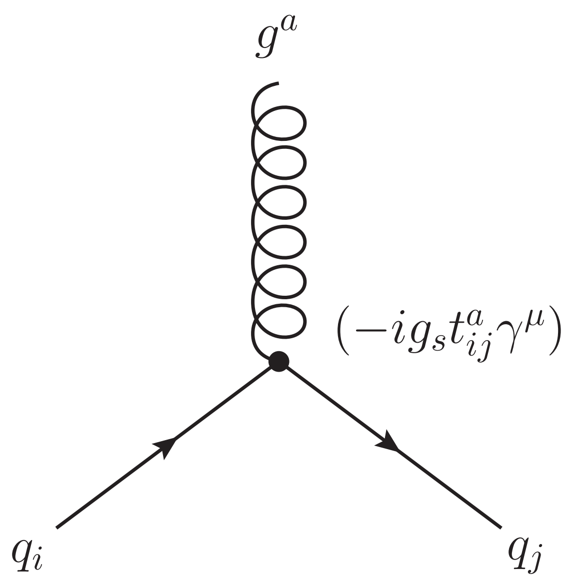
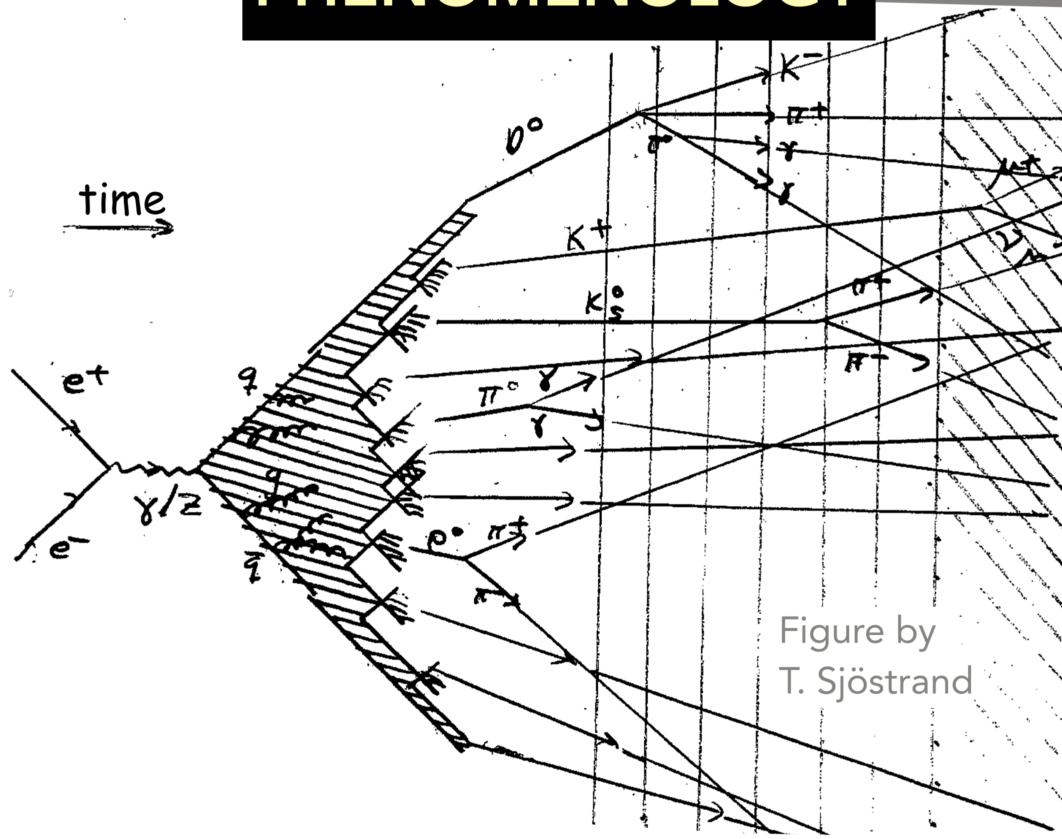
# Introduction to Event Generators

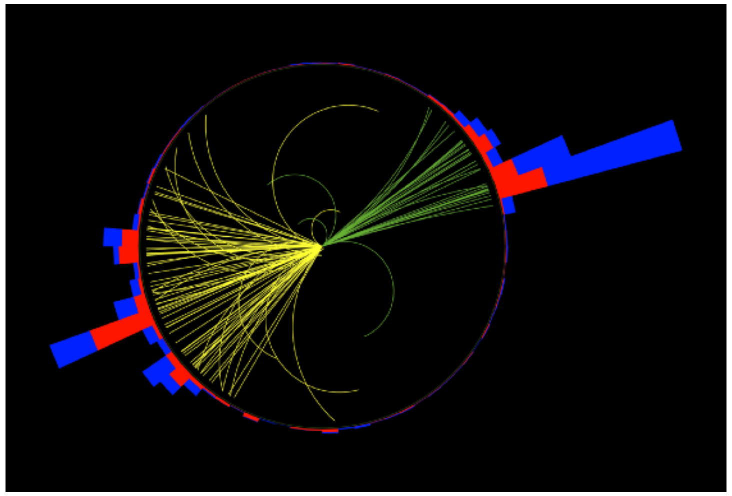
## Lecture 3: Hadronisation and Jets

**THEORY** → **PHENOMENOLOGY** → **EXPERIMENT**




*QCD*



*"Jets"*

← **INTERPRETATION**


Peter Skands (Monash University)


**11th MCnet School, Lund 2017**

# MONTE CARLOS & FRAGMENTATION

## PYTHIA anno 1978

(then called JETSET)

LU TP 78-18
November, 1978

A Monte Carlo Program for Quark Jet Generation

T. Sjöstrand, B. Söderberg

A Monte Carlo computer program is presented, that simulates the **fragmentation of a fast parton into a jet of mesons.** It uses an iterative scaling scheme and is compatible with the jet model of Field and Feynman.

```
      SUBROUTINE JETGEN(N)
      COMMON /JET/ K(100,2), P(100,5)
      COMMON /PAR/ PUD, PS1, SIGMA, CX2, EBEG, WFIN, IFLBEG
      COMMON /DATA1/ MESO(9,2), CMIX(6,2), PMAS(19)
      IFLSGN=(10-IFLBEG)/5
      W=2.*EBEG
      I=0
      IPD=0
C 1 FLAVOUR AND PT FOR FIRST QUARK
      IFL1=IABS(IFLBEG)
      PT1=SIGMA*SQRT(-ALOG(RANF(0)))
      PHI1=6.2832*RANF(0)
      PX1=PT1*COS(PHI1)
      PY1=PT1*SIN(PHI1)
  100 I=I+1
C 2 FLAVOUR AND PT FOR NEXT ANTIQUARK
      IFL2=1+INT(RANF(0)/PUD)
      PT2=SIGMA*SQRT(-ALOG(RANF(0)))
      PHI2=6.2832*RANF(0)
      PX2=PT2*COS(PHI2)
      PY2=PT2*SIN(PHI2)
C 3 MESON FORMED, SPIN ADDED AND FLAVOUR MIXED
      K(I,1)=MESO(3*(IFL1-1)+IFL2,IFLSGN)
      ISPIN=INT(PS1+RANF(0))
      K(I,2)=1+9*ISPIN+K(I,1)
      IF(K(I,1).LE.6) GOTO 110
      TMIX=RANF(0)
      KM=K(I,1)-6+3*ISPIN
      K(I,2)=8+9*ISPIN+INT(TMIX+CMIX(KM,1))+INT(TMIX+CMIX(KM,2))
C 4 MESON MASS FROM TABLE, PT FROM CONSTITUENTS
  110 P(I,5)=PMAS(K(I,2))
      P(I,1)=PX1+PX2
      P(I,2)=PY1+PY2
      PMTS=P(I,1)**2+P(I,2)**2+P(I,5)**2
C 5 RANDOM CHOICE OF X=(E+PZ)MESON/(E+PZ)AVAILABLE GIVES E AND PZ
      X=RANF(0)
      IF(RANF(0).LT.CX2) X=1.-X**(1./3.)
      P(I,3)=(X*W-PMTS/(X*W))/2.
      P(I,4)=(X*W+PMTS/(X*W))/2.
C 6 IF UNSTABLE, DECAY CHAIN INTO STABLE PARTICLES
  120 IPD=IPD+1
      IF(K(IPD,2).GE.8) CALL DECAY(IPD,I)
      IF(IPD.LT.I.AND.I.LE.96) GOTO 120
C 7 FLAVOUR AND PT OF QUARK FORMED IN PAIR WITH ANTIQUARK ABOVE
      IFL1=IFL2
      PX1=-PX2
      PY1=-PY2
C 8 IF ENOUGH E+PZ LEFT, GO TO 2
      W=(1.-X)*W
      IF(W.GT.WFIN.AND.I.LE.95) GOTO 100
      N=I
      RETURN
      END
```

**Note**:
Field-Feynman was an early fragmentation model
Now superseded by the String (in PYTHIA) and Cluster (in HERWIG & SHERPA) models.

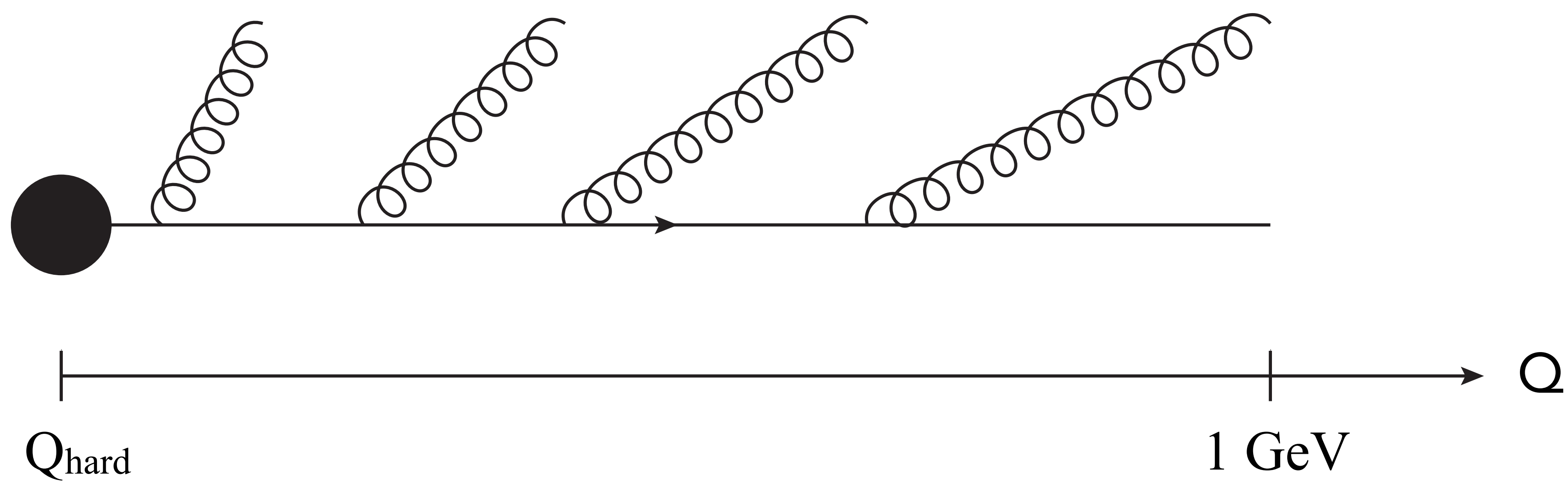
# FROM PARTONS TO PIONS

Here's a fast parton

**Fast:** It starts at a high factorization scale $Q = Q_F = Q_{hard}$

It showers (bremsstrahlung)

It ends up at a low effective factorization scale $Q \sim m_\rho \sim 1$ GeV



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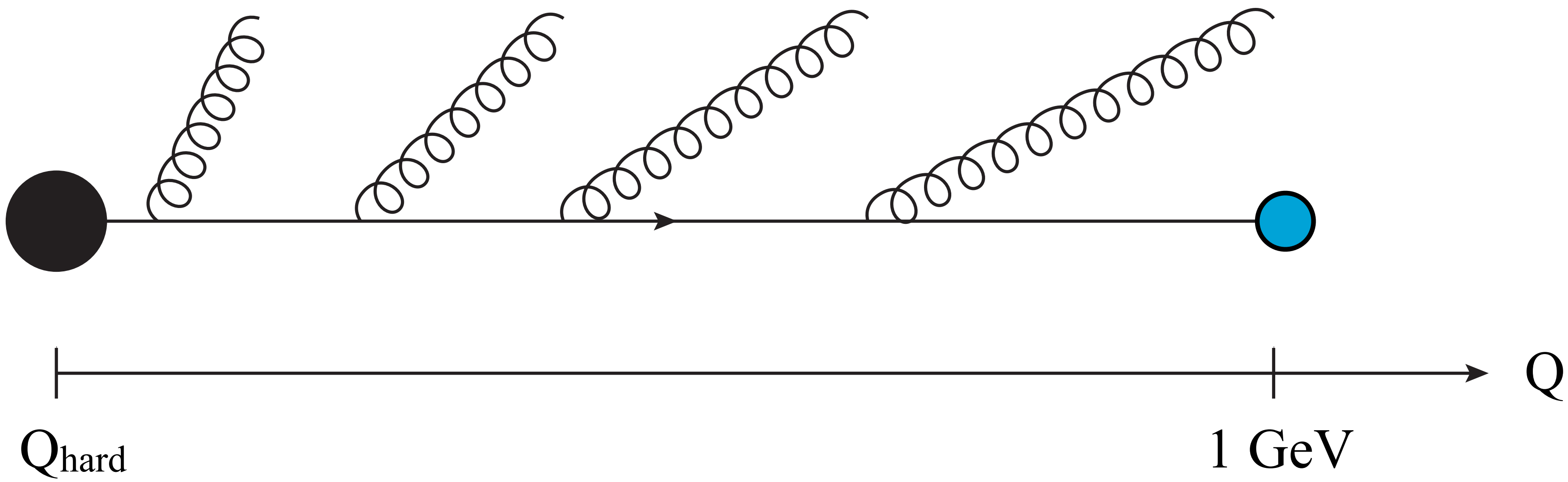



How about I just call it a hadron?

→ "Local Parton-Hadron Duality"

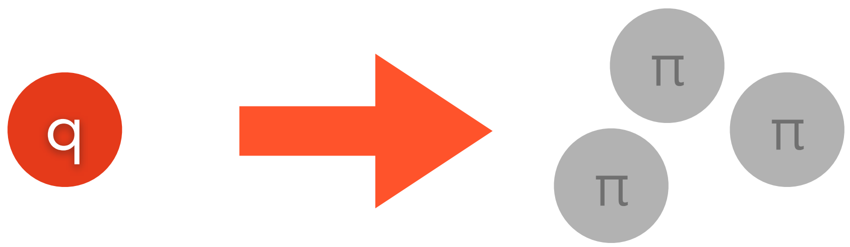
# PARTON → HADRONS?

## Early models: “Independent Fragmentation”

Local Parton Hadron Duality (LPHD) can give useful results for inclusive quantities in collinear fragmentation

Motivates a simple model:

*“Independent Fragmentation”*




## But …

The point of confinement is that partons are coloured

Hadronisation = the process of **colour neutralisation**

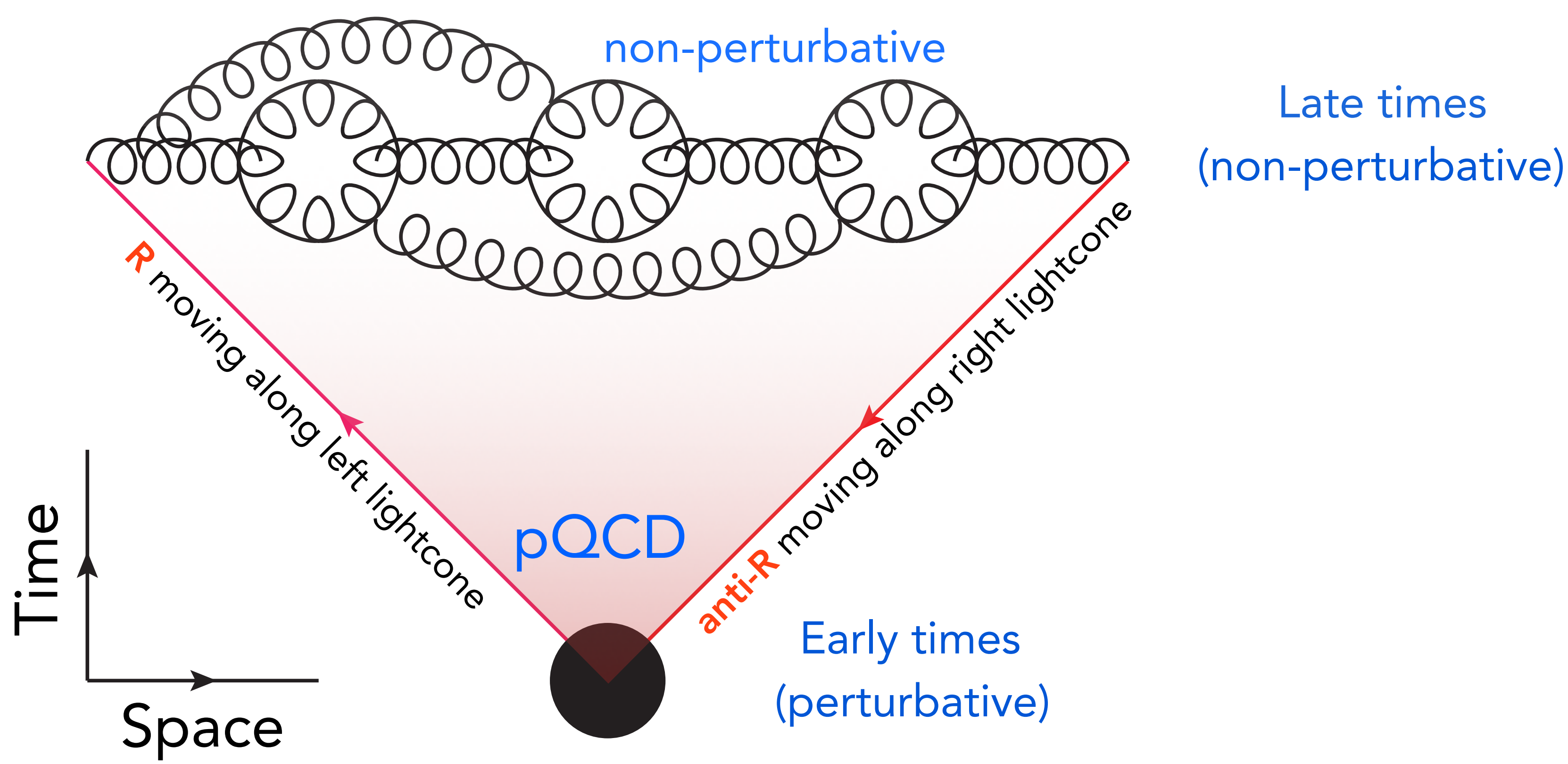
→ Unphysical to think about independent fragmentation of a single parton into hadrons

→ Too naive to see LPHD (inclusive) as a justification for Independent Fragmentation (exclusive)

→ More physics needed

## A physical hadronization model

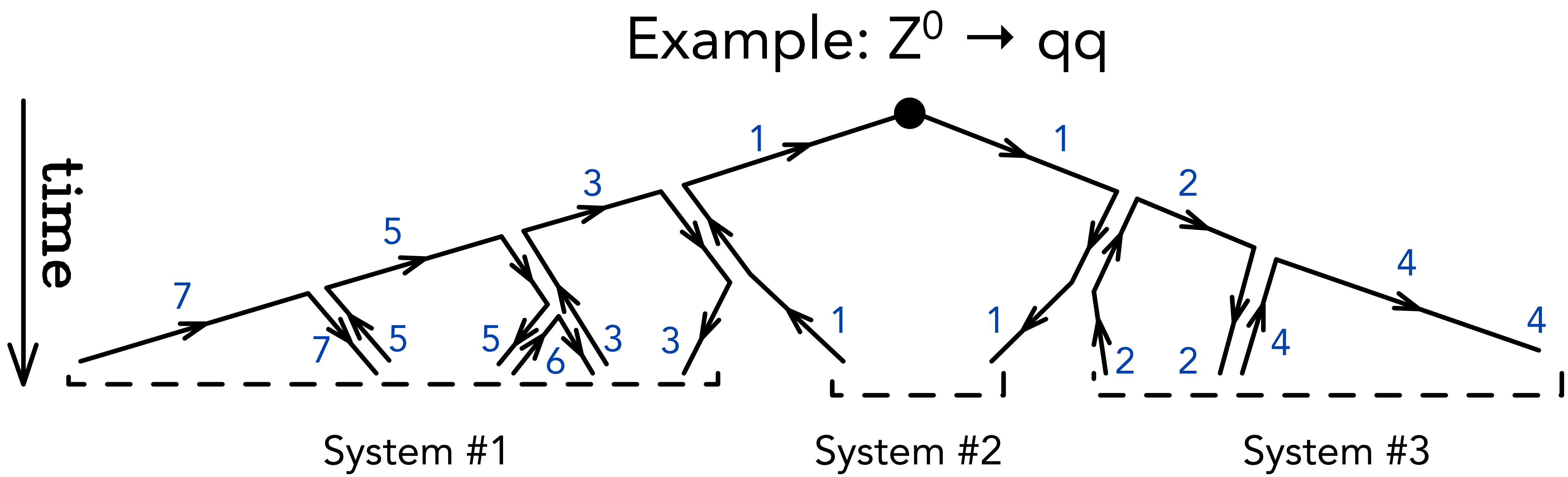
**Should involve at least TWO partons, with opposite color charges (e.g., think of them as R and anti-R)***




Strong "confining" field emerges between the two charges when their separation >~ 1fm

*) Really, a colour singlet state $\frac{1}{\sqrt{3}}\left(|R\bar{R}\rangle + |G\bar{G}\rangle + |B\bar{B}\rangle\right)$

**Colour flow** in parton showers (leading-colour approximation)




**Coherence** of pQCD cascades → not much "overlap" between systems
→ Leading-colour approximation pretty good

(LEP measurements in $e^+e^- \rightarrow W^+W^- \rightarrow$ hadrons confirm this (at least to order 10% ~ $1/N_c^2$))

