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

CMS and ATLAS physics webpages

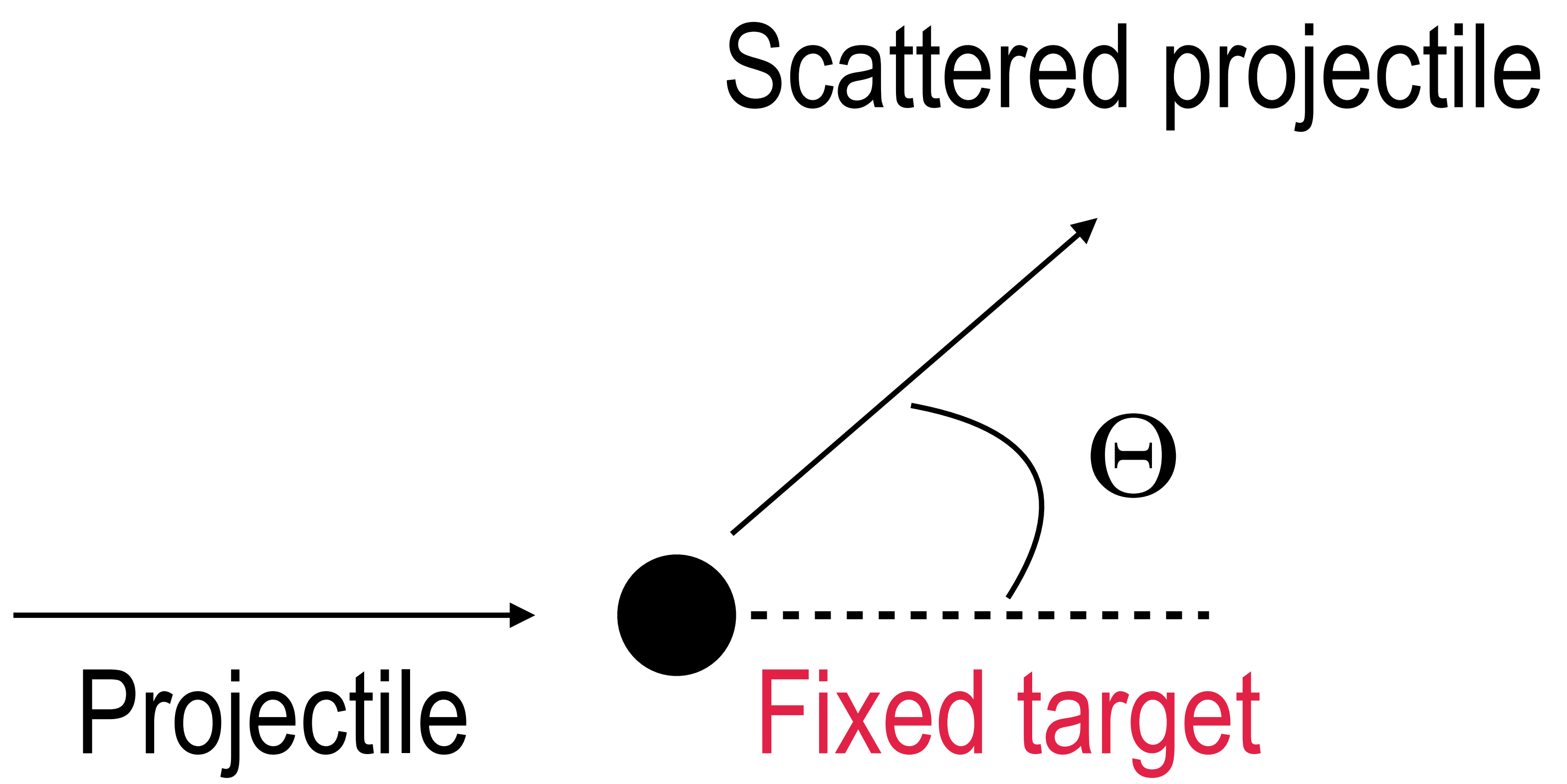
CMS L1 TDR 2020

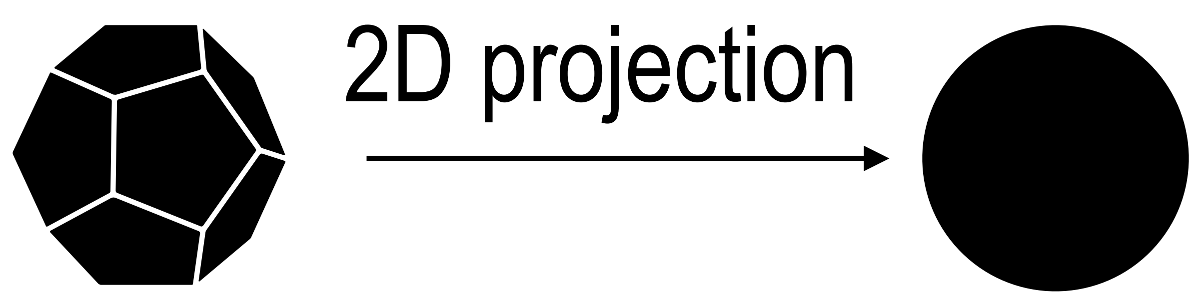
Towards Jetography : G Salam

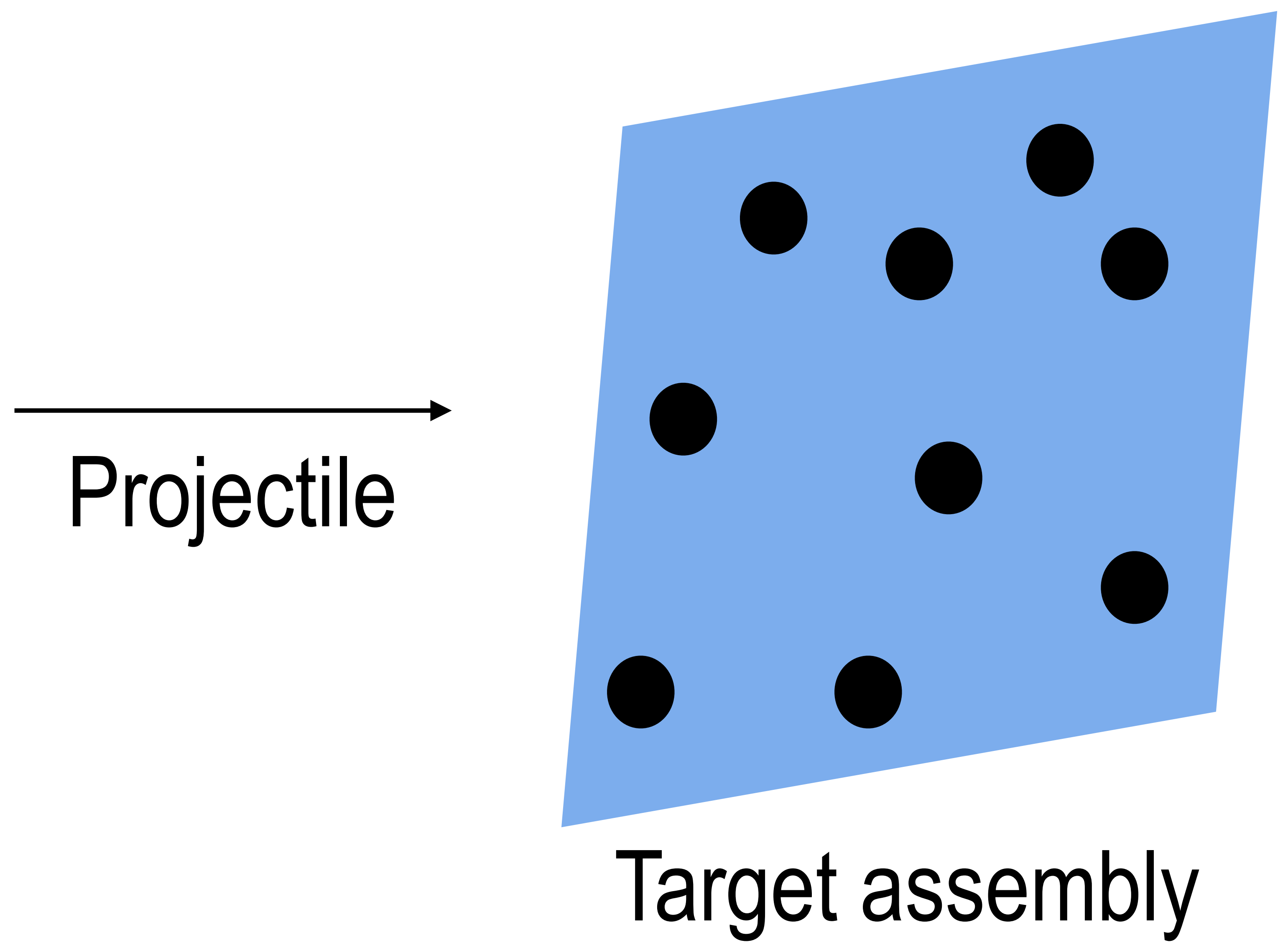
Pileup Mitigation by G. Soyez 1801.09721

Deep Inelastic Scattering and Naive Parton Model

Basic Scattering theory







Scattering can be described in terms of scattering angle and impact parameter

Θ is the scattering angle

N_{target} = Number of target particle per unit area

A = Area of the target assembly

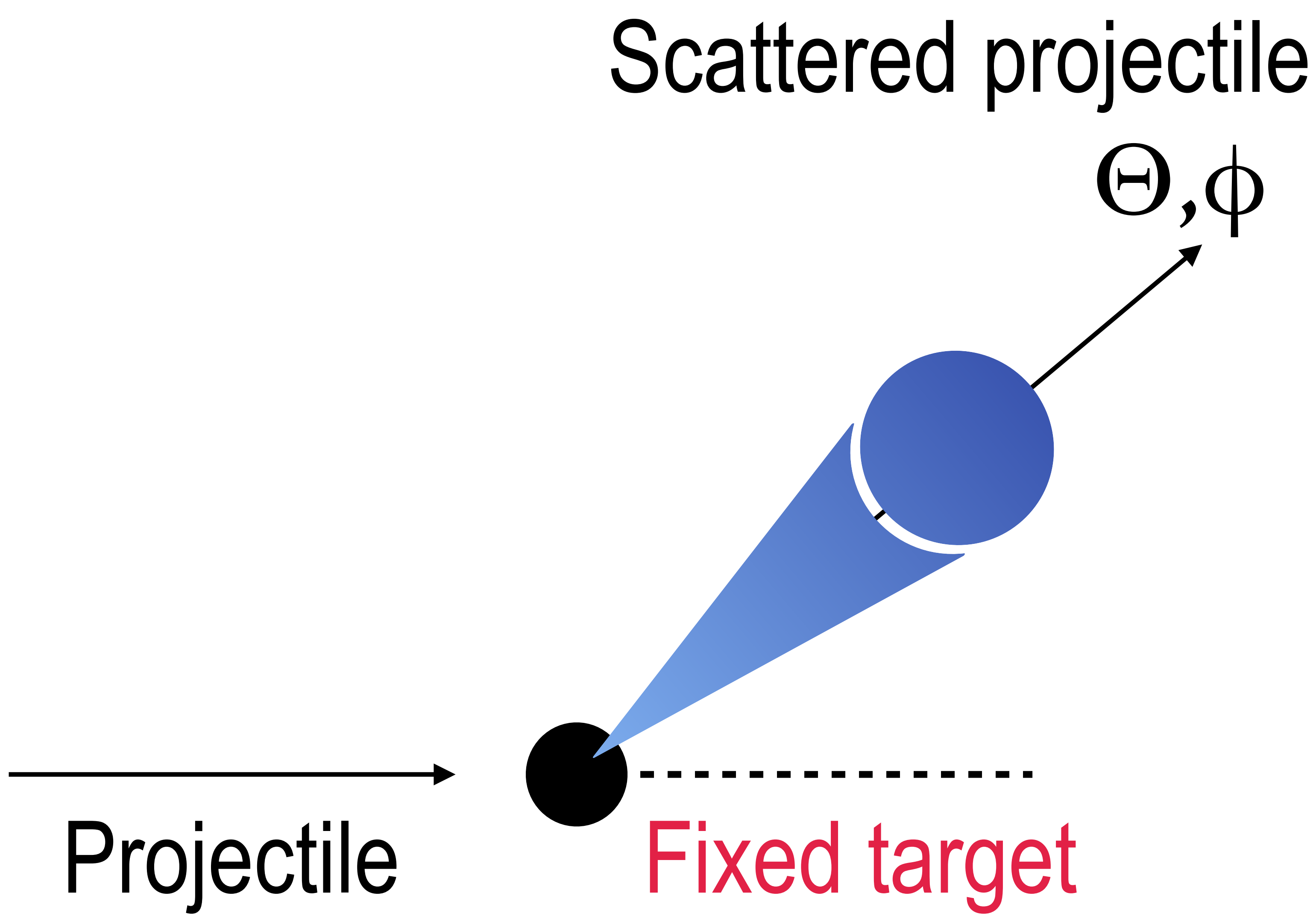
The projectile will visualise the target particle as a circle (2D view of the 3D targets) :

Effective area of the 2D projection/circle of the target as seen by the projectile = σ

N_{inc} = The number of incident particle N_{sc} = The number of scattered particles

$$N_{sc} = N_{target}\, N_{inc}\, \sigma$$

Differential Scattering cross section



Total cross section: We have counted the total number of scattered particles, irrespective Of the scattering angles

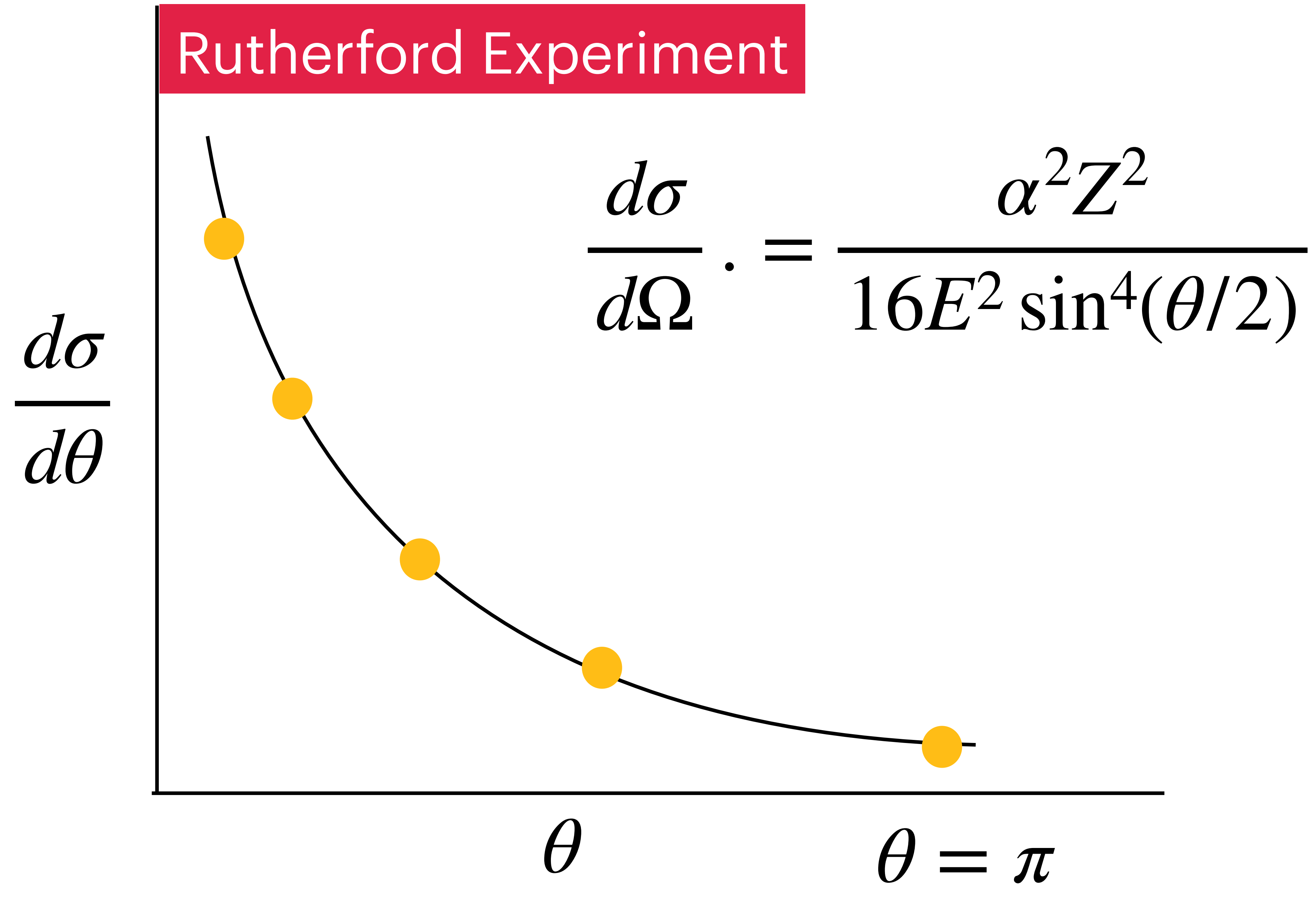
We can also count the number of scattered particles in a a specific direction

$N_{Sc}(into\ d\Omega)$= The number of scattered particles into the solid angle $d\Omega$ in the Direction theta, phi

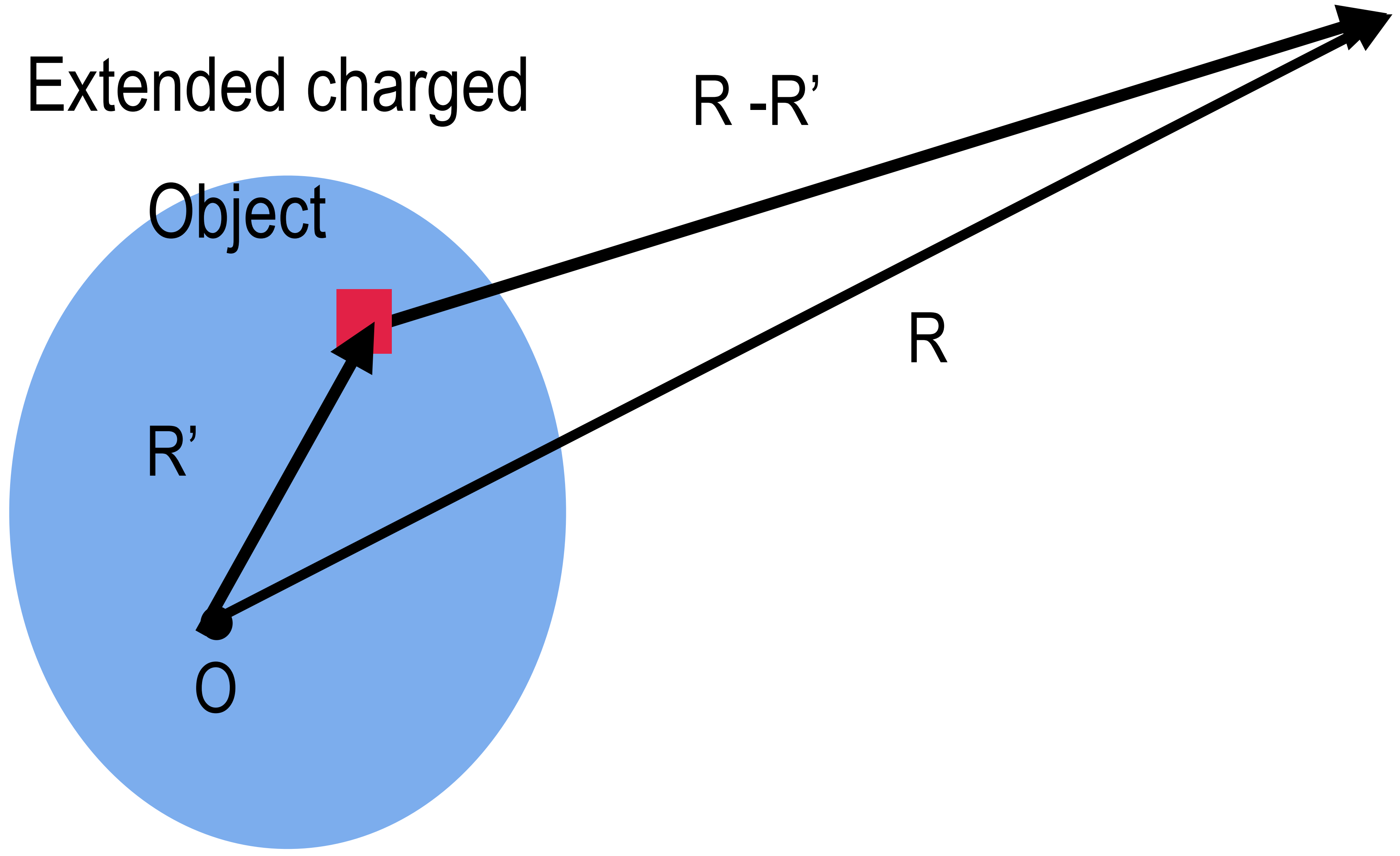
$$N_{sc}(\text{into } d\Omega) = N_{target}\ N_{inc}\ d\sigma(\text{into } d\Omega)$$

$$d\sigma(\text{into } d\Omega) = \frac{d\sigma}{d\Omega}d\Omega$$

$$\sigma = \int \frac{d\sigma}{d\Omega}d\Omega = \int_0^{\pi}\int_0^{2\pi} \sin\theta d\theta d\phi \frac{d\sigma(\theta,\phi)}{d\Omega}$$



Scattering from point-like particle vs extended object



Extended charge distribution : Z e ρ(r)

Potential experienced by a particle with charge e located at r

$$V(R) = -\frac{Ze\,.\,e}{4\pi\epsilon_0}\int \frac{\rho(R')}{|R-R'|}d^3R'$$

$$\frac{d\sigma}{d\Omega}\,.\, = \frac{\alpha^2 Z^2}{16E^2\sin^4(\theta/2)}|F(q)|^2$$

$$F(q) = \text{Form Factor} \;= \int e^{iq.R'/\hbar}\rho(R')\;d^3R'$$

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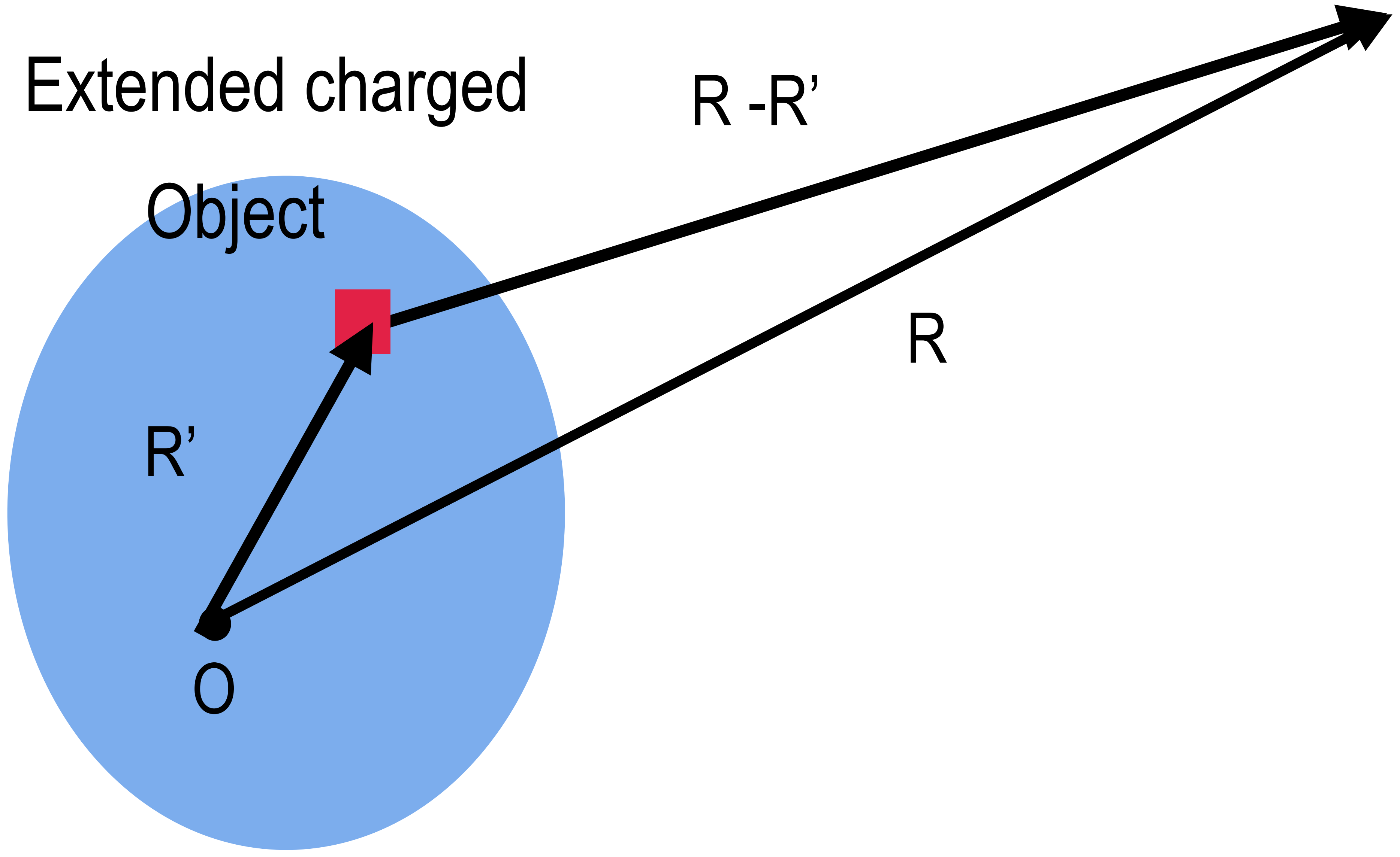

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$$F(q) = \text{Form Factor } = \int e^{iq.R'/\hbar}\rho(R')\ d^3R'$$

Form Factor => 3D Fourier transform of the charge distribution

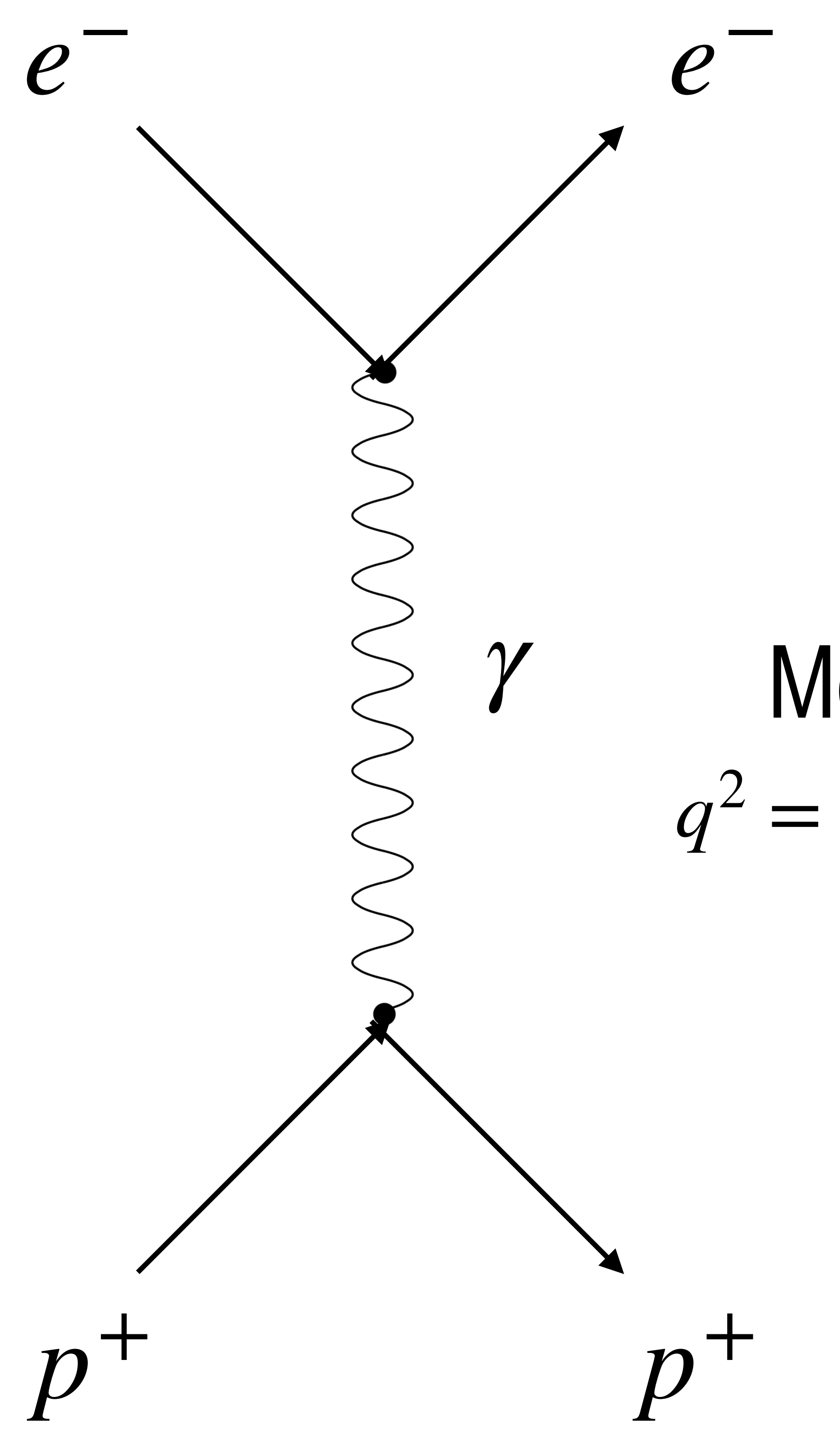
$$F(q) \sim 1 - \frac{q^2}{6} < r^2 >$$

$$< r^2 > = \int r^2 \rho(r) d^3 r$$ Square of the charge radius

For large radius object, form factor decreases quickly with q

Pointlike object F(q) = 1

QED scattering



point-like proton

proton recoil negligible

Consider the scattering of electron from point-like proton

$$e^-(p_1) + p^+(p_2) \to e^-(p_3) + p^+(p_4)$$

Elastic scattering, neglect proton recoil

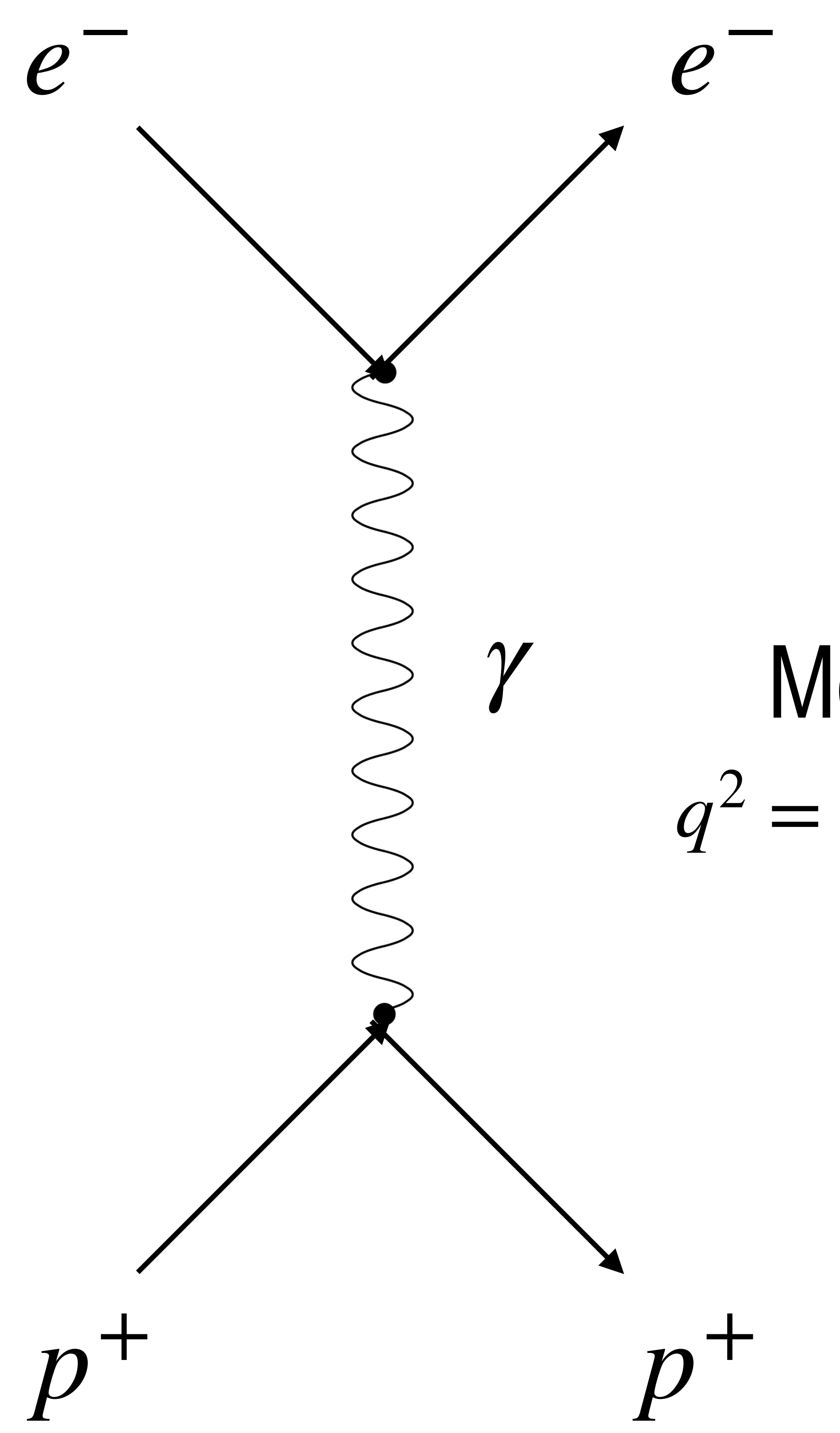
Θ = scattering angle in the Lab frame

Momentum transfer

$$q^2 = (p_1 - p_3)^2 = -4p^2 \sin^2 \frac{\theta}{2}$$

$$< |M|^2 > = \frac{m_p^2 m_e^2 e^4}{p^4 \sin^4(\theta/2)} \left[1 + \beta_e^2 \gamma_e^2 \cos^2(\theta/2) \right]$$

