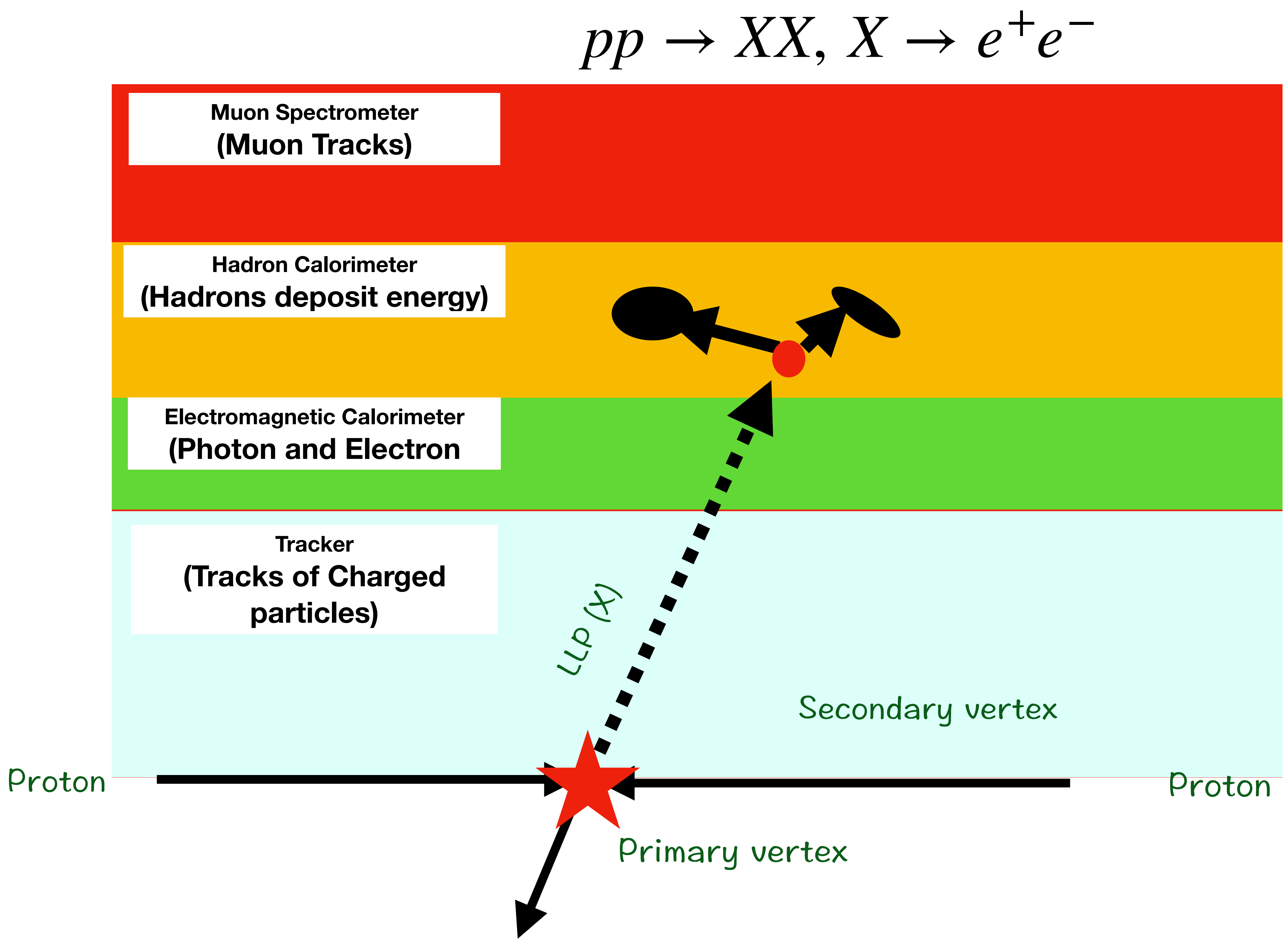


LLP decays inside the tracker

Where LLP decays ?



LLP decays inside the tracker



LLP decays inside the hadronic calorimeter

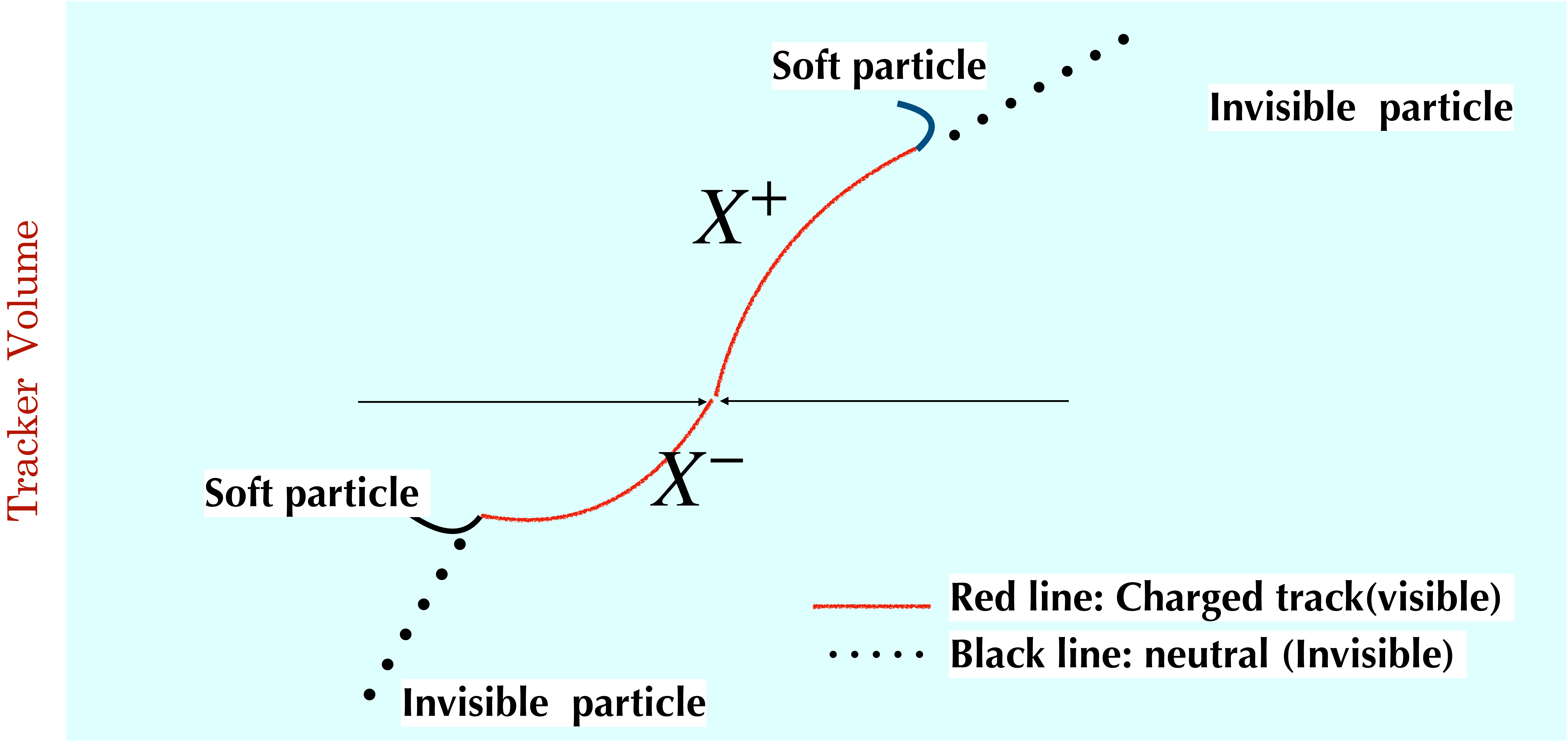
Signatures will be completely different in these two cases

