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Four Lectures on Jet Physics

MITP Summer School

July 25-29, 2016

Outline:

- 1) Introduction to Jets
- 2) Jet Algorithms
- 3) The Soft / Collinear Limit of QCD
- 4) The Substructure (R) evolution

(My full name anagrams to:

"Has realized: Jets!"

Changed middle name to Diaz in 2007

First QCD paper in 2008

(Coincidence? I think not.)

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Part 1: Introduction to Jets

A Renaissance in Jet Physics!

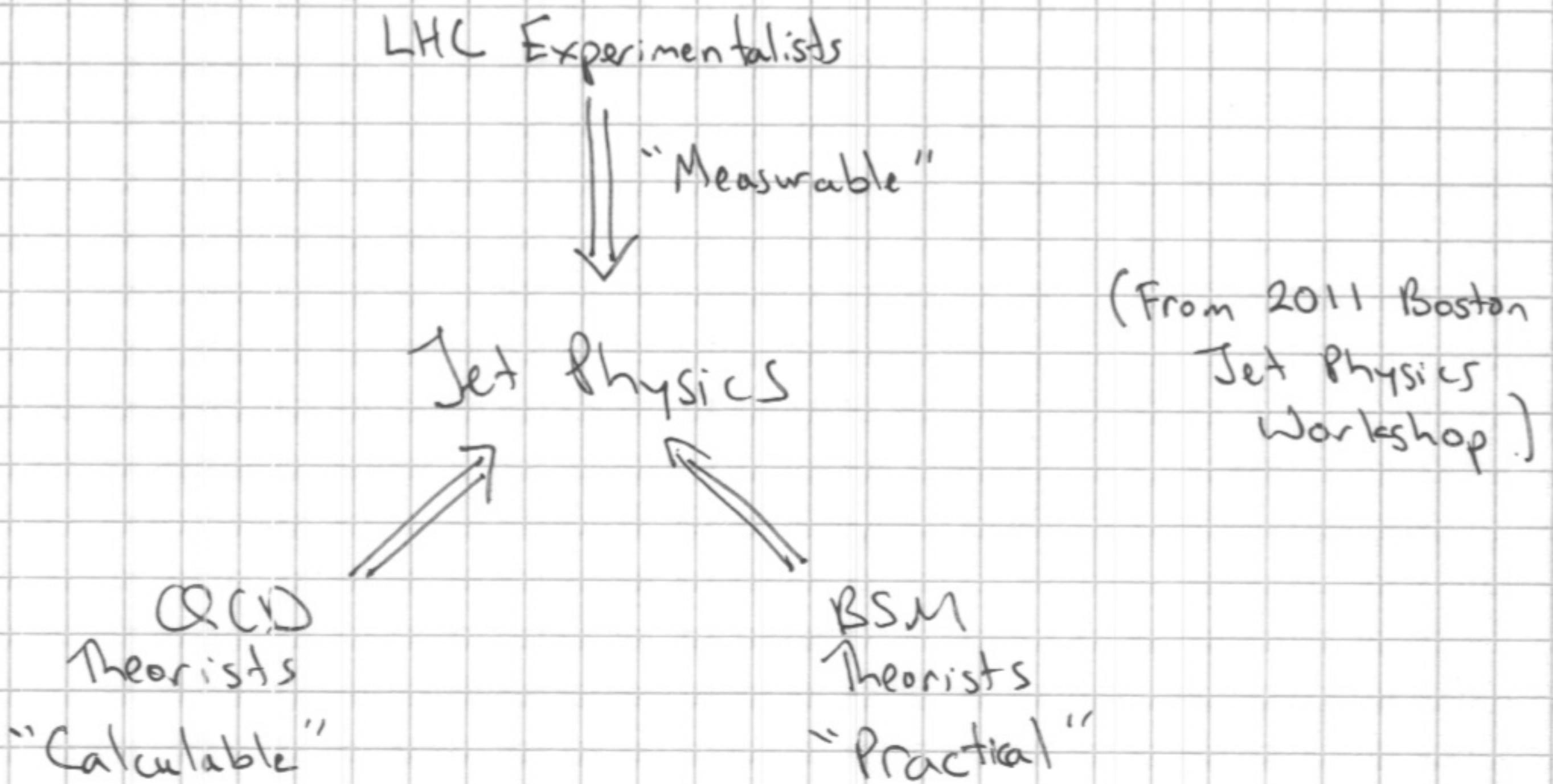
→ First jet algorithms in 1970s (Sterman-Weinberg)

→ First jet algorithm that experimentalists & theorists could agree on: $\overline{\text{anti}-k_T}$

↑ coincidentally, when I entered the field

For me: 8 amazing years learning about structure of QCD, relevance for BSM physics, realities of experimental methods

Convergence of 3 communities



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What's driving this field?

Experiment: Fantastic performance of LHC
 & granularity of ATLAS / CMS
 (increasingly ALICE & LHCb as well)

Compared to TeVatron:

- $\approx \times 7$ higher energy
- $\approx \times 10\text{-}20$ higher luminosity
- $\approx \times 5$ finer segmentation

- Ability to resolve individual hadrons
- Increased sophistication for jet studies

QCD Theory: Automated NLO Jet Cross Sections

NNLO revolution in progress

Sophisticated Monte Carlo Generators
 (parton shower / matrix element matching / merging)

New approaches / applications of factorization / resummation

New control over non-perturbative effects

BSM Theory: Importance of boosted regime

$$\sqrt{s} \gg m_{top}, m_{W/Z}, m_{Higgs} \dots$$

Novel jet observables customized for new physics searches

New approaches to cascade decays
 & multi-body final states
 & non-standard reconstruction
 (with and without jets)

My perspective: Jets are . . .

Boosting the Search for New Physics

→ Dark Matter?

(why I originally
got into jets.)

→ Hierarchy Problem?

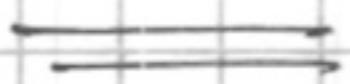
→ Higgs Boson as Probe?

