Jesse Thaler

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.)

Part 1: Introduction to Jets

A Renaissance in Jet Physics!

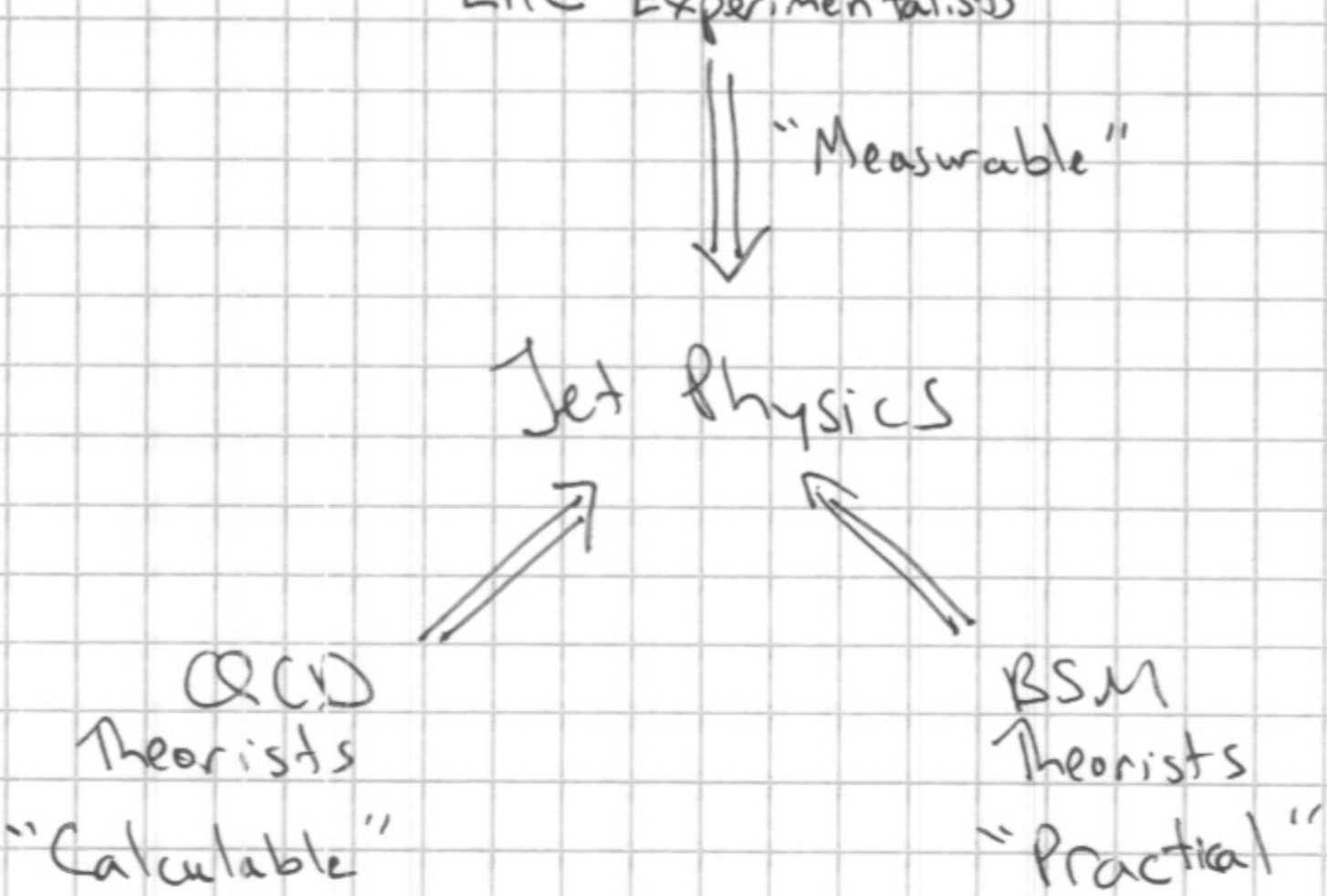
→ First jet algorithms in 1970s (Sterman-Weinberg)

→ First jet algorithm that experimentalists & theorists could agree on: 2008 (anti-k_t)

↑ coincidentally, when I entered the field

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

Convergence of 3 communities



(From 2011 Boston Jet Physics Workshop)

What's driving this field?

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

Compared to TeVatron:
- ≈ x7 higher energy
- ≈ x10-20 higher luminosity
- ≈ x5 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

$\sqrt{\hat{s}} >> m_{top}, m_{W/Z}, m_{Higgs} \ldots$

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?

→ Hierarchy Problem?

→ Higgs Boson as Probe?

(why I originally got into jets.)

Pushing the Boundaries of Quantum Field Theory

→ Jets as Emergent Phenomena?

→ Properties of Gauge Theories?

→ Calculations In & Beyond Perturbation Theory?

(why I continue to work on jets)

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

Remember, all arises from QCD (turning off electroweak for most of these lectures.)