QED scattering



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Non relativistic electron

E = Kinetic energy of electron

$$\left.\frac{d\sigma}{d\Omega}\right|_{Rutherford} = \frac{\alpha^2}{16E_K^2\sin^4(\theta/2)} \qquad \alpha = \frac{e^2}{4\pi}$$

Note: $\sin^4\frac{\theta}{2}$ term comes from the propagator

Relativistic electron

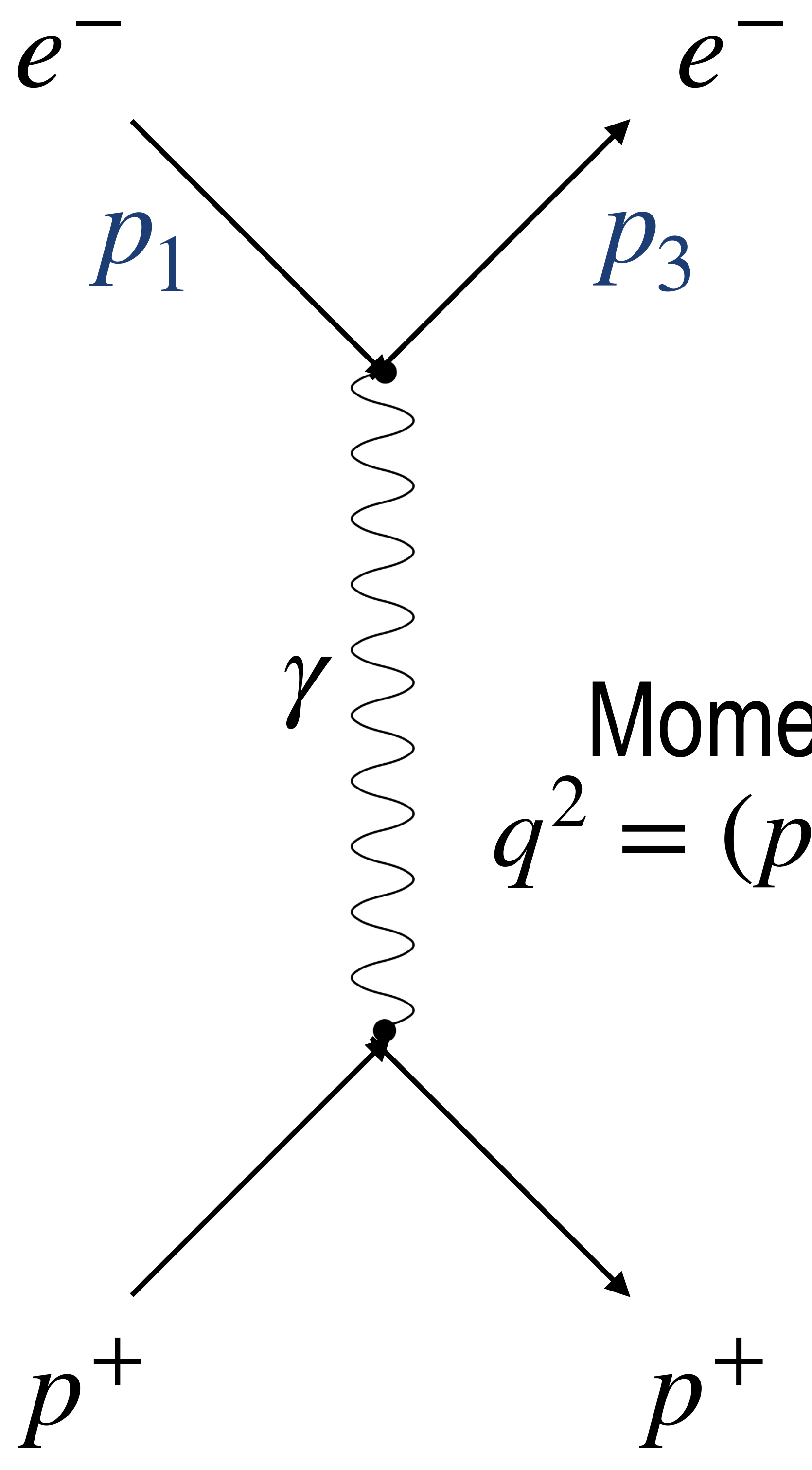
E ~p

Proton recoil neglected

Mott Scattering formula

$$\frac{d\sigma}{d\Omega}. = \frac{\alpha^2}{4E^2\sin^4(\theta/2)}\cos^2\frac{\theta}{2}$$

QED scattering



point-like proton

Momentum transfer

$$q^2 = (p_1 - p_3)^2 = -Q^2$$

Consider the scattering of relativistic electron from point-like proton

$$e^-(p_1) + p^+(p_2) \to e^-(p_3) + p^+(p_4)$$

Scattering of GeV electron => proton recoil cannot be neglected

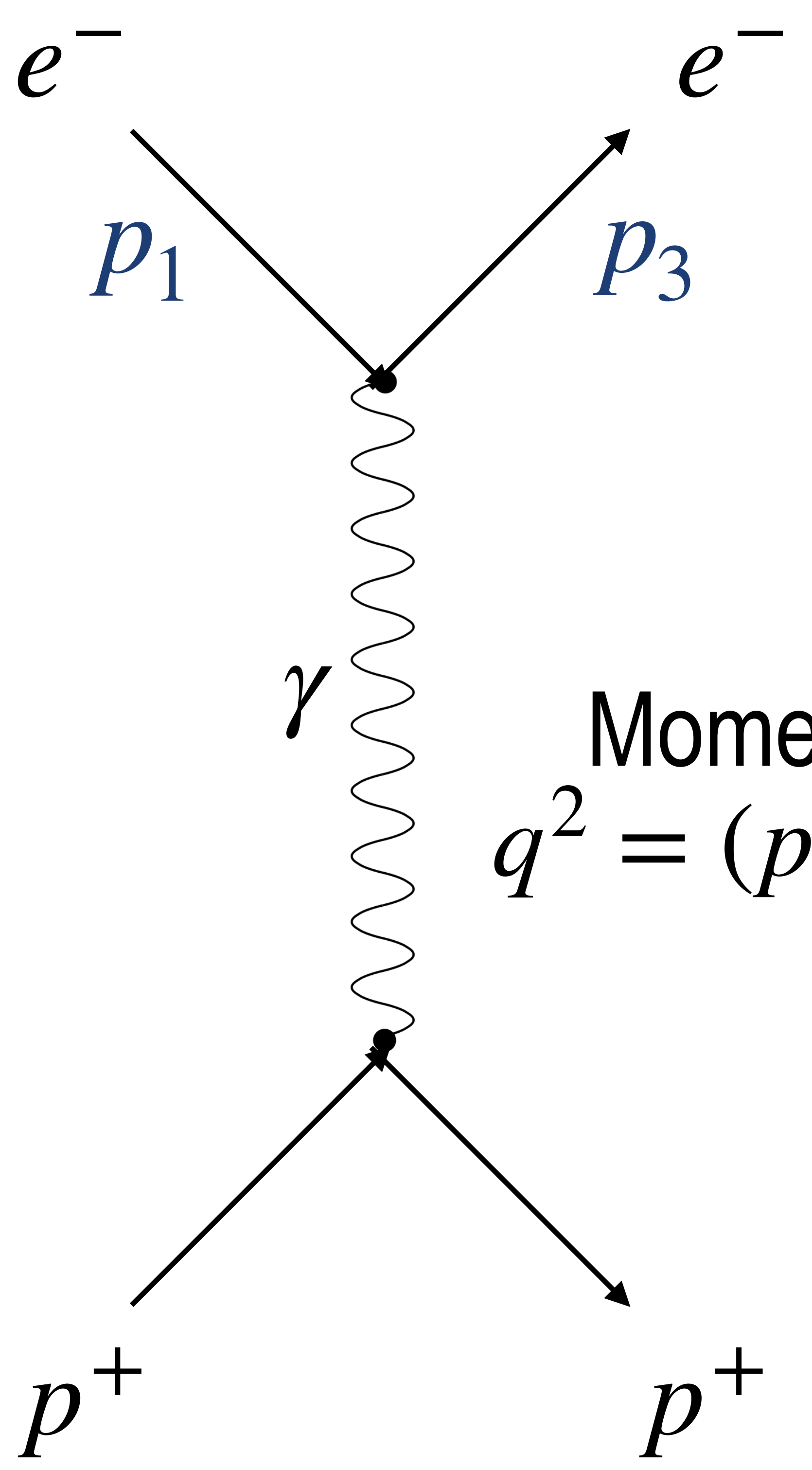
$$p_1 = (E_1, 0, 0, E_1) \quad p_2 = (m_P, 0, 0, 0) \quad p_3 = (E_3, 0, E_3 \sin\theta, E_3 \cos\theta), \quad p_4 = (E_4, \vec{p_4})$$

$$Q^2 = -q^2 = 4E_1E_3 \sin^2\frac{\theta}{2}$$

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4E_1^2 \sin^4(\theta/2)} \frac{E_3}{E_1} \left[\cos^2\frac{\theta}{2} + \frac{Q^2}{2m_P^2} \sin^2\frac{\theta}{2}\right]$$

Differential cross section depends on : θ, Q and E_3 : only one independent variable

QED scattering



Momentum transfer

$$q^2 = (p_1 - p_3)^2 = -Q^2$$

Consider the scattering of relativistic electron from proton

$$e^-(p_1) + p^+(p_2) \to e^-(p_3) + p^+(p_4)$$

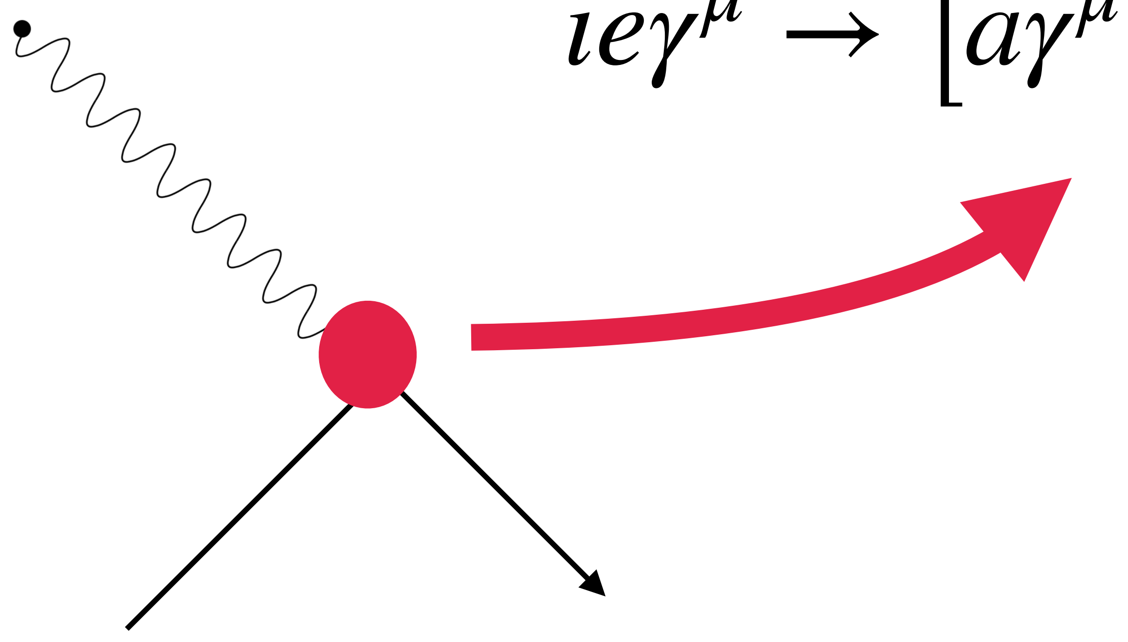
Scattering of GeV electron => proton structure will be important

Proton structure

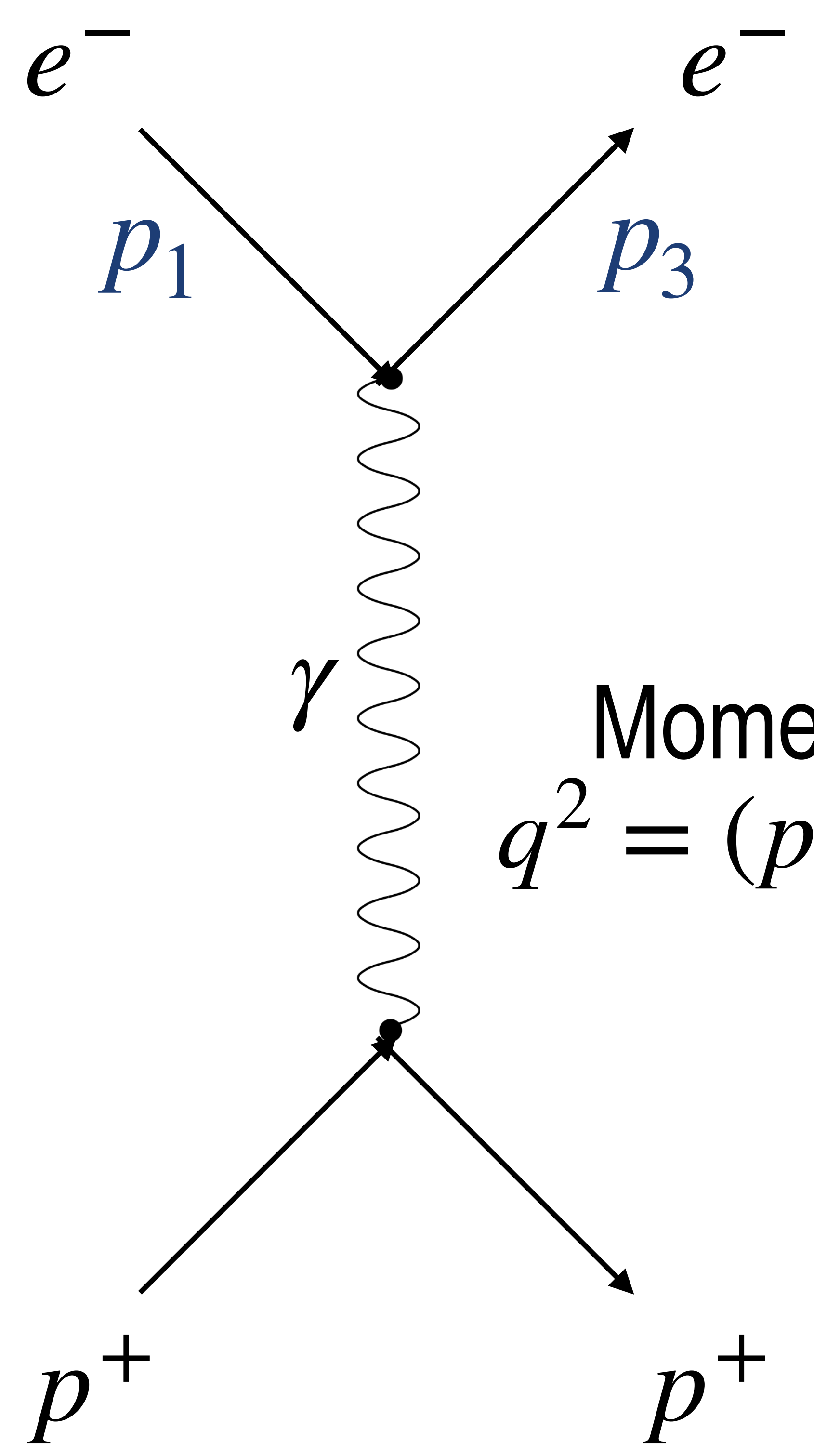
Proton is not a point like particle :

General form of current: $\bar{u}[a\gamma^\mu + b\sigma^{\mu\nu}q_\nu + cq^\mu + d(p_2 + p_4)^\mu]u$

$$ie\gamma^\mu \to \left[a\gamma^\mu + b\frac{i\sigma^{\mu\nu}}{2M_P}q_\nu\right]$$



QED scattering



Momentum transfer
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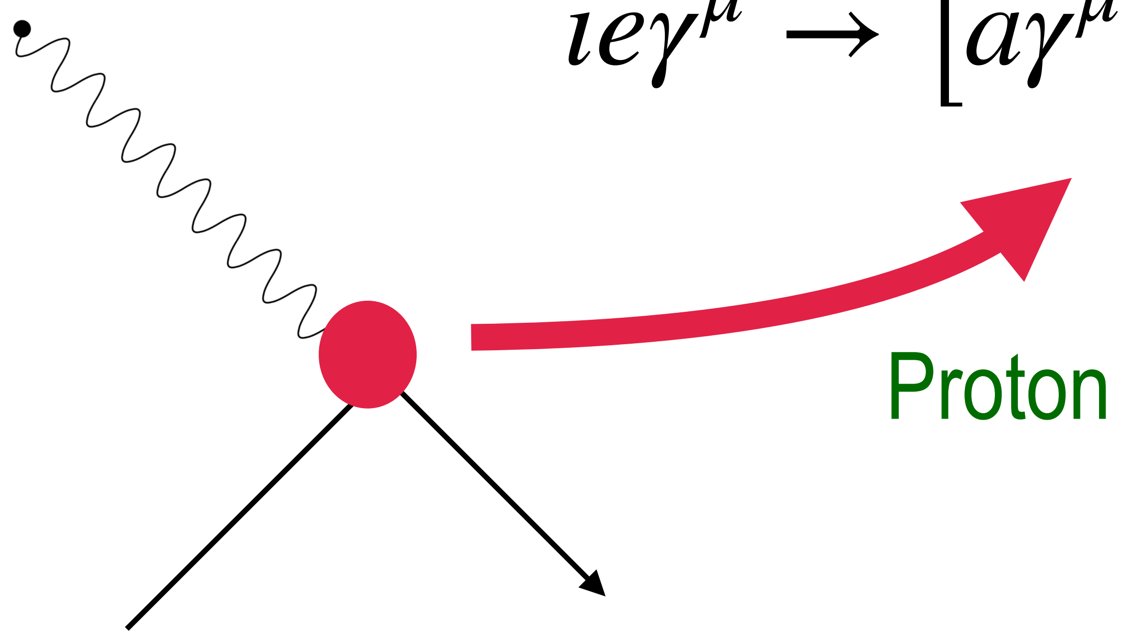


Proton is not a point like particle : Two form factors

a and b required

Form factors will depend on Q^2

Rosenbluth Formula

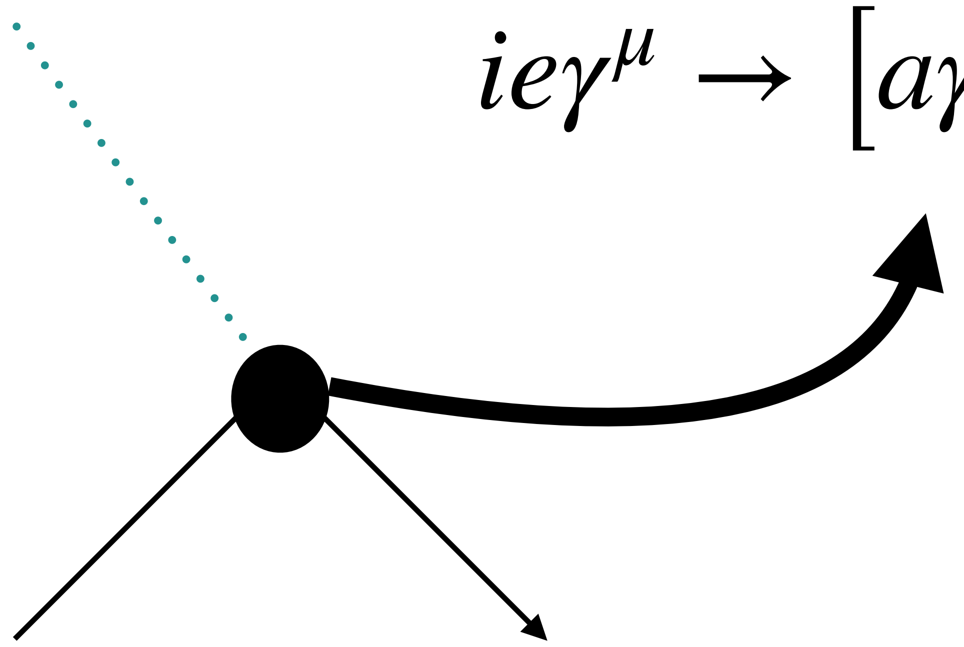
$a, b \to G_E, G_M$

$$\frac{d\sigma}{d\Omega}. = \frac{\alpha^2}{4E_1^2 \sin^4(\theta/2)} \frac{E_3}{E_1} \left[\frac{G_E^2 + \tau G_M^2}{1+\tau} \cos^2\frac{\theta}{2} + 2\tau G_M^2 \sin^2\frac{\theta}{2} \right]$$

$$\tau = \frac{Q^2}{4m_P^2}$$

Form factors

Proton structure



$$ie\gamma^\mu \rightarrow \left[a\gamma^\mu + b\frac{i\sigma^{\mu\nu}}{2M_P}q_\nu\right]$$

Relativistic electron proton scattering

$$e^-(p_1) + p^+(p_2) \rightarrow e^-(p_3) + p^+(p_4)$$

Rosenbluth Formula

$$\frac{d\sigma}{d\Omega}. = \frac{\alpha^2}{4E_1^2\sin^4(\theta/2)}\frac{E_3}{E_1}\left[\frac{G_E^2 + \tau G_M^2}{1+\tau}\cos^2\frac{\theta}{2} + 2\tau G_M^2\sin^2\frac{\theta}{2}\right]$$

G_E and G_M can be measured separately from the experiment

At low Q^2 term proportional to G_E dominates

Measurements of G(q) by varying electron beam energy and measuring the electron in different scattering angle

$$G_{E/M} = \frac{a}{\left(a + \frac{Q^2}{b^2}\right)^2}$$

At high energy $G_{E/M} \sim \frac{1}{Q^4}$

$$\frac{d\sigma}{d\Omega} \propto \frac{1}{Q^6}\left(\frac{d\sigma}{d\Omega}\right)_{Mott}$$

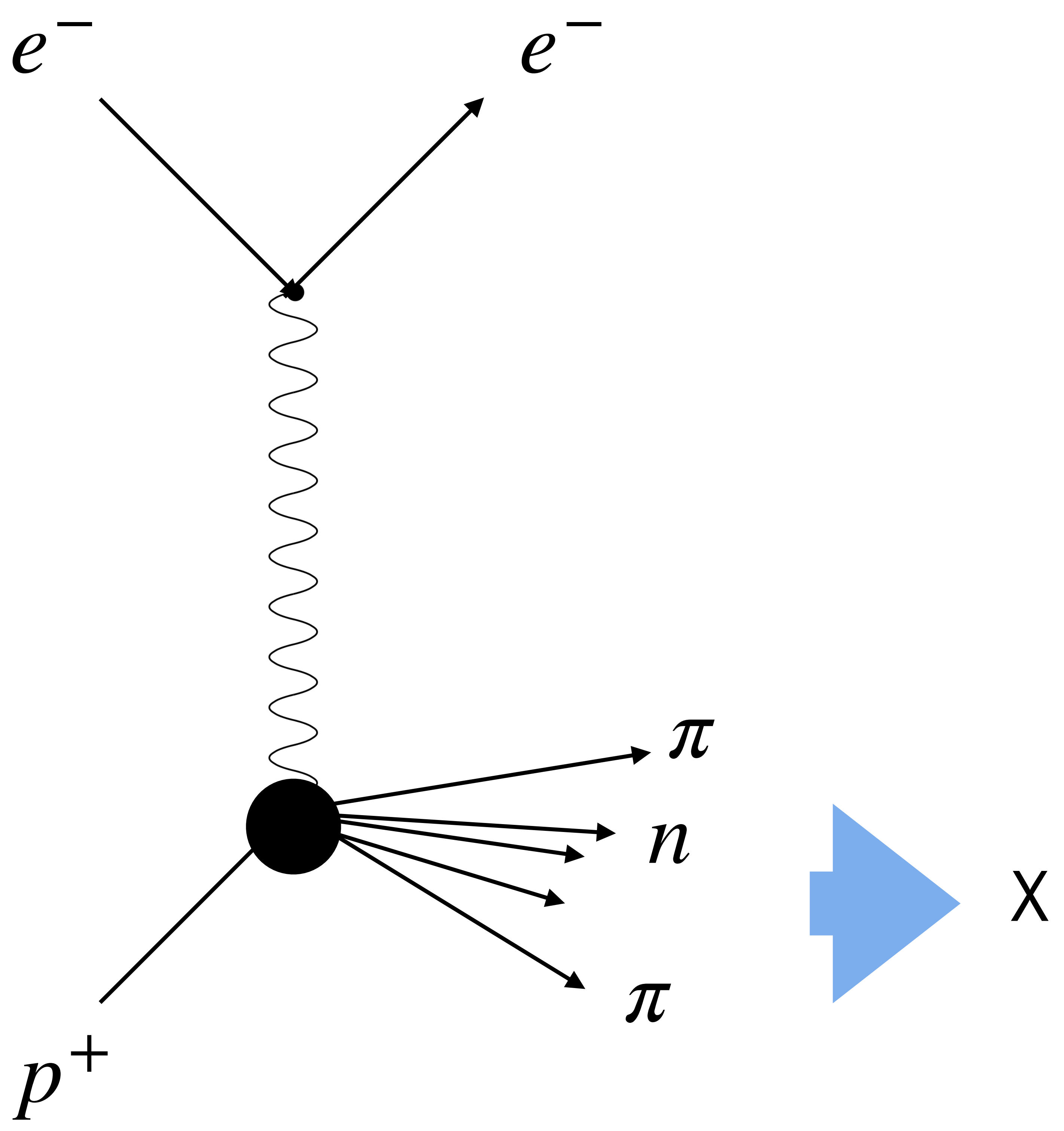
Cross section will decrease rapidly

What happens if we keep increasing the energy of the electron beam ?

Scattering will be dominated by inelastic scattering process

Inelastic Scattering

$$e^-(p_1) + p^+(p_2) \rightarrow e^-(p_3) + X(p_4)$$



X = any particle subject to conservation laws

Example : X= p, p pion , neutron + pion ….