Pushing the Boundaries of Quantum Field Theory

→ Jets as Emergent Phenomena?

(why I continue
to work on jets)

→ Calculations In & beyond
Perturbation Theory?



These lectures: From fundamentals to the future

→ Dynamics of Jet Formation

→ Jet Algorithms

→ Quark jets vs. gluon jets

→ Boosted objects

Apologies: Examples often drawn from my own research,
not a complete survey of the field.

Dynamics of Jet Formation

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Remember, all arises from QCD

(turning off electroweak
for most of these lectures.)

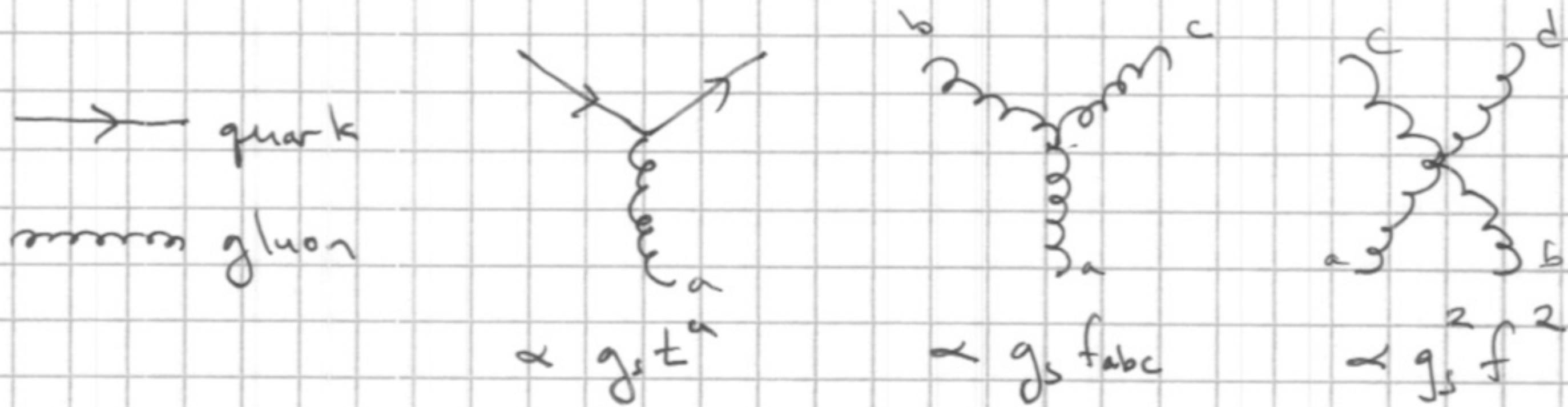
$$\mathcal{L}_{QCD} = -\frac{1}{4g_s^2} G_{\mu\nu}^a G^{a\mu\nu} \quad (a=1,2,3,4,5,6,7,8)$$

$$+ \sum_{i \in \text{quarks}} \left[\bar{t}_i \bar{s}^r D_r t_i + \bar{u}_i \bar{d}^r D_r u_i \right]$$

covariant derivative $\equiv \partial_\mu - i A_\mu^a t^a$

$$- m_i (t_i \bar{t}_i + \bar{u}_i \bar{d}_i) \quad \boxed{\text{quark masses}}$$

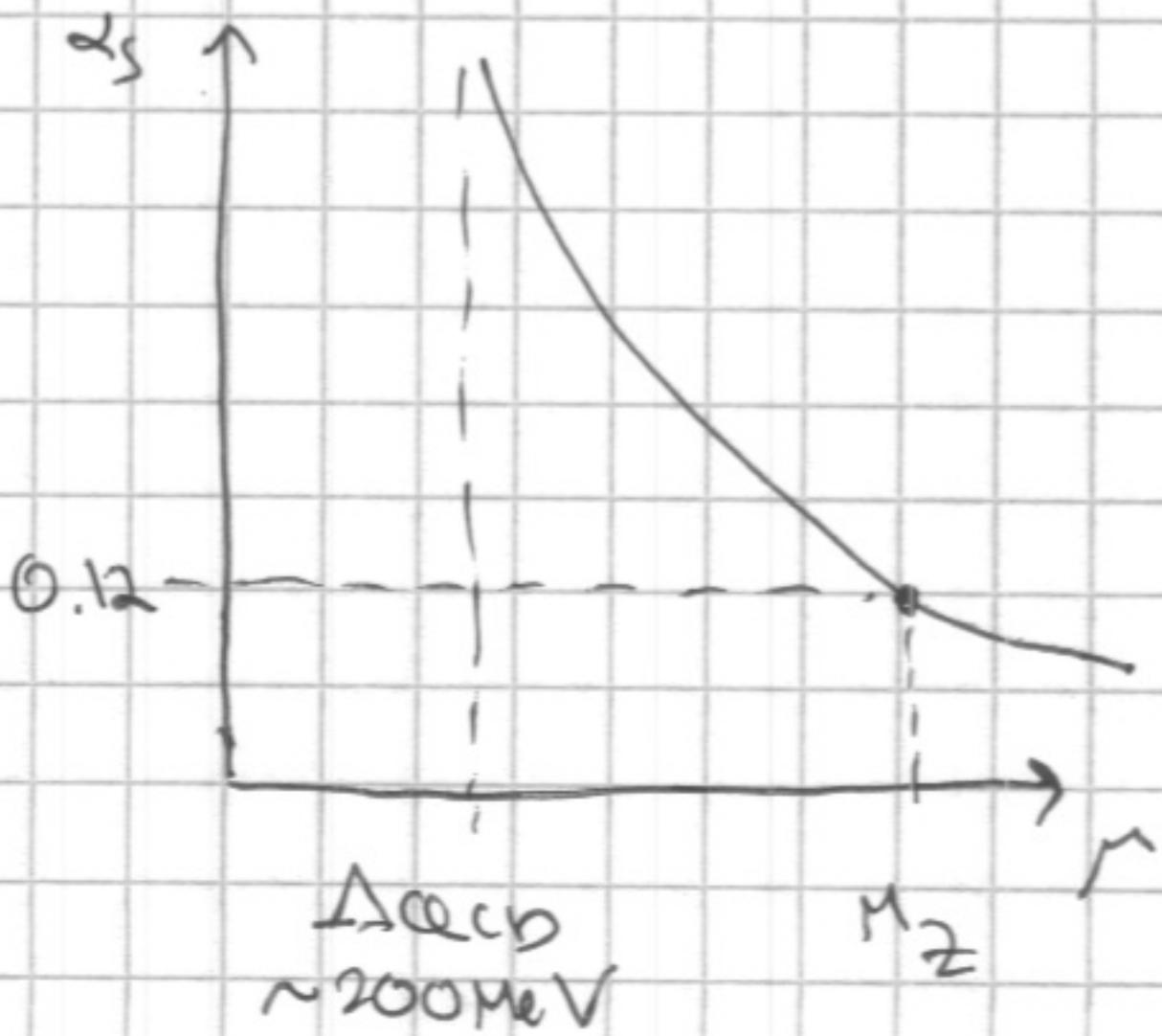
And that's it!



