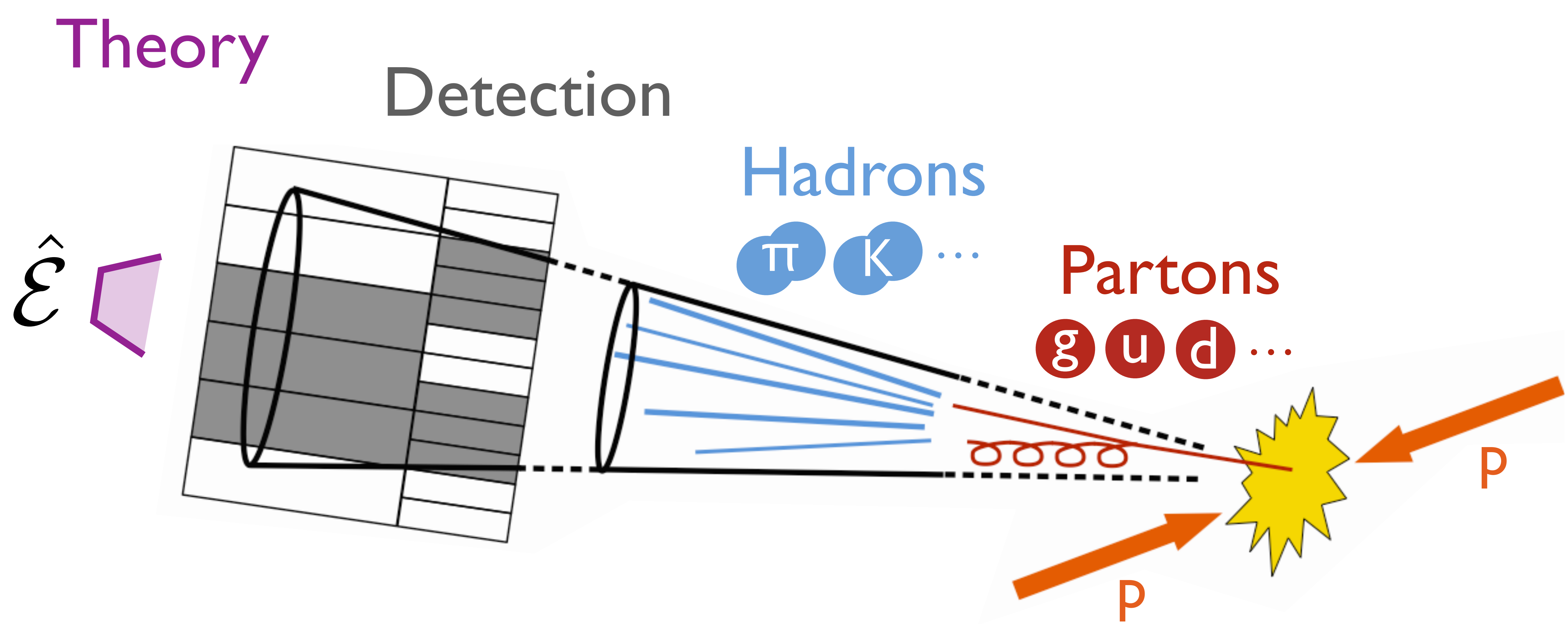
Introduction to Jet Physics from QCD

Jesse Thaler

KEK — January 16, 2017

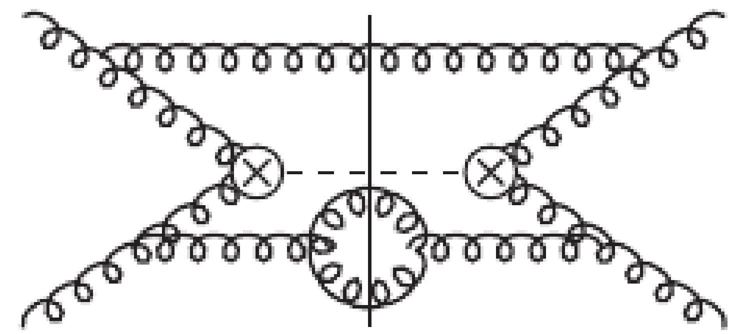
From Last Week

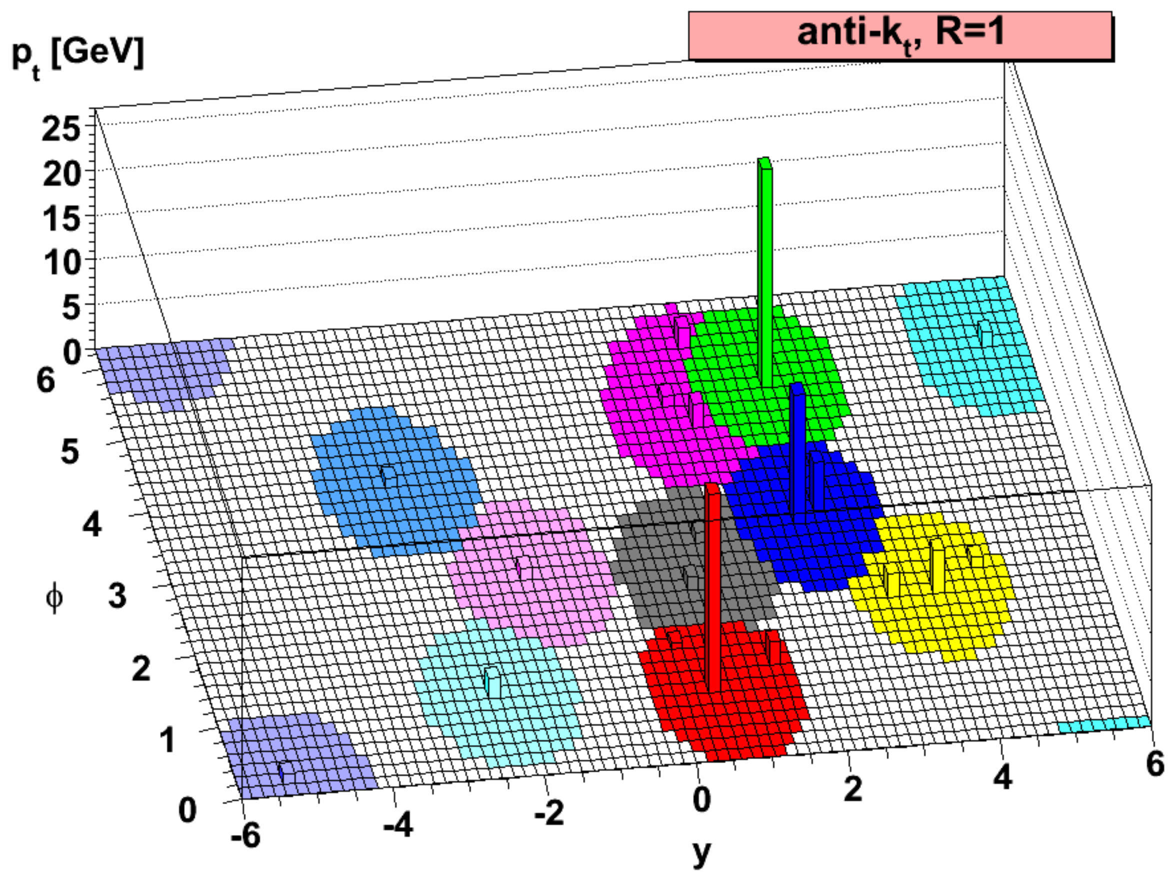


theoretical calculations (energy flow)	reconstruction ≈1-to-1 @ LHC (e.g. particle flow)	nonperturbative confinement (hadronization)	perturbative gluonic radiation (parton shower)	short-distance collision (hard scattering)

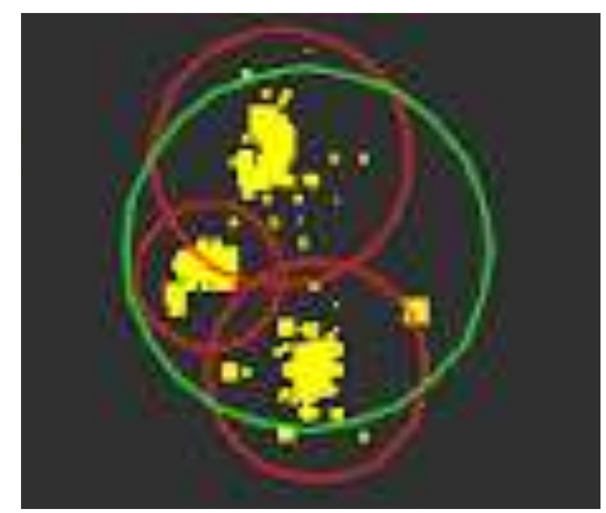
QCD Renaissance

Theory c. 2008–present





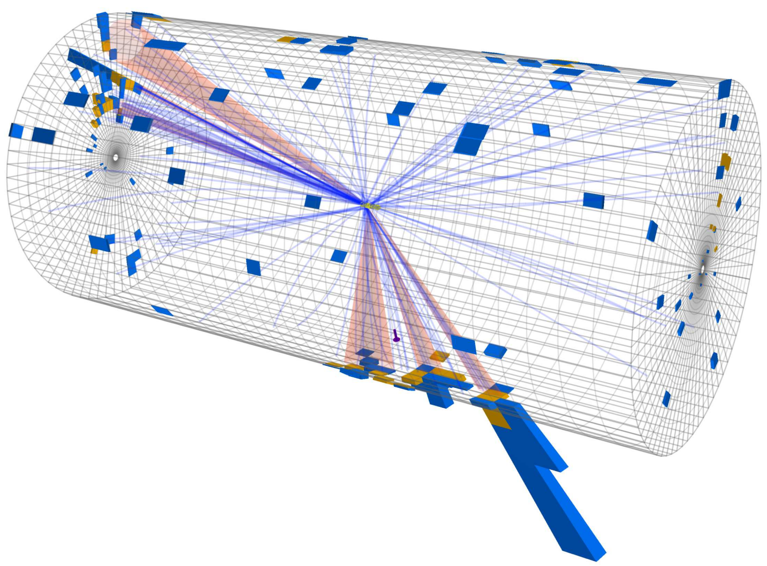
New Jet Algorithms



Jet Substructure

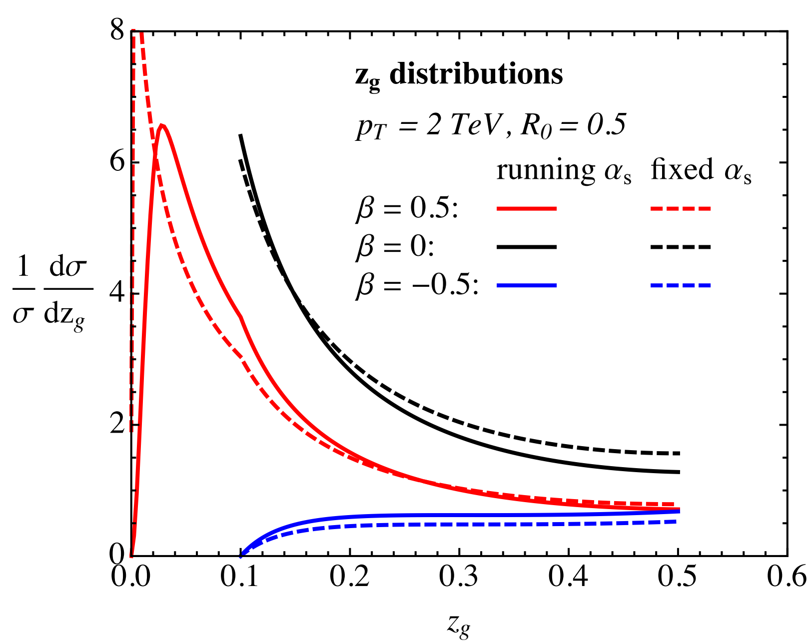
[Anti-k$_T$: Cacciari, Salam, Soyez, 2008; see also Delsart, 2006] [N^{3}LO: Anastasiou, Duhr, Dulat, Herzog, Mistlberger, 2015]
[BDRS: Butterworth, Davison, Rubin, Salam, 2008; see also Seymour, 1991, 1994]

Jet Substructure



Boosting the Search for New Phenomena

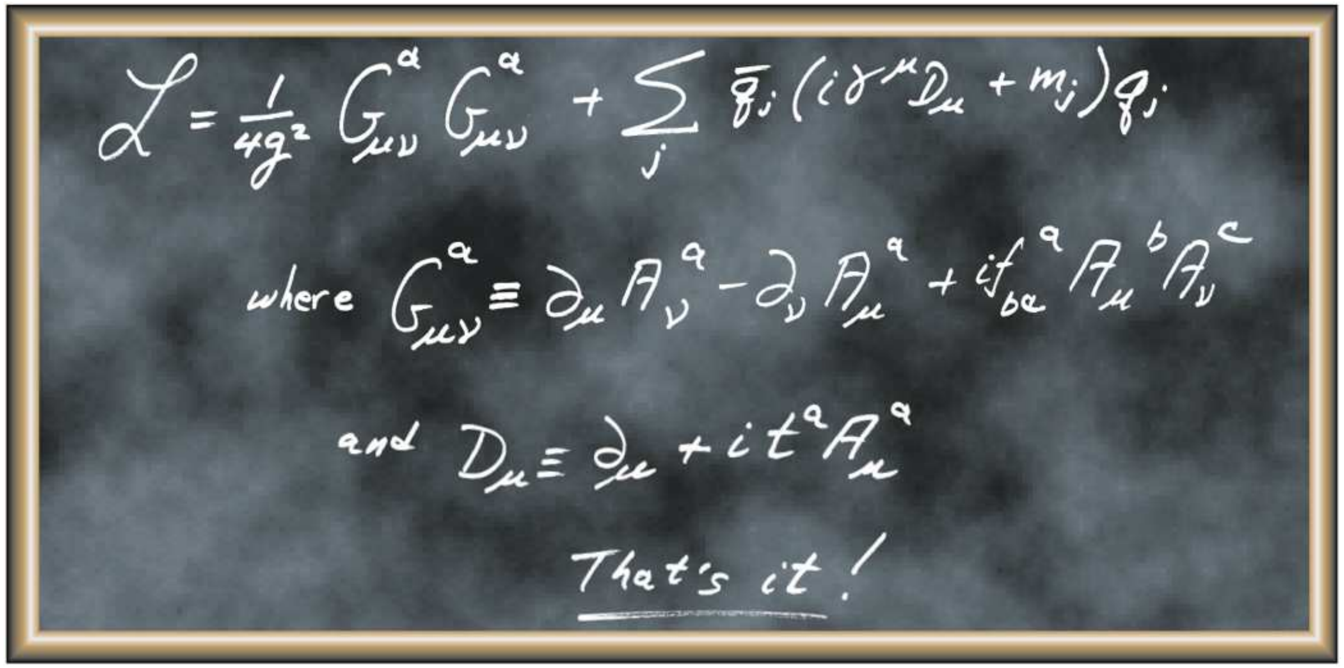
[Last Thursday & Friday]

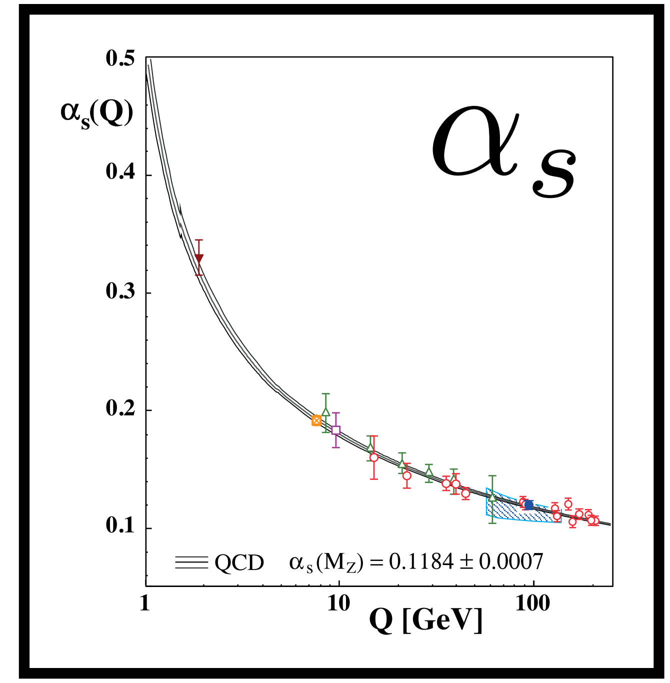


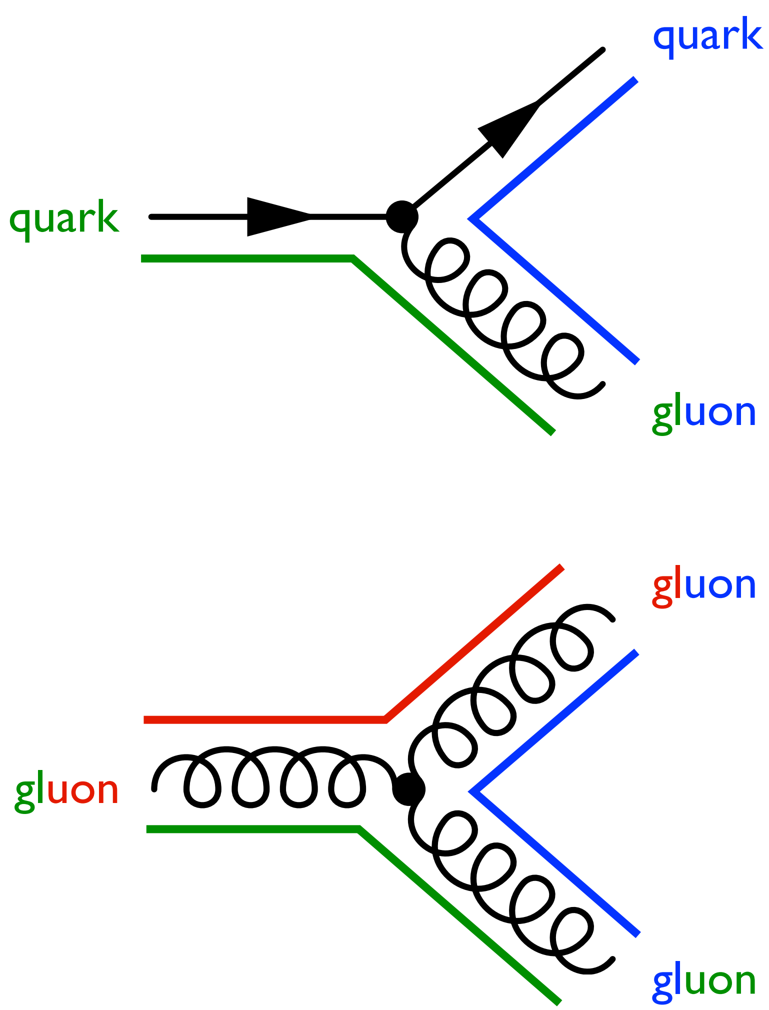
Pushing the Boundaries of Quantum Field Theory

[Today & Tuesday]

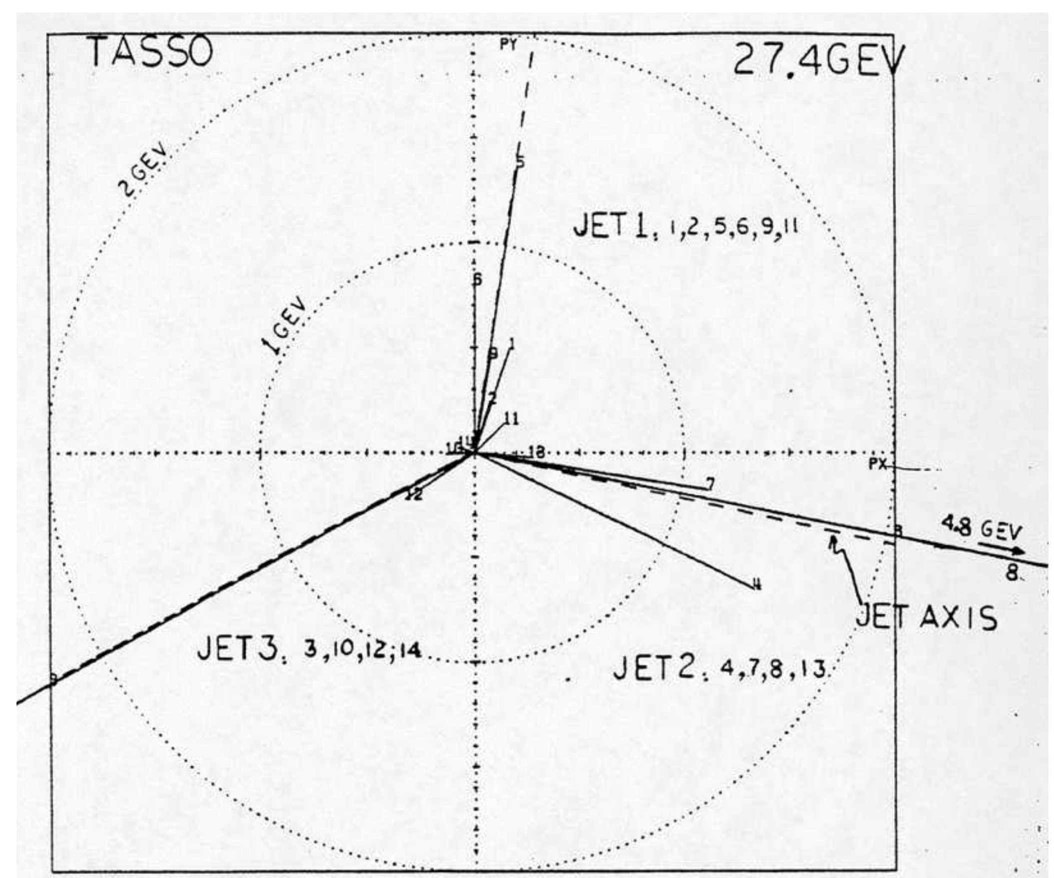
Dynamics of Jet Formation







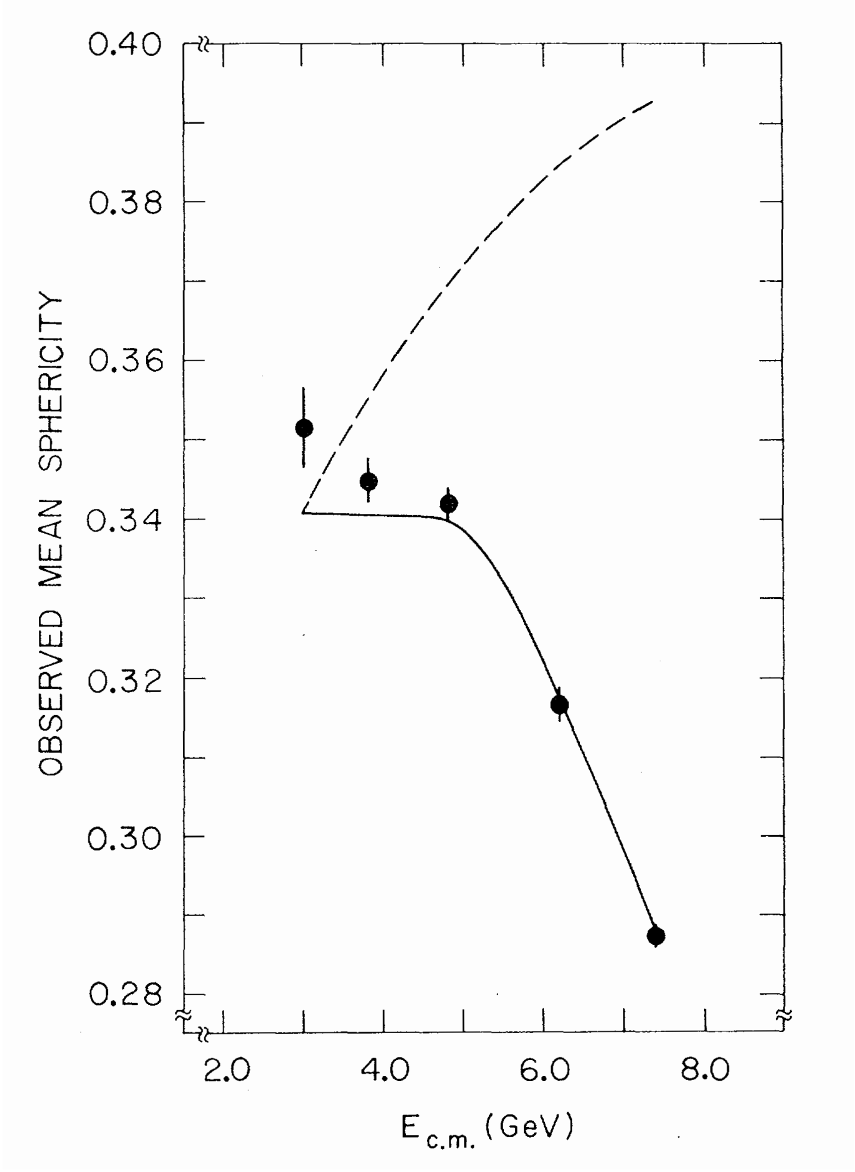
$\Rightarrow$



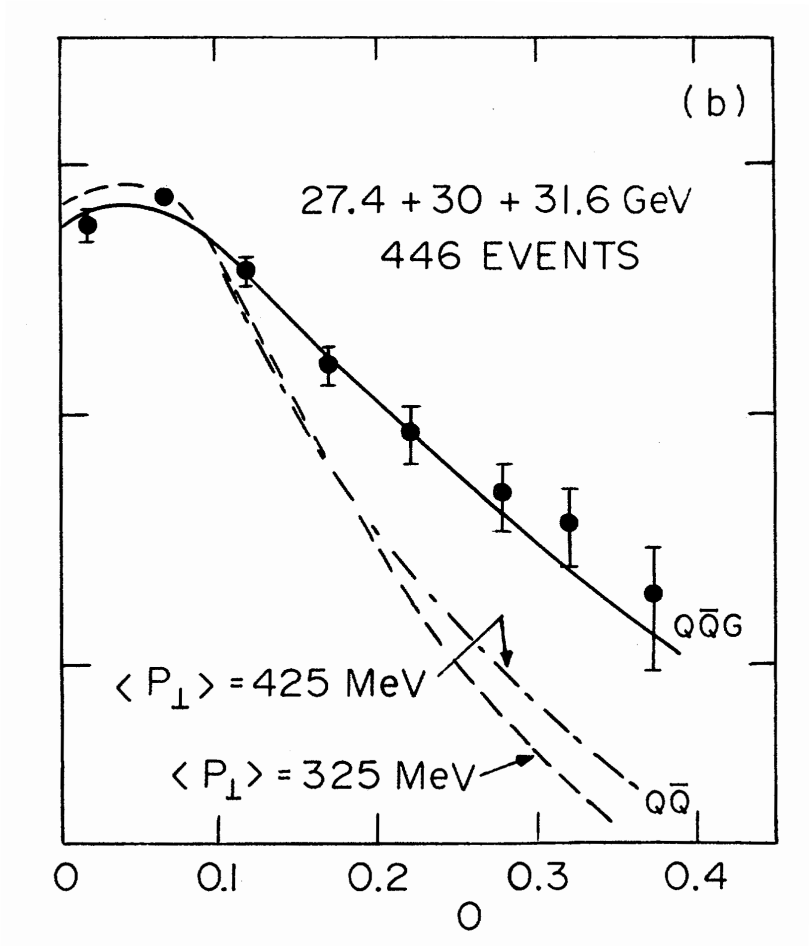
[TASSO @ PETRA @ DESY, 1979]

