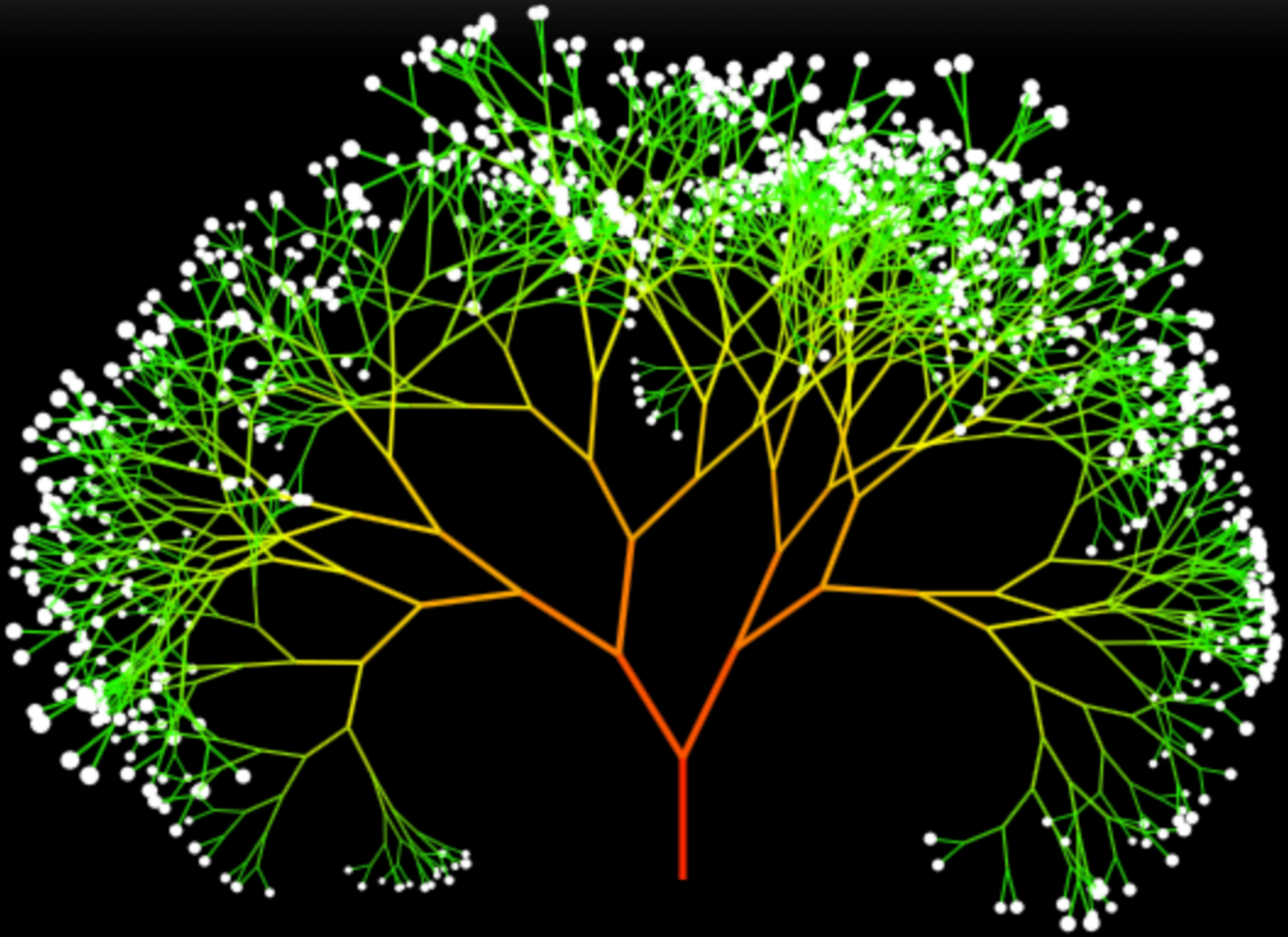
Particle Physics (Phenomenology)

Lecture 2/2

Peter Skands (Monash University)

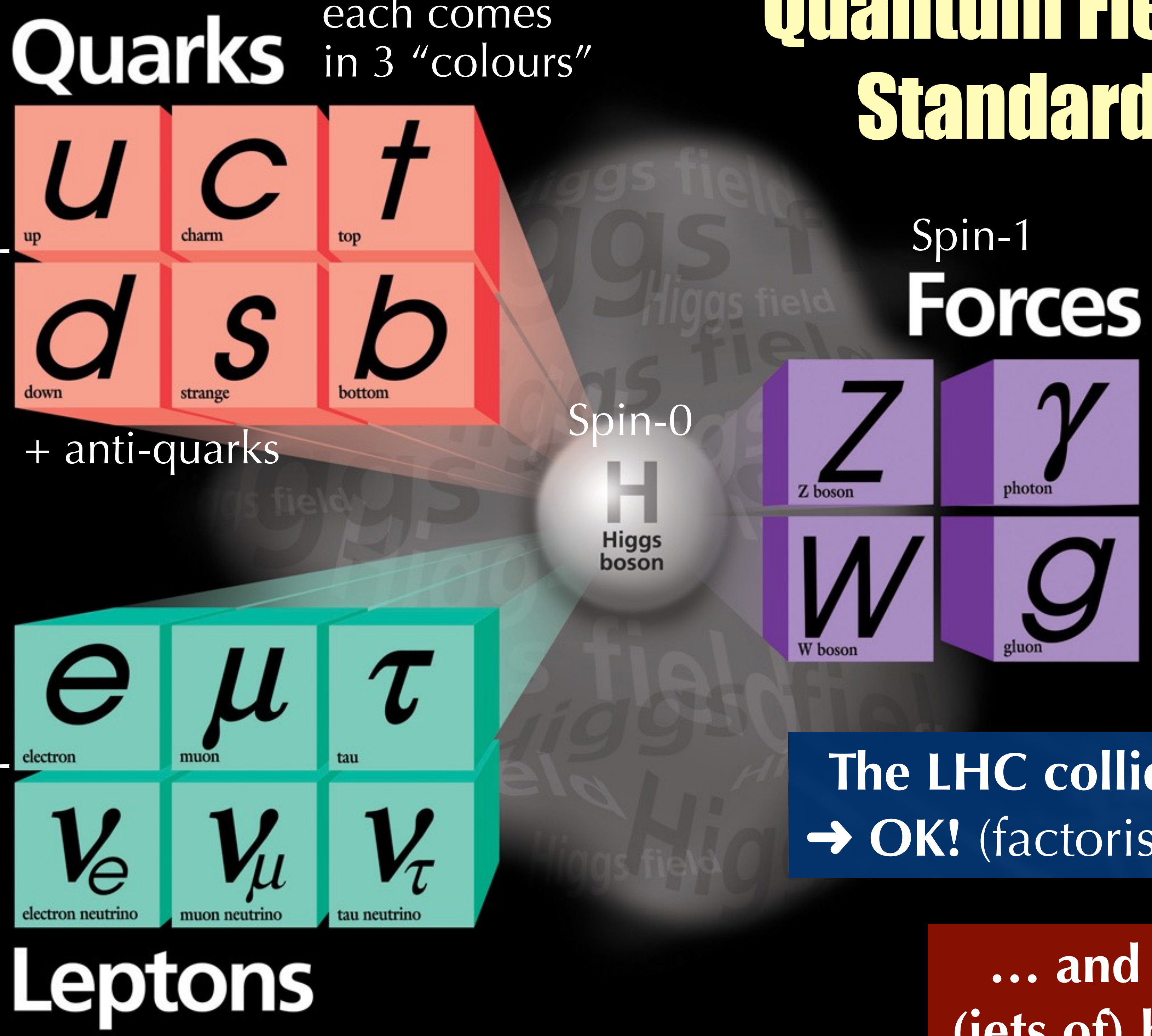


November 2019

Sydney Spring School

What can our (incoming and outgoing) states be?

Quantum Fields of the Standard Model



each comes in 3 “colours”

Spin-1/2

+ anti-quarks

Spin-0

Spin-1

8 “colours” of gluons

Spin-1/2

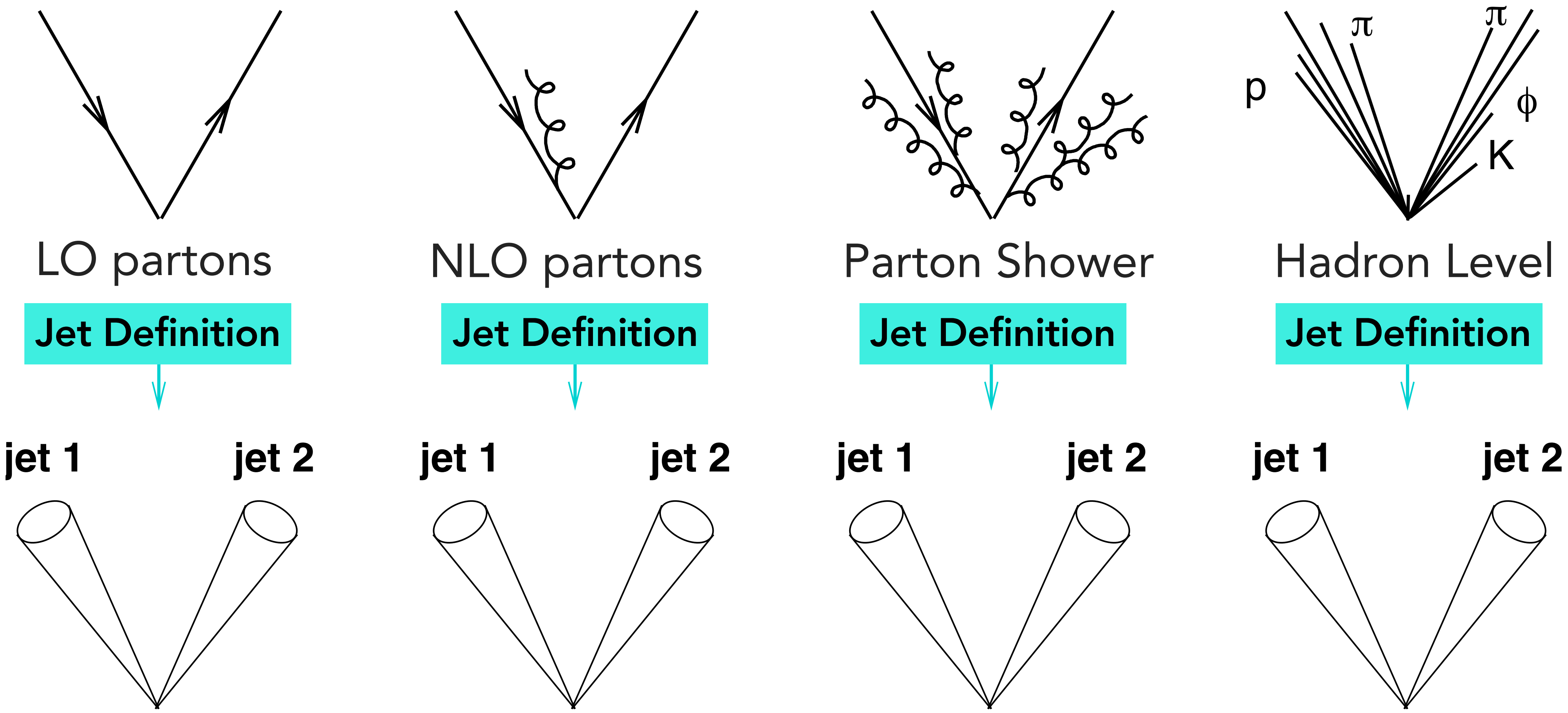
+ anti-leptons

The LHC collides protons
➜ OK! (factorisation; PDFs)

… and observes (jets of) hadrons …

What are Jets?

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



LO partons

Jet Definition

jet 1 **jet 2**

NLO partons

Jet Definition

jet 1 **jet 2**

Parton Shower

Jet Definition

jet 1 **jet 2**

Hadron Level

Jet Definition

jet 1 **jet 2**

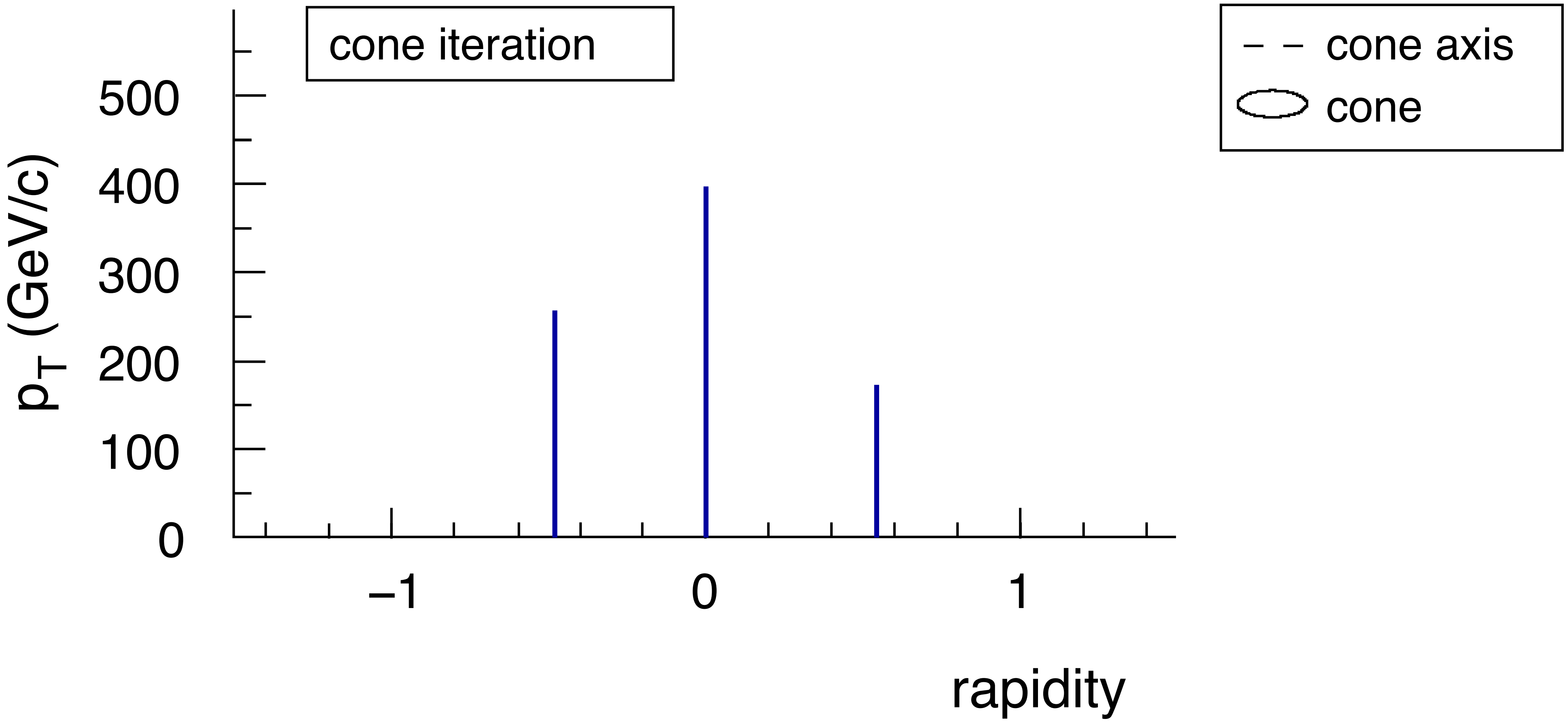
Illustrations by G. Salam

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 modeling of jets

Example of a "bad" algorithm: "Seeded Cone Algorithm"

Start from "hardest" seeds



Simplifed "event" with three energy depositions, at different "rapidities" (essentially different angles to the beam) in the detector

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

Want to find how many jets of a fixed "cone size" there are.

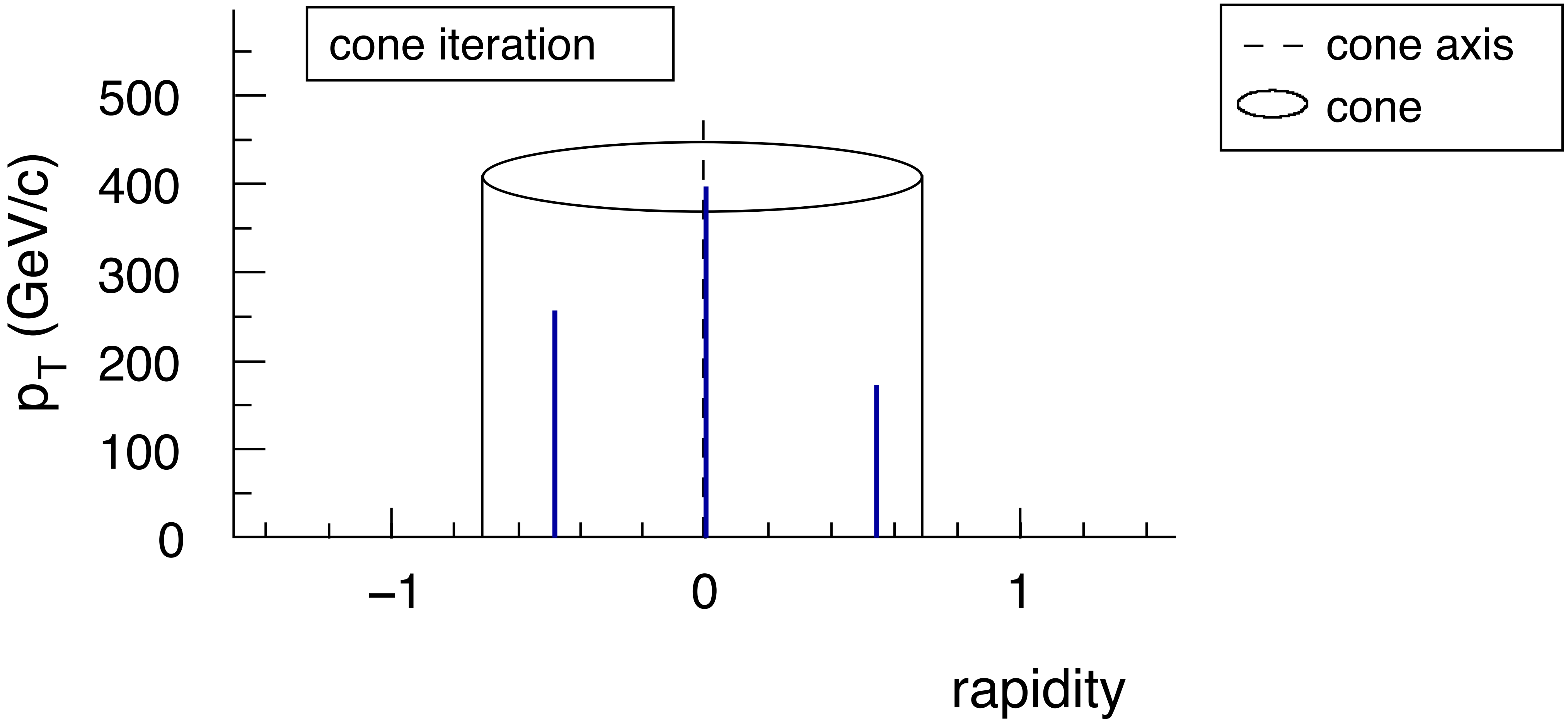
Idea: start from largest energy deposition as seed, and iterate from there.

Slides from G. Salam

Example of a “bad” algorithm: “Seeded Cone Algorithm”

Start from “hardest” seeds

Iterative Cone Progressive Removal



Looks ok but energy-weighted centre of jet ≠ jet axis.