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

$$+ \sum_{i \in \text{quarks}} \Big[\bar{\psi}_i i\bar{\sigma}^\mu D_\mu \psi_i + \bar{\psi}^c_i i\bar{\sigma}^\mu D_\mu \psi_i{}^c$$

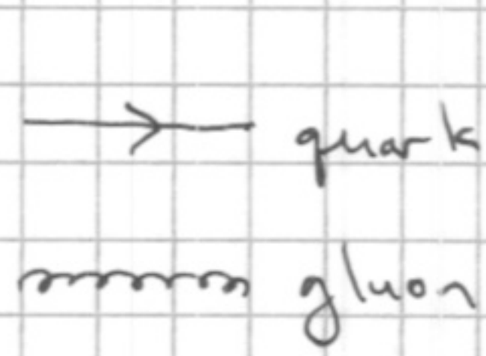
(in two-component notation)

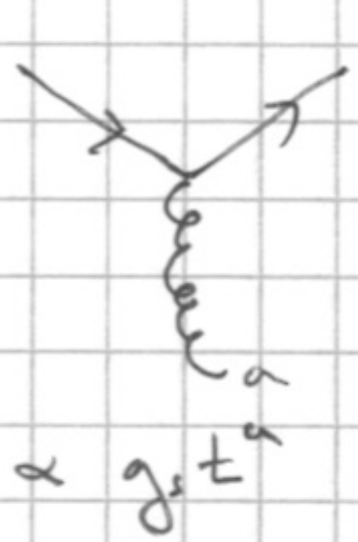
D_μ: covariant derivative $\equiv \partial_\mu - i A_\mu^a t^a$

$$- m_i \left(\psi_i \psi_i{}^c + \bar{\psi}_i \bar{\psi}_i{}^c \right) \Big]$$

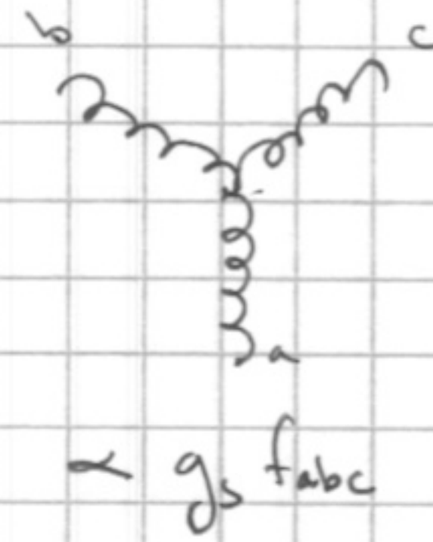
m_i: quark masses

And that's it!