Challenge 4

Signature of LLPs

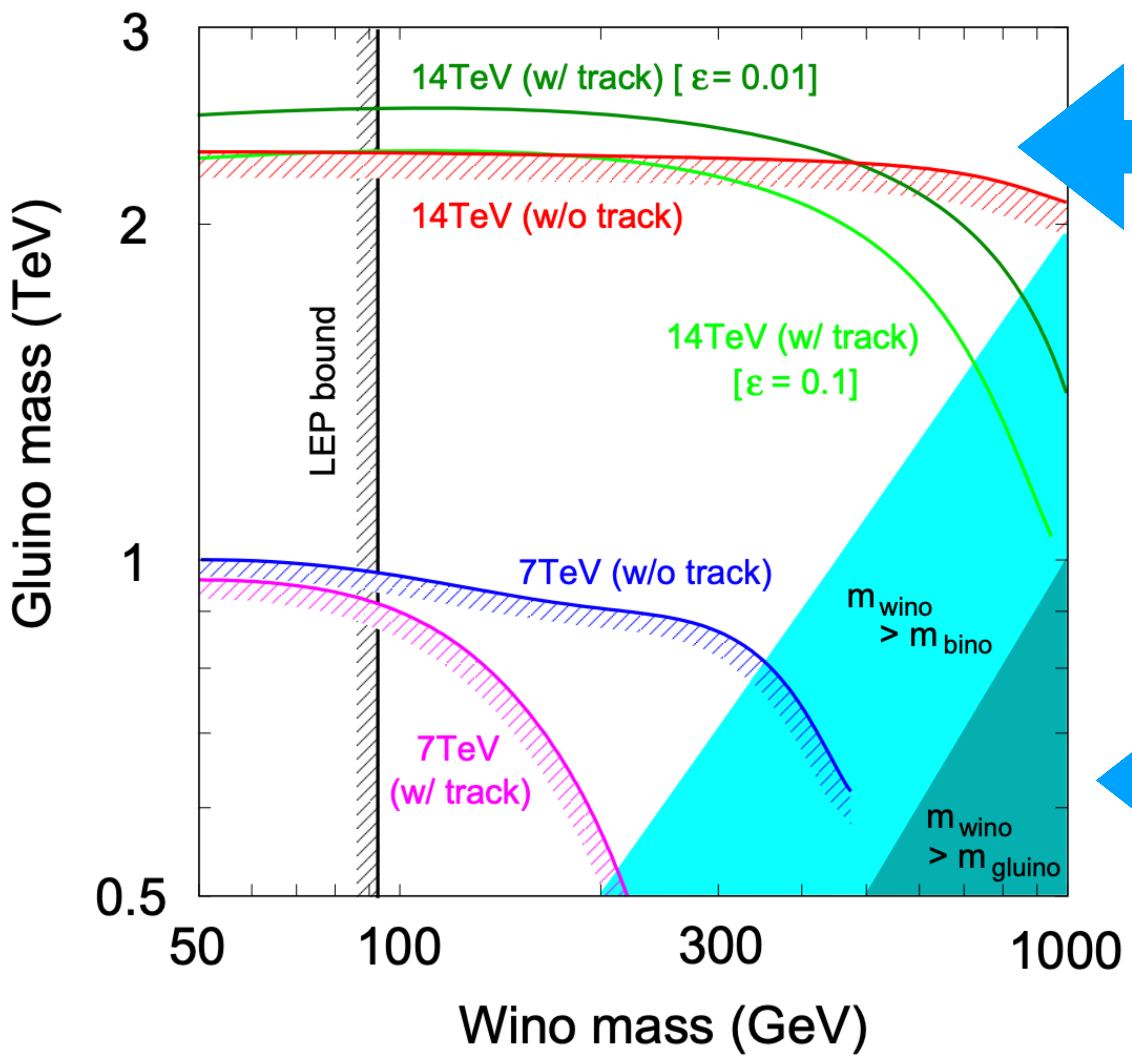
Disappearing Charged track

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



Significant improvements in the analysis techniques

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



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

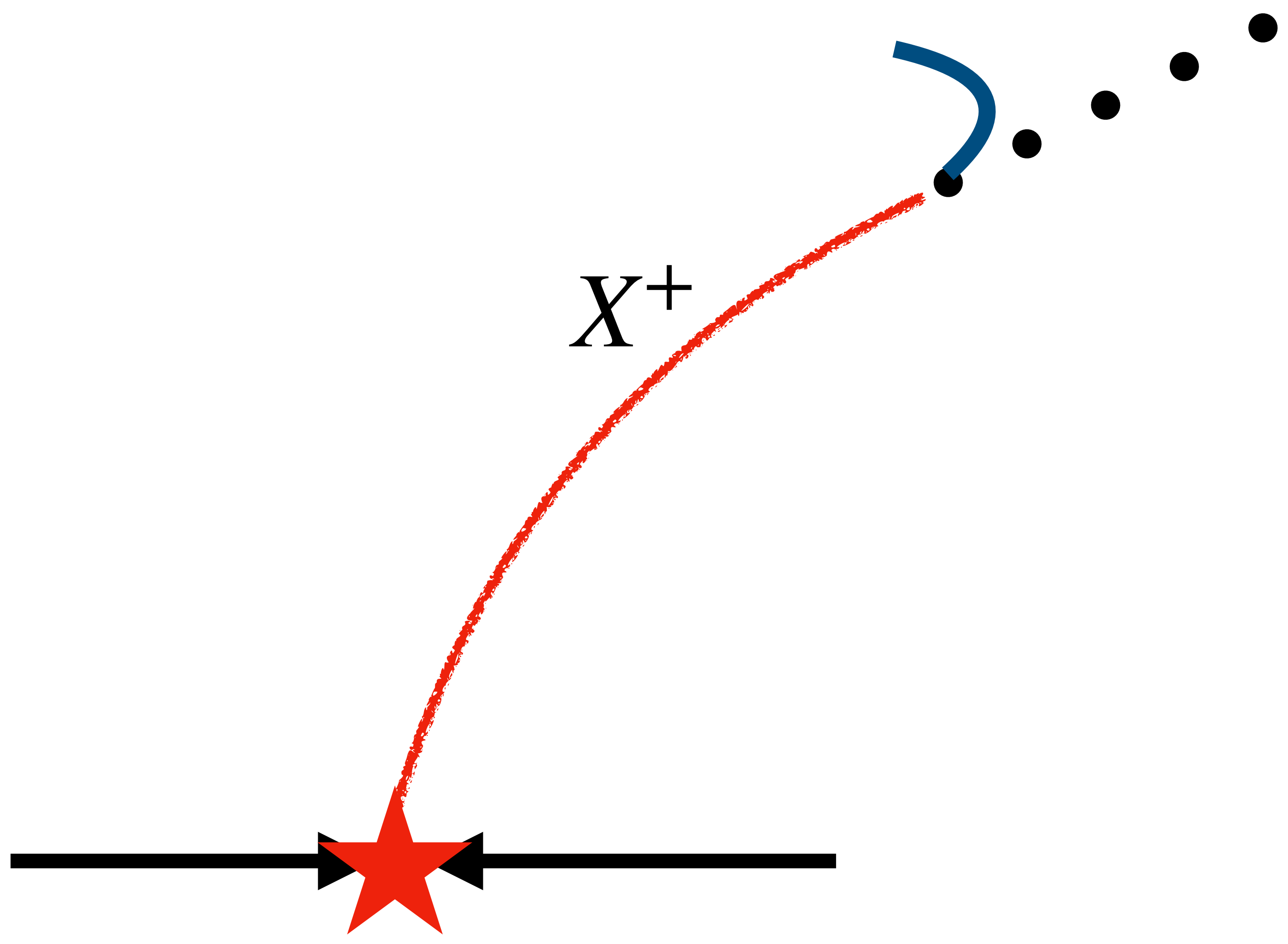
Also by CMS collaboration

Challenge 5

How do we identify LLP events ?

Soft particle

disappearing tracks =>
easy for identification?

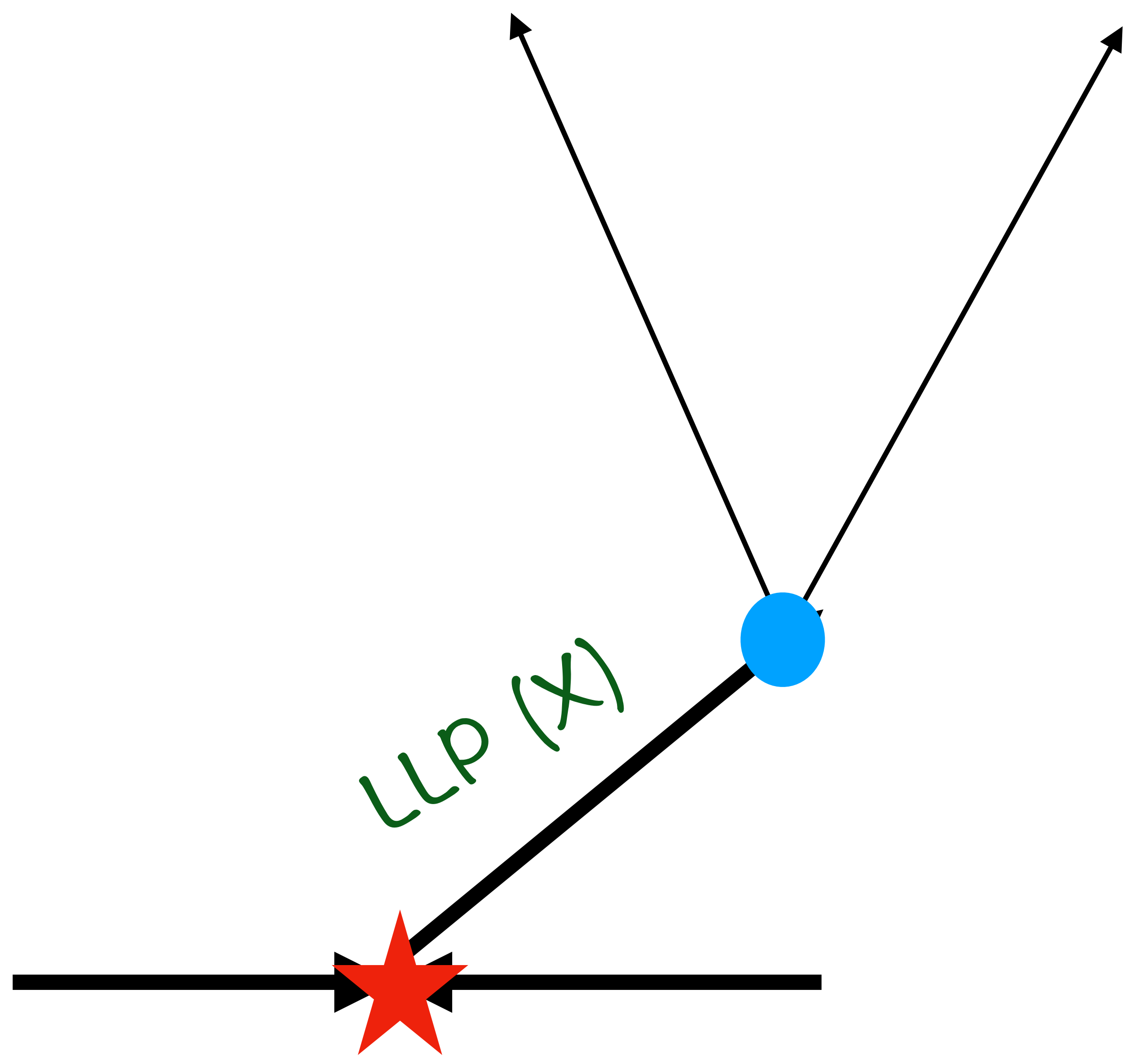


Tracking not available at Level 1
Use jet or Missing Transverse energy(MET) trigger to store the events and reconstruct the disappearing track in the offline analysis