Key: strong coupling constant runs | $\alpha_s = \frac{g_s^2}{4\pi}$

$$\mu \frac{d}{d\mu} \left(\frac{1}{\alpha_s} \right)$$

$$= \frac{1}{4\pi} \left(\frac{11}{3} N_c - \frac{2}{3} N_f \right)$$



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At short distances:

gluons & quarks (up, down, strange
charm, bottom, top)

Long distances \Rightarrow Confinement

Mesons ($q\bar{q}$)

spin-0: $\pi^+ \pi^- \pi^0 \gamma K^+ K^- K^0 \gamma' \dots$

spin-1: $\rho^+ \rho^- \rho^0 \omega K^{*+} K^{*-} K^0 \phi \dots$

Baryons (qqq)

spin-1/2: $p n \Delta^0 \Sigma^+ \Sigma^0 \Sigma^- \Xi^0 \Xi^- \dots$

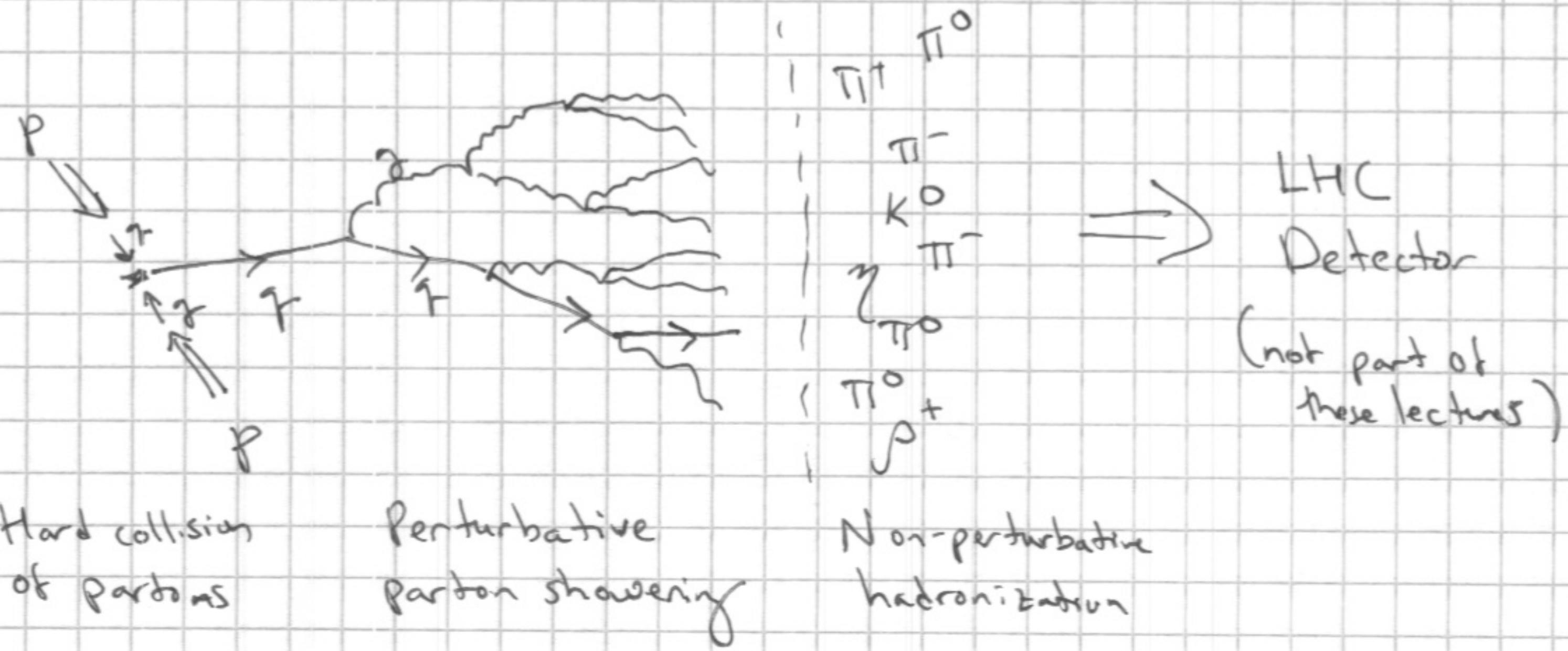
spin-3/2: $\Delta^{++} \Delta^+ \Delta^0 \Delta^- \Sigma^{*-} \Sigma^0 \Sigma^- \Xi^0 \Xi^- \Xi^* \Xi^- \Omega^- \dots$

Recently: tetraquarks & pentaquarks

$q q \bar{q} \bar{q}$

$q q q \bar{q} \bar{q}$

Jets connect these regimes



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Key: Jets are fundamentally ambiguous

No such thing as perfect jet algorithm

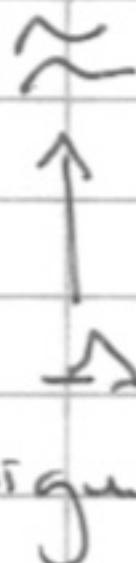
Why?

