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

Tracking and Calorimetry

Tracking

A charged particle bends in the magnetic field=> momentum can be measured from the bending

Need to measure the position of the charged particle at different points => reconstruct the track

The position measurement should not reduce the energy of the charged particle

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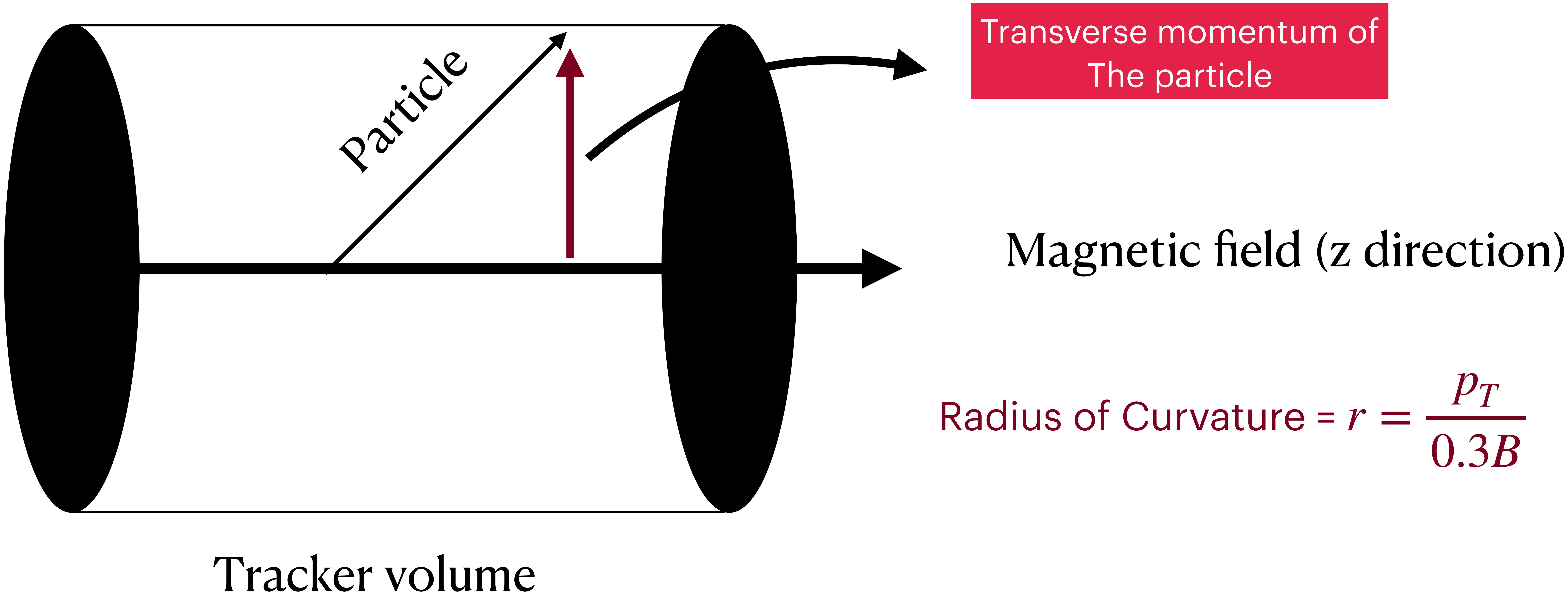
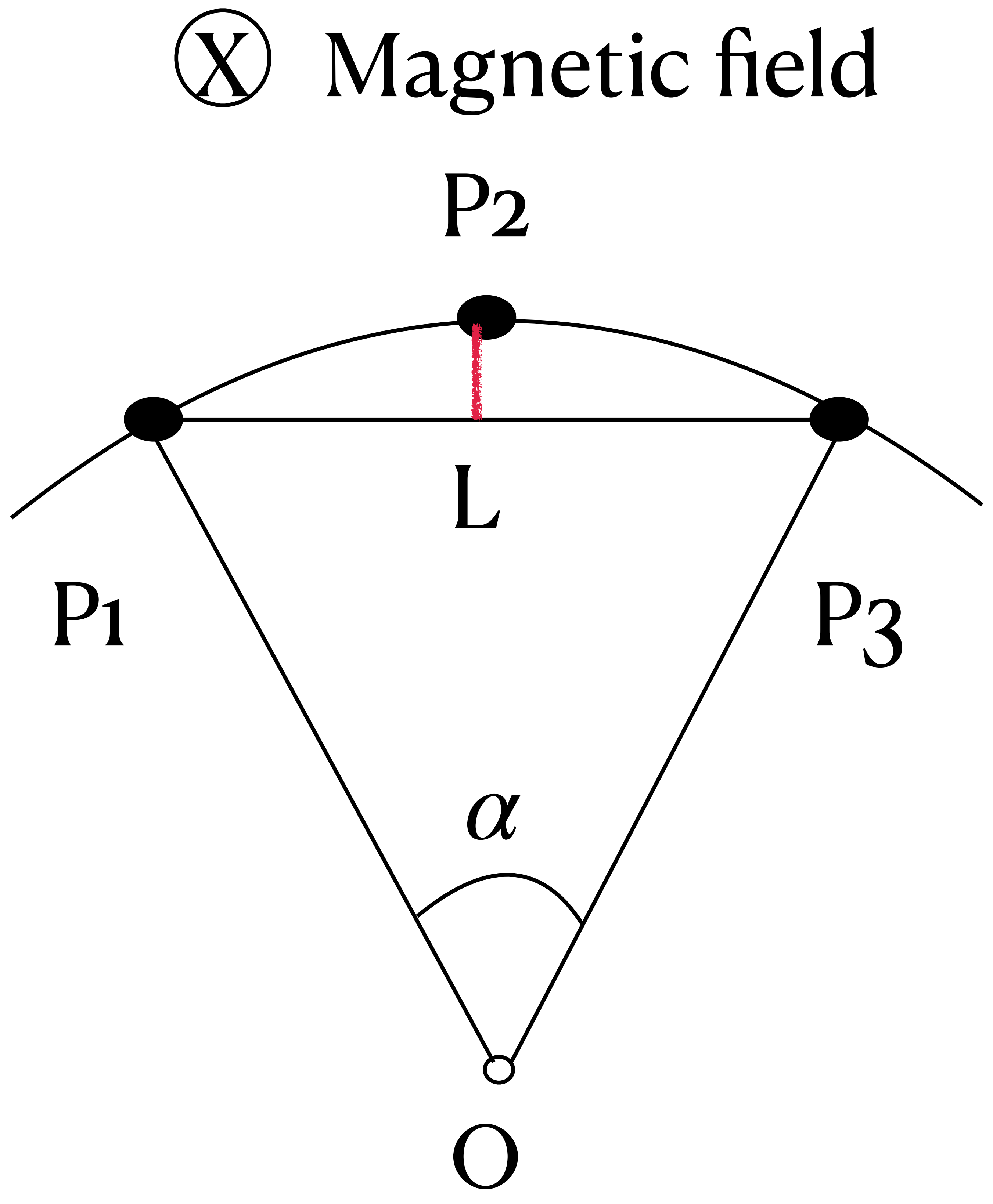


Radius of Curvature = $r = \frac{p_T}{0.3B}$

Tracking



Suppose a charged particle is detected at P1,P2,P3

B = Magnetic field in Tesla

$$\alpha \simeq \frac{L}{r}$$

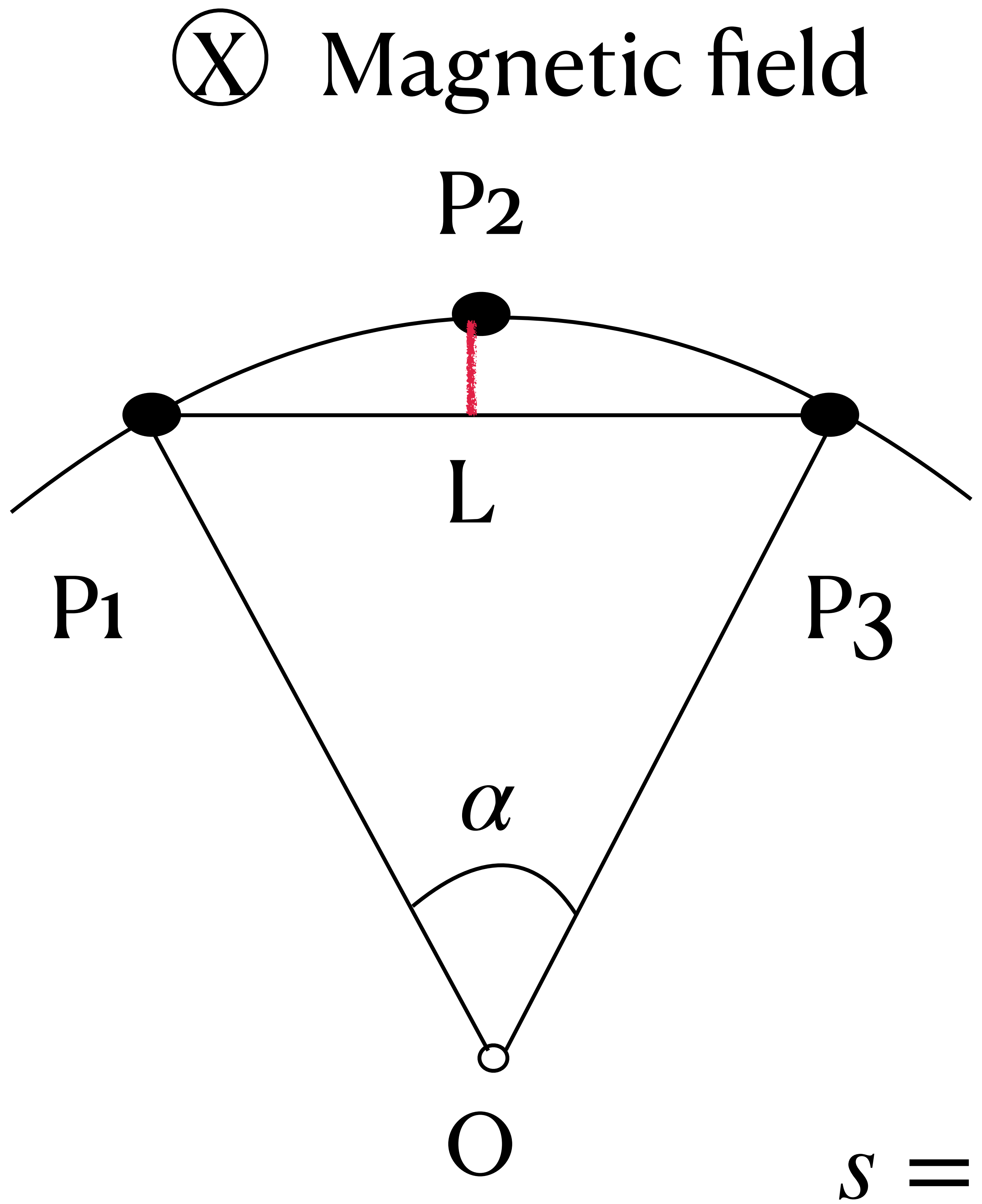
L = The distance between P1 and P3

r = Radius of the circle in Meter

p_T= Momentum of the charged particle = 0.3 B r

S = Depth of the arc, called Sagitta in Meter

Tracking



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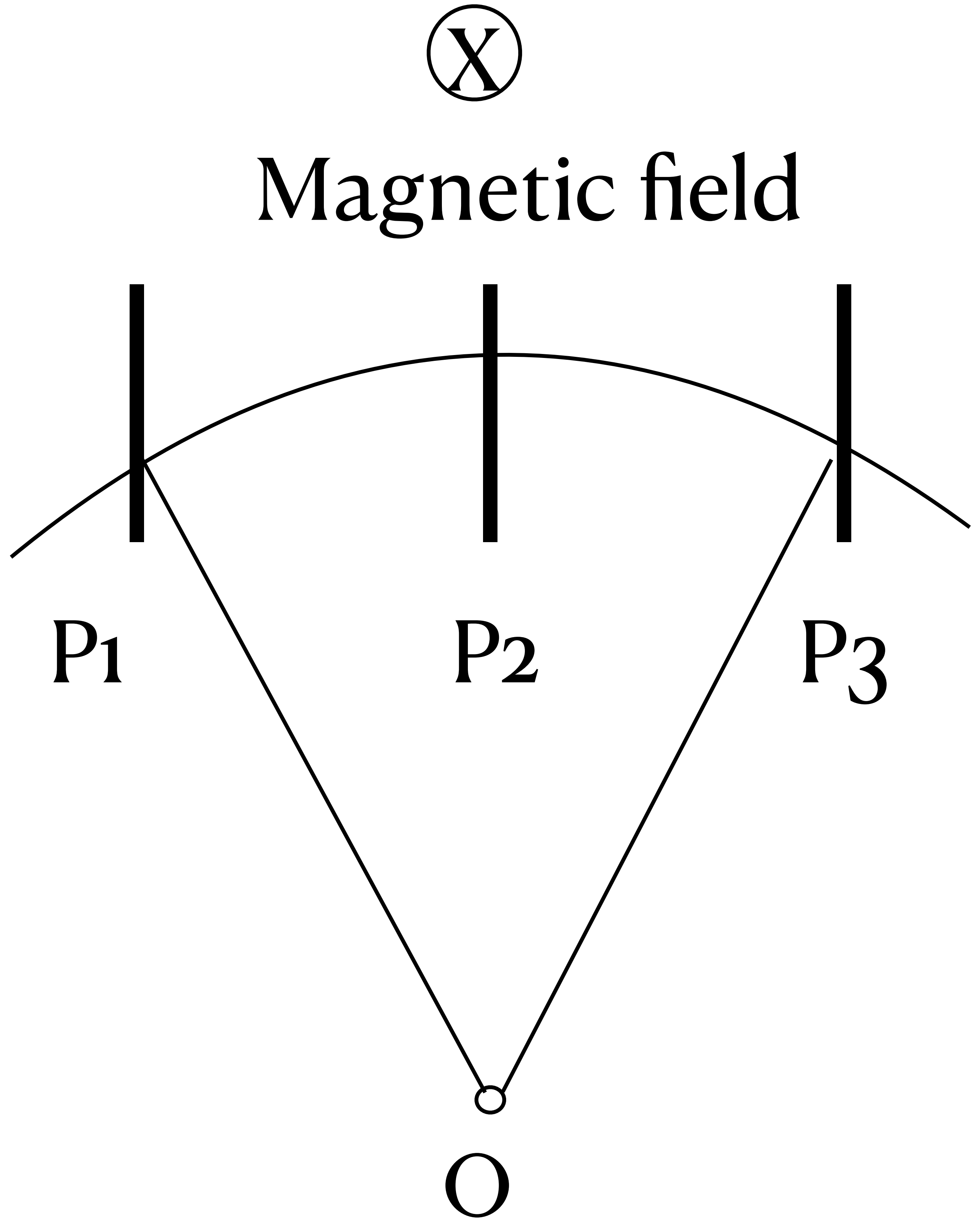
$$s = r\left(1 - \cos\frac{\alpha}{2}\right) \simeq r\left[1 - \left(1 - \frac{1}{2}\frac{\alpha^2}{4}\right)\right] = R\frac{\alpha^2}{8} = \frac{0.3BL^2}{8p_T}$$

Example : for p_T = 1 GeV , L= 1 m and B= 1 T Sagitta (s) is ~ 3.8 cm

Tracking



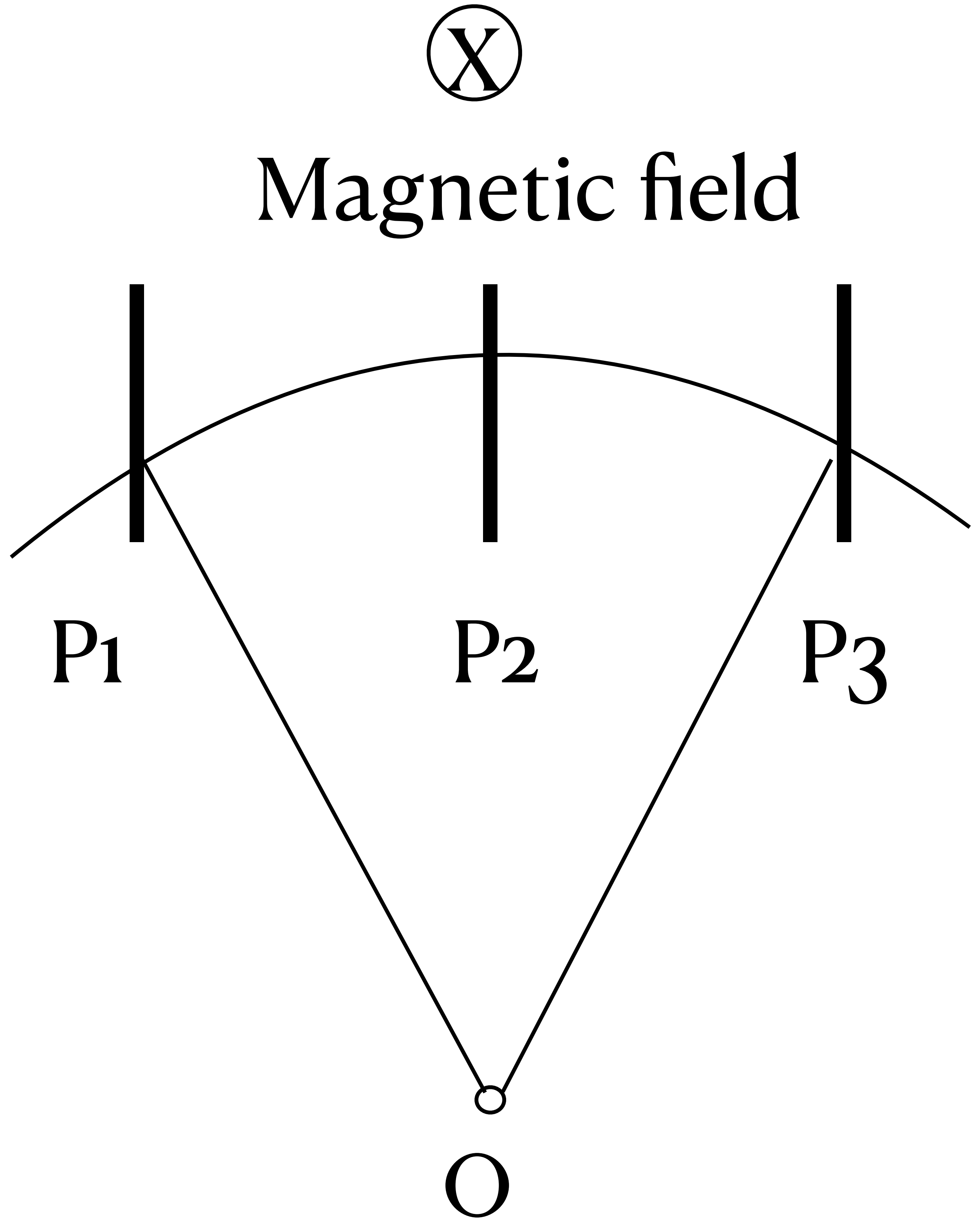
Suppose three points are used to measure the track

$$s = x_2 - \frac{x_1 + x_3}{2}$$

Momentum resolution $\frac{\sigma_{PT}}{p_T} \propto \frac{\sigma}{s} \propto \frac{\sigma 8 p_T}{0.3 B L^2}$

σ is the uncertainty associated with the position measurement

Tracking



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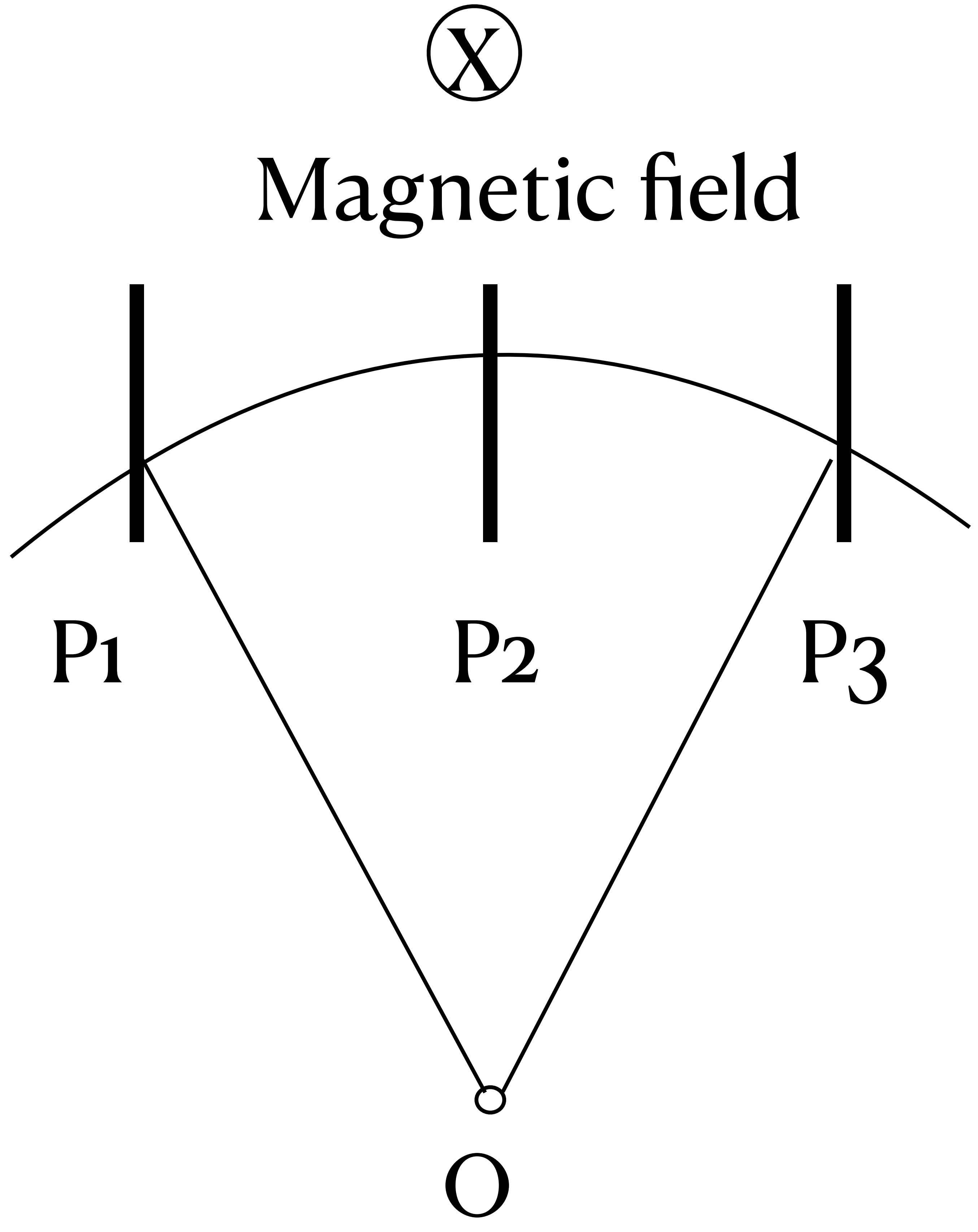
For better measurement we need small σ, large B and large L

