JET PHYSICS

2012 CTEQ summer school

Lima, Peru

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Harvard University

Outline

- Lecture 1: Jets and QCD
  - The physics of jets
    - Including brief history
  - Jets from perturbative QCD
  - Jet algorithms
  - Some data

- Lecture 2: Modern jet physics
  - Jet substructure
  - Jet grooming
  - Jet properties
  - The future of jets

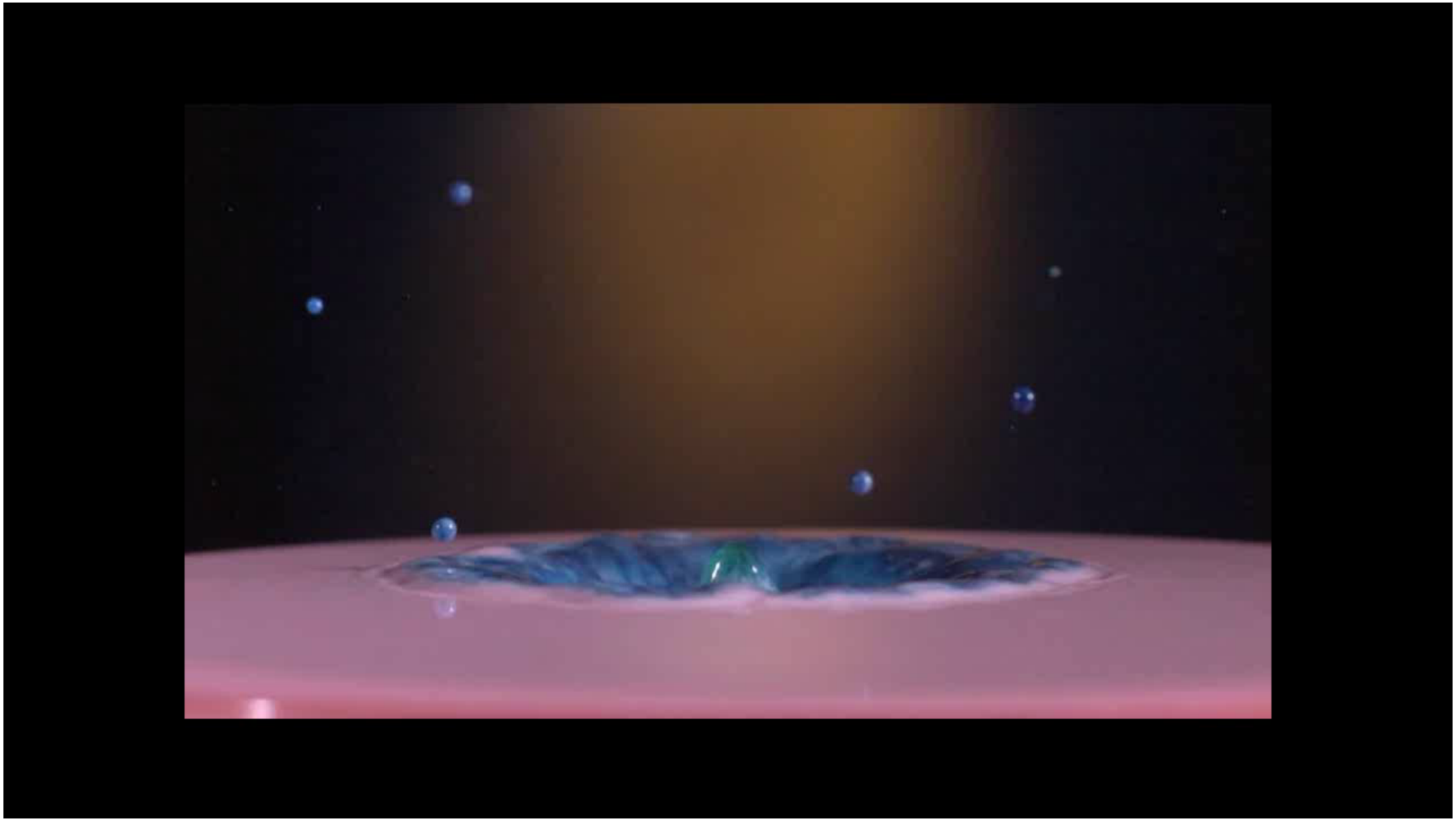
THE PHYSICS OF JETS

What happens in a collision?

Colliding water droplets – what happens?

What happens in a collision?

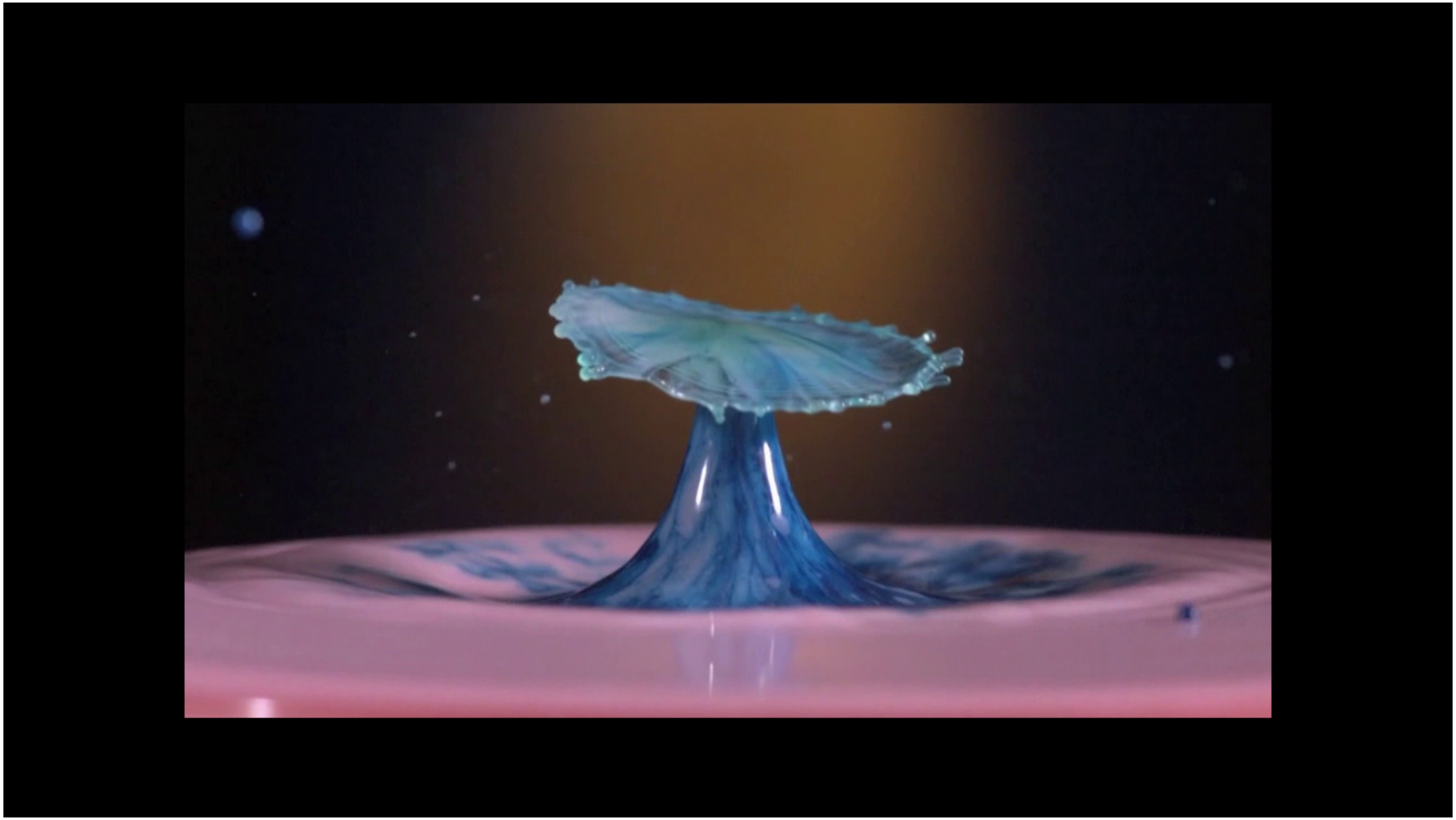
Colliding water droplets – what happens?



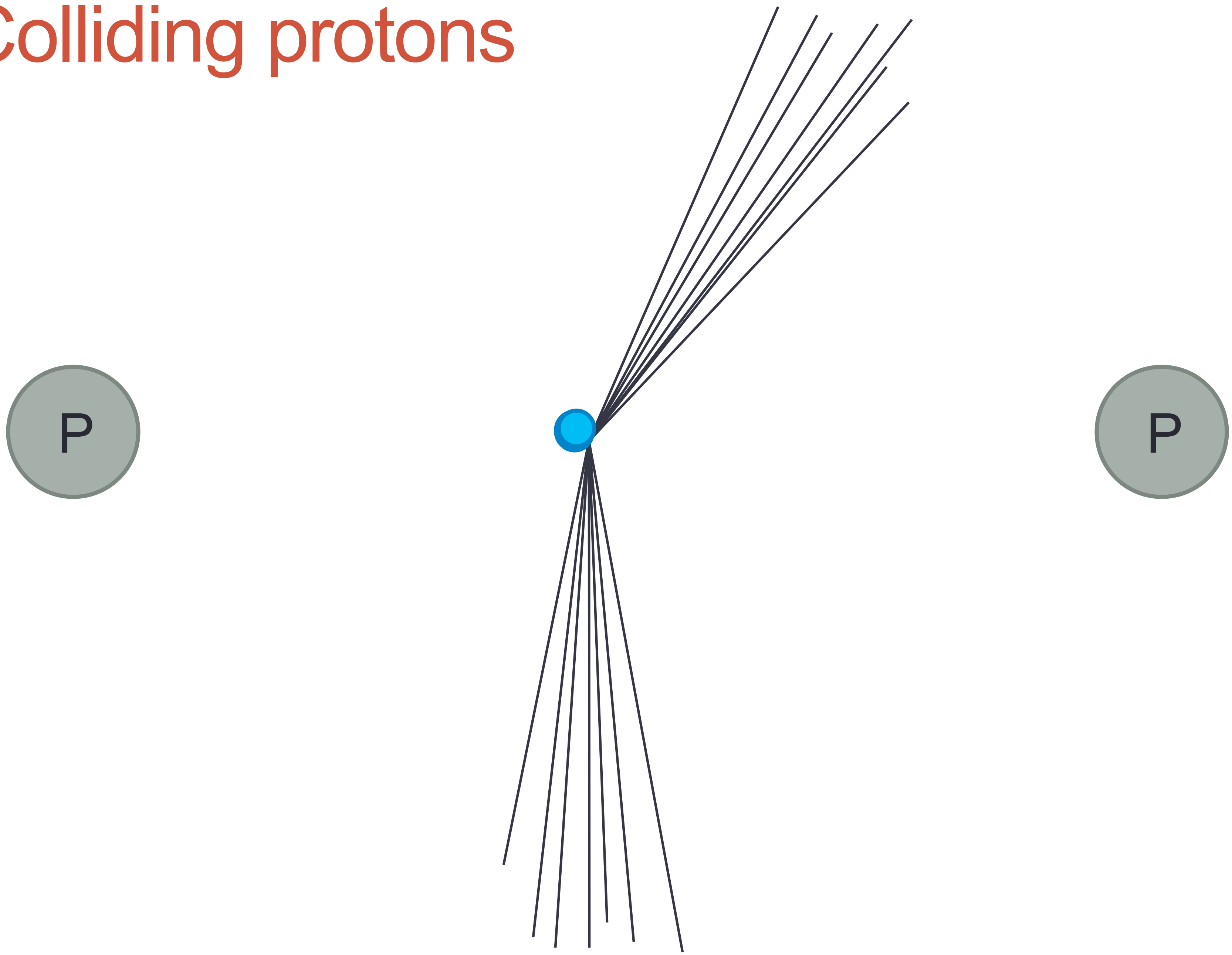
What happens in a collision?

Colliding water droplets – what happens?

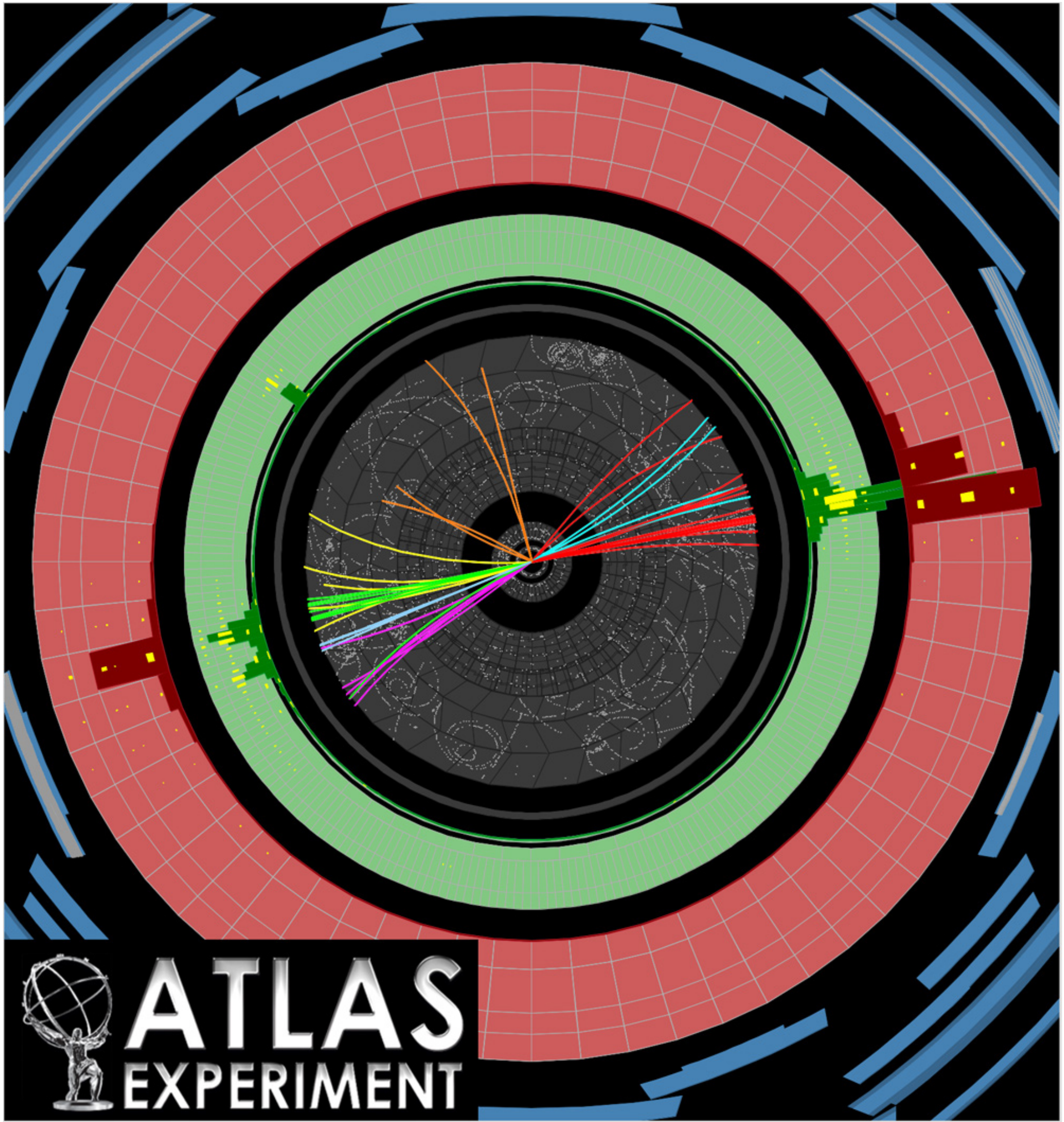
Produces **radially symmetric** distribution



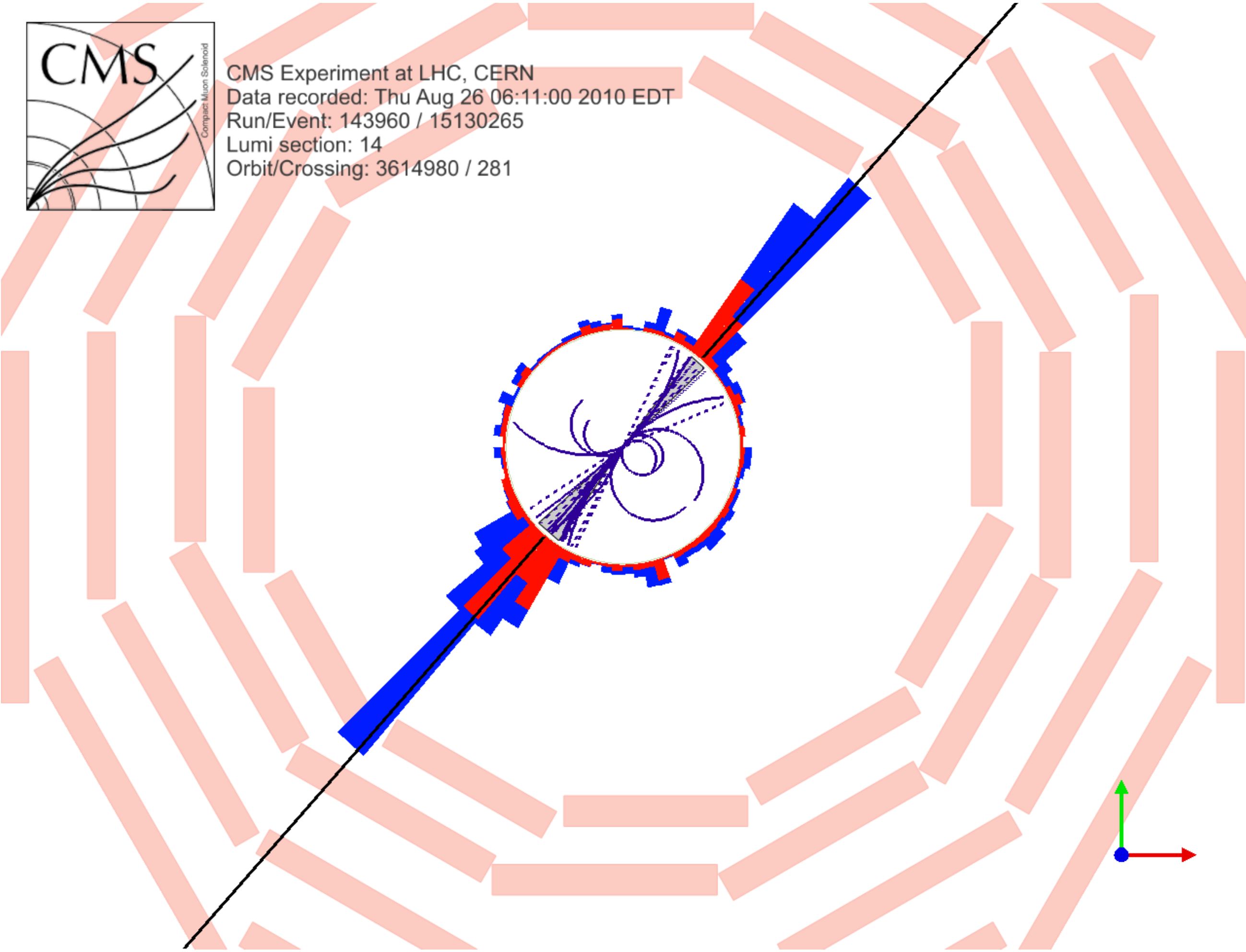
Colliding protons



Colliding protons



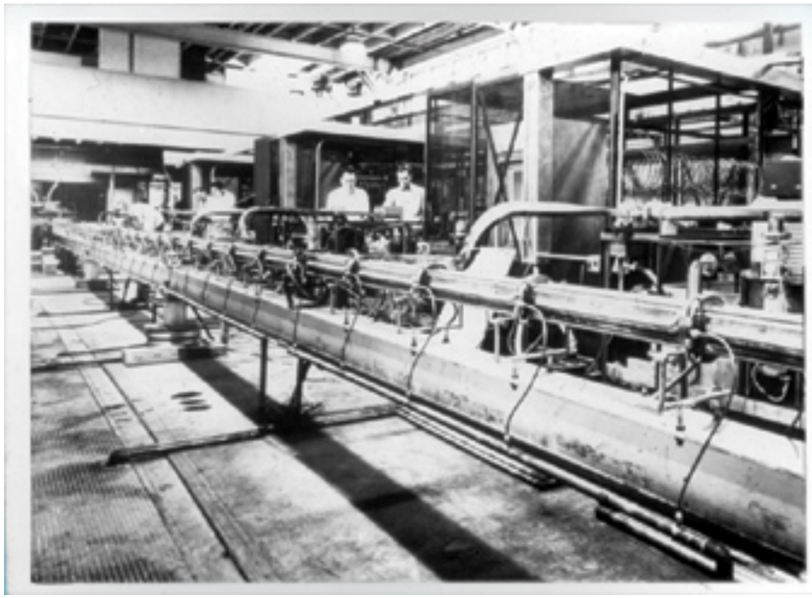
Colliding protons

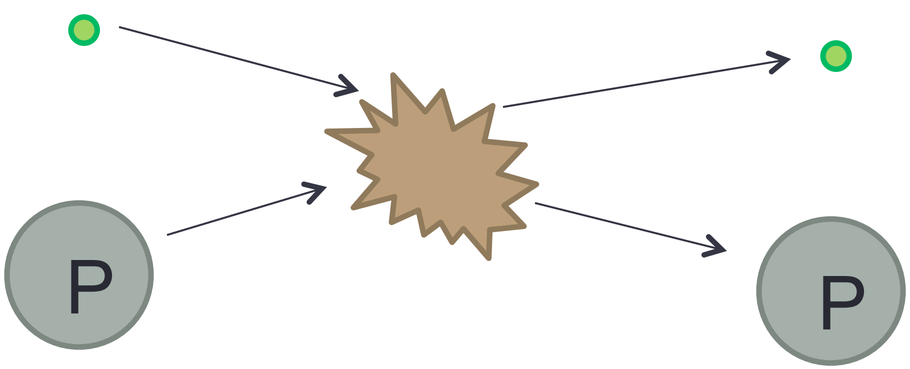


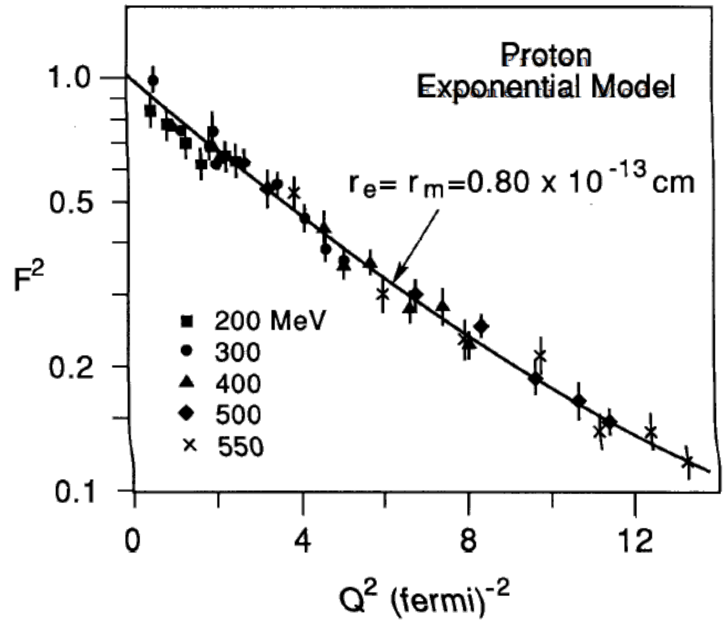
Electron-positron ($e^- P^+$) scattering