Color-carrying partons
vs.

Color-singlet hadrons

Best we can do:

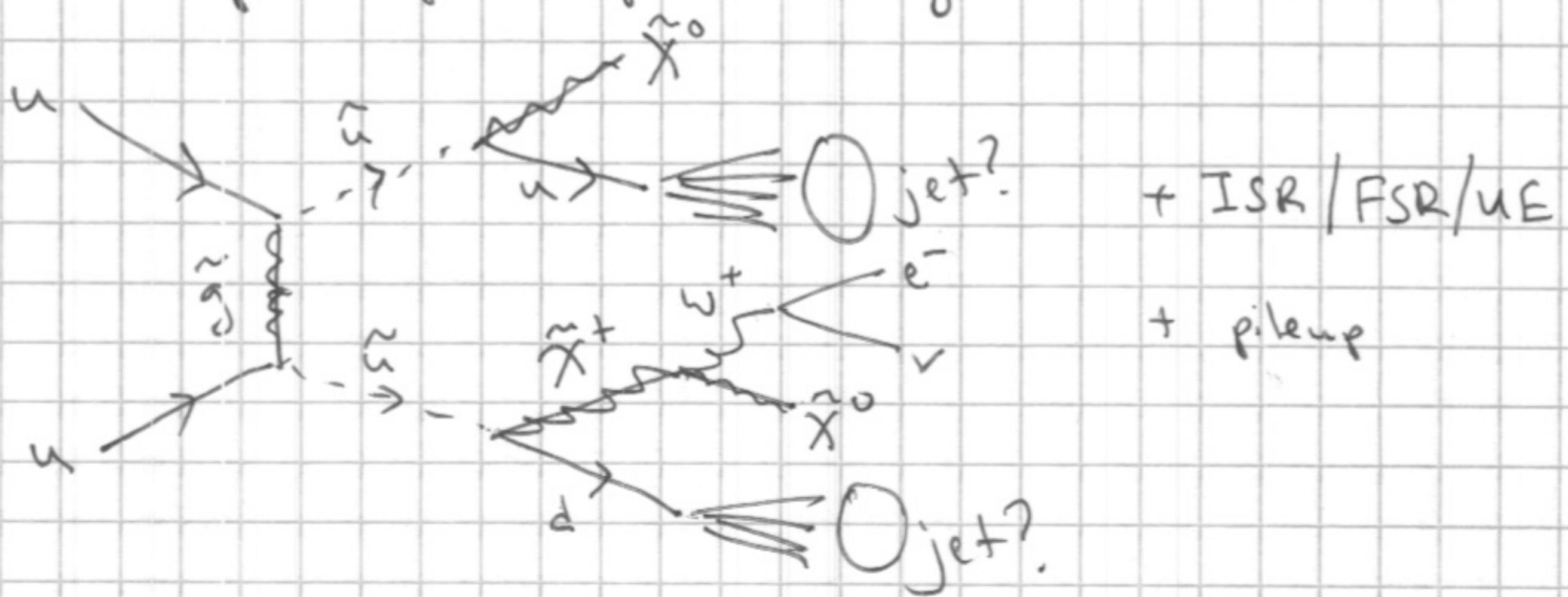
Clusters
of
Partons



Clusters
of
Hadrons

Up to $\Delta QCD/E_{jet}$
ambiguities.