MET >110 GeV

ATLAS analysis 2201.02472

Displaced electron

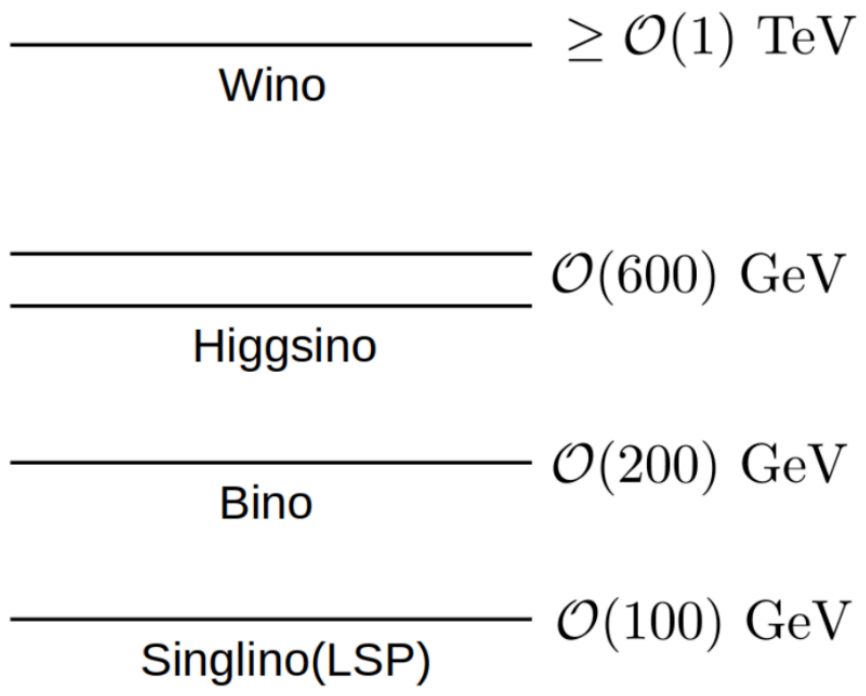


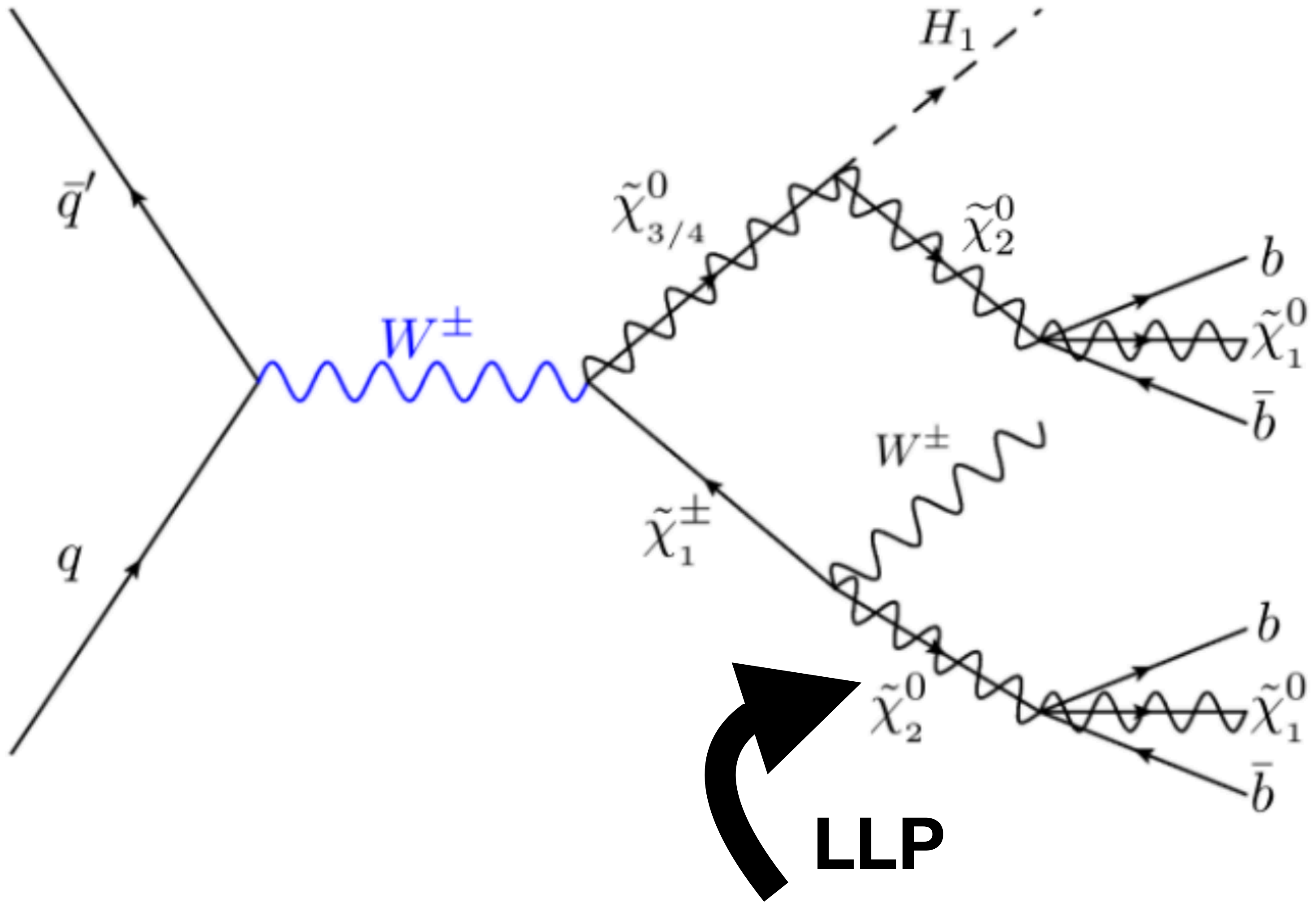
Use single or double photon trigger to store the event
Single photon p_T >140 GeV
Double photon p_T > 50 GeV

ATLAS analysis 1907.10037

LLP:R-parity conserving NMSSM

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



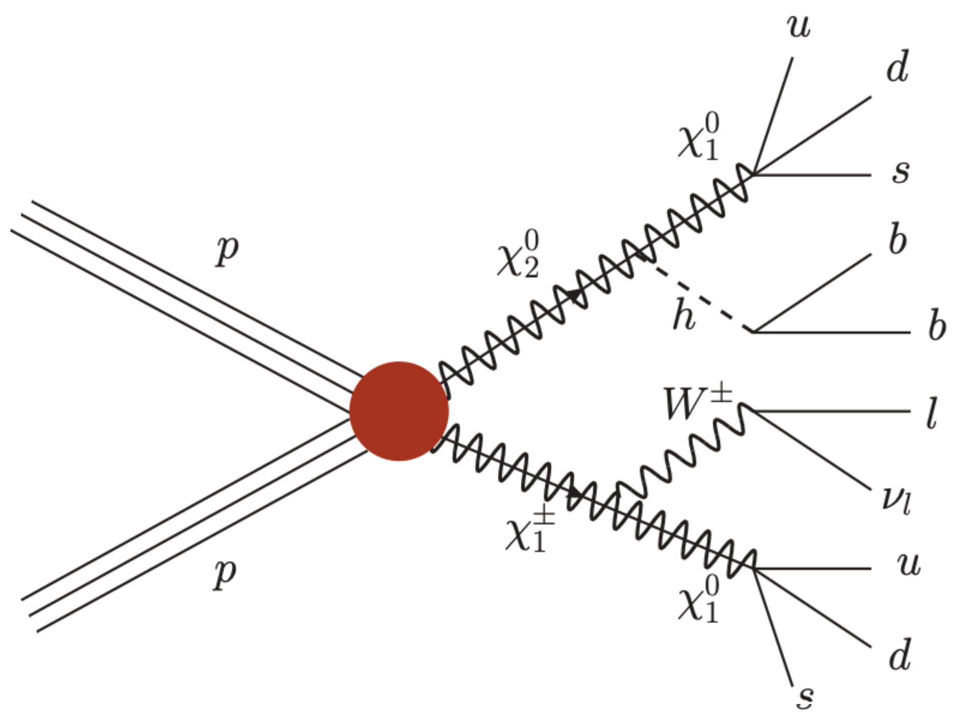


Apply cuts on the number of tracks and invariant mass of the secondary vertex to kill Instrumental background

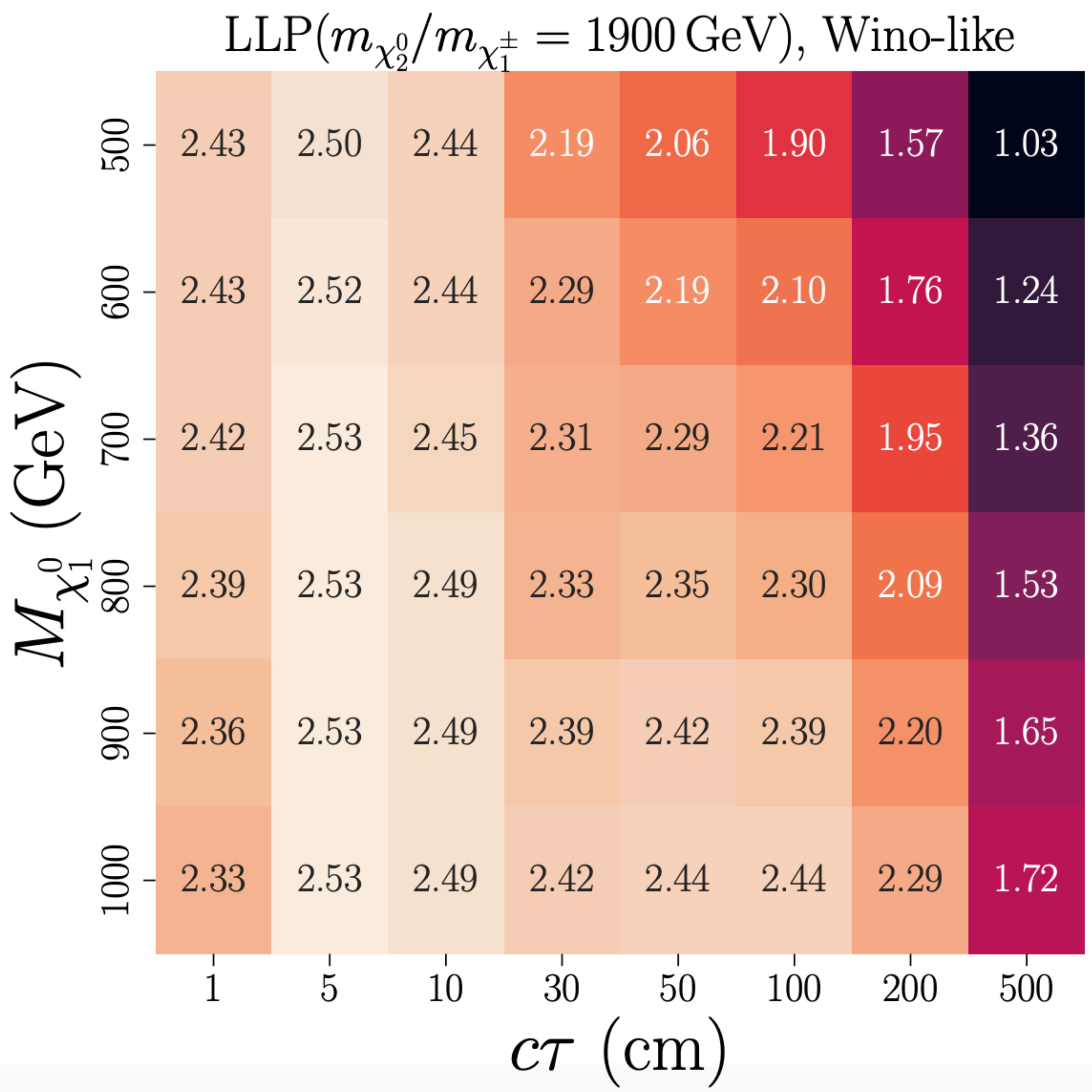
Amit Adhikary, Rahool Kumar Barman, BB, Amandip De, Rohini M. Godbole, Suchita Kulkarni
e-Print: 2207.00600, PRD 2023

