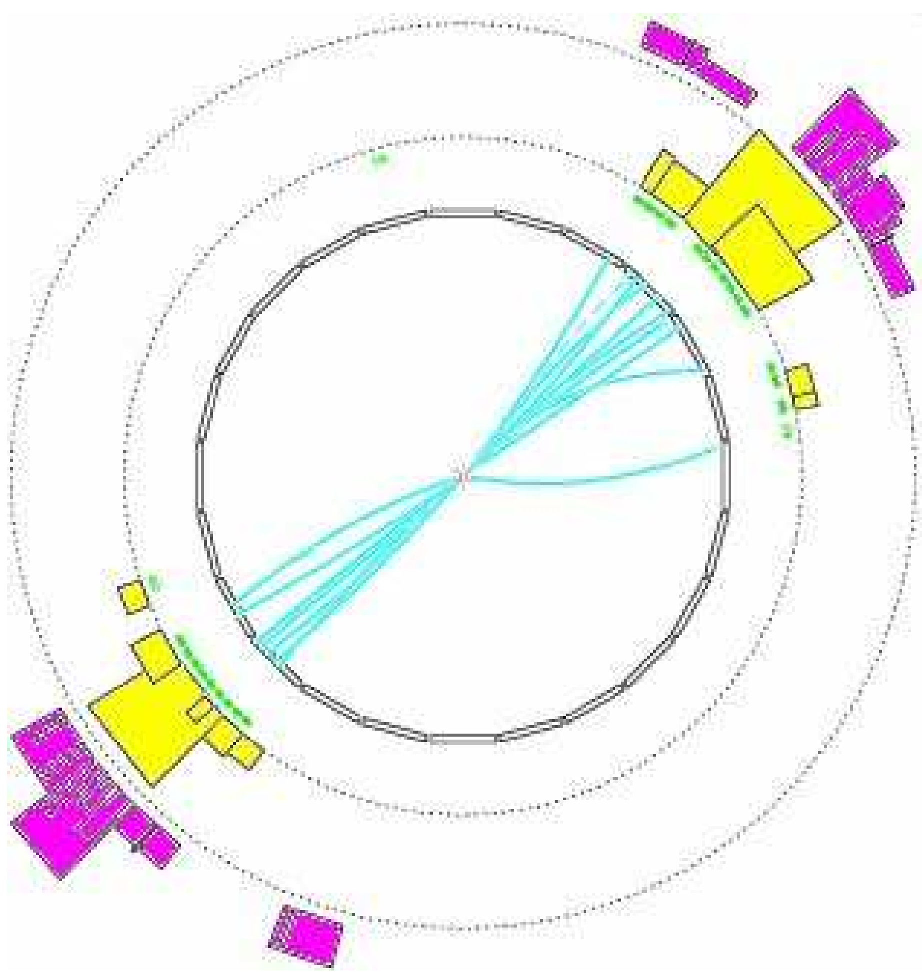
CERN Summer School 2010, Raseborg, Finland

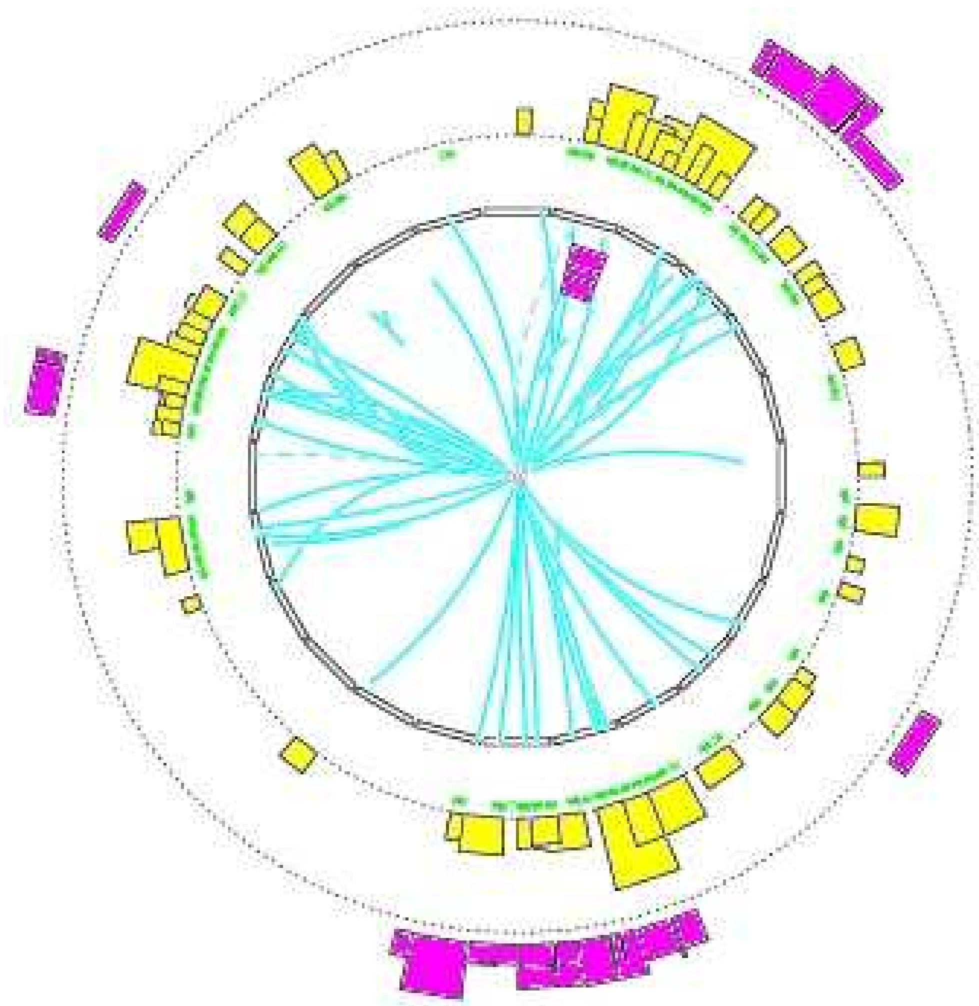
# QCD
# Lecture 5

## Jets and Matching

P. Skands

# "Seeing" vs Defining Jets

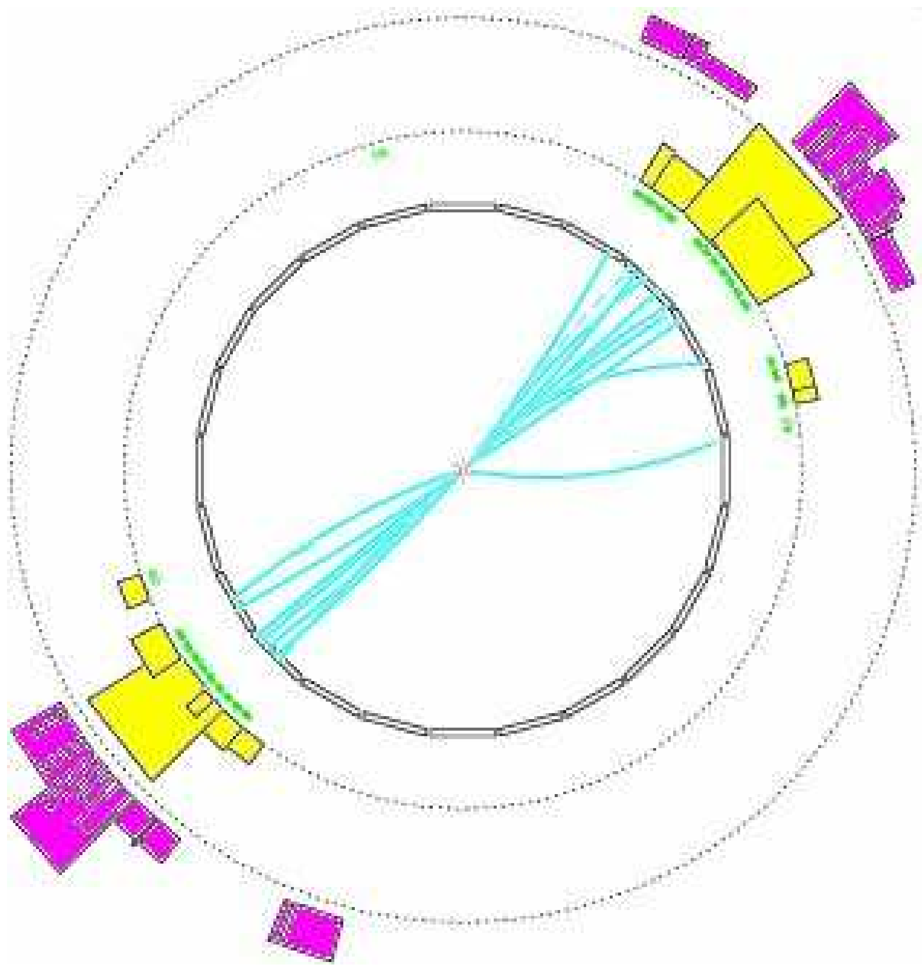


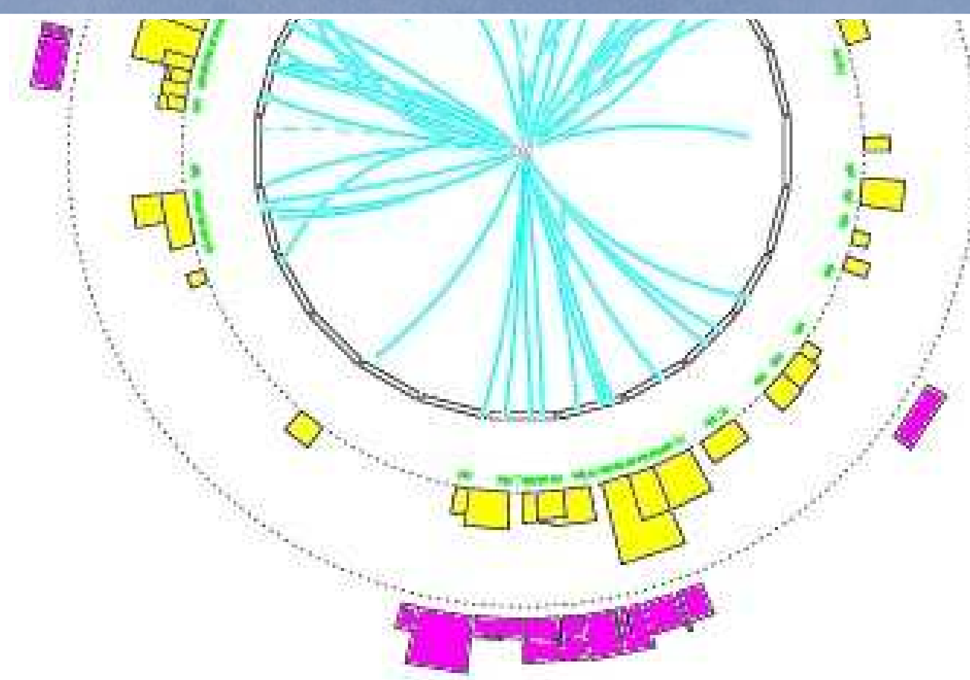


2

How many jets can you see?

# "Seeing" vs Defining Jets



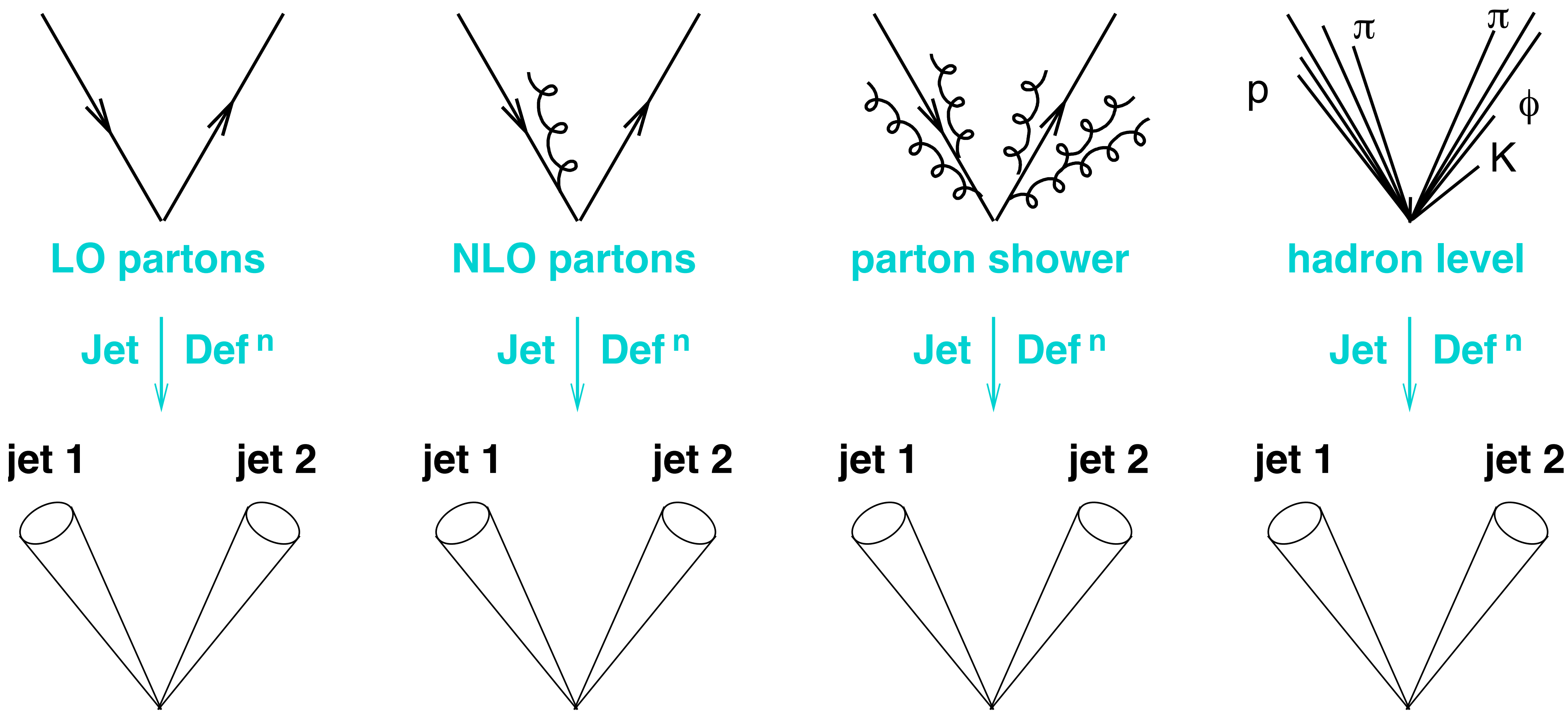


Do you really want to ask yourself this for $10^9$ events?

2

How many jets can you see?

# Jets as Projections




Projections to jets provides a universal view of event

Illustrations by G. Salam

# There is no unique or "best" jet definition

## YOU decide how to look at event

The construction of jets is inherently ambiguous

1. Which particles get grouped together?
   JET ALGORITHM (+ parameters)
2. How will you combine their momenta?
   RECOMBINATION SCHEME (e.g., 'E' scheme: add 4-momenta)

→ **Jet Definition**

Ambiguity complicates life, but gives flexibility in one's view of events → Jets non-trivial!

# Types of Algorithms

## 1. Sequential Recombination

Take your 4-vectors

Combine the vectors that have the lowest 'distance measure'

Different names for different distance measures

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

[ $k_{Ti}^2 = E_i^2(1-\cos\theta_{ij})$ ] (+ beam treated as non-emitting)

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

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

ArClus : $p_T^2 = s_{ij} s_{jk} / s$ [ NB: ARCLUS is 3→2 instead of 2→1 ⇒ can keep all partons on shell, but more possibilities to try ]

→ Now you have a new set of (n-1) 4-vectors

Iterate until A or B (you choose which):

A: all distance measures larger than something

B: you reach a specified number of jets

Look at event at:

- specific resolution (→ A)
- specific $n_{jets}$ (→ B)

# Why $k_T$ (or $p_T$ or $\Delta R$)?

$k_{Ti;j}^2 = E_i^2(1-\cos\theta_{ij})$ $p_{Tj}^2 = s_{ij}s_{jk}/s_{ijk}$ (note: there are also other $p_T$ defs)

Attempt to (approximately) capture universal jet-within-jet-witin-jet... behaviour

Approximate full matrix element

$$\frac{|M_{X+1}^{(0)}(s_{i1}, s_{1k}, s)|^2}{|M_X^{(0)}(s)|^2} \sim 4\pi\alpha_s C_F \left(\frac{2s_{ik}}{s_{i1}s_{1k}} + \ldots\right)$$

"Eikonal"
(universal, always there)

by Leading-Log limit of QCD → universal dominant terms

$$\frac{ds_{i1}ds_{1k}}{s_{i1}s_{1k}} \to \frac{dp_\perp^2}{p_\perp^2}\frac{dz}{z(1-z)} \to \frac{dE_1}{\min(E_i, E_1)}\frac{d\theta_{i1}}{\theta_{i1}} \quad (E_1 \ll E_i,\ \theta_{i1} \ll 1) \quad ,\ldots$$

Rewritings in soft/collinear limits

"smallest" $k_T$ (or $p_T$ or $\theta_{ij}$, or ...) → largest Eikonal

# Types of Algorithms

## 2. "Cone" type

- Motivated by idea of partons ≈ "invariant" directed energy-flow (most of which ends up within a "cone")
- Take your 4-vectors
  - Select a procedure for which "test cones" to draw
  - Different names for different procedures
    - Seeded : start from hardest 4-vectors (and possibly combinations thereof, e.g., CDF midpoint algo) = "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: seeded algorithms are INFRARED UNSAFE**

# Infrared Safety

## Definition

An observable is **infrared 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 particles (conserving the total momentum and energy) should not change the value of the observable

(Not accidentally, these are the two singular limits we encountered before)

# IR Safety

**Theorem:**

For all "IR Safe Observables", hadronization corrections (non-perturbative corrections) are POWER SUPPRESSED

$$\text{IR Safe Corrections} \quad \propto \quad \frac{Q_{\text{IR}}^2}{Q_{\text{UV}}^2}$$

All "non-IR Safe Observables" receive logarithmically divergent pQCD corrections in the IR, which must be canceled by large hadronization corrections → more sensitive to UV→IR transition

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

# IR Safety

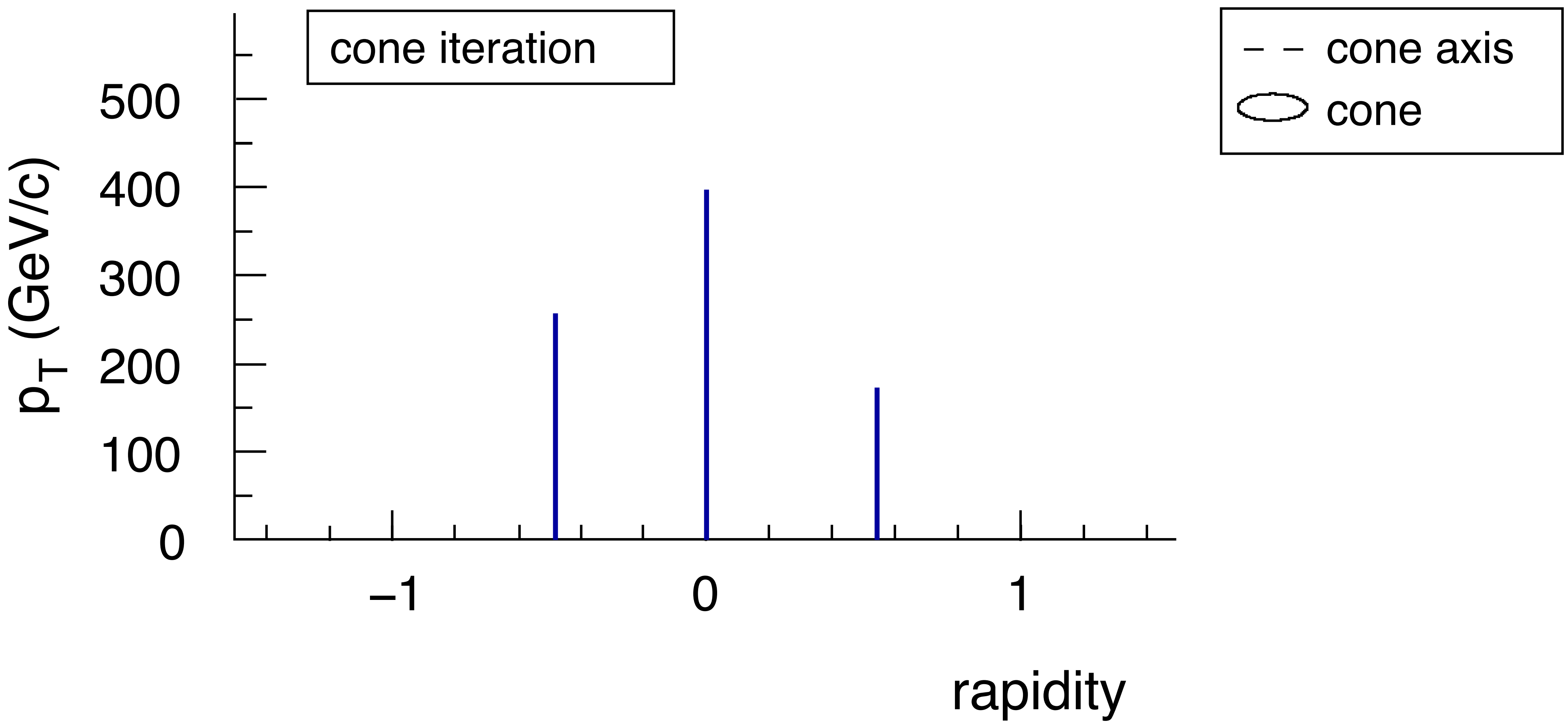
## Compare an IR safe and unsafe Jet

- May look pretty similar in experimental environment
  - (proof that nature has no trouble canceling all divergencies, no matter what the observable)

## So what's the trouble?

- It's not nice to your theory friends ...
  - If they use a truncation of the theory (i.e., pQCD)
    - pQCD badly divergent if IR unsafe, but only power corrections if IR safe
  - Even if they have a hadronization model
    - Dependence on hadronization model → larger uncertainty