**Note**: (much) more color getting kicked around in hadron collisions. More tomorrow.

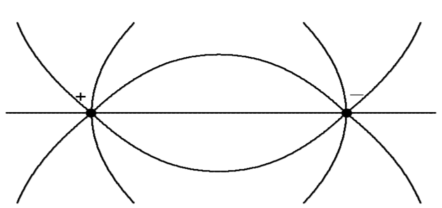
# THE ULTIMATE LIMIT: WAVELENGTHS > $10^{-15}$ M

## Quark-Antiquark Potential

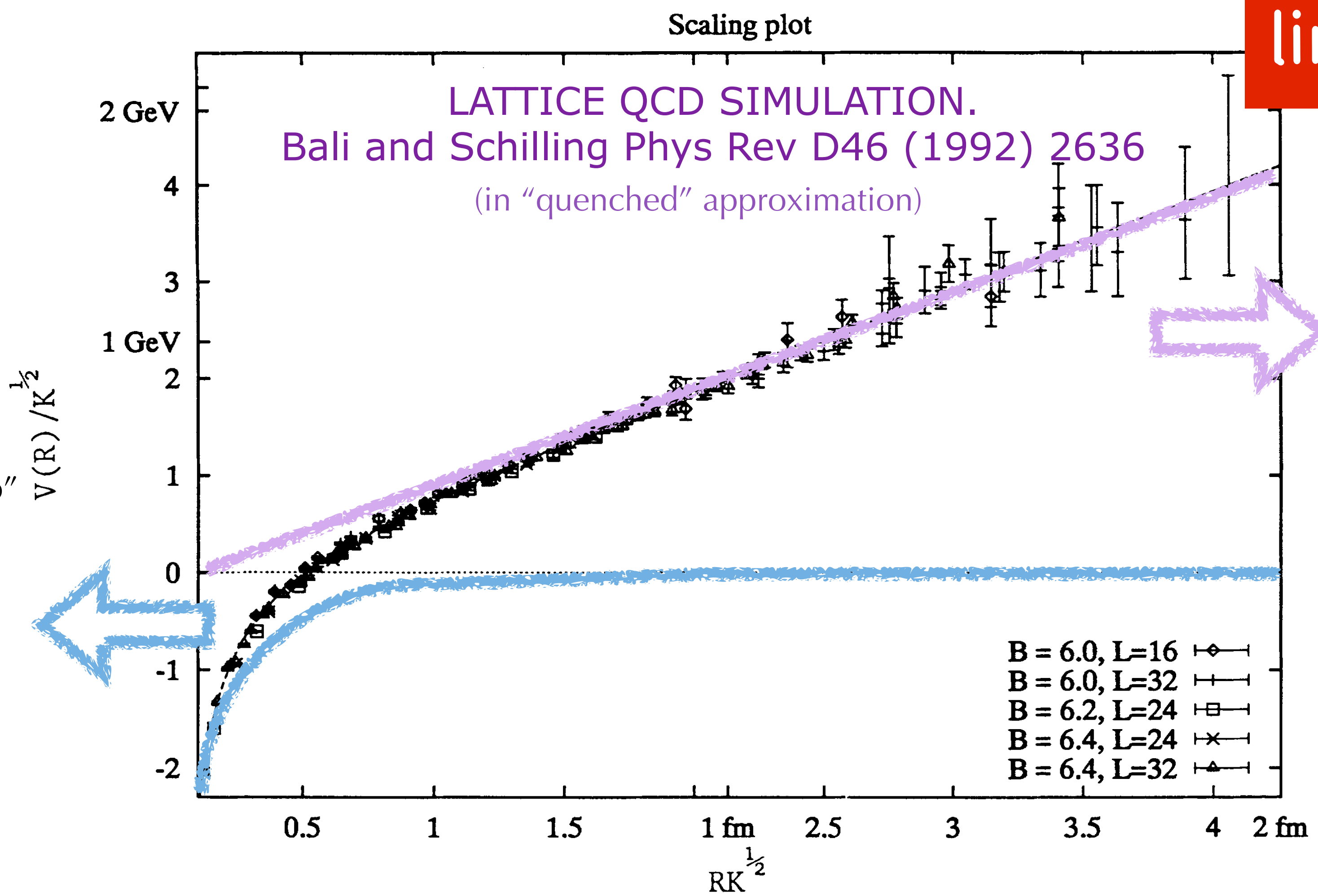
As function of separation distance

What physical system has a linear potential?

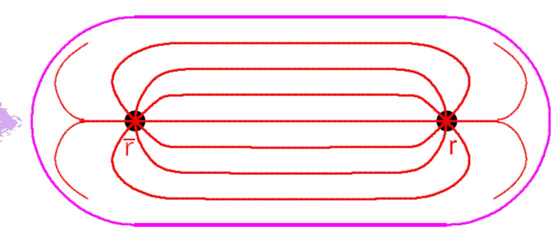
Short Distances ~ "Coulomb"



"Free" Partons




Long Distances ~ Linear Potential



"Confined" Partons
(a.k.a. Hadrons)

$$\boxed{F(r) \approx \mathrm{const} = \kappa \approx 1\ \mathrm{GeV/fm} \quad \Longleftrightarrow \quad V(r) \approx \kappa r}$$

~ Force required to lift a 16-ton truck

# (NOTE ON THE LENGTH OF STRINGS)

## In **Spacetime:**

String tension ≈ 1 GeV/fm → a 5-GeV quark can travel 5 fm before all its kinetic energy is transformed to potential energy in the string.

Then it must start moving the other way (→ "yo-yo" model of mesons. Note: string breaks → several mesons)

## In **Rapidity** :

(convenient variable in momentum space)

$$y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right) = \frac{1}{2}\ln\left(\frac{(E+p_z)^2}{E^2-p_z^2}\right)$$

$$\left(\text{for } m \to 0 \;:\; \frac{1}{2}\ln\left(\frac{1+\cos\theta}{1-\cos\theta}\right) \;=\; -\ln\tan(\theta/2) \;=\; \eta\right)$$

"Pseudorapidity"

Rapidity is useful because it is additive under Lorentz boosts (along the rapidity axis)

$$y' = y + \ln\sqrt{\frac{1-\beta}{1+\beta}}$$

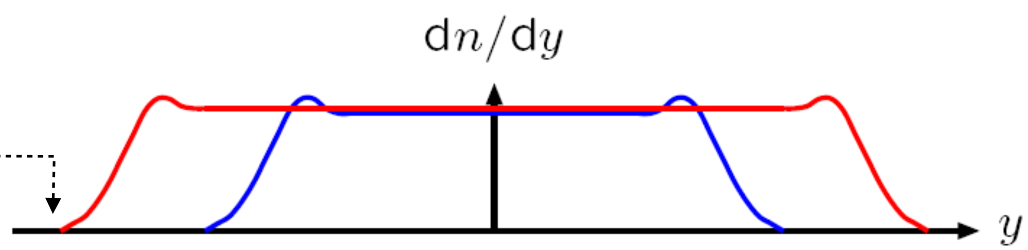
⇒ Δy **difference** is invariant

## Particle Production:

If the quark gives all its energy to a single pion traveling along the z axis

$$y_{\max} \sim \ln\left(\frac{2E_q}{m_\pi}\right)$$

**Scaling** (in "lightcone" $p_\pm = E \pm p_z$; for system along z axis) implies flat central rapidity plateau (+ some endpoint effects)




Increasing $E_q$ → logarithmic growth in rapidity range

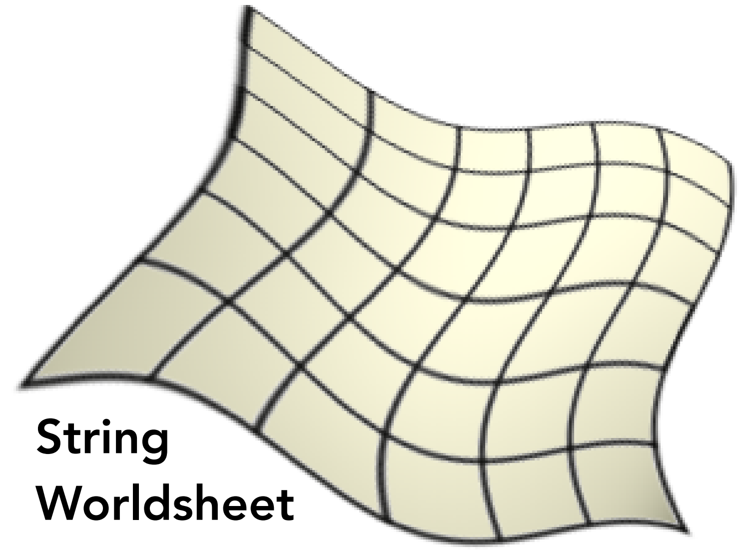
$\langle n_{\rm ch}\rangle \approx c_0 + c_1 \ln E_{\rm cm}$, ~ Poissonian multiplicity distribution

## Motivates a model:

Let color field collapse into a narrow flux tube of uniform energy density

$\kappa \sim 1$ GeV / fm

Limit → Relativistic 1+1 dimensional worldsheet




## In "unquenched" QCD

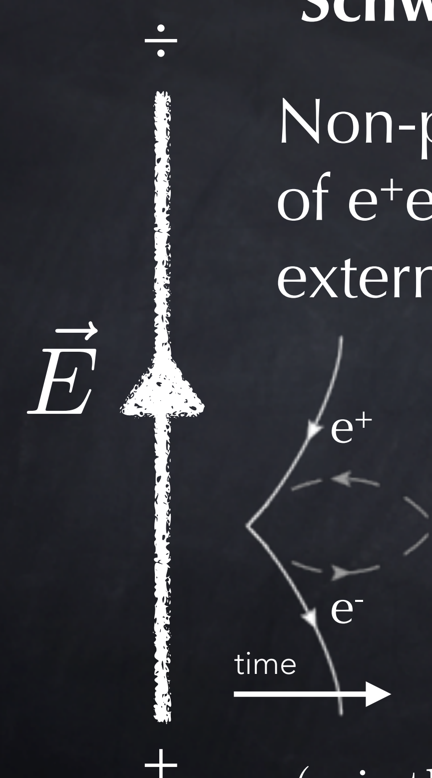
g→qq → The strings will break

→ Gaussian suppression of high $m_T^2 = m_q^2 + p_T^2$

Heavier quarks suppressed. Prob(d:u:s:c) ≈ 1 : 1 : 0.2 : $10^{-11}$

**Schwinger Effect**

Non-perturbative creation of $e^+e^-$ pairs in a strong external Electric field




Probability from Tunneling Factor

$$\mathcal{P} \propto \exp\left(\frac{-m^2 - p_\perp^2}{\kappa/\pi}\right)$$

($\kappa$ is the string tension equivalent)

Pedagogical Review: B. Andersson, *The Lund model.* Camb. Monogr. Part. Phys. Nucl. Phys. Cosmol., 1997.

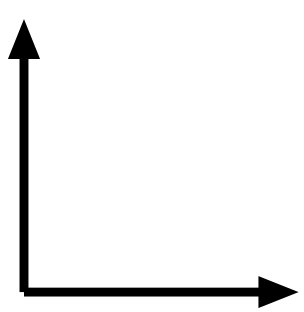
# FRAGMENTATION FUNCTION

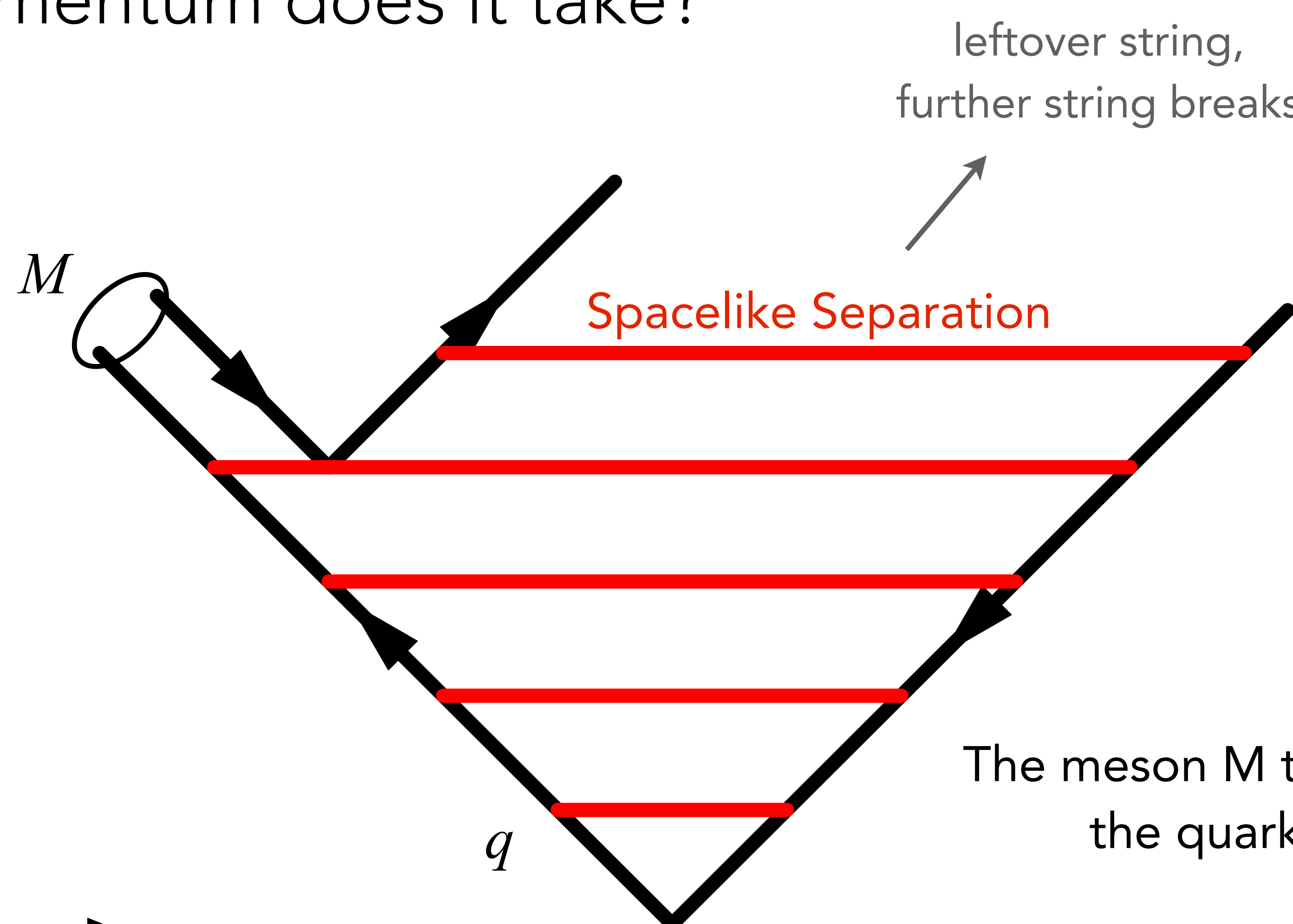
## Having selected a hadron flavor

(see lecture notes for how selection is made between different spin/excitation states)

How much momentum does it take?

Spacetime Picture




The meson M takes a fraction z of the quark momentum,

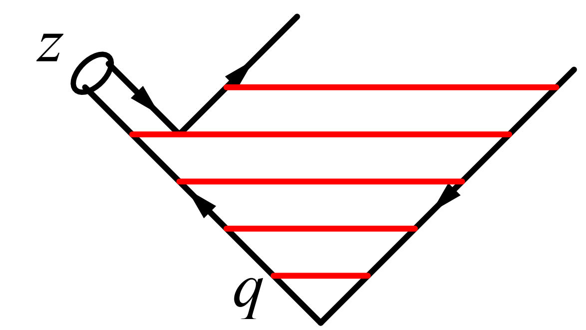
How big that fraction is,
$z \in [0,1]$,
is determined by the *fragmentation function*, $f(z,Q_0^2)$

# LEFT-RIGHT SYMMETRY

Causality → Left-Right Symmetry

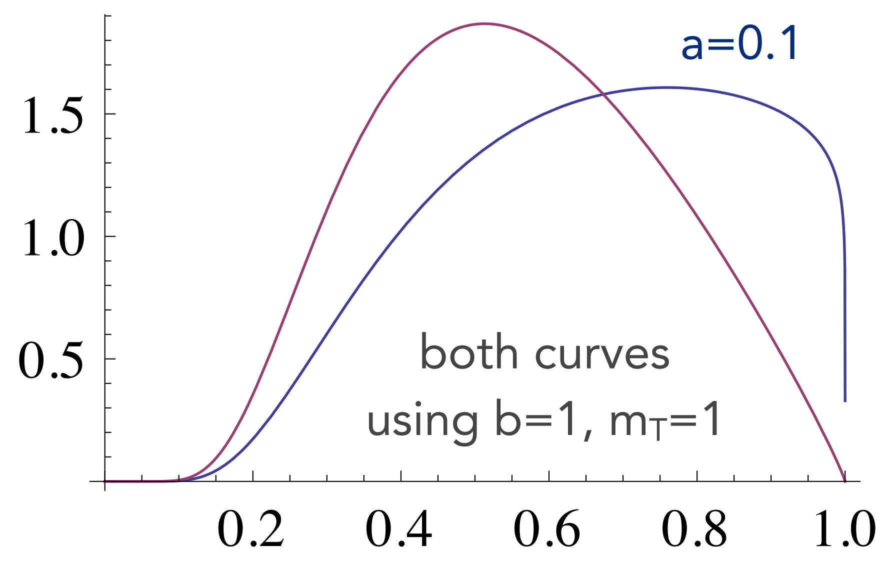
→ Constrains form of fragmentation function!

→ Lund Symmetric Fragmentation Function

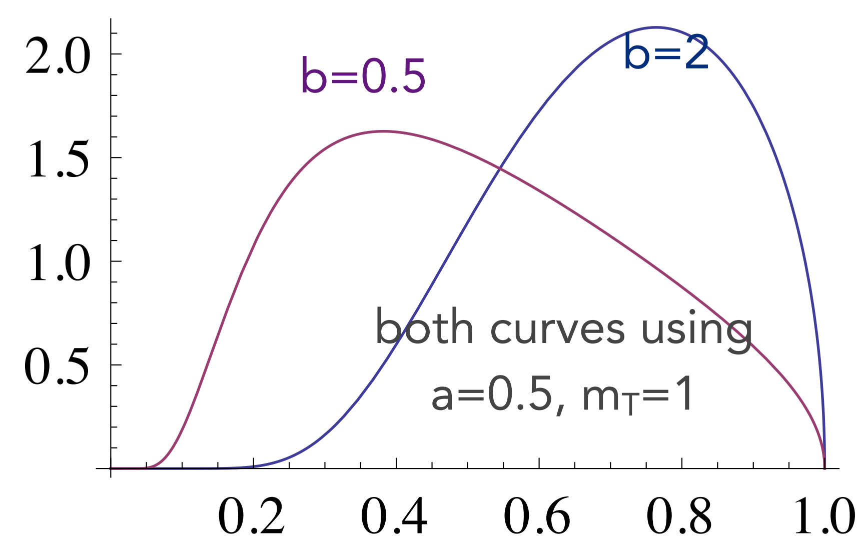



$$f(z) \propto \frac{1}{z}(1-z)^a \exp\left(-\frac{b\,(m_h^2 + p_{\perp h}^2)}{z}\right)$$

Small a
→ "high-z tail"



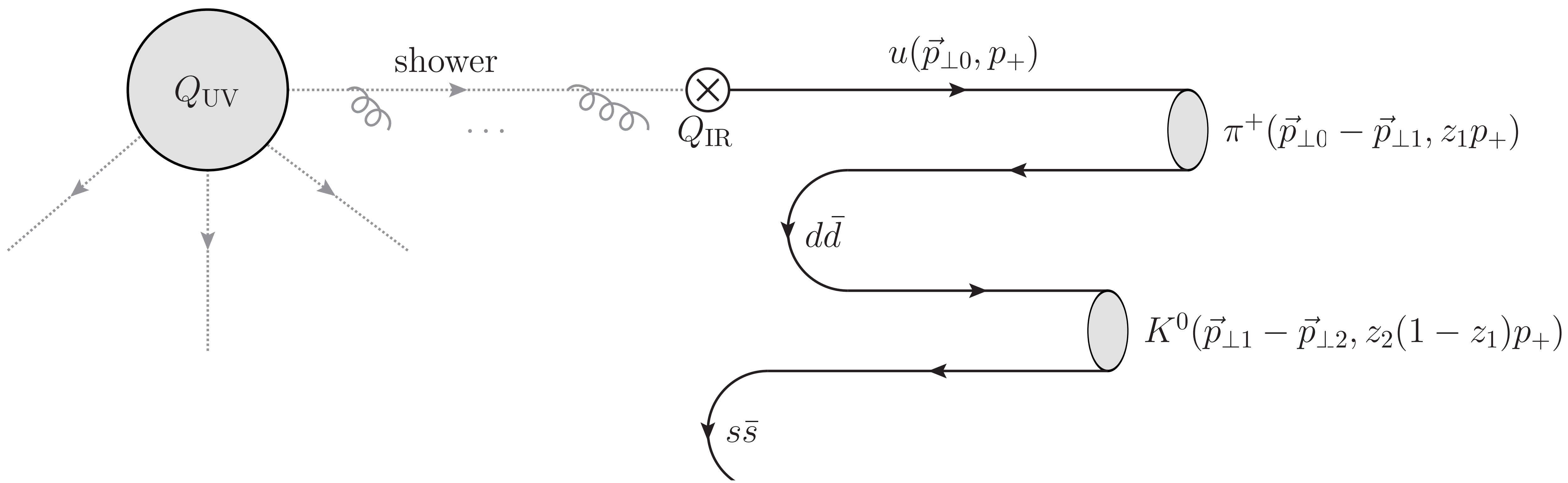

Small b
→ "low-z enhancement"




**Note:** In principle, $a$ can be flavour-dependent. In practice, we only distinguish between baryons and mesons

# ITERATIVE STRING BREAKS

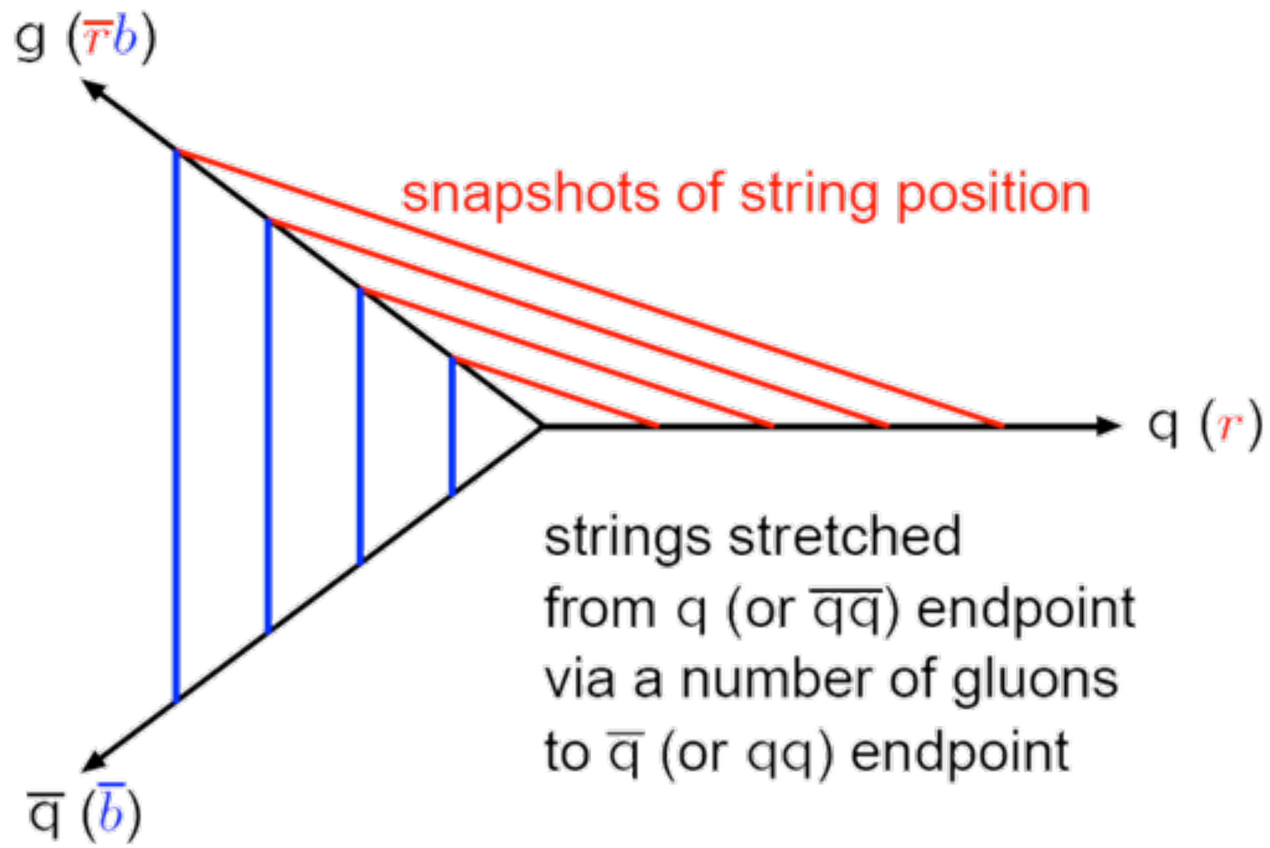
**Causality** → May iterate from outside-in



Main implementation: PYTHIA. (EPOS also implements a string-based hadronisation model.)