E.g. Supersymmetry search for jets,
plus leptons, plus missing momentum

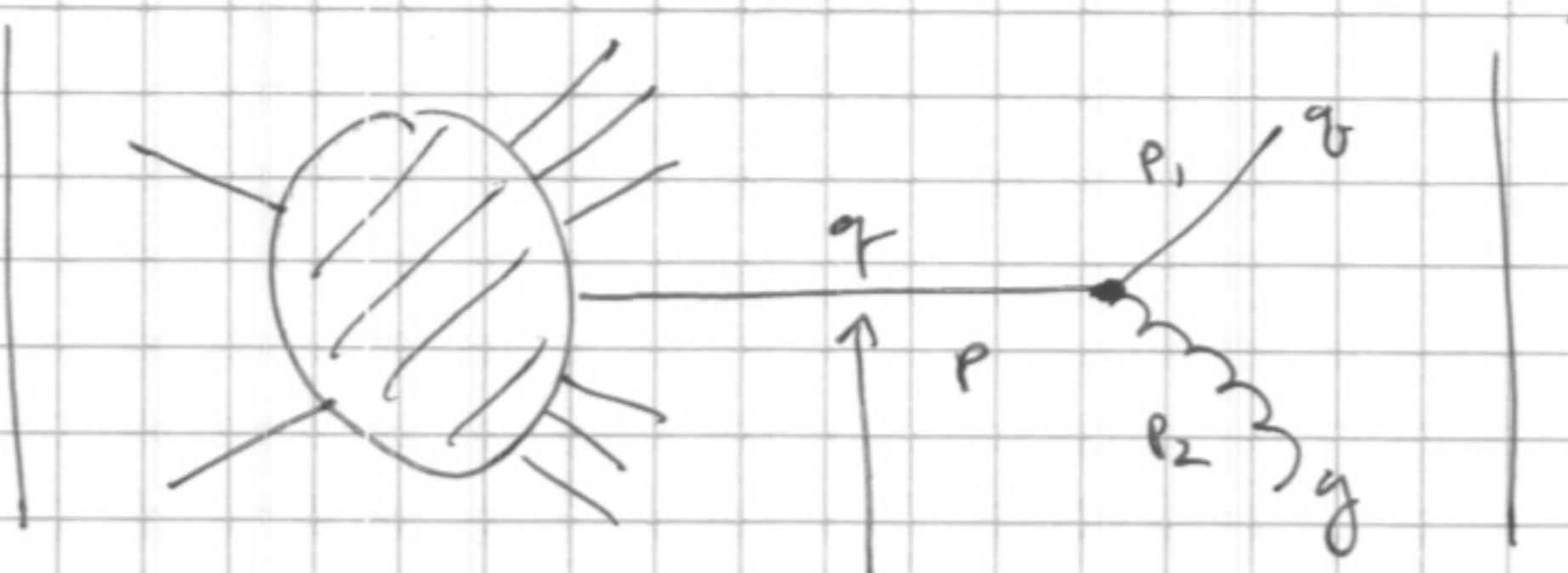


Looks like 2 jet event, but could
easily fall in 1, 2, 3, 4 ... jet bin
depending on algorithm details
and level of contamination.

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Why do jets form?

1) Soft-Collinear Singularities of QCD (more in lecture 3)



Singularity when
propagator goes on shell

$$P = P_1 + P_2 \text{ with } P^2 = P_1^2 = P_2^2 = 0$$

When does $P^2 = 0$?

Collinear limit: $\vec{P}_1 \parallel \vec{P}_2$ (tendency for jets to form)

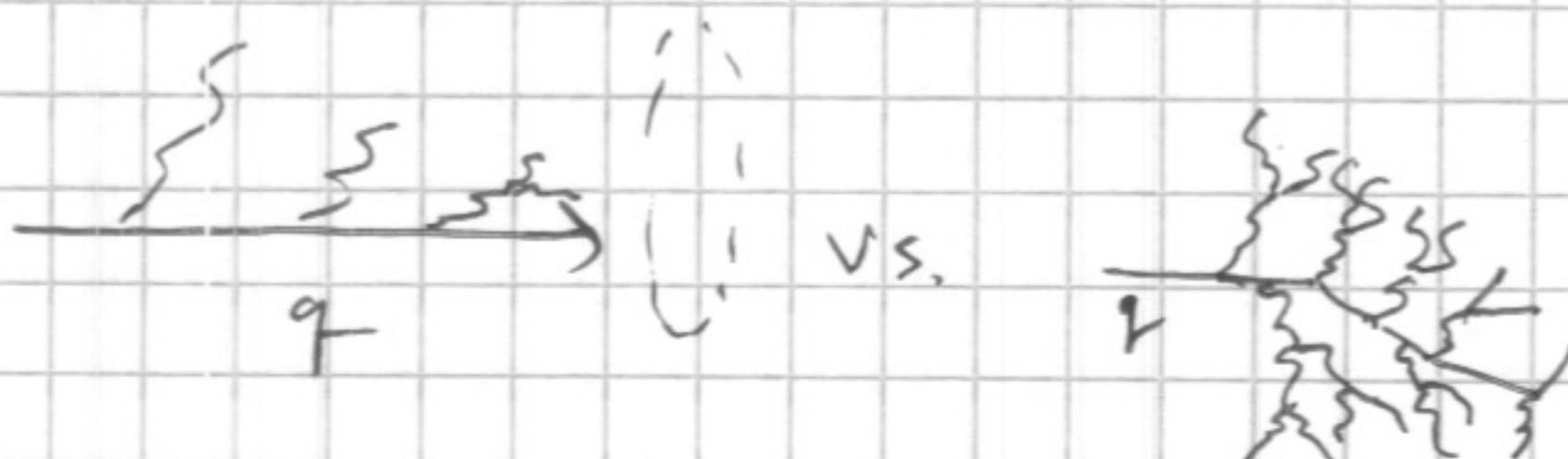
Soft limit $|\vec{P}_1| \rightarrow 0$ (annoyance for precision jet physics)

Note: Jets are a perturbative feature

2) Asymptotic Freedom (α_s small at high enough energies)

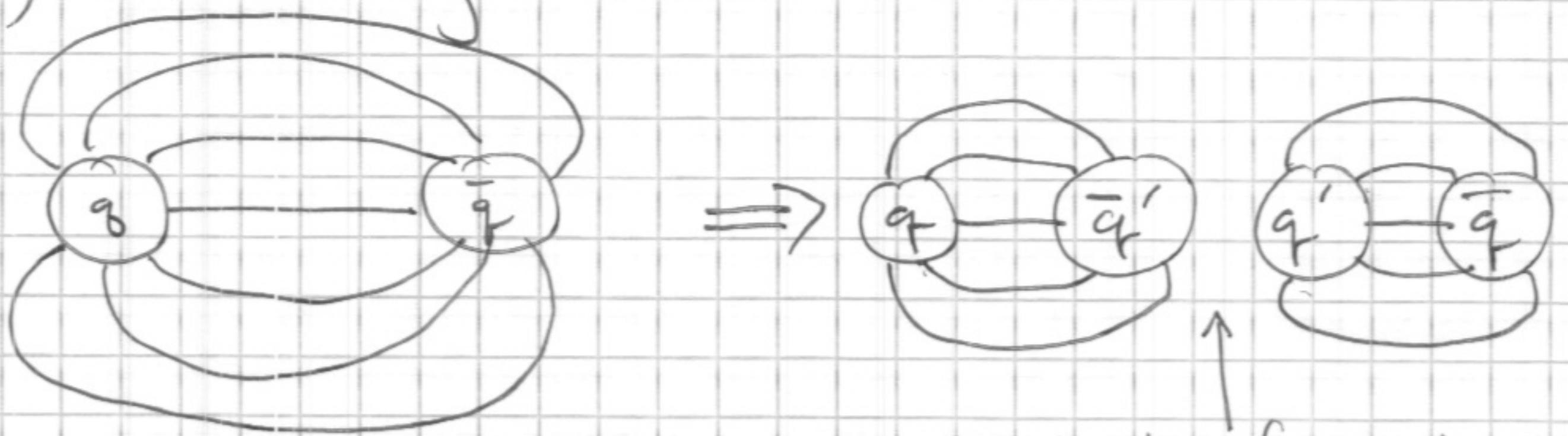
$$\alpha_s(M_Z) \approx 0.12$$

Otherwise, many emissions create ball
(instead of cone) of radiation



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3) Color strings break:



Confining gluon flux

Eventually favorable
to sever flux tube

Otherwise, you would get excited hadron states instead of jets.