# ICPR iteration issue




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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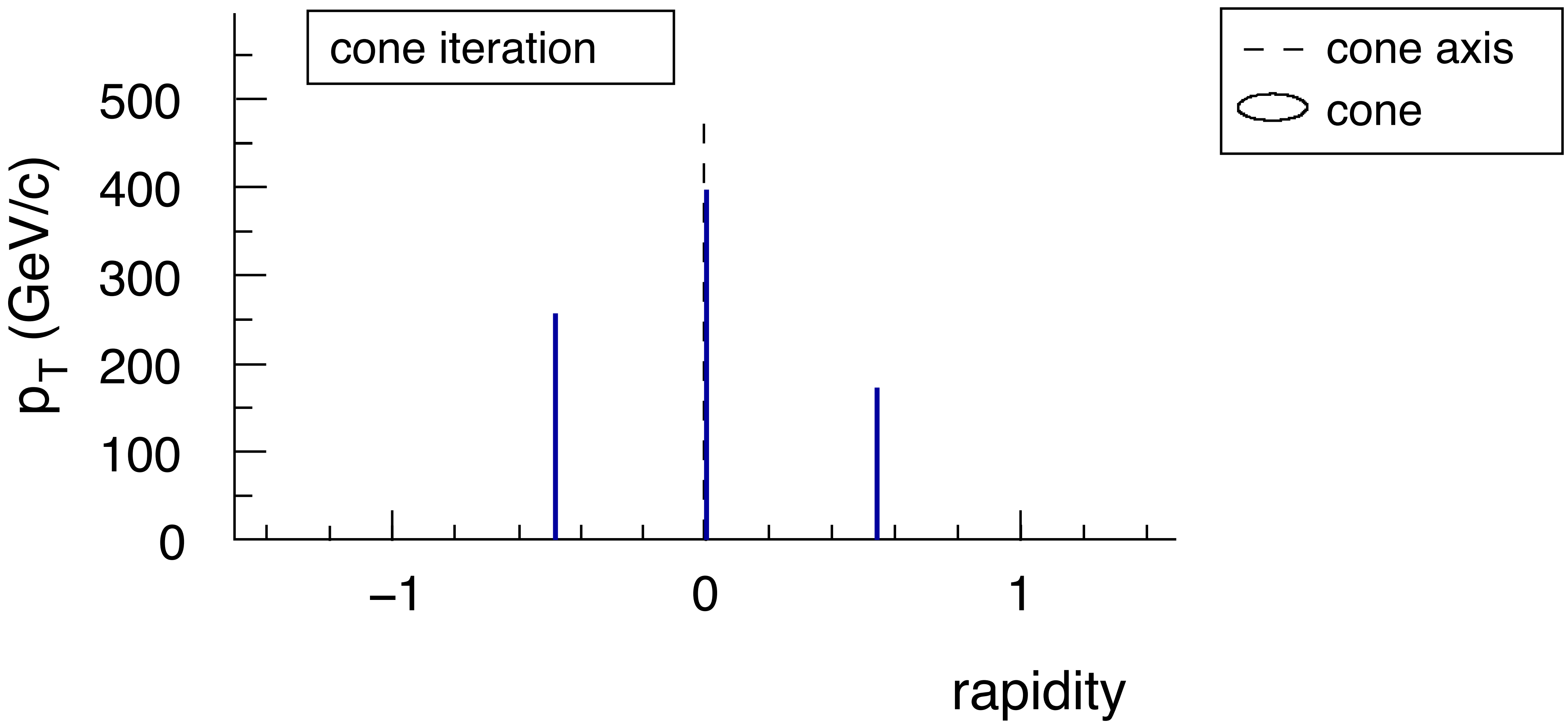


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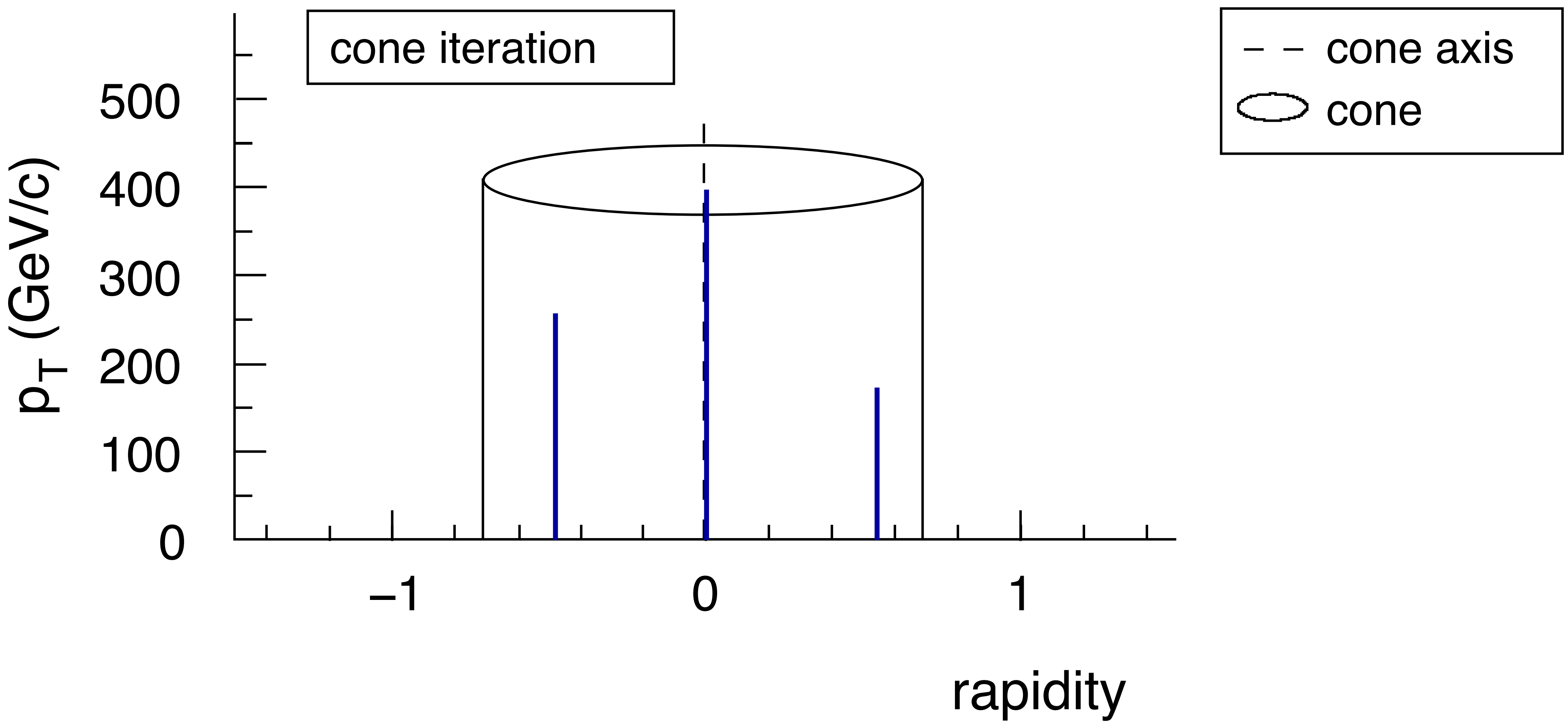


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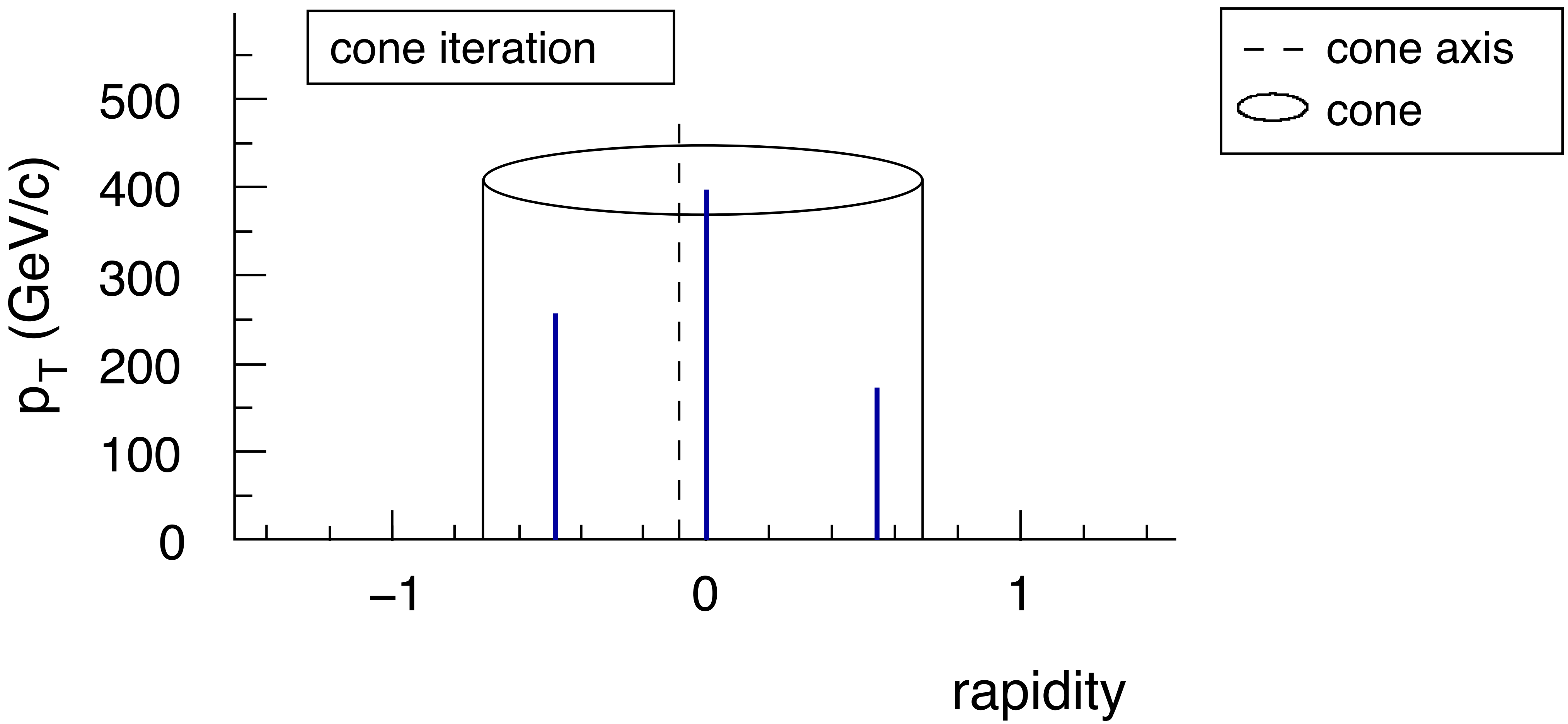


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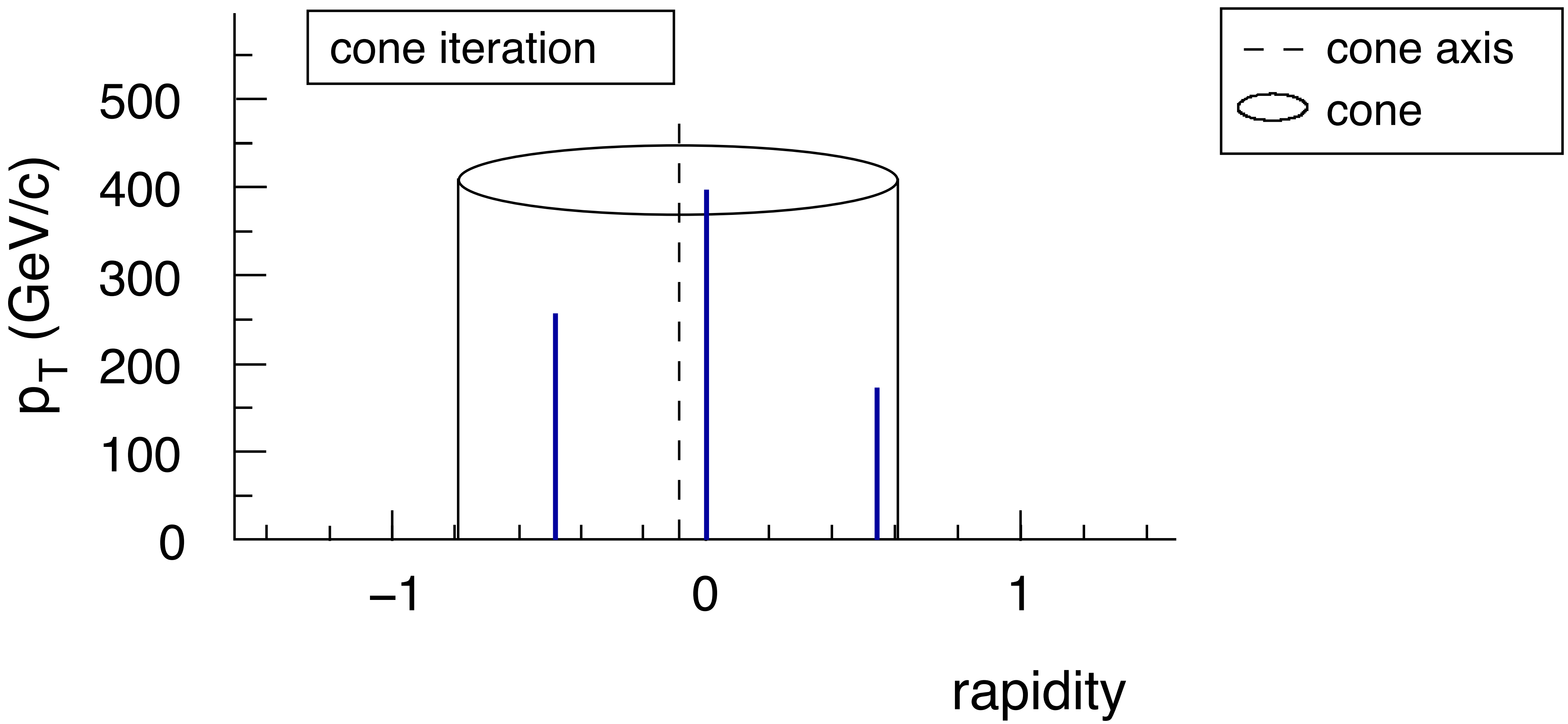


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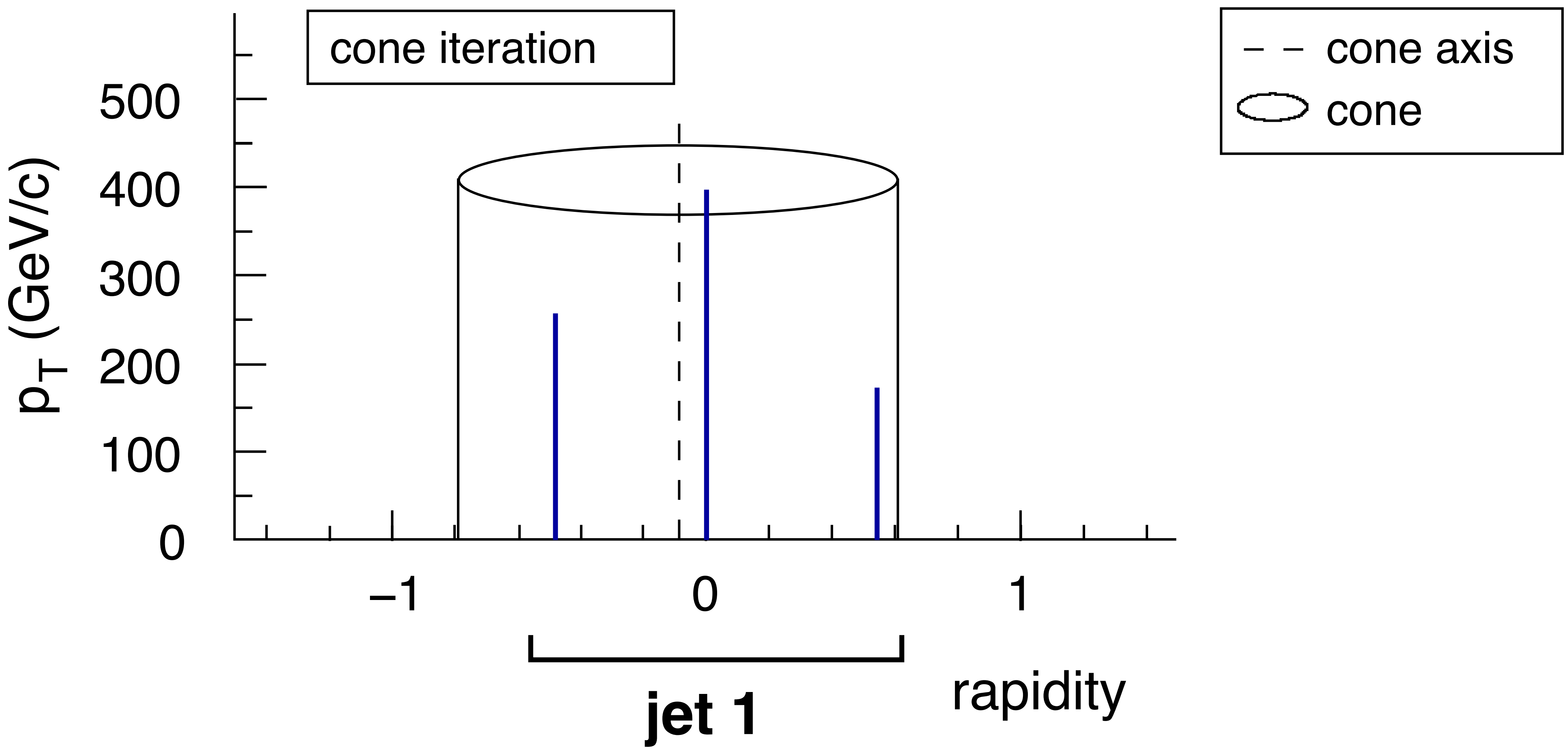


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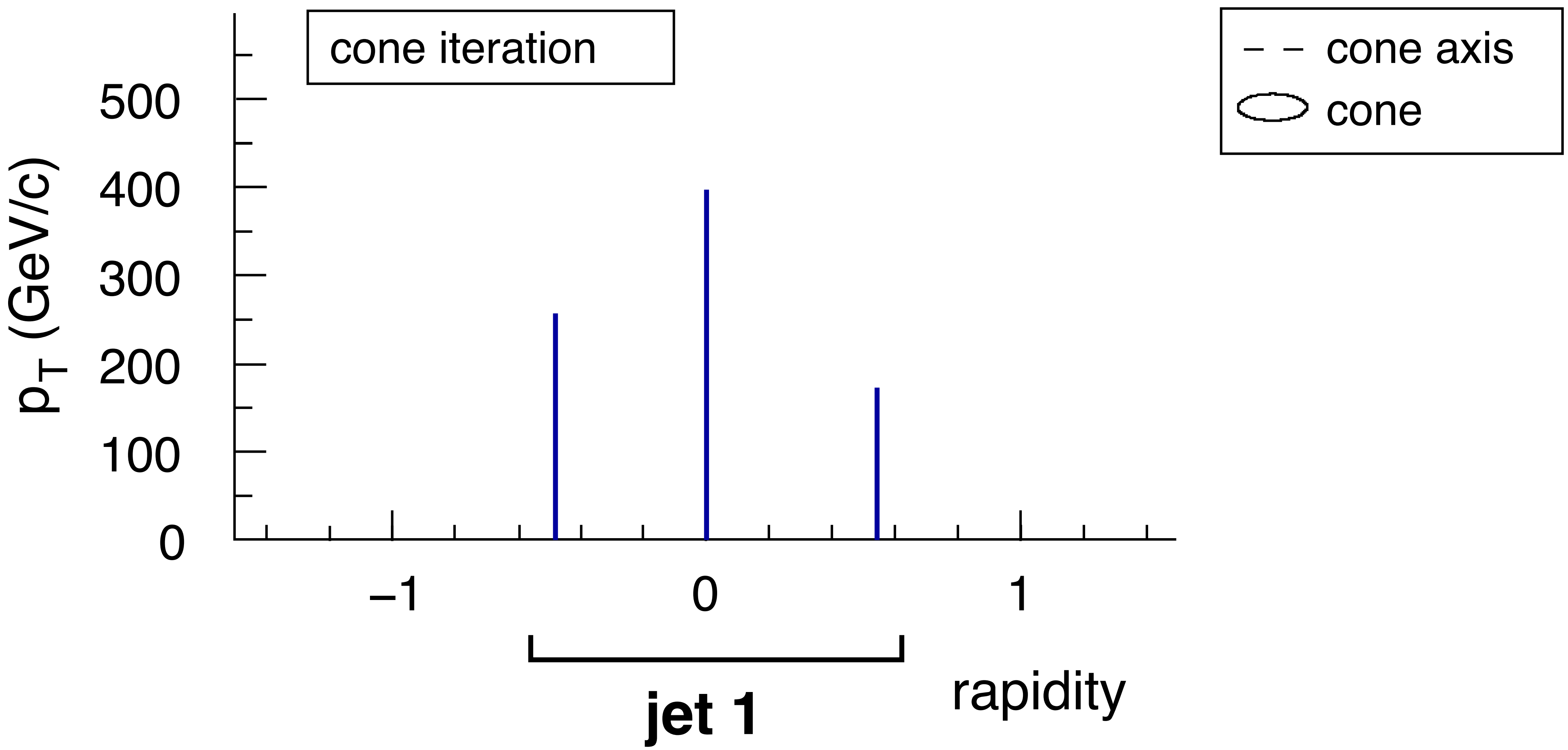


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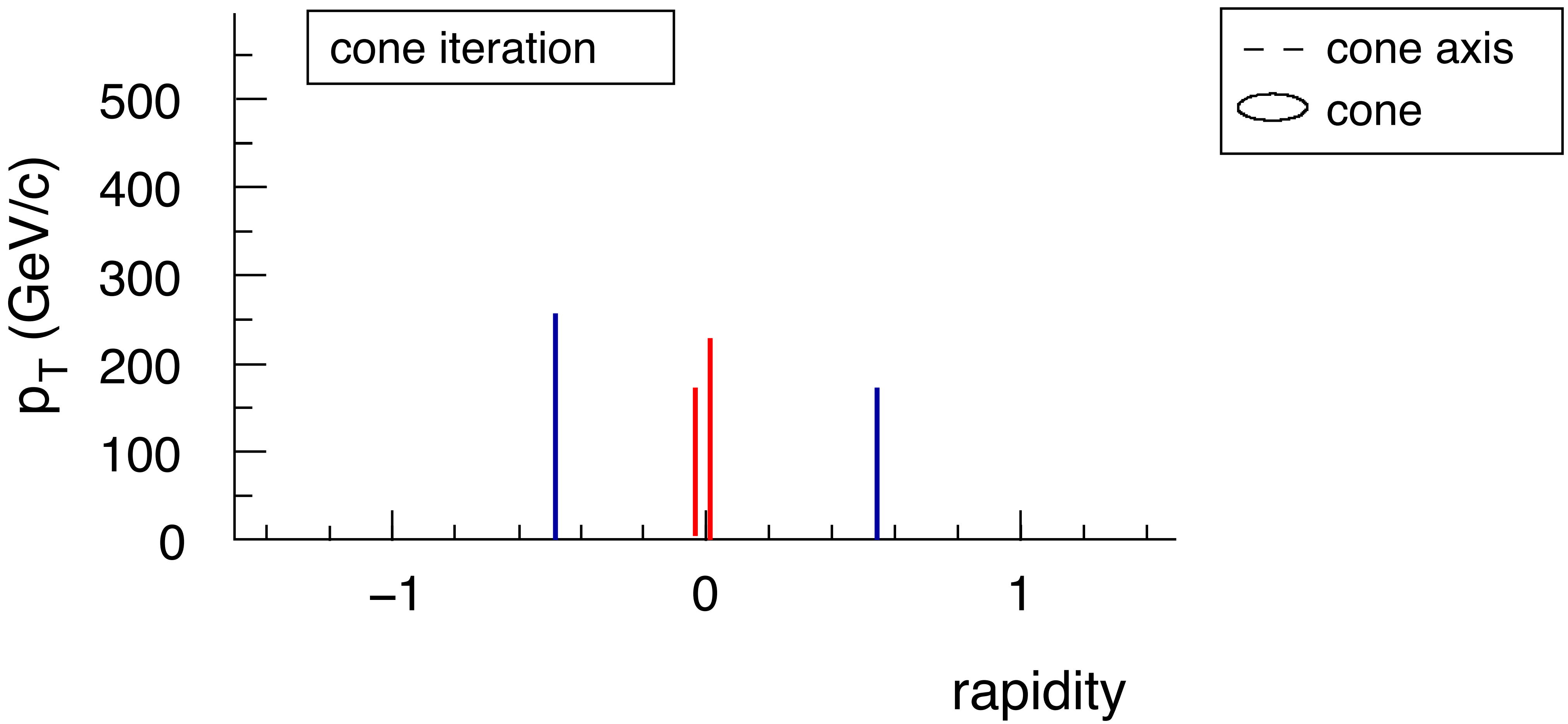