LLP:R-parity violating MSSM

Combining displaced tracking, timing and prompt lepton trigger



Significance grid at the HL-LHC

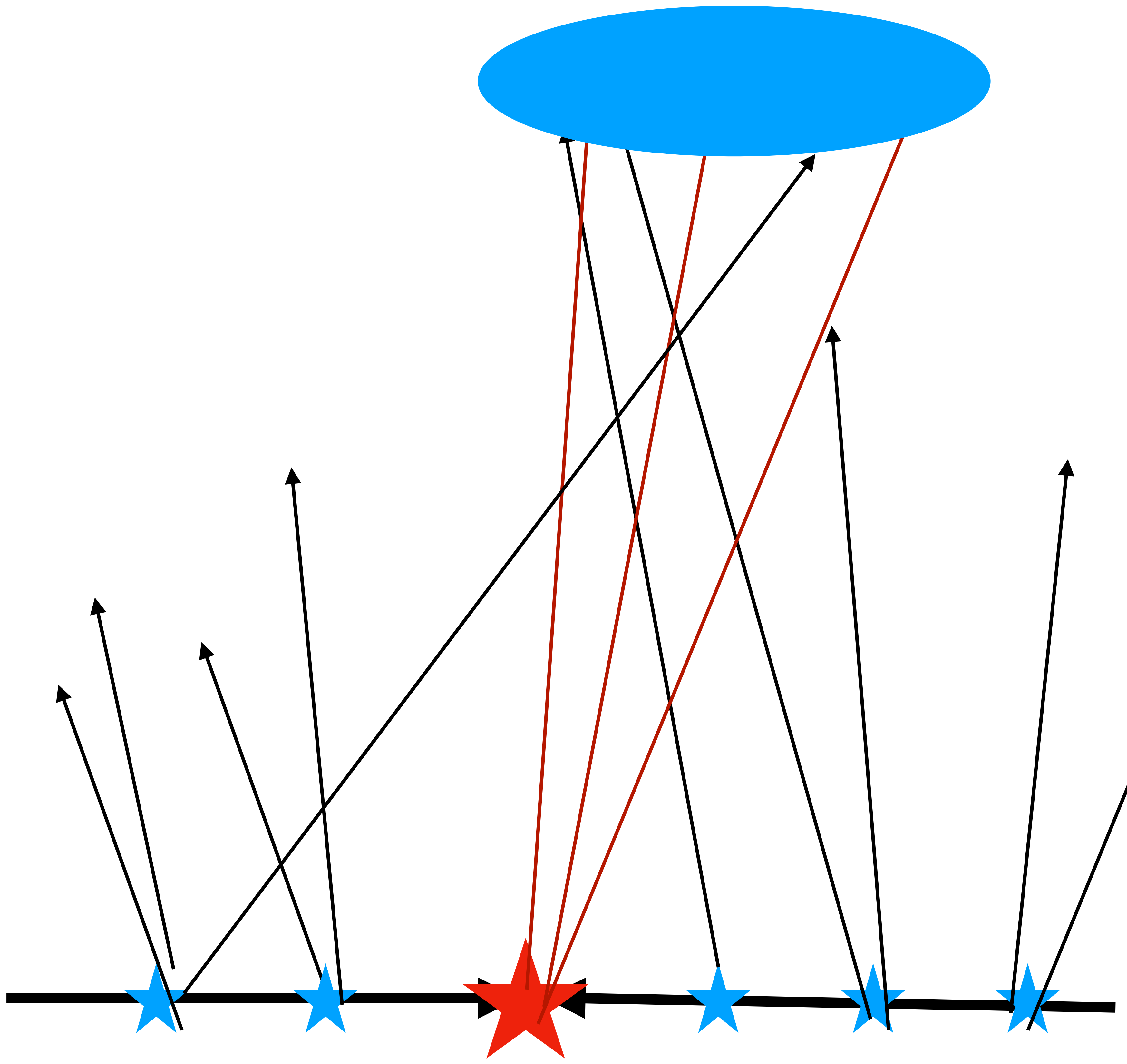


BB and Prabhat Solanki
arXiv:2308.05804, JHEP 23/24

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

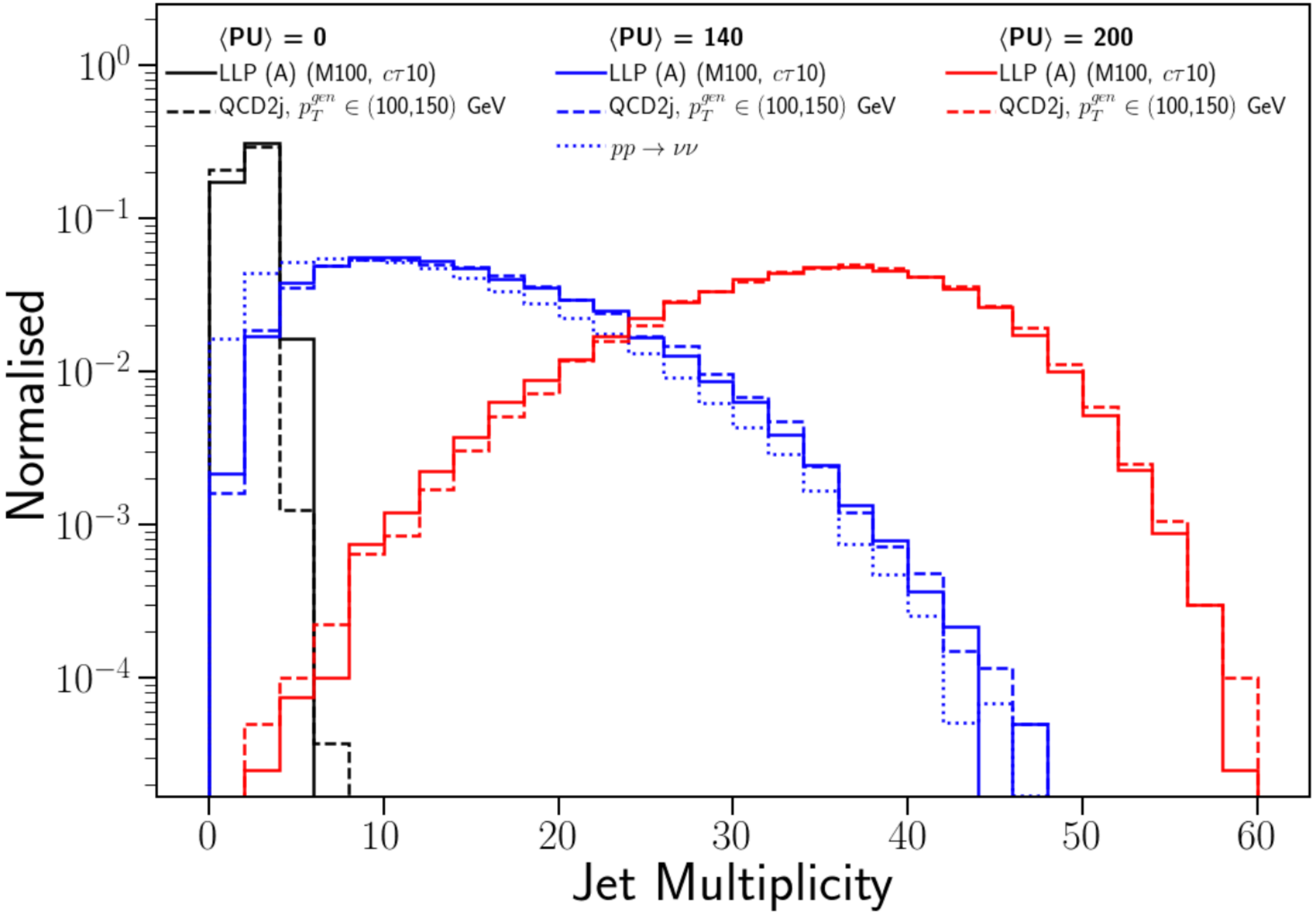


HL-LHC: Triggering challenge more severe because of high pileup

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

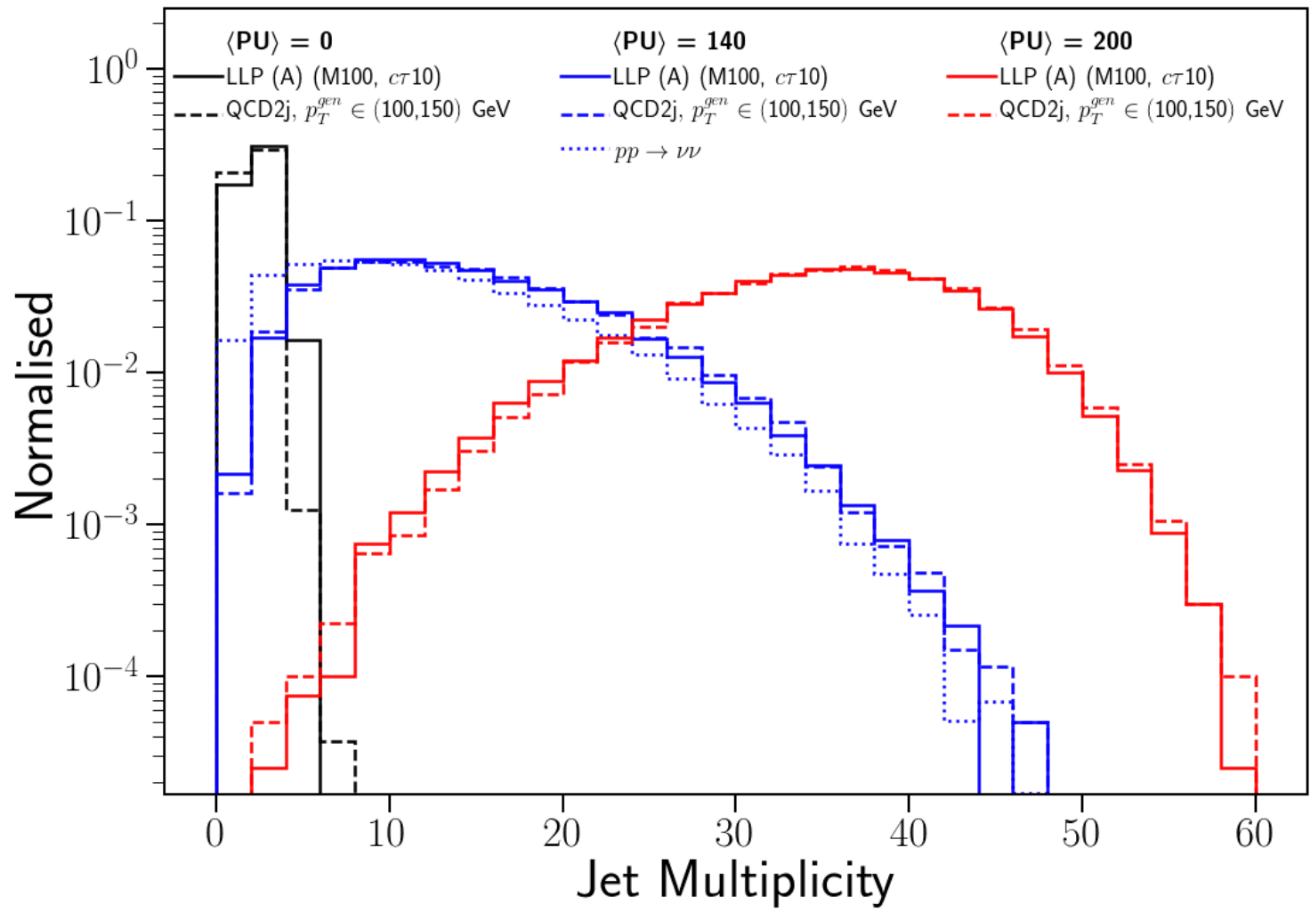