1950s at the Mark III linear collider at Stanford

- Energies of order 200-500 MeV







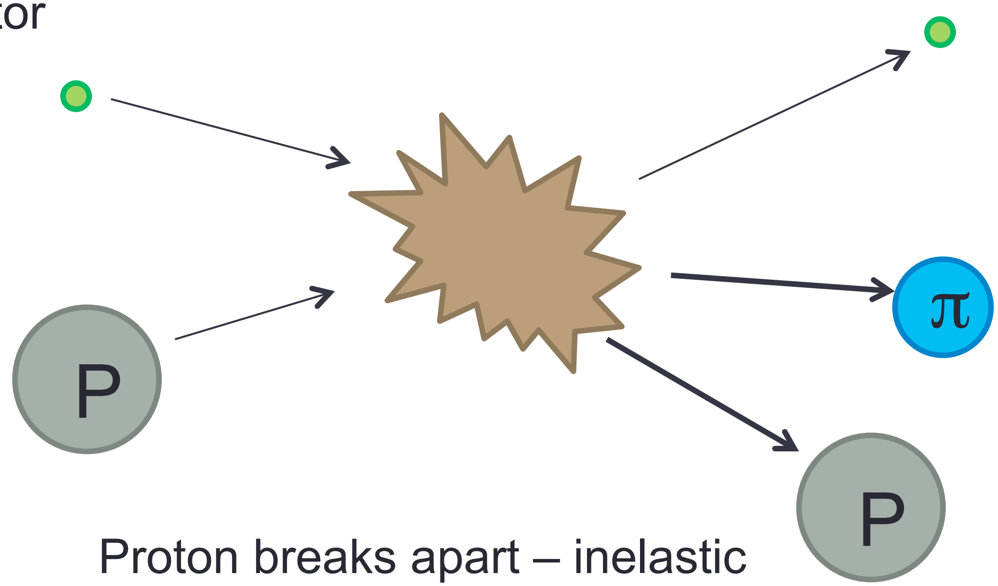
$$F(q^2) \sim \frac{1}{1+\left(\frac{q}{0.71\,\mathrm{GeV}}\right)^2}$$

$$\leftrightarrow \quad V(r) = \frac{1}{r} e^{-(0,7\,\mathrm{GeV})r}$$

Proton has size: r = 10^{-15}m

Higher energy $e^- P^+$ scattering

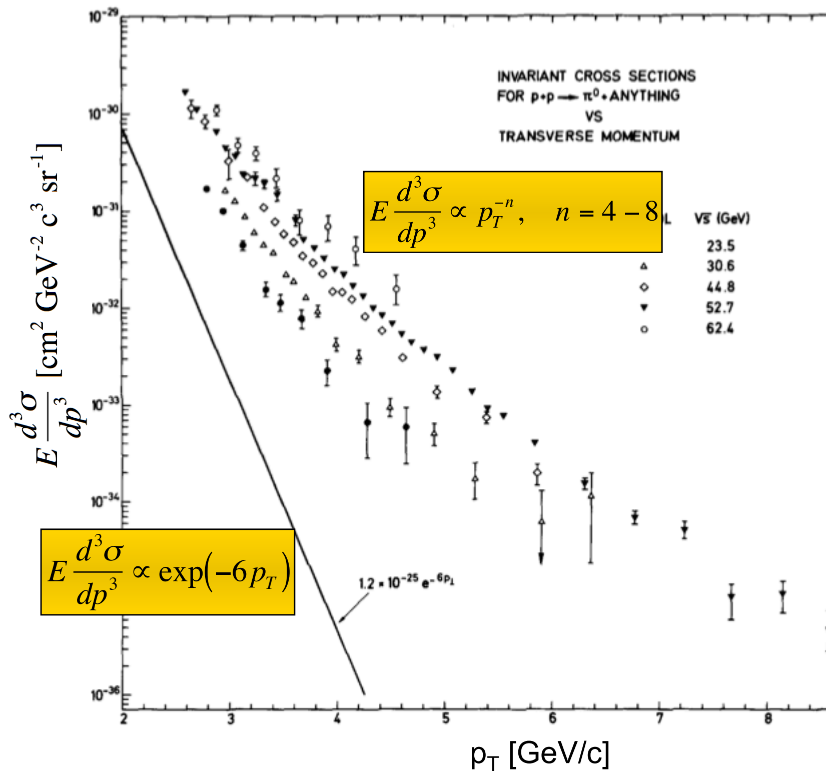
1960s at Stanford Linear Accelerator (SLAC)



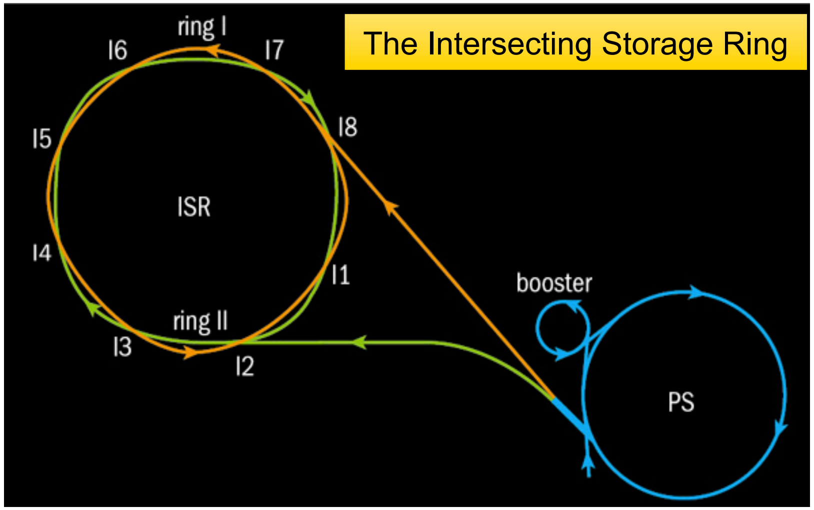
Proton breaks apart – inelastic scattering!

Intersecting Storage Rings (ISR) at CERN

First hadron (pp) collider



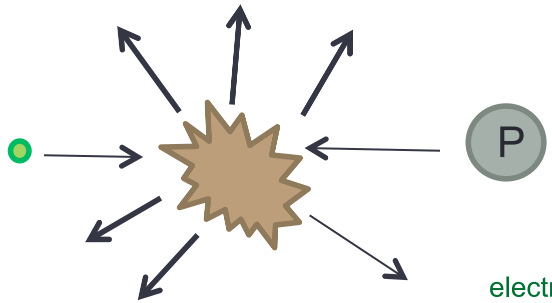
From T. Schörner-Sadenius

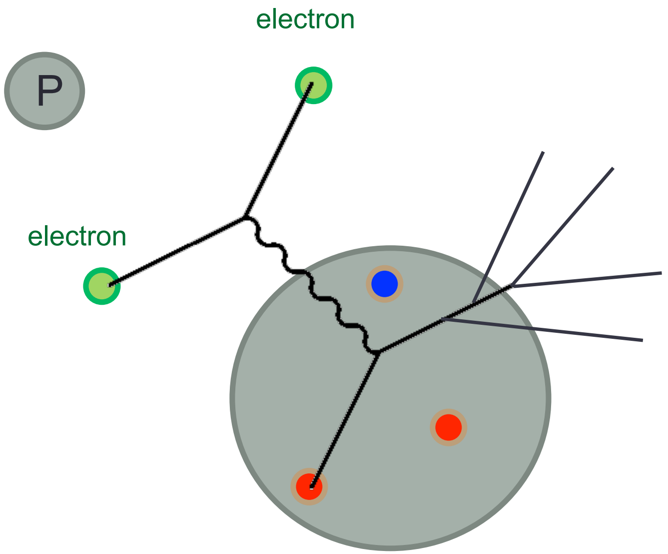


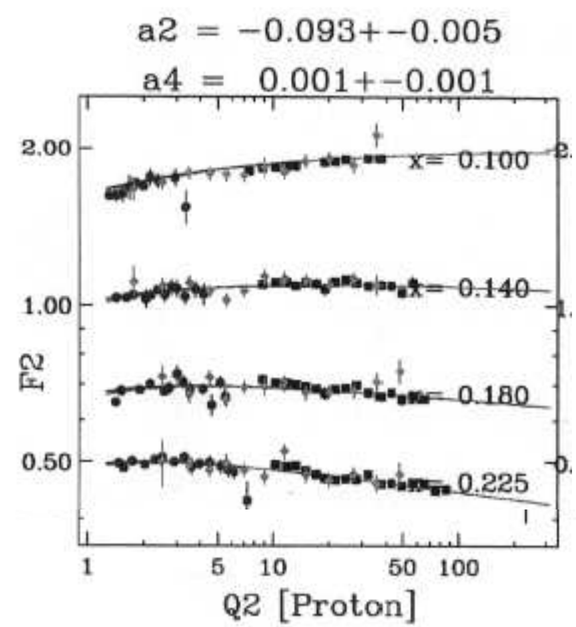
- Unexpected **rise** in the total **pp cross section**
- Large number of particles produced at **high p_T**
- Consistent with (early) expectations from QCD

Very high energy $e^- P^+$ scattering

1960s at SLAC







Now $F(q^2)$ = constant again!

Hard scattering off of
pointlike weakly interacting constituents in the proton

quarks

What happens to the proton?

Hard to tell -- DIS experiments of the 50s and 60s were fixed-target experiments

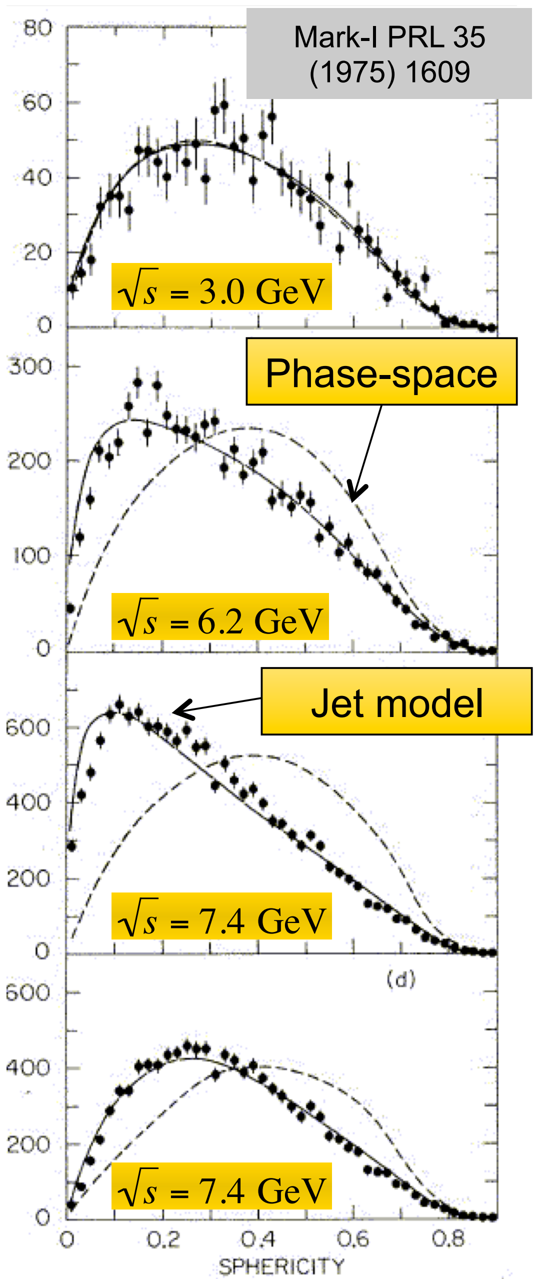
-- not designed to measure the "hadronic" part, just the electron

Spear at SLAC

Mark I -- first 4π detector (1973-1977)

$$S = \frac{3\left(\sum_i p_{T,i}^2\right)}{2\left(\sum_i p_i^2\right)}$$

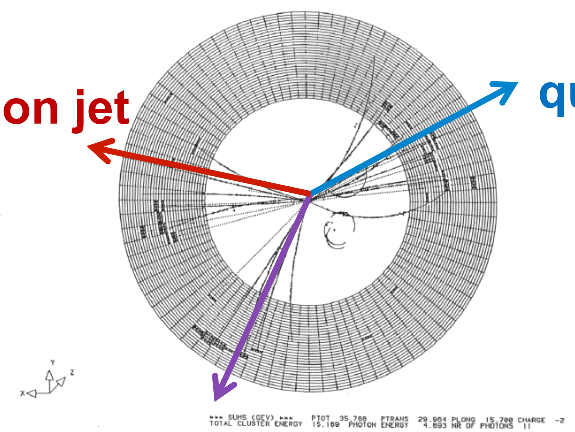
Measured Sphericity (event shape)



From T. Schörner-Sadenius

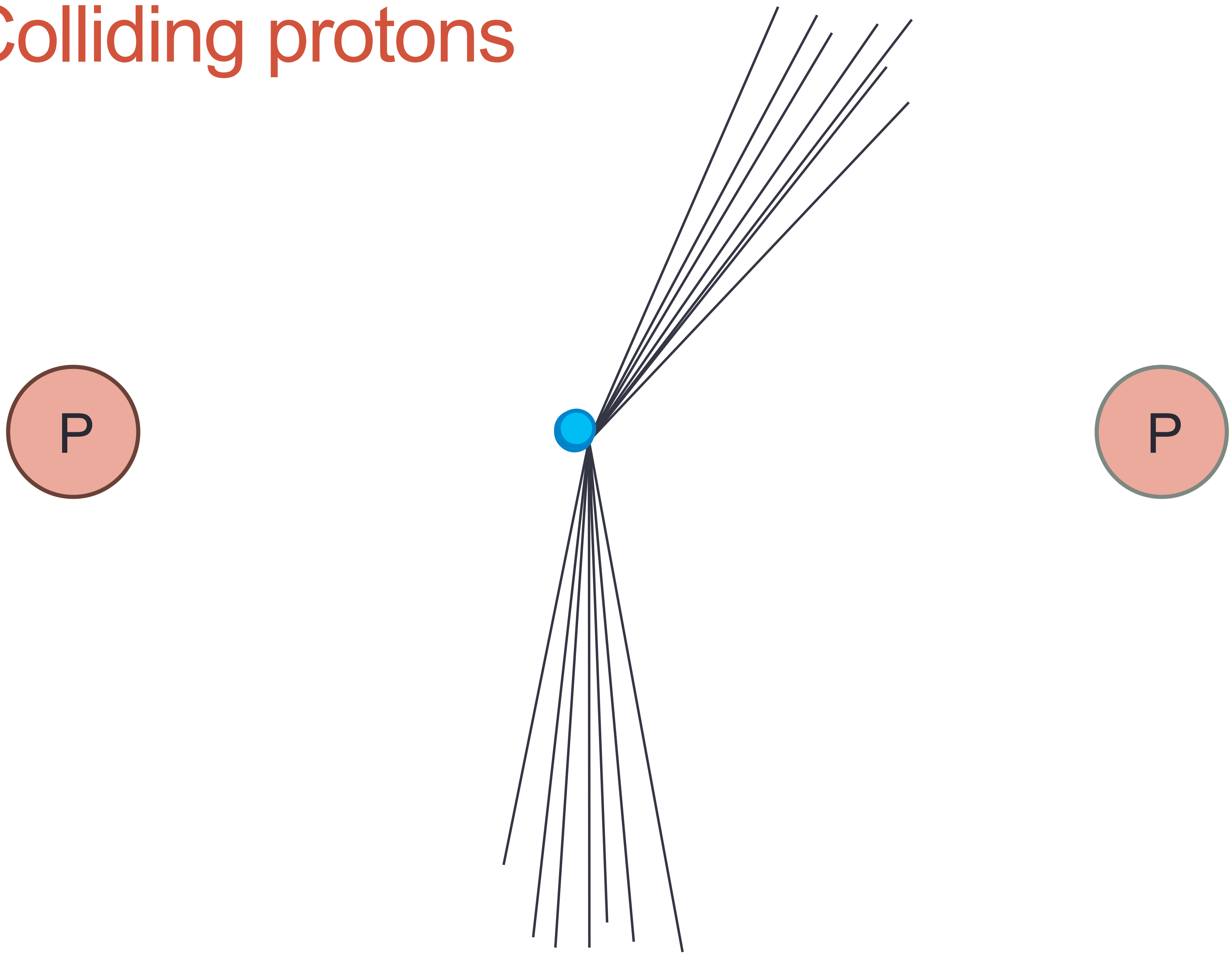
PETRA at DESY (Hamburg)