## Map:

- **Quarks** → String Endpoints
- **Gluons** → Transverse Excitations (kinks)
- Physics then in terms of string worldsheet evolving in spacetime
- Probability of string break (by quantum tunneling) constant per unit area → **AREA LAW**



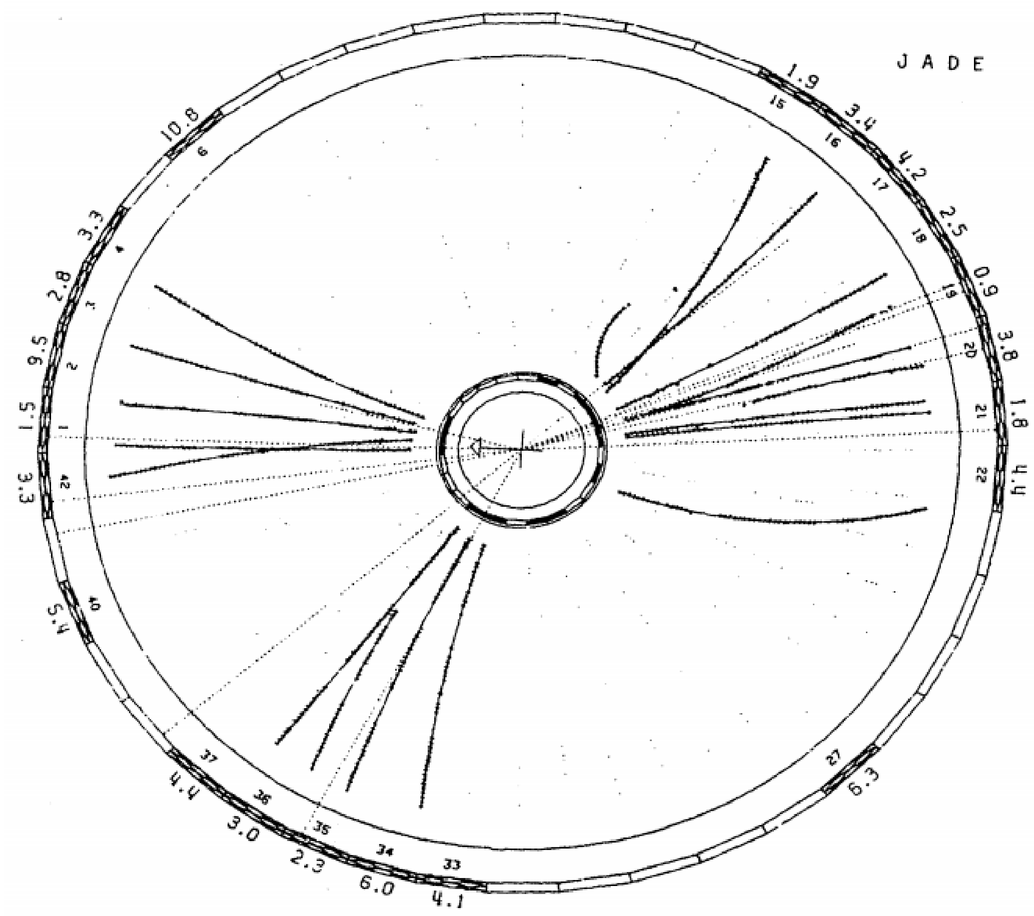

Gluon = kink on string, carrying energy and momentum

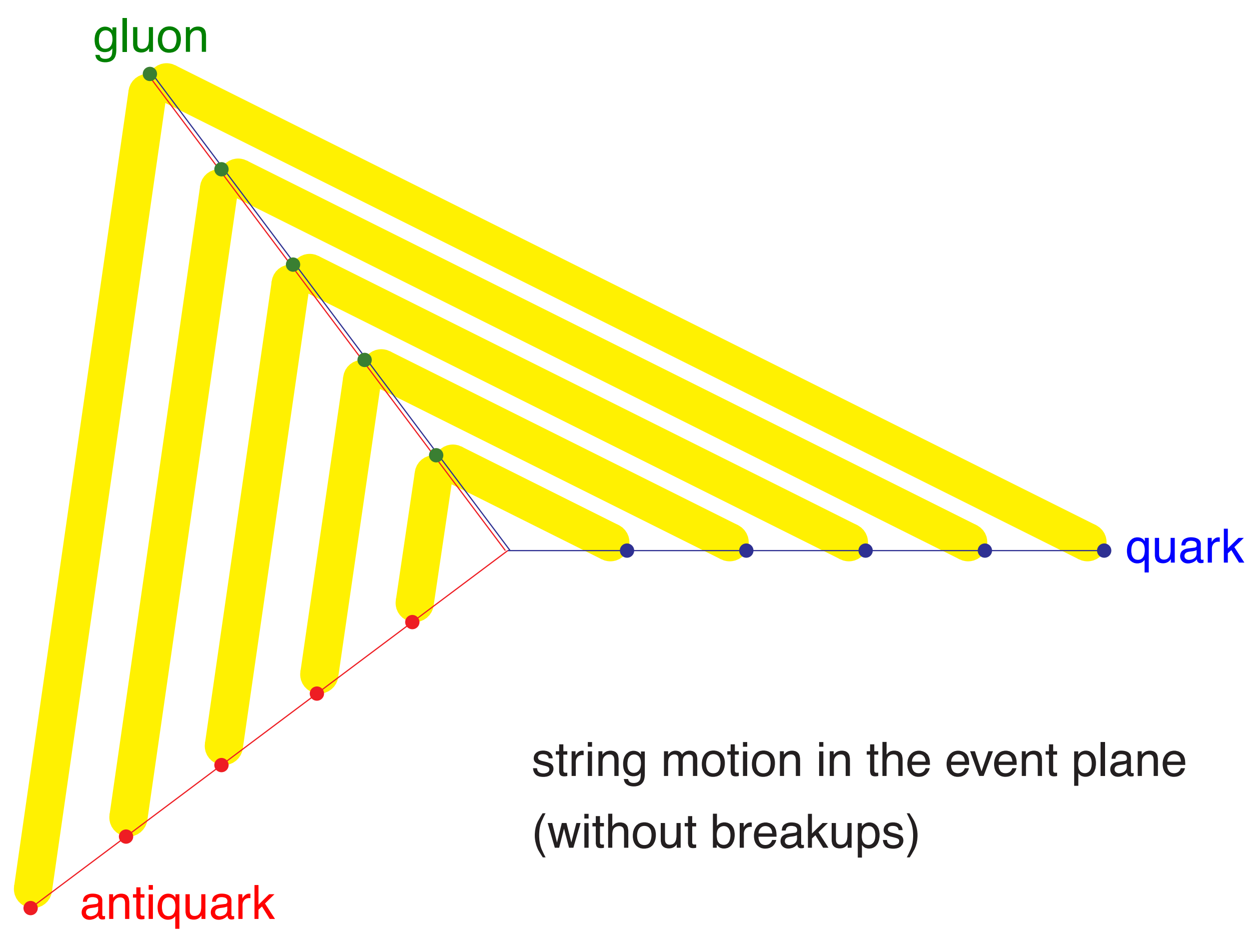
→ **STRING EFFECT**

**Simple space-time picture**

Details of string breaks more complicated (e.g., baryons, spin multiplets)

# 1980: string (colour coherence) effect



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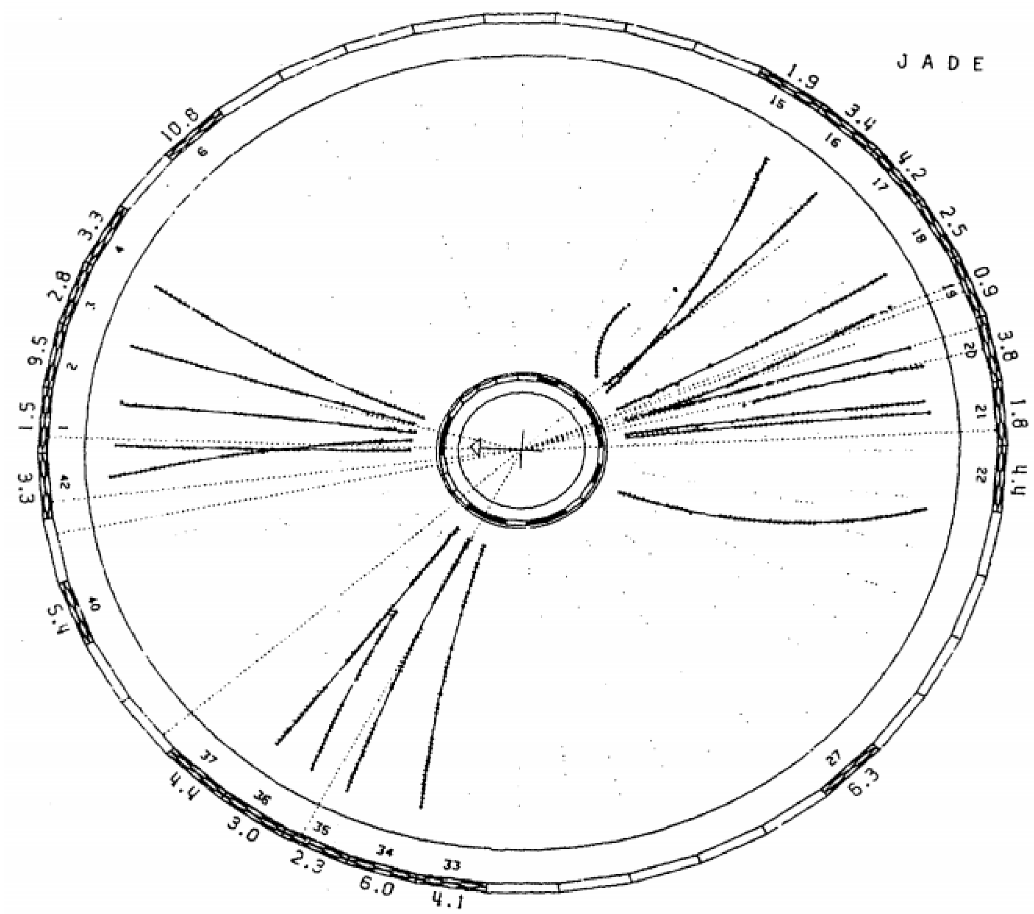
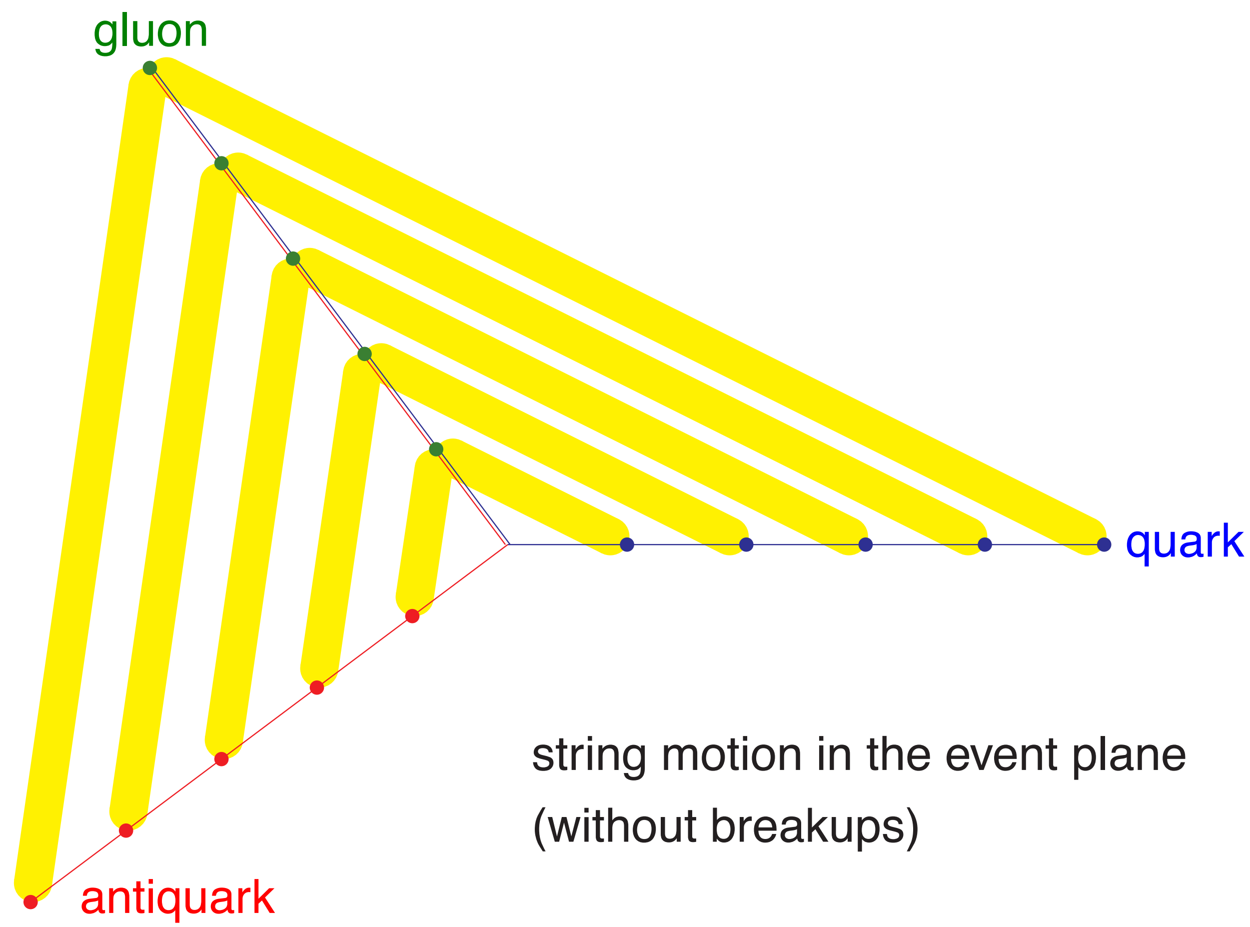
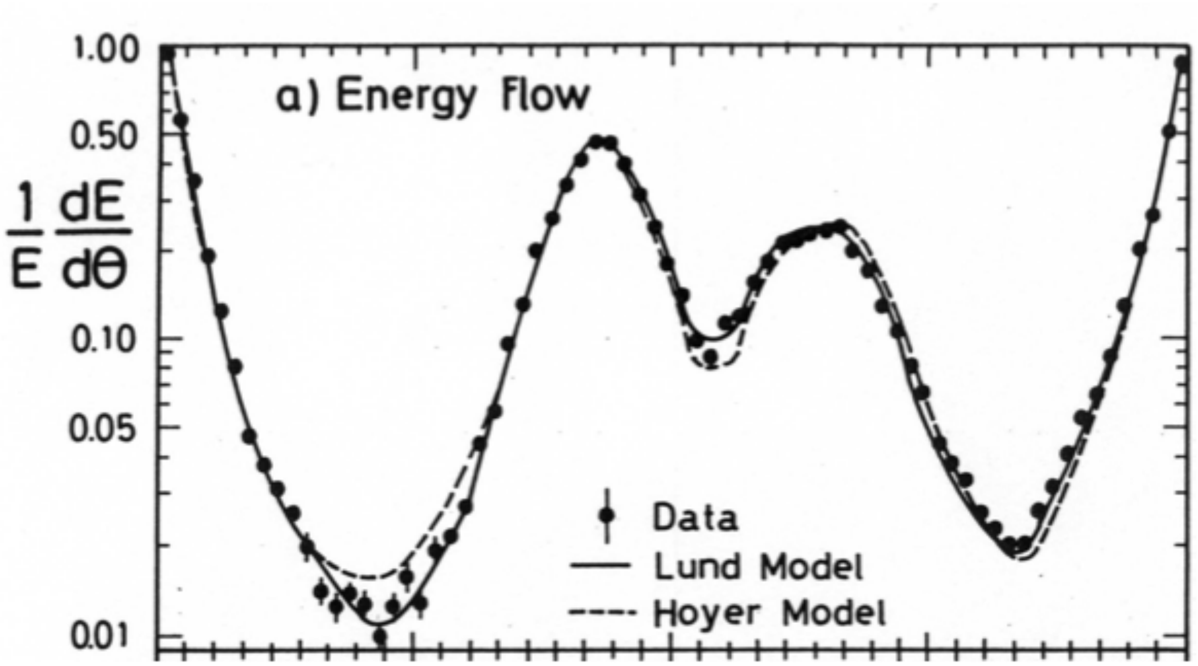



Predicted unique event structure; inside & between jets.

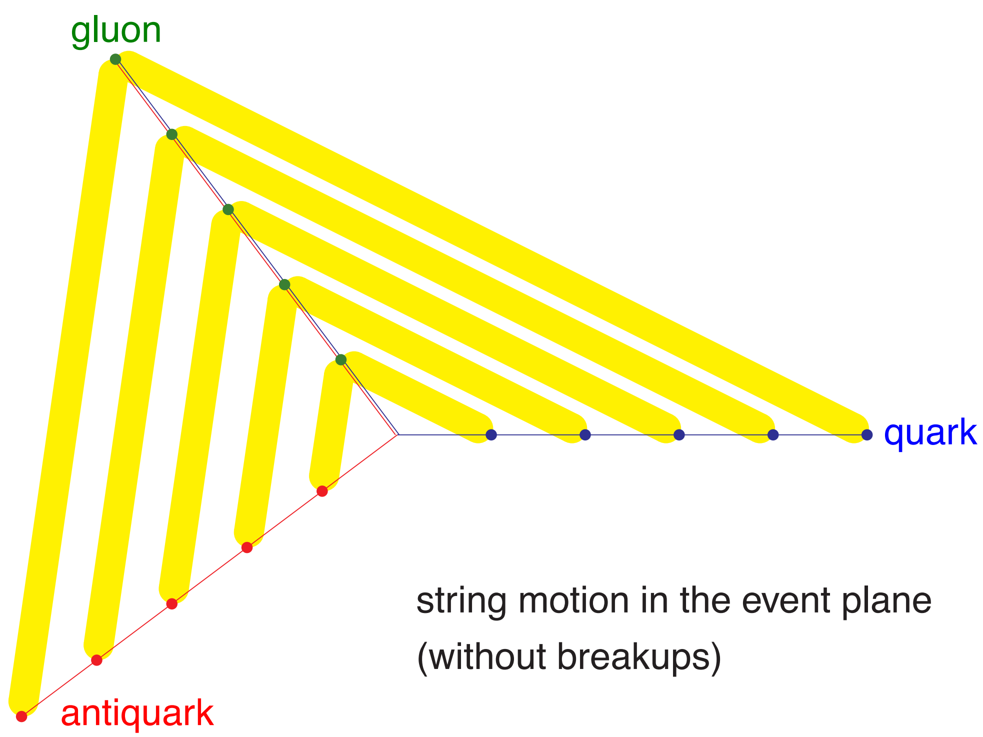
Confirmed first by JADE 1980.