Number of final state particles can be large

Detect only scattered electron

Inelastic Scattering

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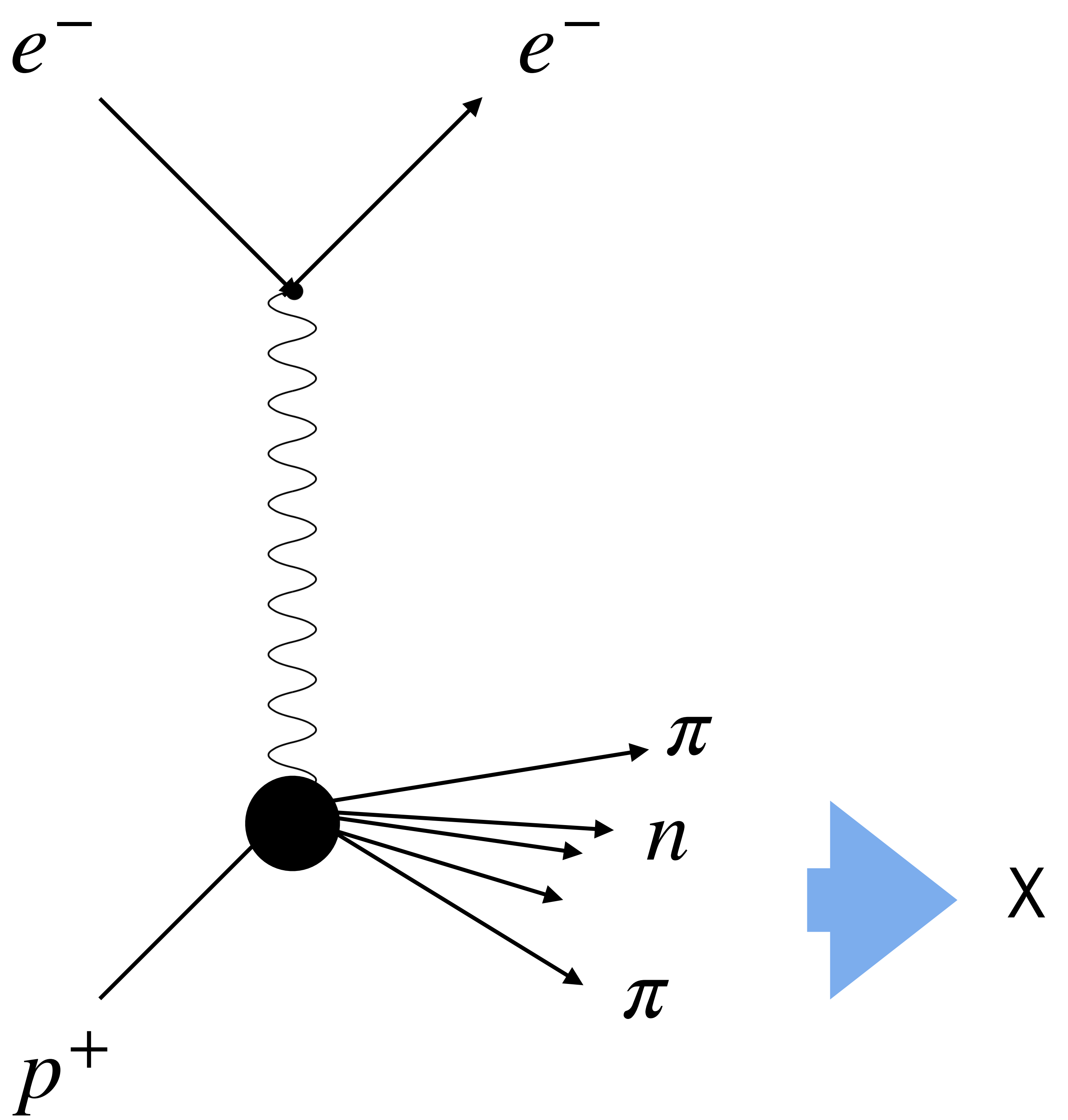

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Example : X= p, p pion , neutron + pion ….

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Detect only scattered electron

Kinematics

Momentum transfer $q = p_1 - p_3$

$$Q^2 = -q^2 = 4E_1E_3\sin^2\frac{\theta}{2}$$

Bjorken $x = \dfrac{Q^2}{2p_2 \cdot q} = . \dfrac{Q^2}{Q^2 + W^2 - m_P^2}$

4 Momentum Square of the hadronic system $W^2 = p_4^2 = (q + p_2)^2$

The final state X must contain at least one baryon W > Mp

$0 \le x \le 1$ [$x = 1$ represents elestic limit]

Two independent variables required to describe the event :
Theory : One can choose Q and x
Experiment: choose E_3 and θ of the electron

Measurement of double differential scattering cross section

$$\frac{d^2\sigma}{dx dQ^2} \text{ or } \frac{d^2\sigma}{d\theta dE_3}$$

Elastic vs Inelastic Scattering

Elastic scattering in terms of Q

$$\frac{d\sigma}{dQ^2} = \frac{4\pi\alpha^2}{Q^4}\left[\left(1 - y - \frac{m_P^2}{Q^2}\right)f_2(Q^2) + \frac{1}{2}y^2 f_1(Q^2)\right]$$

$$y = y(Q^2)$$

Inelastic scattering in terms of Q, and x

$$\frac{d^2\sigma}{dxdQ^2} = \frac{4\pi\alpha^2}{Q^4}\left[\left(1 - y - \frac{m_P^2}{Q^2}\right)\frac{F_2(x, Q^2)}{x} + y^2 F_1(x, Q^2)\right]$$

$F_{1/2}(Q^2, x)$ => structure functions

Depends on Q and x => not the Fourier transform of charge or magnetic moment distribution

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Experimental setup

MIT-SLAC collaboration Experiment at SLAC (1967-1973)

Electron beam up to 20 GeV

E_1 = Energy of electron is fixed

Measure scattered electron at some fixed angle: θ *and* E_3

Calculate $Q^2 = 4E_1E_3\sin^2\frac{\theta}{2}$

$x = \frac{Q^2}{2m_P(E_1 - E3)}$. → measure x

$y = 1 - \frac{E_3}{E_1}$

Count the number of scattered electrons in the range Q, Q+dQ and x,x+dx

=> Measurement of $\frac{d^2\sigma}{dxdQ^2}$

Expectation : F1 and F2 should behave similar to From factor as we increase Q

Parton Model

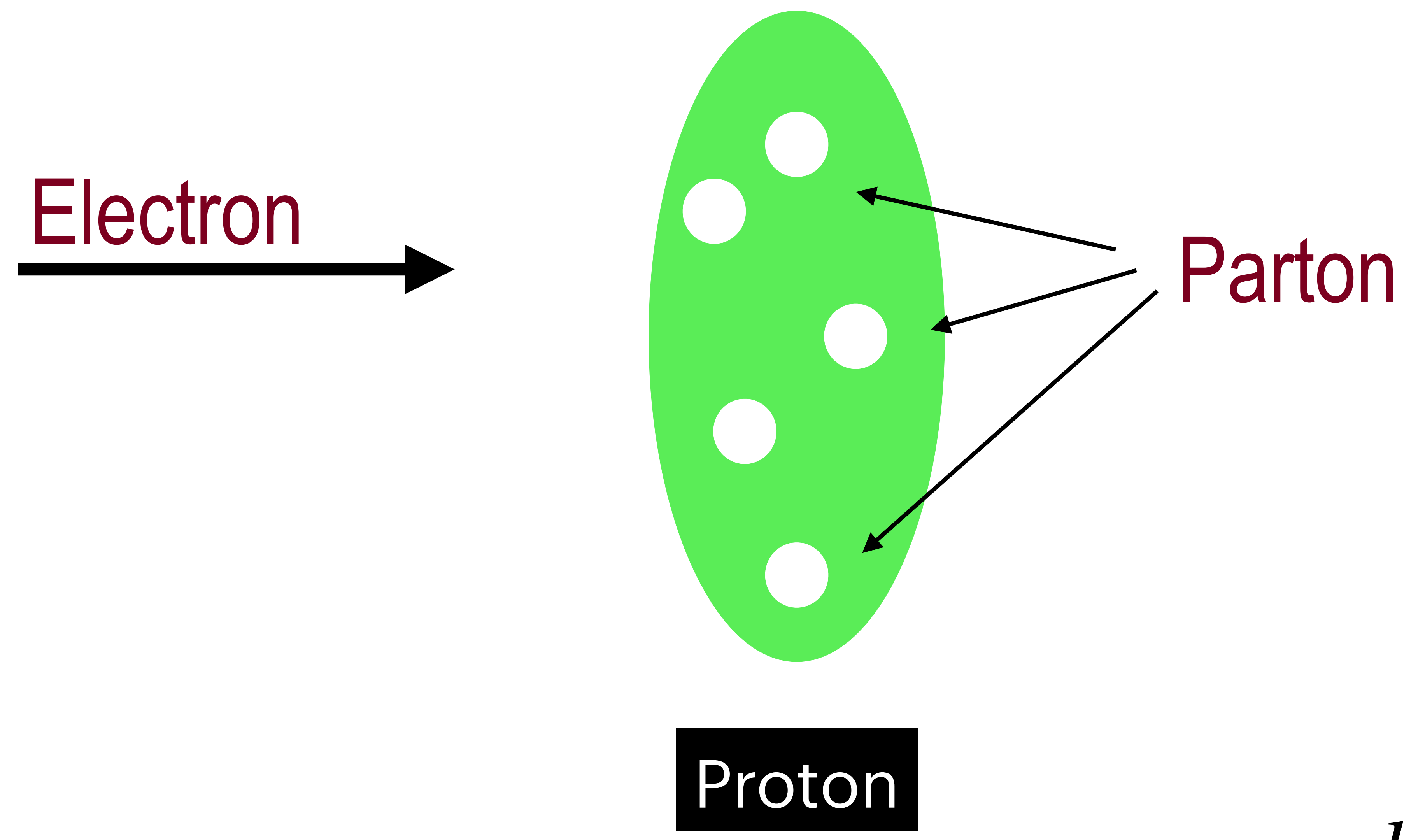
Observations

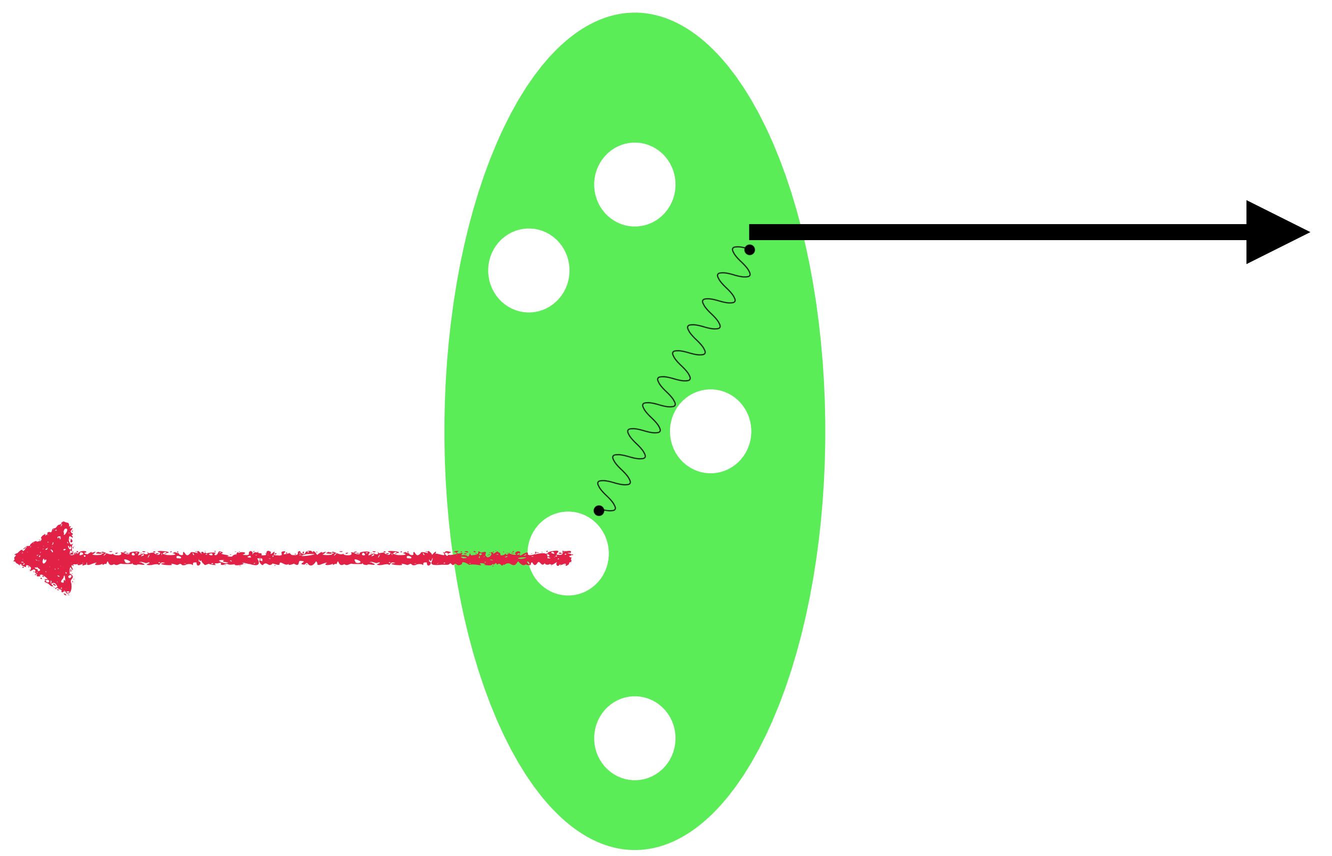
1. In the DIS limit F_1 and F_2 are almost independent of Q^2 $\quad F_{1/2}(x, Q^2) \rightarrow F_{1/2}(x)$

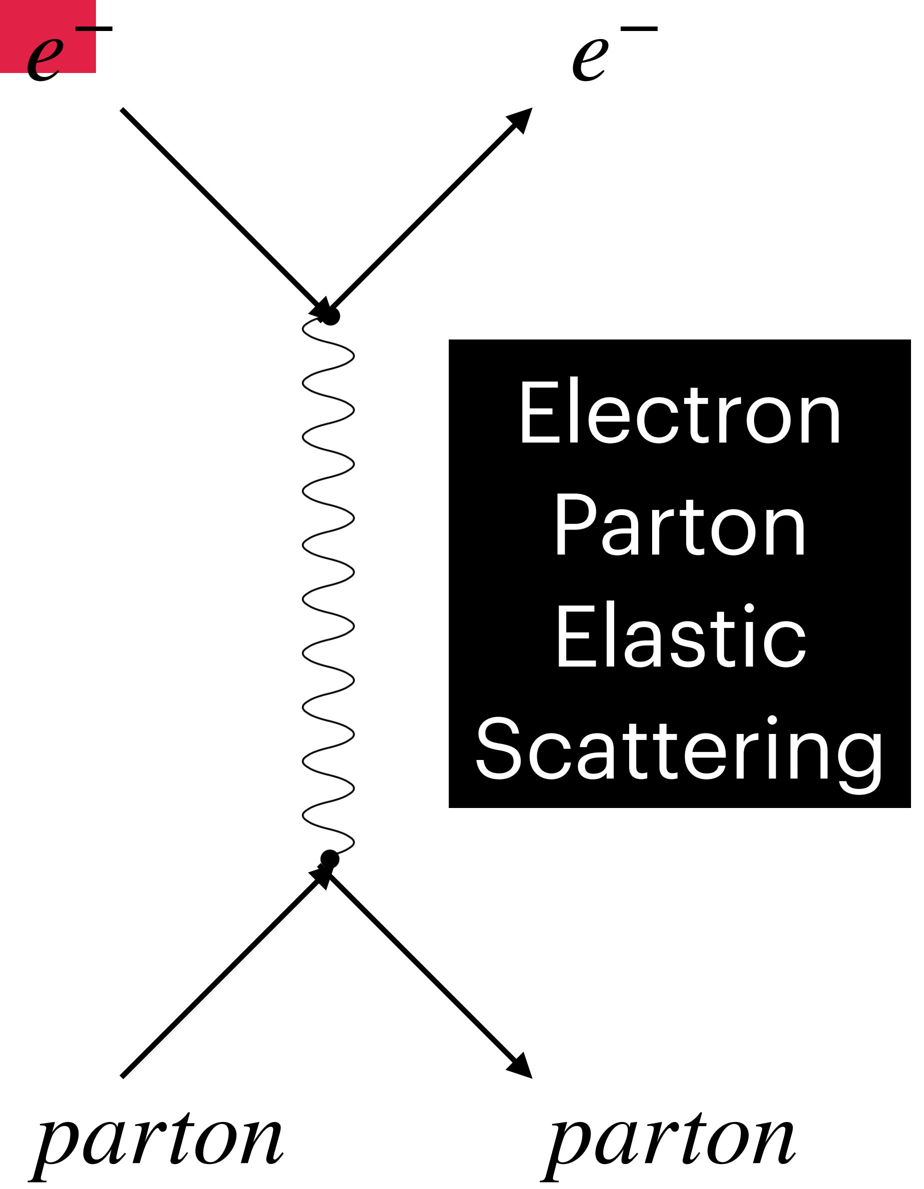
1. Callan-Gross relation $\quad F_2(x) = 2xF_1(x)$

Remember: Extended object : Q^2 dependence in the form factor (point like particle no Q^2 dependence)

Explanation: electron proton scattering is actually elastic scattering of photon from a point like spin-half particle inside the proton called quark/parton







$$\frac{d\sigma}{dQ^2} = \frac{4\pi\alpha^2}{Q^4}\left[(1-y) + \frac{y^2}{2}\right]$$

Parton carries a fraction of the proton momentum = Bjorken x variable

Structure function is related to the momentum distribution of Parton inside the proton

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Naive Parton Model

Observations

1. In the DIS limit F_1 and F_2 are almost independent of Q^2 $\quad F_{1/2}(x, Q^2) \to F_{1/2}(x)$

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Remember: Extended object : Q^2 dependence in the form factor (point like particle no Q^2 dependence)

Explanation: electron proton scattering is actually elastic scattering of photon from a point like spin-half particle inside the proton called quark/parton

Parton Model:

Inside the proton, free point like constituent, can be charged or neutral

It carries some fraction of the proton's momentum: x-dependence of the structure functions can be related to the momentum distribution of the partons inside the proton

$q^p(x)dx =$ Number of q parton inside the proton with momentum fraction between x and x+dx

Parton Distribution Function(PDF)

$q^p(x)dx =$ Number of q parton inside the proton with momentum fraction between x and x+dx

Relation between structure functions and pdfs

$$F_2(x, Q^2) = 2xF_1(x, Q^2) = x\sum Q_i^2 q_i^p(x)$$

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PDFs can be measured from DIS data

Electron Proton deep inelastic scattering

$$F_2^p(x) = x \sum Q_i^2 q_i^p(x) = x \left[\frac{4}{9} u^p(x) + \frac{1}{9} d^p(x) \right]$$

SU(2) isospin Symmetry

Electron Neutron deep inelastic scattering

$$F_2^n(x) = x \left[\frac{4}{9} u^n(x) + \frac{1}{9} d^n(x) \right] = x \left[\frac{4}{9} d^p(x) + \frac{1}{9} u^p(x) \right]$$

Use both e-P data and e-N data to find u(x) and d(x)

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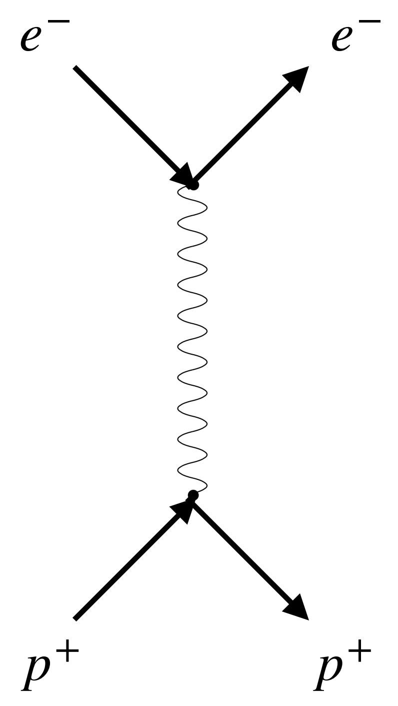
Use both e-P data and e-N data to find u(x) and d(x)

Protons also contain anti quarks : photon probe cannot discriminate

We need to use W boson probe



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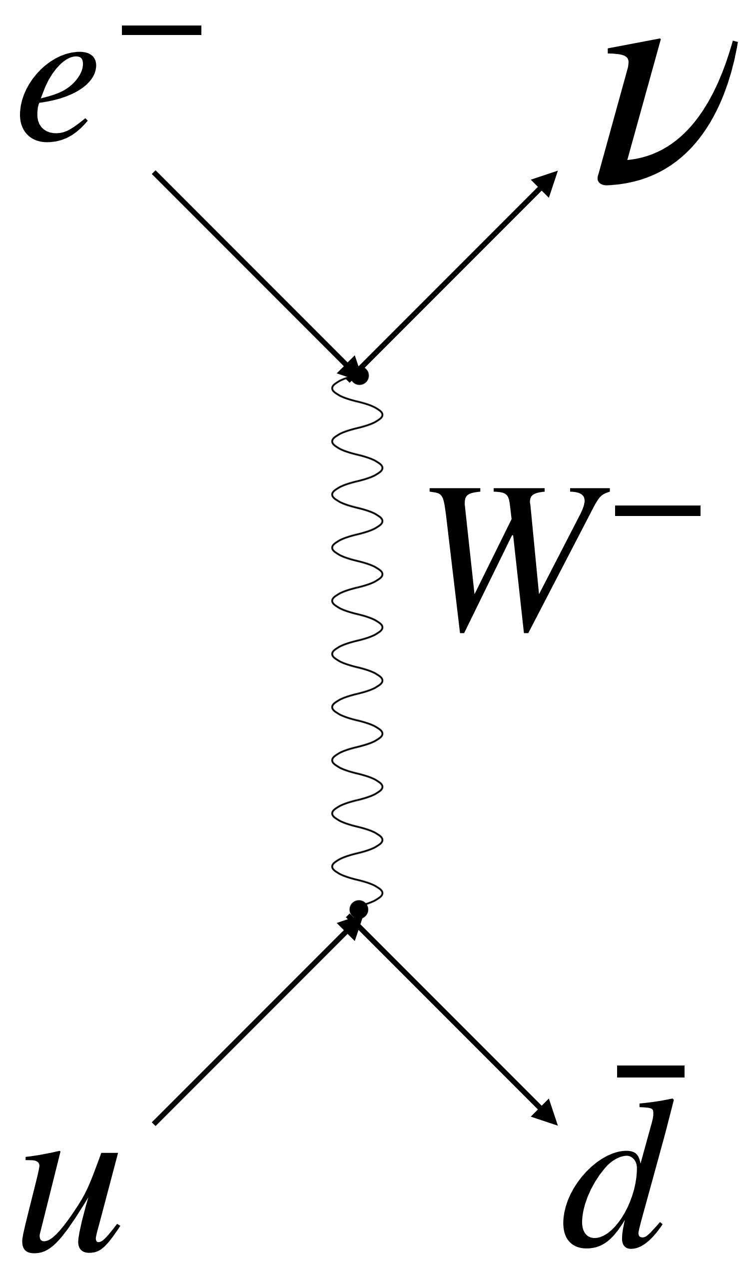
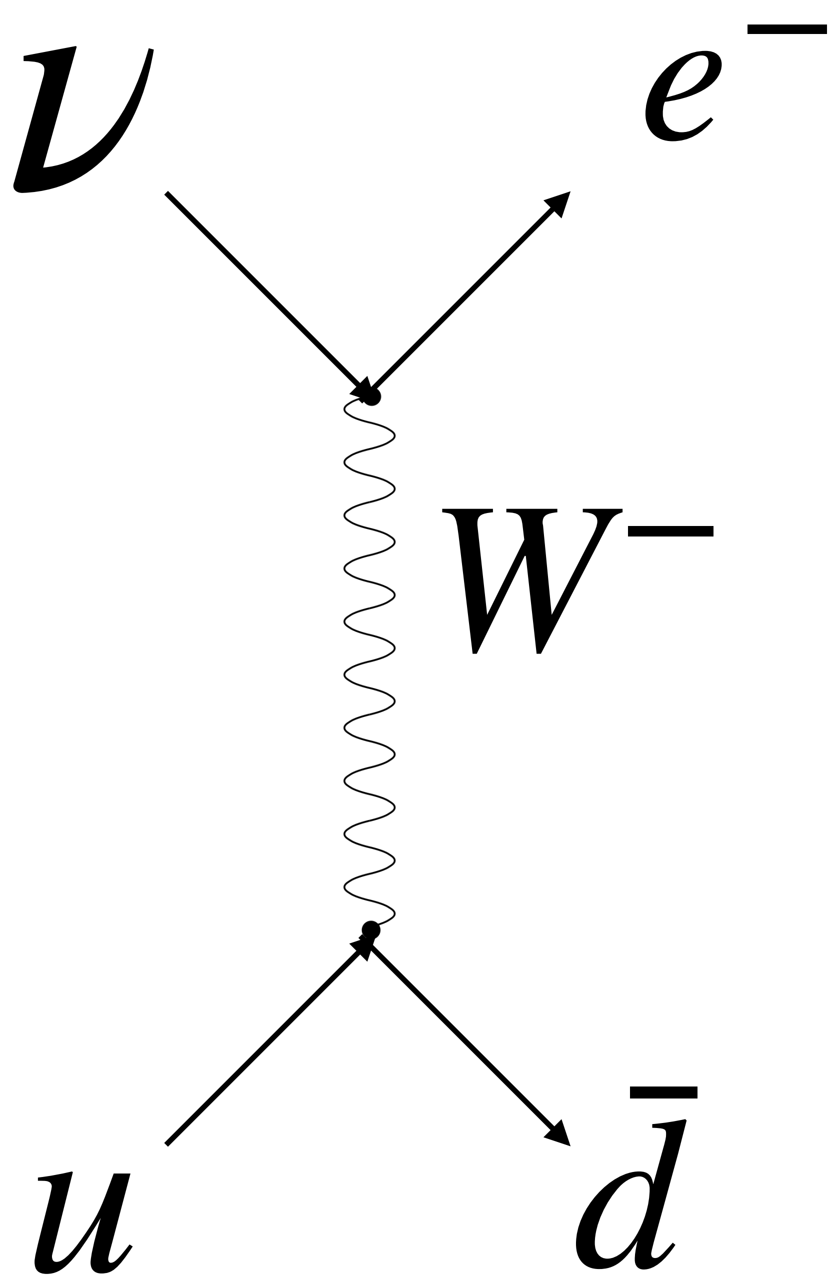


However detection of the neutrino in the final state is difficult

Use neutrino beam in the initial state and detect the final state charged lepton



Actual measurement more complicated

Three structure Functions F1, F2, F3

Parton distribution Function(PDF)

Protons not only contain quarks but also contain anti-quarks

P= uud (valance quarks)

However $u\bar{u}, d\bar{d}\,..$ can be produced inside the proton (called sea quarks)

This populates the low momentum fraction region (low x region)

$$\int dx[u + \bar{u}] \to \infty \qquad \int dx[u - \bar{u}] = 2$$

$$\int \sum_i xq_i(x) = 1$$ Momentum conservation

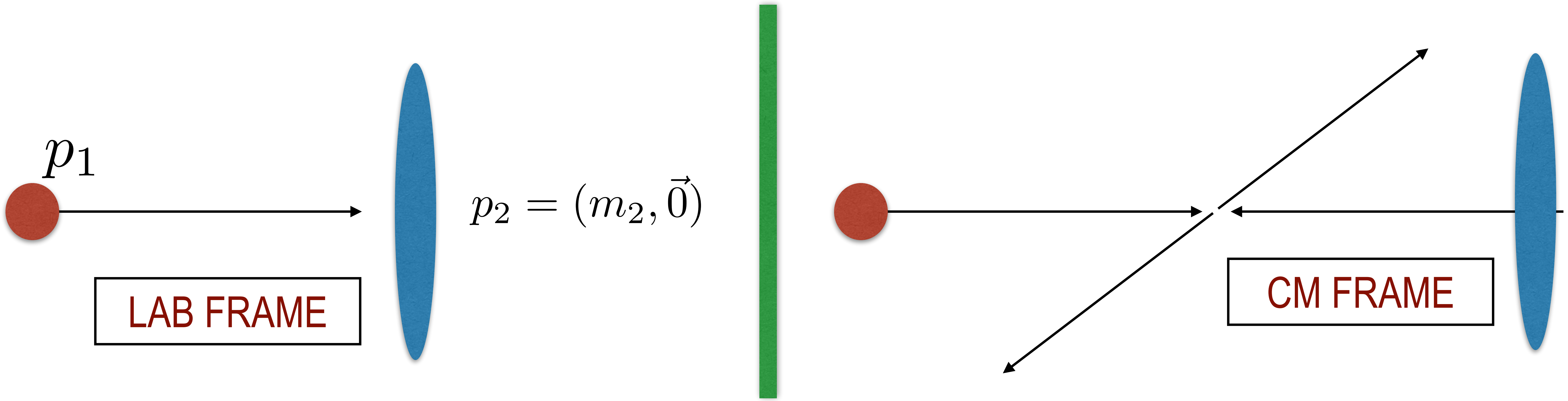
Sum over quarks ~ 0.55 => about 50% of the total momentum missing

Something is not taking in the eP DIS scattering => gluon

Fixed Target and Collider Experiments

Fixed Target Experiment

REF:hep-ph/0508097



$$s = (p_1 + p_2)^2 = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2$$

$$s = m_1^2 + m_2^2 + 2(E_1 E_2 - \vec{p}_1 \cdot \vec{p}_2)$$

Fixed target : $\vec{p_2} = 0$ $\quad For\ m_1 \sim 0\ and\ E_1 \gg m_2 \quad \sqrt{s} \sim \sqrt{2E_1 m_2}$