First Light on Jets

Jets @ SPEAR, 1975



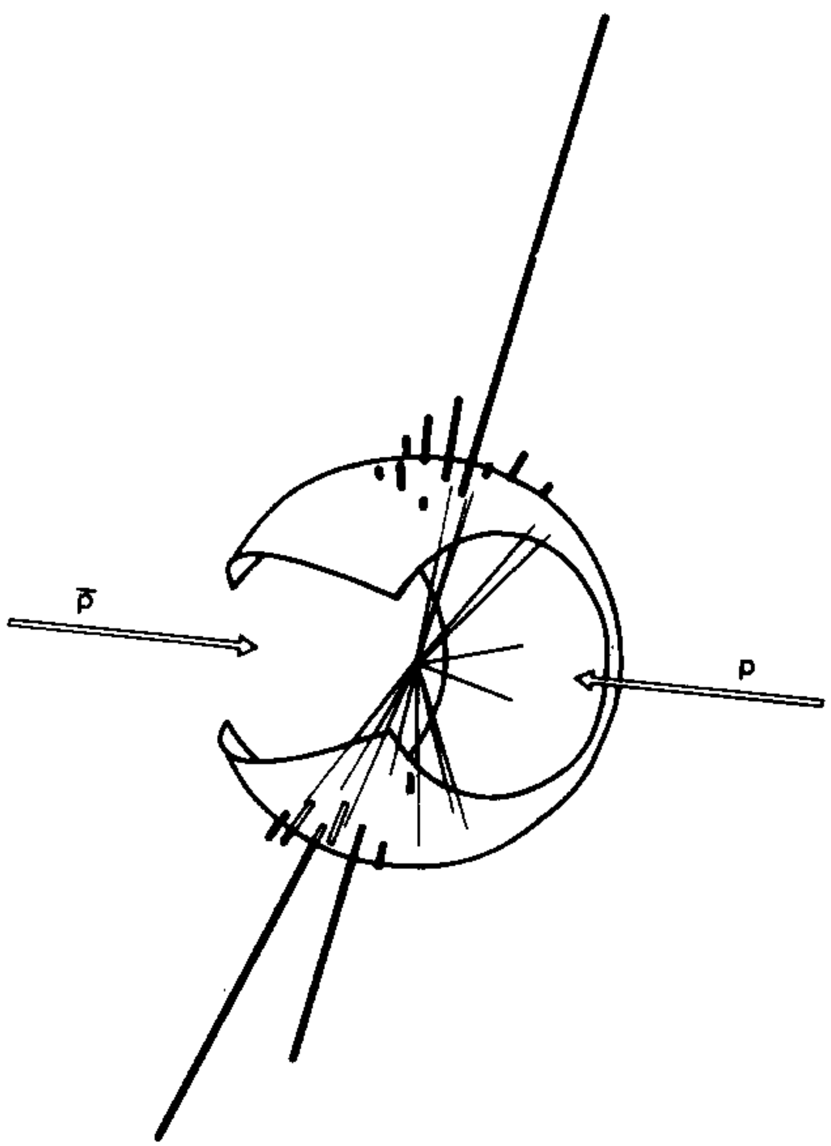
Gluons @ PETRA, 1979

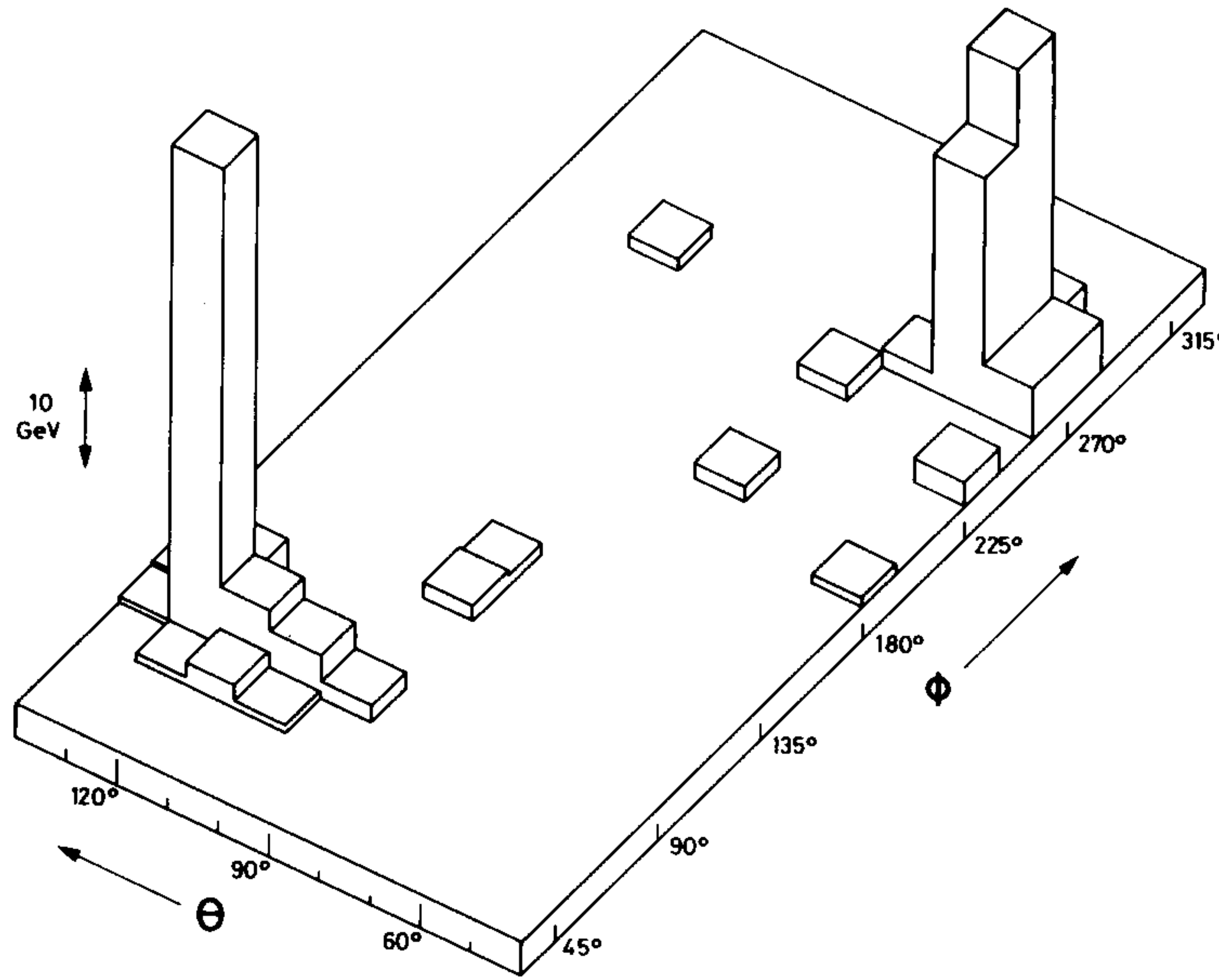


Event shapes to probe jet formation

Four Decades of Jets and QCD

UA2, 1982

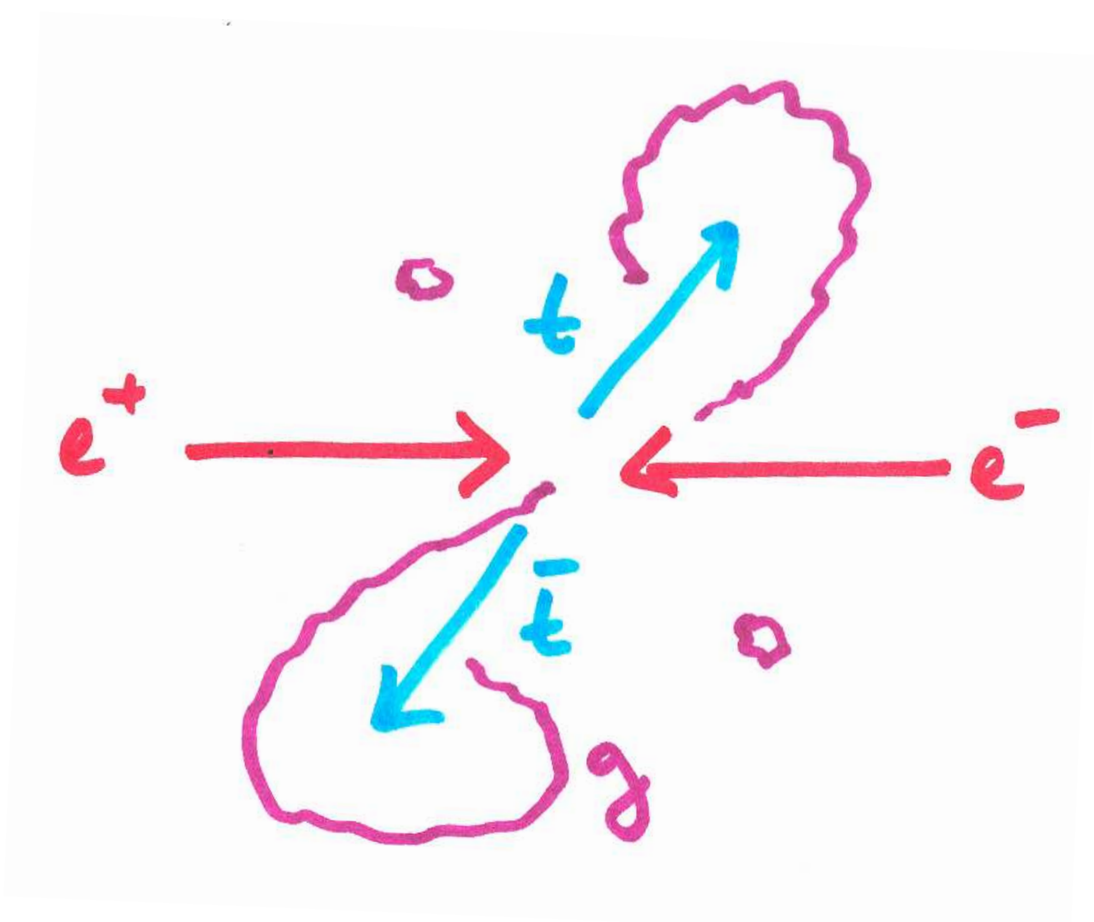




Jet algorithms: interpret cluster of hadrons as quasi-parton

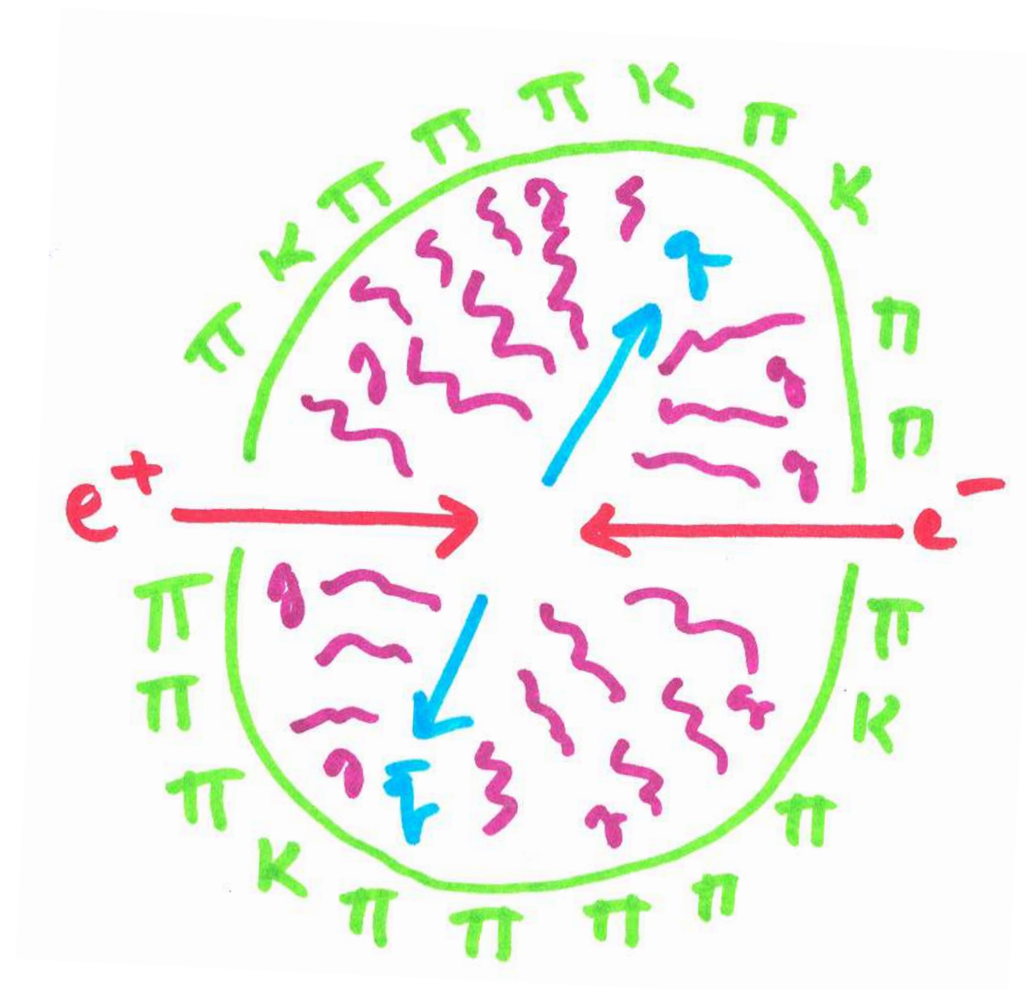
Jets are not automatic!

Quirky World
(QCD with only top quark)



Can't break color flux tubes!
Just "toponium" and glueballs!

Quasi-Conformal World
($\beta \approx 0, g \approx 4\pi$)

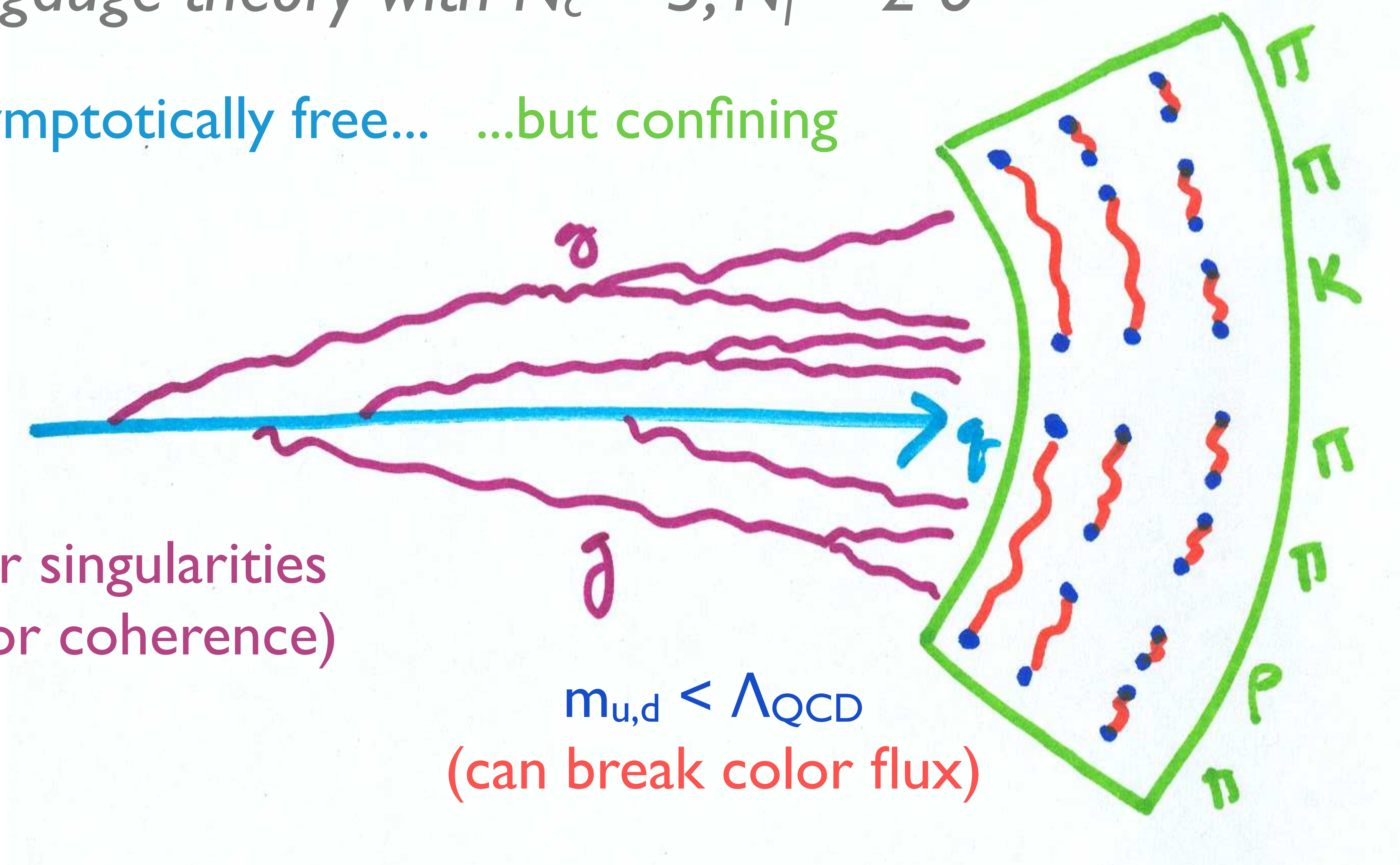


No hierarchy of scales!
All "spherical" events!

Jets are emergent property of QCD

Non-abelian gauge theory with $N_c = 3$, $N_f = 2\text{-}6$

Asymptotically free... ...but confining



Collinear singularities
(and color coherence)

$m_{u,d} < \Lambda_{QCD}$
(can break color flux)

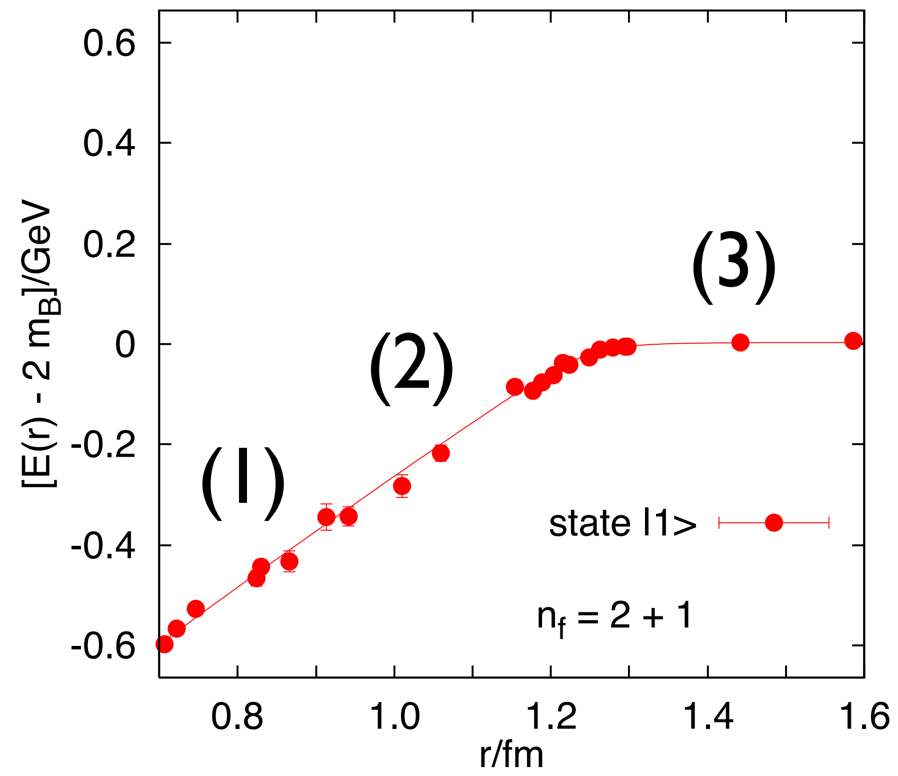
Energy flow in UV
(where partons go)

$\Rightarrow$

Energy flow in IR
(where hadrons go)

Jet = quark/gluon + radiation + ambiguities ($m_J \approx 10\% \, p_{TJ}$)

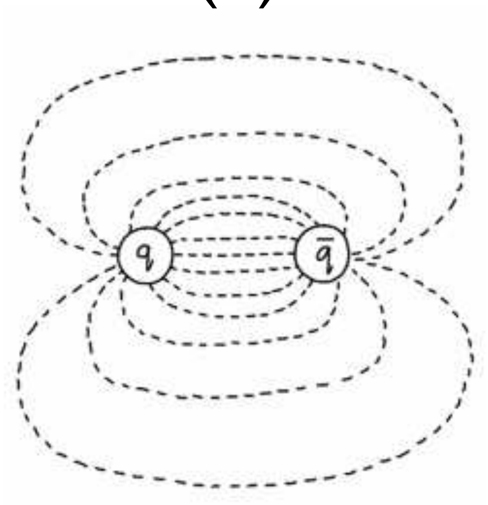
Confinement/Liberation



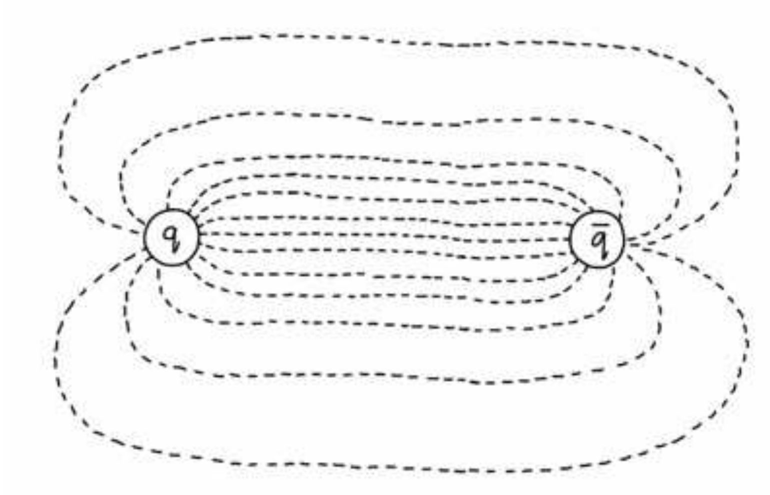
Potential between two heavy quarks (from lattice calculation)

[SESAM, 2005]

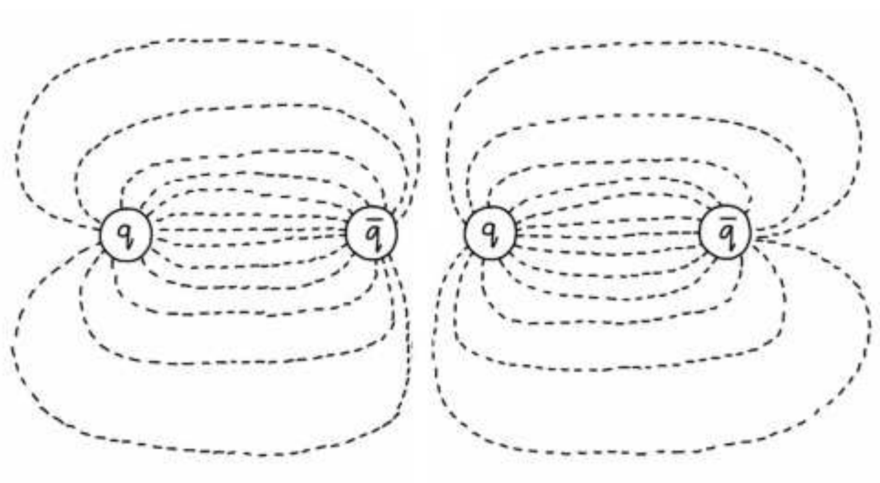
(1)



(2) = linear confinement



(3) = string breaking

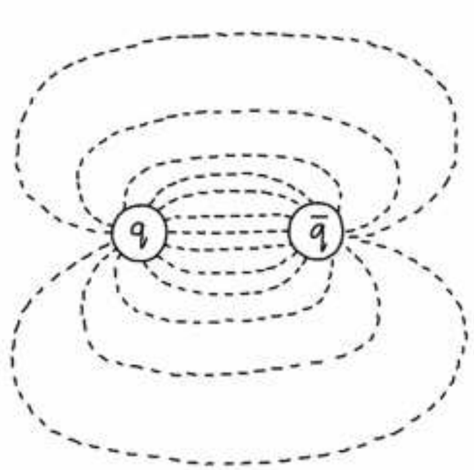


[pictures from coffeeshopphysics.com]

