JET PHYSICS

2012 Cargese summer school

August 25, 2012

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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

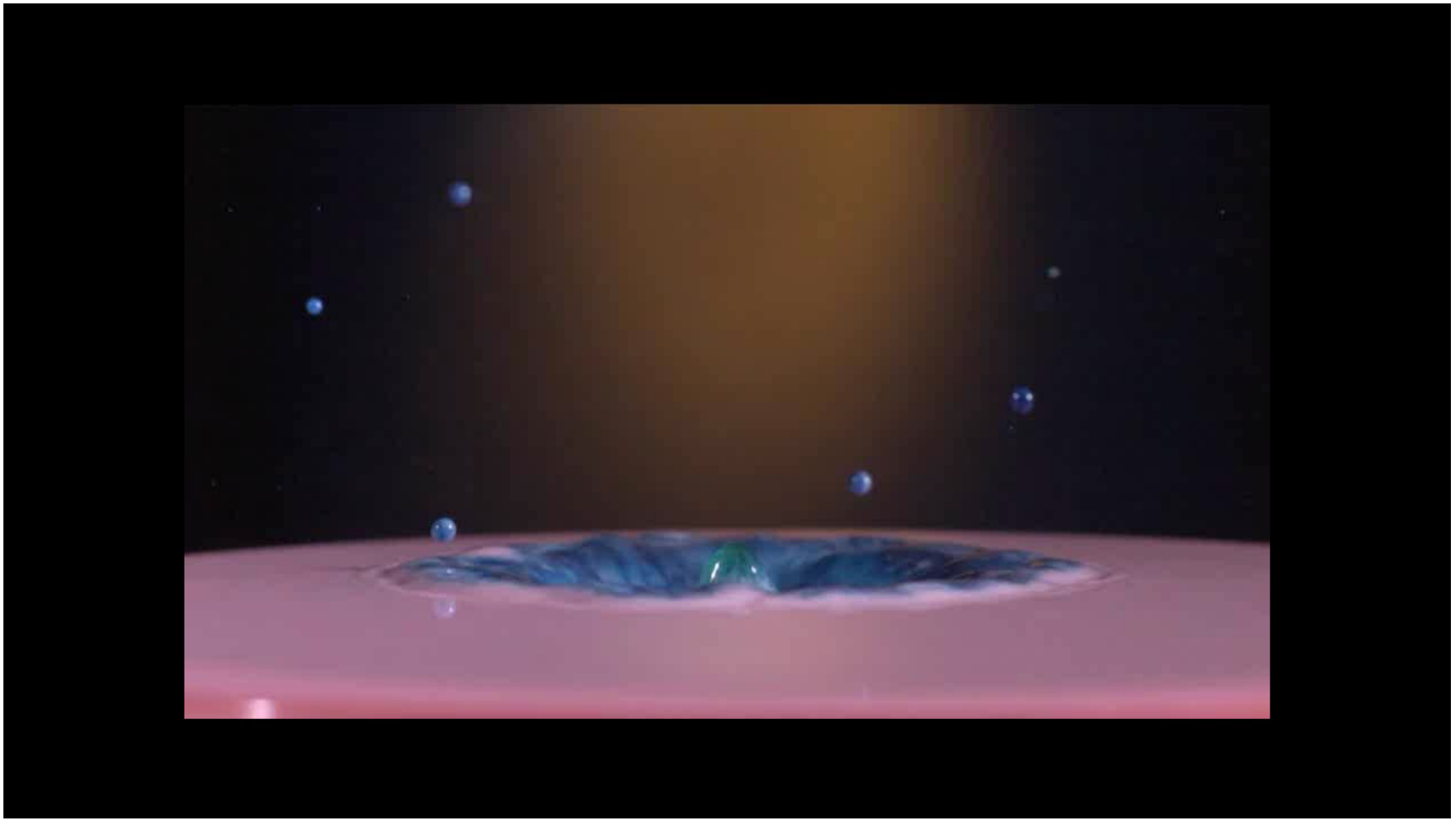
THE PHYSICS OF JETS

What happens in a collision?