Gluon jets



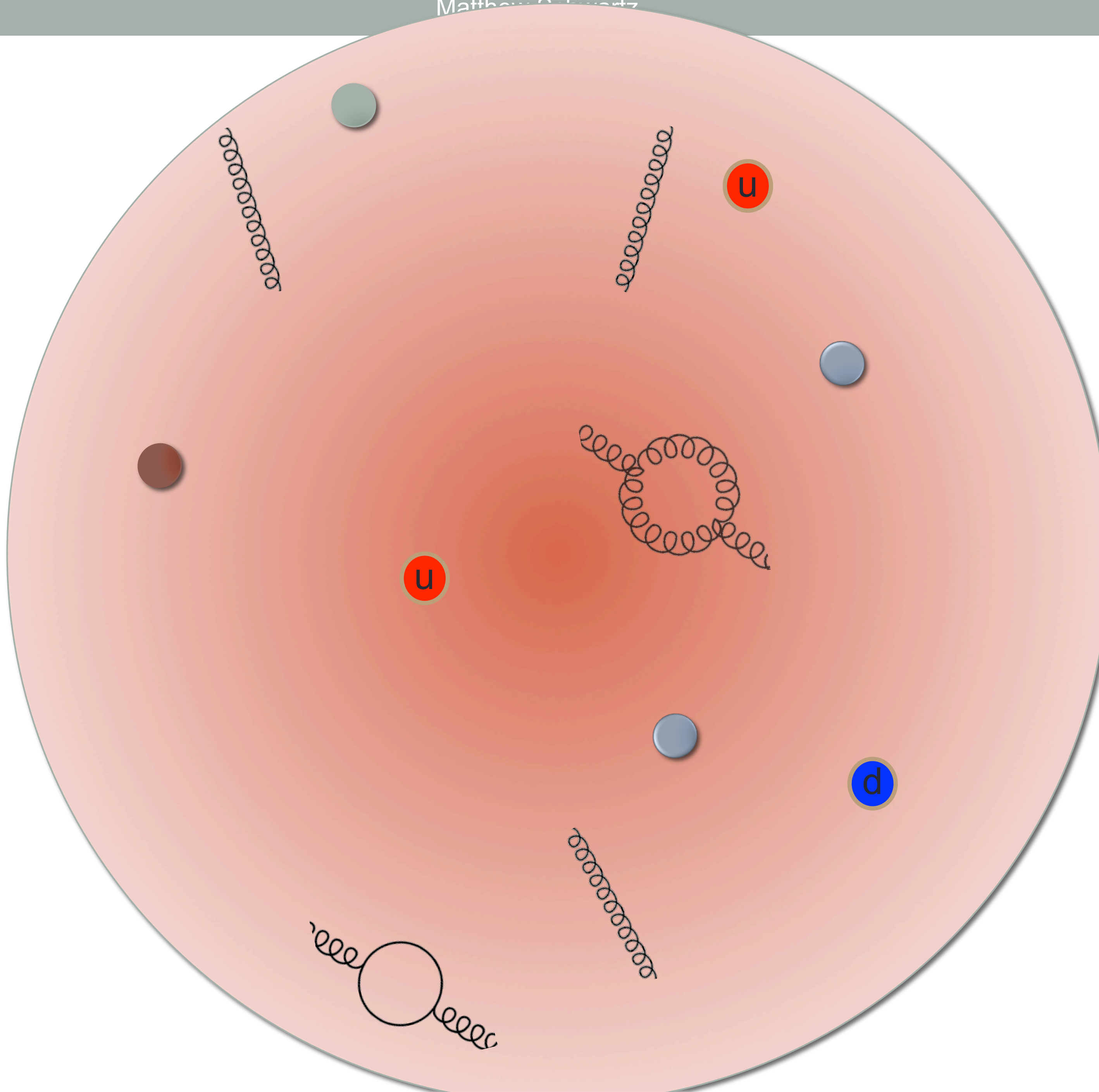
PETRA (DESY) 1979

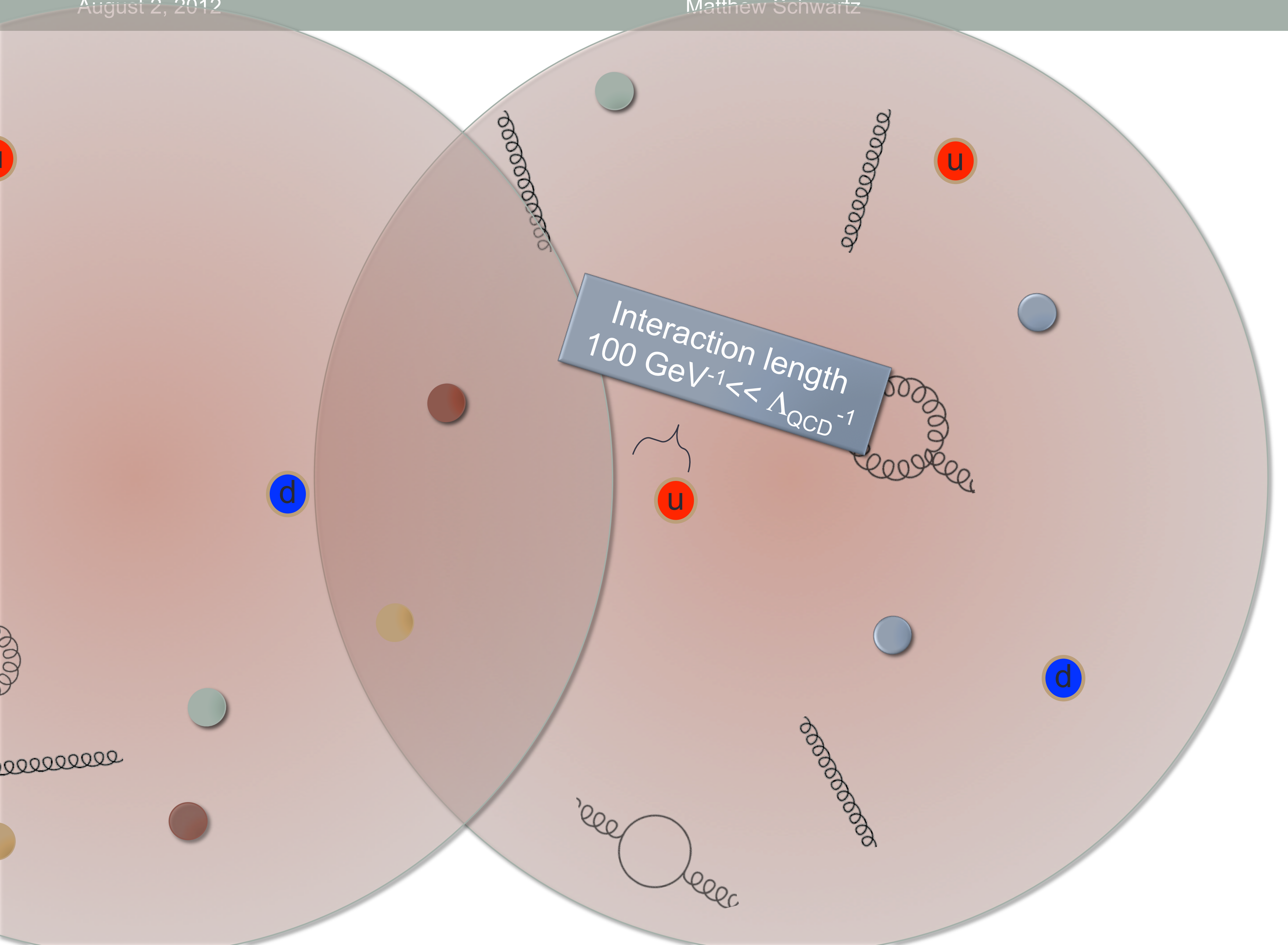
Colliding protons



Colliding protons

Size is
1 fm ~ Λ_{QCD}^{-1}

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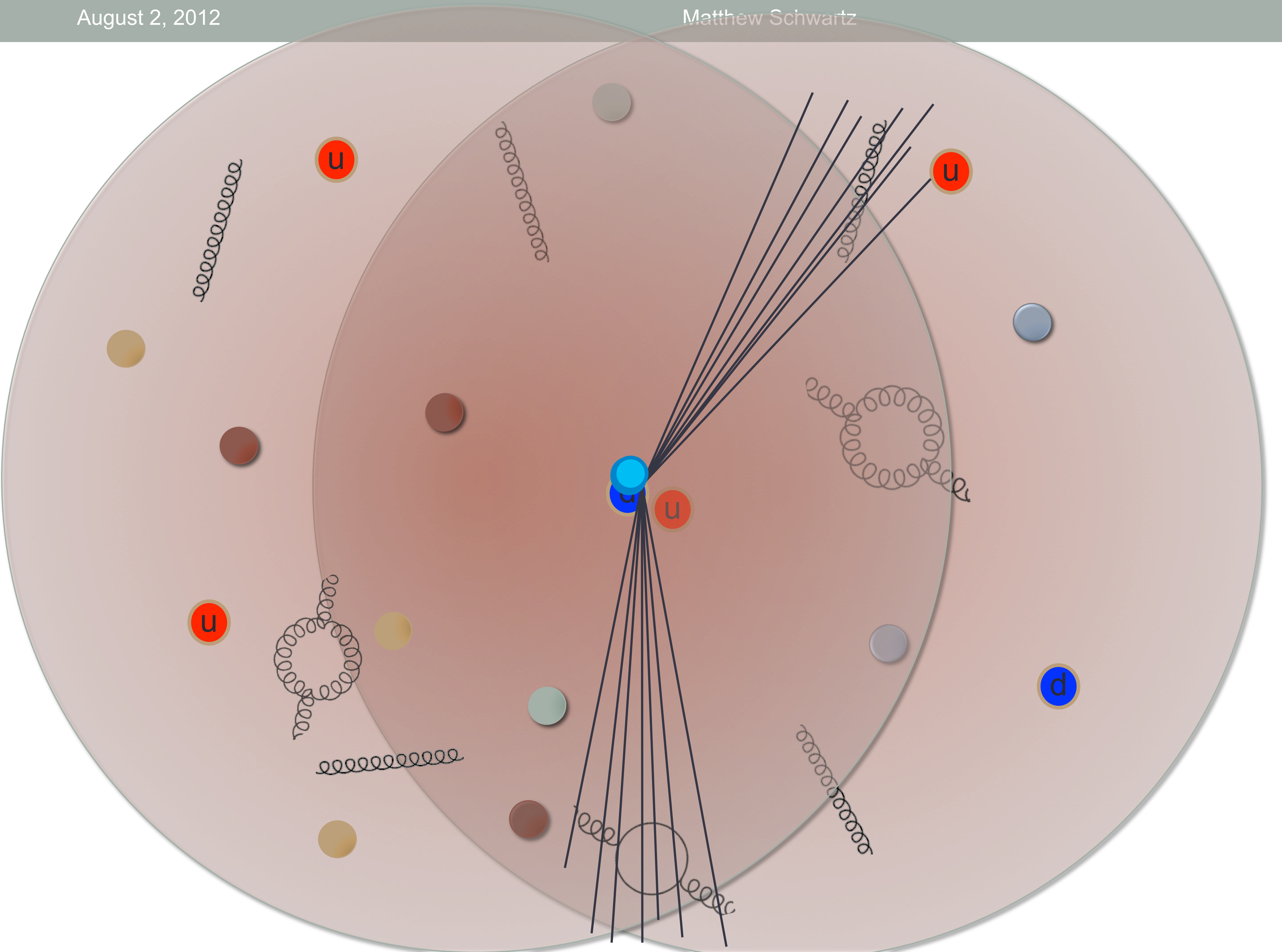
d
Interaction length
100 GeV^{-1} << Λ_{QCD}^{-1}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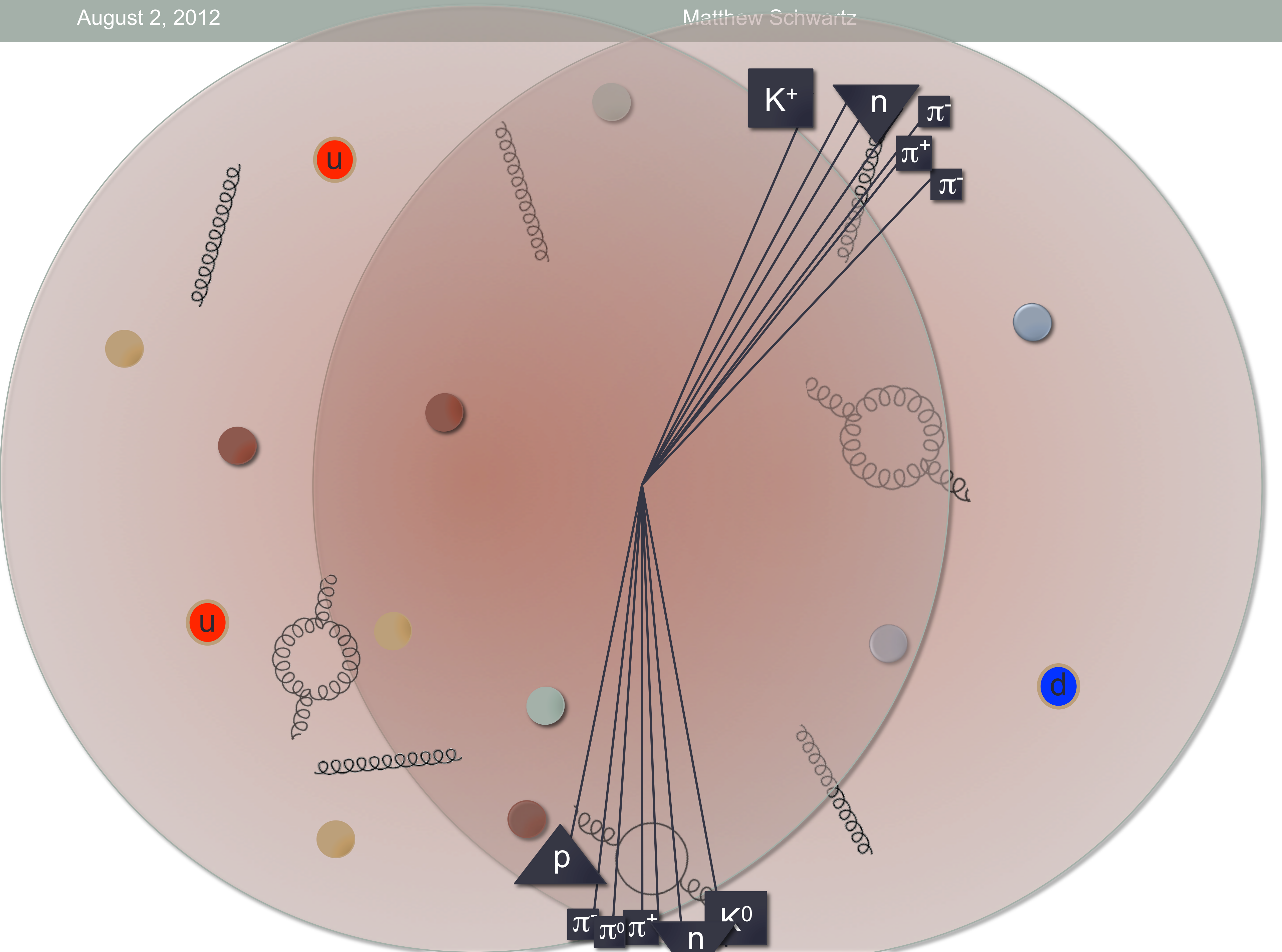
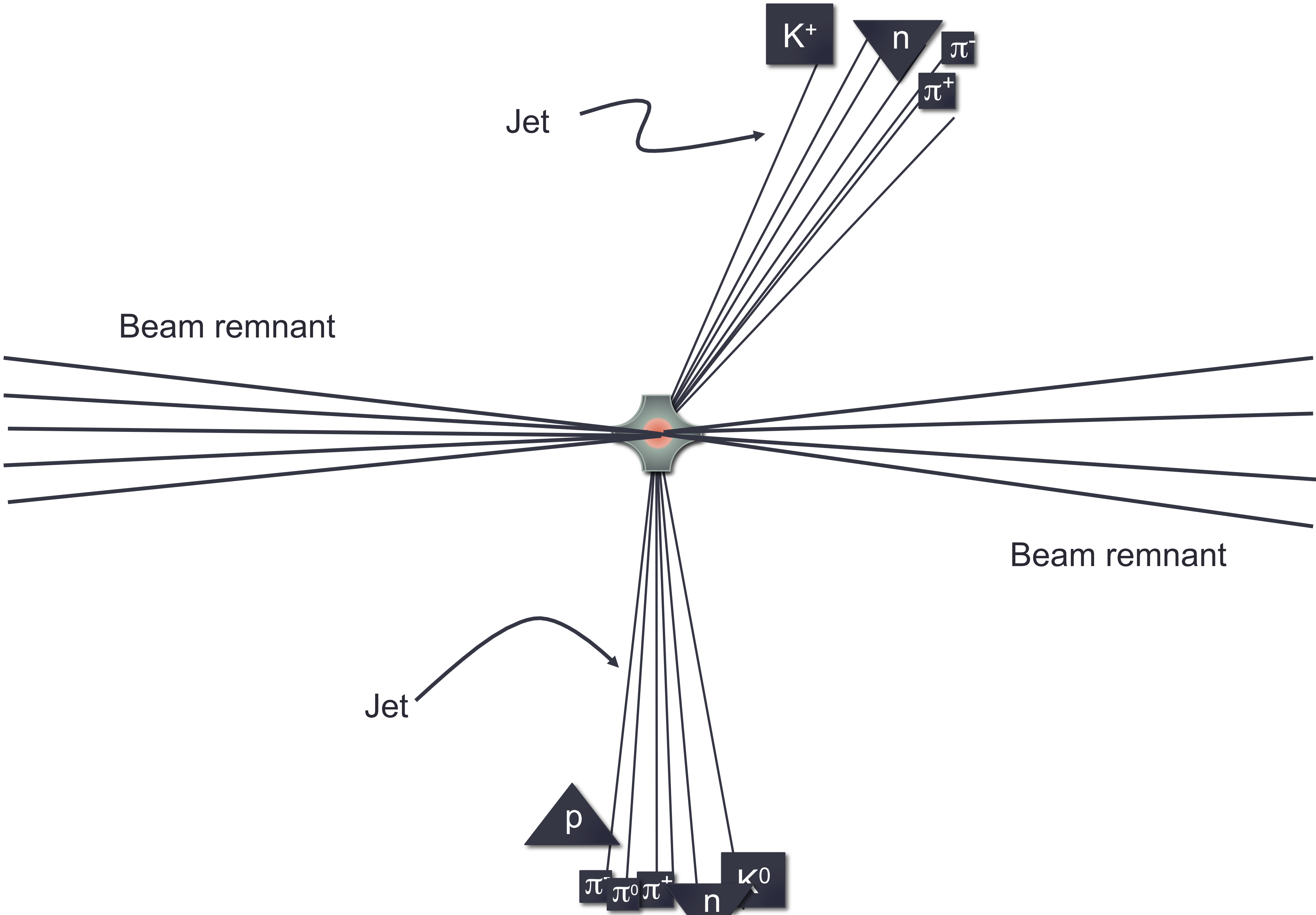
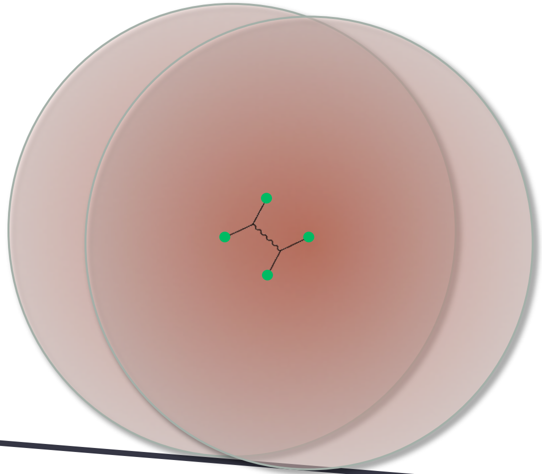
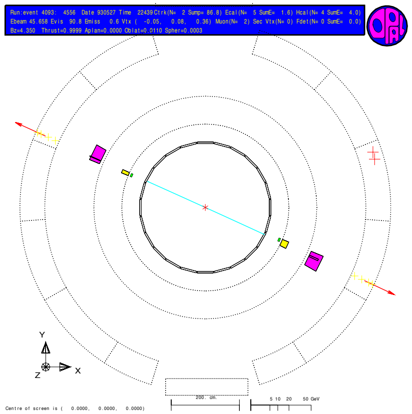

K+
n
π-
π+
π-
u
u
d
p
π-
π0
π+
n
K0


K+
n
π-
π+
Jet
Beam remnant
Beam remnant
Jet
p
π-
π0
π+
n
K0

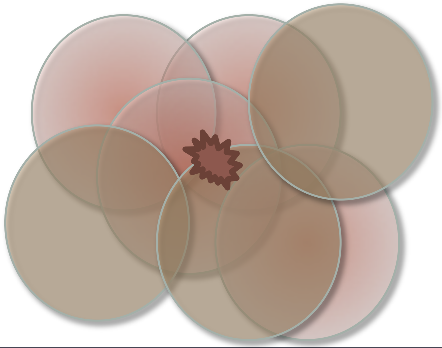
at **short distances**
QCD is like QED
- Electrons in, electrons out

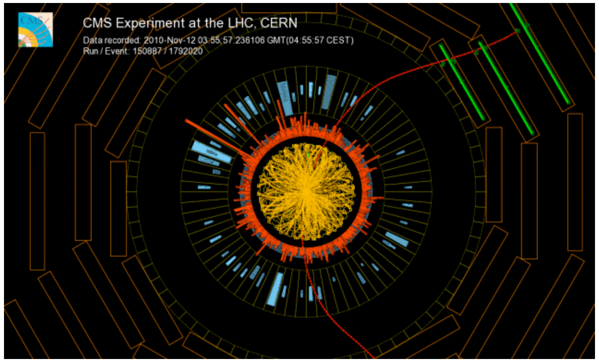




OPAL $e^+e^- \rightarrow \mu^+\mu^-$ event

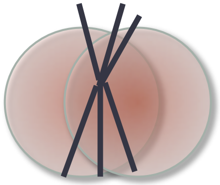
at **long distances** QCD is a mess
- Nuclei in, hadrons out

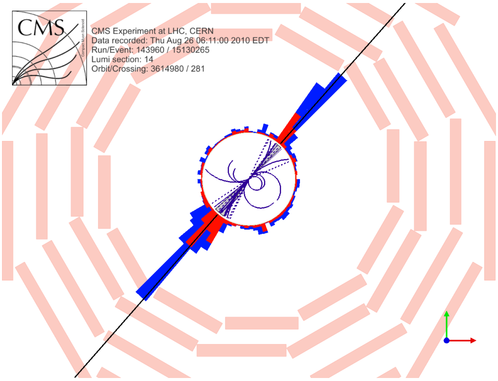




CMS
Heavy ion event

Proton-proton collisions are just right
intermediate between QED and a mess





CMS
Dijet event

QCD predicts jets

1. Quarks and gluons (partons) are produced at short distance, where QCD is weak → **Production**
2. As they propagate outward, they radiate more partons → **Radiation**
3. At distances~ Λ_{QCD}^{-1} they form uncolored hadrons → **Hadronization**
   Hadrons leave the proton and
   do not interact strongly until detected

$$d\sigma = [\text{PDFs}] \times [\text{production}] \times [\text{parton shower}] \times [\text{hadronization}]$$

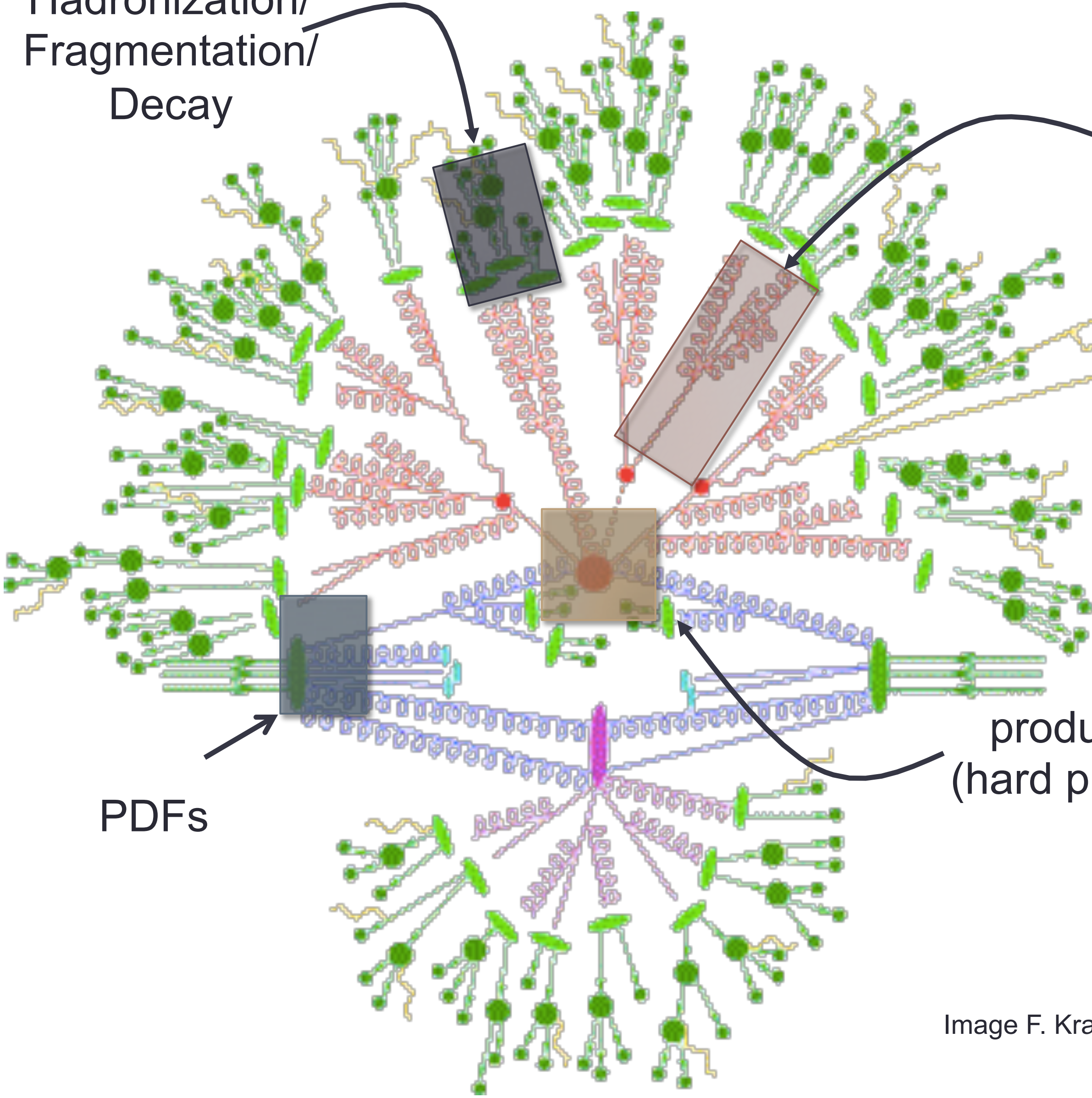
short distance — long distance

Factorization

- Physics at different length scales can be calculated separately and then combined

$d\sigma$ =[PDFs] x [production] x [parton shower] x [hadronization]

Hadronization/
Fragmentation/
Decay



Parton shower/
Jet formation

Subject of my lectures

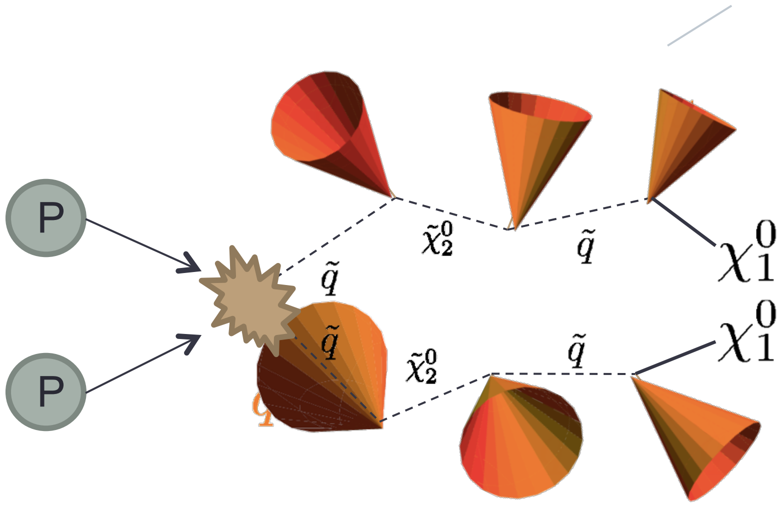
production
(hard process)

PDFs

Image F. Krauss

Factorization

- Partons produced at short distances



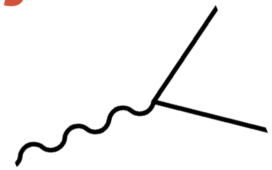
6 Jets

- Radiation and hadronization cannot change parton momentum by much

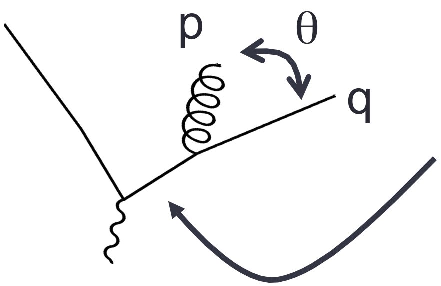
Short distance physics imprinted on **jets**!