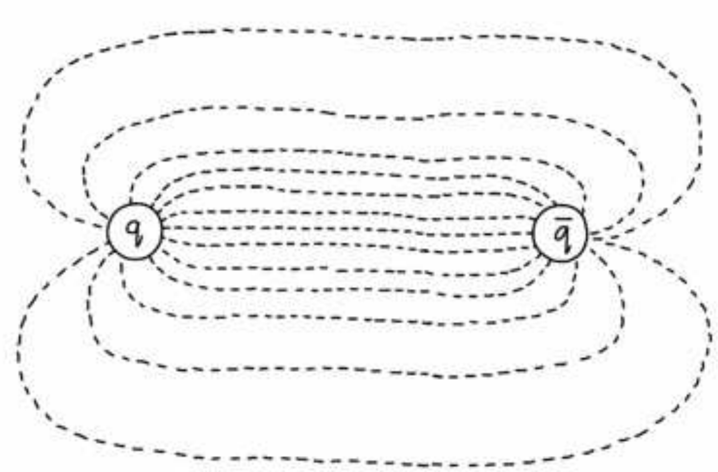
String picture gives jet basics

String breaks easily:	Quark/gluon direction $\approx$ Jet direction
String has energy density:	Massless quarks/gluons $\rightarrow$ Massive jet
String breaks by popping quarks:	Jets are mostly $q\,\bar{q}$ bound states (mesons)
String is color singlet:	Jets are fundamentally ambiguous

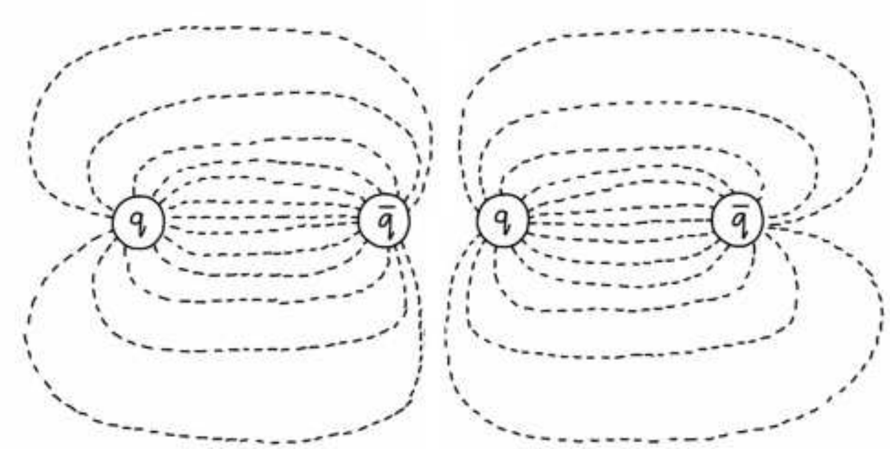
(1)



(2) = linear confinement

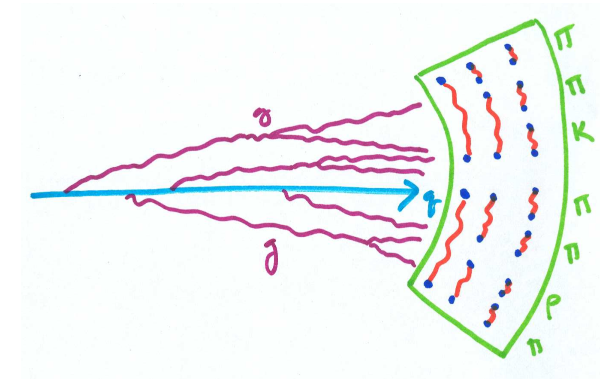


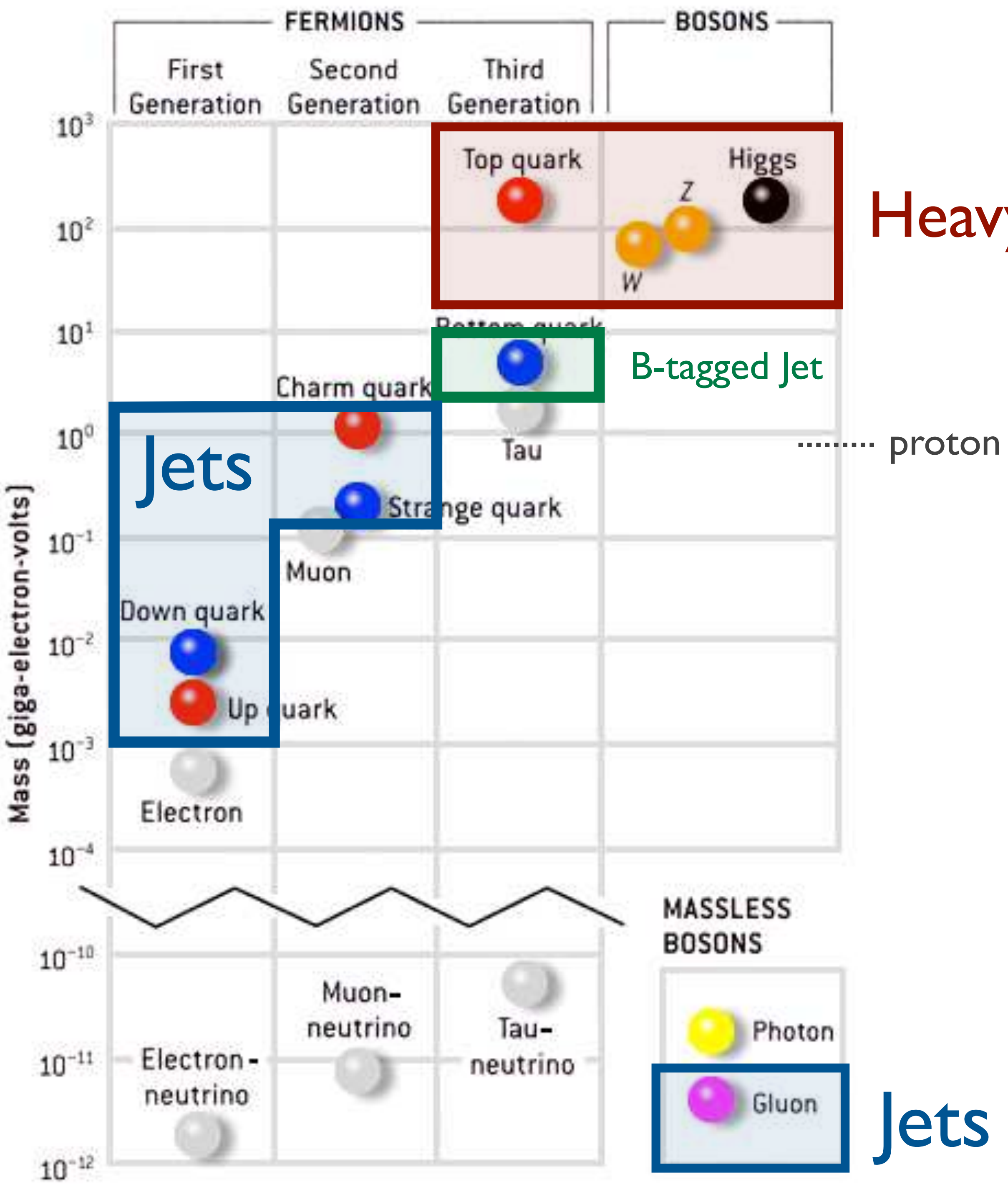
(3) = string breaking



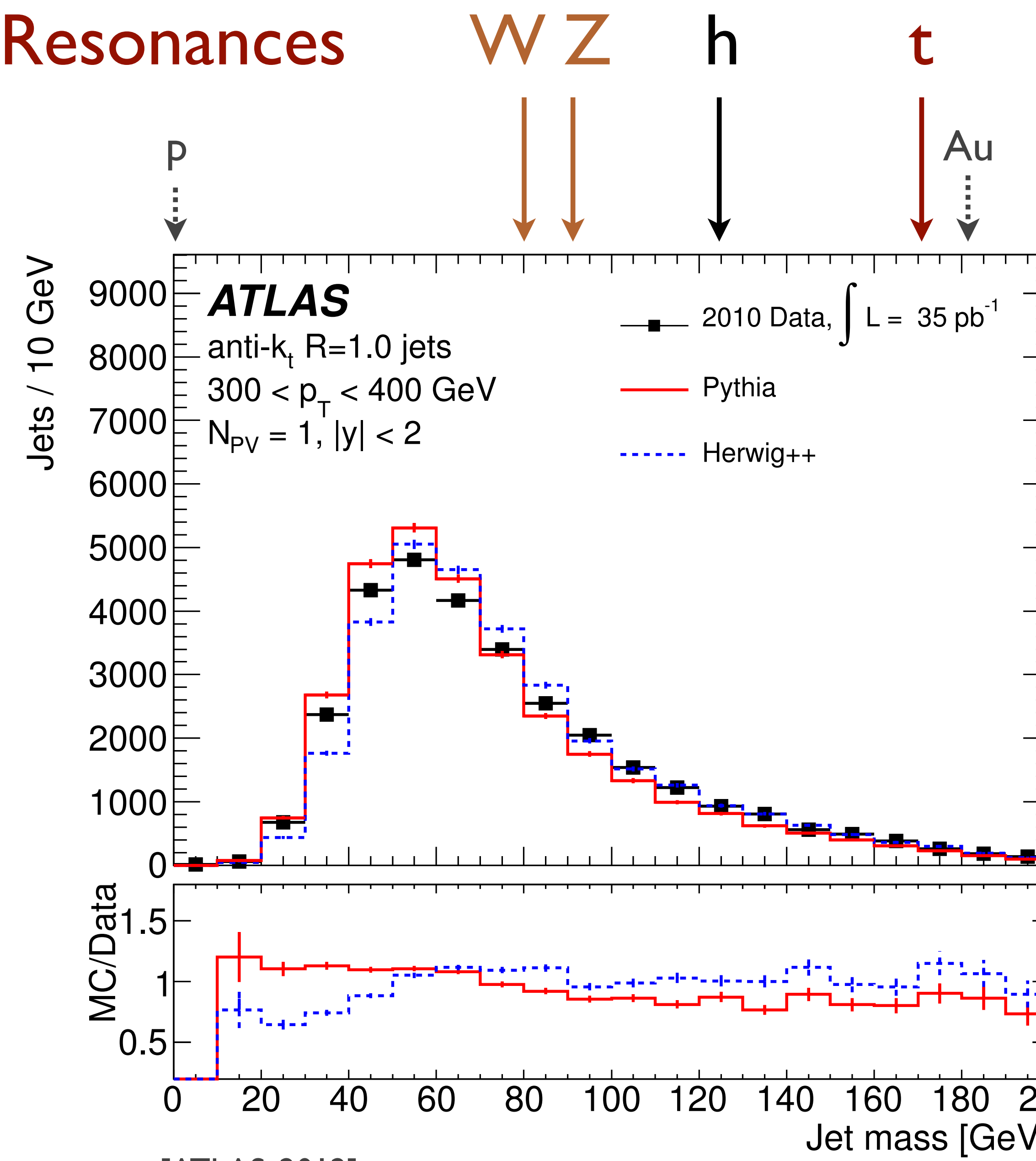
[pictures from coffeeshopphysics.com]

Yes, jets really are massive





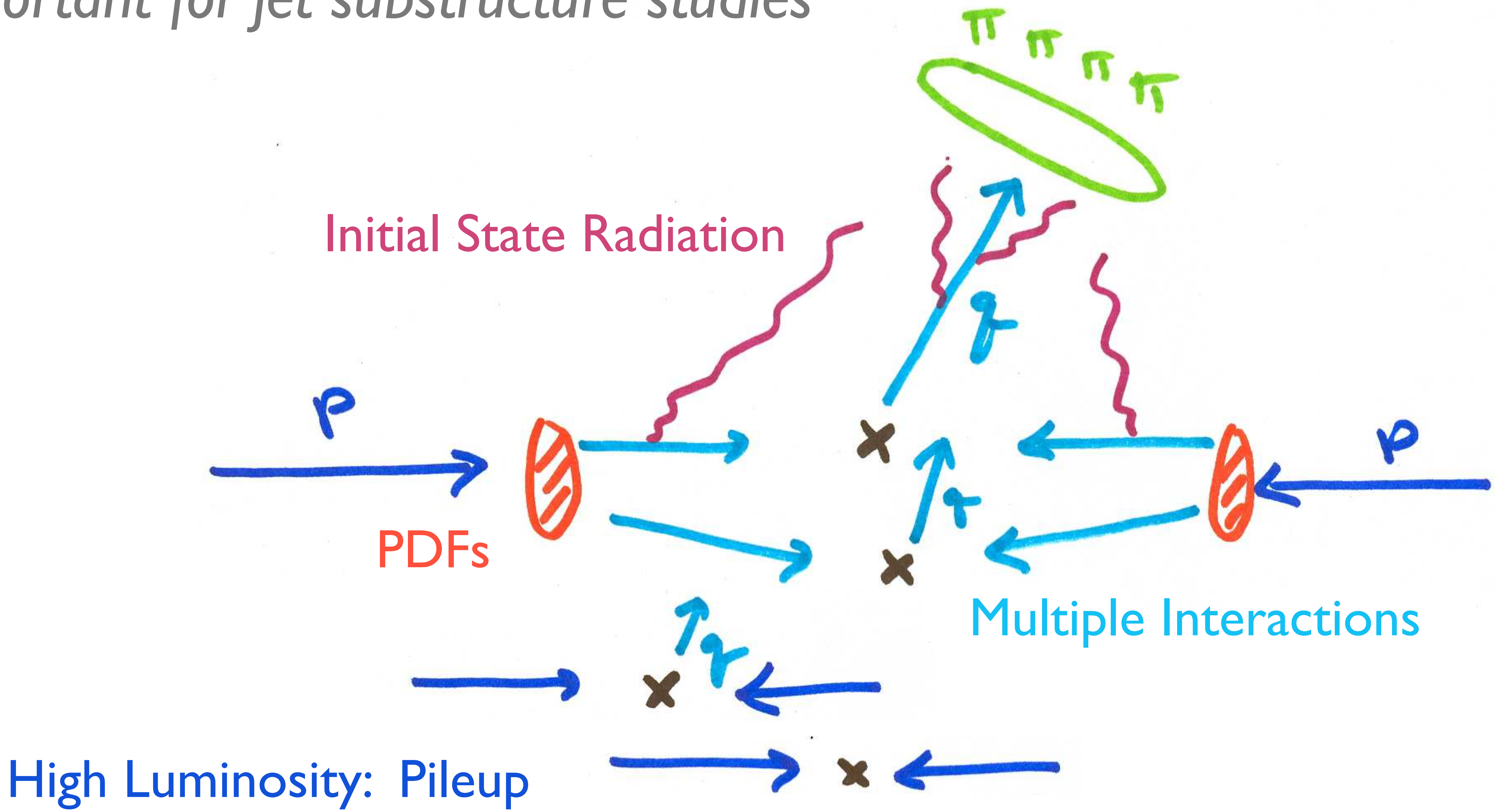
Heavy Resonances



[ATLAS, 2012]

Messiness is also a property of QCD

Important for jet substructure studies



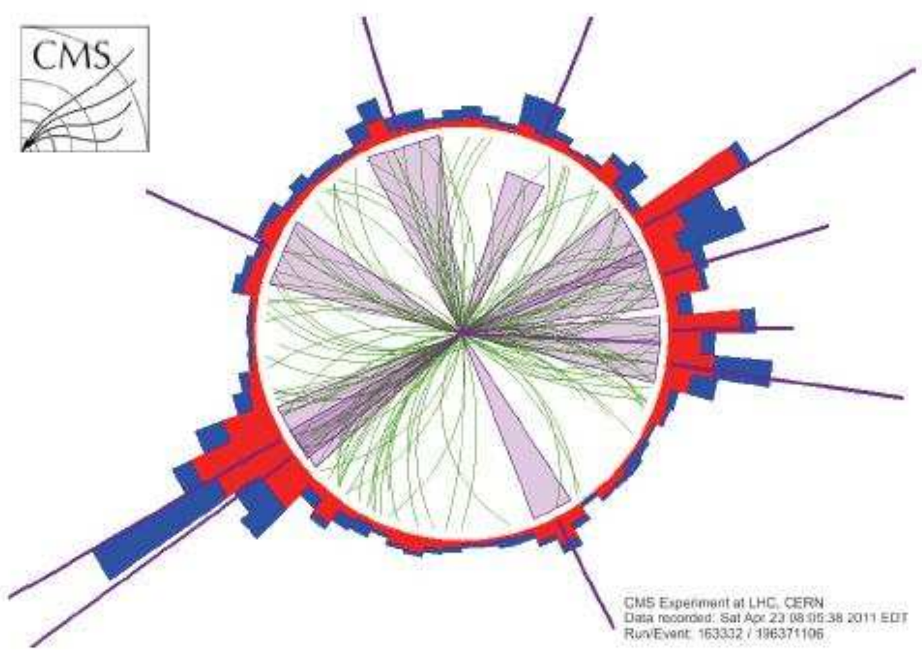
Jet = desired radiation from hard quark/gluon
+ additional contamination

Identifying Jets

What is a Jet?

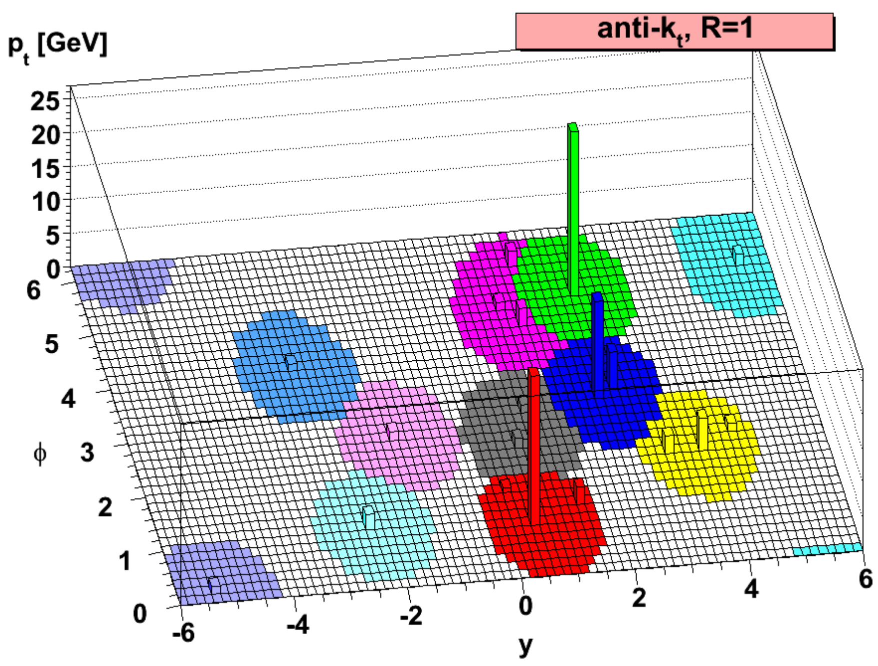
A physical phenomena:

Emergent feature of confining gauge theories



An analysis technique:

Method to interpret hadronic final states



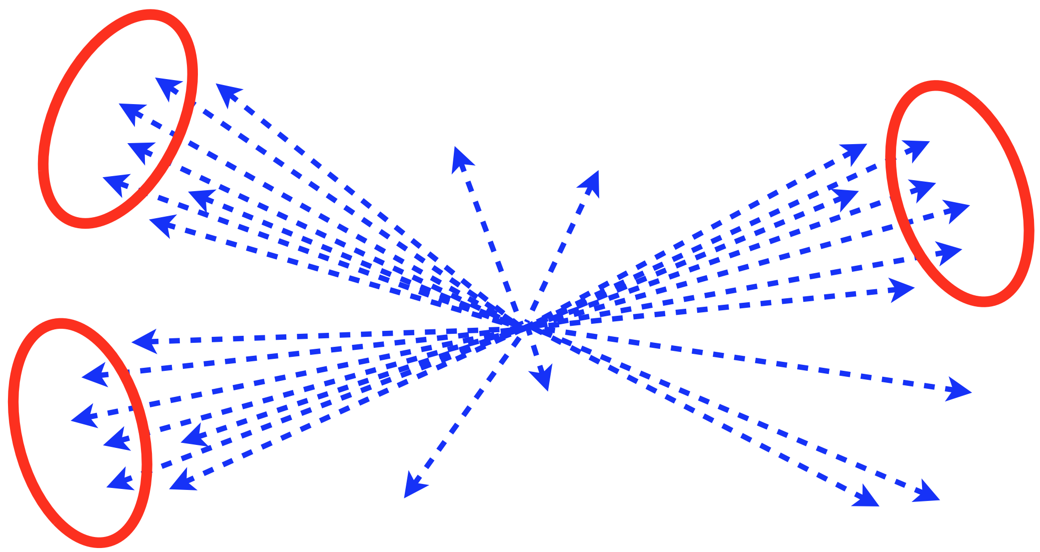
Freedom to use different analysis strategies for different physical questions

Generic Jet Algorithm

Inputs: **Outputs:**

$$\{p_1, p_2, \ldots, p_k\}_{\text{hadrons}} \Rightarrow \{p_1, p_2, \ldots, p_N\}_{\text{jets}}$$

Unless otherwise stated: $$\sum_{i \in \text{jet}} p_i = p_{\text{jet}}$$ (aka "E-scheme recombination", other schemes also plausible)



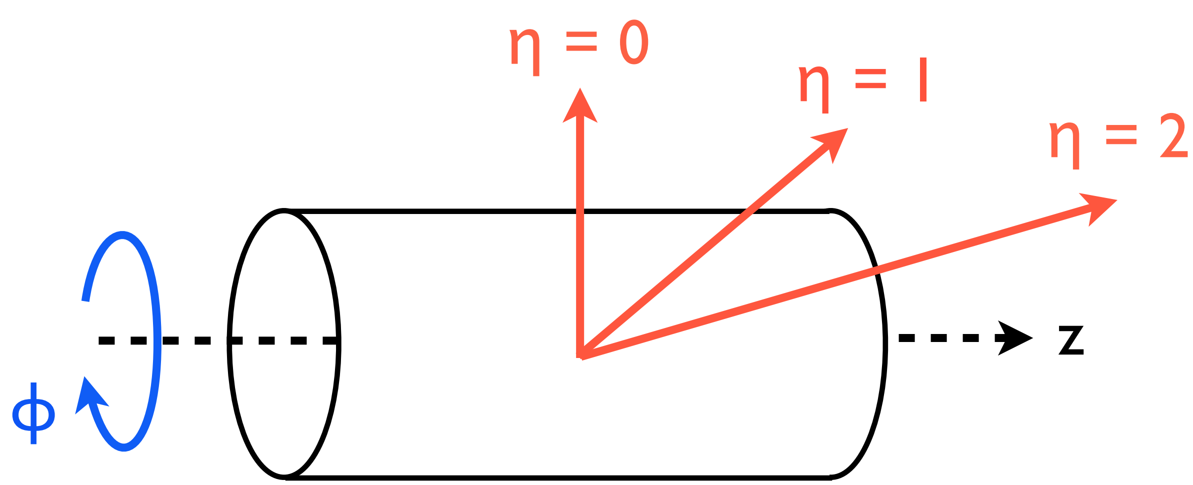
Remember, jets are massive: $$p_{\text{jet}}^2 = \left(\sum_{i \in \text{jet}} p_i \right)^2 \geq \sum_{i \in \text{jet}} m_i^2 \geq m_{\text{quark/gluon}}^2$$

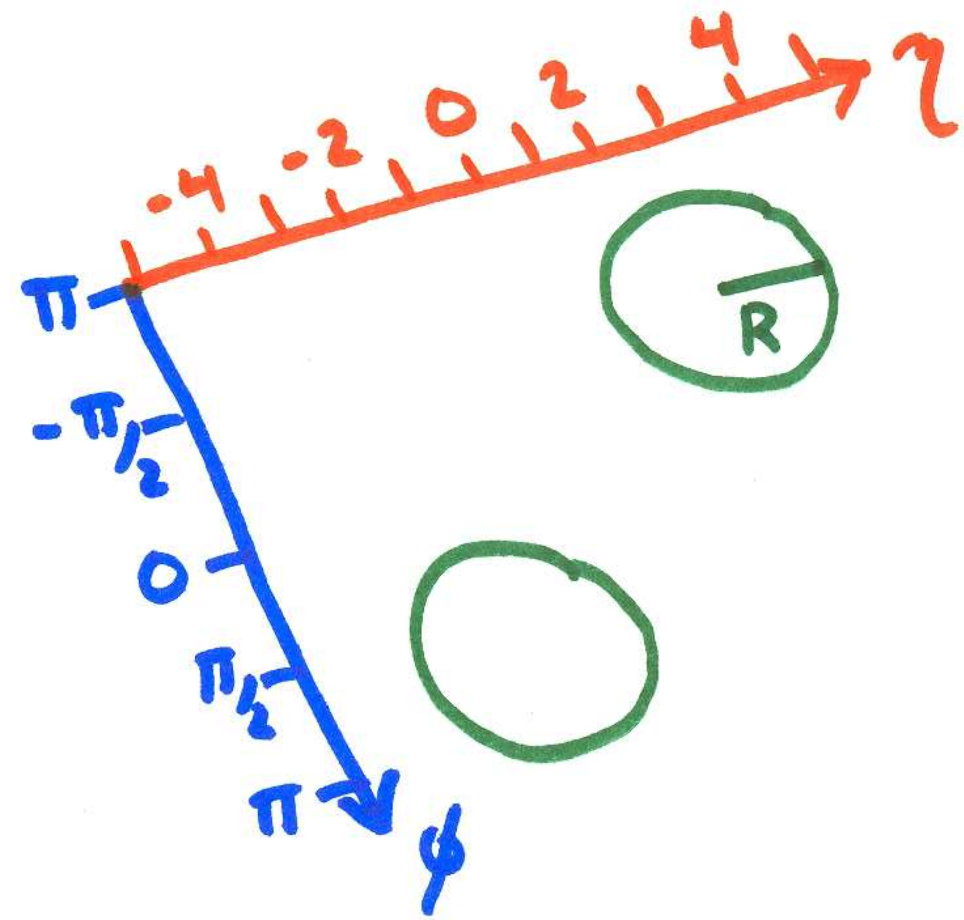
Coordinate System for Jets

Invariant to longitudinal boosts along beam direction

Better to use true rapidity *y*

$$p_T = \sqrt{p_x^2 + p_y^2} \qquad \Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$$