Colliding water droplets – what happens?

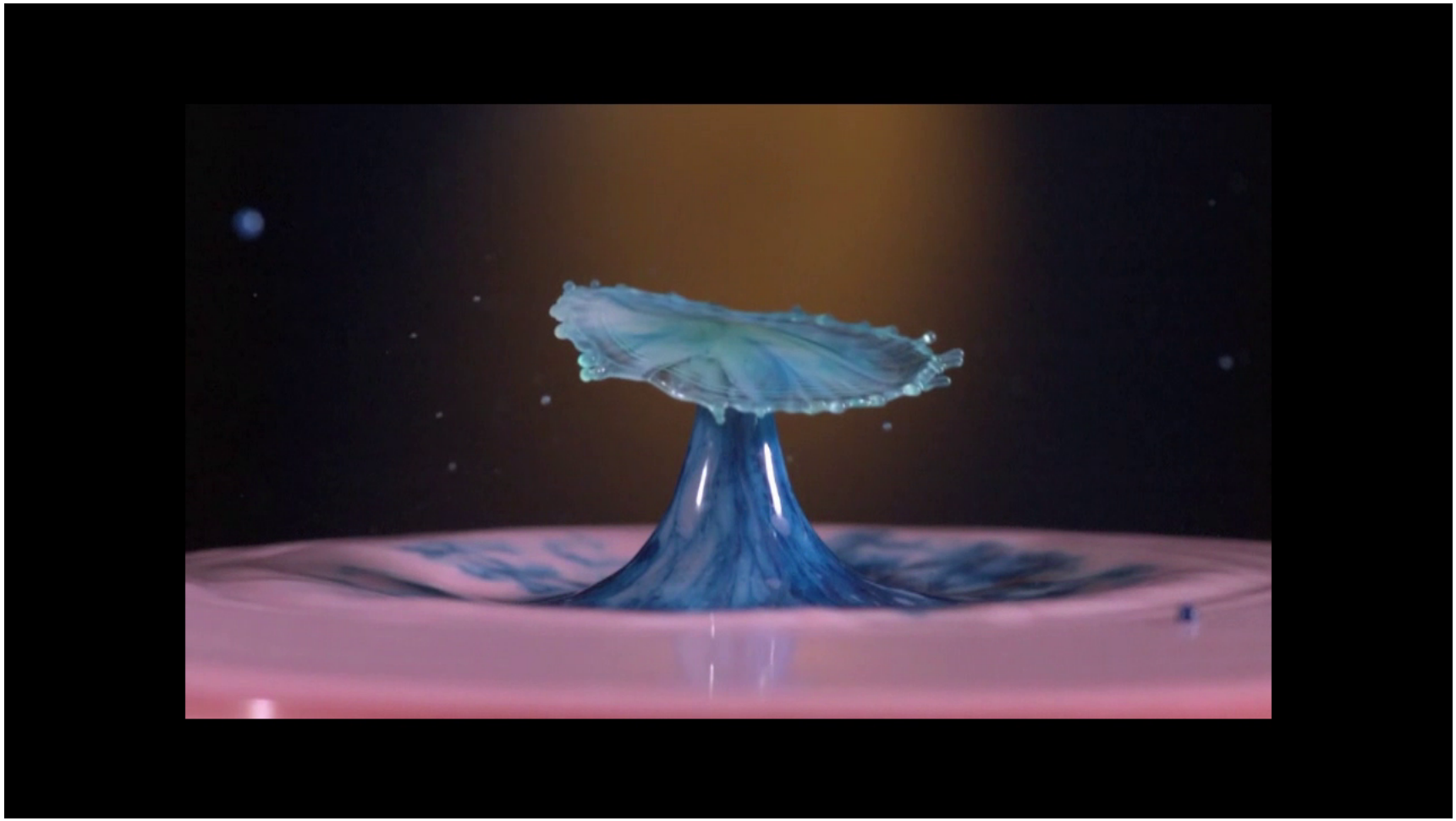
What happens in a collision?