JETS FROM PERTBUATIVE QCD

Why jets?



Leading order: R=0, Energy = E



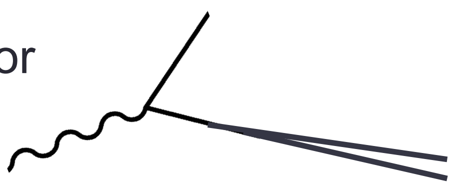
Propagator factor: $\frac{1}{(p+q)^2} = \frac{1}{2p\cdot q} = \frac{1}{E_p E_q(1-\cos\theta)} = \frac{1}{2E_q E_p \sin^2\frac{\theta}{2}}$

Blows up when E=0 (soft divergence)
Or θ = 0 (collinear divergence)

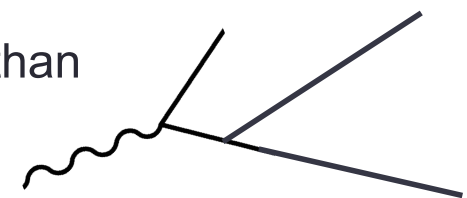
$$d\sigma \sim \alpha_s \int_0^R \frac{\mathrm{d}\theta}{\theta}\frac{\mathrm{d}E}{E} \sim \alpha_s \ln R \ln E$$

Sudakov double logartihms

Rate for

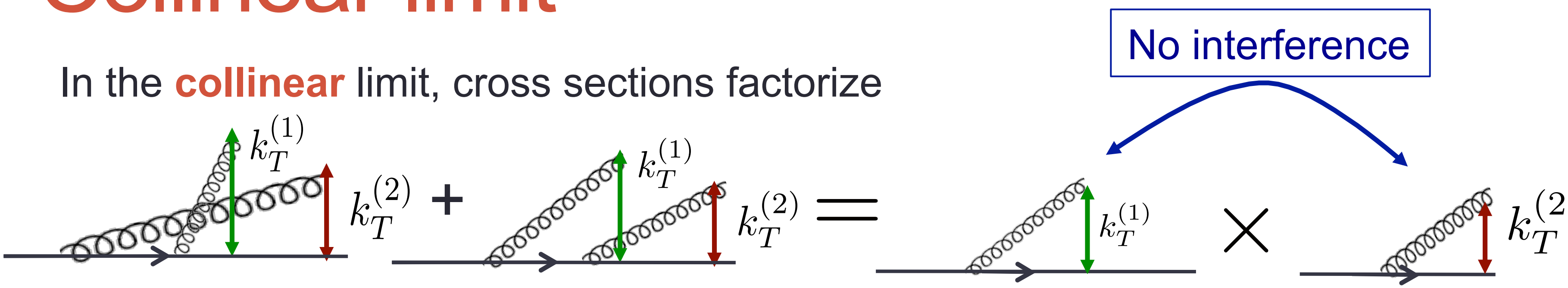


much greater than



Collinear limit

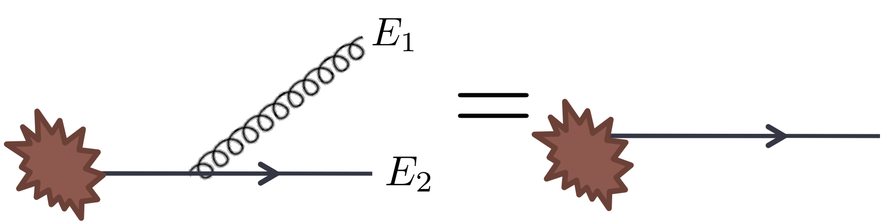
In the **collinear** limit, cross sections factorize



when $k_T^{(2)} \ll k_T^{(1)} \ll E_{\text{jet}}$

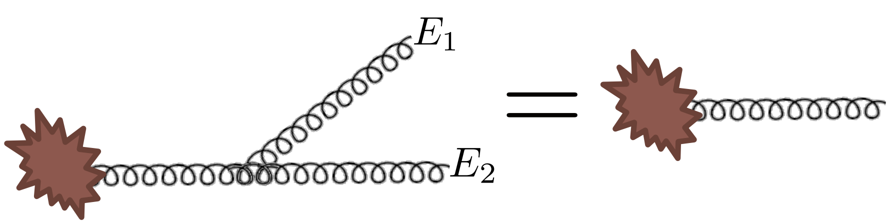
In the collinear limit, cross sections given by **DGLAP splitting functions**

$$z = \frac{E_1}{E_1 + E_2}$$



$\times\ P_{q\to qg}$

$$\frac{4}{3}\frac{\alpha}{2\pi}\frac{1+z^2}{1-z}$$

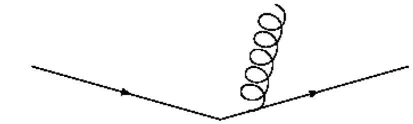


$\times\ P_{g\to gg}$

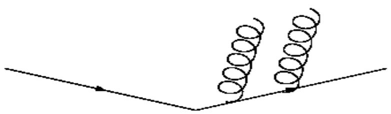
$$3\frac{\alpha}{2\pi}\left[\frac{z}{1-z}+\frac{1-z}{z}\right]$$

Parton shower

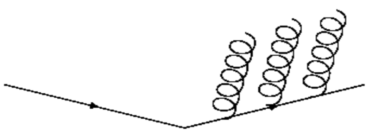
Semi-classical interpretation



$$\sigma \sim \alpha_s \ln R \ln E$$



$$\sigma \sim \frac{1}{2}(\alpha_s \ln R \ln E)^2$$



$$\sigma \sim \frac{1}{3!}(\alpha_s \ln R \ln E)^3$$

probability of emission

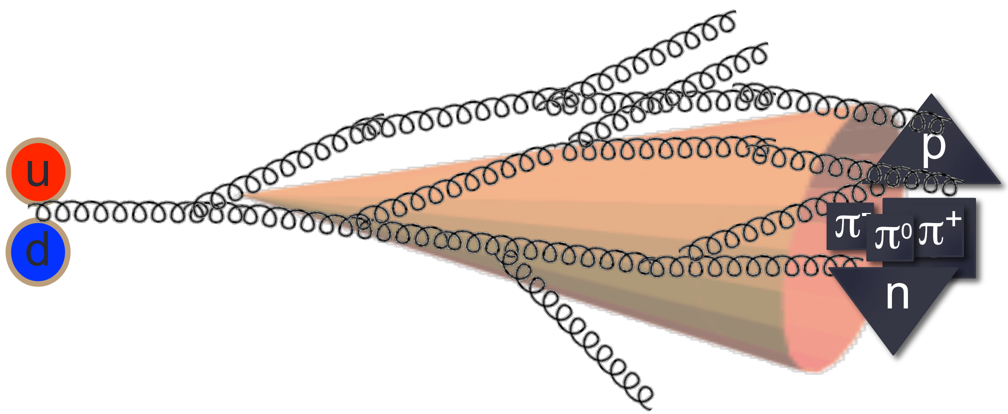
$$\mathrm{d}P \sim \alpha_s \frac{1}{\theta}\frac{1}{E}\mathrm{d}\theta \mathrm{d}E$$

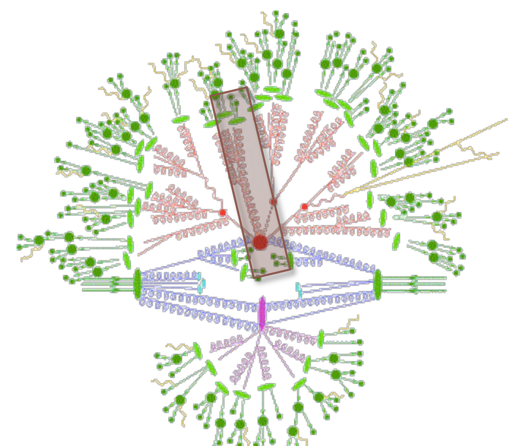
probability of no emission

Sudakov factor

$$\Gamma \sim \exp(-\int \mathrm{d}P)$$

$$\sim \exp(-\alpha_s \ln R \ln \frac{E_0}{E_1})$$





Parton “evolves” from hard scale to Λ_{QCD}

Parton shower

- Semi-classical model which agrees with perturbative QCD in collinear limit at leading-logartihmic level

$$d\sigma = e^{-\int dP} dP$$

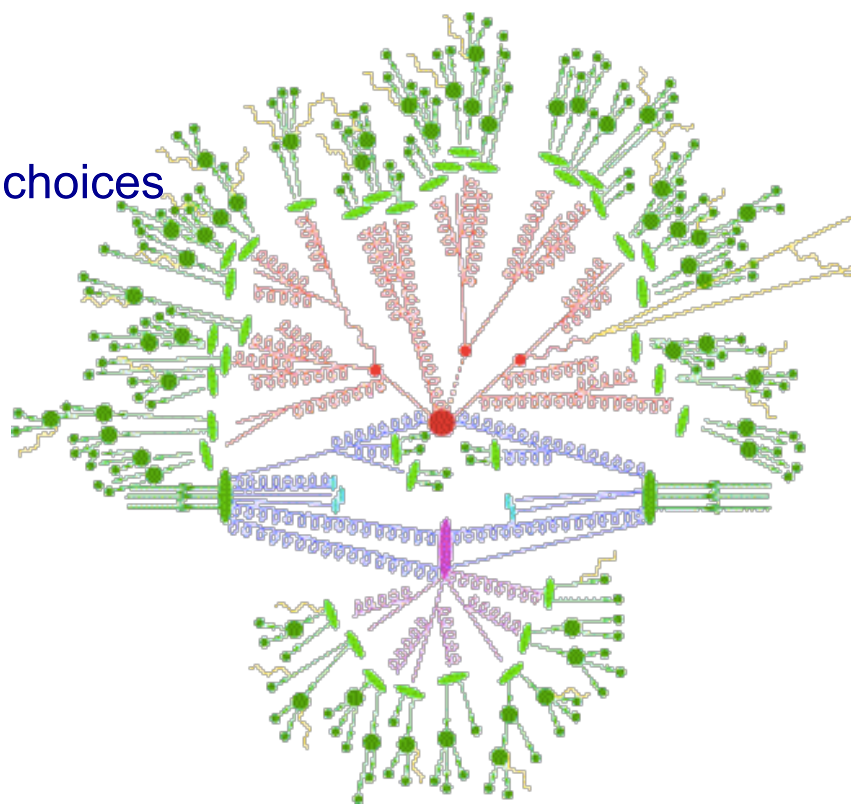
$$\sim e^{-\alpha \ln^2\left(\frac{\mu_1}{\mu_2}\right)} \left(\frac{\alpha_s}{2\pi} \frac{1+z}{1-z^2}\right) dz$$

Leading log resummation

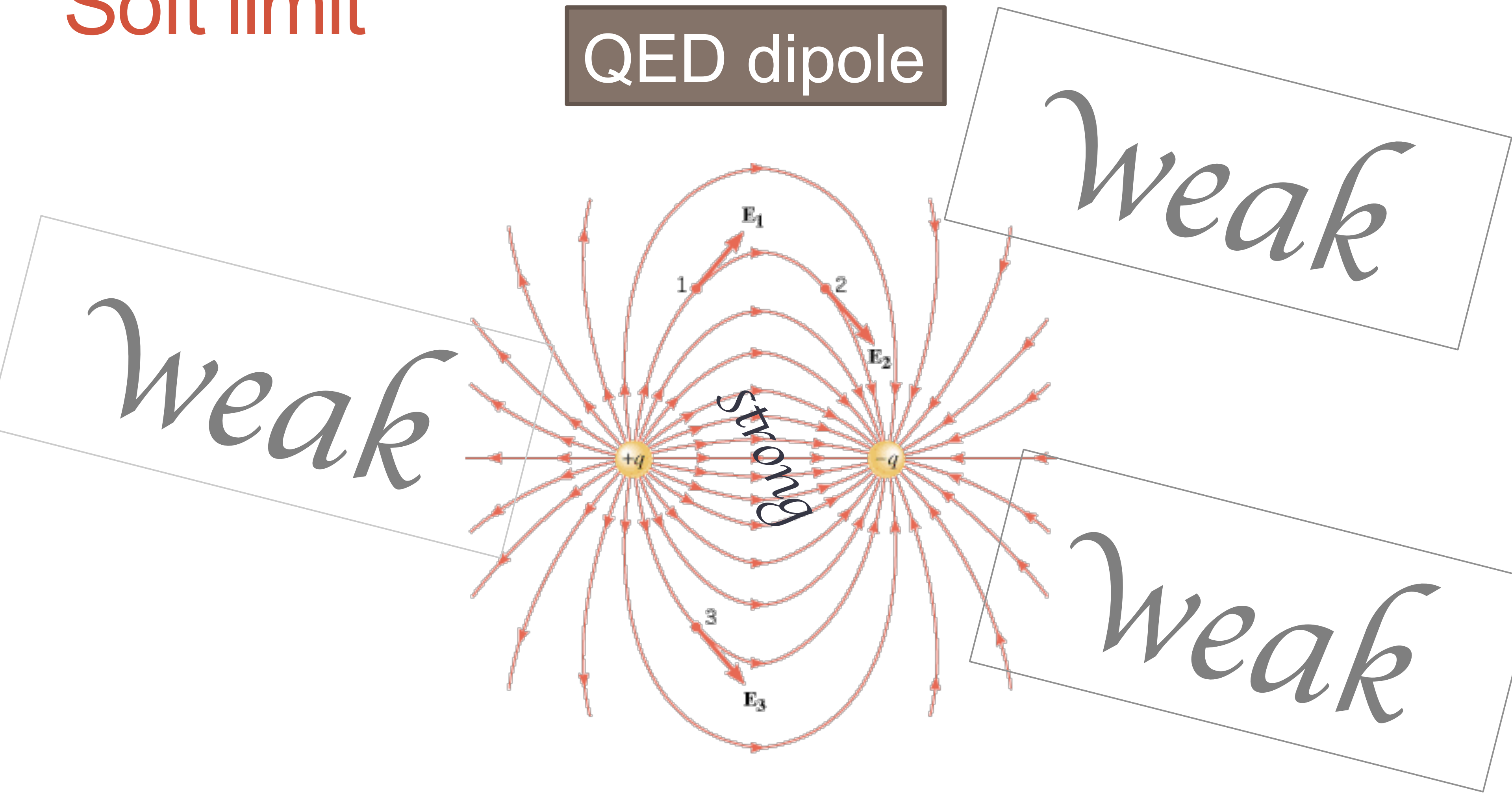
DGLAP splitting functions

- Formally correct at this order for many scale choices

- Common scale choices motivated by **soft physics**



Soft limit

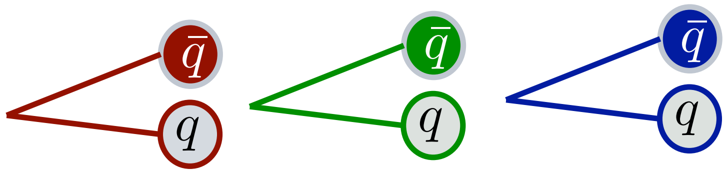


- In soft limit (large distance limit), field from + and – charges cancel
- Coherent destructive **interferece**

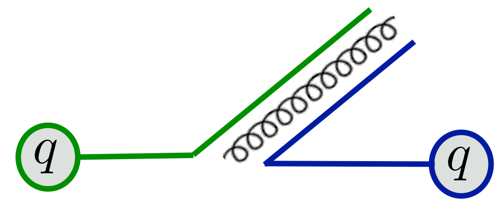
Soft limit

QCD

3 quark color dipoles

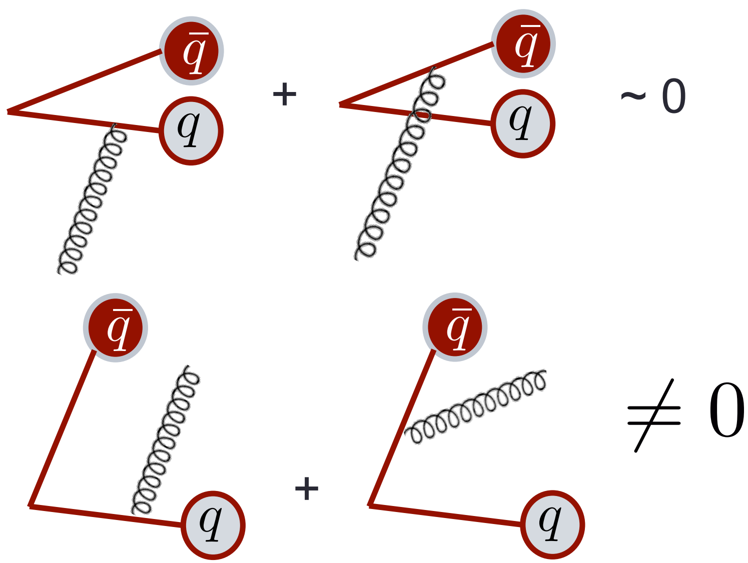


Gluons act like ends of 2 dipoles



Accurate up to $1/N^2$ ~10% effects

Destructive interference

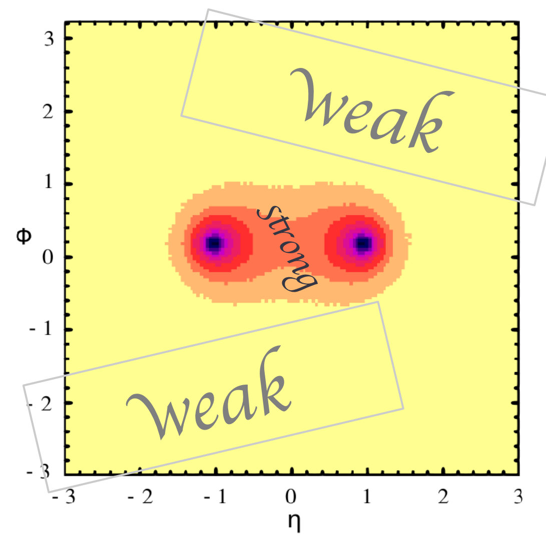


Constructive interference

Color coherence

⇕

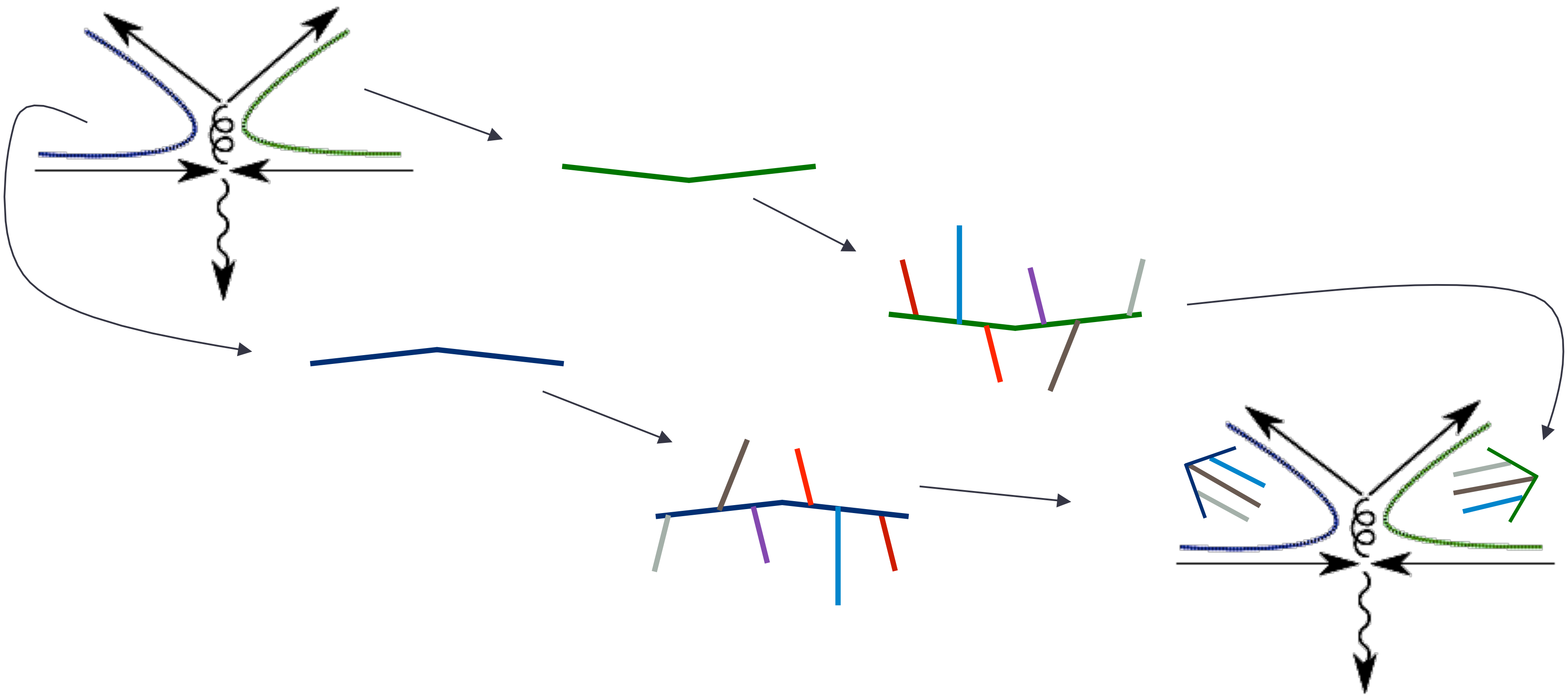
Angular ordering



Pythia simulation

Dipole shower

Dipole showers in its rest frame



- Boost → **string showers** in **dipole-momentum** direction
- Alternative to angular ordering