Move jet axis to energy-weighted centre, and iterate until stable jet axis found

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

Slides from G. Salam

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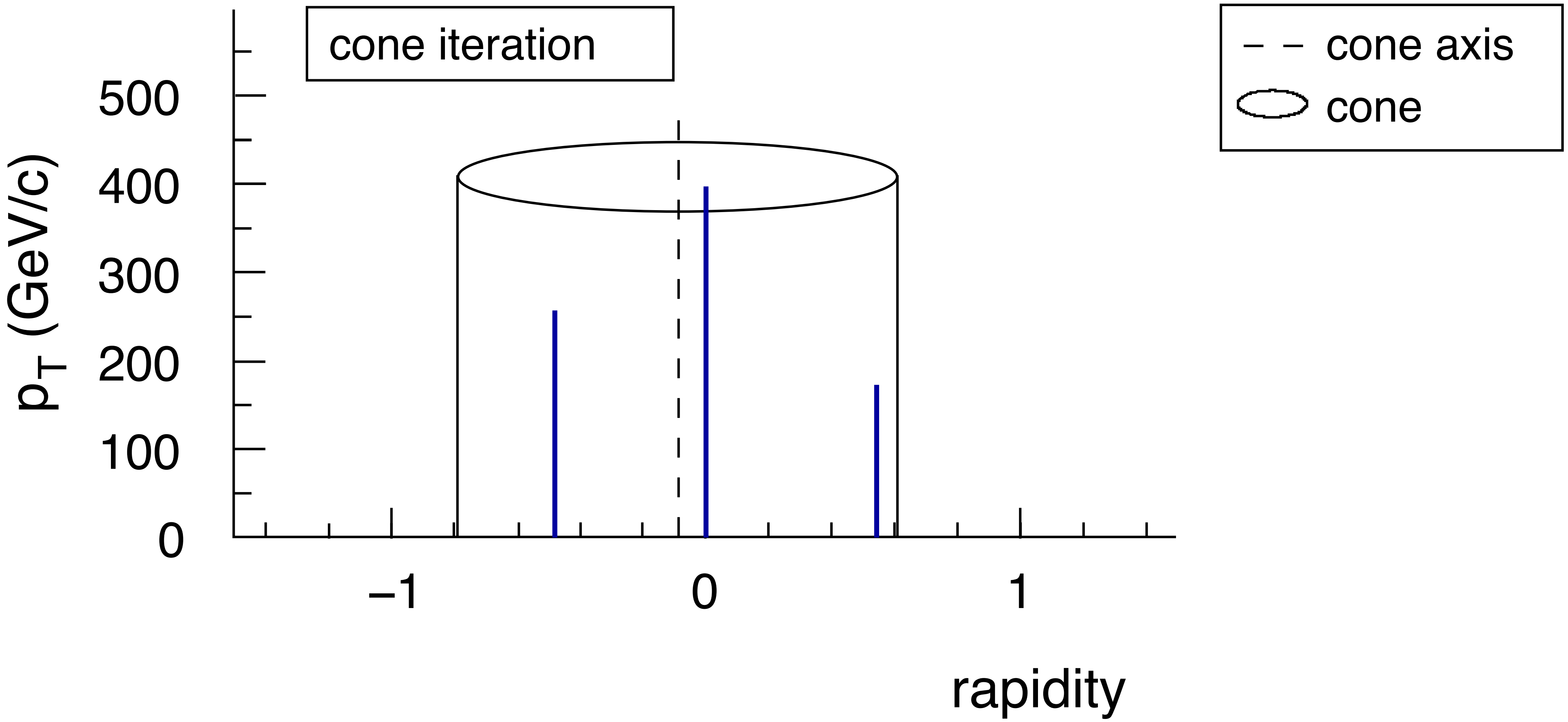

Stable.

Jet axis now gives us energy-weighted centre of jet.

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

Slides from G. Salam

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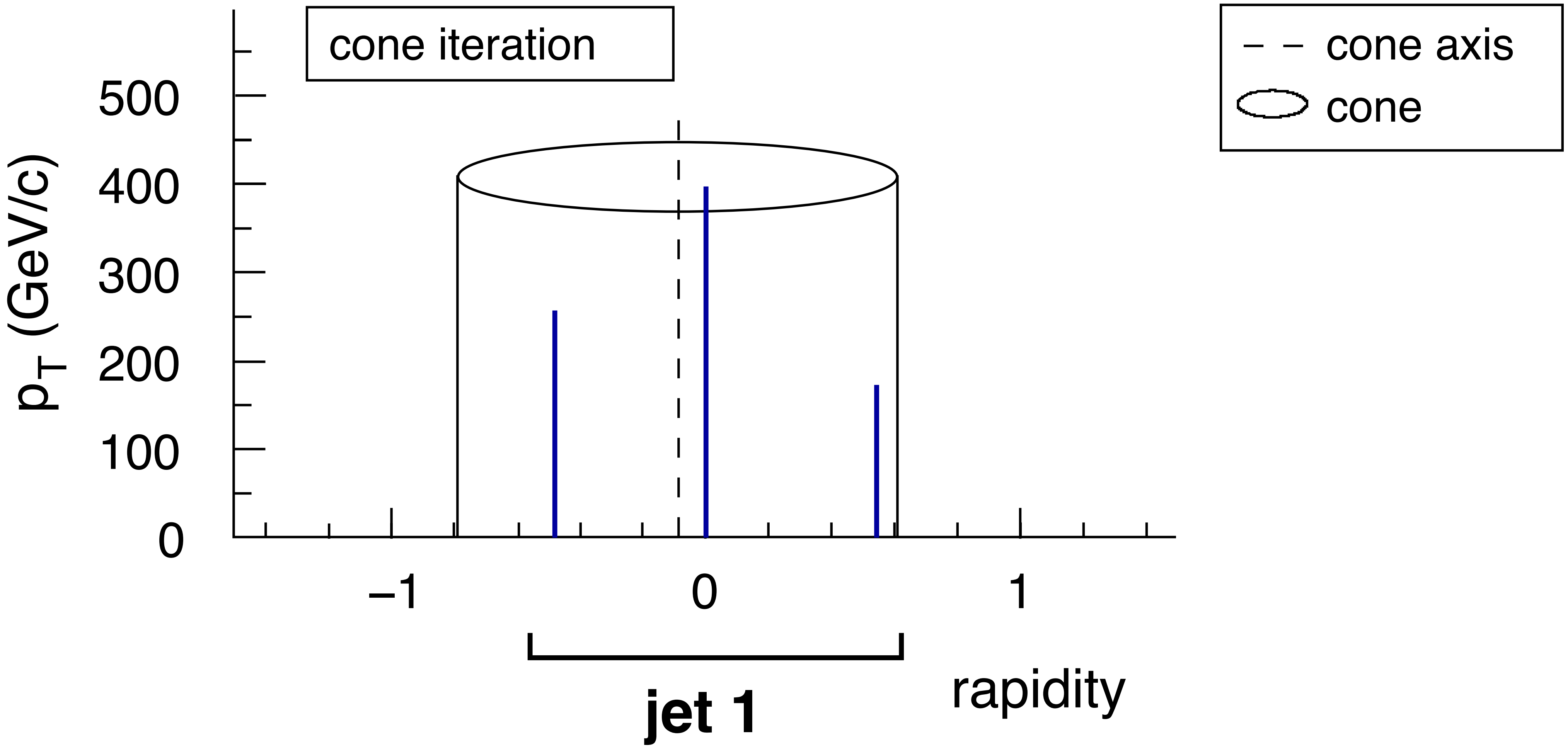

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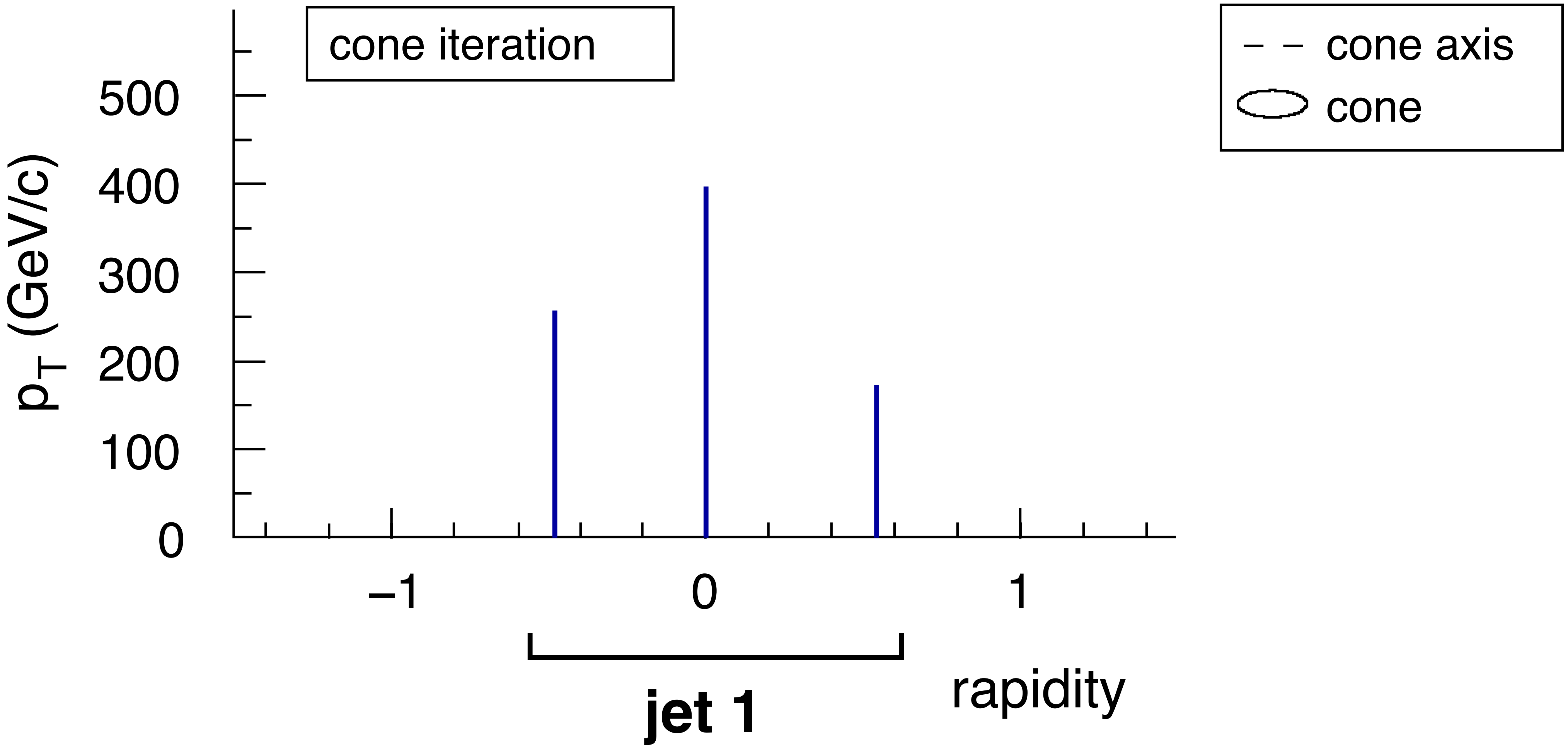

Looks fair. **Why is this bad?**

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

Slides from G. Salam

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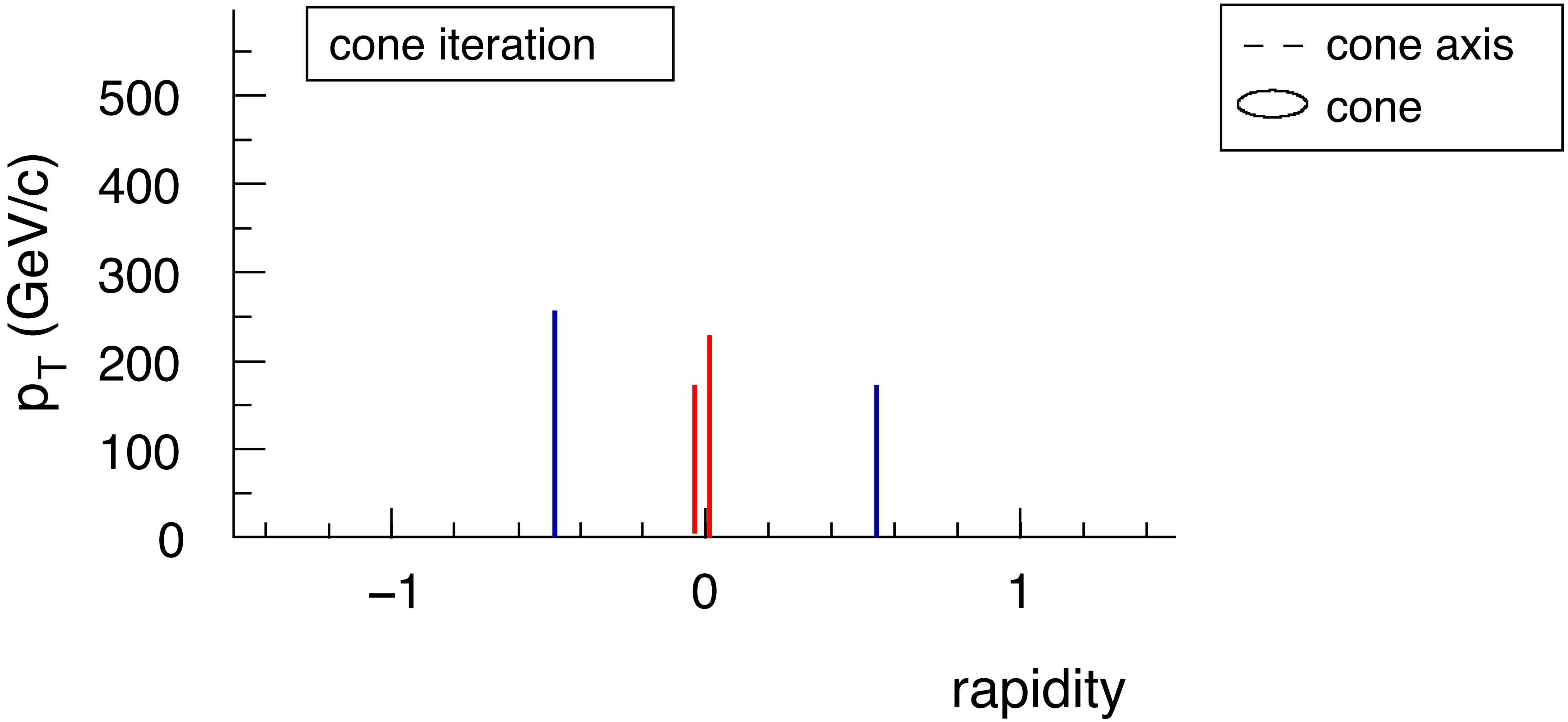
Start from “hardest” seeds



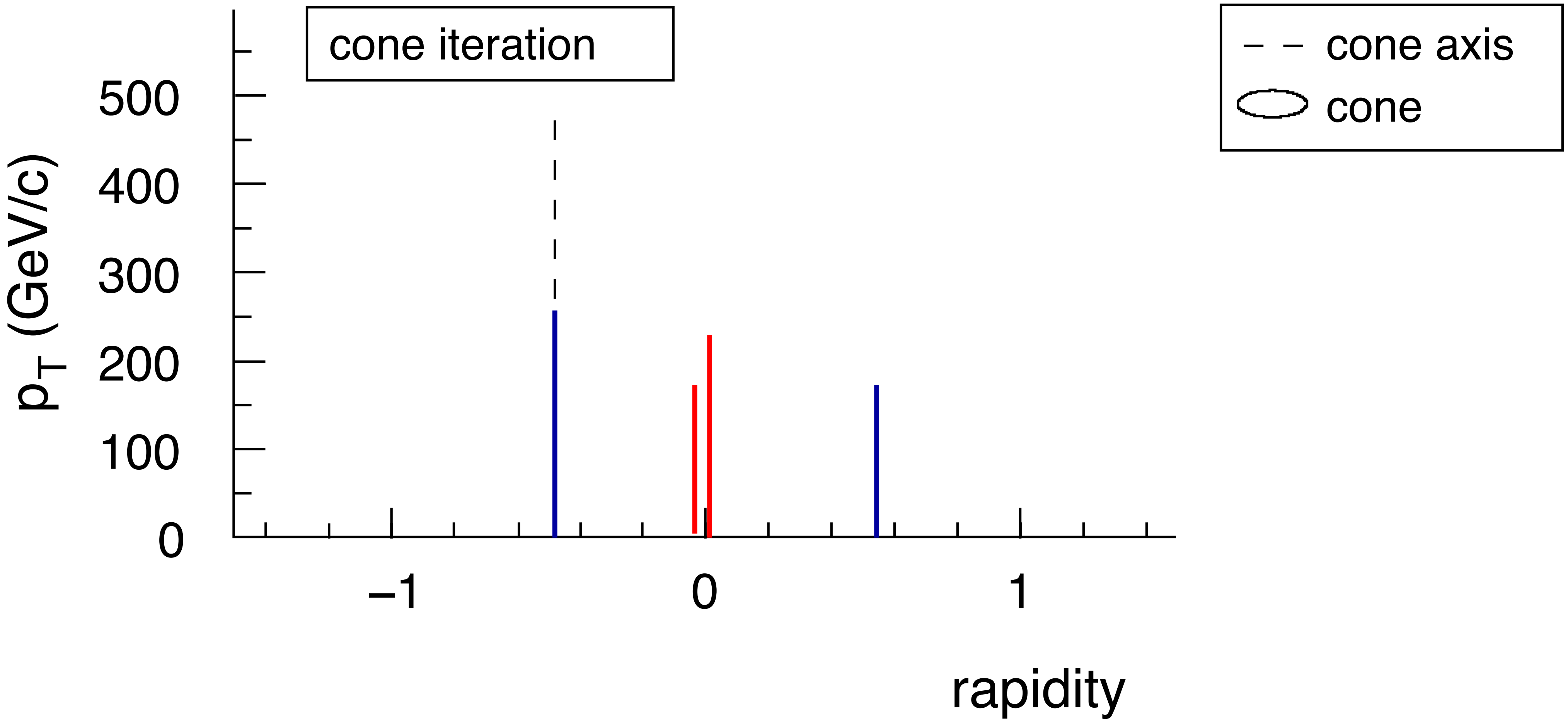
Here’s the same event, with the highest energy “seed” split into two separate (but almost “collinear”) cells

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

Slides from G. Salam

Example of a "bad" algorithm: "Seeded Cone Algorithm"

Start from "hardest" seeds



Now we would use a different seed to start from

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

Slides from G. Salam

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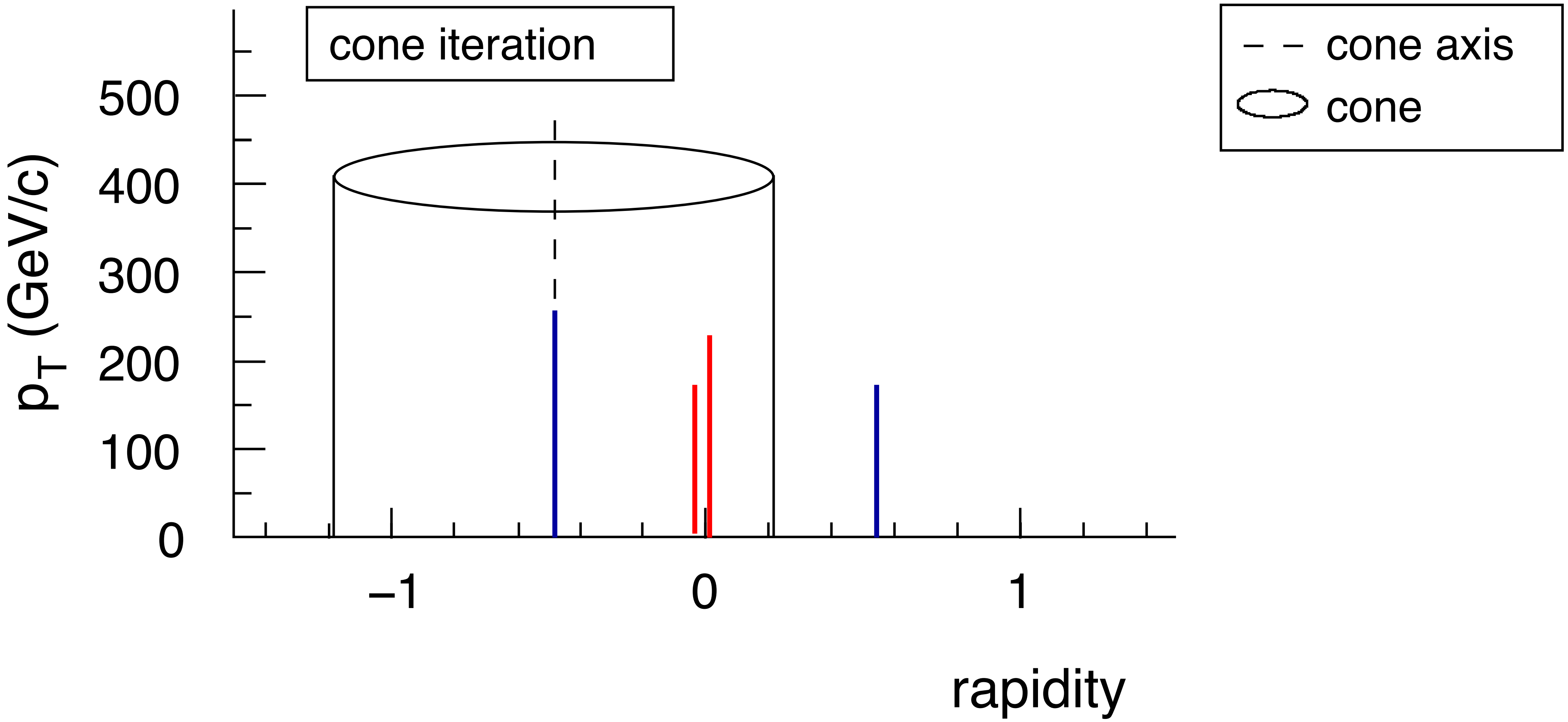
Start from "hardest" seeds