Colliding water droplets – what happens?

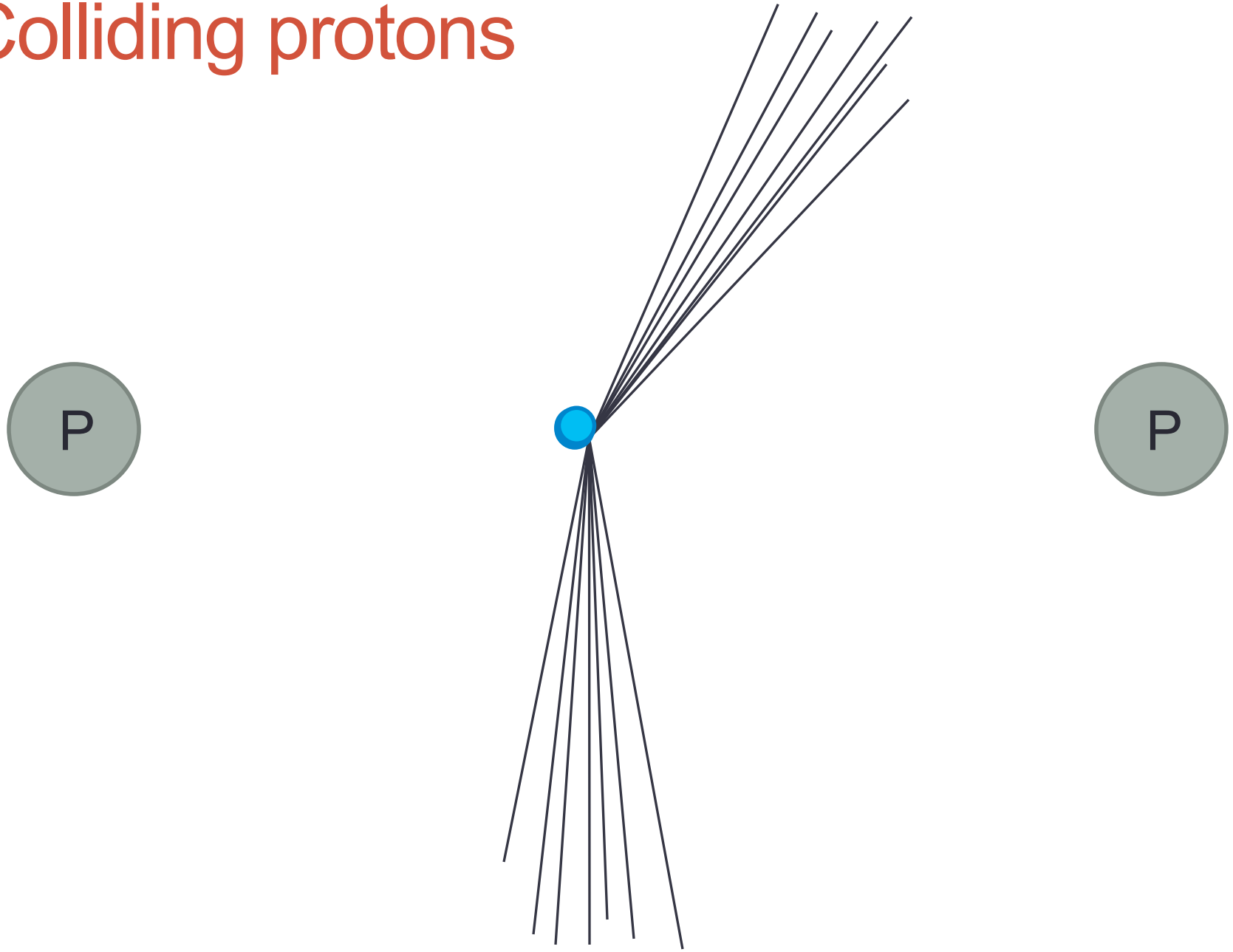


What happens in a collision?