String picture explains a lot, actually

→ Strings break easily: direction of quark/gluon ≈ direction of jet

→ String has energy density: massless quark/gluon \Rightarrow massive jet
 $m_{\text{jet}} \sim \alpha_s R E_{\text{jet}}^2$ (see lecture 4)

→ String severed by $q\bar{q}$ pairs: jets are mostly mesons

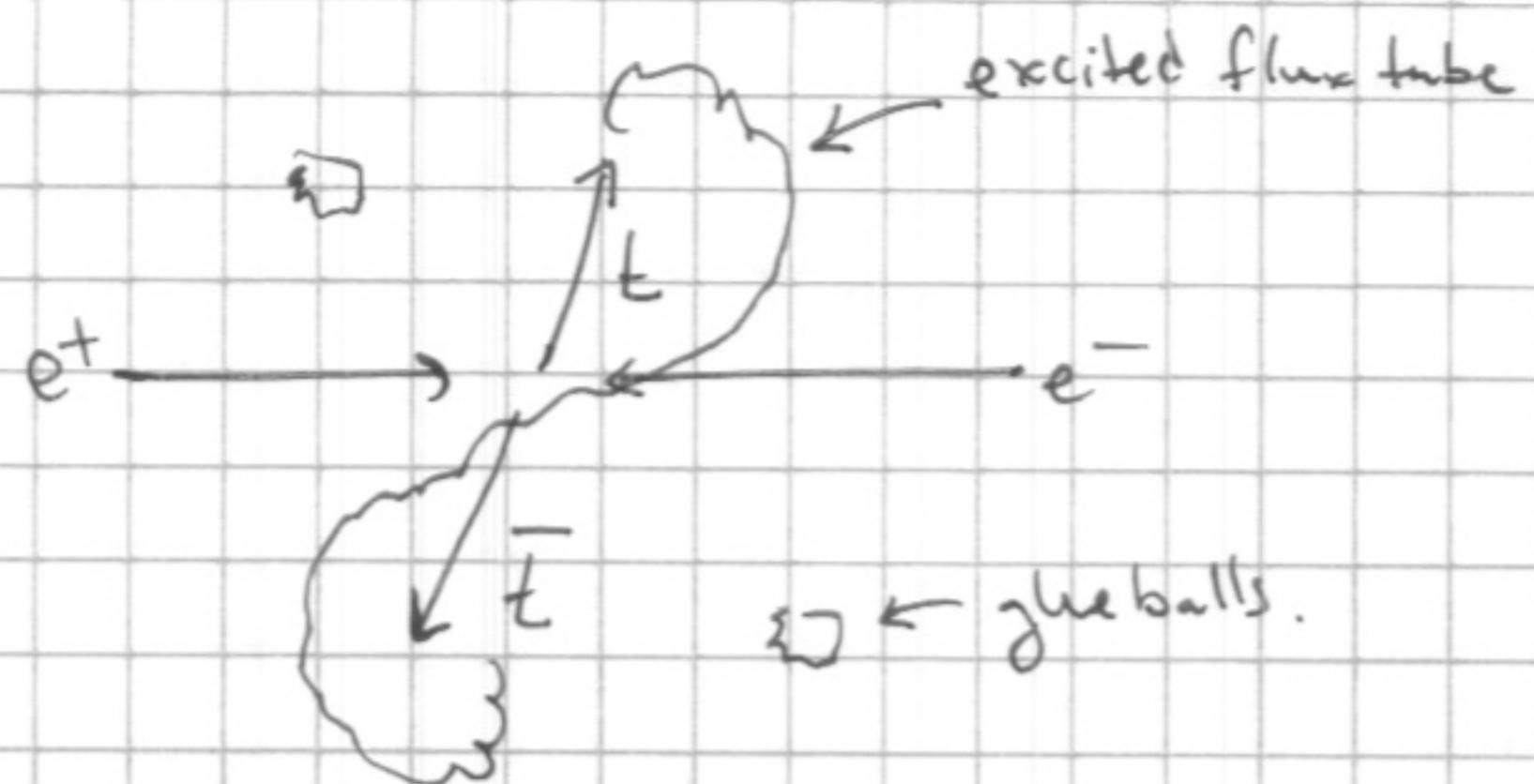
$$\text{jet} \approx \underbrace{\pi^+ \pi^-}_{80\%} + \underbrace{K^+ K^-}_{15\%} + \text{else} \quad 5\%$$

→ String is color singlet: jets are ambiguous
 (where exactly does string break?)

Sets are not automatic!)

Quirky world

(QCD with only top quarks)