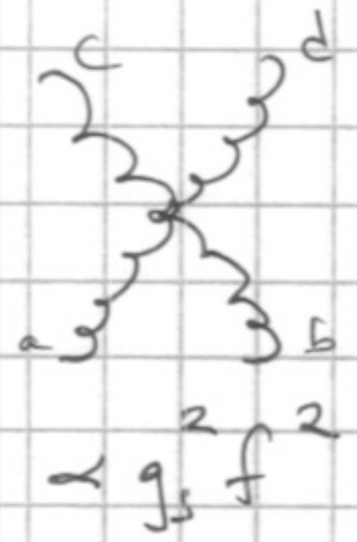




$\propto g_s t^a$



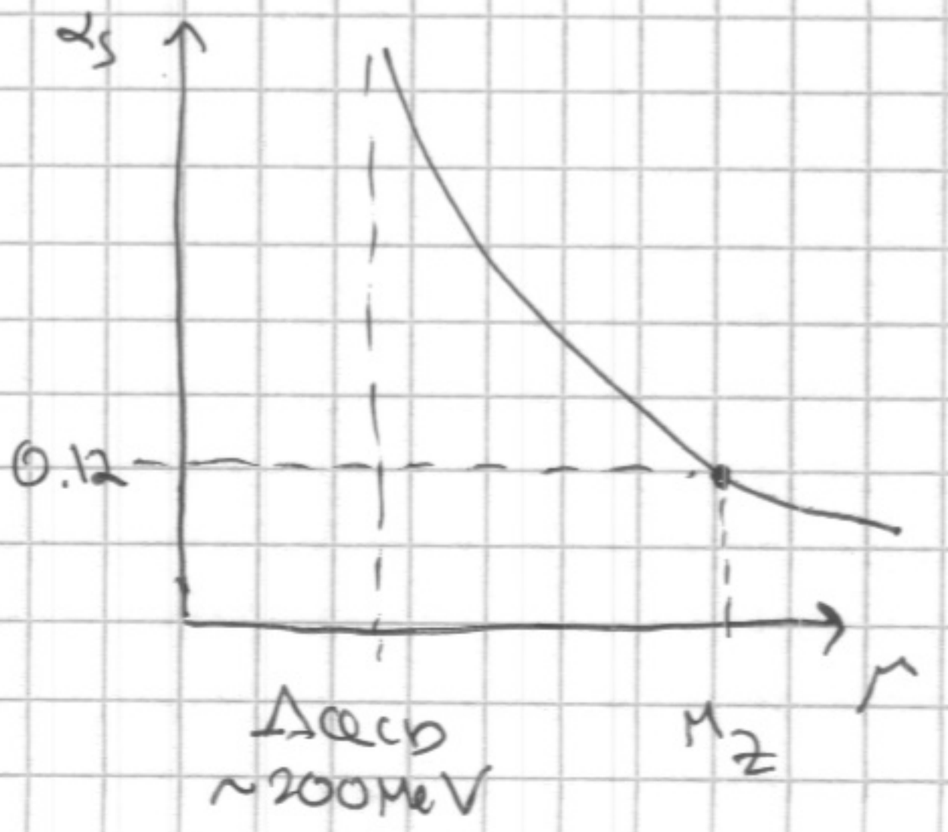
$\propto g_s f_{abc}$



$\propto g_s^2 f^2$

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

$$\mu \frac{\partial}{\partial \mu} \left(\frac{1}{\alpha_s} \right) = \frac{1}{4\pi} \left(\frac{11}{3} N_C - \frac{2}{3} N_f \right)$$



At short distances:

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

Long distances $\Rightarrow$ Confinement

Mesons ($q\bar{q}$)

spin-0: $\pi^+ \pi^- \pi^0 \eta K^+ K^- K^0 \eta' \ldots$

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

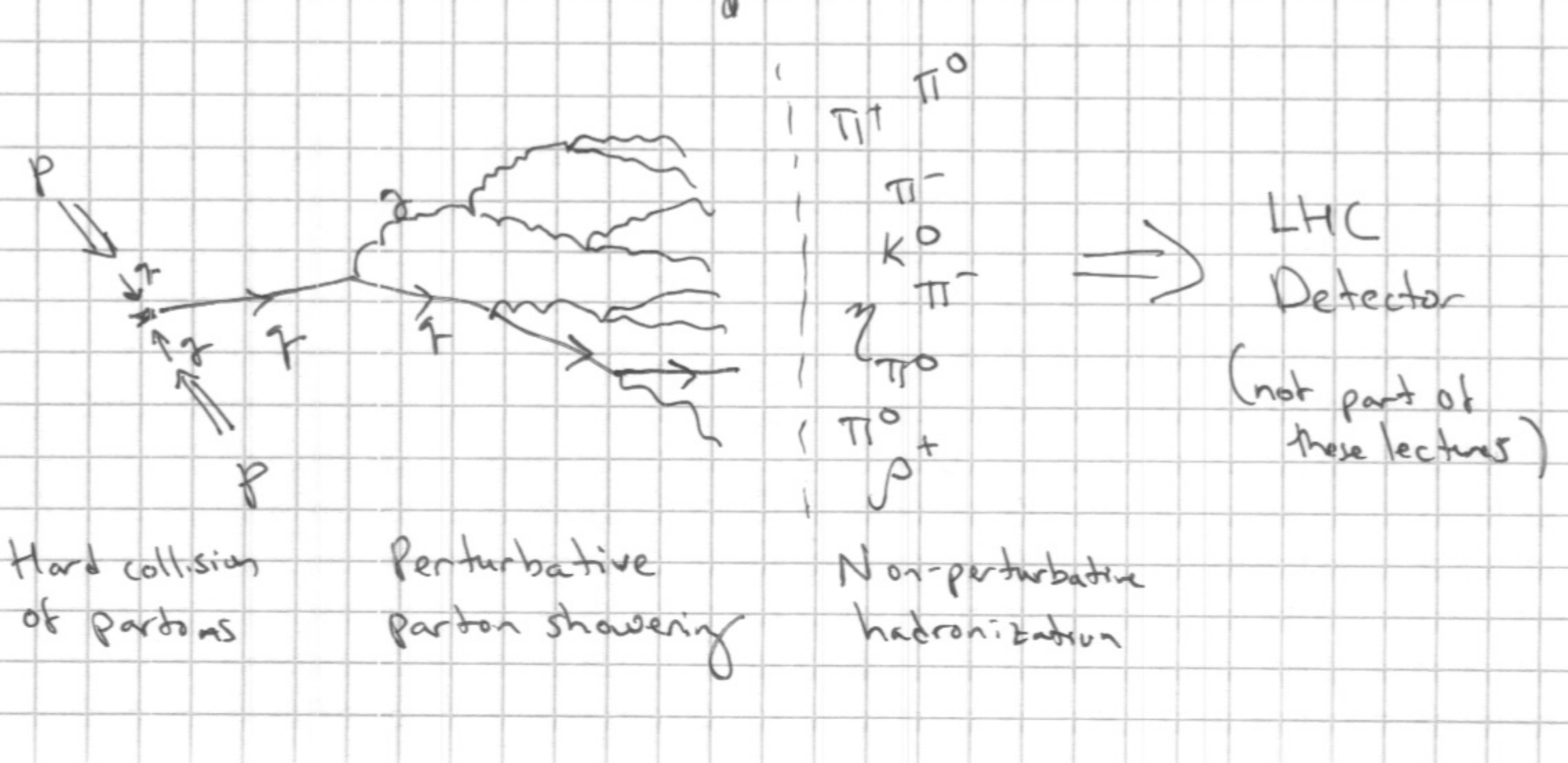
Baryons (qqq)