**Generator crucial to sell physics!**

(today: PS, M&M, MPI, . . . )

**More recent study (LHC)**

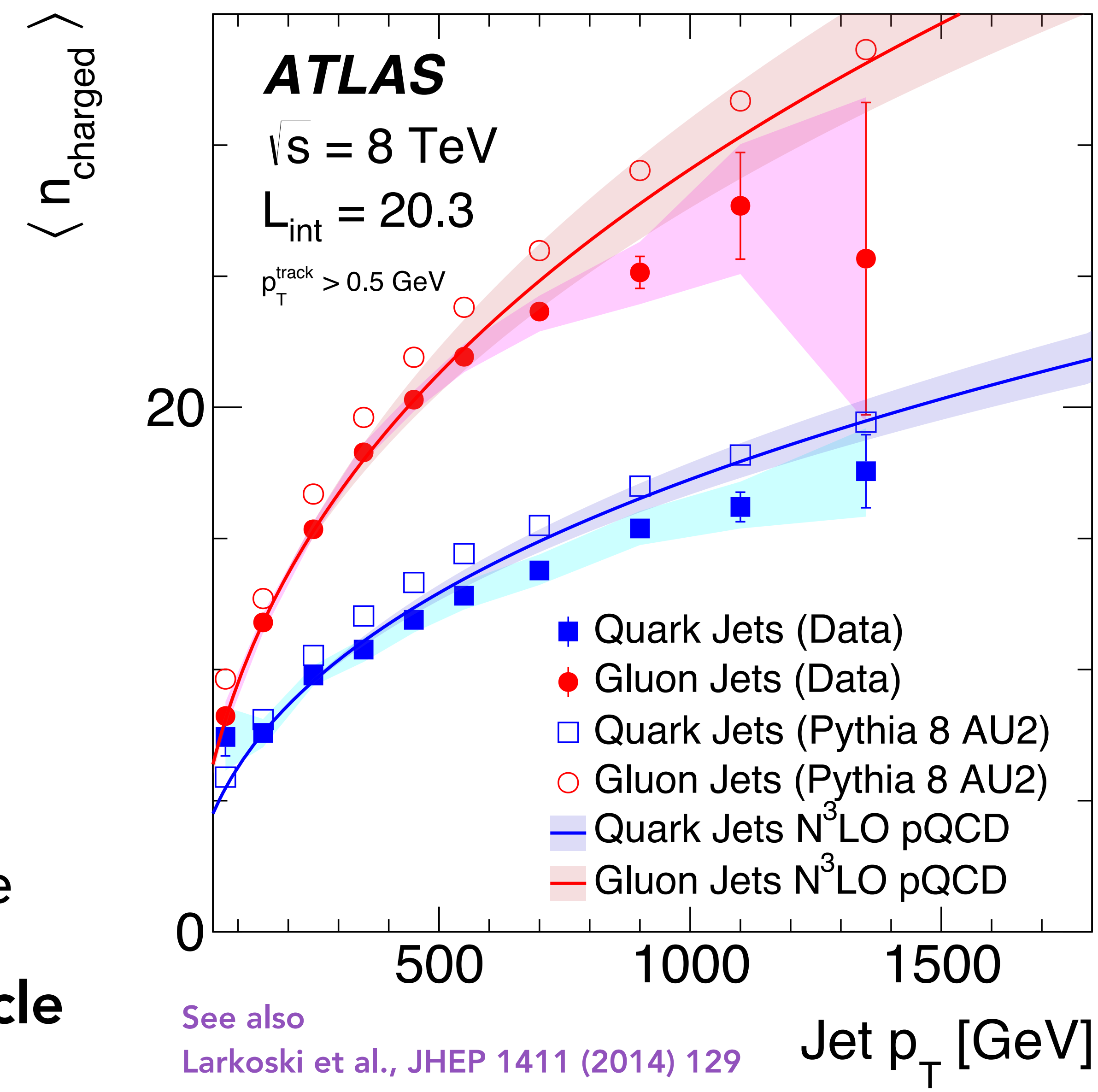
Gluon connected to two string pieces




Each quark connected to one string piece

→ **expect factor 2 ~ $C_A/C_F$ larger particle multiplicity in gluon jets vs quark jets**

ATLAS, Eur.Phys.J. C76 (2016) no.6, 322




See also
Larkoski et al., JHEP 1411 (2014) 129
Thaler et al., Les Houches, arXiv:1605.04692

Can be hugely important for discriminating new-physics signals (decays to quarks vs decays to gluons, vs composition of background and bremsstrahlung combinatorics )

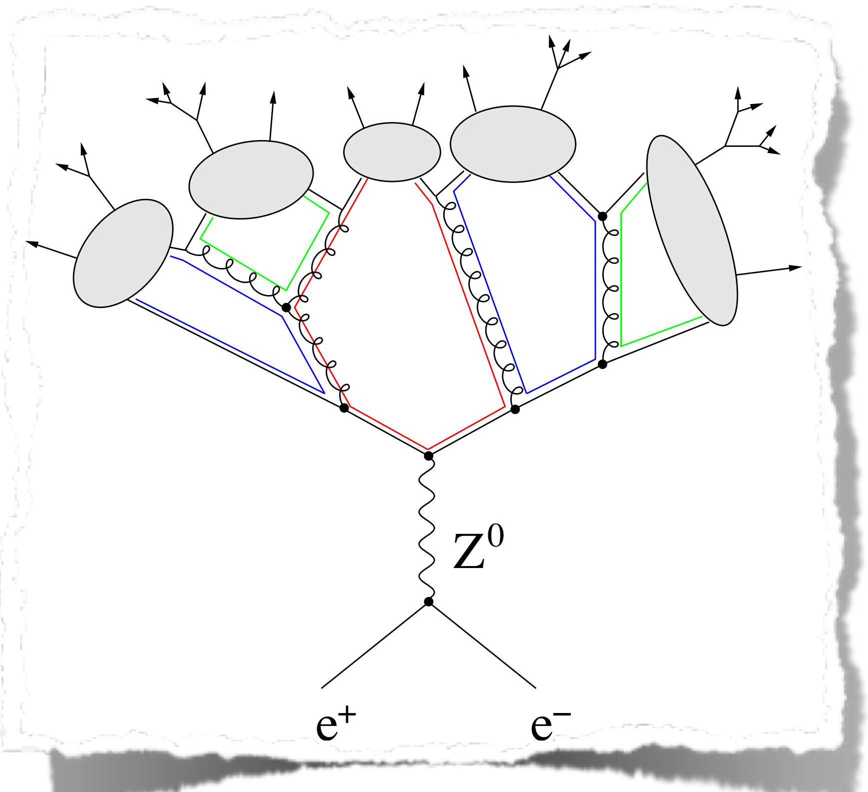
## Starting observation: "Preconfinement"

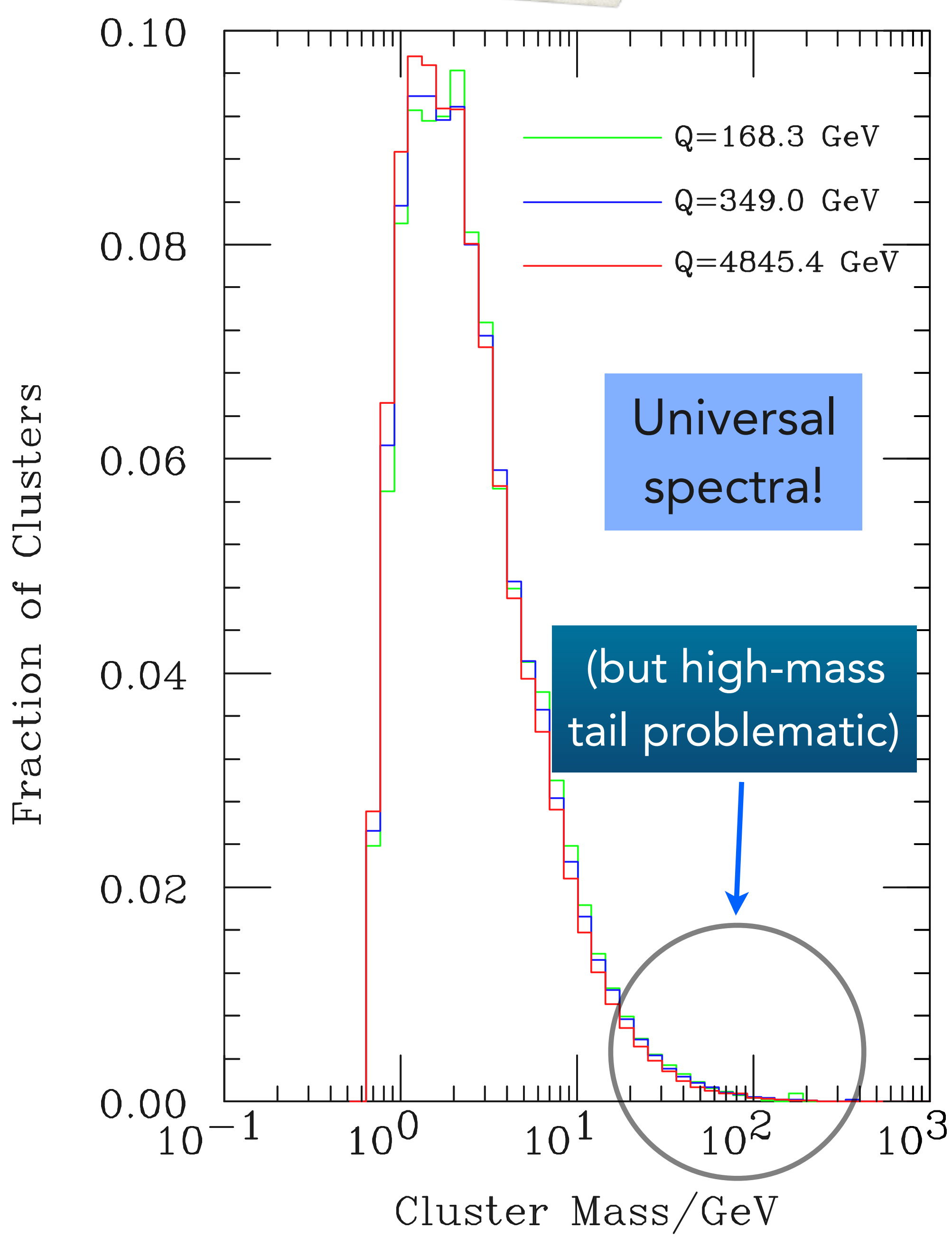
**+ Force g→qq splittings at $Q_0$**

→ high-mass q-qbar "clusters"

Isotropic 2-body decays to hadrons

according to PS ≈ $(2s_1+1)(2s_2+1)(p^*/m)$

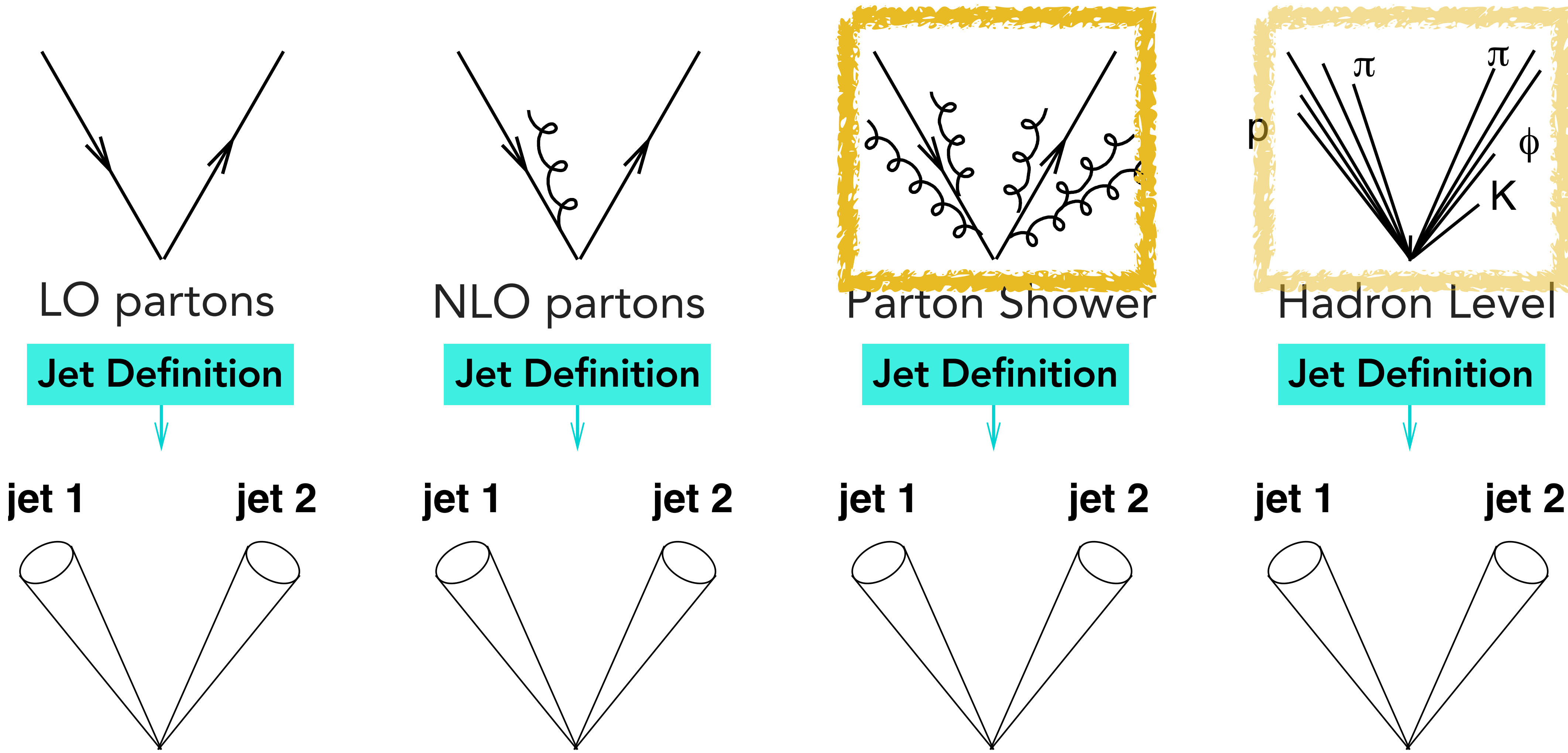



Large clusters → string-like. (In PYTHIA, small strings → cluster-like).

# JETS

**Think of jets as projections that provide a universal view of events**



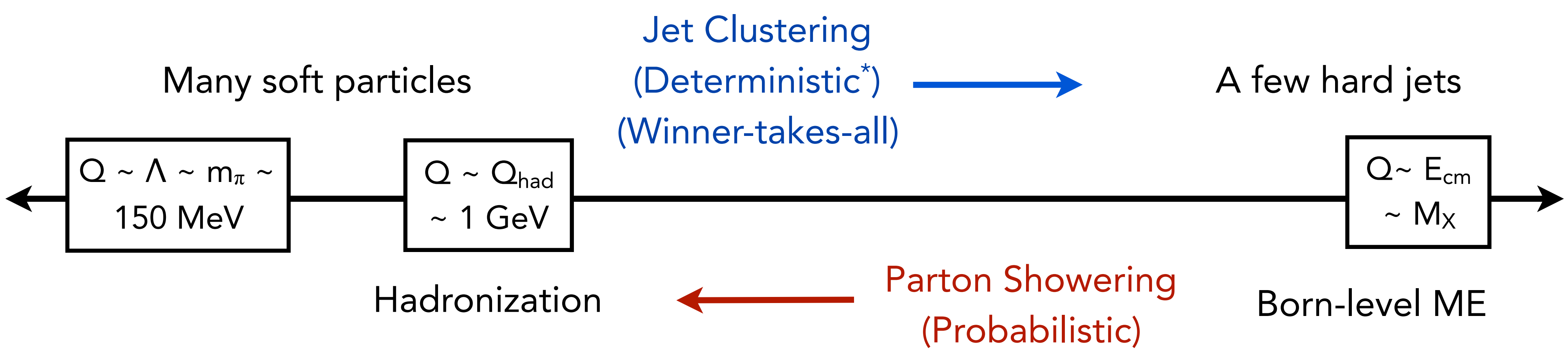

Illustrations by G. Salam

I'm not going to cover the many different types of jet clustering algorithms ($k_T$, anti-$k_T$, C/A, cones, …) - see e.g., lectures & notes by G. Salam.

➤ Focus instead on the physical origin and MC modeling of jets

## Jet clustering algorithms

Map event from low E-resolution scale (i.e., with many partons/hadrons, most of which are soft) to a higher E-resolution scale (with fewer, hard, IR-safe, jets)




## Parton shower algorithms

Map a few hard partons to many softer ones

Probabilistic → closer to nature.

Not uniquely invertible by any jet algorithm*

(* See "Qjets" for a probabilistic jet algorithm, arXiv:1201.1914)

(* See "Sector Showers" for a deterministic shower, arXiv:1109.3608)

**Definition: an observable is infrared safe if it is *<u>in</u>sensitive* to**

**<u>SOFT</u> <u>radiation:</u>**

Adding any number of infinitely *soft* particles (zero-energy) should not change the value of the observable

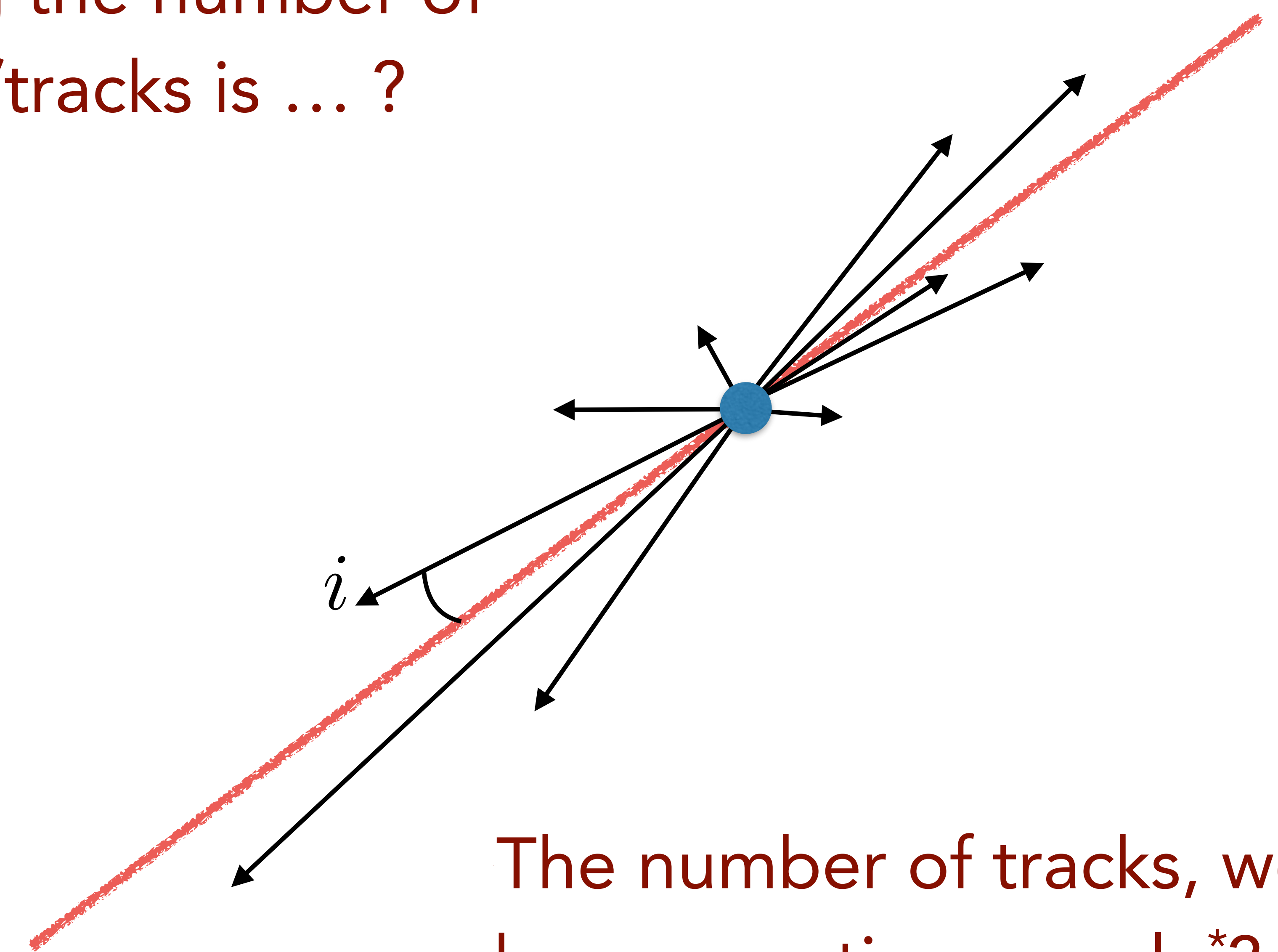
**<u>COLLINEAR</u> <u>radiation:</u>**

Splitting an existing particle up into two *comoving* ones (conserving the total momentum and energy) should not change the value of the observable

*Note: some people use the word "infrared" to refer to soft only. Hence you may also hear "infrared and collinear safety". Advice: always be explicit and clear what you mean.*

# EXAMPLE

Counting the number of particles/tracks is … ?