CMS uses stronger magnetic field than ATLAS

ATLAS uses bigger L than CMS

Resolution degrades with the momentum

Tracking



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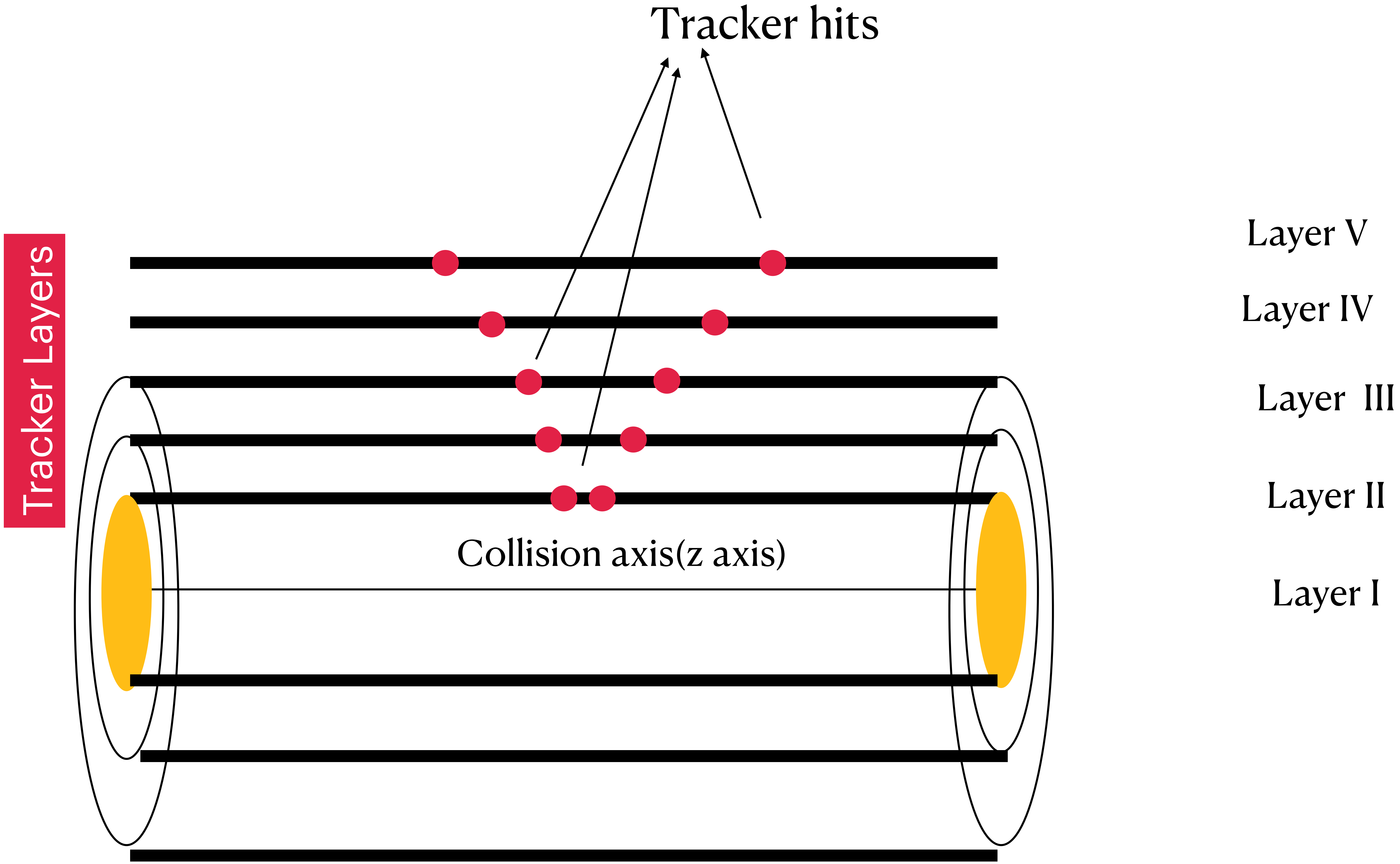
Resolution degrades with the momentum

Charged particle inside the thick material undergoes multiple scatterings : This increases the error in the measurement of the Sagitta : Low Z , high radiation length and thin material reduces this effect

Basic Tracker Design



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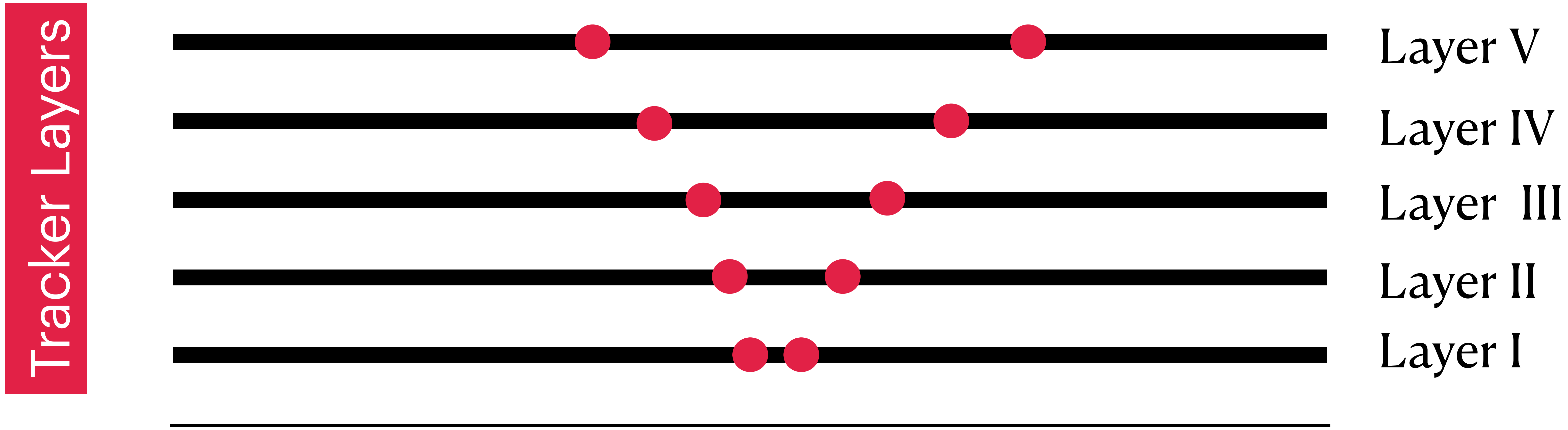

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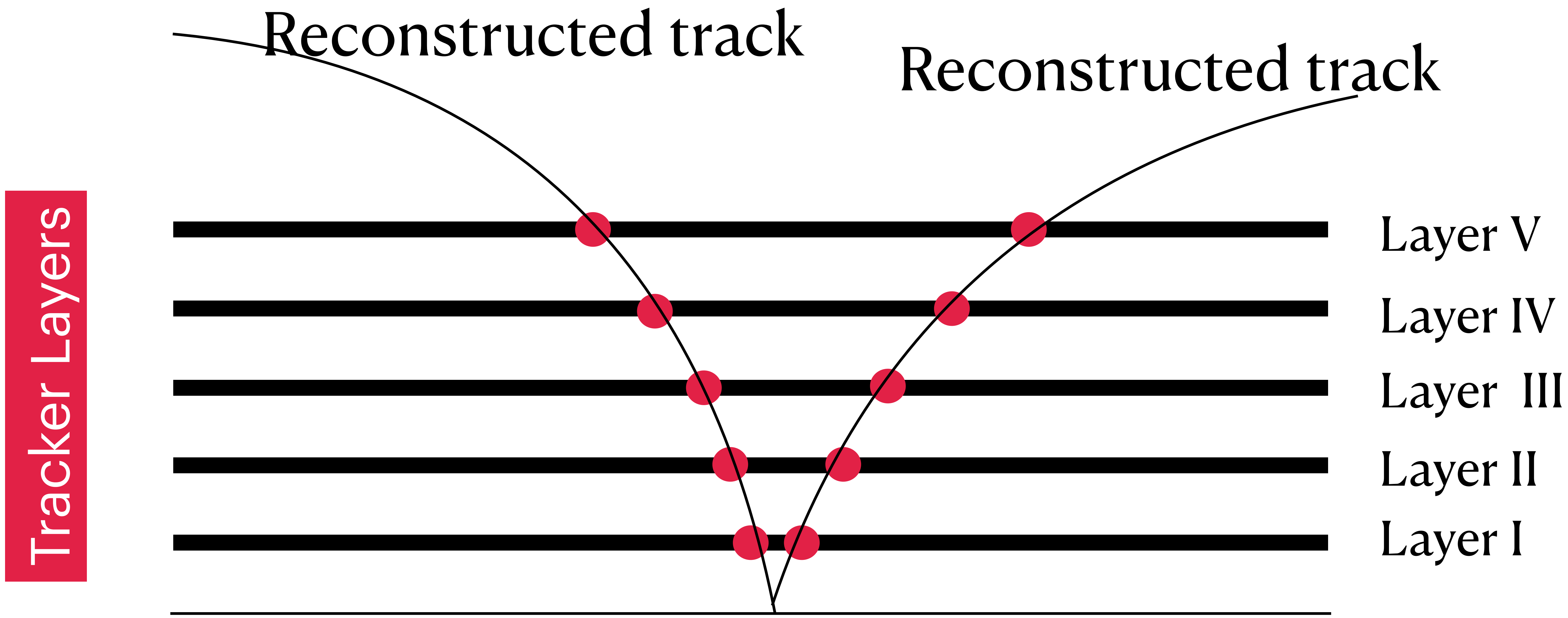
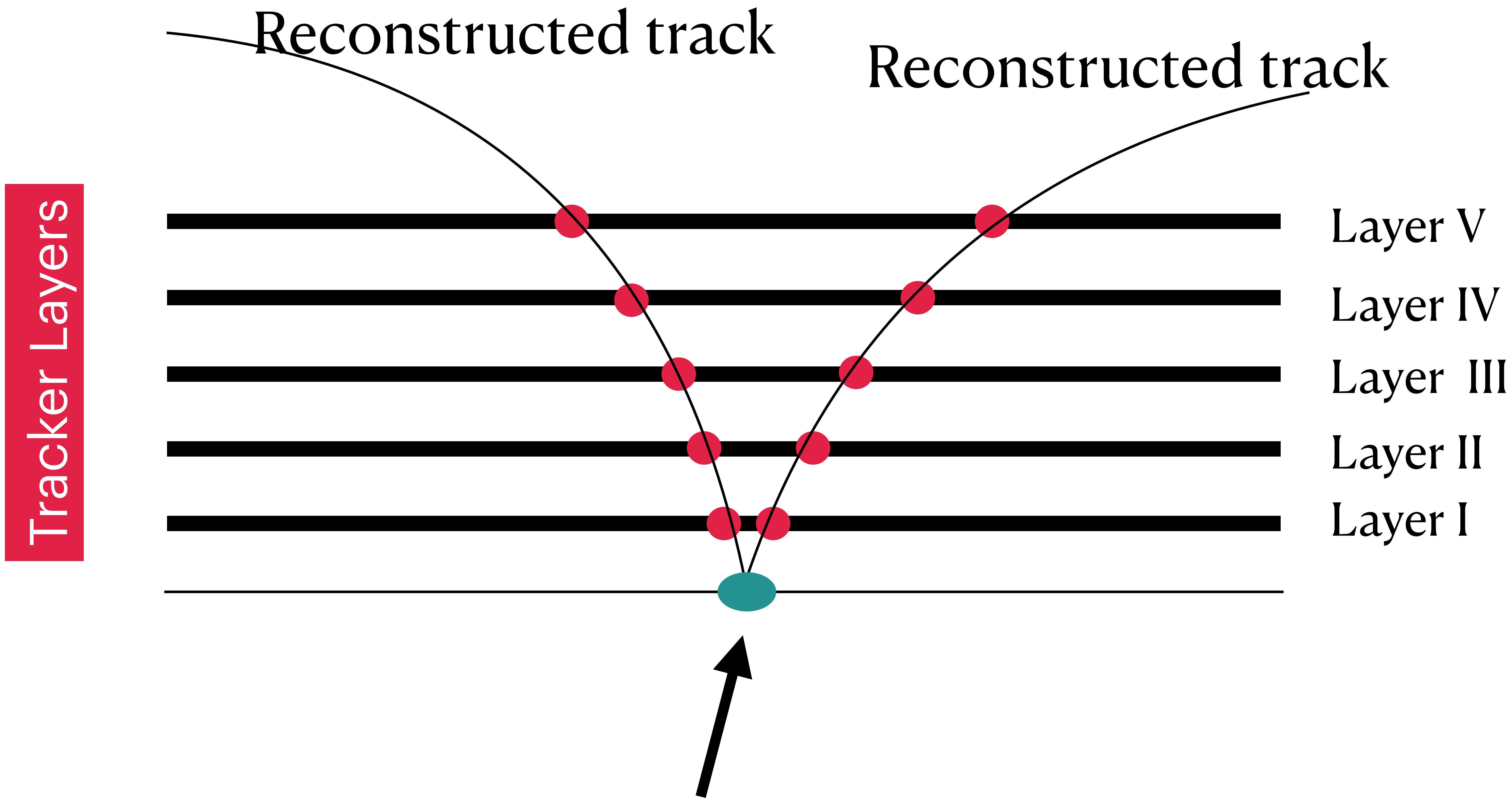


Iterative track finding algorithms (time consuming)

Basic Tracker Design



Reconstructed track

Reconstructed track

Tracker Layers

Layer V

Layer IV

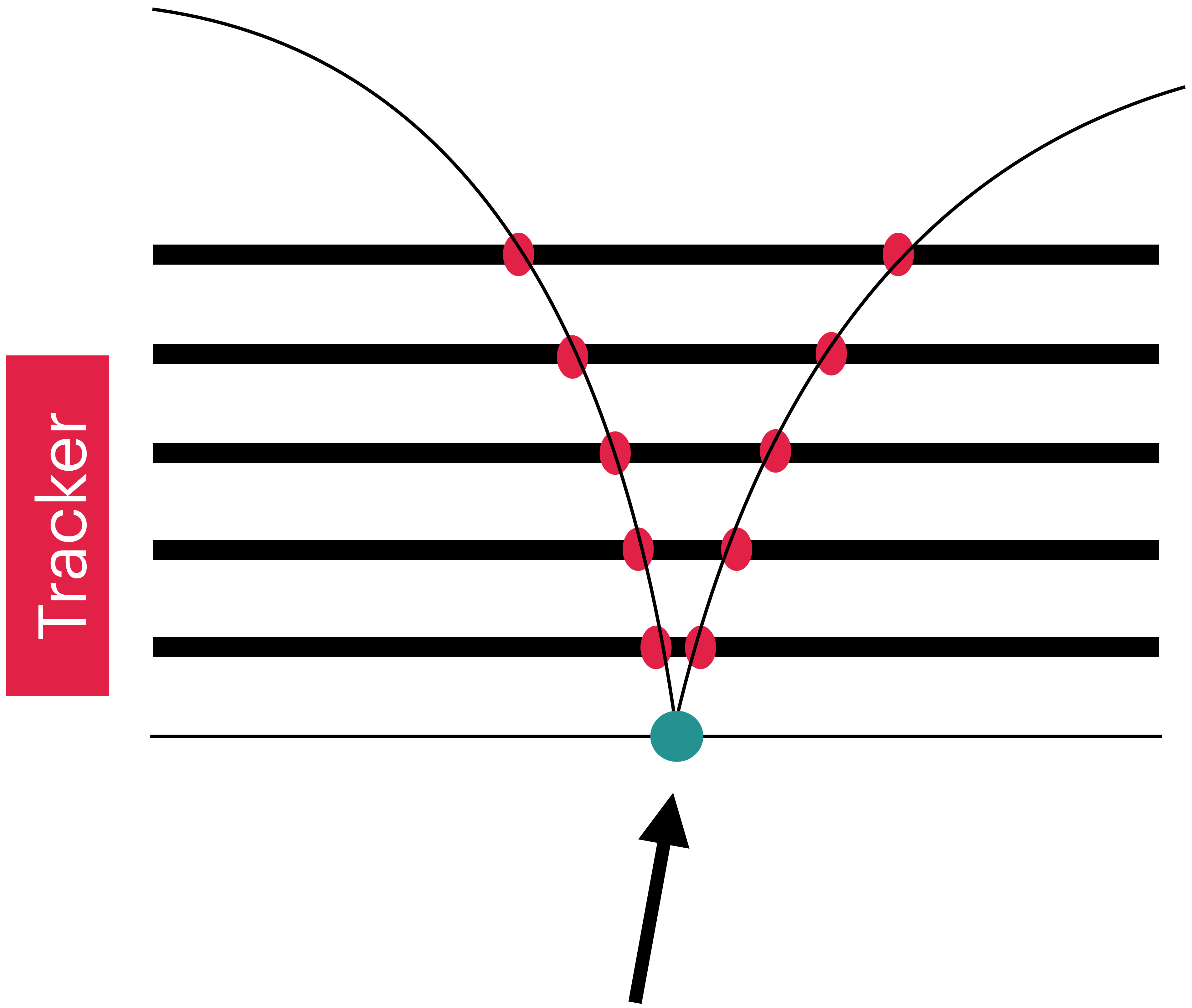
Layer III

Layer II

Layer I

Extrapolate tracks and find the vertex

Basic Tracker Design



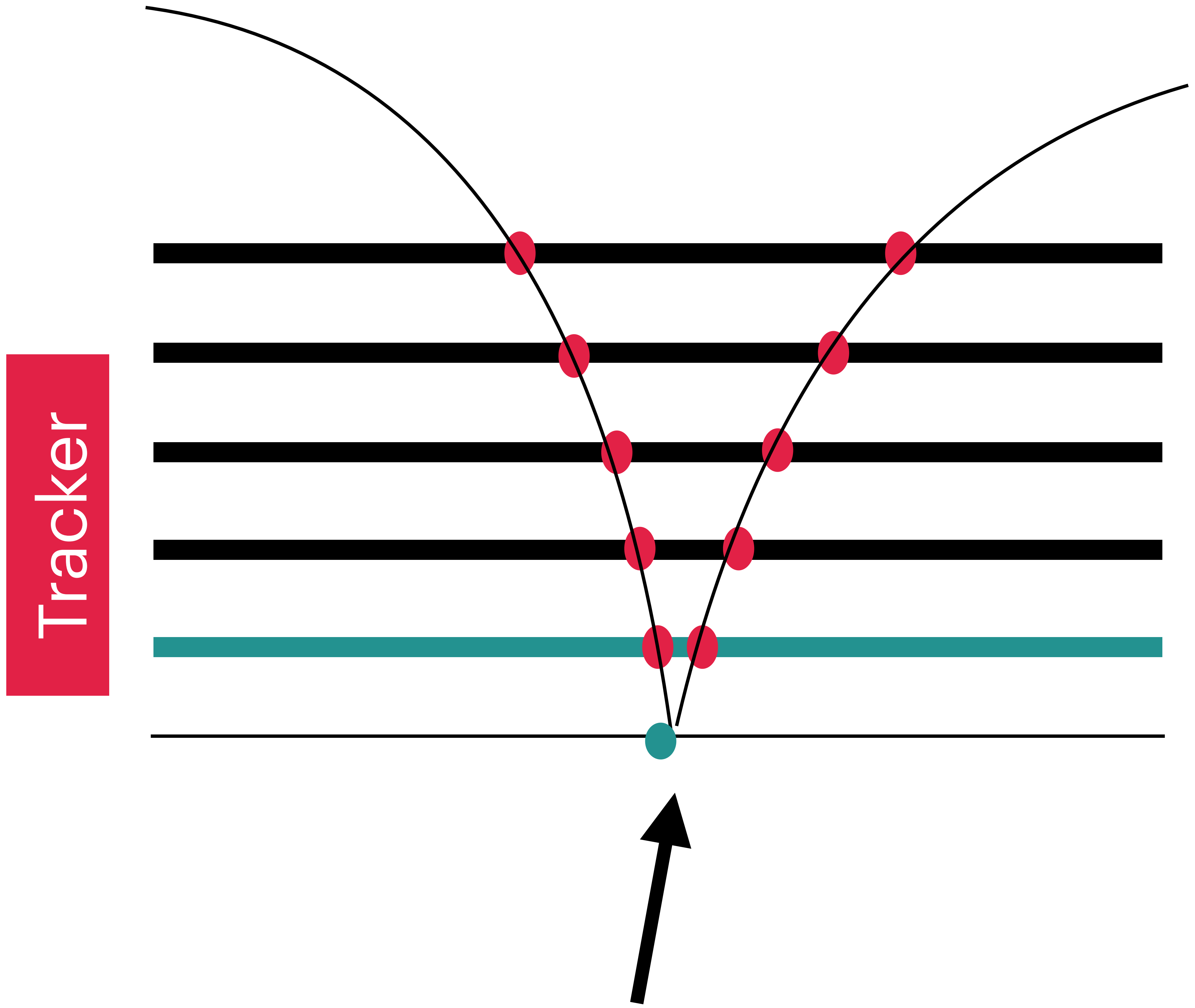
Extrapolate tracks and
find the vertex

Iterative track finding algorithms (time consuming)

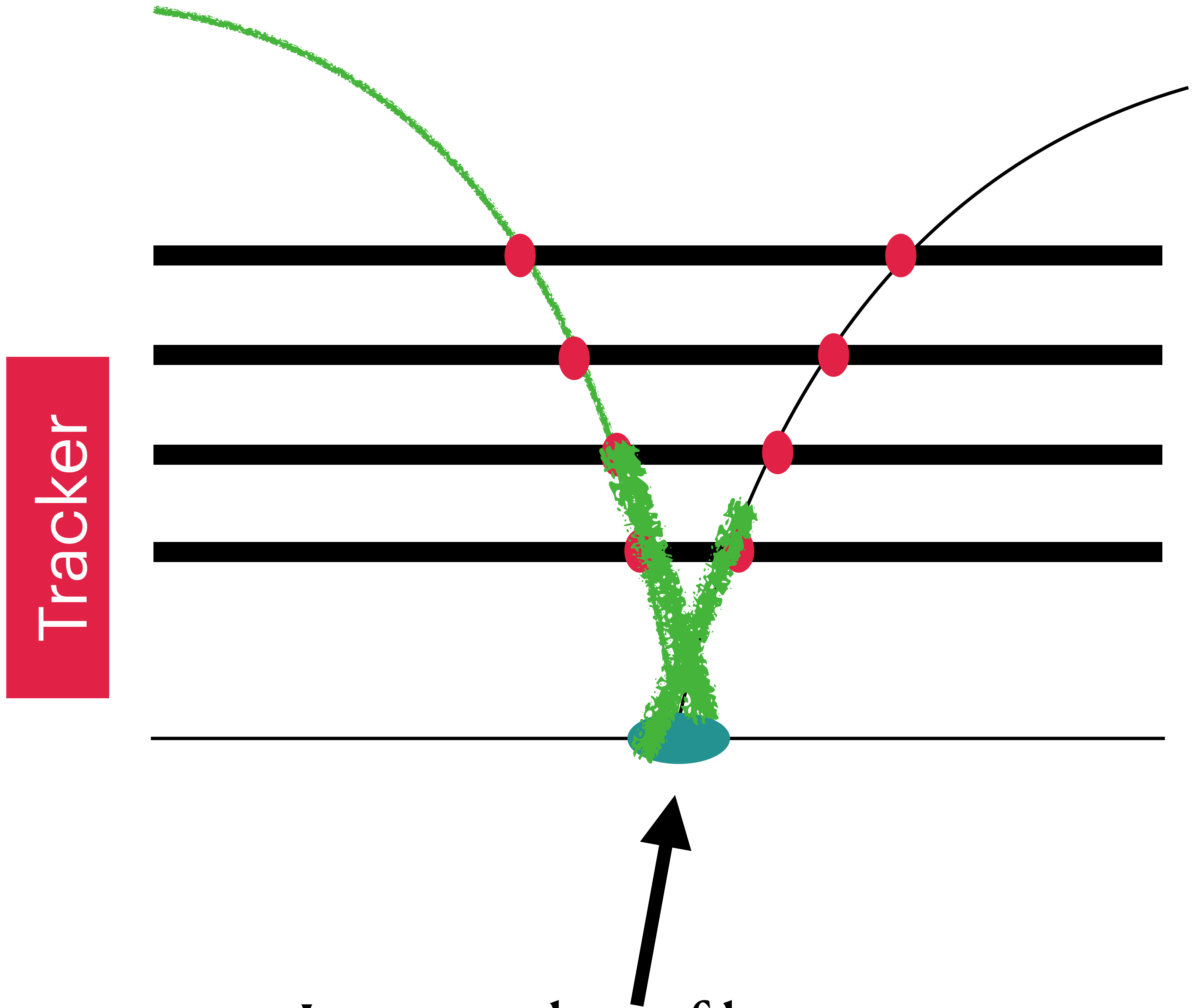
track fitting algorithms => Momentum measurement

Efficiency increases with the number of hits

Basic Tracker Design



Layer close to the vertex increase the accuracy of the vertex



Less number of layers : vertex position error increases

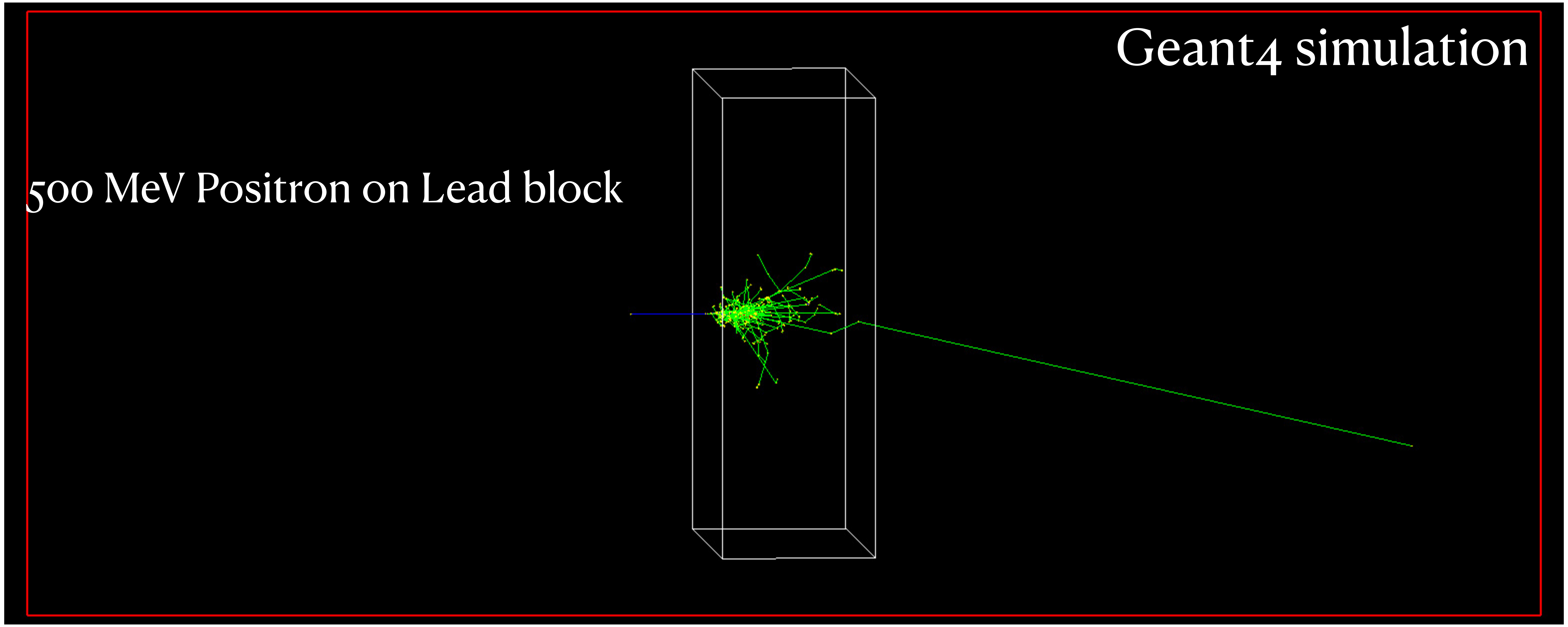
Addition of 4th layer in CMS and ATLAS tracker

Calorimetry

Calorimeter measures energy of charged and neutral hadrons(HCAL),

electron and photon (ECAL) => destructive measurement unlike tracker

Interaction of particle with the detector generates shower => identification of particle



Segmentation helps measure the position / direction of the particle

Calorimetry

Active material: which measures the shower energy

Passive material: which causes the particle to shower(high Z material)

Two Types of calorimeters :

Homogeneous: single active material

Advantage : excellent energy resolution

Disadvantage: costly **Example:** CMS ECAL

Sampling: alternative layers of active and passive materials

Advantage : optimal choice of absorber and active material possible , can be made compact

Cheap passive material

Disadvantage: Only some of the energy is deposited in the detector, energy resolution worse than homogeneous calorimeter

Example: CMS HCAL, ATLAS ECAL and HCAL

Electromagentic Shower

Incoming particle loses energy=> production of secondary particle

Cascade of secondary electron/positron and photons produced due to the interaction of the particle with the detector material.