Jet parameter = 0.4
p_T >60 GeV
$|\eta|$ <2.5

Calorimeter jet multiplicity dominated by PU jets

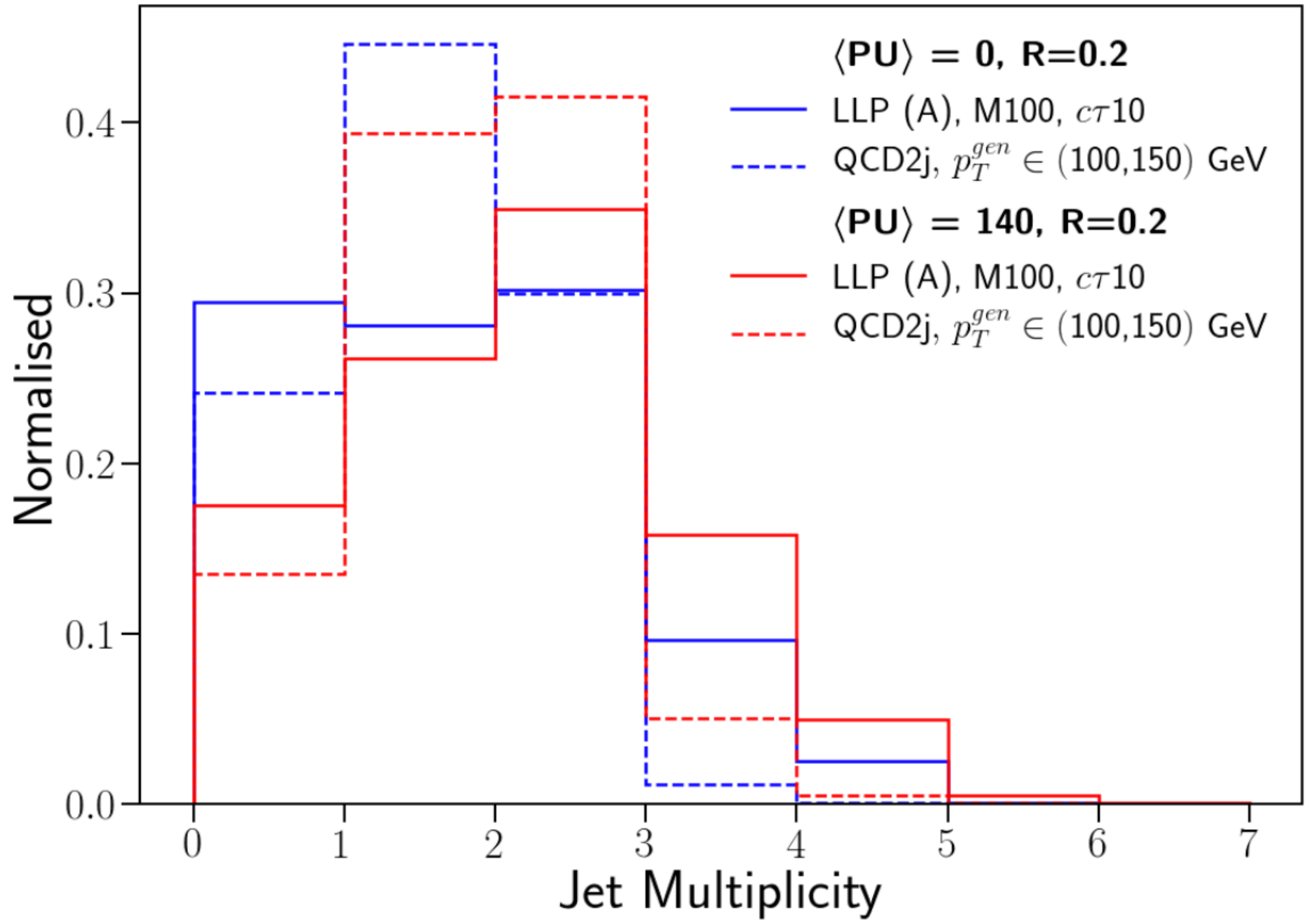
Narrow jets for LLP

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 !!



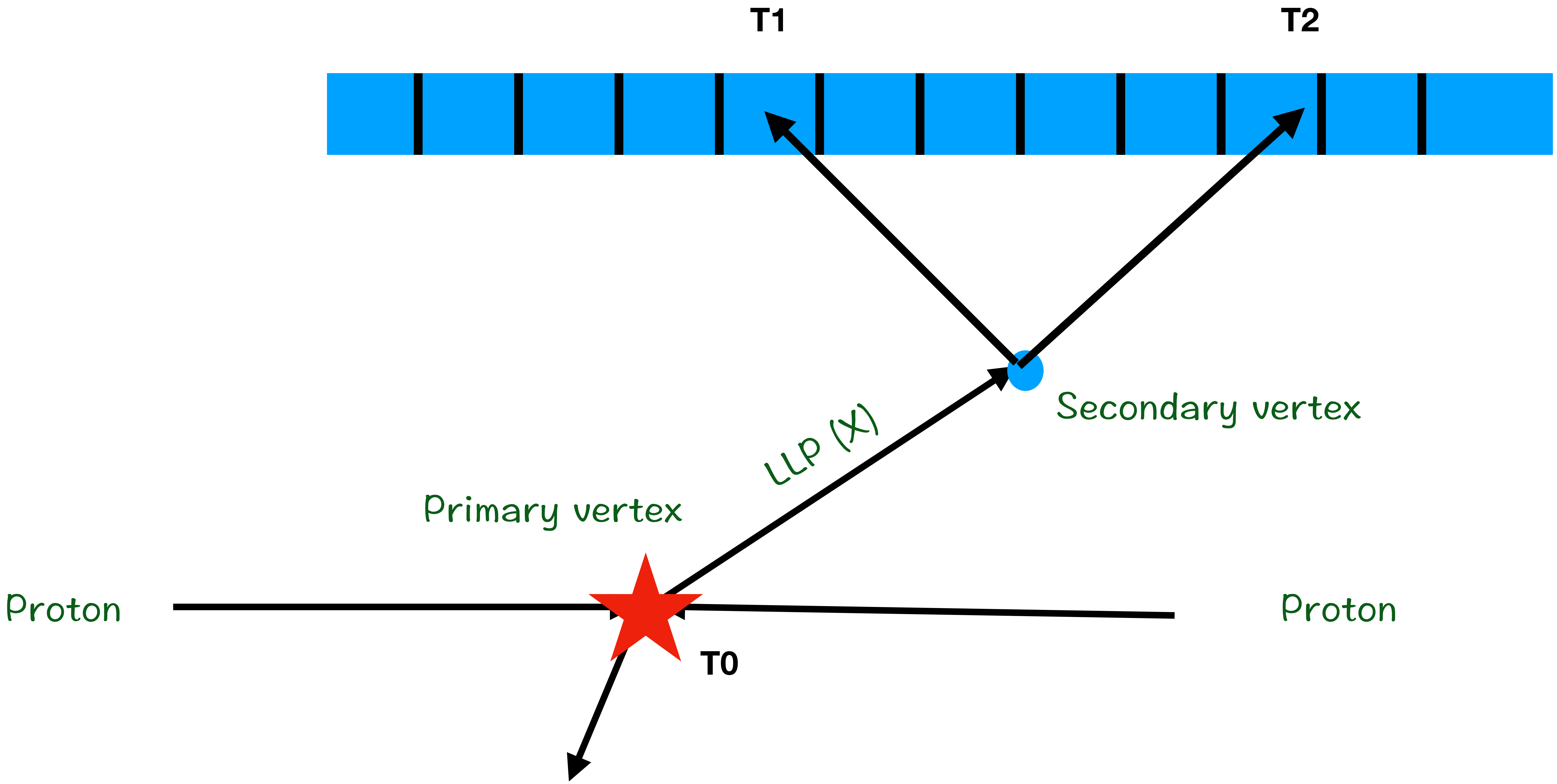
Only narrow jet will not be sufficient to suppress background
Many Variables can be constructed
Single narrow jet trigger with pT >60 GeV with strict cuts on tracking variables may be used.