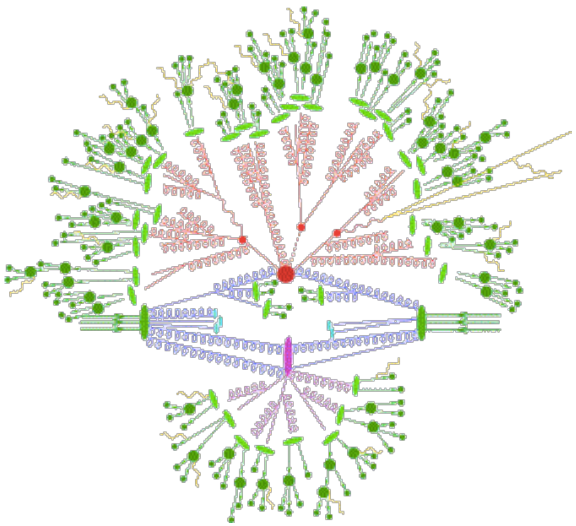
Parton shower

- Semi-classical model which agrees with perturbative QCD in collinear limit at leading-logartihmic level

$$d\sigma = e^{-\int dP} dP$$

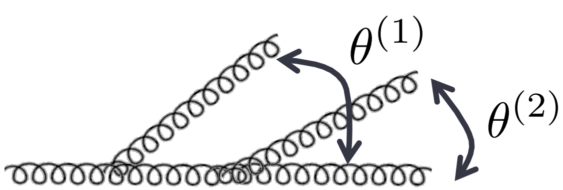
$$\sim \underbrace{e^{-\alpha \ln^2\left(\frac{\mu_1}{\mu_2}\right)}} \left(\frac{\alpha_s}{2\pi}\frac{1+z}{1-z^2}\right) dz$$

Suadkov factor
(leading log resummation)

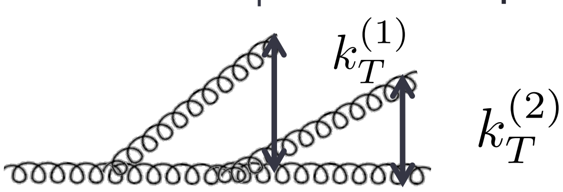


- Formally correct at **leading log** in the **collinear limit**

Herwig uses an angle ordered shower



Pythia uses a k_T ordered dipole shower

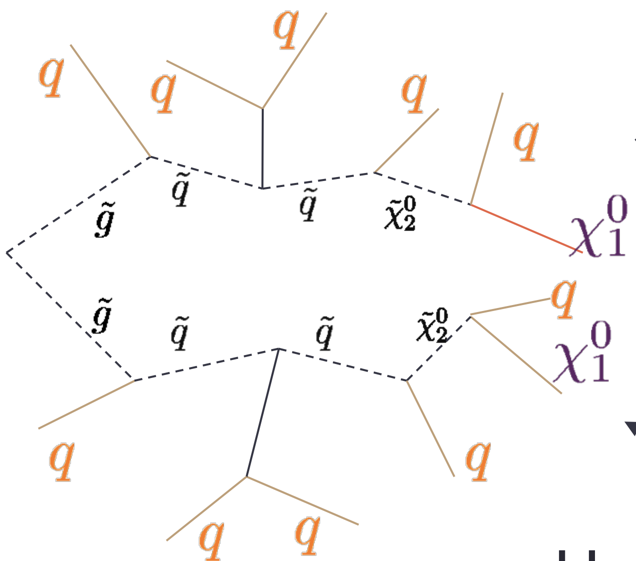


- Both incorporate **color coherence**
- Neither gets soft limit exactly right
- Parton showers give **amazingly accurate** simulations of complicated final states

JET ALGORITHMS

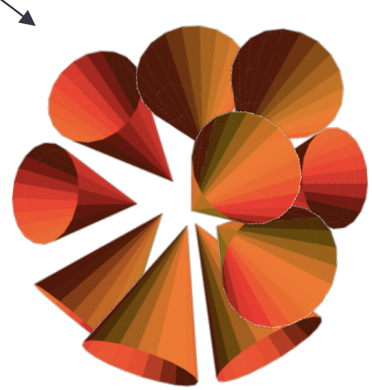
Jet-parton-map

We want to see quarks and gluons:



Parton shower

We observe jets:



+ missing energy

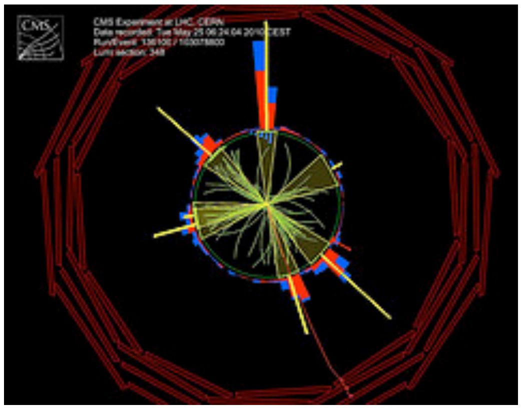
How can we **invert** ?

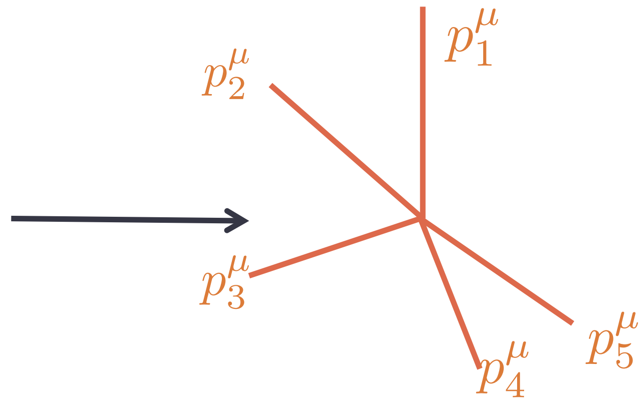
⇓

- Find jet momenta
- Set quark momenta = jet momenta

Jet algorithms

- Construct jet 4-momentum from observed particle 4-momenta





Desirable properties

- Good match between jet and parton momenta
- Insensitive to hadronization
- Calculable in pertubative QCD = infrared safe
- Experiment friendly
  - Easy to calibrate
  - Insensitive to pileup
- Fast

Cone algorithms

- Conceptually simple
- Difficulties with infrared safety

Iterative algorithms

- Popular
- Efficient

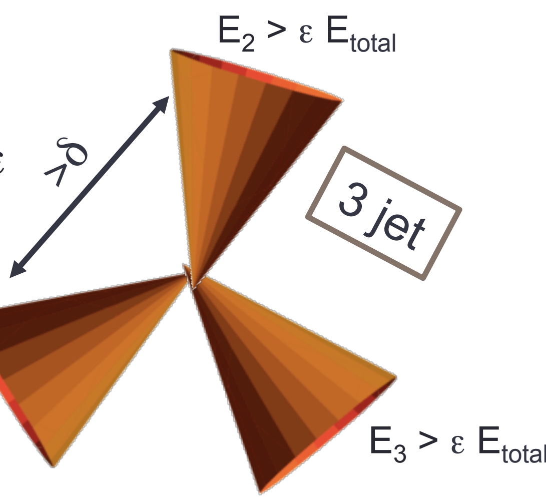
Sterman-Weinberg jets (1977)

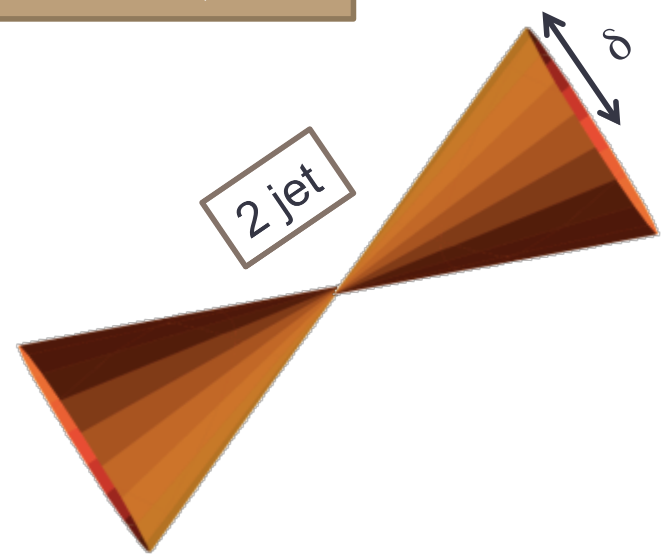
Jets from pertubative QCD

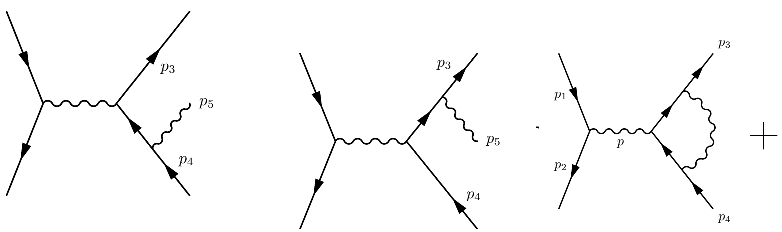
e⁺e⁻ to 2 or 3 jets

3 jets if:

- Angles greater than δ
- Energies greater than ε







Would blow up if
We just asked for cones
(no energy restriction)

2 jet cross section at order α

$$\sigma_{2\text{jet}} = \sigma_0 \left[1 + \frac{\alpha_s}{2\pi} \left(\ln\delta \ln\epsilon + \ln\delta - \frac{3}{4} + \cdots \right) \right]$$

- This jet definition is **infrared safe** (finite in perturbation theory)

Cone jets

Generalizations to hadron colliders

- Where are the cones centered
  - Seeded cones, Fixed cones, Midpoints
- Is it still infrared safe
  - Maybe, maybe not. Does it matter?

Finding cones \ Processing	Progressive Removal	Split–Merge	Split–Drop
Seeded, Fixed (FC)	GetJet CellJet		
Seeded, Iterative (IC)	CMS Cone	JetClu (CDF)† ATLAS cone	
Seeded, It. + Midpoints (IC_{mp})		CDF MidPoint D0 Run II cone	PxCone
Seedless (SC)		SISCone	

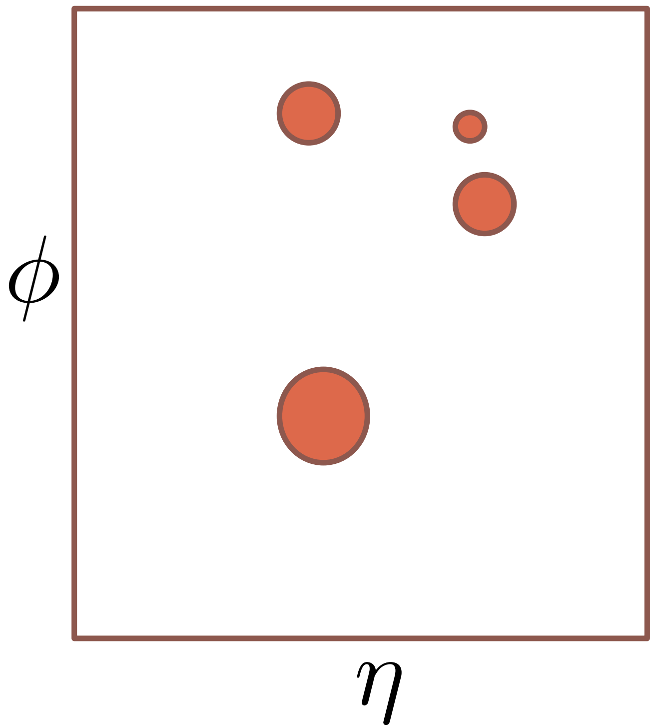
G. Salam

Iterative jet algorithms

- Start with input 4-vectors
  - e.g. stable particles, topoclusters, calorimiter cells, etc.

- **Calculate** the pairwise distances

$$R_{ij} = \sqrt{(\theta_i - \theta_j)^2 + (\eta_i - \eta_j)^2}$$



Iterative jet algorithms

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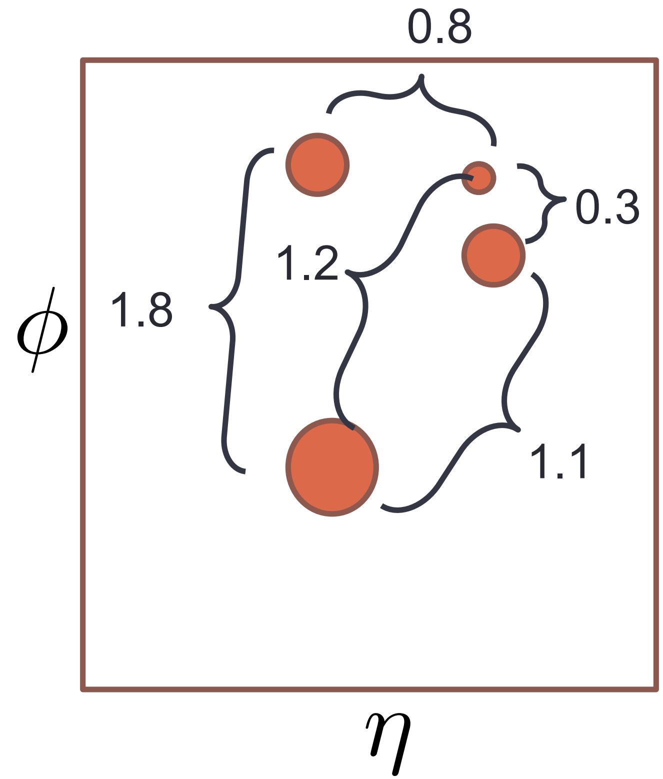
- **Calculate** the pairwise distances

$$R_{ij} = \sqrt{(\theta_i - \theta_j)^2 + (\eta_i - \eta_j)^2}$$

- **Merge** the two closest particles



Iterative jet algorithms

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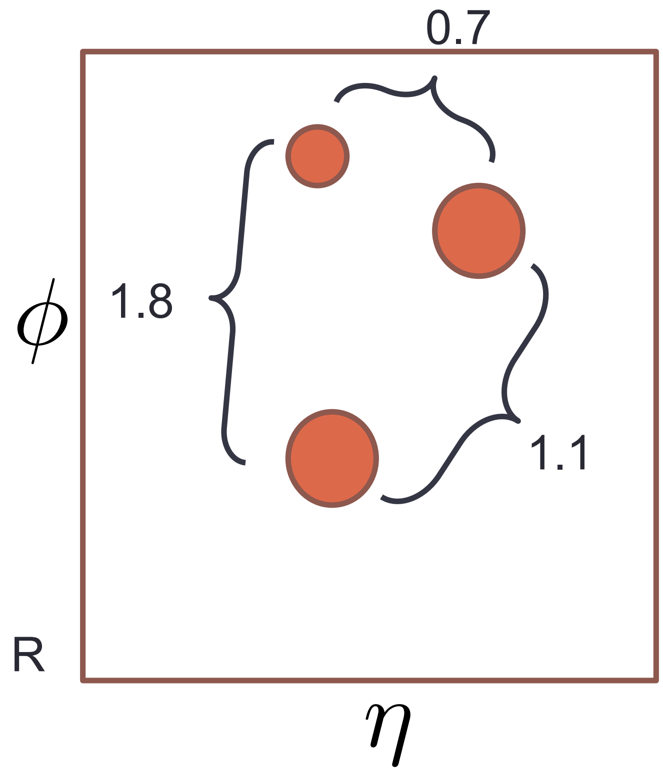
- **Calculate** the pairwise distances

$$R_{ij} = \sqrt{(\theta_i - \theta_j)^2 + (\eta_i - \eta_j)^2}$$

- **Merge** the two closest particles
- **Repeat** until no two particles are closer than R



Iterative jet algorithms

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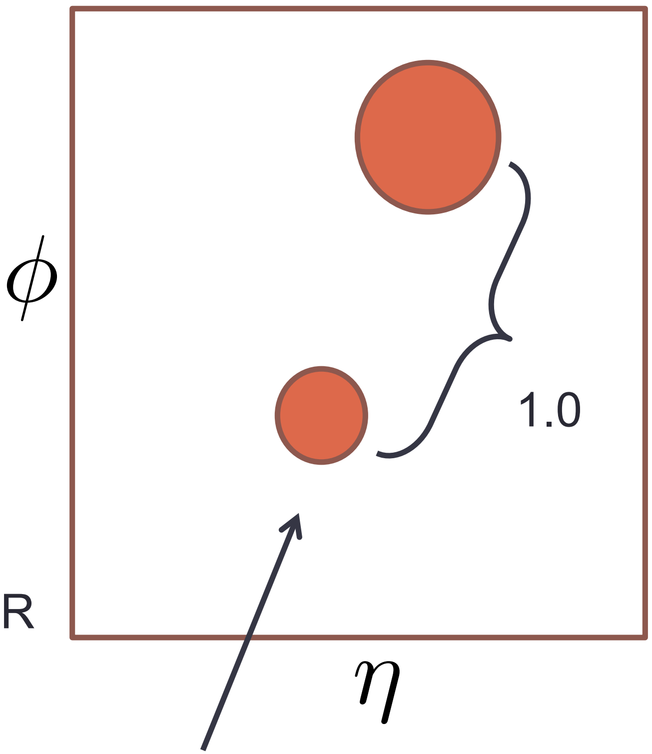


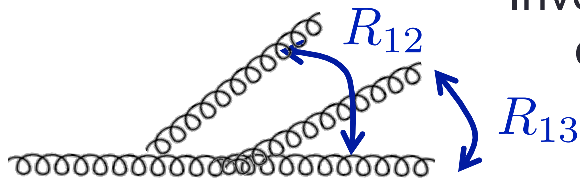
Two R=1.0 Jets

Different distance measures

Cambride/Aachen algorithm

$$d_{ij} = \left(\frac{R_{ij}}{R_0}\right)^2$$

- clusters closest radiation first

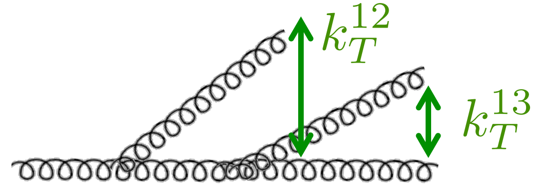


Inversion of **Herwig shower**

k_T algorithm

$$d_{ij} = \min(p_{Ti}^2, p_{Tj}^2)\left(\frac{R_{ij}}{R_0}\right)^2$$

- clusters hard collinear radiation first



Inversion of **Pythia shower**

anti k_T algorithm

$$d_{ij} = \min(p_{Ti}^{-2}, p_{Tj}^{-2})\left(\frac{R_{ij}}{R_0}\right)^2$$

- Clusters farthest first
- No inverse parton-shower interpretation

- Produces round jets
- Almost exclusively used by ATLAS and CMS

Jet algorithms

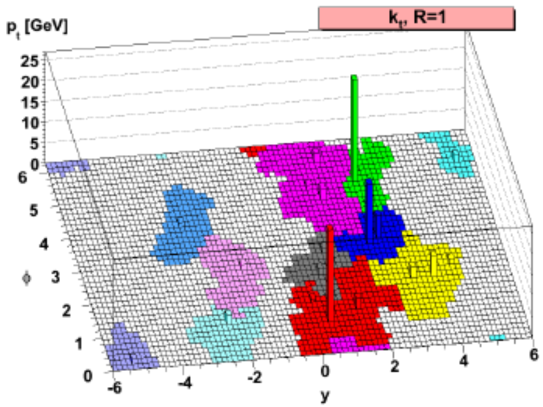
Cacciari, Salam, Soyez JHEP 0804:063 (2008)

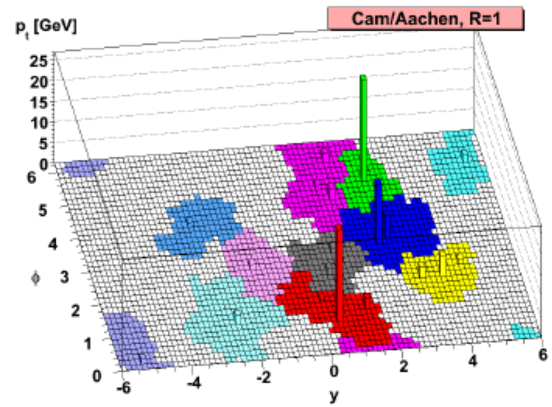
k_T

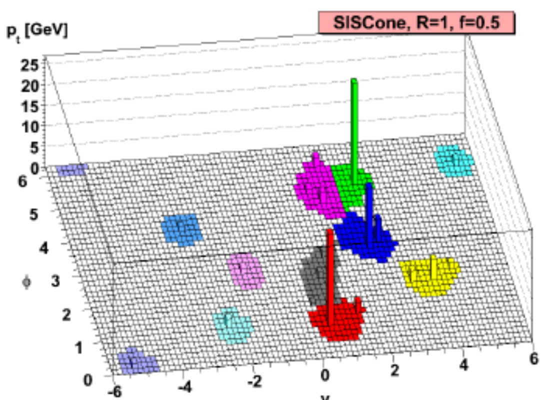
- popular at Tevatron
- Good for QCD theory
- Non-compact regions – hard to calibrate

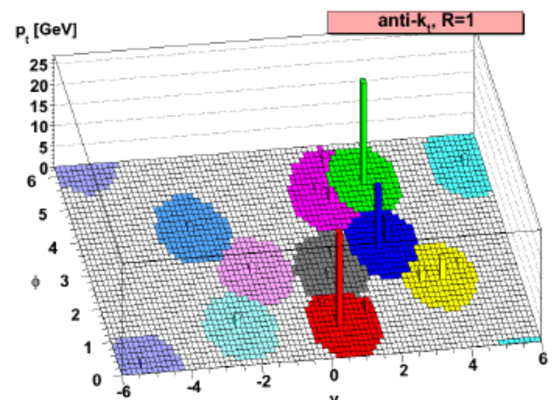
Cambridge/Aachen

- Based on angles
- Closer to cones









SICcone

- Infrared safe cone algorithm
- Not cones at all

Anti k_T

- Very round jets
- No parton shower interpretation
- Great for calibration

What R is best?