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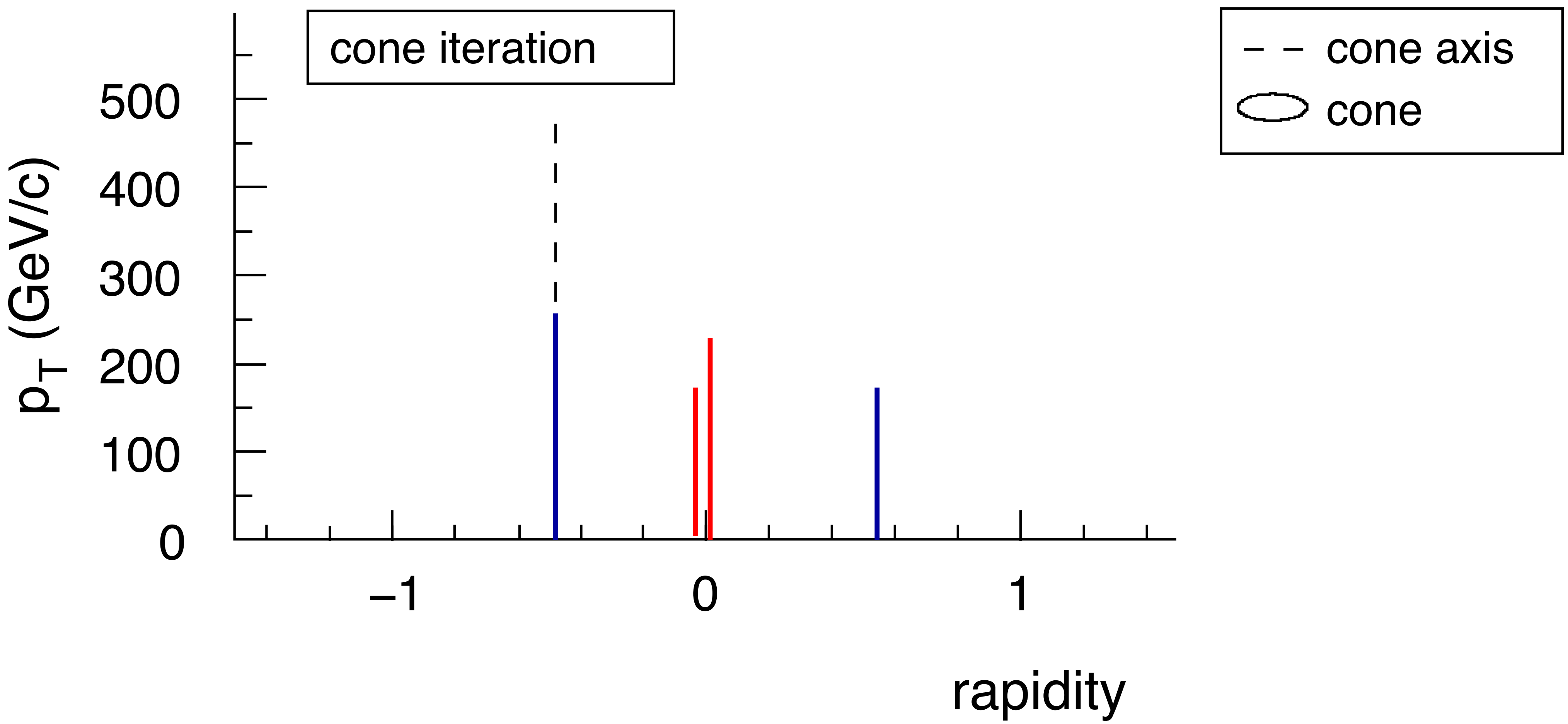


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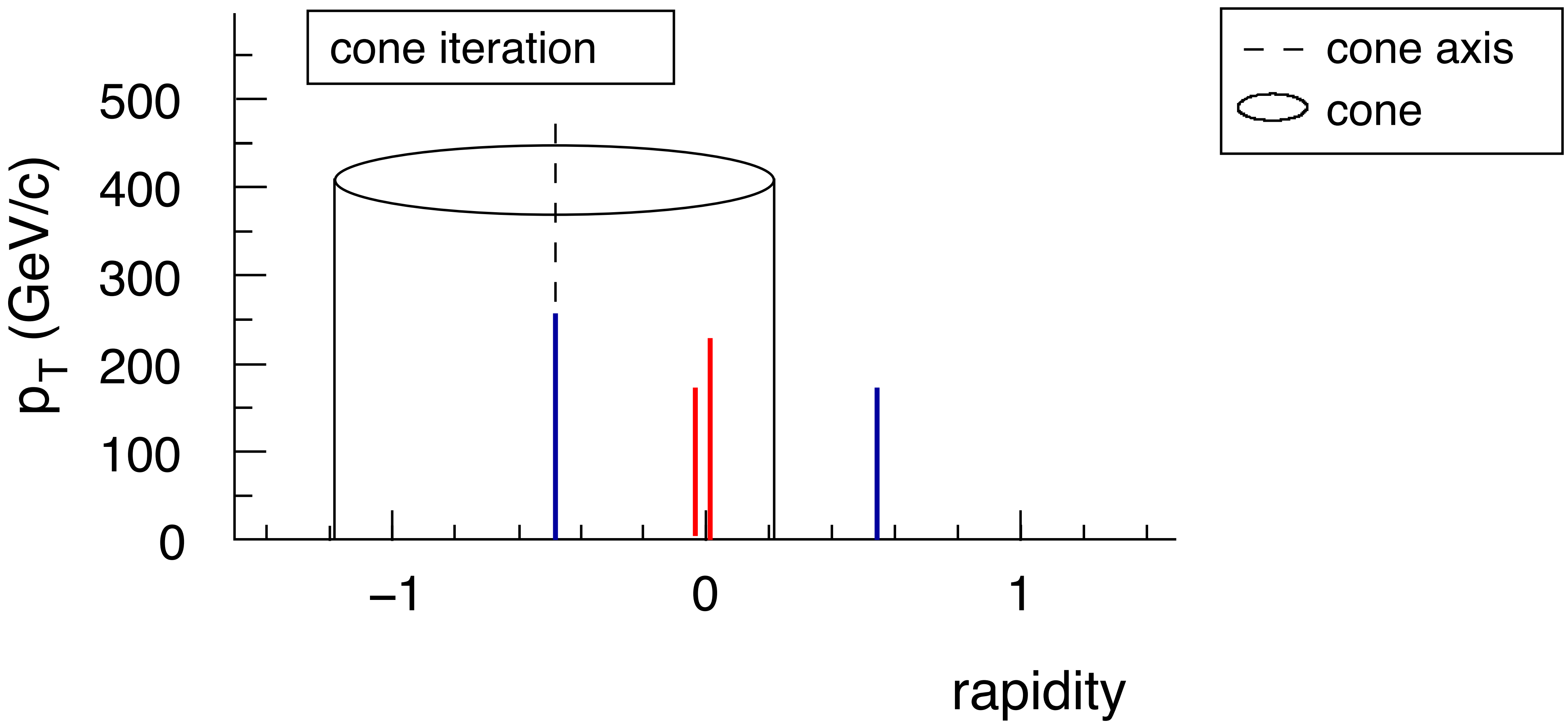


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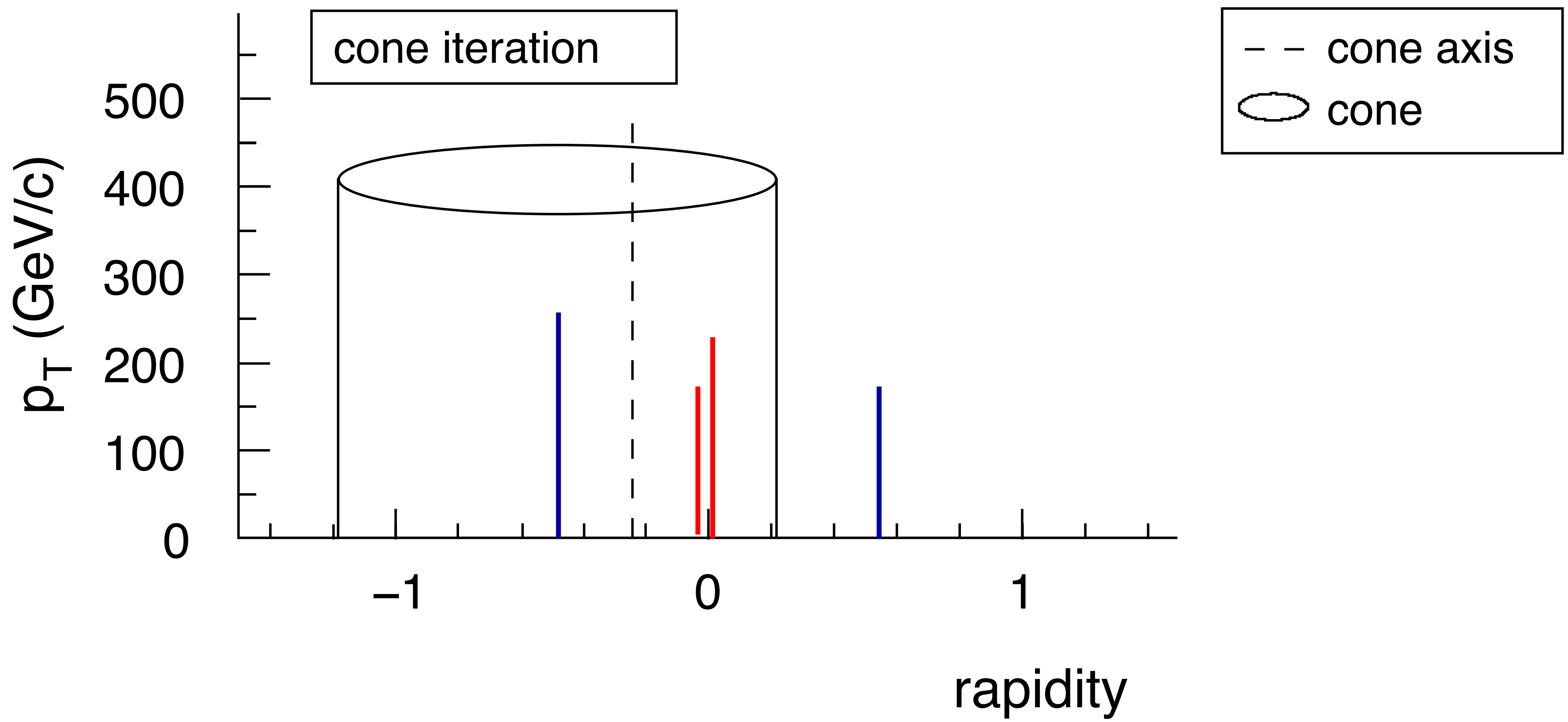


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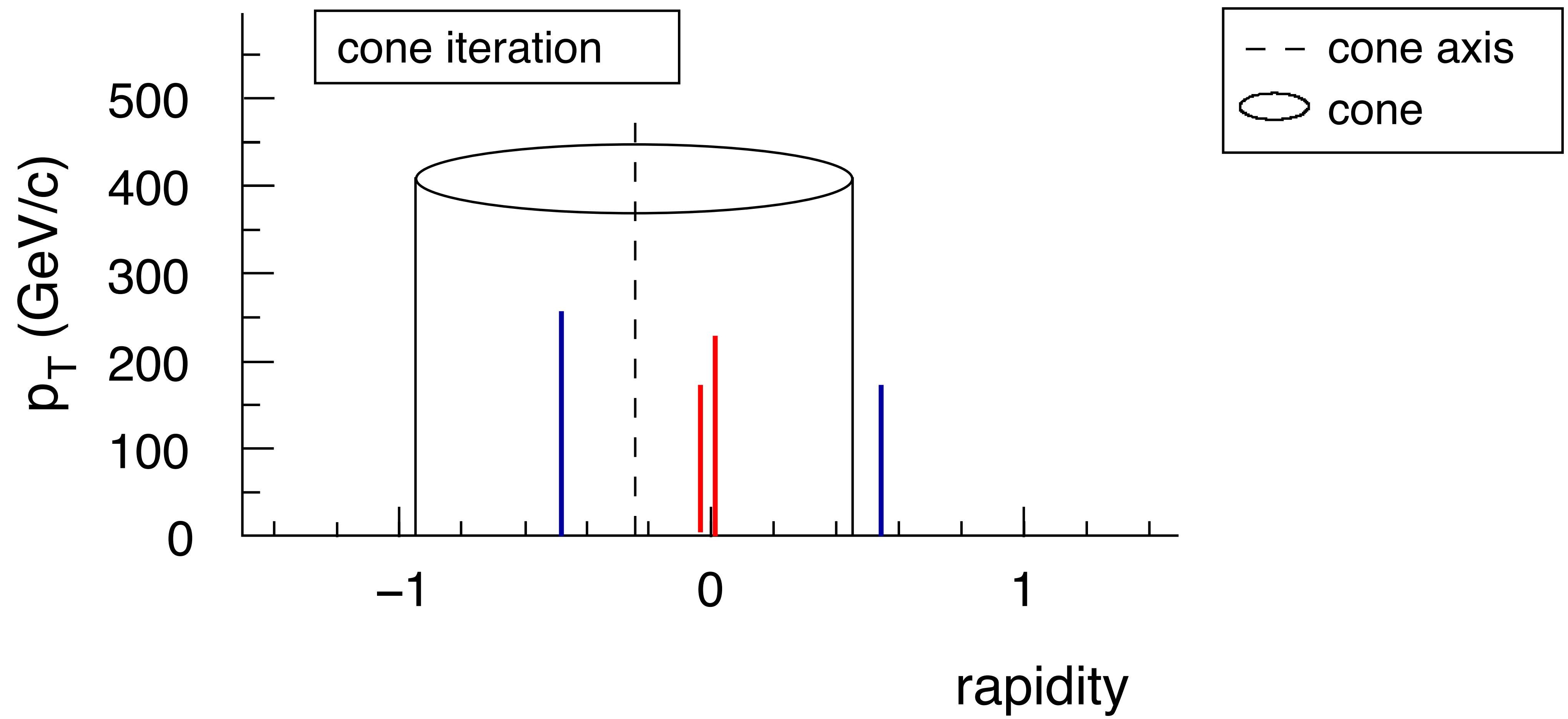


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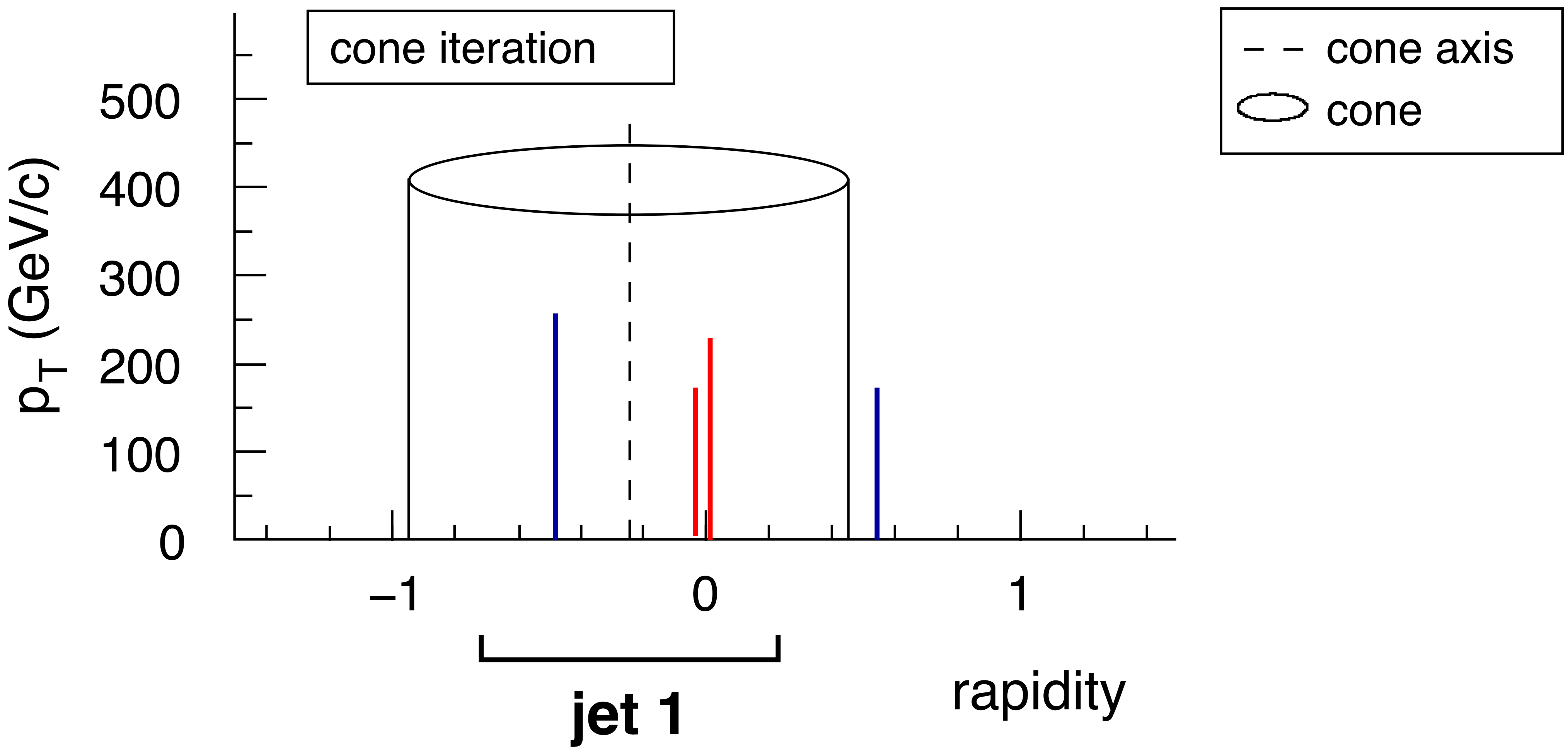


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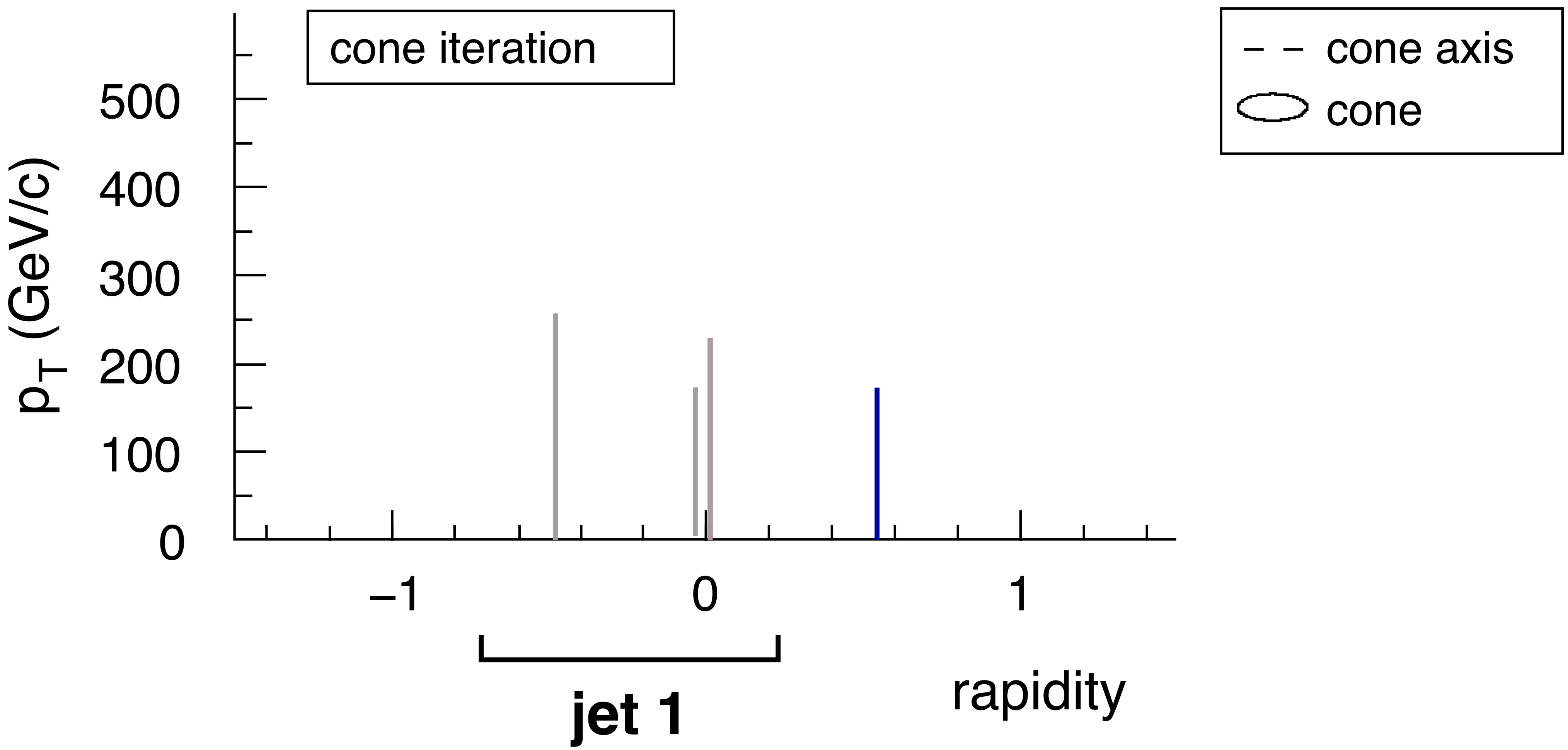