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

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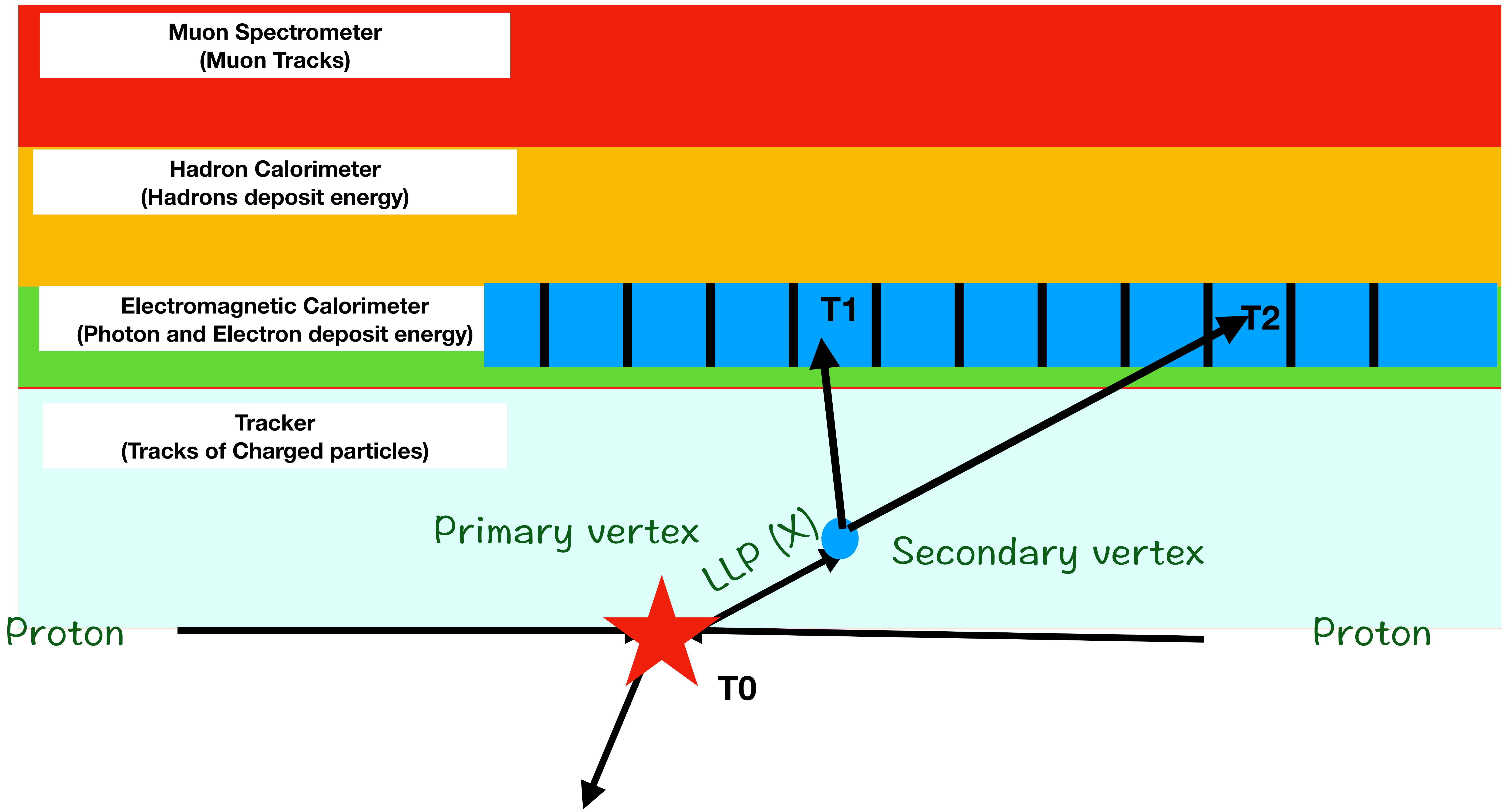
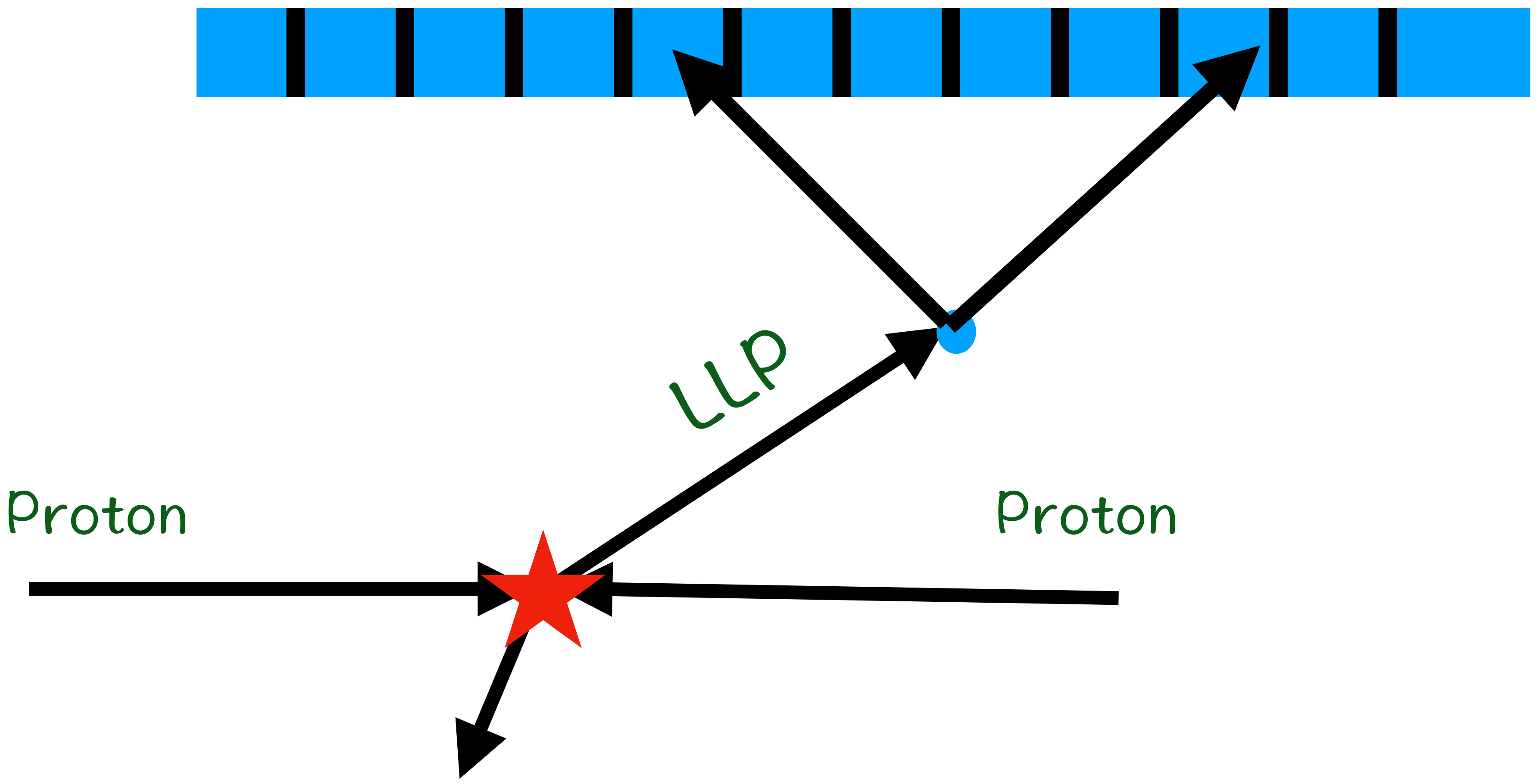
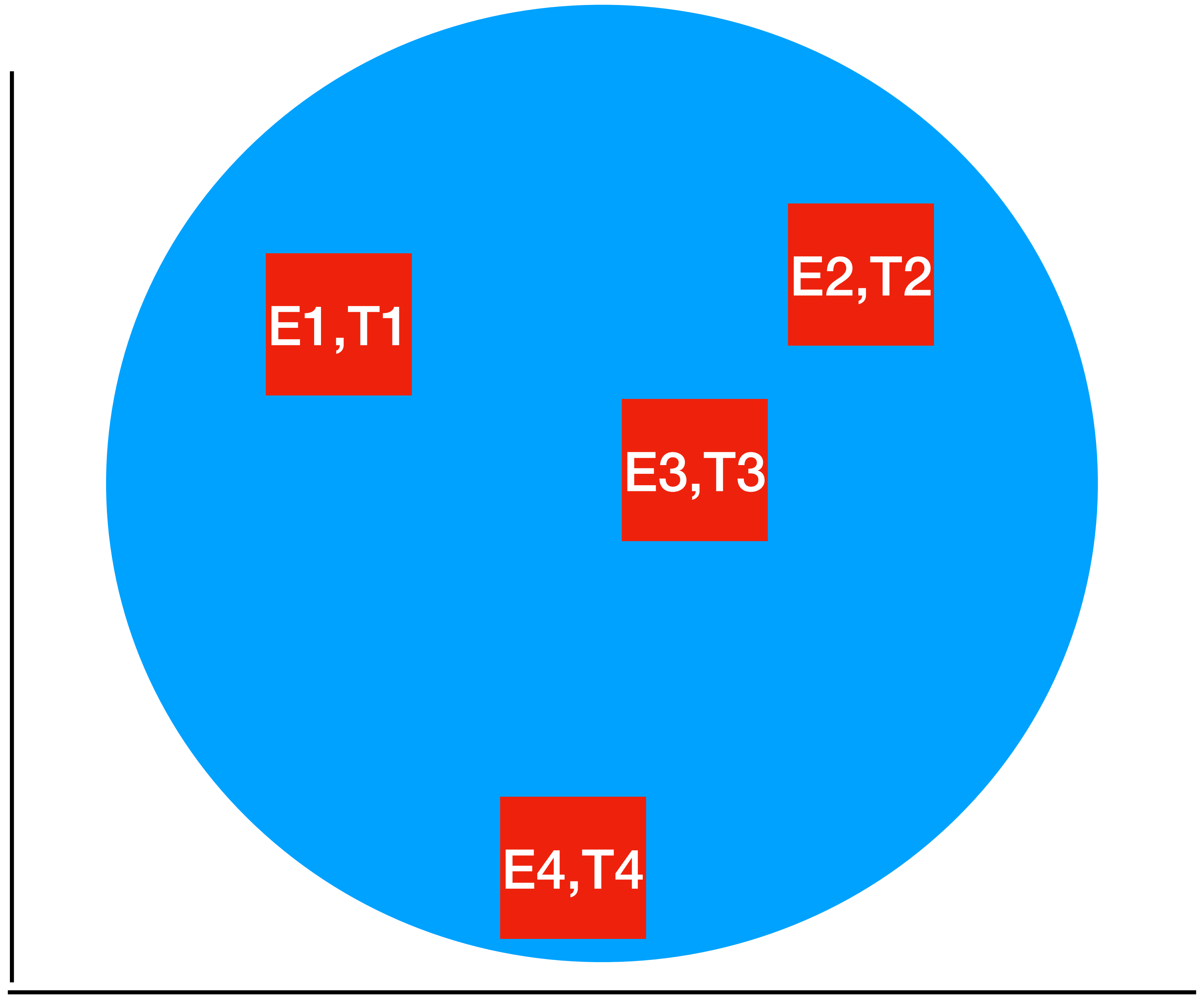