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Ionisation. : emission of electrons from the detector material atoms (dominant at low energy)

Bremsstrahlung: incoming electron emits photon in the coulomb field of the nuclei (proportional to energy and m^{-2})

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$$\frac{dE}{dx} = \frac{E}{X_0}$$

, **Xo is called Radiation length**

Radiation length: The average distance over which the electron loses its 63% of the energy inside the detector material

$$X_0 \propto \frac{1}{Z^2}$$

(For air X~ 30000 cm, lead = 0.5 cm)

Electromagentic Shower

For photon

**Photo-electric effect : **it dominates in the low energy range

$$\sigma_{photoelectric} \propto \frac{1}{E^{3.5}}$$

Electrons are emitted

Mostly isotropically

Compton Scattering: dominates in the mid energy range

$$\sigma_{compton} \sim \frac{ln(E)}{E}$$

Pair production: dominates in the high energy range (above 1.02 MeV) $\gamma \to e^+e^-$(in the vicinity of the atomic nucleus)

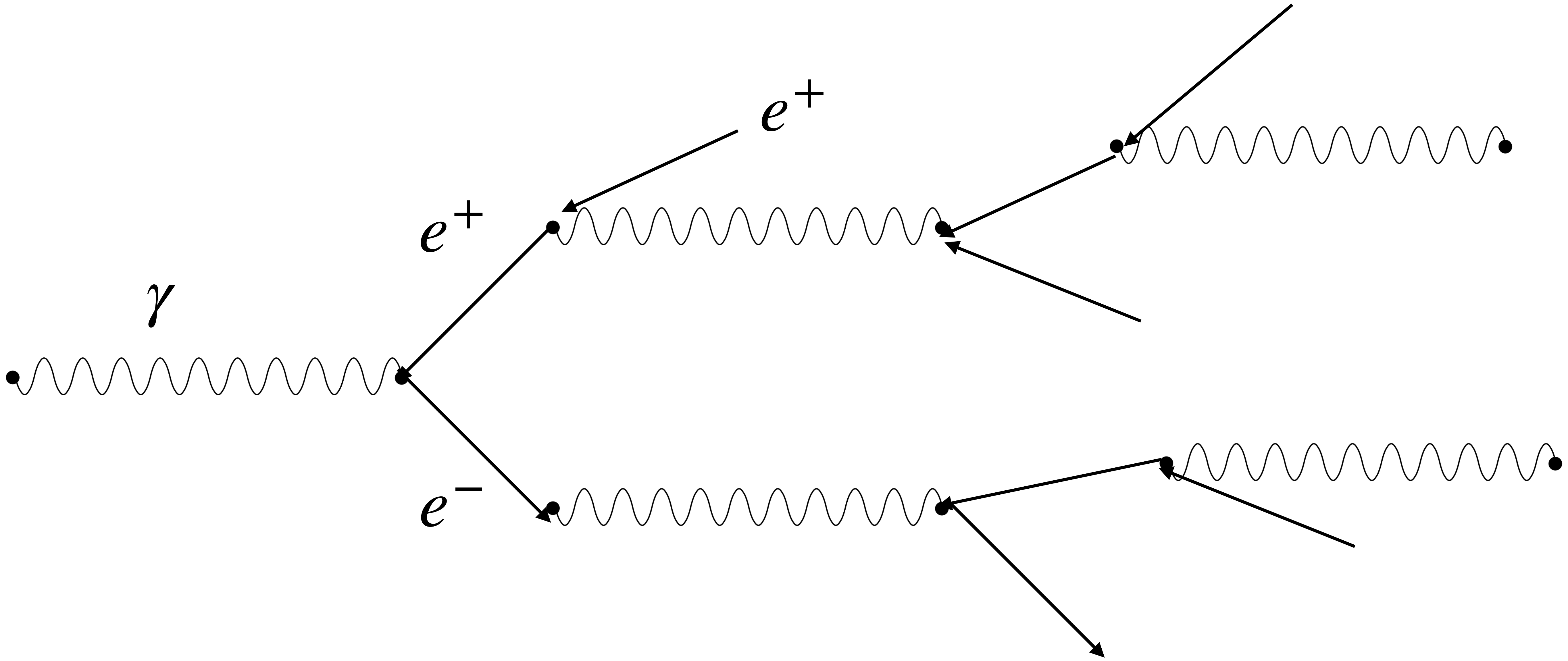
$$\sigma_{pair} \propto \frac{1}{AX_0}$$

Electron and positron

Pair mostly moves in

The direction of the photon

Electromagnetic Shower

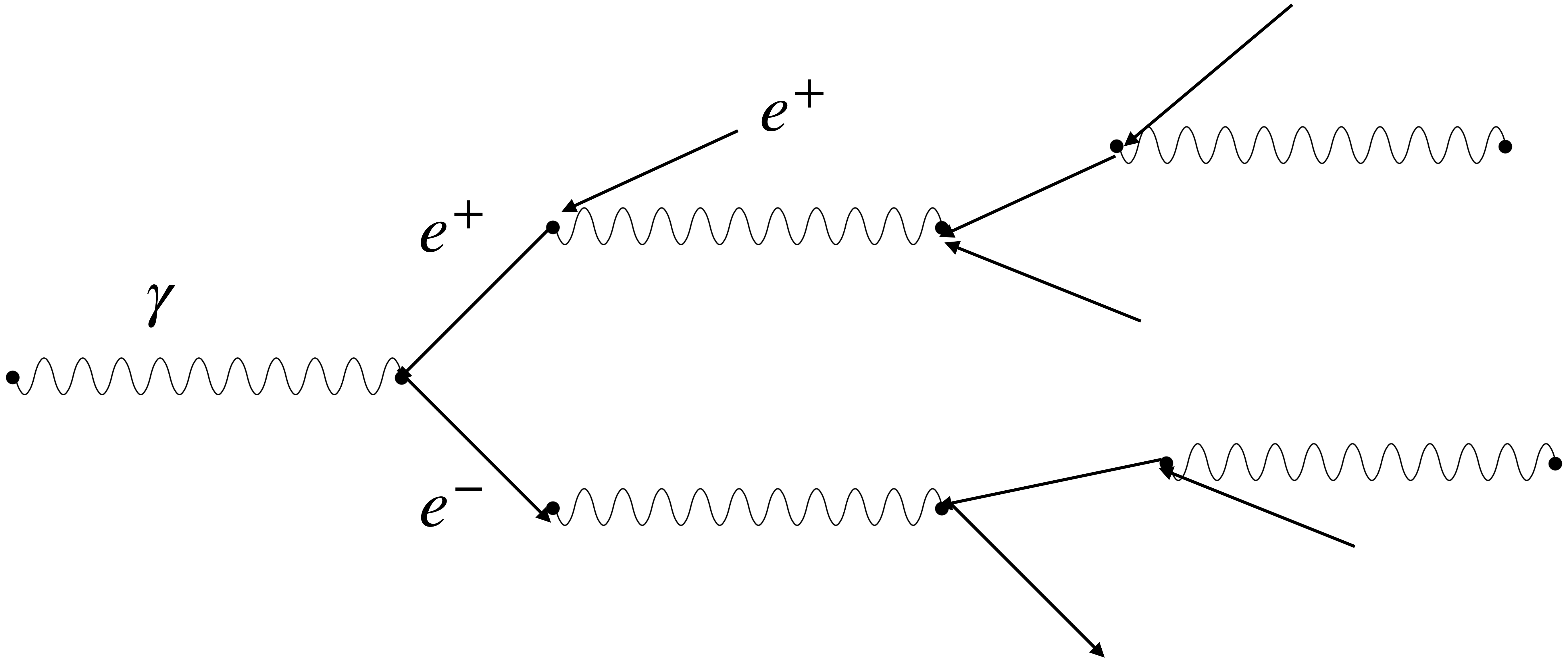


Below a threshold energy

ionisation dominates ,

Number of secondary particles reduced and finally stopped

Electromagnetic Shower



Below a threshold energy

ionisation dominates ,

Number of secondary
particles reduced and
finally stopped

Shower development is determined by radiation length , it takes an absorber of about 25 radiation length to contain most of the shower

Moeller radius : The transverse development of the shower is determined by Moliere radius

$$R_M \propto X_0$$

99% of the energy is contained in cylinder of radius $5R_M$

Hadronic Shower

Very similar to the EM shower, more complex => many more processes

Elastic scattering : $hadron + nucleus \rightarrow hadron + nucleus$ (no shower produced)

Inelastic scattering : $hadron + nucleus \rightarrow \pi + \pi + .. + nucleus^* \ etc.$

Charge exchange processes: $\pi^- + n \rightarrow \pi^0 + p$

Nuclear spallation : high energy nucleus hits a nucleus, a large number of particles and debris nucleus are emitted.

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Nuclear spallation : high energy nucleus hits a nucleus, a large number of particles and debris nucleus are emitted.

Non detectable part: nuclear binding energy, neutrinos etc.

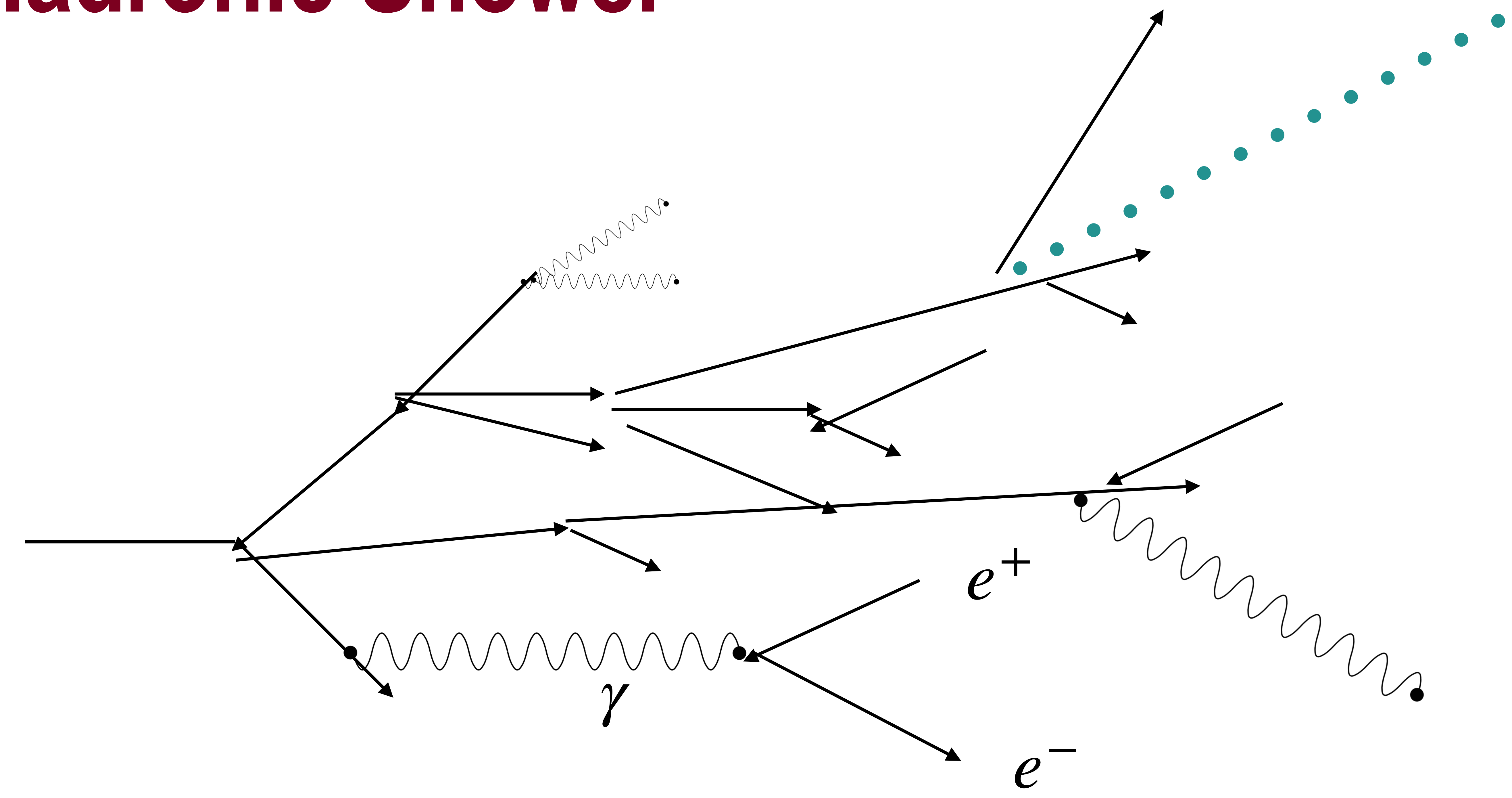
Shower has two component : hadronic and electromagnetic (photons also come from neutral

Pion decay, nuclear de-excitations) => large fluctuations of EM and hadronic components (event by event)

Shower development determined by mean free length between subsequent inelastic collisions

$$\lambda_{Interaction\ length} \sim 35\ A^{1/3} \text{ in cm}$$

Hadronic Shower



Hadronic shower has more depth than EM shower

Mean fraction of EM showers $\propto ln(E)$

Production of secondary hadrons from the inelastic collision, sequential inelastic collisions

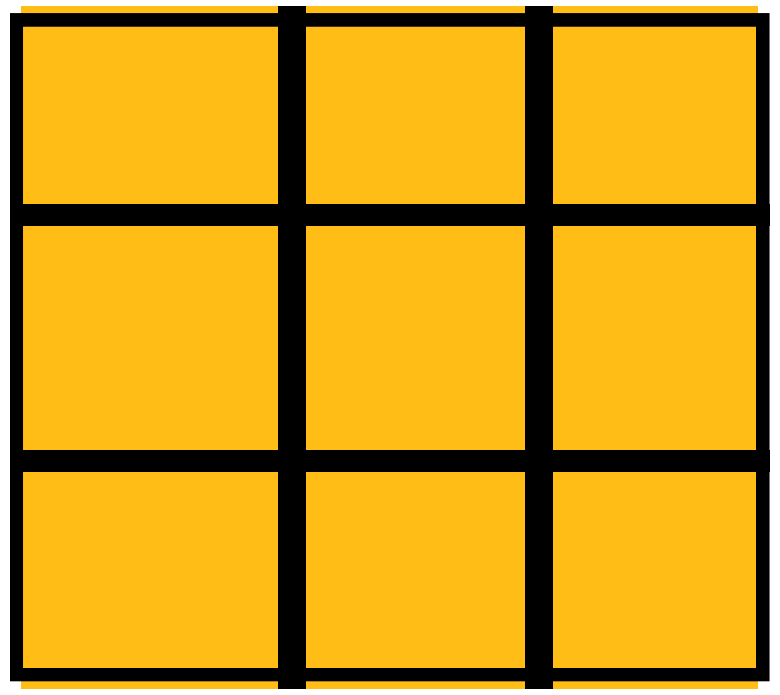
Inelastic collision stops below prion production energy threshold => ionisations starts

Decays of pion to photons (hadronic shower contains a substantial electromagnetic fraction)

Missing part: neutrinos, nuclear binding energy, delayed photons from nuclear de-excitation, low energy neutron etc.)

some part is compensated by neutron capture (fission) -> release of energy

CMS and ATLAS Calorimeter



CMS ECAL

Homogeneous calorimeter

$PbWO_4$ crystal $\mathbf{X_0 \sim 0.9}$ cm and $\mathbf{R_M \sim 2.2}$cm

23 cm long crystal with a front face 2.2 cm X 2.2 cm

3 X 3 or 5X 5 crystals contain the energy of the electron/photon

ATLAS ECAL

Sampling calorimeter

Active material: Liquid Argon and absorber: Pb

$24X_0$ total length

Longitudinal segmentation

CMS and ATLAS HCAL : sampling type

Energy resolution

Accuracy in the energy measurement in the Calorimeter

$$\frac{\sigma}{E} = \left(\frac{\sigma}{E}\right)_{stat} + \left(\frac{\sigma}{E}\right)_{instru} + \left(\frac{\sigma}{E}\right)_{sys}$$

$$\left(\frac{\sigma}{E}\right)_{stat} = \frac{\sqrt{N}}{N} = \frac{a}{\sqrt{E}}$$

$$\left(\frac{\sigma}{E}\right)_{Instru} = \frac{b}{E}$$

$$\left(\frac{\sigma}{E}\right)_{syst} = c$$

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Energy proportional to the number

of secondary particles N

$$\left(\frac{\sigma}{E}\right)_{Instru} = \frac{b}{E}$$

Noise independent of energy

$$\left(\frac{\sigma}{E}\right)_{syst} = c$$

Some systematics increases with

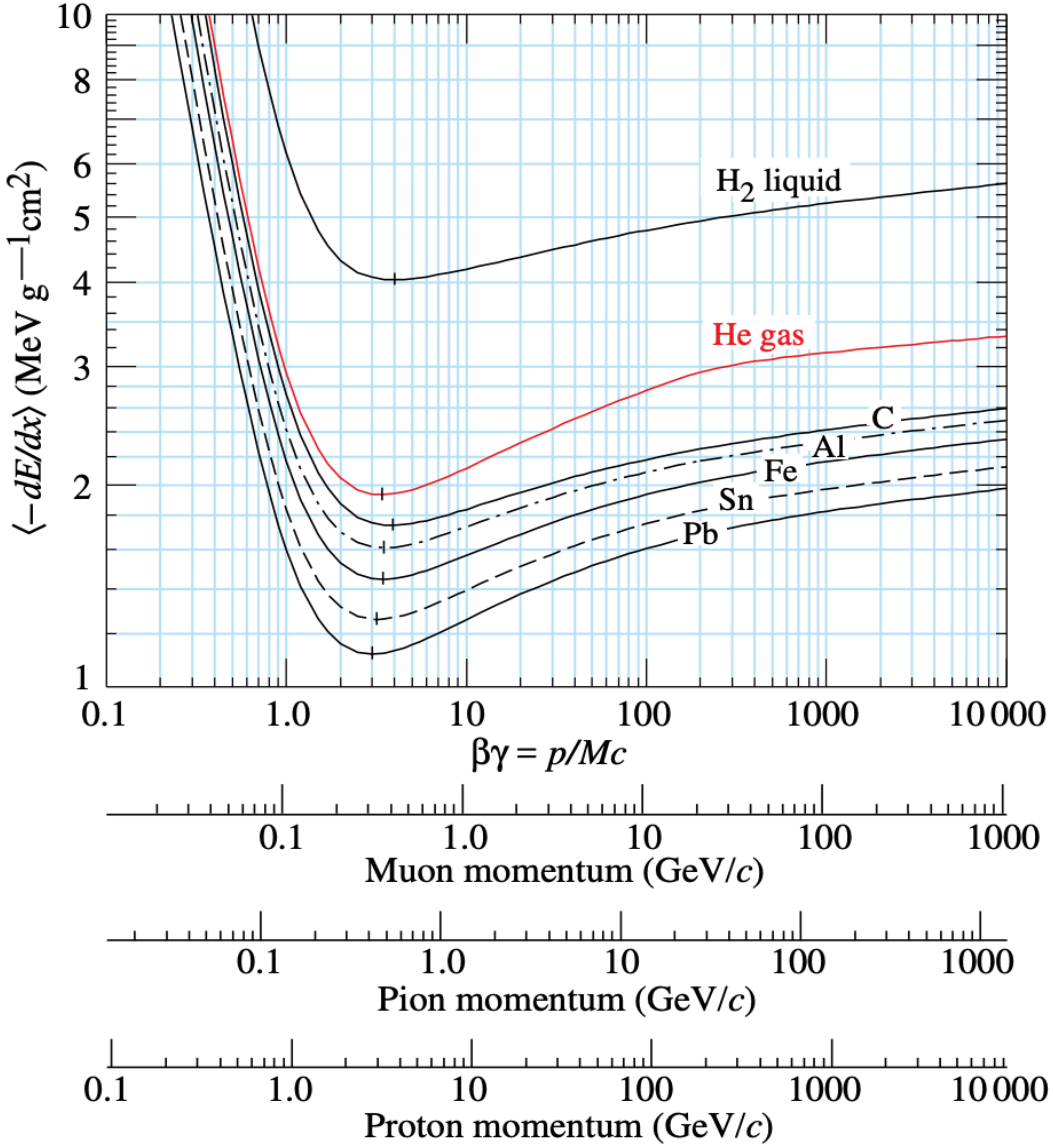
Energy (non uniformity of the calorimeter)