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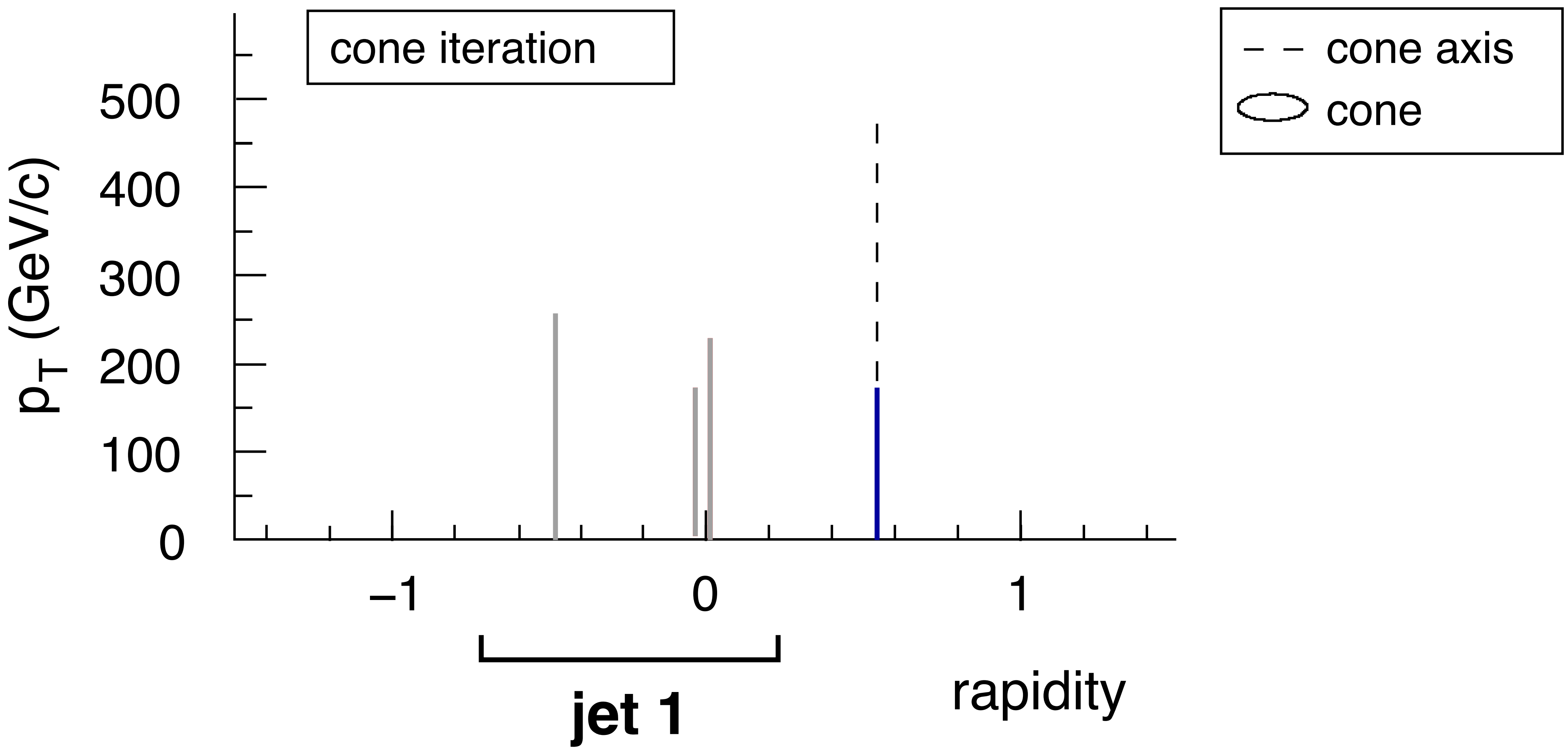


Collinear splitting can modify the hard jets: ICPR algorithms are collinear unsafe ⟹ perturbative calculations give ∞

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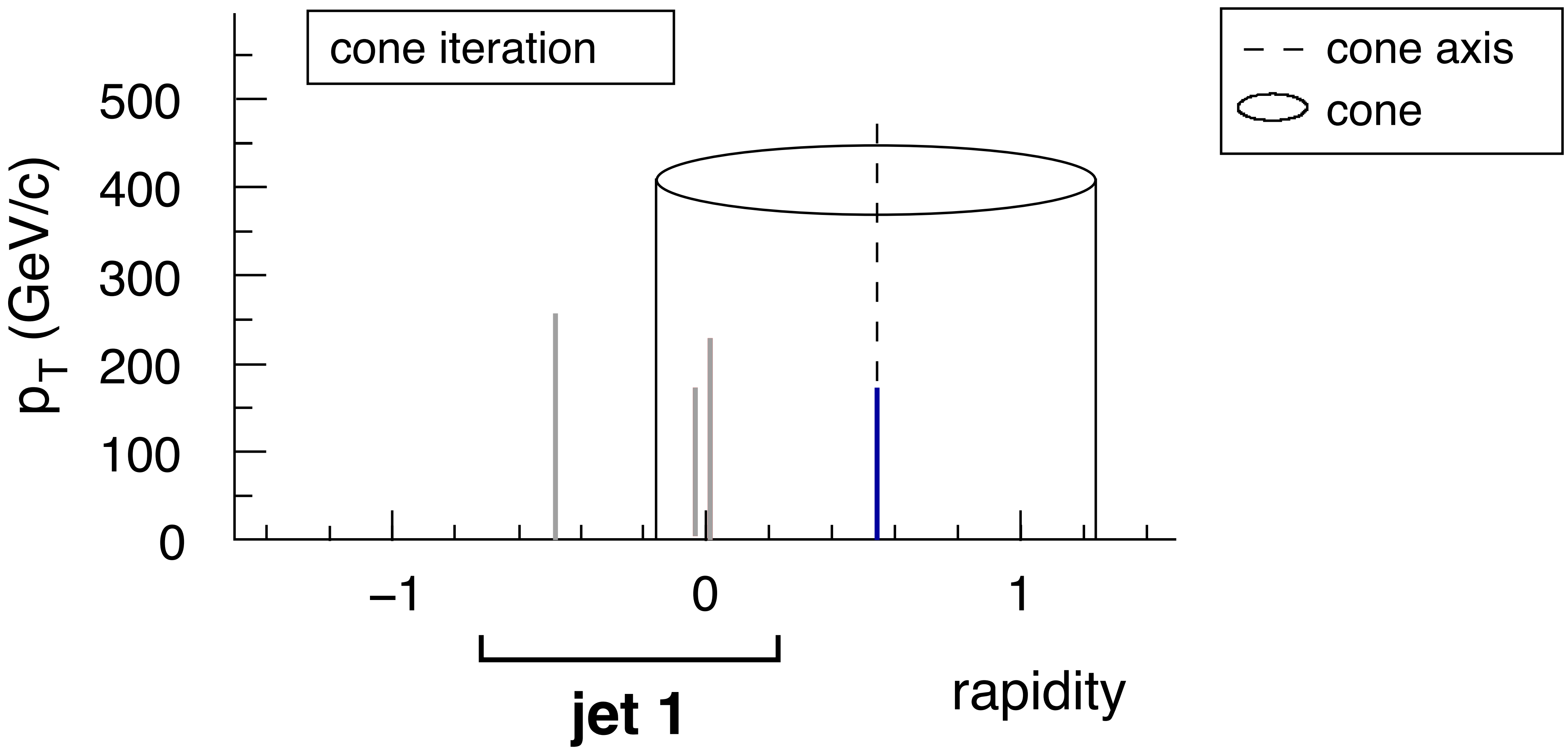


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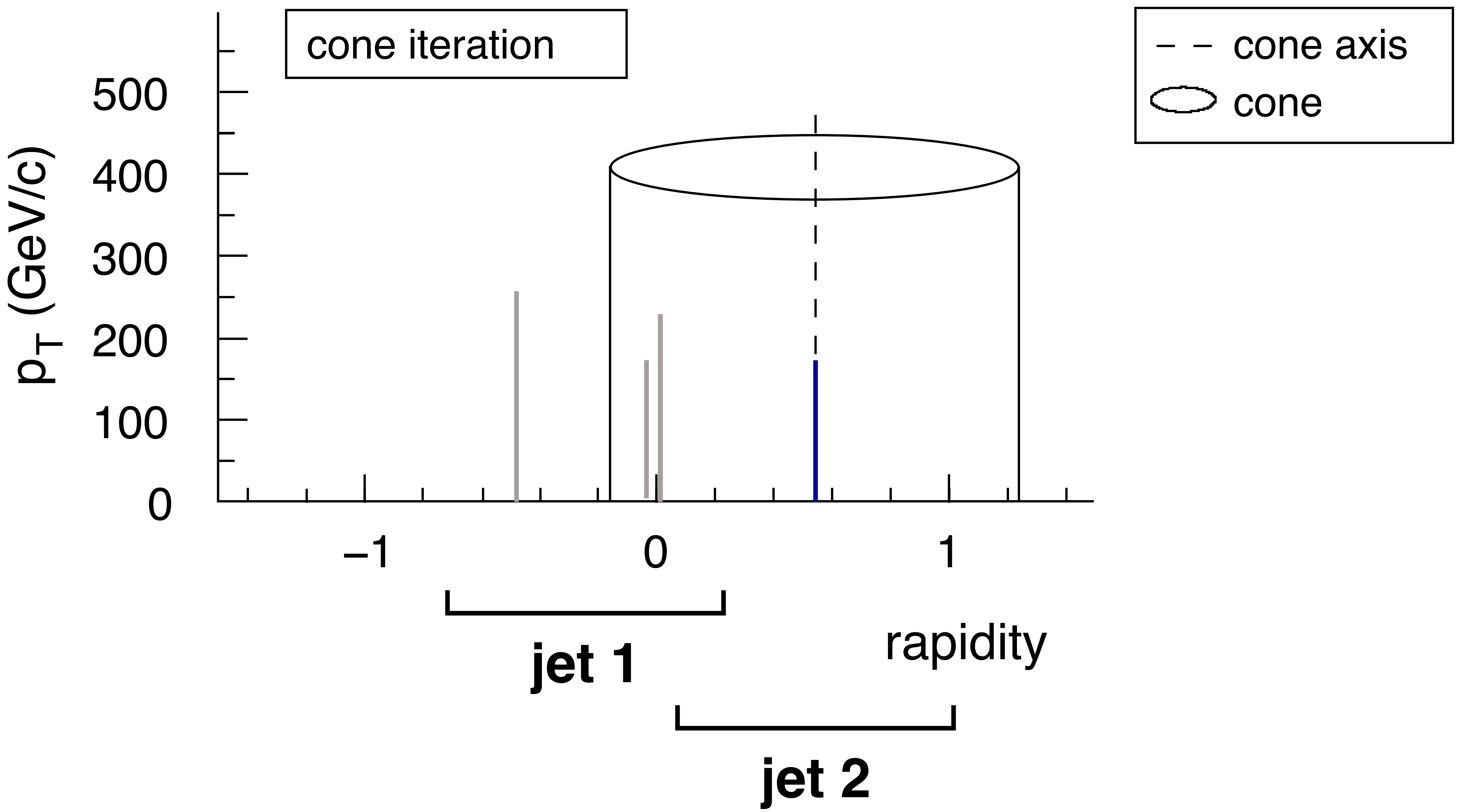


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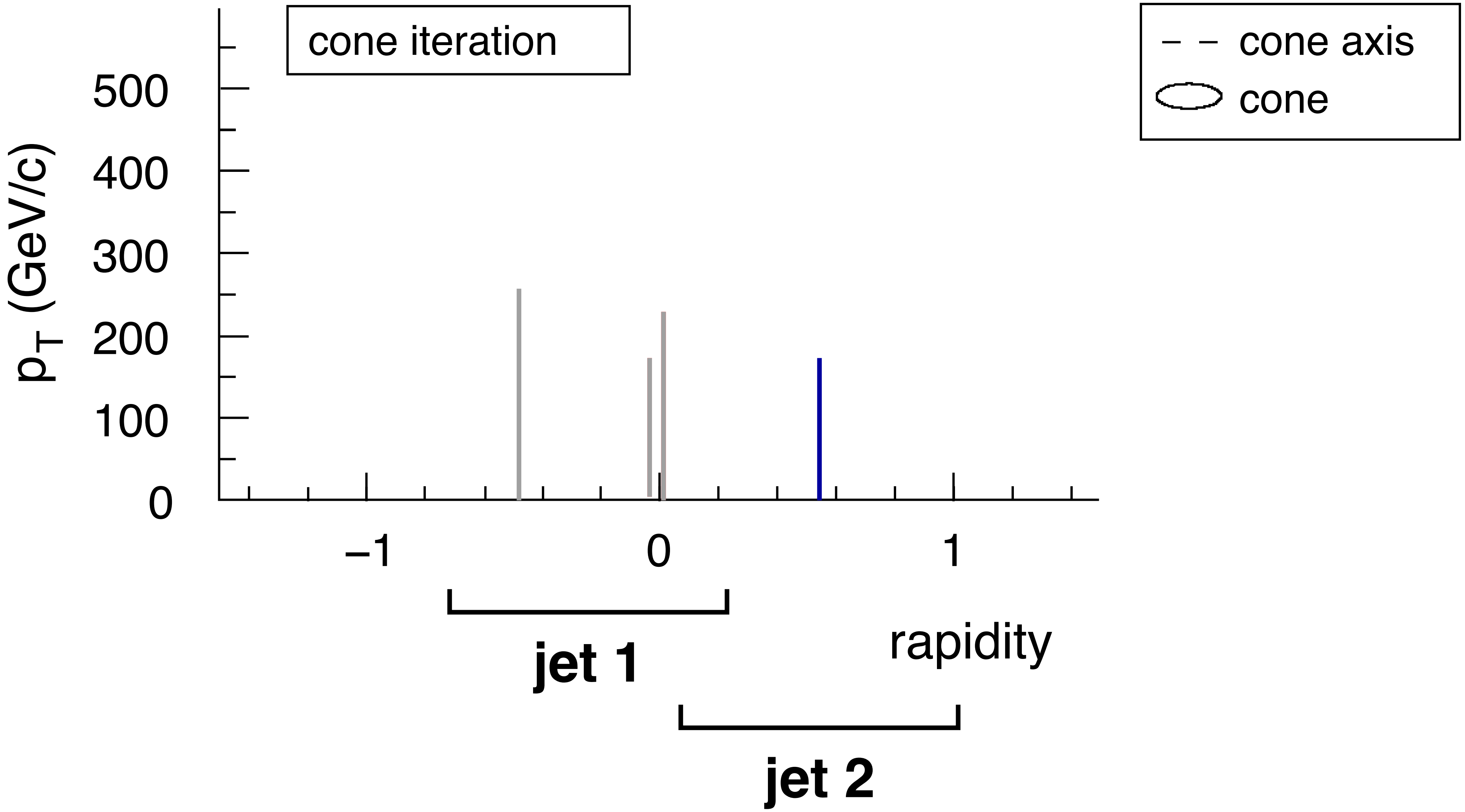


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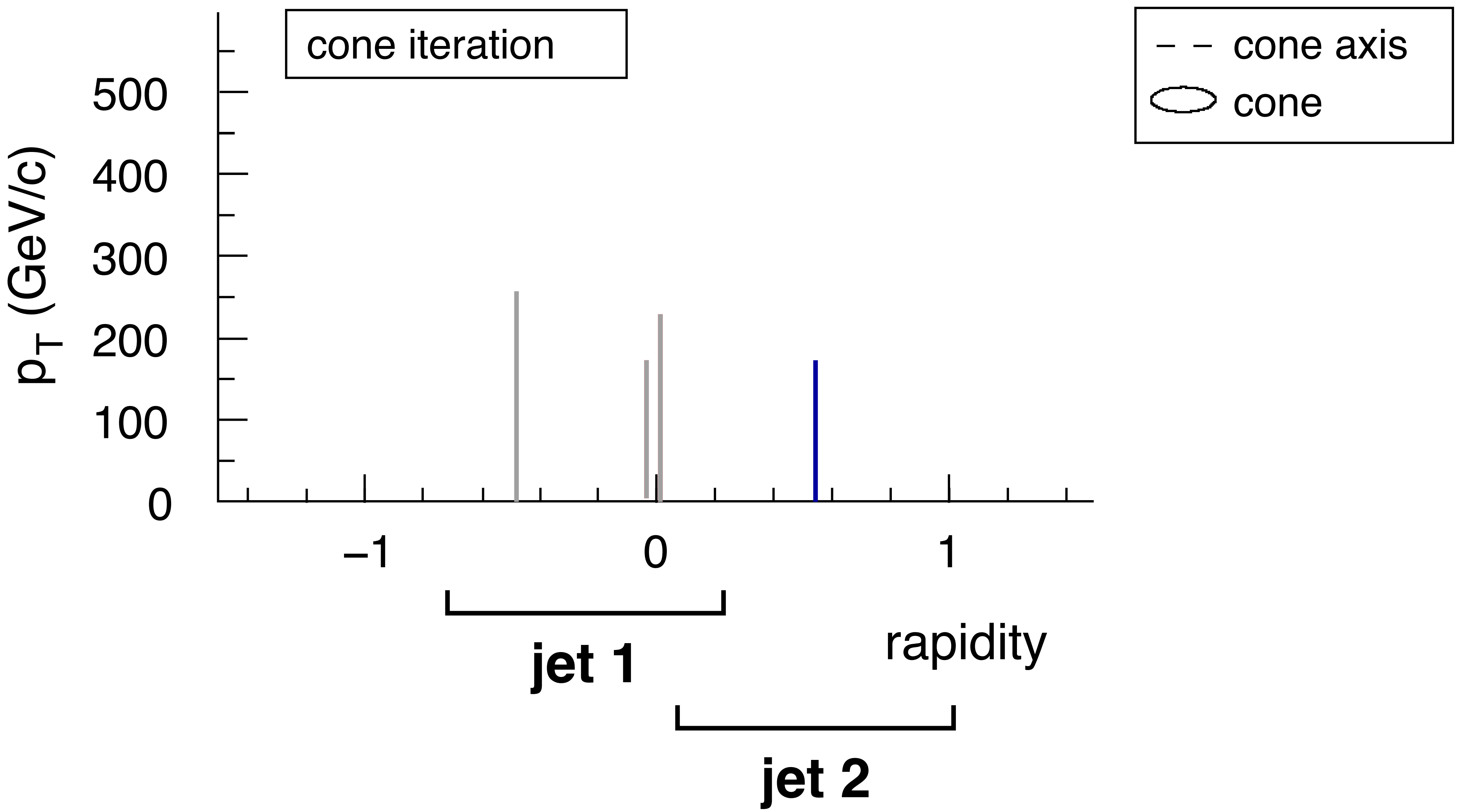


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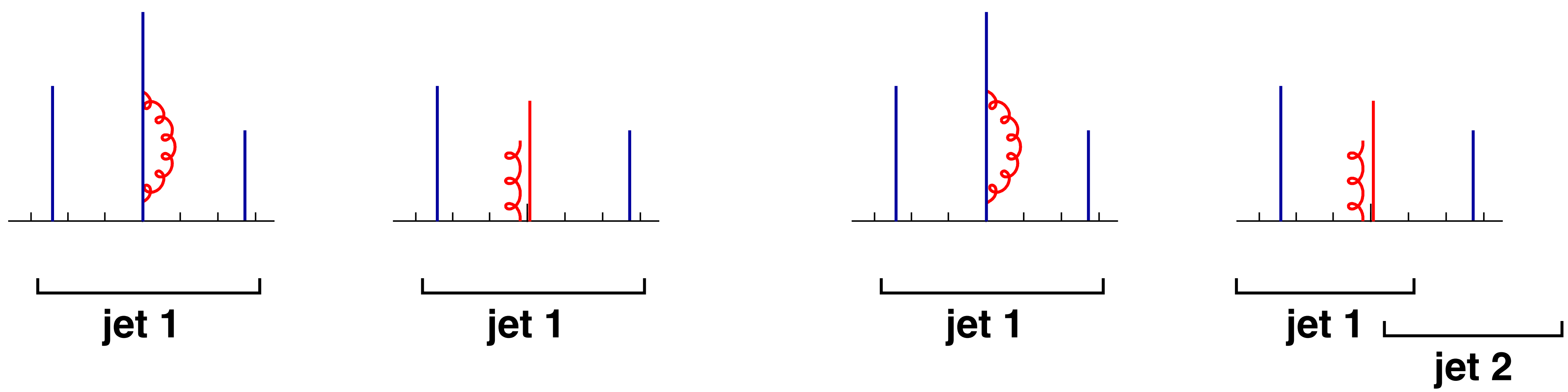
# Consequences of Collinear Unsafety

**Collinear Safe** | **Collinear Unsafe**




$\alpha_s^n \times (-\infty)$ $\quad$ $\alpha_s^n \times (+\infty)$ $\quad$ $\alpha_s^n \times (-\infty)$ $\quad$ $\alpha_s^n \times (+\infty)$

**Infinities cancel** | **Infinities do not cancel**

Invalidates perturbation theory

# IR Safety & Real Life

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

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

Among consequences of IR unsafety:

| | *Last meaningful order* | | | |
|---|---|---|---|---|
| | JetClu, ATLAS cone [IC-SM] | MidPoint [IC$_{mp}$-SM] | CMS it. cone [IC-PR] | Known at |
| Inclusive jets | LO | NLO | NLO | NLO ($\to$ NNLO) |
| $W/Z$ + 1 jet | LO | NLO | NLO | NLO |
| 3 jets | **none** | LO | LO | NLO [nlojet++] |
| $W/Z$ + 2 jets | **none** | LO | LO | NLO [MCFM] |
| $m_{\rm jet}$ in $2j + X$ | **none** | **none** | **none** | LO |

NB: 50,000,000\$/£/CHF/€ investment in NLO

# Stereo Vision

## Use IR Safe algorithms

- To study short-distance physics
- These days, ≈ as fast as IR unsafe algos and widely implemented (e.g., FASTJET), including

> "Cone-like": SiSCone, Anti-kT, ...
> "Recombination-like": kT, Cambridge/Aachen, ...