Goal: reconstruct parton momentum in Monte Carlo

- Include all final state radiation (FSR)

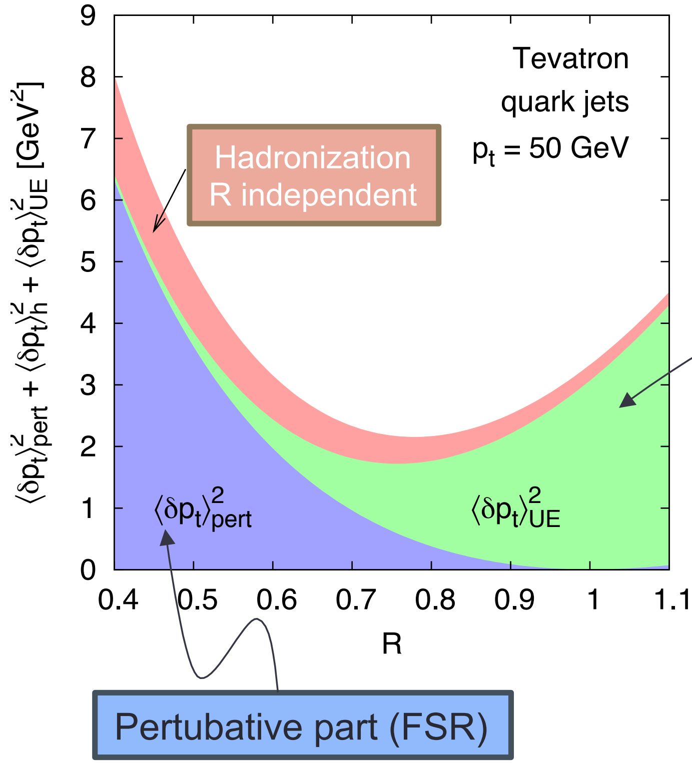
Bigger R

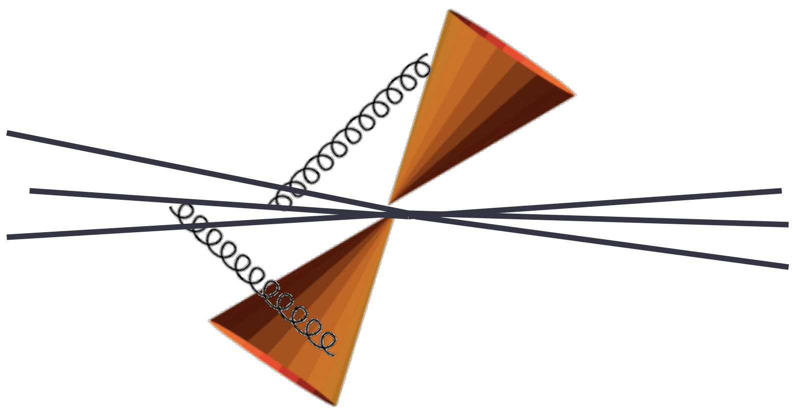
- Include little initial state radiation
- Include little pileup

Smaller R

Jet p_T versus parton p_T

From arXiv:0712.3014

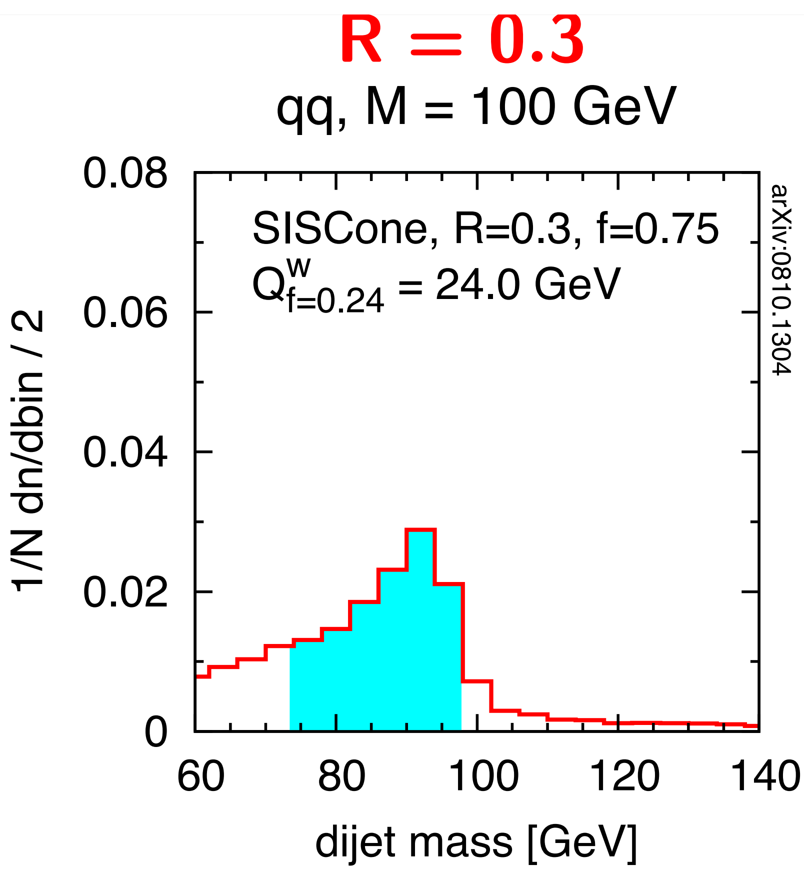


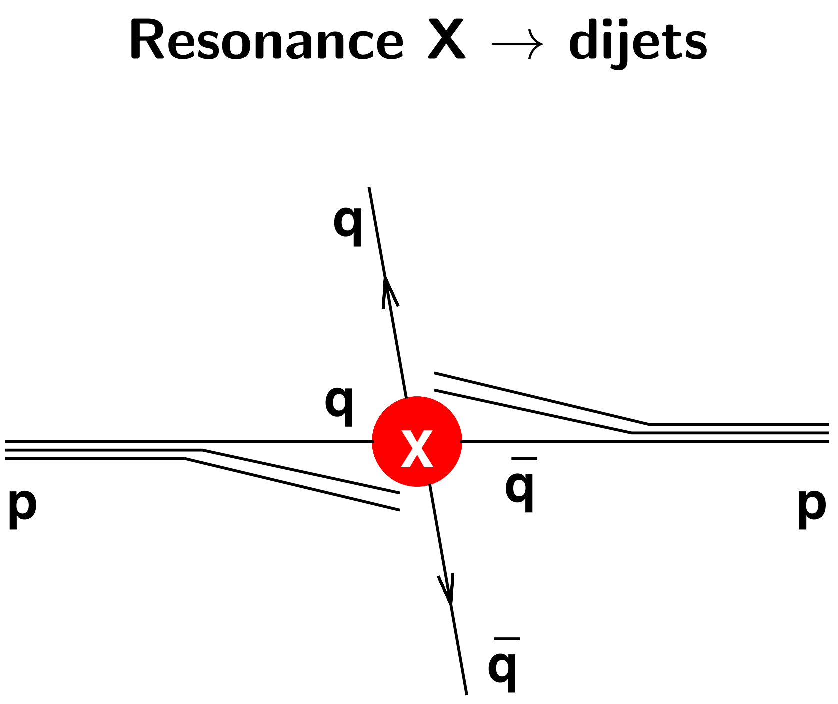


In practice

- R~0.4-0.7 works best
- Must optimize for each study

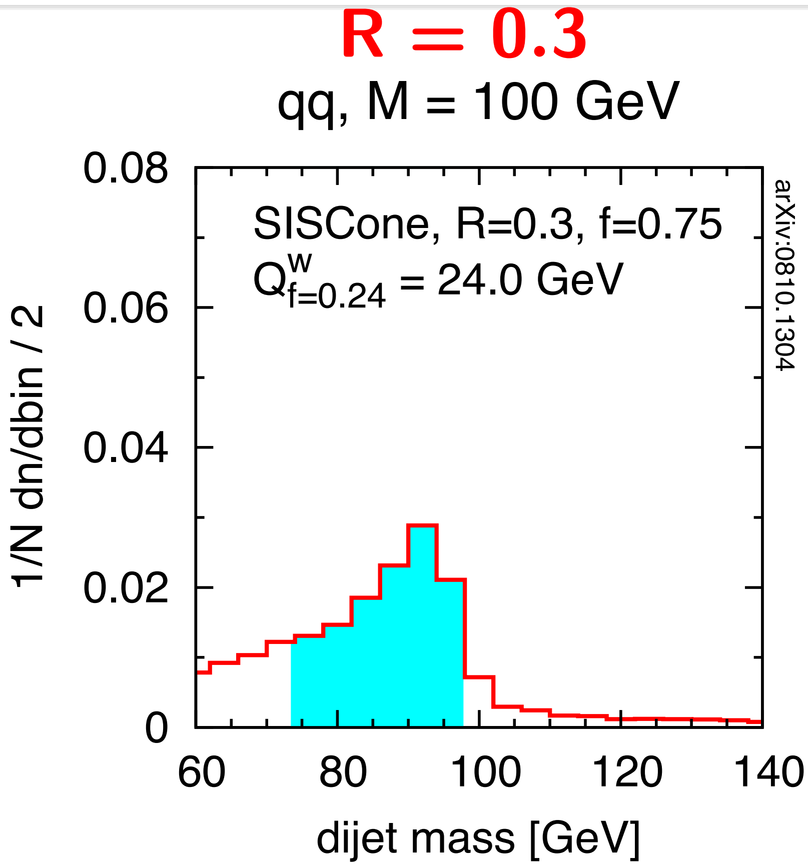
Resonance peak various R

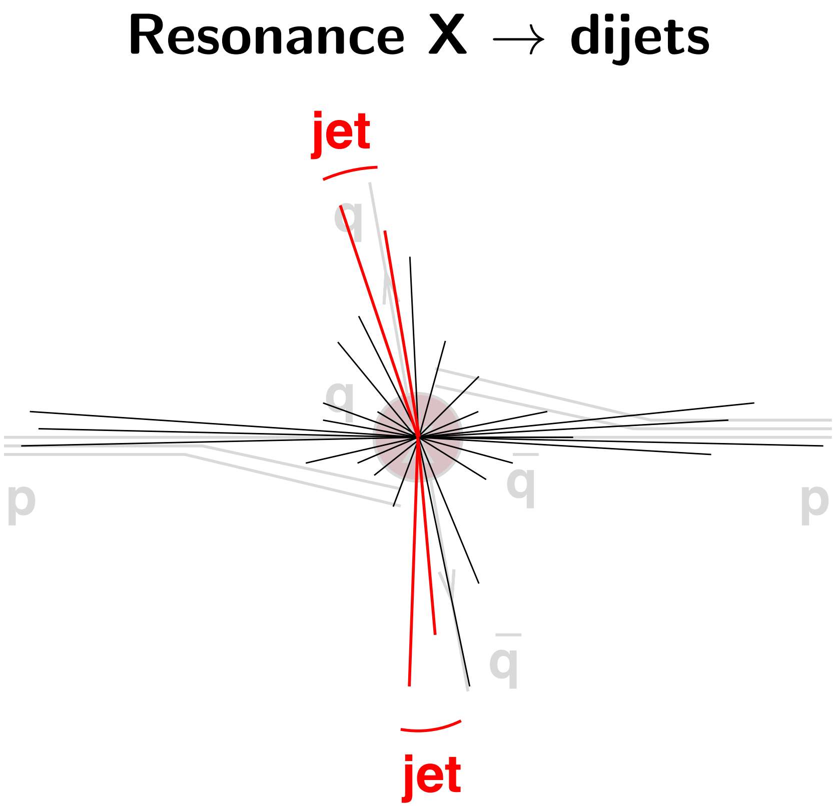




from G. Salam
http://www.lpthe.jussieu.fr/~salam/jet-quality/

Resonance peak various R





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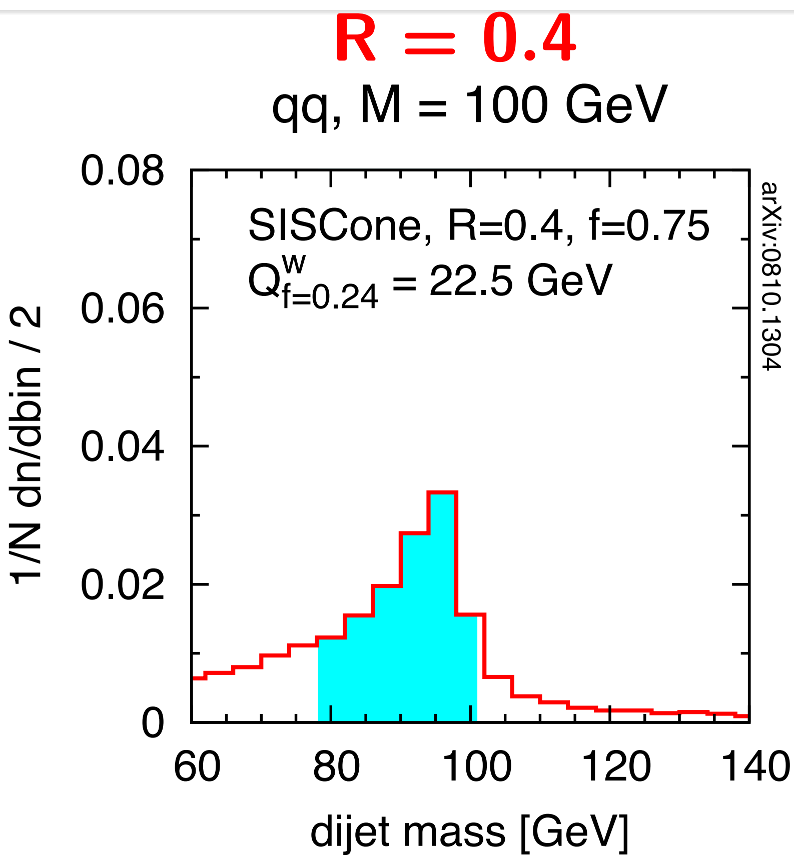

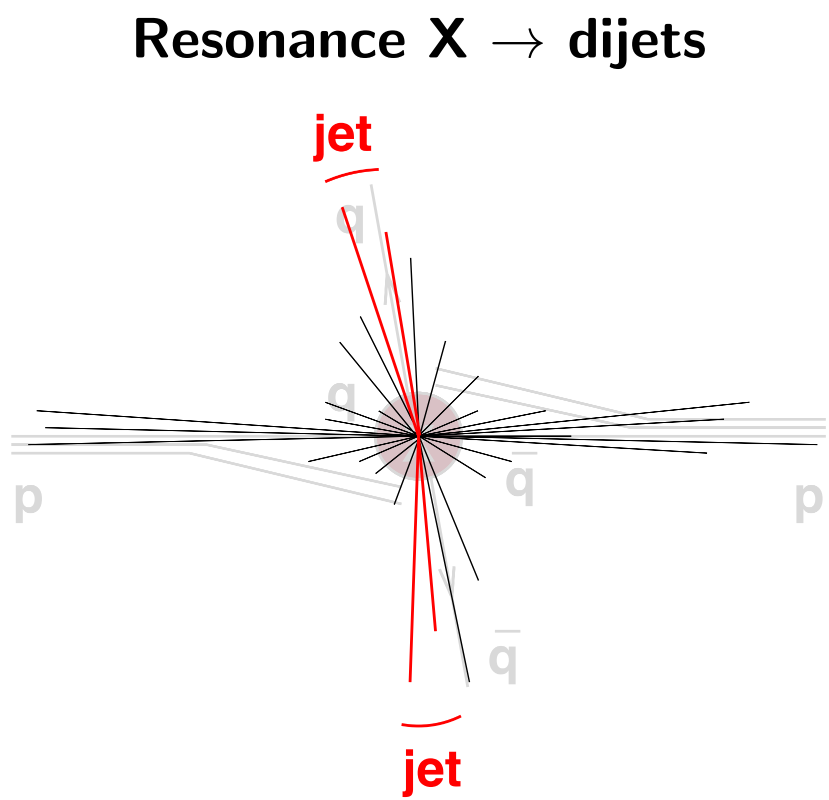

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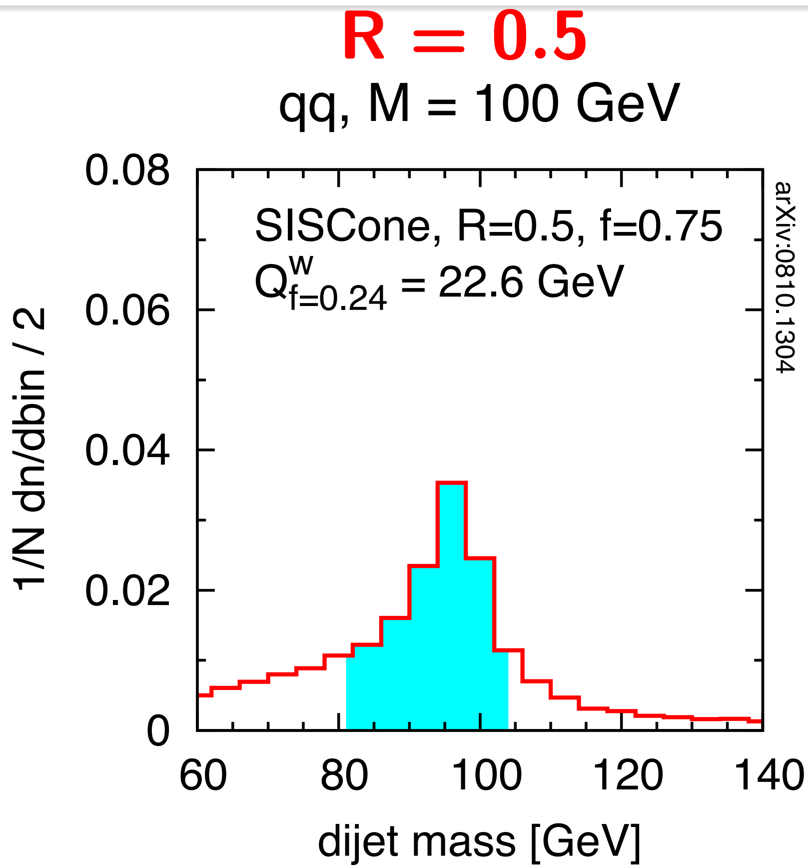

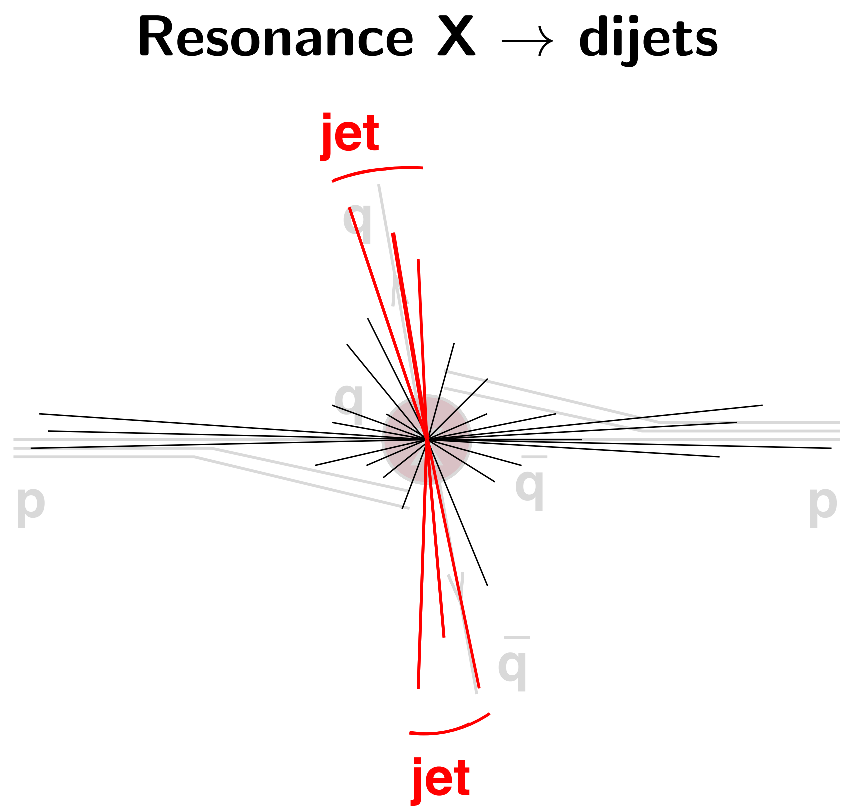

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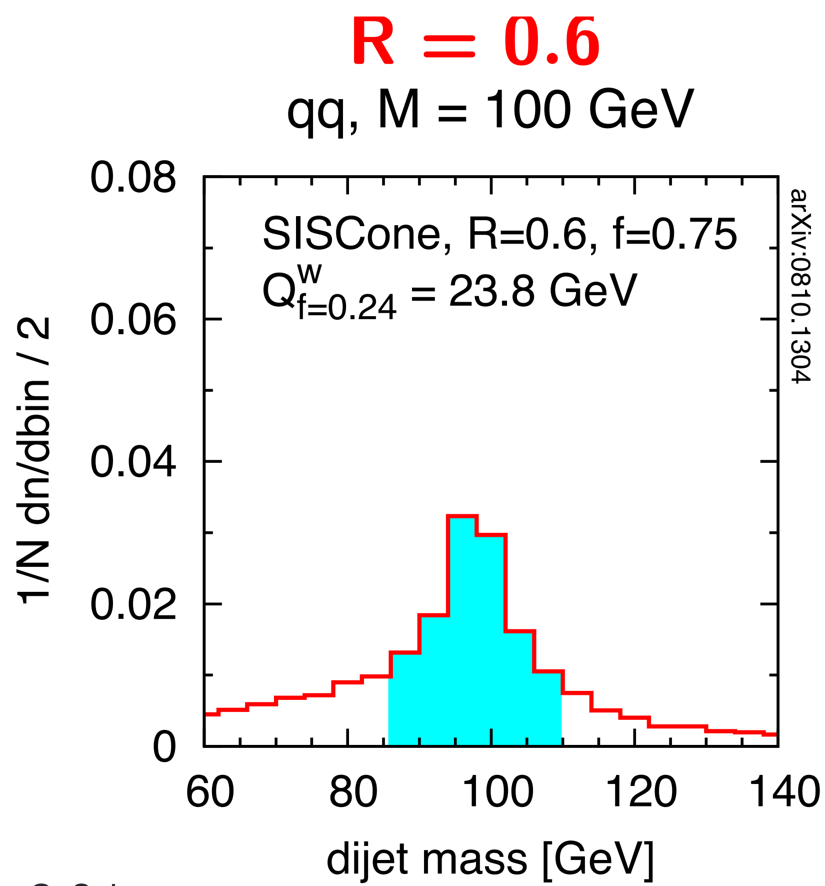

