Jets and Heavy Flavor
Part 1

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Organization of the lectures

Today (Part 1): Introduction to jets and heavy flavor

- Why are heavy quarks interesting?
- What can we learn from measurements of heavy flavor hadrons?
- What are jets, how do we reconstruct them, and what can we learn with them?

Tomorrow (Part 2): Focus on measurements involving jets and heavy flavor at the EIC

Organization of the lectures

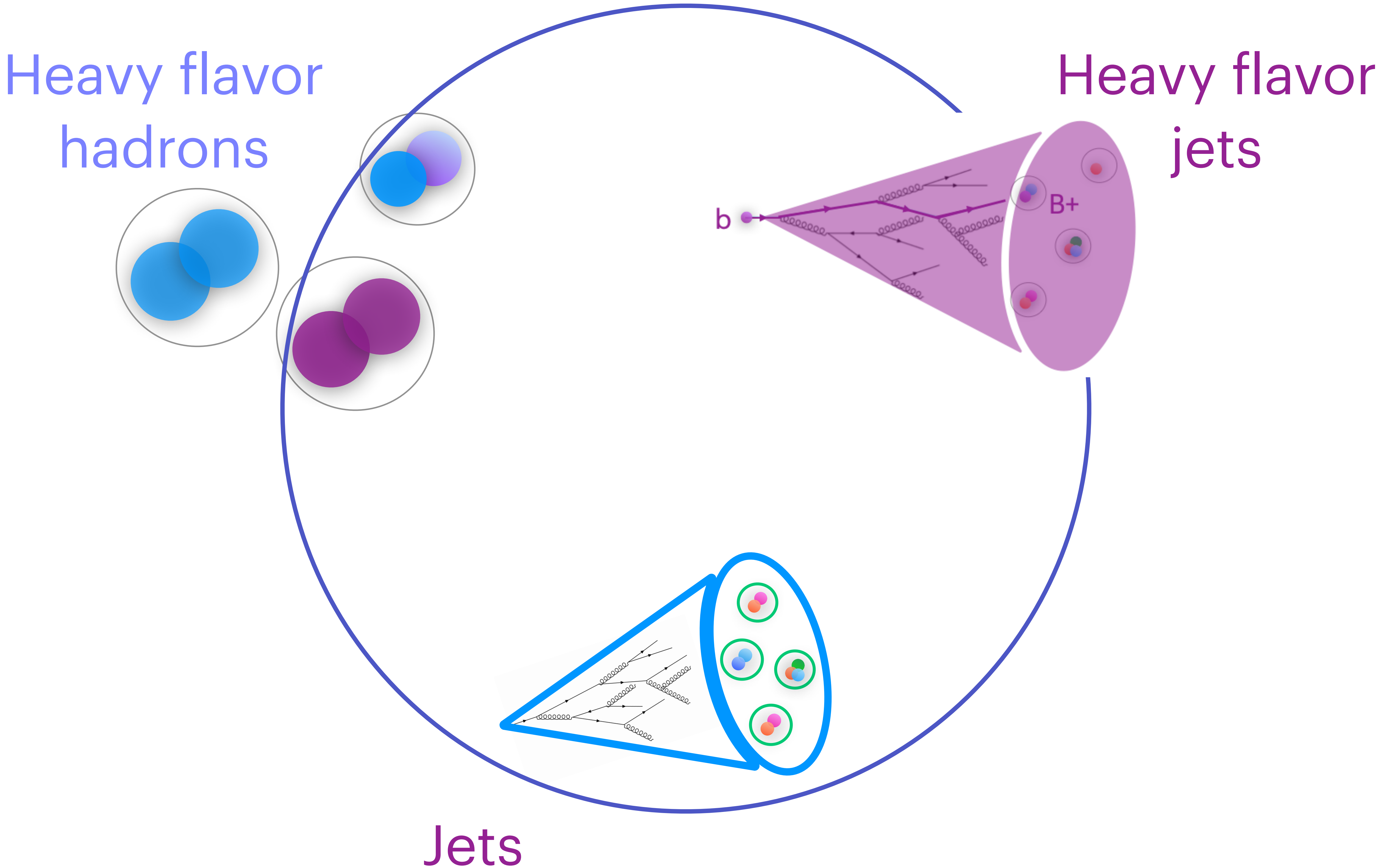
Today (Part 1):
Introduction to jets and heavy flavor

- Why are heavy quarks interesting?
- What can we learn from measurements of heavy flavor hadrons?
- What are jets, how do we reconstruct them, and what can we learn with them?

A few caveats:

- I am not a theorist! These lectures will be more from an experimental point of view, although I have tried to include some theory as well
- We could easily do a summer school only on jets or only on heavy flavor! These are huge subfields, and these lectures do not cover everything :)

This lecture: Introduction to HF and jet probes



What do we mean by heavy flavor?

"Light flavor" quarks:
up, down, strange

u	2.2 MeV/c²
d	4.7 MeV/c²
s	95 MeV/c²

"Heavy flavor" quarks:
charm, beauty, top

c	1.275 GeV/c²
b	4.18 GeV/c²
t	173 GeV / c²

When we talk about "heavy flavor" we typically mean beauty and charm quarks, or hadrons that contain them

Why don't we include the top quark?

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Why don't we include the top quark?

- It decays before it has time to hadronize, so it doesn't form bound states
- Quarks hadronize on a timescale of $1/\Lambda_{QCD}$, where Λ_{QCD} is the scale at which non-perturbative effects begin to dominate, and perturbative QCD can't be applied

What's so special about heavy flavor?

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up, down, strange

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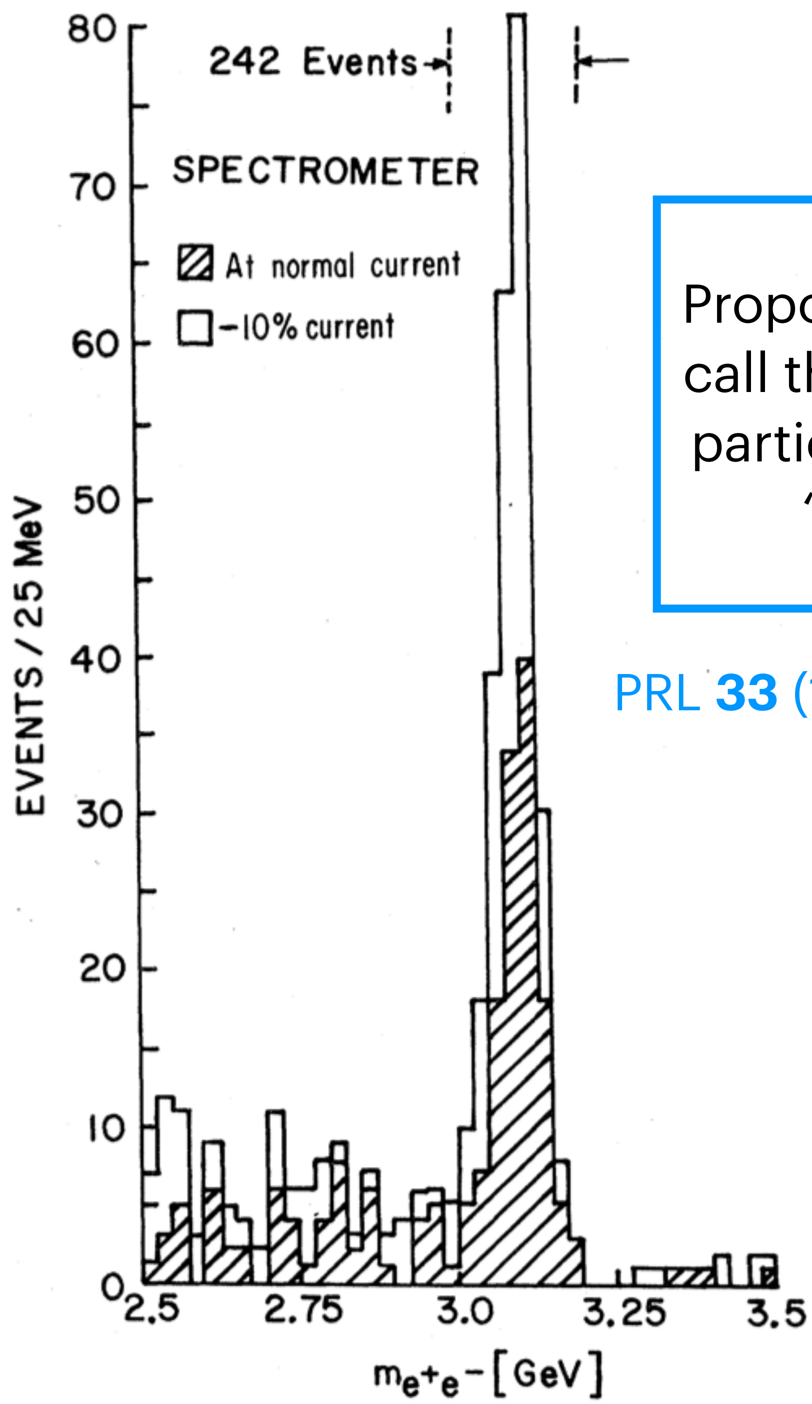
- Λ_{QCD} ~ 200 MeV
- $m_b, m_c > \Lambda_{QCD}$ → heavy quark production can be computed using perturbative QCD. This means that measurements involving heavy flavor are **good tests of perturbative QCD**
- Large masses imply that charm and beauty quarks are typically produced early in a hard scattering event

Discovery of the charm quark

*p*Be collisions

@ Brookhaven National Lab (United States)



Proposed to call the new particle the "J"

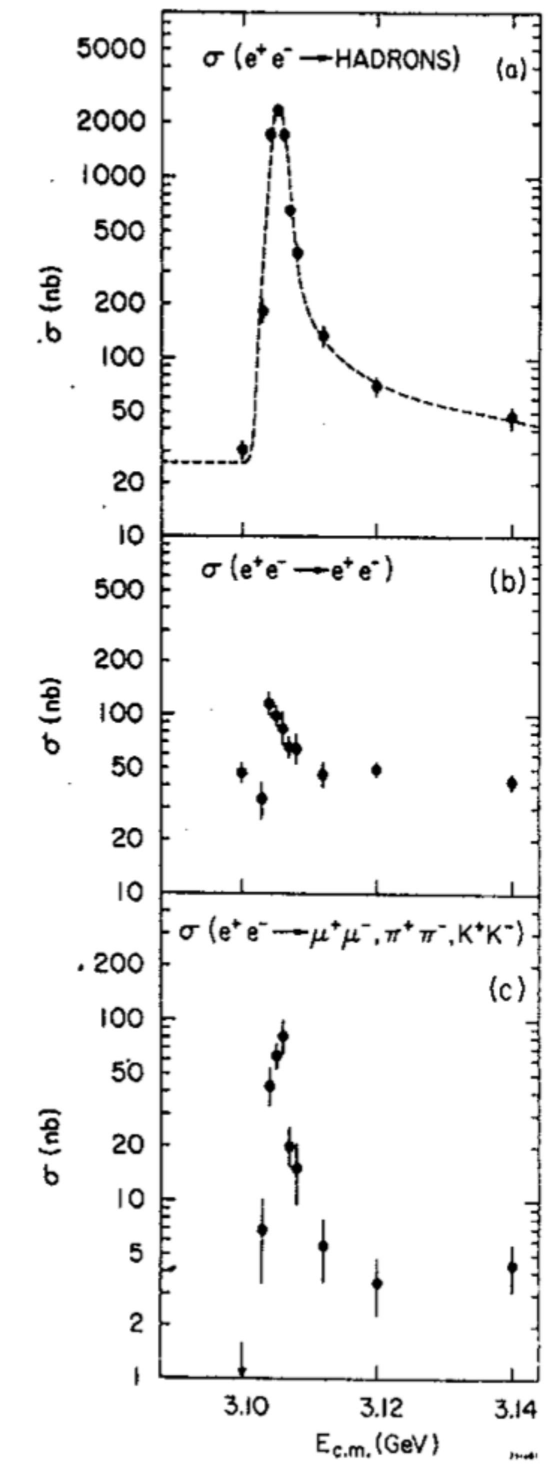
PRL **33** (1974) 1406

e^+e^- collisions

@ SLAC (United States)

Proposed to call the new particle the "ψ"

PRL **33** (1974) 1404



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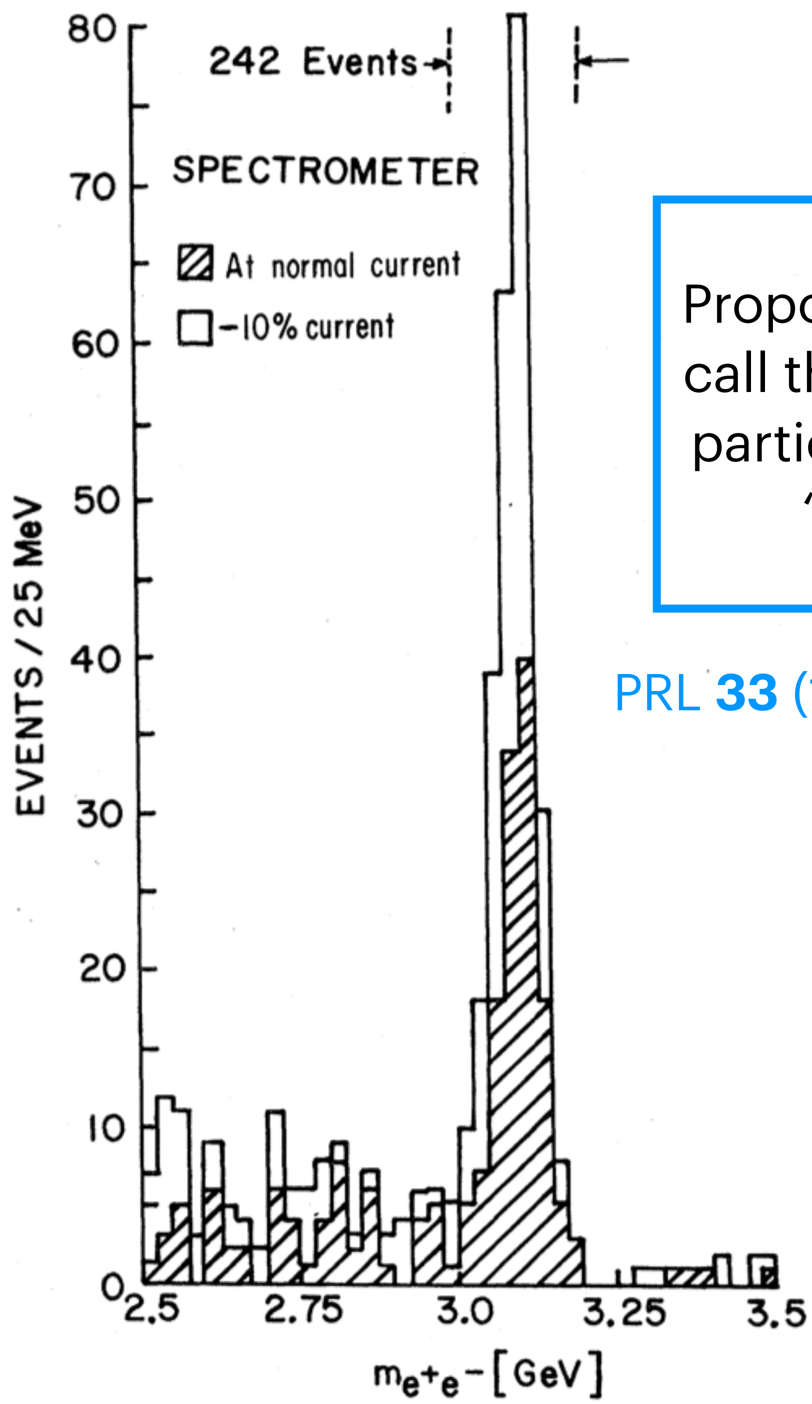

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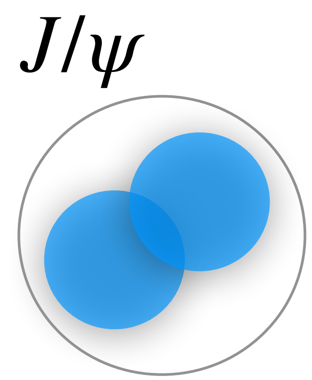

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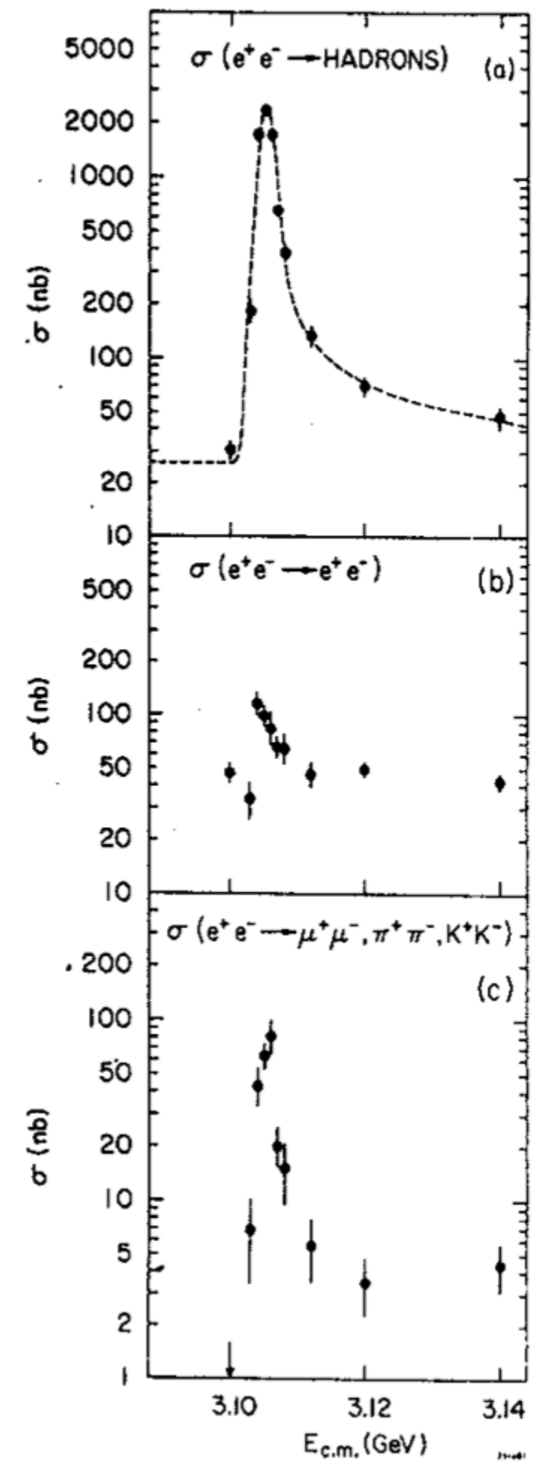

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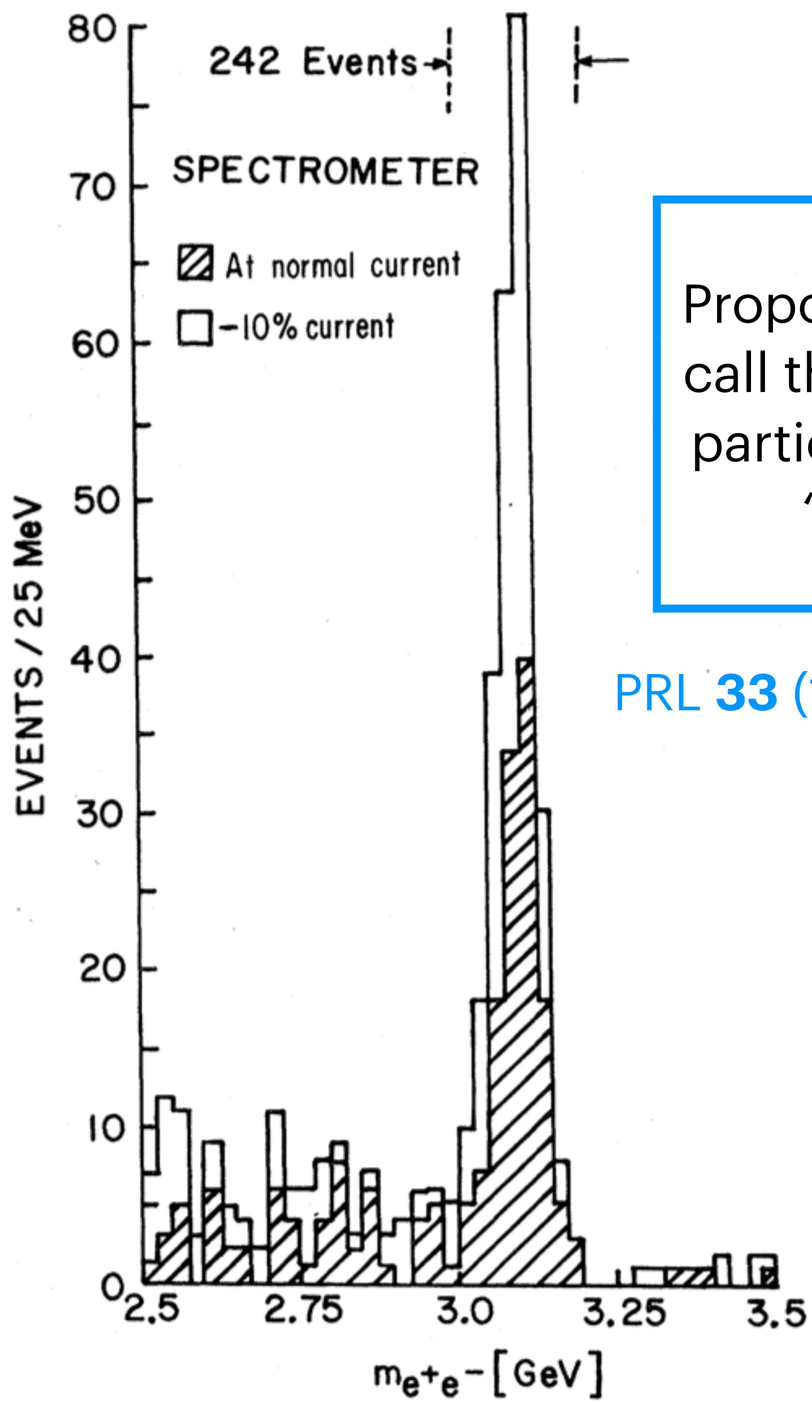

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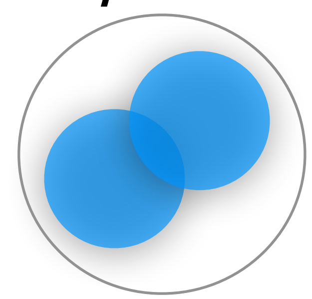

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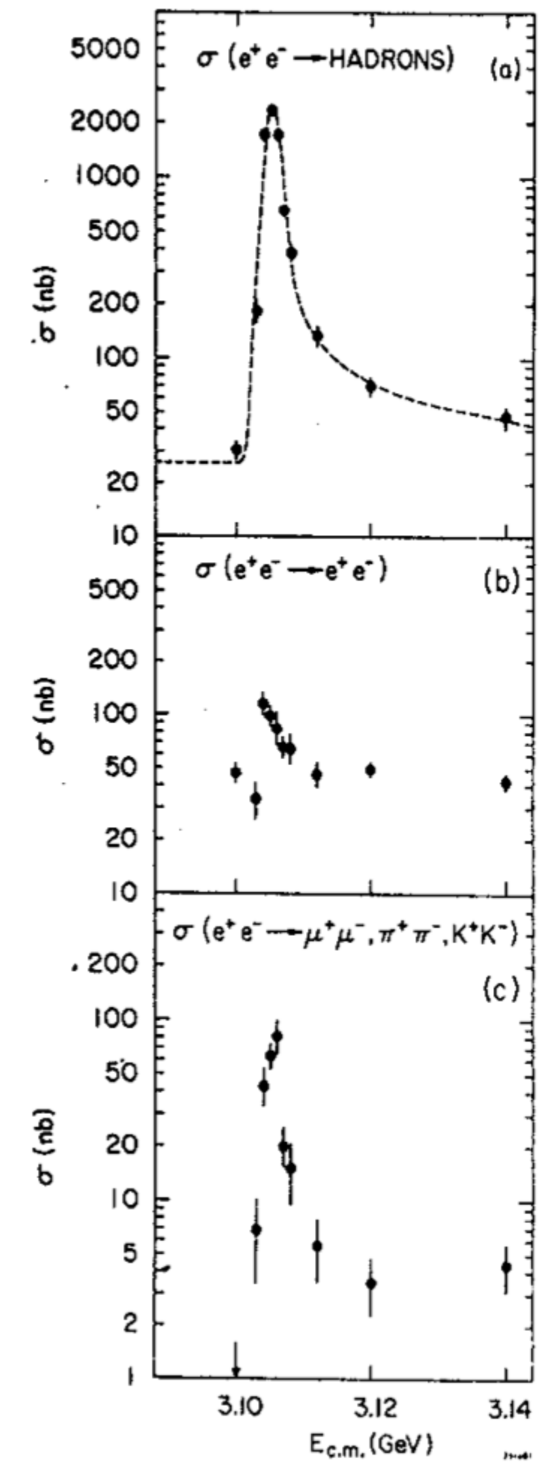
PRL **33** (1974) 1406

PRL **33** (1974) 1404

Discovered at the same time!

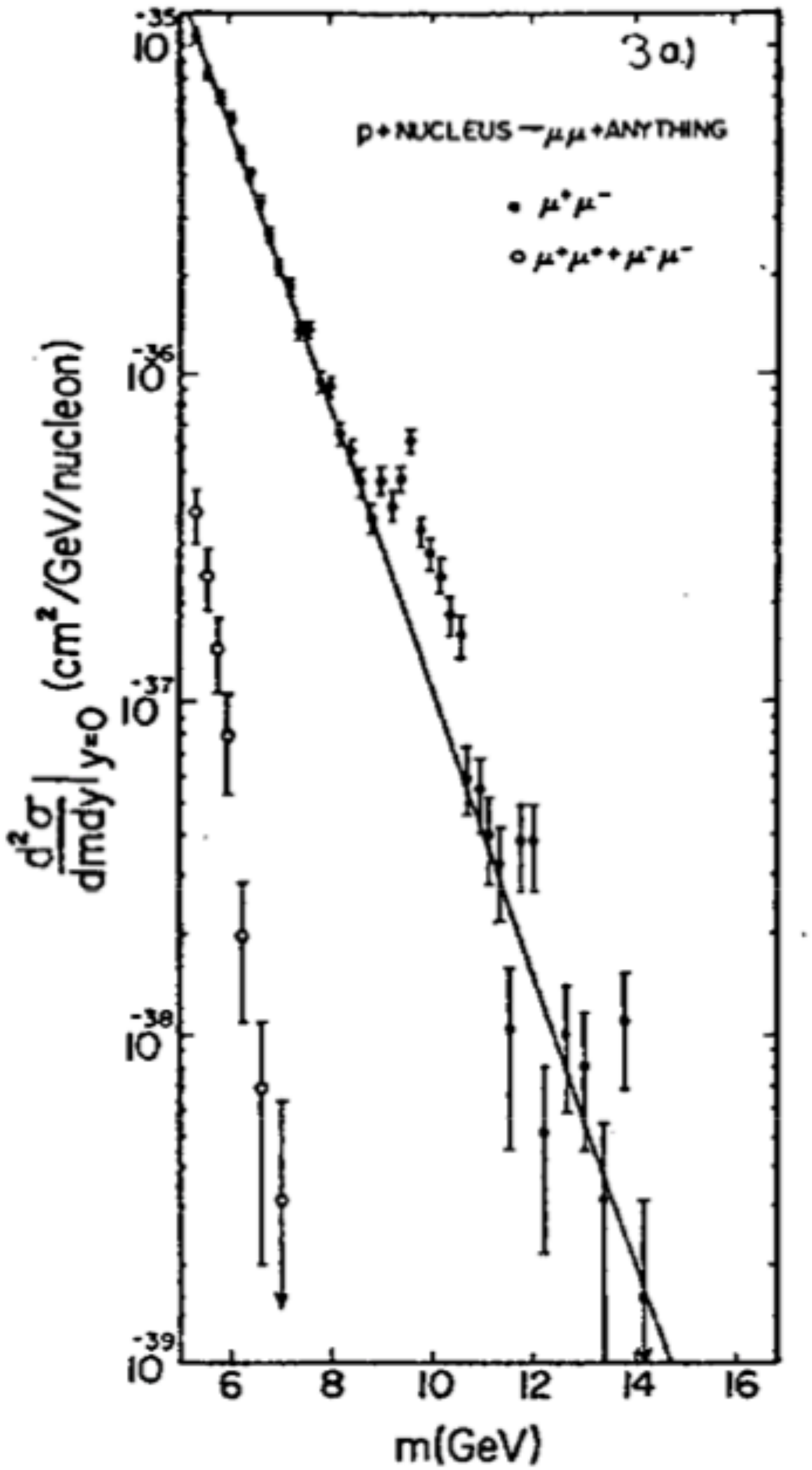
Nobel Prize 1976

"for.. the discovery of a heavy elementary particle of a new kind"

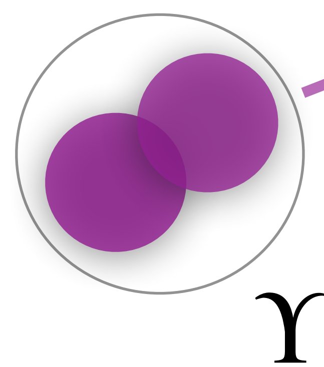


Discovery of the beauty quark

pCu + pPt collisions @ Fermilab (United States) PRL **39** (1977) 252



background subtracted →



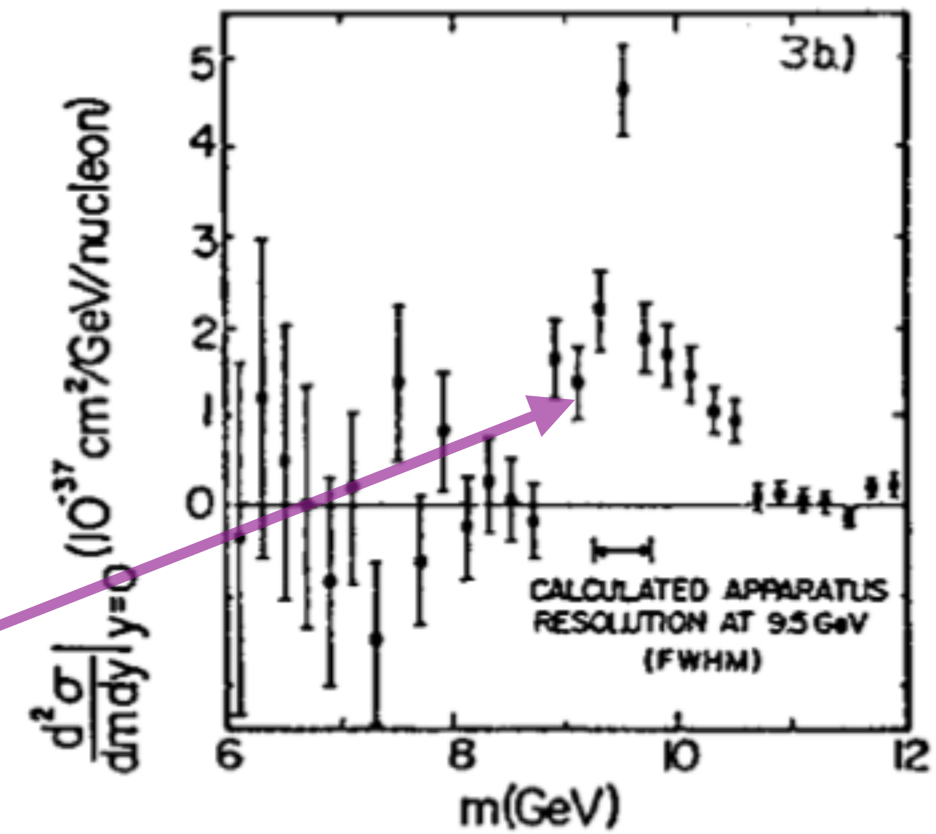
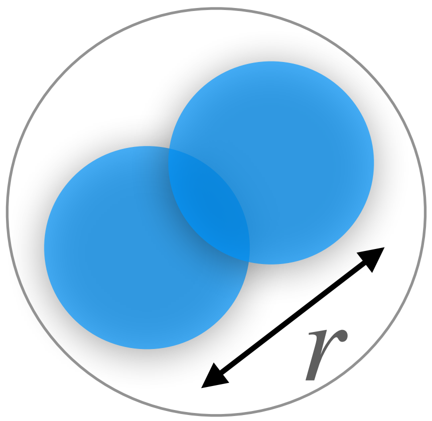


Fig. 3

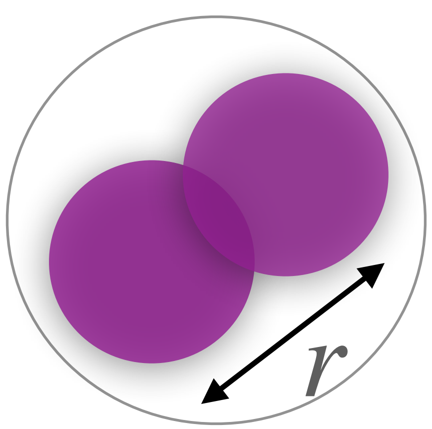
- "Strong enhancement" seen at 9.5 GeV in the dimuon mass spectrum
- 1977: Discovery of Upsilon states, and the beauty quark!