## Then use IR Sensitive observables

- E.g., number of tracks, identified particles, ...
- To explicitly check hadronization and other IR models

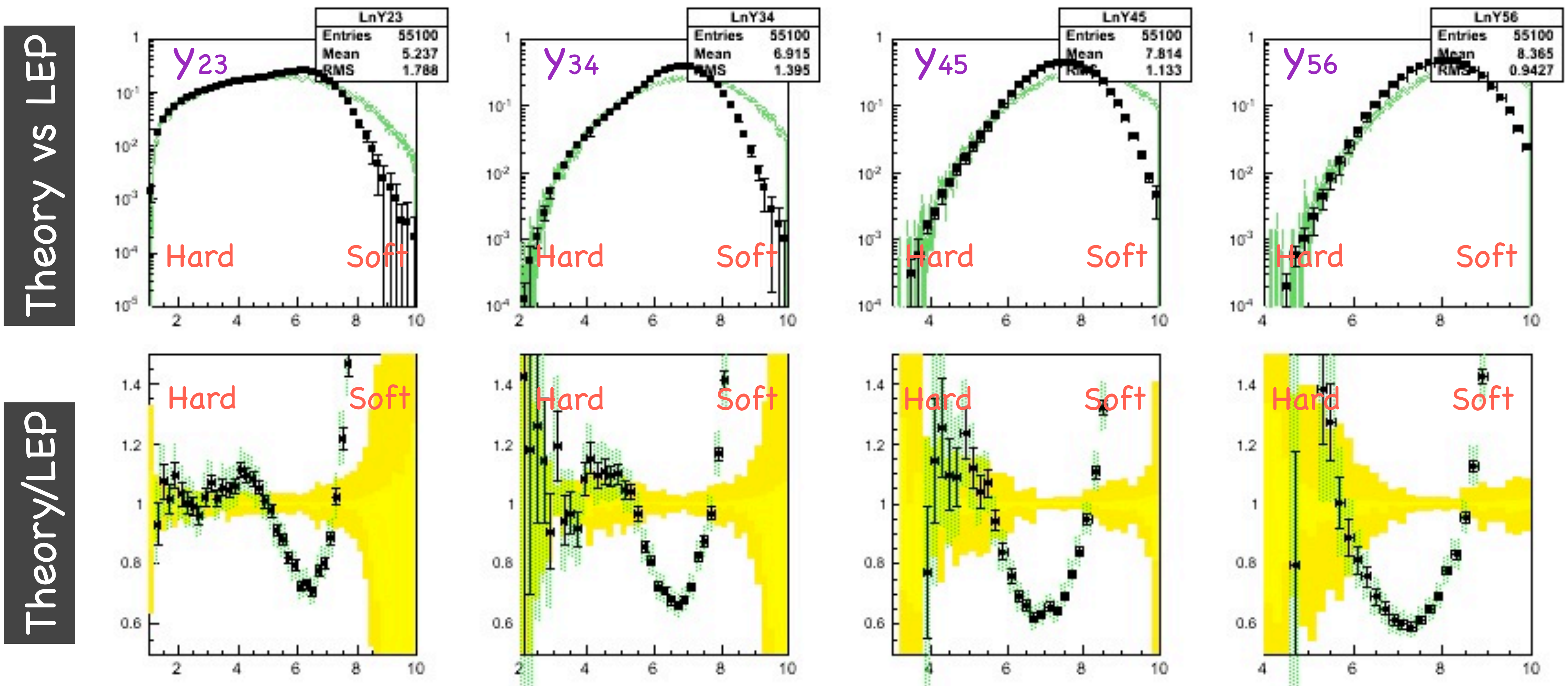
# Jet Rates

At $E_{vis}$ = 91 GeV
y=2 → $k_T$ ≈ 33 GeV
y=4 → $k_T$ ≈ 12 GeV
y=6 → $k_T$ ≈ 4.5 GeV
y=8 → $k_T$ ≈ 1.6 GeV
y=10 → $k_T$ ≈ 0.6 GeV

## Jet Resolution

**Parton Level**

E.g., $y_{23} = k_T^2 / E_{vis}^2$ = scale where event goes from having 2 to 3 jets




(default PYTHIA 8.135)

# Jet Rates

At $E_{vis}$ = 91 GeV
y=2 → $k_T \approx$ 33 GeV
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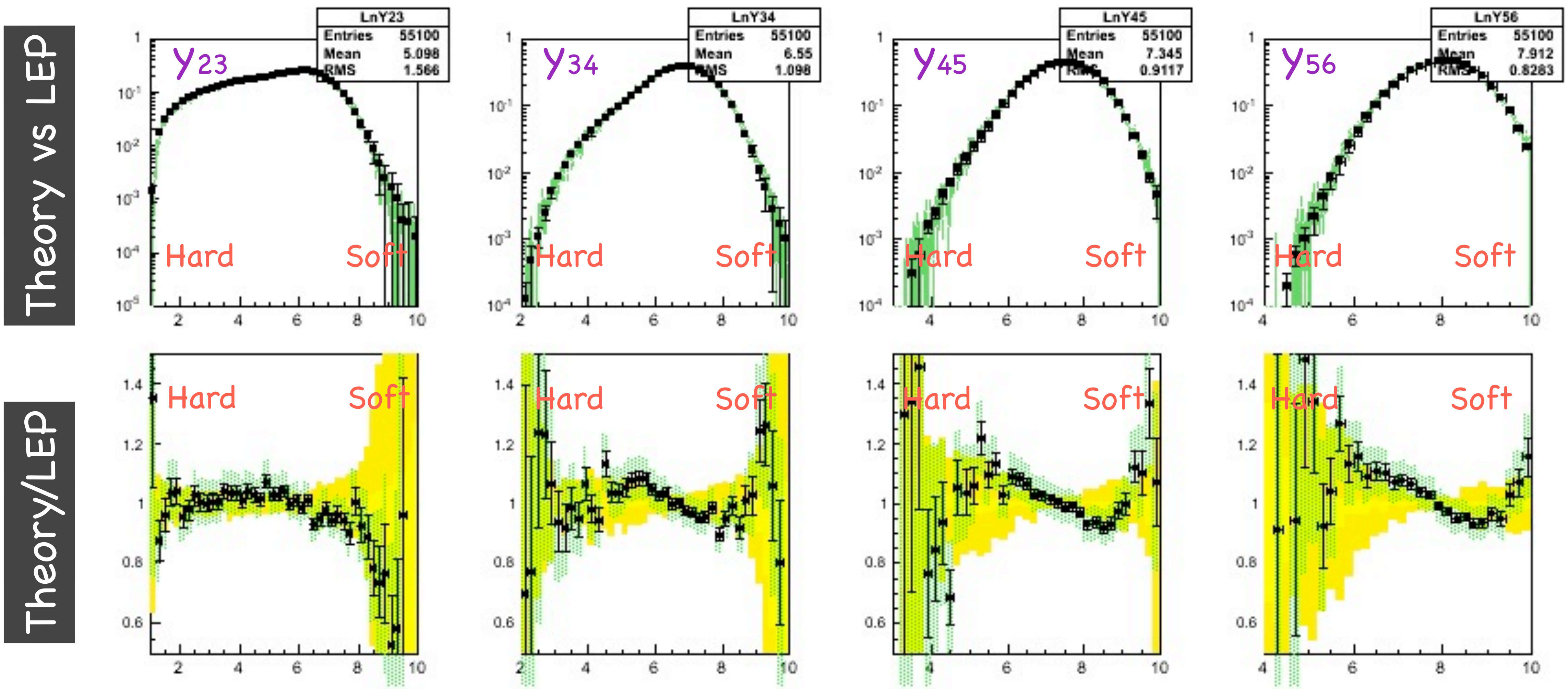
## Jet Resolution

**Hadron level**

E.g., $y_{23} = k_T^2 / E_{vis}^2$ = scale where event goes from having 2 to 3 jets

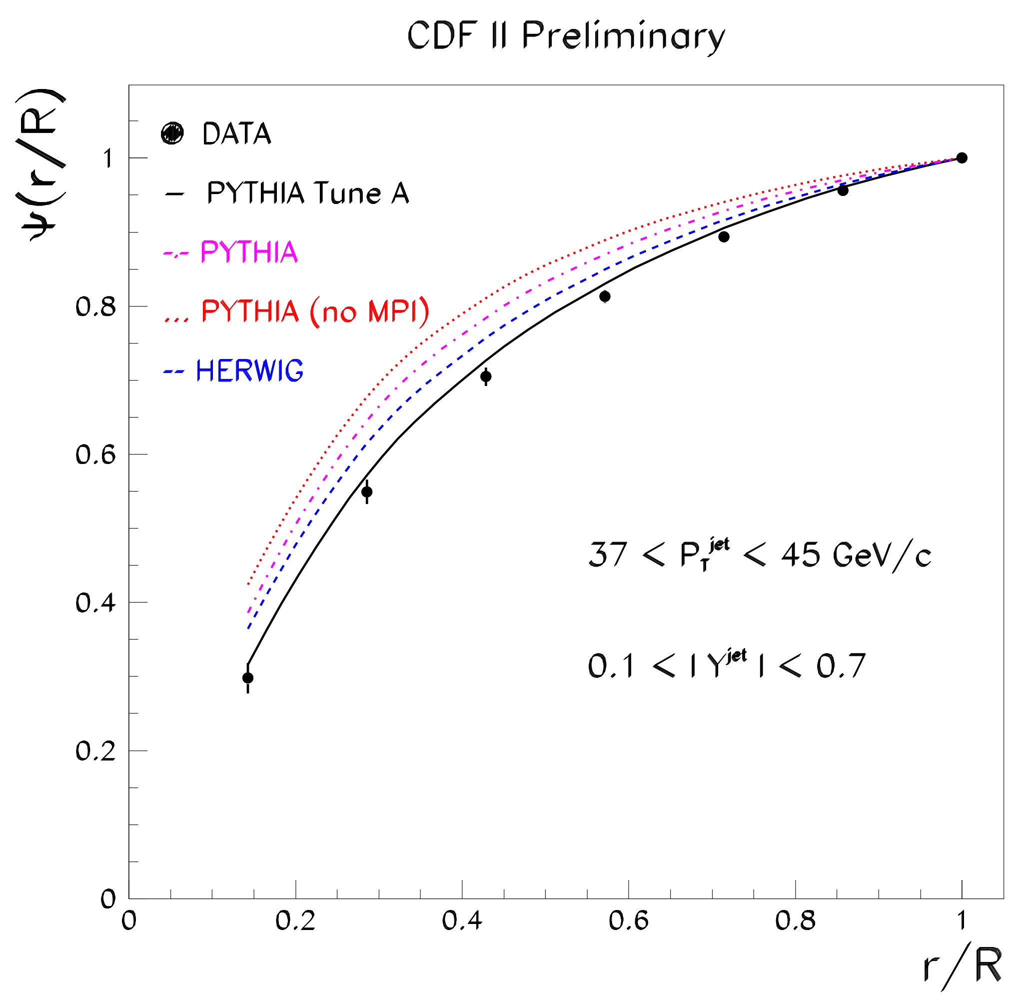


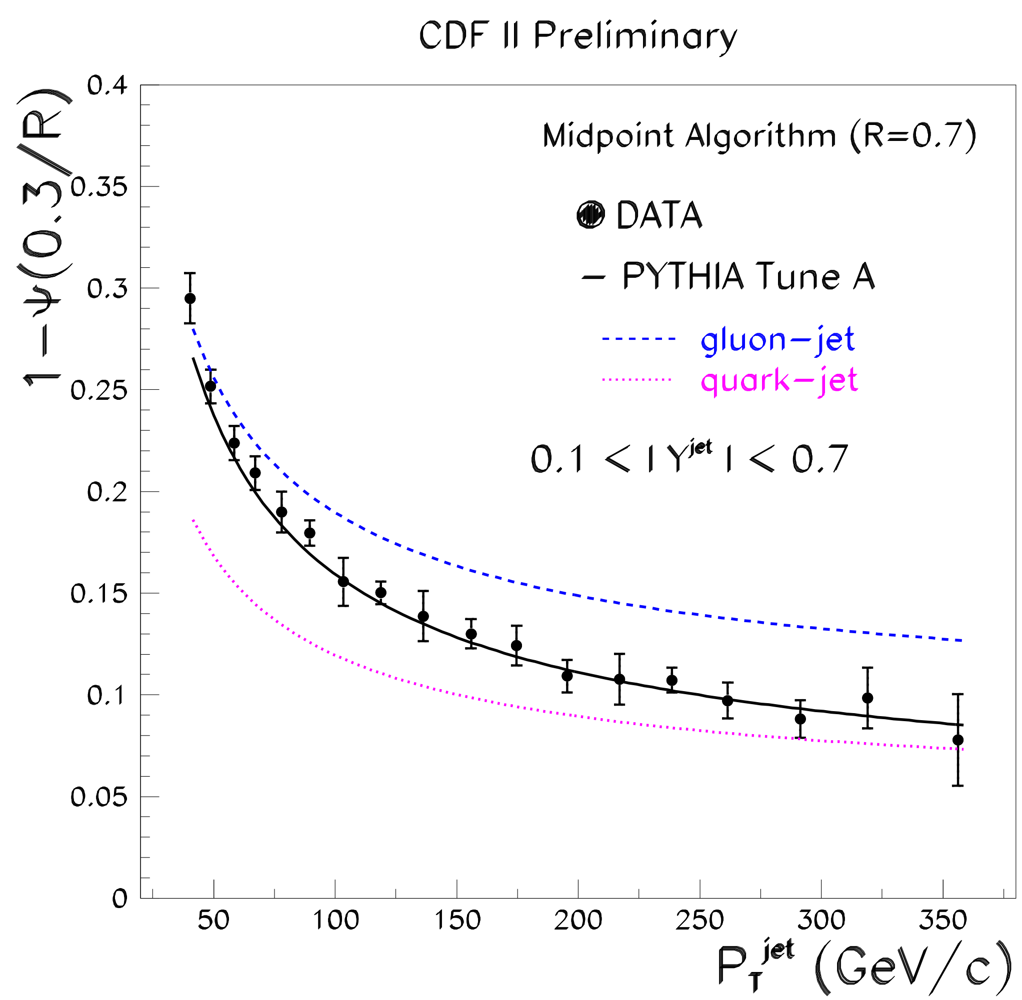

(default PYTHIA 8.135)

# Jet Universality

At LEP: mostly quark jets with lots of c & b

At Tevatron/LHC: mostly gluon jets and light-quark jets

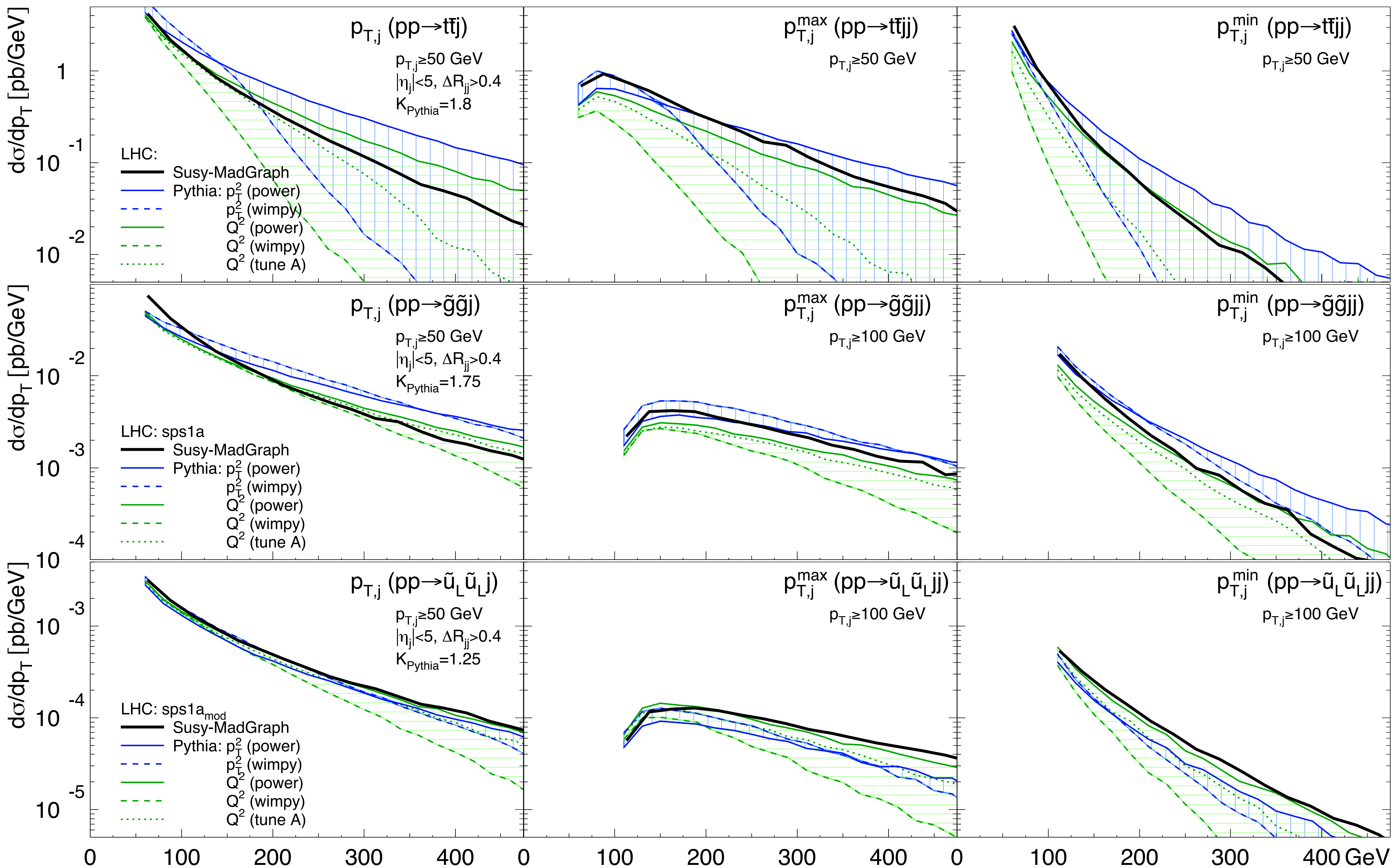


# Matching

Note: tough subject
Not required to understand everything
Don't loose yourselves in the details,
Just try to understand the overall reasoning

$p_\perp$(1 jet) $\quad p_\perp^{\text{max}}$(2 jets) $\quad p_\perp^{\text{min}}$(2 jets)




power: $Q^2_{\text{max}} = s$; $\quad$ wimpy: $Q^2_{\text{max}} = m_\perp^2$; $\quad$ tune A: $Q^2_{\text{max}} = 4m_\perp^2$

$m_{\text{t}} = 175$ GeV, $\quad m_{\tilde{\text{g}}} = 608$ GeV, $\quad m_{\tilde{\text{u}}_L} = 567$ GeV

(T. Plehn, D. Rainwater, P. Skands)

# Matching

- A (Complete Idiot's) Solution – Combine
  1. $[X]_{ME}$ + showering
  2. $[X + 1\ \text{jet}]_{ME}$ + showering
  3. …

Run generator for X (+ shower)

Run generator for X+1 (+ shower)

Run generator for … (+ shower)

Combine everything into one sample

# Matching

- A (Complete Idiot's) Solution – Combine
  1. $[X]_{ME}$ + showering
  2. $[X + 1\ jet]_{ME}$ + showering
  3. …

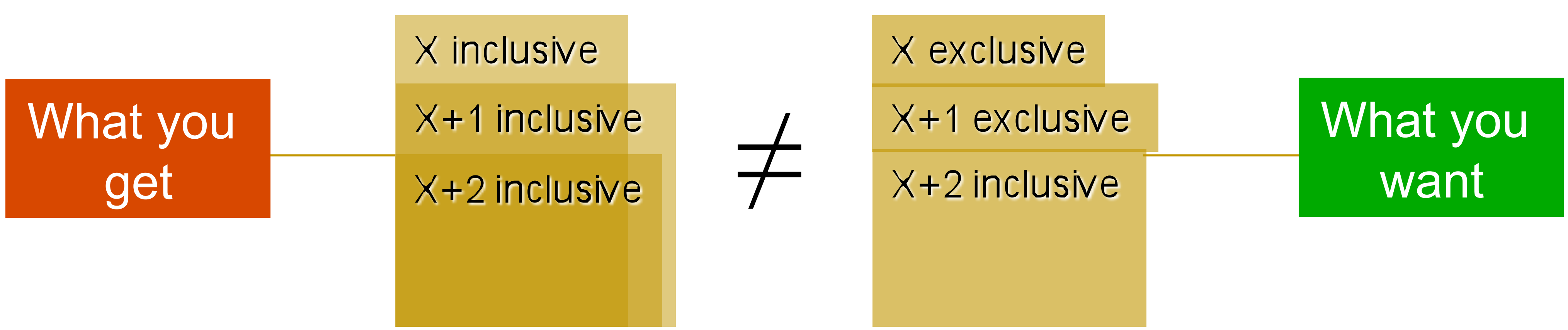
Run generator for X (+ shower)

Run generator for X+1 (+ shower)

Run generator for … (+ shower)

Combine everything into one sample

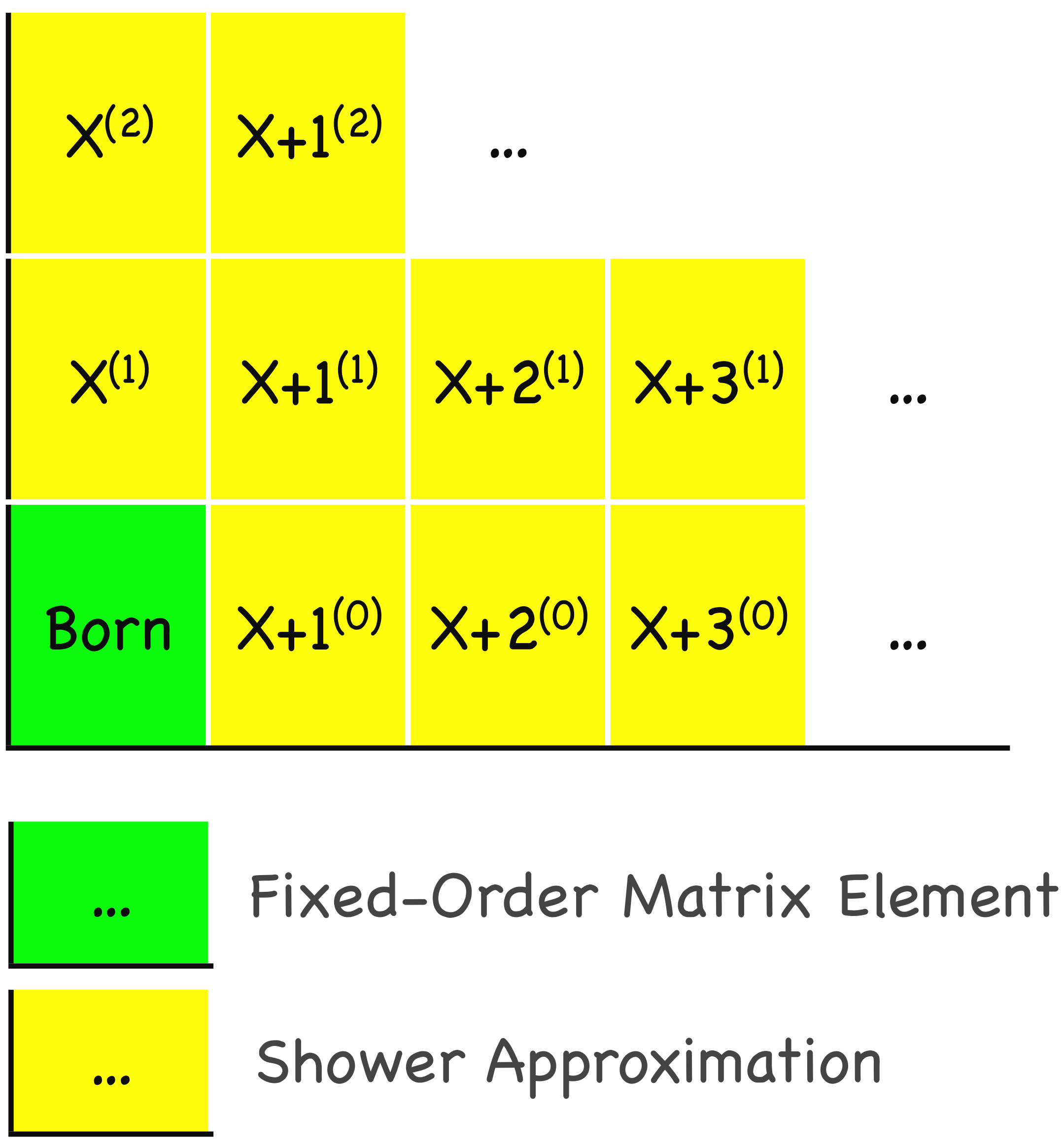
- Doesn't work
  - [X] + shower is inclusive
  - [X+1] + shower is also inclusive