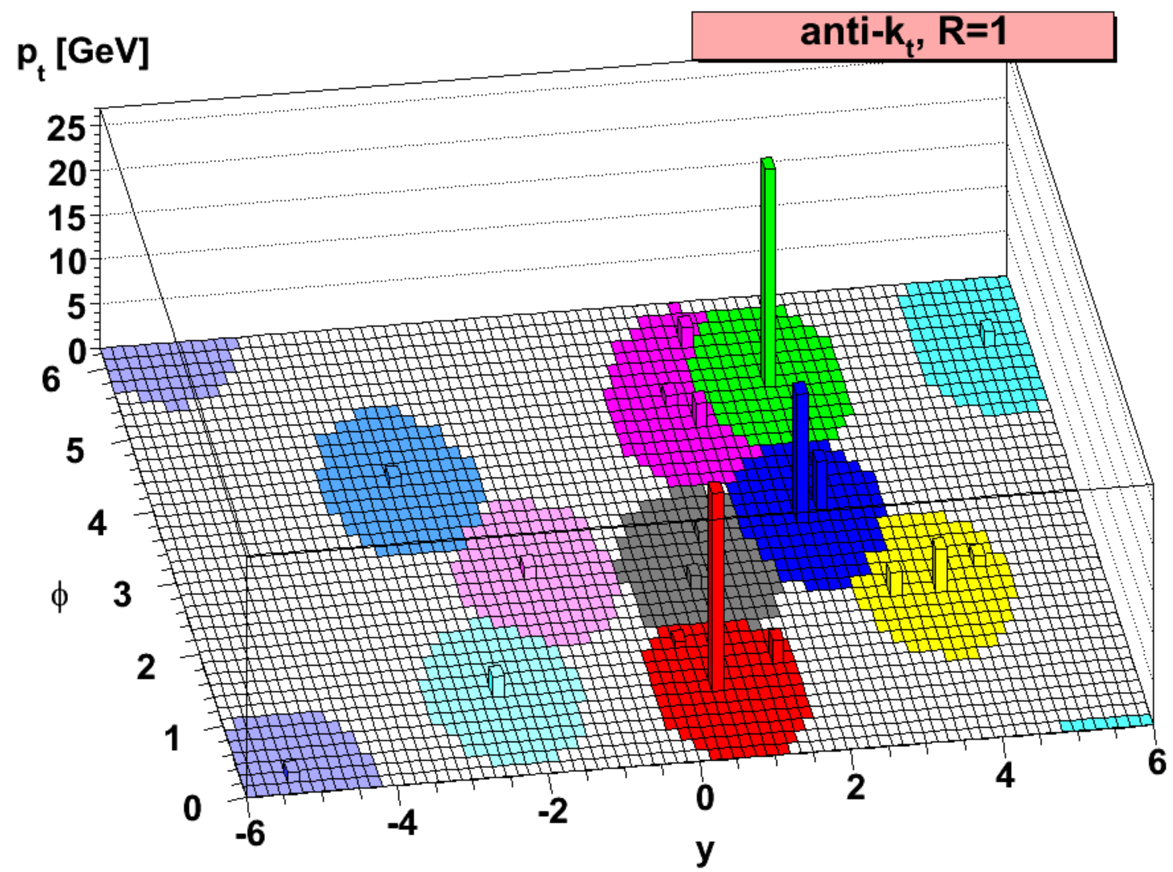




Typically: Cluster hadrons within characteristic radius R

Anti-k_t Sequential Recombination

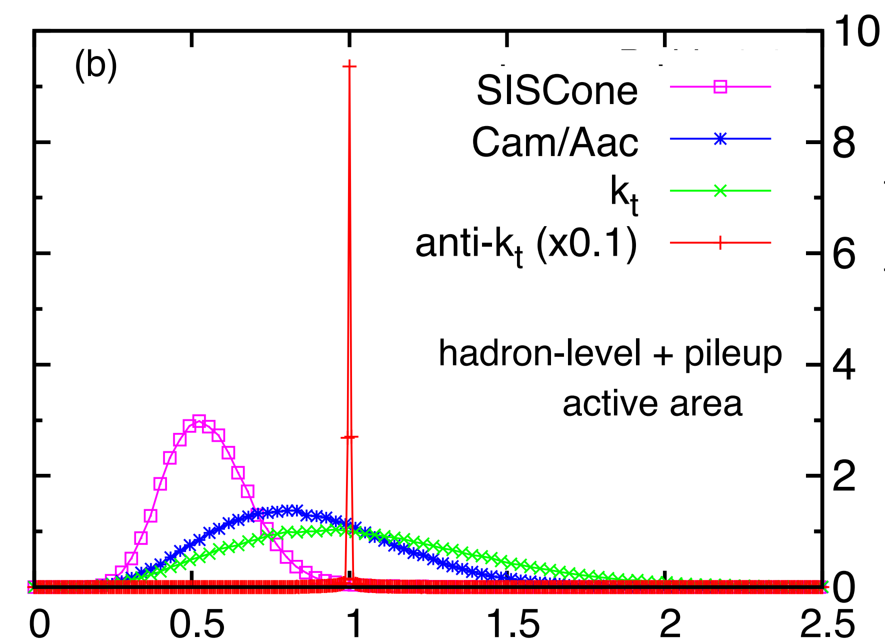
Ask me offline if you want to learn more

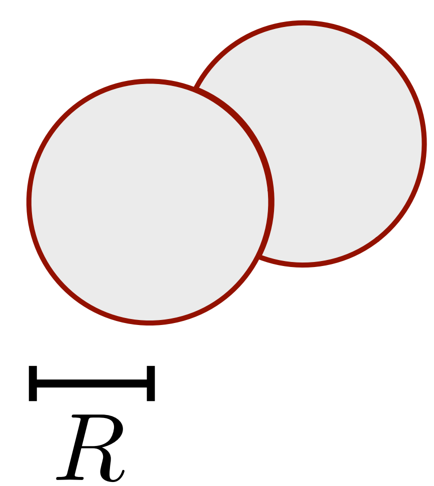


[Cacciari, Salam, Soyez, 2008]

Uniform catchment area

(for hardest jet)



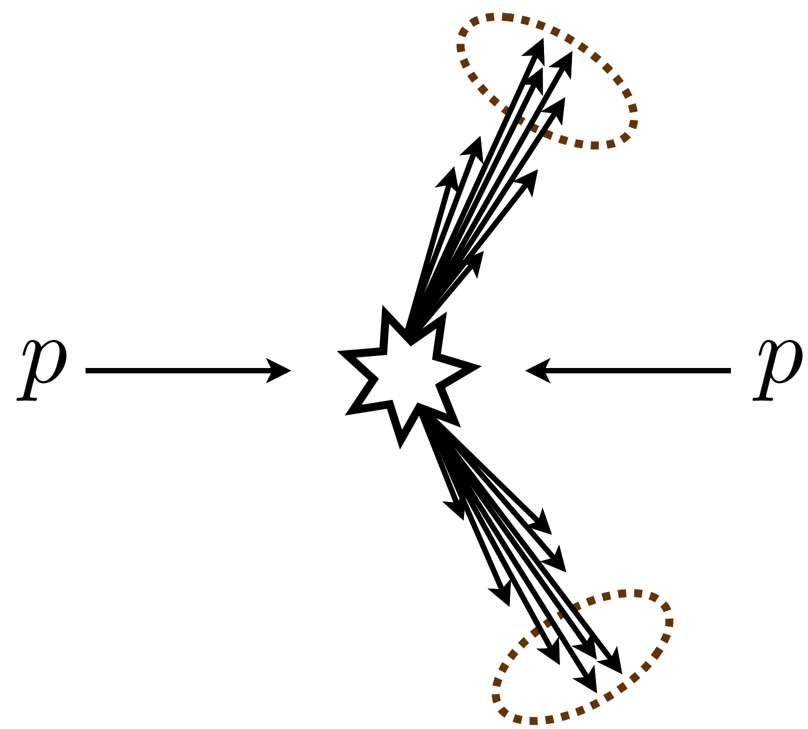


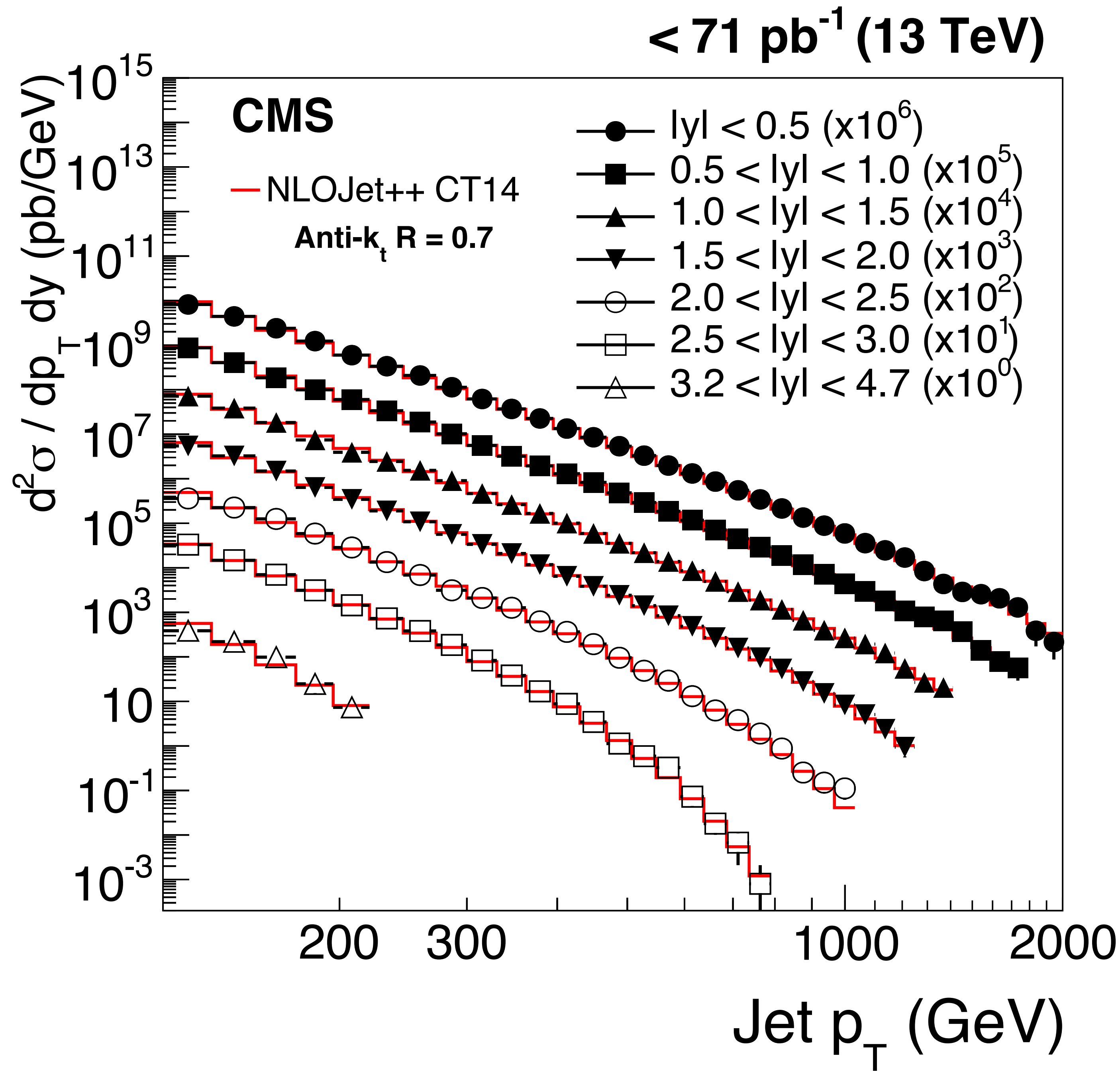
At LHC:

R = 0.4 for standard jets

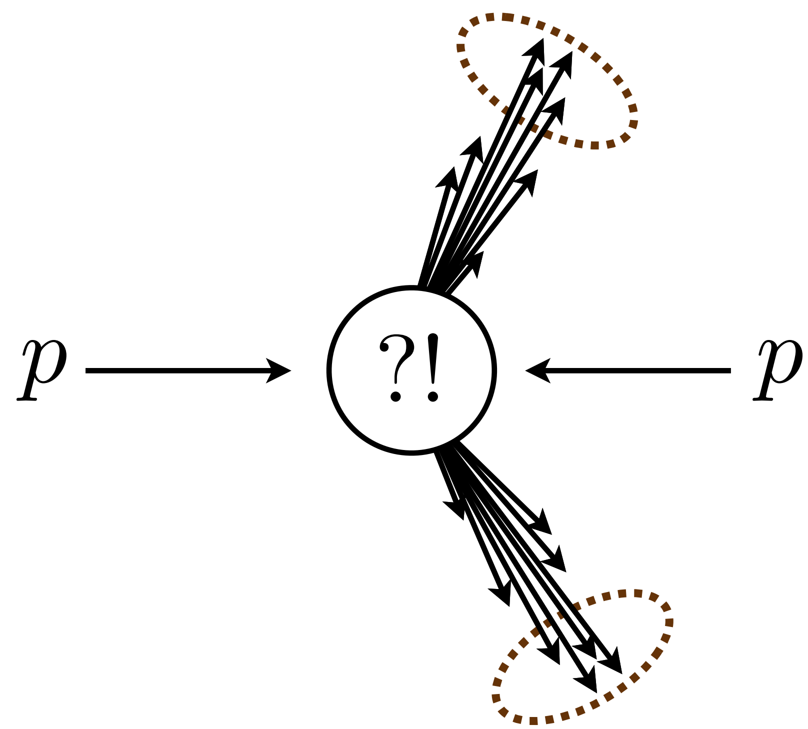
R = 0.8 for “fat” jets

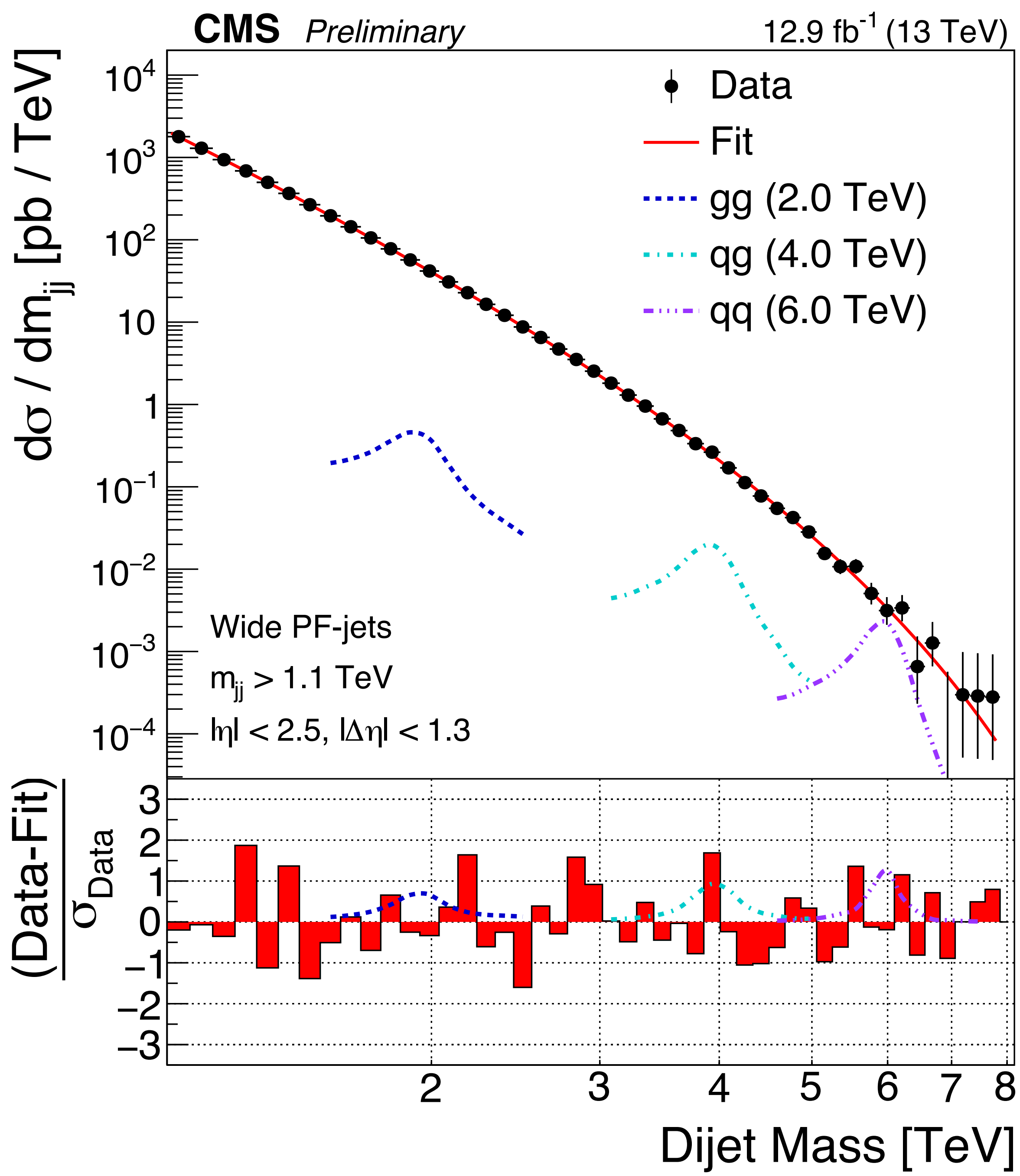
Dijet Spectrum



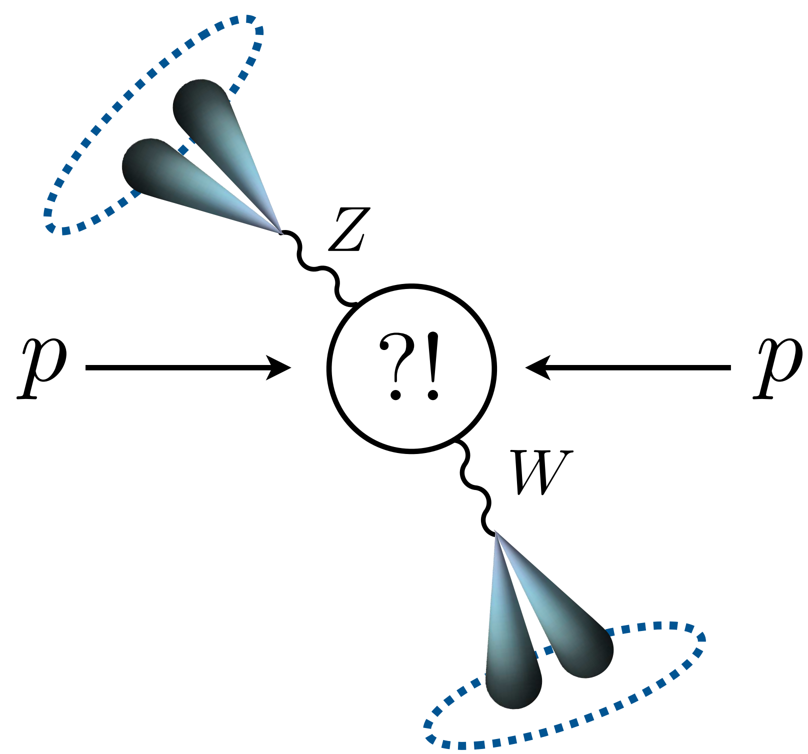


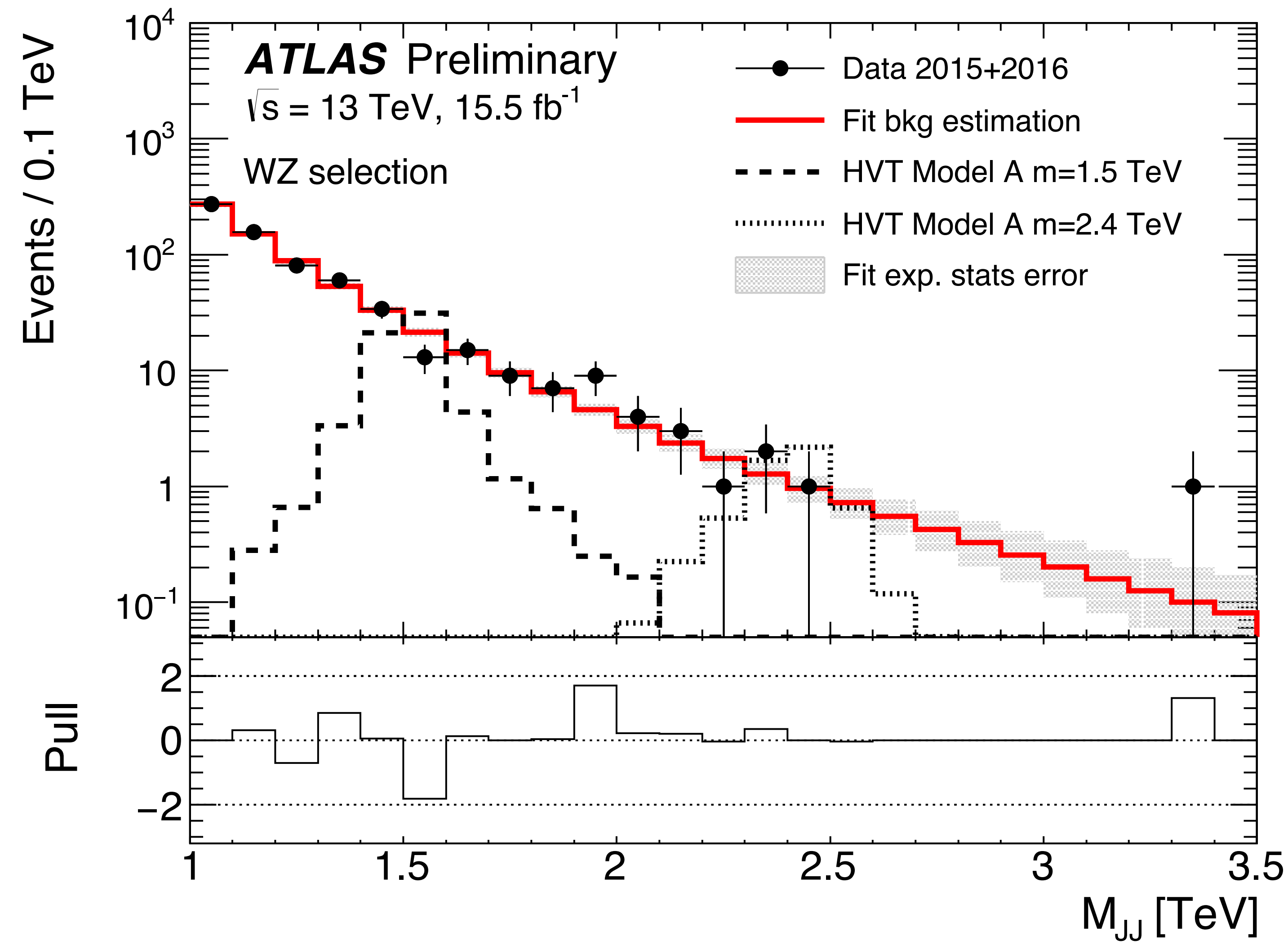
Dijet Resonance?