Iterative Cone Progressive Removal



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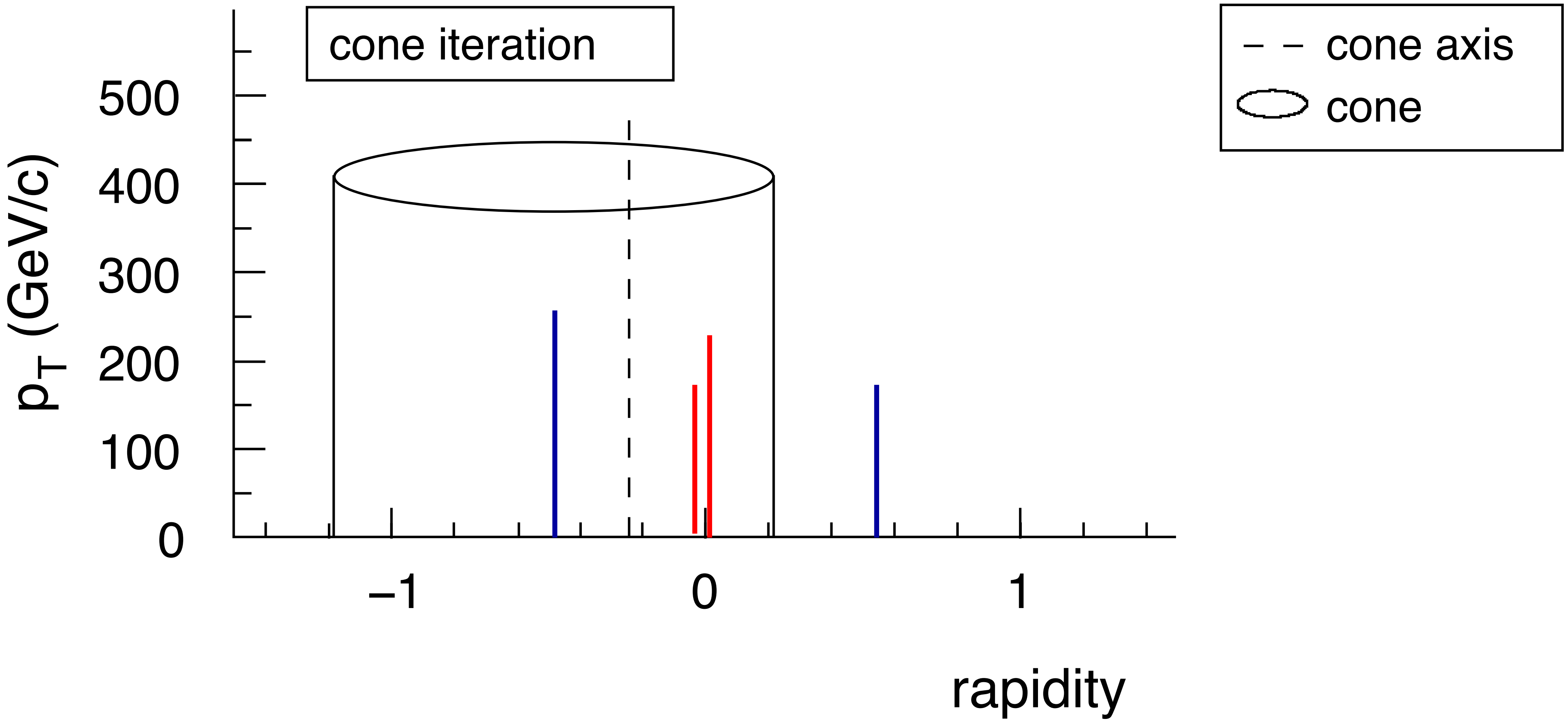

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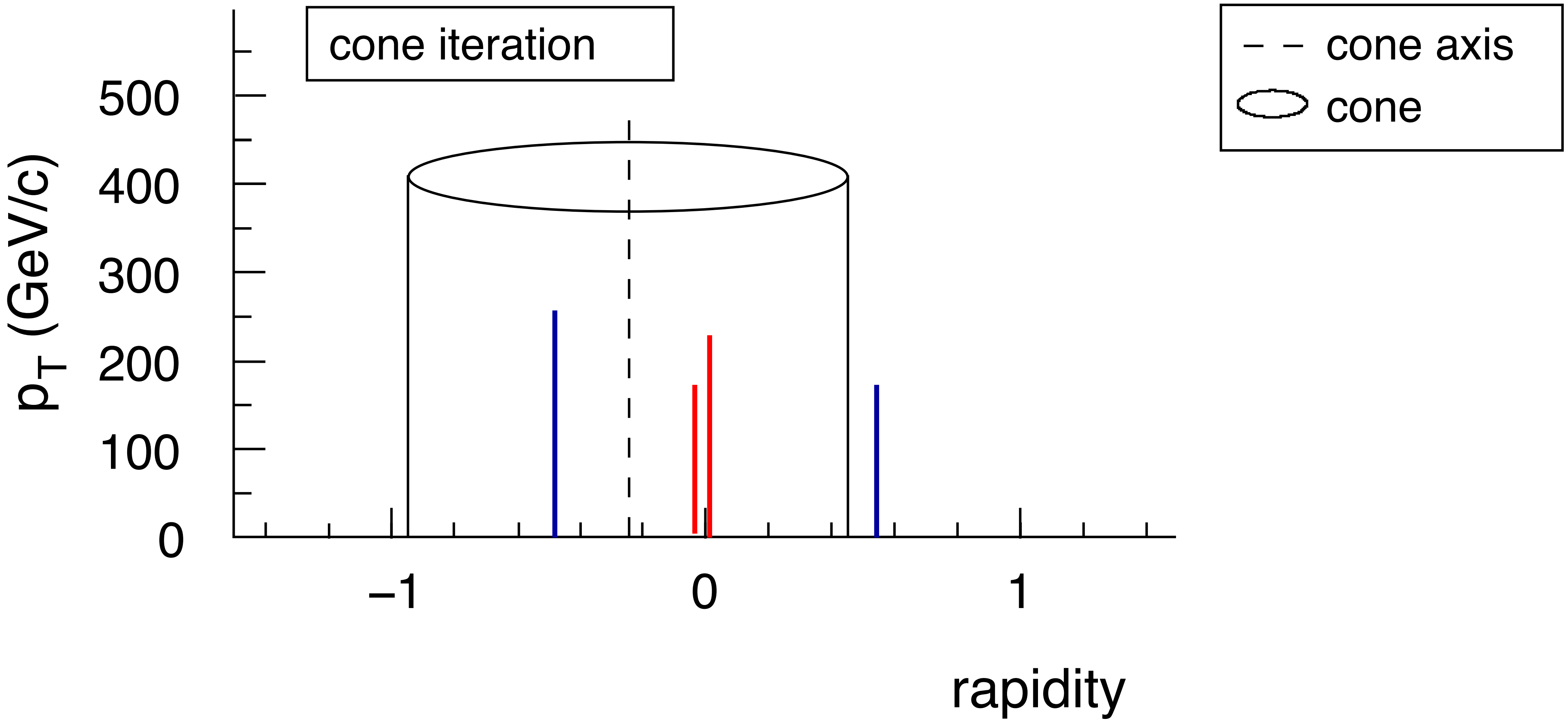

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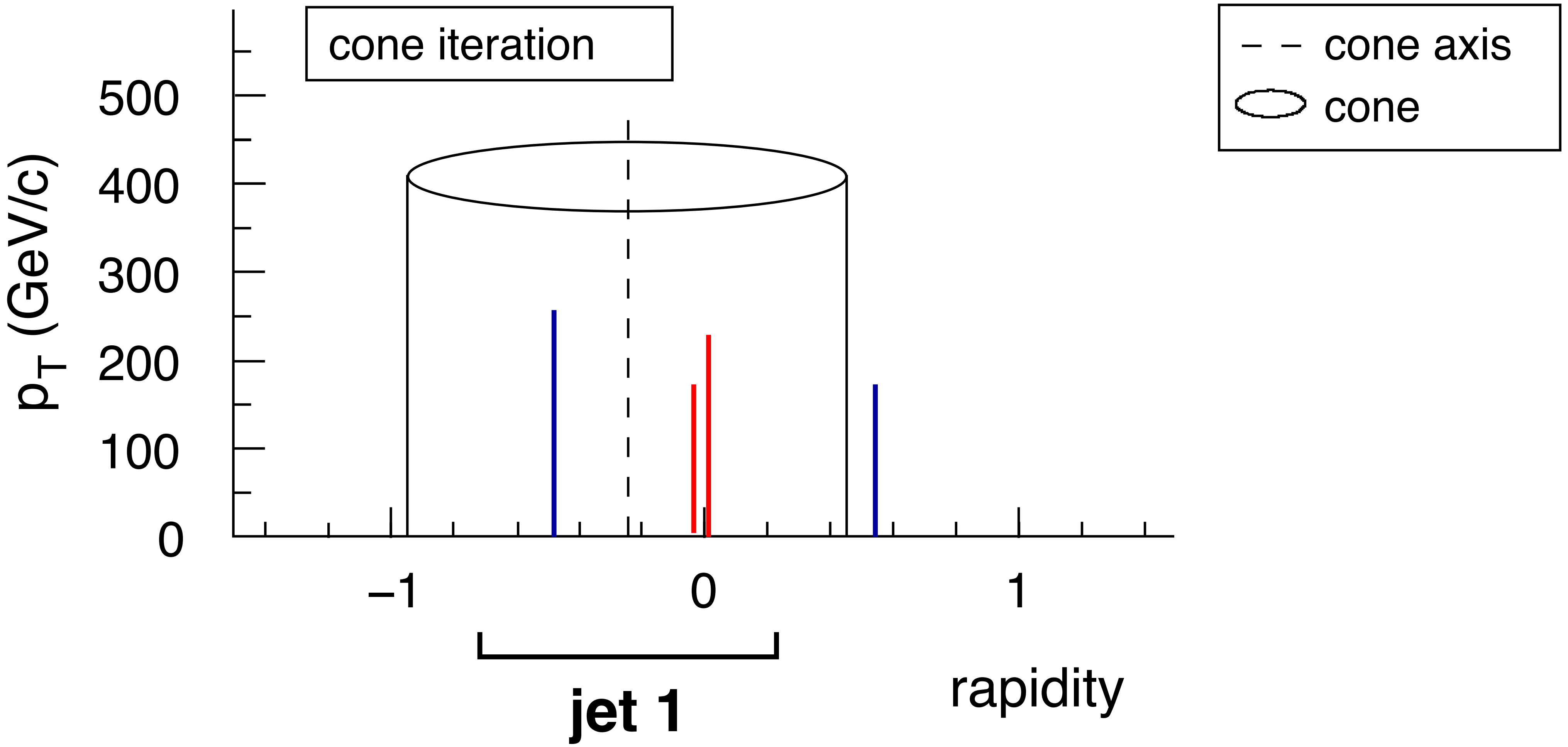

Slides from G. Salam

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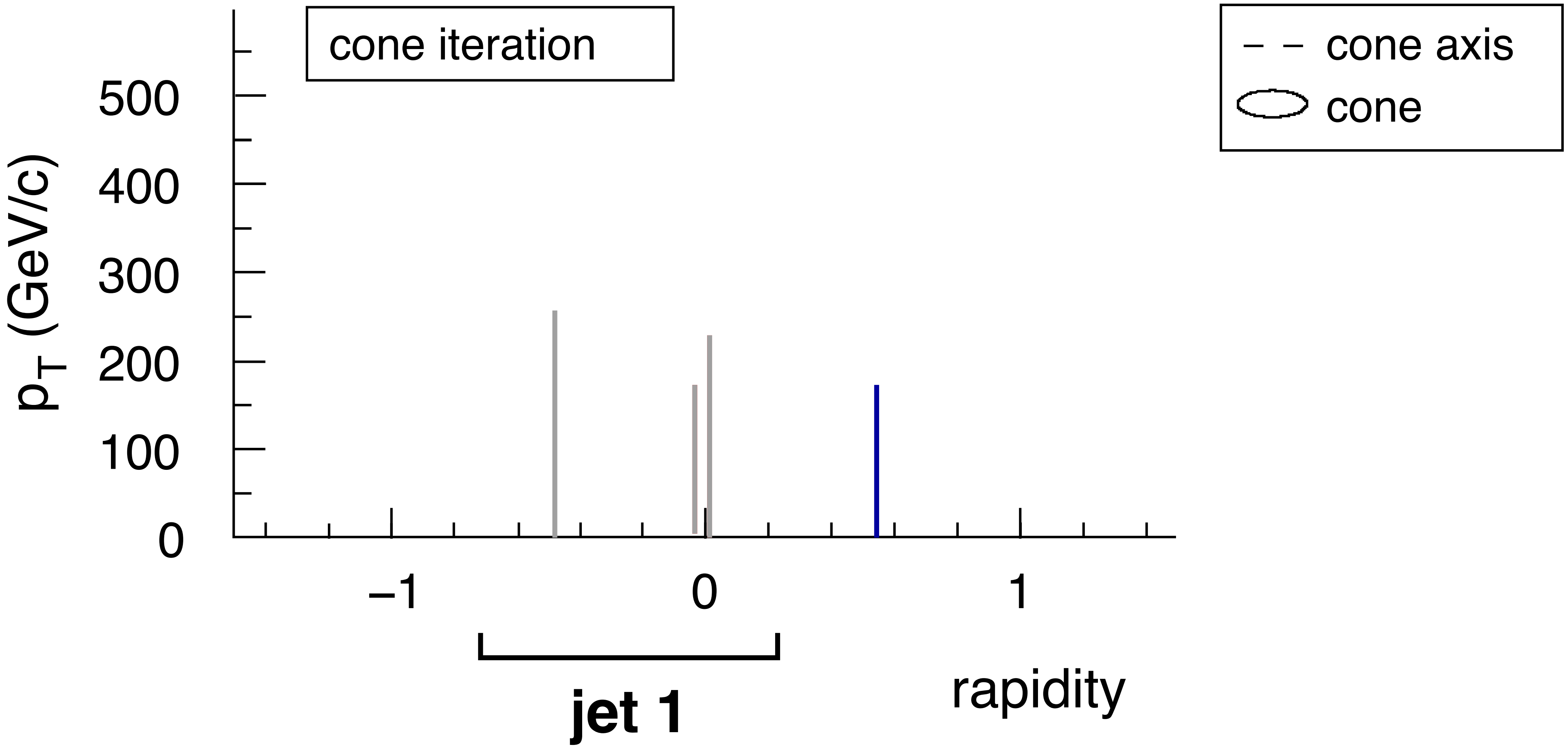

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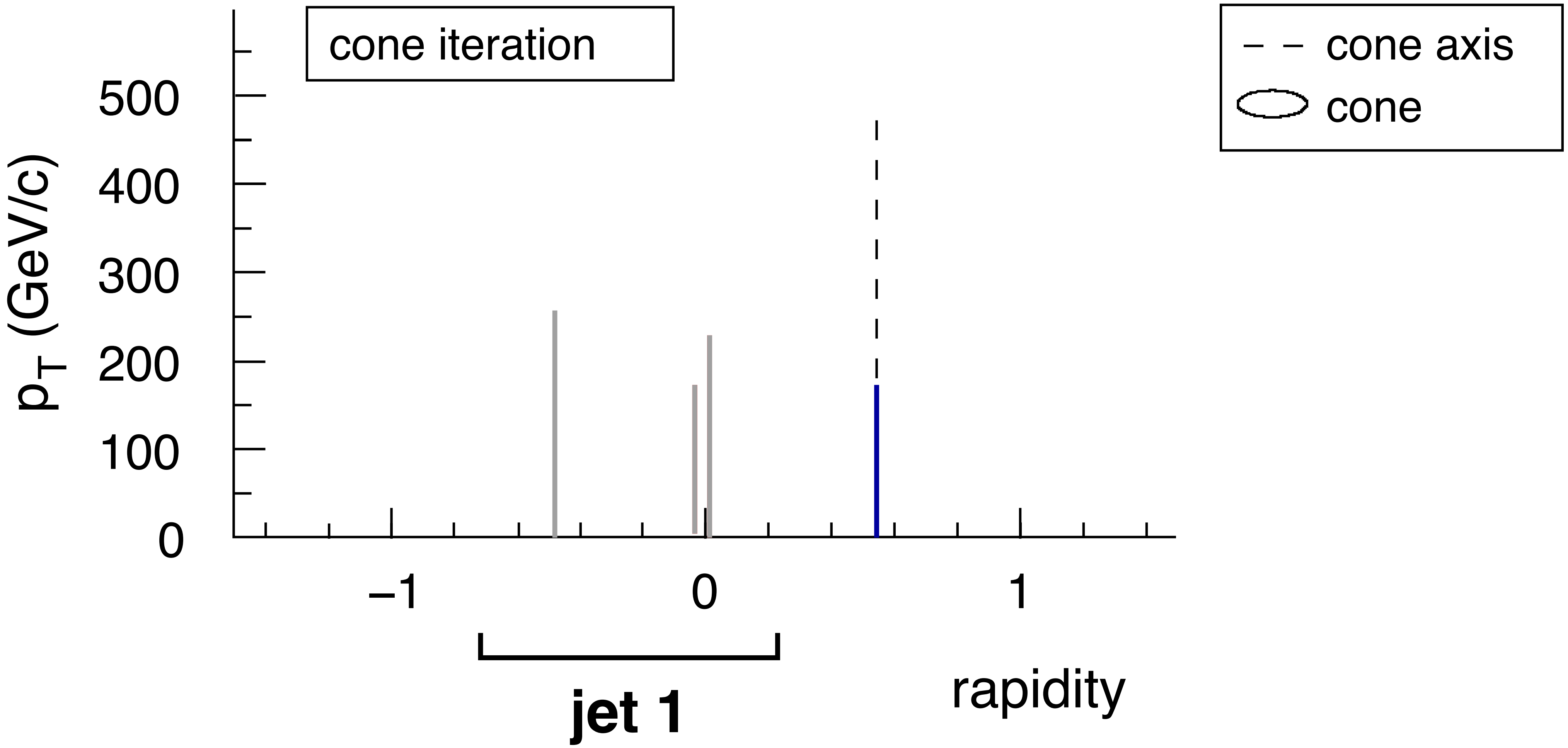

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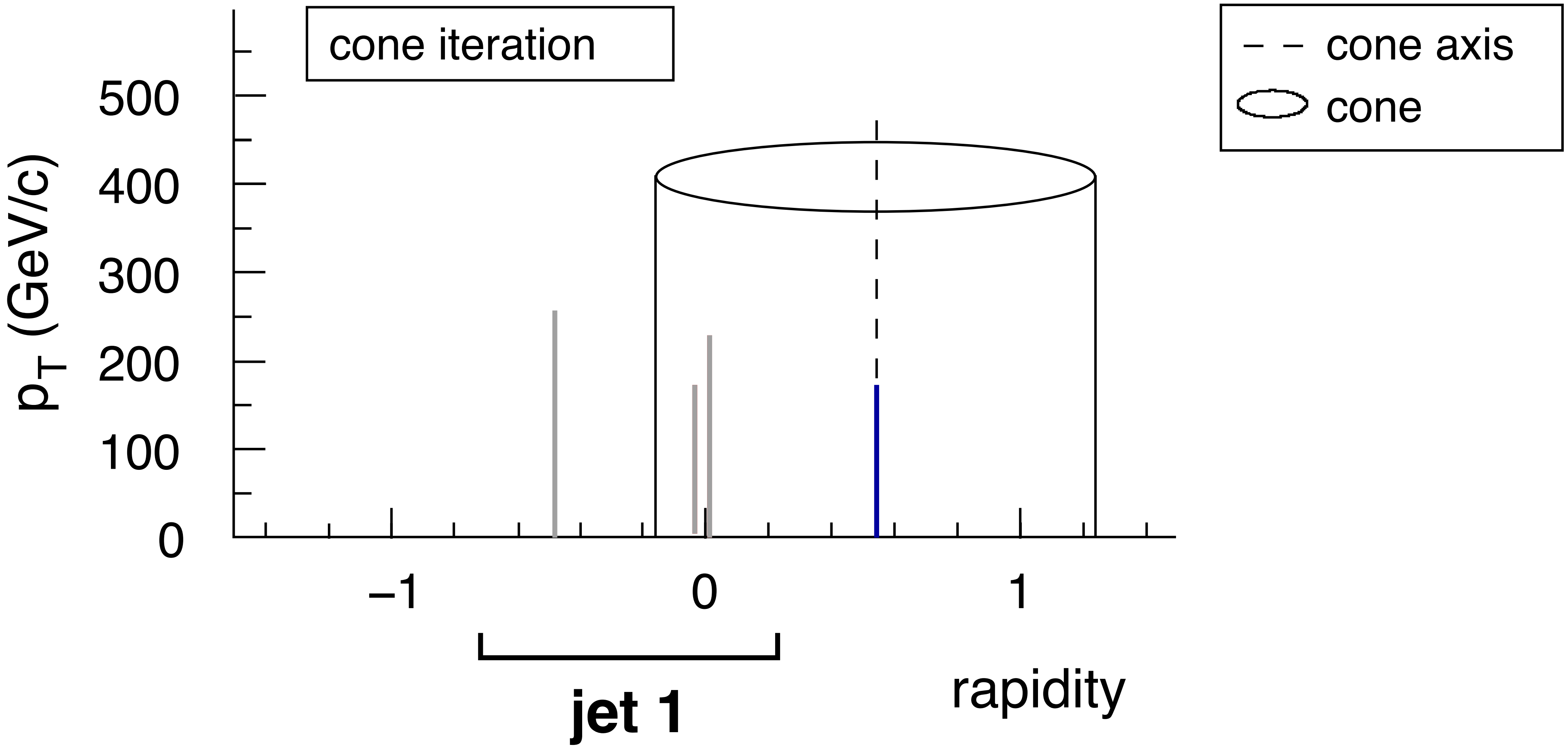