Quarkonia: "hydrogen atoms of QCD"



J/ψ

mass: 3.096 GeV



$\Upsilon(1S)$

mass: 9.460 GeV

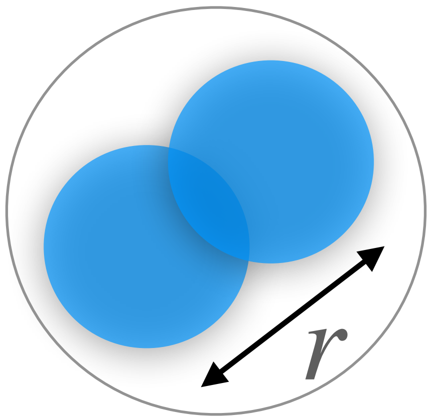
Can be described with a simple potential model:

$$V(r) = -C_F \frac{\alpha_s}{r}$$

"Coulomb-like" potential
at short distances

$C_F =$ Casimir color factor

Quarkonia: "hydrogen atoms of QCD"



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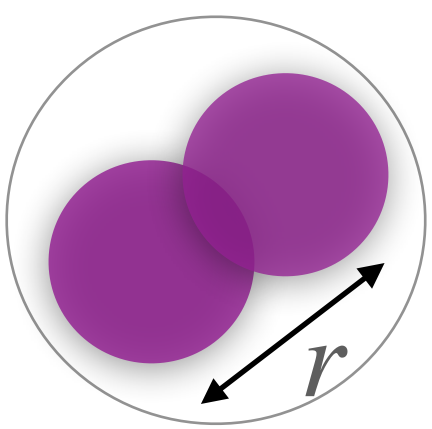


$\Upsilon(1S)$

mass: 9.460 GeV

Can be described with a simple potential model:

$$V(r) = -C_F\frac{\alpha_s}{r} + \sigma r$$

"Coulomb-like" potential at short distances

quark confinement at large distances

$C_F =$ Casimir color factor

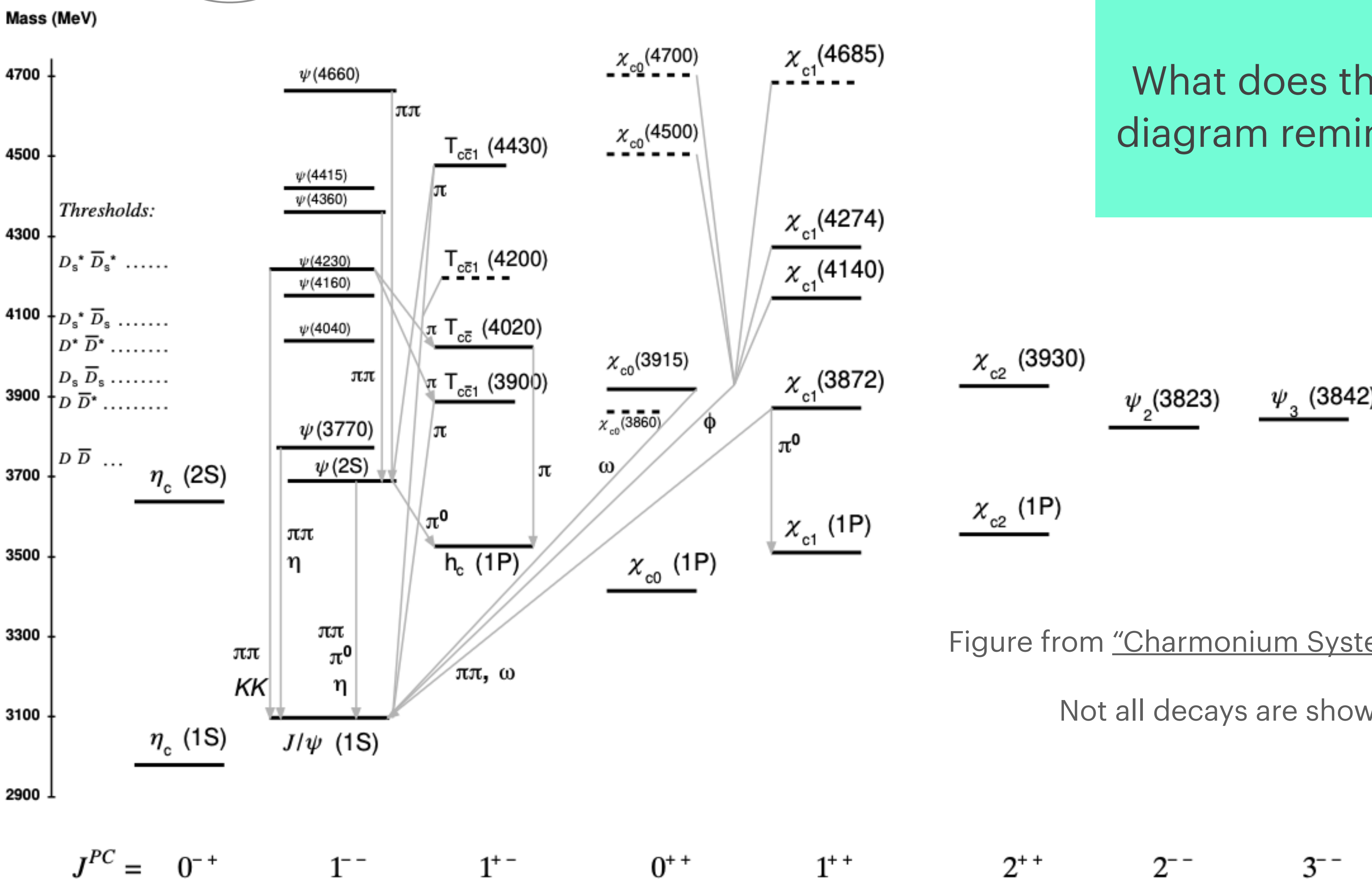
Direct analogy to hydrogen atom wave functions and energy levels:

Orbital angular momentum $L = 0$: S-wave states

$L = 1$: P-wave states

$L = 2$: D-wave states

Charmonium states



What does this kind of diagram remind you of?

Figure from "Charmonium System" PDG review

Not all decays are shown here!

Quantum numbers: $J =$ Total angular momentum $P = (-1)^{L+1}$ $C = (-1)^{L+S}$

L = orbital angular momentum S = spin

Bottomonium states

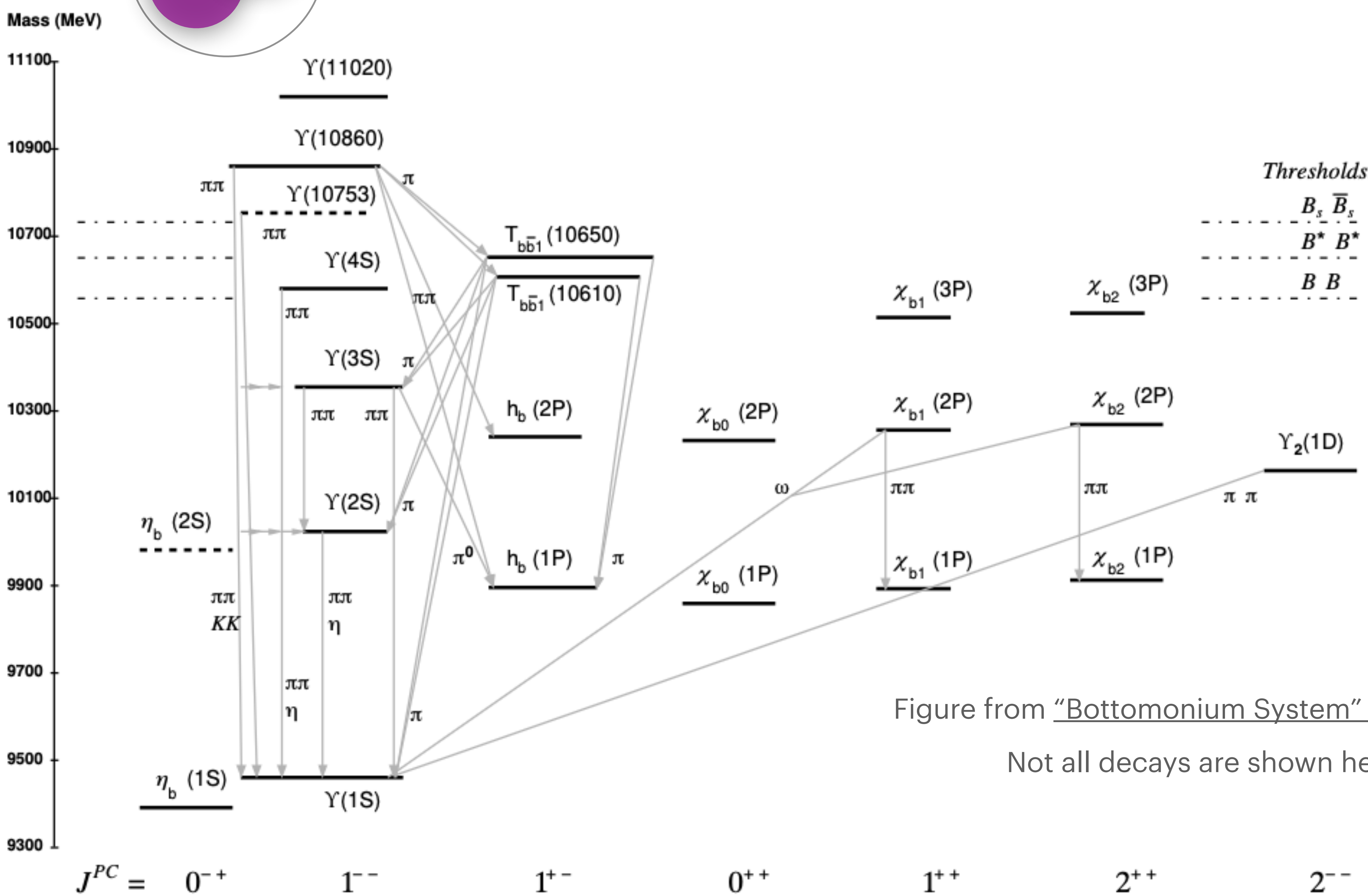


Figure from "Bottomonium System" PDG review

Not all decays are shown here!

Quantum numbers: $J =$ Total angular momentum $P = (-1)^{L+1}$ $C = (-1)^{L+S}$

L = orbital angular momentum S = spin

How are quarkonia formed?

- We know that heavy quark production in QCD can be calculated perturbatively
- However, the hadronization part into a quarkonium state is non-perturbative

→ **Factorize** heavy quark production (perturbative) from hadronization (non-perturbative)

Despite having experimentally confirmed their existence in 1974, we still don’t understand the mechanism by which quarkonia are formed!

3 “main” theories (+ many more recent extensions/updates)

1. Non-relativistic QCD (NRQCD)

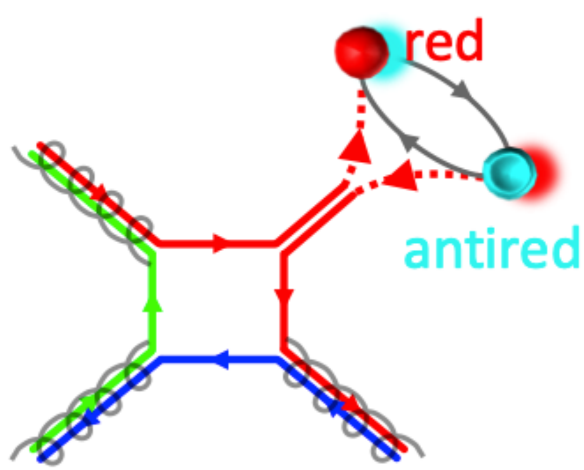
2. Color Singlet Model (CSM)

3. Color Evaporation Model (CEM)

How are quarkonia formed?

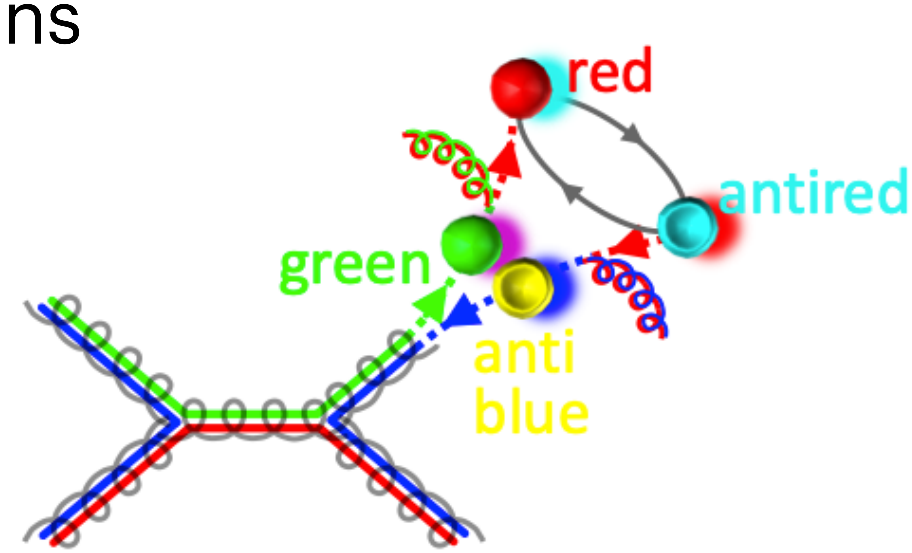
1. Non-relativistic QCD (NRQCD)

- Why might "non-relativistic" work for quarkonium?
- Perturbative QCD model: Expansion in α_s and in the heavy quark velocity v
- Hadronisation of quarkonium is parametrised with non-perturbative Long Distance Matrix Elements (LDMEs) → must be extracted from data
- Allows the Color-Octet mechanism: a quarkonium state can change its quantum numbers through gluon emissions



Colour Singlet state

Quarkonium state has same quantum numbers as initial q and $\overline{q}$ pair



Colour Octet state

Quarkonium state has different quantum numbers as initial q and $\overline{q}$ pair

How are quarkonia formed?

2. Color Singlet Model (CSM)

- Quarkonium is produced with the same quantum numbers as the initial q and $\overline{q}$ pair
- Based on perturbative QCD like NRQCD

3. Color Evaporation Model (CEM)

- Assume that above the mass threshold for two heavy quarks, and below the threshold for two open heavy flavor hadrons, the heavy quark pair has a certain probability P to hadronize into a specific quarkonium state
- P is assumed to be process-independent (universal)

Cross section to produce a $Q\overline{Q}$ pair

$$\sigma_{J/\psi} = P_{J/\psi} \int_{m_{2m_c}}^{m_{2m_D}} \frac{d\sigma_{c\bar{c}}}{dm_{c\bar{c}}} dm_{c\bar{c}}$$

Cross section to produce a specific quarkonium state (ex: J/psi)

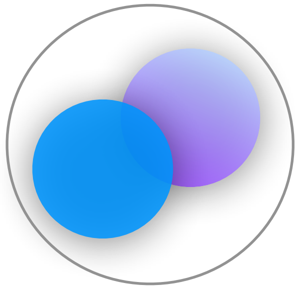
"Open" heavy flavor hadrons contain heavy and light quarks

B^0 mass: 5.2796 GeV
$c\tau$ = 455.7 μm

B^+ mass: 5.2793 GeV
$c\tau$ = 491.1 μm

B_s^0 mass: 5.3669 GeV
$c\tau$ = 452.4 μm

Λ_b^0 mass: 5.6196 GeV
$c\tau$ = 440.7 μm



D^+ mass: 1.8696 GeV
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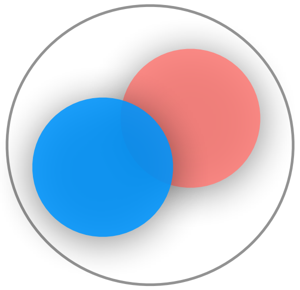
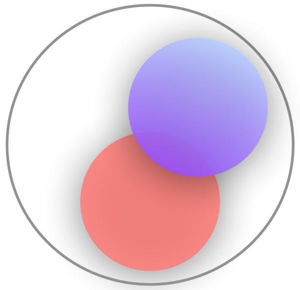
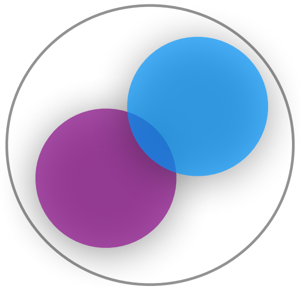


D^0 mass: 1.8648 GeV
$c\tau$ = 122.9 μm

D_s^+ mass: 1.9683 GeV
$c\tau$ = 151.2 μm



Λ_c^+ mass: 2.2865 GeV
$c\tau$ = 59.9 μm



B_c^+ Quarkonia or not?

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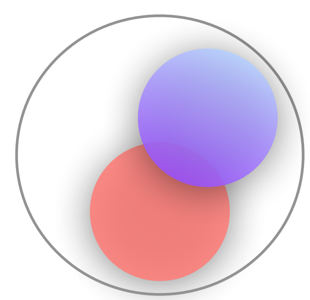

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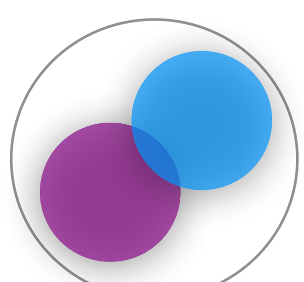

B_c^+ It's considered to be more similar to quarkonium!

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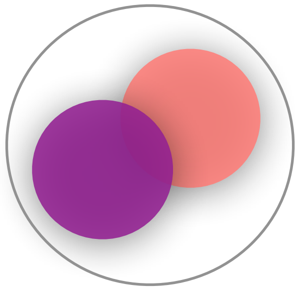

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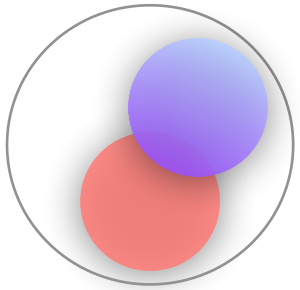
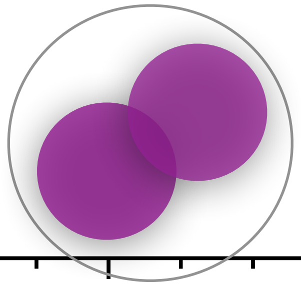


Λ_c^+ mass: 2.2865 GeV
$c\tau$ = 59.9 μm

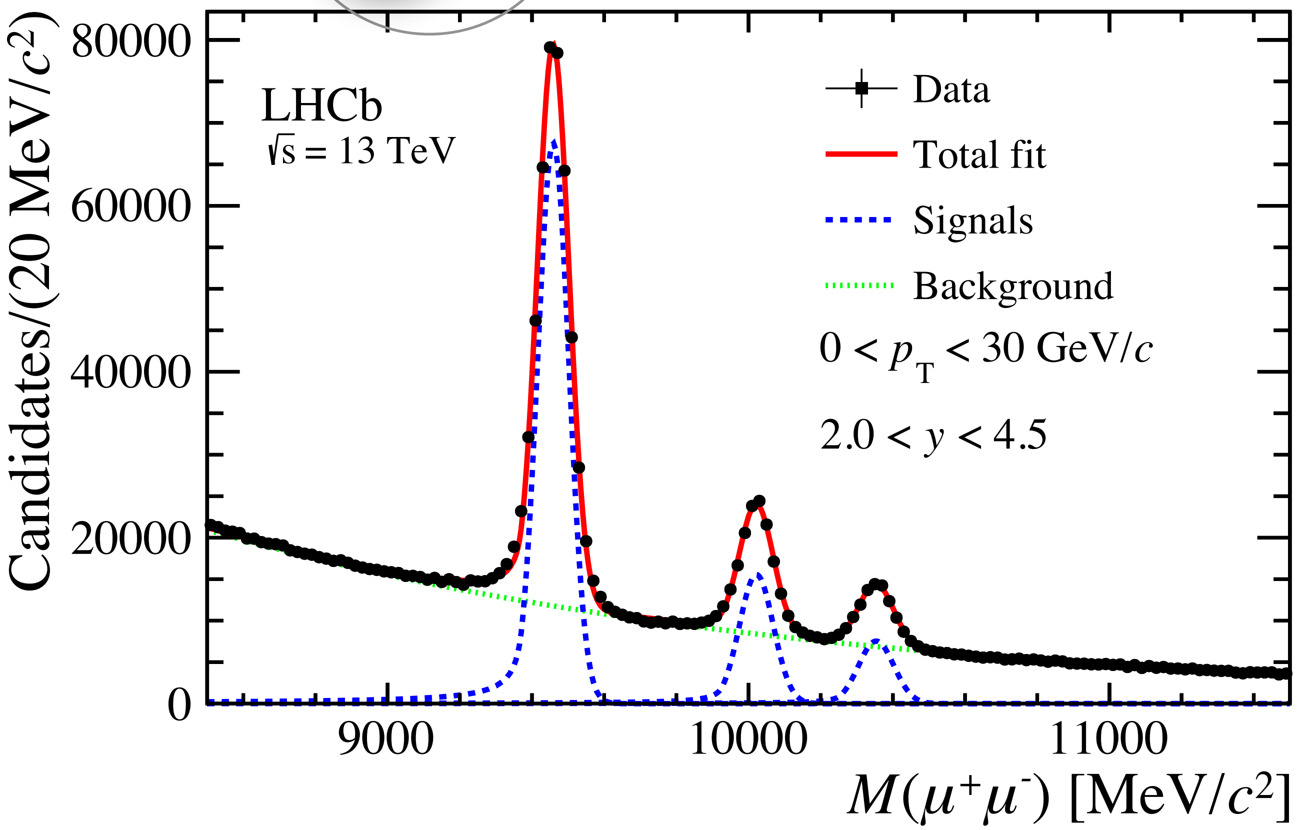
+ many other heavy flavor baryons and excited states

Experimental reconstruction of heavy flavor hadrons

- Quarkonia have large branching fractions to hadrons, but for those that decay to leptons we typically prefer the lepton channels. Why?



$\Upsilon(1S), \Upsilon(2S), \Upsilon(3S) \rightarrow \mu^+\mu^-$ at LHCb



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Very clean!

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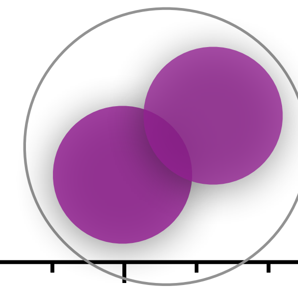

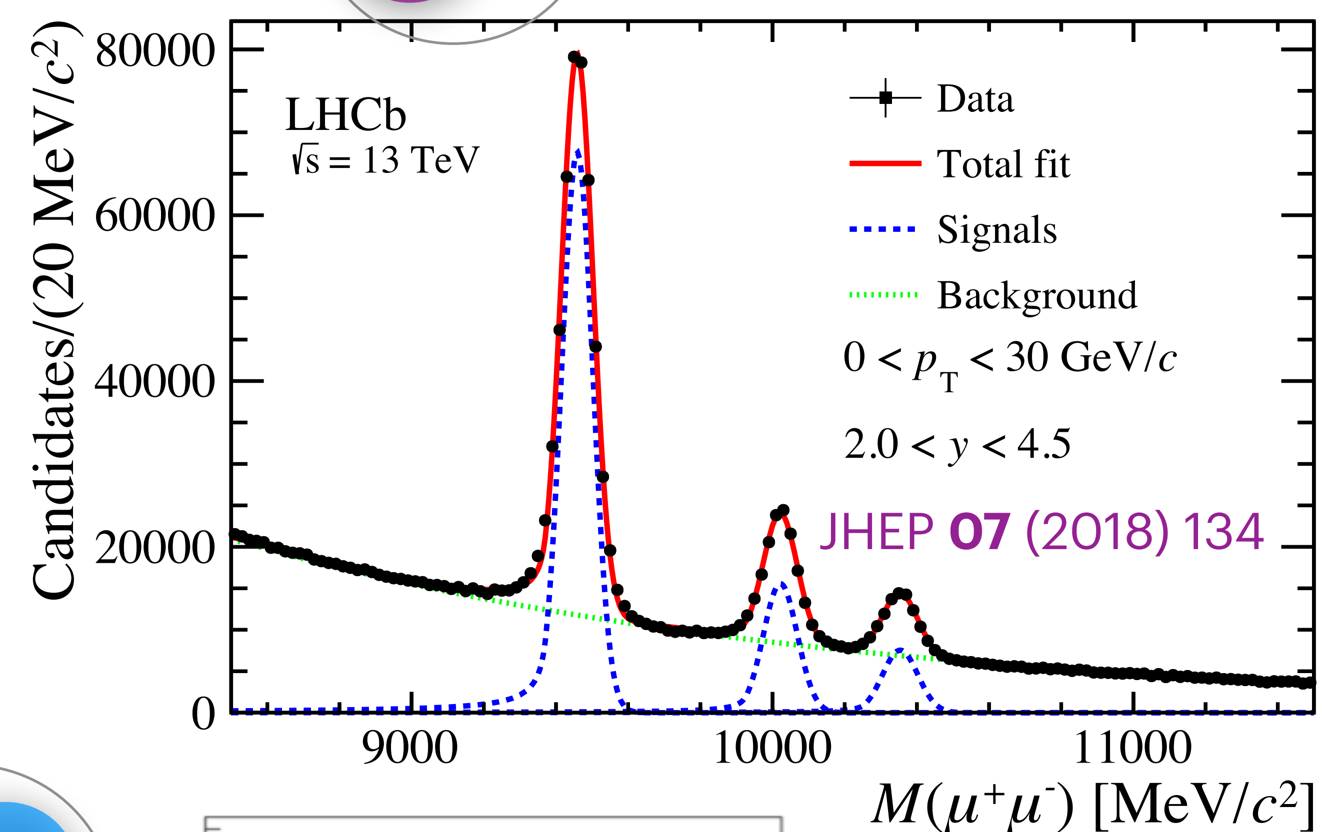

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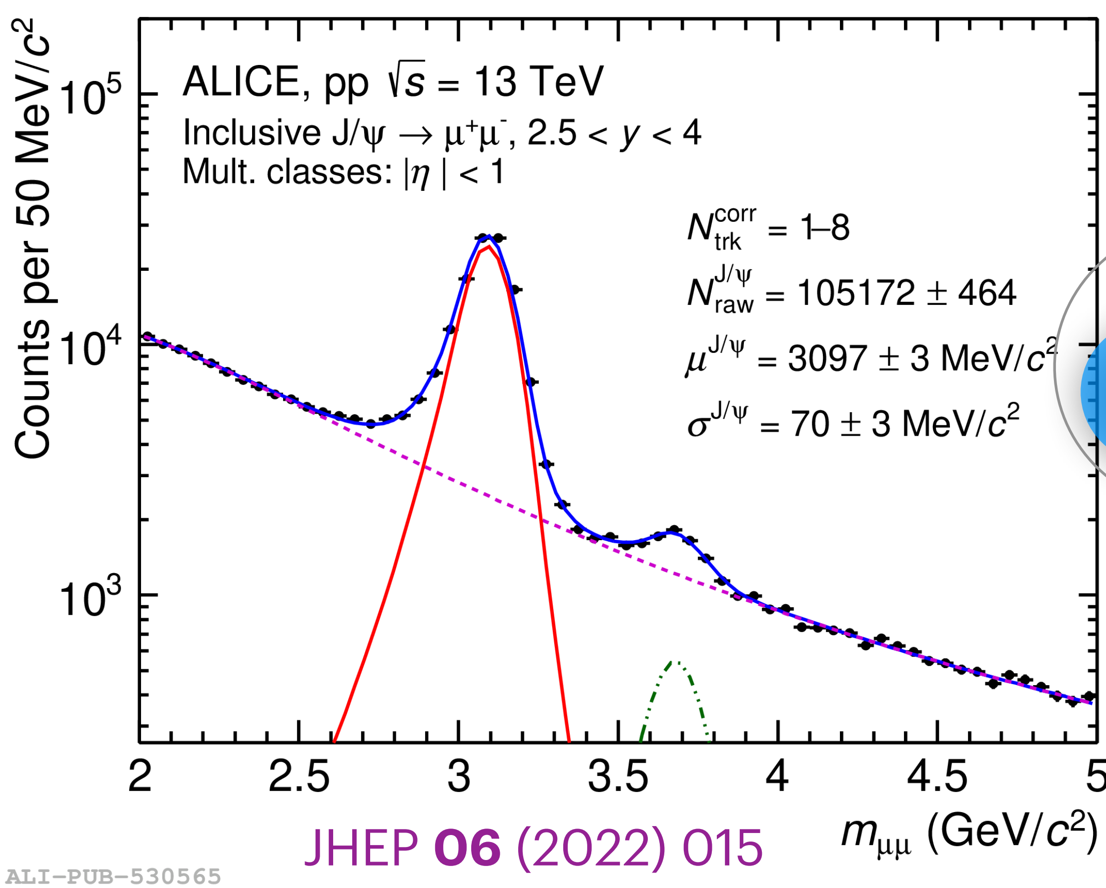
$J/\psi, \psi(2S) \rightarrow \mu^+\mu^-$ at ALICE



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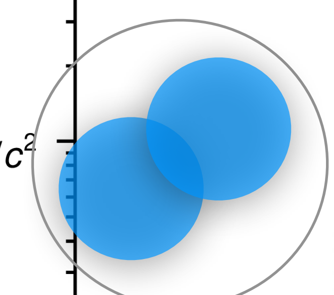
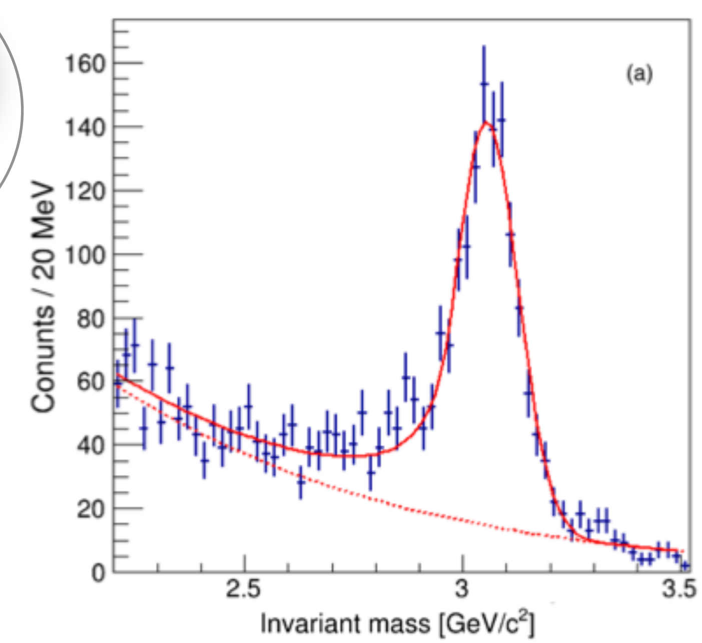


$J/\psi \rightarrow e^+e^-$ at PHENIX



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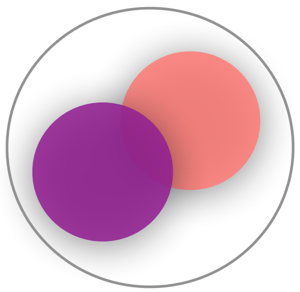
Experimental reconstruction of heavy flavor hadrons

- Open heavy flavor hadrons have many possible decay channels. Many have small branching fractions!