spin-$1/2$: $p\ n\ \Lambda^0 \Sigma^+ \Sigma^0 \Sigma^- \Xi^0 \Xi^- \ldots$

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

Recently: tetraquarks & pentaquarks
$qq\bar{q}\bar{q}$ $qqqq\bar{q}$

Jets connect these regimes



Hard collision of partons

Perturbative parton showering

Non-perturbative hadronization

Key: Jets are fundamentally ambiguous

No such thing as perfect jet algorithm

Why? Color-carrying partons
vs.
Color-singlet hadrons

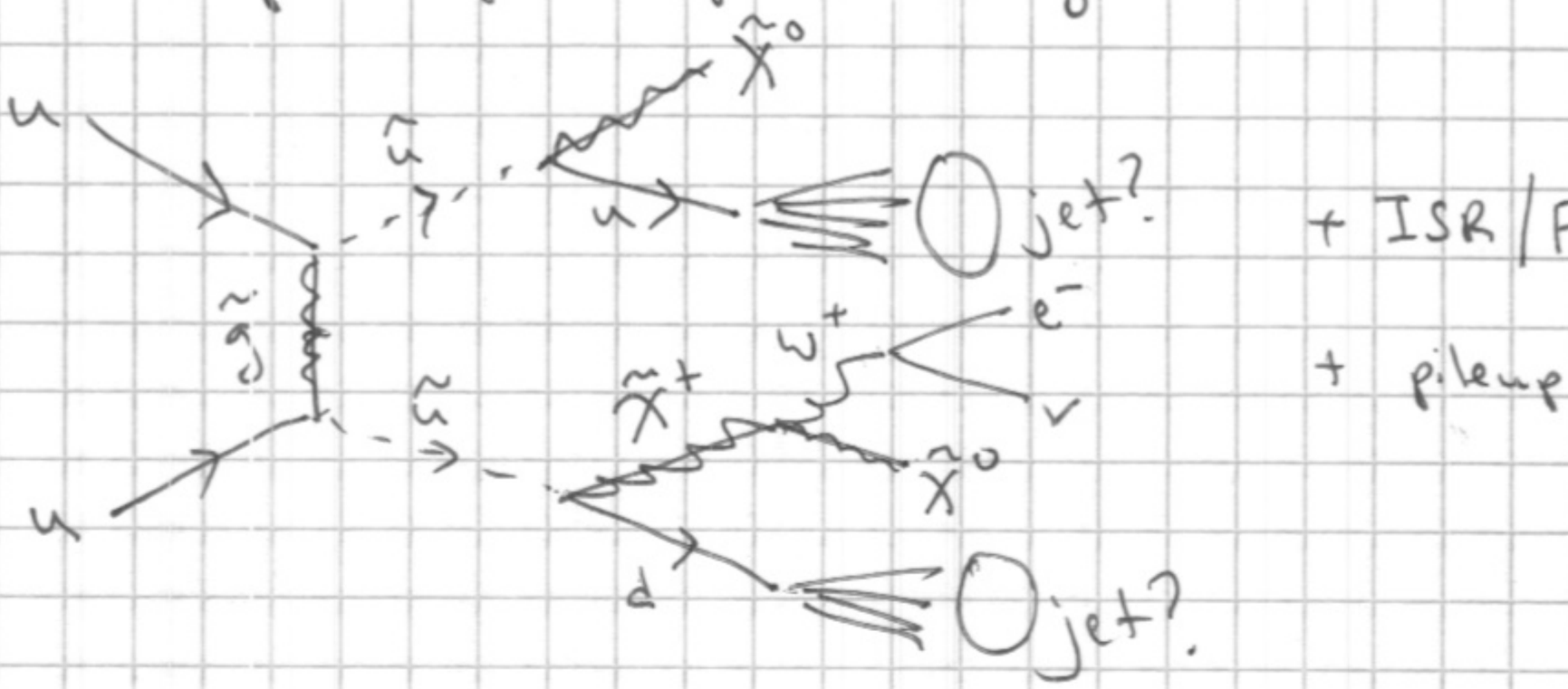
Best we can do:

Clusters of Partons $\approx$ Clusters of Hadrons

$\uparrow$

Up to Λ_{QCD}/Ejet ambiguities.