Additional error comes from the sampling

Muon Detection

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

The region where Bethe Block formula is valid



Minimum Ionizing particle : whose energy loss is close to minimum

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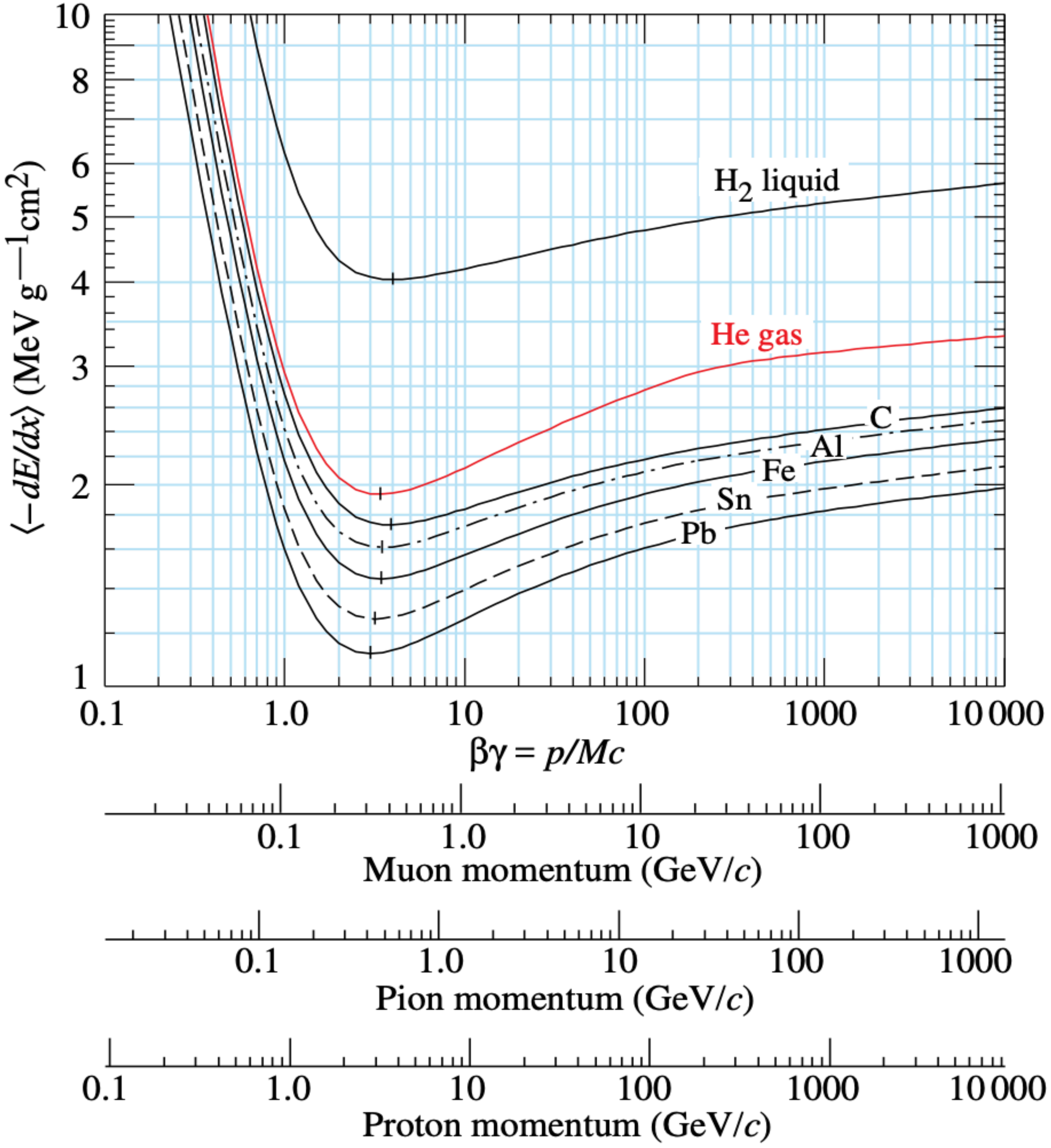
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Minimum Ionizing particle : whose energy loss is close to minimum

Muon in 100 cm thick Iron block

$$\left\langle \frac{dE}{dX} \right\rangle \Bigg|_{muon} = 1.5 \mathrm{MeV} g^{-1} cm^2$$

$$\rho(Fe) = 7.87 g cm^{-3}$$

Energy loss = $1.5 \times 100 \times 7.8 \sim 1\mathrm{GeV}$

Muon penetrates through ECAL and HCAL

Significant bremsstrahlung from Muon starts with energy above 1 TeV

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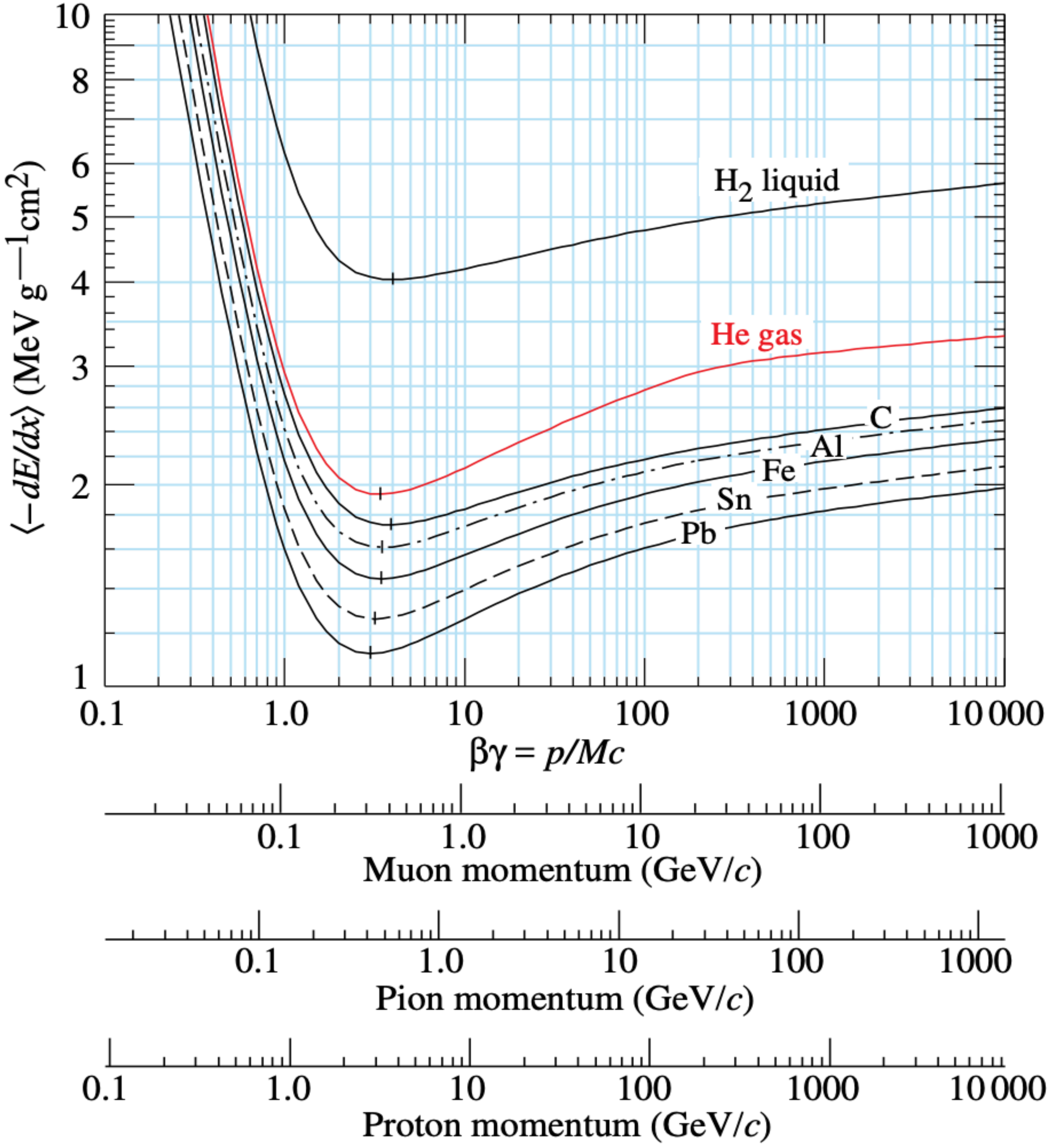

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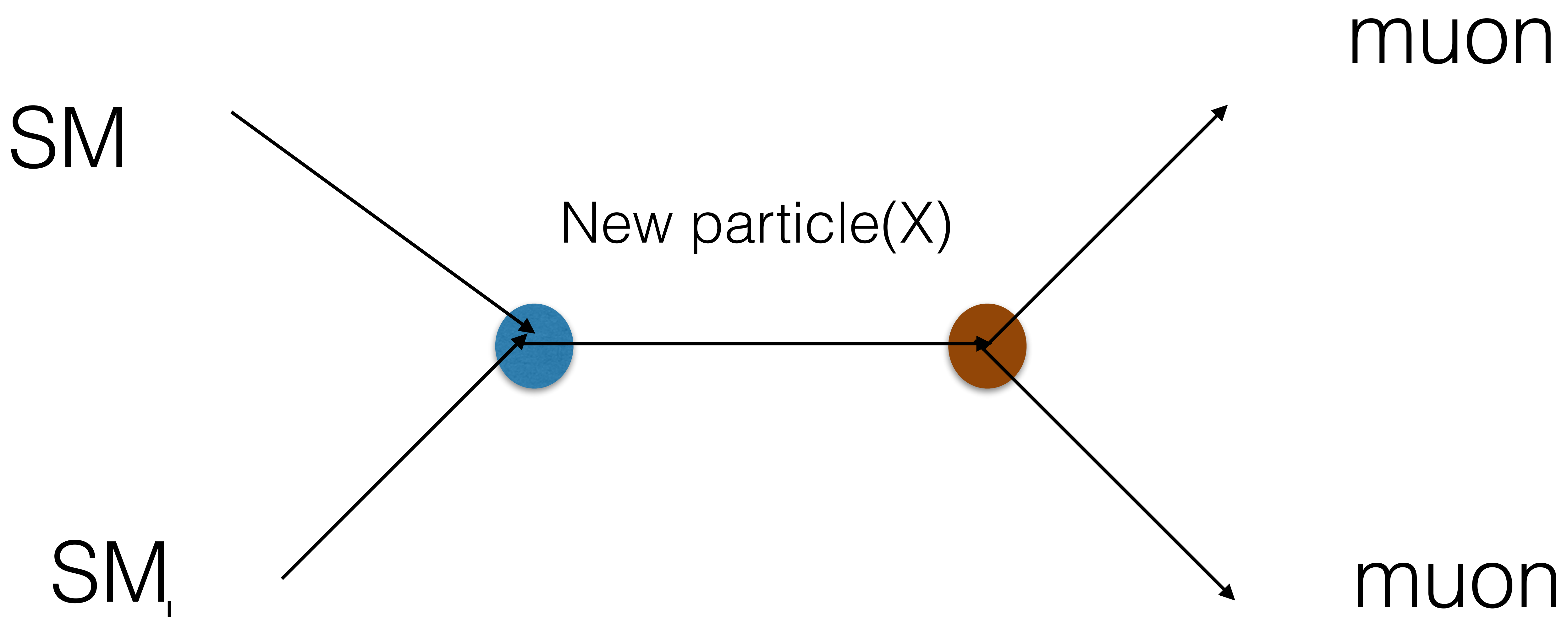
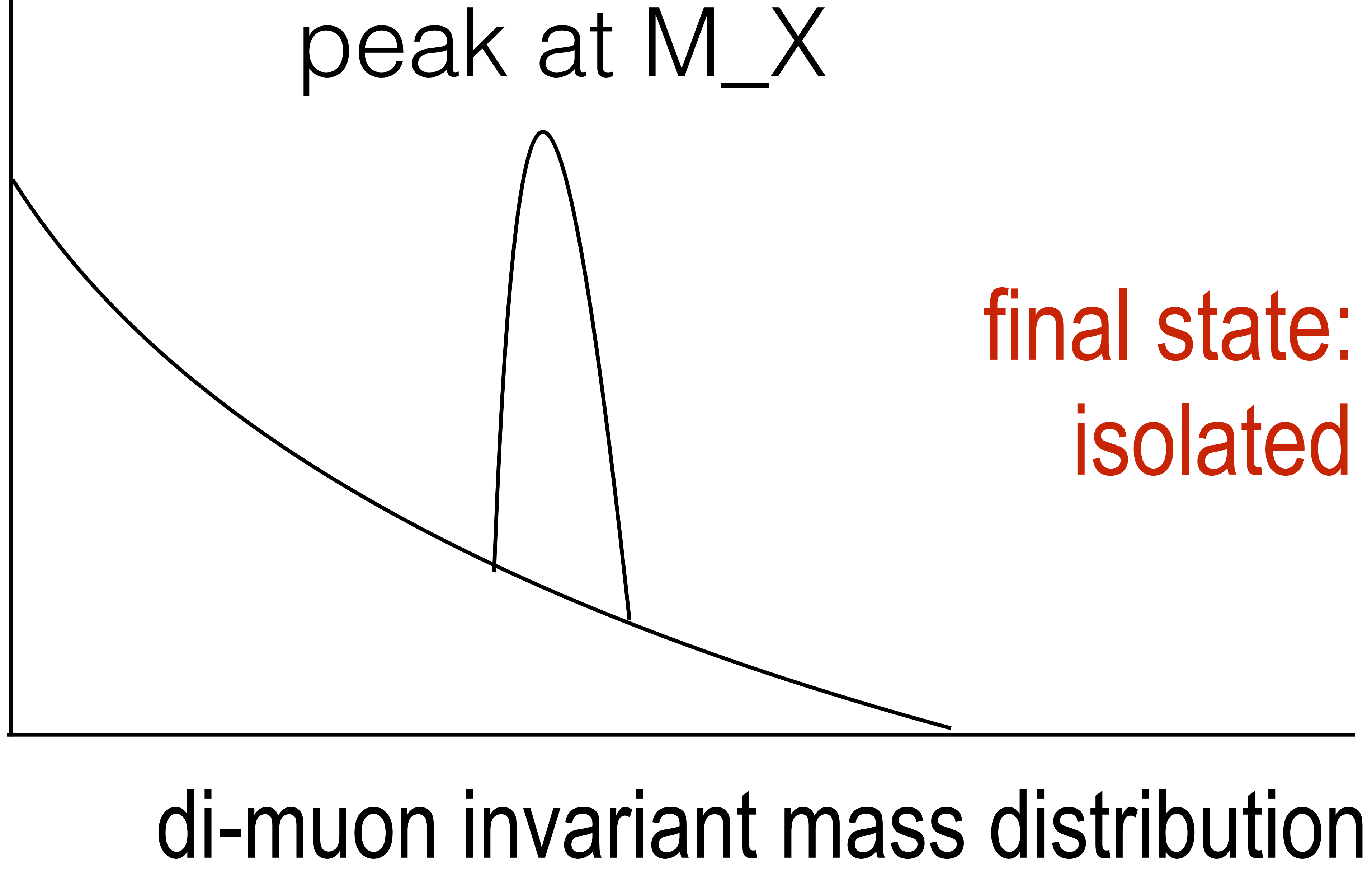
New Physics searches : Variables

New physics Search: Resonance

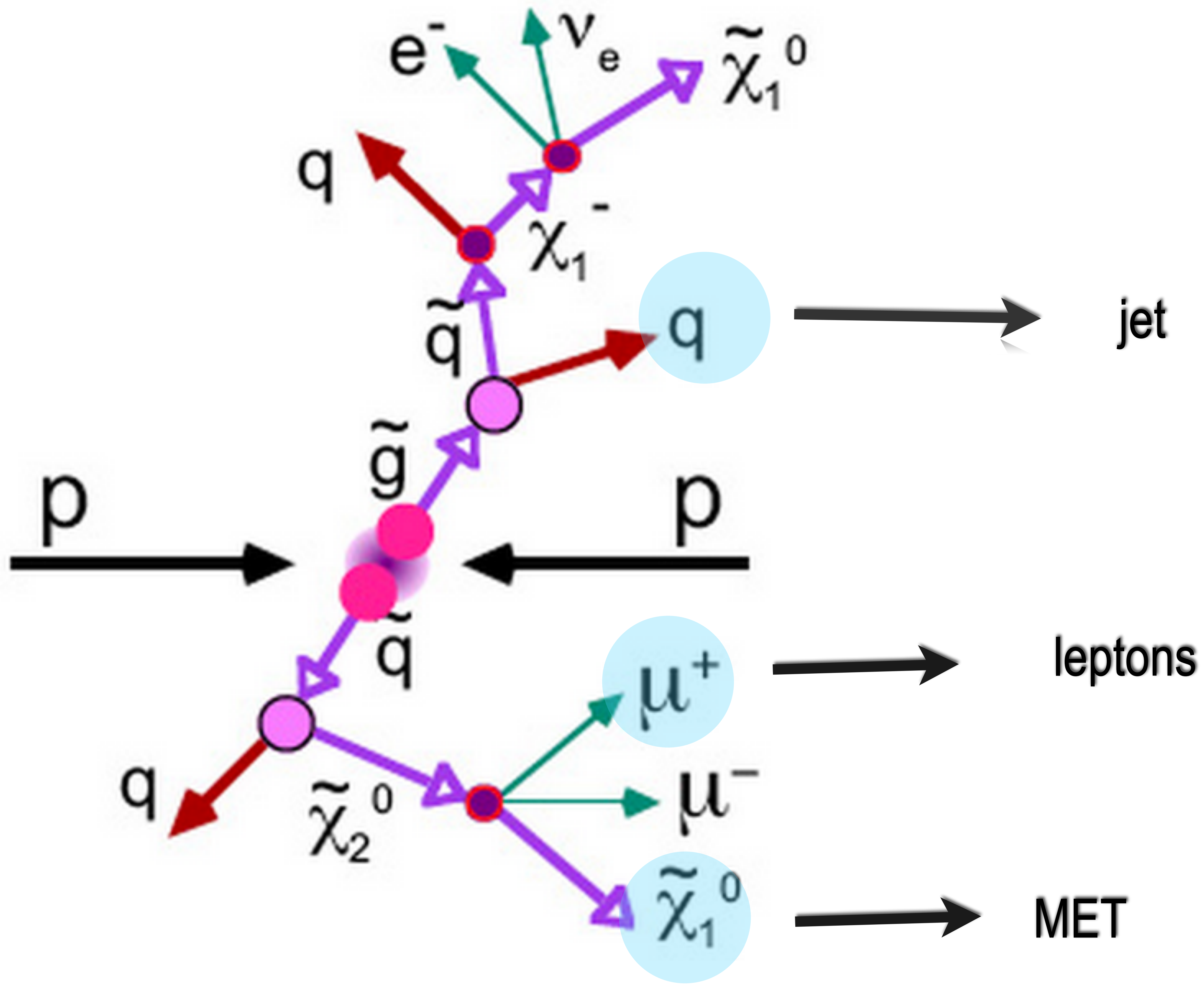
The decay products of the new particle are visible SM particles





final state: 2 high P_T isolated muons

New physics Search: Cascade



Final state

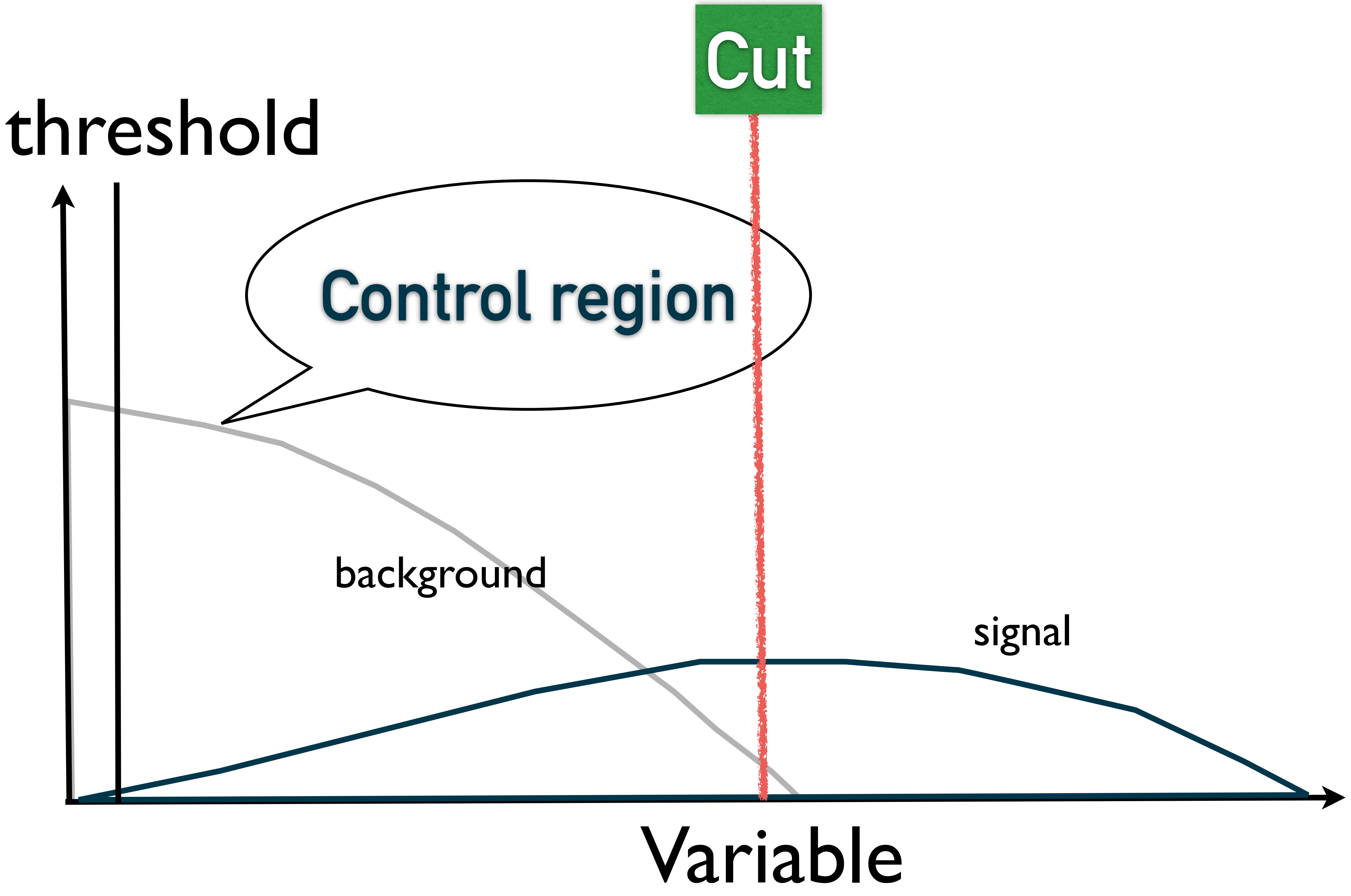
Jets
+
leptons
+
missing transverse
energy

R- parity conserved

Lightest SUSY
particle is stable
(dark matter
candidate)
Missing transverse
energy

Signal vs Background : Cuts

Define variables which can discriminate signal and background



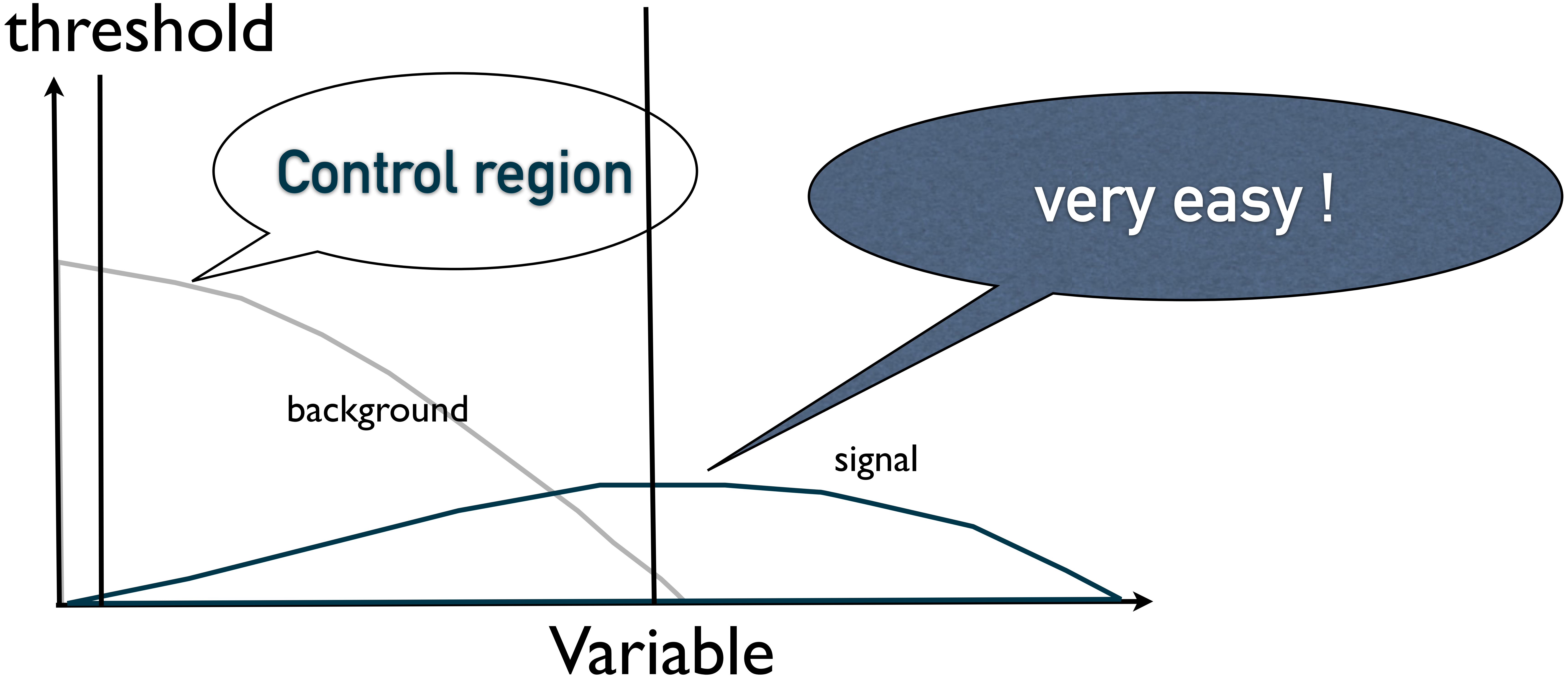
Some numbers
SM cross sections (background)
QCD(pt>100 GeV) = 2000000 pb
W + jets = 20000 pb (W decays to electron)
top pair =900 pb