Example: some B+ decay modes from the PDG

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
	Semileptonic and leptonic modes			
Γ_1	$\ell^+ \nu_\ell X$	[a]	(10.99 ± 0.28) %	
Γ_2	$e^+ \nu_e X_c$		(10.8 ± 0.4) %	
Γ_3	$e^+ \nu_e X$		(10.8 ± 2.7) %	
Γ_4	$\mu^+ \nu_\mu X$		(11.3 ± 3.5) %	
Γ_5	$\ell^+ \nu_\ell X_u$	[a]	$(1.65 \pm 0.21) \times 10^{-3}$	
Γ_6	$D \ell^+ \nu_\ell X$	[a]	(9.0 ± 0.6) %	
Γ_7	$\overline{D}^0 \ell^+ \nu_\ell$	[a]	(2.26 ± 0.07) %	
Γ_8	$\tau^+ \nu_\tau X$		(2.5 ± 0.4) %	
Γ_9	$\overline{D}^0 \tau^+ \nu_\tau$		$(7.7 \pm 2.5) \times 10^{-3}$	
Γ_{10}	$\overline{D}^*(2007)^0 \ell^+ \nu_\ell$	[a]	(5.26 ± 0.10) %	
Γ_{11}	$\overline{D}^*(2007)^0 e^+ \nu_e$			
Γ_{12}	$\overline{D}^*(2007)^0 \mu^+ \nu_\mu$			
Γ_{13}	$\overline{D}^*(2007)^0 \tau^+ \nu_\tau$		(1.88 ± 0.20) %	
Γ_{14}	$D^{(*)} n\pi \ell^+ \nu_\ell (n \geq 1)$	[a]	(1.74 ± 0.23) %	
Γ_{15}	$D^- \pi^+ \ell^+ \nu_\ell$	[a]	$(3.82 \pm 0.20) \times 10^{-3}$	
Γ_{16}	$\overline{D}_2^*(2460)^0 \ell^+ \nu_\ell,\ \overline{D}_2^{*0} \to D^- \pi^+$	[a]	$(1.59 \pm 0.10) \times 10^{-3}$	
Γ_{17}	$\overline{D}_0^*(2420)^0 \ell^+ \nu_\ell,\ \overline{D}_0^{*0} \to D^- \pi^+$	[a]	$(9 \pm 5) \times 10^{-4}$	S=2.6
Γ_{18}	$D^{*-} \pi^+ \ell^+ \nu_\ell$	[a]	$(5.42 \pm 0.28) \times 10^{-3}$	
Γ_{19}	$\overline{D}_1(2420)^0 \ell^+ \nu_\ell,\ \overline{D}_1^0 \to D^{*-} \pi^+$	[a]	$(2.84 \pm 0.17) \times 10^{-3}$	S=1.1
Γ_{20}	$\overline{D}_1'(2430)^0 \ell^+ \nu_\ell,\ \overline{D}_1'^0 \to D^{*-} \pi^+$	[a]	$(1.7 \pm 0.6) \times 10^{-3}$	S=1.8

	***D*, *D**, or *D*$_s$ modes**			
Γ_{57}	$\overline{D}^0 \pi^+$		$(4.61 \pm 0.10) \times 10^{-3}$	
Γ_{58}	$D_{CP(+1)} \pi^+$	[b]	$(2.04 \pm 0.20) \times 10^{-3}$	
Γ_{59}	$D_{CP(-1)} \pi^+$	[b]	$(2.1 \pm 0.4) \times 10^{-3}$	
Γ_{60}	$\overline{D}^0 \rho^+$		$(9.7 \pm 1.1) \times 10^{-3}$	S=2.1
Γ_{61}	$\overline{D}^0 K^+$		$(3.64 \pm 0.15) \times 10^{-4}$	
Γ_{62}	$D_{CP(+1)} K^+$	[b]	$(1.81 \pm 0.08) \times 10^{-4}$	
Γ_{63}	$D_{CP(-1)} K^+$	[b]	$(2.04 \pm 0.13) \times 10^{-4}$	
Γ_{64}	$D^0 K^+$		$(3.60 \pm 0.24) \times 10^{-6}$	
Γ_{65}	$[K^- \pi^+]_D K^+$	[c]	$< 2.8 \times 10^{-7}$	CL=90%
Γ_{66}	$[K^+ \pi^-]_D K^+$	[c]	$< 1.6 \times 10^{-5}$	CL=90%

	Charmonium modes		
Γ_{270}	$\eta_c K^+$	$(1.10 \pm 0.07) \times 10^{-3}$	S=1.1
Γ_{271}	$\eta_c K^*(892)^+$	$(1.2 \ {}^{+0.5}_{-0.4}) \times 10^{-3}$	
Γ_{272}	$\eta_c K^+ \pi^+ \pi^-$	$< 3.9 \times 10^{-4}$	CL=90%
Γ_{273}	$\eta_c K^+ \omega(782)$	$< 5.3 \times 10^{-4}$	CL=90%
Γ_{274}	$\eta_c K^+ \eta$	$< 2.2 \times 10^{-4}$	CL=90%
Γ_{275}	$\eta_c K^+ \pi^0$	$< 6.2 \times 10^{-5}$	CL=90%
Γ_{276}	$\eta_c(2S) K^+$	$(4.4 \pm 1.0) \times 10^{-4}$	
Γ_{277}	$\eta_c(2S) K^+,\ \eta_c \to p\overline{p}$	$(3.5 \pm 0.8) \times 10^{-8}$	
Γ_{278}	$\eta_c(2S) K^+,\ \eta_c \to K_S^0 K^\mp \pi^\pm$	$(3.4 \ {}^{+2.3}_{-1.6}) \times 10^{-6}$	
Γ_{279}	$\eta_c(2S) K^+,\ \eta_c \to p\overline{p}\pi^+\pi^-$	$(1.12 \pm 0.18) \times 10^{-6}$	
Γ_{280}	$h_c(1P) K^+,\ h_c \to J/\psi \pi^+ \pi^-$	$< 3.4 \times 10^{-6}$	CL=90%
Γ_{281}	$X(3730)^0 K^+,\ X^0 \to \eta_c \eta$	$< 4.6 \times 10^{-5}$	CL=90%

Experimental reconstruction of heavy flavor hadrons

- Open heavy flavor hadrons have many possible decay channels. Many have small branching fractions!

Example: some B+ decay modes from the PDG

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
	Semileptonic and leptonic modes			
Γ_1	$\ell^+ \nu_\ell X$	[a]	$(10.99 \pm 0.28)\ \%$	
Γ_2	$e^+ \nu_e X_c$		$(10.8 \pm 0.4)\ \%$	
Γ_3	$e^+ \nu_e X$		$(10.8 \pm 2.7)\ \%$	
Γ_4	$\mu^+ \nu_\mu X$		$(11.3 \pm 3.5)\ \%$	
Γ_5	$\ell^+ \nu_\ell X_u$	[a]	$(1.65 \pm 0.21) \times 10^{-3}$	
Γ_6	$D \ell^+ \nu_\ell X$	[a]	$(9.0 \pm 0.6)\ \%$	
Γ_7	$\overline{D}^0 \ell^+ \nu_\ell$	[a]	$(2.26 \pm 0.07)\ \%$	
Γ_8	$\tau^+ \nu_\tau X$		$(2.5 \pm 0.4)\ \%$	
Γ_9	$\overline{D}^0 \tau^+ \nu_\tau$		$(7.7 \pm 2.5) \times 10^{-3}$	
Γ_{10}	$\overline{D}^*(2007)^0 \ell^+ \nu_\ell$	[a]	$(5.26 \pm 0.10)\ \%$	
Γ_{11}	$\overline{D}^*(2007)^0 e^+ \nu_e$			
Γ_{12}	$\overline{D}^*(2007)^0 \mu^+ \nu_\mu$			
Γ_{13}	$\overline{D}^*(2007)^0 \tau^+ \nu_\tau$		$(1.88 \pm 0.20)\ \%$	
Γ_{14}	$D^{(*)} n\pi \ell^+ \nu_\ell (n \geq 1)$	[a]	$(1.74 \pm 0.23)\ \%$	
Γ_{15}	$D^- \pi^+ \ell^+ \nu_\ell$	[a]	$(3.82 \pm 0.20) \times 10^{-3}$	
Γ_{16}	$\overline{D}_2^*(2460)^0 \ell^+ \nu_\ell,\ \overline{D}_2^{*0} \to D^- \pi^+$	[a]	$(1.59 \pm 0.10) \times 10^{-3}$	
Γ_{17}	$\overline{D}_0^*(2420)^0 \ell^+ \nu_\ell,\ \overline{D}_0^{*0} \to D^- \pi^+$	[a]	$(9 \pm 5) \times 10^{-4}$	S=2.6
Γ_{18}	$D^{*-} \pi^+ \ell^+ \nu_\ell$	[a]	$(5.42 \pm 0.28) \times 10^{-3}$	
Γ_{19}	$\overline{D}_1(2420)^0 \ell^+ \nu_\ell,\ \overline{D}_1^0 \to D^{*-} \pi^+$	[a]	$(2.84 \pm 0.17) \times 10^{-3}$	S=1.1
Γ_{20}	$\overline{D}_1'(2430)^0 \ell^+ \nu_\ell,\ \overline{D}_1'^0 \to D^{*-} \pi^+$	[a]	$(1.7 \pm 0.6) \times 10^{-3}$	S=1.8

Γ_{57} Γ_{58} Γ_{59} Γ_{60} Γ_{61} Γ_{62} Γ_{63} Γ_{64} Γ_{65} Γ_{66} … =2.1 … 90% … 90%

"Exclusive" reconstruction: measure every particle in the decay to fully reconstruct the heavy flavor hadron

Examples:

$$D^0 \to K^- \pi^+, B^+ \to J/\psi K^+$$

Charmonium modes

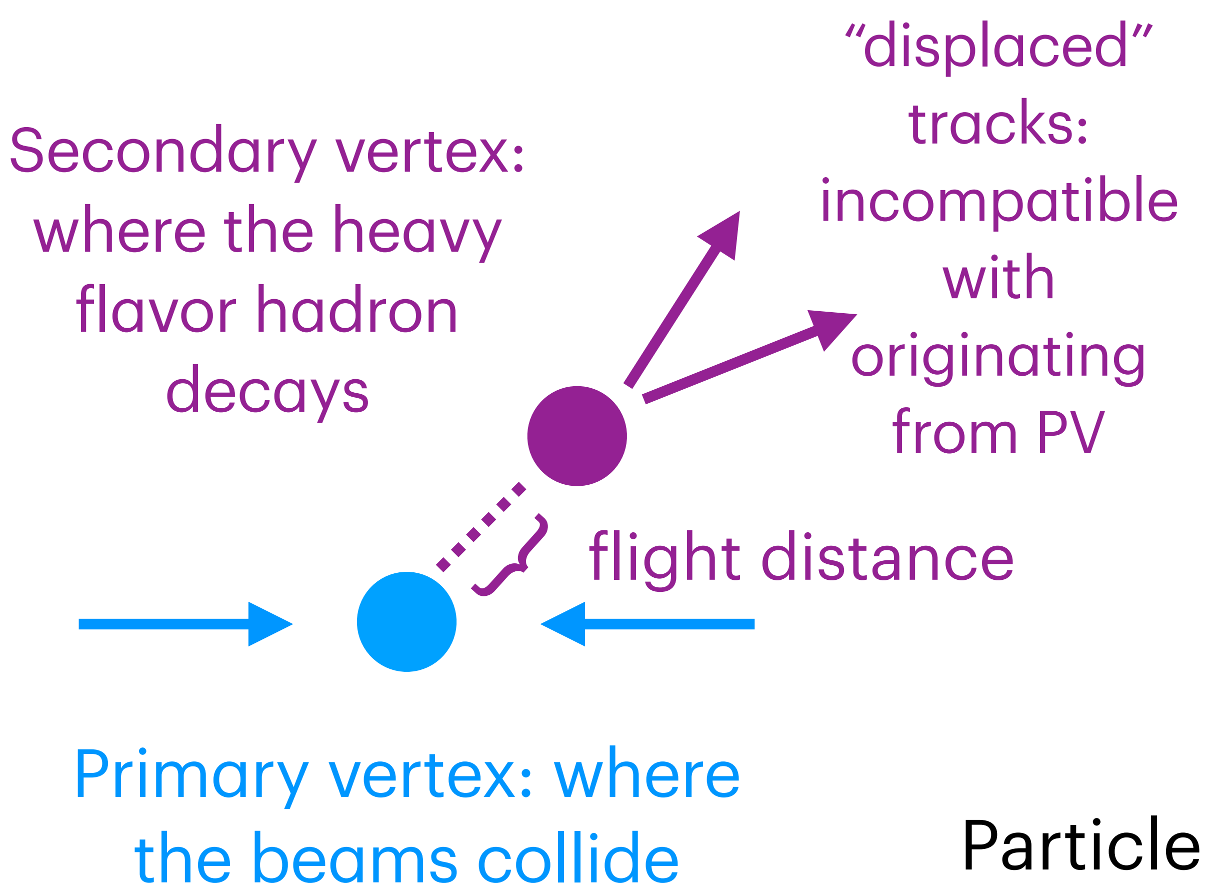
Γ_{270} Γ_{271} Γ_{272} Γ_{273} Γ_{274} Γ_{275} Γ_{276} Γ_{277} Γ_{278} Γ_{279} Γ_{280} Γ_{281} … 1.1 … 0% … 0% … 0% … 0% … 0% … 0%

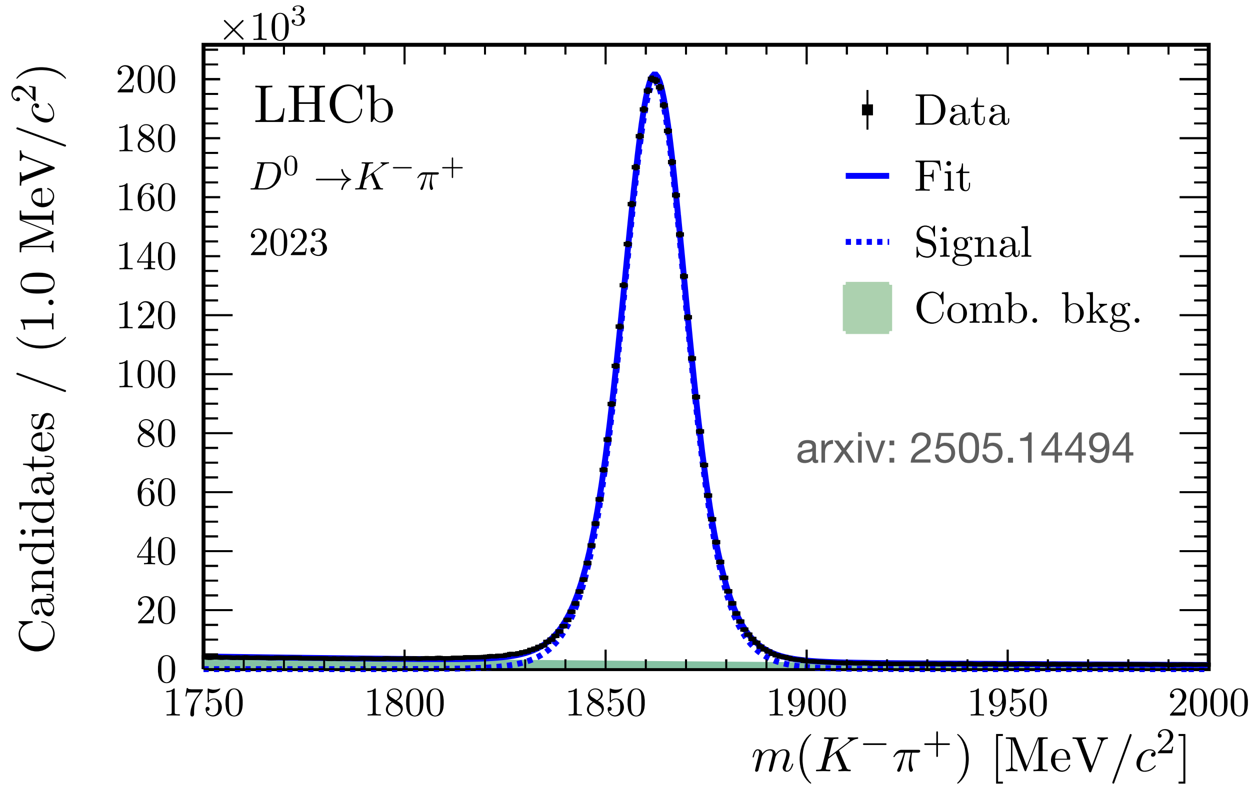
"Inclusive" reconstruction: measure part of the decay but not all of it

Examples: $B \to D^0 X$

Experimental reconstruction of heavy flavor hadrons

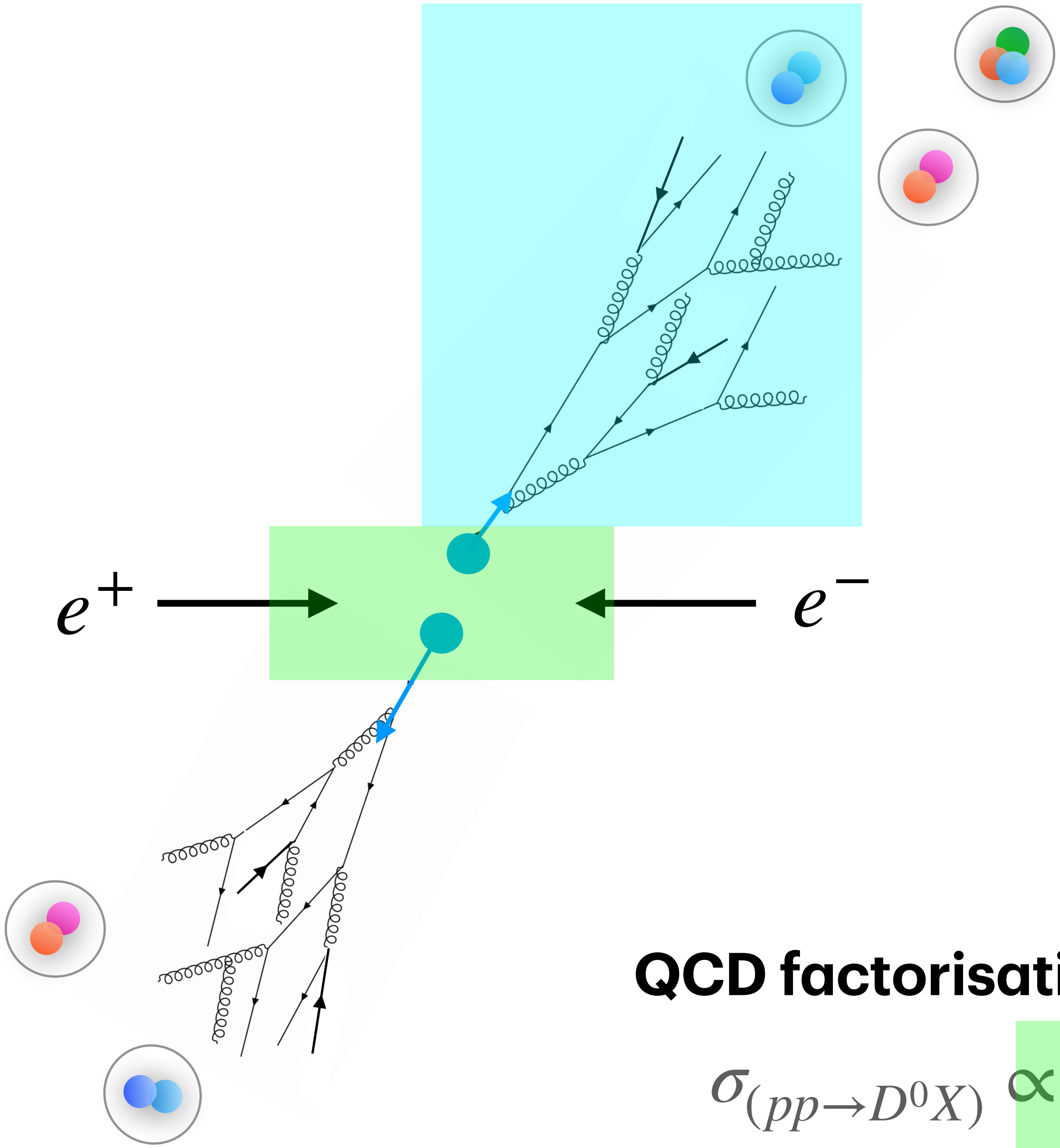
- Open heavy flavor hadrons have many possible decay channels. Many have small branching fractions!
- For good heavy flavor reconstruction, it's critical to have **precision tracking capabilities** to reconstruct heavy flavor decay vertices





Particle identification detectors also help discriminate between pions, kaons, and protons which helps reduce combinatorial background

Heavy quark production in e^+e^- collisions



- We can't measure heavy quarks directly, because of confinement in QCD which forces quarks to be bound within hadrons
- We *can* measure heavy flavor hadrons, which can be used as proxies for heavy flavor quarks

QCD factorisation for e^+e^- collisions:

$$\sigma_{(pp\to D^0X)} \propto \sigma_{e^+e^-\to c\bar{c}} \otimes D_c^{D^0}(z)$$

hard scattering cross section

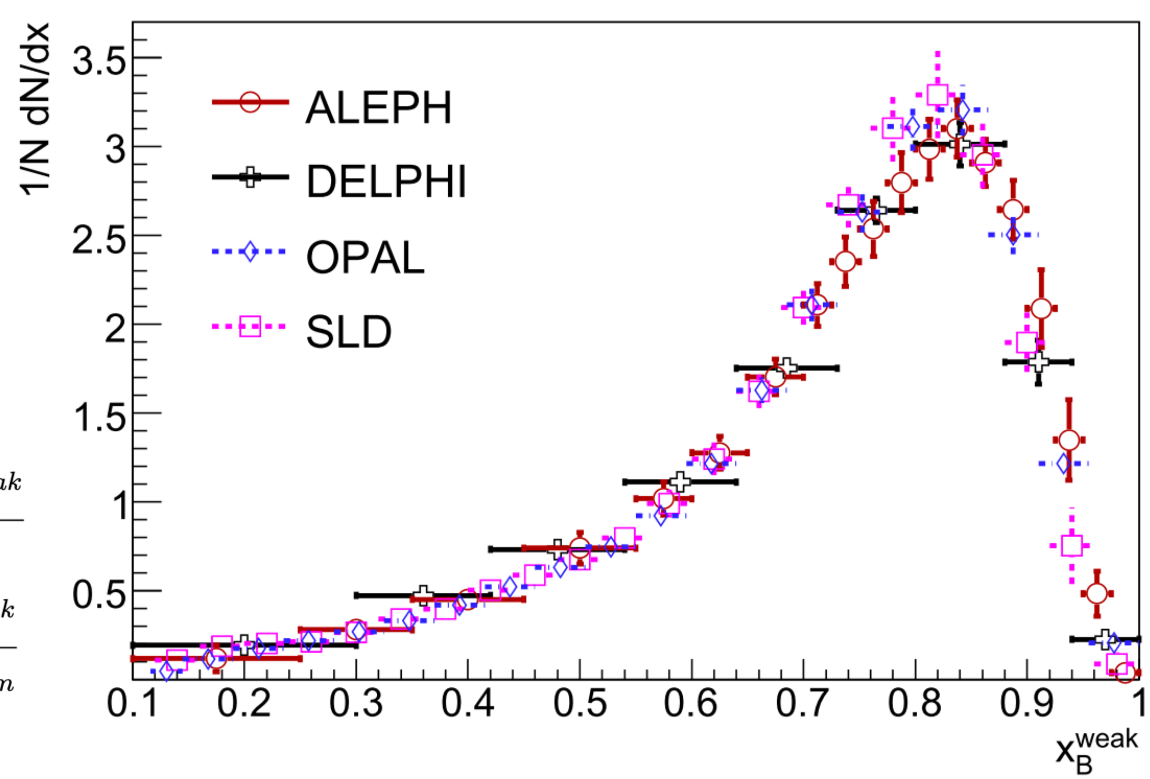
Fragmentation Function

Heavy flavor fragmentation functions

- Fragmentation functions of heavy flavor hadrons were directly measured at e^+e^- colliders

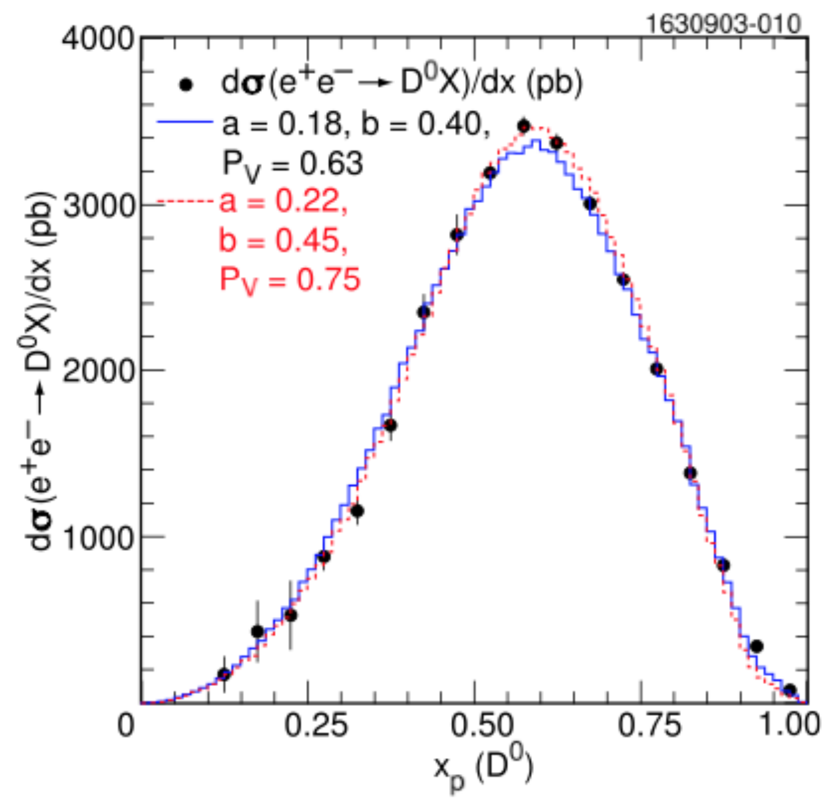
Inclusive collinear b->B FF measurement in e^+e^- collisions

$$x_B^{weak} = \frac{2E_B^{weak}}{\sqrt{s}} = \frac{E_B^{weak}}{E_{beam}}$$



B hadron takes around ~80% of the momentum of the initial b quark

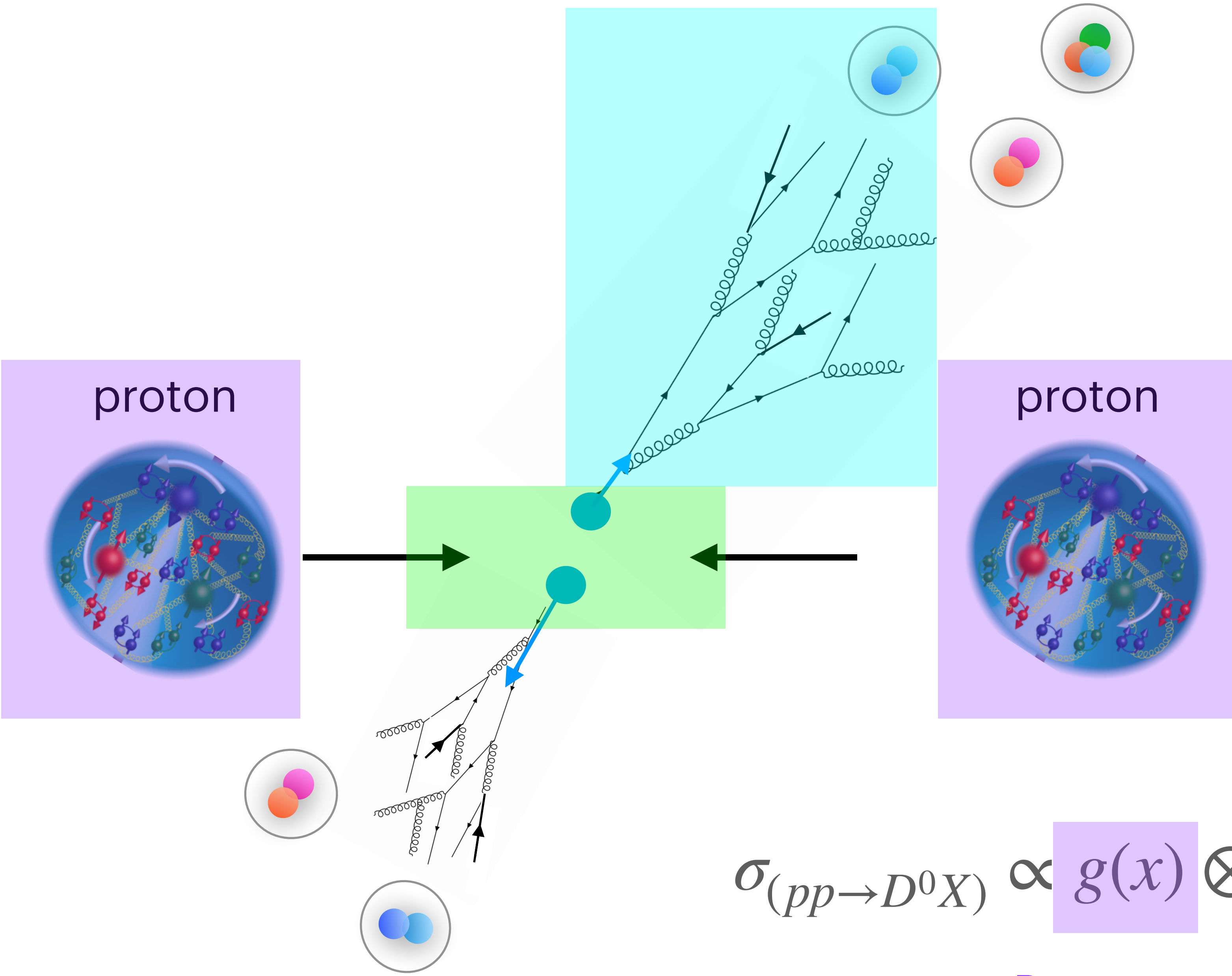
Inclusive collinear c->D⁰ FF measurement in e^+e^- collisions



Charm hadron takes around 50-60% of the momentum of the initial c quark

PRD **70**, 112001 (2004)
EPJC **71**, 1557 (2011)

Heavy quark production in *pp* collisions



- Initial state is more complex
- What can we learn here that we can't study in e^+e^- collisions?

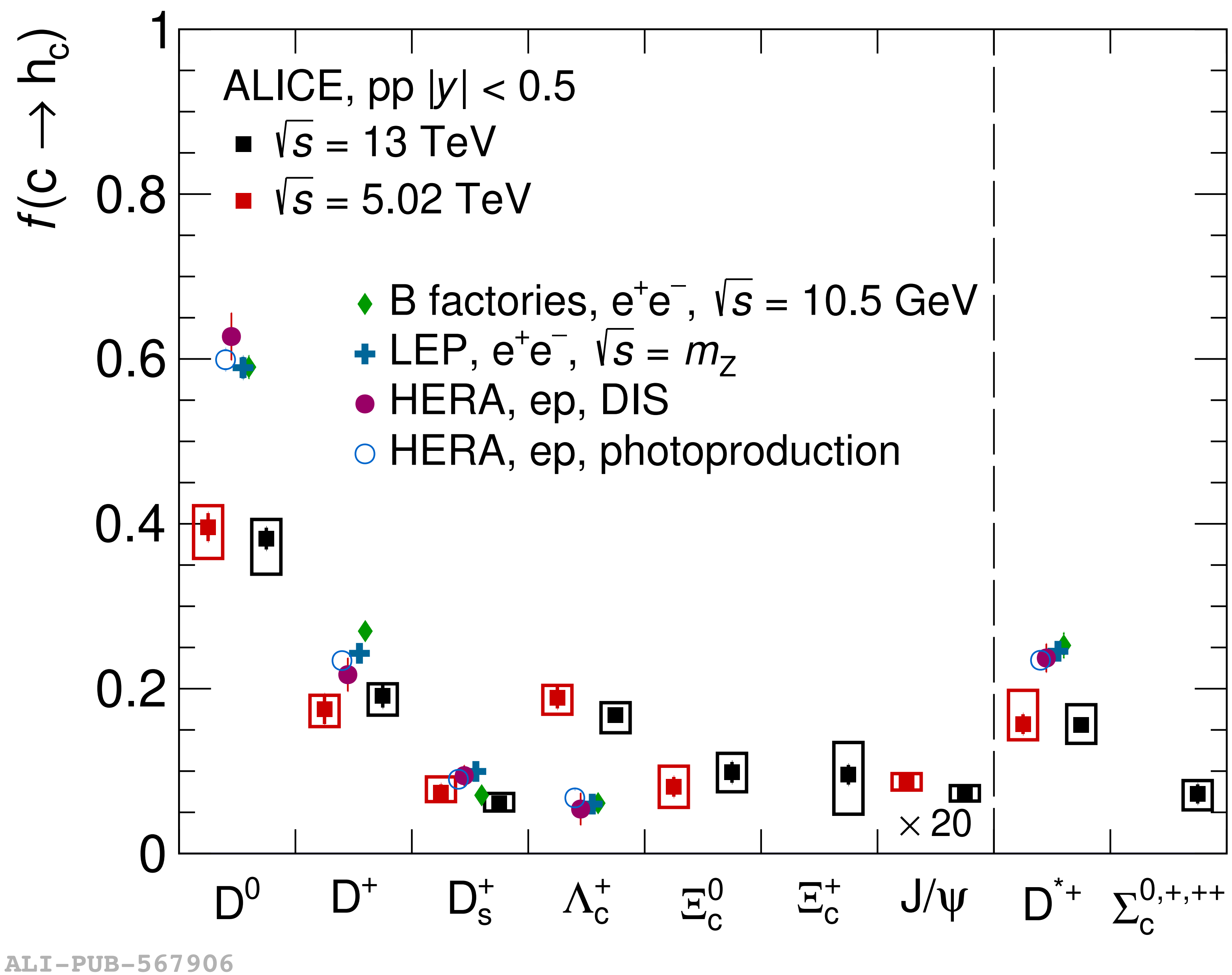
Fragmentation Function

$$\sigma_{(pp\to D^0 X)} \propto g(x) \otimes g(x) \otimes \sigma_{gg\to c\bar{c}} \otimes D_c^{D^0}(z)$$

Parton Distribution Functions

hard scattering cross section

(non-) Universality ?