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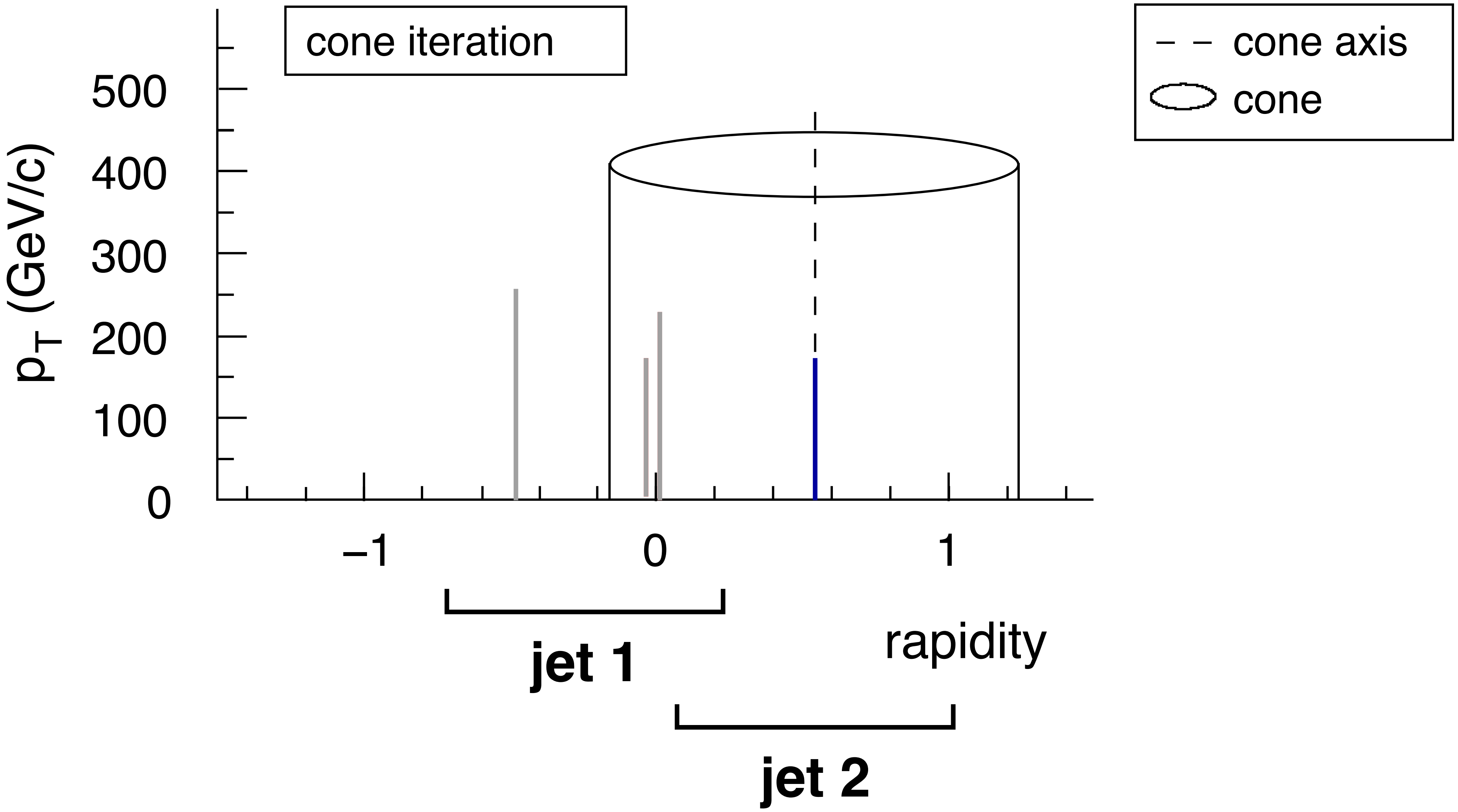
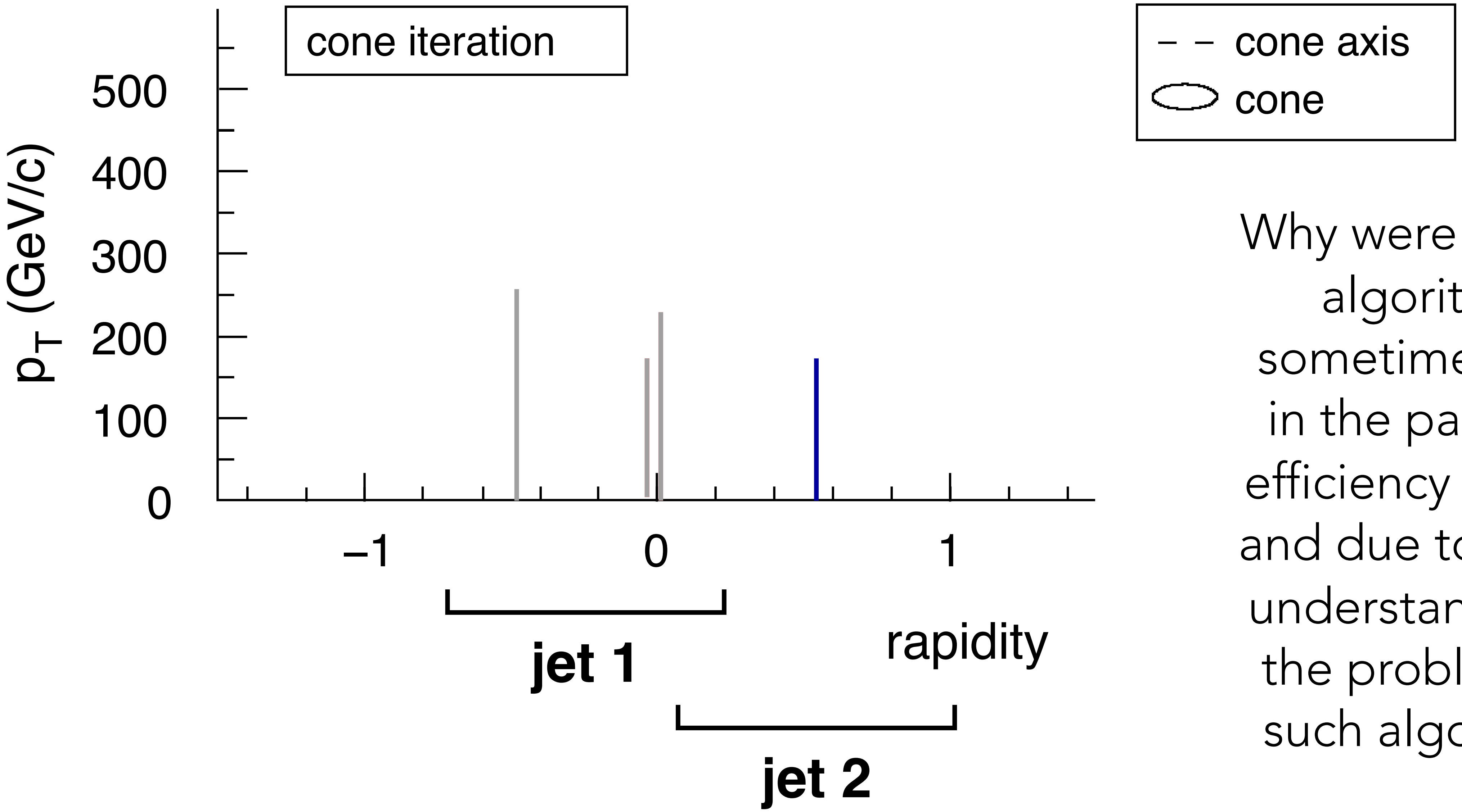


This time, we found not one, but two jets

Example of a "bad" algorithm: "Seeded Cone Algorithm"

Start from "hardest" seeds

Iterative Cone Progressive Removal



Why were seeded algorithms sometimes used in the past? For efficiency reasons and due to lack of understanding of the problems of such algorithms

Problem with seeded algorithms in general: Not "**collinear safe**".

By splitting a parton into two, we got a different number of jets.

Why is this bad? One parton physically indistinguishable from two collinear ones (if they sum to same 4-momentum) $\Longrightarrow$ ill-defined jet number

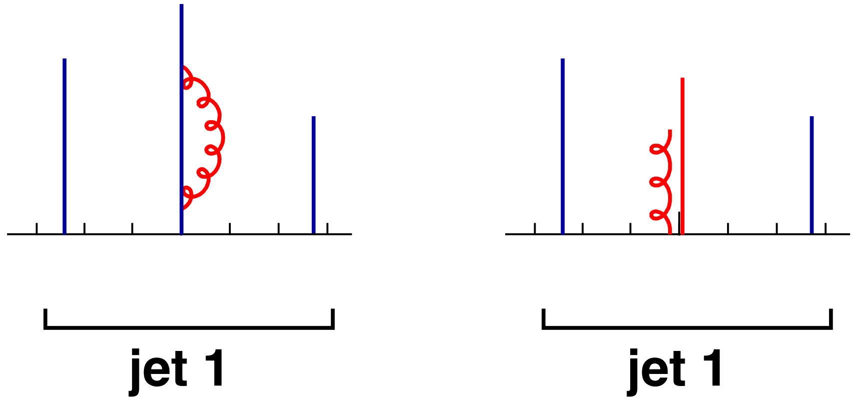
Note on Observables

(example by G. Salam)

Not all observables (called "IRC safe") **can be computed perturbatively**:

Collinear Safe

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



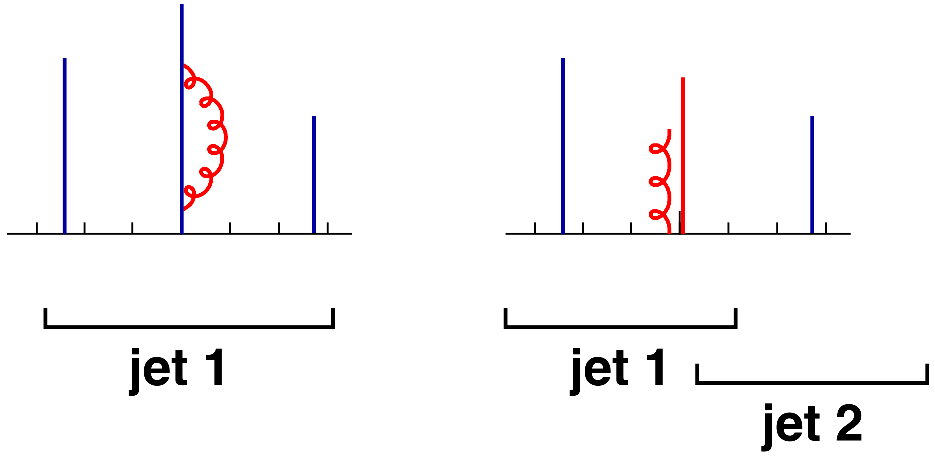
α_s^n x $(-\infty)$ α_s^n x $(+\infty)$

Infinities cancel

(KLN: 'degenerate states')

Collinear Unsafe

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



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

Infinities do not cancel

Invalidates perturbation theory

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

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

$\Longrightarrow$ Infrared and Collinear Safety

Definition: **an observable is infrared and collinear safe if it is *insensitive* to**

SOFT radiation:

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

COLLINEAR radiation:

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

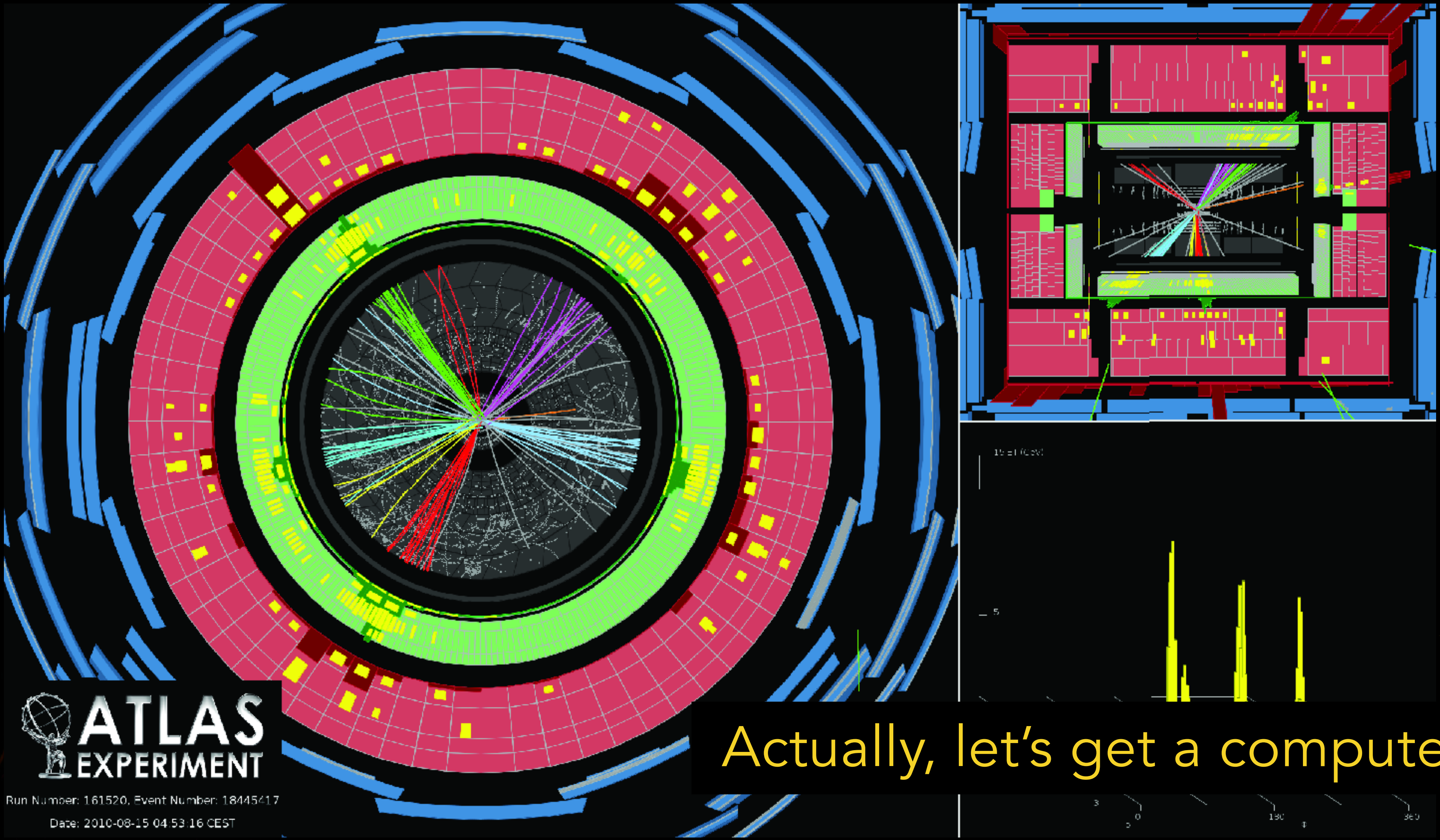
These properties are true of **all jet algorithms** and **all event-shape measures** used at LHC (but not true of **all LHC observables**)

Calculating jets; how hard can it be?

Approximate all contributing amplitudes for this …

To all orders…then square including interference effects, …

+ non-perturbative effects



… integrate it over a ~300-dimensional phase space

(+ collider delivers 40 million events per second)

Let's do it!

Actually, let's get a computer to do it …

Calls for numerical methods ➤ **Event Generators**

Aim: generate events in as much detail as mother nature

→ Make stochastic choices ~ as in Nature (Q.M.) → Random numbers

Factor complete event probability into separate universal pieces, treated independently and/or sequentially (Markov-Chain MC)

Improve lowest-order (perturbation) theory by including 'most significant' corrections

Resonance decays (e.g., $t \to bW^+$, $W \to qq'$, $H^0 \to \gamma^0\gamma^0$, $Z^0 \to \mu^+\mu^-$, …)

Bremsstrahlung (FSR and ISR, exact in collinear and soft* limits)

Hard radiation (matching & merging)

Hadronization (strings / clusters)

Additional Soft Physics: multiple parton-parton interactions, Bose-Einstein correlations, colour reconnections, hadron decays, …

Interference effects (coherence)

Soft radiation → Angular ordering or Coherent Dipoles/Antennae

The Main Workhorses

PYTHIA (begun 1978)

Originated in hadronisation studies: Lund String model

Still significant emphasis on soft/non-perturbative physics

HERWIG (begun 1984)

Originated in coherence studies: angular-ordered showers

Cluster hadronisation as simple complement

SHERPA (begun ~2000)

Originated in Matrix-Element/Parton-Shower matching (CKKW-L)

Own variant of cluster hadronisation

+ Many more specialised:

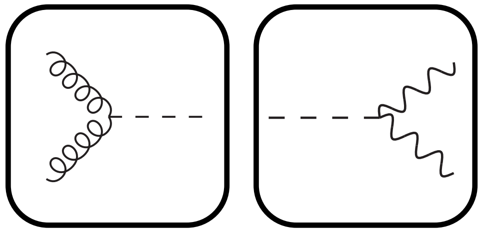
Matrix-Element Generators, Matching/Merging Packages, Resummation packages, Alternative QCD showers, Soft-QCD MCs, Cosmic-Ray MCs, Heavy-Ion MCs, Neutrino MCs, Hadronic interaction MCs (GEANT/FLUKA; for energies below $E_{CM} \sim 10$ GeV), **(BSM) Model Generators** (FeynRules, LanHep, …), Decay Packages, …

Organising the Calculation

Divide and Conquer → Split the problem into many (nested) pieces

Physics Separation of time scales ➤ Factorisations **Maths**

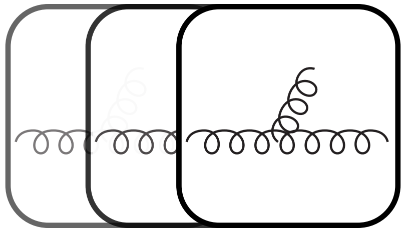
$$\mathcal{P}_{\text{event}} = \mathcal{P}_{\text{hard}} \otimes \mathcal{P}_{\text{dec}} \otimes \mathcal{P}_{\text{ISR}} \otimes \mathcal{P}_{\text{FSR}} \otimes \mathcal{P}_{\text{MPI}} \otimes \mathcal{P}_{\text{Had}} \otimes \ldots$$



Hard Process & Decays: OK! (We did it yesterday)

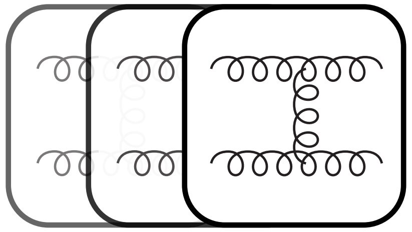
Use process-specific (N)LO matrix elements (e.g., $gg \to H^0 \to \gamma\gamma$)

→ Sets "hard" resolution scale for process: Q_{MAX}



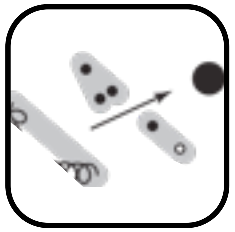
ISR & FSR (Initial- & Final-State Radiation): Will do today!

Driven by differential (e.g., DGLAP) evolution equations, dP/dQ^2, as function of resolution scale; from Q_{MAX} to Q_{HAD} ~ 1 GeV



MPI (Multi-Parton Interactions) Sorry, not in this course

Protons contain lots of partons → can have additional (soft) parton-parton interactions → Additional (soft) "Underlying-Event" activity



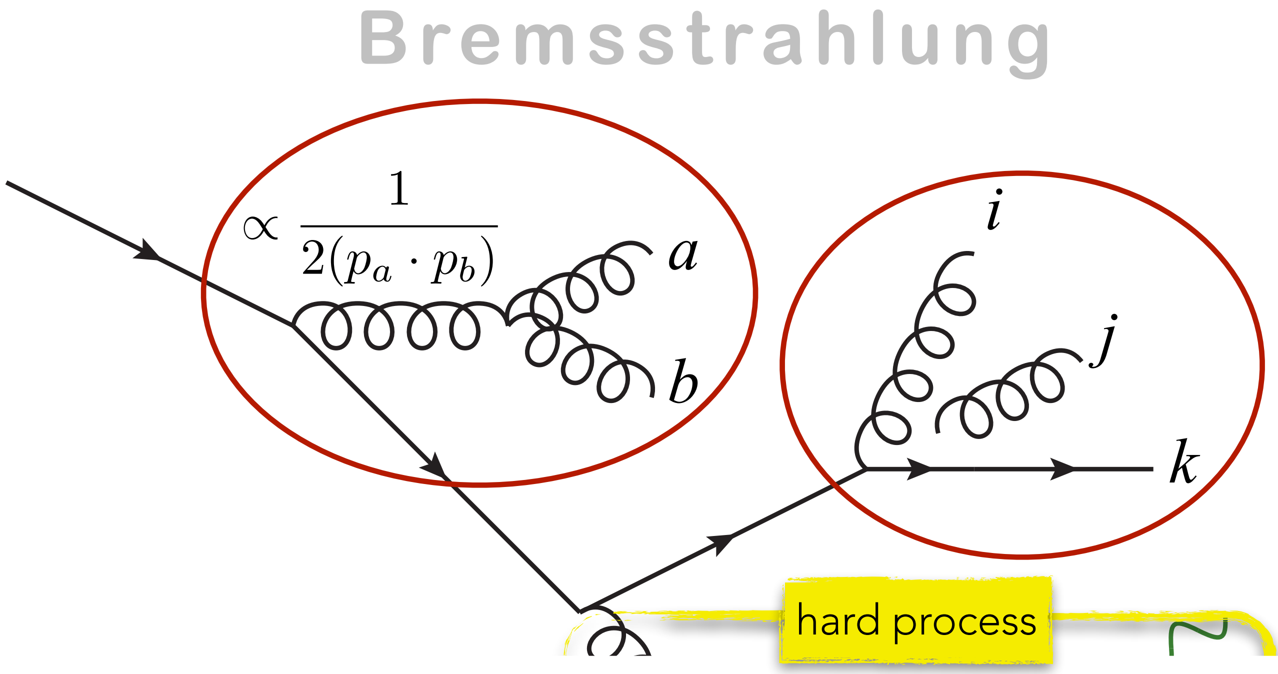
Hadronisation Will do today!