SUSY cross sections (signal)
Gluino pair (mass = 1 TeV)
~ 450 fb
stop pair(mass = 1TeV)
~ 10 fb

Signal vs Background : Cuts

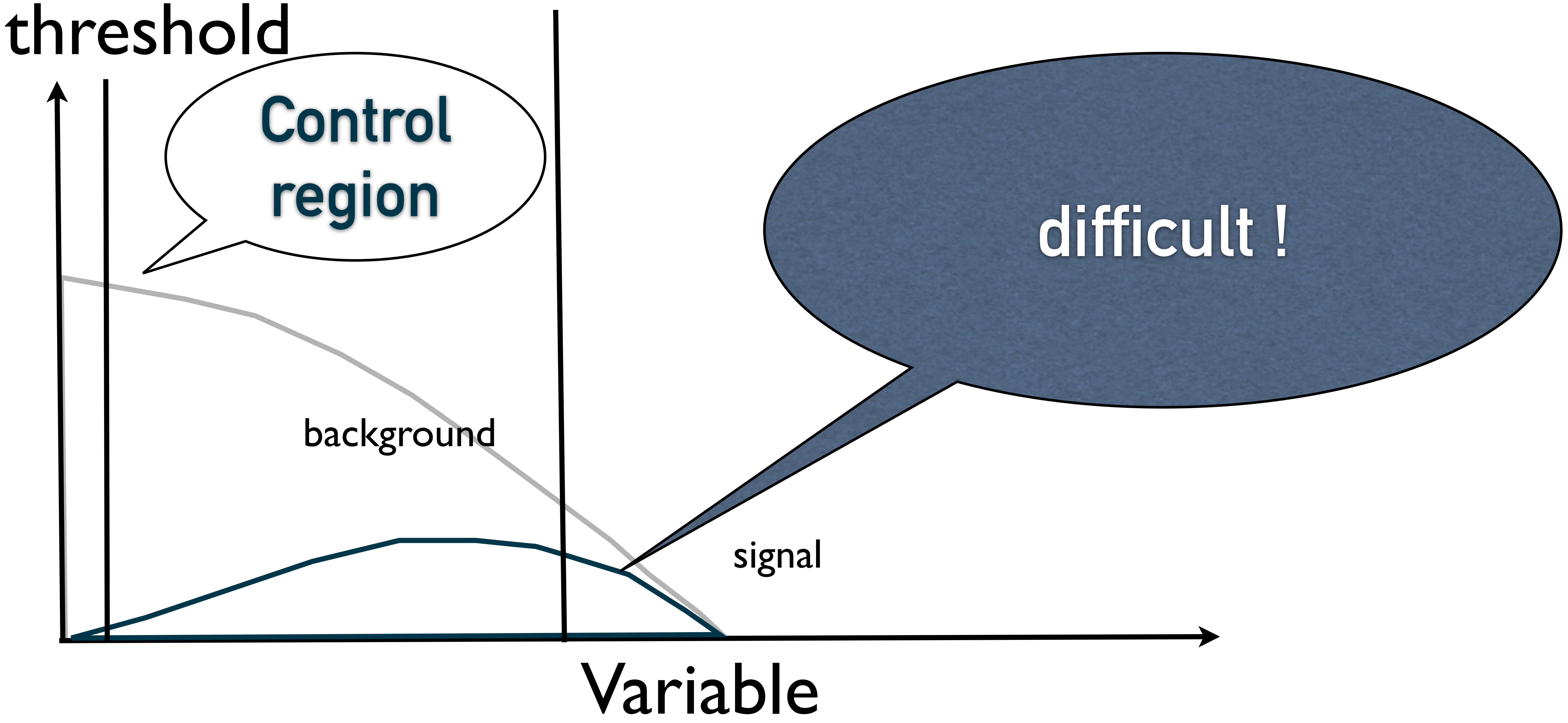
Define variables which can discriminate signal and background

Typical variable for SUSY : missing transverse energy, effective mass



Signal vs Background : Cuts

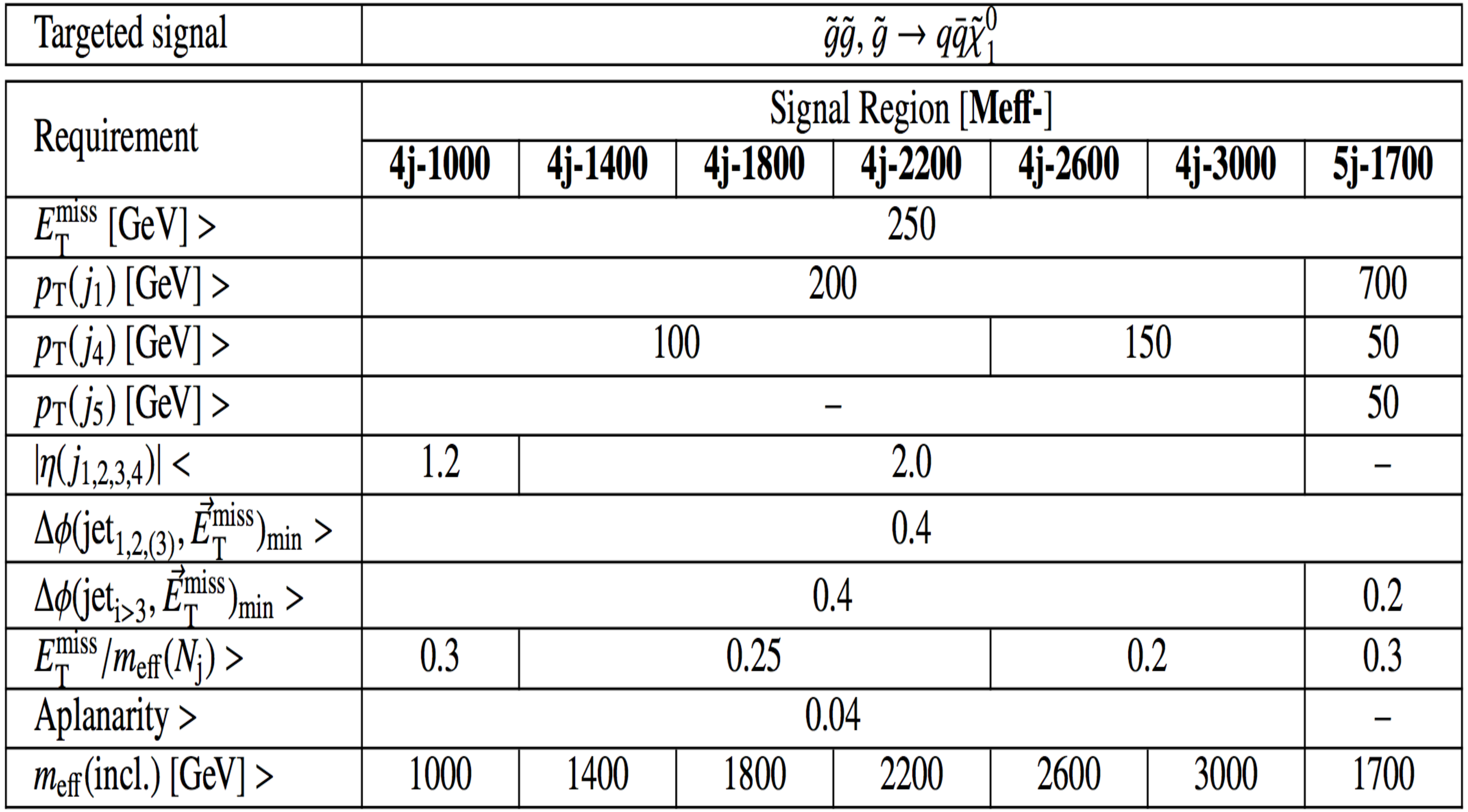
It is not always possible to construct observables which can easily discriminate signal from backgrounds



SUSY search: Multi-jet + MET

ATLAS-CONF-2017-022

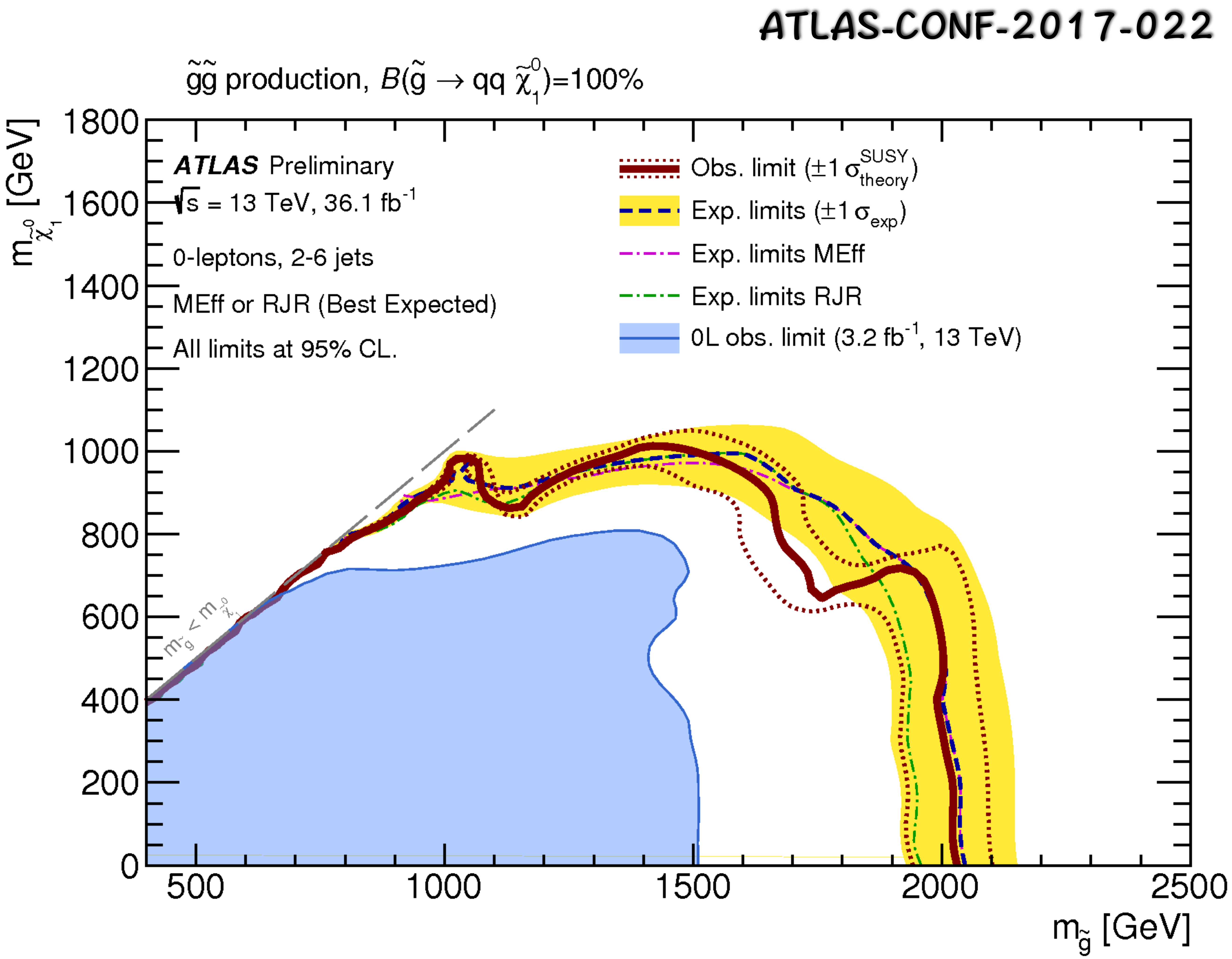
Not the most updated one



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
$\lvert\eta(j_{1,2,3,4})\rvert$ <	1.2	2.0					–
$\Delta\phi(\text{jet}_{1,2,(3)}, \vec{E}_T^{\text{miss}})_{\text{min}}$ >	0.4						
$\Delta\phi(\text{jet}_{i>3}, \vec{E}_T^{\text{miss}})_{\text{min}}$ >	0.4						0.2
$E_T^{\text{miss}}/m_{\text{eff}}(N_j)$ >	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