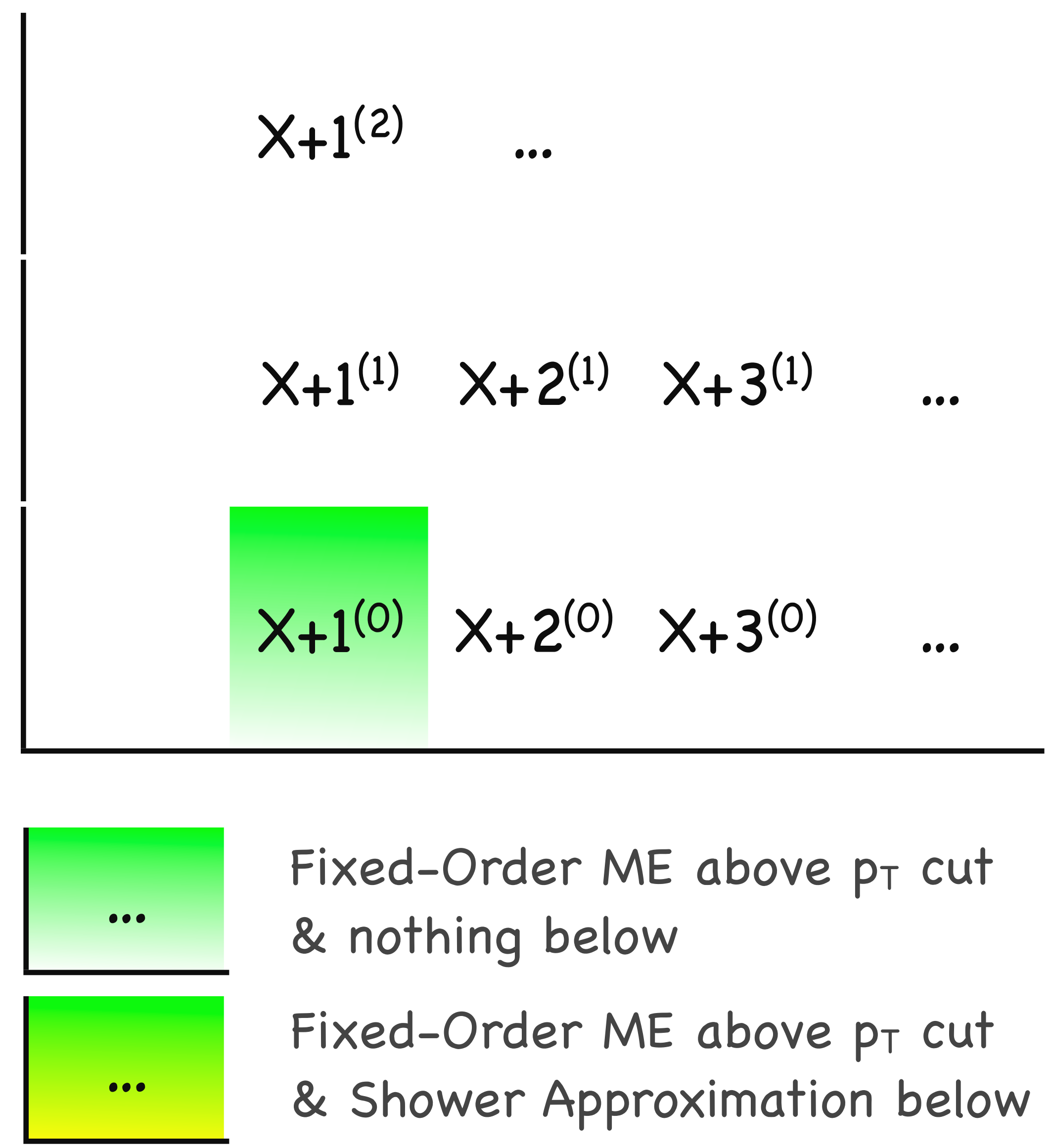

Overlapping "bins" One sample

# Loops and Legs

## Born × Shower

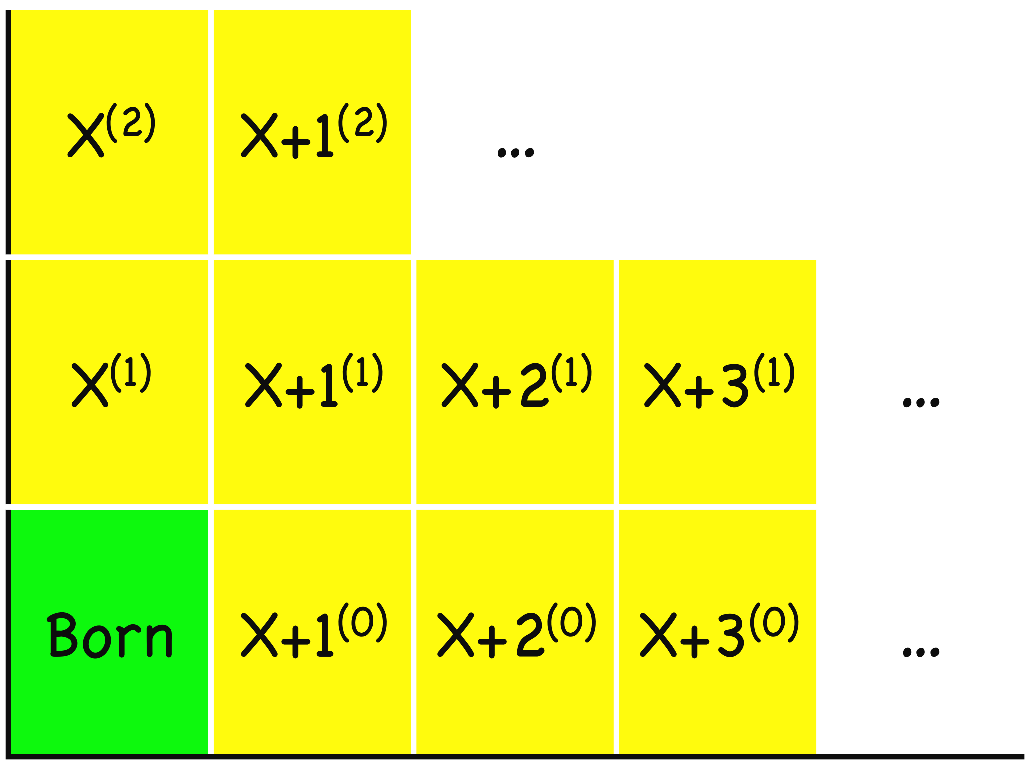



## X+1 @ LO



# Loops and Legs

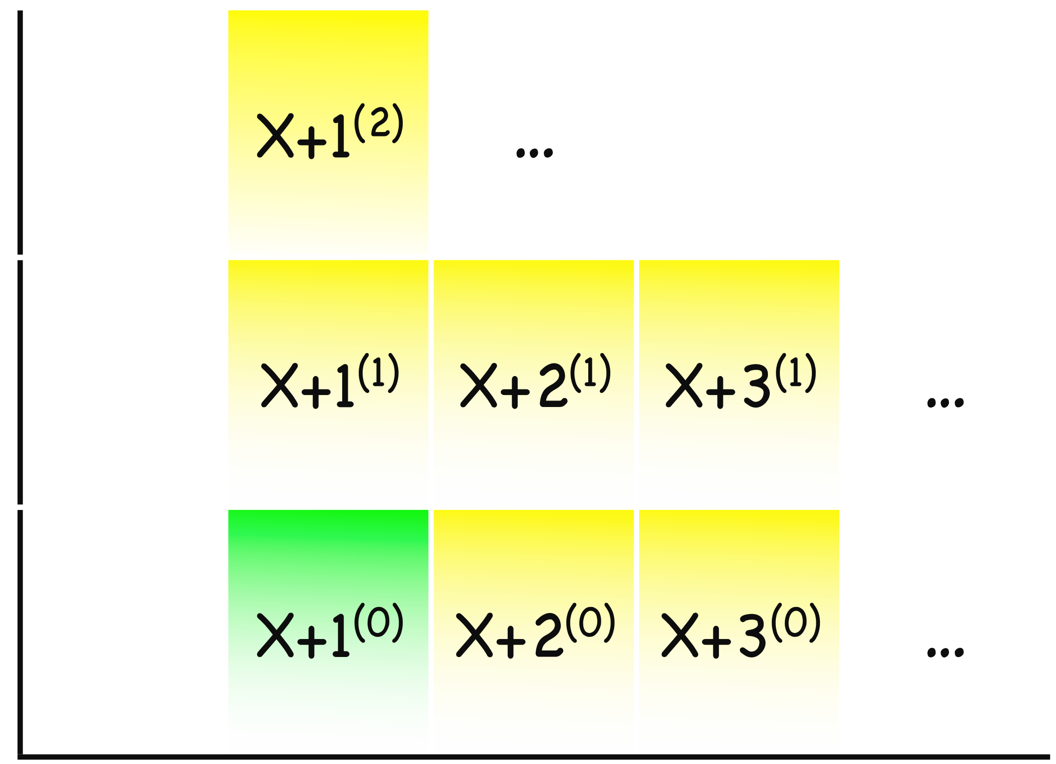
## Born × Shower




... Fixed-Order Matrix Element

... Shower Approximation

## X+1 @ LO × Shower



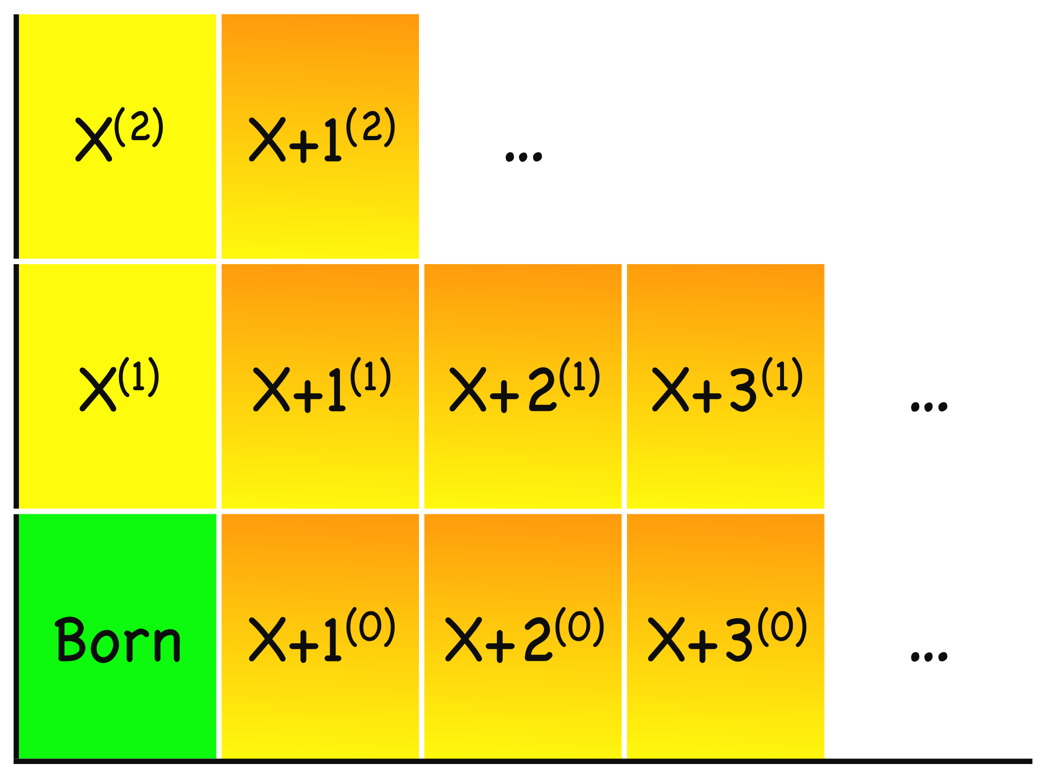

... Fixed-Order ME above $p_T$ cut & nothing below

... Fixed-Order ME above $p_T$ cut & Shower Approximation below

# Loops and Legs

Born × Shower + (X+1) × shower

Double Counting of terms present in both expansions




Worse than useless

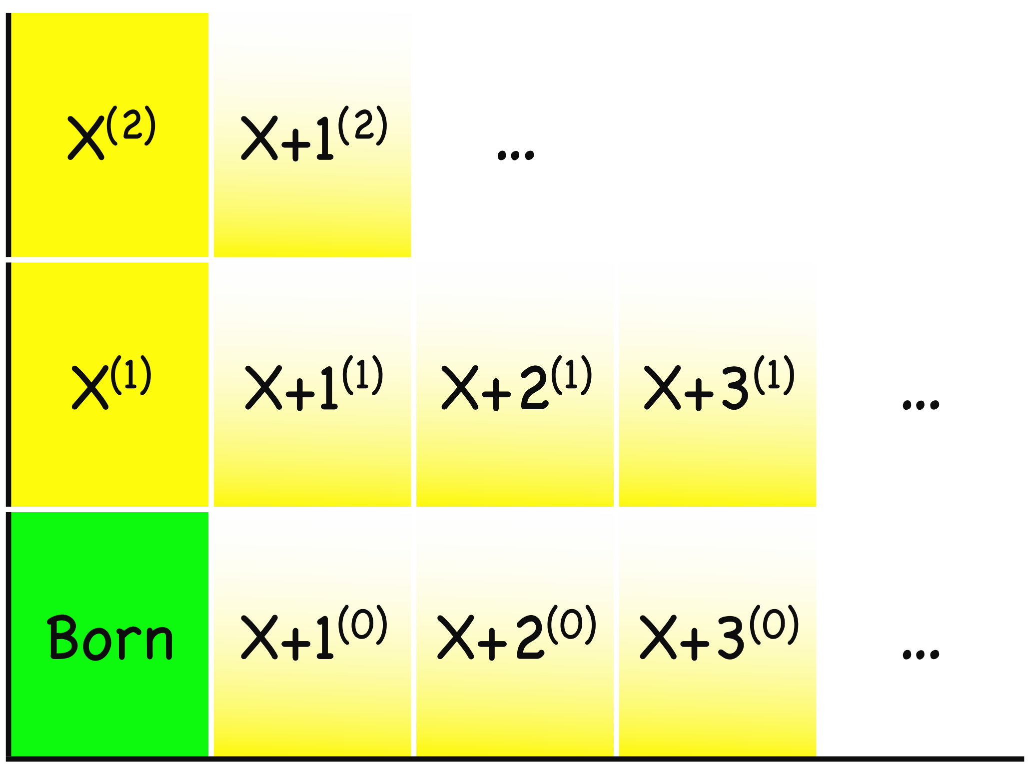
- ... Fixed-Order Matrix Element
- ... Shower Approximation
- ... Fixed-Order ME above $p_T$ cut & nothing below
- ... Fixed-Order ME above $p_T$ cut & Shower Approximation below

# Phase Space Slicing

(with "matching scale")

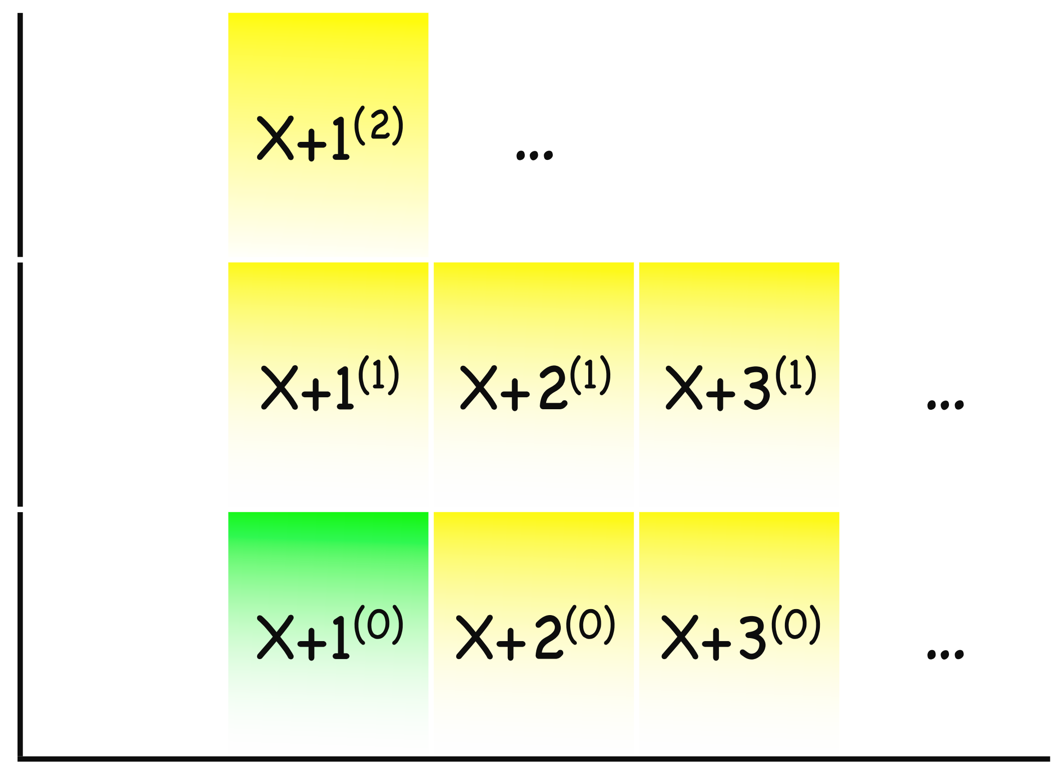
## Born × Shower

+ shower veto above $p_T$




## X+1 @ LO × Shower

with 1 jet above $p_T$




... Fixed-Order Matrix Element

... Shower Approximation

... Fixed-Order ME above $p_T$ cut & nothing below

... Fixed-Order ME above $p_T$ cut & Shower Approximation below

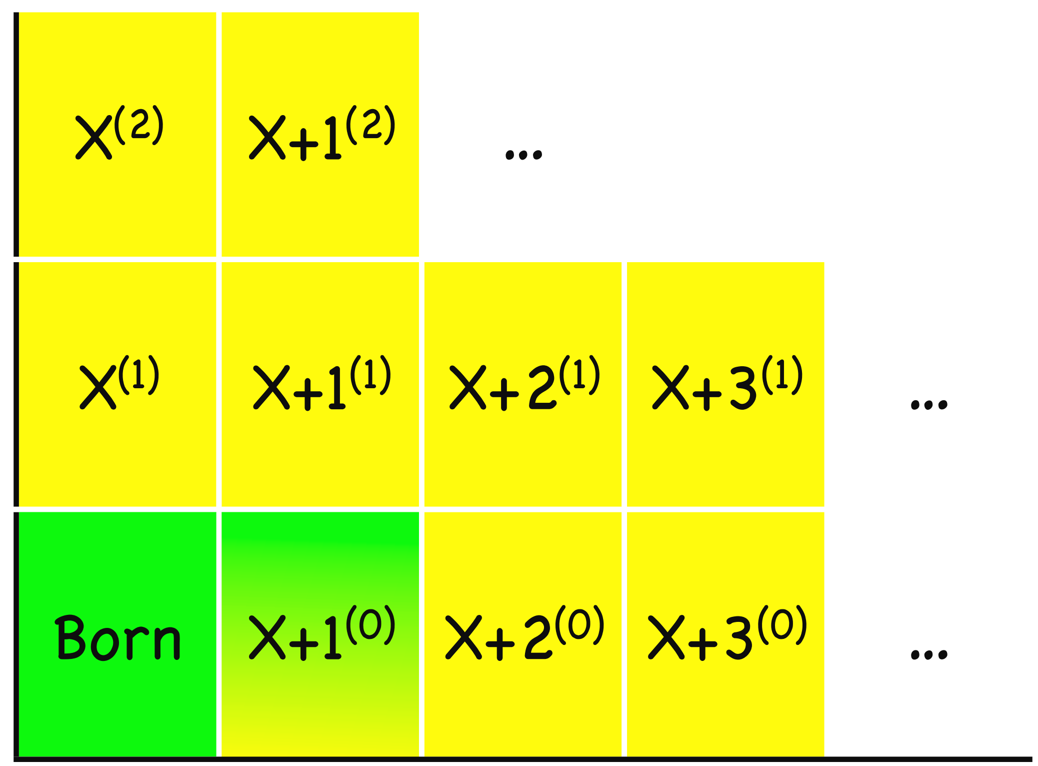
# Phase Space Slicing

(with “matching scale”)

Born × Shower + X+1 @ LO × Shower

+ shower veto above $p_T$ — with 1 jet above $p_T$

X+1 now correct in both soft and hard limits




Attention! Must use the SAME $p_T$ cut in both samples

But still … : $\alpha_s$ and “splitting functions” usually discontinuous

- ... Fixed-Order Matrix Element
- ... Shower Approximation
- ... Fixed-Order ME above $p_T$ cut & nothing below
- ... Fixed-Order ME above $p_T$ cut & Shower Approximation below

# Multi-Leg Slicing

(a.k.a. CKKW or MLM matching)

CKKW: Catani, Krauss, Kuhn, Webber, JHEP 0111:063,2001.