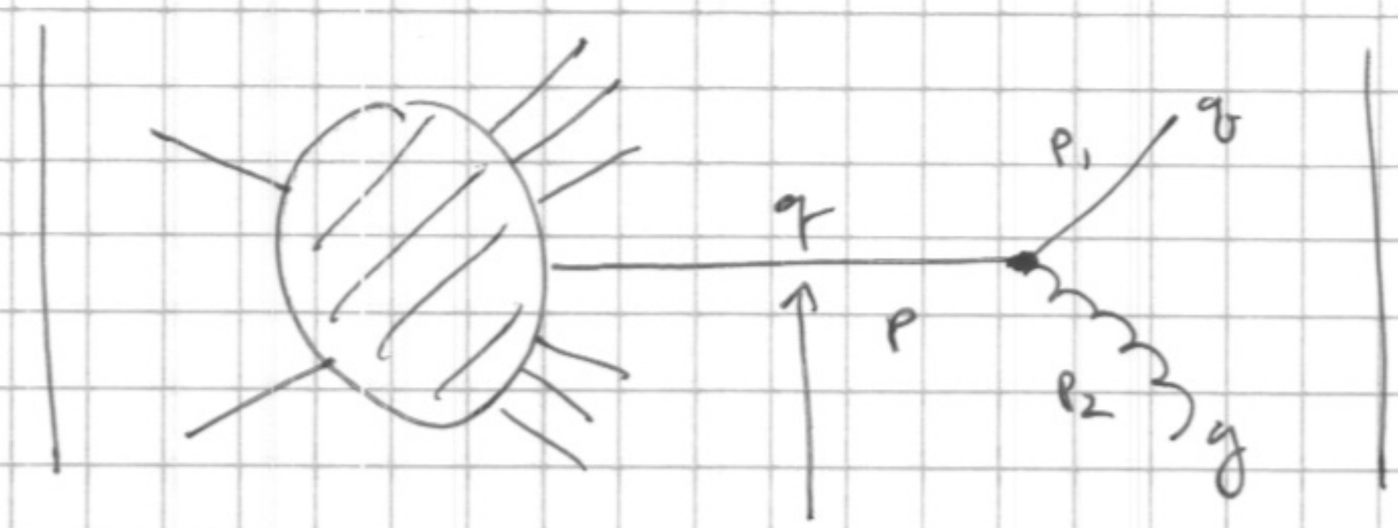
E.g. Supersymmetry search for jets plus leptons, plus missing momentum



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

Why do jets form?

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



singularity when propagator goes on shell

$p = p_1 + p_2$ with $p_1^2 = p_2^2 = 0$

When does $p^2 = 0$?

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

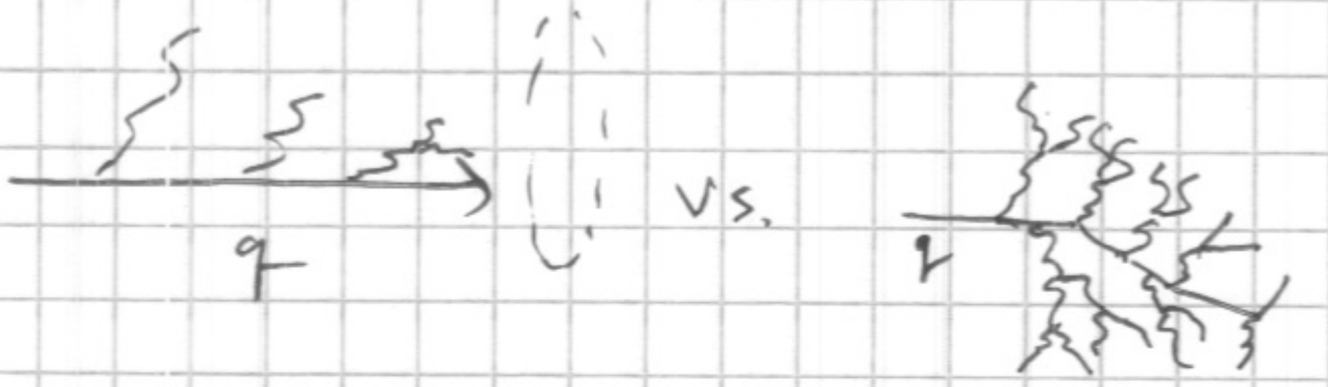
Soft limit $|\vec{p}_1| \to 0$ (annoyance for precision jet physics)