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

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

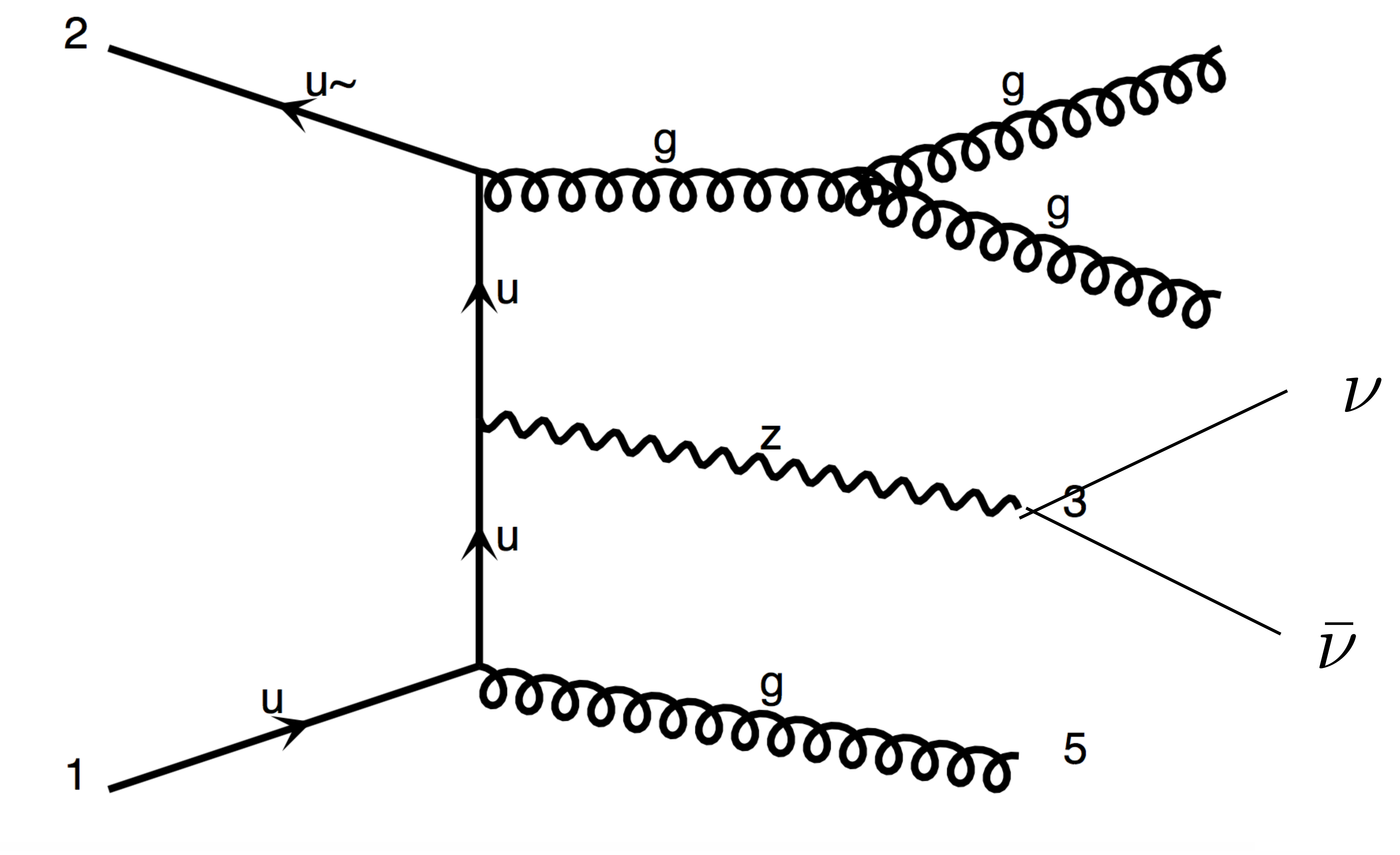
$$pp \rightarrow \tilde{q}\tilde{q}$$

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

Final state : *Multiple jets* + *MET*

SM backgrounds

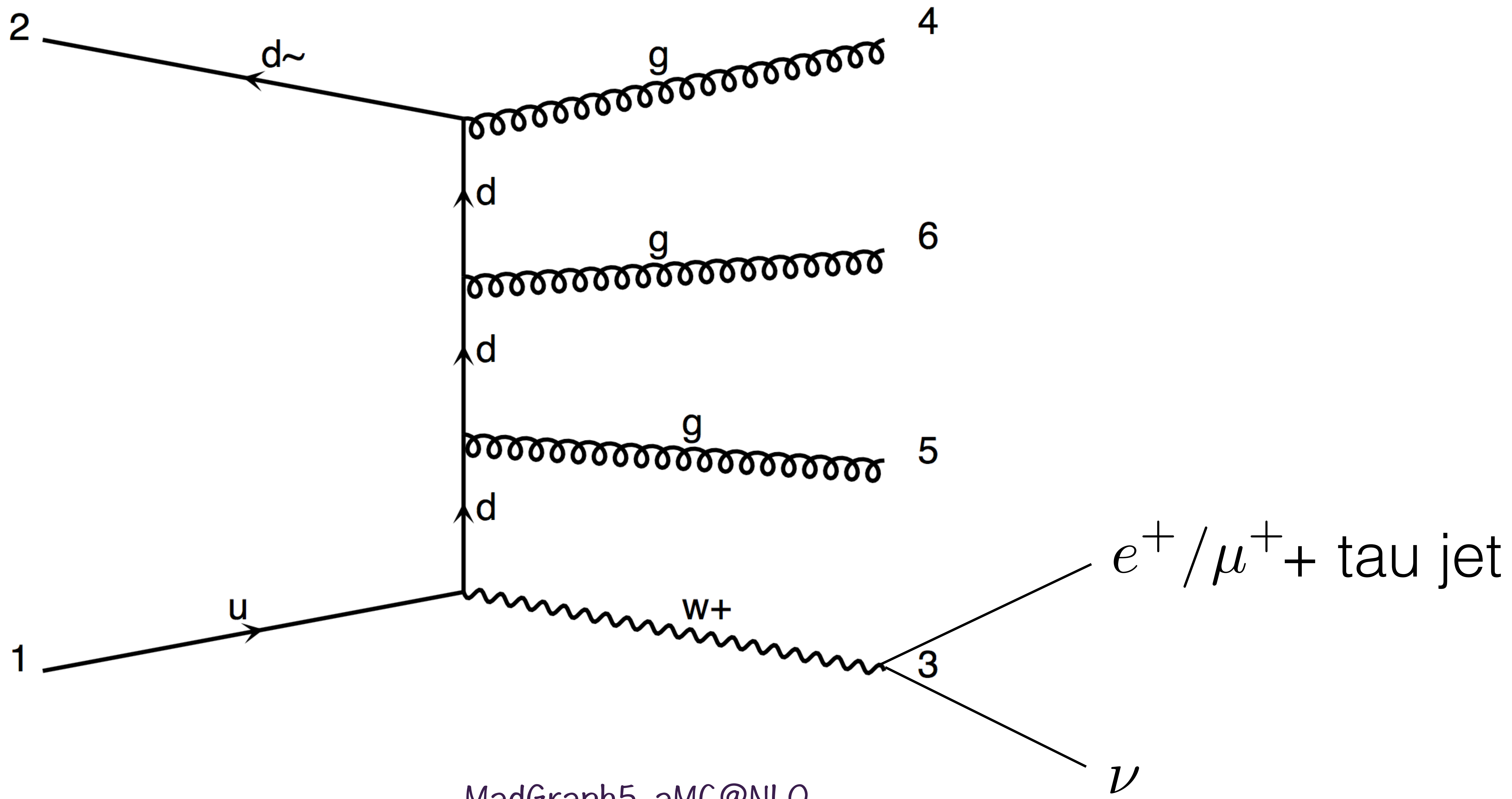
Z + jets



MadGraph5_aMC@NLO

SM backgrounds

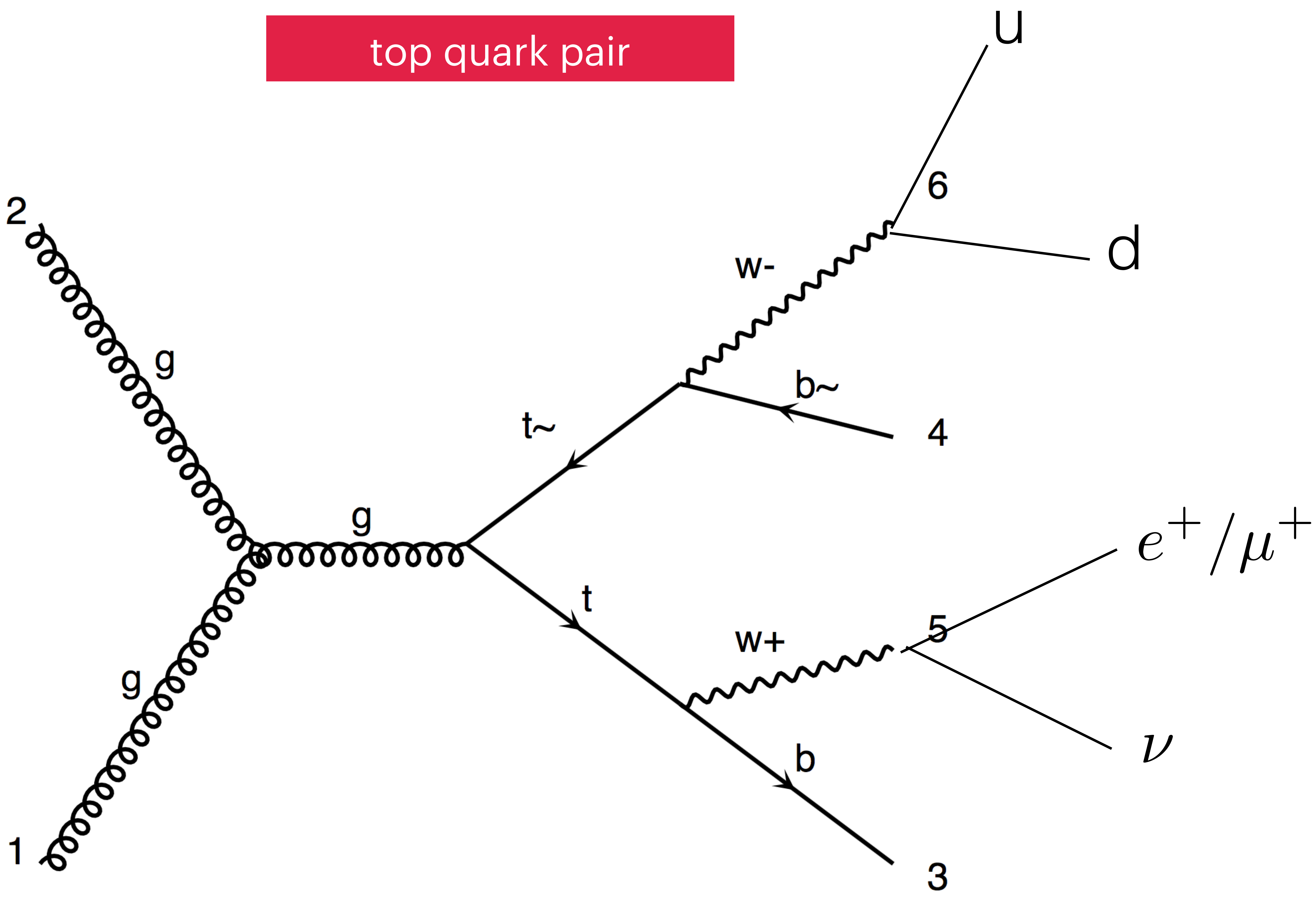
W + jets



MadGraph5_aMC@NLO

SM backgrounds

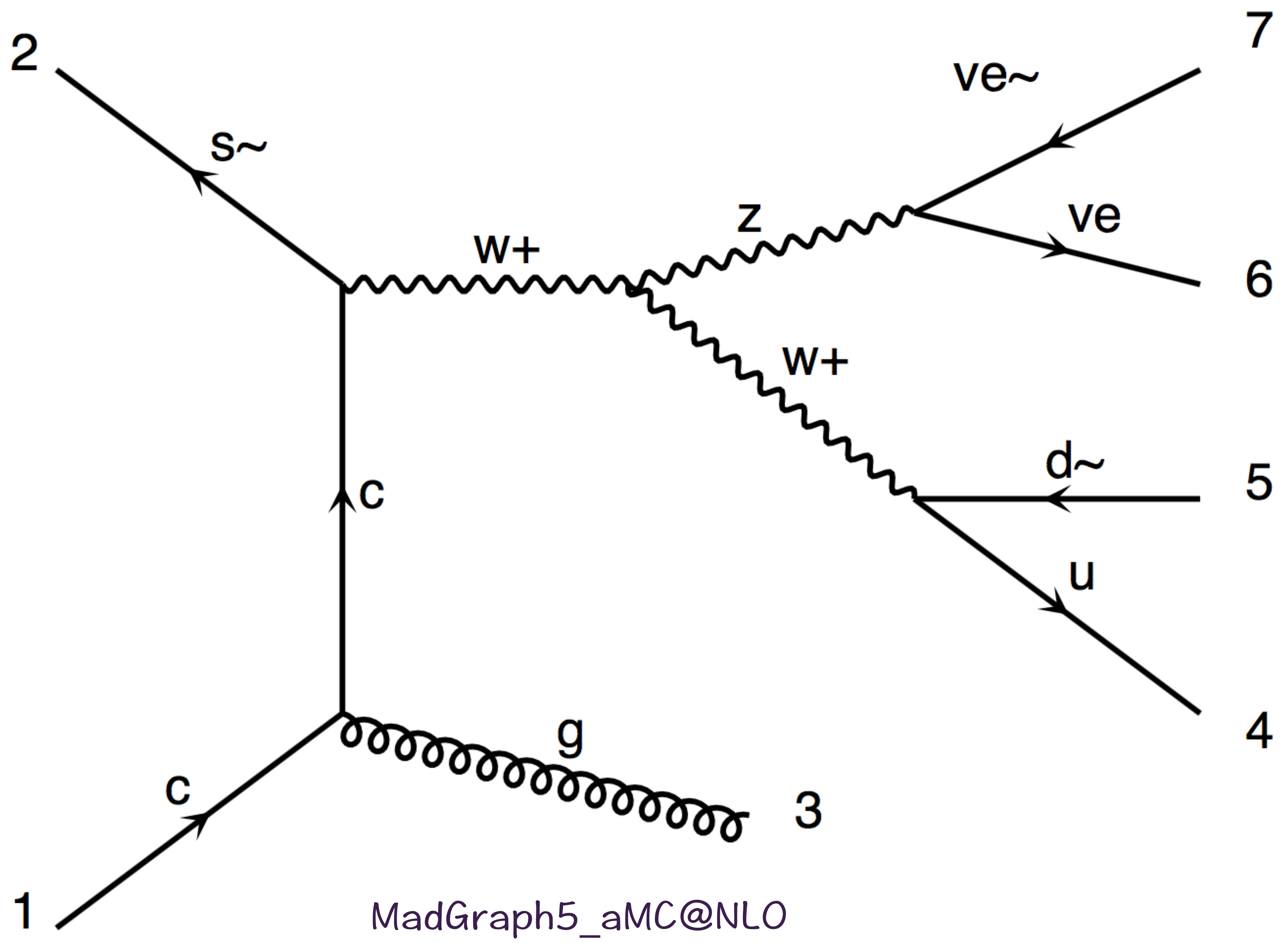
top quark pair



MadGraph5_aMC@NLO

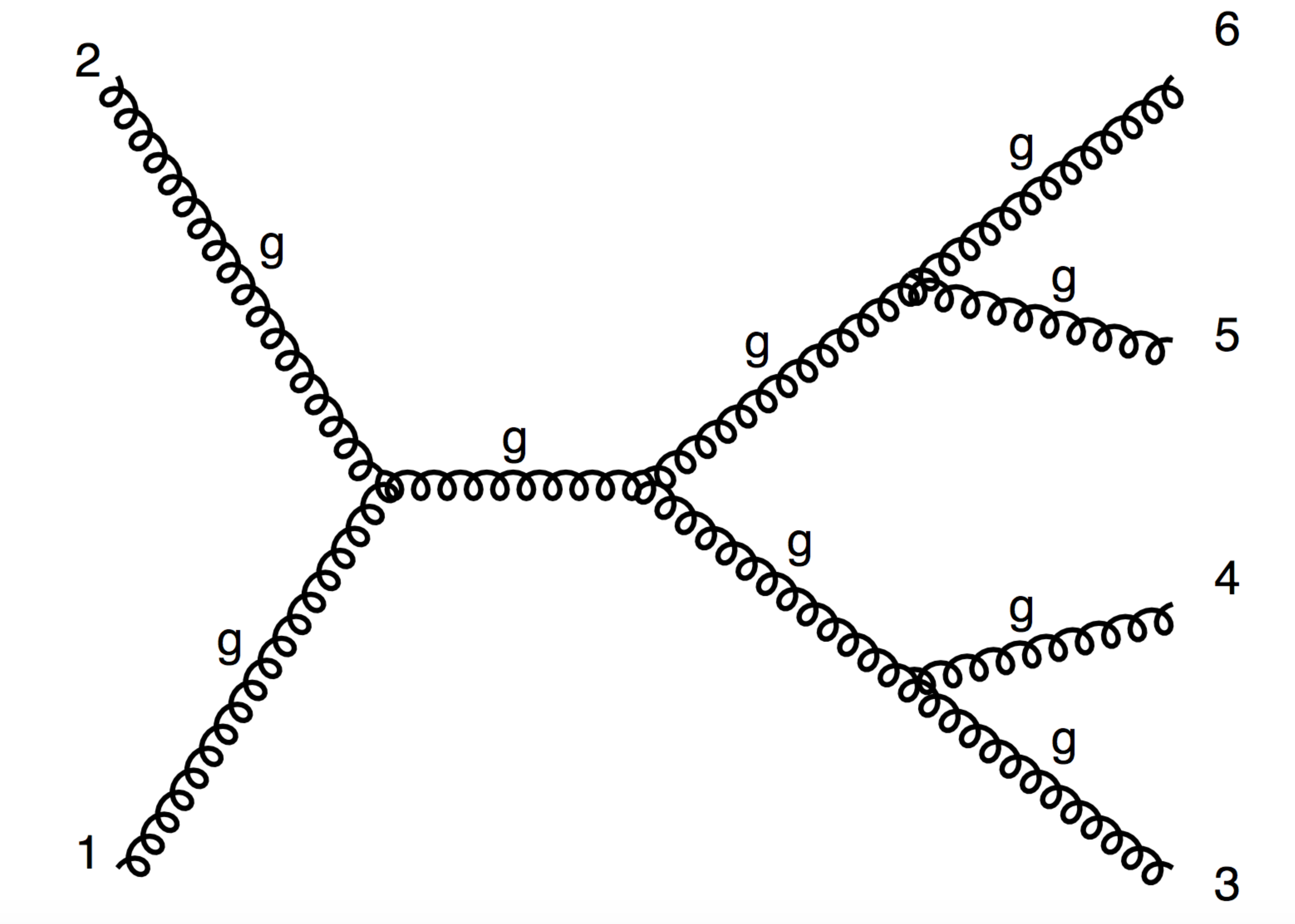
SM backgrounds

Other subdominant backgrounds VV + jets , single top



SM backgrounds

QCD Multi-jet background



MadGraph5_aMC@NLO

Simple Illustration

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

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

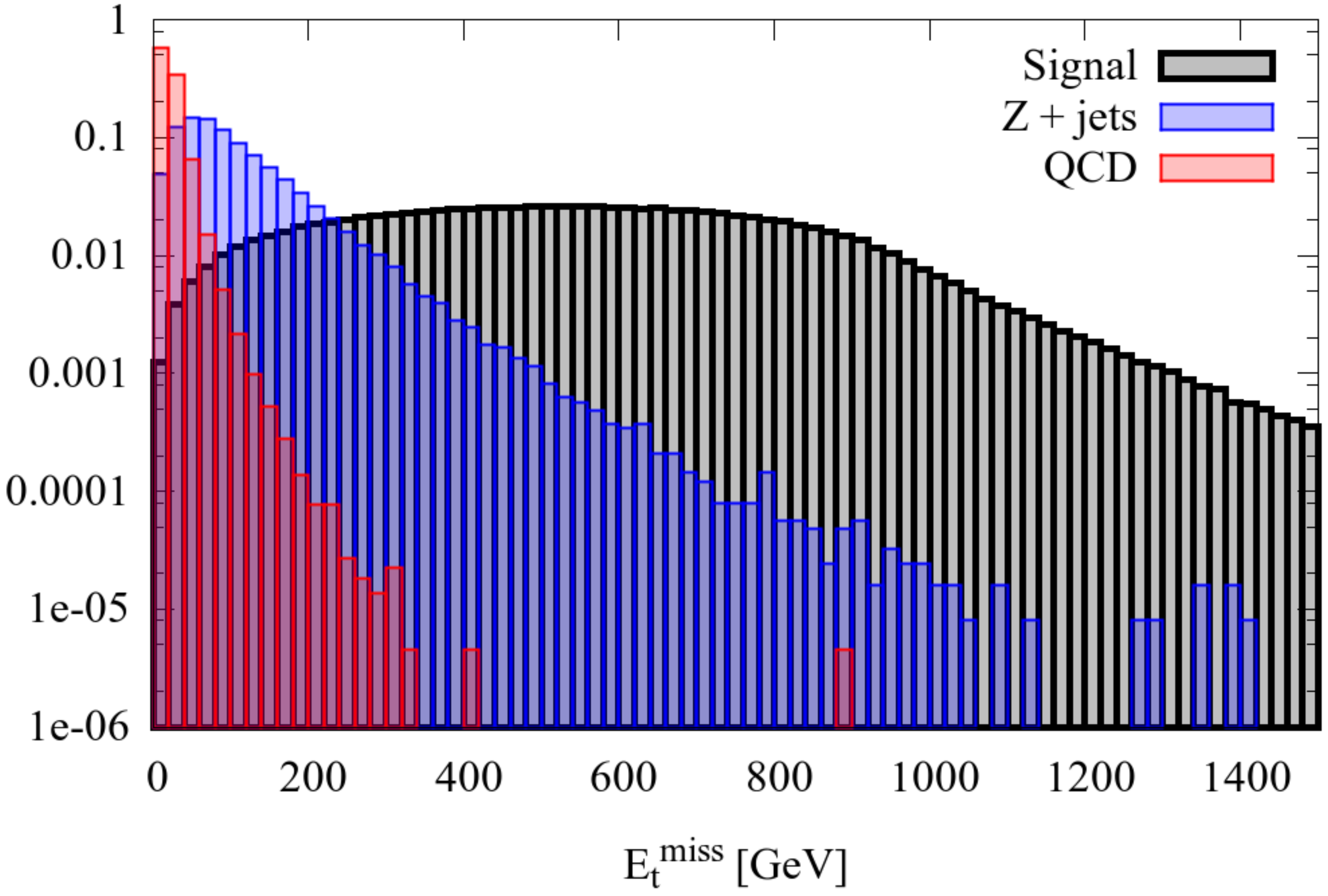
squark pair production (Mass = 1 TeV) using Pythia-6
squark to quark + neutralino (mass = 100 GeV)
Delphes 3 simulation
backgrounds: Z+ 2 jets , QCD dijet
(This is only for illustration)

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

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)

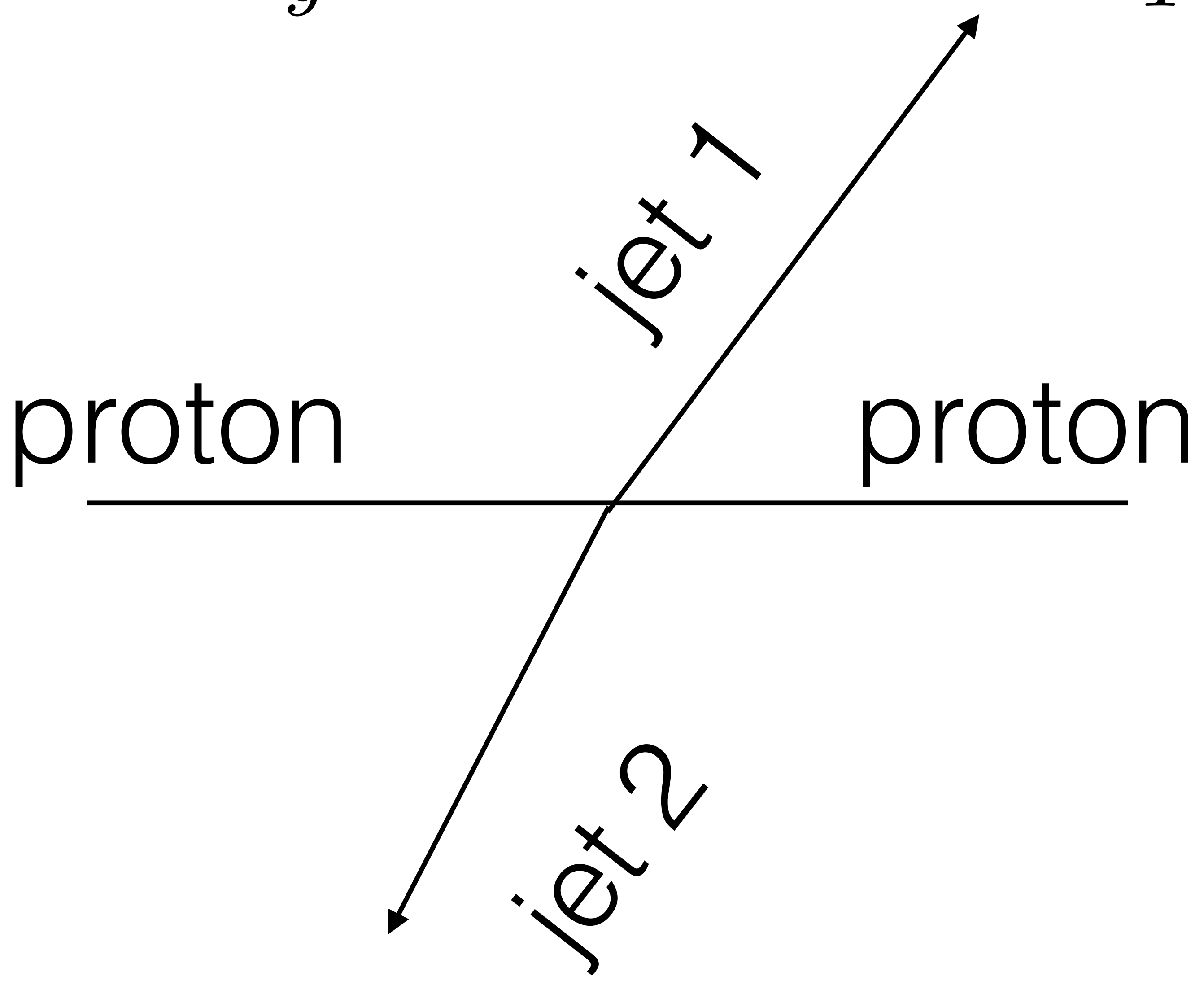
Gluino pair (mass = 1 TeV)
~ 450 fb
stop pair(mass = 1TeV)
~ 10 fb