MLM: Michelangelo L Mangano

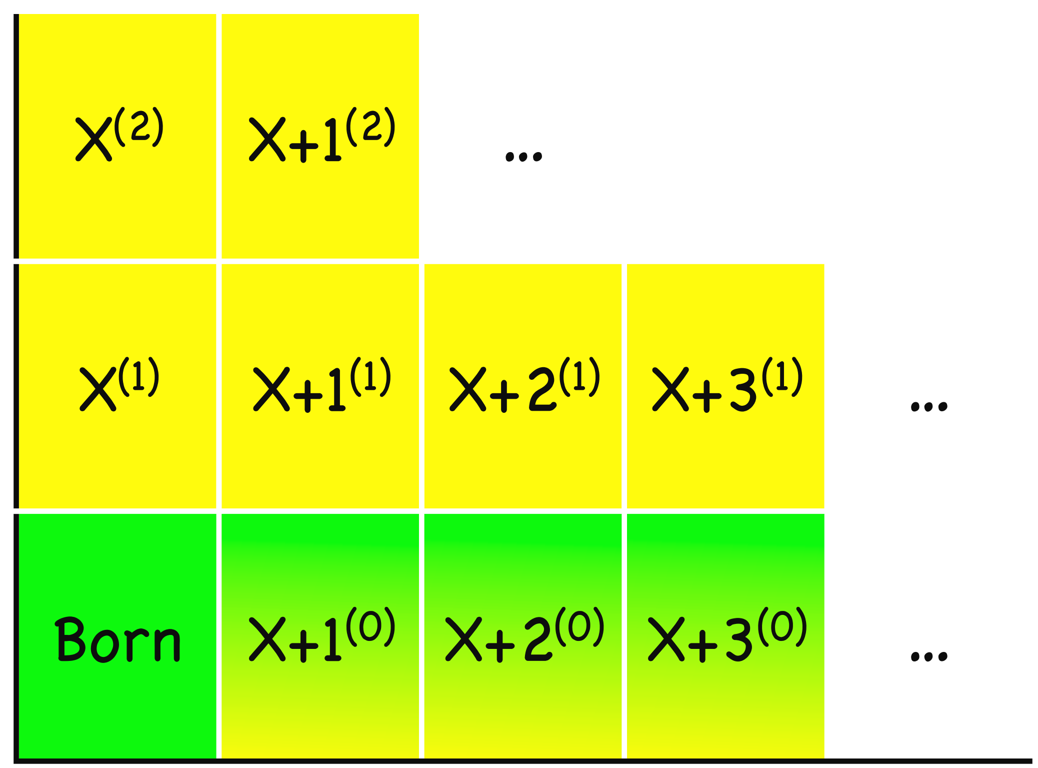
## Keep going

Veto all shower emissions above "matching scale"

(except for the highest-multiplicity matrix element)

LO: when all jets hard

LL: for soft emissions




→ Multileg Tree-level matching

# Vetoed Parton Showers

(used in Phase Space Slicing, a.k.a. CKKW or MLM matching)

## Common (at ME level):

1. Generate one ME sample for each of $\sigma_n(p_{Tcut})$ (using large, fixed $\alpha_{s0}$)
2. Use a jet algorithm (e.g., $k_T$) to determine an approximate shower history for each ME event
3. Construct the would-be shower $\alpha_s$ factor and reweight

$$w_n = \mathrm{Prod}[\alpha_s(k_{Ti})]/\alpha_{s0}^n$$

→ "Renormalization-improved" ME weights

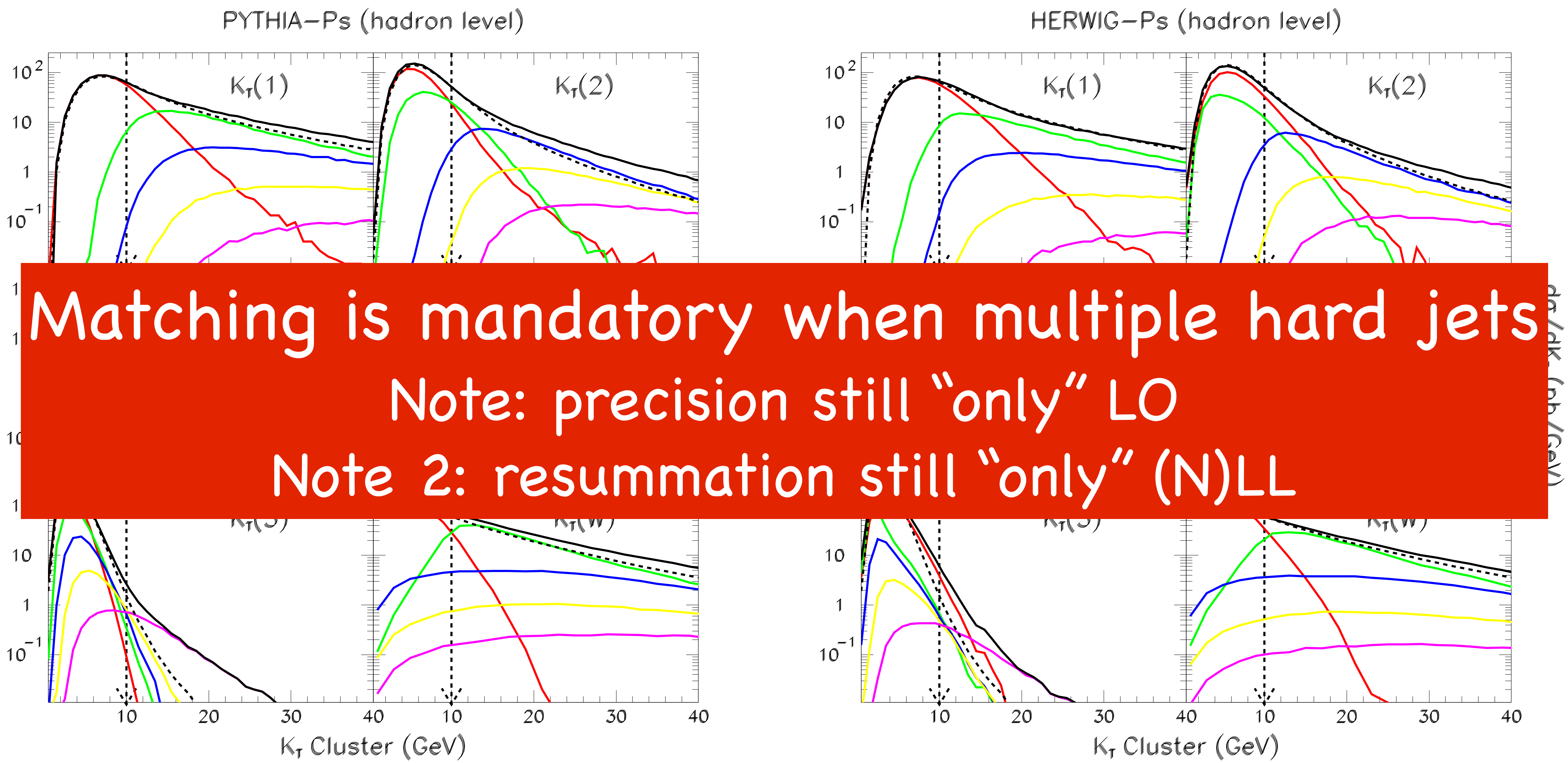
## CKKW and CKKW-L

1. Apply Sudakov $\Delta(t_{start},t_{end})$ for each reconstructed internal line (NLL for CKKW, trial-shower for CKKW-L)
2. Accept/Reject: $w_n \times= \mathrm{Prod}[\Delta_i]$
3. Do parton shower, vetoing any emissions above cutoff

## MLM

1. Do normal parton showers
2. Cluster showered event (cone)
3. Match ME partons to jets
4. If {all partons matched && $n_{partons} == n_{jets}$} Accept : Reject;

# Multi-Jet Samples




**Matching is mandatory when multiple hard jets**

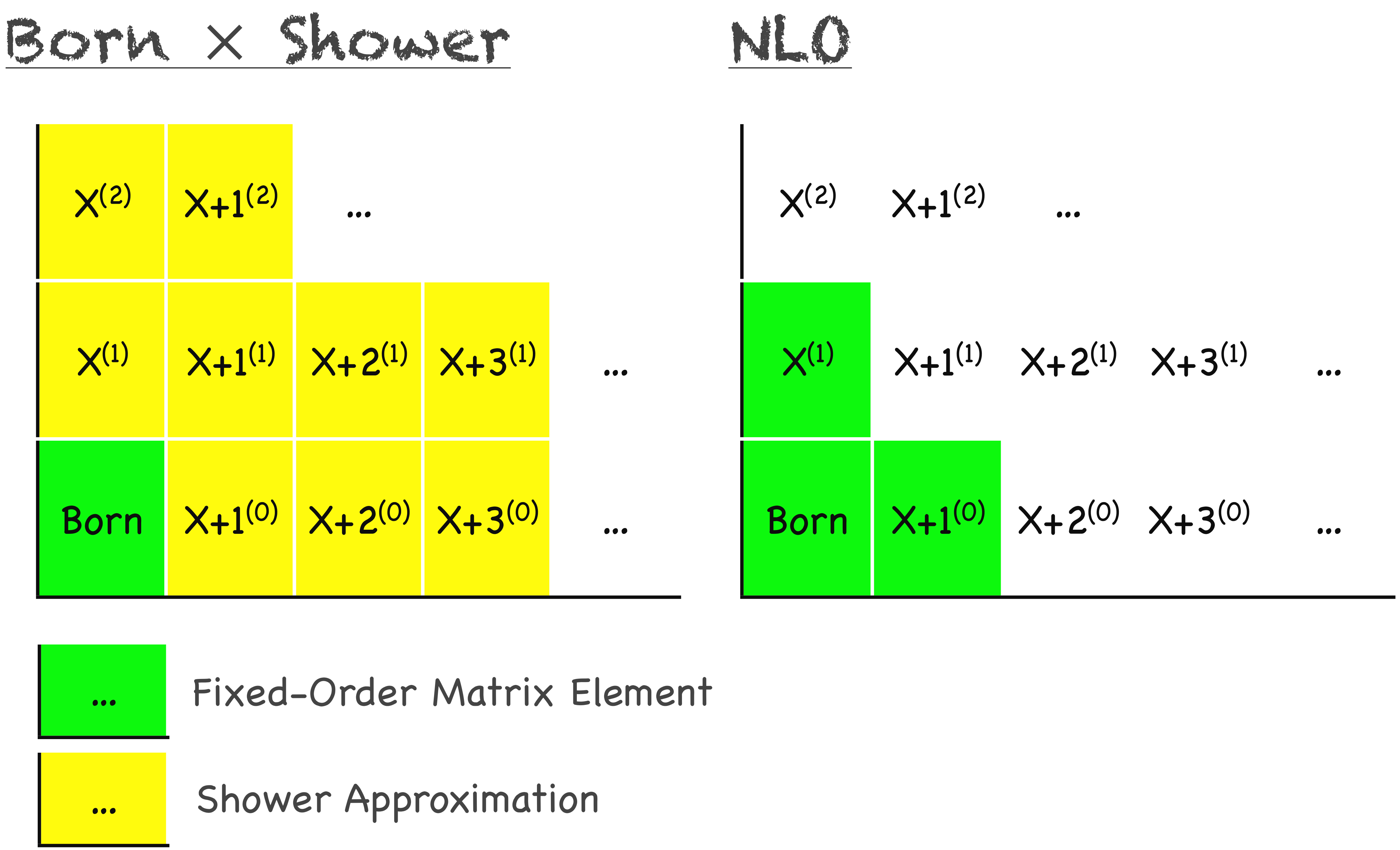
Note: precision still "only" LO

Note 2: resummation still "only" (N)LL

(S.Mrenna, P. Richardson)

# MC@NLO

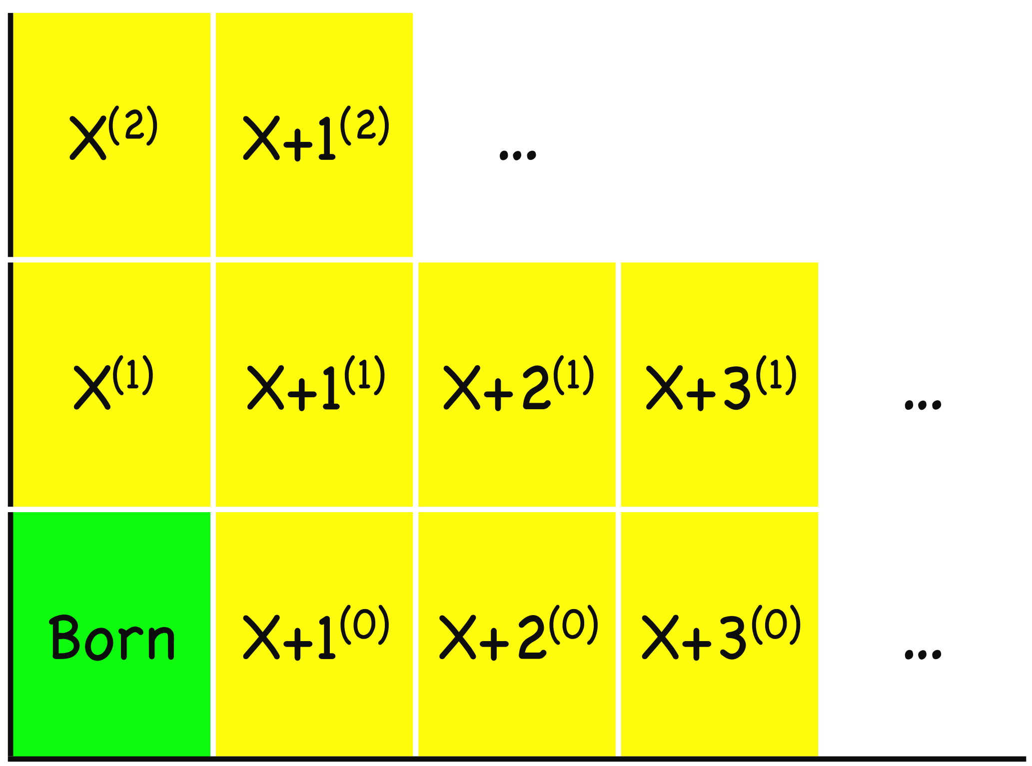
# "Additive" Matching



MC@NLO

# "Additive" Matching

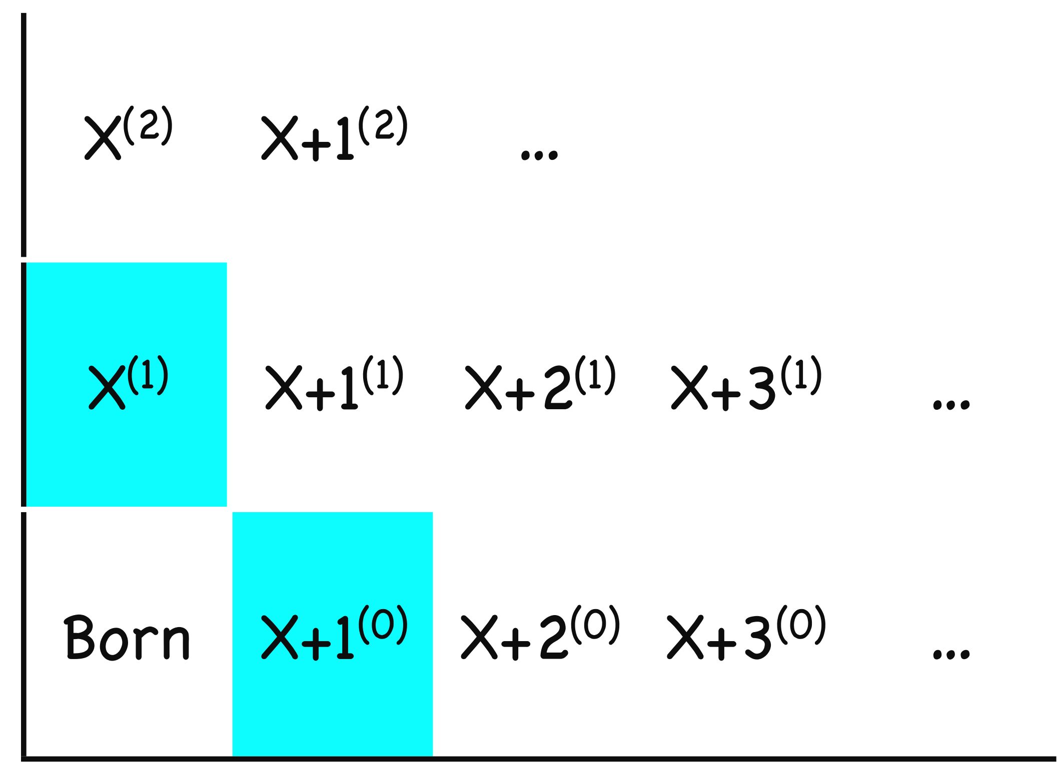
## Born × Shower




... Fixed-Order Matrix Element

... Shower Approximation

## NLO − Shower




Expand shower approximation to NLO analytically, then subtract:

... Fixed-Order ME minus Shower Approximation (NOTE: can be $< 0$!)

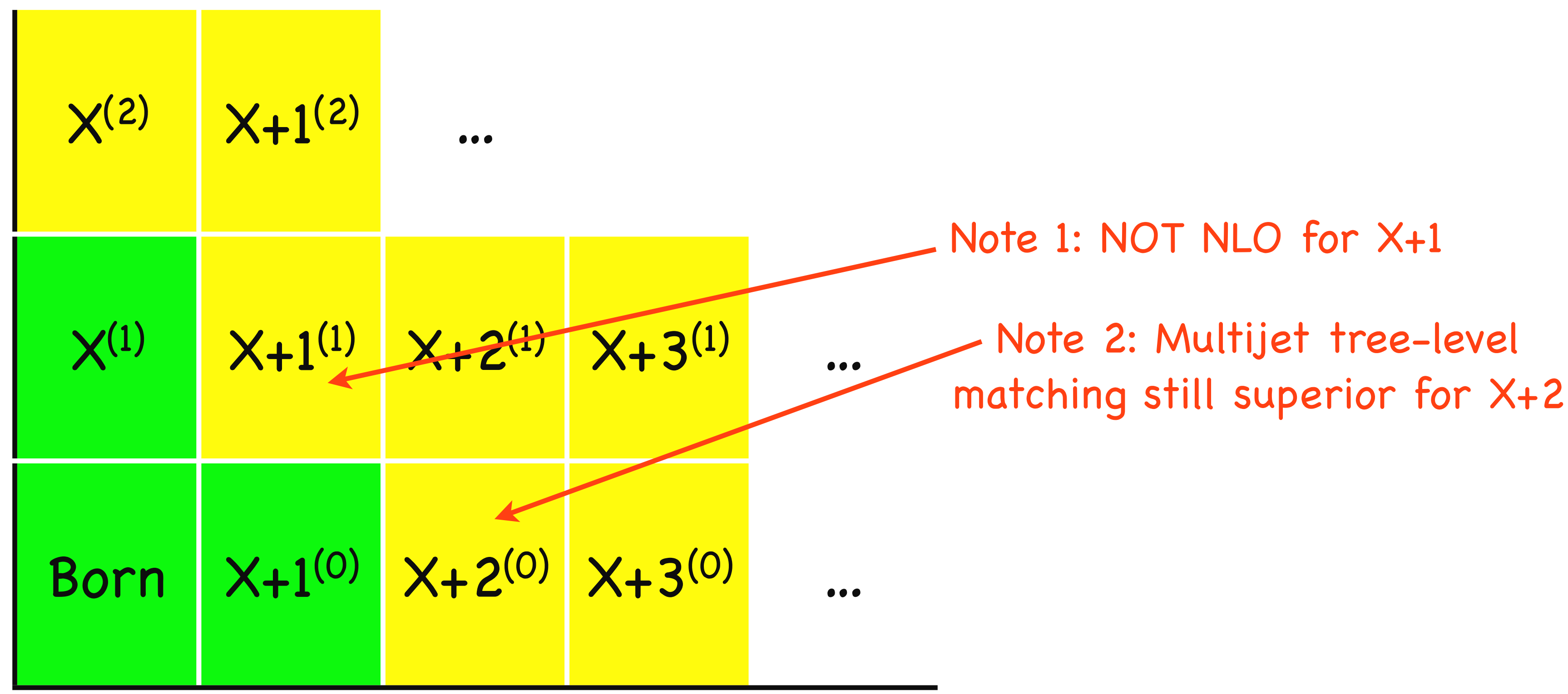
## MC@NLO

# "Additive" Matching

### Add

Born + shower-subtracted $O(\alpha_s)$ matrix elements

NLO: for X inclusive
LO for X+1
LL: for everything else



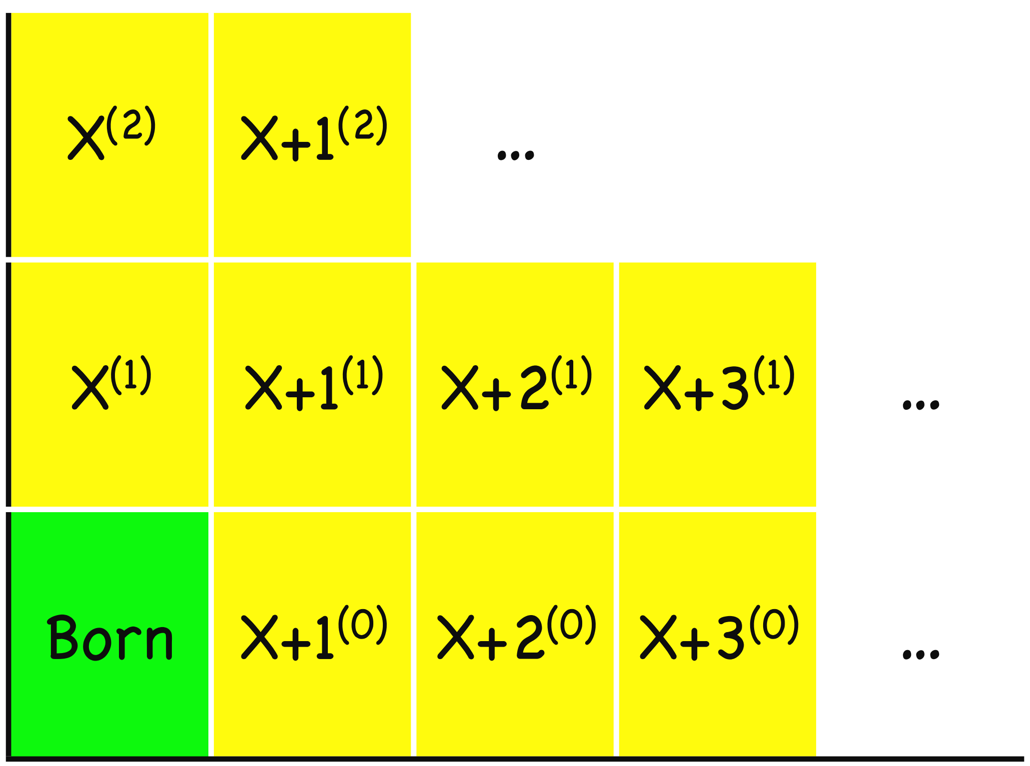

→ NLO + parton shower

(however, the "correction events" can have w<0)