Note: Jets are a perturbative feature

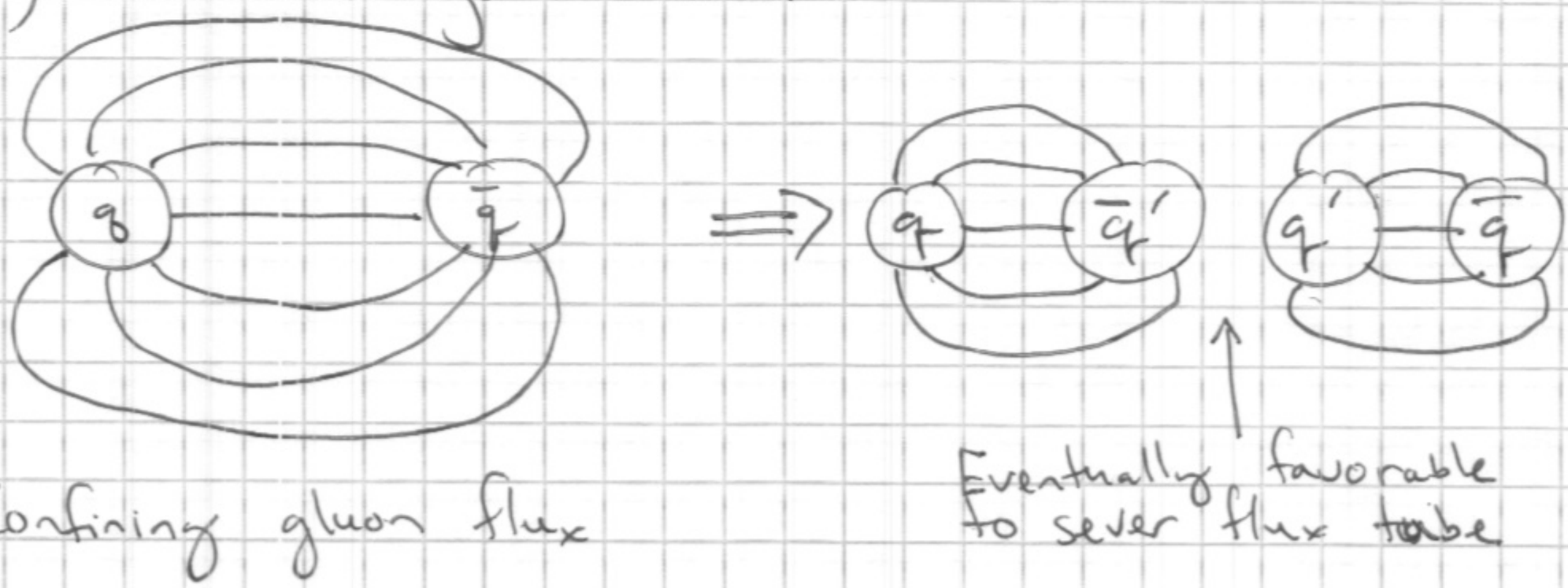
2) Asymtotic Freedom (α_s small at high enough energies)

$$\alpha_s(M_Z) \simeq 0.12$$

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



3) Color strings break:



Confining gluon flux

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

String picture explains a lot, actually

→ Strings break easily: direction of quark/gluon $\approx$ direction of jet

→ String has energy density: massless quark/gluon $\Rightarrow$ massive jet

$m_{jet}^2 \sim \alpha_s R E_{jet}^2$ (see lecture 4)

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

$$jet \approx \underbrace{\pi^I \pi^0}_{\sim 80\%} + \underbrace{K^+ K^0}_{15\%} + \underbrace{else}_{5\%}$$

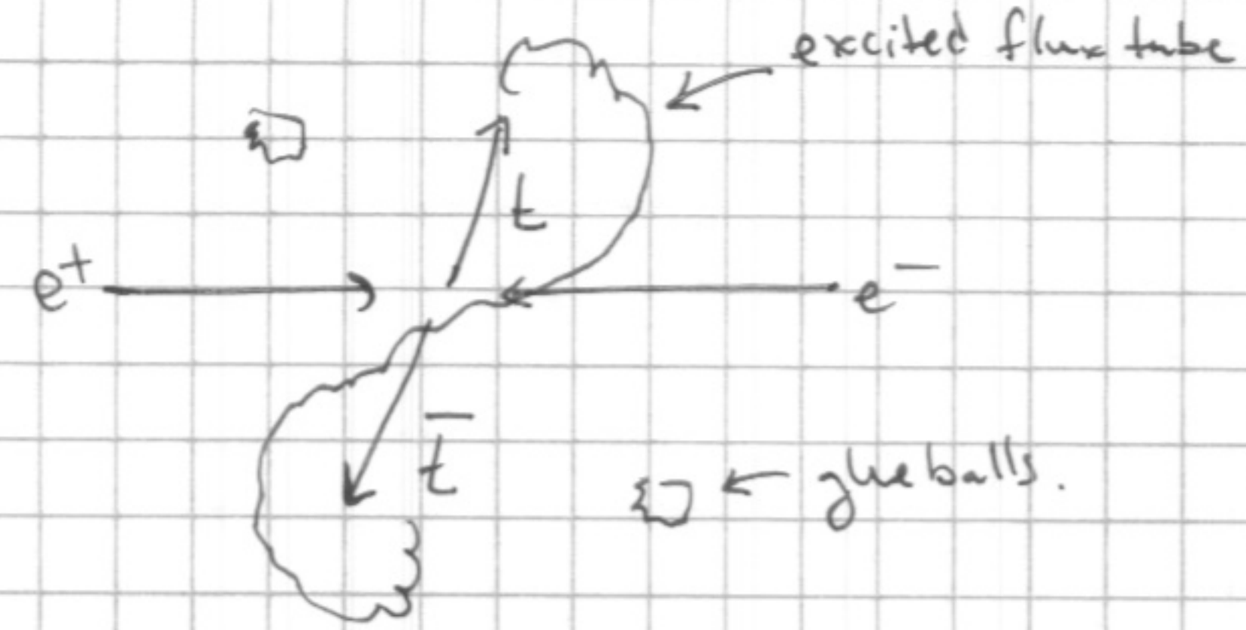
→ String is color singlet: jets are ambiguous

(where exactly does string break?)

Jets are not automatic!

Quirky world

(QCD with only top quarks!)