The number of tracks, weighted by energy times angle*?

angle*: with respect to some principal axis representing the "collinear" direction (e.g., jet axis or "event-shape" axis)

# WHY DO WE CARE?

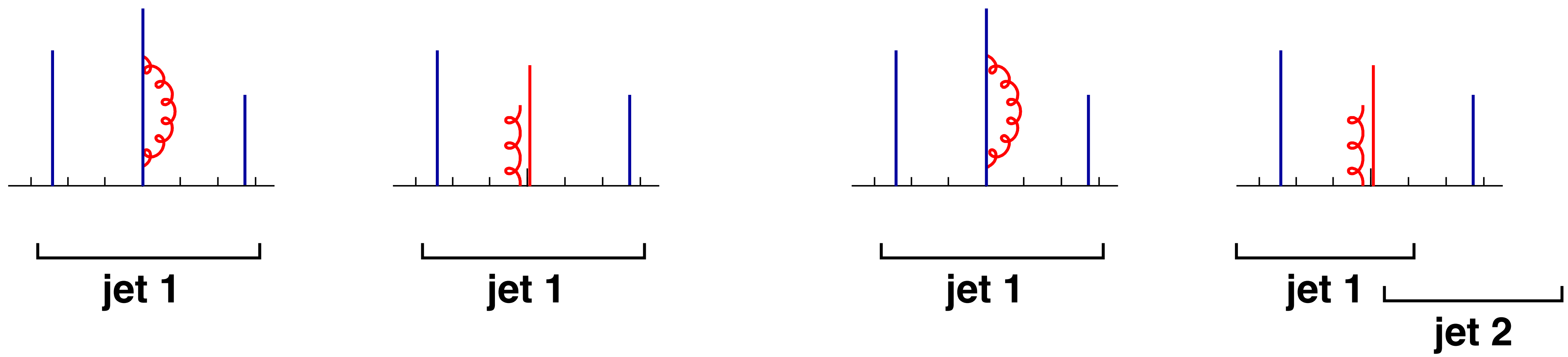
*(example by G. Salam)*

## Collinear Safe

Virtual and Real go into **same bins!**

## Collinear Unsafe

Virtual and Real go into **different bins!**




$\alpha_s^n$ x $(-\infty)$ $\alpha_s^n$ x $(+\infty)$ $\alpha_s^n$ x $(-\infty)$ $\alpha_s^n$ x $(+\infty)$

**Infinities cancel**

(KLN: 'degenerate states')

**Infinities do not cancel**

Invalidates perturbation theory

Real life does not have infinities, but pert. infinity leaves a real-life trace

$$\alpha_s^2 + \alpha_s^3 + \alpha_s^4 \times \infty \to \alpha_s^2 + \alpha_s^3 + \alpha_s^4 \times \ln p_t/\Lambda \to \alpha_s^2 + \underbrace{\alpha_s^3 + \alpha_s^3}_{\text{BOTH WASTED}}$$

# THERE IS NO UNIQUE OR "BEST" JET DEFINITION

## YOU decide how to look at event

The construction of jets is inherently ambiguous

| Jet Definition | 1. Which particles get grouped together?<br>JET ALGORITHM<br>(+ size/resolution parameters)<br>2. How will you combine their momenta?<br>RECOMBINATION SCHEME<br>(e.g., 'E' scheme: add 4-momenta) |
|---|---|

Ambiguity complicates life, but gives flexibility in one's view of events
→ At what resolution / angular size are you looking for structure(s)?
→ Do you prefer "circular" or "QCD-like" jet areas? (Collinear vs Soft structure)
→ Sequential clustering → substructure (veto/enhance?)

# TYPES OF ALGORITHMS

## 1. Sequential Recombination

→ Take your 4-vectors. Combine the ones that have the lowest 'distance measure'

Different names for different distance measures

Durham $k_T$ : $\Delta R_{ij}^2 \times \min(k_{Ti}^2, k_{Tj}^2)$

Cambridge/Aachen : $\Delta R_{ij}^2$

Anti-$k_T$ : $\Delta R_{ij}^2 / \max(k_{Ti}^2, k_{Tj}^2)$

ArClus (3→2): $p_\perp^2 = s_{ij} s_{jk} / s_{ijk}$

$$k_{Ti}^2 = E_i^2 (1 - \cos\theta_{ij})$$

$$\Delta R_{ij}^2 = (\eta_i - \eta_j)^2 + \Delta\phi_{ij}^2$$

+ Prescription for how to combine 2 momenta into 1 (or 3 momenta into 2)

→ New set of (n-1) 4-vectors

**Iterate until A or B** *(you choose which)*:

A: all distance measures larger than something ← specific resolution

B: you reach a specified number of jets ← specific $n_{jets}$

Look at event at:

specific resolution

specific $n_{jets}$

# WHY $K_T$ (OR $P_T$ OR $\Delta R$)?

Attempt to (approximately) capture universal jet-within-jet-witin-jet… behavior

Recall: Approximate full matrix element

$$\frac{|M^{(0)}_{X+1}(s_{i1}, s_{1k}, s)|^2}{|M^{(0)}_X(s)|^2} = 4\pi\alpha_s C_F \left( \frac{2s_{ik}}{s_{i1}s_{1k}} + \ldots \right)$$

"Eikonal"
(universal, always there)

by Leading-Log limit of QCD → universal dominant terms

$$\frac{\mathrm{d}s_{i1}\mathrm{d}s_{1k}}{s_{i1}s_{1k}} \to \frac{\mathrm{d}p_\perp^2}{p_\perp^2}\frac{\mathrm{d}z}{z(1-z)} \to \frac{\mathrm{d}E_1}{\min(E_i, E_1)}\frac{\mathrm{d}\theta_{i1}}{\theta_{i1}} \quad (E_1 \ll E_i,\ \theta_{i1} \ll 1) \quad ,\ldots$$

Rewritings in soft/collinear limits

"smallest" $k_T$ (or $p_T$ or $\theta_{ij}$, or …) → largest Eikonal (and/or most collinear)

## 2. "Cone" type

Take your 4-vectors. Select a procedure for which "test cones" to draw

- Different names for different procedures
  - Seeded (obsolete): start from hardest 4-vectors (and possibly combinations thereof, e.g., CDF midpoint algorithm) = "seeds"
  - Unseeded : smoothly scan over entire event, trying everything
- Sum momenta inside test cone → new test cone direction
- Iterate until stable (test cone direction = momentum sum direction)

Warning: to optimise speed, **seeded** algorithms were sometimes used in the past. INFRARED UNSAFE

# (IR SAFE VS UNSAFE OBSERVABLES)

May look pretty similar in experimental environment …

But IR unsafe is not nice to your (perturbative) theory friends …

**Unsafe**: badly divergent in pQCD → large IR corrections:

$$\text{IR Sensitive Corrections} \propto \alpha_s^n \log^m\left(\frac{Q^2_{\text{UV}}}{Q^2_{\text{IR}}}\right) \quad , \quad m \leq 2n$$

Even if we have a hadronization model which computes these corrections, the dependence on it is larger → uncertainty

**Safe** → IR corrections power suppressed:

$$\text{IR Safe Corrections} \propto \frac{Q^2_{\text{IR}}}{Q^2_{\text{UV}}}$$

Can still be computed (MC) but can also be neglected (pure pQCD)

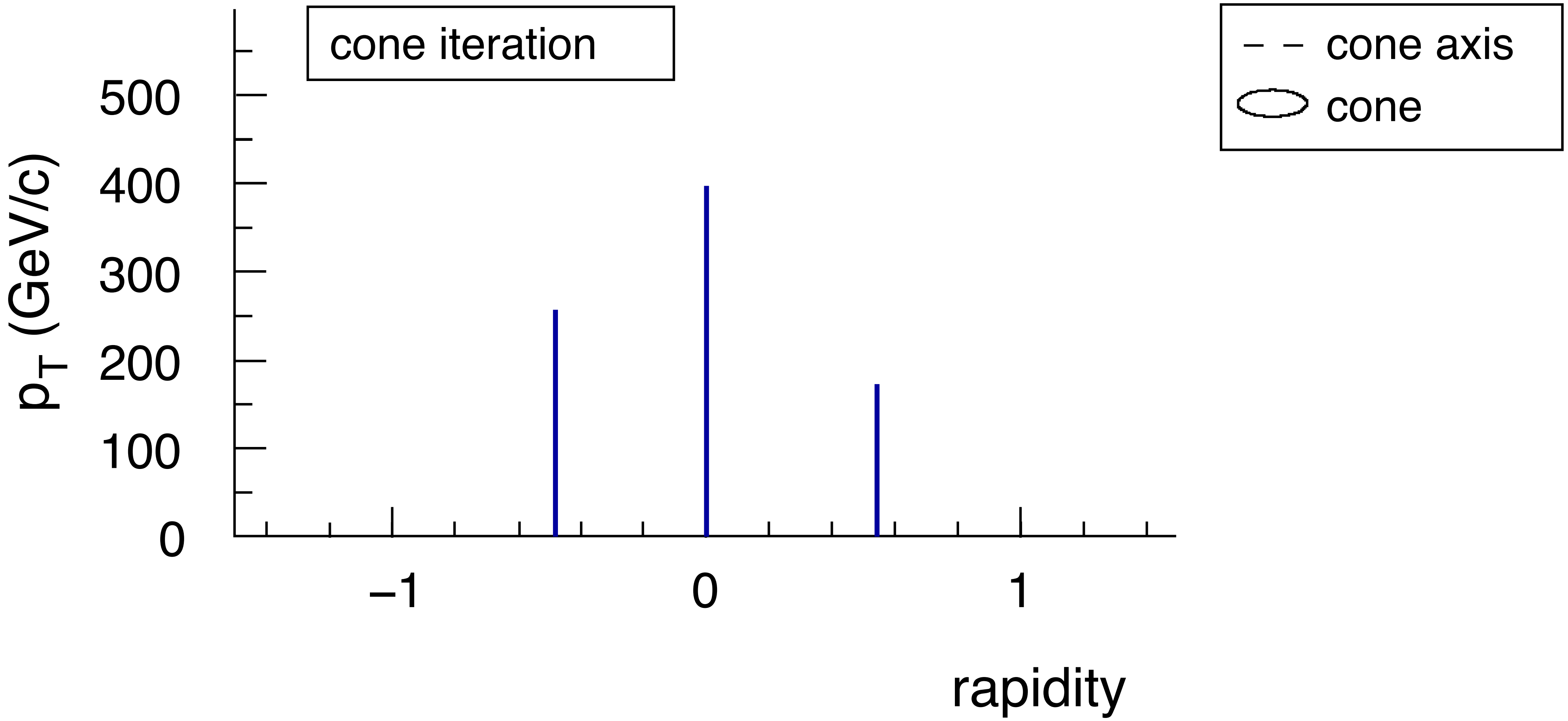
Let's look at an example …

# ICPR iteration issue

Iterative Cone Progressive Removal

"Seeded Cone Algorithm"

Start from "hardest" seeds




Collinear splitting can modify the hard jets: ICPR algorithms are collinear unsafe $\Longrightarrow$ perturbative calculations give $\infty$

Slides from G. Salam

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Start from "hardest" seeds

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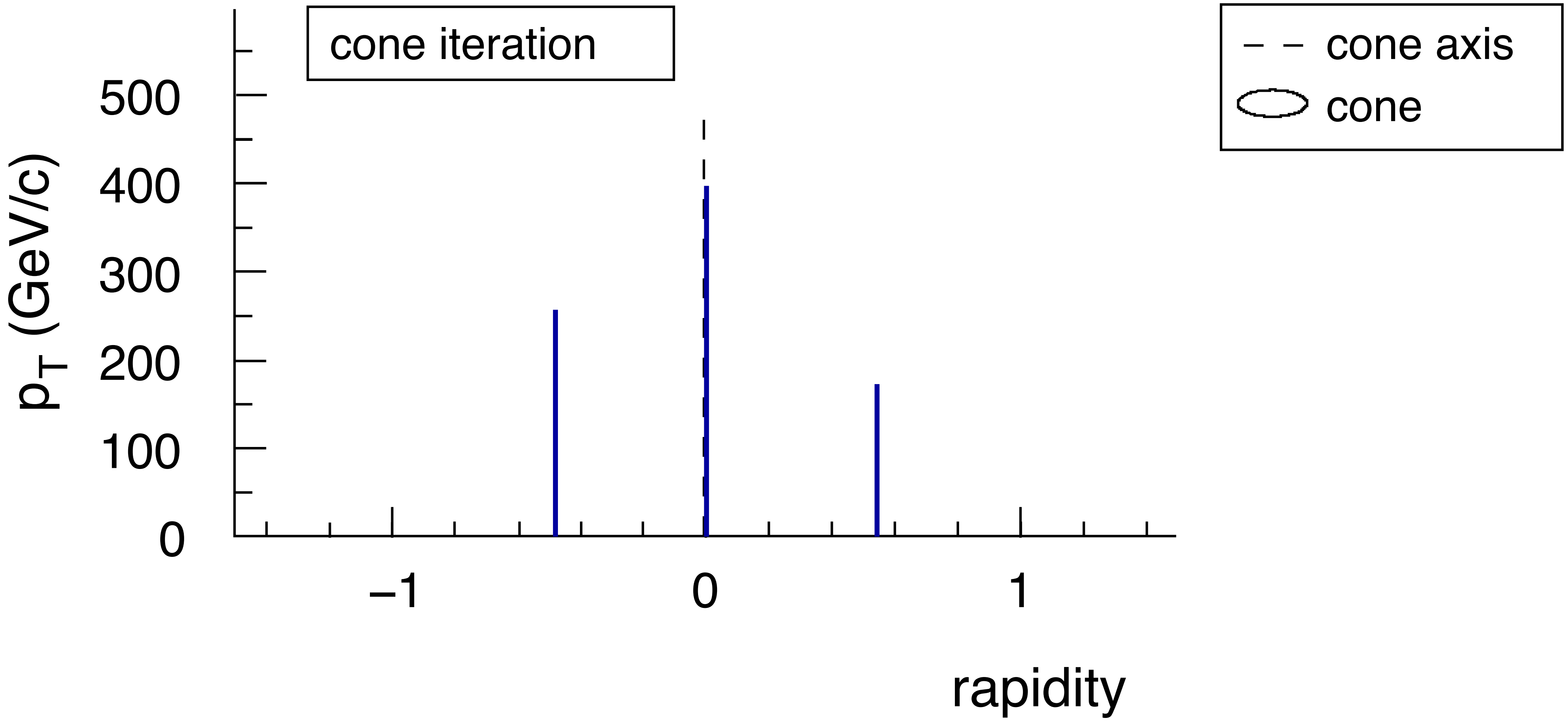


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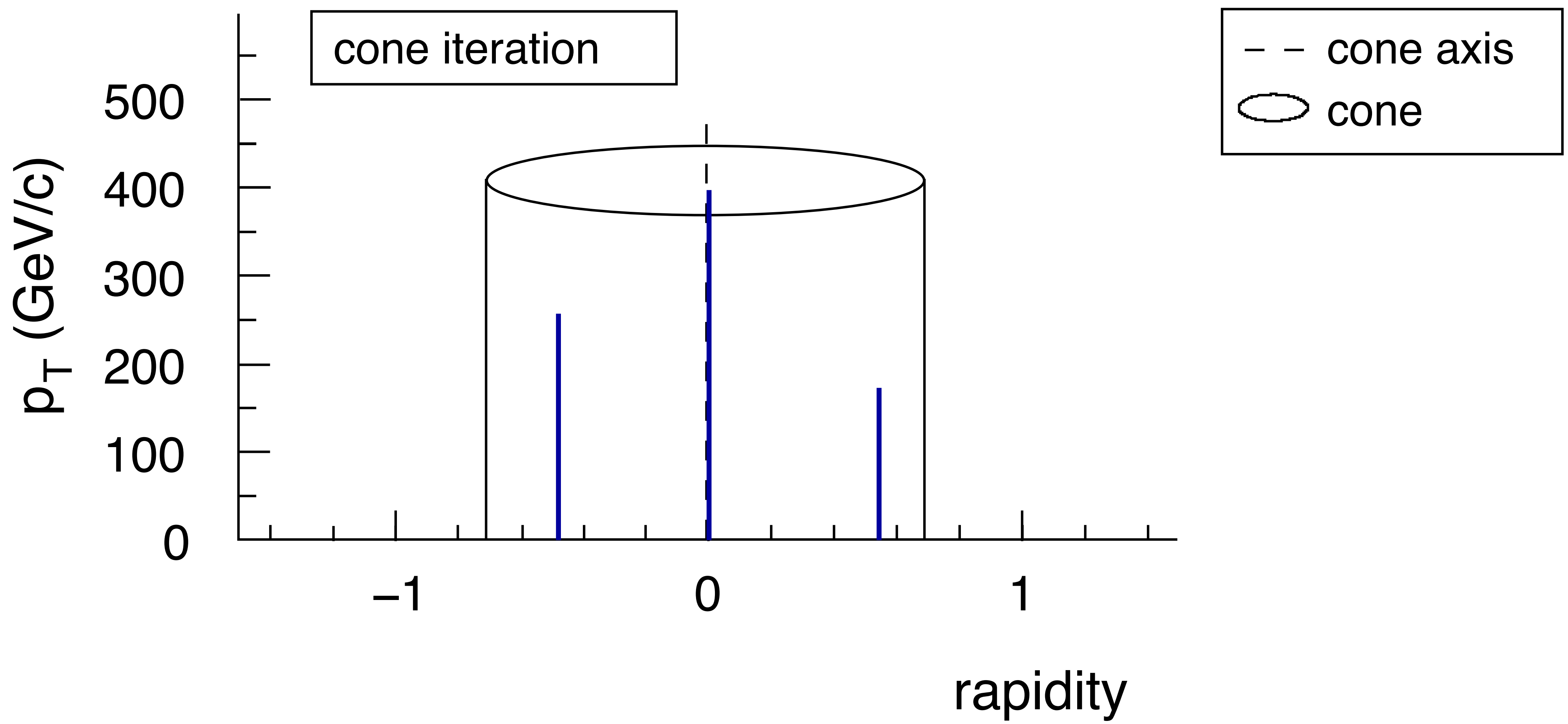


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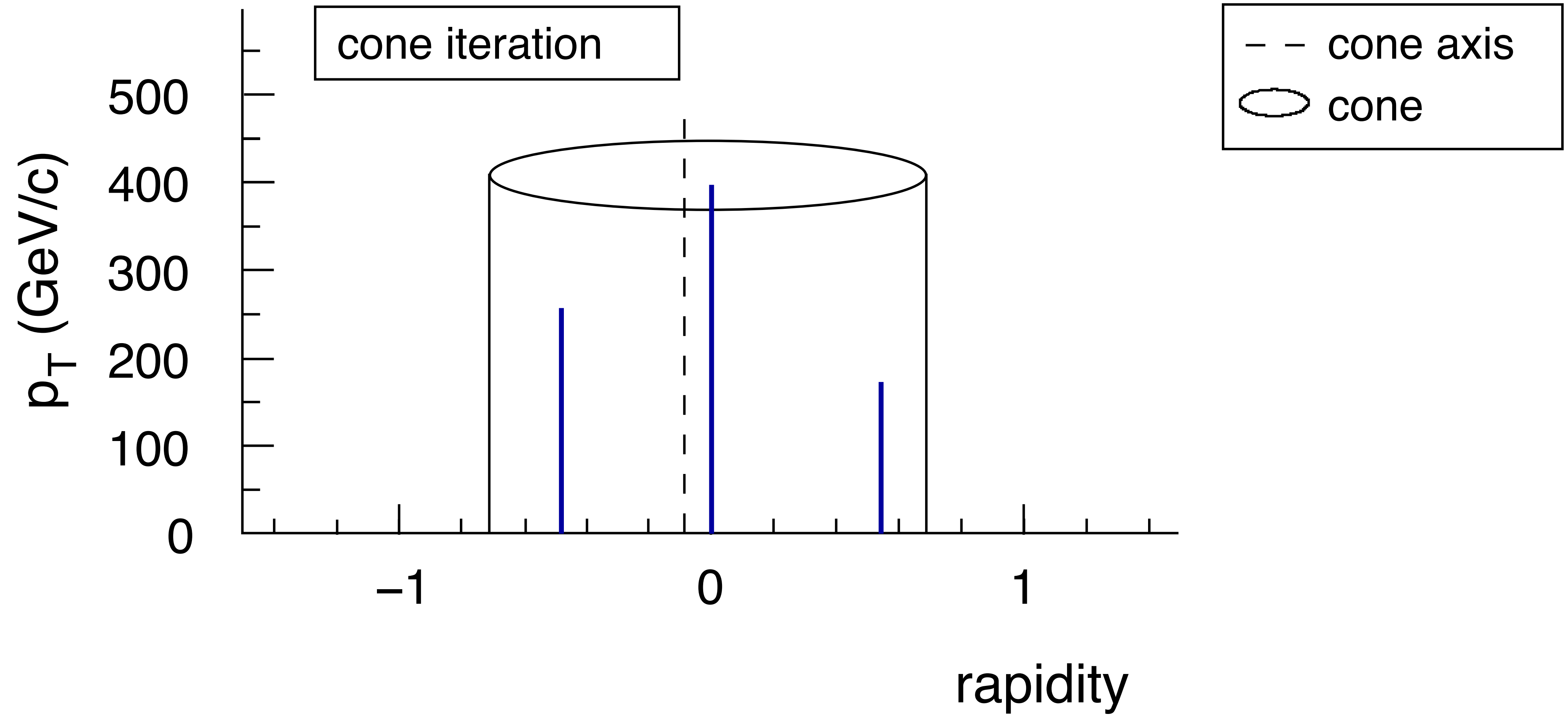


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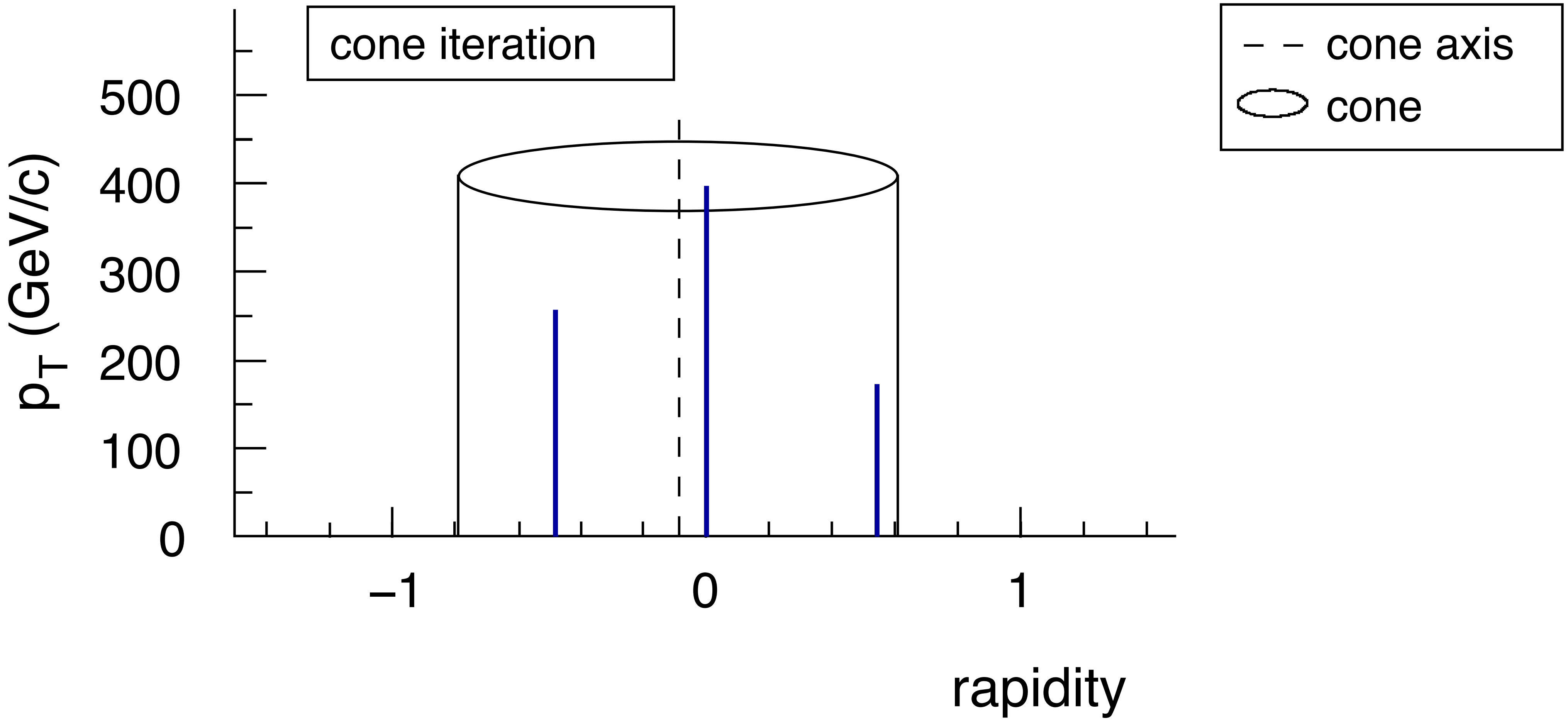