MC@NLO

# "Additive" Matching

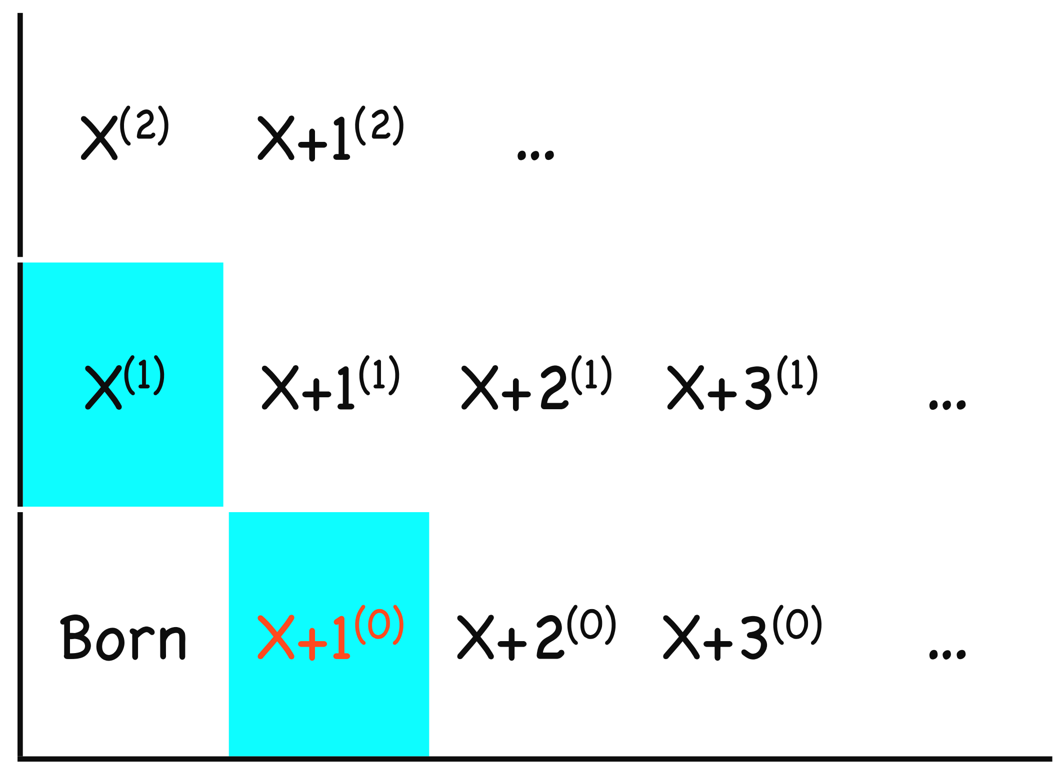
## Born × Shower




... Fixed-Order Matrix Element

... Shower Approximation

## NLO − Shower

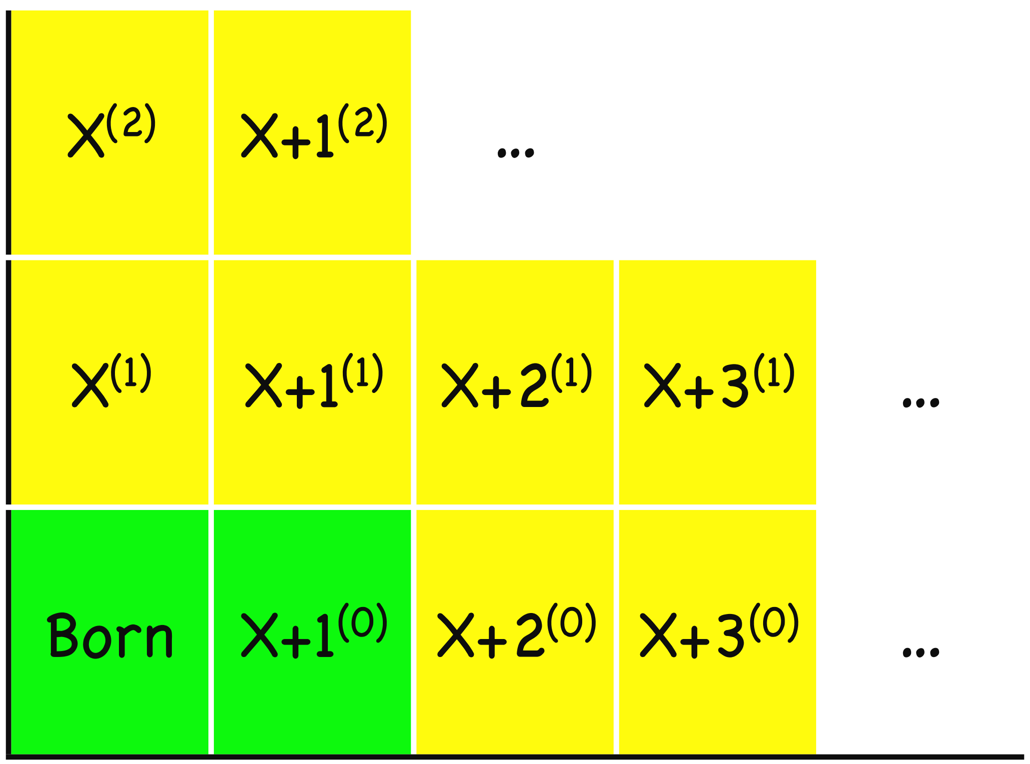


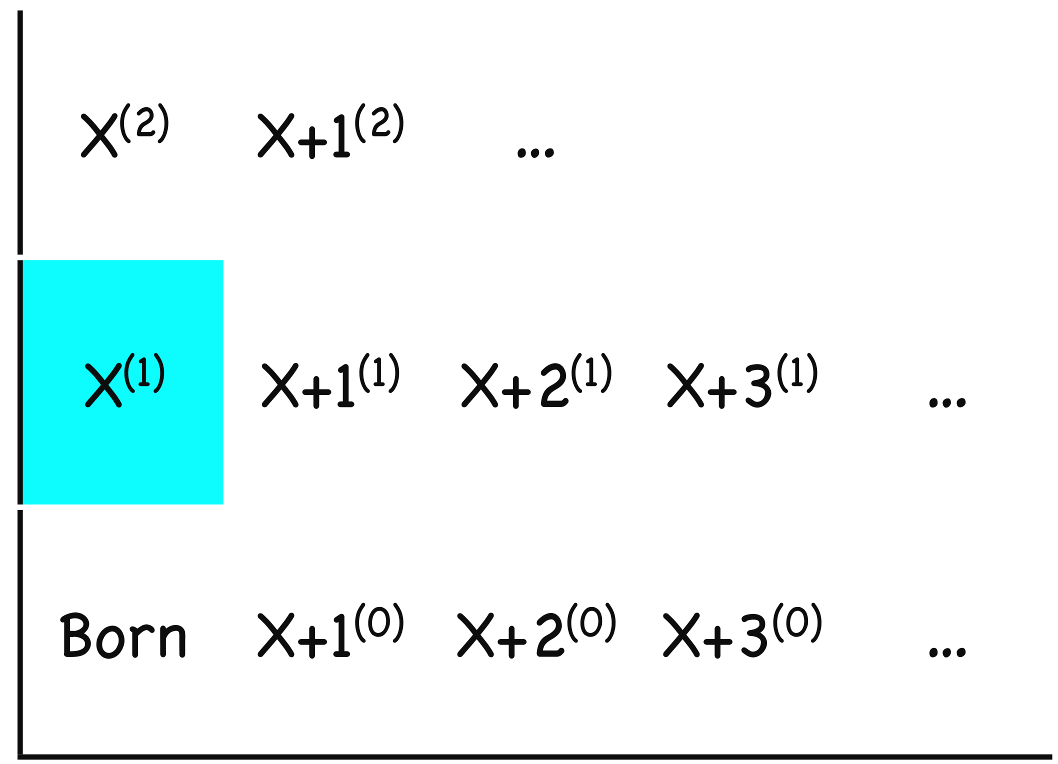

Expand shower approximation to NLO analytically, then subtract:

... Fixed-Order ME minus Shower Approximation (NOTE: can be < 0!)

# PYTHIA / POWHEG
# "Merging"

## Born × First-Order Corrected Shower



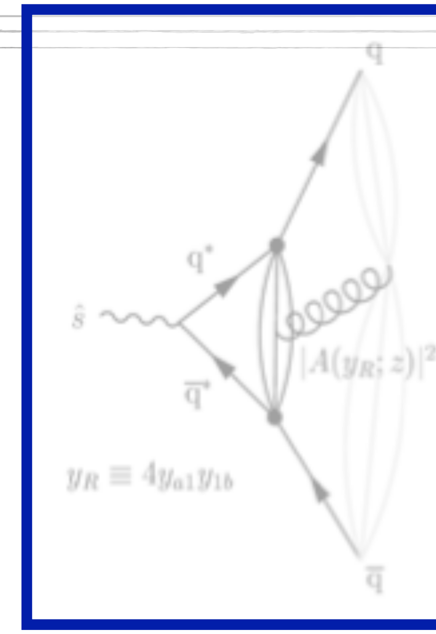

... Fixed-Order Matrix Element

... Shower Approximation

Use exact (process-dependent) splitting function for first splitting

... Fixed-Order ME minus Shower Approximation

# NLO Matching in 1 Slide



- First Order Shower expansion

PS $\quad \int \mathrm{d}\Phi_2 \, [\text{Born}] \int_{Q^2_{\mathrm{had}}}^{s} \frac{\mathrm{d}\Phi_3}{\mathrm{d}\Phi_2} \, [\text{LL}] \, \delta\left(\mathcal{O} - \mathcal{O}(\{p\}_3)\right)$

Unitarity of shower ➔ 3-parton real = − 2-parton "virtual"

- 3-parton real correction ($A_3 = |M_3|^2/|M_2|^2$ + finite terms; $\alpha$, $\beta$)

$$[\text{X+1}^{(0)}] = [\text{X+1}^{(0)}] - \left( \frac{[\text{X+1}^{(0)}]}{[\text{Born}]} + \frac{4\pi\alpha_s \hat{C}_F}{s}\left(\alpha + \beta\frac{s_{ar}+s_{rb}}{s}\right)\right)[\text{Born}]$$

$$= -\frac{4\pi\alpha_s \hat{C}_F}{s}\left(\alpha + \beta\frac{s_{ar}+s_{rb}}{s}\right)|M_2^{(0)}|^2 \quad \Rightarrow$$

Finite terms cancel in 3-parton $O$

- 2-parton virtual correction (same example)

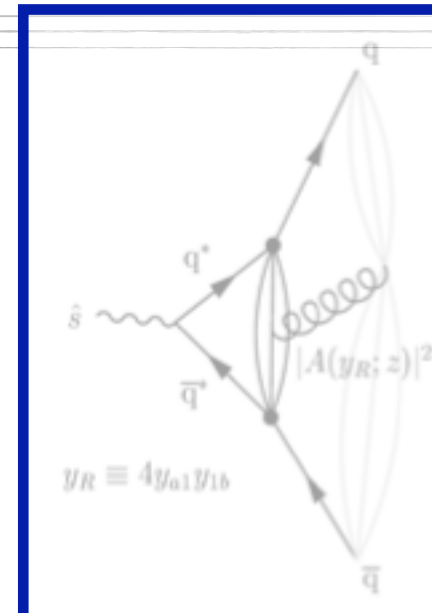
$$[\text{X}^{(1)}] = [\text{X}^{(1)}] + [\text{Born}] \int_0^s \frac{\mathrm{d}\Phi_3}{\mathrm{d}\Phi_2}[\text{LL}] + \int_0^{Q^2_{\mathrm{had}}} \frac{\mathrm{d}\Phi_3}{\mathrm{d}\Phi_2}[\text{X+1}^{(0)}]$$

$$= \frac{\alpha_s \hat{C}_F}{2\pi}\left(2I^{(1)}_{q\bar{q}}(\epsilon, s) - 4 - 2I^{(1)}_{q\bar{q}}(\epsilon, s) + \frac{19 + \alpha + \frac{2}{3}\beta}{4}\right)[\text{Born}]$$

$$= \frac{\alpha_s}{\pi}\left(1 + \frac{1}{3}\left(\alpha + \frac{2}{3}\beta\right)\right)[\text{Born}] \quad \Rightarrow$$

Finite terms cancel in 2-parton $O$ (normalization)

# NLO Matching in 1 Slide



- First Order Shower expansion

PS $$\int \mathrm{d}\Phi_2 \, |M_2^{(0)}|^2 \int_{Q^2_{\mathrm{had}}}^{s} \frac{\mathrm{d}\Phi_3}{\mathrm{d}\Phi_2} A_{q\bar{q}}(\ldots) \delta\left(\mathcal{O} - \mathcal{O}(\{p\}_3)\right)$$

Unitarity of shower ➔ 3-parton real = ÷ 2-parton "virtual"

- 3-parton real correction ($A_3 = |M_3|^2/|M_2|^2$ + finite terms; $\alpha$, $\beta$)

$$w_3^{(R)} = |M_3^{(0)}|^2 - \left( A_3^0(\ldots) + \frac{4\pi\alpha_s \hat{C}_F}{s} \left( \alpha + \beta \frac{s_{ar} + s_{rb}}{s} \right) \right) |M_2^{(0)}|^2$$

$$= -\frac{4\pi\alpha_s \hat{C}_F}{s} \left( \alpha + \beta \frac{s_{ar} + s_{rb}}{s} \right) |M_2^{(0)}|^2 \quad \Rightarrow$$

Finite terms cancel in 3-parton $O$

- 2-parton virtual correction (same example)

$$w_2^{(V)} = 2\mathrm{Re}\left[ M_2^{(1)} M_2^{(0)*} \right] + |M_2^{(0)}|^2 \int_0^s \frac{\mathrm{d}\Phi_3}{\mathrm{d}\Phi_2} A_{q\bar{q}}(\ldots) + \int_0^{Q^2_{\mathrm{had}}} \frac{\mathrm{d}\Phi_3}{\mathrm{d}\Phi_2} w_3^{(R)}$$

$$= \frac{\alpha_s \hat{C}_F}{2\pi} \left( 2 I_{q\bar{q}}^{(1)}(\epsilon, s) - 4 - 2 I_{q\bar{q}}^{(1)}(\epsilon, s) + \frac{19 + \alpha + \frac{2}{3}\beta}{4} \right) |M_2^{(0)}|^2$$

$$= \frac{\alpha_s}{\pi} \left( 1 + \frac{1}{3} \left( \alpha + \frac{2}{3}\beta \right) \right) |M_2^{(0)}|^2 \quad \Rightarrow$$

Finite terms cancel in 2-parton $O$ (normalization)

# Matching - Summary

**LL Showers are correct**

- When all emissions are strongly ordered
- (= dominant QCD structures)
- But they are unpredictive for hard jets
    - Often too soft (but not guaranteed! Can be too hard!)

**Matrix elements are correct**

- When all jets are hard and no hierarchies
    - (single-scale problem)
    - (= small corner of phase space, but an important one!)
- But they are unpredictive for strongly ordered emissions

**ME-PS matching** → study both regions with ONE sample

# Approaches on the Market

## Hw/Py standalone

1st order matching for many processes, especially resonance decays

## Alpgen + Hw/Py

MLM with HW or PY

NOTE: If you just write "AlpGen" on a plot, we assume AlpGen standalone! (no showering or matching!) - very different from Alp+Py/Hw

## MadGraph + Hw/Py

MLM with HW or PY

## Sherpa

CKKW + CS-dipole showers

## Ariadne

CKKW-L + Lund-dipole showers

## MC@NLO

NLO with subtraction, 10% w<0
+ Herwig showers

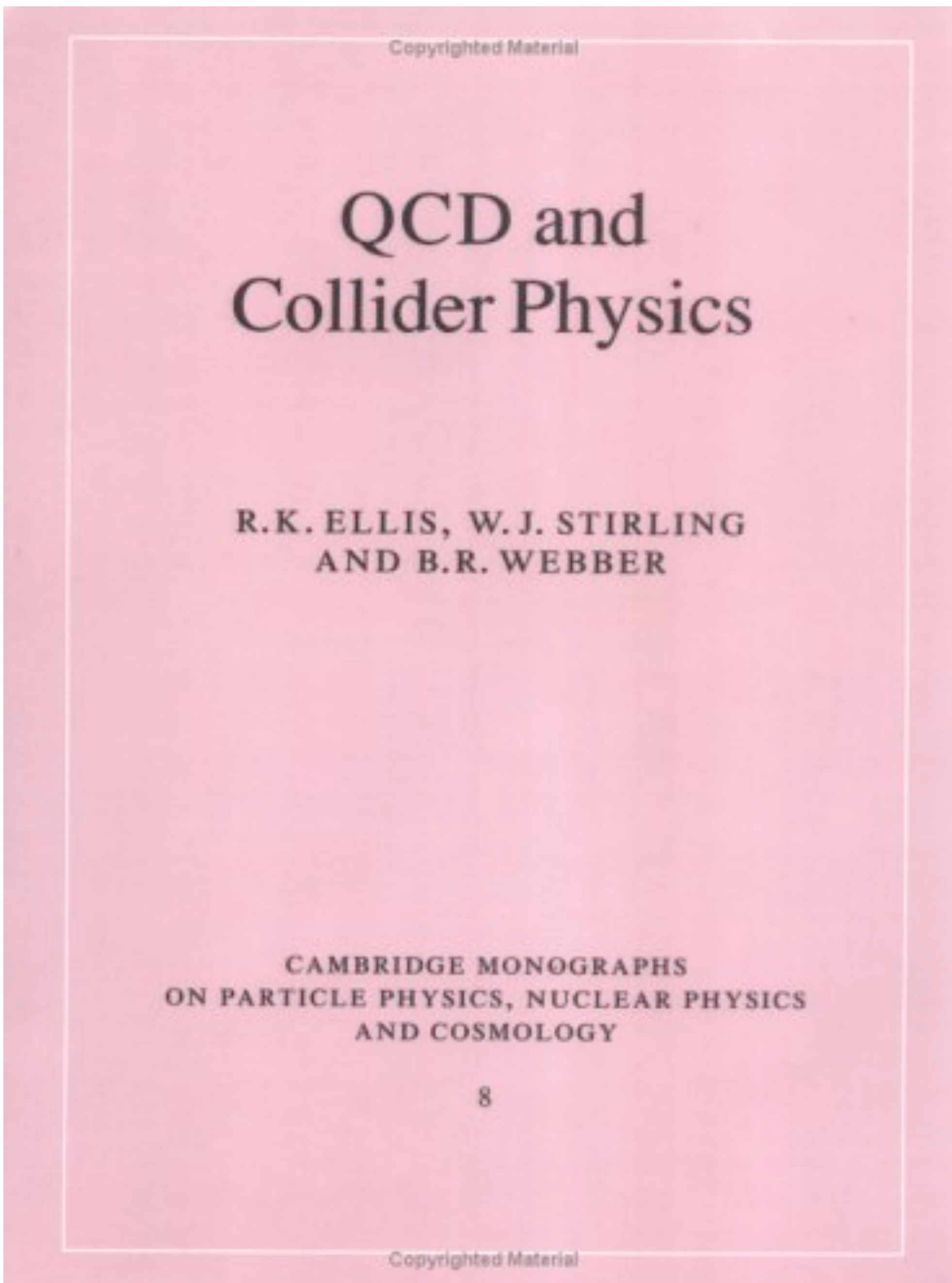
## POWHEG

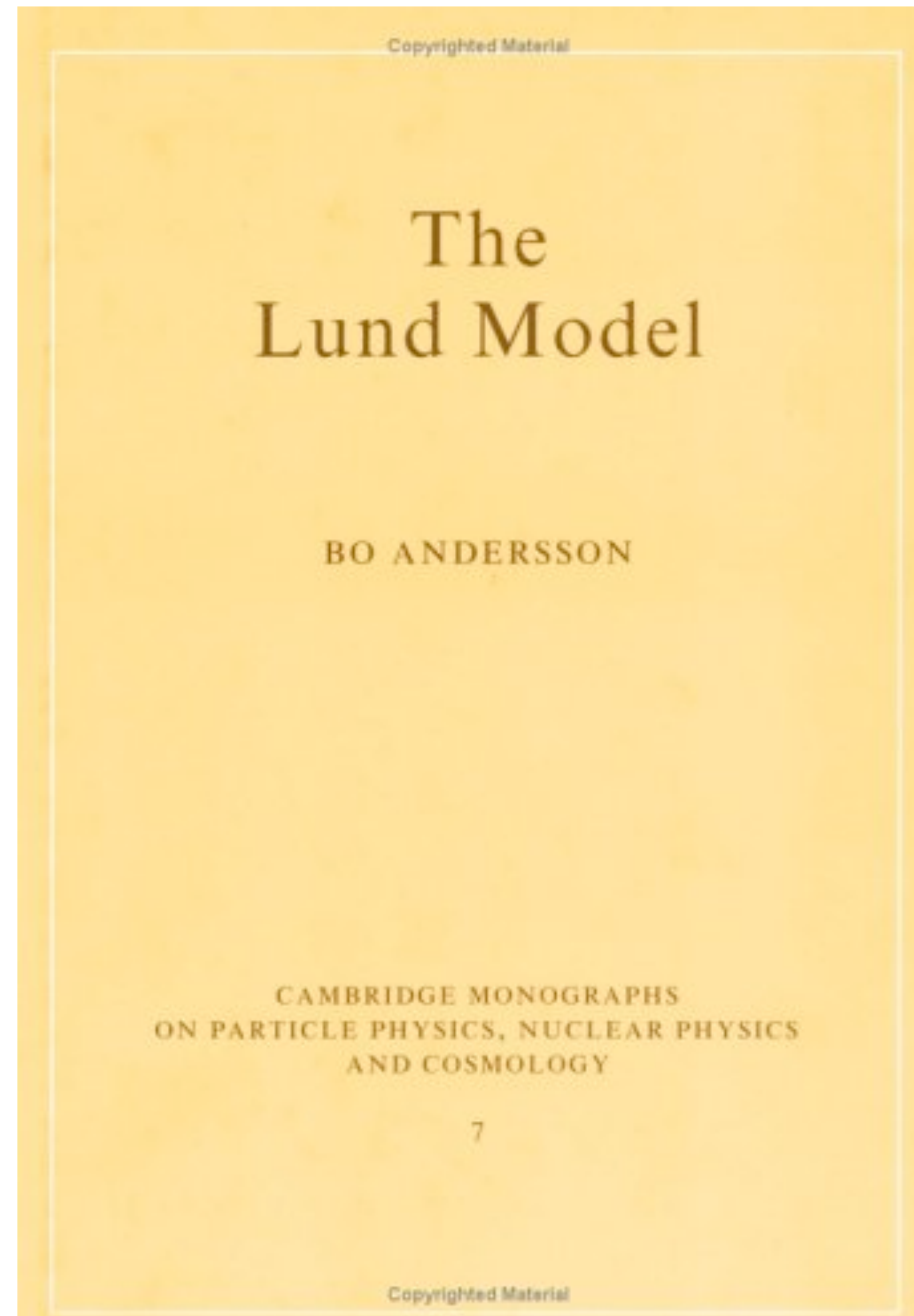
NLO with merging; 0% w<0
+ "truncated" showers

## (Vincia+Py8)

NLO + multileg a la GeeKS
+ dipole-antenna showers

# Recommended Reading



# Recommended Reading

## RTFM : Pythia 6.4 physics and manual

Contains useful pheno-oriented introductions to many topics, ≈ 600p

Sjöstrand, Mrenna, PS; hep-ph/0603175

## Les Houches Guidebook to MC Generators

Sections on PDFs, matching, fixed order, etc (+ MCnet update ≈ 2011)

M. Dobbs et al., hep-ph/0403045

## Les Houches Accords for generators

Les Houches conventions + LHEF file structure

hep-ph/0109068 (org LHA conventions) + hep-ph/0609017 (LHEF) + hep-ph/0712.3311 (BSM-LHEF)

## Papers on Multiple Parton Interactions

Sjöstrand, van Zijl; Phys.Rev.D36(1987)2019 (main ideas + org MPI model + pheno)

Sjöstrand, PS; hep-ph/0408302 (interleaved model) & hep-ph/0402078 (beam remnants)

Butterworth, Forshaw, Seymour hep-ph/9601371 (JIMMY), + see hepforge

# Additional Slides

# PDF DGLAP : Details

**We Wrote:**

$$\frac{dq(x,\mu^2)}{d\ln\mu^2} = \underbrace{\frac{\alpha_s}{2\pi}\int_x^1 dz\, P_{qq}(z)\,\frac{q(x/z,\mu^2)}{z}}_{P_{qq}\otimes q},$$

More properly, it's a gain-loss equation (same equation, rewritten):

$$\frac{dq(x,\mu^2)}{d\ln\mu^2} = \frac{\alpha_s}{2\pi}\int_x^1 dz\, p_{qq}(z)\,\frac{q(x/z,\mu^2)}{z} - \frac{\alpha_s}{2\pi}\int_0^1 dz\, p_{qq}(z)\, q(x,\mu^2)$$

$p_{qq}$ is real $q \leftarrow q$ **splitting kernel:** $p_{qq}(z) = C_F\frac{1+z^2}{1-z}$

First term: some partons flow from higher y=x/z to x (POSITIVE)
Second term: some partons at x flow to lower y=zx (NEGATIVE)

How can they be the same equation?

Slide material from G. Salam

# PDF DGLAP : Details

Awkward to write real and virtual parts separately. Use more compact notation:

$$\frac{dq(x,\mu^2)}{d\ln\mu^2} = \frac{\alpha_s}{2\pi} \underbrace{\int_x^1 dz\, P_{qq}(z)\, \frac{q(x/z,\mu^2)}{z}}_{P_{qq}\otimes q}, \qquad P_{qq} = C_F\left(\frac{1+z^2}{1-z}\right)_+$$

This involves the *plus prescription:*

$$\int_0^1 dz\, [g(z)]_+\, f(z) = \int_0^1 dz\, g(z)\, f(z) - \int_0^1 dz\, g(z)\, f(1)$$

$z = 1$ divergences of $g(z)$ cancelled if $f(z)$ sufficiently smooth at $z = 1$

Slide material from G. Salam