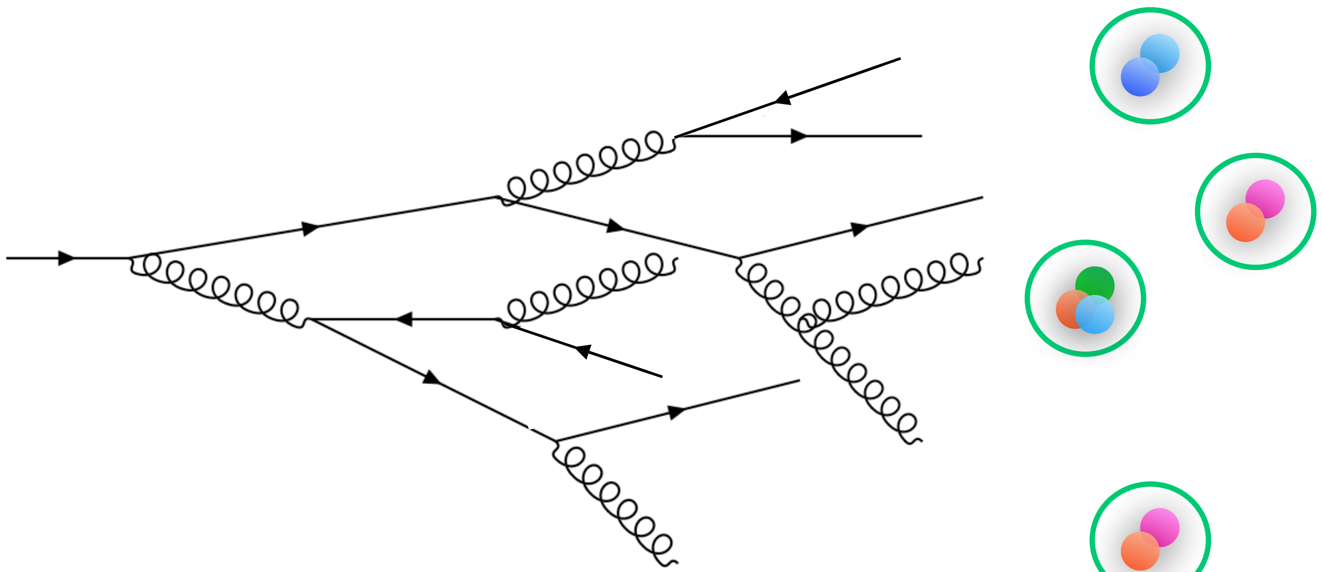


JHEP **12** (2023) 086

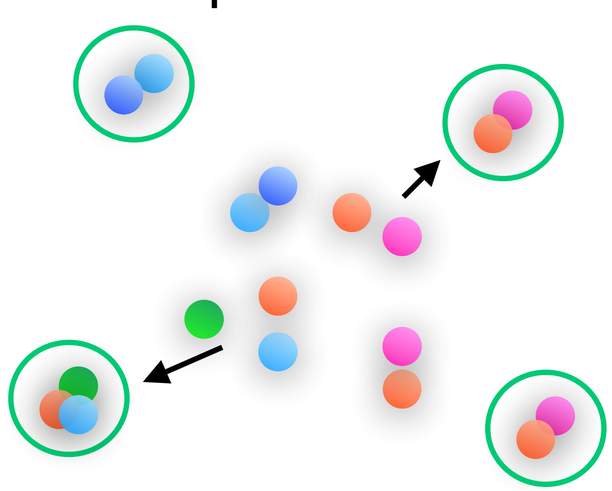
What might cause different fractions of certain charm hadrons in *pp* collisions vs. e^+e^-/ep?

Fragmentation vs. coalescence

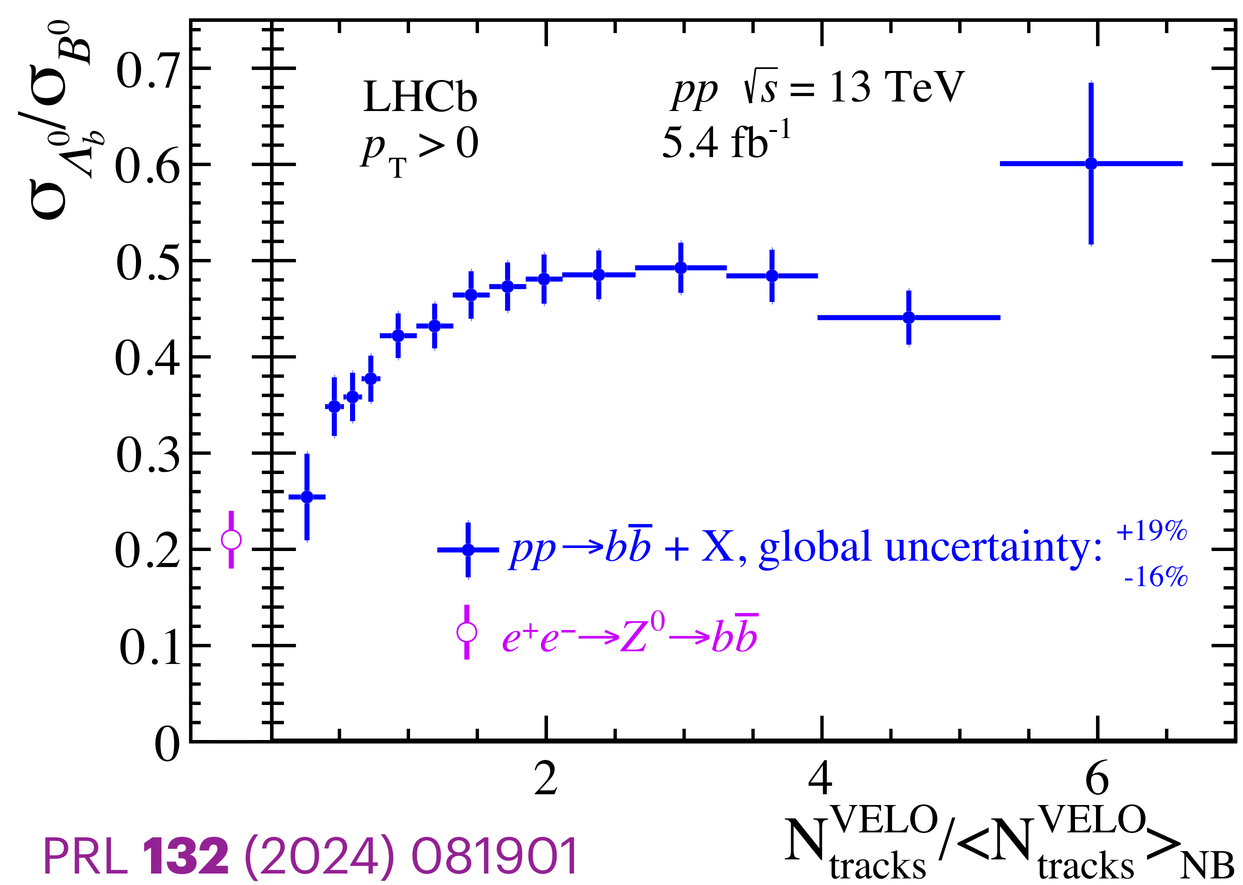
Fragmentation: high-energy parton shower and subsequent hadronization



Coalescence: typically associated with low-energy partons that are close together in phase space and hadronize



Multiplicity-dependent measurements of hadron production probe fragmentation vs. coalescence mechanisms

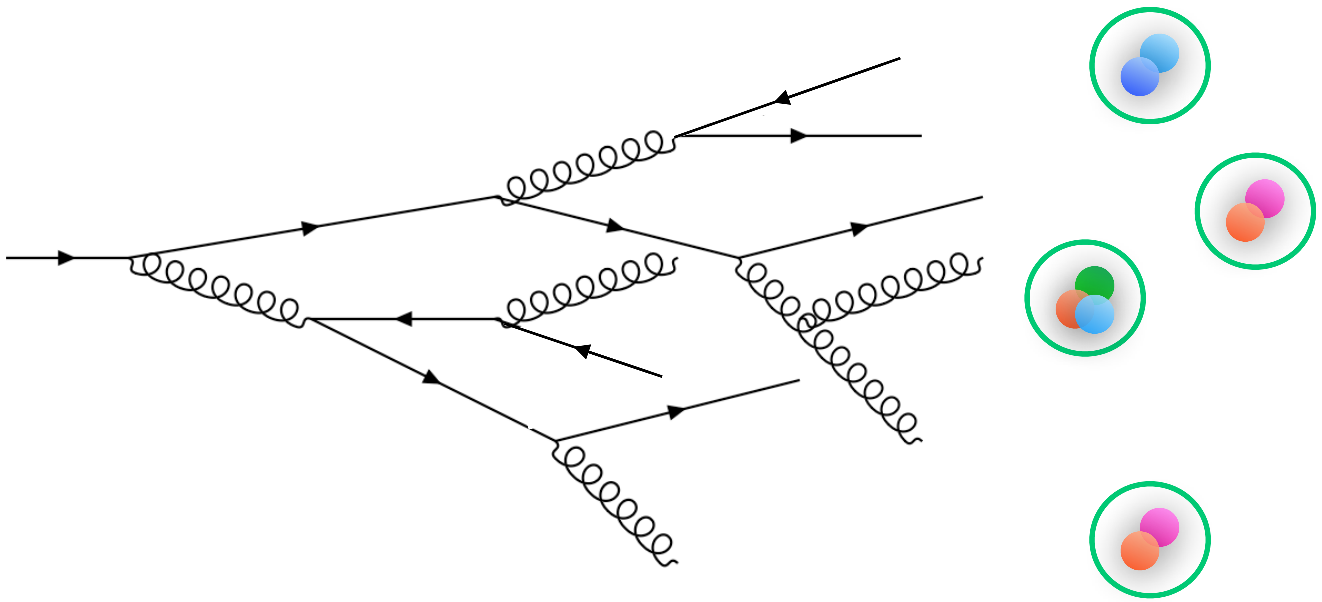


PRL **132** (2024) 081901

Increasing # of particles measured in the event (increasing multiplicity)

Fragmentation vs. coalescence

Fragmentation: high-energy parton shower and subsequent hadronization



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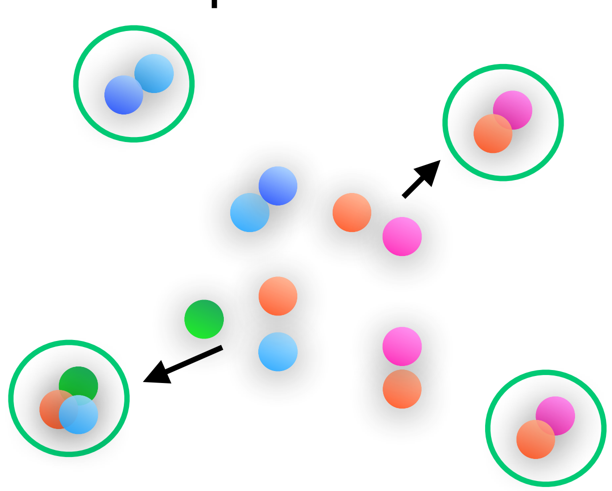

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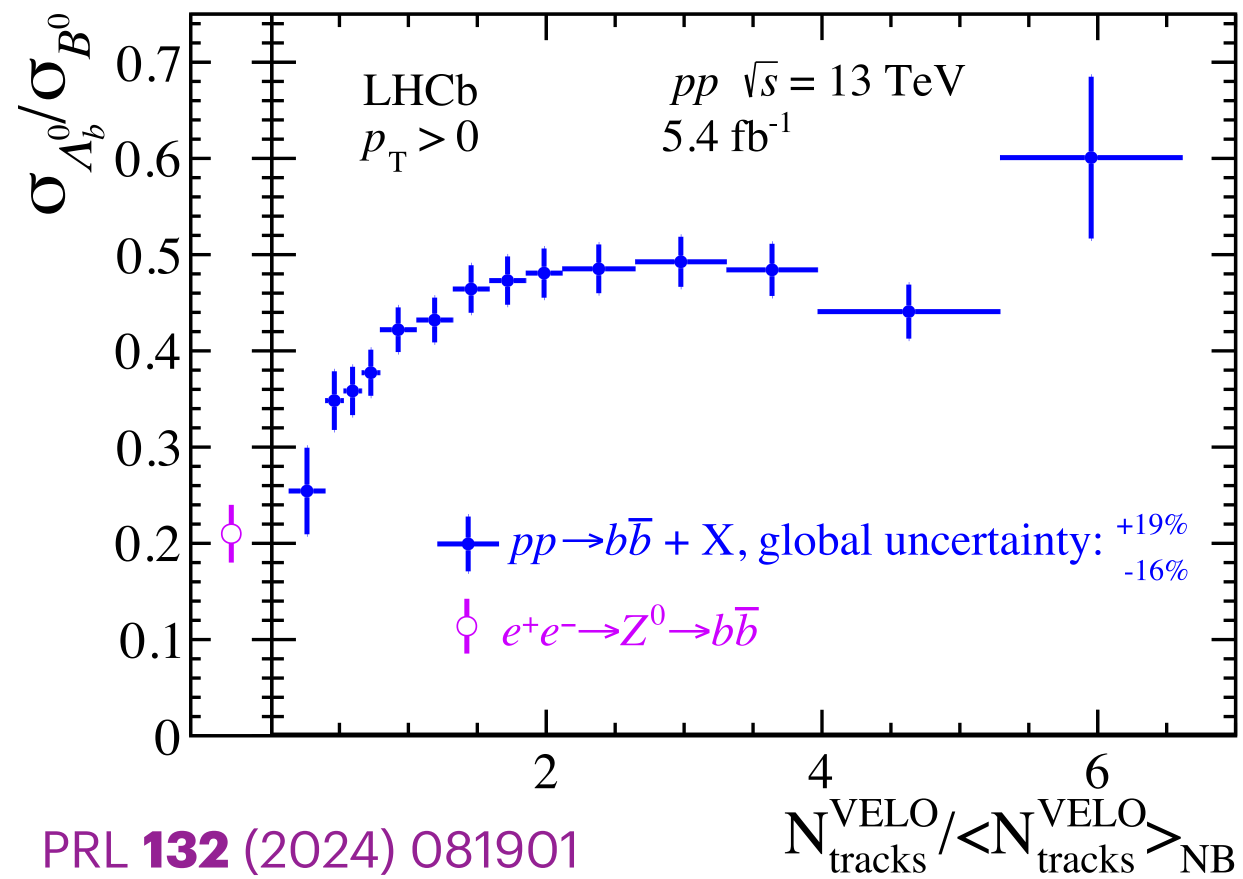


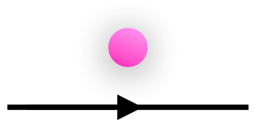
PRL **132** (2024) 081901

In high multiplicity *pp* collisions, we see more Λ_b^0 produced!

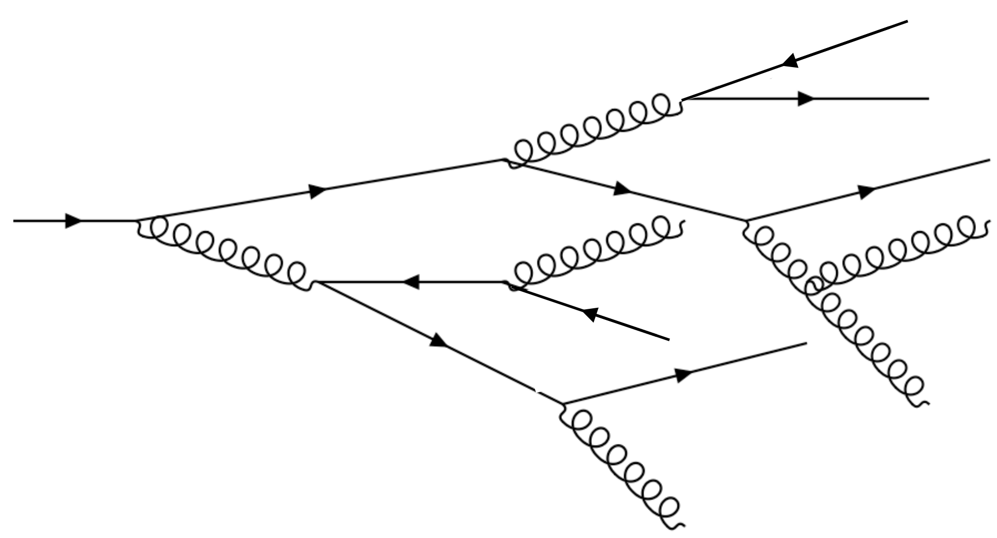
What is a jet?

- A jet is a *proxy* for a single parton (quark or gluon)
- Formed when a high-energy parton undergoes fragmentation and hadronization, forming a correlated "spray" of particles in the detector
- Identified with **jet reconstruction algorithms** that cluster particles consistent with originating from the hadronization of a single high-energy parton

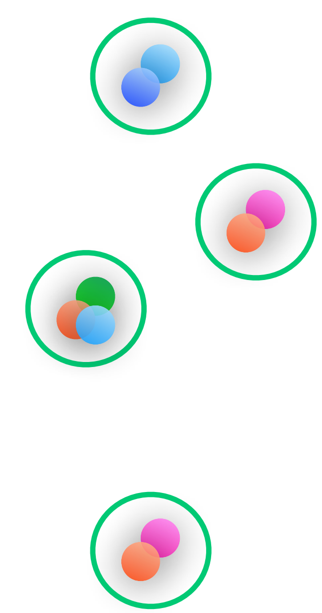
Initial quark
(or gluon)



Fragmentation:
high energy parton shower



Hadronization



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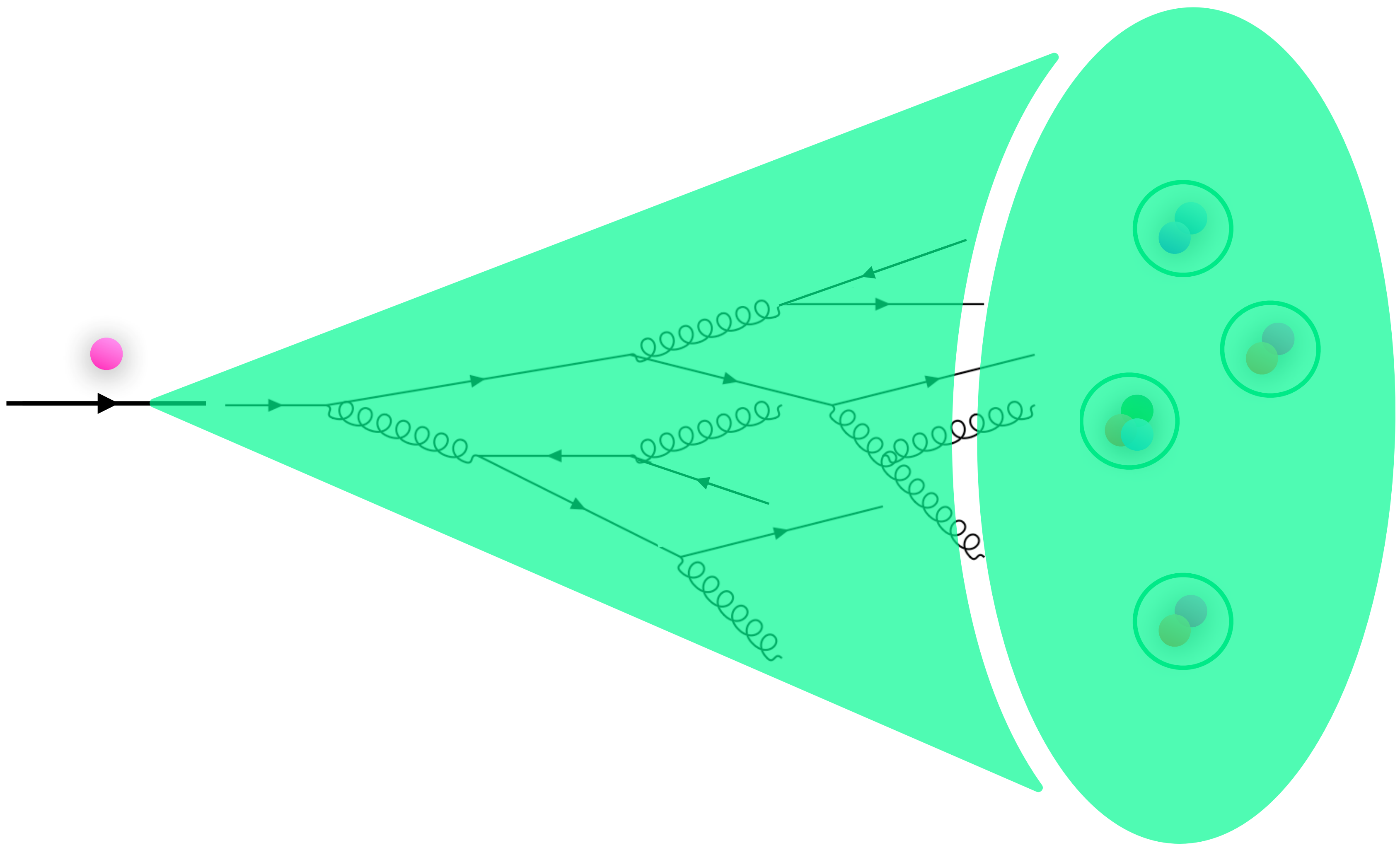
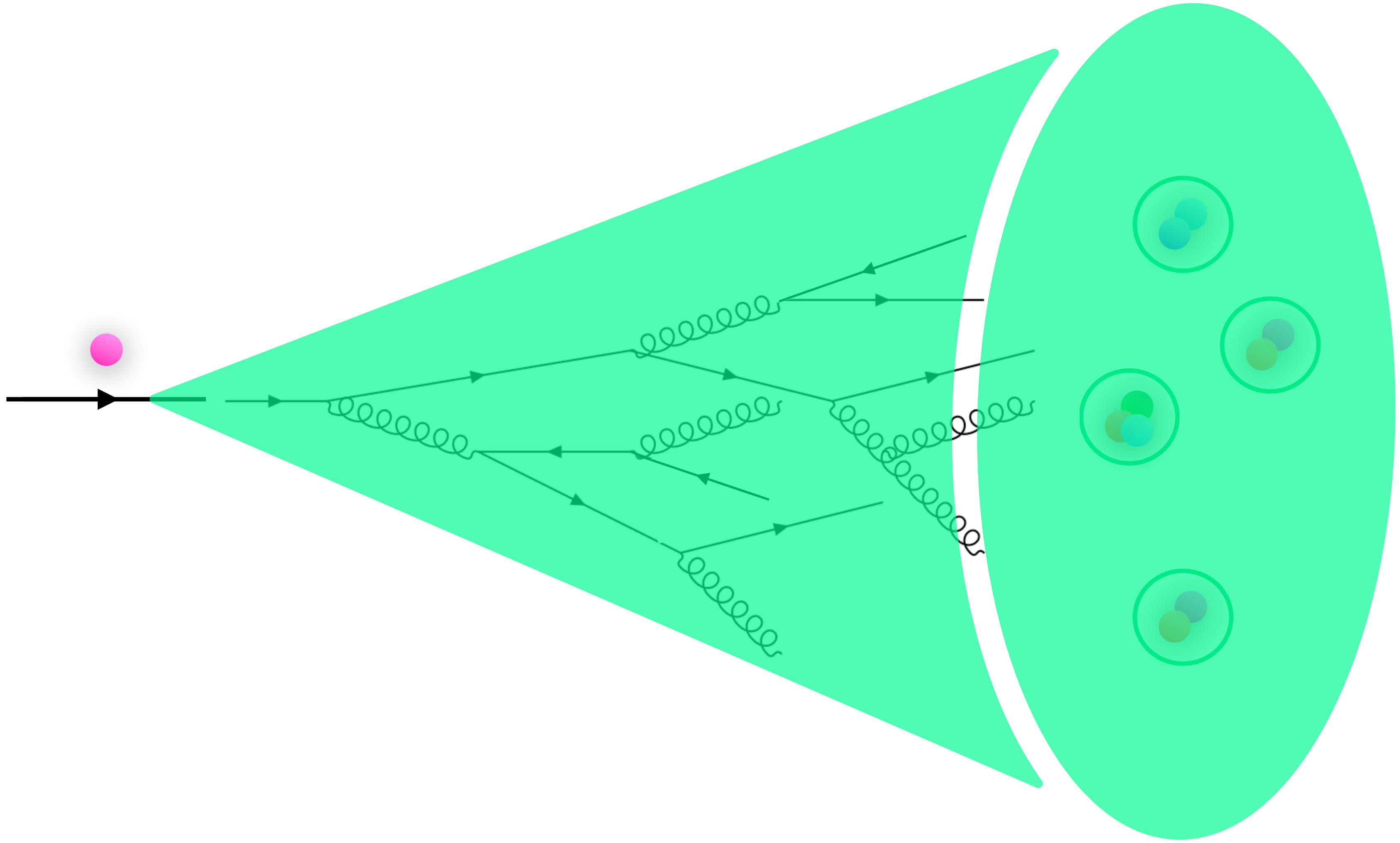


A jet **correlates** hadrons to the original quark or gluon they originated from!

Why are jets useful?

- Jets provide the closest experimental access we can get to parton-level kinematics
- **Parton-level kinematics** -> provide access to timescales before hadronization, inaccessible with many other probes
- They provide **excellent, precision tests of perturbative QCD**



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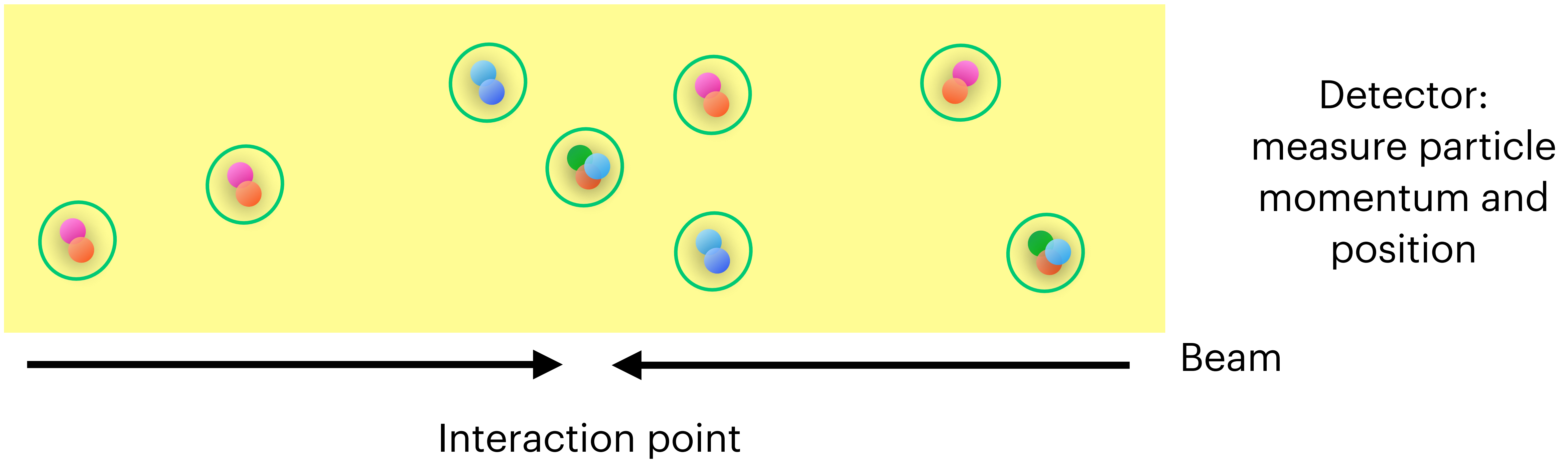
How do we reconstruct jets?

- Basic idea: determine which particles are correlated to each other, and which are not
- Given a bunch of hadrons measured in a detector, how might I determine if they are correlated or not?

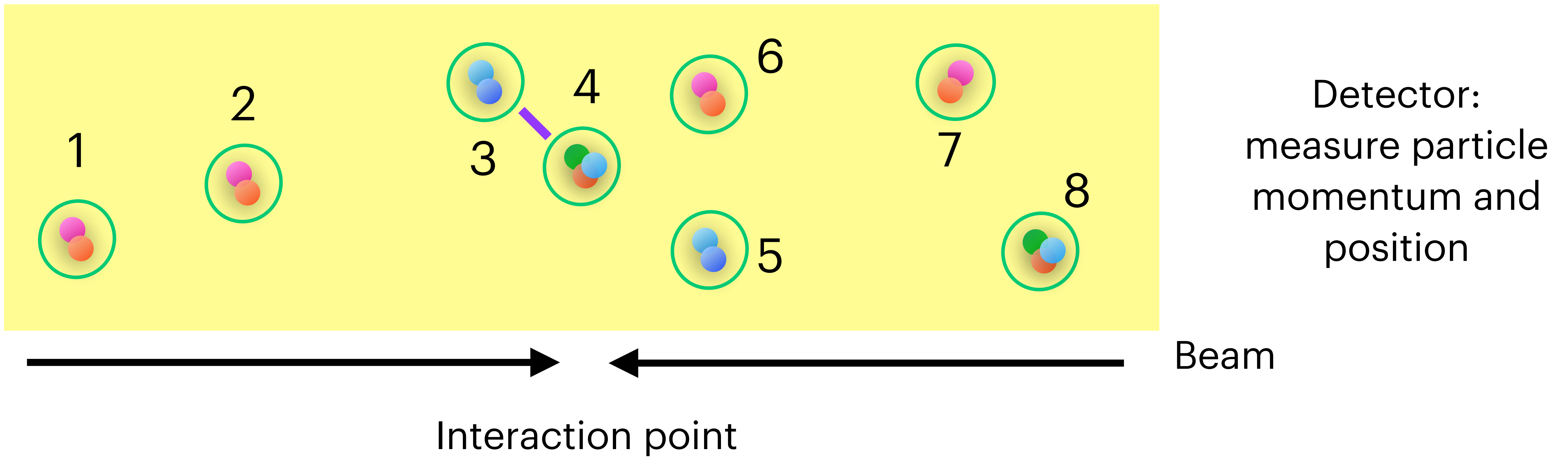


Let's build a jet

- Idea #1: Let's group particles based on how close they are to each other
- Compute the distance between all possible pairs of particles:

$$\Delta_{ij} = \sqrt{(y_i - y_j)^2 + (\phi_i - \phi_j)^2}$$

- Pick your desired jet radius R. Let's choose R = 0.5
- Find the smallest Δ_{ij}. If $\Delta_{ij} < R$, the particles i and j are "combined"



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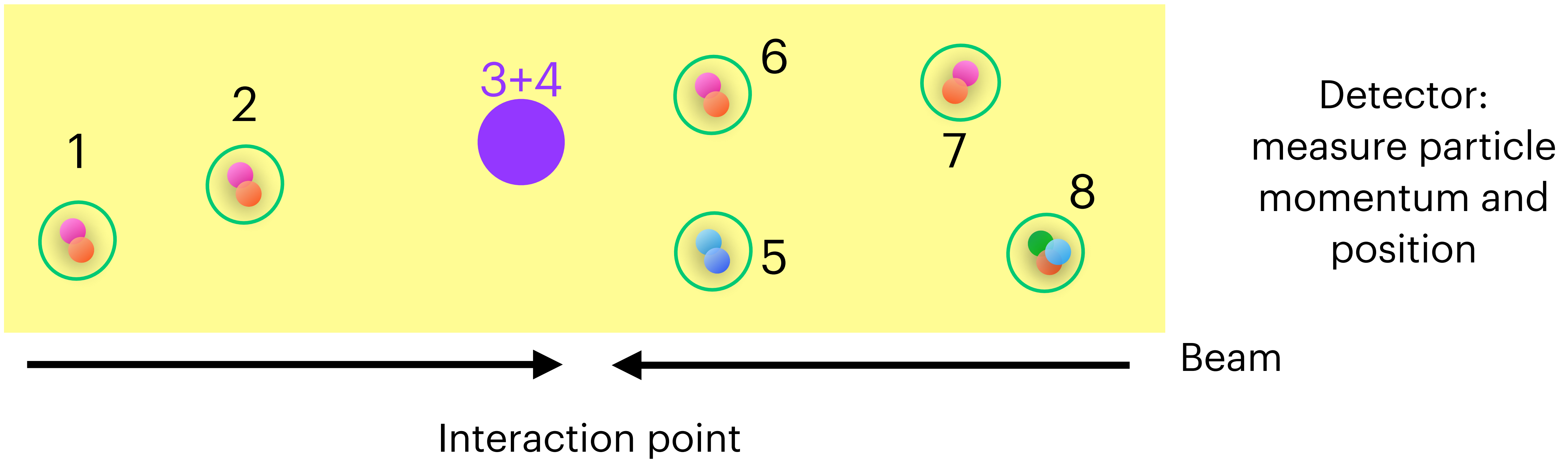

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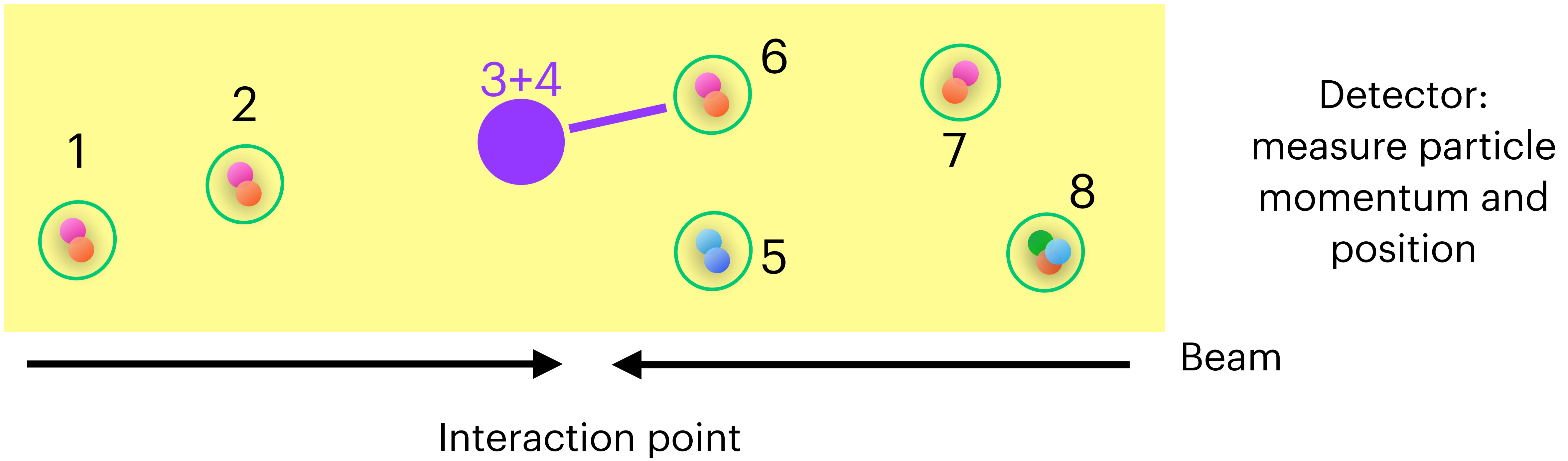