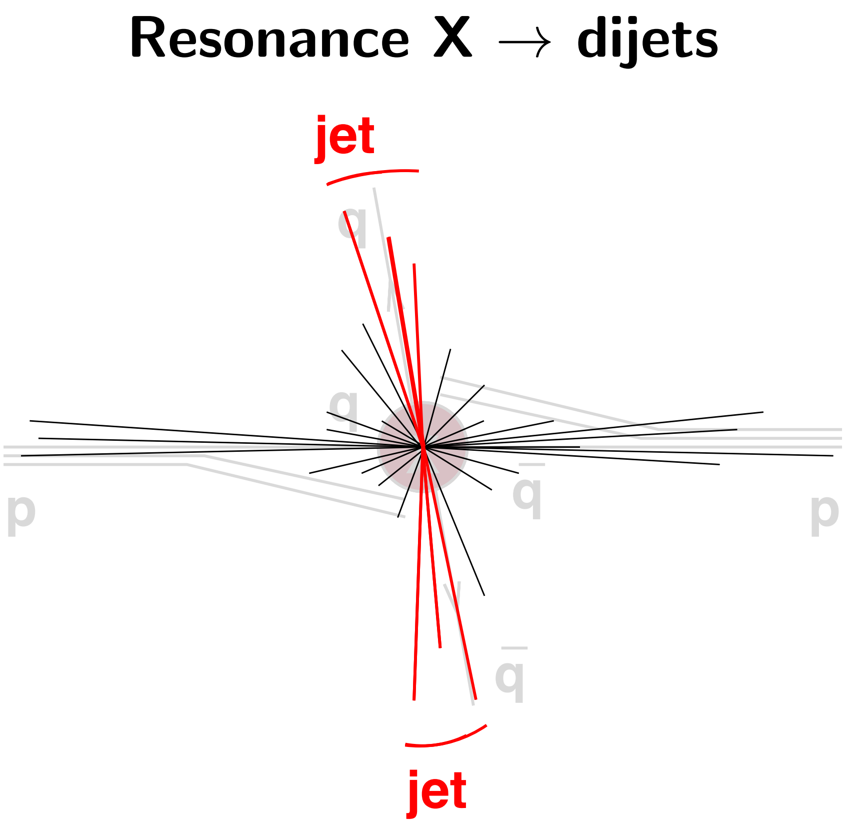

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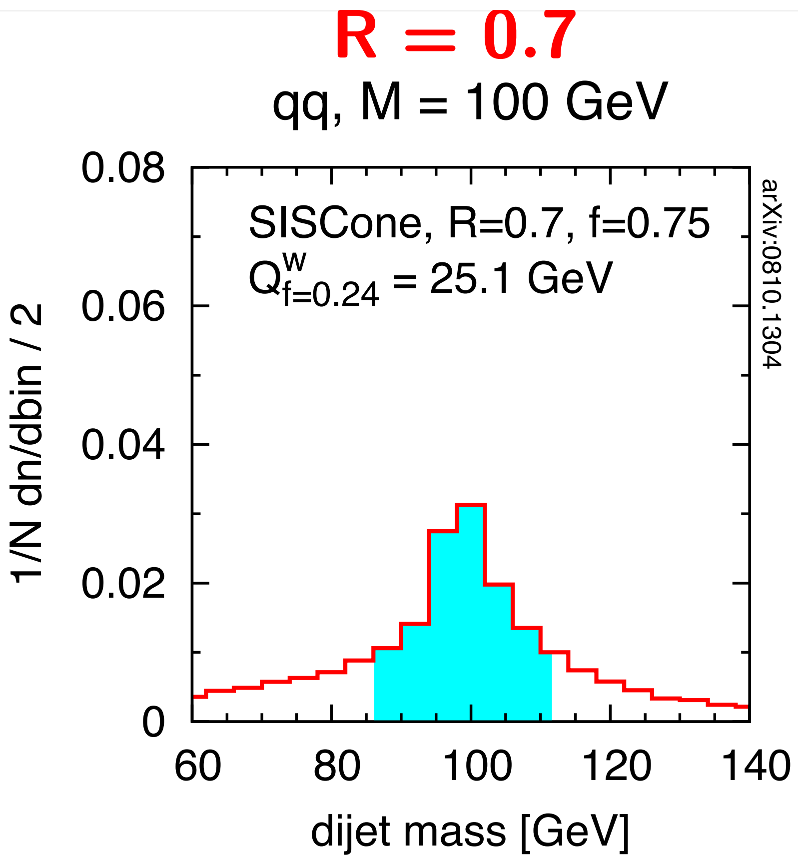

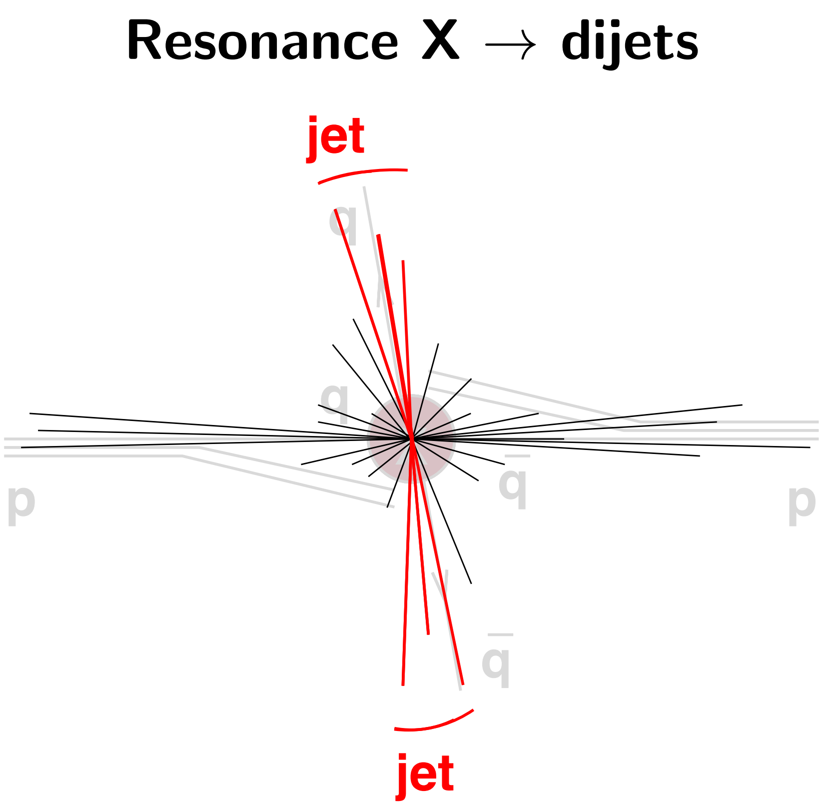

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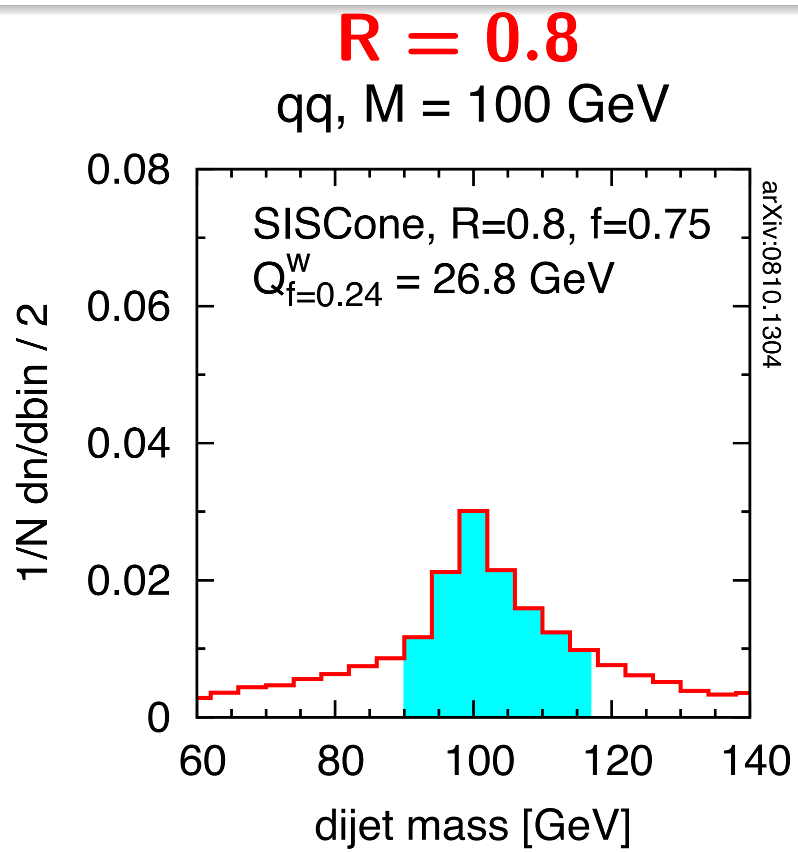

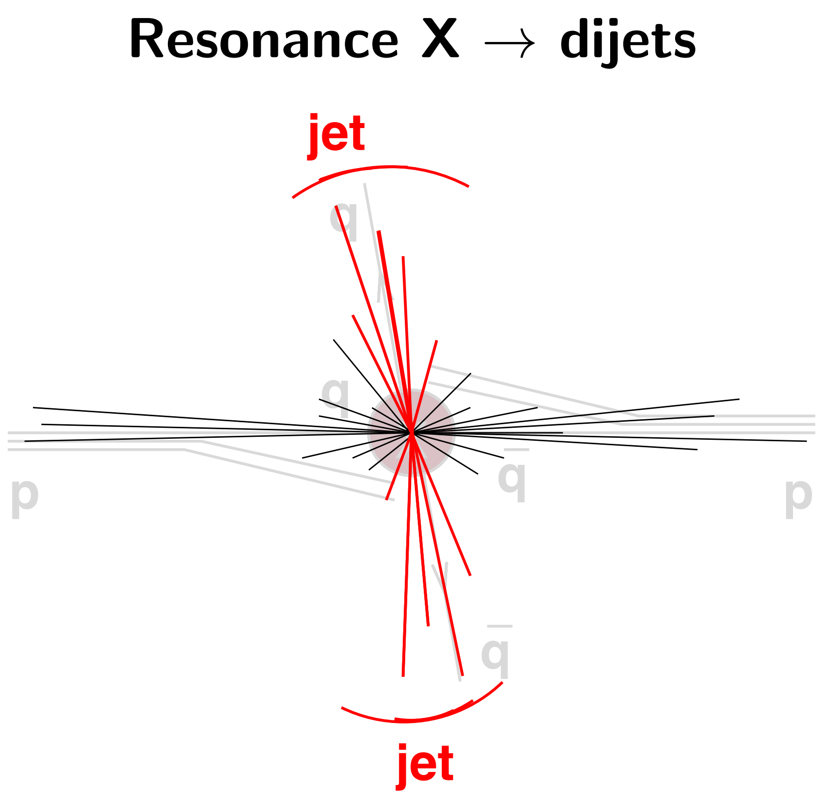

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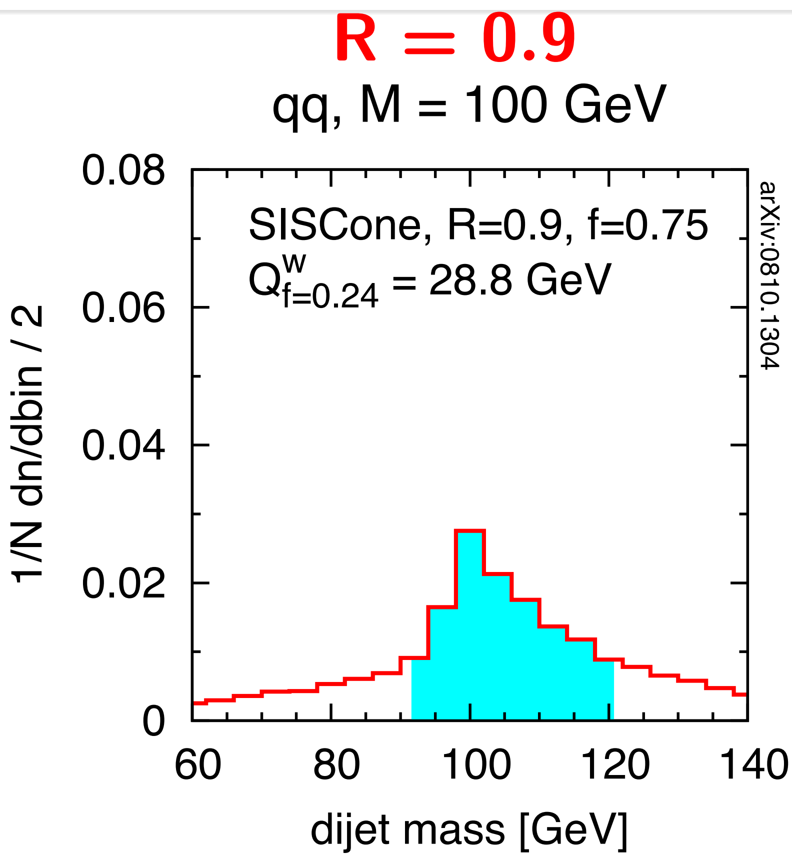

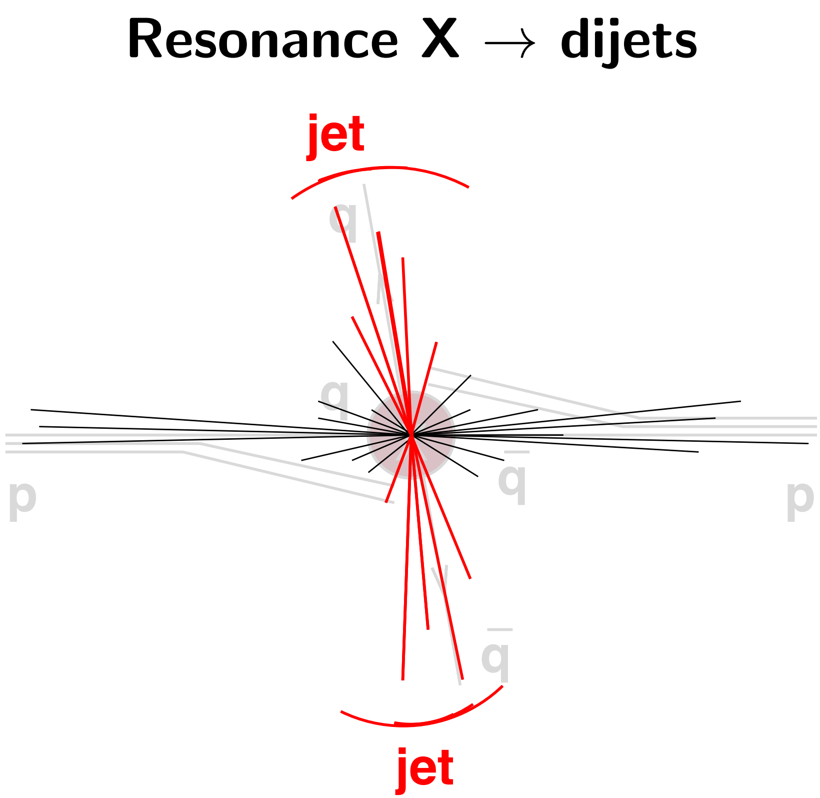

from G. Salam
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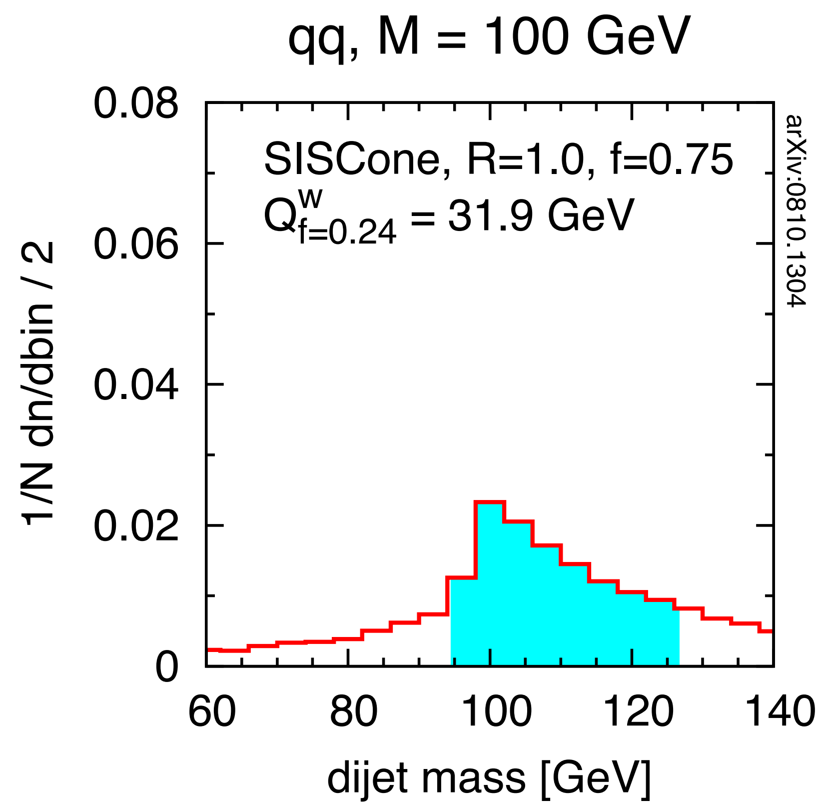
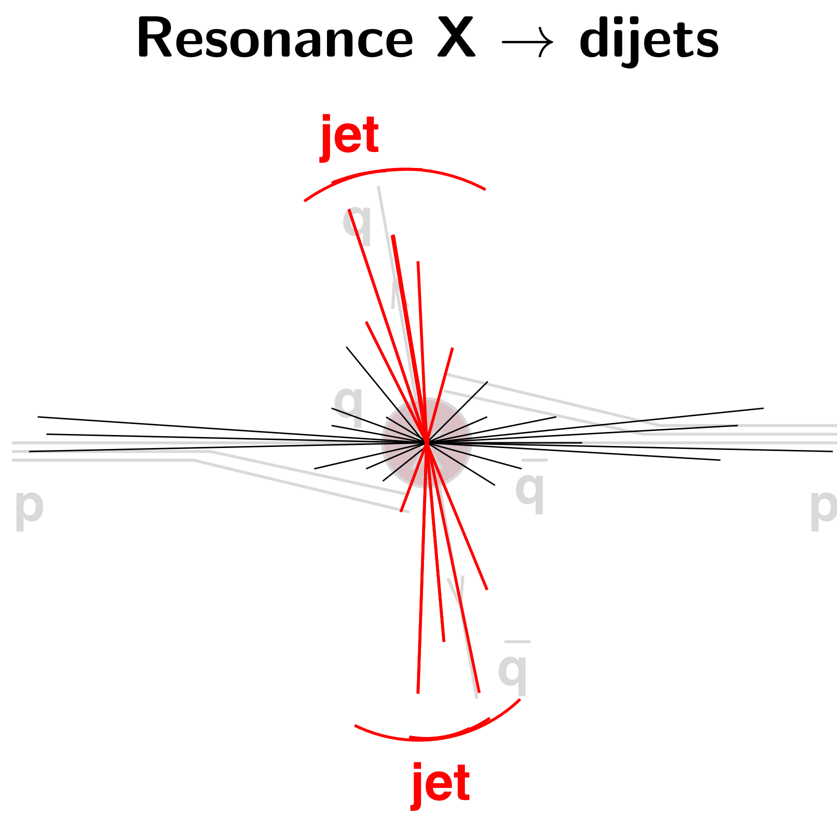
Resonance peak various R

R = 1.0





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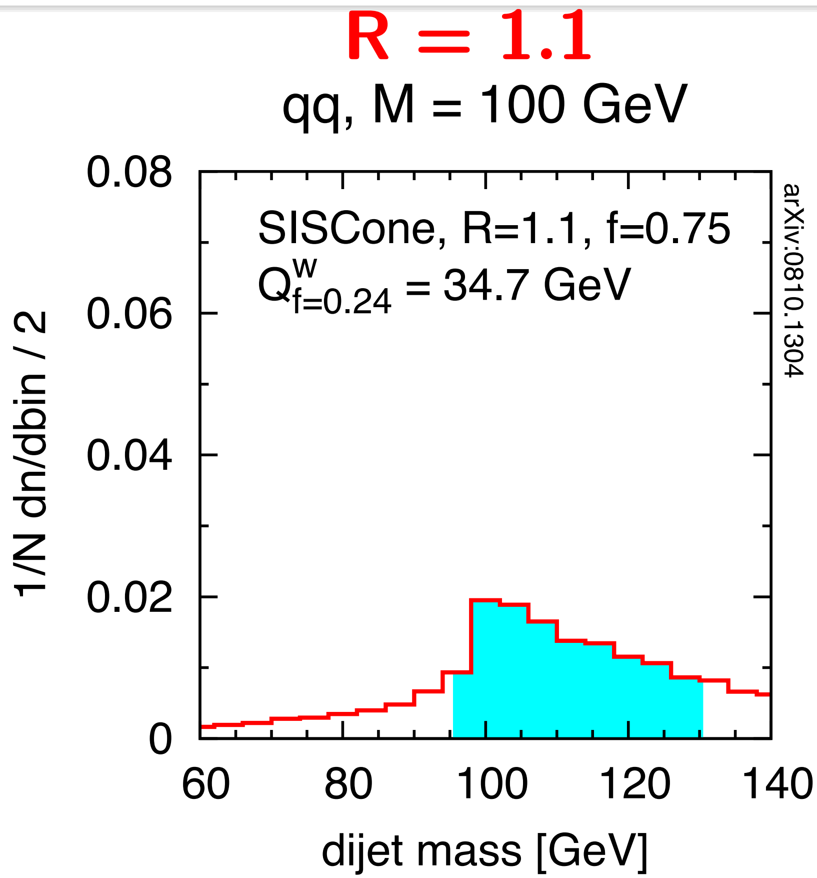

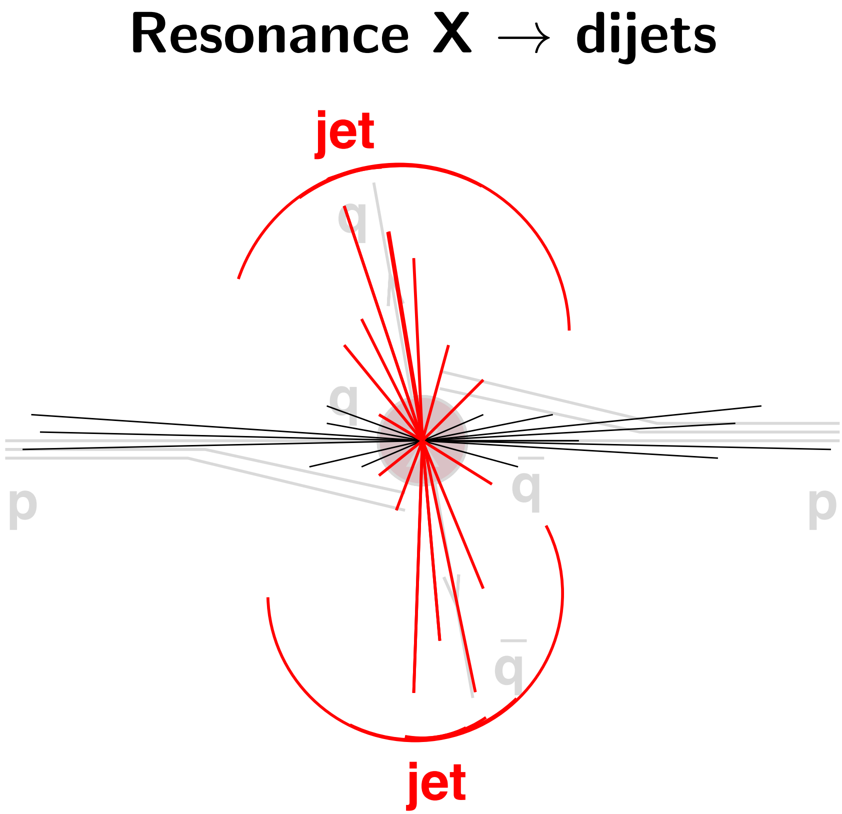

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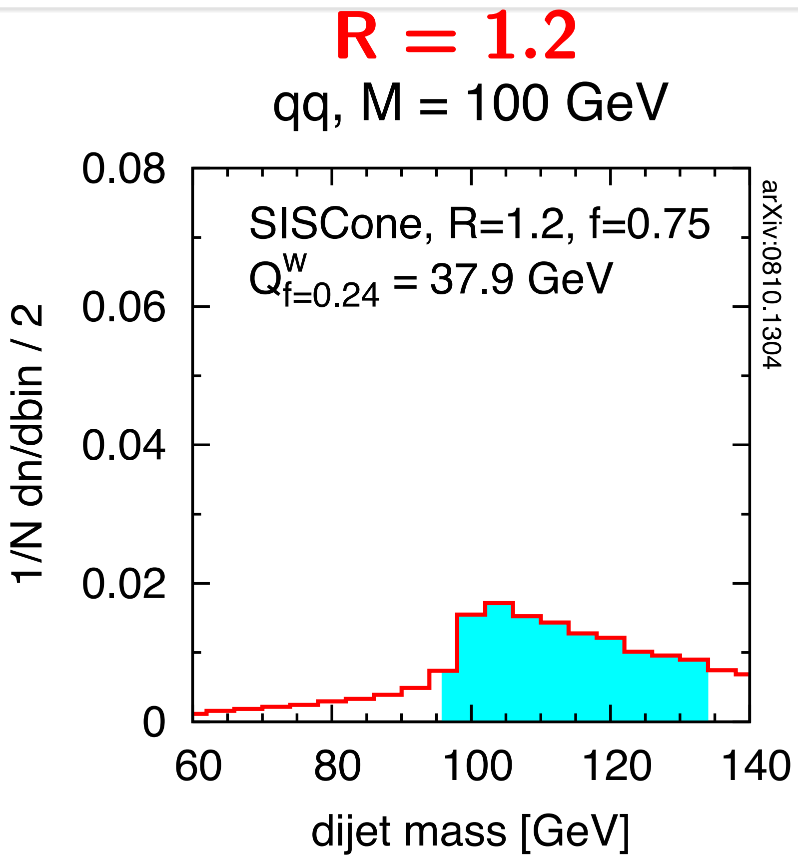