Non-perturbative modeling of partons → hadrons transition

ISR and FSR: cascades of perturbative radiation

Most bremsstrahlung is driven by **divergent propagators** → simple structure

Amplitudes *factorise* in singular limits (→ universal "scale-invariant" or "conformal" structure)



Partons ab → "collinear":

P(z) = DGLAP splitting kernels, with z = energy fraction = $E_a/(E_a+E_b)$

$$|\mathcal{M}_{F+1}(\ldots,a,b,\ldots)|^2 \overset{a||b}{\to} g_s^2 \mathcal{C} \frac{P(z)}{2(p_a \cdot p_b)} |\mathcal{M}_F(\ldots,a+b,\ldots)|^2$$

Gluon j → "soft":

Coherence → Parton j really emitted by (i,k) "colour antenna"

$$|\mathcal{M}_{F+1}(\ldots,i,j,k\ldots)|^2 \overset{j_g\to 0}{\to} g_s^2 \mathcal{C} \frac{(p_i \cdot p_k)}{(p_i \cdot p_j)(p_j \cdot p_k)} |\mathcal{M}_F(\ldots,i,k,\ldots)|^2$$

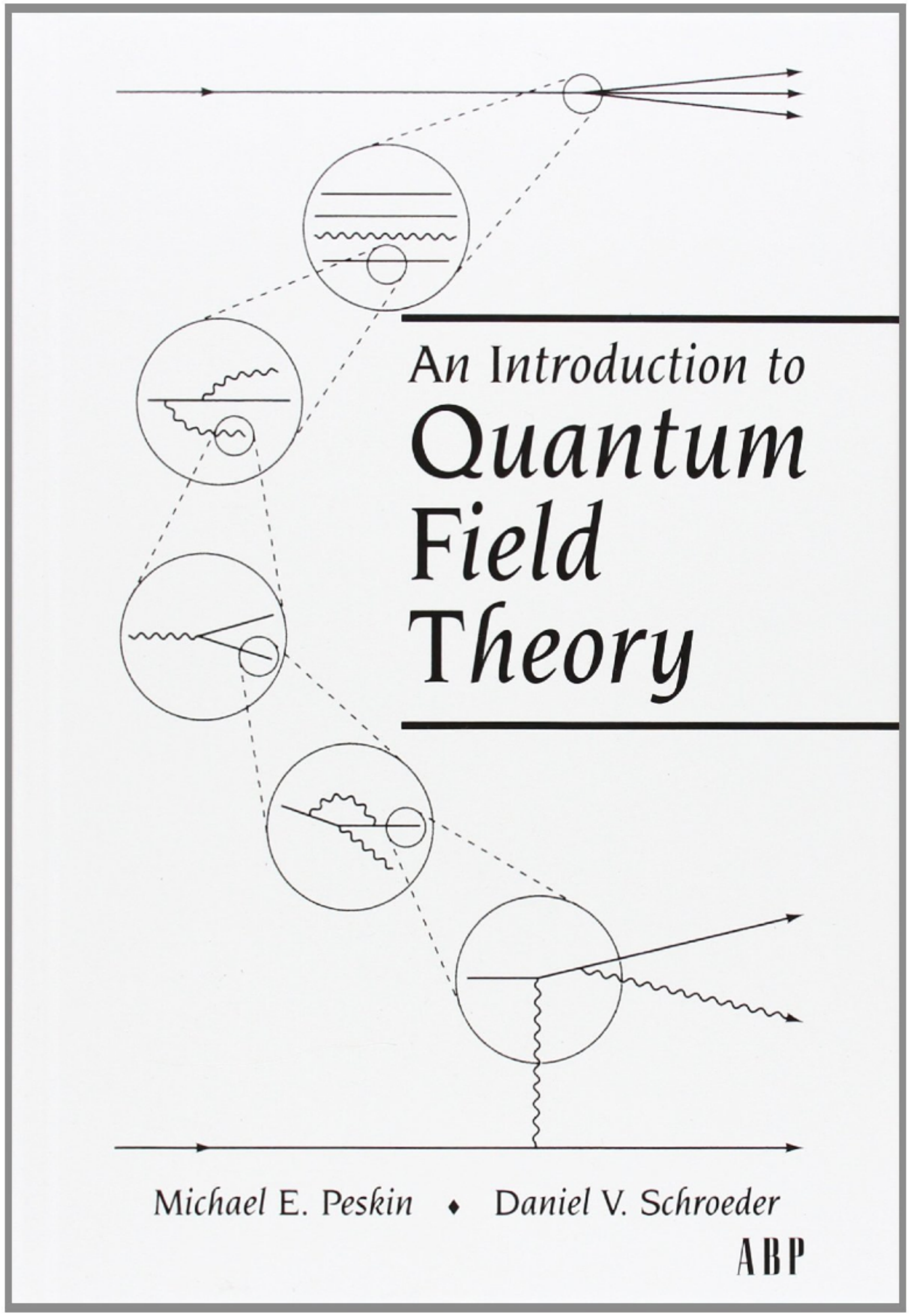
+ scaling ***violation***: $g_s^2 \longrightarrow 4\pi\alpha_s(Q^2)$

Can apply this many times → nested factorizations

The Structure of Quantum Fields

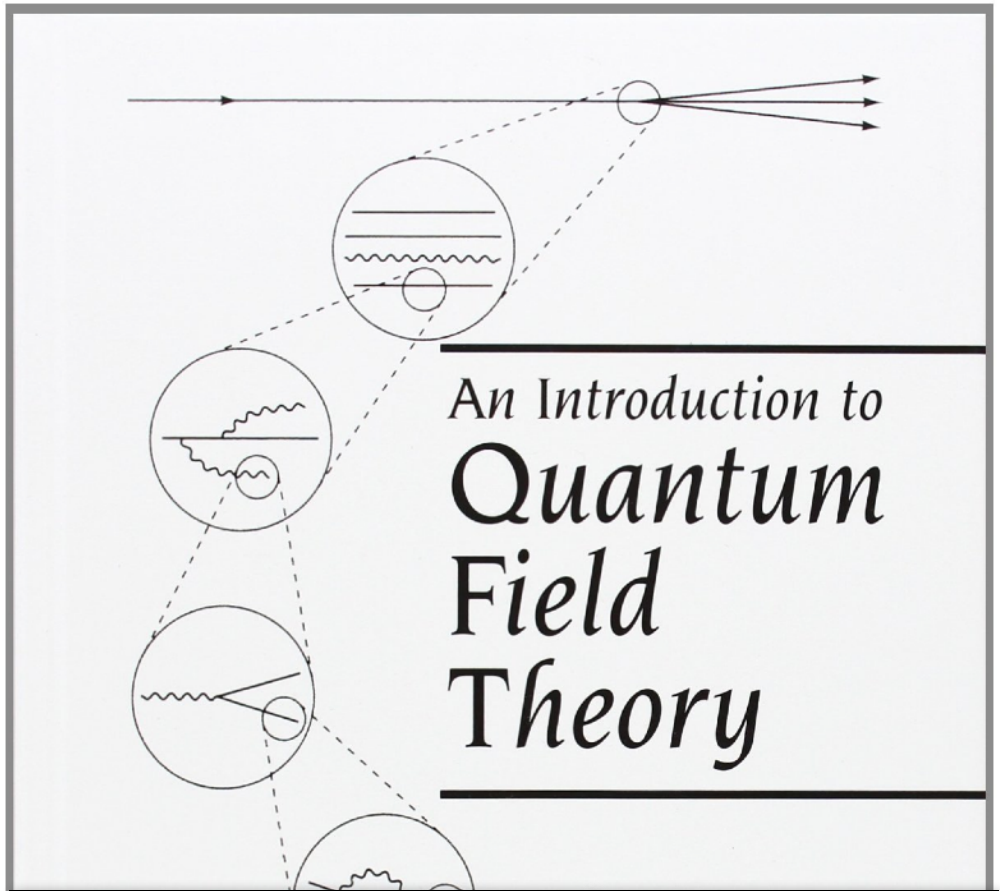
What we actually see when we look at a “jet”, or inside a proton

- An ever-repeating self-similar pattern of quantum fluctuations
- At increasingly smaller energies or distances : ***scaling*** (modulo α(Q) scaling violation)
- To our best knowledge, this is what a fundamental (‘elementary’) particle really looks like


An Introduction to
Quantum
Field
Theory
Michael E. Peskin ♦ Daniel V. Schroeder
ABP

The Structure of Quantum Fields

- What we actually see when we look at a “jet”, or inside a proton
  - An ever-repeating self-similar pattern of quantum fluctuations
  - At increasingly smaller energies or distances : ***scaling*** (modulo $\alpha(Q)$ scaling violation)
  - To our best knowledge, this is what a fundamental (‘elementary’) particle really looks like
- Nature makes copious use of such structures
  - Called **Fractals**



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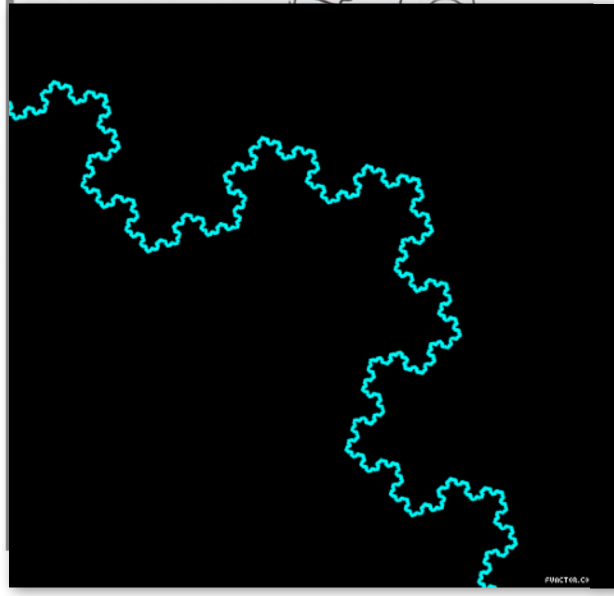


Note: this is not an elementary particle, but a different fractal, illustrating the principle

How soft Is soft?

Naively, QCD radiation suppressed by $\alpha_s \approx 0.1$

→ Truncate at fixed order = LO, NLO, …

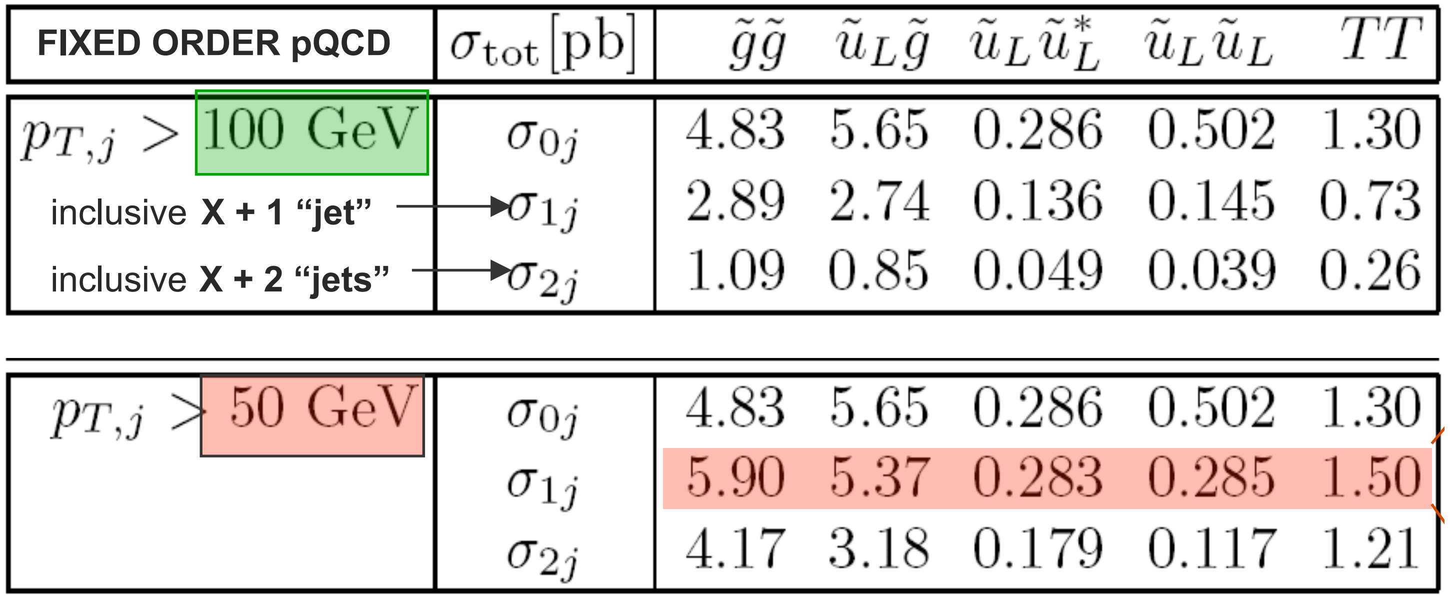
But beware the jet-within-a-jet-within-a-jet …

Example: 100 GeV can be "soft" at the LHC

SUSY pair production at LHC_{14}, with $M_{\mathrm{SUSY}} \approx 600$ GeV

LHC - sps1a - m~600 GeV

Plehn, Rainwater, PS PLB645(2007)217



FIXED ORDER pQCD	$\sigma_{\mathrm{tot}}[\mathrm{pb}]$	$\tilde{g}\tilde{g}$	$\tilde{u}_L\tilde{g}$	$\tilde{u}_L\tilde{u}_L^*$	$\tilde{u}_L\tilde{u}_L$	TT
$p_{T,j} >$ 100 GeV	σ_{0j}	4.83	5.65	0.286	0.502	1.30
inclusive **X + 1 "jet"** →	σ_{1j}	2.89	2.74	0.136	0.145	0.73
inclusive **X + 2 "jets"** →	σ_{2j}	1.09	0.85	0.049	0.039	0.26
$p_{T,j} >$ 50 GeV	σ_{0j}	4.83	5.65	0.286	0.502	1.30
	σ_{1j}	5.90	5.37	0.283	0.285	1.50
	σ_{2j}	4.17	3.18	0.179	0.117	1.21

(Computed with SUSY-MadGraph)

σ for X + jets much larger than naive factor-α_s estimate

σ for 50 GeV jets ≈ larger than total cross section
→ what is going on?

All the scales are high, Q >> 1 GeV, so perturbation theory **should** be OK

Apropos Factorisation

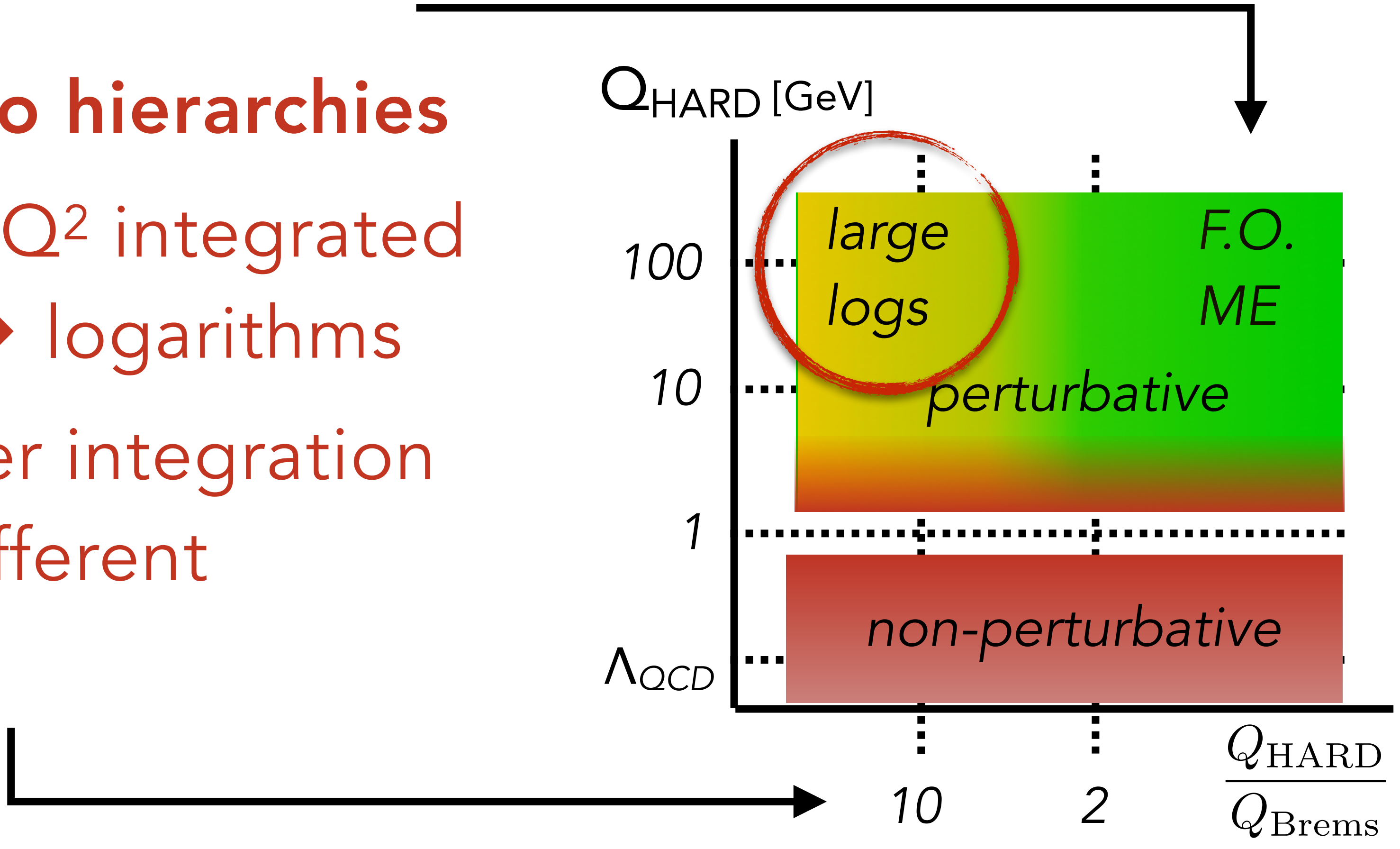
F.O. QCD requires **Large scales** (α_s small enough to be perturbative → high-scale processes)

Why are Fixed-Order QCD matrix elements not enough?