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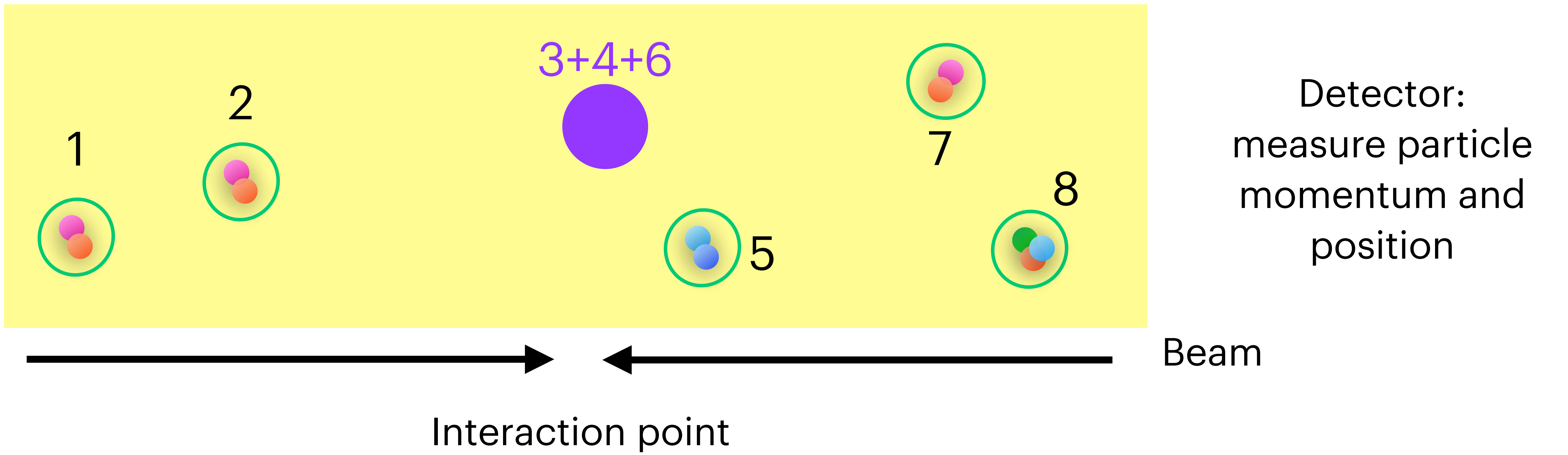

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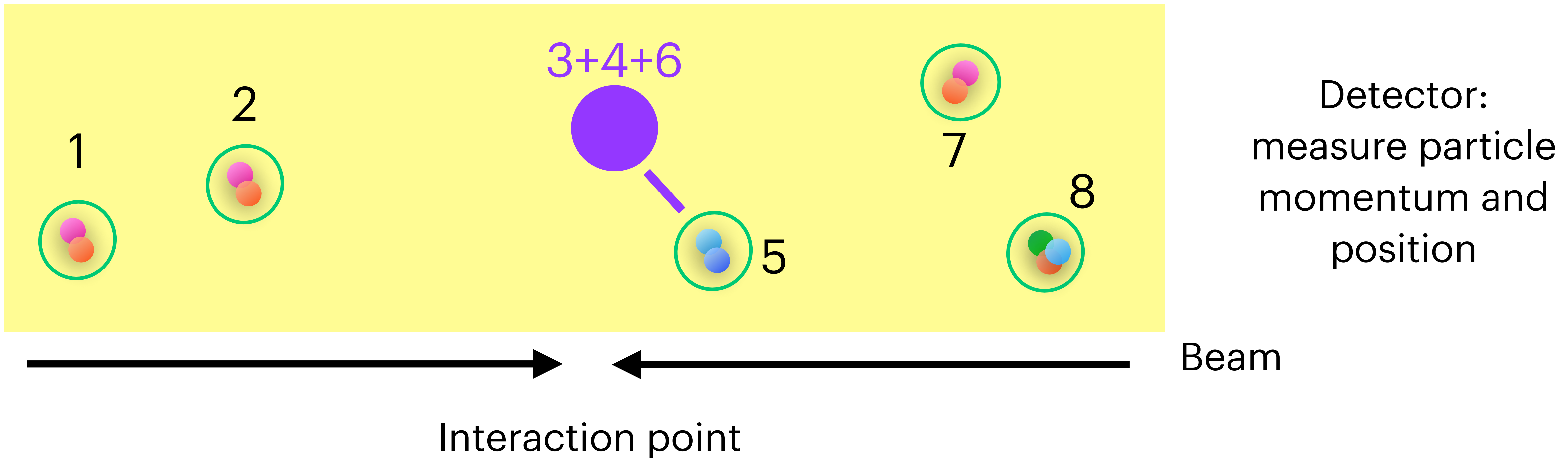
- And again



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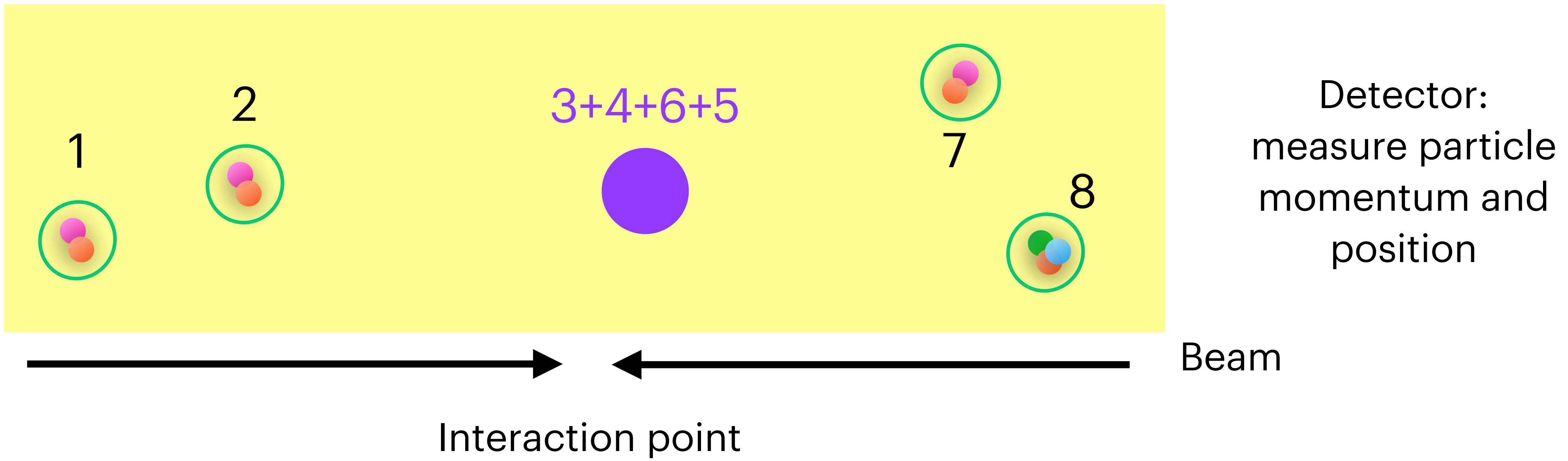
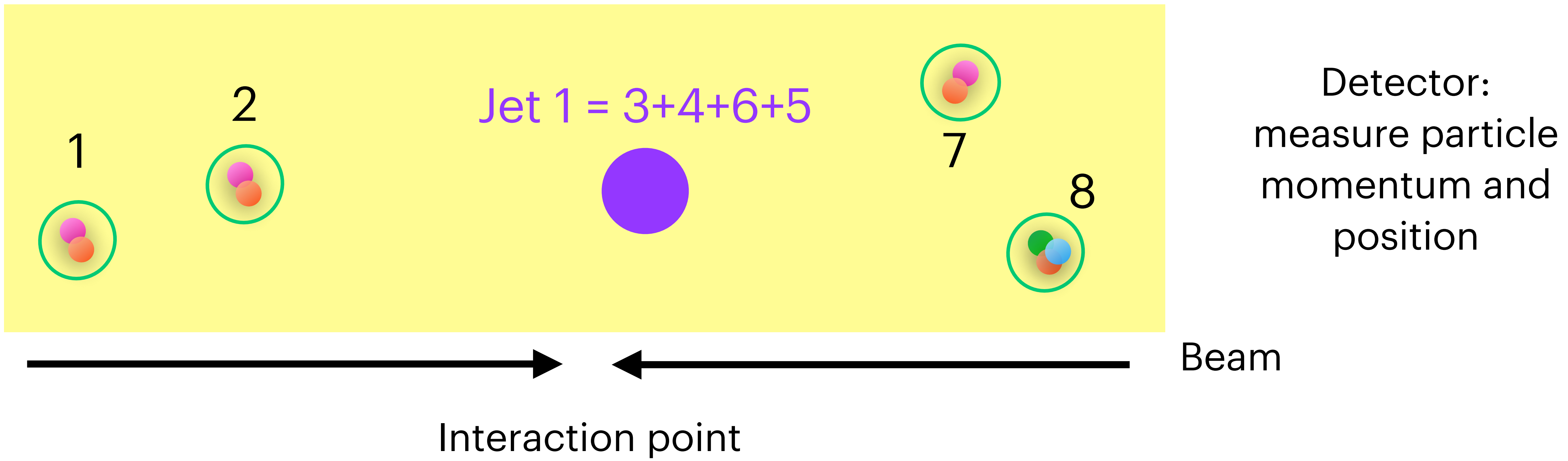


Let's build a jet

- Idea #1: Let's group particles based on how close they are to each other
- Now all possible Δ_{ij} are larger than my chosen jet radius, R = 0.5!

$$\Delta_{ij} = \sqrt{(y_i - y_j)^2 + (\phi_i - \phi_j)^2}$$

- So now I can't add any more particles to this jet



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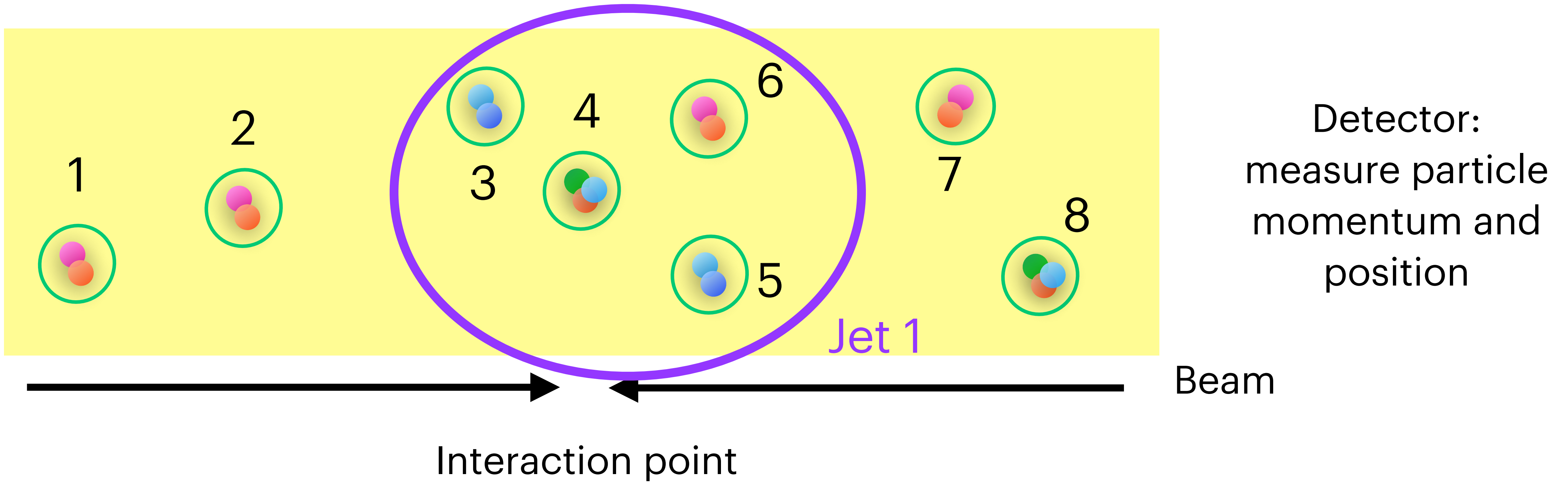
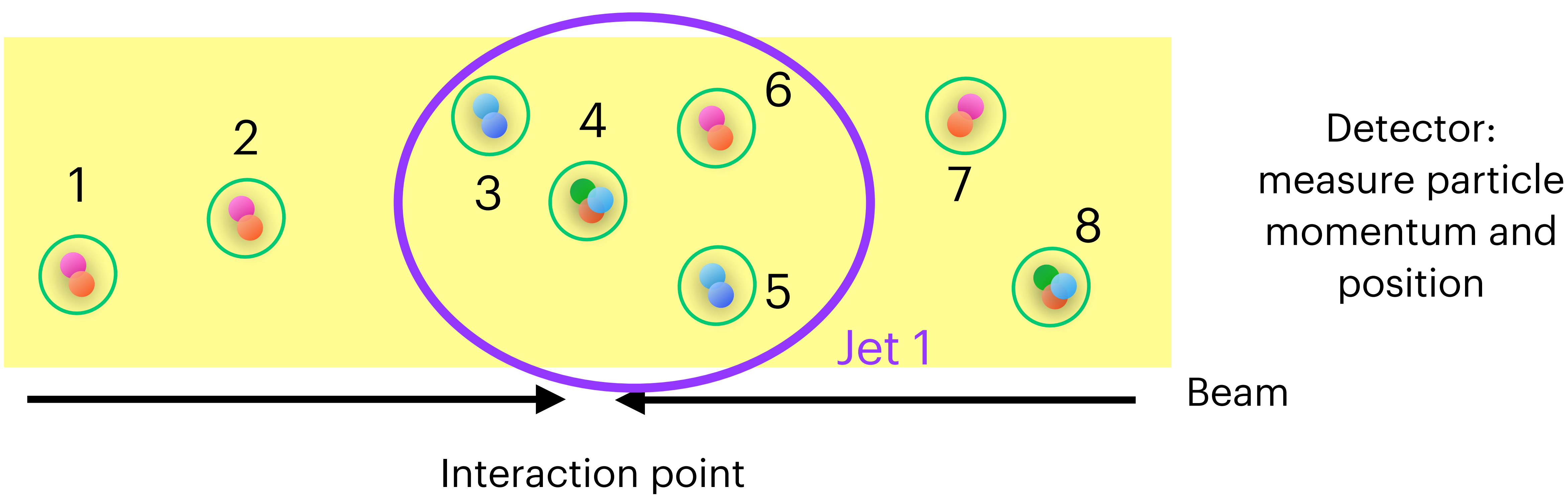
- So now I can't add any more particles to this jet
- What we have just done is known as **Cambridge-Aachen sequential clustering.** It is known for preserving angular ordering of the parton shower



Let's build a jet

- You might be thinking: "won't I end up with a lot of jets if I follow this procedure?"
- The answer is: yes! This is why we always have to define a minimum jet p_T requirement, which determines what we consider a "hard" object
- In hadronic collisions this is usually not less than 5 GeV/c, and often quite a bit higher. Between 10-20 GeV/c is common for a minimum jet p_T



Let's build another jet

- Idea #2: Let's group particles based on how close they are to each other AND taking into account their transverse momentum
- Compute the distance between all possible pairs of particles:

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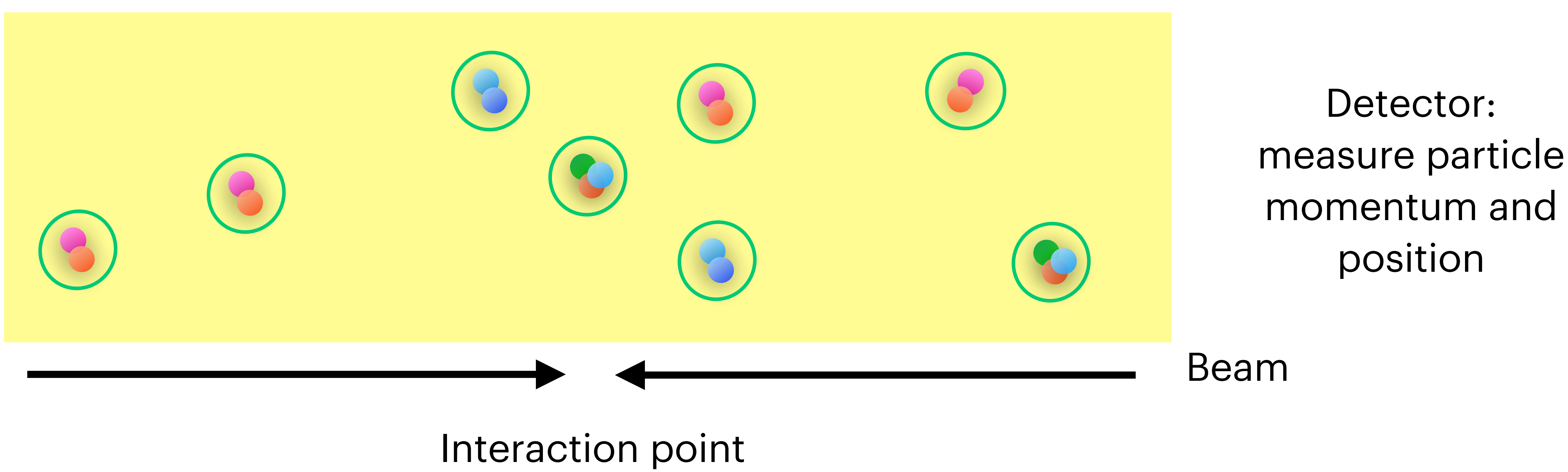
- Pick your desired jet radius R. Let's choose R = 0.5



Let's build another jet

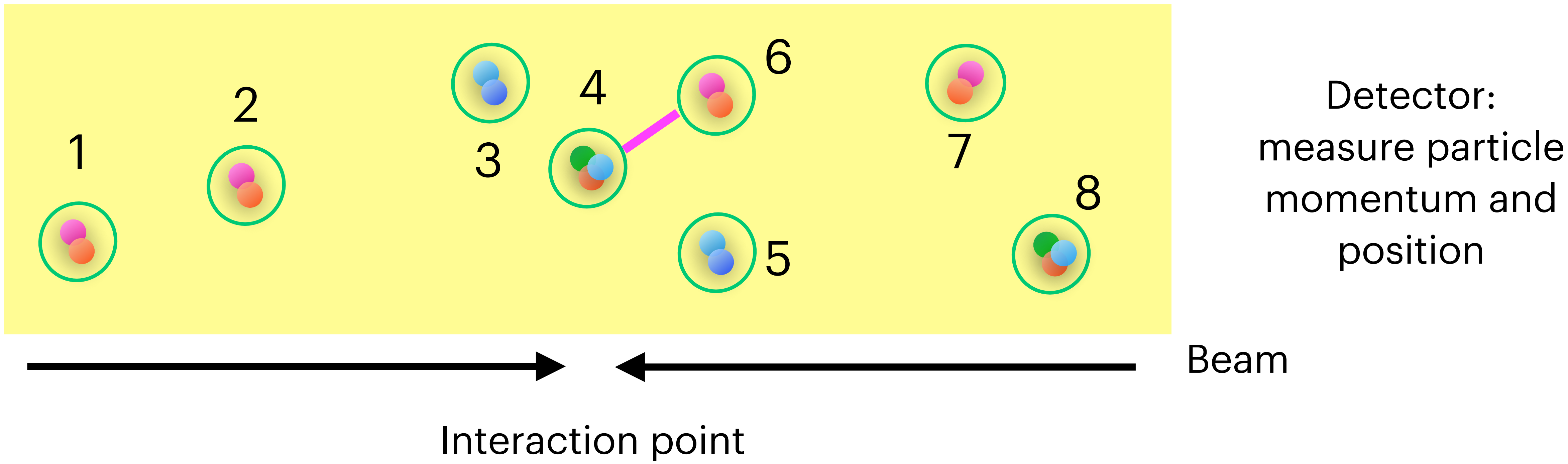
- Idea #2: Let's group particles based on how close they are to each other AND taking into account their transverse momentum

- Let's now weight Δ_{ij} by the transverse momentum of the heavier particle:

$$d_{ij} = \min(k_{ti}^{-2}, k_{tj}^{-2})\frac{\Delta_{ij}^2}{R^2}$$

k_{ti} = transverse momentum of particle i

- And we will compare this weighted metric d_{ij} to another metric, $d_{iB} = k_{ti}^{-2}$
- In this case, the clustering order can differ from what we had with Cambridge-Aachen!



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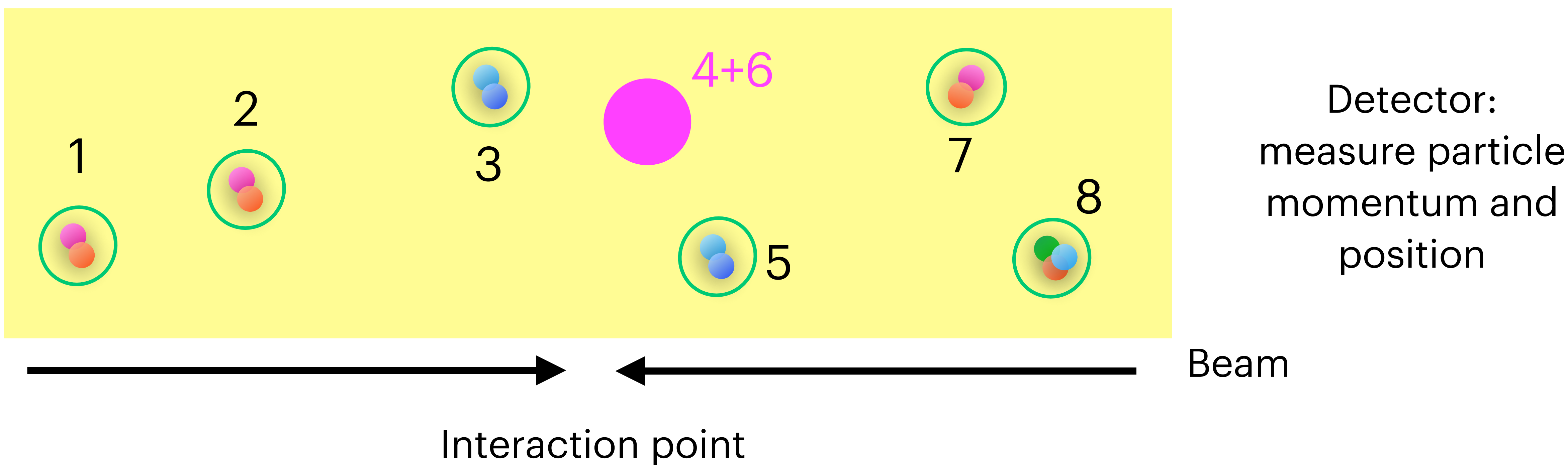

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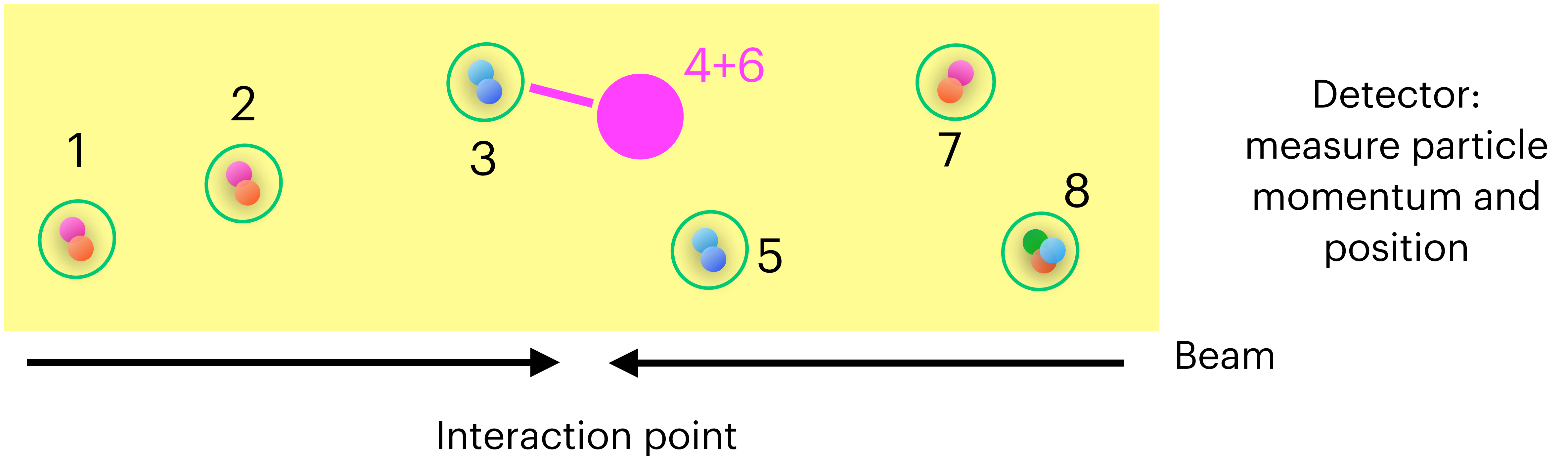

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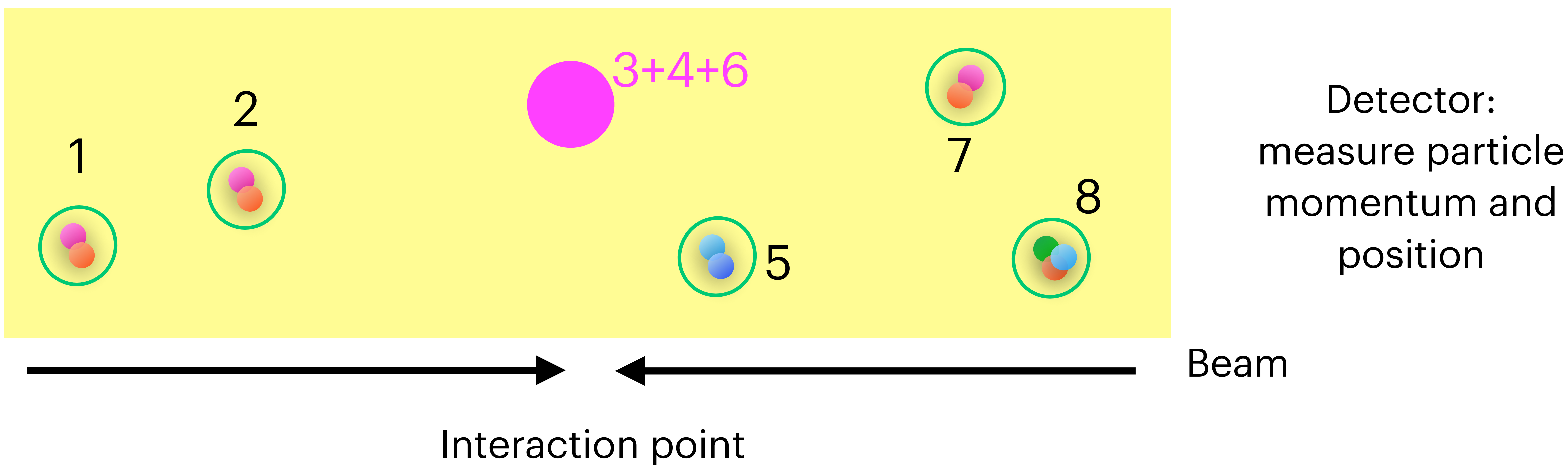

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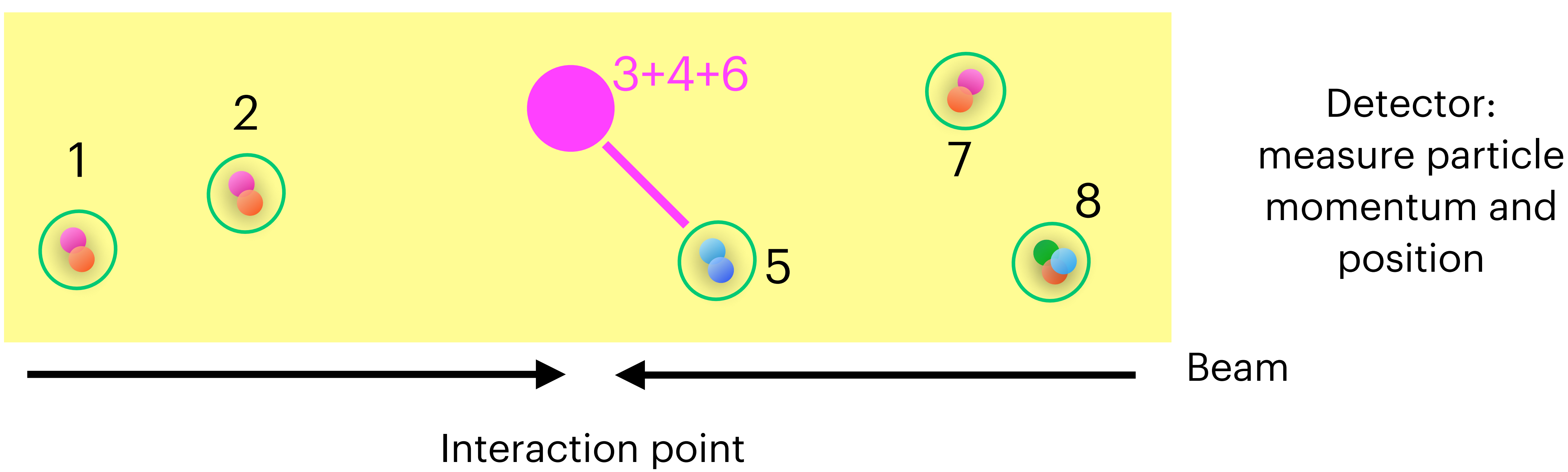
k_{ti} = transverse momentum of particle i

- And we will compare this weighted metric d_{ij} to another metric, $d_{iB} = k_{ti}^{-2}$
- Let's say particle 3 has a much larger transverse momentum than particle 5



Let's build another jet

- Idea #2: Let's group particles based on how close they are to each other AND taking into account their transverse momentum

- Let's now weight Δ_{ij} by the transverse momentum of the heavier particle:

$$d_{ij} = \min(k_{ti}^{-2}, k_{tj}^{-2})\frac{\Delta_{ij}^2}{R^2}$$

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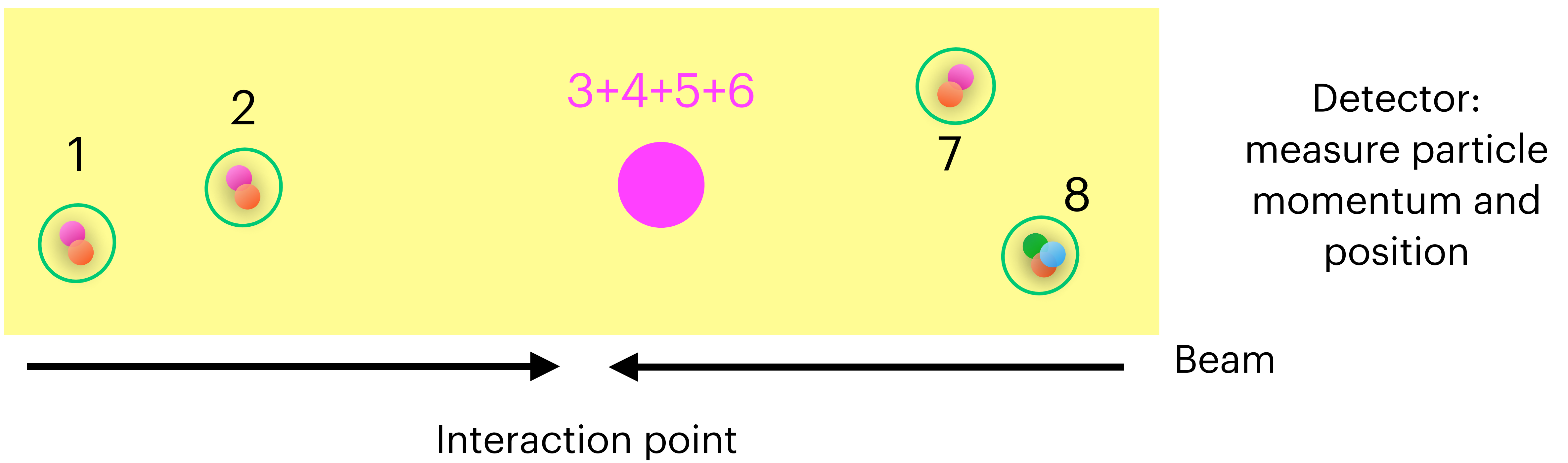