Diboson Resonance? (all hadronic channel)

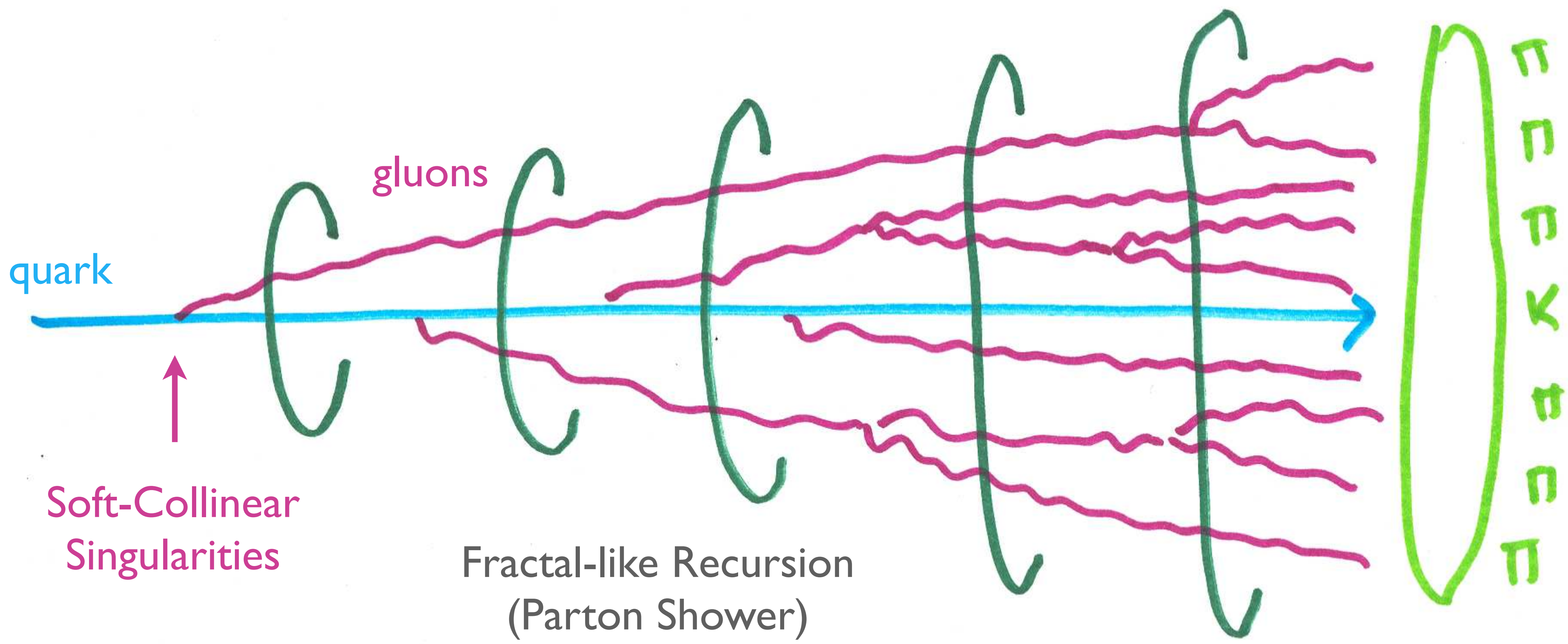




Inspiration to study the substructure of jets

The Soft/Collinear Limit of QCD

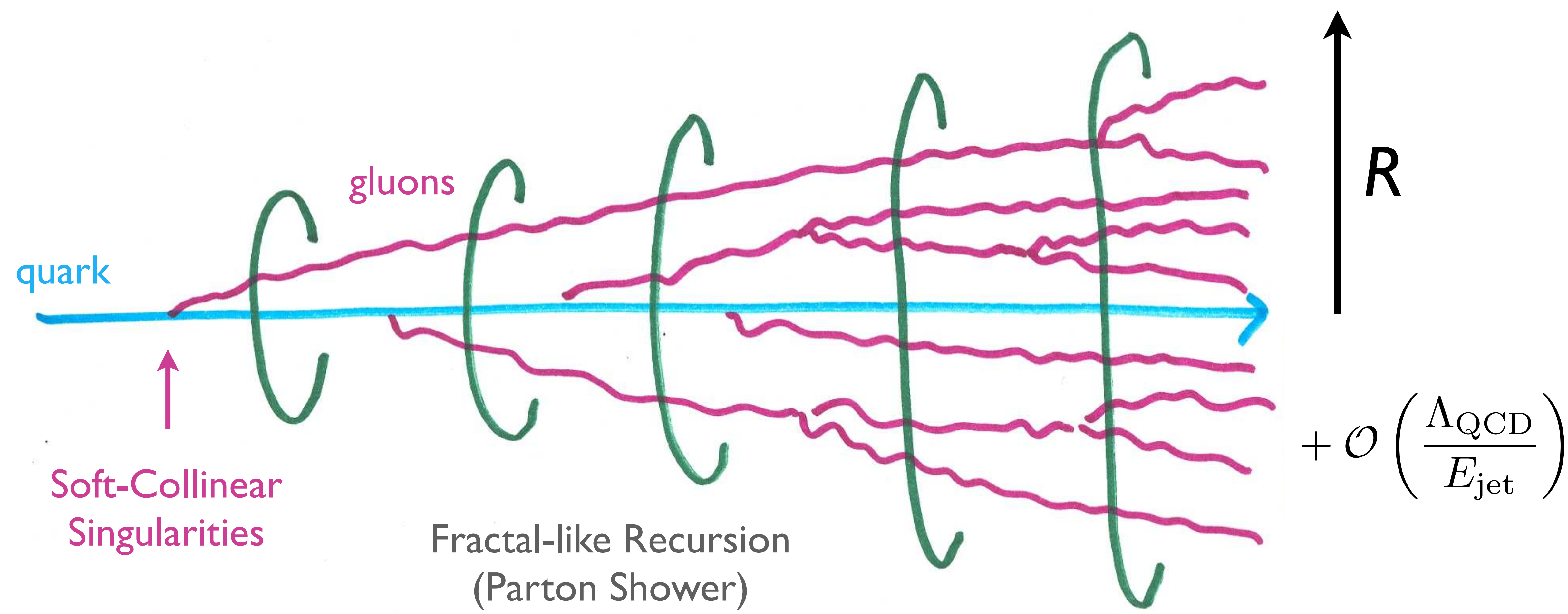
Calculational Control



Energy flow of partons $\Longrightarrow$ Energy flow of hadrons

Relies crucially on string breaking

Perturbative Jet Calculations



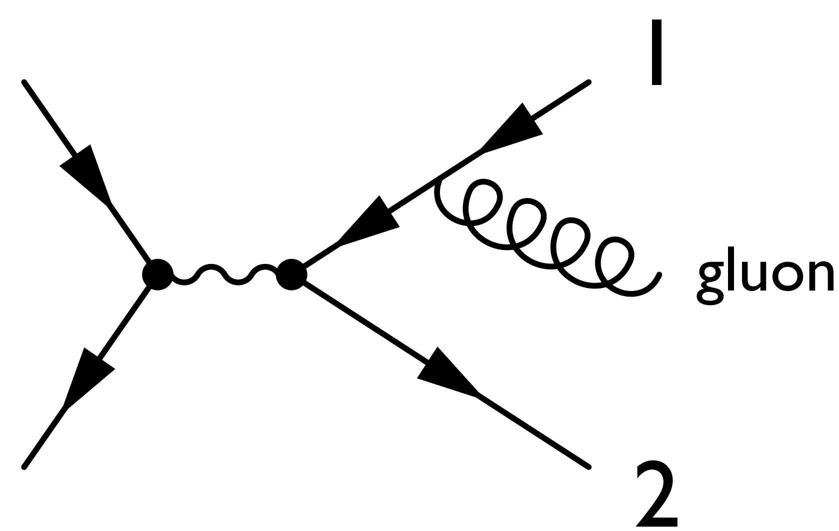
Energy flow of partons $\Rightarrow$ Good approximation to jet structure

For jet substructure: multiple soft/collinear emissions (resummation) typically more important than single hard emission (fixed order)

An Instructive Calculation

Every theorist should do this once

$$e^+e^- \to q\bar{q}g$$



$$t_1 = \frac{m_{1,\mathrm{gluon}}^2}{E_{\mathrm{CM}}^2}$$

$$t_2 = \frac{m_{2,\mathrm{gluon}}^2}{E_{\mathrm{CM}}^2}$$

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}t_1\mathrm{d}t_2} = \sigma_0 \frac{\alpha_s}{2\pi} C_F \frac{(1-t_1)^2 + (1-t_2)^2}{t_1 t_2}$$

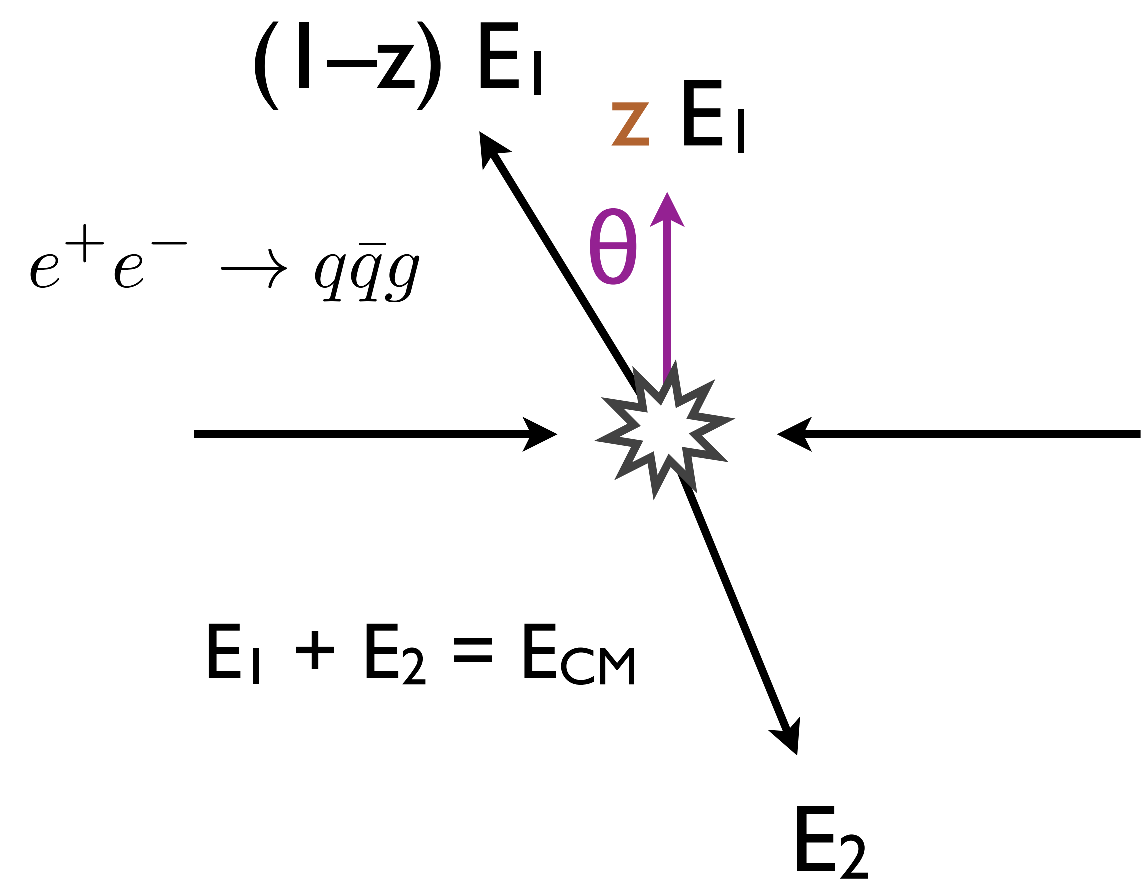
Born 2 → 2 cross section

Casimir factor

$$\sum_a T_{ij}^a T_{jk}^a = C_F \delta_{ik}$$

Collinear Limit

Gluon close to quark



2→3 process
5 total phase space variables
3 Euler angles
5 – 3 = 2 relevant variables

As θ→0: $$t_1 \simeq \frac{1}{4} z(1-z)\theta^2 \qquad t_2 \simeq z$$

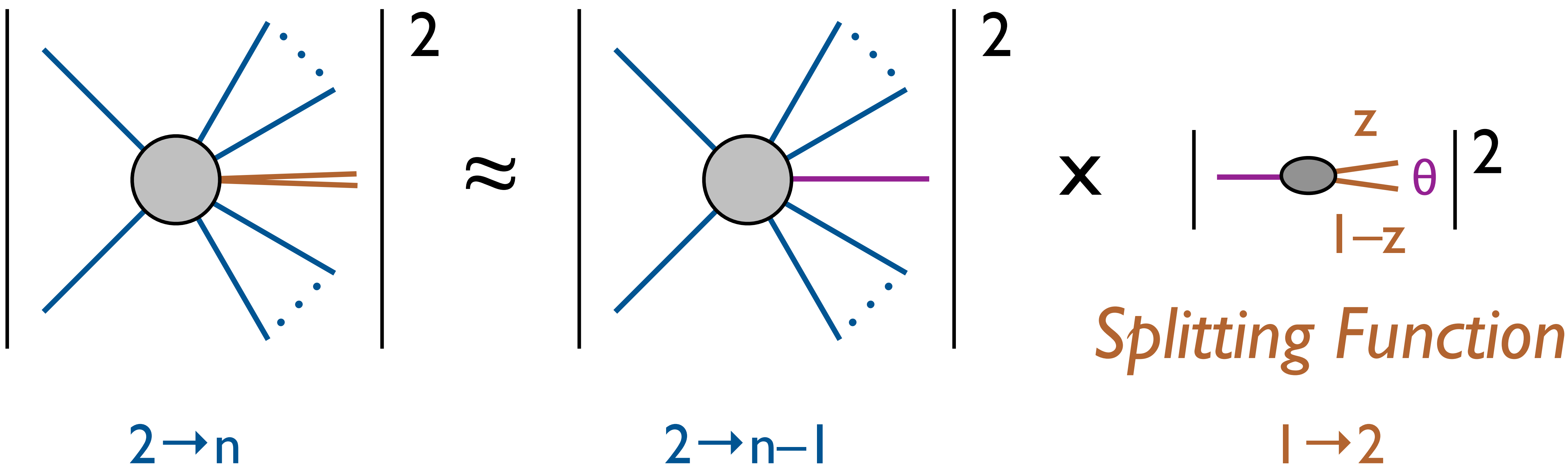
$$\frac{d^2\sigma}{dz\, d\theta} \simeq \sigma_0 \frac{\alpha_s}{\pi} C_F \frac{1}{\theta} \frac{1+(1-z)^2}{z}$$

(remember the Jacobian!)

Collinear singularity

Key: Collinear Limit is Universal

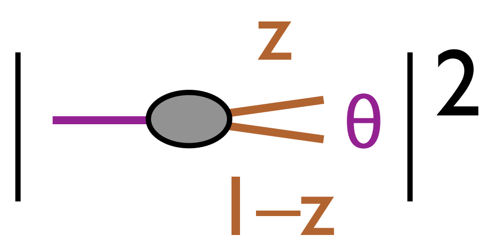
Collinear splittings are process independent



$$\mathrm{d}\sigma_{2\to n} = \mathrm{d}\sigma_{2\to n-1}\,\mathrm{d}P_{i\to jk}$$

$$\mathrm{d}P_{i\to jk} = \underbrace{\frac{\mathrm{d}\theta}{\theta}}_{\text{Collinear singularity}}\,\mathrm{d}z\,\underbrace{P_{i\to jk}(z)}_{\text{Altarelli-Parisi splitting function}}$$

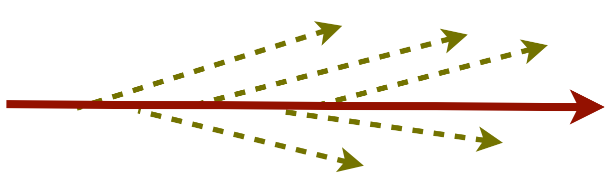
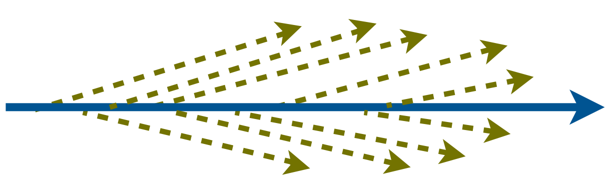
Soft & collinear limit particularly simple

$\theta \to 0$ & $z \to 0$: 

Splitting Probability:

$$\mathrm{d}P_{i\to ig} = \frac{2\alpha_s}{\pi} C_i \underbrace{\frac{\mathrm{d}\theta}{\theta}}_{\text{Collinear singularity}} \underbrace{\frac{\mathrm{d}z}{z}}_{\text{Soft singularity}}$$

In this limit, only difference between hard quark and hard gluon is C_i
(i.e. both emit soft gluons)

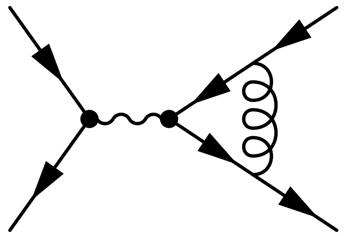
Color Factors:	SU(N)	SU(3)	
Quark: C_F	$(N^2 - 1)/(2N)$	4/3	
Gluon: C_A	N	3	

What about soft/collinear singularities?

Splitting Probability:
$$\mathrm{d}P_{i\to ig} = \frac{2\alpha_s}{\pi} C_i \frac{\mathrm{d}\theta}{\theta} \frac{\mathrm{d}z}{z}$$

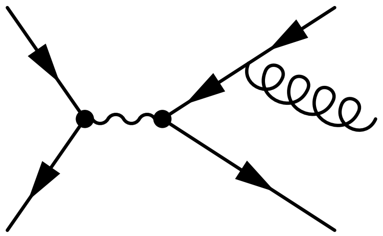
KLN Theorem:

Virtual Diagrams



$\Leftrightarrow$

$\sum$ Real Emissions



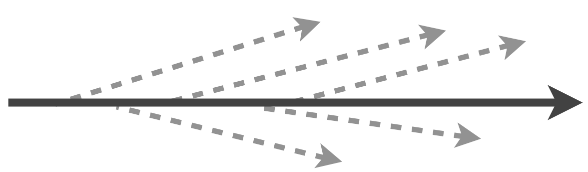
IRC divergences cancel by order-by-order in α_s expansion

Effectively:
$$\text{virtual} + \int \frac{\mathrm{d}\theta}{\theta} \frac{\mathrm{d}z}{z} = \text{finite}$$

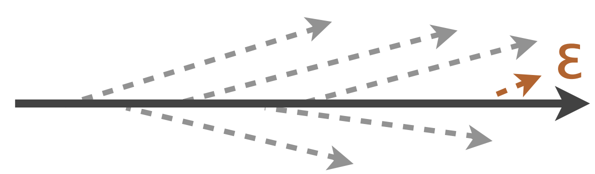
Note: Restricting integration range gives logarithms (possibly large)

Infrared/Collinear Safety

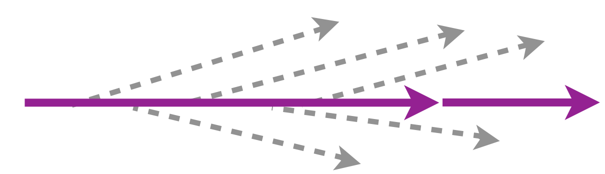
Original Jet



Infrared



Collinear



IRC Safe Observable: Insensitive to IR or C emissions

Standard Lore:		IRC Safe	IRC Unsafe
	Calculable in pQCD?	✓	✗
	Controlled Λ_{QCD} Effects?	✓	✗

[Tomorrow’s talk will challenge this lore!]

Examples from Jet Substructure

Jet p_T: $$\sum_{i \in \text{jet}} p_{T,i}$$ IRC Safe

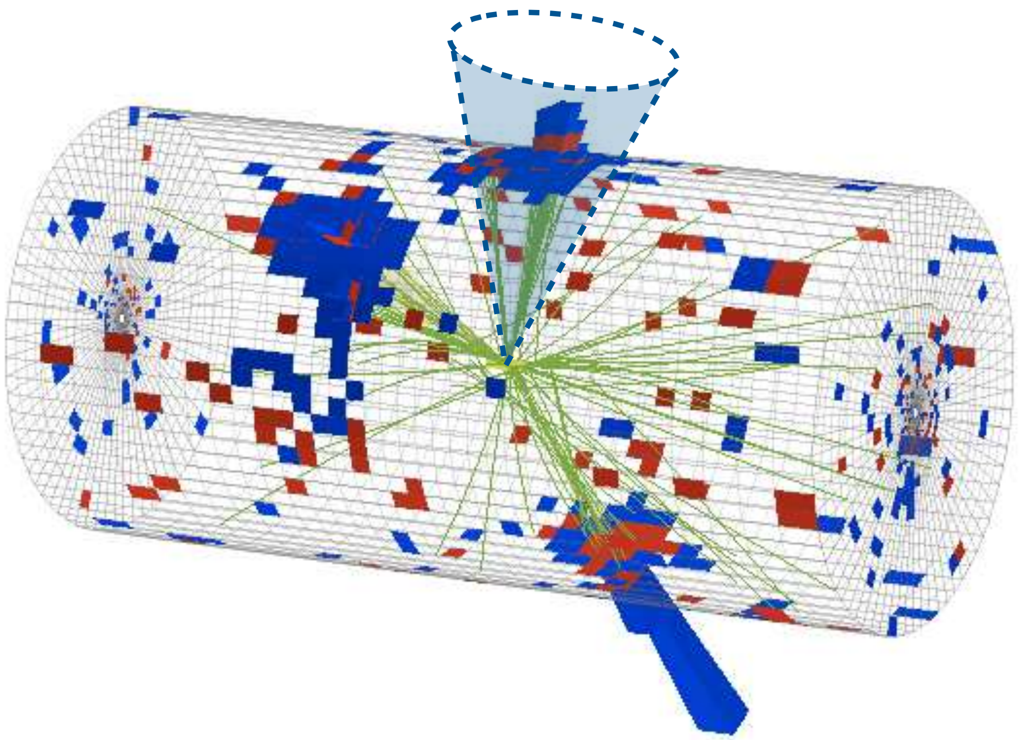
p_T^D: [CMS HIG-11-027] $$\sum_{i \in \text{jet}} \frac{p_{T,i}^2}{p_{T\text{jet}}^2}$$ IR Safe
C Unsafe

Multiplicity: $$\sum_{i \in \text{jet}} 1$$ IRC Unsafe

Jet Mass: $$\sum_{i,j \in \text{jet}} p_i \cdot p_j$$ IRC Safe

N-subjettiness: $$\sum_{i \in \text{jet}} p_{T,i} \min \left\{ \Delta R_{i,1}, \Delta R_{i,2}, \ldots, \Delta R_{i,N} \right\}^\beta$$ IRC Safe

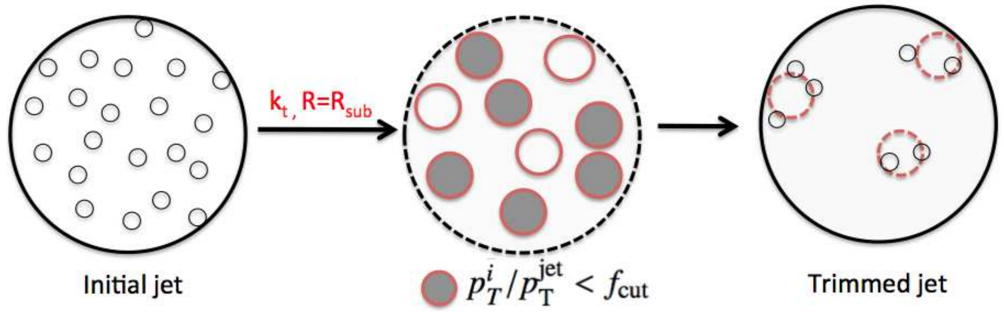
[JDT, Van Tilburg, 1011.2268, 1108.2701]



Grooming from First Principles

From Last Week

Jet Trimming

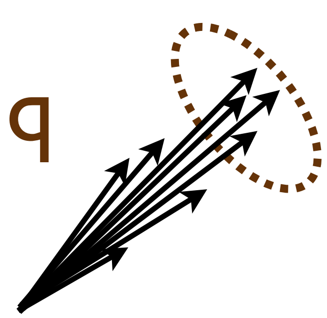


[Krohn, JDT, Wang, 0912.1342; diagram from ATLAS, 1306.4945]

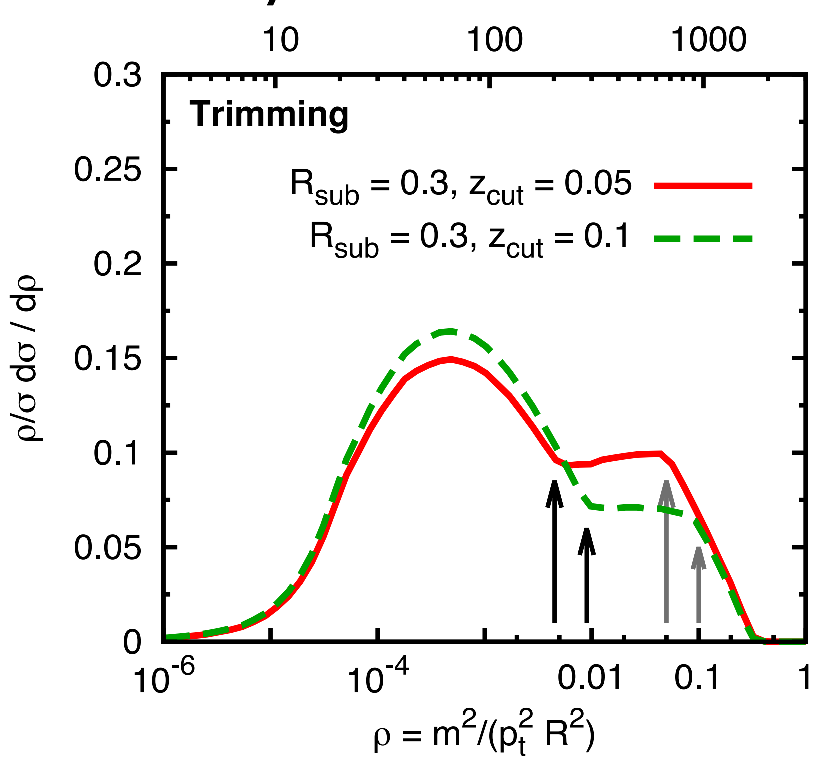
R_{sub}: subjet radius
z_{cut}: fractional energy threshold

Trimmed Jet Mass:

3 TeV quark jets



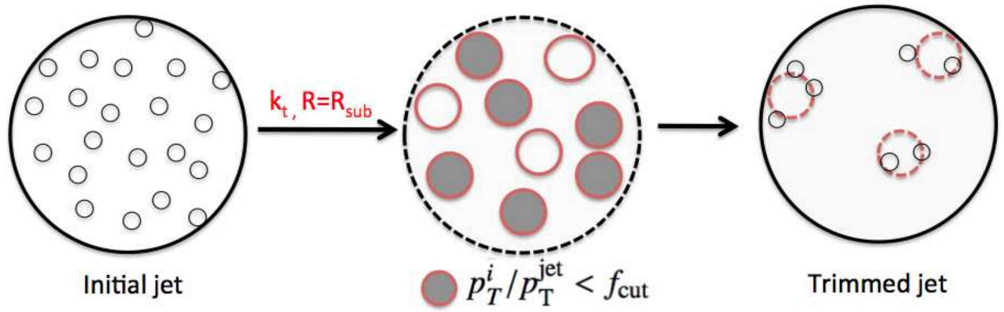
Pythia 6 Simulation



[Dasgupta, Fregoso, Marzani, Salam, 1307.0007]