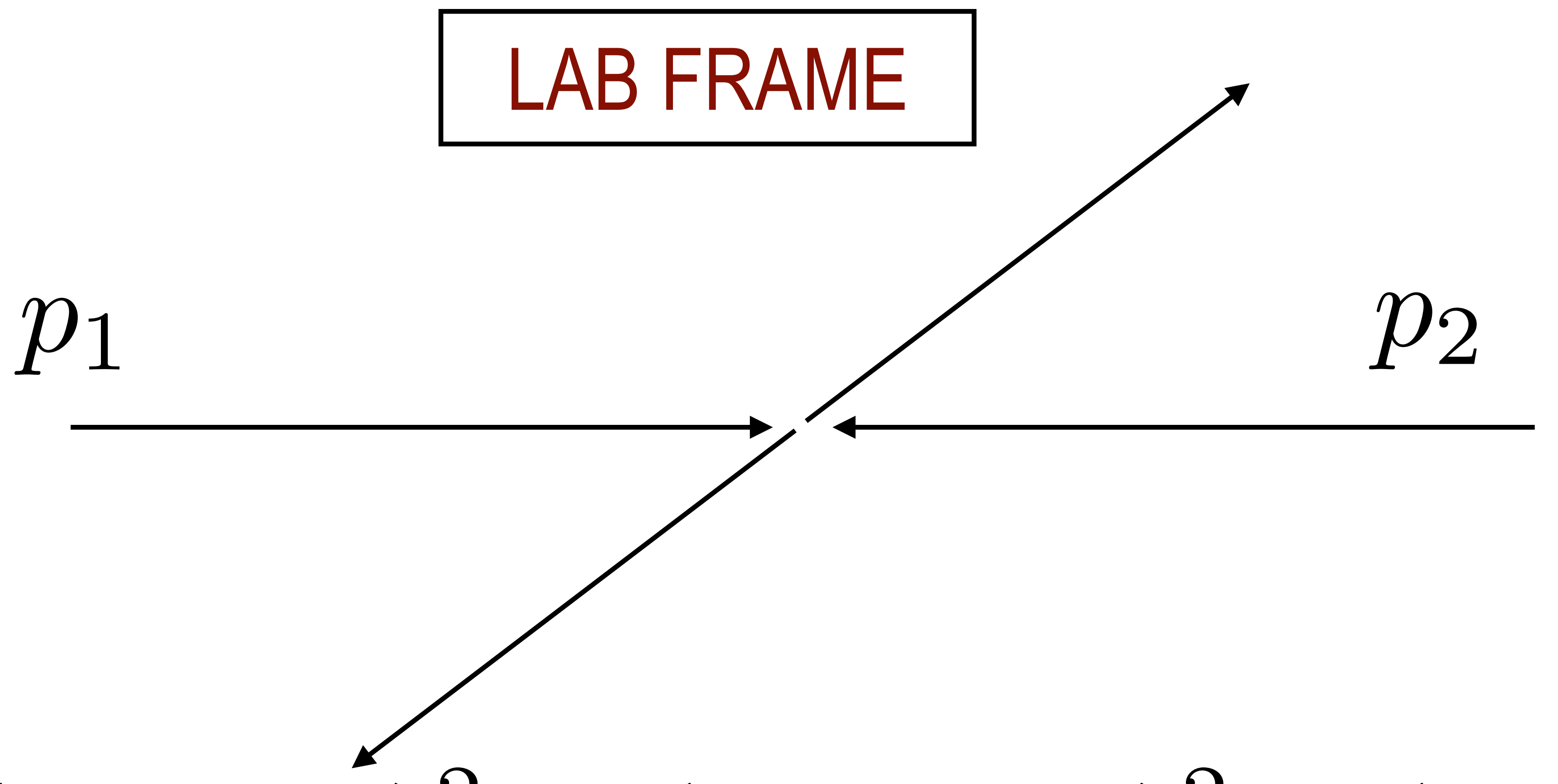
Example $\quad m_2 = 1\ GeV, \quad E_1 = 14000\ GeV \quad = 14\ TeV, \quad m_1 \sim 0$

$$\sqrt{s} \sim 100 \quad \mathrm{GeV}$$

Very light particle production is still possible in fixed target experiment (Beam dump experiments)

Collider Experiment

REF:hep-ph/0508097



$$s = (p_1 + p_2)^2 = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2$$
$$s = m_1^2 + m_2^2 + 2(E_1 E_2 - \vec{p}_1 \cdot \vec{p}_2)$$

Collision :

$$p_1 = (E_p, \vec{p}), \quad p_2 = (E_p, -\vec{p})$$
$$m_1 = m_2 \sim 0 \quad \cos(\theta) = -1.0$$ (head on)

$$\sqrt{s} = 2E_p$$ (head on)

collision experiments are essential for the production of heavy particles

Collider Experiment

Electron positron collider :

zero charge, zero lepton number, energy profile well understood
beam polarisation possible, reasonably low background

Large synchrotron radiation —> linear collider

Hadron Collider

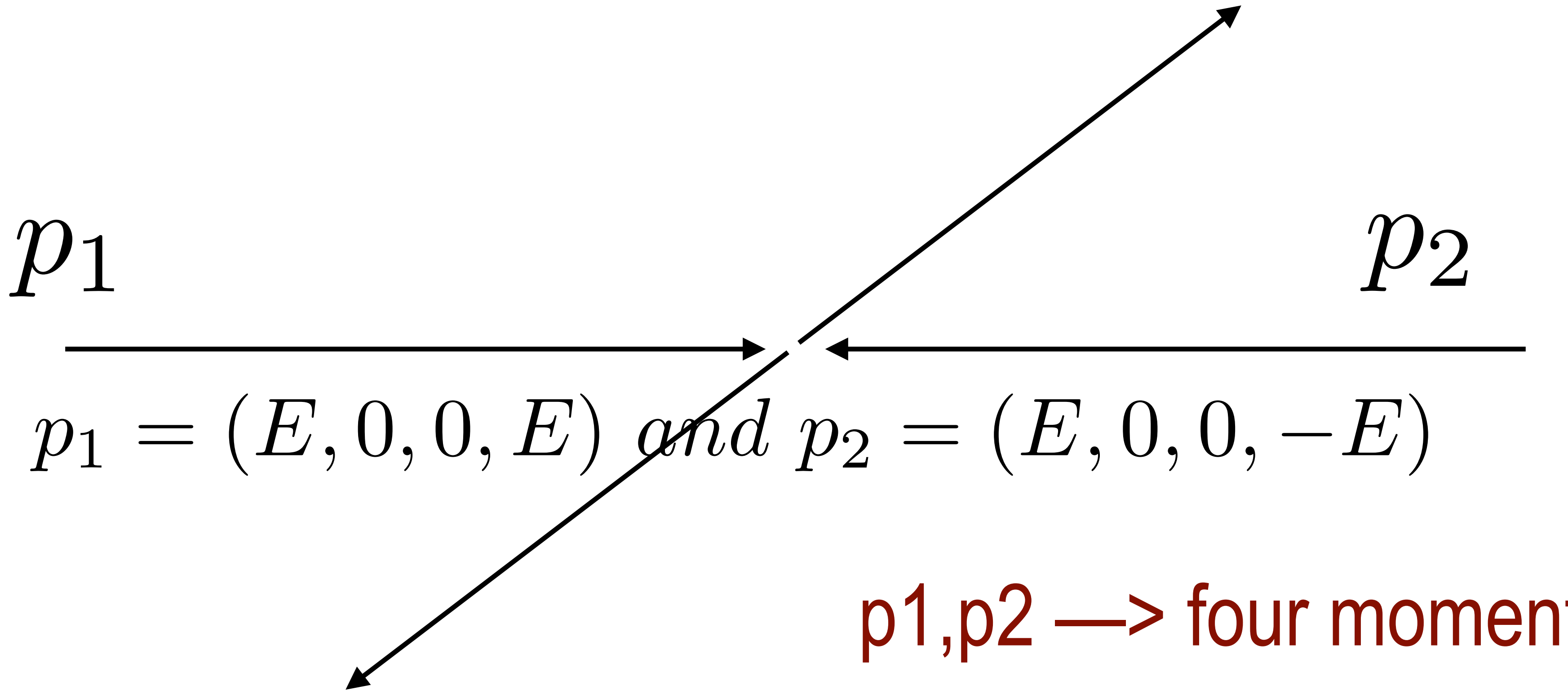
energy of colliding partons are unknown: it can scan a wide energy range —>
particularly useful for the search of new particle of unknown mass
Multiple final states possible (different spin, charge …)
High luminosity option available

huge backgrounds, additional challenges including multiple interaction, pile-up …

Hadron Collider

REF:hep-ph/0508097

LAB FRAME : proton proton collision



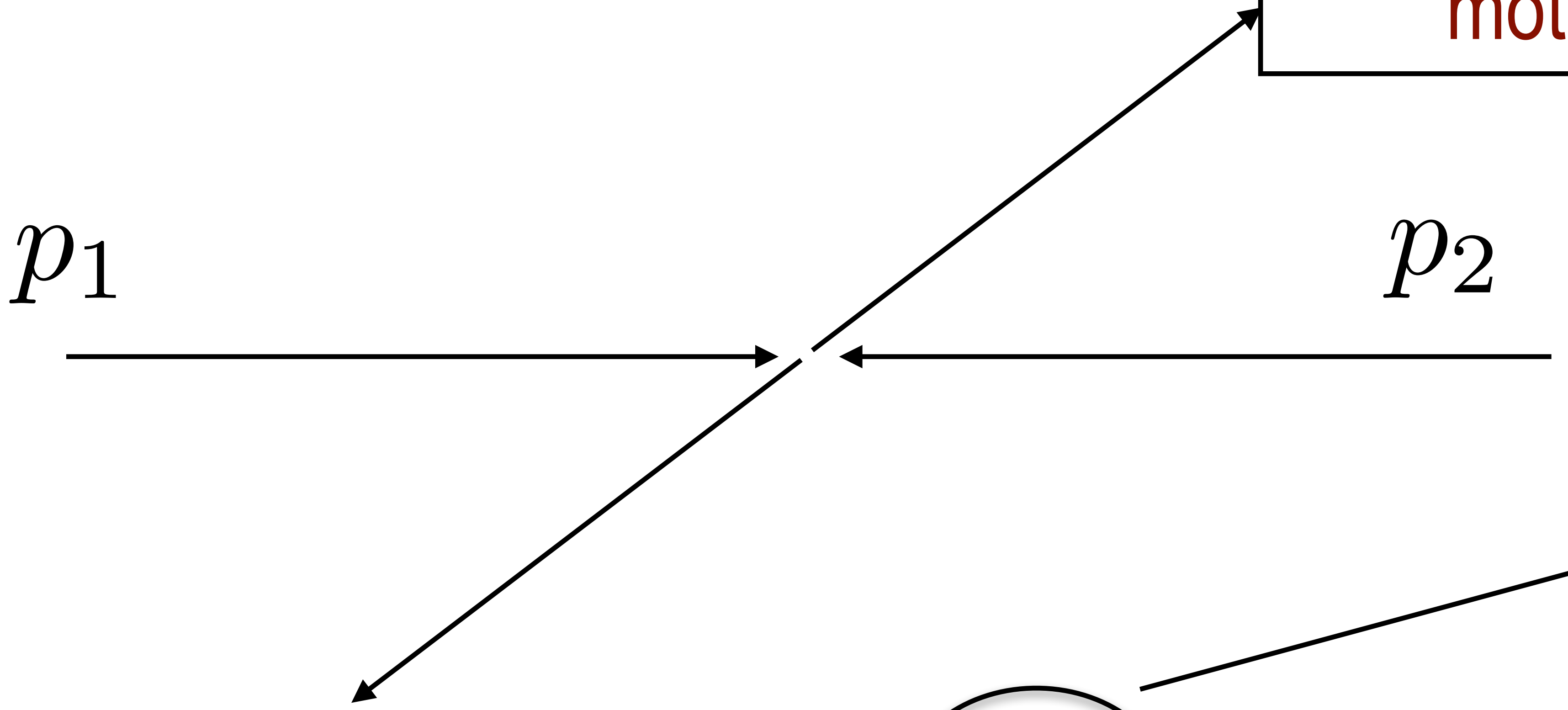
$$p_1 = (E, 0, 0, E) \ and \ p_2 = (E, 0, 0, -E)$$

p1,p2 —> four momenta of colliding protons

partons carry much less energy than the protons

parton 4 momentum in the lab frame

initial state partons have a relative motion in the LAB frame



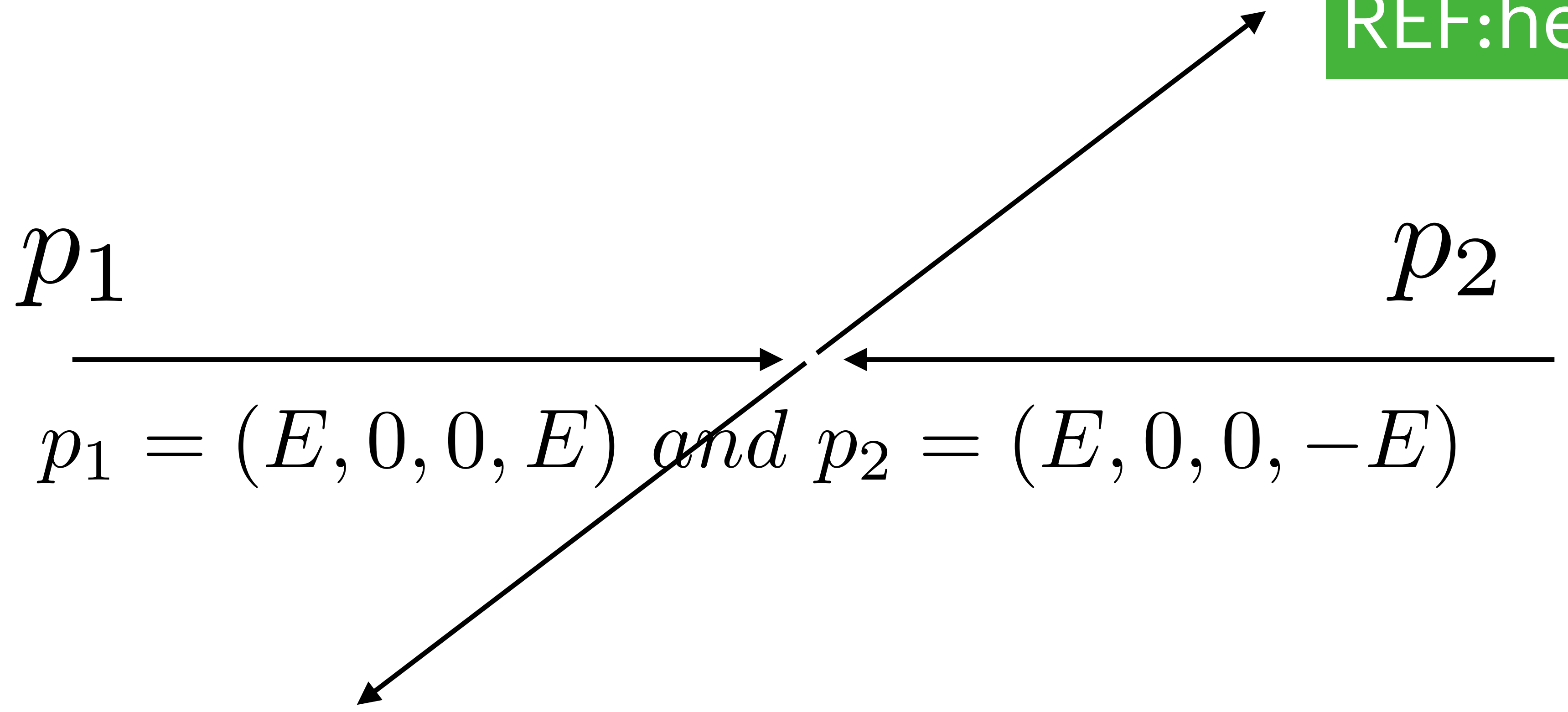
fraction

$$\hat{p}_1 = x_1(E, 0, 0, E) \ and \ \hat{p}_2 = x_2(E, 0, 0, -E)$$

Hadron Collider

REF:hep-ph/0508097

Proton proton CM frame = LAB Frame



$p_1 = (E, 0, 0, E)$ *and* $p_2 = (E, 0, 0, -E)$

Parton system moves in the LAB frame with 4 Momentum $\left((x_1 + x_2)E,\ 0,\ 0,\ (x_1 - x_2)E\right)$ or with speed $\dfrac{x_1 - x_2}{x_1 + x_2}$

Proton Proton CM energy = 2E $=\sqrt{S}$, In the parton CMframe= $s = x_1 x_2 S$

Express 4 momentum of a particle in terms of rapidity(y), transverse momentum(p_T) and azimuthal angle (phi) about the z axis (collision axis)

$$y = \frac{1}{2} ln \frac{E+P_z}{E-P_Z}, \quad p_T = \sqrt{p_x^2 + p_y^2}$$

transverse momentum(p_T) and azimuthal angle (phi) about the z axis (collision axis) are invariant under longitudinal boost, rapidity changes only by a constant

4 Momentum of a particle $p^\mu = (E_T \cosh y, p_T \cos\phi, p_T \sin\phi, E_T \sinh y)$ $\quad E_T = \sqrt{p_T^2 + m^2}$

Production Cross section

REF:hep-ph/0508097

Hard scattering cross section

Parton level cross section

$$\sigma(AB \to FX) = \sum_{a,b} \int dx_1 dx_2 P_{a/A}(x_1, Q^2) P_{b/B}(x_2, Q^2) \boxed{\hat{\sigma}(ab \to F)}$$

Scattering of two hadrons A and B to produce a final state particle X

Pa/A => probability of finding a Parton a inside the hadron A

Question: Parton distribution function also depends on Q : Why ?

Production Cross section

REF: 0901.0002

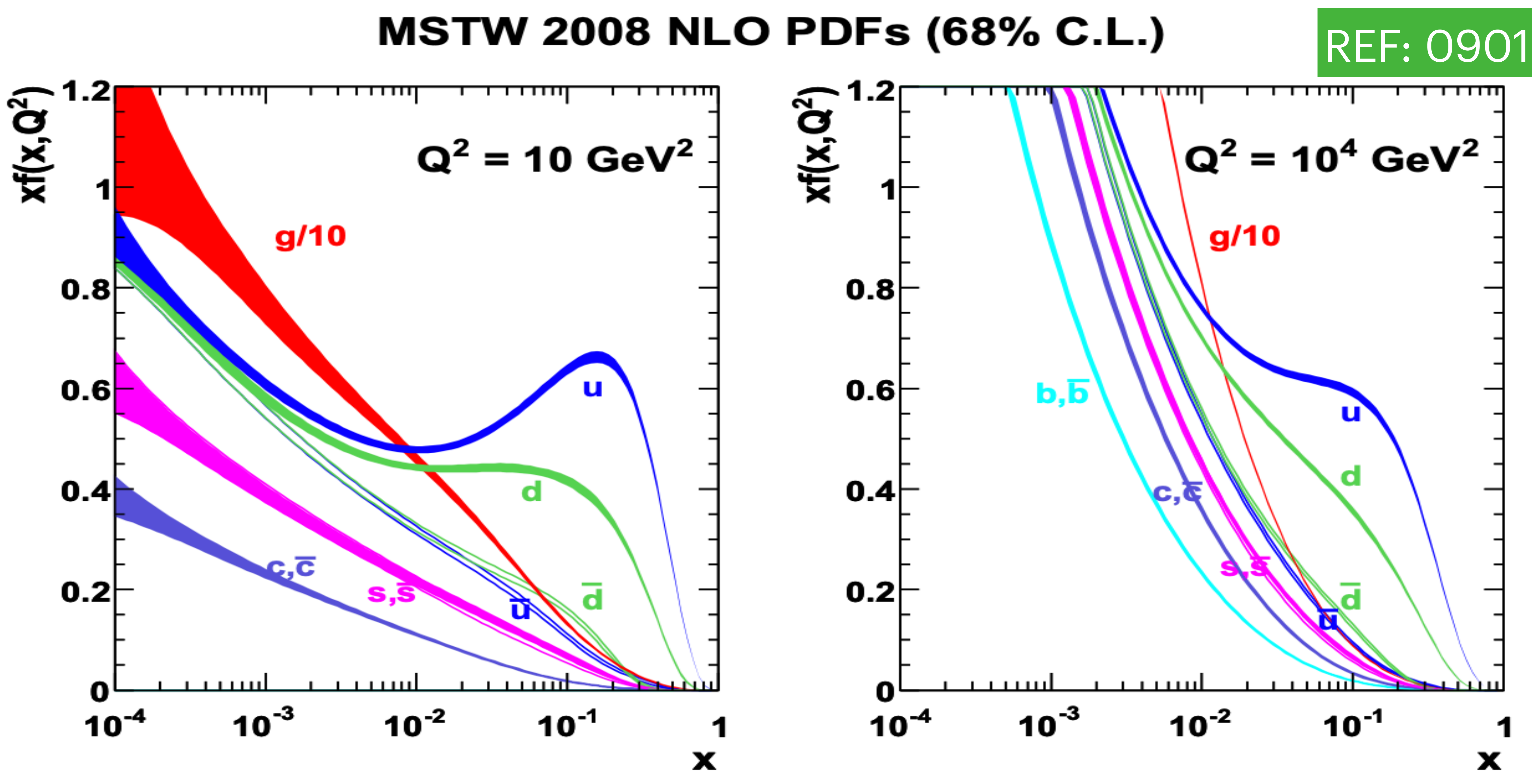


Figure 1: MSTW 2008 NLO PDFs at $Q^2 = 10$ GeV^2 and $Q^2 = 10^4$ GeV^2.

Example : $pp \rightarrow Z$

Multiple parton level processes : $u\bar{u} \rightarrow Z, d\bar{d} \rightarrow Z, s\bar{s} \rightarrow Z\ldots$

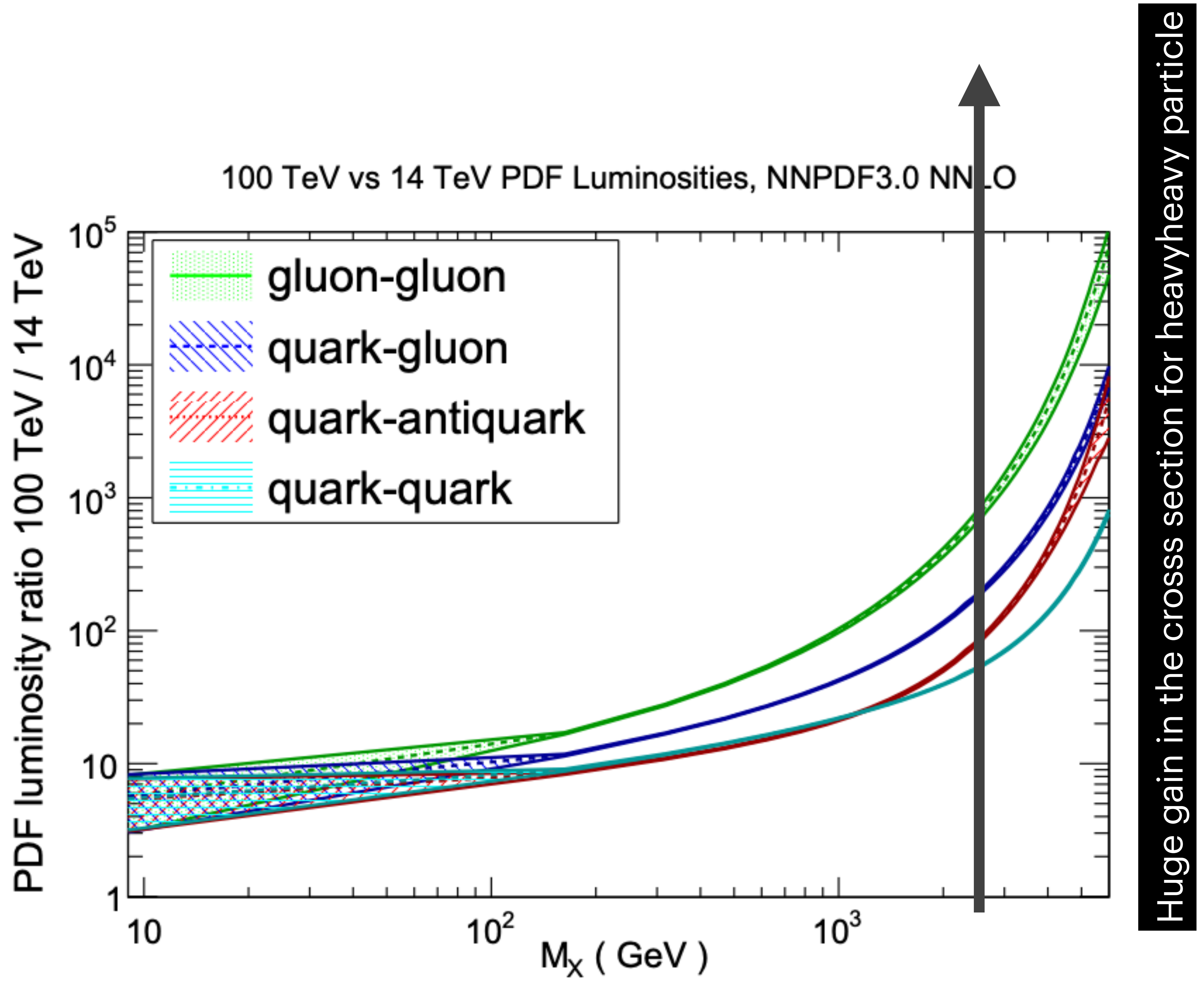
Example : $pp \rightarrow h$

Dominant parton level processes : $gg \rightarrow h$

Increase the Z /h mass keeping couplings constant => Should Higgs cross section decrease quickly ??

Production Cross section : 14 TeV vs 100 TeV

REF: hep-ph:1607.01831



For 125 GeV Higgs boson gain ~150 in the ggF channel and ~ 400 in the di-Higgs, ~ 500 in the ttH

Event in hadronic collision

REF: hep-ph/0508097

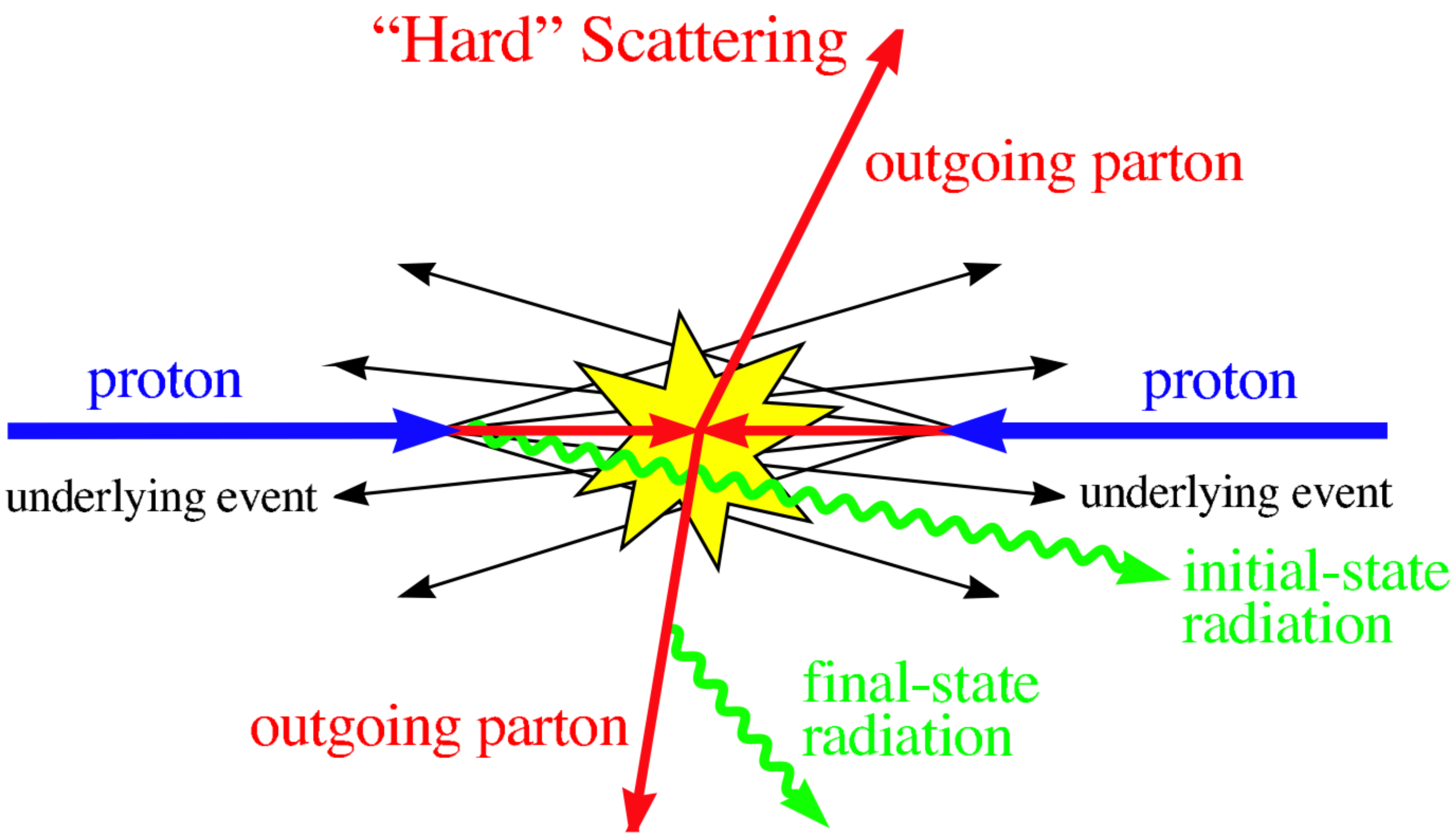


FIG. 4: An illustrative event in hadronic collisions.