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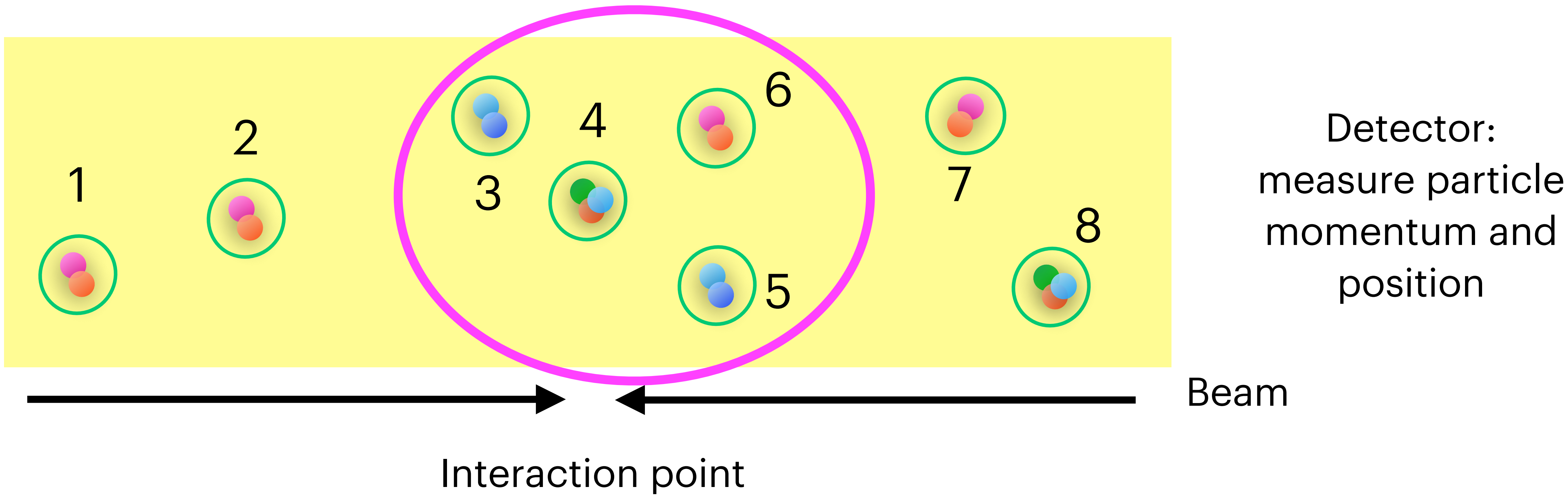
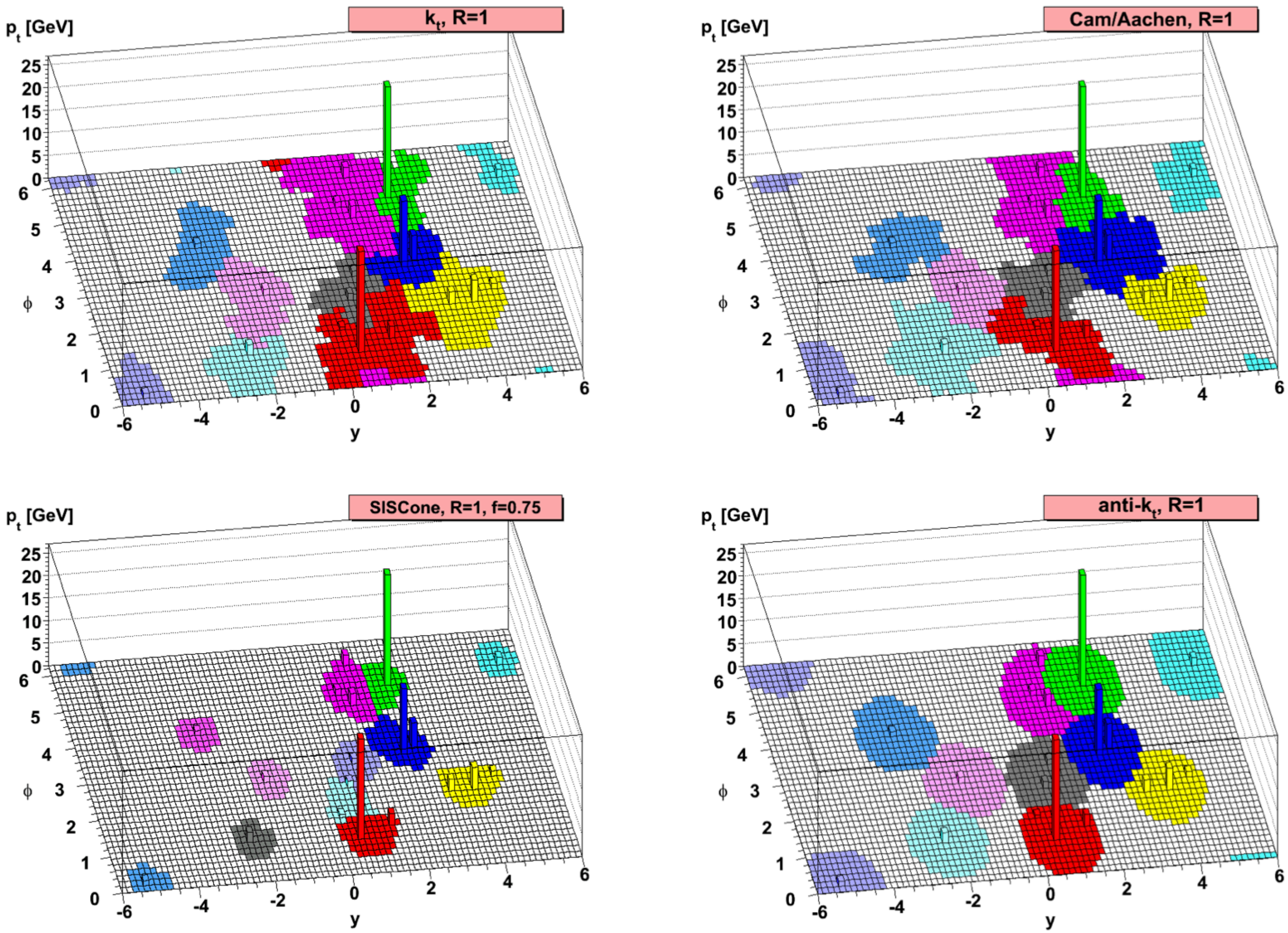
- What we have done this time is known as the anti-k_T clustering algorithm



Why is the anti-k_T algorithm preferred?



Nice, conical jets: regular jet boundary

Infrared and collinear safe jet definition

Original anti-kt paper: JHEP **04** (2008) 063

Summary: How do we reconstruct jets?

- Compute two distance metrics:

between all possible pairs of particles:

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p})\frac{\Delta_{ij}^2}{R^2}$$

between each particle and the beam:

$$d_{iB} = k_{ti}^{2p}$$

p = -1 anti-k_T algorithm

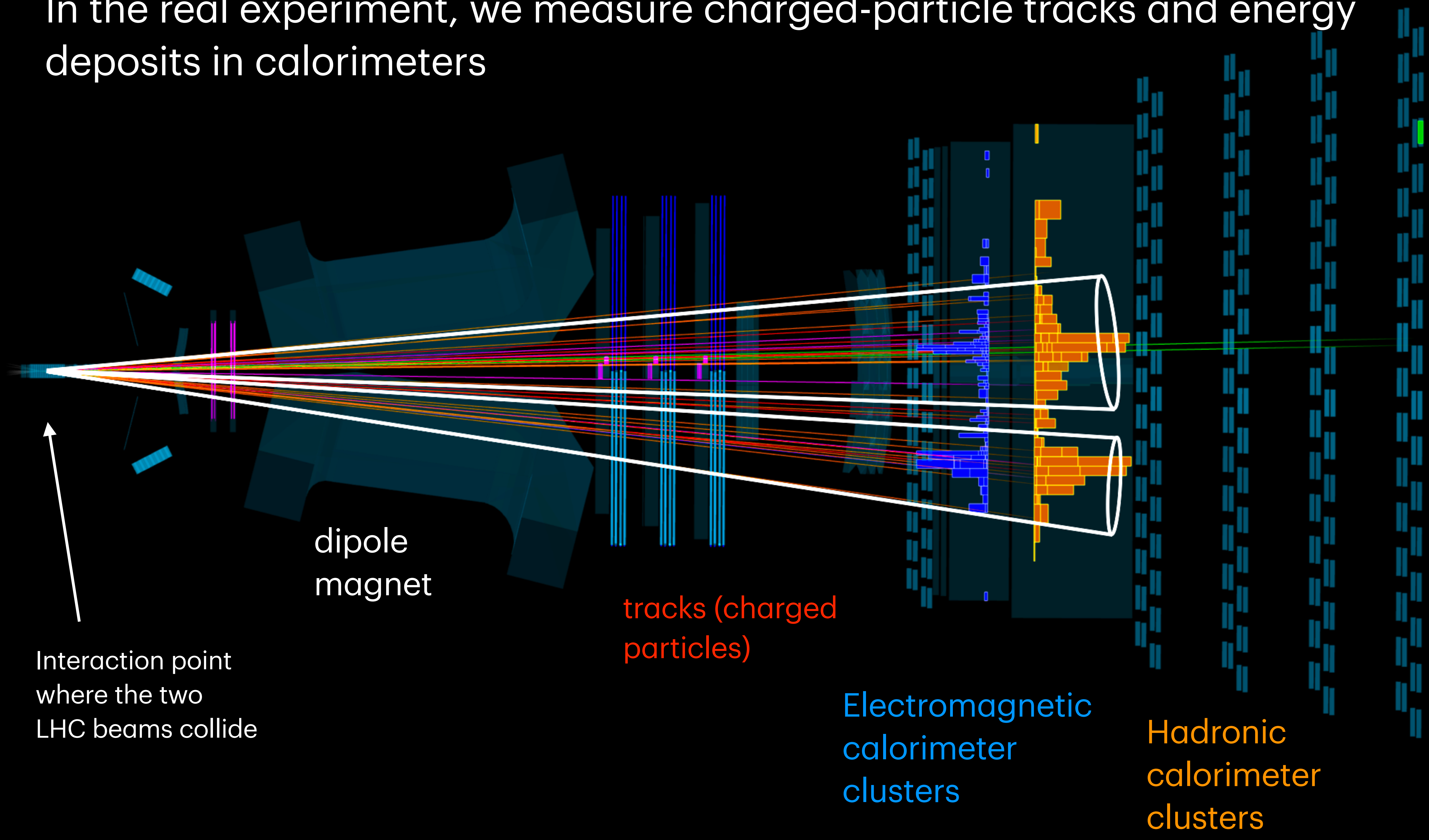
p = 0 Cambridge-Aachen algorithm

p = 1 k_T algorithm

- If $d_{ij} < d_{iB}$, particles i and j are clustered into a jet.
- The process is repeated until no more particles (or "proto-jets": the clusters of particles created during the algorithm) satisfy the criteria $d_{ij} < d_{iB}$
- It's actually not very complicated! However, we started with fully-reconstructed particles…

Di-jet event in an LHCb pp collision

In the real experiment, we measure charged-particle tracks and energy deposits in calorimeters



"Particle Flow": preparing inputs to the jet reconstruction

Particle Flow: an algorithm that converts detector-level quantities (calorimeter clusters, tracks, etc.) into particle hypotheses

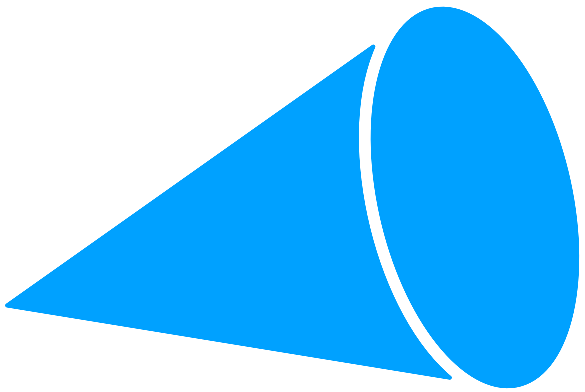
- Match tracks to calorimeter clusters → charged particle hypothesis
- Calorimeter clusters without track matches → neutral particle hypothesis
- Can also pass fully reconstructed and identified particles as inputs ($ex: K_s^0 \rightarrow \pi^+\pi^-$)
- Algorithm avoids double-counting inputs - once a cluster is "matched" it cannot be re-used for a different particle

Particle Flow is not the only way to select inputs for the jet reconstruction algorithm, but many experiments use it because it is fast and efficient.

Two categories of jet measurements

Jets as parton proxies:

Measure the jet, then treat it like it's a parton



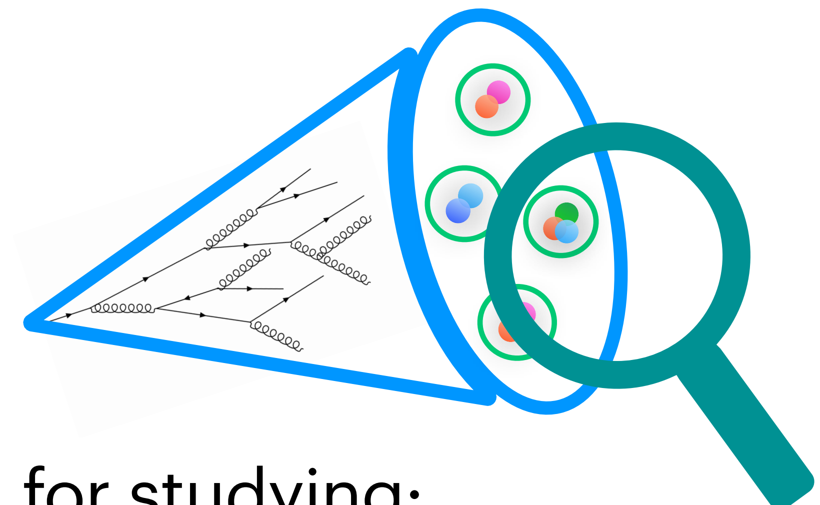
= quark or gluon

Ideal for **cross-section measurements** with a parton in the final state: $b\bar{b}$, $c\bar{c}$, Z+l/c/b

Jet cross sections are excellently described by perturbative QCD

Jets as hadronization/parton shower probes:

Measure the jet *substructure*: the particles within the jet



Ideal for studying:

- **hadronization:** can constrain fragmentation functions, initial/final state known for heavy flavor
- **parton shower dynamics:** QCD "dead cone", measurements of QCD splitting functions,...

Studying fragmentation functions with jets

- Since jets are by definition produced from the hadronization of a quark or gluon, they are ideal for studying hadronization!

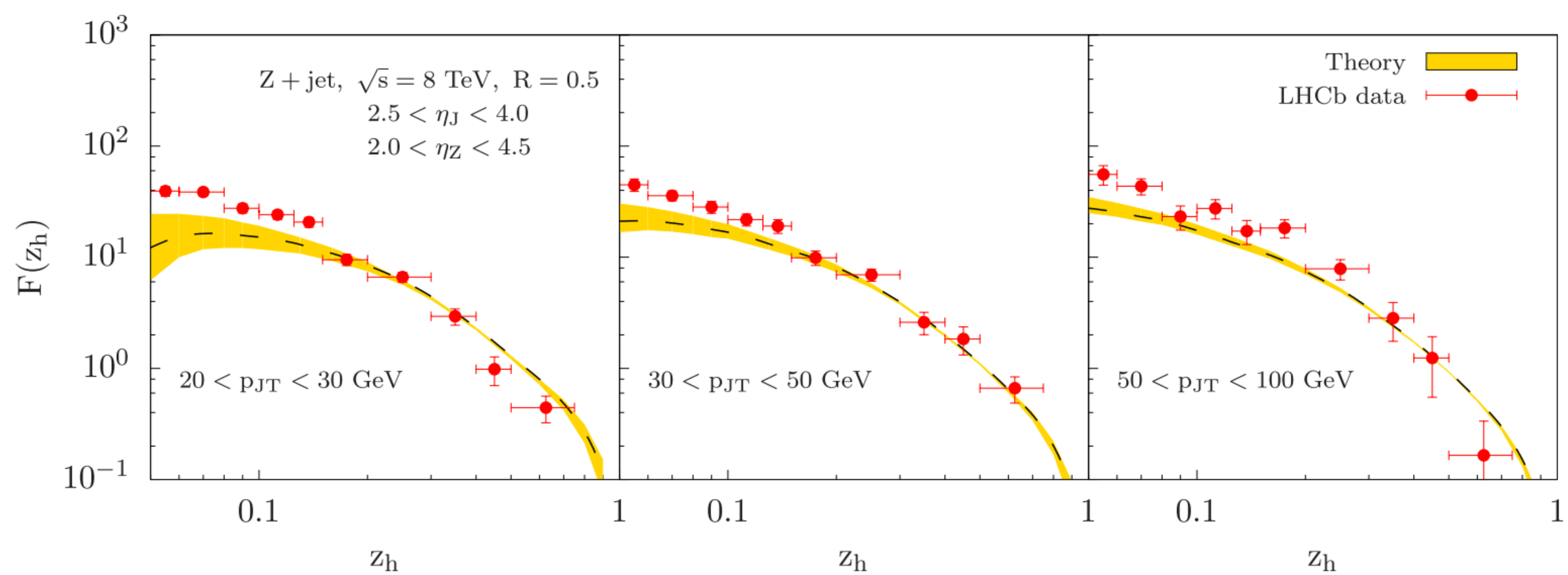
- Factorization theorems have been developed to describe hadron production within a jet

- These theorems replace the single-hadron fragmentation function with a **Fragmenting Jet Function (FJF)**:

$$\frac{d\sigma^{pp\to(jet h)X}}{dp_T d\eta dz_h d^2\mathbf{j}_\perp} = \sum_{a,b,c} f_a(x_a,\mu) \otimes f_b(x_b,\mu) \otimes H^c_{ab}(x_a,x_b,\eta,p_T/z,\mu) \otimes G^h_c(z,z_h,\omega_J R,\mathbf{j}_\perp,\mu)$$

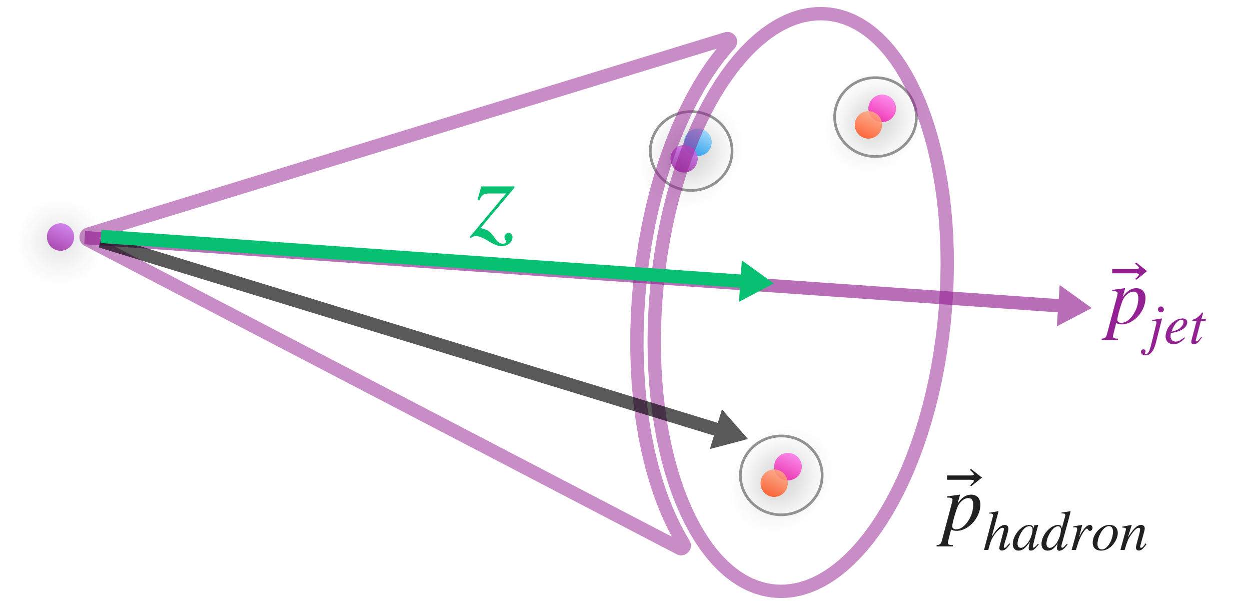
PDF PDF hard scattering cross section FJF

- The FJFs are related to the single-hadron FFs, therefore **measurements of hadrons in jets also help to constrain the single hadron FFs**



Kang, Lee, Terry, Xing PLB **798**, 134978 (2019)

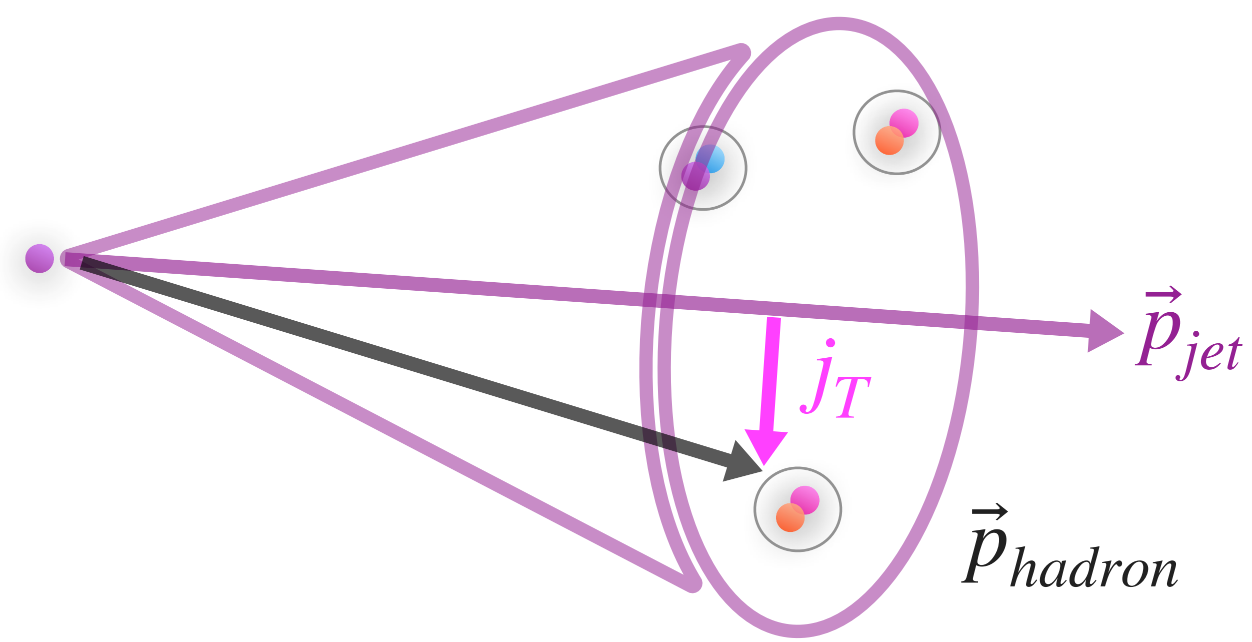
Studying fragmentation functions with jets



z: longitudinal momentum fraction

$$z = \frac{\vec{p}_{jet} \cdot \vec{p}_{hadron}}{|\vec{p}_{jet}|^2}$$

sensitive to collinear FFs

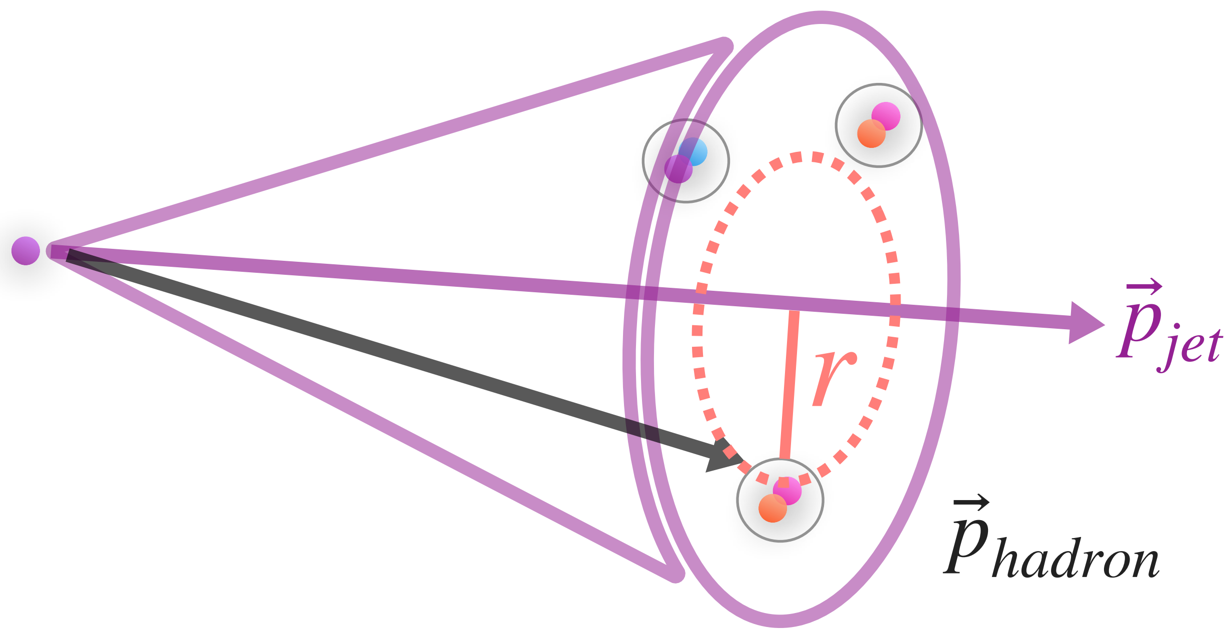


j_T: transverse momentum of hadron relative to the jet axis

$$j_T = \frac{|\vec{p}_{jet} \times \vec{p}_{hadron}|}{|\vec{p}_{jet}|}$$

sensitive to transverse momentum dependent (TMD) FFs

Studying fragmentation functions with jets

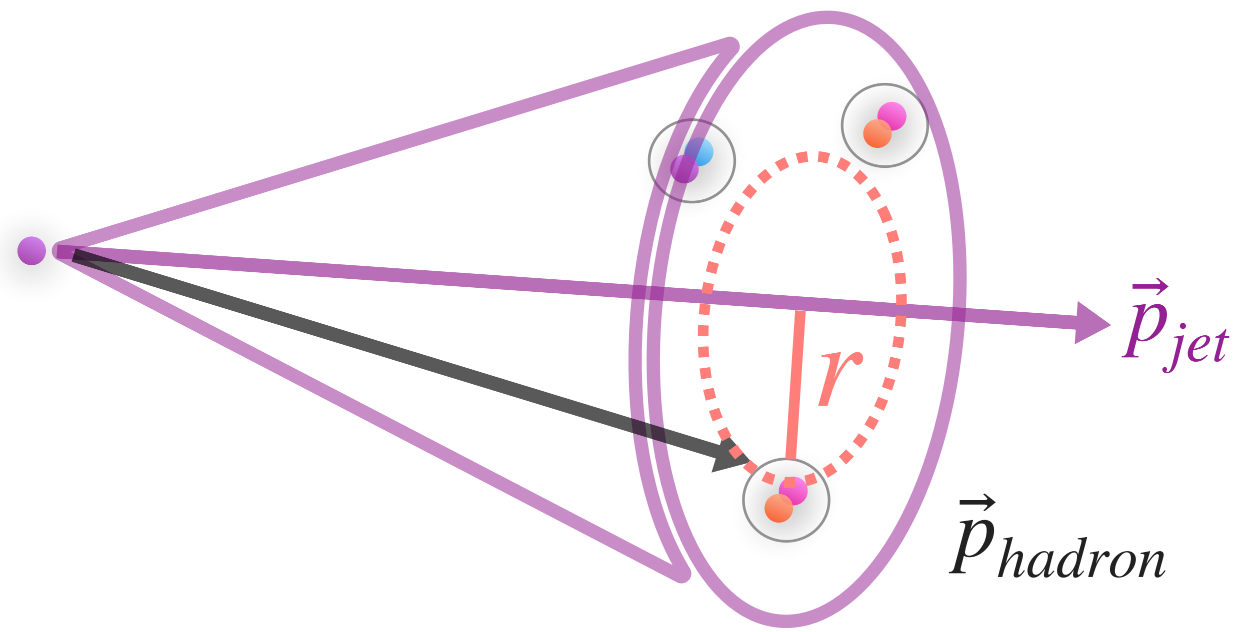


r: **radial position of hadrons in the jet**

$$r = \sqrt{(\phi_{jet} - \phi_{hadron})^2 + (\eta_{jet} - \eta_{hadron})^2}$$

- Why is r interesting?