From Last Week

Jet Trimming

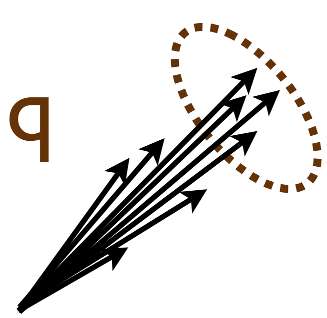


[Krohn, JDT, Wang, 0912.1342; diagram from ATLAS, 1306.4945]

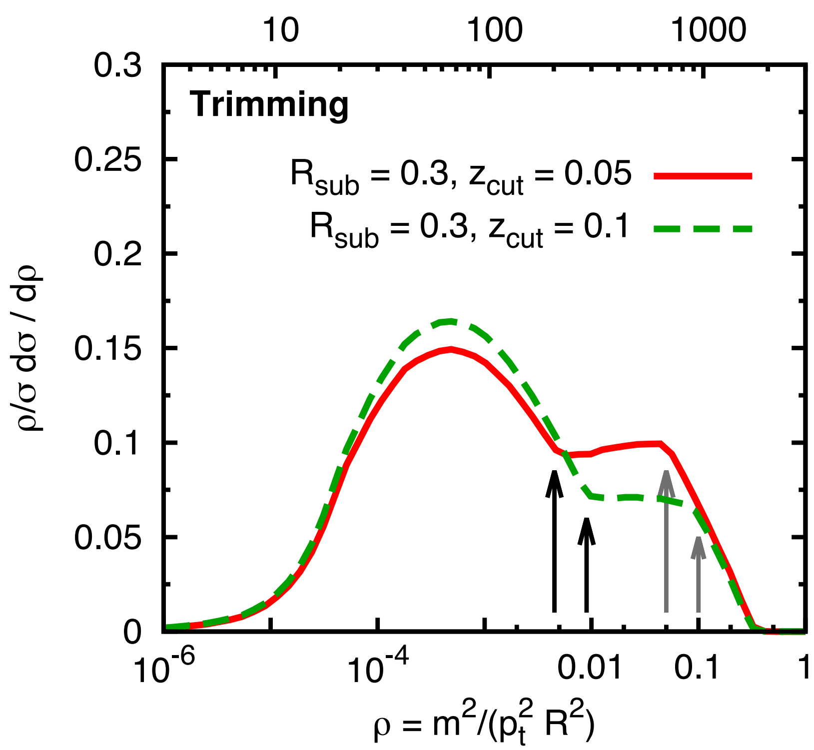
R_{sub}: subjet radius
z_{cut}: fractional energy threshold

Trimmed Jet Mass:

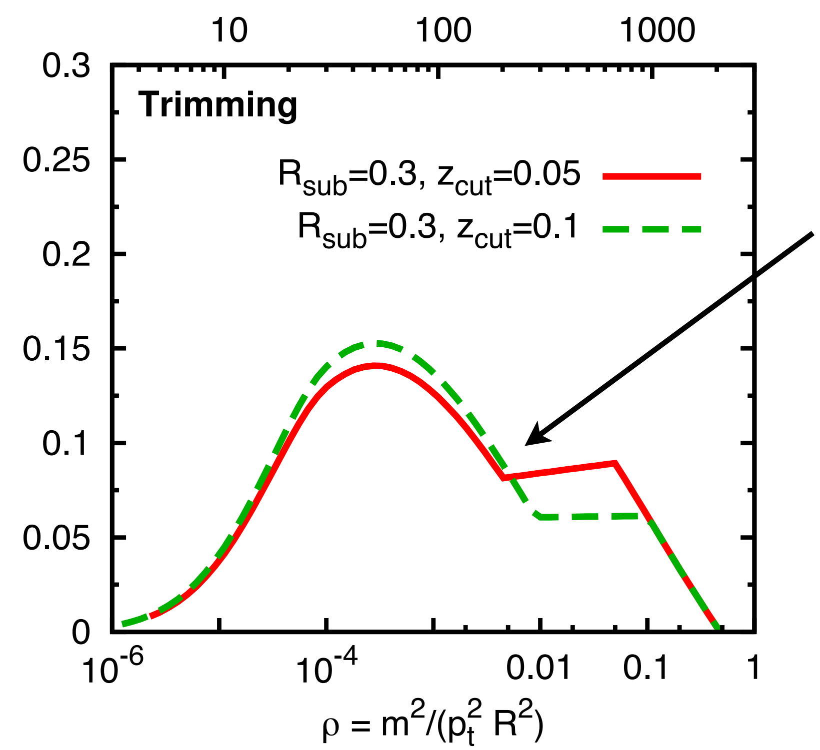
3 TeV quark jets



Pythia 6 Simulation



First-principles QCD (MLL)



Analytically understand Sudakov peak, kink, and plateau

[Dasgupta, Fregoso, Marzani, Salam, 1307.0007]

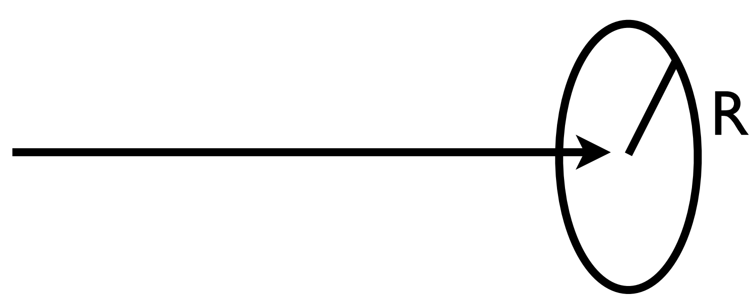
Soft/Collinear Phase Space

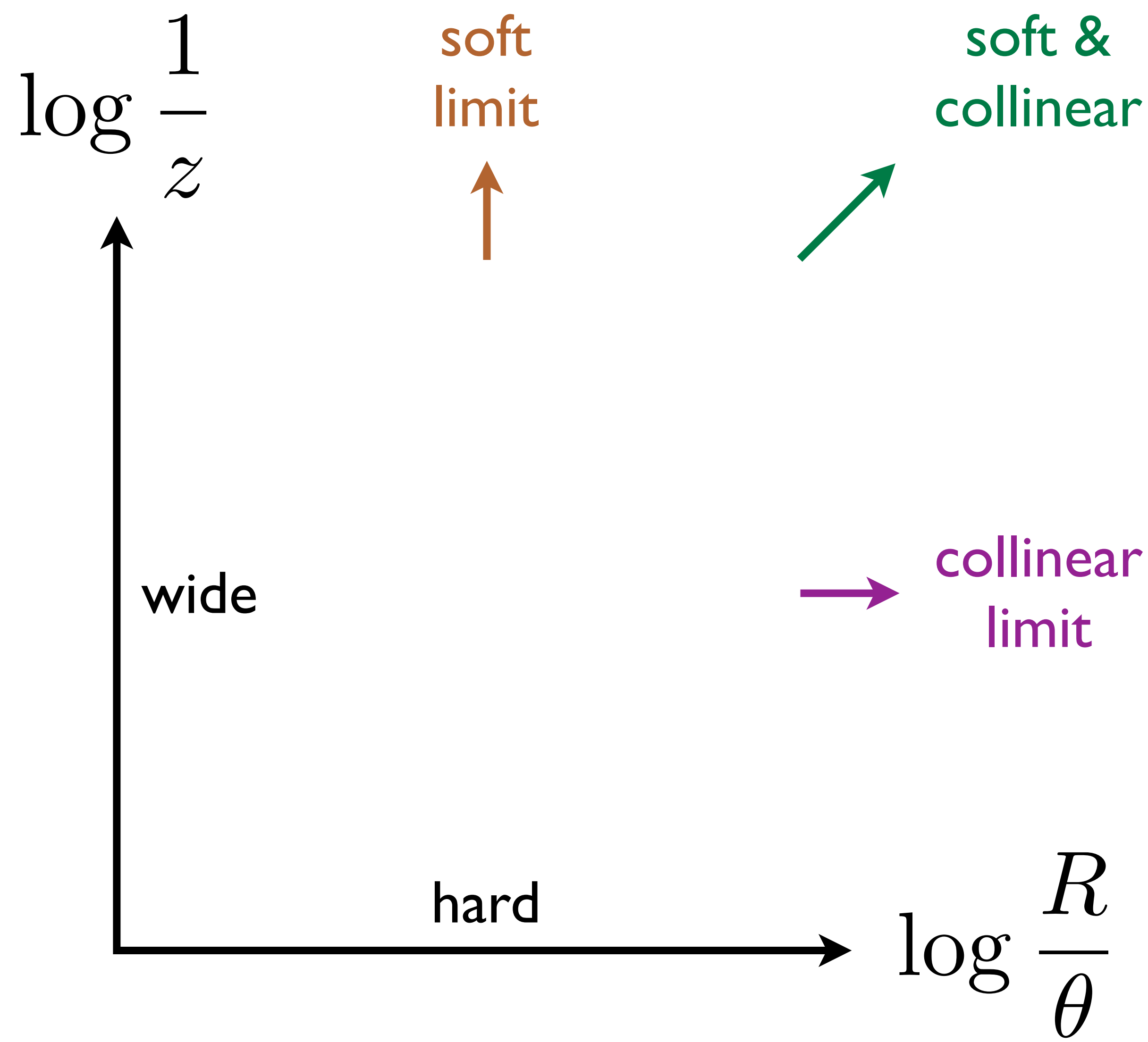
Basis for parton shower

$$\mathrm{d}P_{i\to ig} = \frac{2\alpha_s}{\pi} C_i \frac{\mathrm{d}\theta}{\theta} \frac{\mathrm{d}z}{z}$$

Uniform in logarithmic plane

Eikonal Hard Quark/Gluon…



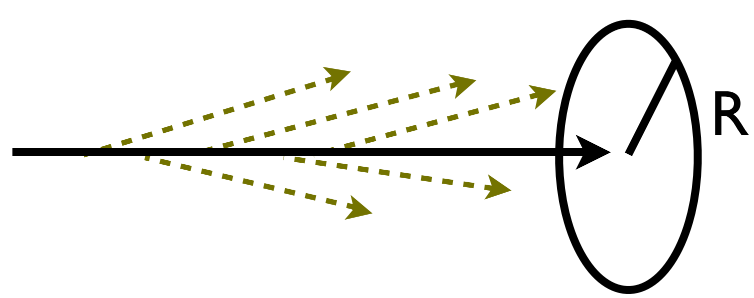


Soft/Collinear Phase Space

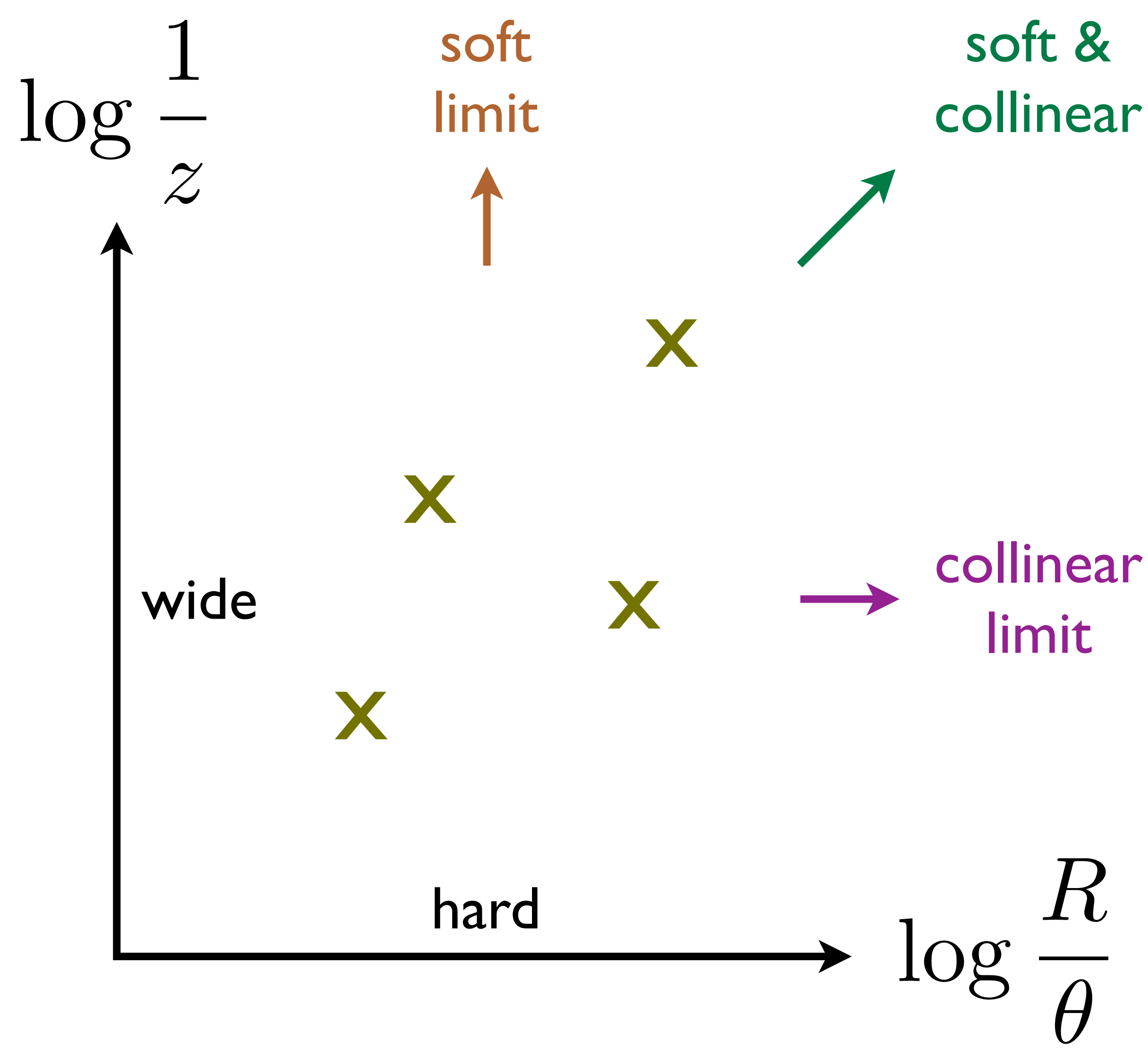
Basis for parton shower

$$\mathrm{d}P_{i \to ig} = \frac{2\alpha_s}{\pi} C_i \underbrace{\frac{\mathrm{d}\theta}{\theta} \frac{\mathrm{d}z}{z}}_{\text{Uniform in logarithmic plane}}$$

Eikonal Hard Quark/Gluon…

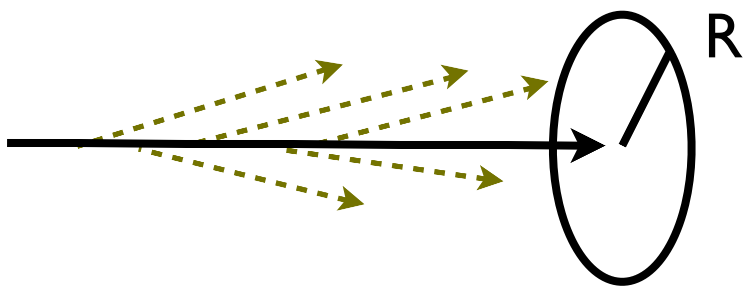


…Surrounded by Soft Gluon Haze



Soft/Collinear Phase Space

Basis for parton shower



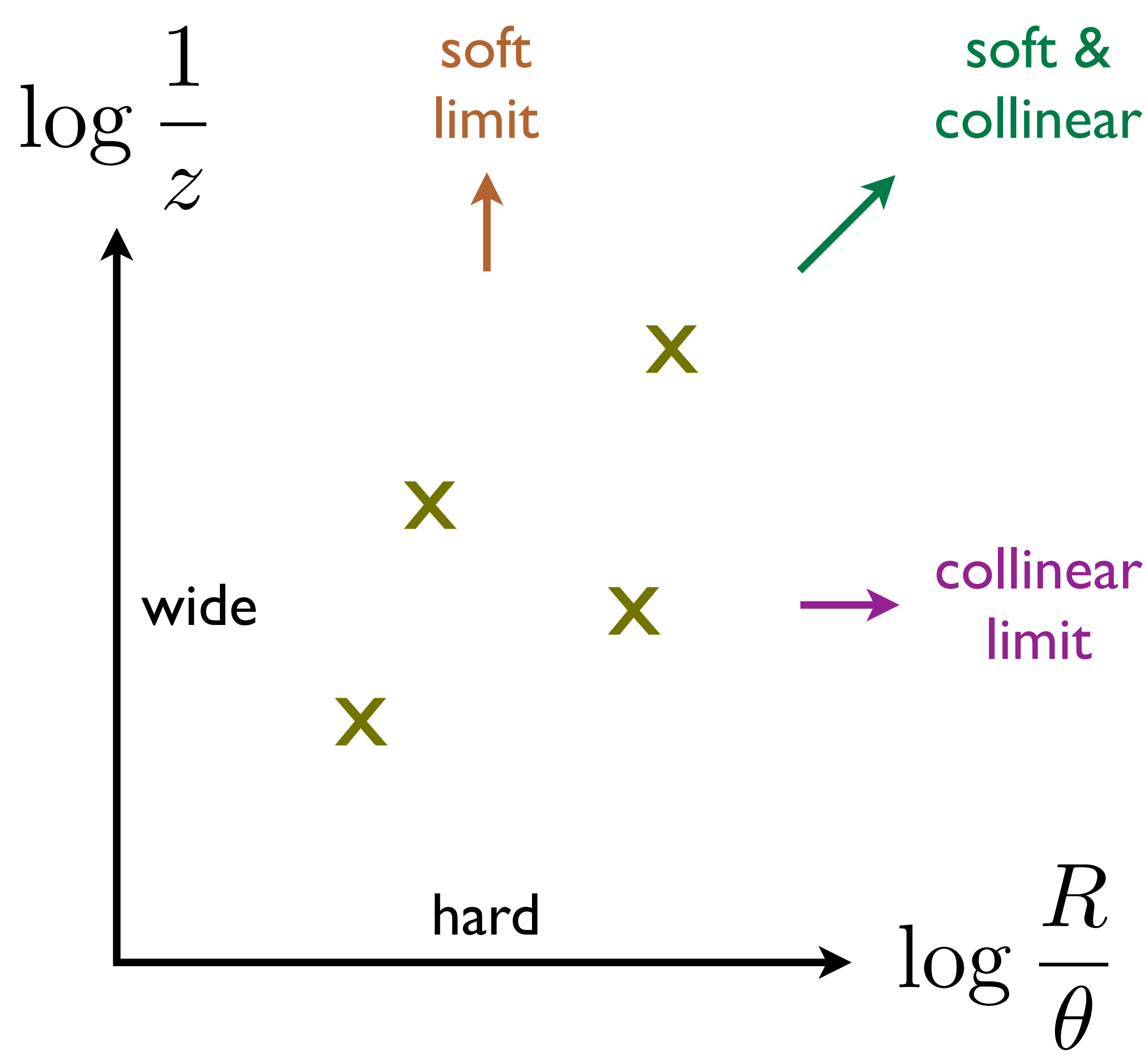
$$\mathrm{d}P_{i\to ig} = \frac{2\alpha_s}{\pi} C_i \frac{\mathrm{d}\theta}{\theta} \frac{\mathrm{d}z}{z}$$

Immediate Observations:

Arbitrary emissions?
Captures (some) physics
at all orders in α_s

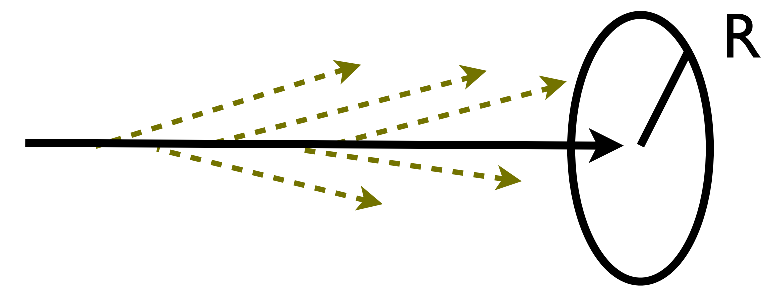
Soft/collinear singularities?
Logarithmic plane extends
up and to the right

IRC safe observables?
Smooth behavior in singular limit
(virtual contributions at infinity)



Soft/Collinear Phase Space

Basis for parton shower



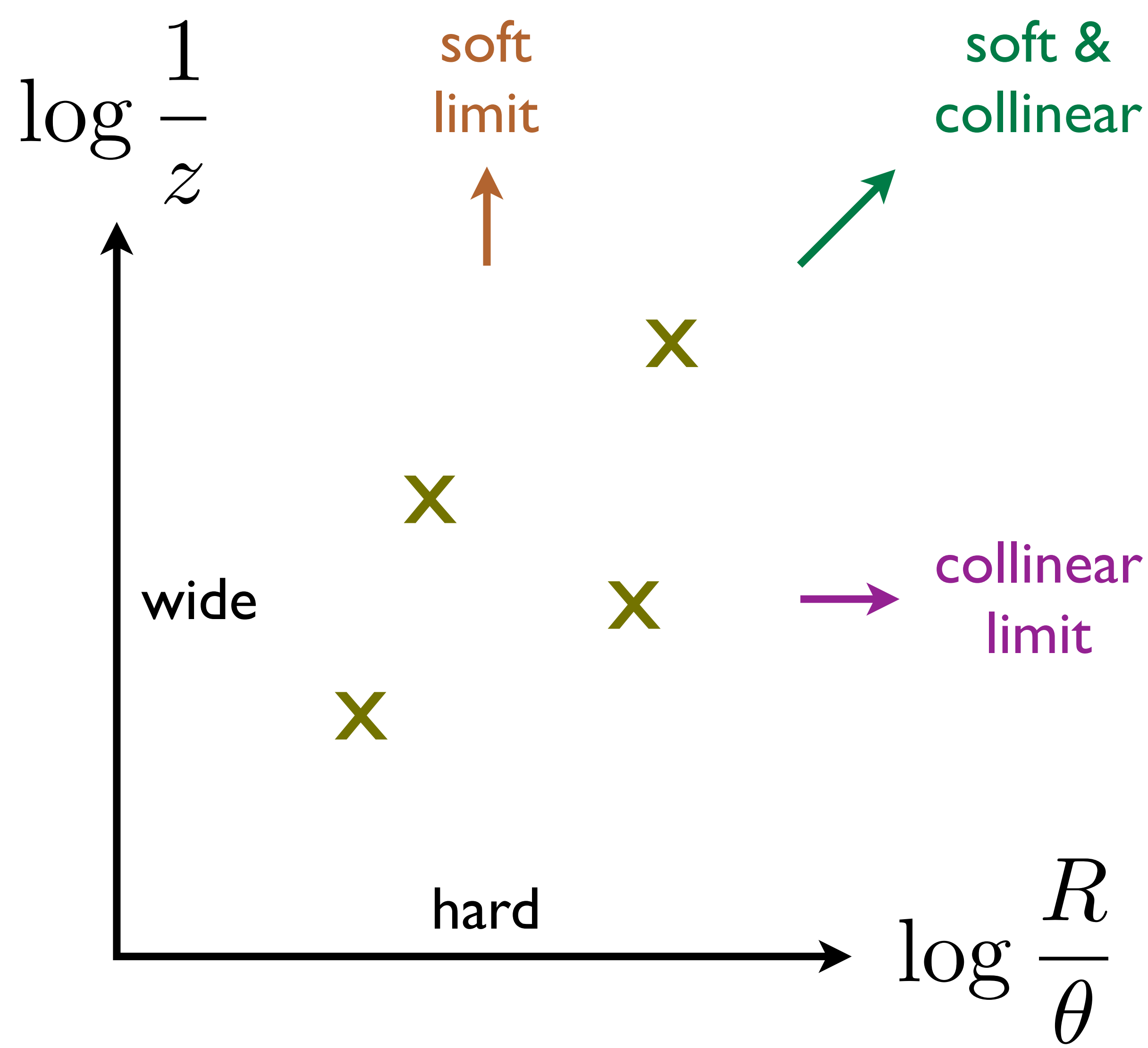
$$\mathrm{d}P_{i\to ig} = \frac{2\alpha_s}{\pi} C_i \frac{\mathrm{d}\theta}{\theta} \frac{\mathrm{d}z}{z}$$

Other Known Effects:

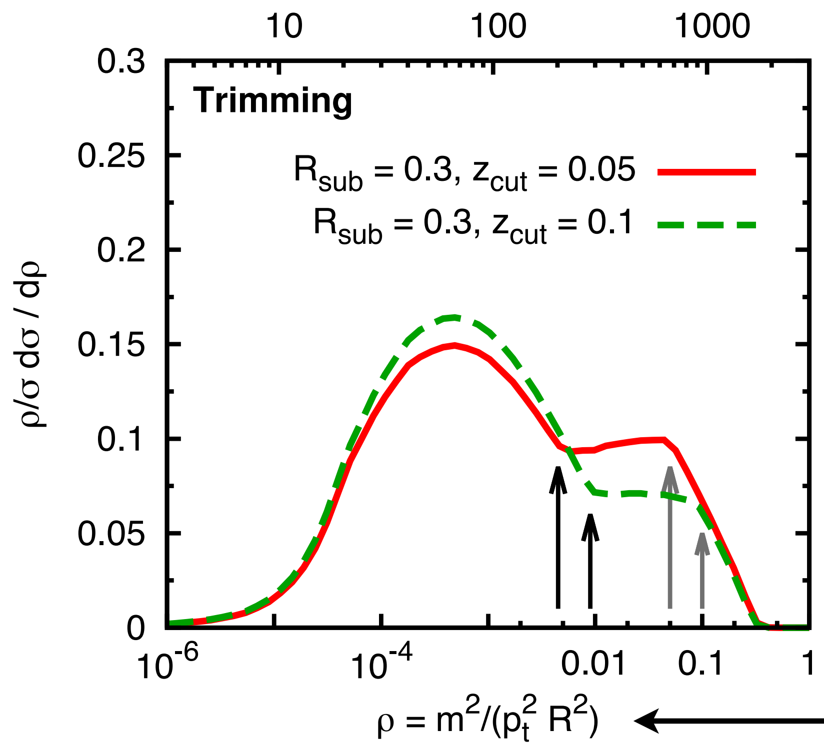
Color coherence?
At large N, emissions effectively ordered by angle