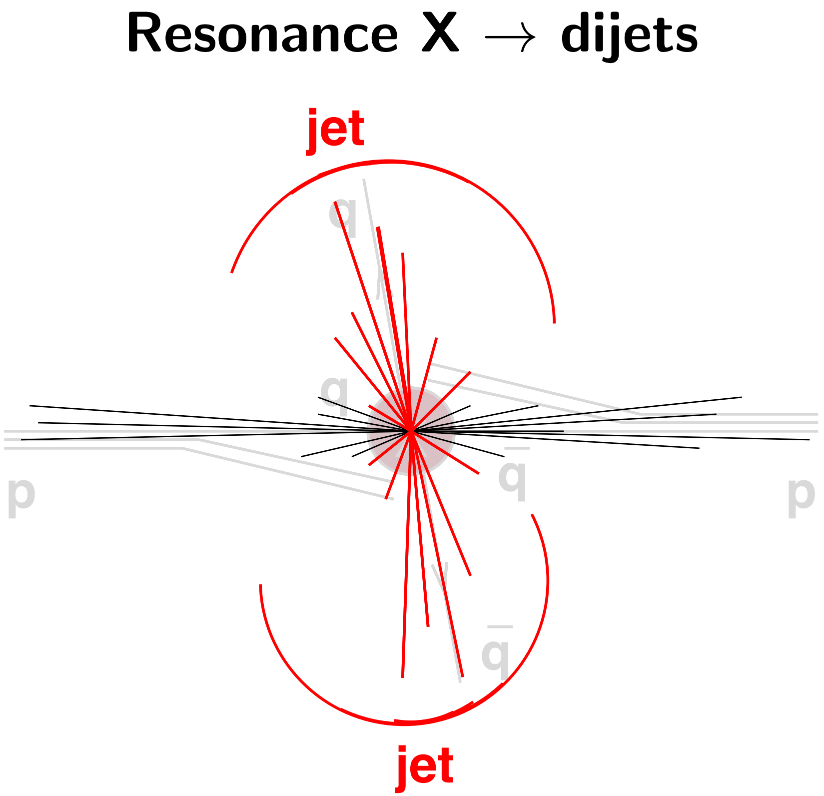

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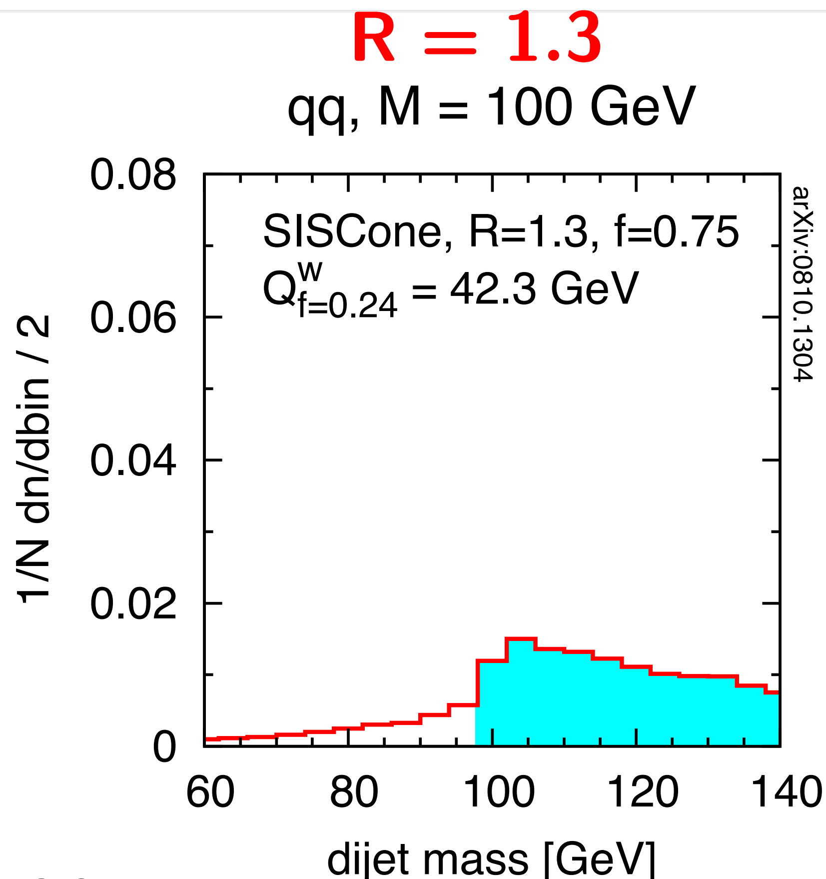

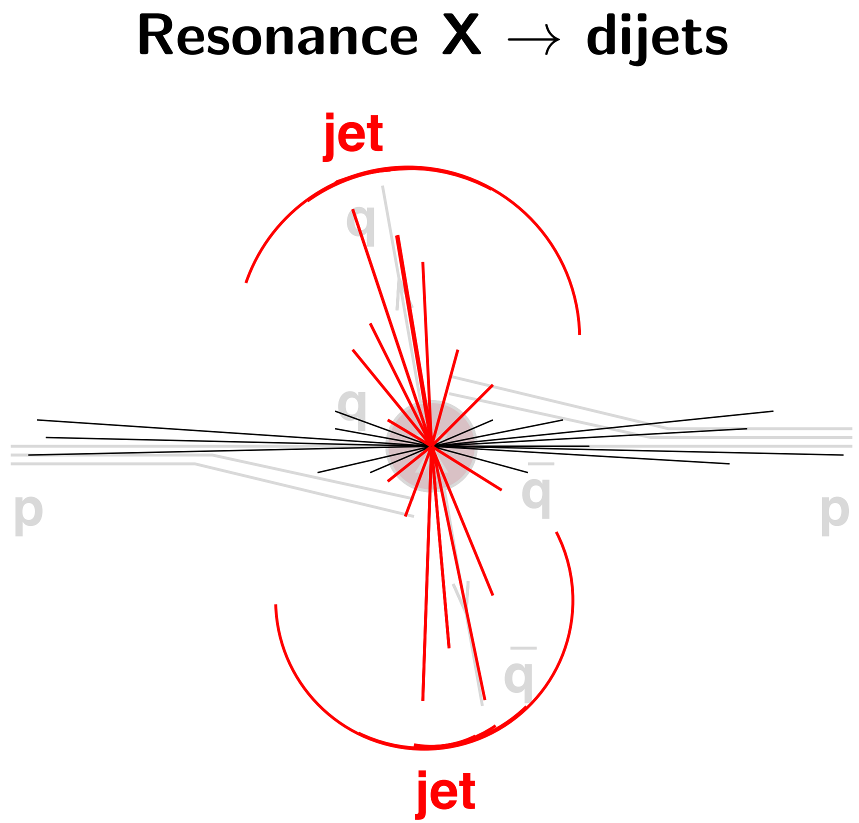

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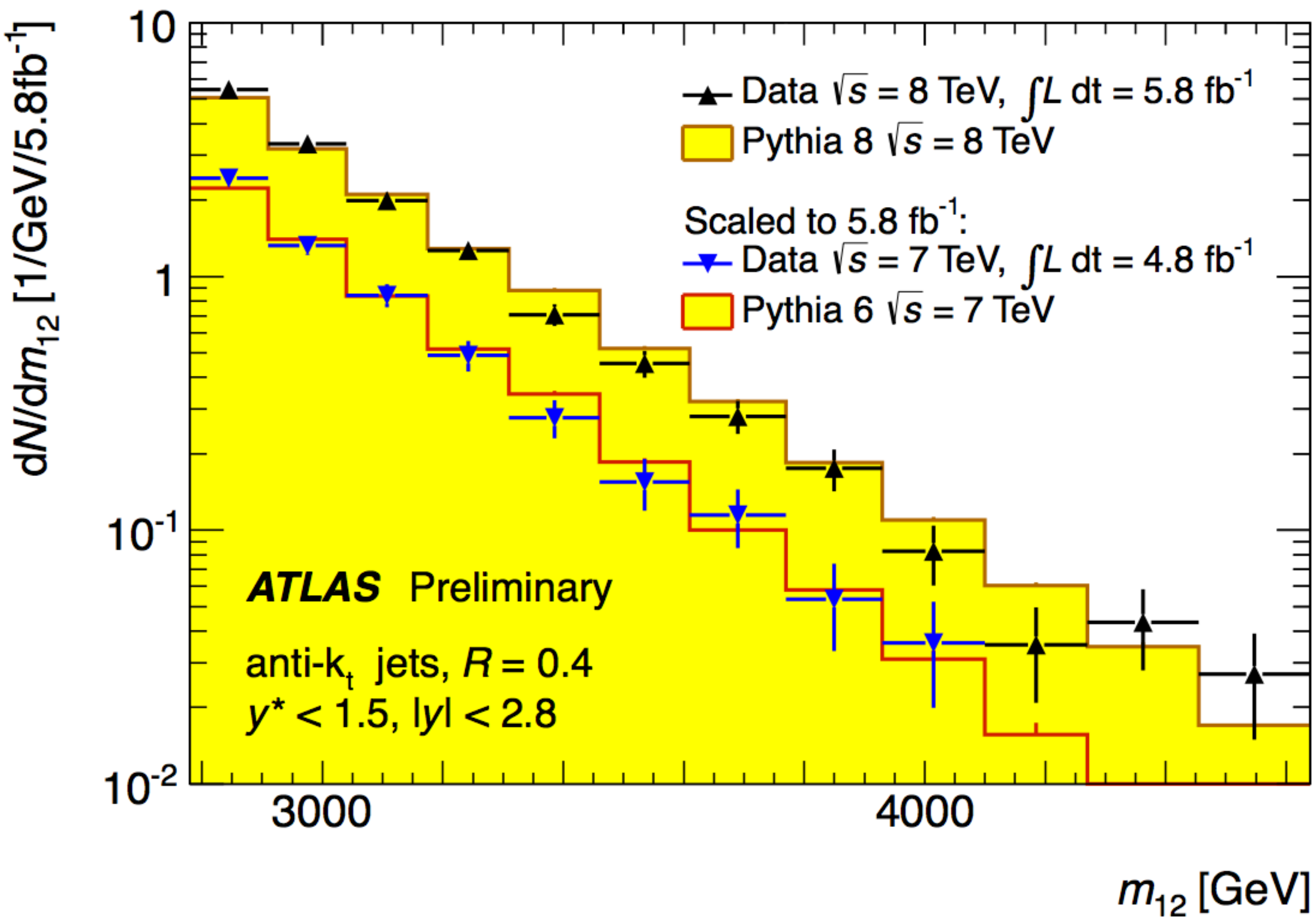
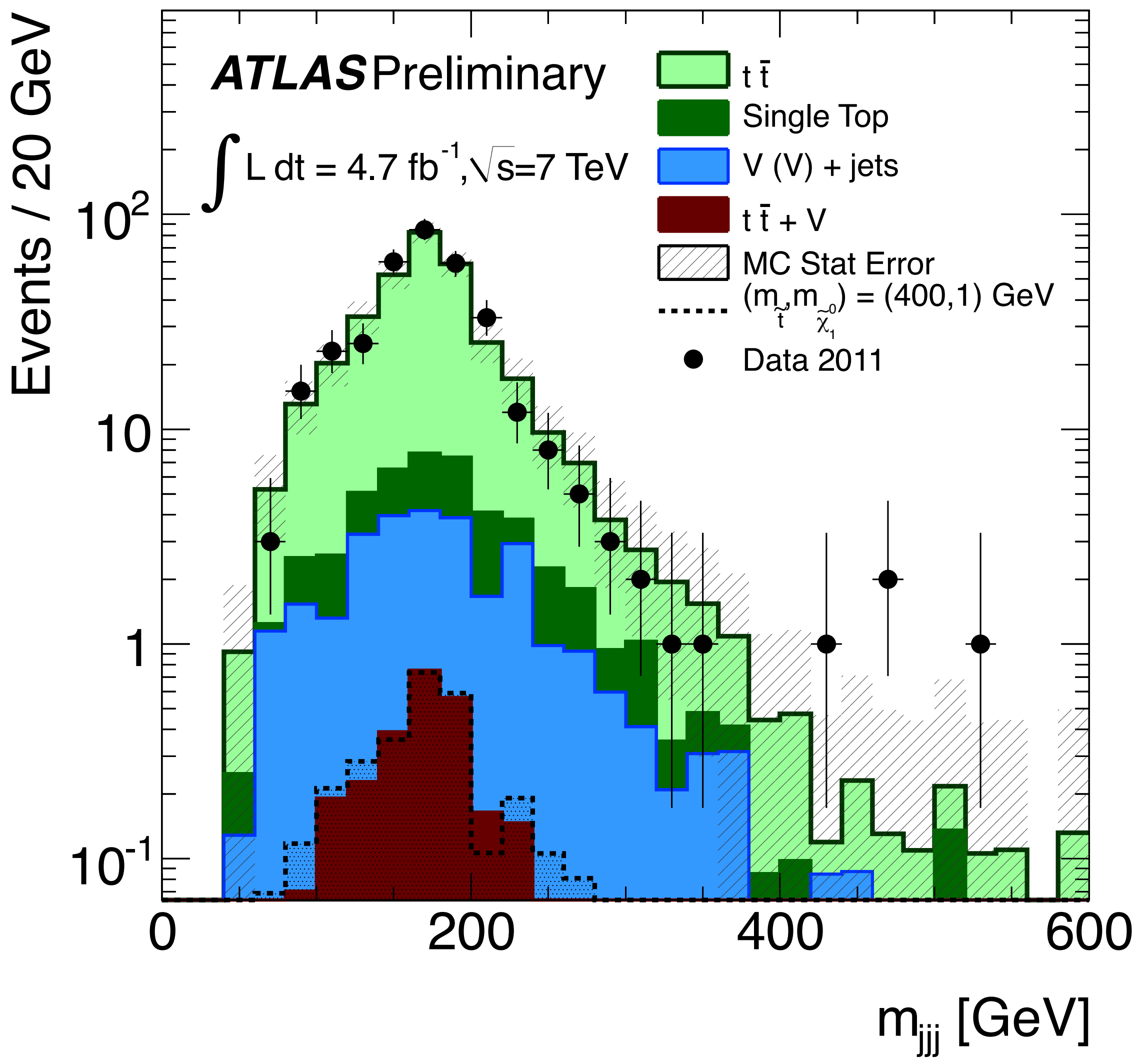
Dijet invariant mass

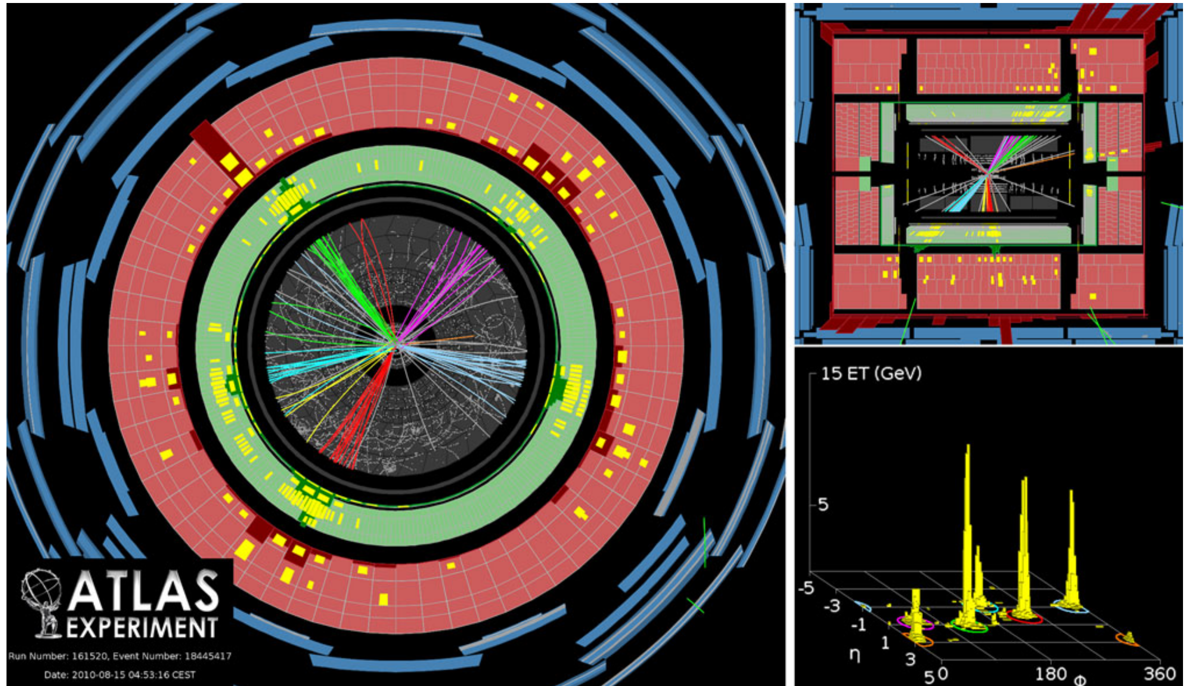
Atlas dijet invariant mass (anti-k_T R=0.4)



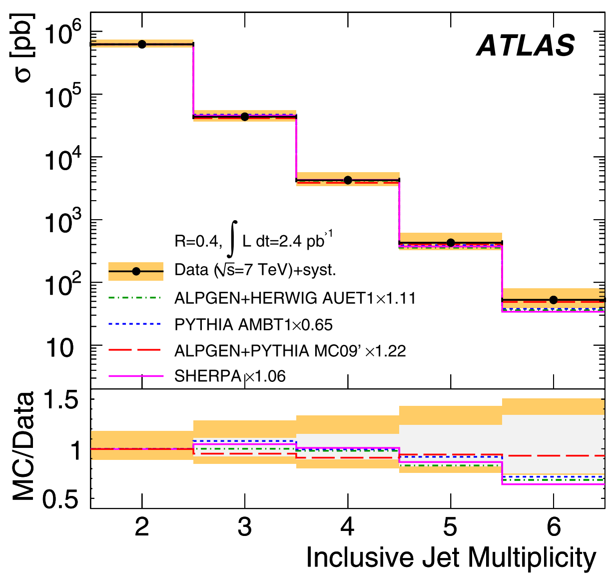
Tri-jet invariant mass

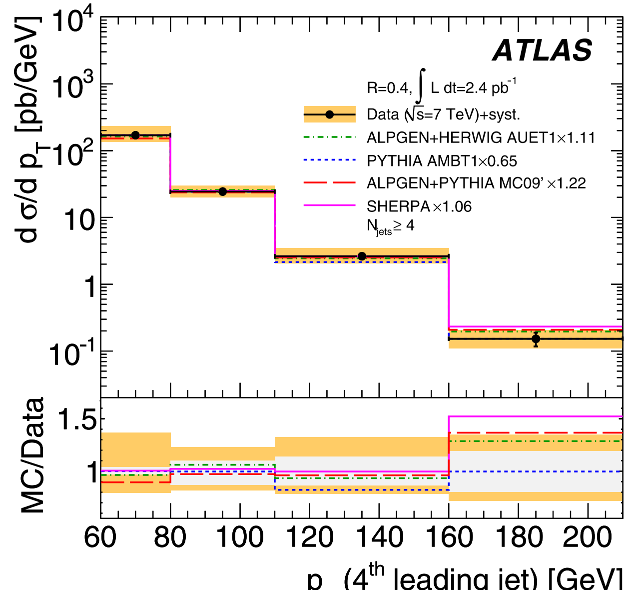


Multijets

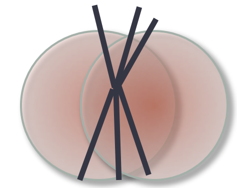


Multijet data
Agrees very well
with theory



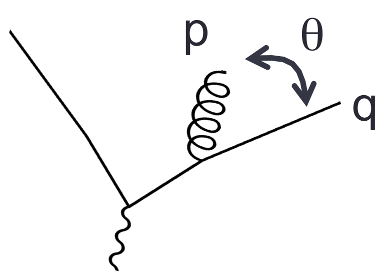


Summary



- Jets exist because QCD is weakly coupled at short distances and strongly coupled at long distances

- Collinear and soft regions dominate cross sections

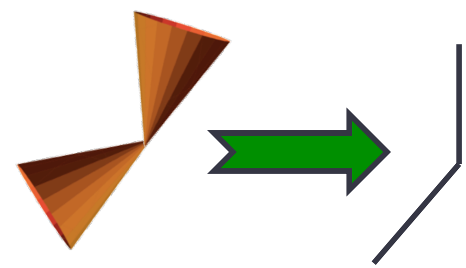


$$\mathrm{d}\sigma = e^{-\int \mathrm{d}P}\mathrm{d}P$$

$$\sim e^{-\alpha \ln^2\left(\frac{\mu_1}{\mu_2}\right)} \left(\frac{\alpha_s}{2\pi}\frac{1+z}{1-z^2}\right)\mathrm{d}z$$

- Semi-classical approximation “Sudakov factors and splitting-functions” works excellently

- Jet algorithms reconstruct parton momenta from jets



- Different algorithms Different goals

Cone algorithms
Cambrideg/Aachen
k_T
Anti-k_T

↔

Reconstruct parton momenta
Infrared safe
Insensitive to pileup
Easy to calibrate experimentally

- Excellent agreement of theory with data