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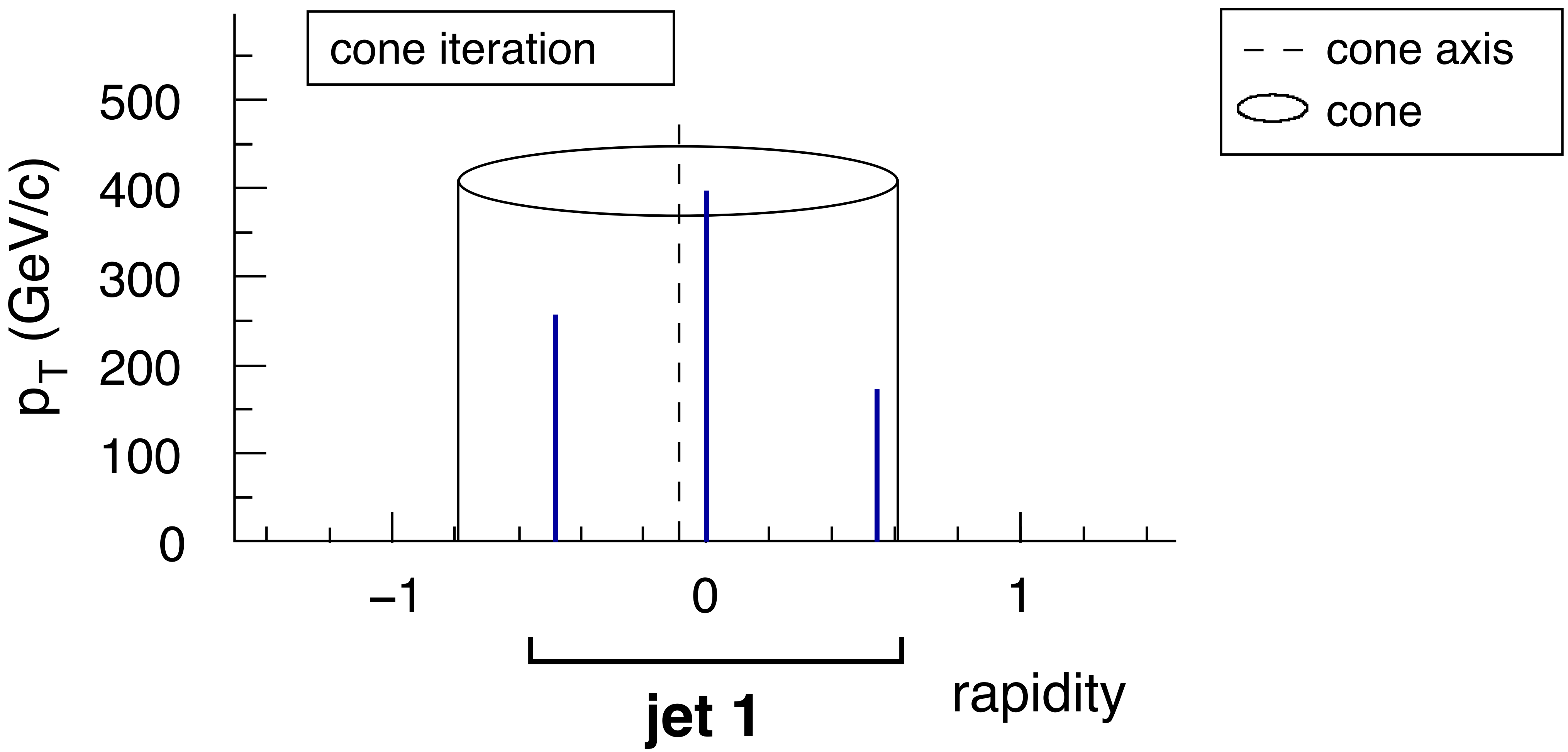


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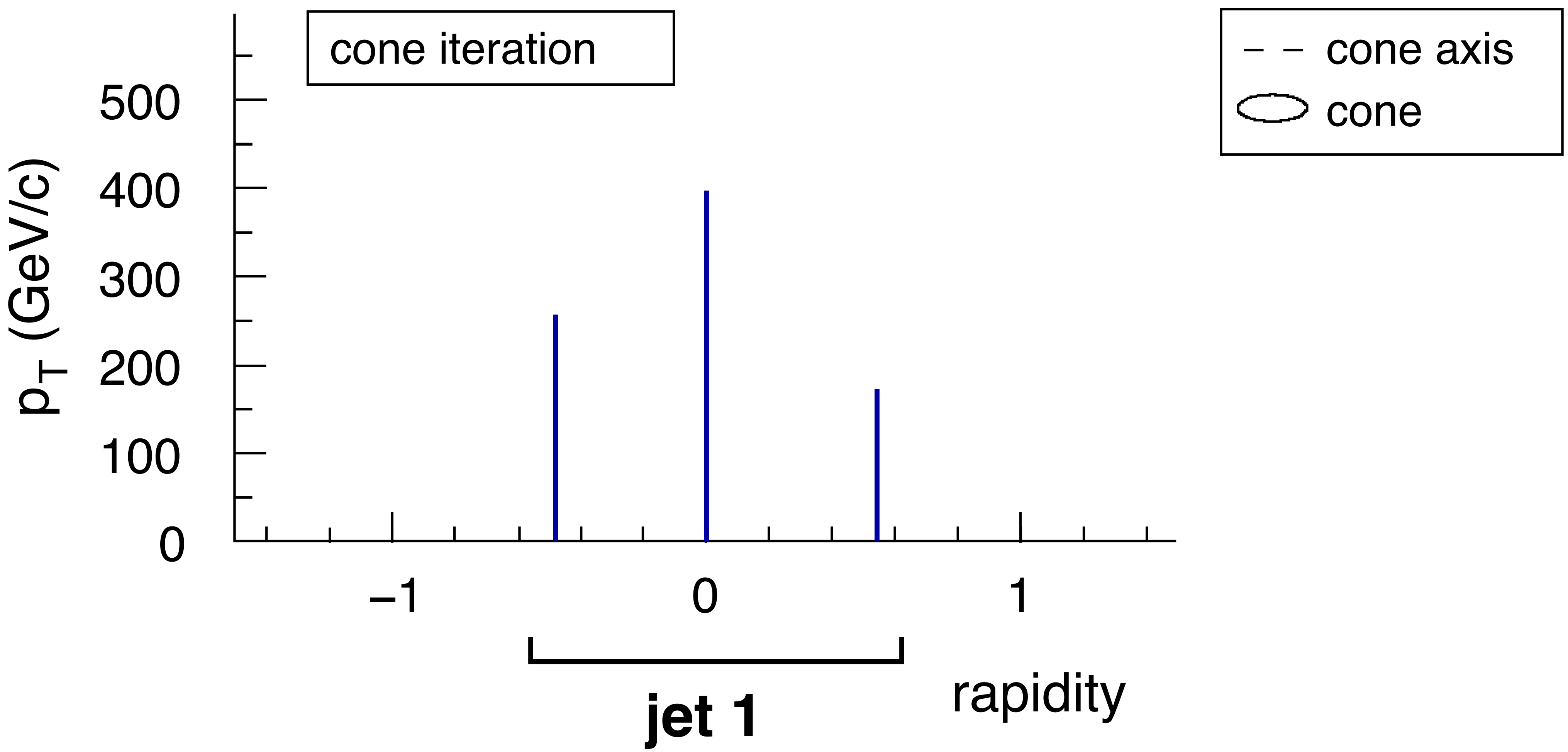


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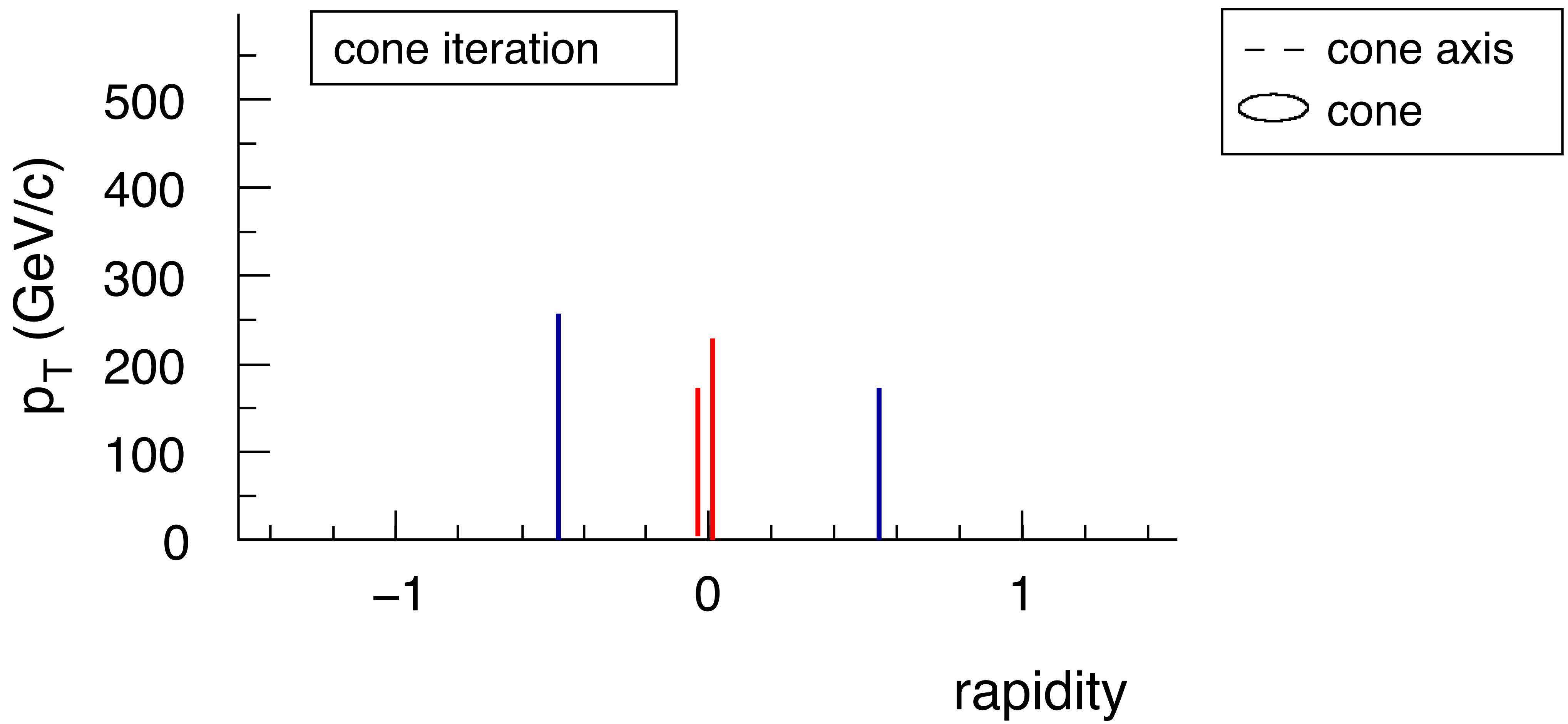


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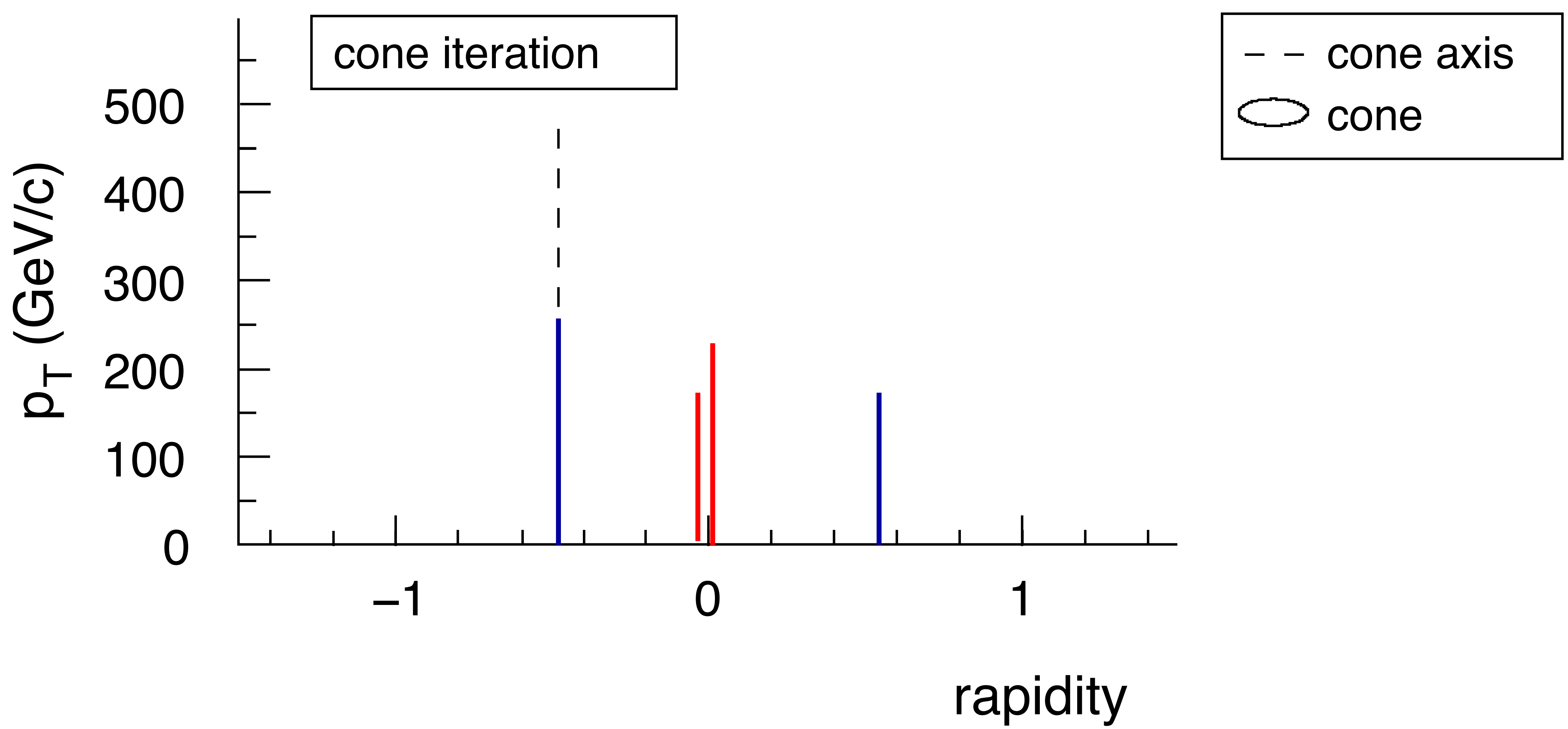


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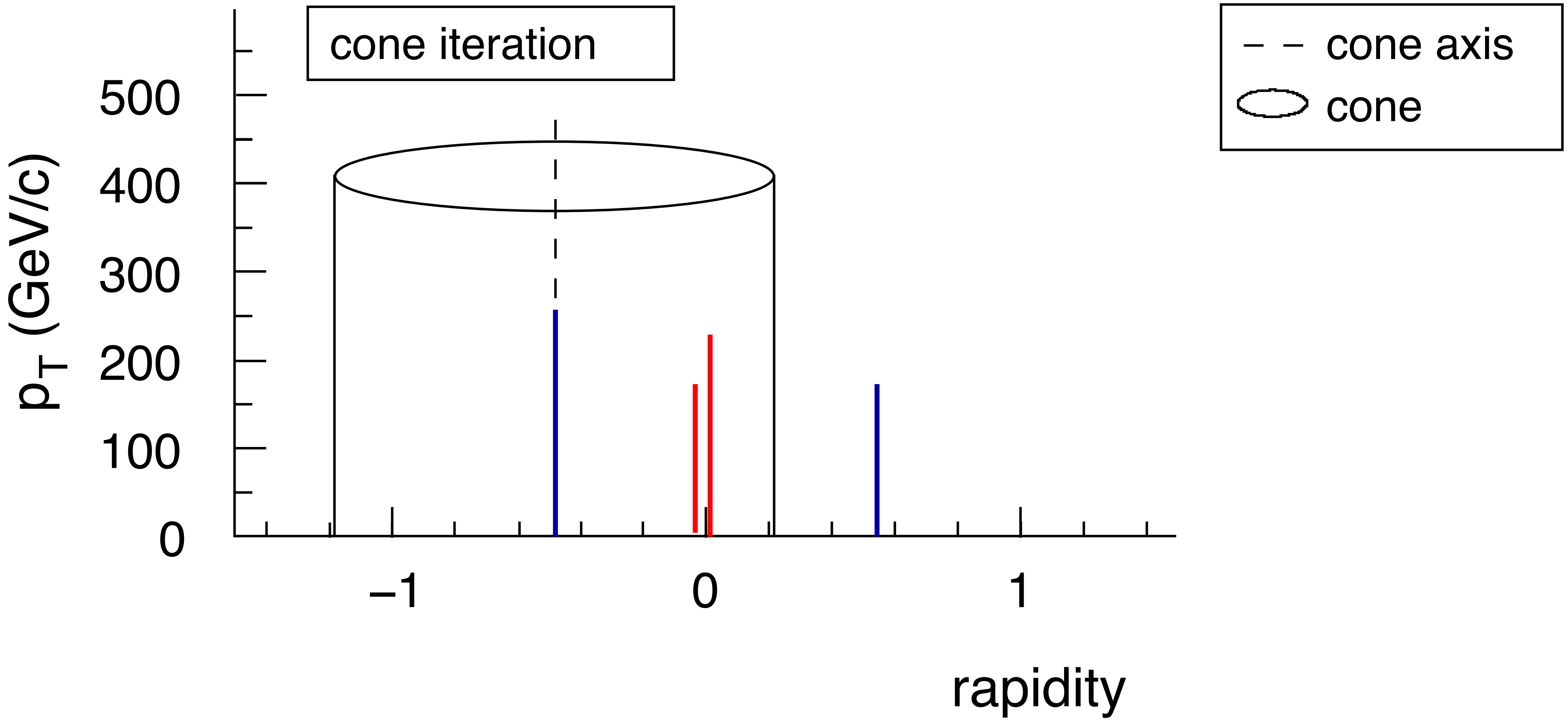


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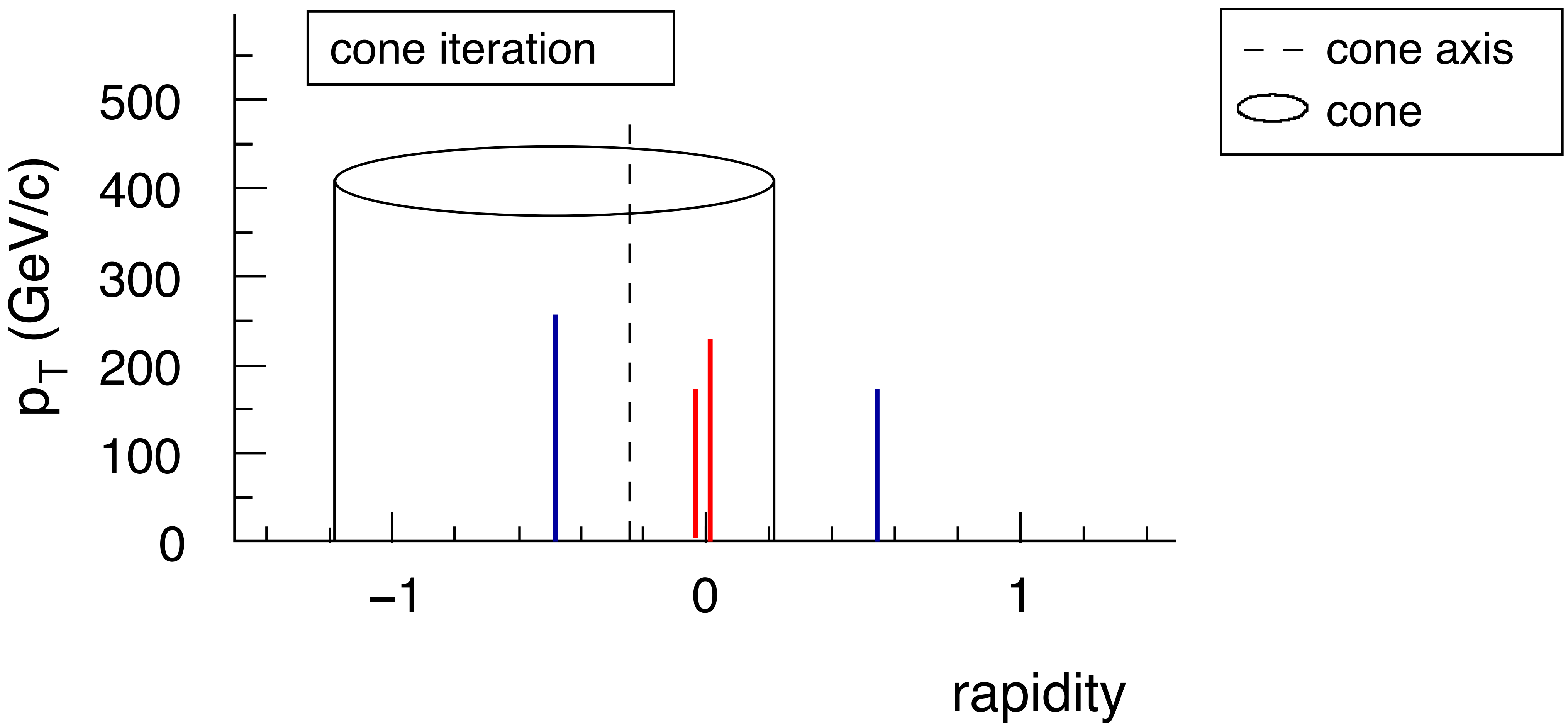