Various effects :

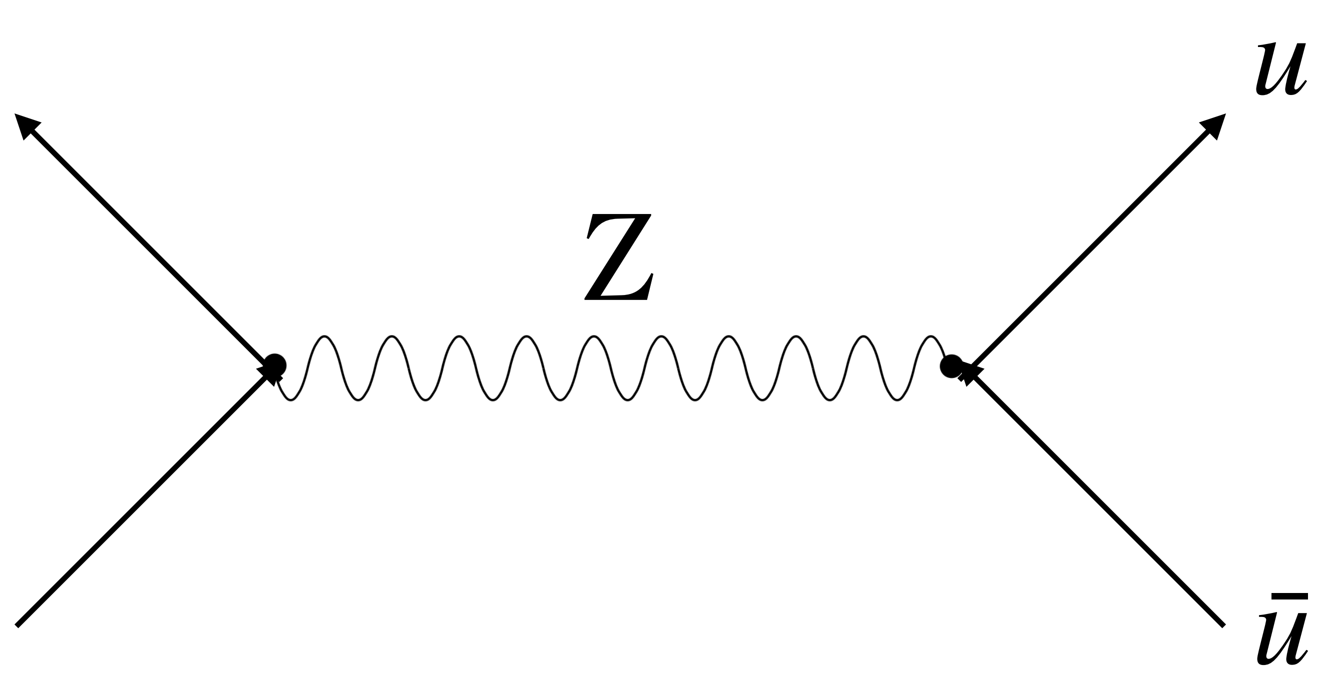
Hard Process

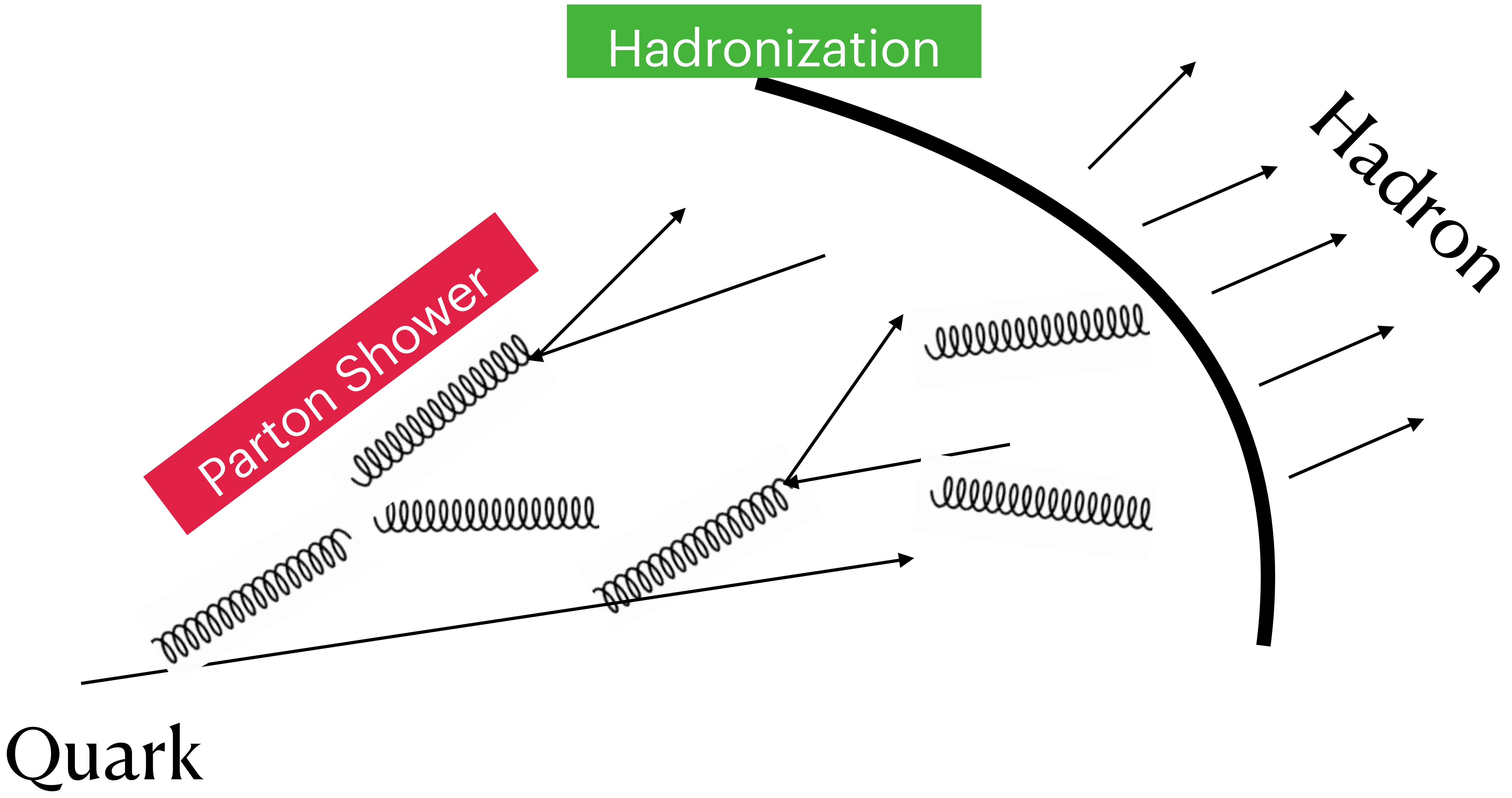
Initial State Radiation

Final State radiation

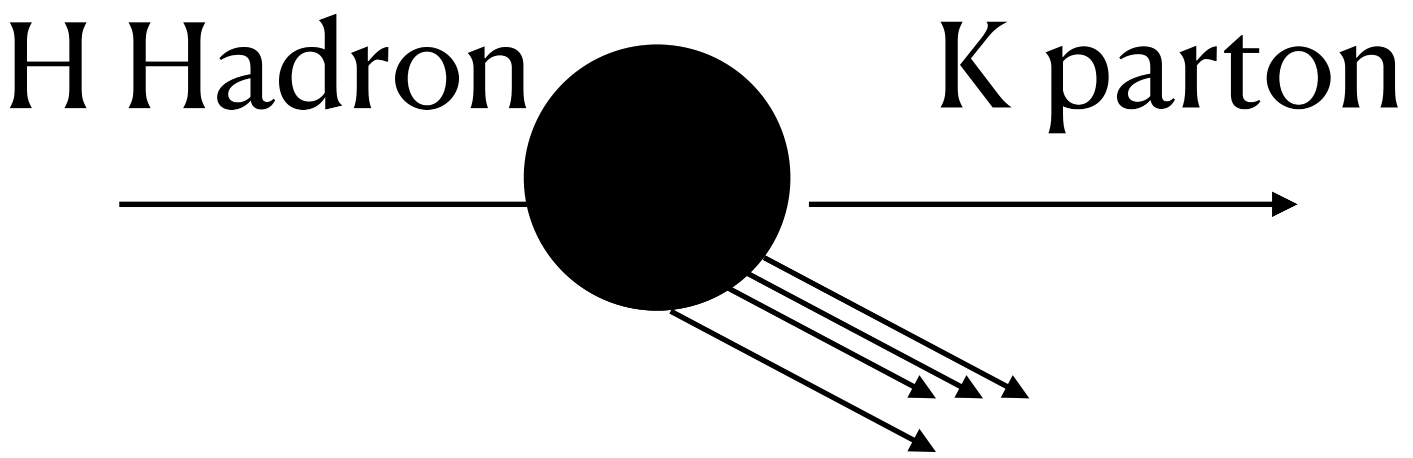
Multiple-Partonic Interactions(MPI)

Shower and fragmentation

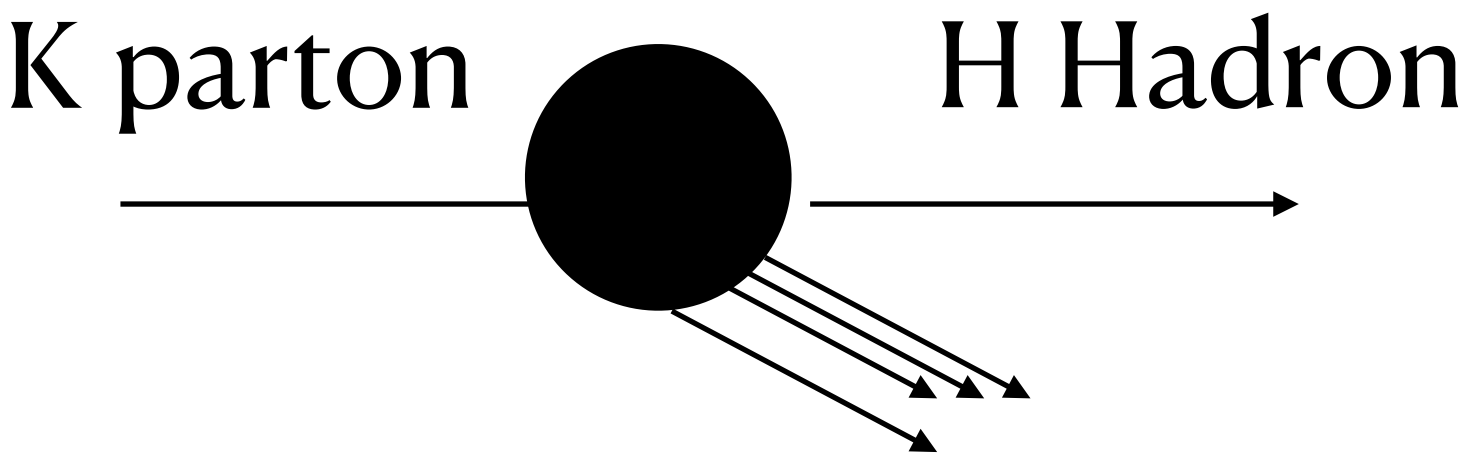




Quark/gluon to hadrons : cannot be calculated (must be measured like PDF in experiment)



Parton distribution function



Fragmentation function $D_k^h(z, Q^2)$

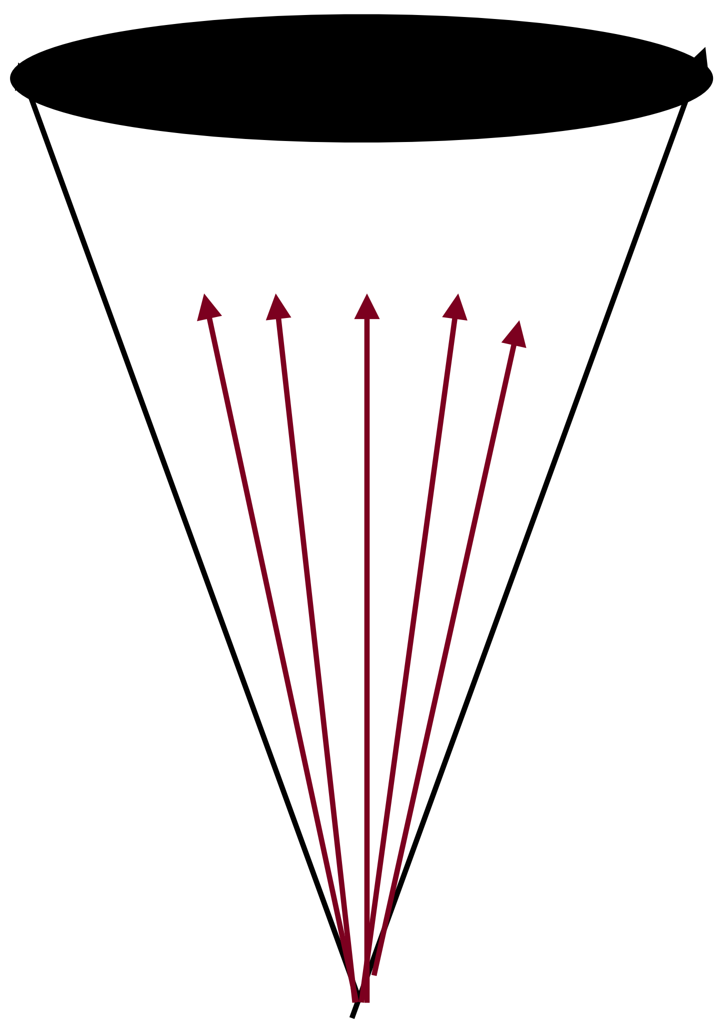
Jets and substructure

Jet formation

Jets : collimated spray of particles comes from the shower and and hadronization of quark/gluon

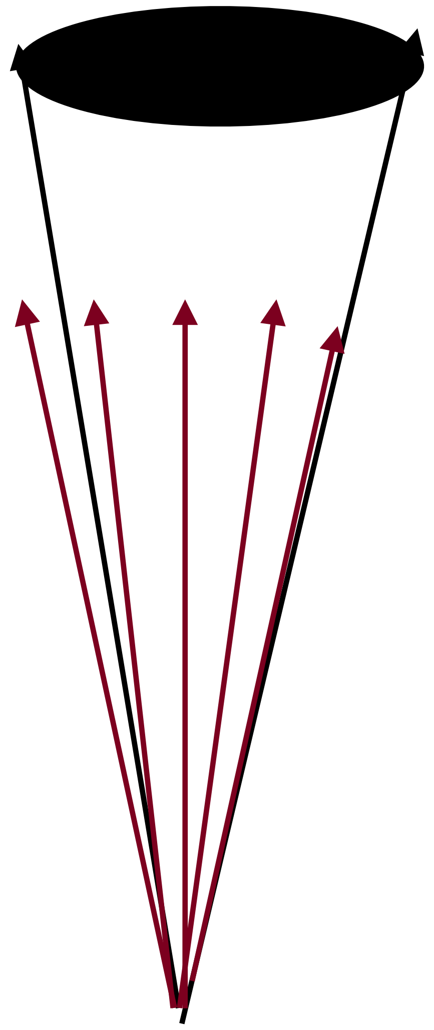
Jets : link between parton and colourless stable hadrons

Basic idea : construct a cone which captures all the hadrons from the parton



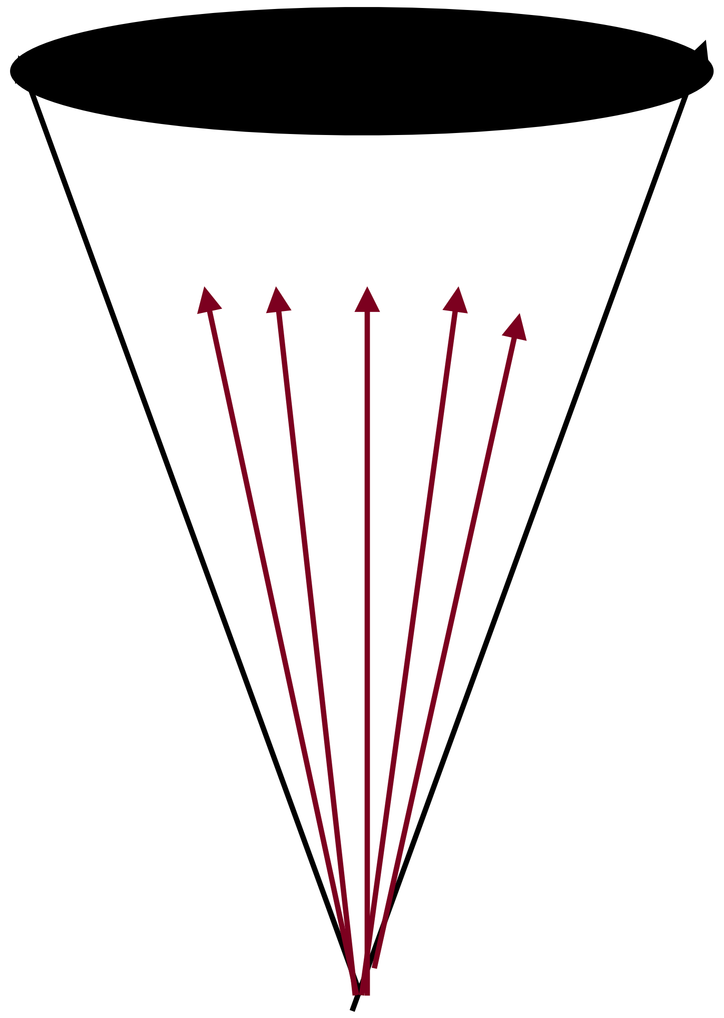
Small Jet vs Large Jet radius

Narrow cone



May not
Capture
All the
particles

Large cone



Capture
All the
particles

Contaminated by Underlying events and Pileup

Sequential Jet formation algorithm (IRC safe)

Starts with N stable particles

Distance variable between two particles : $d_{ij} = min(p_{Ti}^a, p_{Tj}^a) \dfrac{R_{ij}^2}{R^2}$

Angular separation between to particles $R_{ij}^2 = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2$

Distance variable(momentum distance from beam axis) : $d_{iB} = p_{Ti}^2$

Procedure

Two parameters : R and a

Find the minimum of $\{d_{ij}, d_{iB}\}$ for the entire set of N particles

If some d_{ij} is minimum => combine i and j particle into one particle (number of particle is reduced to N-1)

If some d_{iB} is minimum => i^{th} particle is declared as a jet and removed from the list

Iterate until all particles are exhausted(inclusive) or a certain number of jets are formed(exclusive)

Kt anti-Kt and CA algorithms

$$d_{ij} = min(p_{Ti}^2, p_{Tj}^2)\,\frac{R_{ij}^2}{R^2}$$

$$d_{iB} = p_{Ti}^2$$

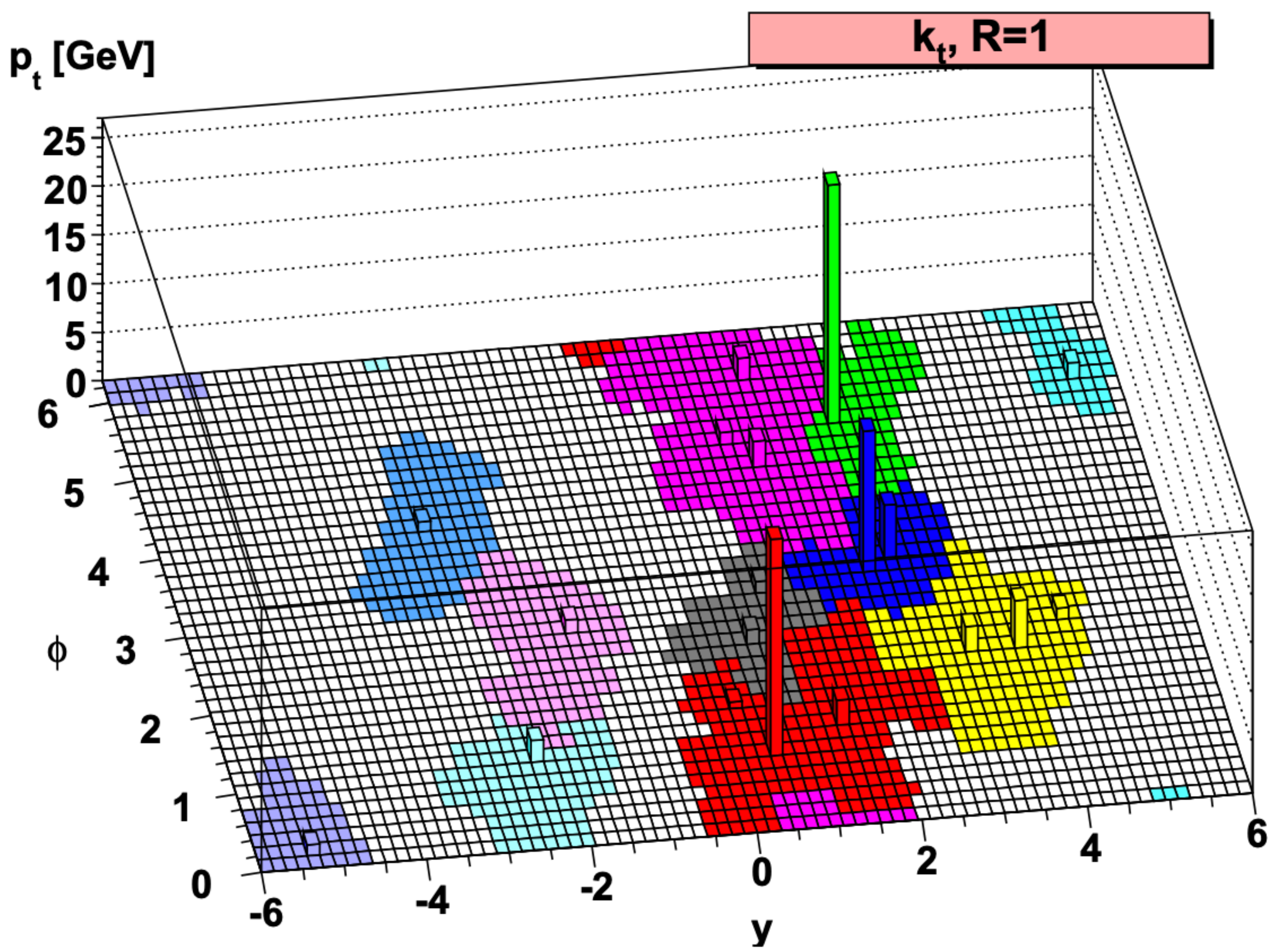
$$d_{ij} = min\left(\frac{1}{p_{Ti}^2}, \frac{1}{p_{Tj}^2}\right)\frac{R_{ij}^2}{R^2}$$

$$d_{iB} = \frac{1}{p_{Ti}^2}$$

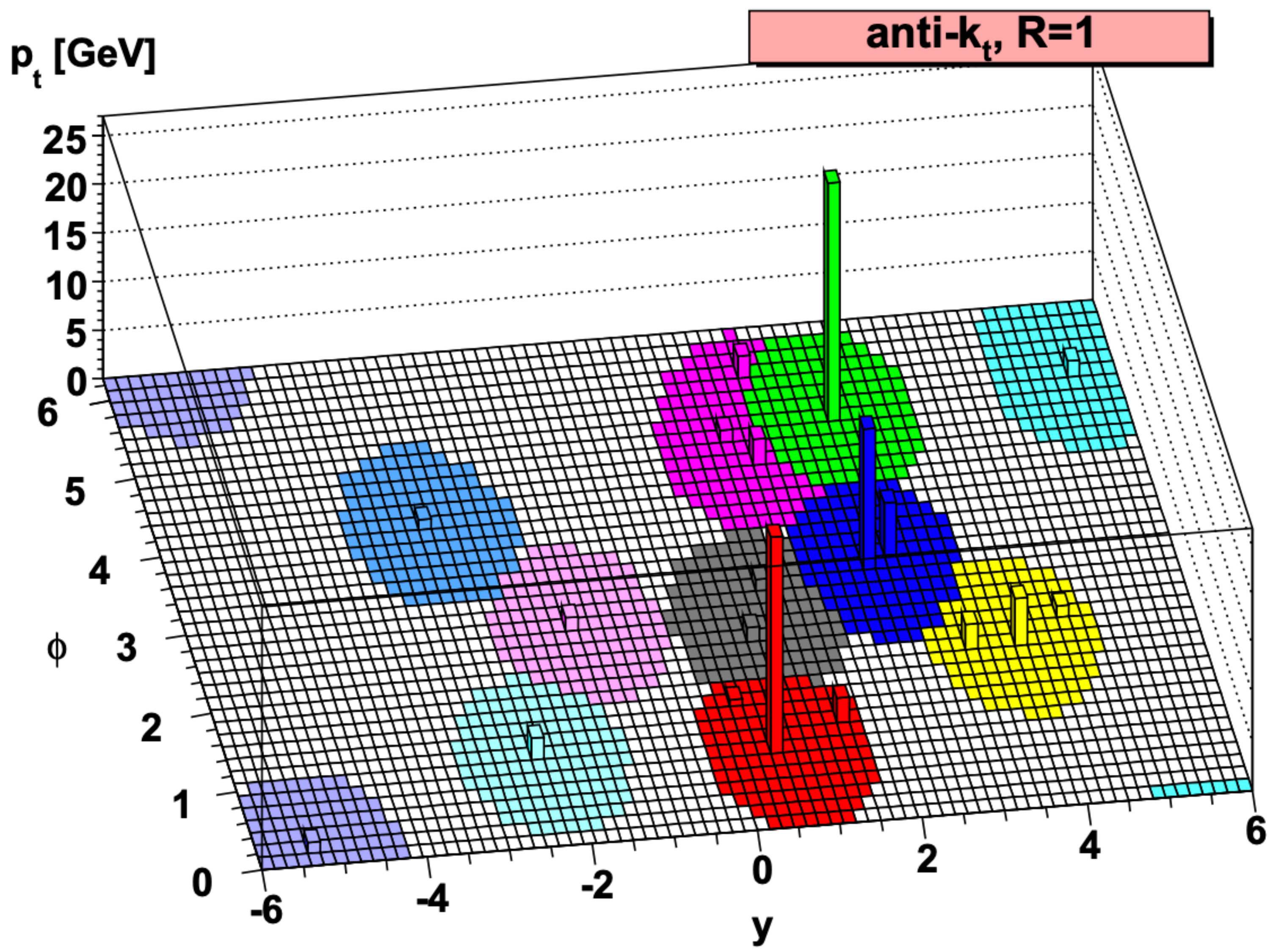
$$d_{ij} = \frac{R_{ij}^2}{R^2}$$

$$d_{iB} = 1$$

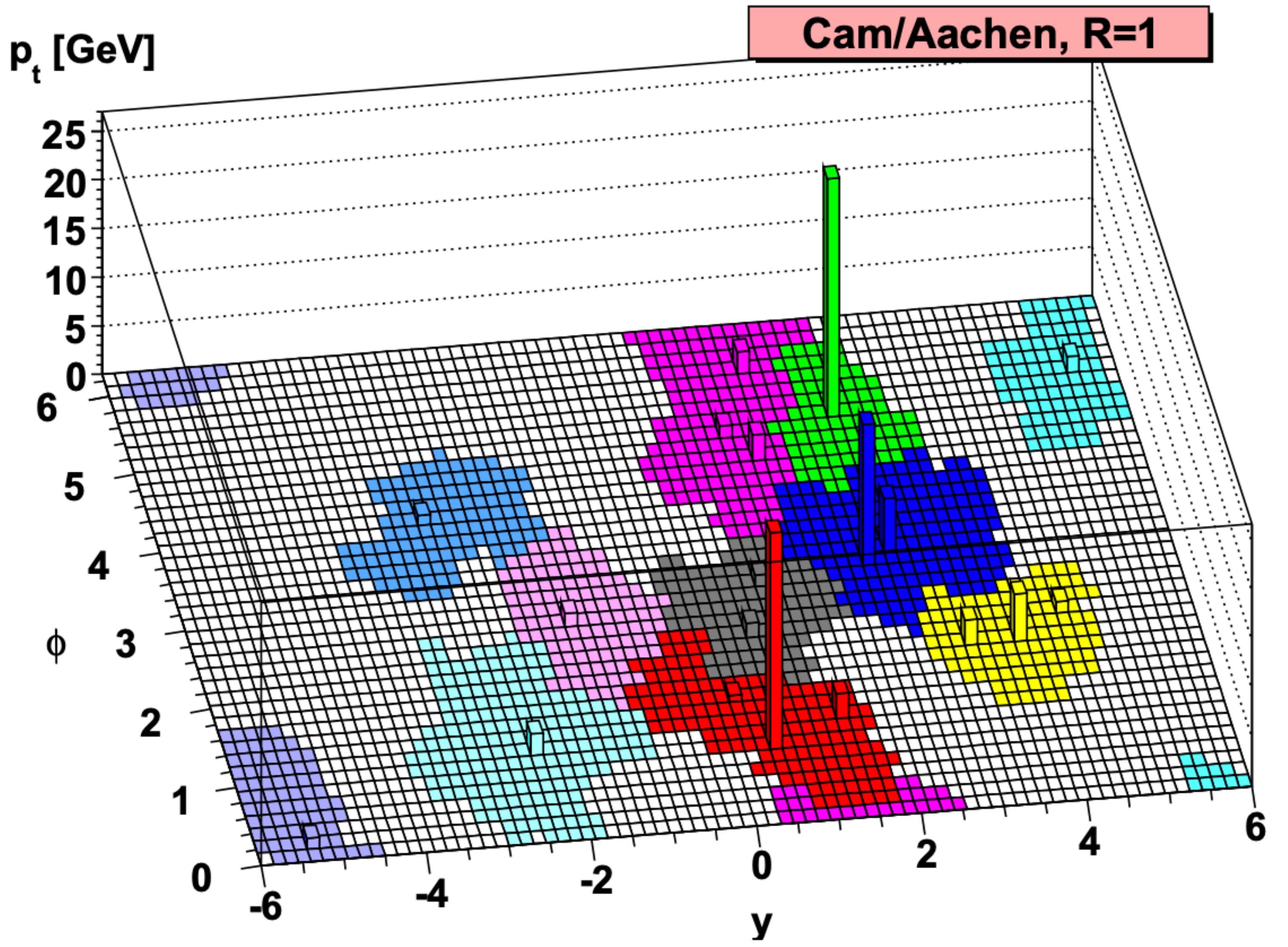
Kt algorithm (a=2)



Anti-Kt algorithm (a=-2)



Cambridge Aachen algorithm (a=0)