Multiple emissions?
Calculations below assume one emission sets observable

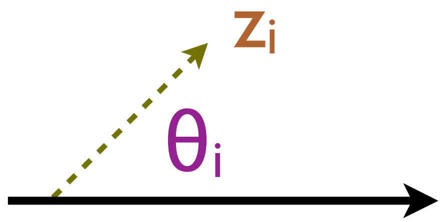
Matrix element corrections?
Should supplement semi-classical picture with quantum effects



Predicting Trimmed Jet Mass



Straightforward to replace $E_{jet} \to p_{Tjet}$



$$\rho = \frac{m^2}{E_{\rm jet}^2 R^2} \simeq \sum_{i \in {\rm jet}} z_i \left(\frac{\theta_i}{R}\right)^2$$

soft/collinear limit

When strongly ordered, one emission dominates:

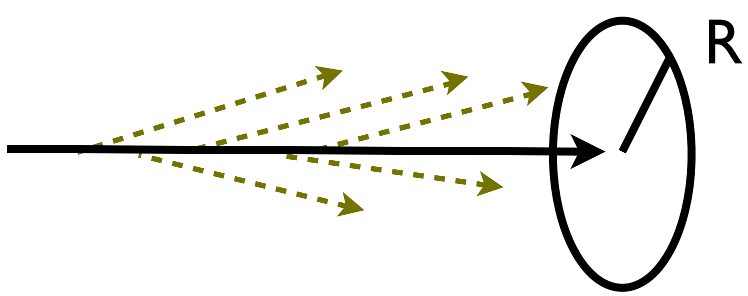
$$\log \frac{1}{\rho} \simeq \log \frac{1}{z_{\rm dom}} + 2 \log \frac{R}{\theta_{\rm dom}}$$

Restrictions from trimming:

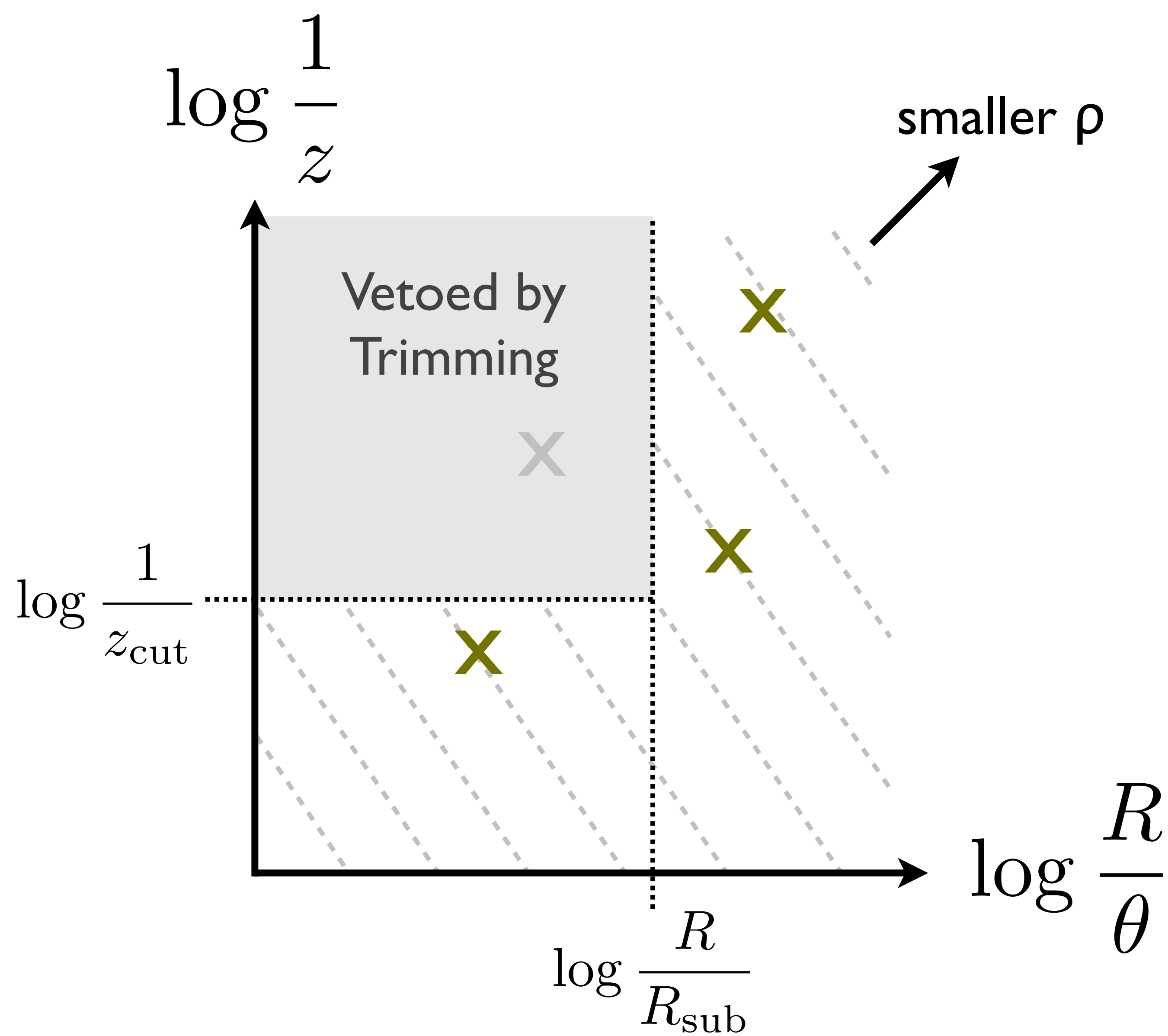
$$\theta_{\rm dom} < R_{\rm sub} \quad \Rightarrow \quad \text{No restriction}$$

$$\theta_{\rm dom} > R_{\rm sub} \quad \Rightarrow \quad z_{\rm dom} > z_{\rm cut}$$

Trimmed Phase Space

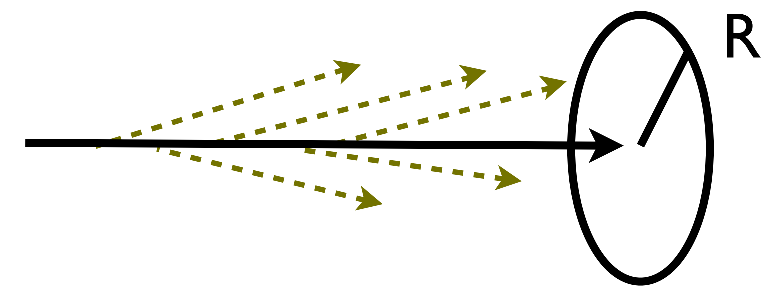


$$dP_{i\to ig} = \frac{2\alpha_s}{\pi} C_i \frac{d\theta}{\theta} \frac{dz}{z}$$

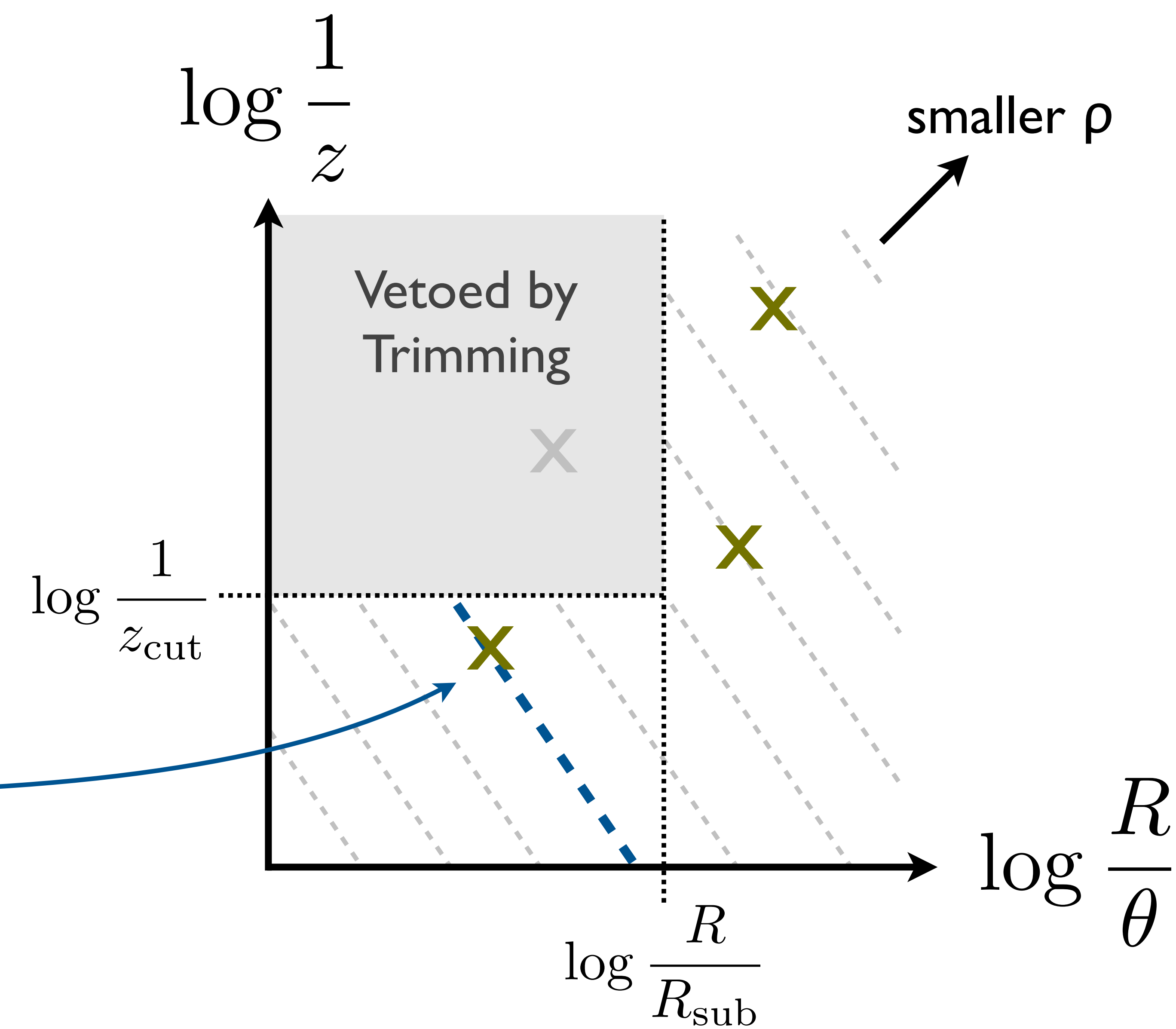


$$\log \frac{1}{\rho} \simeq \log \frac{1}{z_{\text{dom}}} + 2 \log \frac{R}{\theta_{\text{dom}}}$$

Trimmed Phase Space



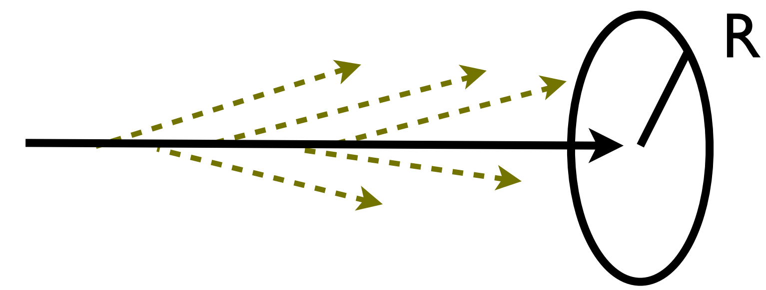
$$dP_{i\to ig} = \frac{2\alpha_s}{\pi} C_i \frac{d\theta}{\theta} \frac{dz}{z}$$



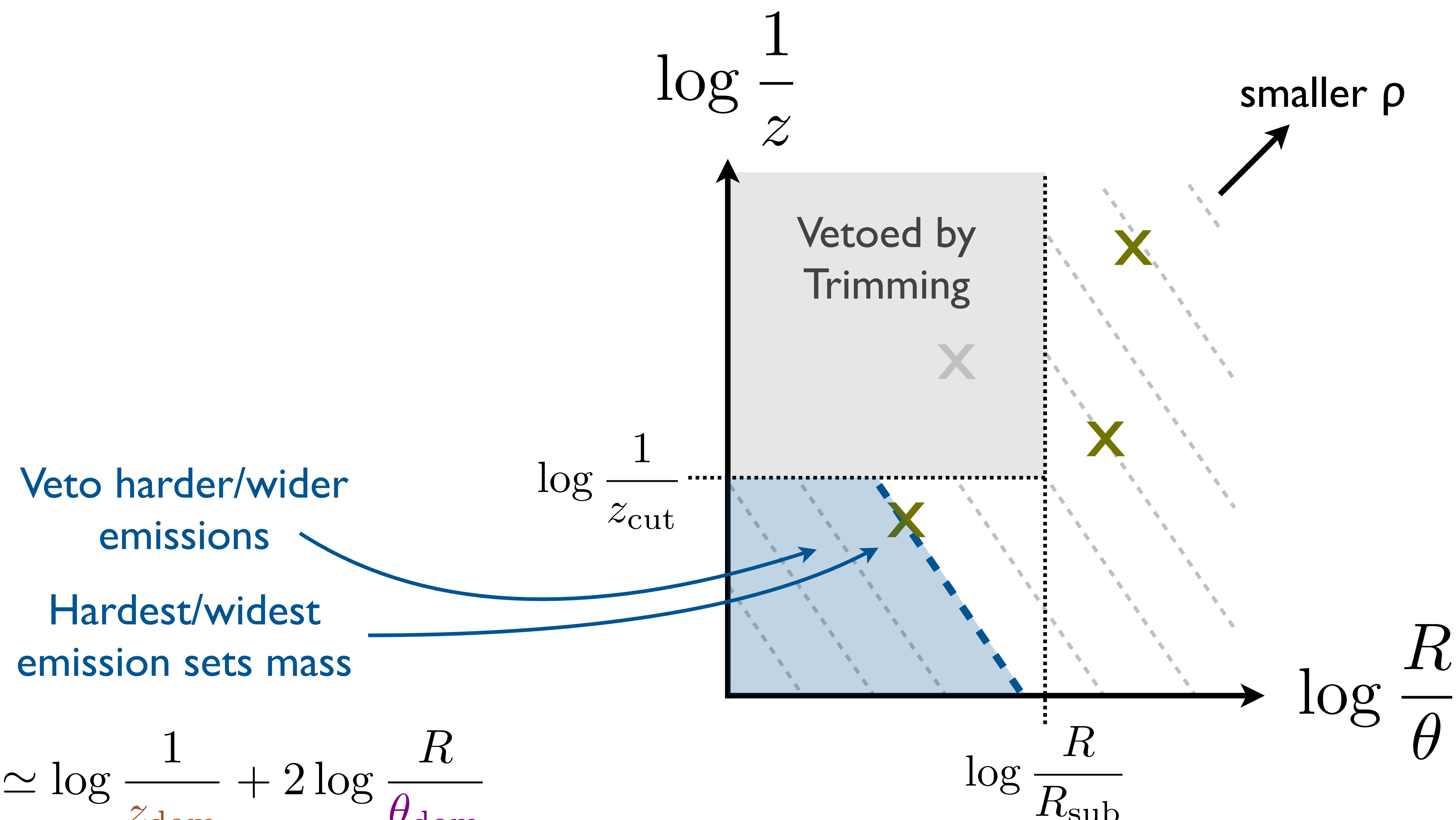
Hardest/widest emission sets mass

$$\log \frac{1}{\rho} \simeq \log \frac{1}{z_{\text{dom}}} + 2 \log \frac{R}{\theta_{\text{dom}}}$$

Trimmed Phase Space

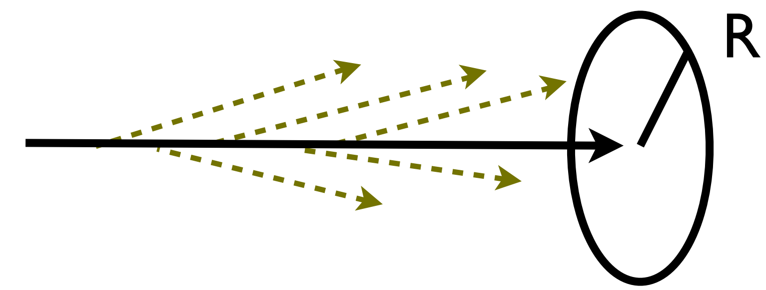


$$dP_{i\to ig} = \frac{2\alpha_s}{\pi} C_i \frac{d\theta}{\theta} \frac{dz}{z}$$



$$\log \frac{1}{\rho} \simeq \log \frac{1}{z_{\text{dom}}} + 2 \log \frac{R}{\theta_{\text{dom}}}$$

Trimmed Phase Space

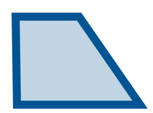


$$dP_{i \to ig} = \frac{2\alpha_s}{\pi} C_i \frac{d\theta}{\theta} \frac{dz}{z}$$

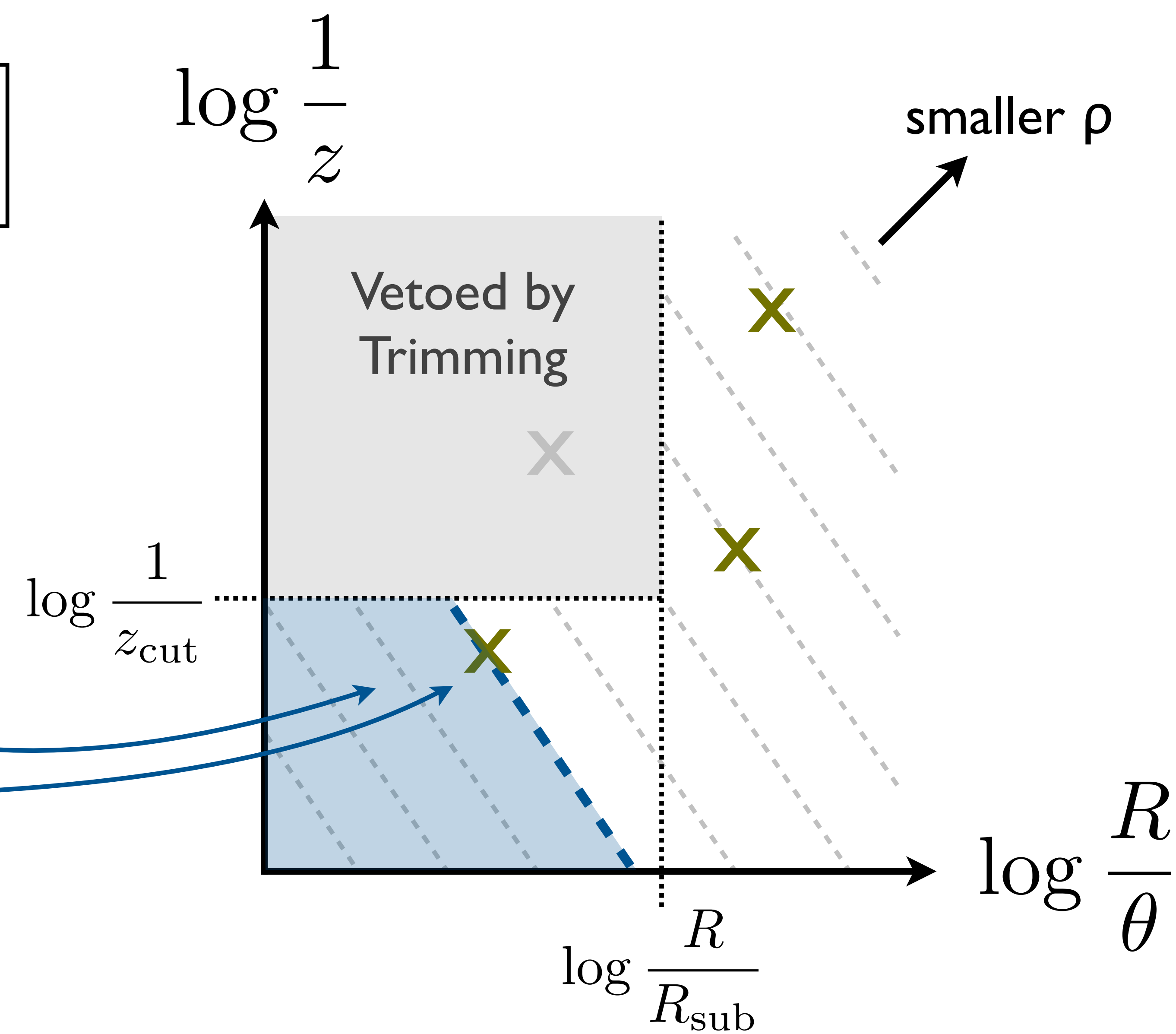
Cumulative Probability:

i.e. trimmed mass is below some maximum value

$$\Delta(\rho^{\max}) = \exp\left[-\frac{2\alpha_s}{\pi} C_i \right]$$



Differentiate to find cross section

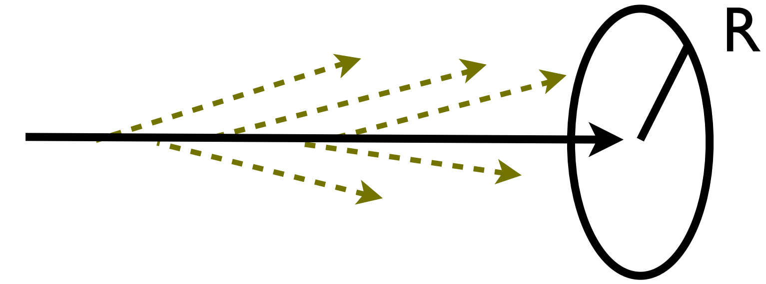


Veto harder/wider emissions

Hardest/widest emission sets mass

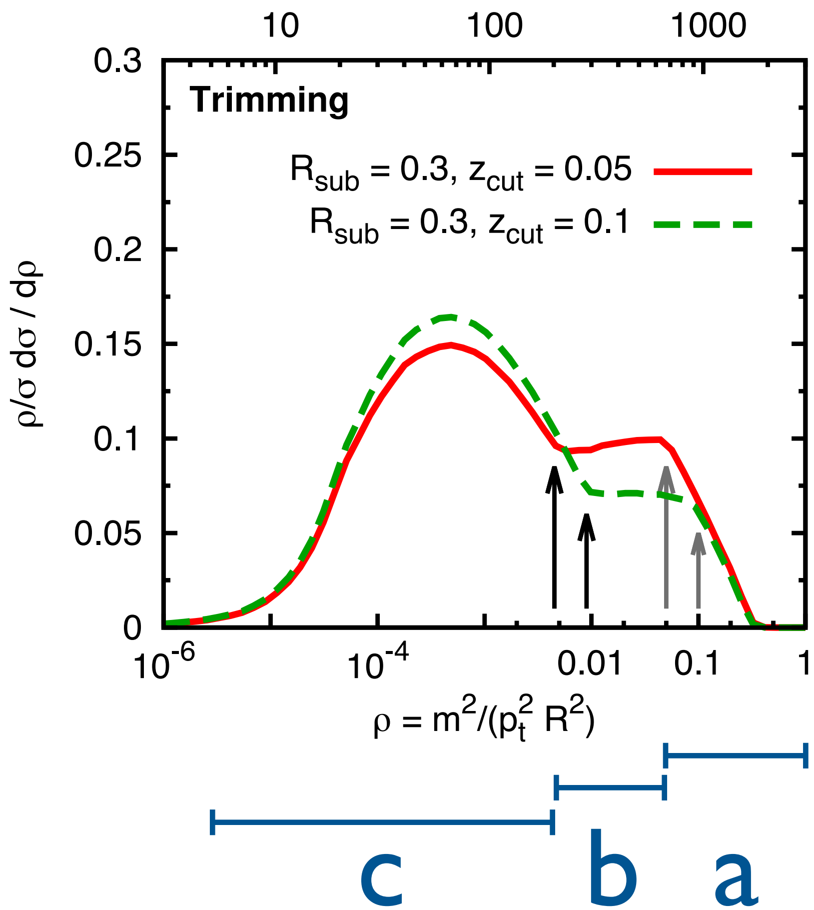
$$\log \frac{1}{\rho} \simeq \log \frac{1}{z_{\mathrm{dom}}} + 2 \log \frac{R}{\theta_{\mathrm{dom}}}$$