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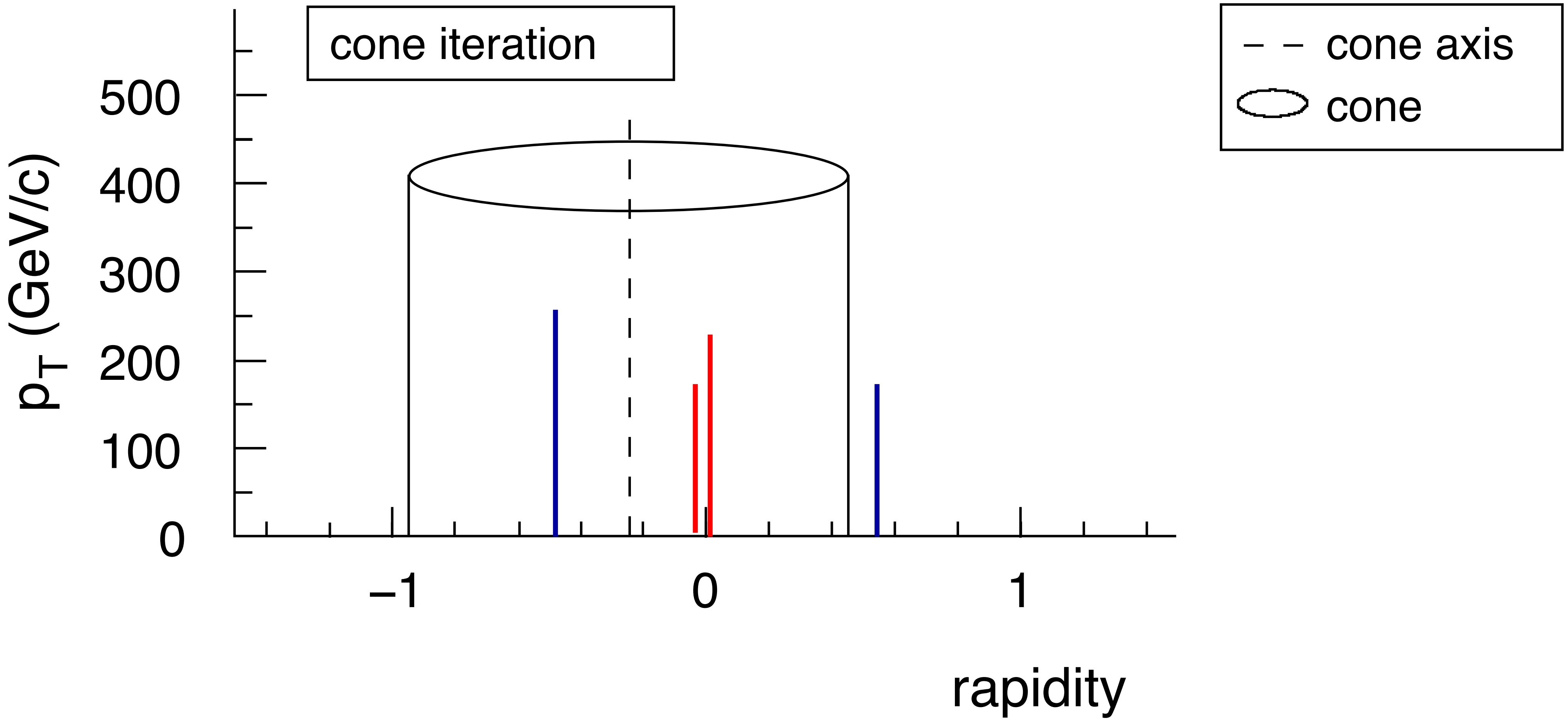


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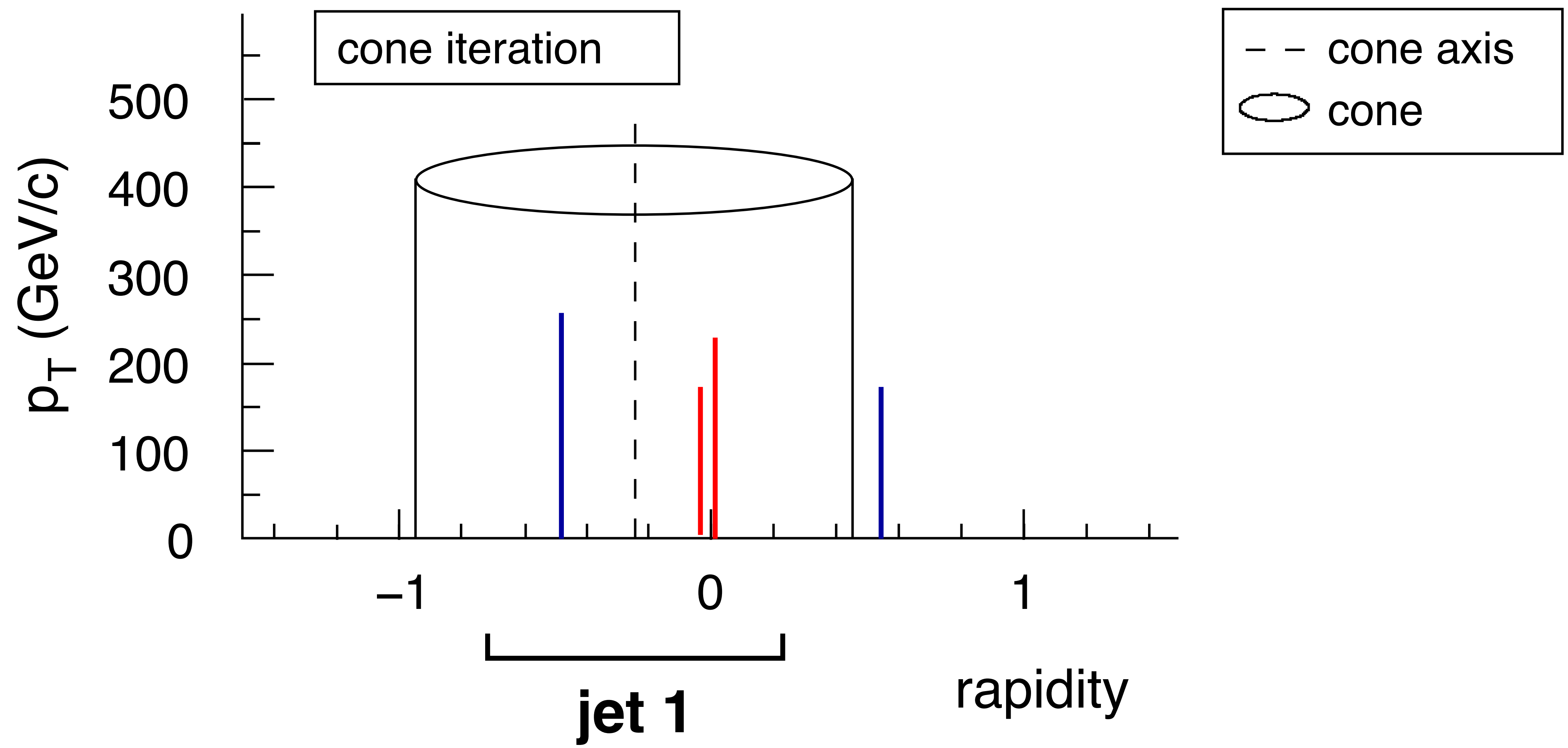


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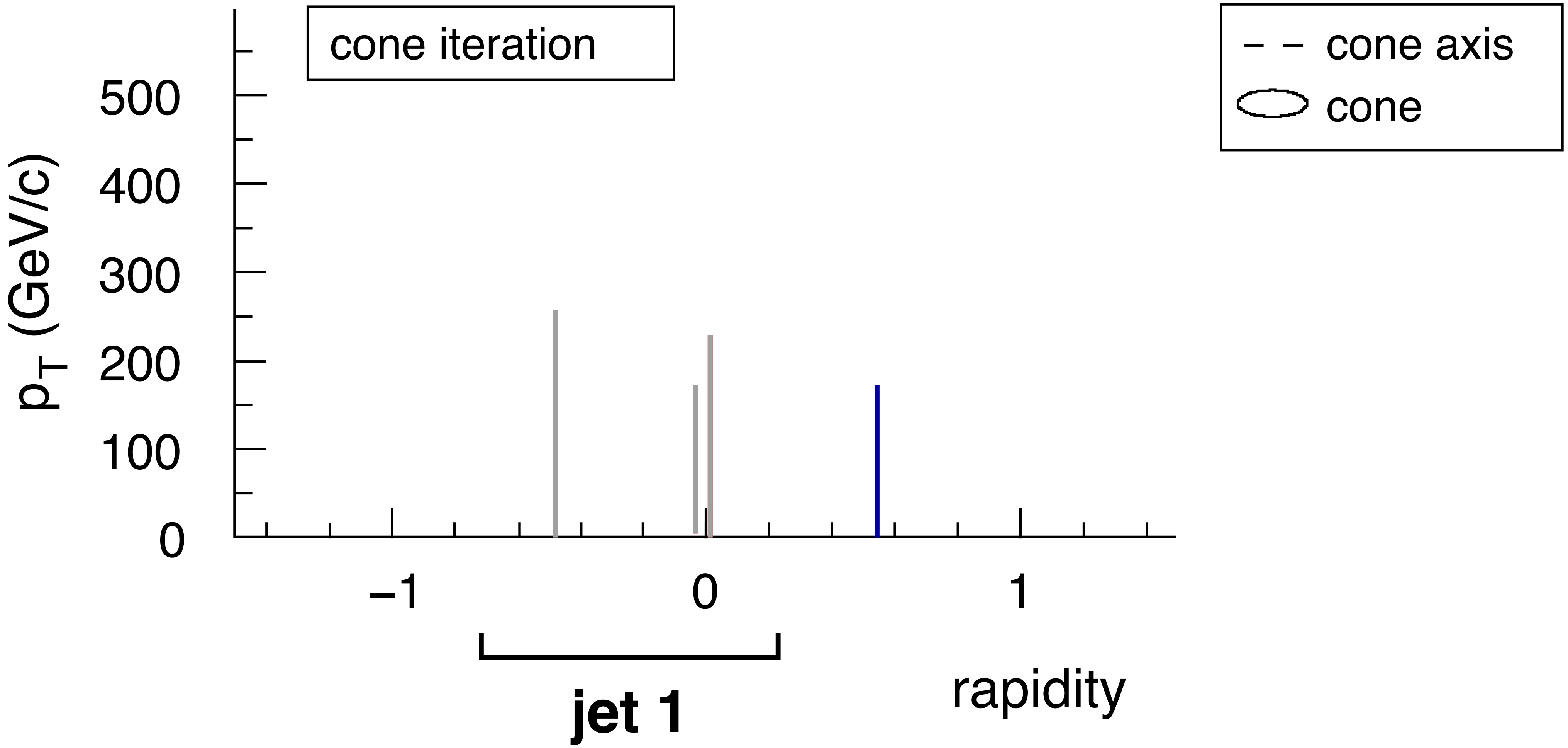


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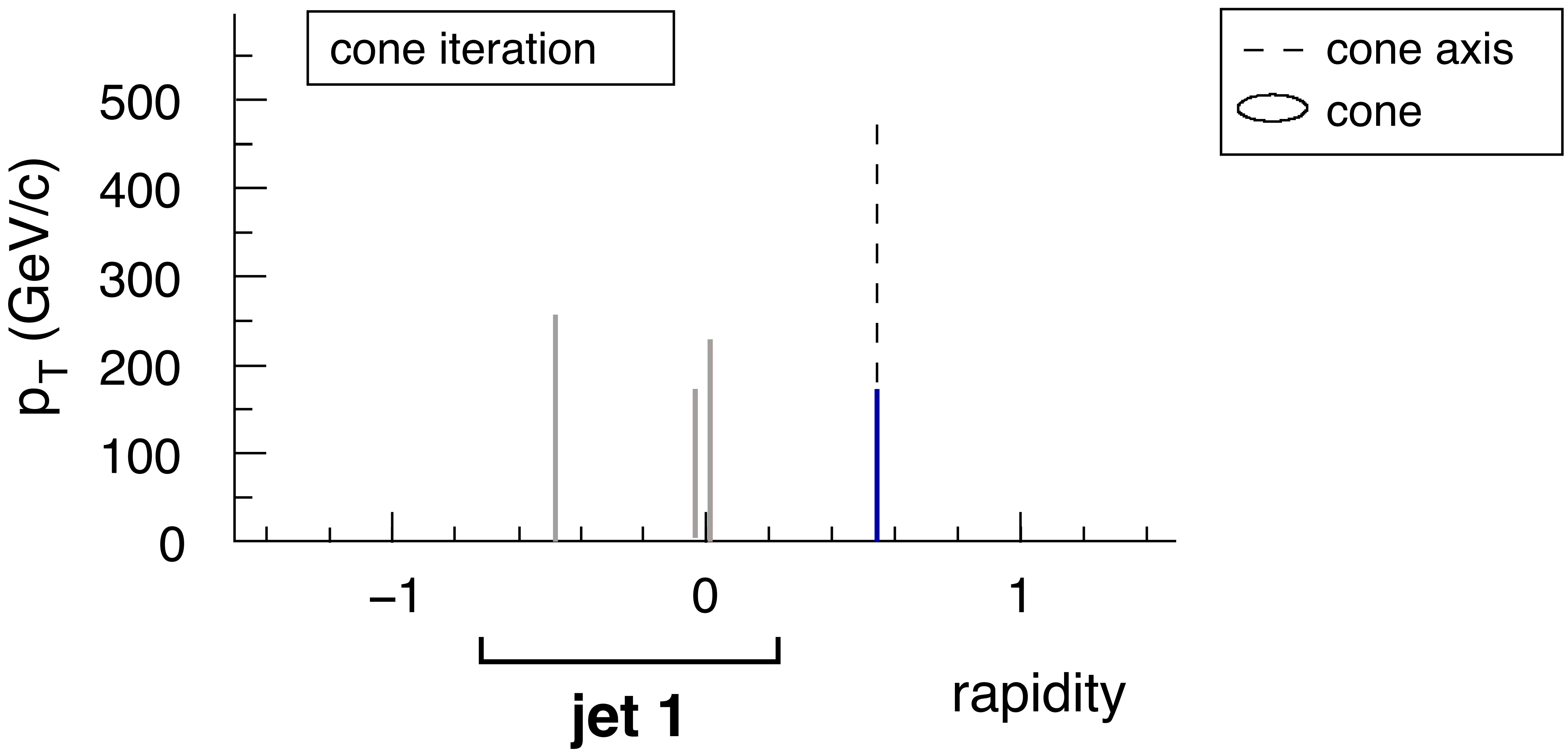


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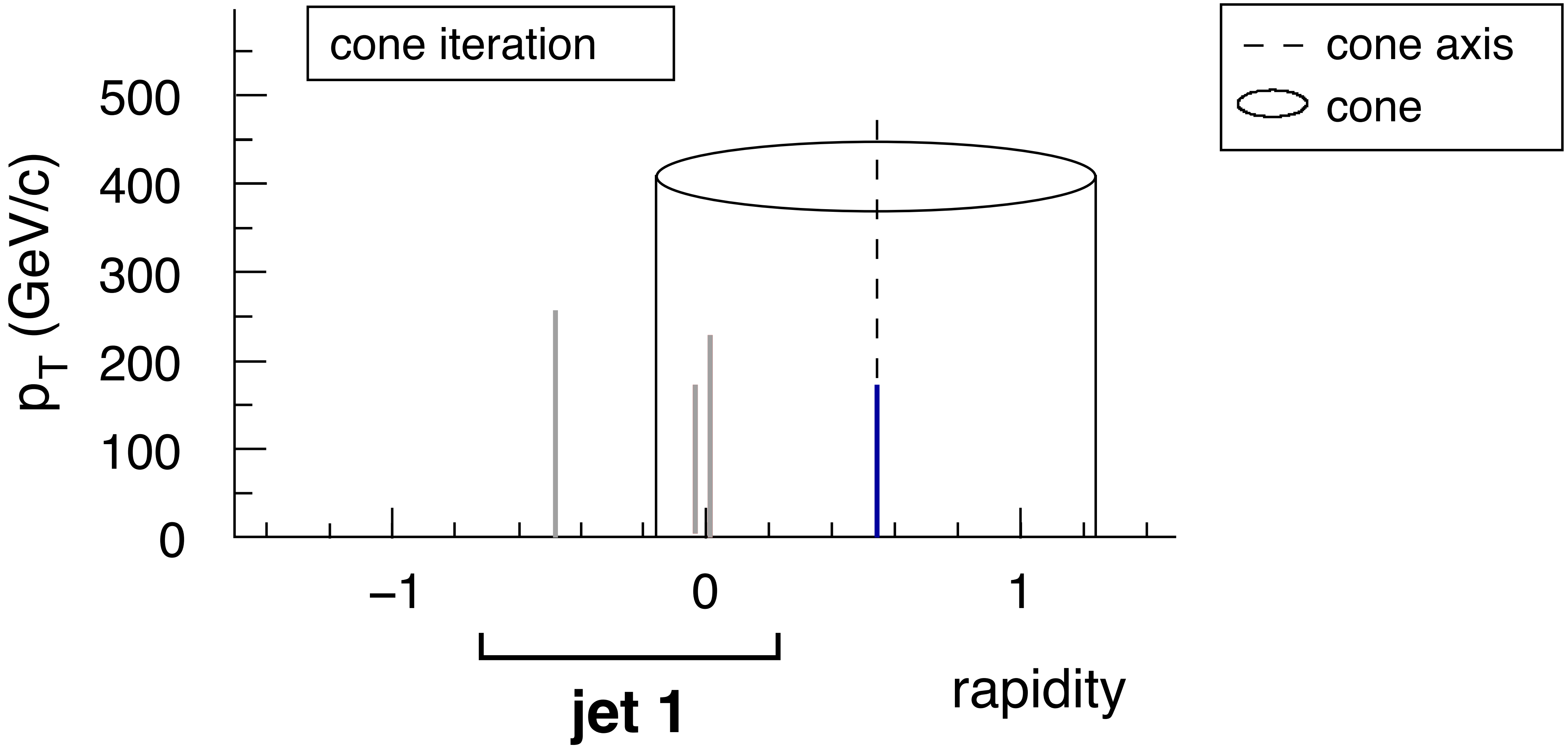


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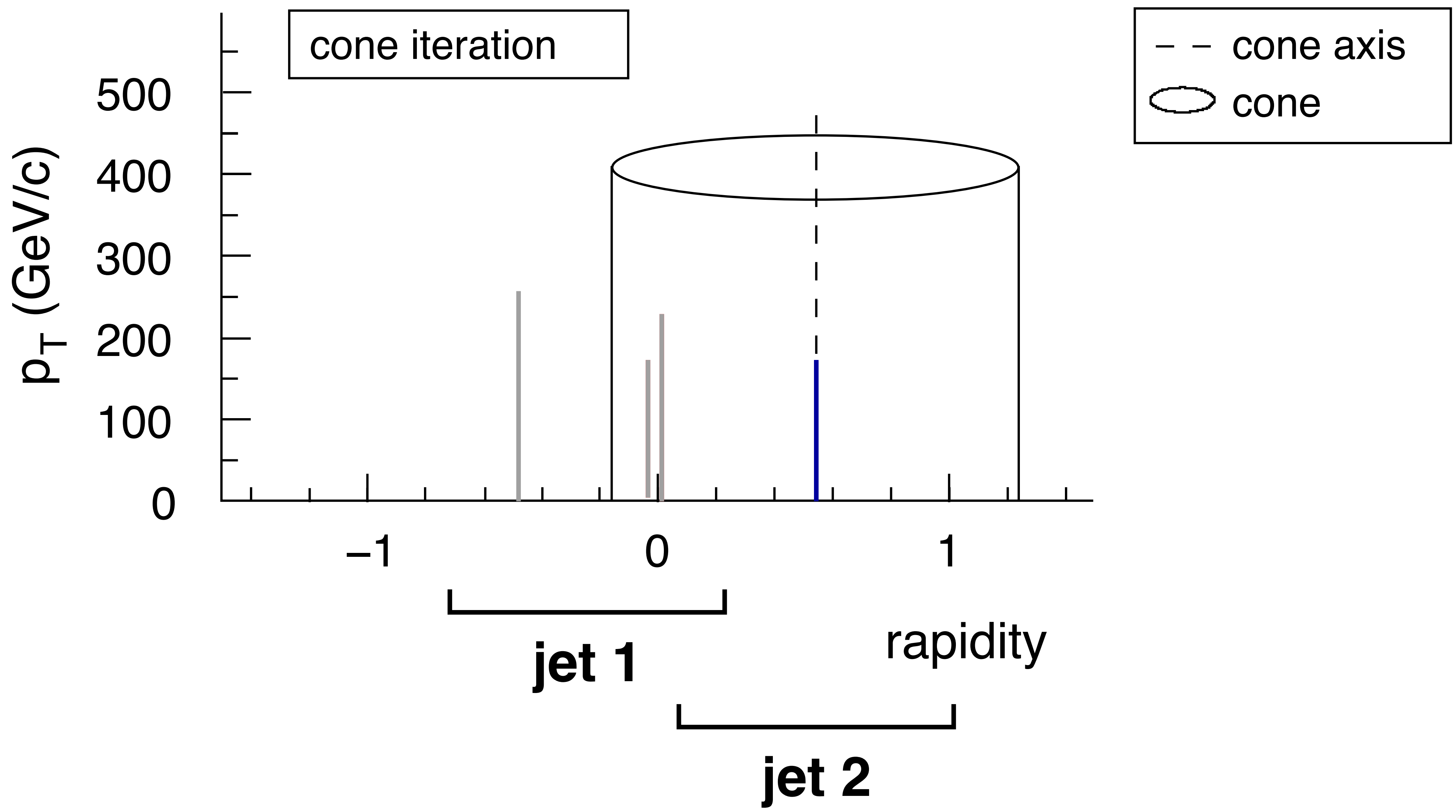