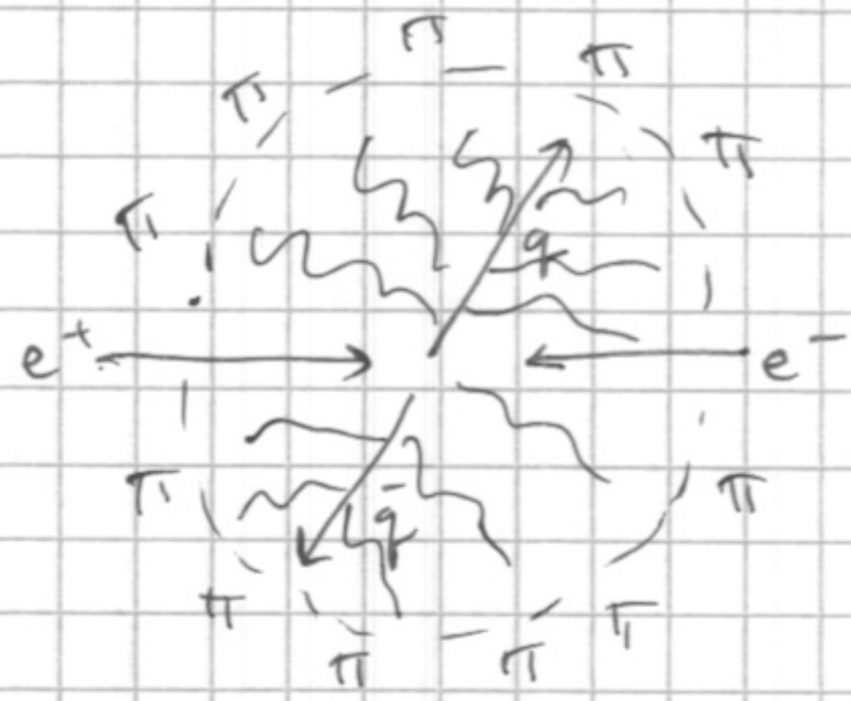


Can't break strings!

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

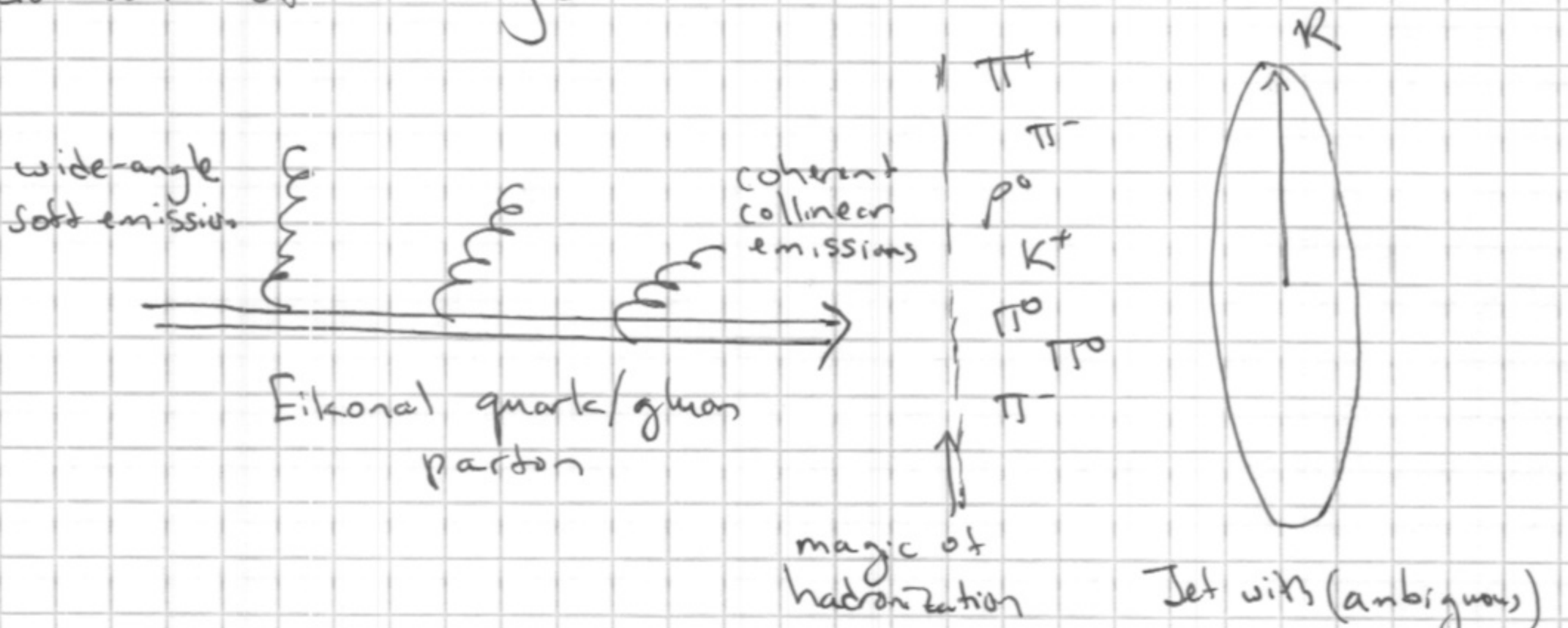
$N_c = 3$ $N_f = 2-5$ (or 6)

→ Collinear singularity + Color coherence

→ Asymptotically free... but confining

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

Cartoon of a jet



Energy flow of partons $\approx$ Energy flow of hadrons.