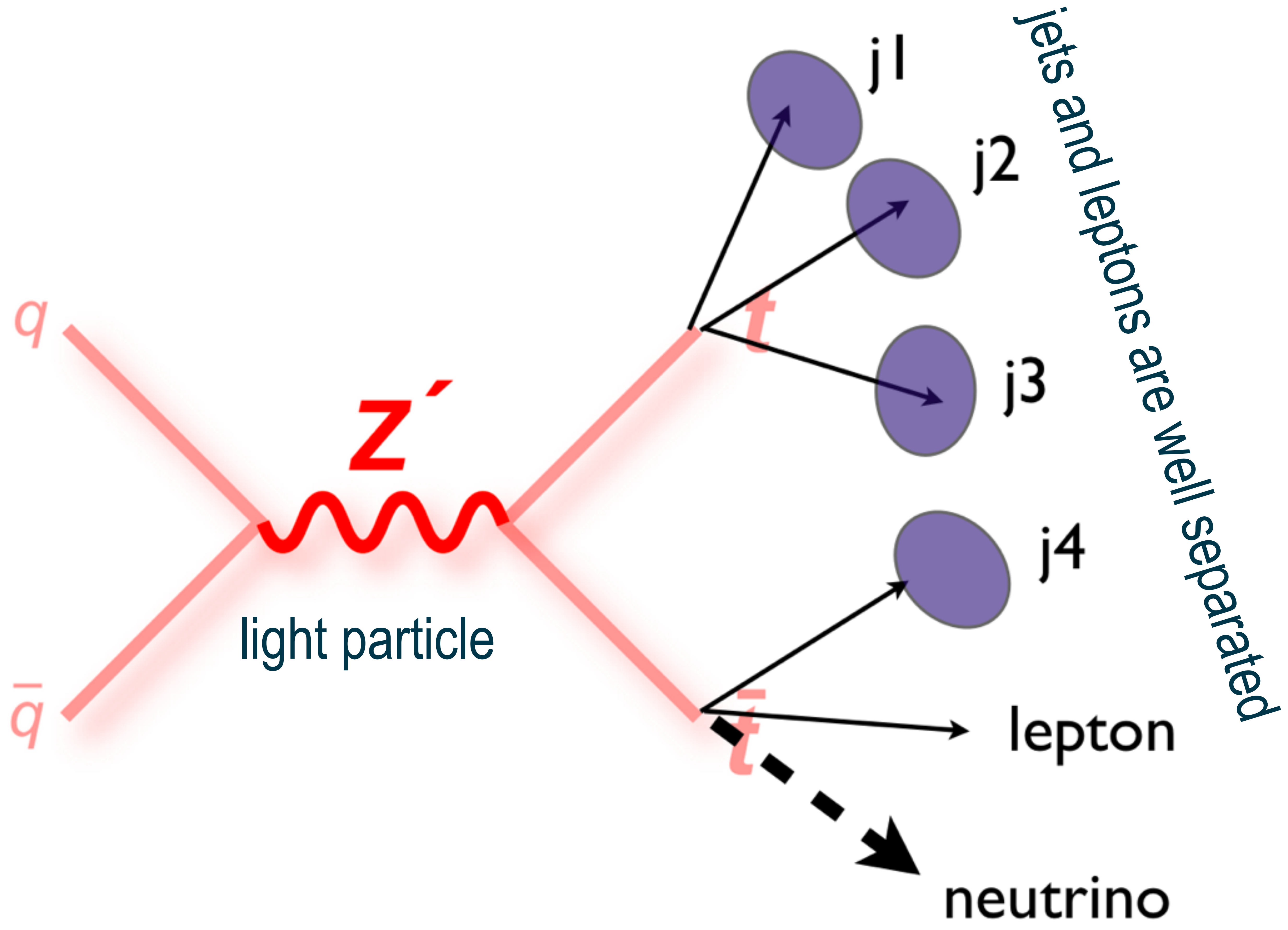


REF: 0906.1833

Non Isolated Objects

LHC current bounds indicate that the new particles will possibly be heavy

Assumption: New particles will be produced at the 14 TeV LHC

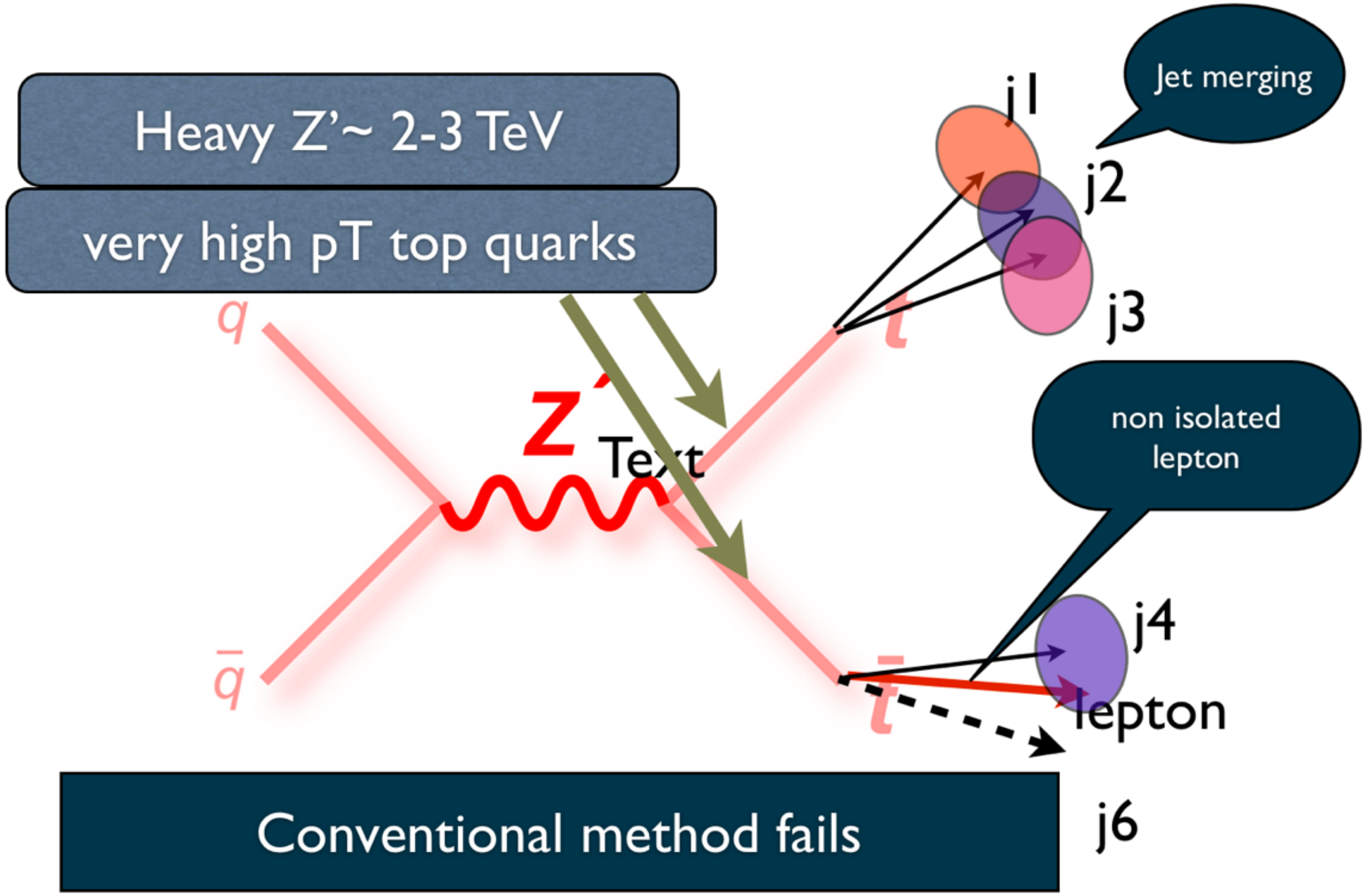


Jet substructure

LHC current bounds indicate that the new particles will possibly be heavy

Assumption: New particles will be produced at the 14 TeV LHC

The decay of new heavy particle to SM particles may give large Lorentz boost



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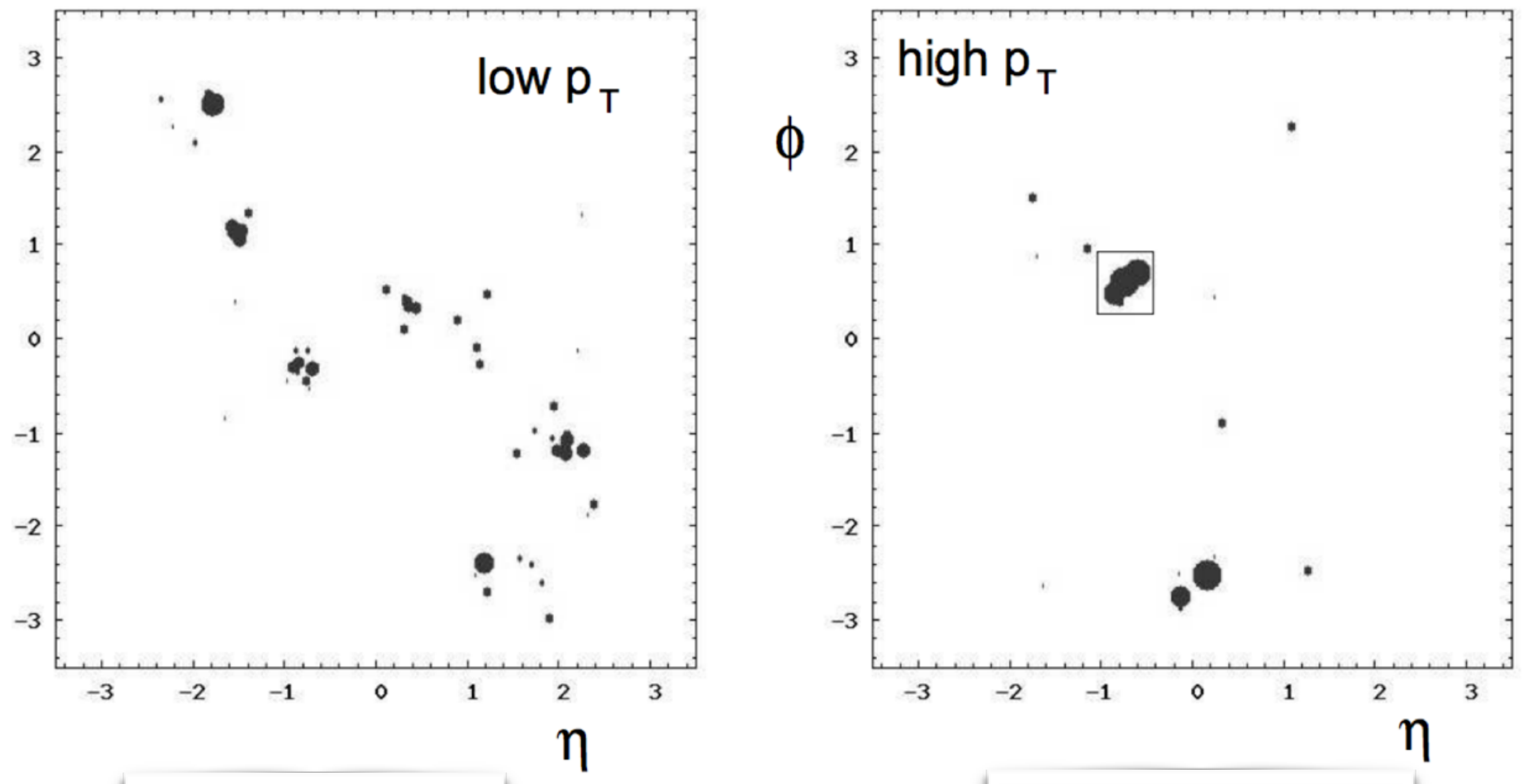


low p_T top

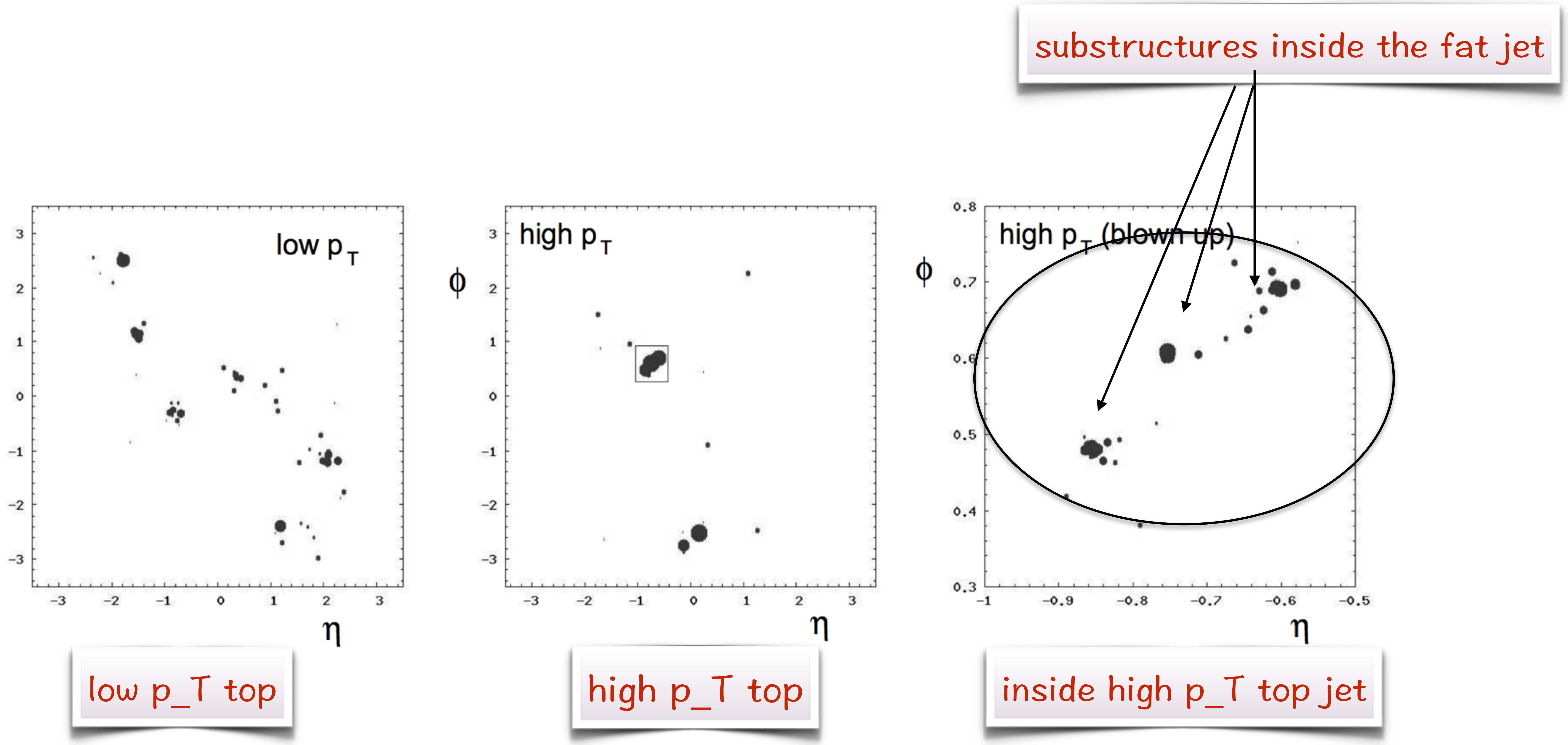
high p_T top

Jet substructure

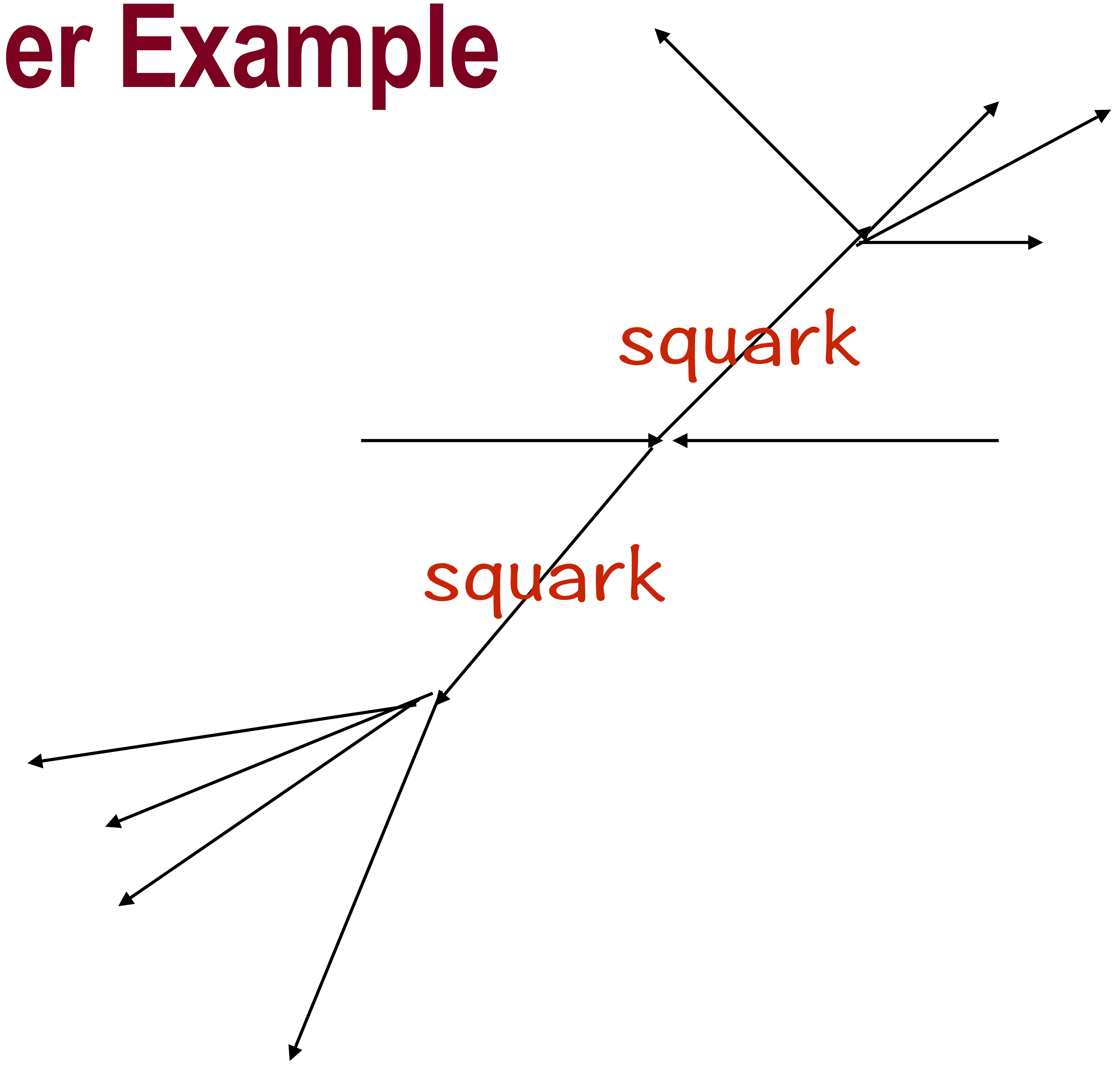
LHC current bounds indicate that the new particles will possibly be heavy

Assumption: New particles will be produced at the 14 TeV LHC

The decay of new heavy particle to SM particles may give large Lorentz boost



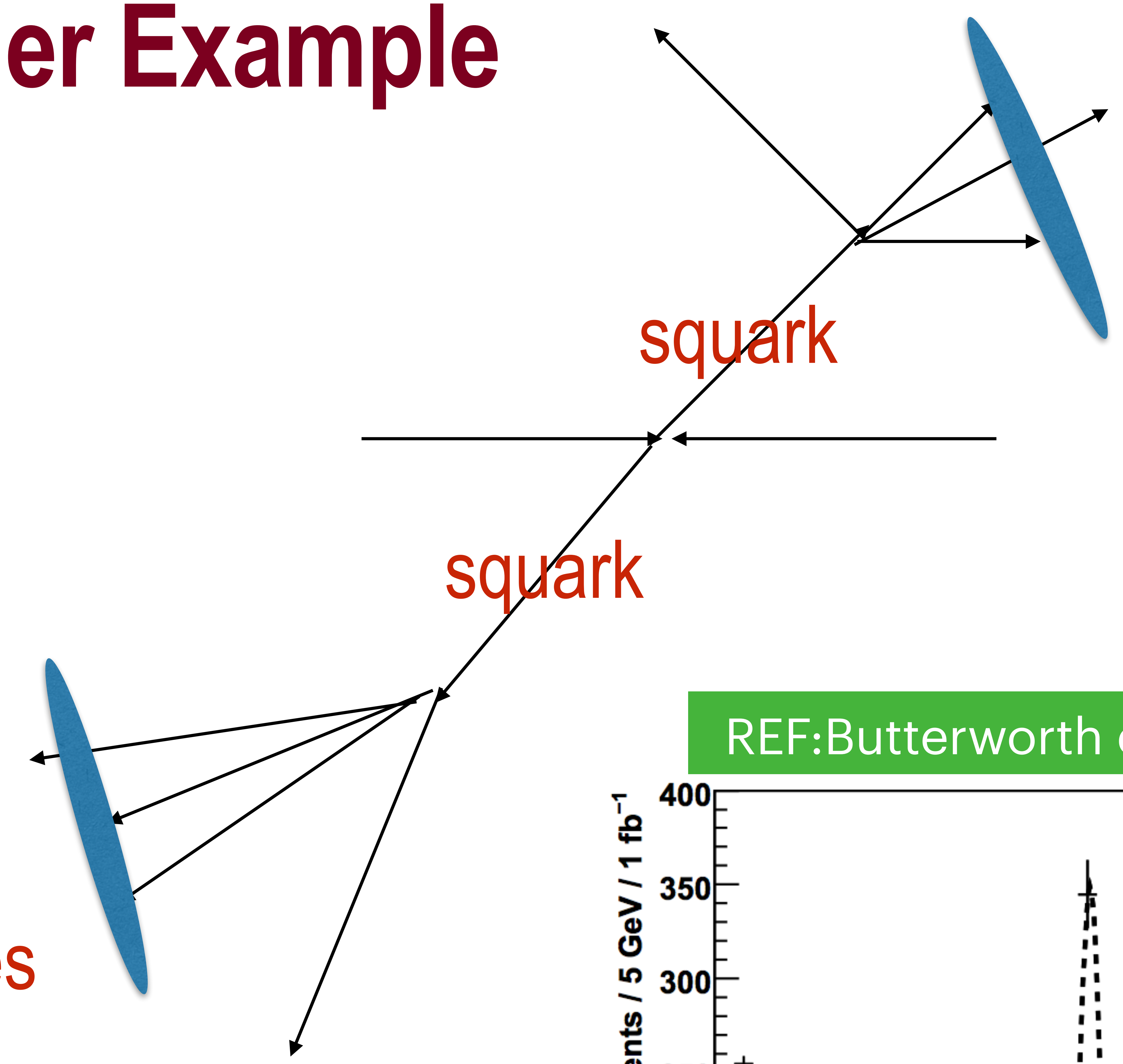
Jet substructure: Another Example



$$pp \to \tilde{q}\tilde{q}, \quad \tilde{q} \to q\chi_1^0 \quad \chi_1^0 \to jjj$$

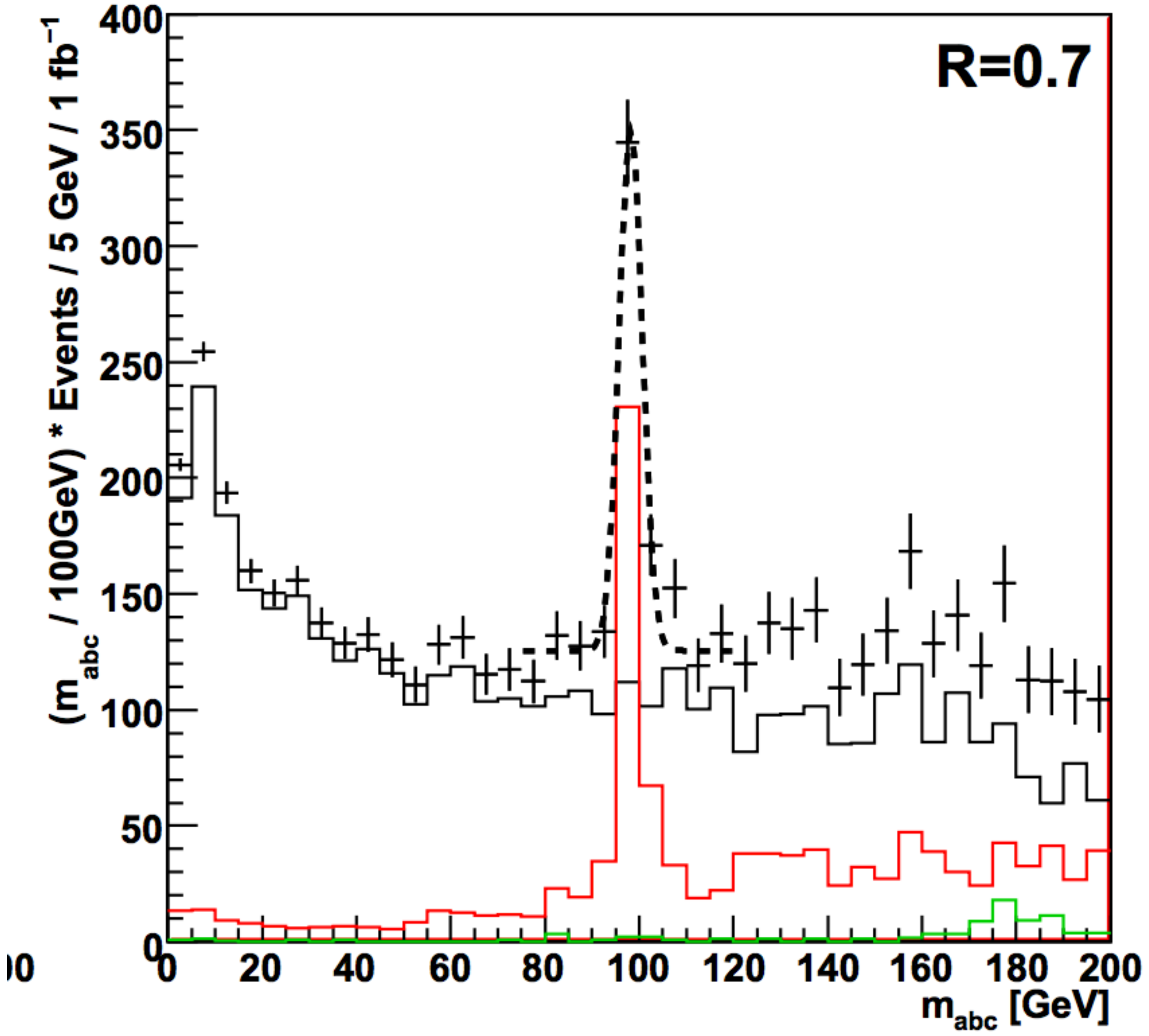
multijet signal, large QCD background (hopeless ??)

Jet substructure: Another Example



neutralino jet
with 3 substructures

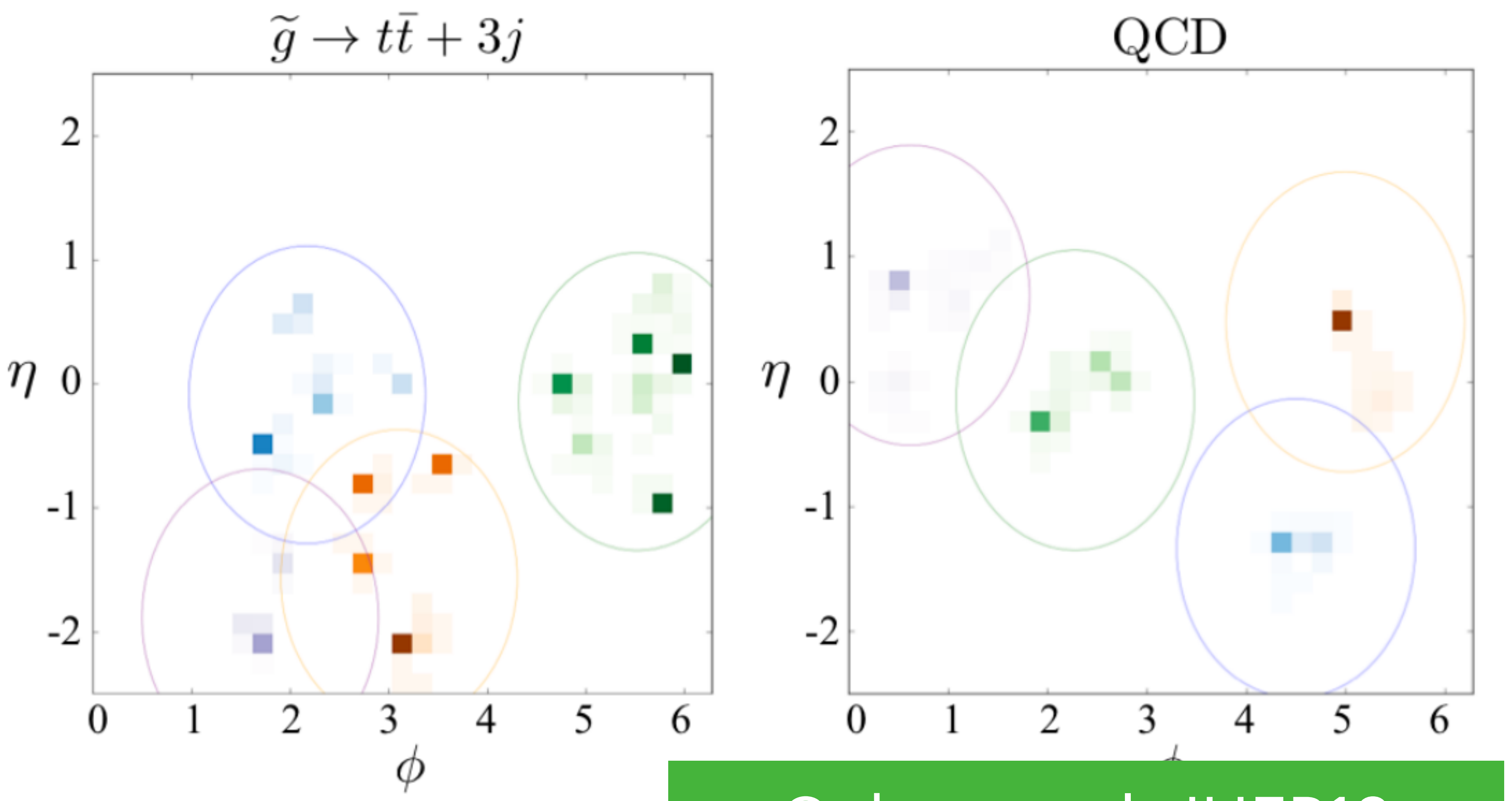
REF:Butterworth et al. PRL09



Many techniques: filtering, grooming ….