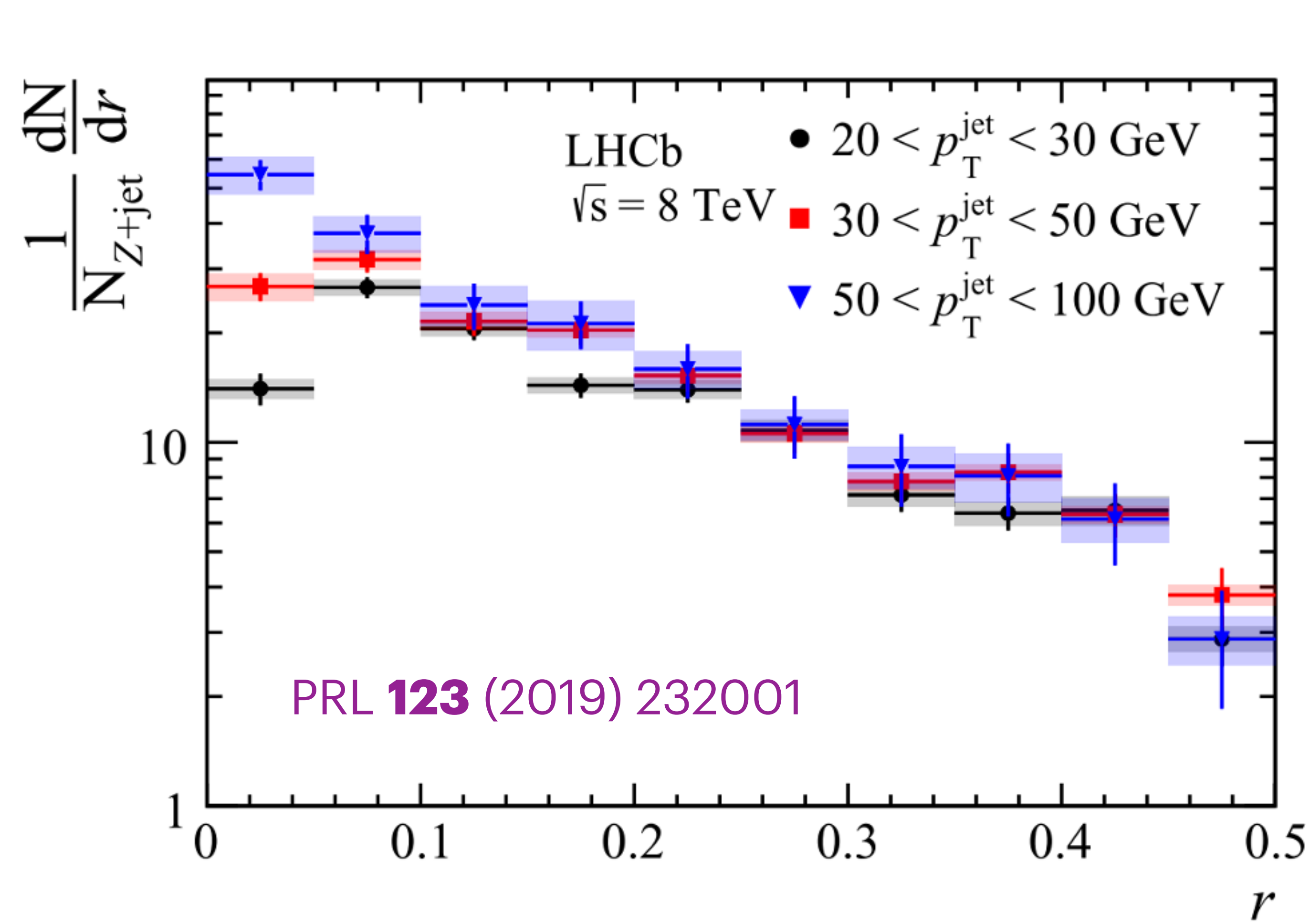
Studying fragmentation functions with jets



r: radial position of hadrons in the jet

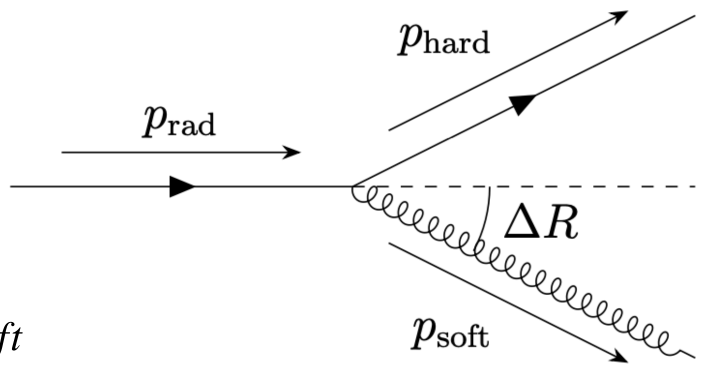
$$r = \sqrt{(\phi_{jet} - \phi_{hadron})^2 + (\eta_{jet} - \eta_{hadron})^2}$$

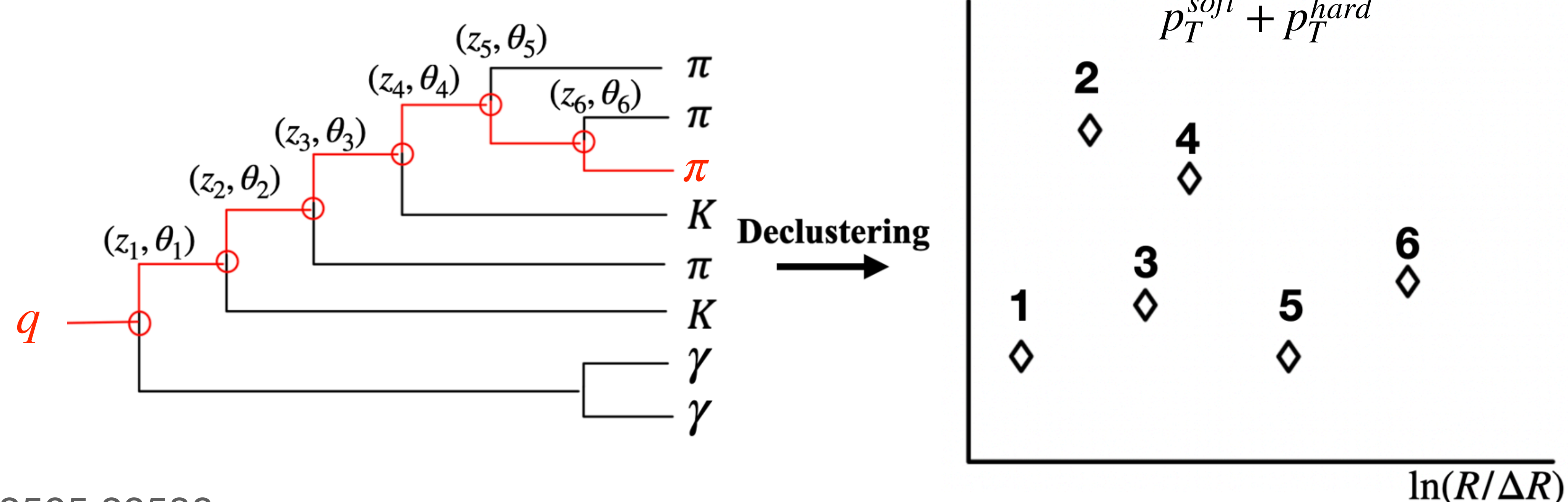
- Why is r interesting?
- z and j_T give us a three-dimensional picture of hadronization in momentum space. r gives us an image ir position space



The Lund Plane

- Reconstruct jets with anti-k_T algorithm, then "re-cluster" with the Cambridge-Aachen algorithm
- C/A algorithm gives us the angular ordering of the particles in the jet -> reconstruction of the parton shower history
- Follow the "hardest" particle in the jet. Calculate variables z and ΔR between the "hard" branch and the "soft" branch in each splitting





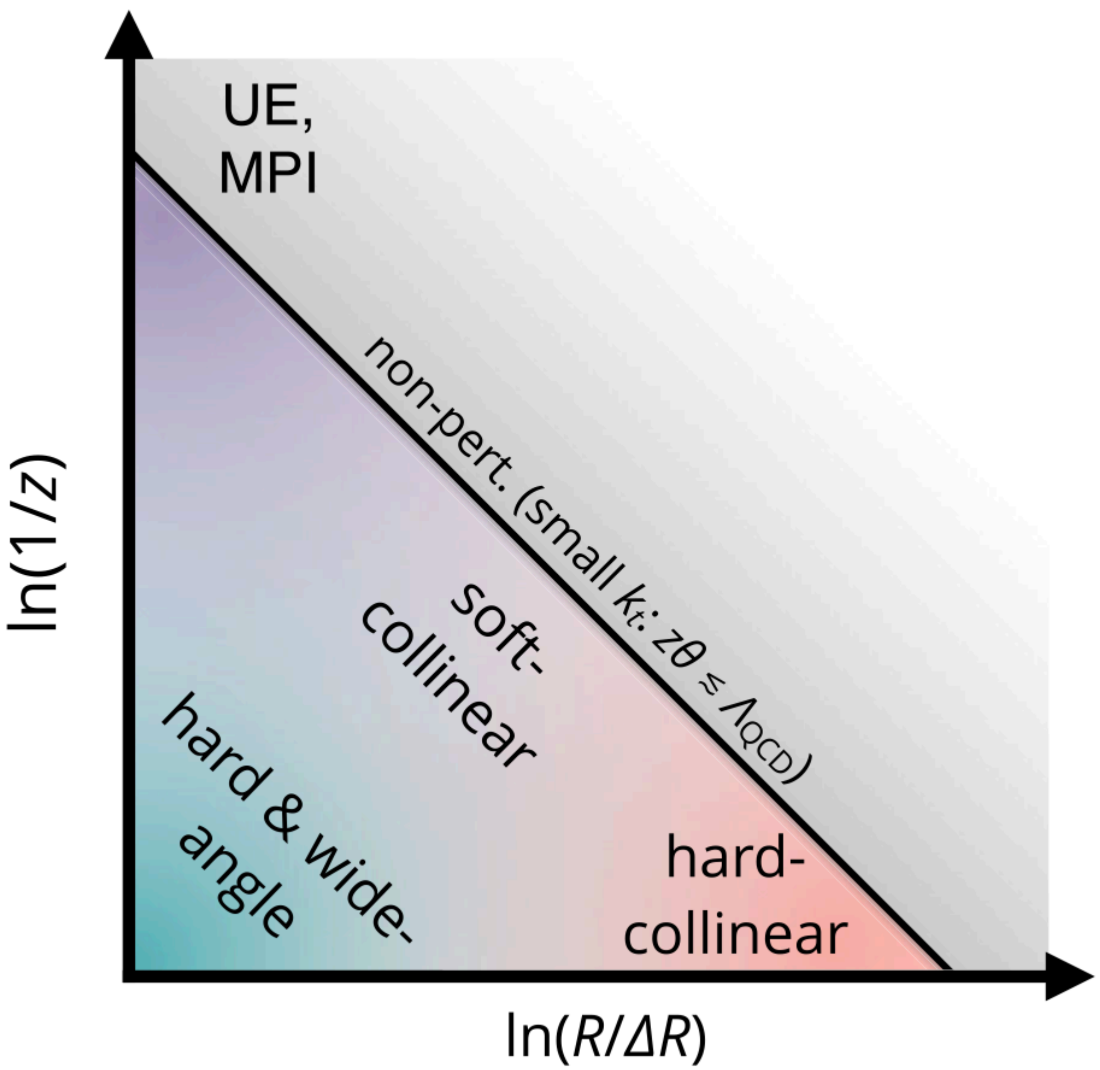
$$z = \frac{p_T^{soft}}{p_T^{soft} + p_T^{hard}}$$

arxiv: 2505.23530

$$\Delta R = \sqrt{(y_{soft} - y_{rad})^2 + (\phi_{soft} - \phi_{rad})^2}$$

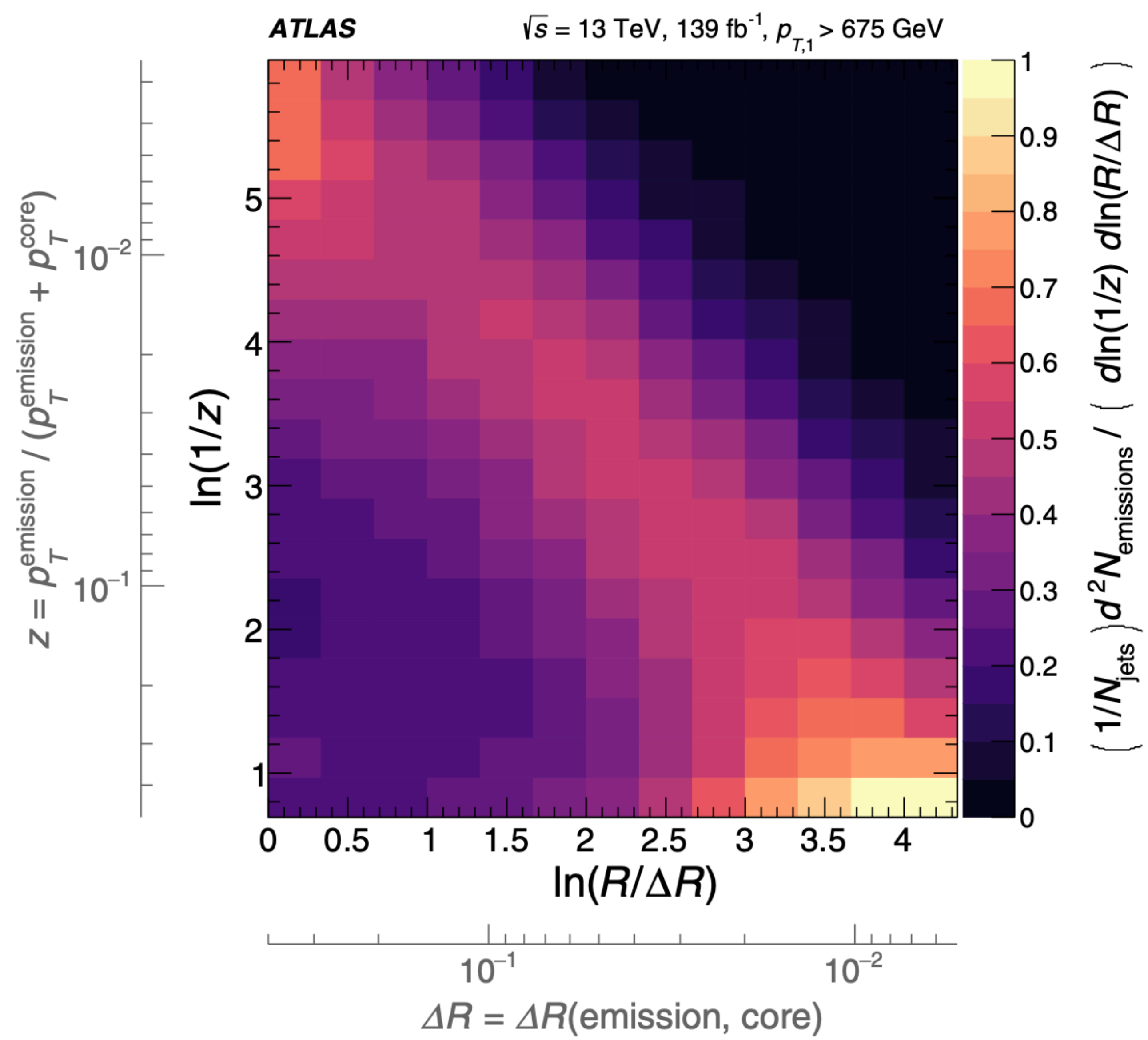
The Lund Plane

Types of parton splittings in the Lund plane



Lund plane = a way to image the parton shower in a jet!

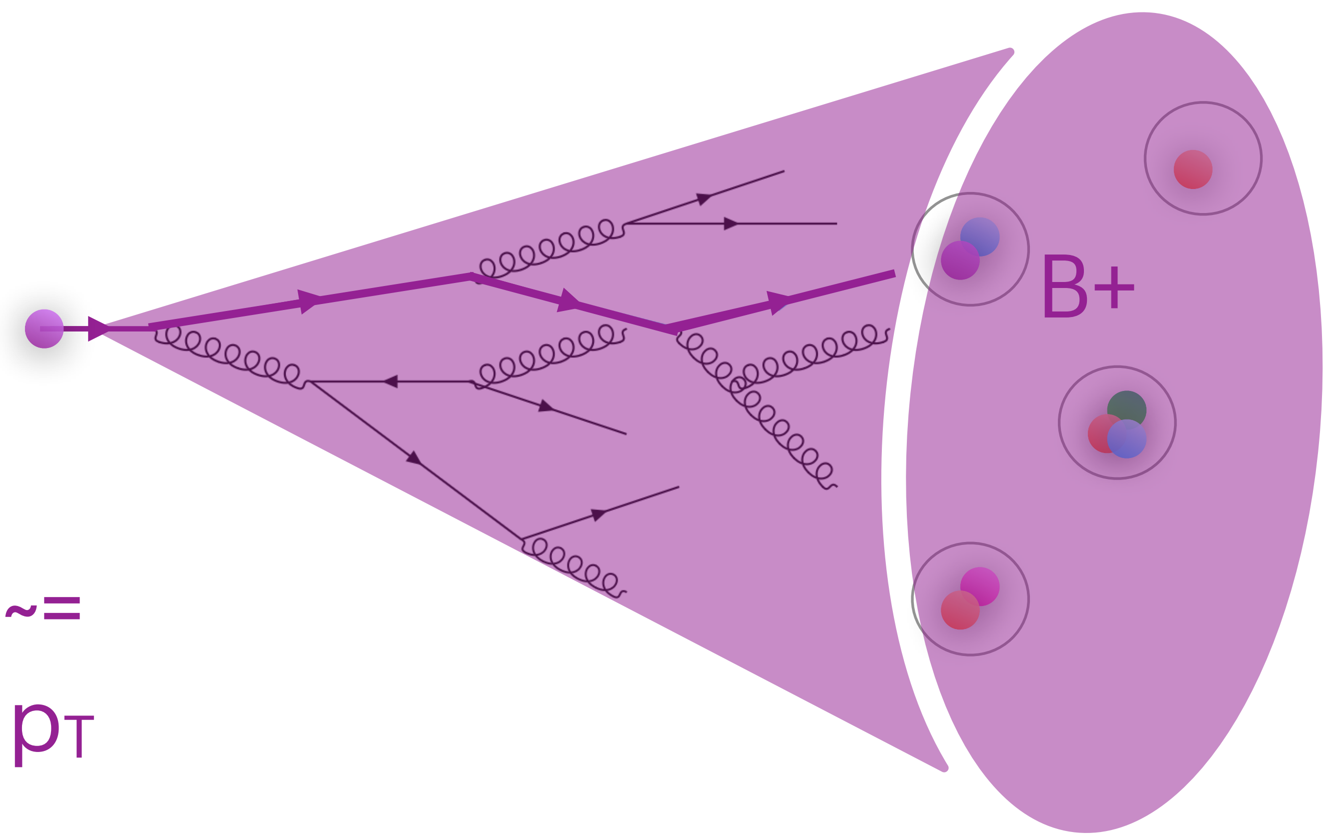
Inclusive jets in pp collisions @ ATLAS



PRL 124 (2020) 222002

Heavy flavor jets

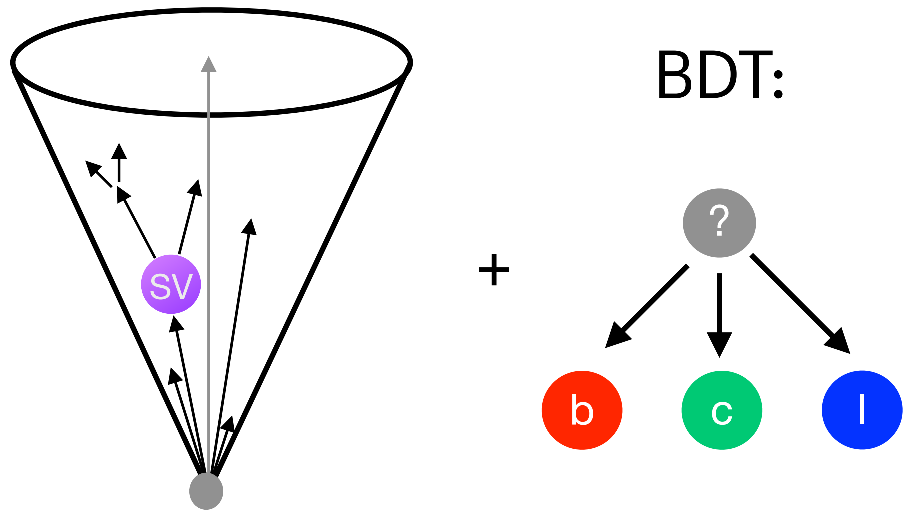
- Heavy flavor jets can be experimentally identified due to the presence of a heavy flavor hadron within the jet
- Ideal for studying hadronisation, as both the initial parton flavor and the final hadrons produced during the hadronisation process are known!
- Example: measuring a b-jet will provide a better approximation of the b-quark kinematics than only measuring a B-hadron

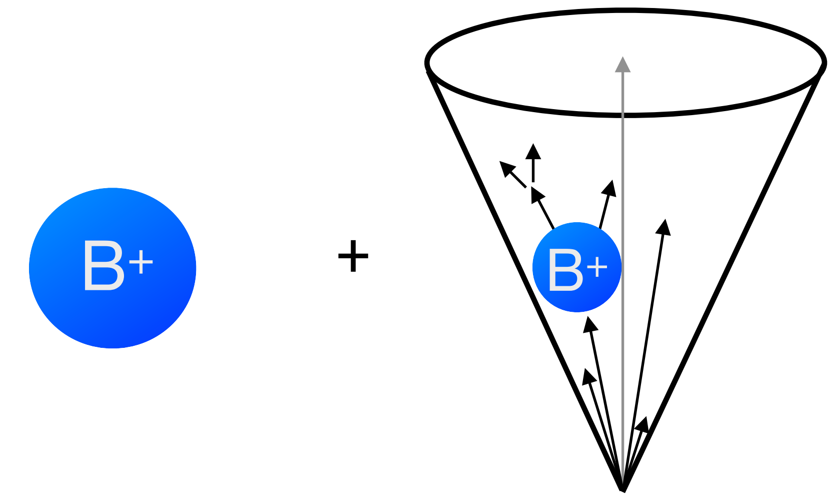


b-jet p_T ~= b-quark p_T

-> **complementary probe** to single hadron open heavy flavor measurements

Heavy flavor jets: accessing b- and c-quark kinematics





Inclusive tagging:

1. Reconstruct a secondary vertex (SV) inside a jet that originates from a heavy flavor decay.

2. Use machine learning techniques (Boosted Decision Trees at LHCb) to separate beauty/charm/light jets
   JINST 10, P06013 (2015)

Advantage: huge statistics

Exclusive tagging:

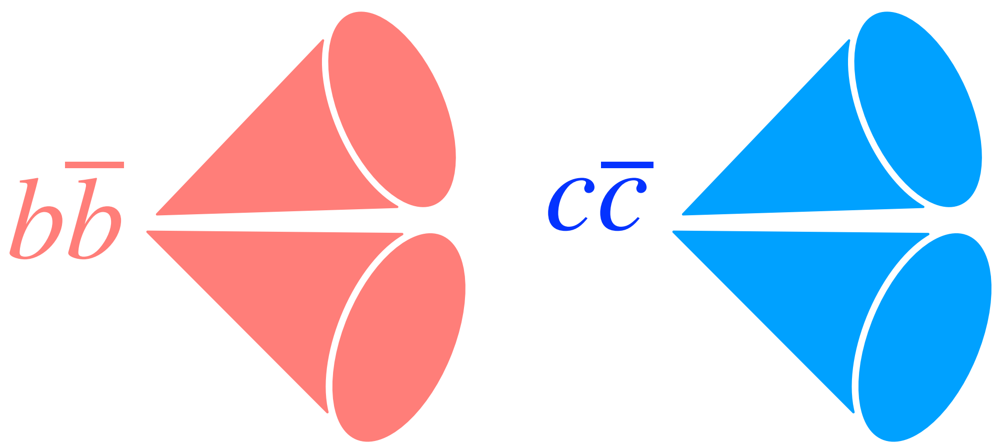
1. Fully reconstruct an exclusive decay of a heavy flavor hadron

2. Pass the heavy flavor hadron as input to the jet reconstruction algorithm -> find jets containing that hadron

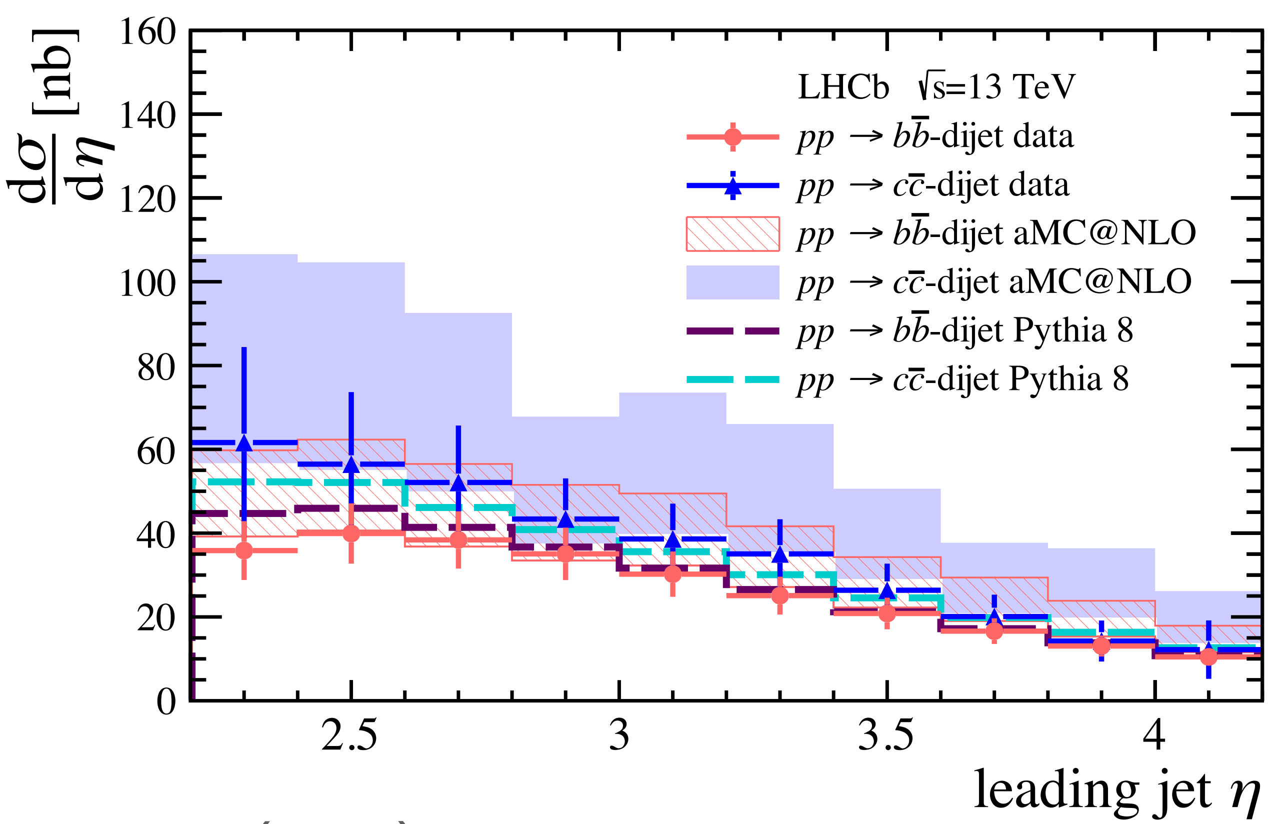
Advantage: study flavor dependence ($b/\bar{b}$), hadronization in strange/light sector

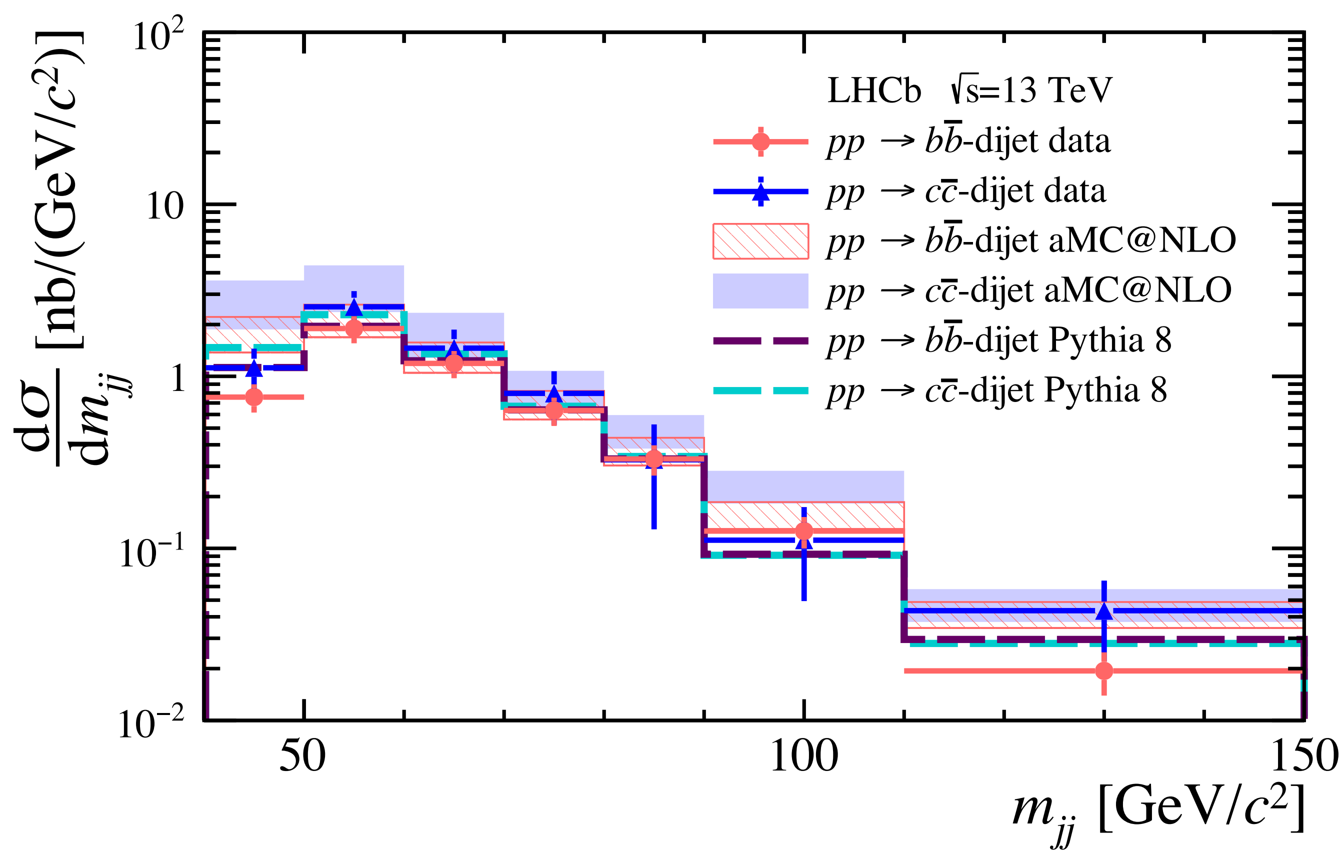
Using jets as proxies for heavy quarks

- Precision $b\bar{b}$ and $c\bar{c}$ measurements from the LHCb Run 2 data -> first inclusive direct measurement of the differential $c\bar{c}$ cross section at a hadron collider



No substructure here, just measuring two heavy quark jets and comparing to models of $b\bar{b}$ and $c\bar{c}$ production

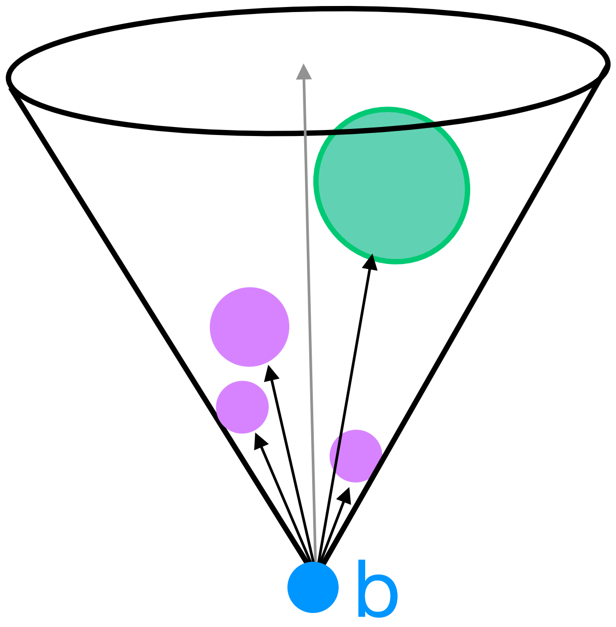




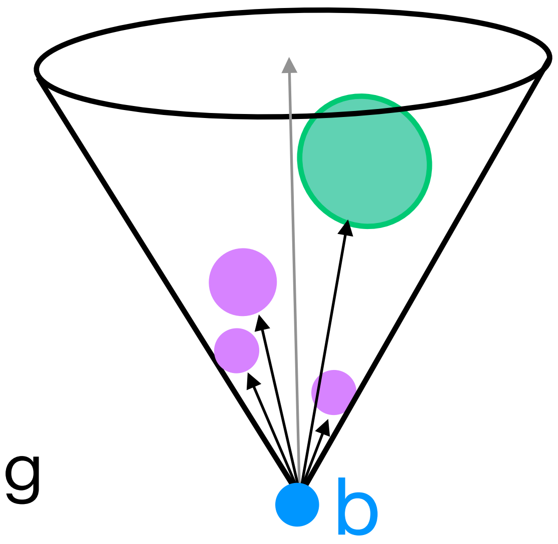
JHEP 02 (2021) 023

Heavy flavor fragmentation functions in jets

Can measure FFs of a single heavy flavor hadron in the jet (**single HF FFs**), or FFs of charged particles in the jet (**jet FFs**)



Heavy flavor fragmentation functions in jets

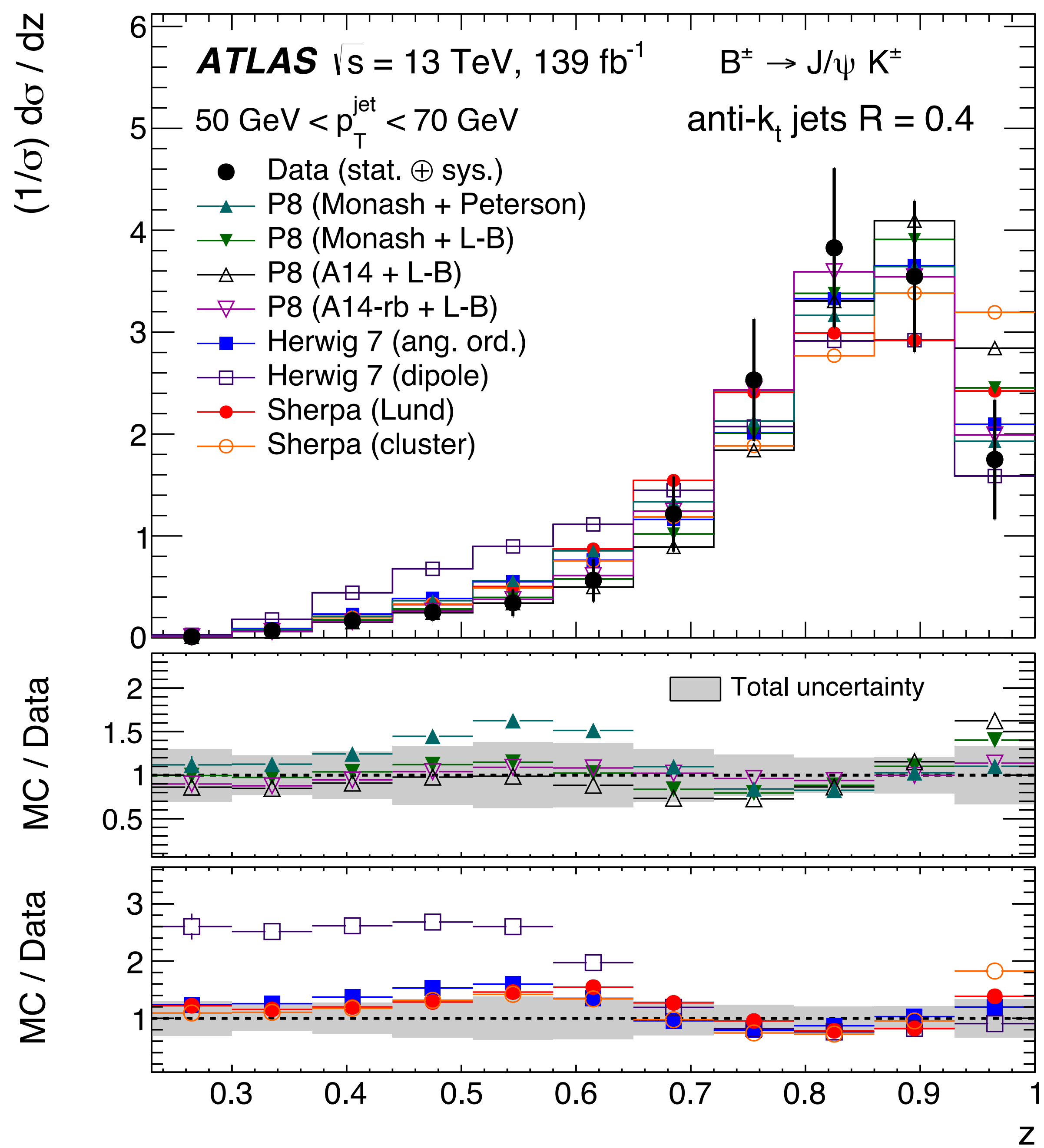


Can measure FFs of a single heavy flavor hadron in the jet (**single HF FFs**), or FFs of charged particles in the jet (**jet FFs**)