F.O. QCD also requires **No hierarchies**

Bremsstrahlung poles ∝ $1/Q^2$ integrated over phase space ∝ dQ^2 → logarithms

→ large if upper and lower integration limits are hierarchically different



Parton Showers

So it's not like you can put a cut at X (e.g., 50, or even 100) GeV and say: "ok, now fixed-order matrix elements will be OK"

Harder Processes are Accompanied by Harder Jets

The hard process will "kick off" a shower of successively softer radiation

If you look at $Q_{\text{Resolved}}/Q_{\text{HARD}} \ll 1$, you **will** resolve shower structure

Extra radiation:

Will generate **corrections to your kinematics**

Is an unavoidable aspect of the **quantum description of quarks and gluons** (no such thing as a bare quark or gluon; they depend on how you look at them)

Extra jets from bremsstrahlung can be important **combinatorial background** especially if you are looking for decay jets of similar p_T scales (often, $\Delta M \ll M$)

This is what parton showers are for

Evolution ~ Fine-Graining

(E.g., starting from QCD 2→2 hard process)

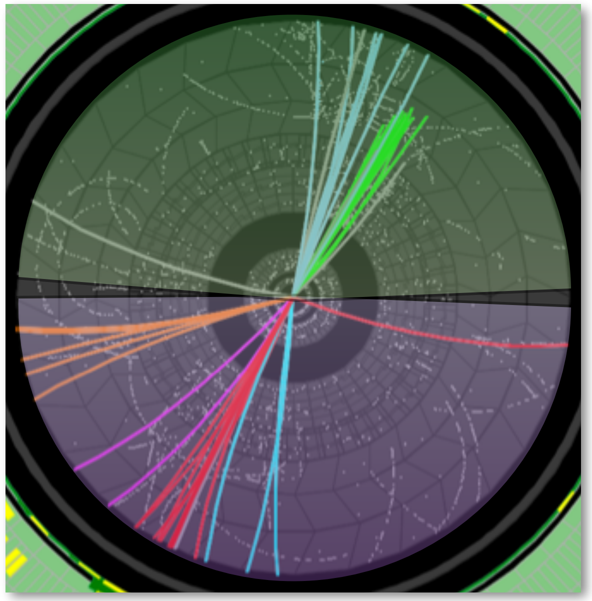
Resolution Scale

$Q \sim Q_{\mathrm{HARD}}$

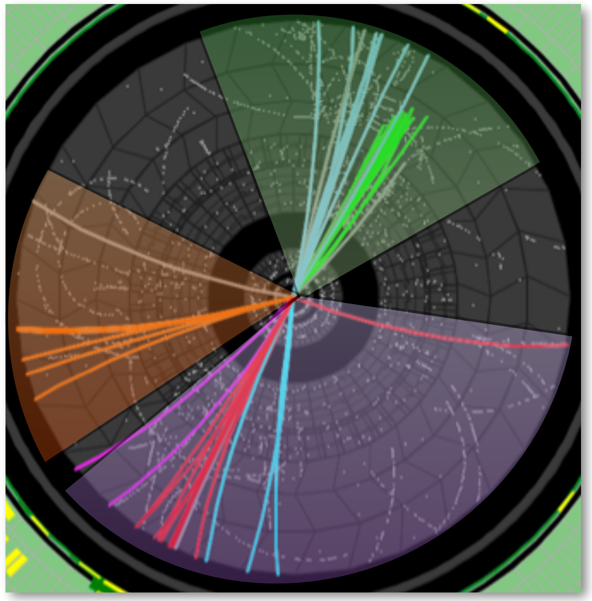
$Q_{\mathrm{HARD}}/Q < \text{“A few”}$

$Q \ll Q_{\mathrm{HARD}}$

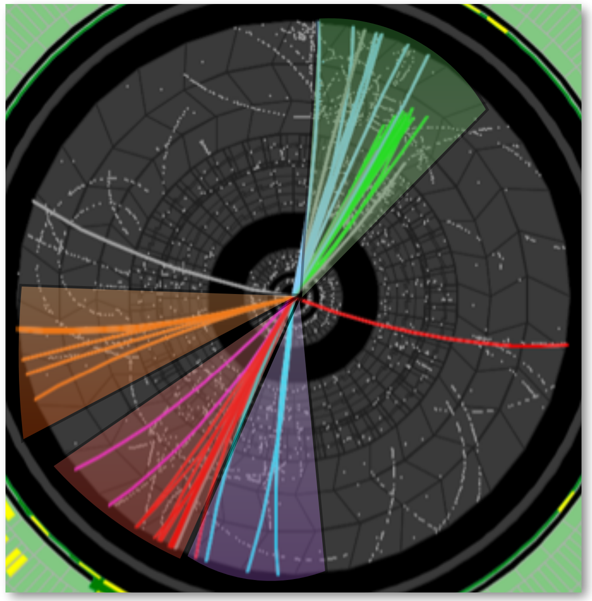
Scale Hierarchy!



At most inclusive level
“Everything is 2 jets”



At (slightly) finer resolutions,
some events have 3, or 4 jets



At high resolution, **most** events have >2 jets

Cross sections

Fixed order:
$\sigma_{\mathrm{inclusive}}$

Fixed order:
$\sigma_{X+n} \sim \alpha_s^n \, \sigma_X$

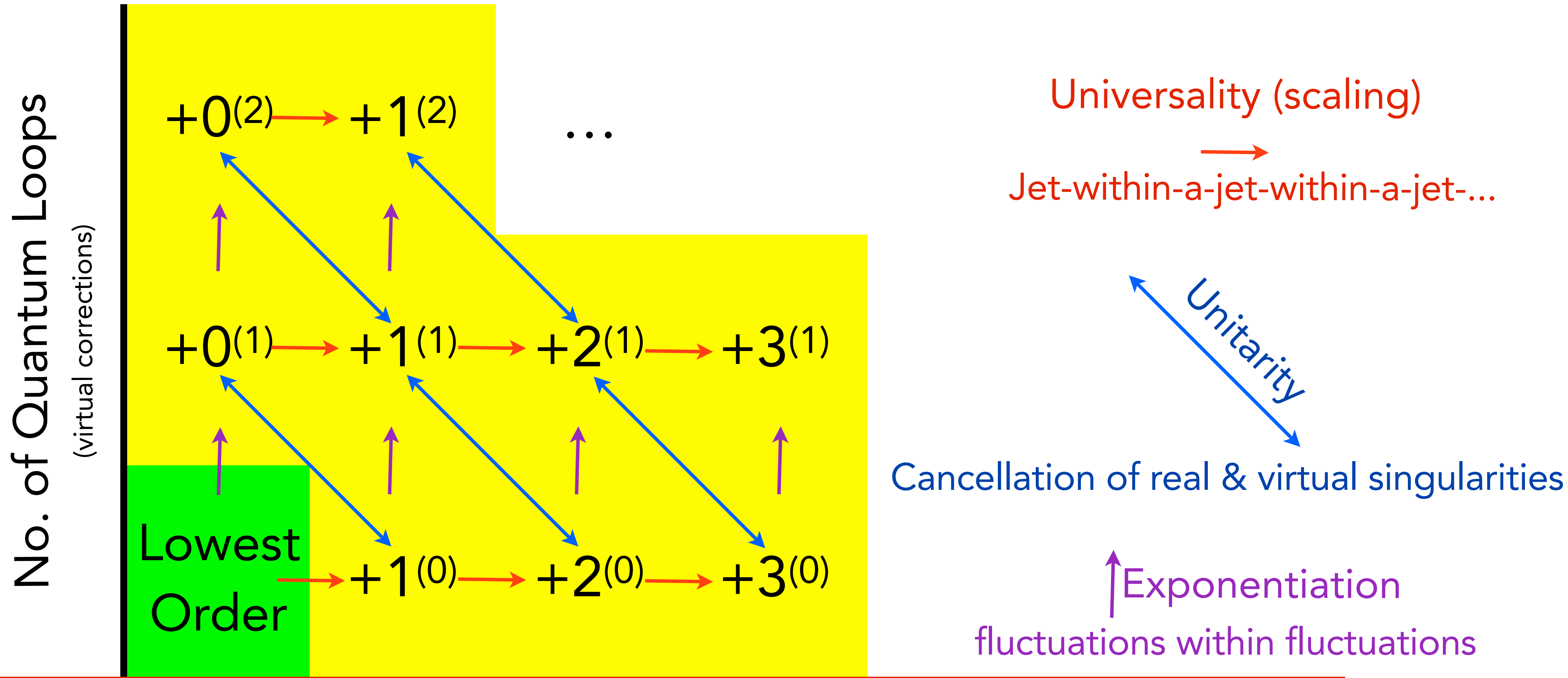
Fixed order diverges:
$\sigma_{X+n} \sim \alpha_s^n \ln^{2n}(Q/Q_{\mathrm{HARD}})\sigma_X$

Unitarity: **Reinterpret** as *number of emissions diverging*, while cross section remains $\sigma_{\mathrm{inclusive}}$

Bootstrapped Perturbation Theory

Start from an **arbitrary lowest-order** process (green = QFT amplitude squared)

Parton showers generate the (LL) bremsstrahlung terms of the rest of the perturbative series (approximate infinite-order resummation)



Note! LL ≠ full QCD! (→ matching, merging, MECs)

(real corrections)

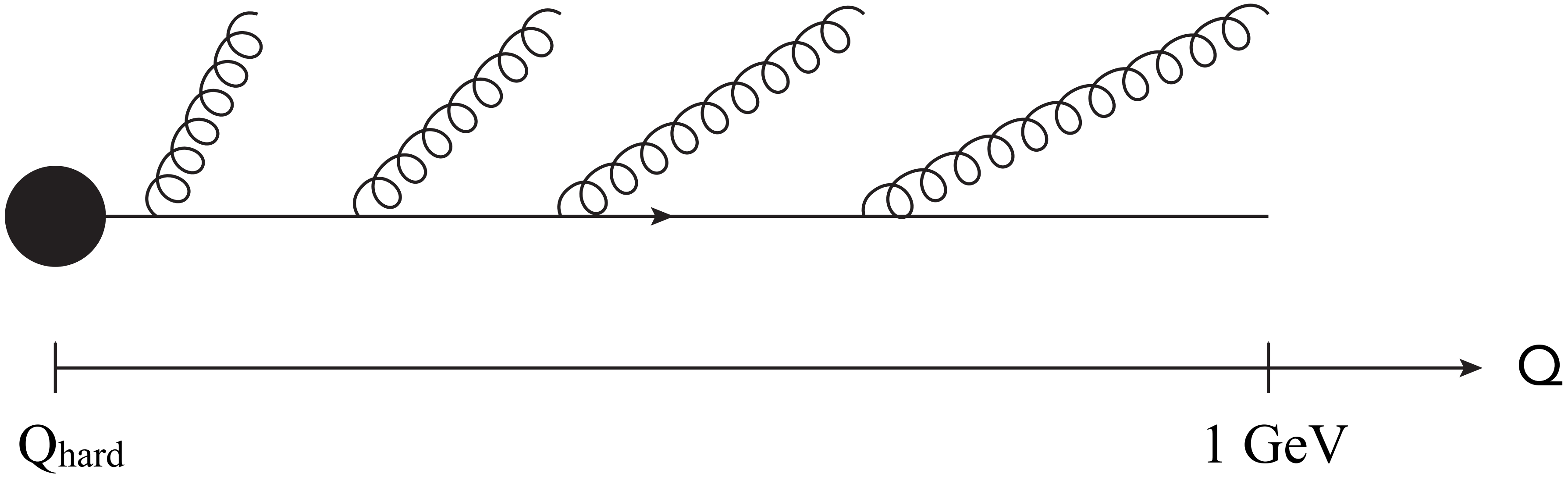
From Partons to Pions

Here's a hard parton

Hard: 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



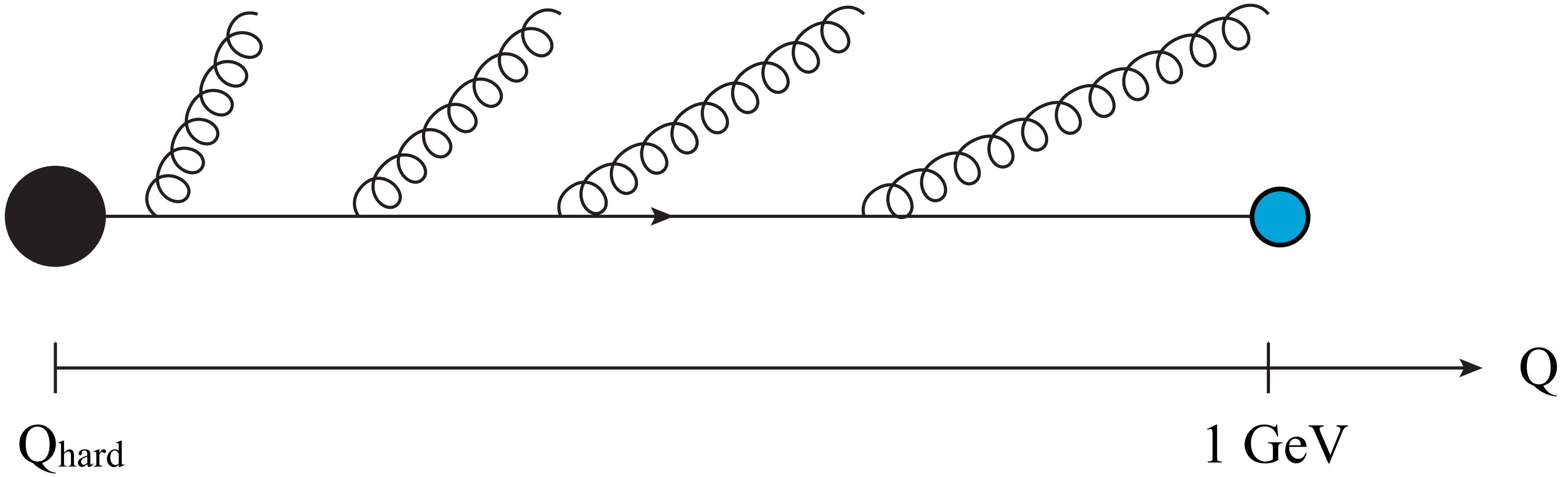
From Partons to Pions

Here's a fast parton

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

It showers (bremsstrahlung)

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



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

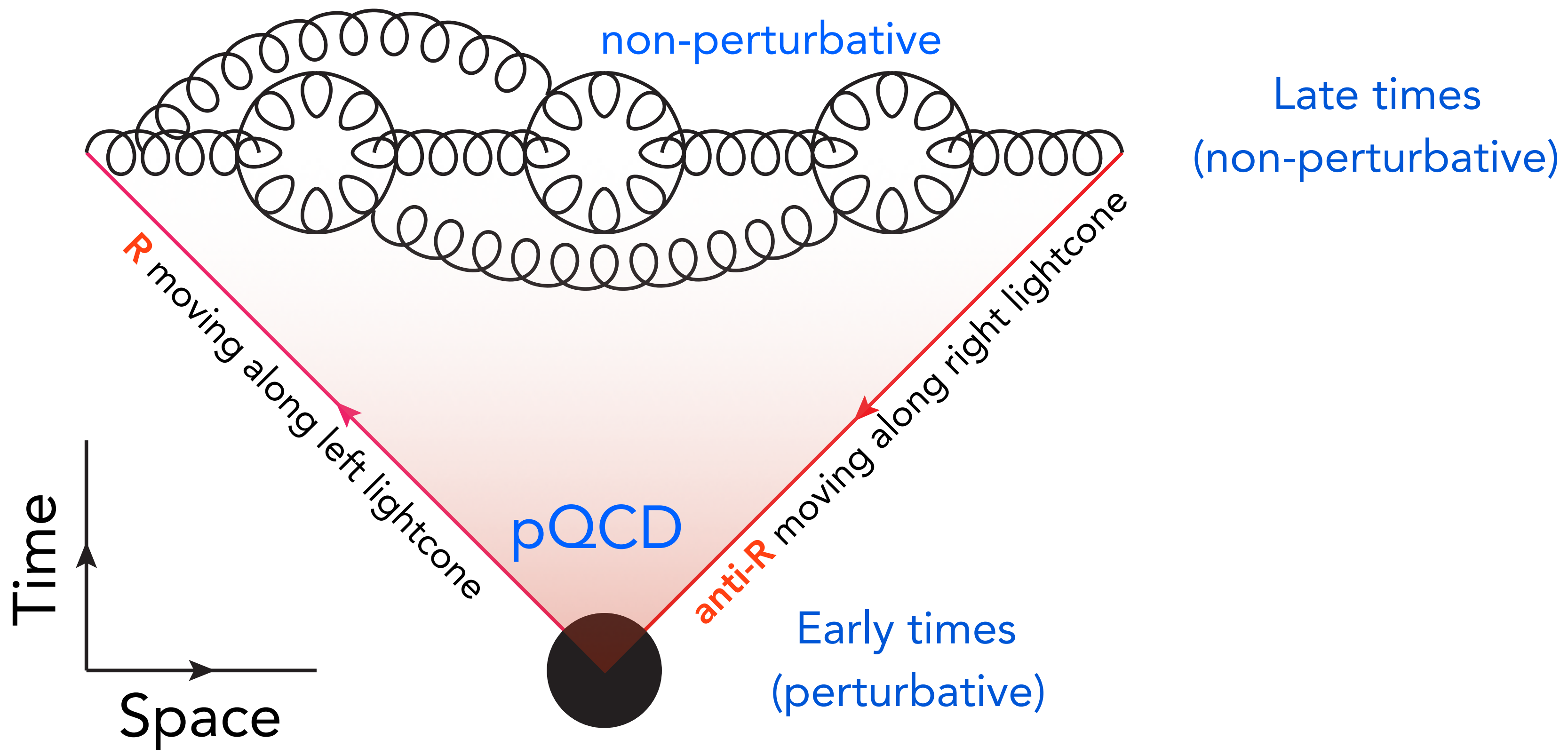
→ Too naive to see LPHD (inclusive) as a justification for Independent Fragmentation (exclusive)

→ More physics needed

Colour Neutralisation

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 $\frac{1}{\sqrt{3}}\left(|R\bar{R}\rangle + |G\bar{G}\rangle + |B\bar{B}\rangle\right)$

Tracing colours

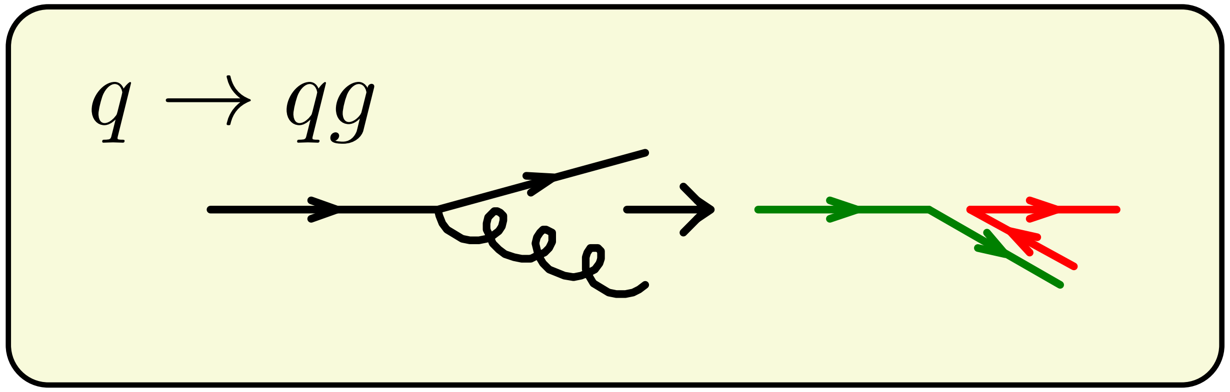
MC generators use a simple set of rules for "colour flow"

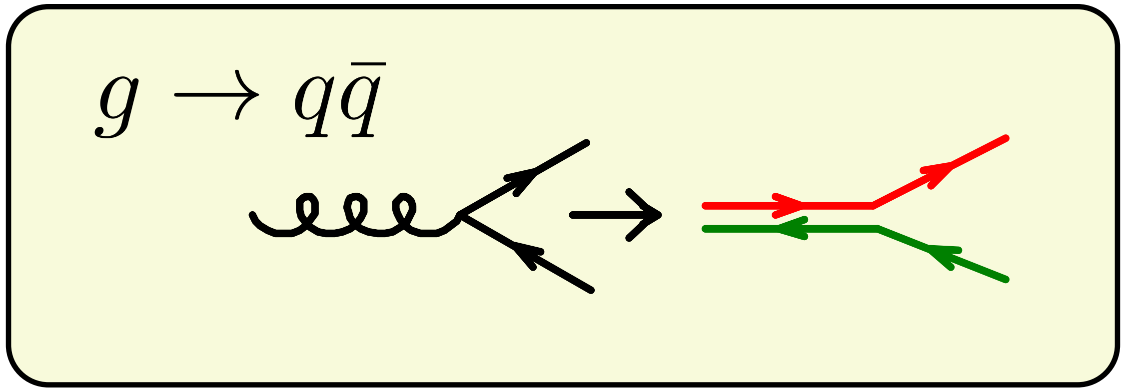
Based on **"Leading Colour"** (LC)

$$8 = \boxed{3 \otimes \bar{3}} \ominus 1$$

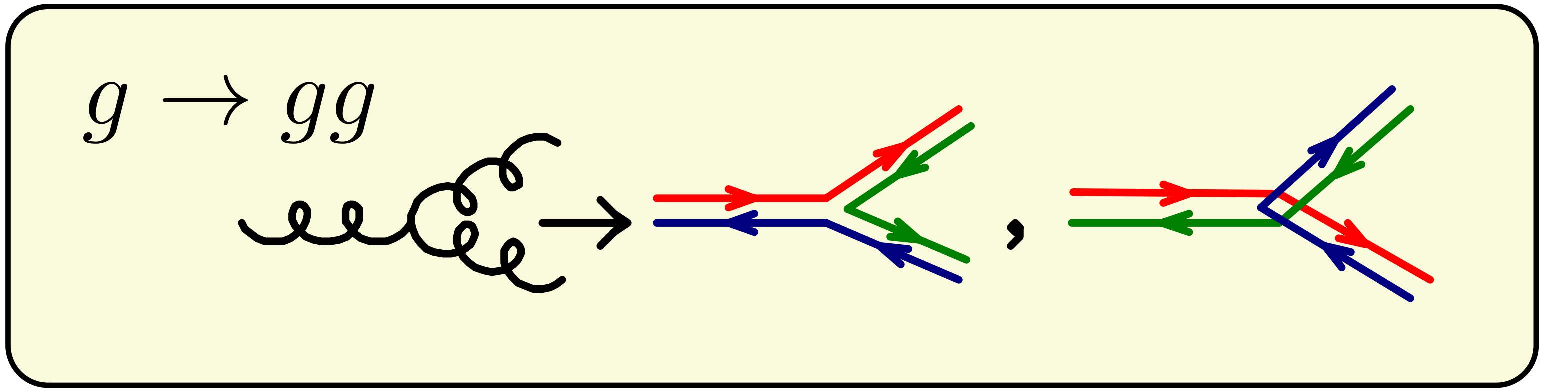
LC: gluons = outer products of triplet and antitriplet

($\Rightarrow$ valid to ~ $1/N_C^2$ ~ 10%)





Illustrations from PDG Review on *MC Event Generators*

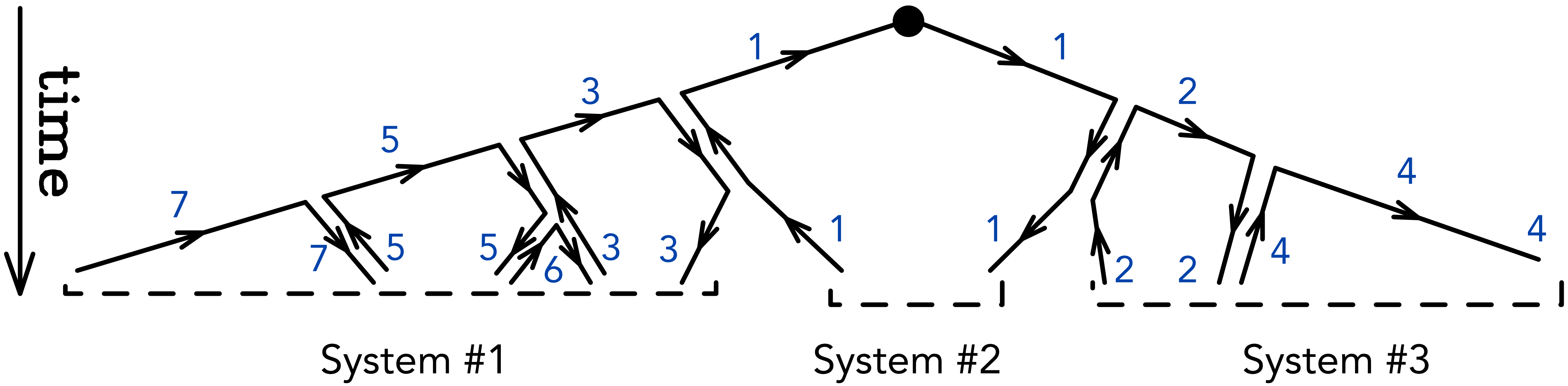


Colour Flow Example

Showers (can) generate lots of partons, $\mathcal{O}(10\text{-}100)$.