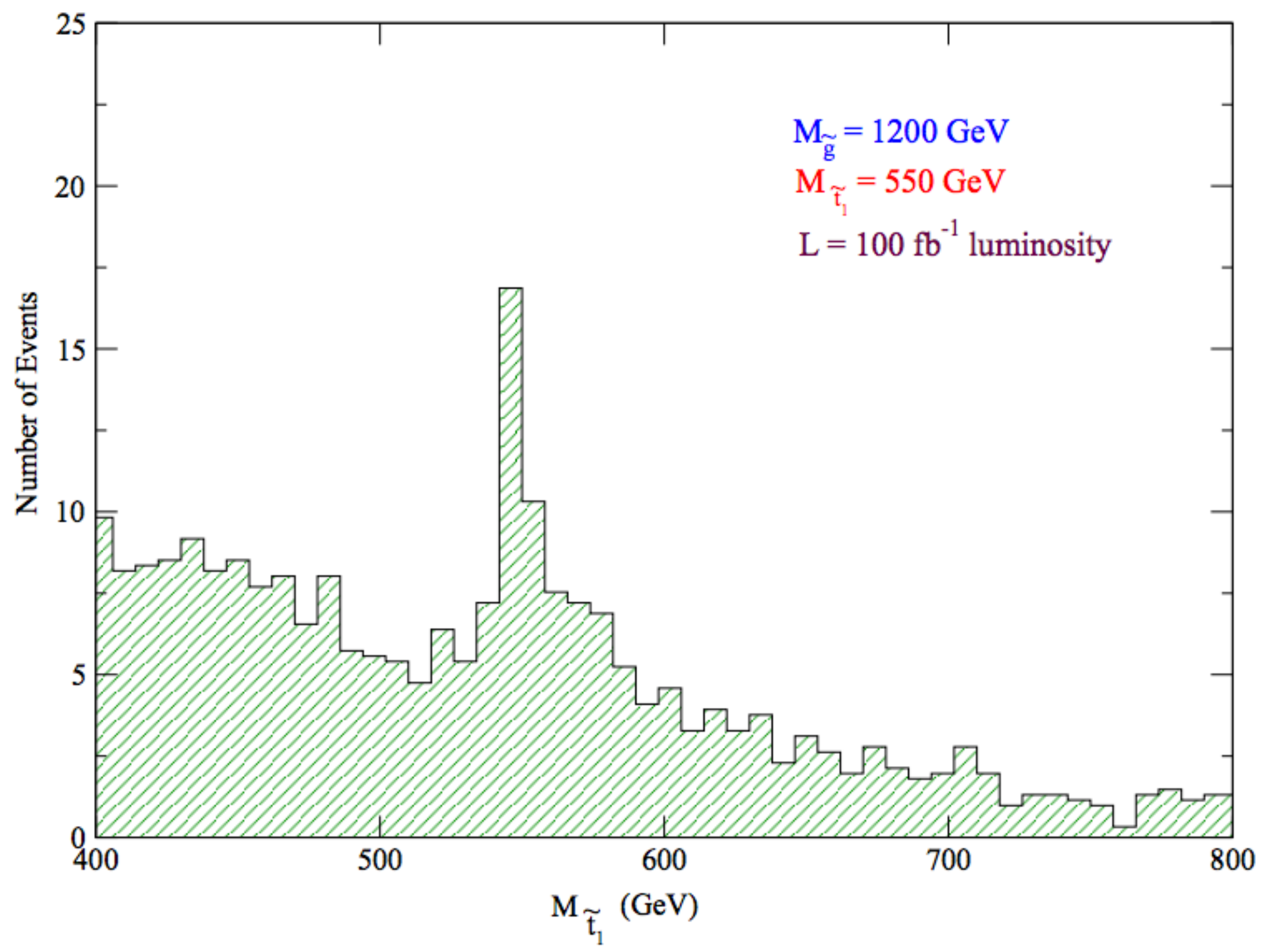
Jet substructure: Another Example

Jet substructure by accident

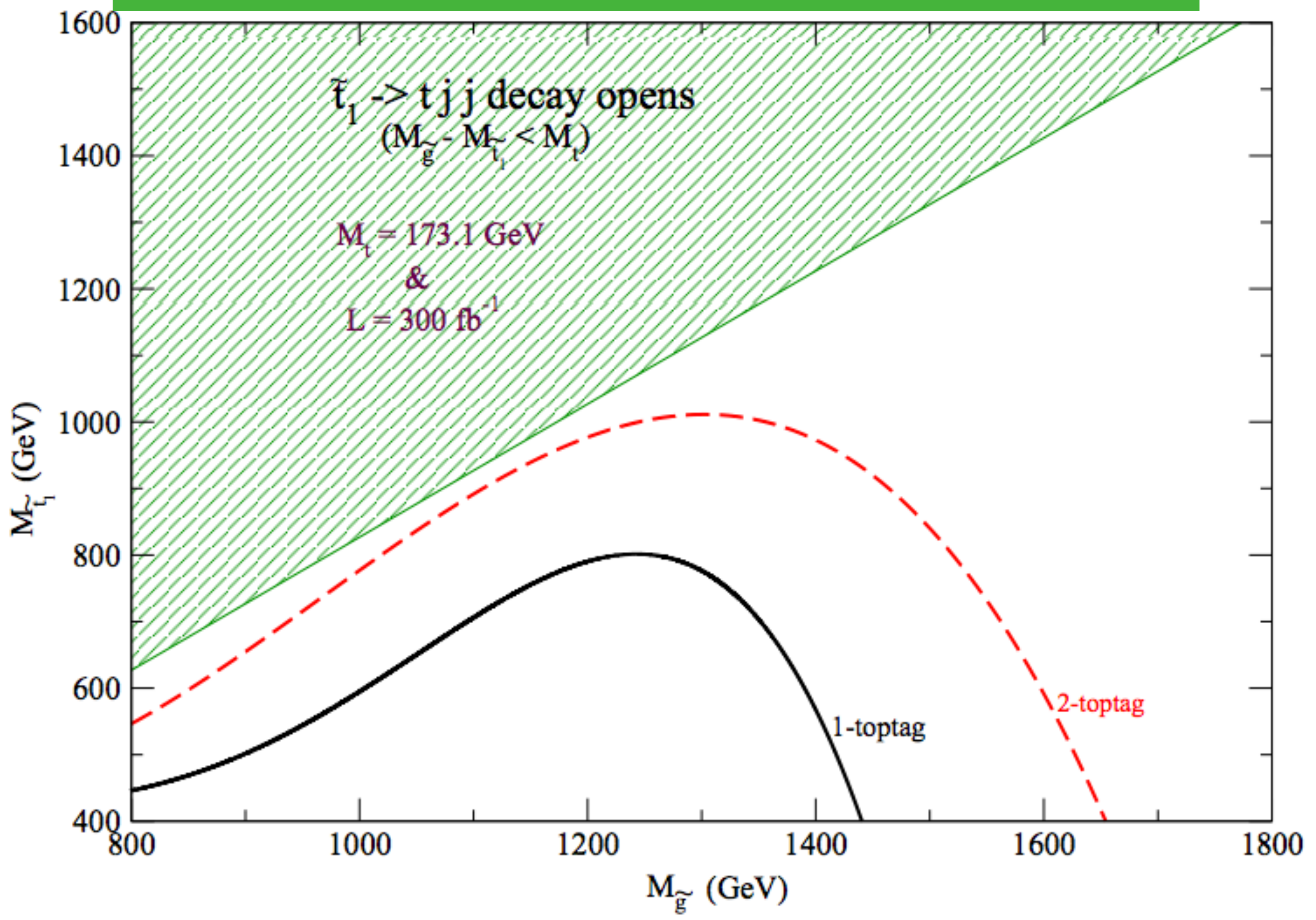


Cohen et al. JHEP13

BB and Chakraborty, PRD14

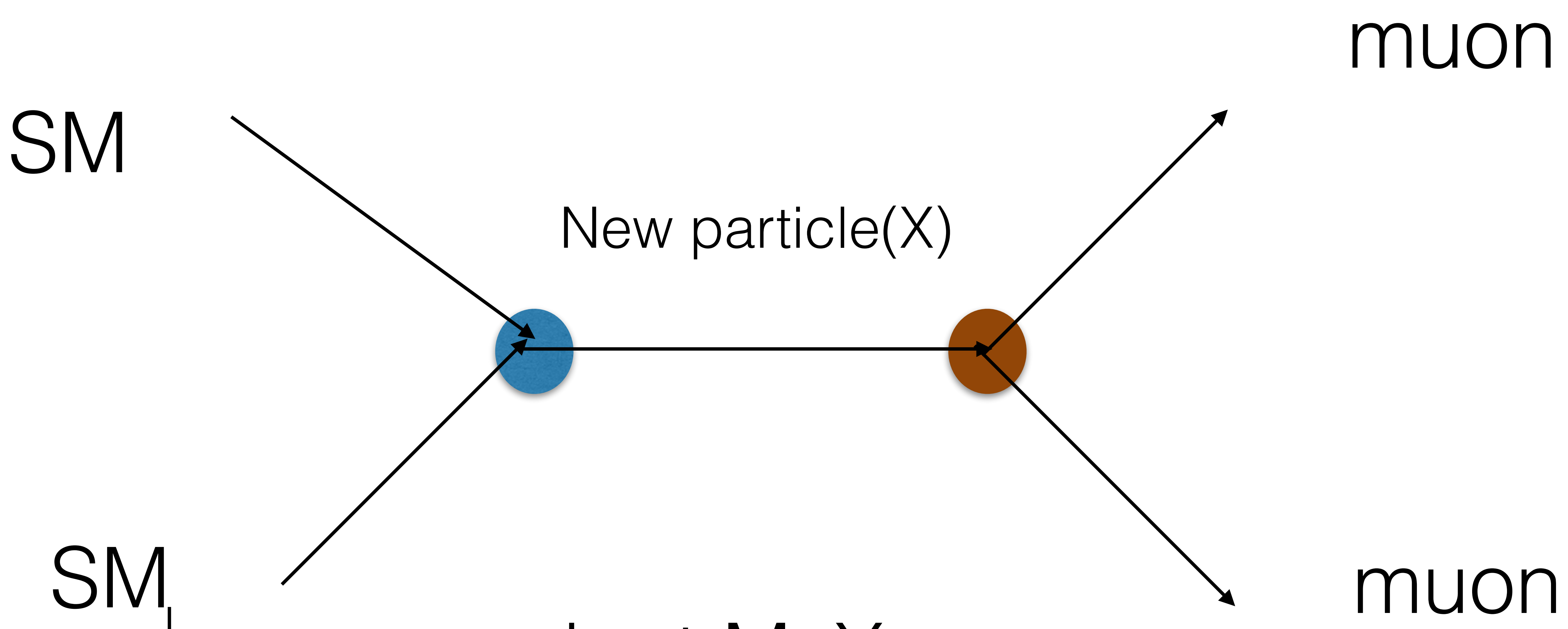


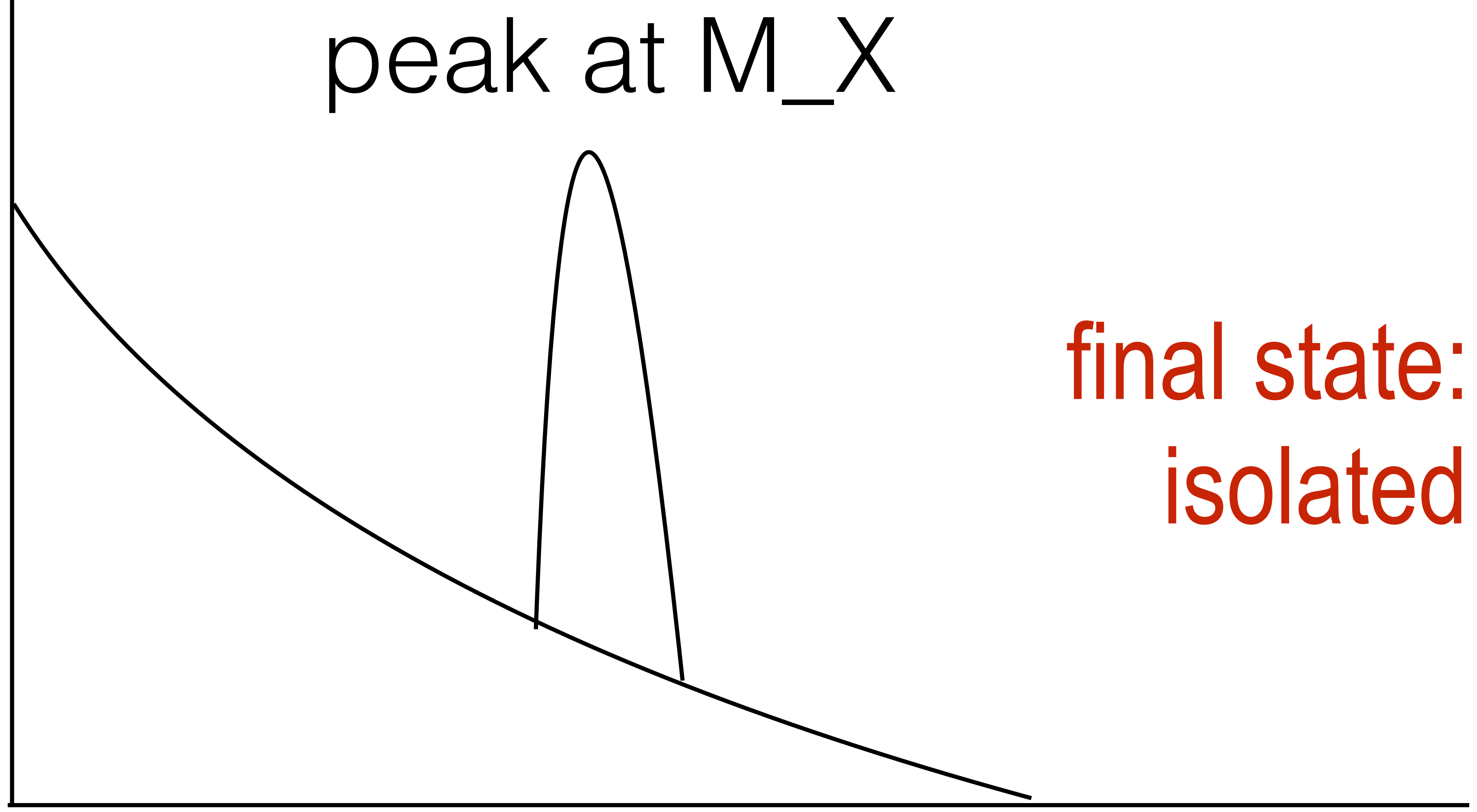
BB and Chakraborty, PRD14



New physics Search: Resonance

The decay products of the new particle are visible SM particles

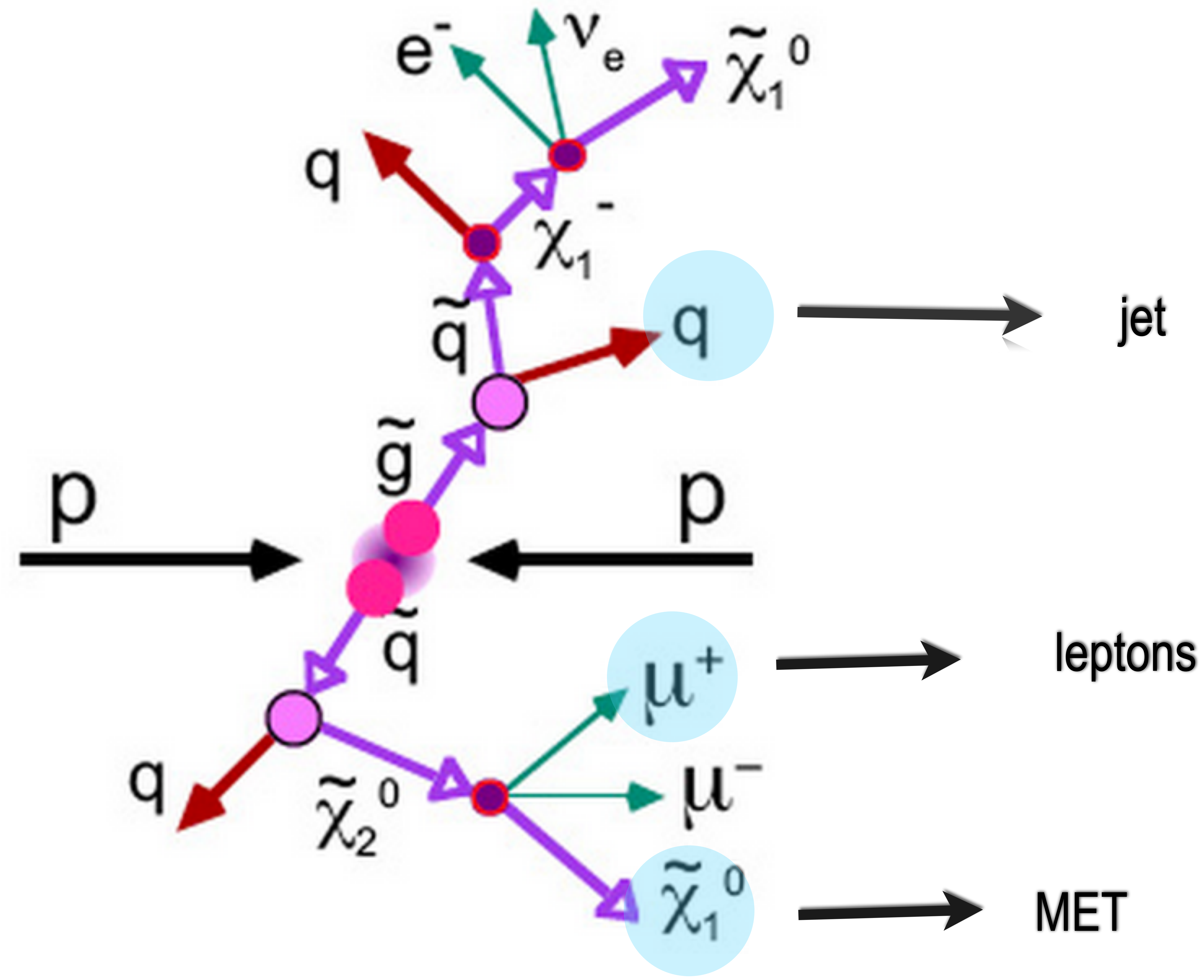




di-muon invariant mass distribution

final state: 2 high P_T isolated muons

New physics Search: Cascade



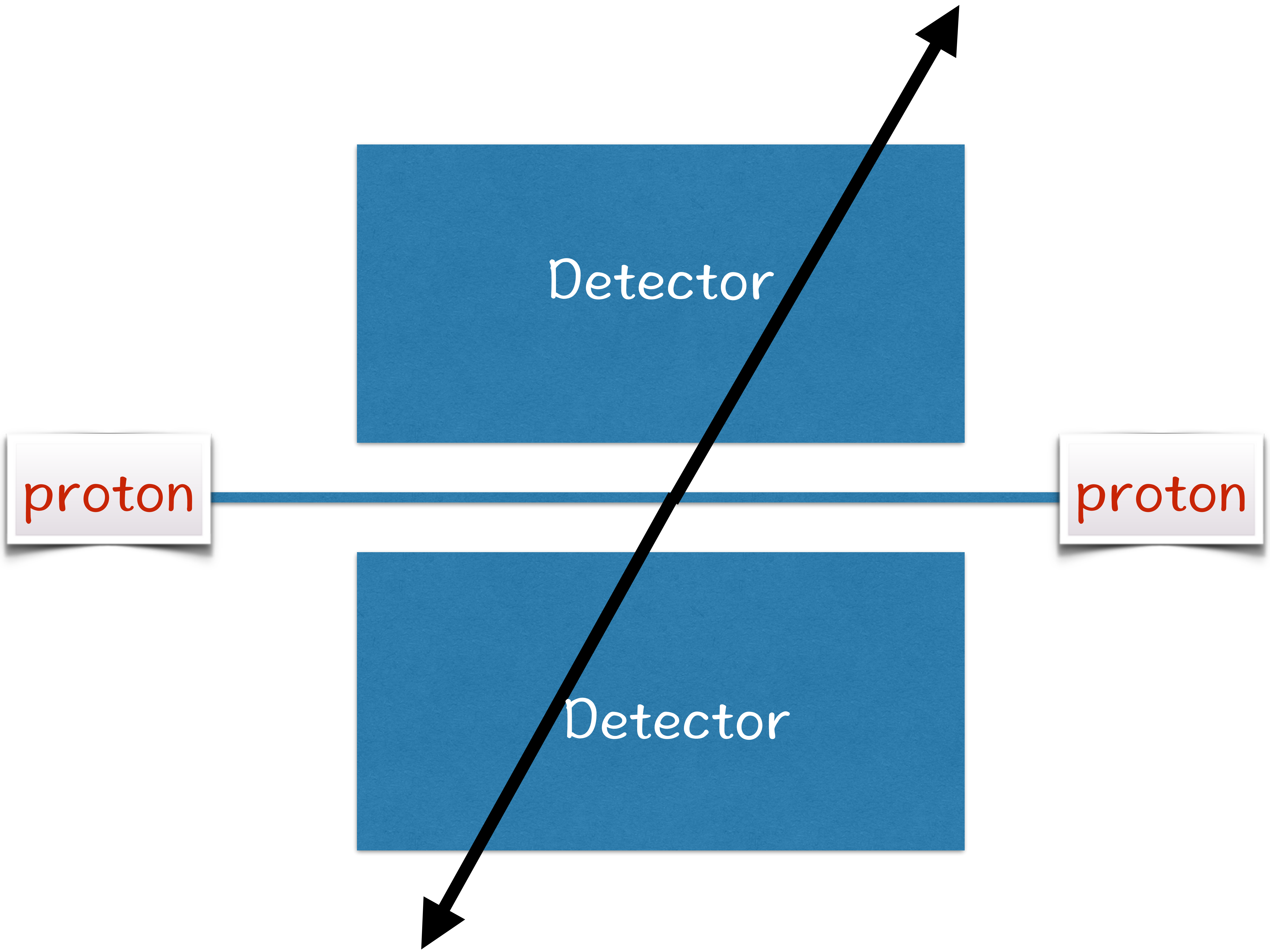
Final state

Jets
+
leptons
+
missing transverse energy

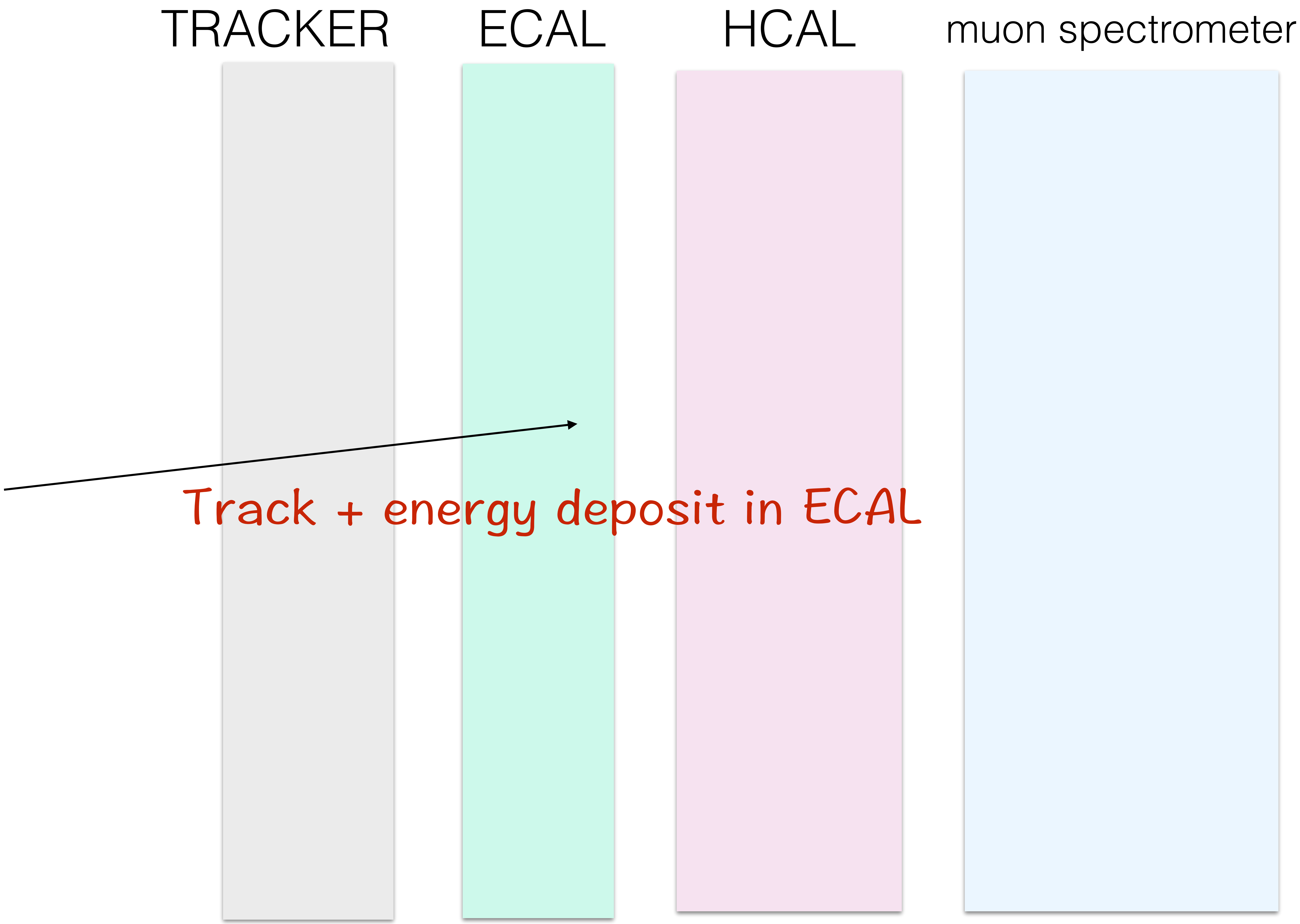
R- parity conserved

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

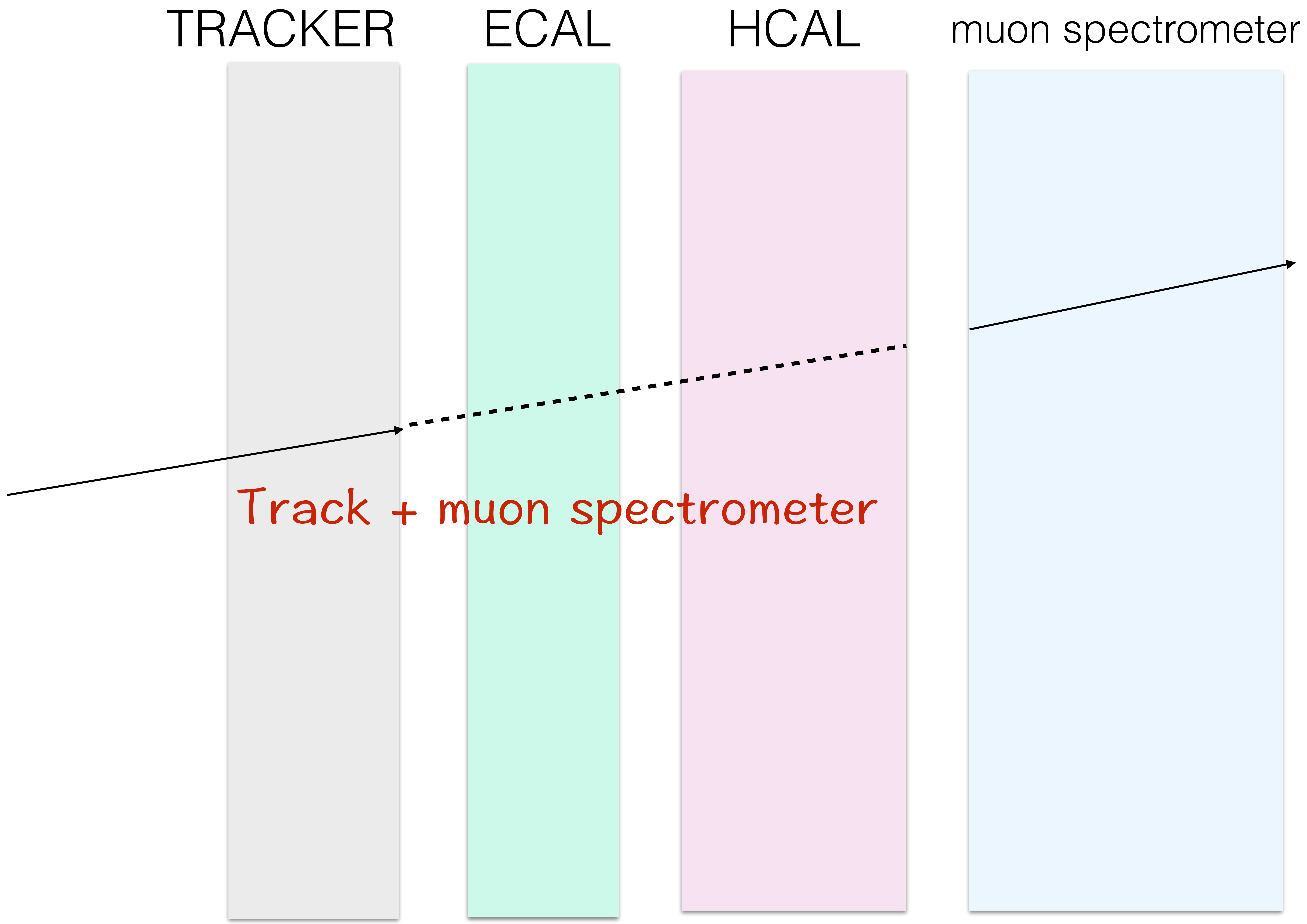
Detector



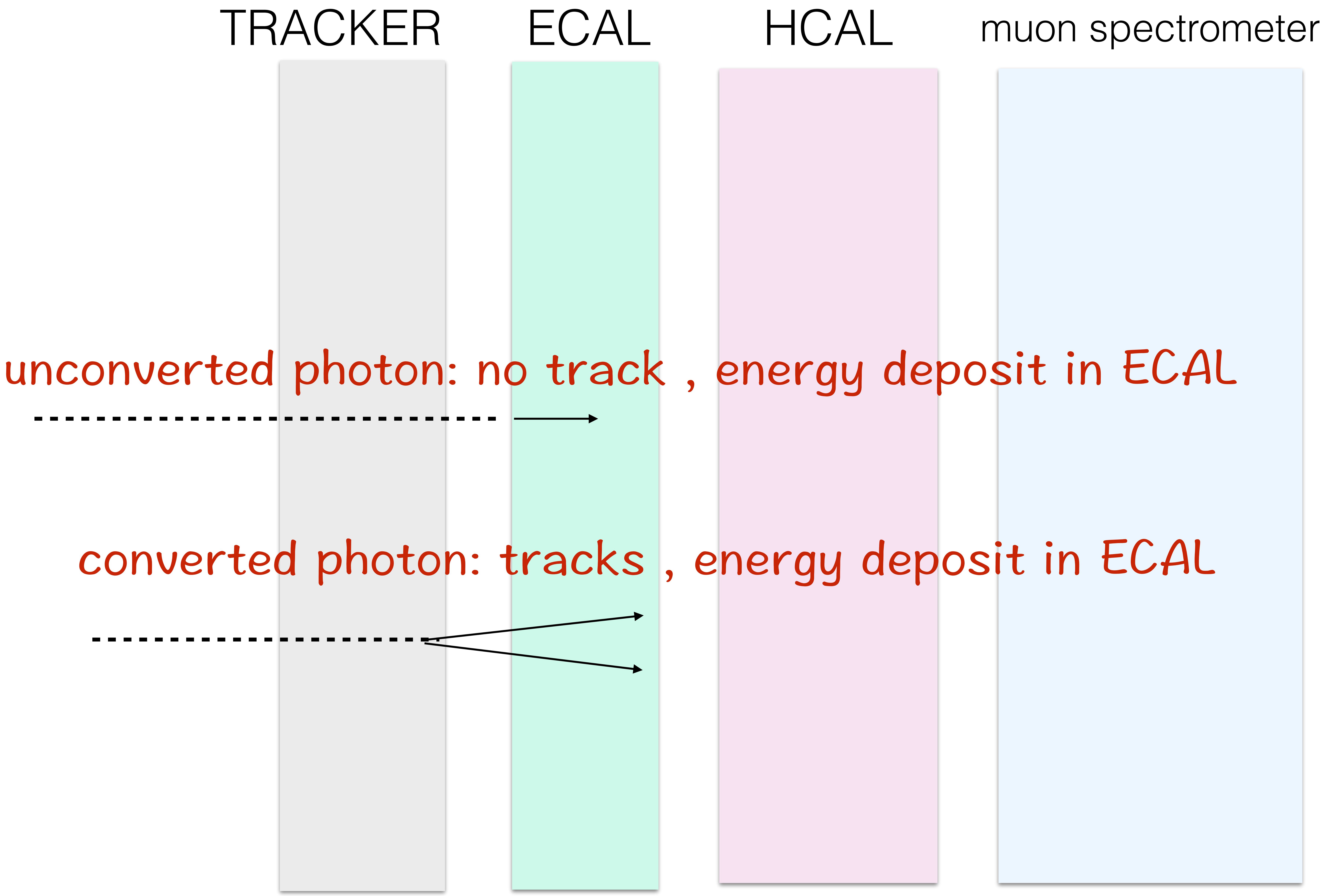
Electron


TRACKER
ECAL
HCAL
muon spectrometer
Track + energy deposit in ECAL

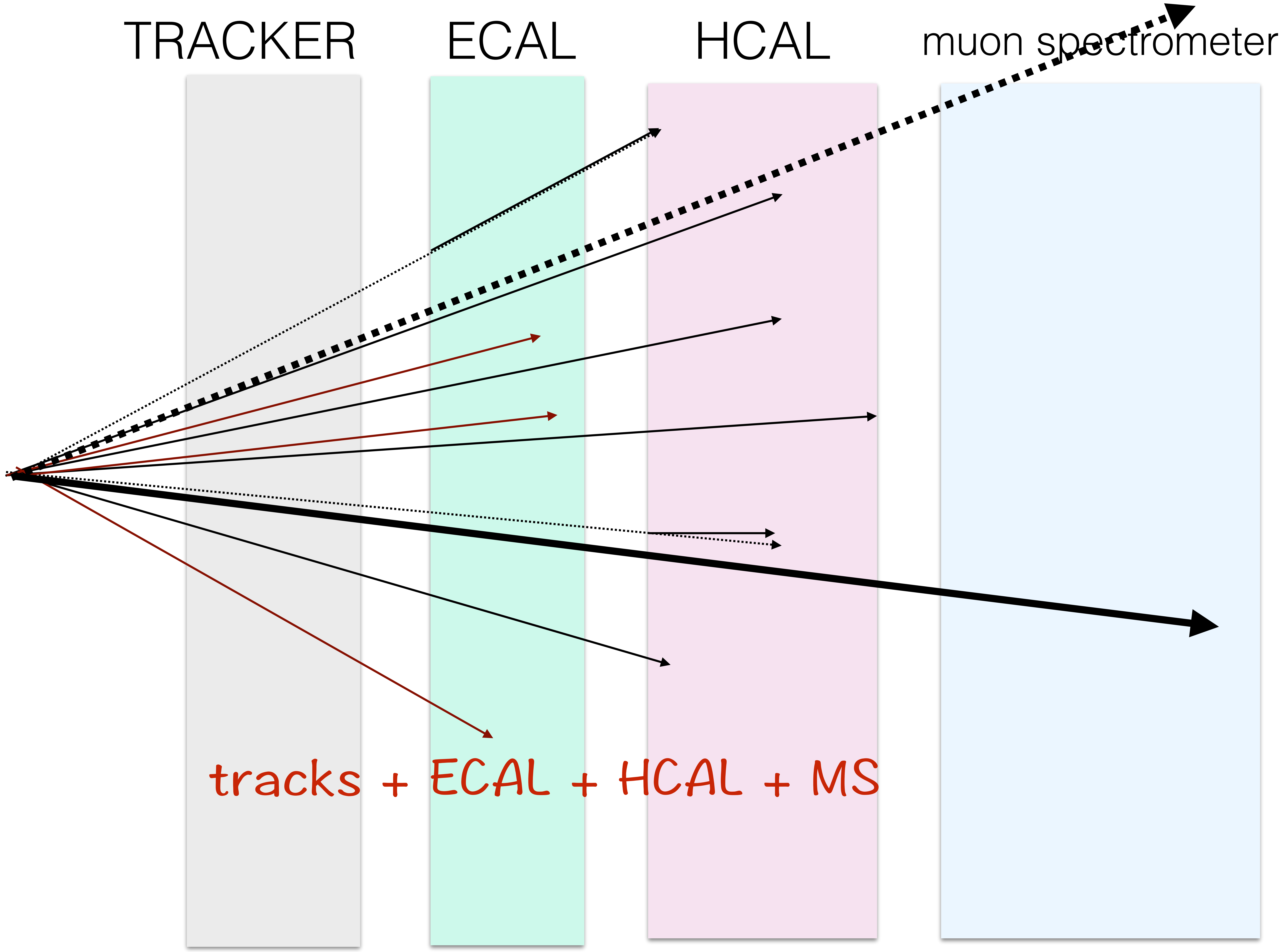
Muon


TRACKER
ECAL
HCAL
muon spectrometer
Track + muon spectrometer

Photon

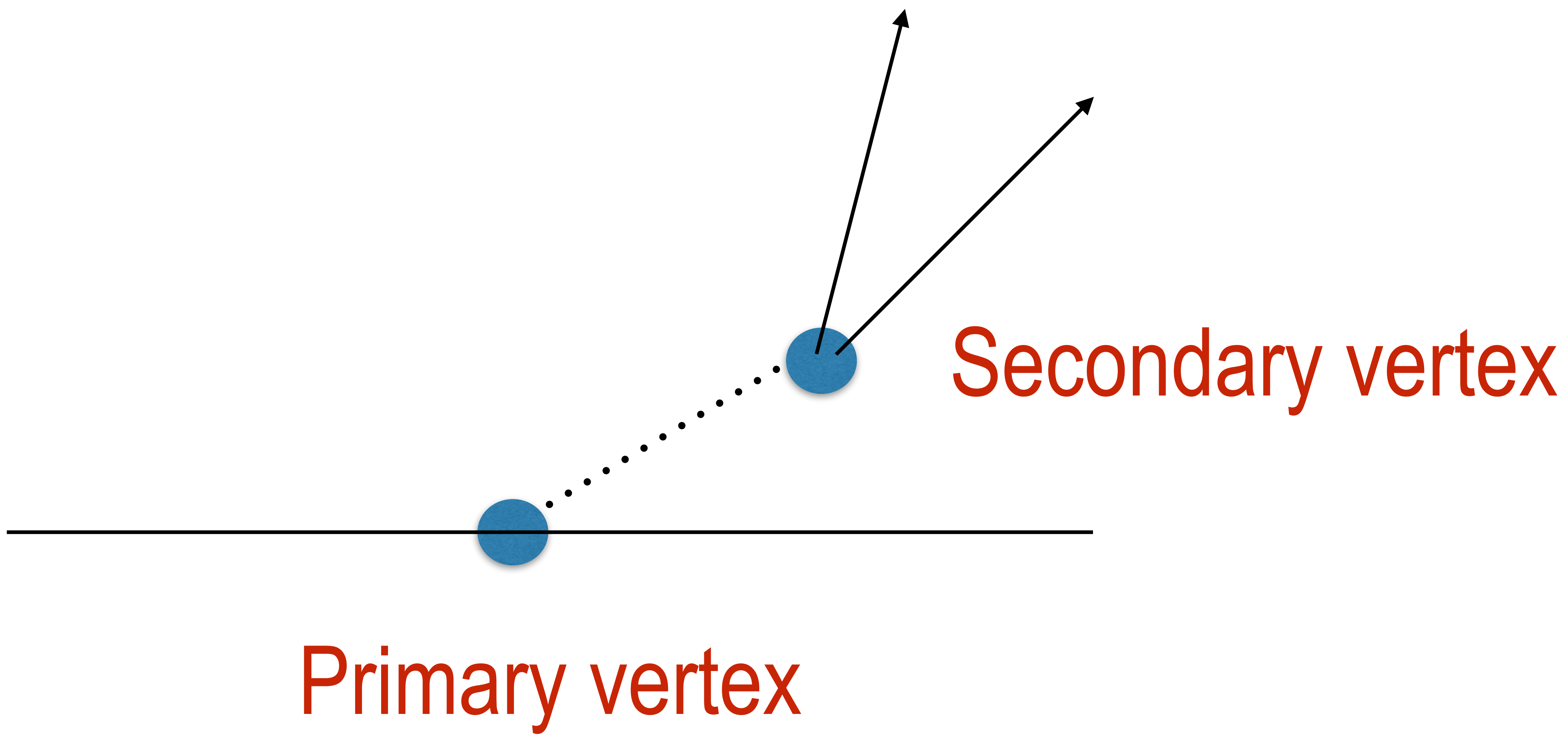

TRACKER
ECAL
HCAL
muon spectrometer
unconverted photon: no track , energy deposit in ECAL
converted photon: tracks , energy deposit in ECAL

Jets



b-Jets

decay length of an unstable particle $\beta\gamma c\tau$



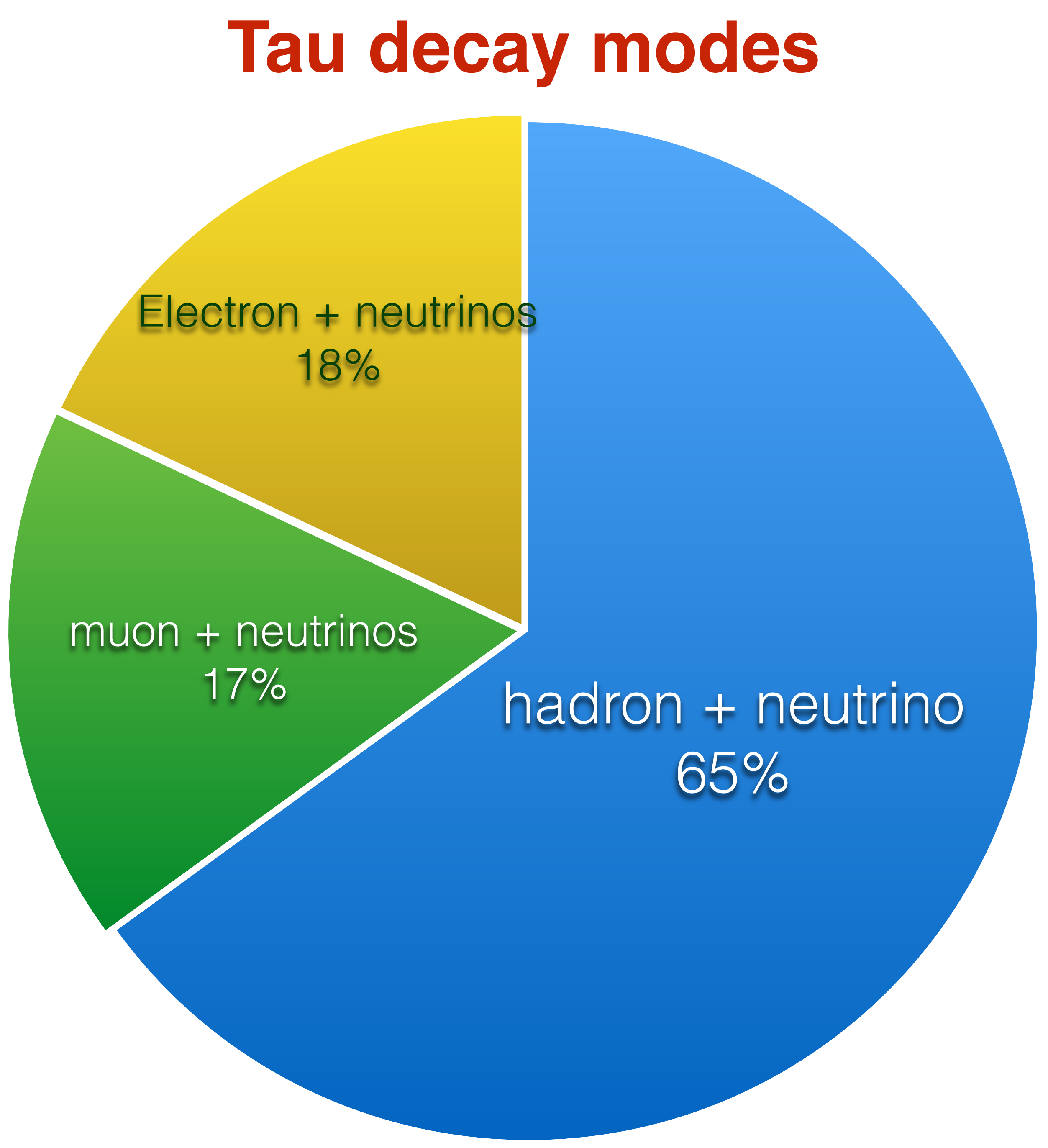
impact parameter is important

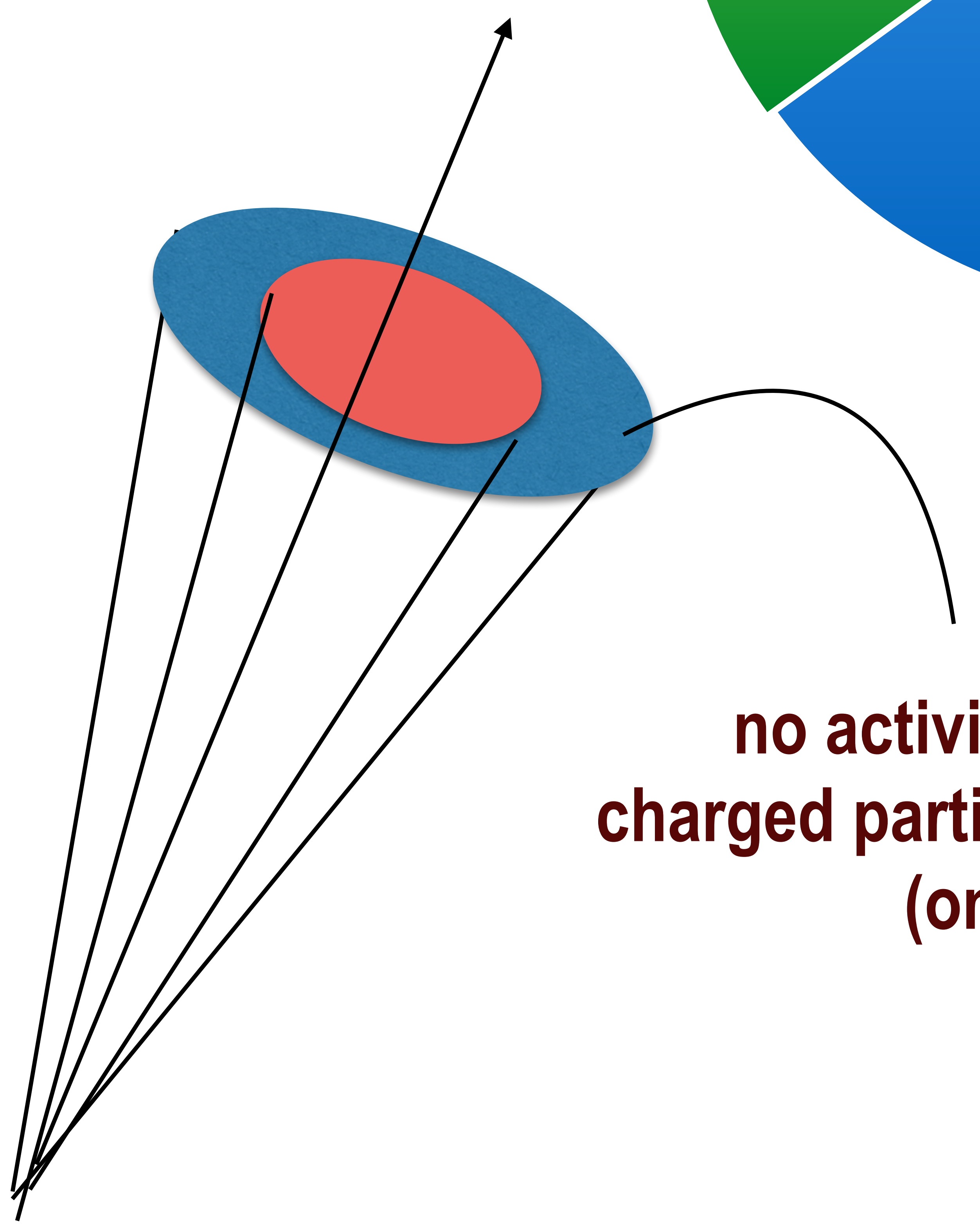
Tau-Jets

The branching ratio tau decays :