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

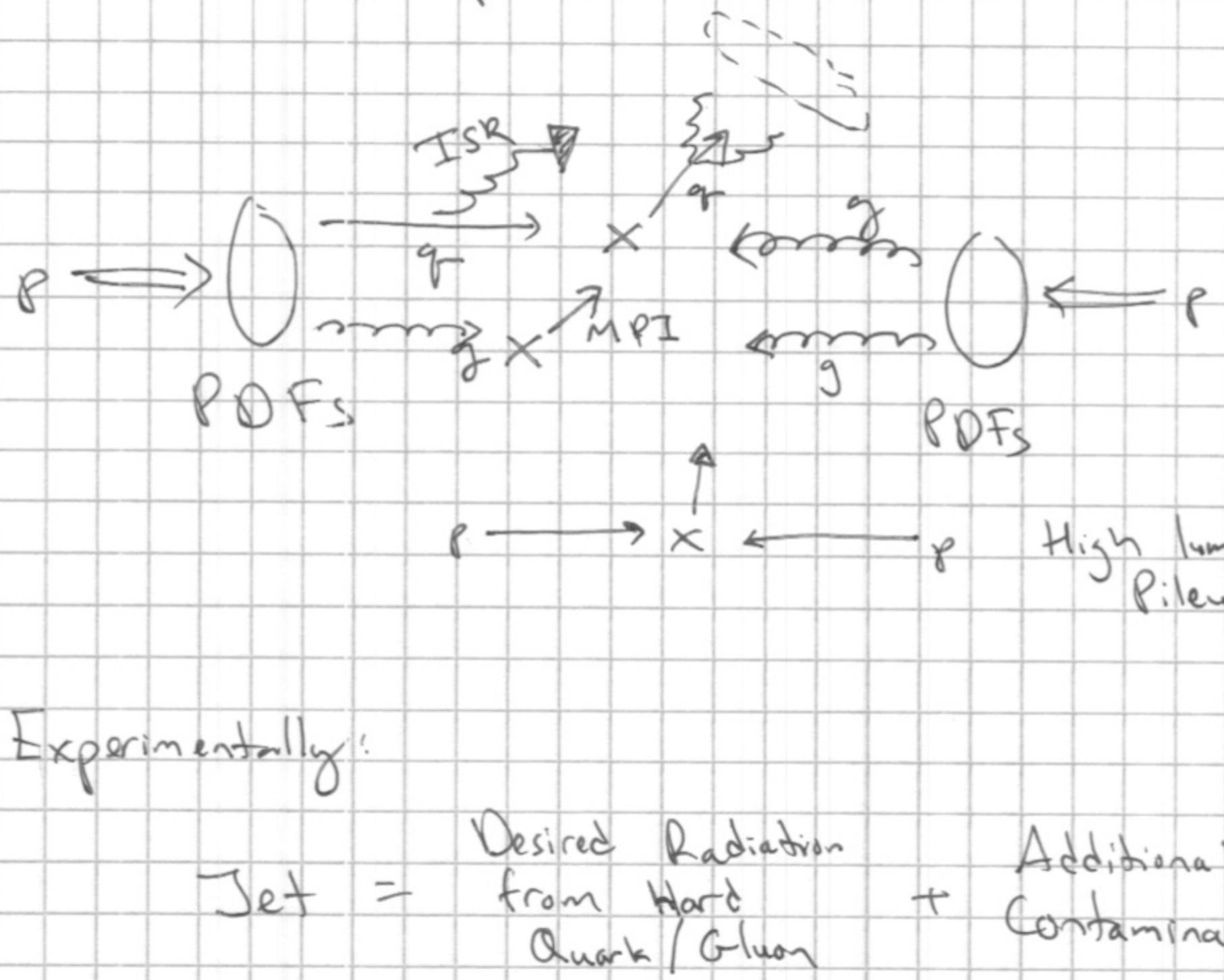
Messiness is also emergent property of QCD

→ Initial State Radiation

→ Multiple Parton Interactions (aka, underlying event)

→ Pileup

} Partially mitigated by jet grooming (lecture 4)



Experimentally:

Jet = Desired Radiation from Hard Quark/Gluon + Additional Contamination

Where are we going?

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

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

→ Cleaning / Classification with Jet Substructure

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

Not Jets : e μ τ ν_1 ν_2 ν_3 γ

↑ microjets

Jets : u d s c b g

heavy flavor tagging with longlived D and B mesons.

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

$Z \to q\bar{q}$

$H \to b\bar{b}$

$t \to bW \to q\bar{q}'$

Relevant in highly boosted regime

Ignore hadronic final states at your peril!