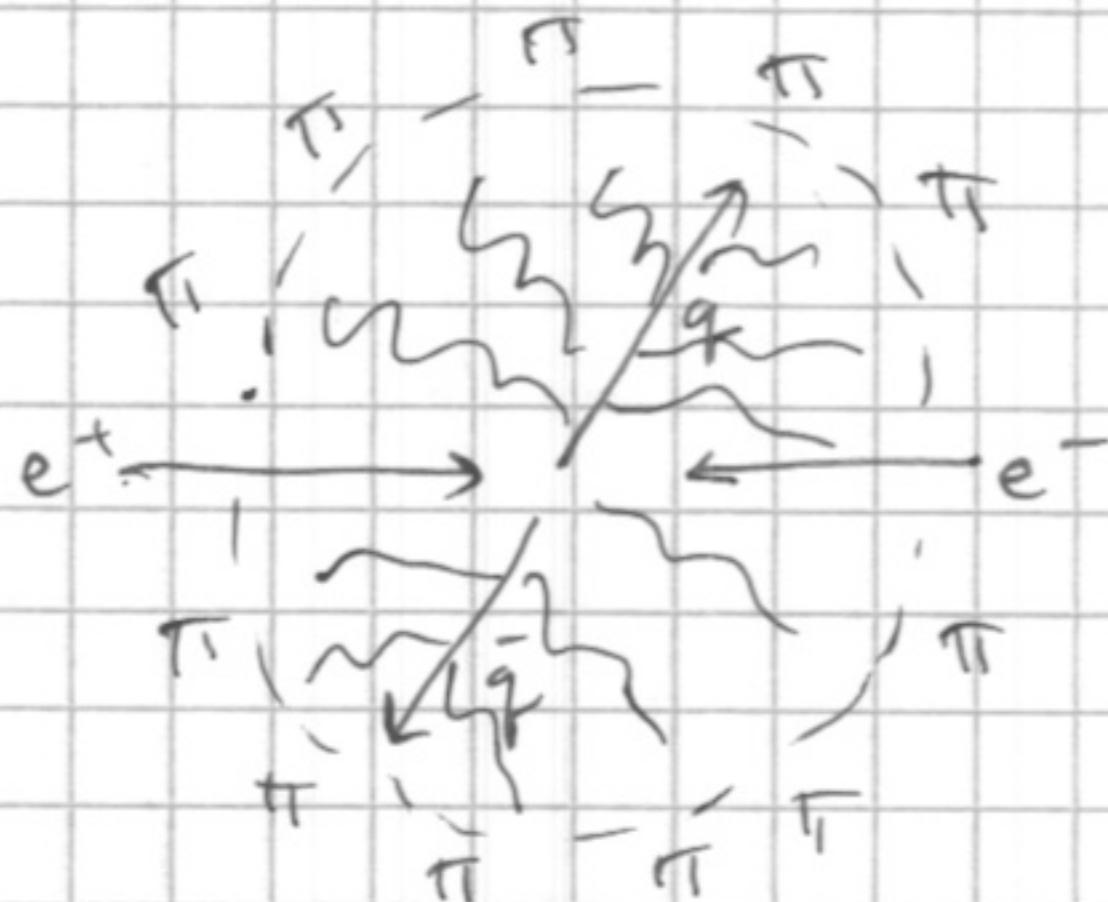


Can't break strings!

Only toponium & glueballs.

Quasi-Conformal world

$(\beta \approx 0, g \approx 4\pi)$



No hierarchy of scales

Most likely: spherical events.

See AdS/QCD

Jets are emergent property of QCD

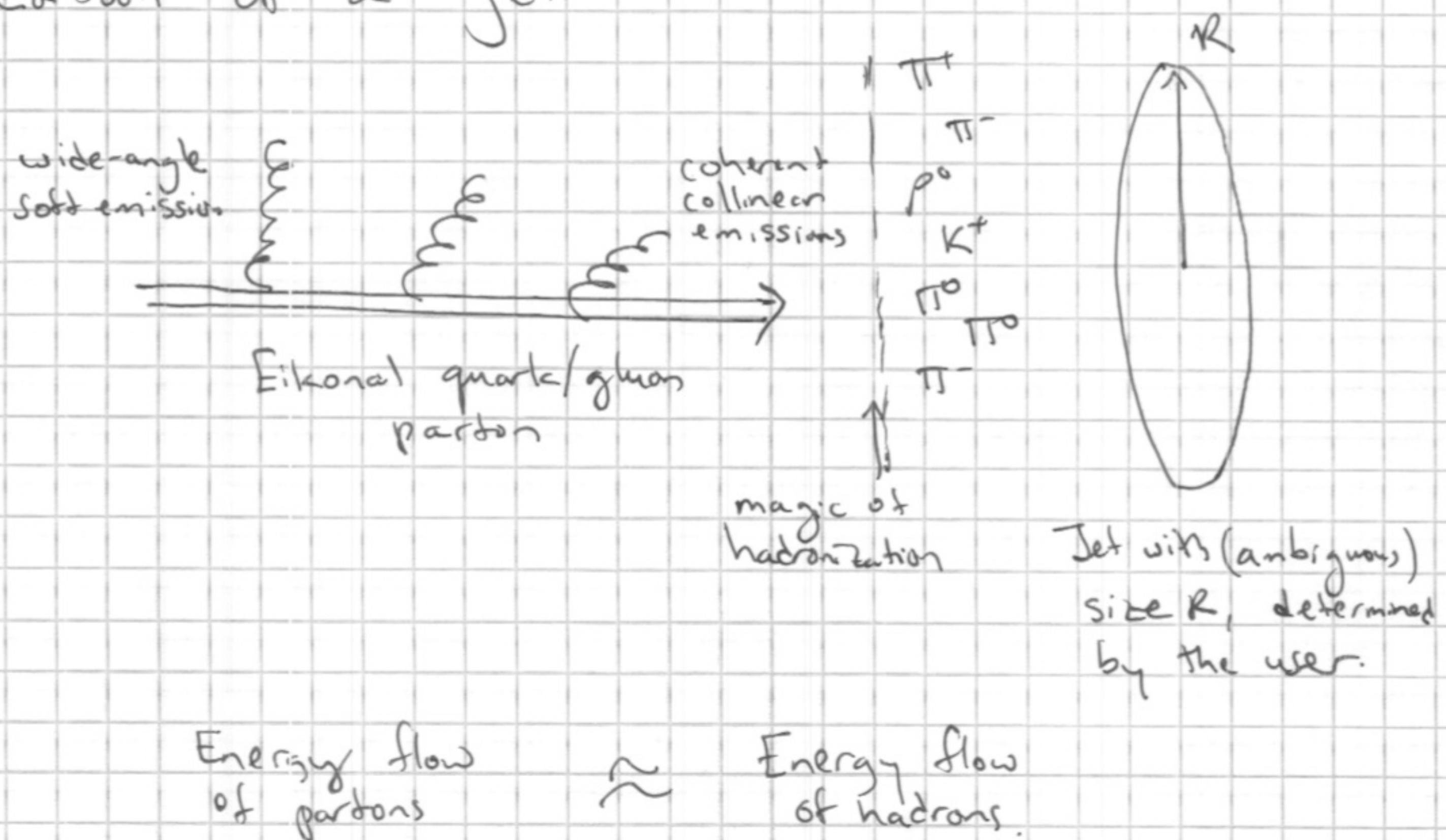
$$N_c = 3 \quad N_f = 2 - 5 \text{ (or 6)}$$