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

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

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

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

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

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

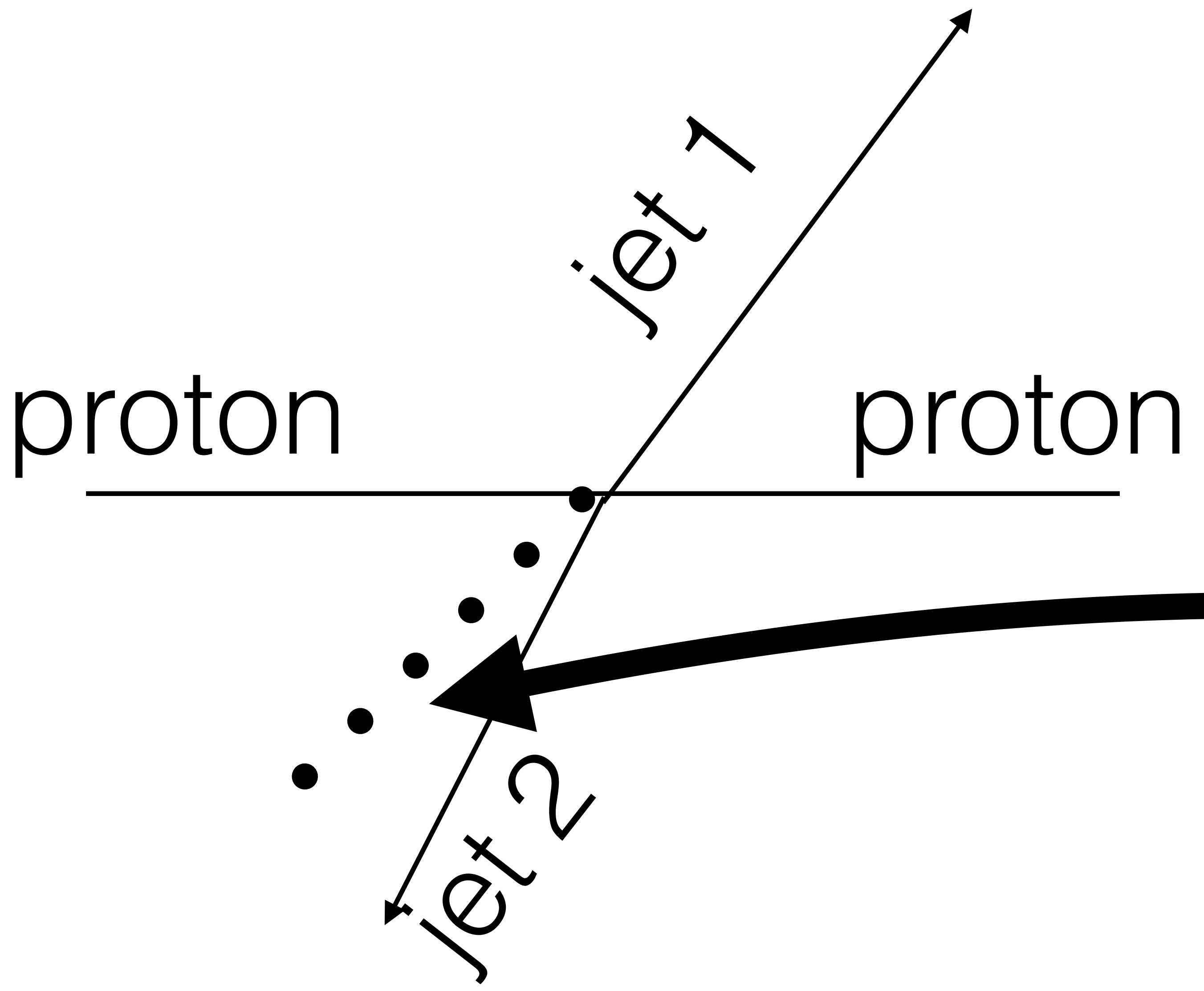
perfectly balanced di-jet

MET~ 0 GeV

MET from QCD

real example

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



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

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

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

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

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

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

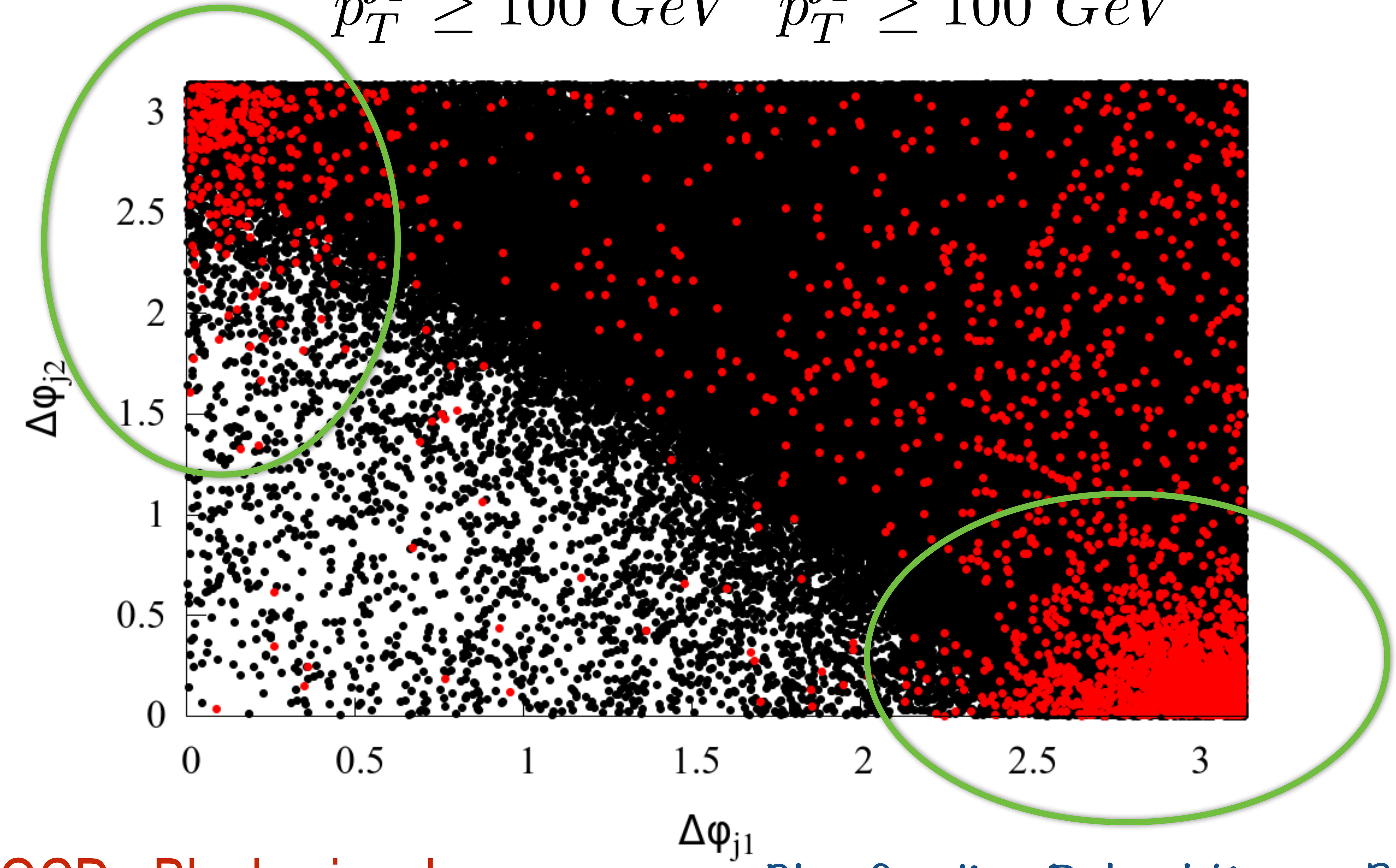
jet 2 is badly mis-measured

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

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

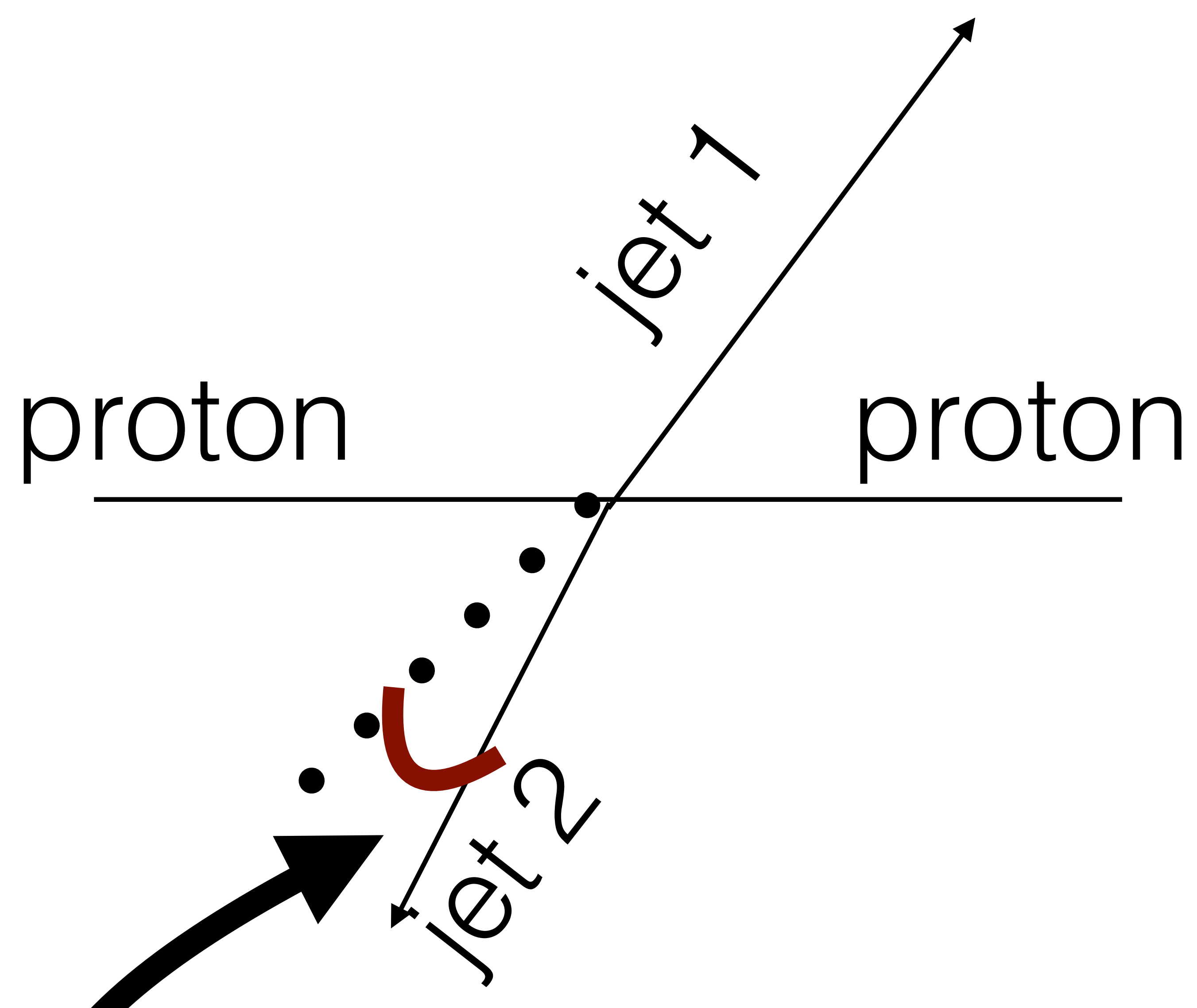


Red : QCD , Black: signal

Plot Credit : Rahool Kumar Barman

MET from QCD

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



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

jet 2 is badly mis-measured

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

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

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

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

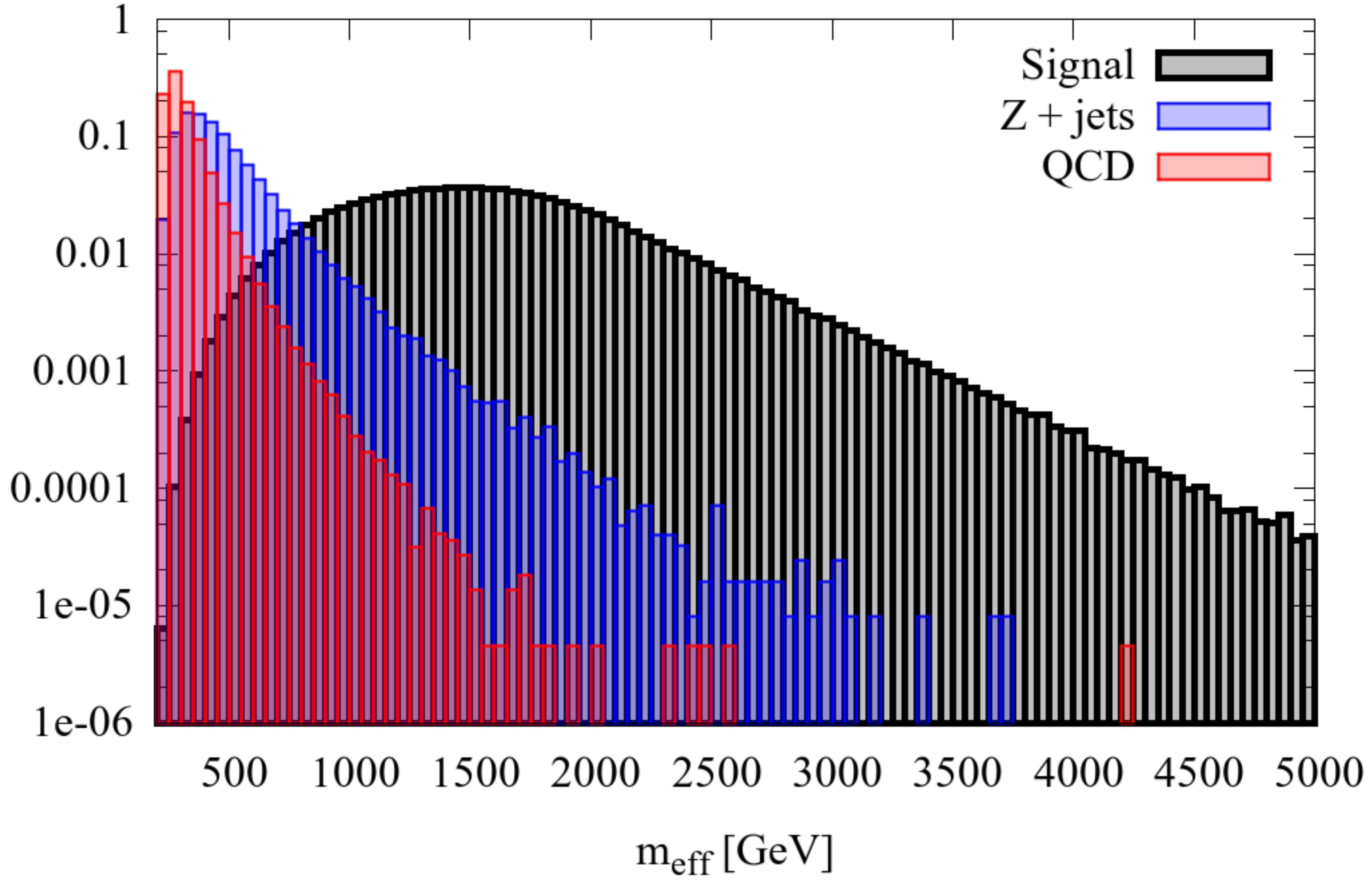
$$p_T^{missing} = 219 \text{ GeV}$$

(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

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



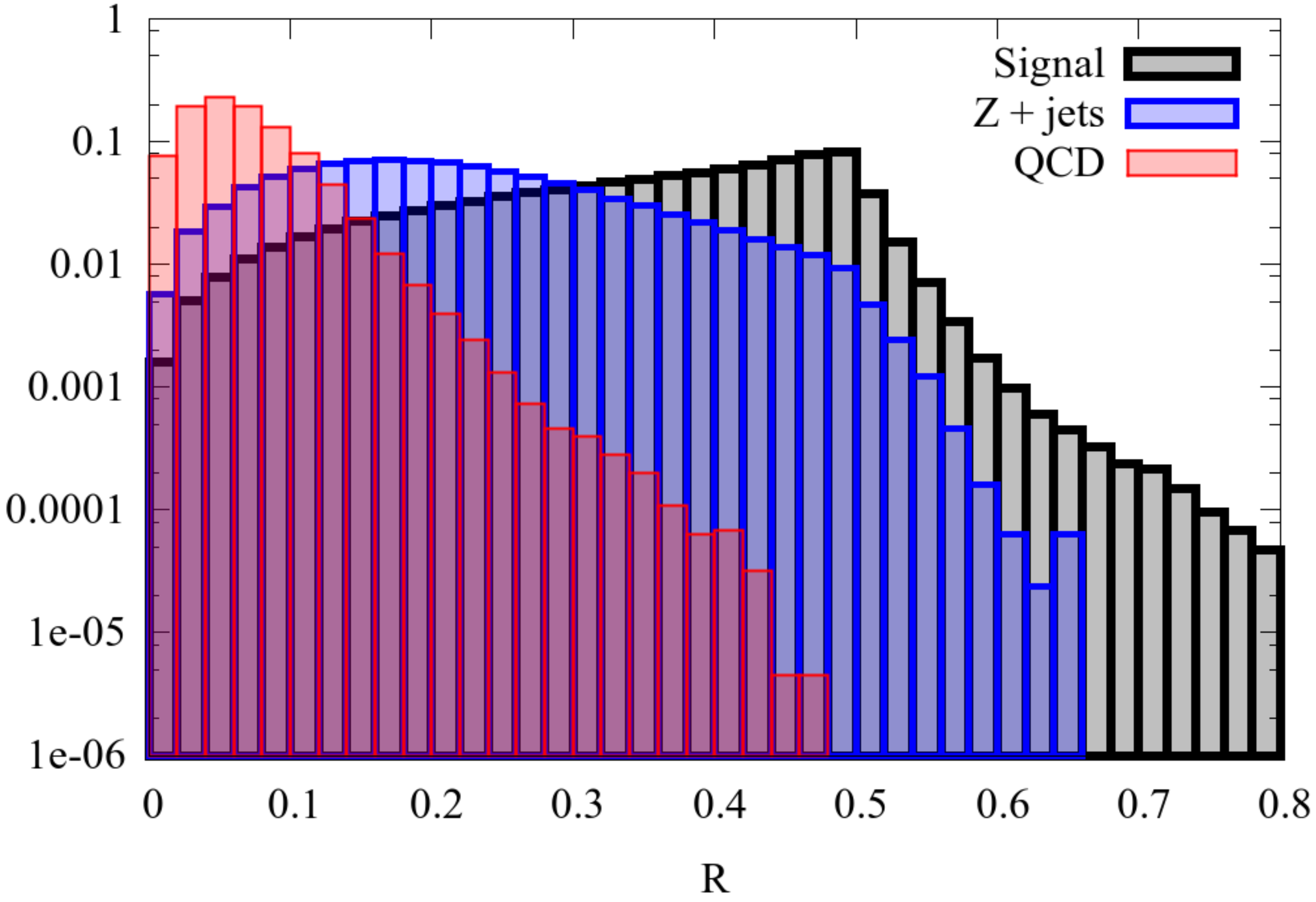
$$\boxed{m_{eff} = \sum p_T^{jets} + p_T^{mis}}$$

Plot Credit : Rahool Kumar Barman

MET/ Effective Mass Cut

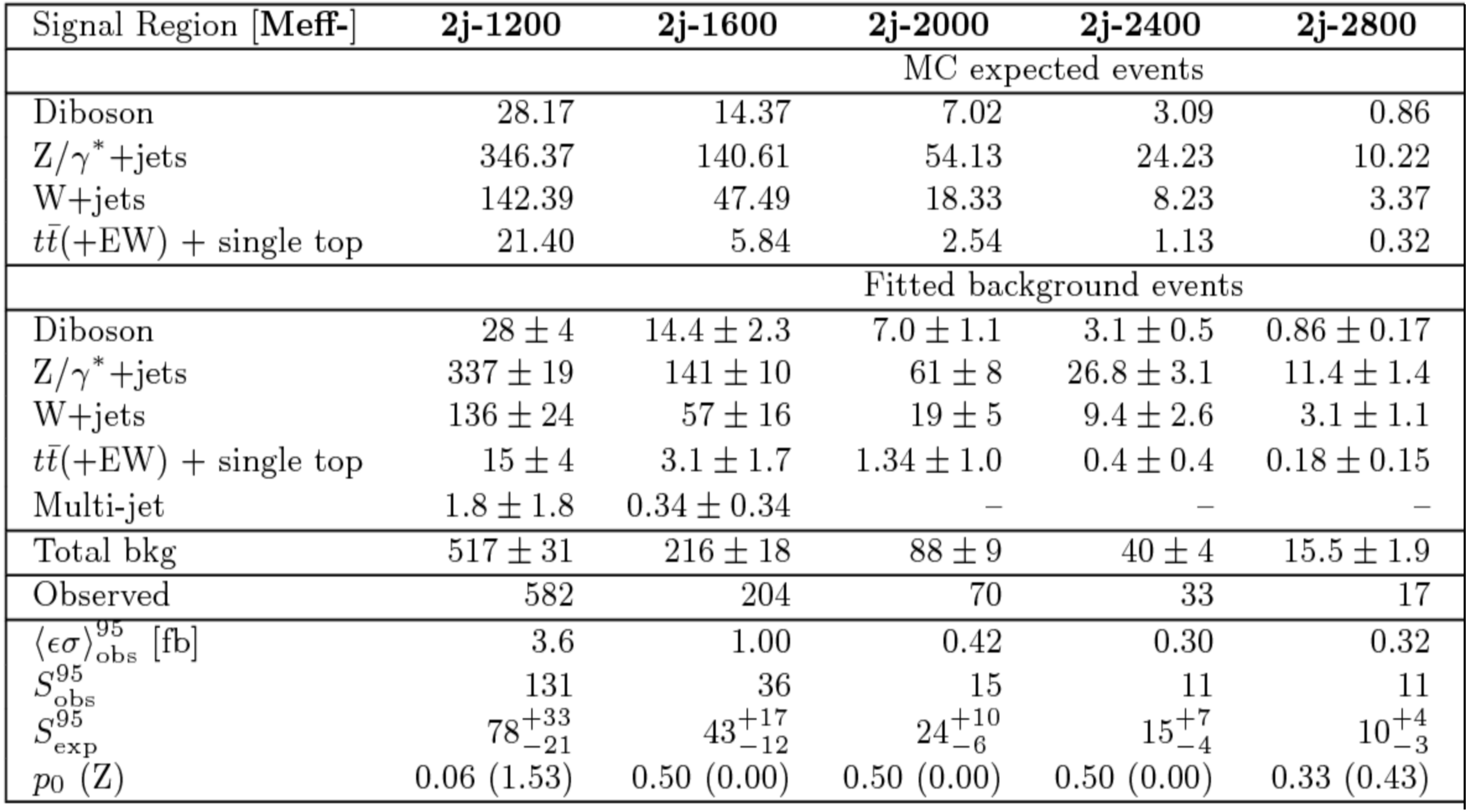
squark pair production (Mass = 1 TeV) using Pythia-6
squark to quark + neutralino (mass = 100 GeV)
Delphes 3 simulation

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



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
$\langle \epsilon\sigma \rangle^{95}_{\mathrm{obs}}$ [fb]	3.6	1.00	0.42	0.30	0.32
S^{95}_{obs}	131	36	15	11	11
S^{95}_{exp}	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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$$M_A^2 = M_B^2 + M_X^2 + 2(E_T^B E_T^X \cosh(\Delta\eta_{BX}) - \mathbf{p}_T^B \cdot \mathbf{p}_T^X)$$

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

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

Suppose B and X are massless

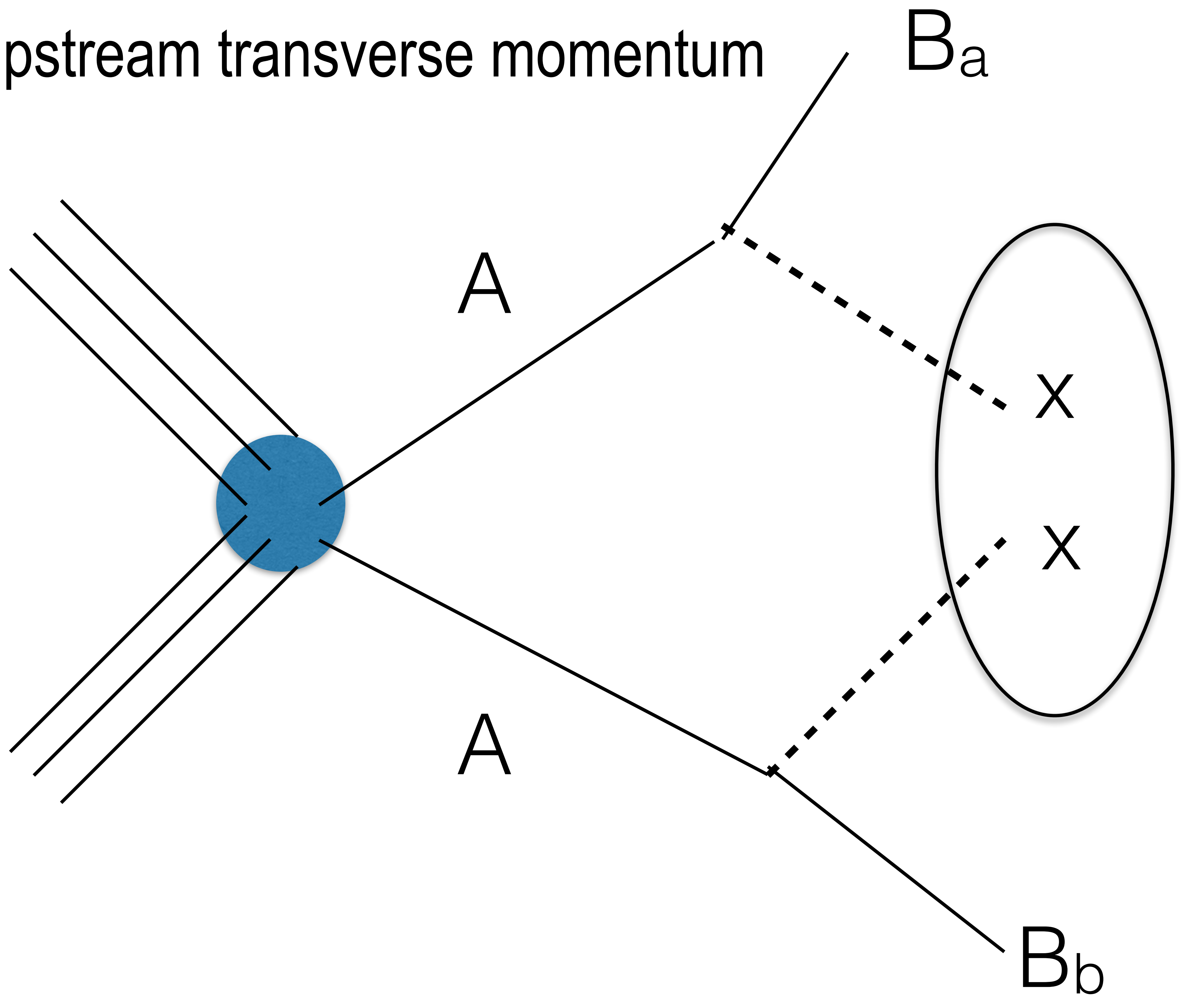
Suppose B and X are massless

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

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

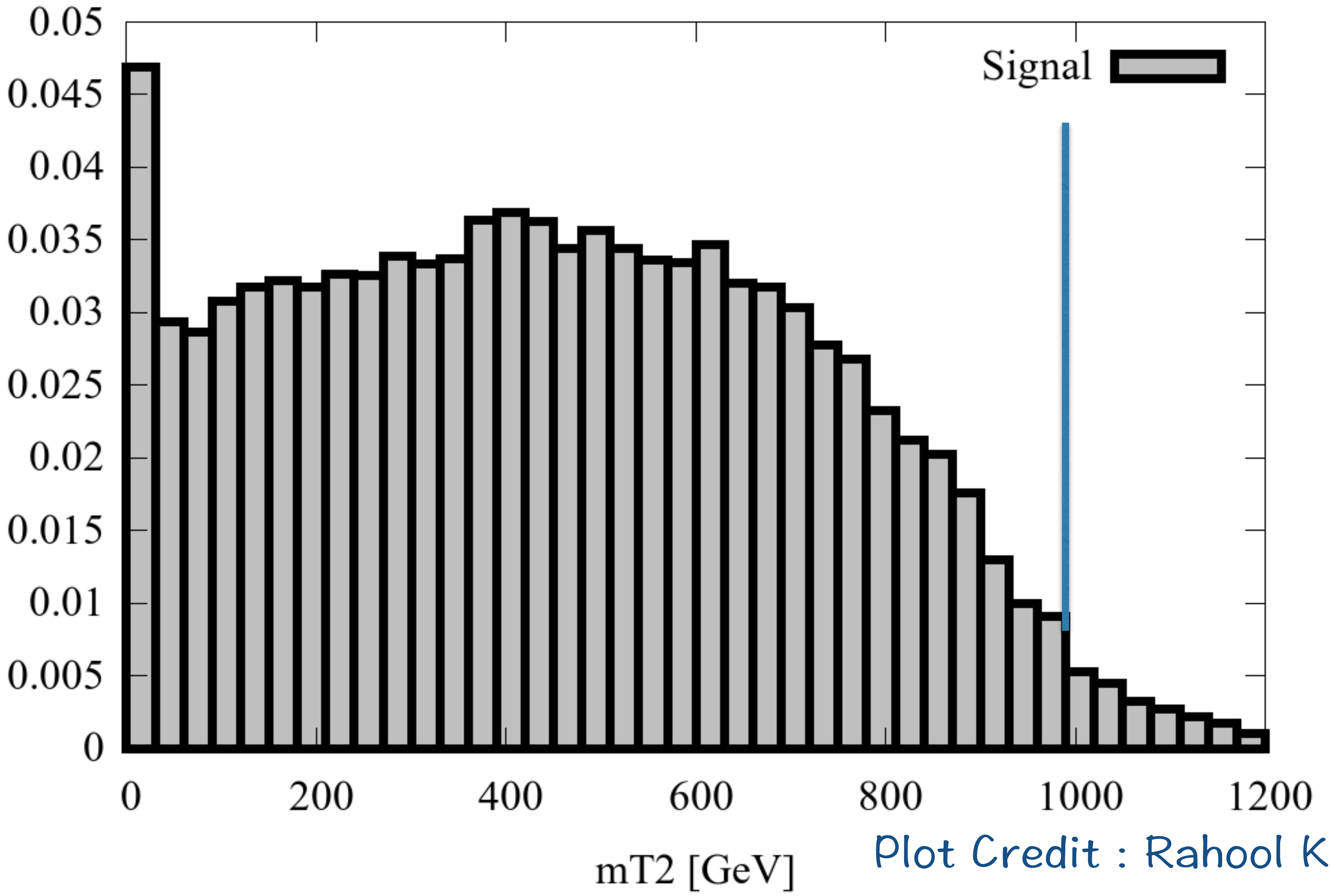
Now vary the MET splitting* which minimises the Max($M_T(x_a, B_a)M_T(x_b, B_b)$)

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

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

MT2 Variable

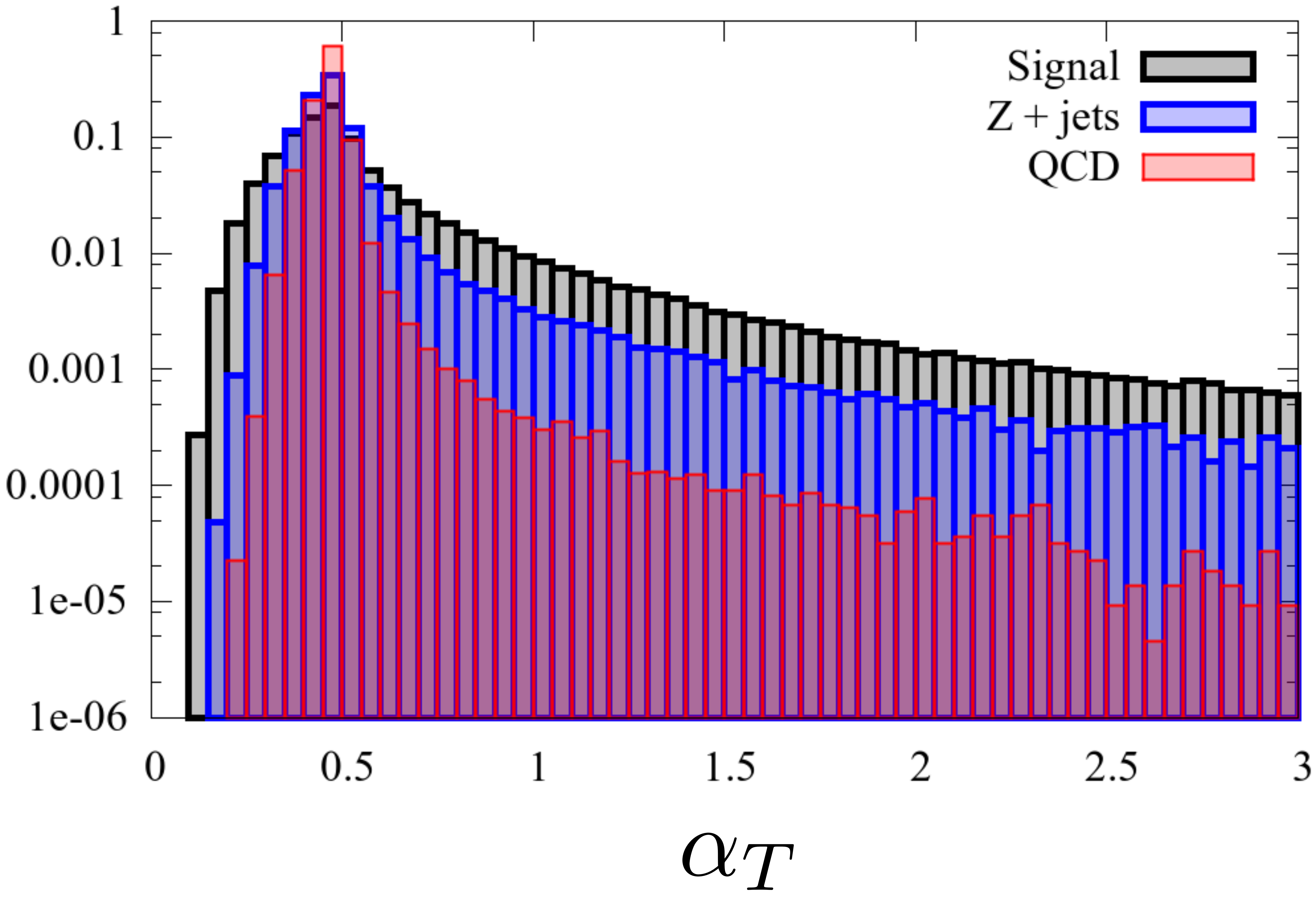
squark pair production (Mass = 1 TeV) using Pythia-6
squark to quark + neutralino (mass = 100 GeV)
Delphes 3 simulation
(naively written code for MT2, slight discrepancy in result when compared with the public code)