ECAL timing

ECAL barrel detector will also provide precise timing information

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





Electromagnetic energy deposits inside a jet

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

ECAL timing

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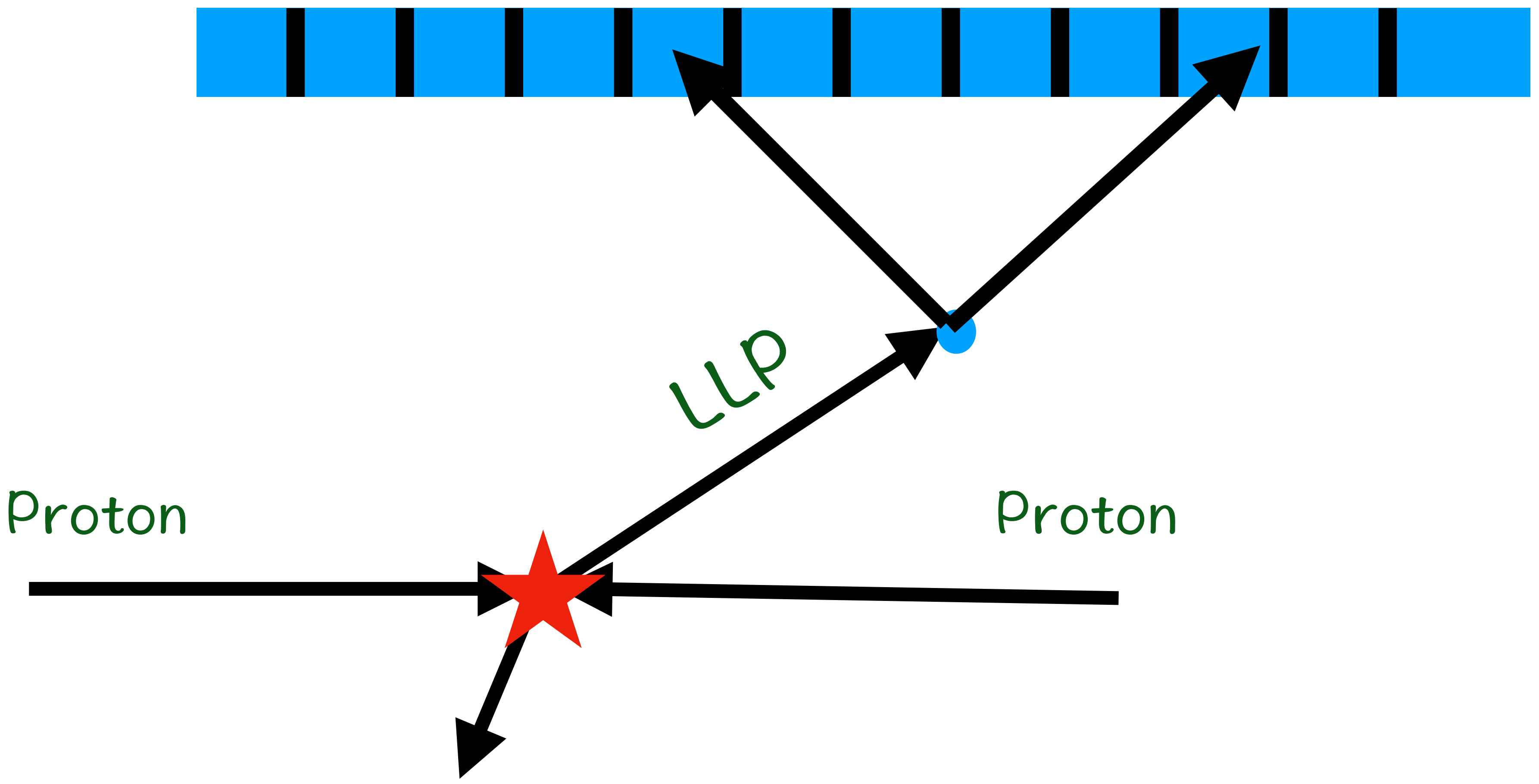
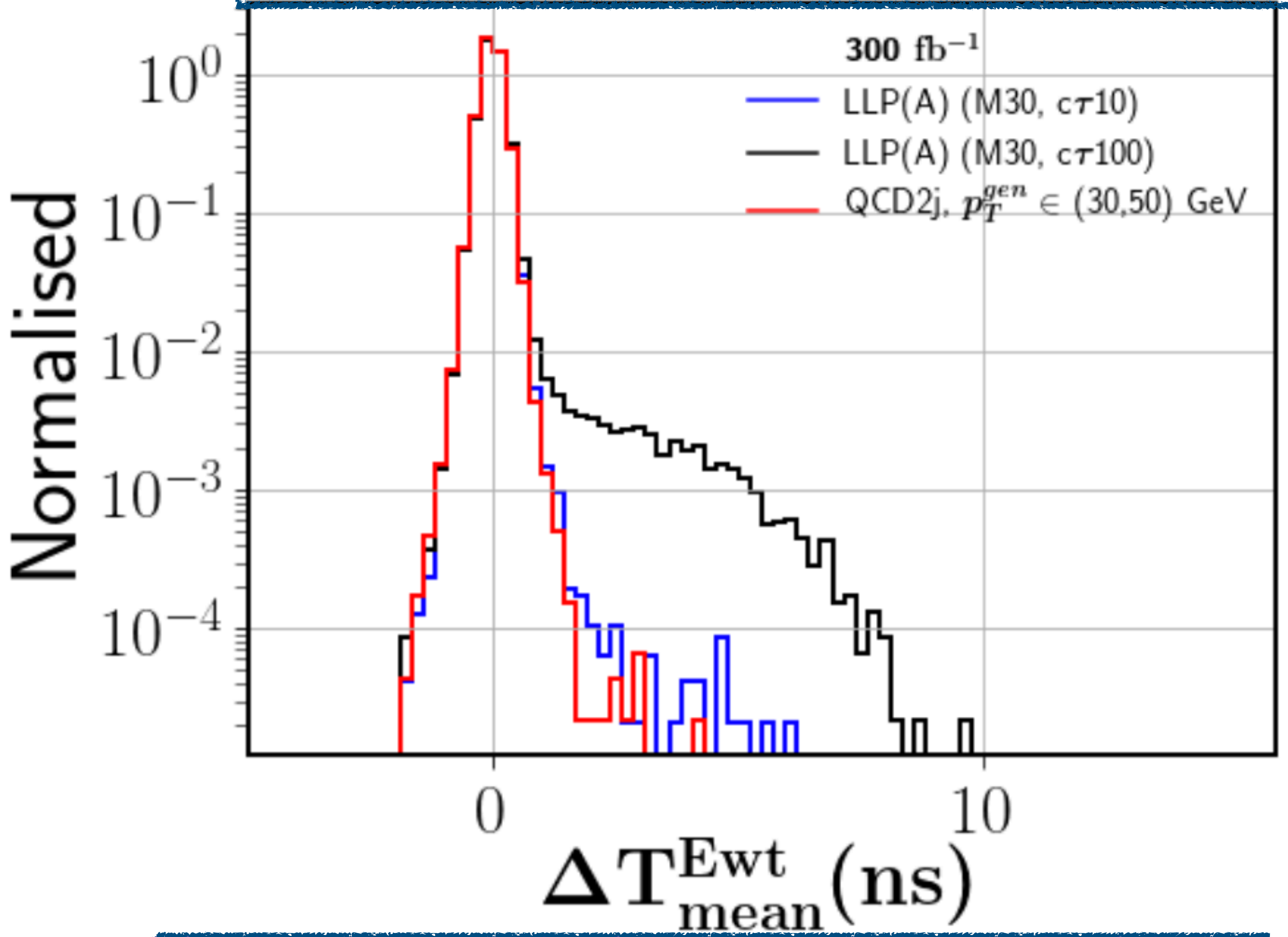