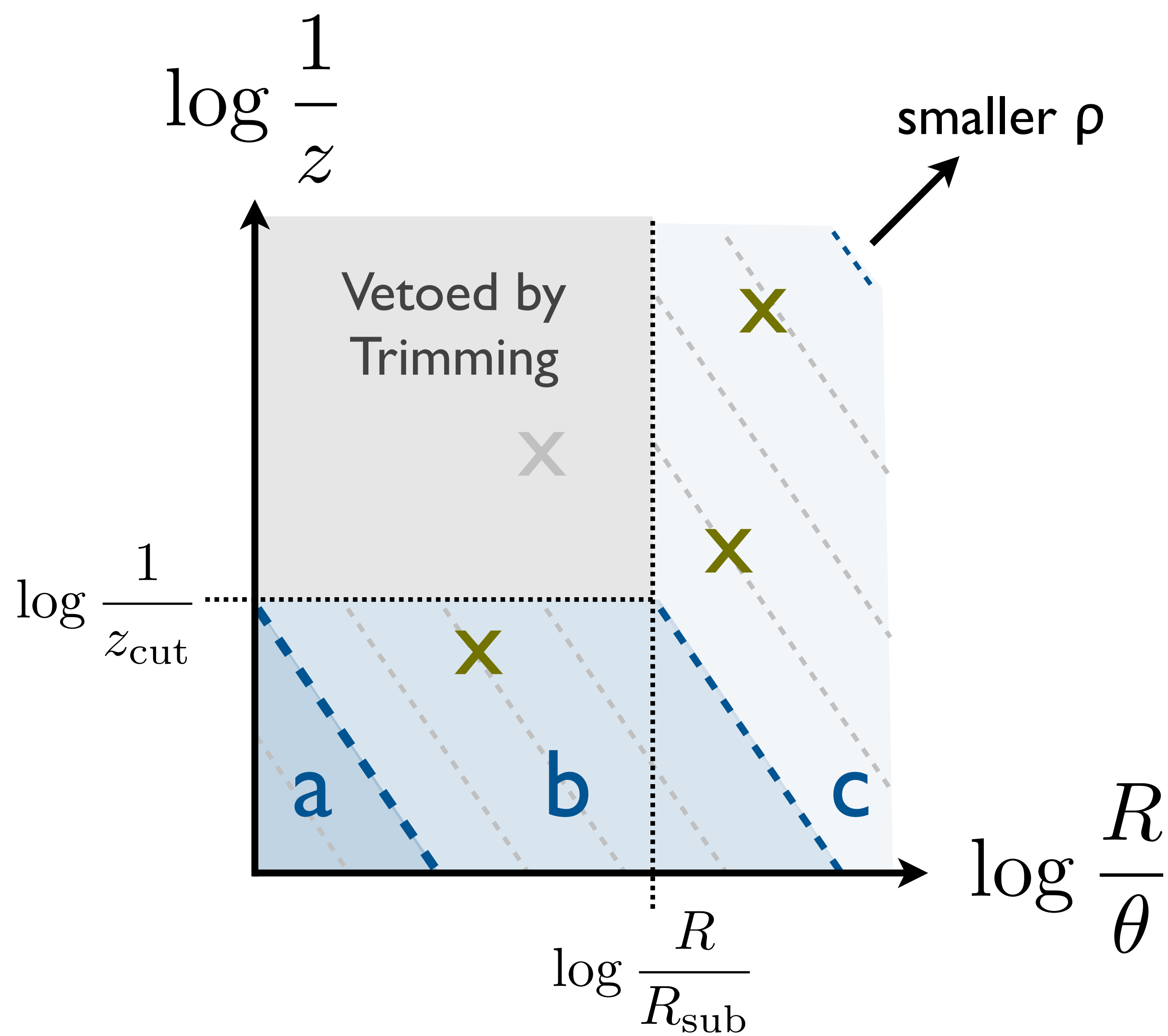
Trimmed Phase Space



$$dP_{i\to ig} = \frac{2\alpha_s}{\pi} C_i \frac{d\theta}{\theta} \frac{dz}{z}$$

Immediately understand kink locations

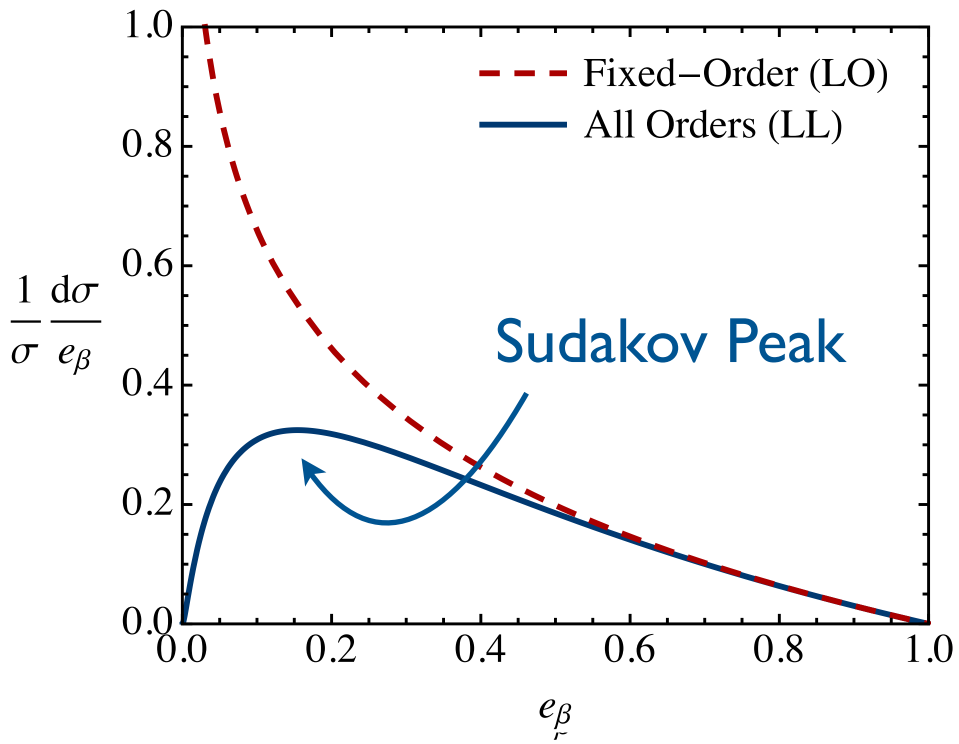




$$\Delta = e^{-\frac{2\alpha_s}{\pi} C_i}$$

Resummation vs. Fixed-Order

Ordinary jet mass



$$\Delta = \exp\left[-\frac{2\alpha_s}{\pi} C_i \; \blacktriangle \right]$$

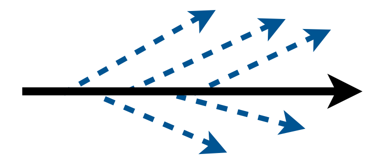
$$\uparrow$$

$$\frac{1}{4}\log^2\frac{m^2}{p_T^2 R^2}$$

Sudakov double logs dominate distribution

All α_s Orders

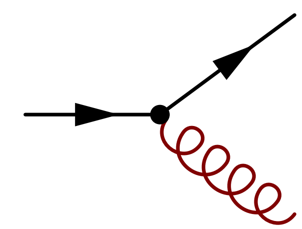
(resumed logs)



m=0 suppressed

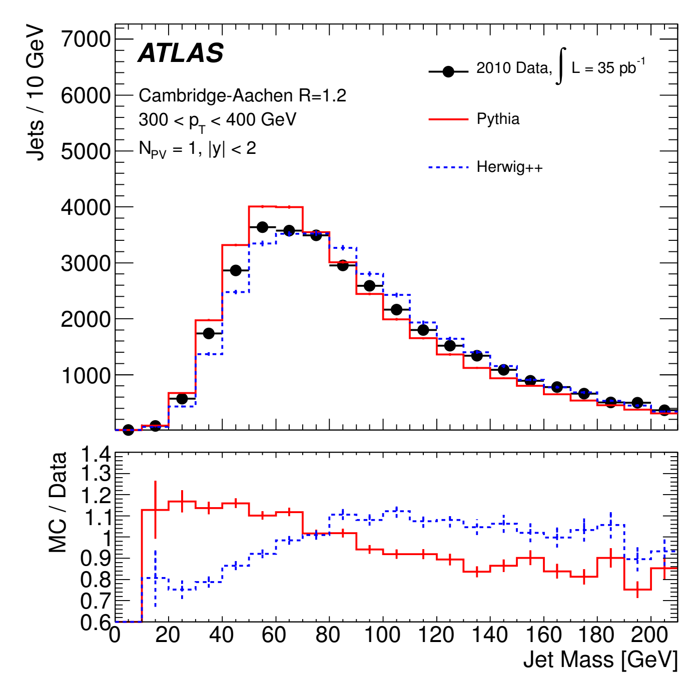
vs.

Fixed $O(\alpha_s)$

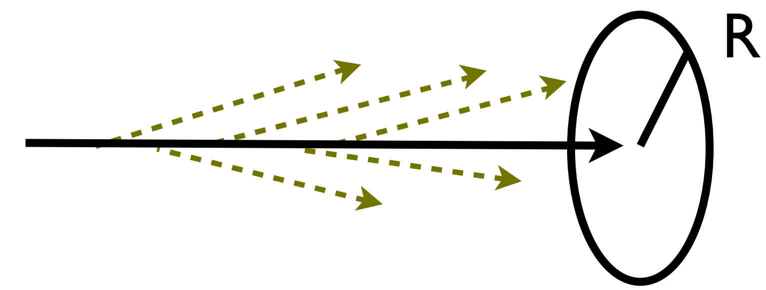


m=0 singular

Recall Jet Mass Data



Systematically Improvable

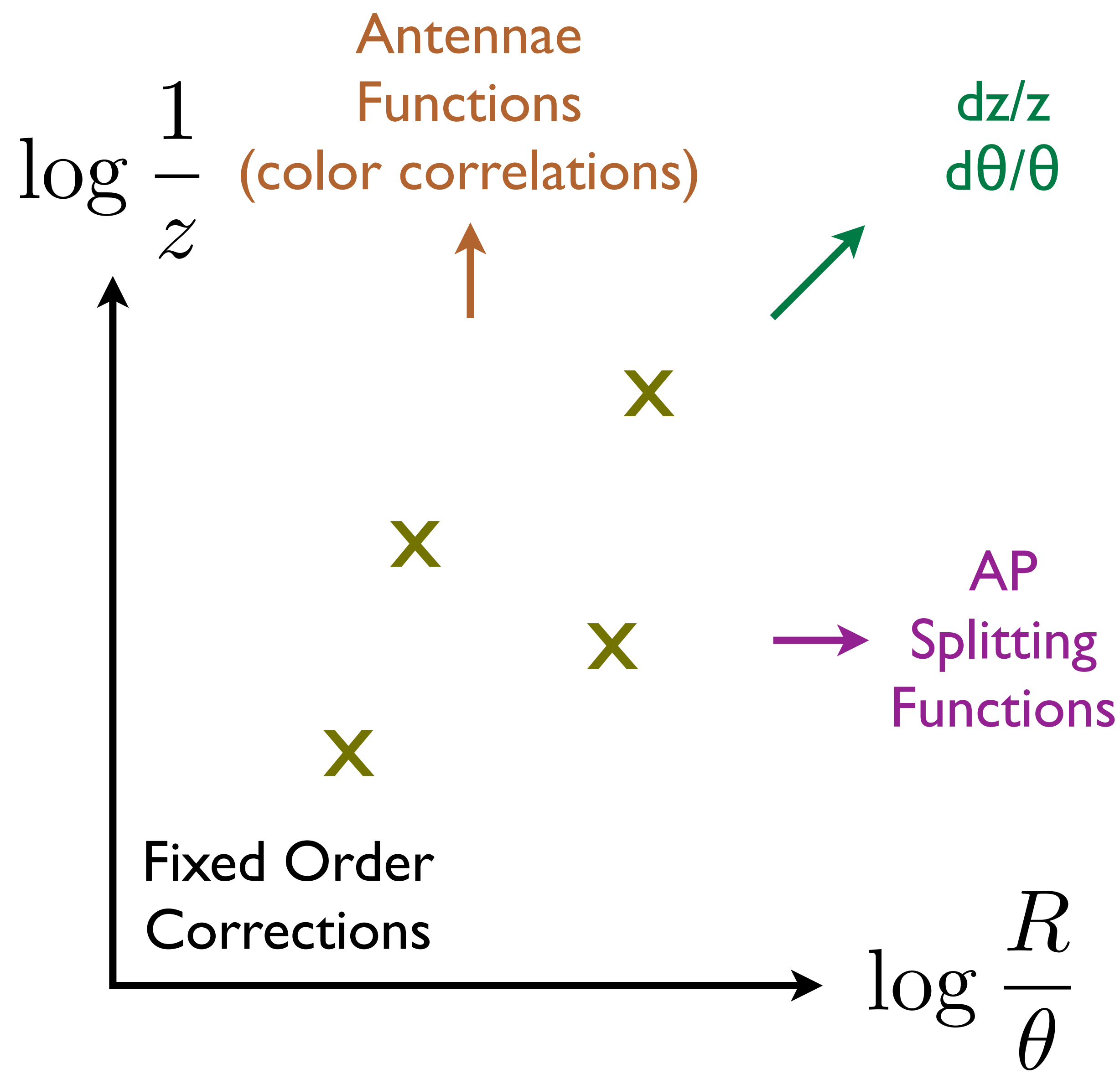


$$dP_{i\to ig} = \frac{2\alpha_s}{\pi} C_i \frac{d\theta}{\theta} \frac{dz}{z}$$

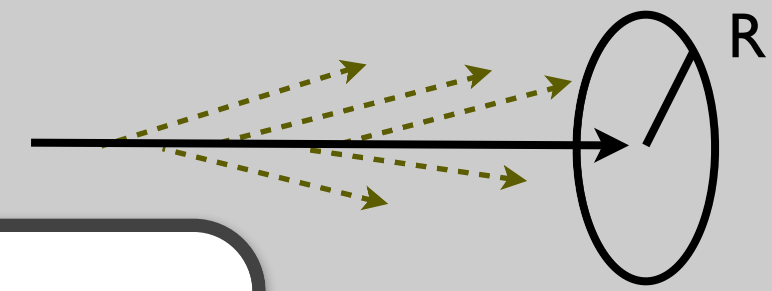
Strongly-Ordered Limit:
Leading logarithmic terms
(i.e. $\alpha_s \log^2 \rho$)

Higher-Order Effects:
Running α_s,
Multiple Emissions,
Energy/Momentum Recoil
Full Splitting Functions,
Soft Color Correlations,
Fixed-Order Corrections,
Non-global Logarithms, ...

(Many effects already included in realistic parton showers)



Systematically Improvable



Strongly-

Leading lo

(i.e.

$$= \frac{2\alpha_s}{\pi} C_i \frac{d\theta}{\theta} \frac{dz}{z}$$

Higher-

Ru

Multip

Energy/Mo

Full Split

Soft Colo

Fixed-Ord

Non-globa

ns)

dz/z
dθ/θ

x

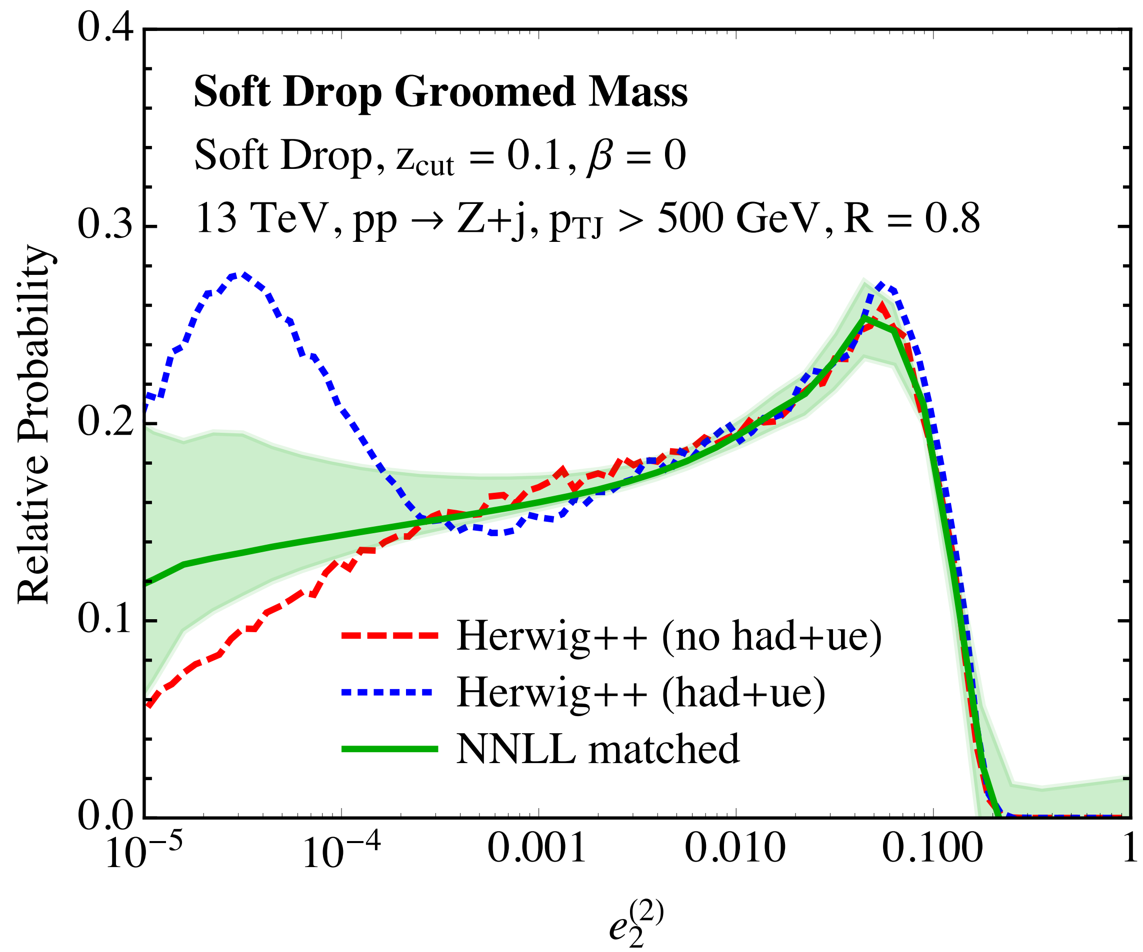
x

AP
Splitting
Functions

(Many effect
realistic p

$$\log \frac{R}{\theta}$$

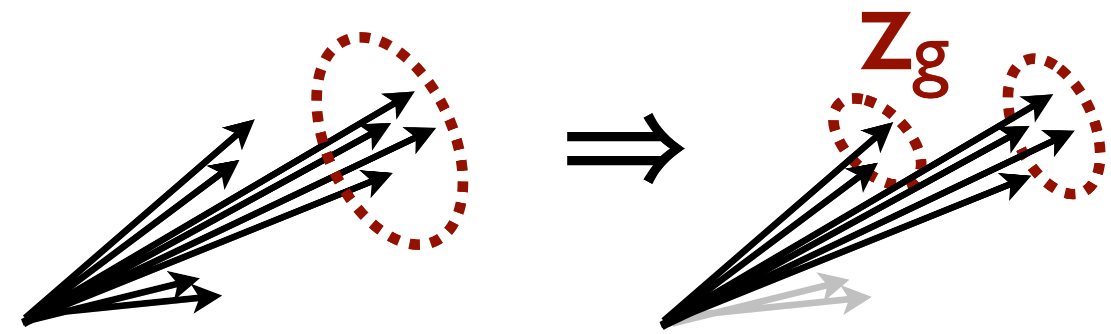
First NNLL + O(α_s^2) calculation for substructure in pp



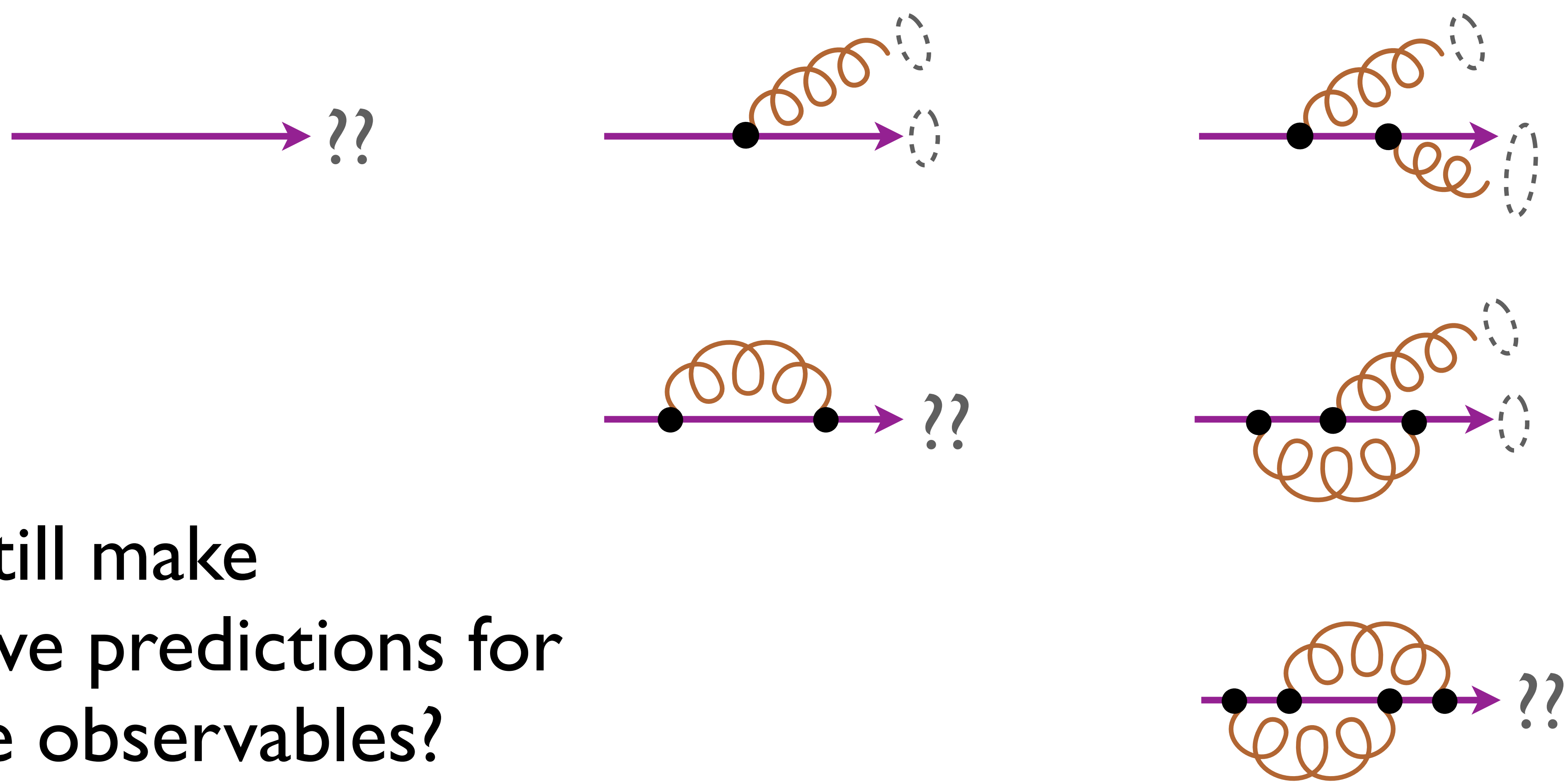
[Frye, Larkoski, Schwartz, Yan, 1603.06375, 1603.09338]

Preview of Tomorrow

Unsafe Calculations?

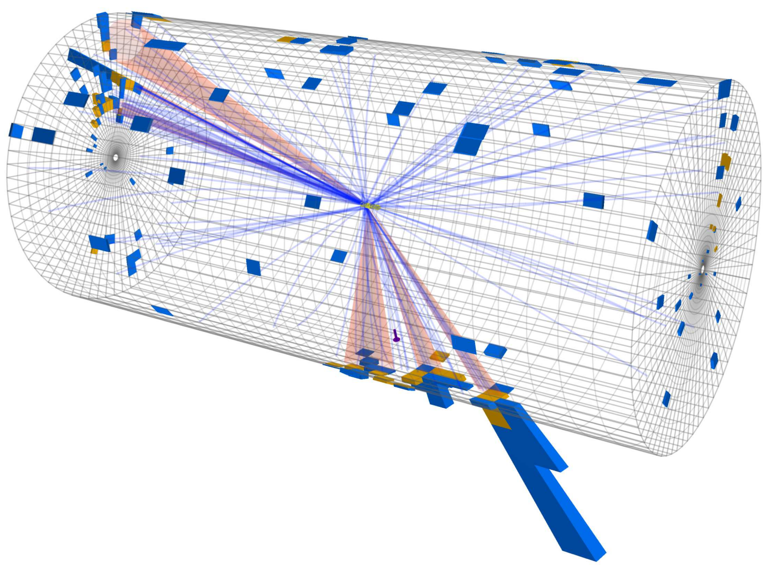


$$p(z_g) = \Big(\ \textit{undefined}\ \Big) + \alpha_s\Big(\ \textit{infinity}\ \Big) + \alpha_s^2\Big(\ \textit{infinity}^2\ \Big) + \ldots$$



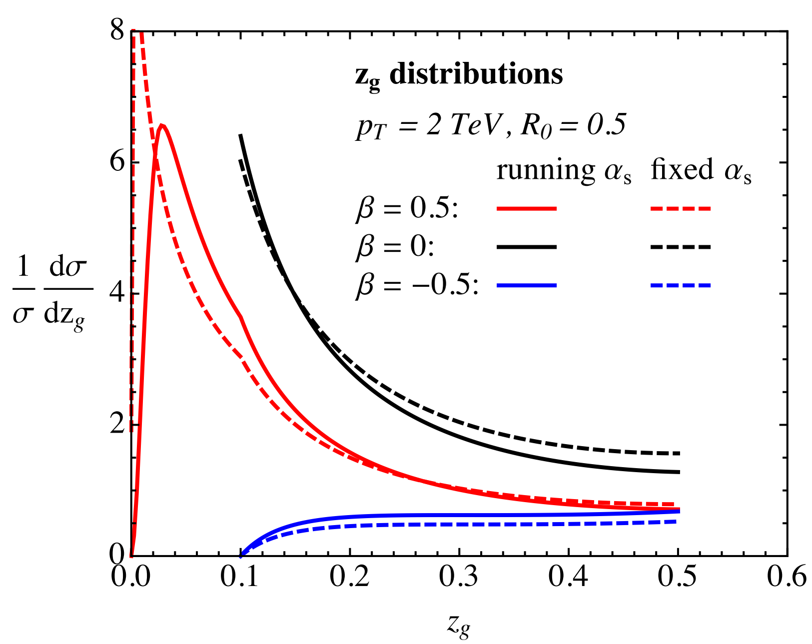
Can you still make perturbative predictions for IRC unsafe observables?

Jet Substructure



Boosting the Search for New Phenomena

[Last Thursday & Friday]



Pushing the Boundaries of Quantum Field Theory

[Today & Tuesday]