Colour Flow used to determine ***between which partons confining potentials arise***

Example: $Z^0 \to qq$



Coherence of pQCD cascades → suppression of "overlapping" systems
→ Leading-colour approximation pretty good

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

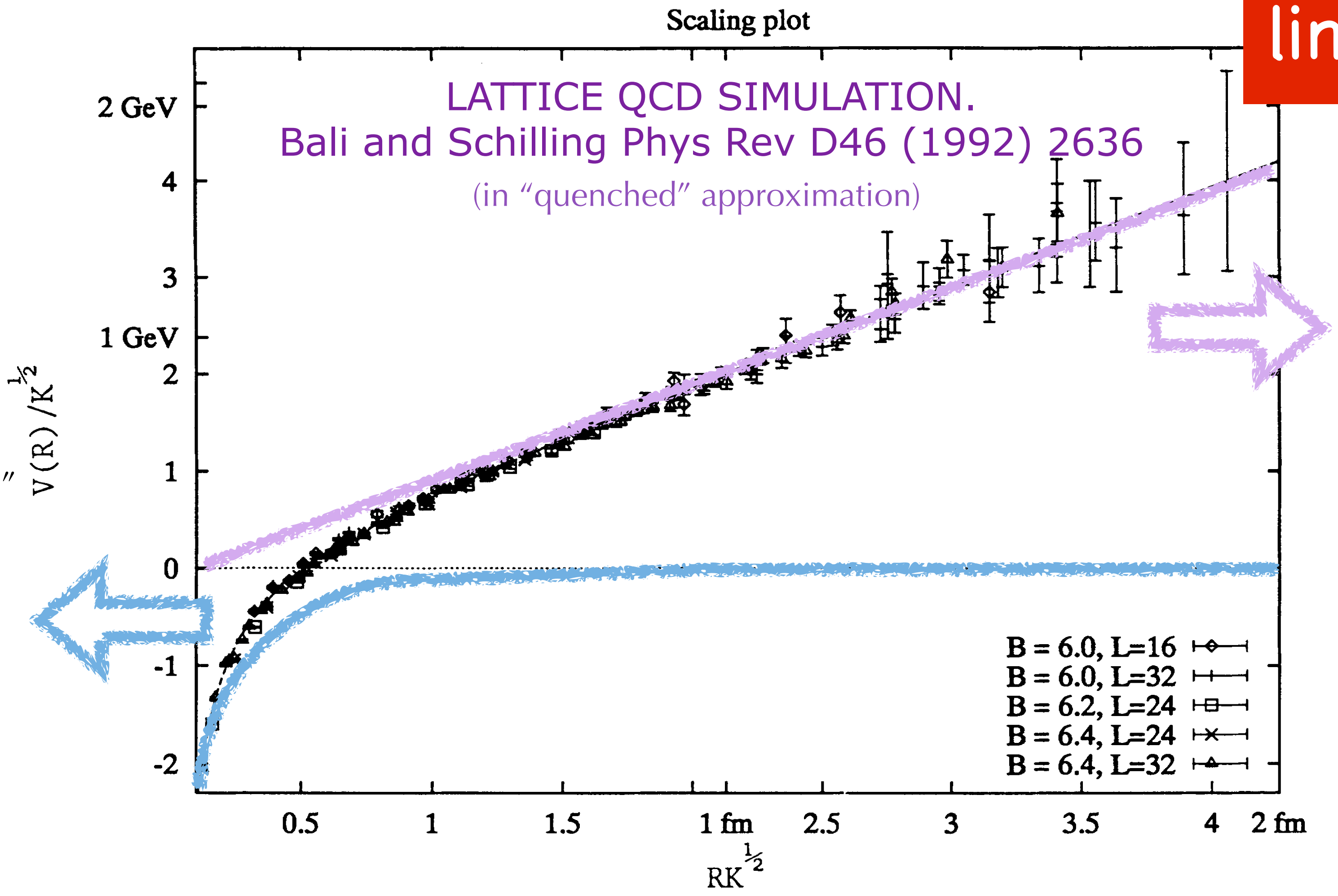
Note: (much) more color getting kicked around in hadron collisions.
Intesting signs that LC approximation is breaking down there, but not today's topic

The Ultimate Limit: Wavelengths > 10^{-15} m

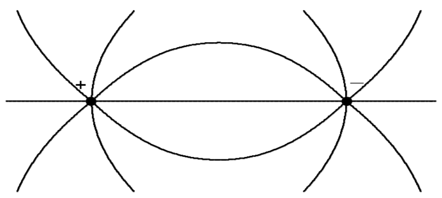
Quark-Antiquark Potential

As function of separation distance

What physical system has a linear potential?

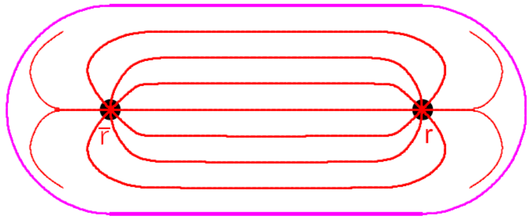


Short Distances ~ "Coulomb"



"Free" Partons

Long Distances ~ Linear Potential



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

$$F(r) \approx \text{const} = \kappa \approx 1\ \text{GeV/fm} \iff V(r) \approx \kappa r$$

~ Force required to lift a 16-ton truck

From Partons to Strings

Motivates a model:

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

κ ~ 1 GeV / fm

Limit → Relativistic 1+1 dimensional worldsheet

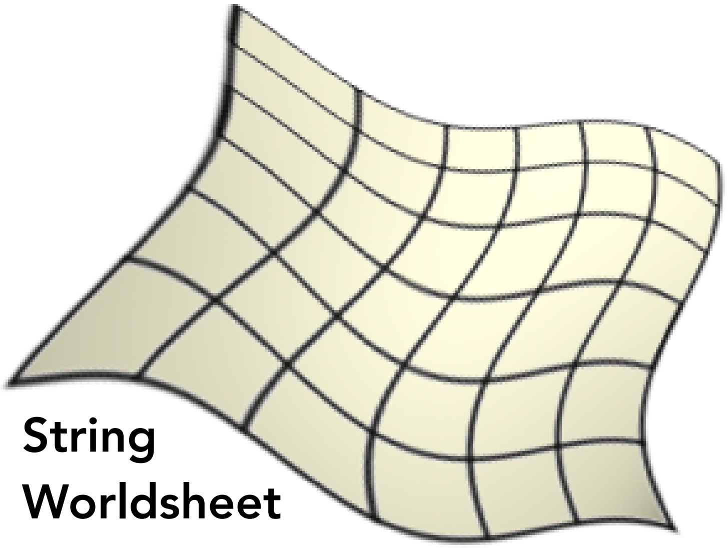
In "unquenched" QCD

g→qq → The strings will break

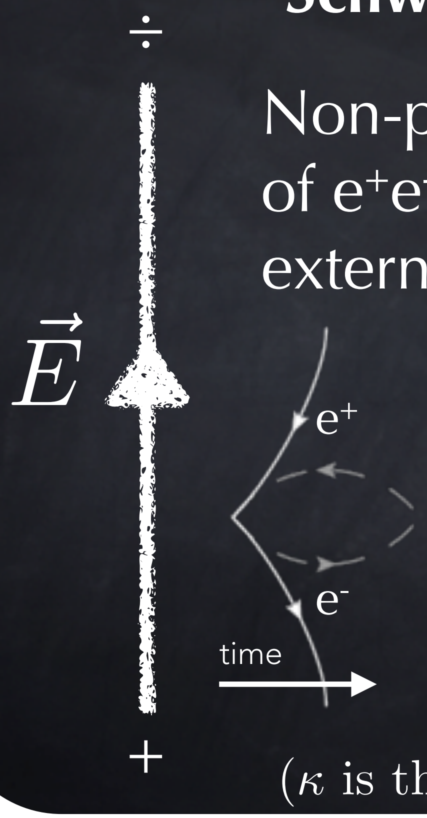
→ Gaussian suppression of high $m_T^2 = m_q^2 + p_T^2$

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

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



Schwinger Effect



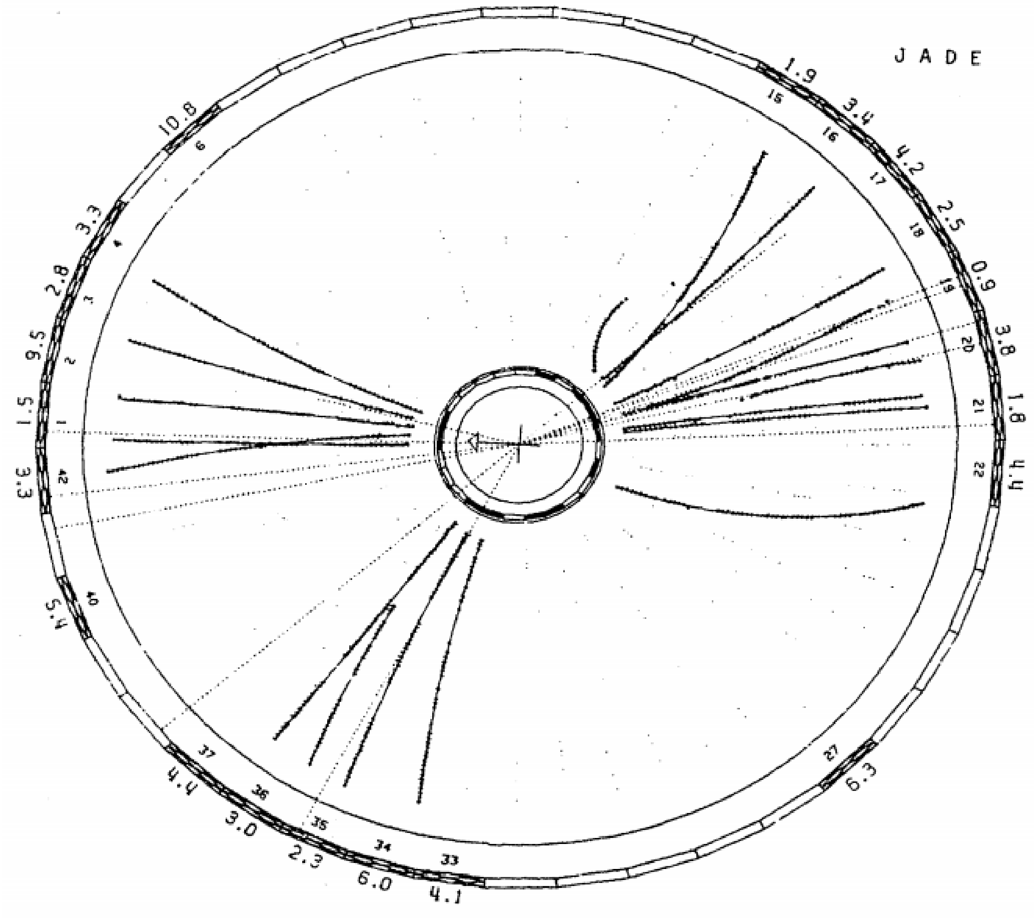
Non-perturbative creation of e^+e^- pairs in a strong external Electric field

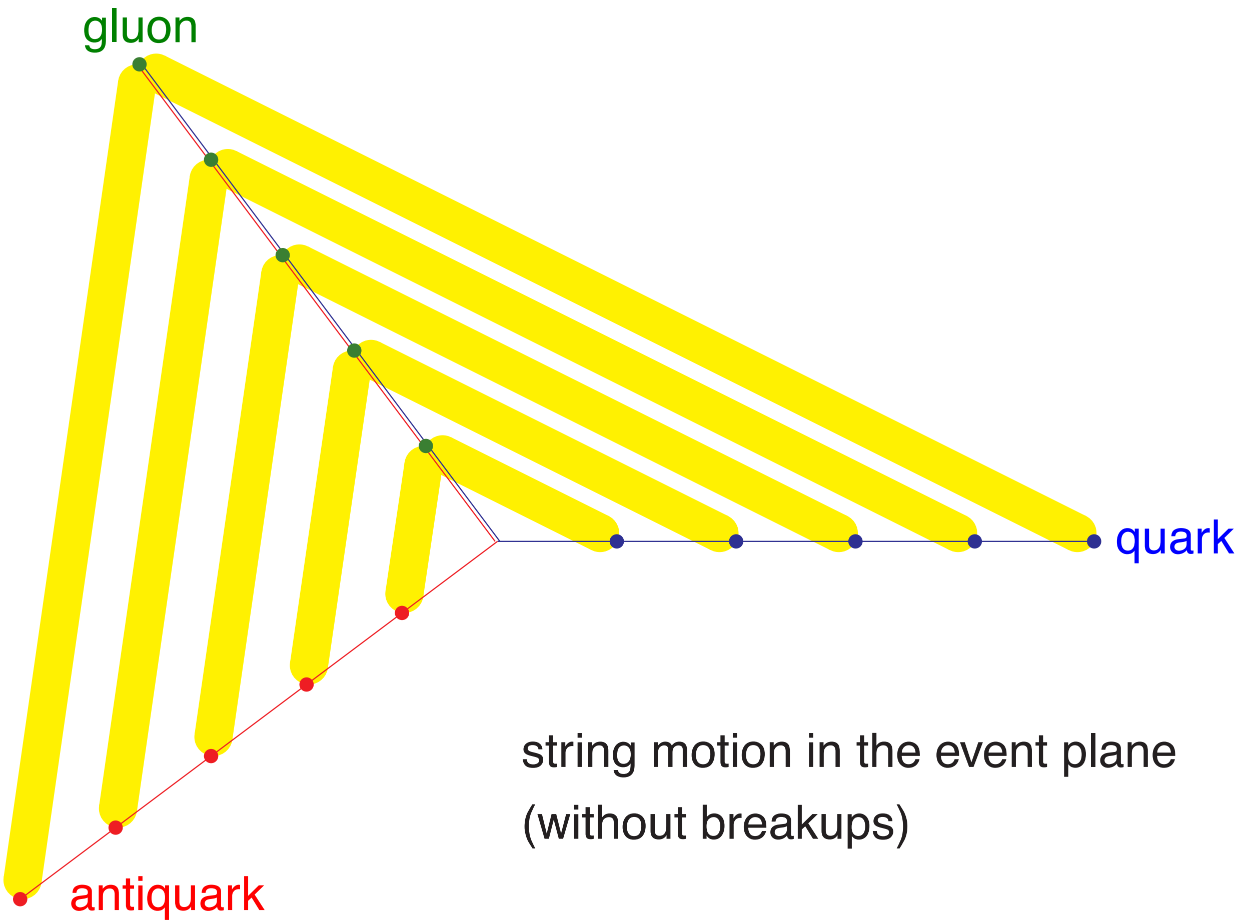
Probability from Tunneling Factor

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

(κ is the string tension equivalent)

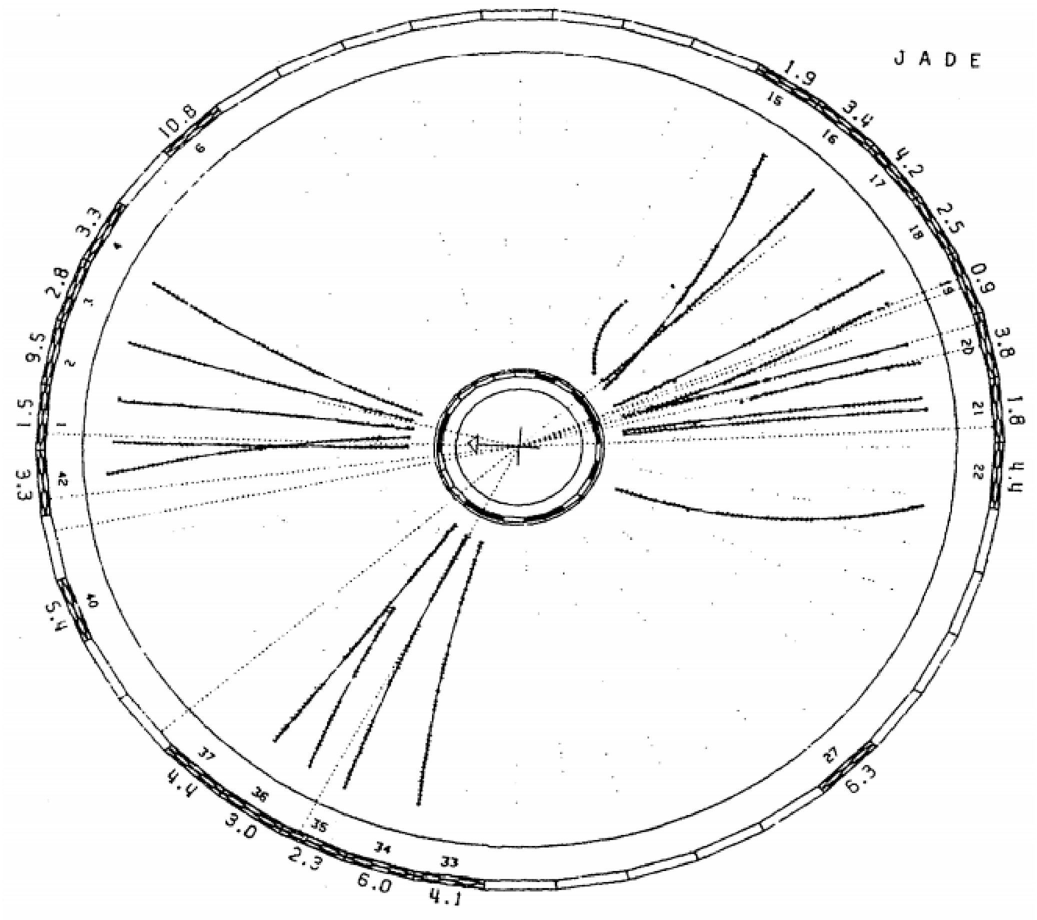
1980: string (colour coherence) effect

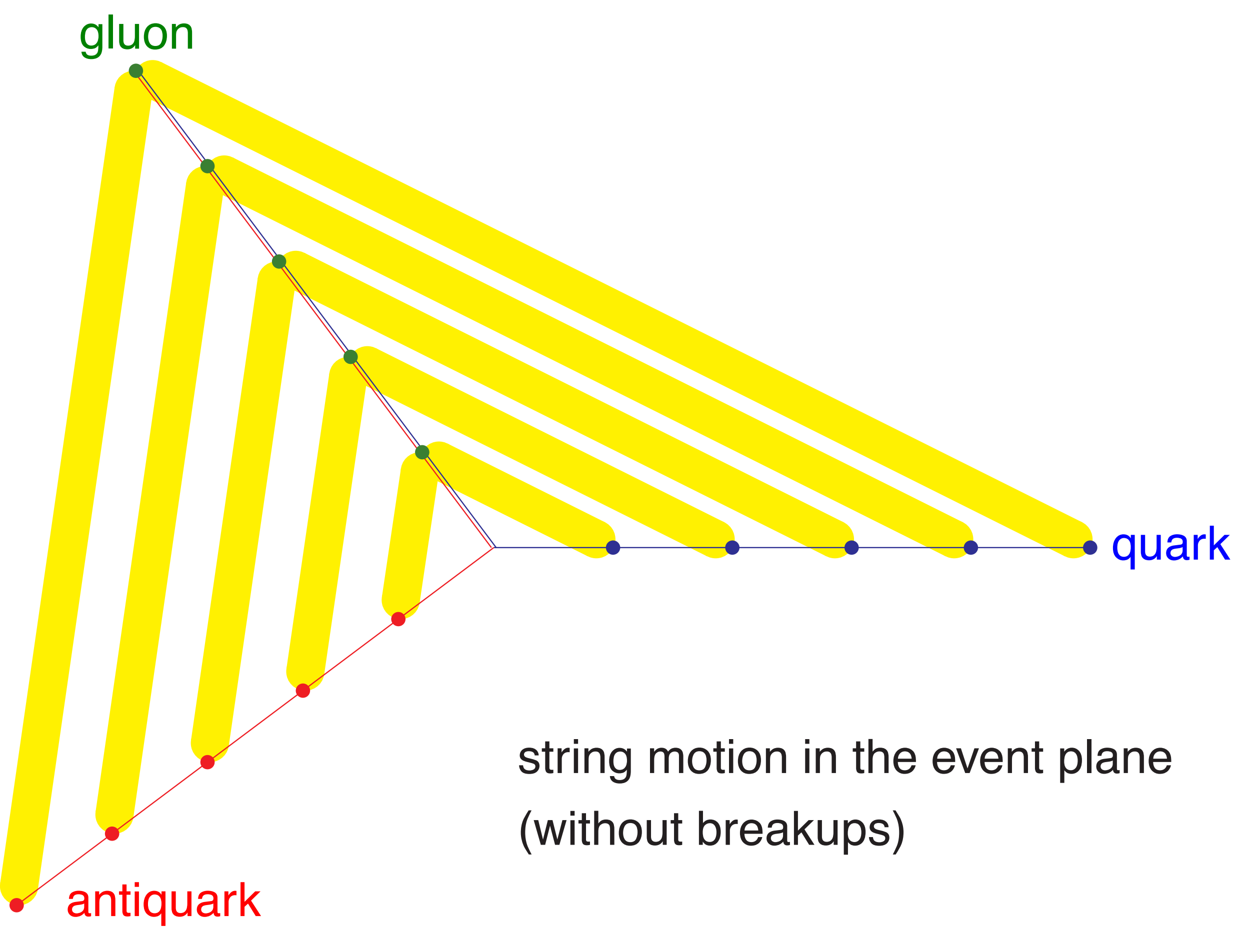




string motion in the event plane
(without breakups)