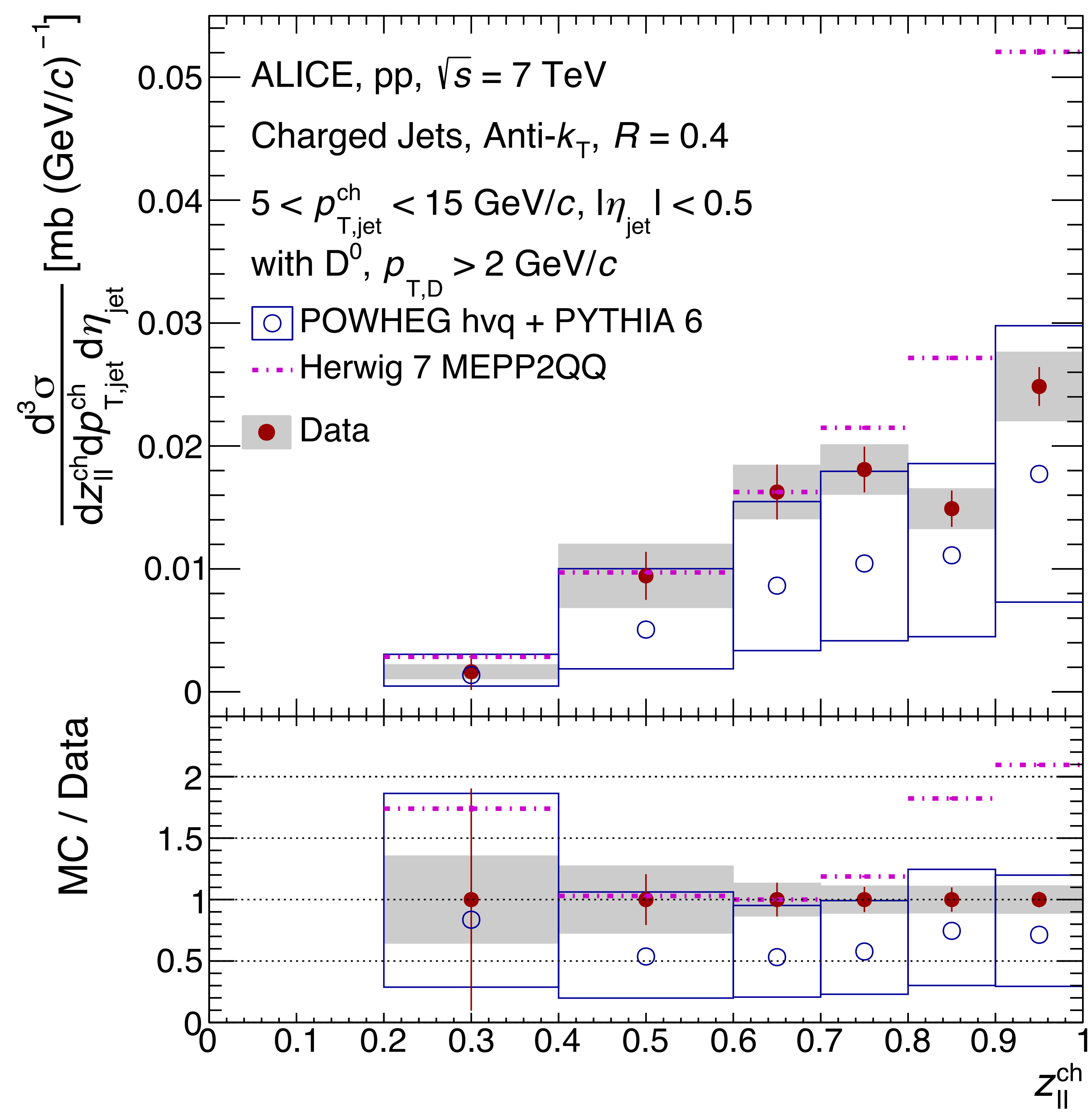
- **Single HF FFs:** when you measure the fragmentation of a specific heavy flavor hadron (e.g. D^0), you are directly probing the hadronization of a heavy flavor quark with a light flavor quark
- **Jet FFs (multi-hadron FFs):** when you measure the fragmentation of charged particles, you are probing how multiple hadrons are produced from a single quark or gluon. This is important because fragmentation always involves multiple hadrons being produced
- **Both are important!** They give complementary information, and are both needed to fully understand heavy flavor hadronization, since both originate from the hadronization of a single heavy quark

Heavy flavor fragmentation functions in jets

Collinear b→ B± FF in jets



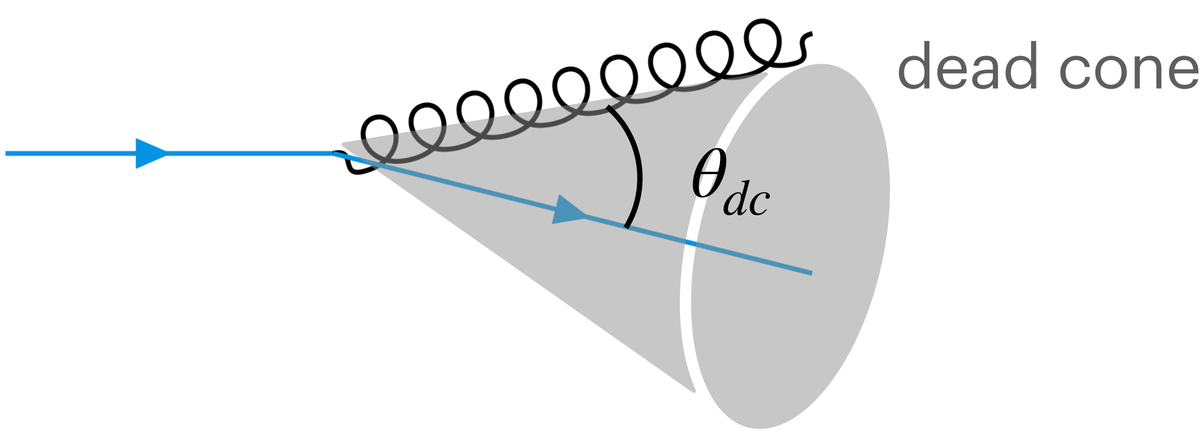
Collinear c→ D⁰ FF in jets



JHEP **12**, 131 (2021) JHEP **08**, 133 (2019)

The dead cone effect

- The dead cone effect is a fundamental prediction of gauge theories that states that quarks do not emit radiation within a cone of angle $\theta_{dc} \sim \frac{m_q}{E_q}$
- Since the dead cone angle is proportional to mass, it is larger for heavy quarks
- Why is it important to measure?
- How can we measure this?



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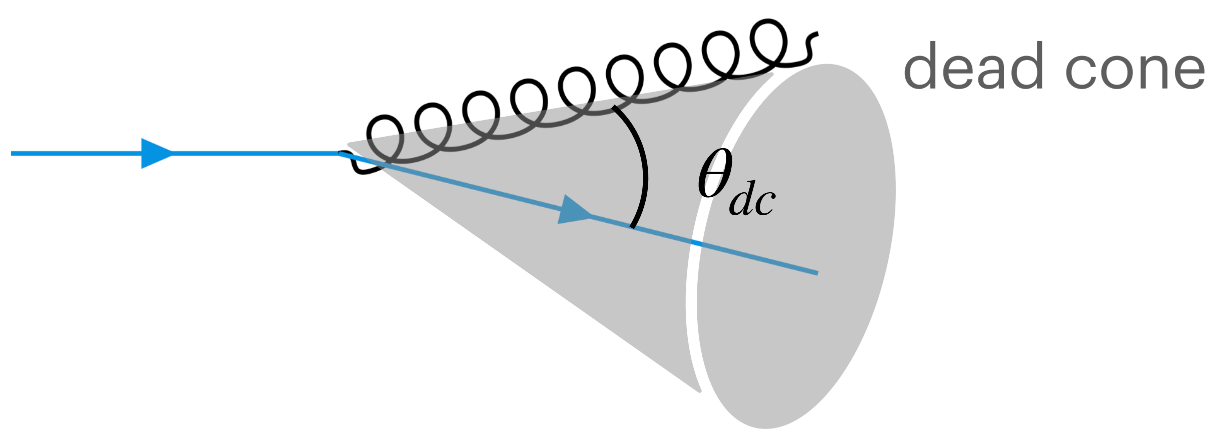
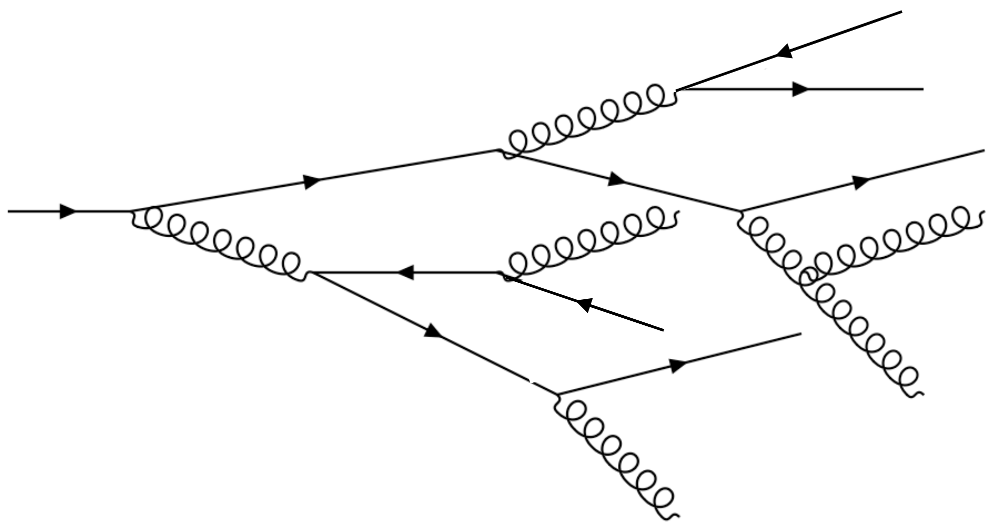
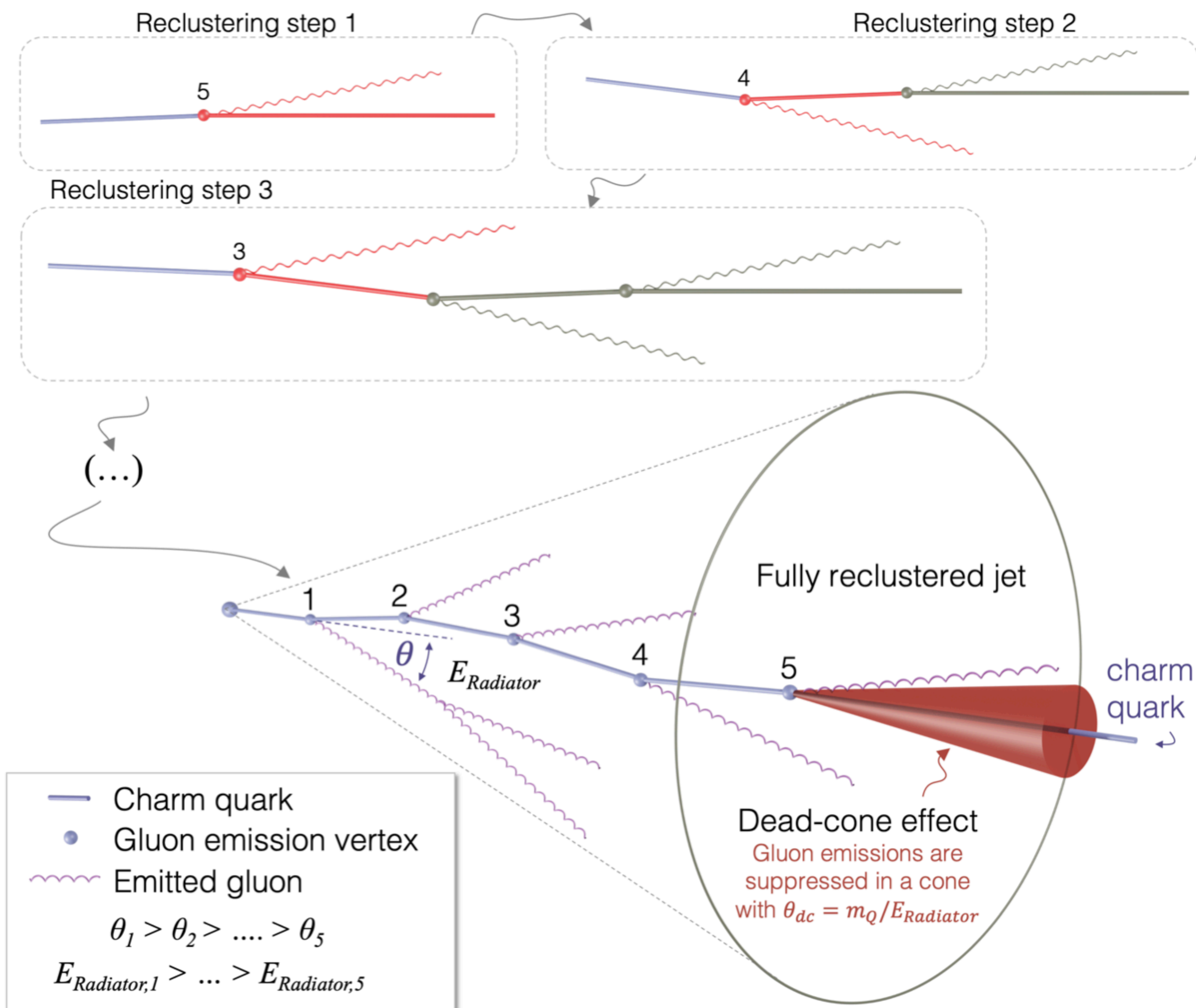


The dead cone is everywhere in the parton shower!



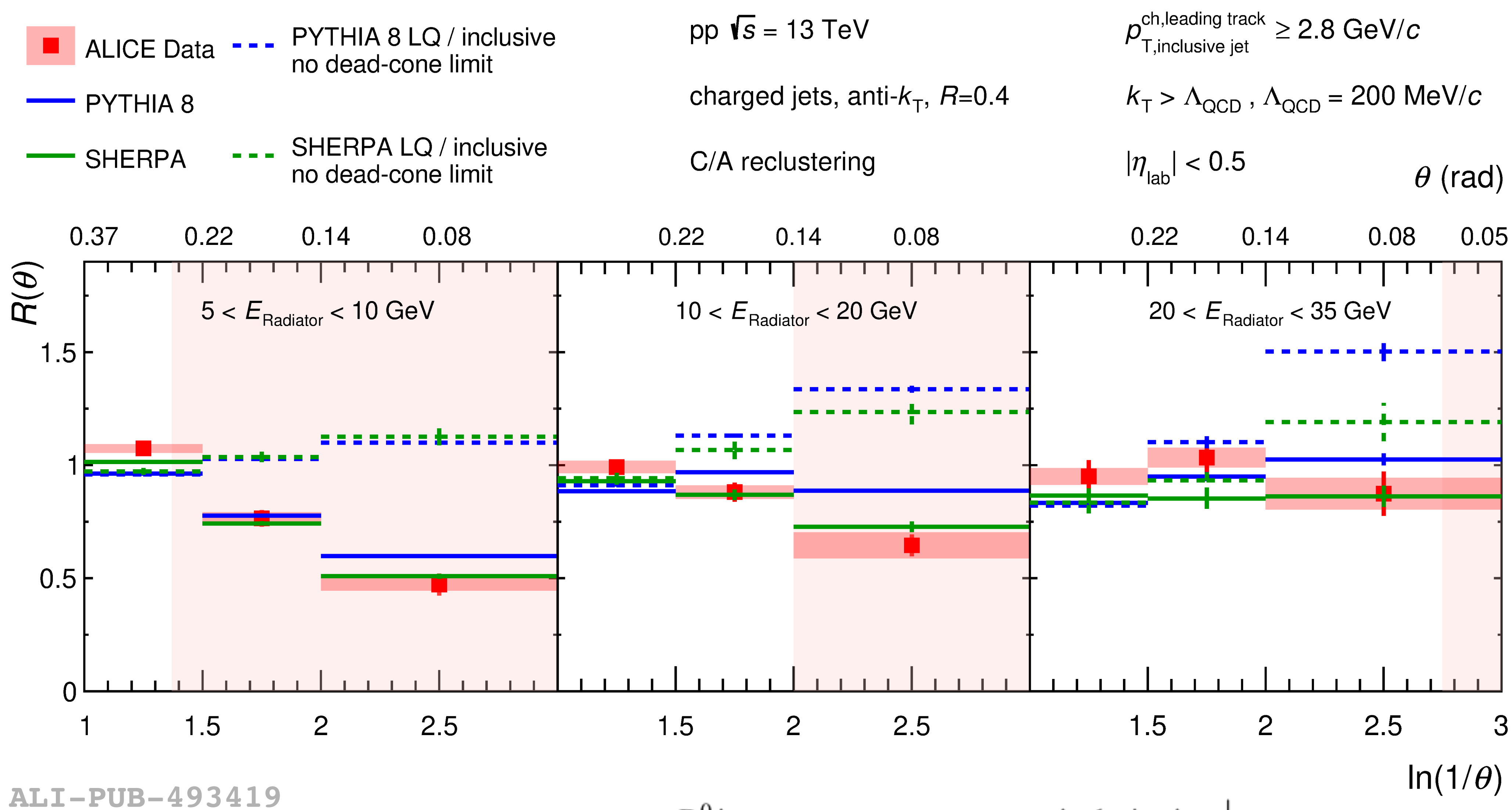
The dead cone plays a huge role in the heavy quark parton shower, which is important to understand in order to fully understand heavy flavor hadronization

Measuring the dead cone with Cambridge-Aachen reclustering



Nature 605 (2022) 440-446

The charm dead cone



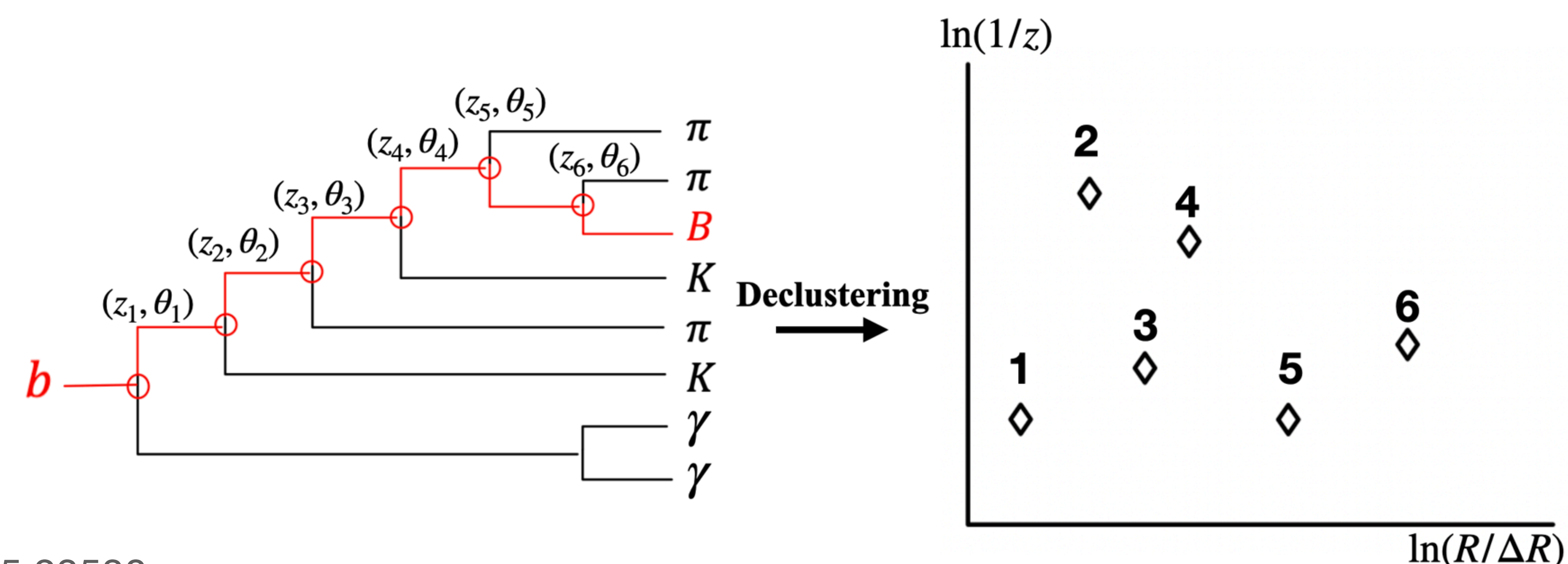
$$R(\theta) = \frac{1}{N^{\mathrm{D^0\,jets}}} \frac{\mathrm{d}n^{\mathrm{D^0\,jets}}}{\mathrm{d}\ln(1/\theta)} \Bigg/ \frac{1}{N^{\mathrm{inclusive\,jets}}} \frac{\mathrm{d}n^{\mathrm{inclusive\,jets}}}{\mathrm{d}\ln(1/\theta)} \Bigg|_{k_\mathrm{T}, E_\mathrm{Radiator}}$$

- Distinct effect from hadronization, but it influences the dynamics associated with heavy flavor hadronization

Nature 605 (2022) 440-446

The beauty Lund plane

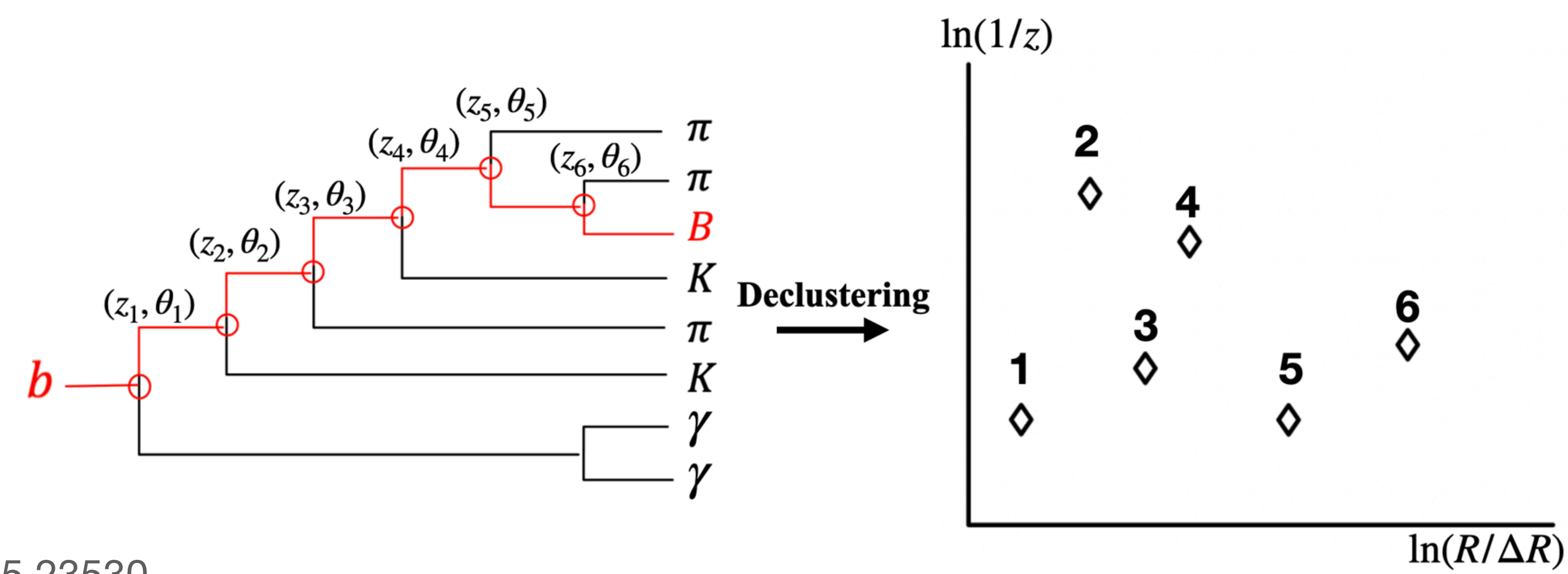
- We can measure the Lund plane in heavy flavor jets by reconstructing the emissions of the heavy flavor hadron in the jet
- Why is this interesting?



arxiv: 2505.23530

The beauty Lund plane

- We can measure the Lund plane in heavy flavor jets by reconstructing the emissions of the heavy flavor hadron in the jet
- Why is this interesting? Because beauty jets are quark-initiated jets, and because you know the original flavour of the parton that initiated the jet
- Where should the dead cone show up in the Lund plane?

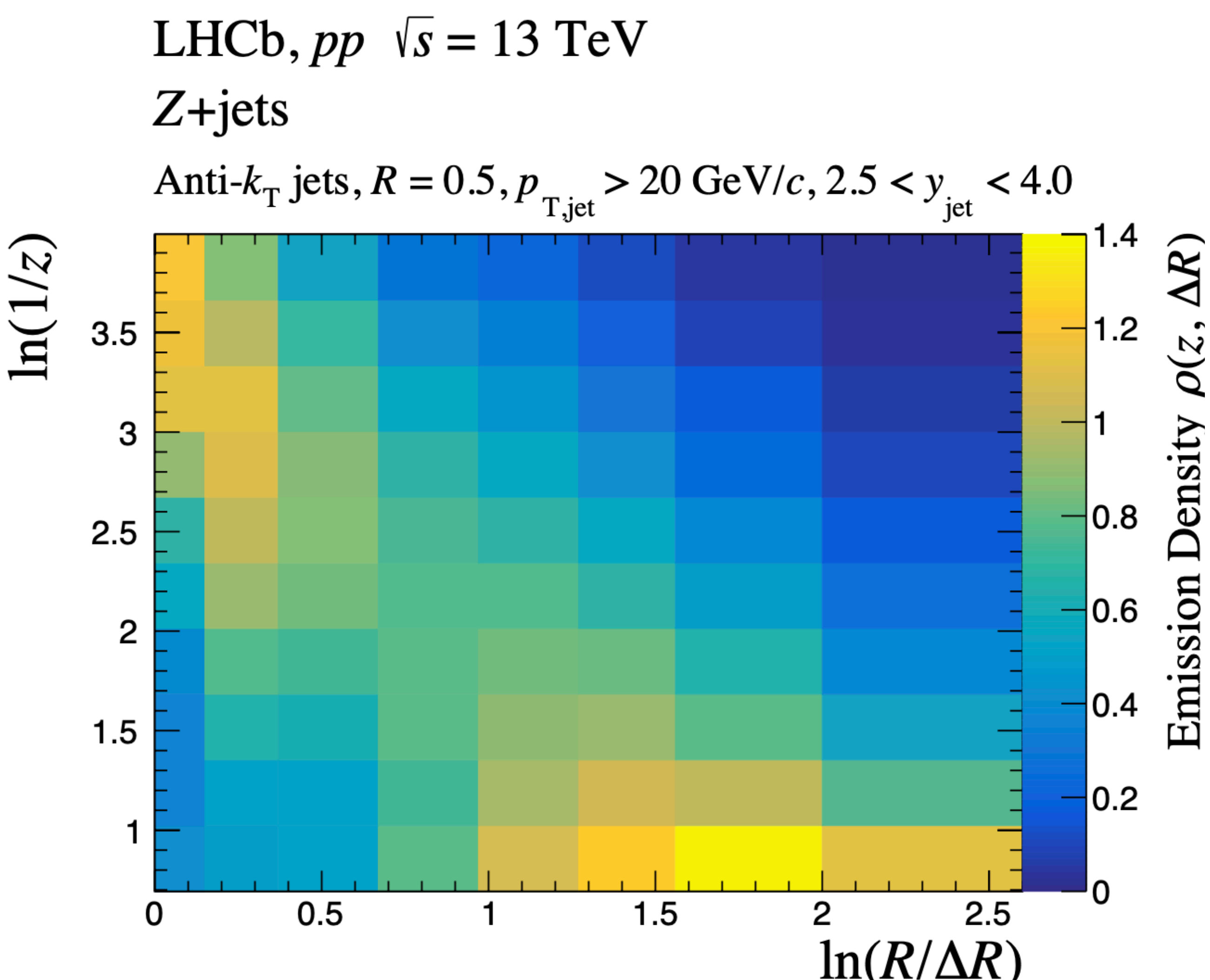


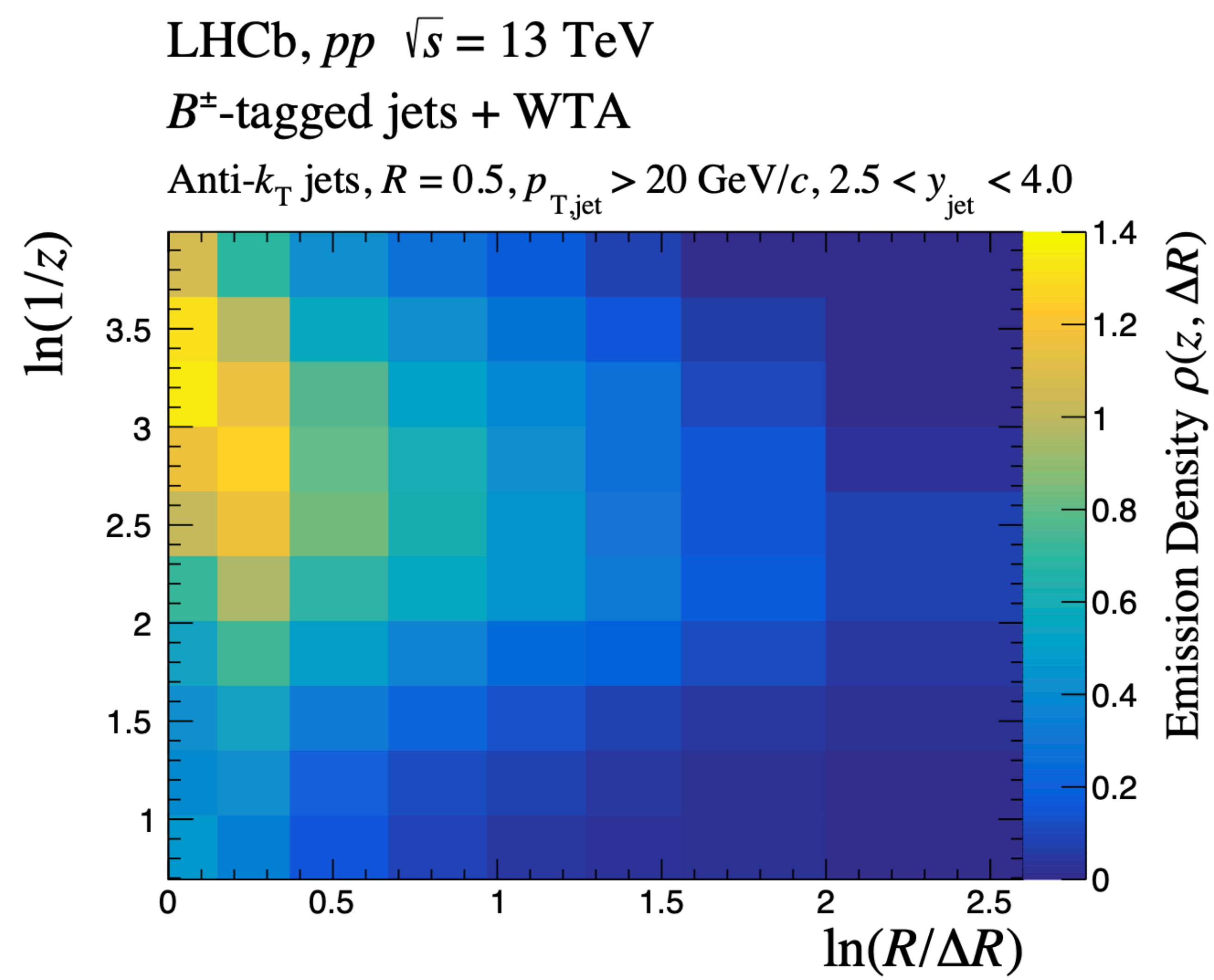
arxiv: 2505.23530

Imaging beauty vs light-quark-initiated jets

Z-tagged jets: primarily light-quark-initiated at forward rapidities (LHCb)

B-tagged jets: primarily beauty-quark initiated





arxiv: 2505.23530

To think about:

- Of the measurements we discussed today, which one do you think would be most interesting to measure at the EIC? Why?
- One of the big physics programs at the EIC will be studying hadronization. What are the pros and cons of using heavy flavor hadrons vs jets/heavy flavor jets to study this?
- Today we discussed mostly pp collisions (and some e^+e^-). What might change, or what else might you observe, when using the jet and heavy flavor probes we discussed today in *e*A collisions?

Summary: Lecture 1

- Heavy quarks are useful probes of QCD because their production can be perturbatively calculated, and they form many different kinds of hadrons that serve as good probes for studying hadronization (study b/c quark hadronization with other quark flavours)

- Jets are good proxies for individual partons (quarks or gluons). They also have interesting substructure that allows us to study the parton shower and hadronization

- Heavy quark jets are particularly useful because they allow us to know the flavor of the parton that initiated the jet. This allows us to study mass-dependent parton shower effects, such as the dead cone, and to have a better handle on hadronization studies