LLP Model: $pp \to h \to XX, X \to q\bar{q}$



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

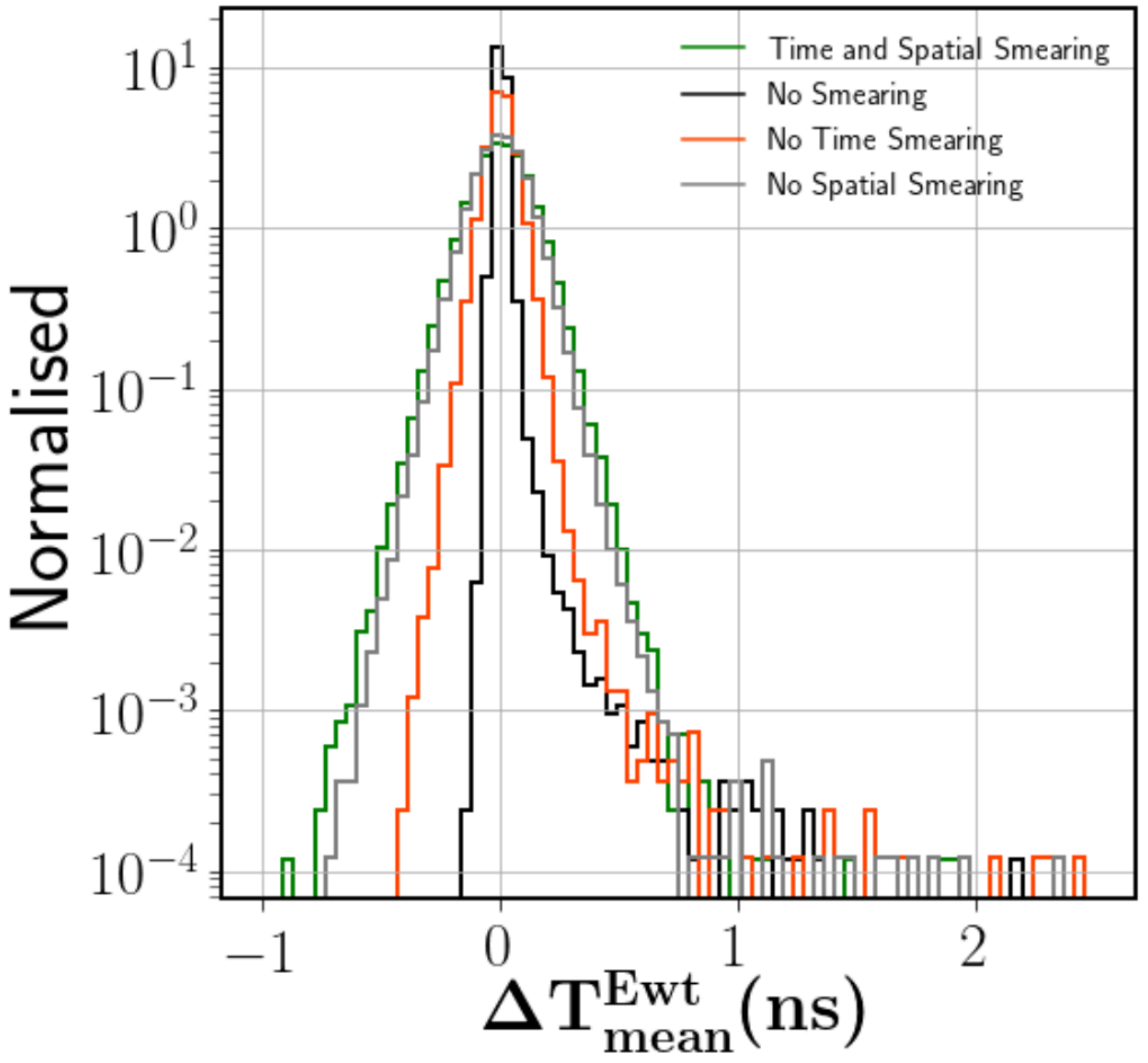
distribution is different for high decay length

QCD jets can also have a long tail

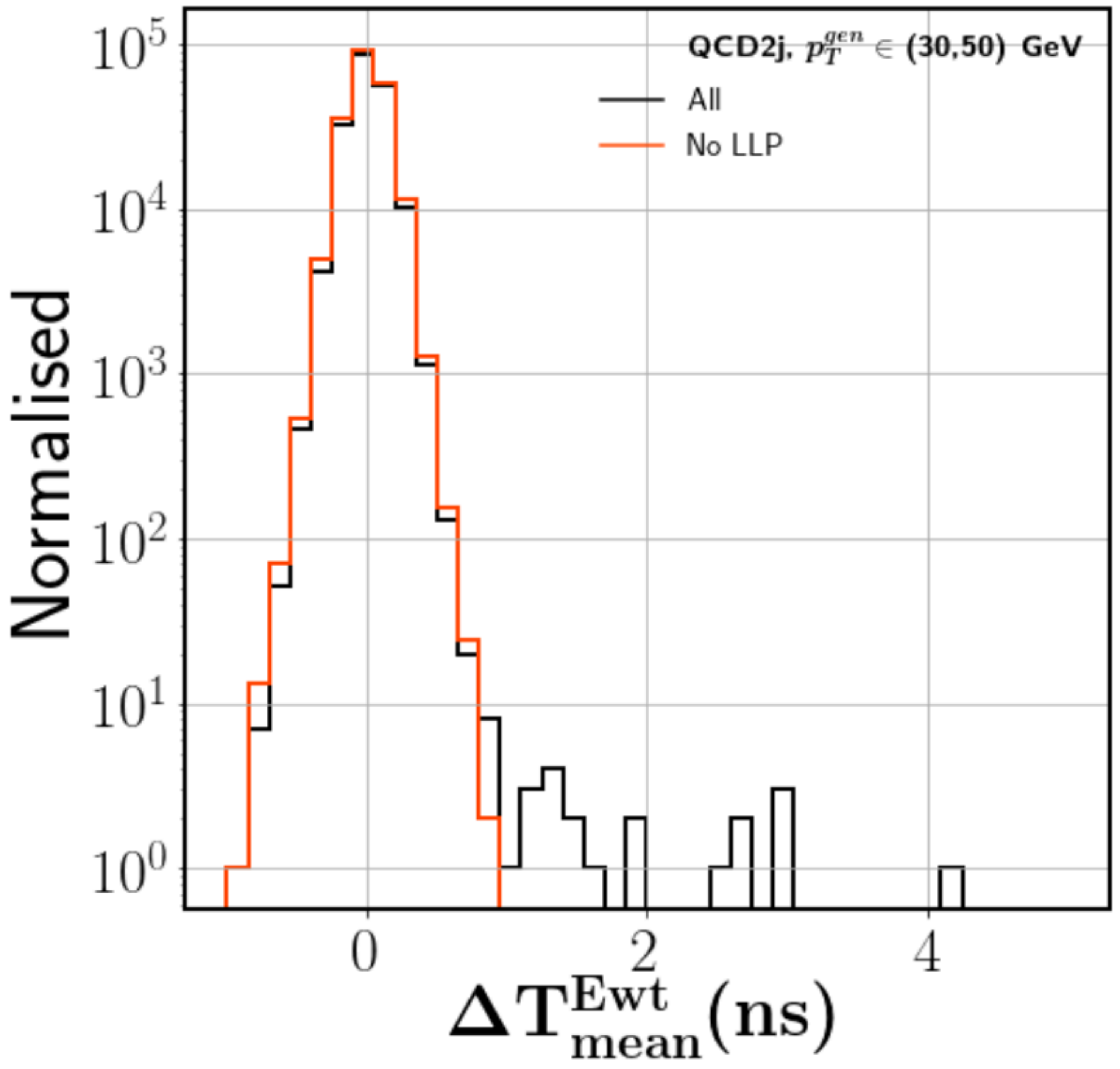
BB, Tapasi Ghosh , Rhitaja Sengupta , Prabhat Solanki
e-Print: 2112.04518, JHEP 2022

Why do prompt QCD jets having high time delays?

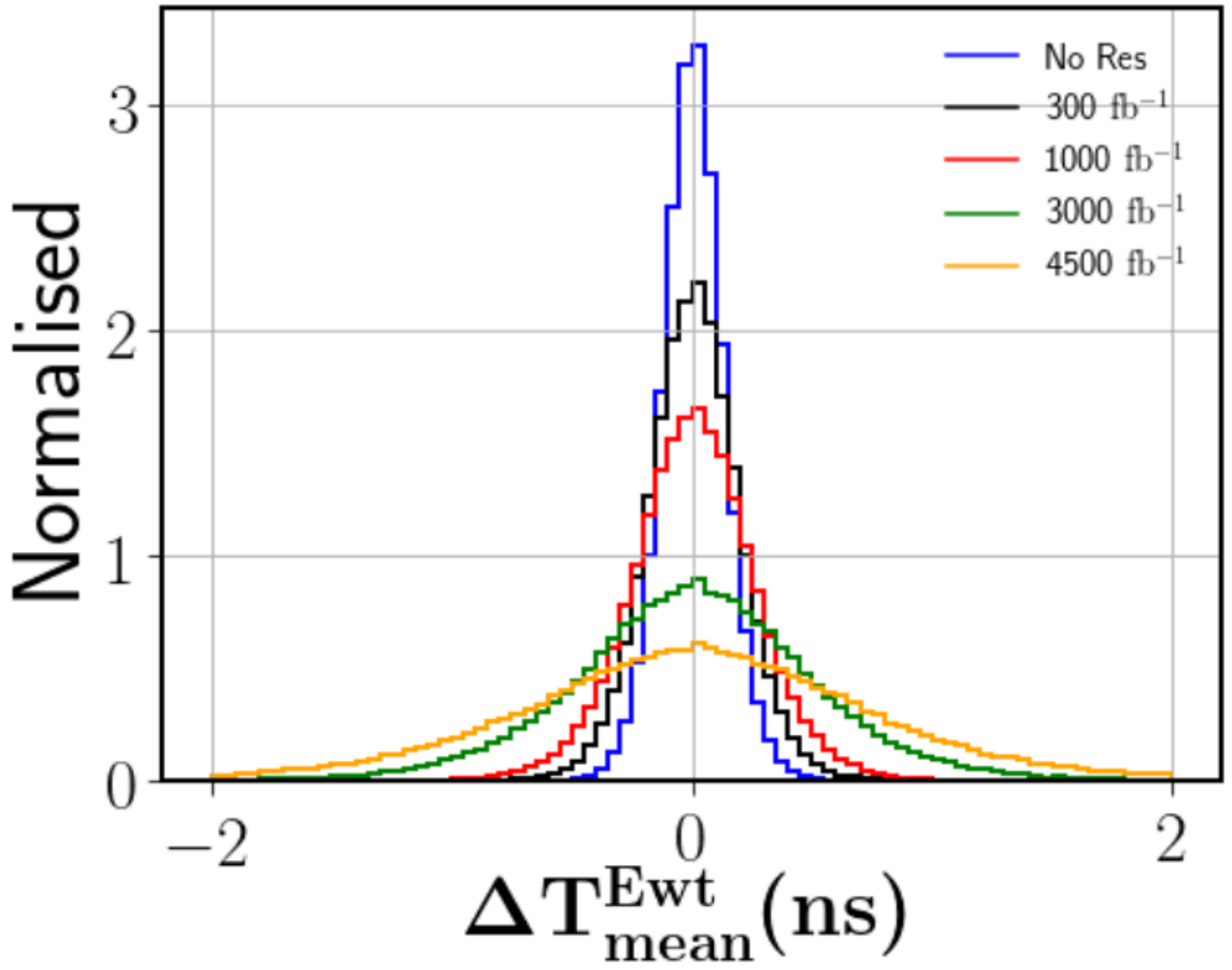
BB, Tapasi Ghosh , Rhitaja Sengupta , Prabhat Solanki
e-Print: 2112.04518, JHEP 2022



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