1980: string (colour coherence) effect





string motion in the event plane
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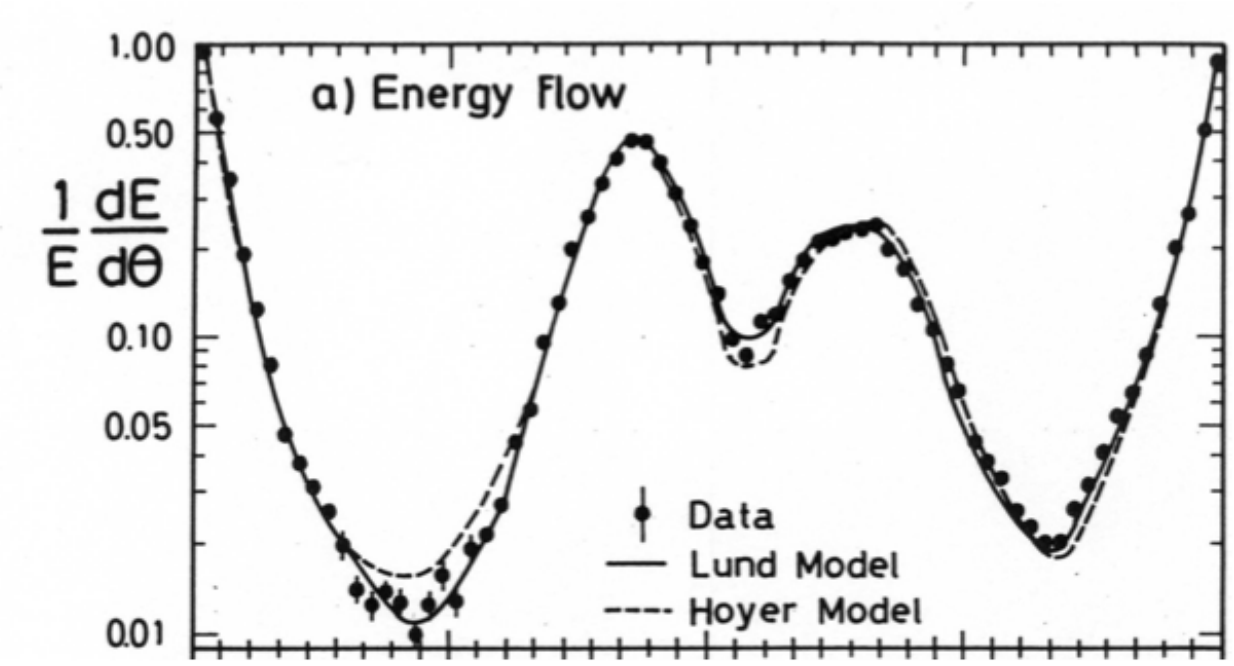


Predicted unique event structure;
inside & between jets.

Confirmed first by JADE 1980.

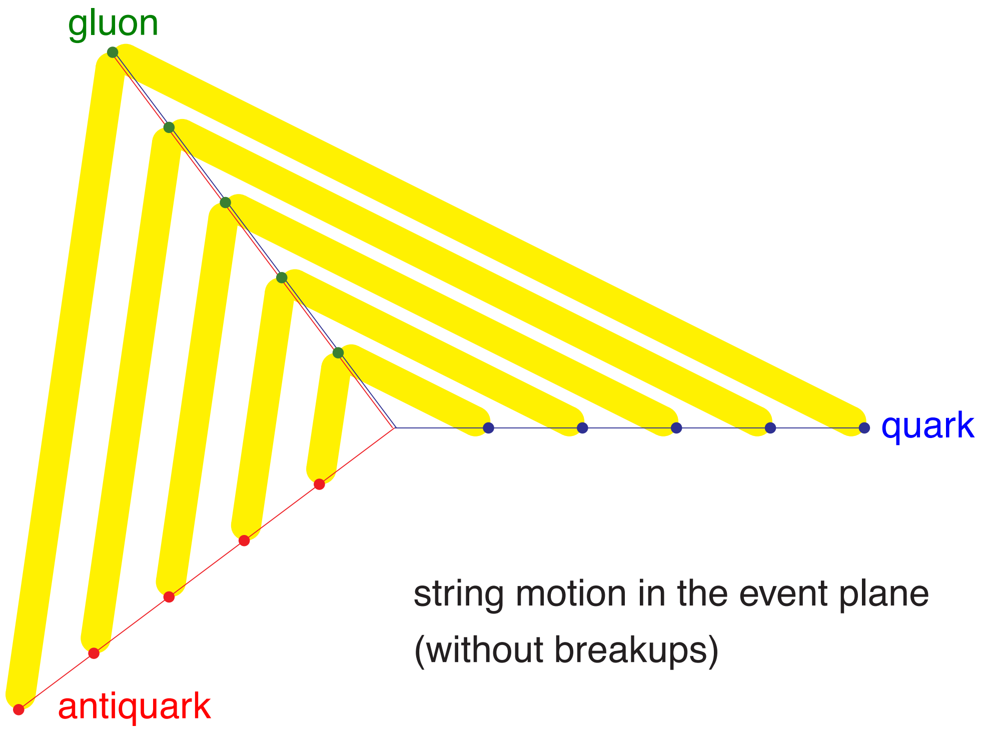
Generator crucial to sell physics!

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

Differences Between Quark and Gluon Jets

More recent study (LHC)

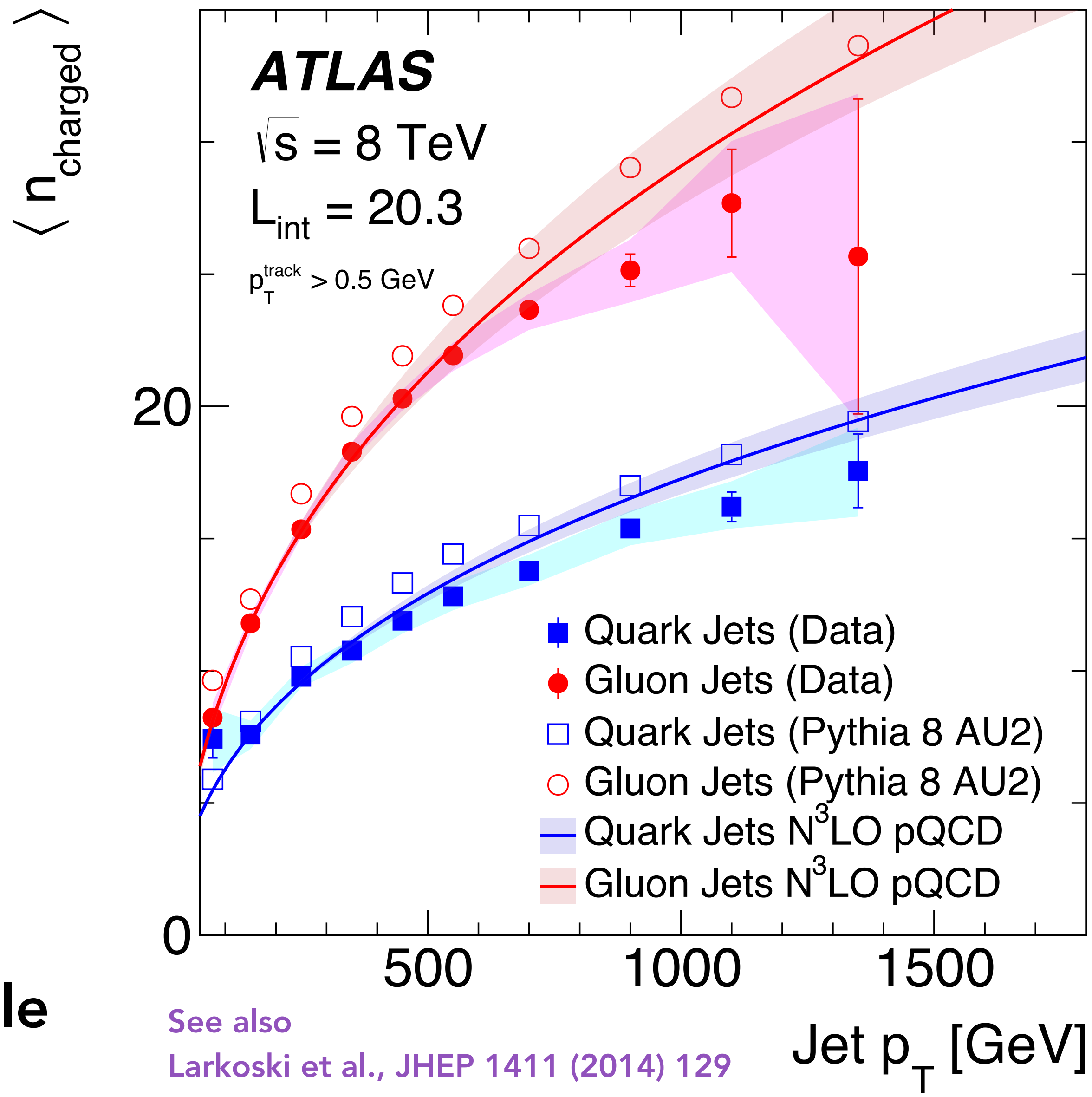
Gluon connected to two string pieces



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)

Summary 1/4: Two ways to compute Quantum Corrections

Fixed Order Paradigm: consider a single physical process

Explicit solutions, process-by-process (often automated, eg MadGraph)

Standard Model: typically NLO (+ many NNLO, not automated)

Beyond SM: typically LO or NLO

Accurate for hard process, to given perturbative order

Limited generality

Event Generators (Showers): consider all physical processes

Universal solutions, applicable to any/all processes

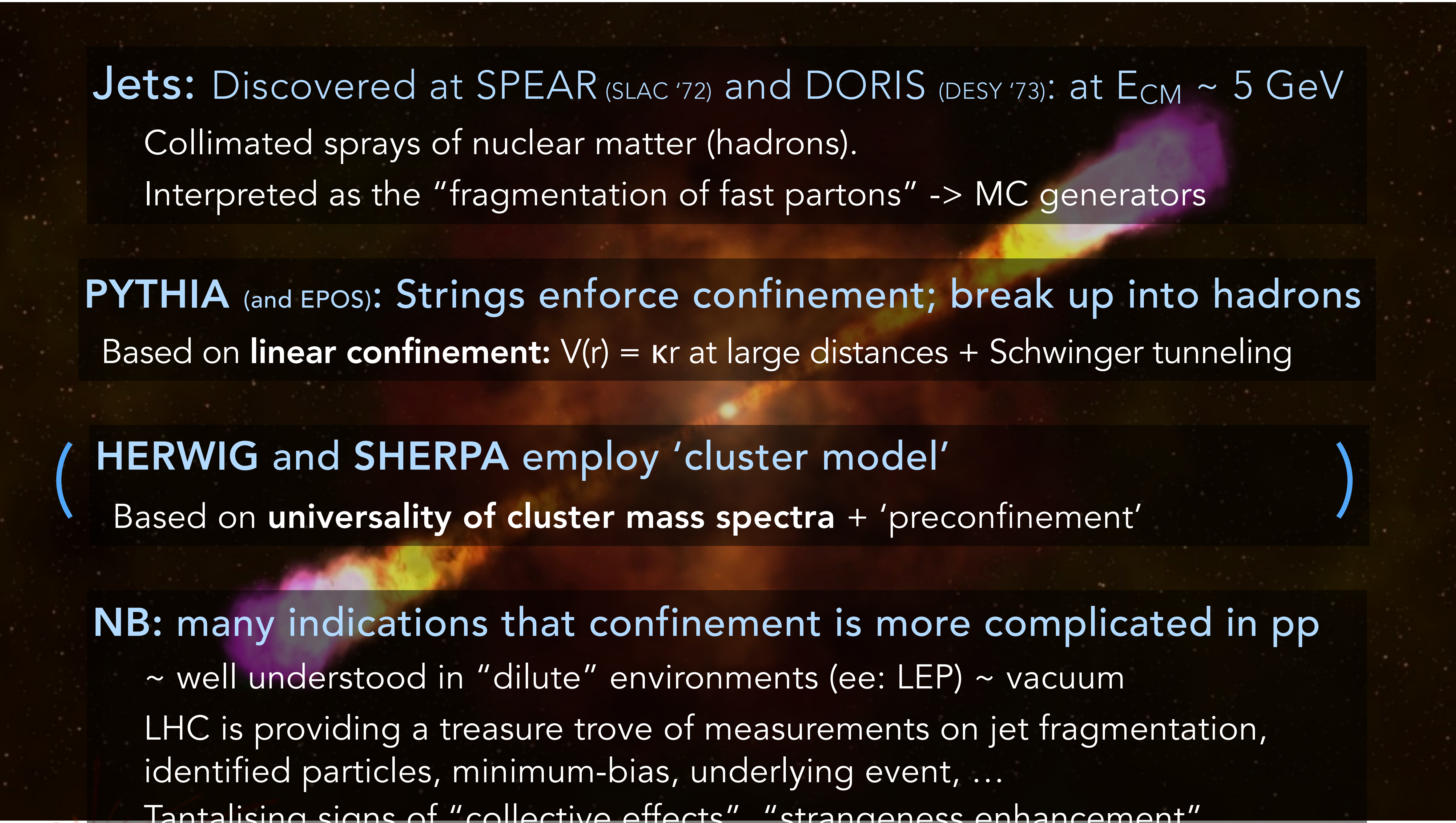
Process-dependence = subleading correction (→ matrix-element corrections / matching / merging)

Maximum generality

Common property of all processes is, e.g., limits in which they factorise!

Accurate in strongly ordered (soft/collinear) limits (=bulk of radiation)

Summary 2/4: Jets and Hadronisation



Jets: Discovered at SPEAR (SLAC '72) and DORIS (DESY '73): at E_{CM} ~ 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

(**HERWIG** and **SHERPA** employ 'cluster model'

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

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, …

Tantalising signs of "collective effects", "strangeness enhancement", …

Highly active area of current research activity

Summary 3/4: 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?
   JET ALGORITHM
   (+ size/resolution parameters)
2. How will you combine their momenta?
   RECOMBINATION SCHEME
   (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?)

Summary 4/4: IRC safe vs IRC sensitive observables

Use IRC Safe observables …

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

To study short-distance physics

Recombination-type jet 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)


Image Credits: Richard Seaman

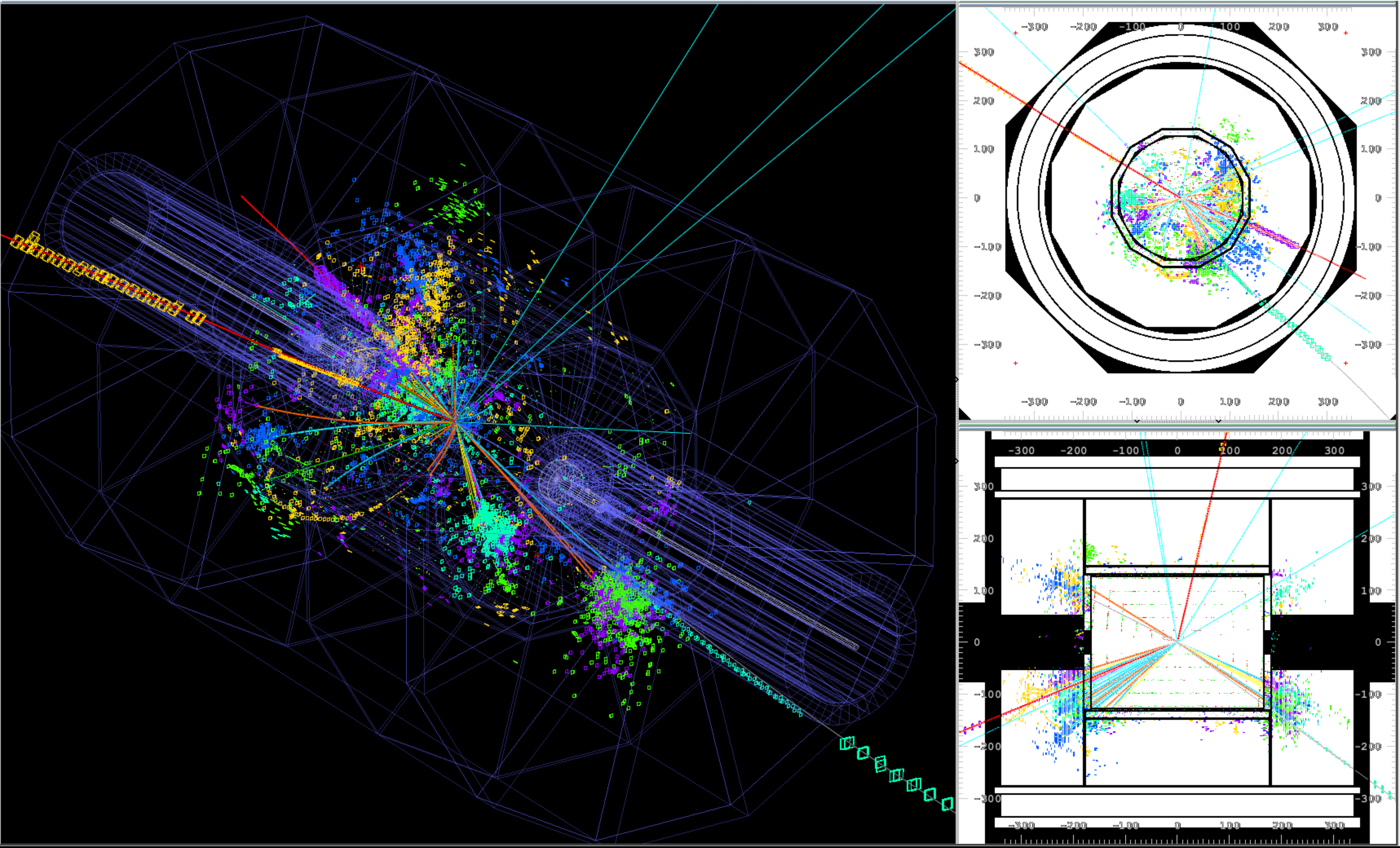
Use IRC Sensitive observables …

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.

Thank you



(Simulated ttH event for the Compact Linear Collider)