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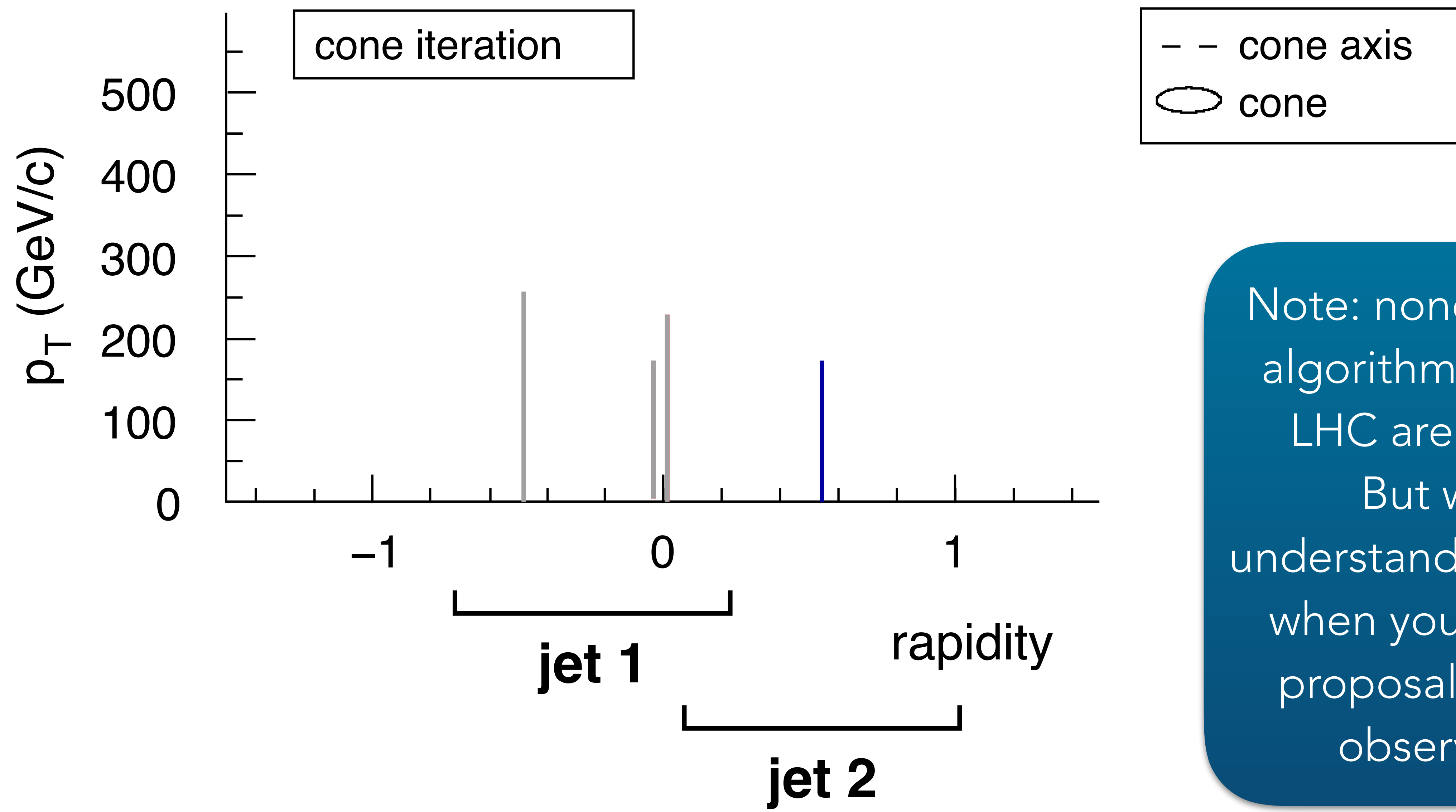



Note: none of the jet algorithms in use at LHC are seeded. But worth understanding issue if/ when you consider proposals for new observables

**Collinear splitting can modify the hard jets: ICPR algorithms are collinear unsafe** $\Longrightarrow$ perturbative calculations give $\infty$

Slides from G. Salam

# STEREO VISION

## Use IR Safe algorithms

(e.g., FASTJET)
*http://www.fastjet.fr/*

To study short-distance physics

Recombination-type algos → "inverse shower"

→ can study jet substructure → test shower properties + distinguish BSM

"Cone-like": **SiSCone** (unseeded)

"Recombination-like": **$k_T$, Cambridge/Aachen**

"Hybrid": **Anti-$k_T$** (cone-shaped jets from recombination-type algorithm; note: clustering history not ~ shower history)


## Use IR Sensitive observables

E.g., number of tracks, identified particles, …

To explicitly study hadronisation and models of IR physics

→ message is not to avoid IR unsafe observables at all costs. But to know when and how to use them.

# SUMMARY

## Jets

Discovered at SPEAR (SLAC '72) and DORIS (DESY '73): $E_{CM} \sim 5$ GeV

Collimated sprays of nuclear matter (hadrons).

Interpreted as the "fragmentation of fast partons" -> MC generators

## PYTHIA (and EPOS): Strings enforce confinement; break up into hadrons

Based on **linear confinement:** $V(r) = \kappa r$ at large distances + Schwinger tunneling

Powerful energy-momentum picture, with few free parameters

Not very predictive for flavour/spin composition; many free parameters

## HERWIG and SHERPA employ 'cluster model'

Based on **universality of cluster mass spectra** + 'preconfinement'

Algorithmically simpler; flavour/spin composition largely from hadron masses

## NB: many indications that confinement is more complicated in pp

~ well understood in "dilute" environments (ee: LEP) ~ vacuum

LHC is providing a treasure trove of measurements on jet fragmentation, identified particles, minimum-bias, underlying event, … tomorrow's lecture!

# Extra Slides

# THE EFFECTS OF HADRONISATION

## Generally, expect few-hundred MeV shifts by hadronisation

Corrections to IR safe observables are “power corrections”

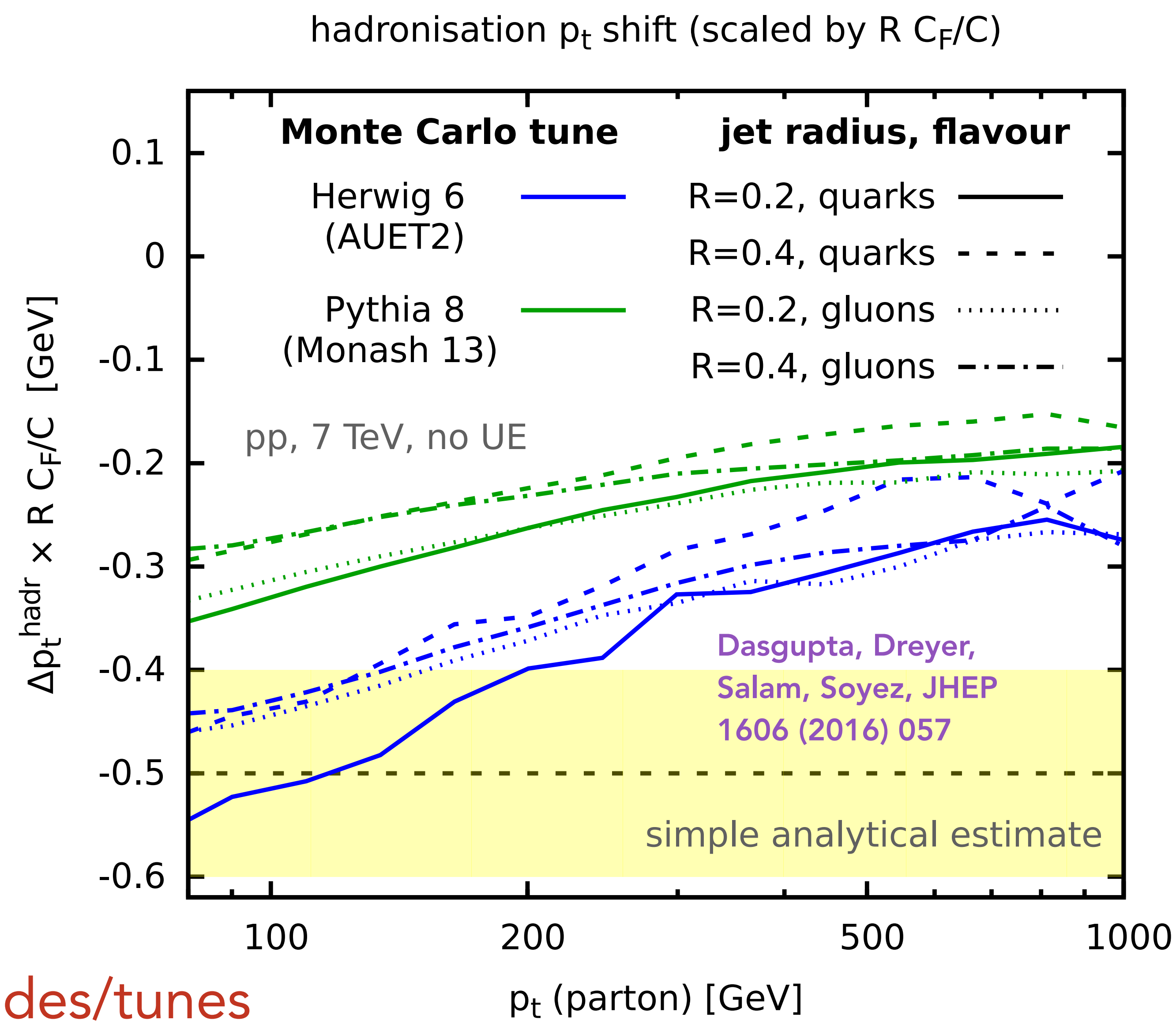
$$\propto \Lambda^2_{\mathrm{QCD}}/Q^2_{\mathrm{OBS}}$$

Corrections for jets of radius $R = \Delta\eta \times \Delta\phi$

$$\propto 1/R$$

See
Korchemsky, Sterman, NPB 437 (1995) 415
Seymour, NPB 513 (1998) 269
Dasgupta, Magnea, Salam, JHEP 0802 (2008) 055

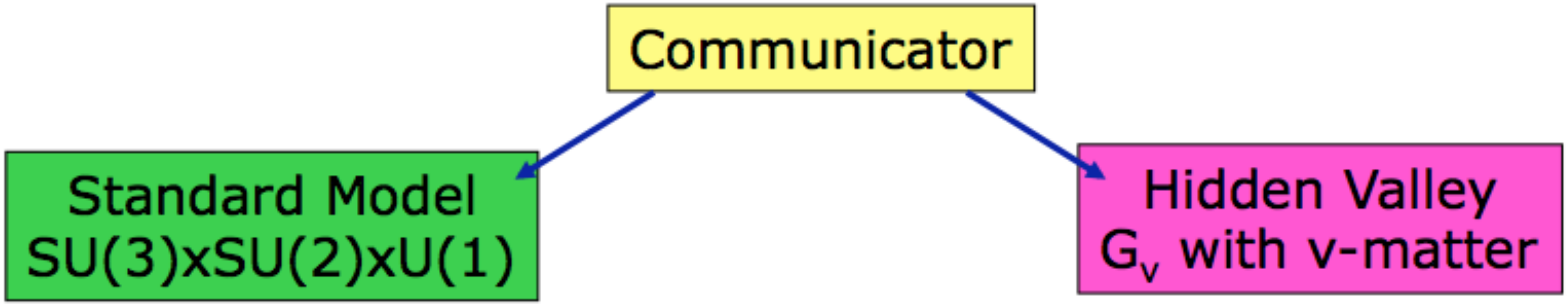
Simple analytical estimate
→ ~ 0.5 GeV / R correction from hadronisation
(scaled by colour factor)

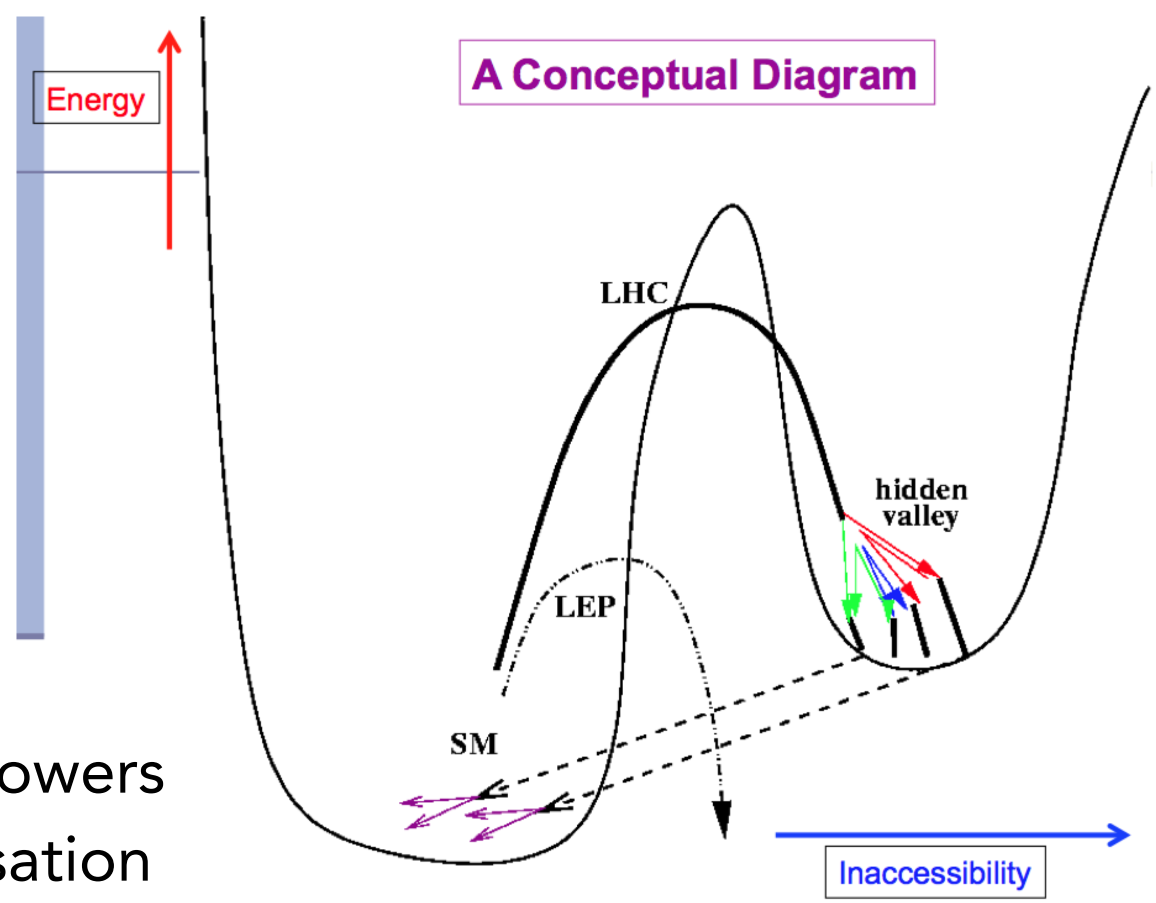



Significant differences between codes/tunes
→ **important to pin down with precise QCD hadronisation measurements at LHC**

# HIDDEN VALLEYS / EMERGING JETS

M. Strassler, K. Zurek, Phys. Lett. B651 (2007) 374; . . .




Hidden Valley
aka "Dark" Sector
aka "Hidden" Sector

Courtesy
M. Strassler

Hidden-Valley Showers
+ Valley Hadronisation

→ L. Carloni & TS, JHEP 1009, 105; L. Carloni, J. Rathsman & TS, JHEP 1104, 091

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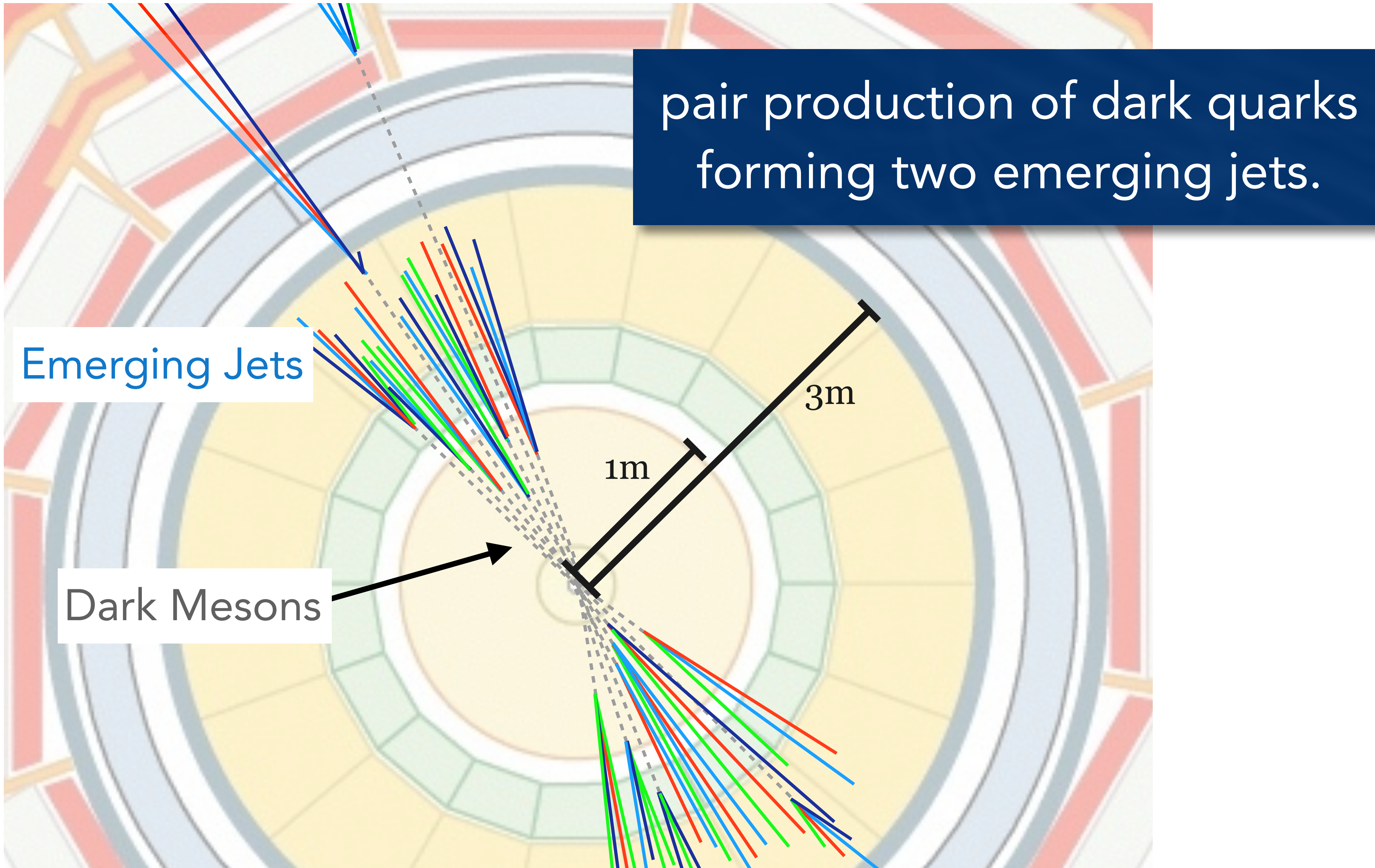



Requirements for a model to produce emerging jet phenomenology:

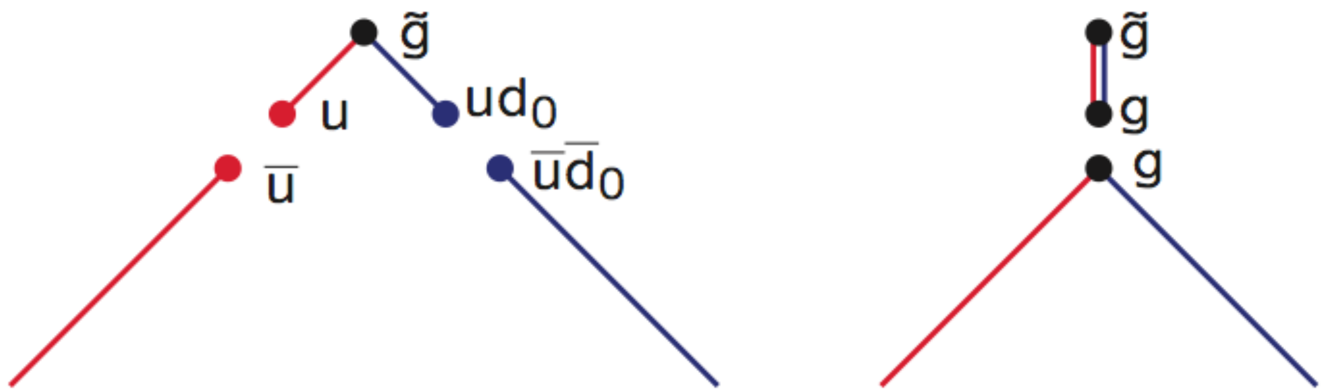
- Hierarchy between the mediator mass and hidden sector mass.
- Strong coupling in hidden sector → large particle multiplicity.
- Macroscopic decay lengths of hidden sector fields back to the visible sector

Schwaller, Stolarski, Weiler
JHEP 1505 (2015) 059

# R-HADRONS

$\Rightarrow$ PYTHIA allows for hadronization of 3 generic states:

- colour octet uncharged, like $\tilde{g}$, giving $\tilde{g}u\bar{d}$, $\tilde{g}uud$, $\tilde{g}g$, ...,
- colour triplet charge $+2/3$, like $\tilde{t}$, giving $\tilde{t}\bar{u}$, $\tilde{t}ud_0$, ...,
- colour triplet charge $-1/3$, like $\tilde{b}$, giving $\tilde{b}\bar{c}$, $\tilde{b}su_1$, ....




Gluino fragmenting to baryon or glueball

Most hadronization properties by analogy with normal string fragmentation, but glueball formation new aspect, assumed $\sim$ 10% of time (or less).

R-hadron interactions with matter: part of detector simulation, i.e. GEANT, not PYTHIA
Freight-train BSM particle surrounded by light pion/gluon cloud → little dE/dx
+ charge flipping ! A.C. Kraan, Eur. Phys. J. C37 (2004) 91; M. Fairbairn et al., Phys. Rep. 438 (2007) 1