Plot Credit : Rahool Kumar Barman

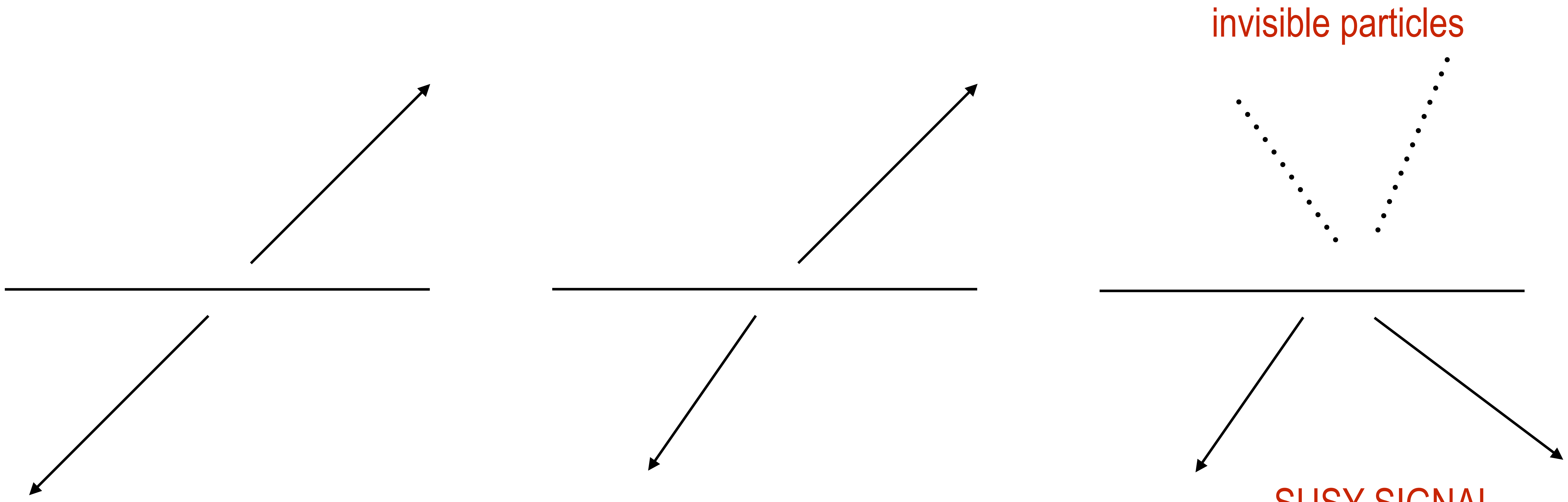
α_T Variable

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



α_T Variable

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



invisible particles

well balanced di-jet system

$$\Delta\phi = \pi$$

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

$$\alpha_T = 0.5$$

one jet mismeasured

$$\alpha_T < 0.5$$

SUSY SIGNAL
(rare configuration for QCD)

$$\alpha_T > 0.5$$

Pile up

Luminosity

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

Colliding beams

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

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

The proportionality constant is called Luminosity

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

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

Luminosity

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

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

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

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

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)

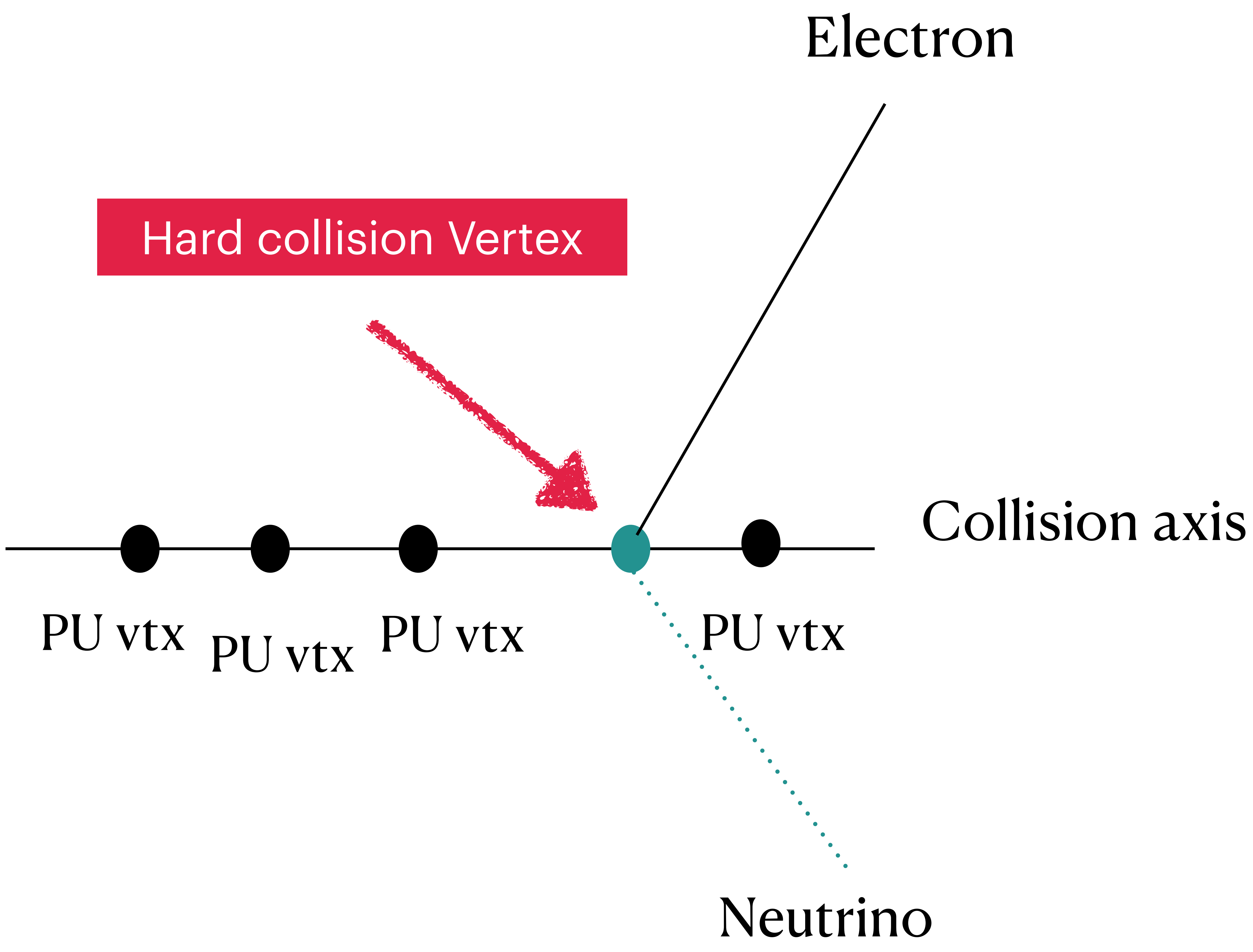
Event rate = $10^{7}mb^{-1}Hz \times 100mb = 10 \times 10^{8}\ Hz$

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

Each PU vertex generally produce a few tens of soft hadrons

The detected final state particles will be the superposition

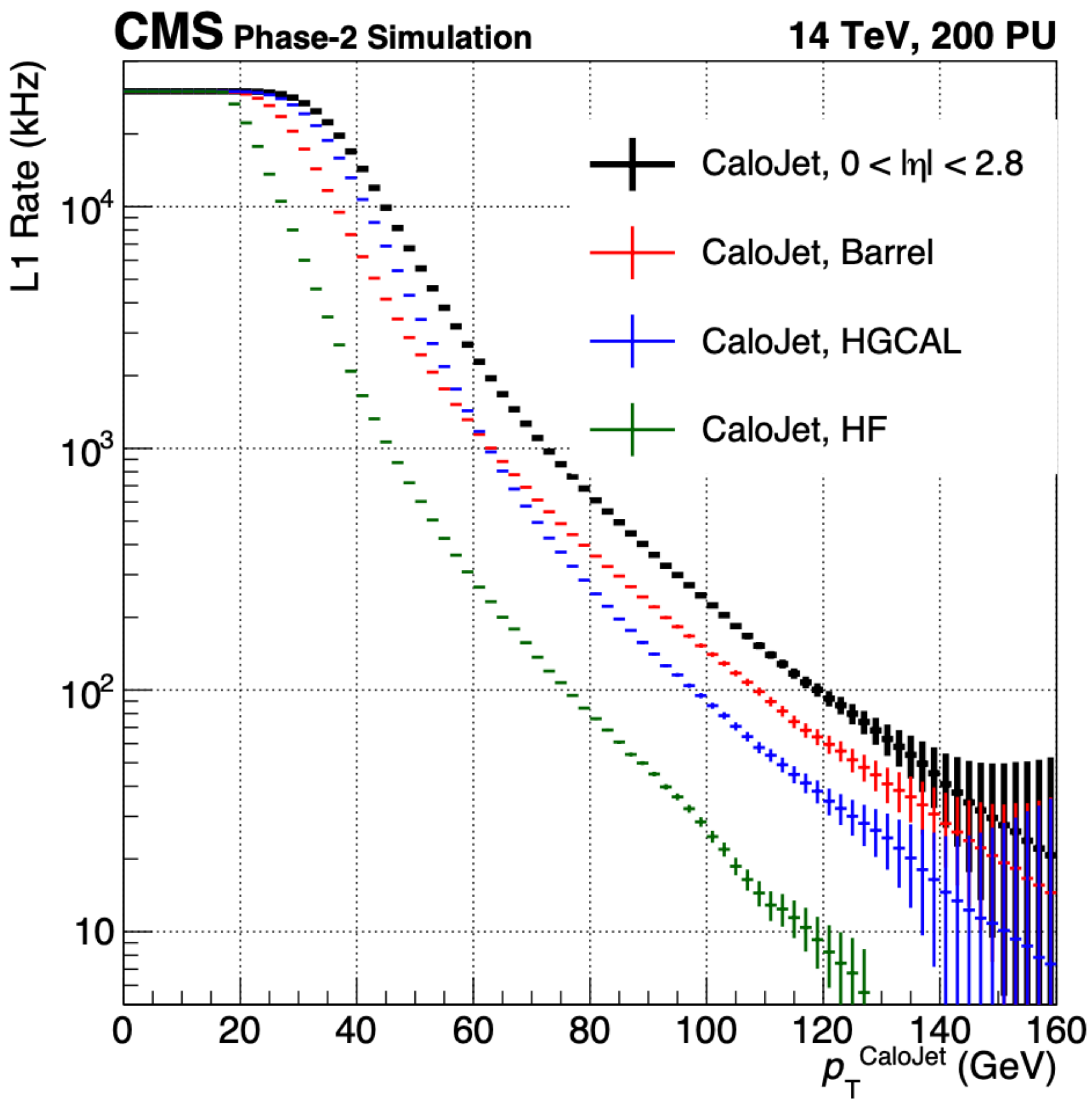
Of particles coming from hard process and soft particles

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 !!

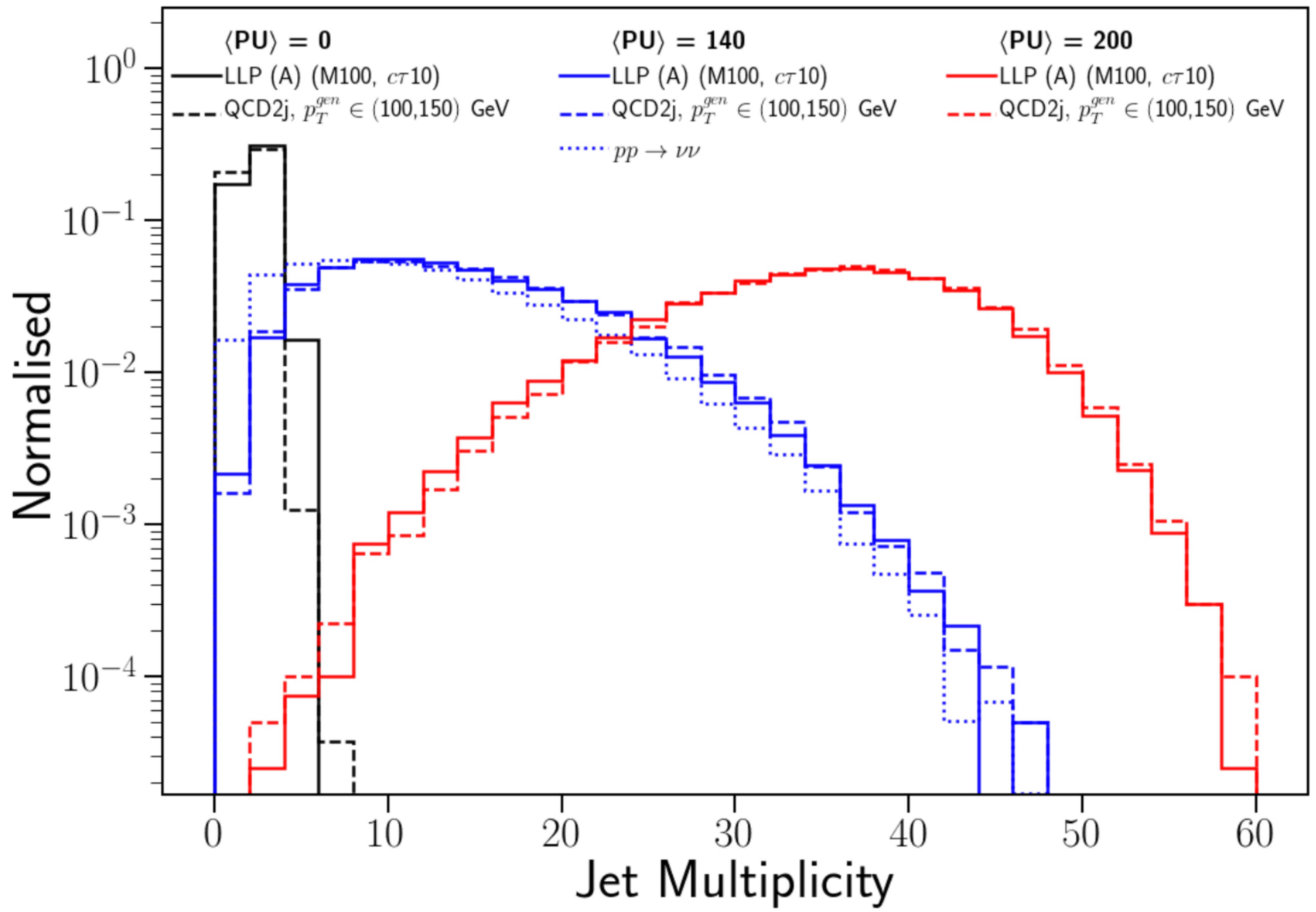
Jets@HL-LHC

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

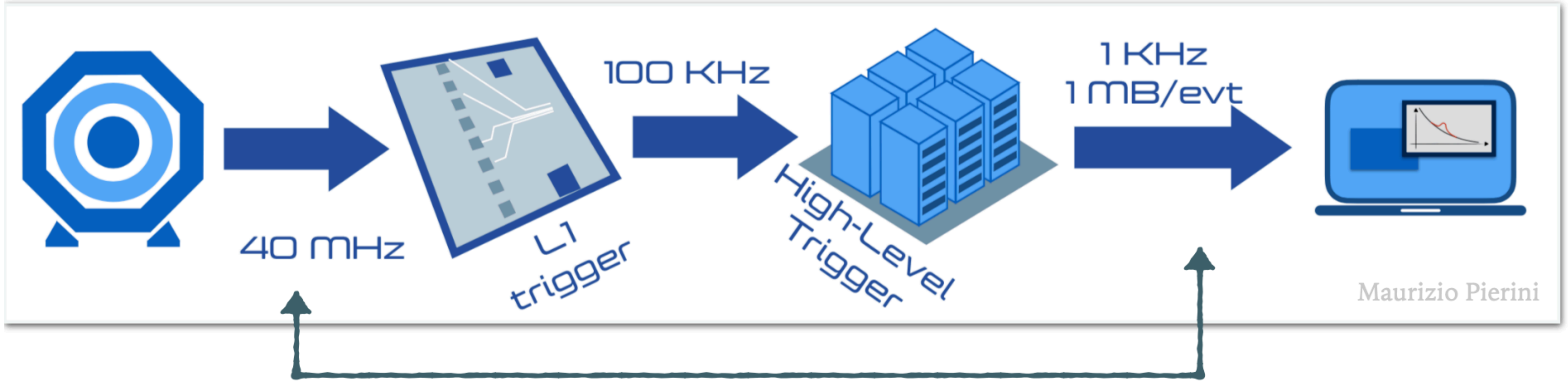
Dedicated selection conditions required to select a few interesting events => Trigger

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

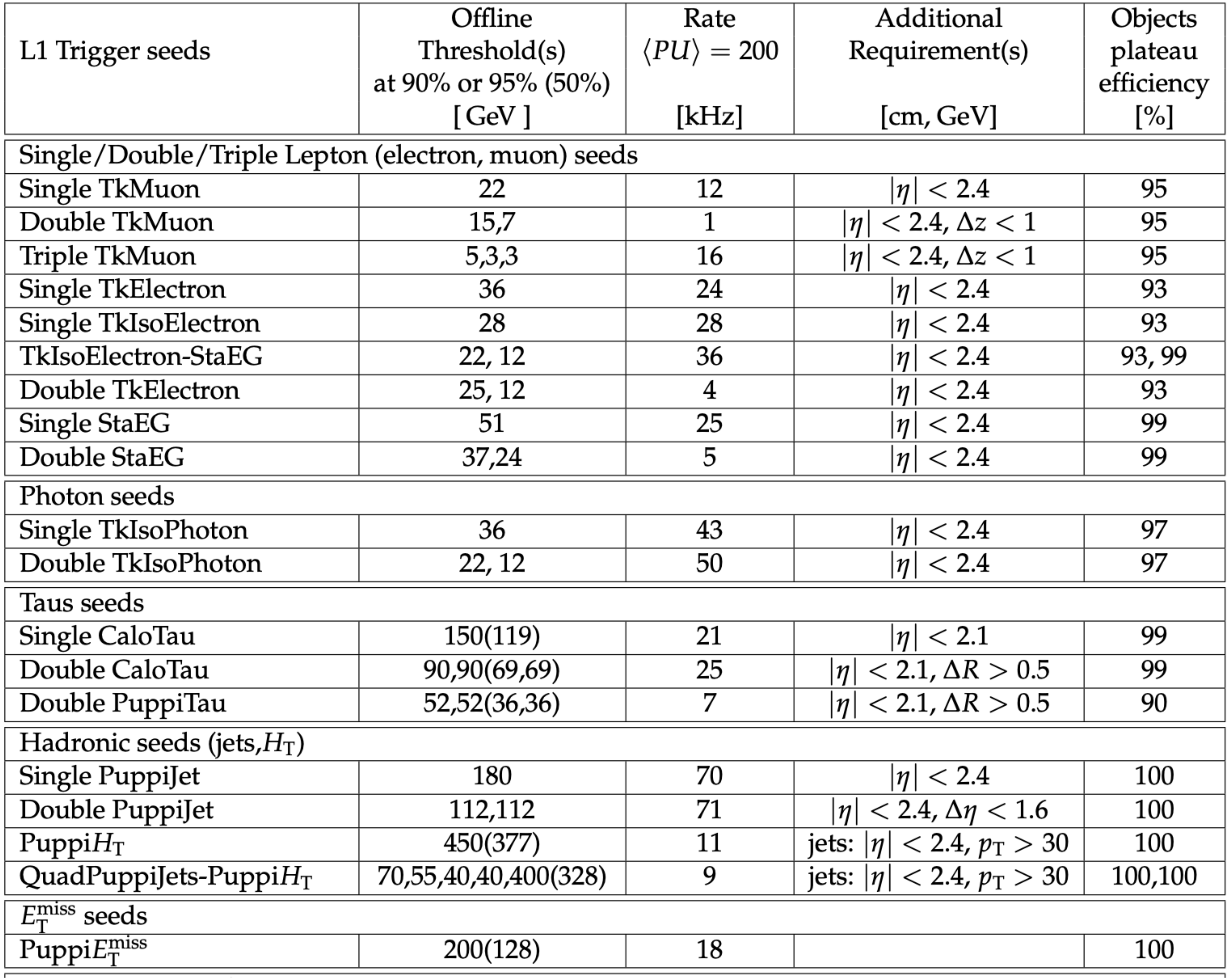
Low or zero sensitivity to new physics with low-mass.



Maurizio Pierini

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

Trigger Menu@ HL-LHC(PU=200)

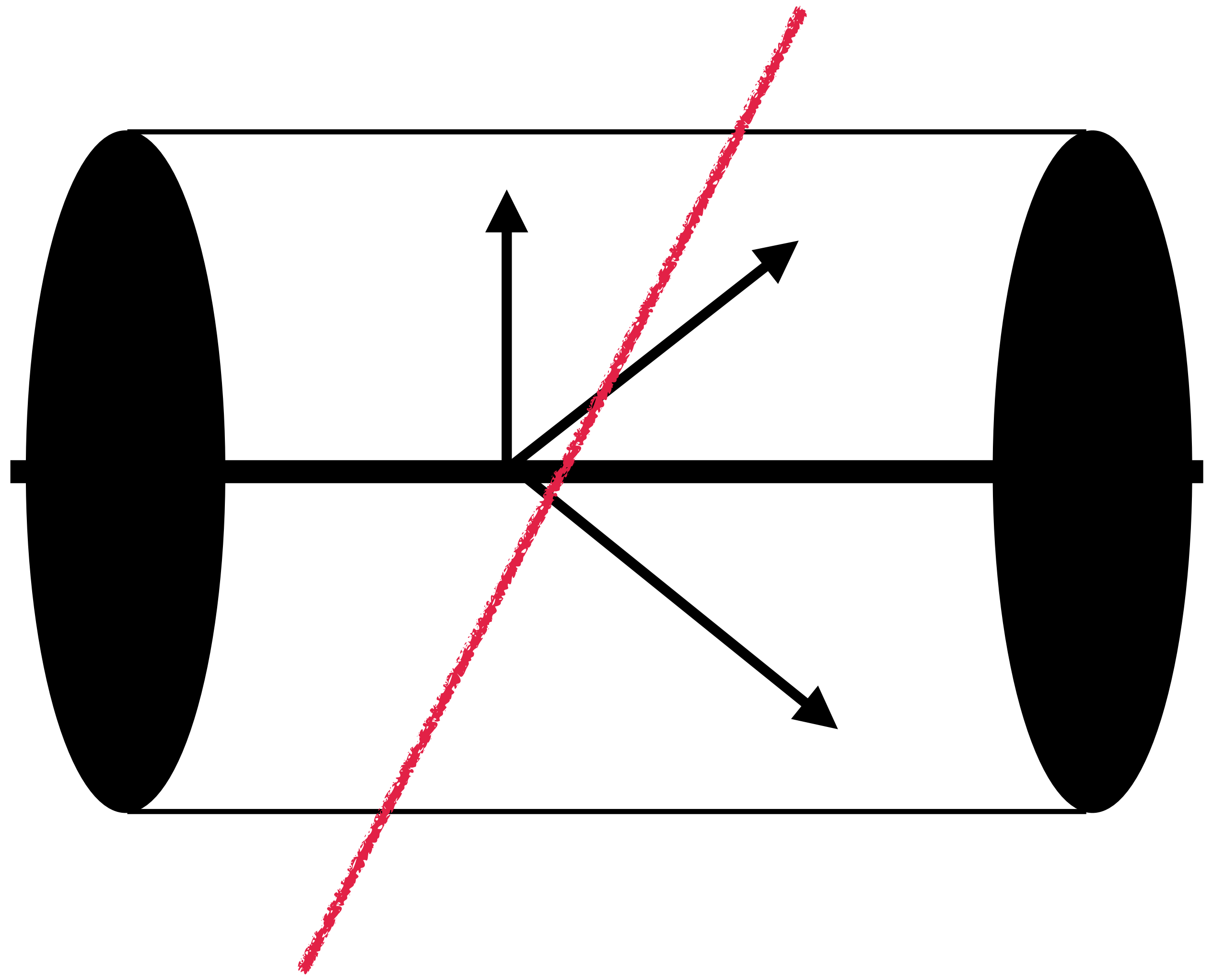


L1 Trigger seeds	Offline Threshold(s) at 90% or 95% (50%) [GeV]	Rate $\langle PU \rangle = 200$ [kHz]	Additional Requirement(s) [cm, GeV]	Objects plateau efficiency [%]
Single/Double/Triple Lepton (electron, muon) seeds				
Single TkMuon	22	12	$\|\eta\| < 2.4$	95
Double TkMuon	15,7	1	$\|\eta\| < 2.4, \Delta z < 1$	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