~23% for decay into a charged pion, a neutral pion, and a tau neutrino;
11% for decay into a charged pion and a tau neutrino;
9% for decay into a charged pion, two neutral pions, and a tau neutrino;
9% for decay into three charged pions and a tau neutrino;
3% for decay into three charged pions, a neutral pion, and a tau neutrino;
1% for decay into three neutral pions, a charged pion, and a tau neutrino.

hadronic branching fraction ia about 65 %

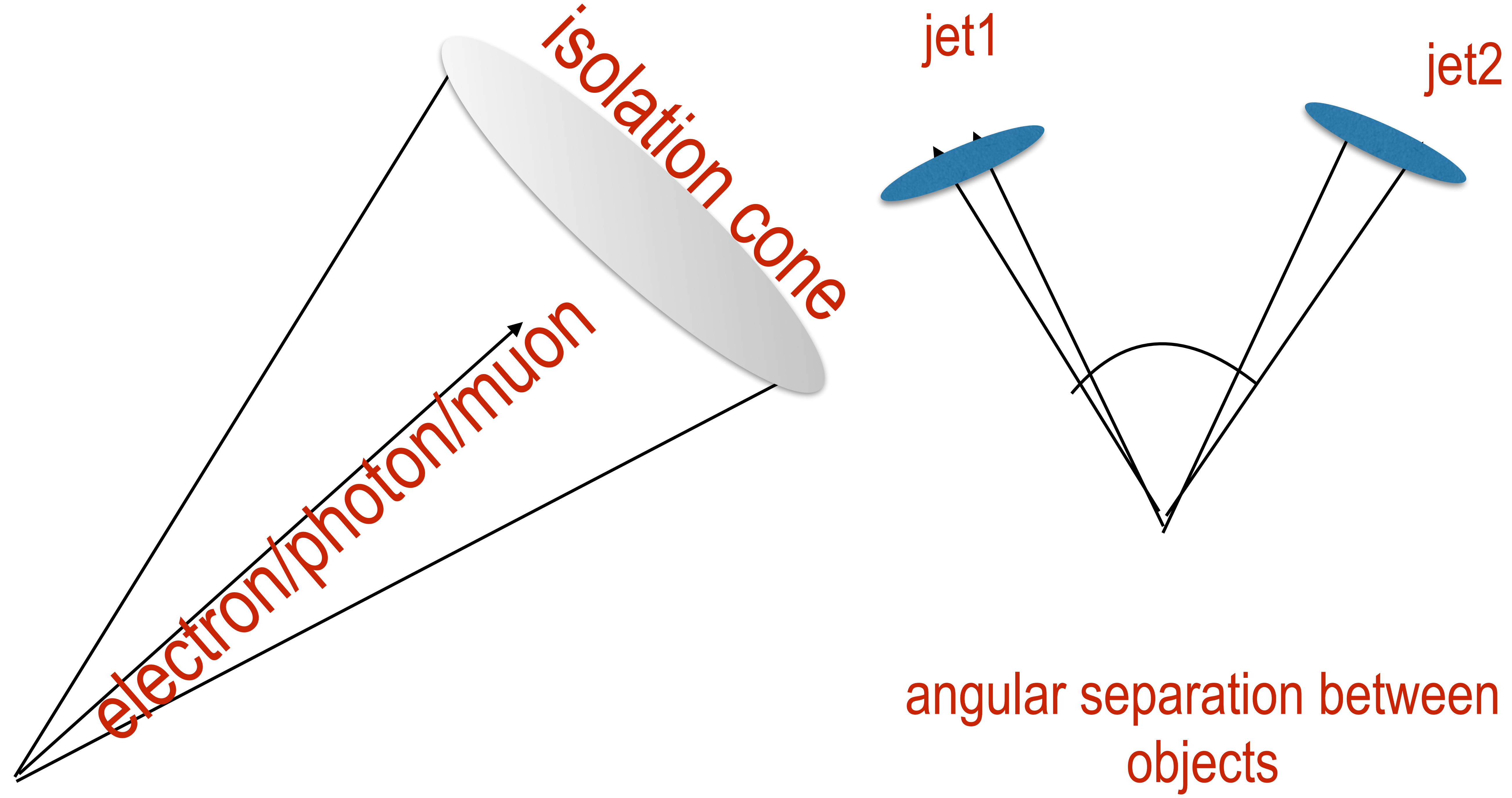




no activity outside the smaller cone
charged particles are inside the smaller cone
(one/three prong decay)

Isolation

Objects should be isolated: to reject QCD background



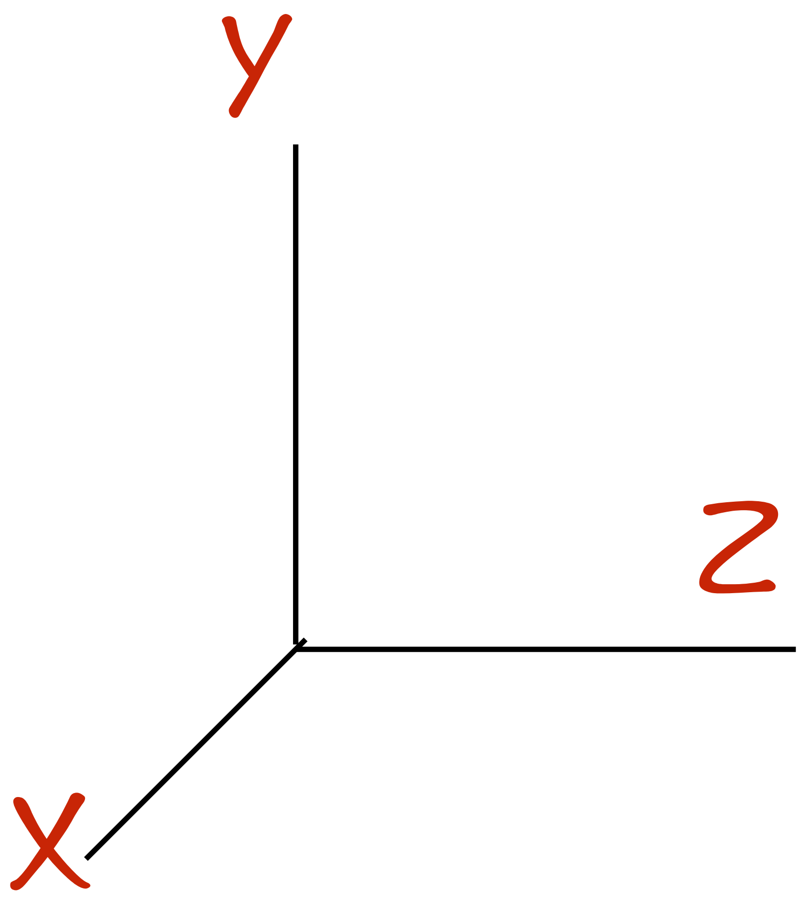
angular separation between objects

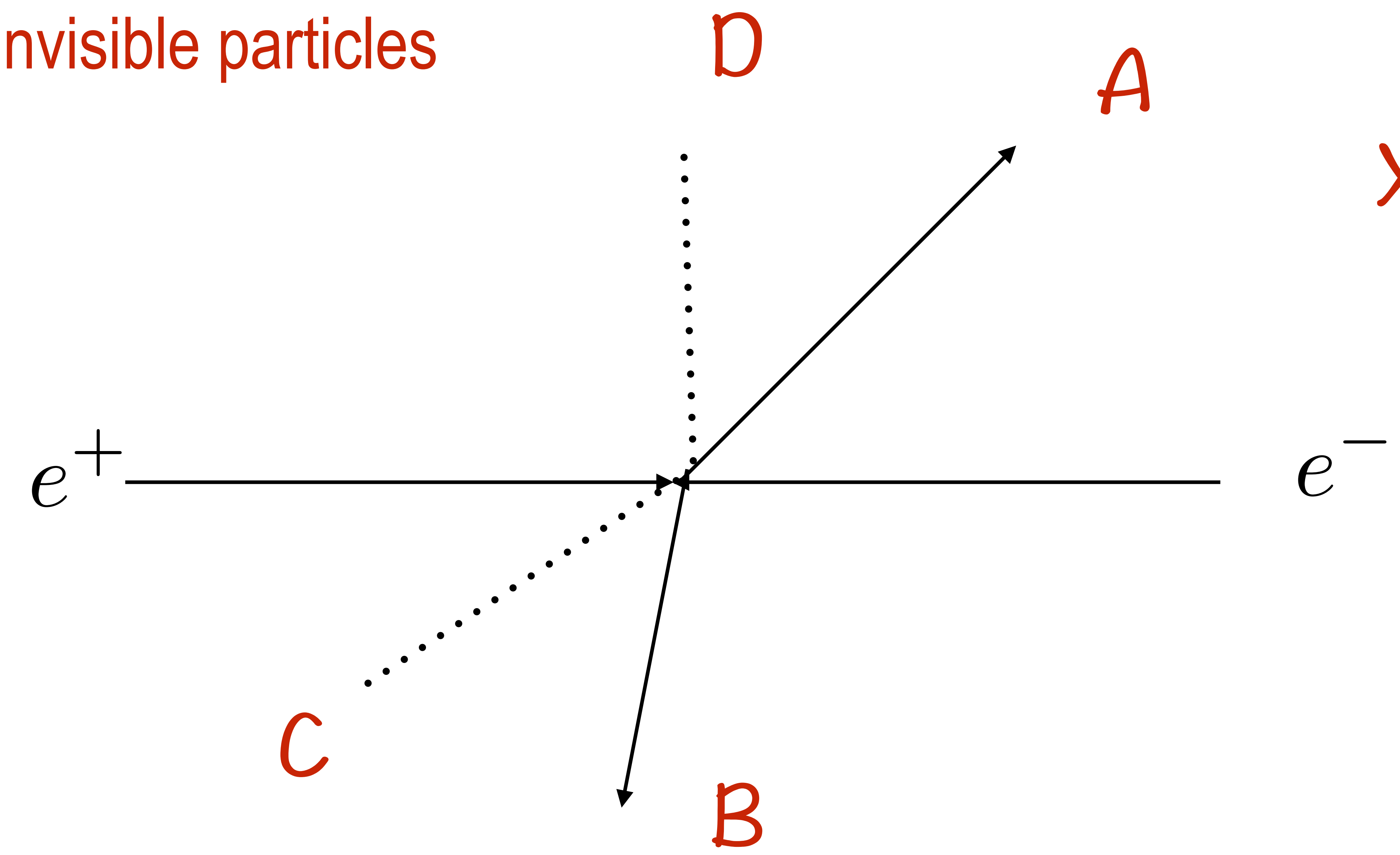
Energy deposited (excluding the object)inside the isolation cone should be small

Missing Energy

$$e^- \ e^+ \to A \ B \ C \ D$$

C and D are invisible particles





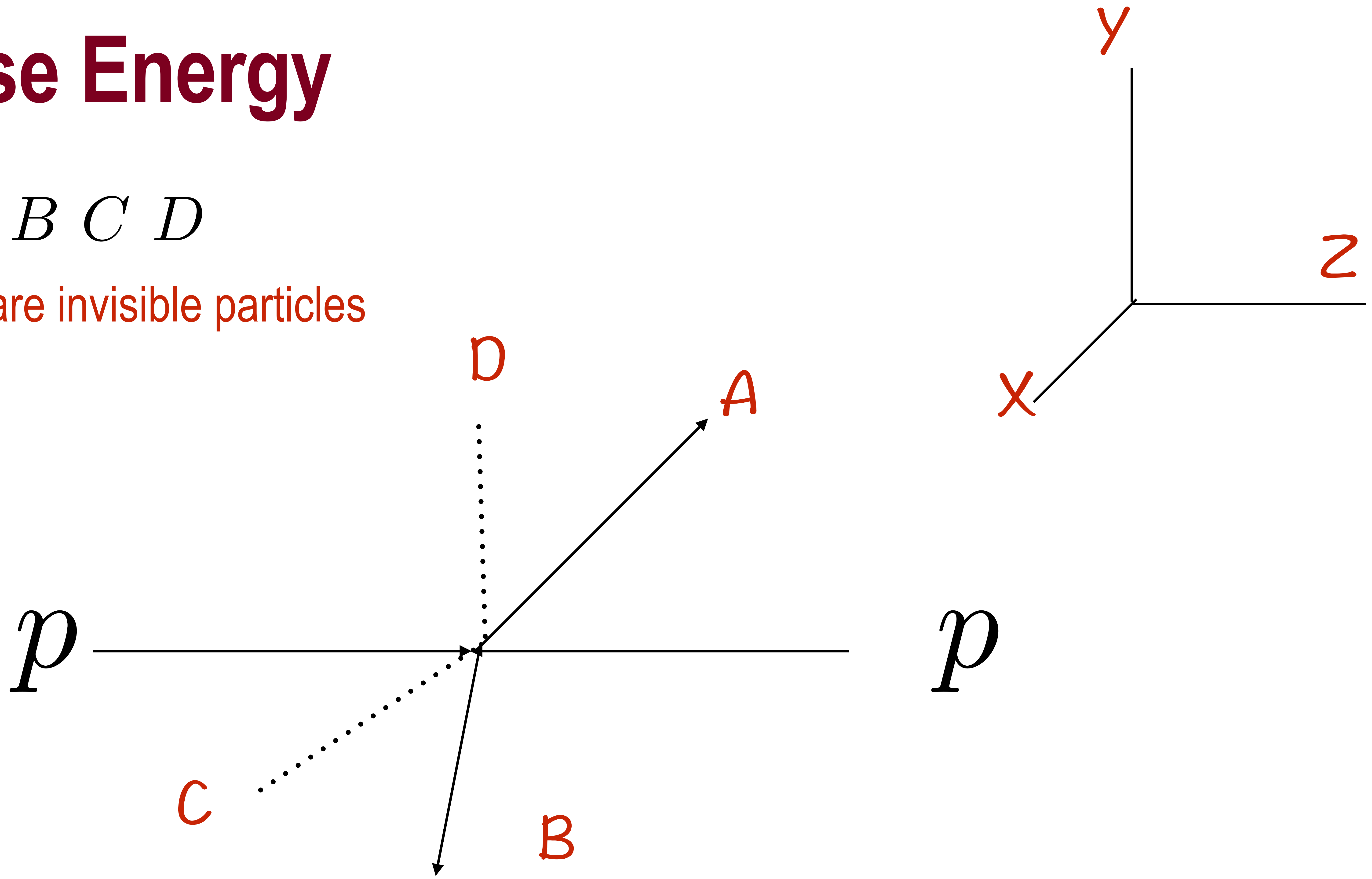
electron and a positron collide head-on at equal speeds in the lab frame

net momentum of outgoing particles indicates a missing energy
(Typical signal of R parity conserving SUSY)

Missing Transverse Energy

$$p\ p \to A\ B\ C\ D$$

C and D are invisible particles



partons collide head-on with unequal speeds in the lab frame

Net momentum in the transverse direction of outgoing particles indicates invisible particles
(Typical signal of R parity conserving SUSY)