→ Collinear singularity + Color coherence

→ Asymptotically free... but confining

→ Color strings break ($m_{u,d} \ll \Lambda_{QCD}$)

Cartoon of a jet



Allows us to study jets at partonic level
up to Λ_{QCD} non-perturbative effects.

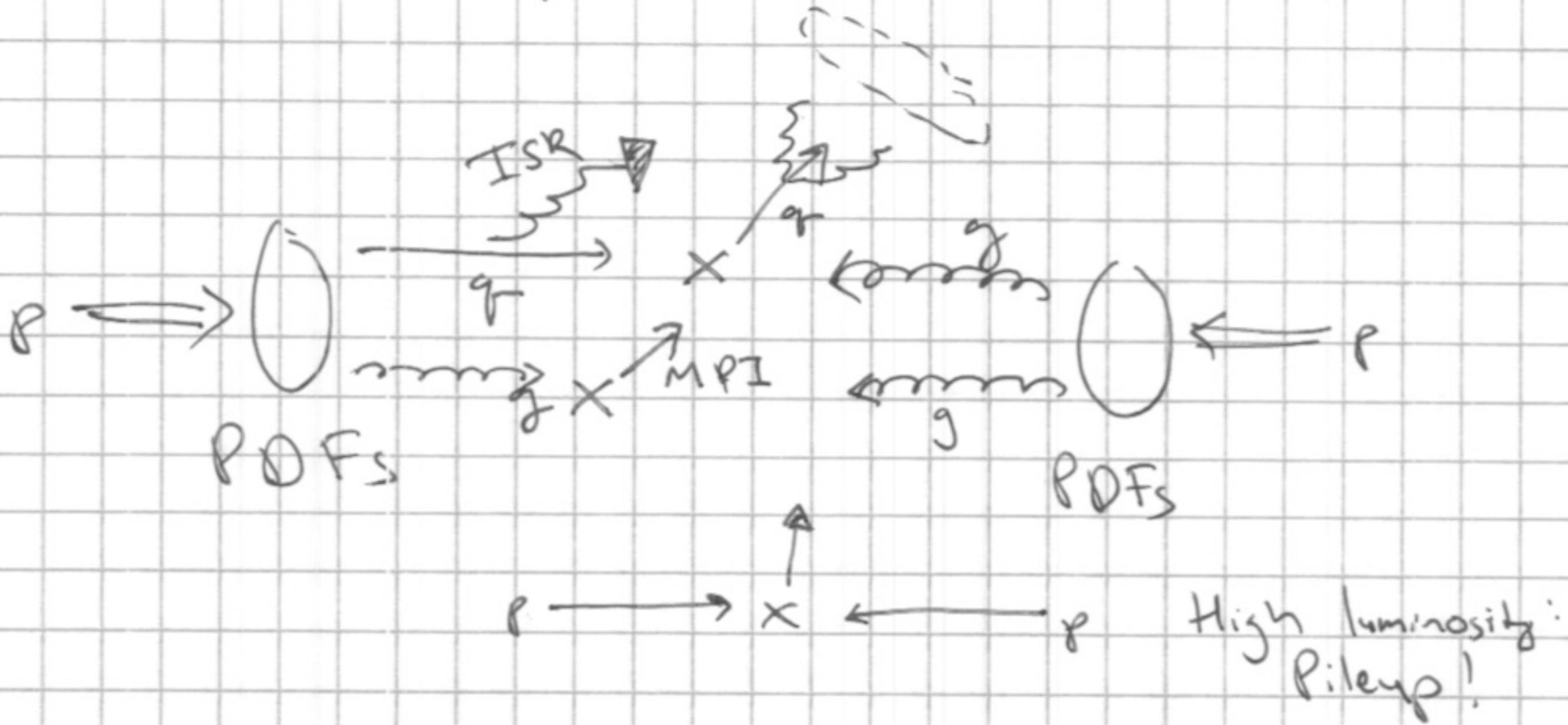
Messiness is also emergent property of QCD

→ Initial State Radiation

→ Multiple Parton Interactions
(aka, underlying event)

→ Pileup

Partially
mitigated by
jet grooming
(lecture 4)



Experimentally:

$$\text{Jet} = \begin{matrix} \text{Desired Radiation} \\ \text{from Hard} \\ \text{Quark/Gluon} \end{matrix} + \begin{matrix} \text{Additional} \\ \text{Contamination} \end{matrix}$$

Where are we going?

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→ Jet Algorithms (how do define jets experimentally and theoretically)

→ Soft / Collinear Limit (example calculation of quark/gluon separation)

→ Cleaning / Classification
with Jet Substructure

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To maximize discovery potential of LHC, have to use all standard model particles as probes.

Not Jets: $e \mu \tau v_1 v_2 v_3 \gamma$
 \uparrow
microjets

Jets: $u d s c b g$
 $\underbrace{c b}$
heavy flavor
tagging with longlived D and B mesons.

Fat Jets : $W \rightarrow q\bar{q}'$

$Z \rightarrow q\bar{q}$

Relevant
in highly
boosted
regime

$H \rightarrow b\bar{b}$

$t \rightarrow b W$

$\hookrightarrow q\bar{q}'$

Ignore hadronic final states at your peril !