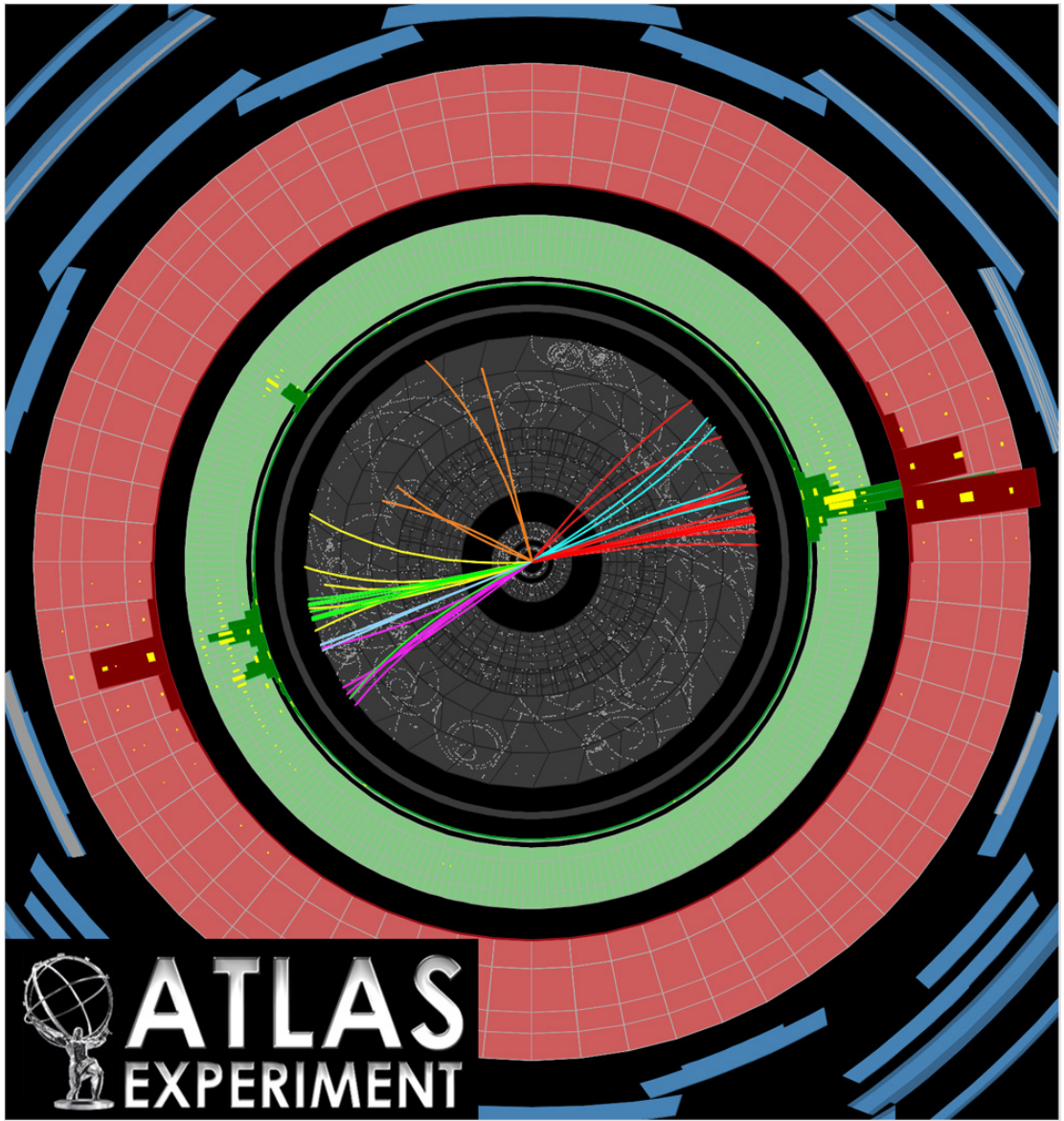
Colliding water droplets – what happens?
Produces **radially symmetric** distribution



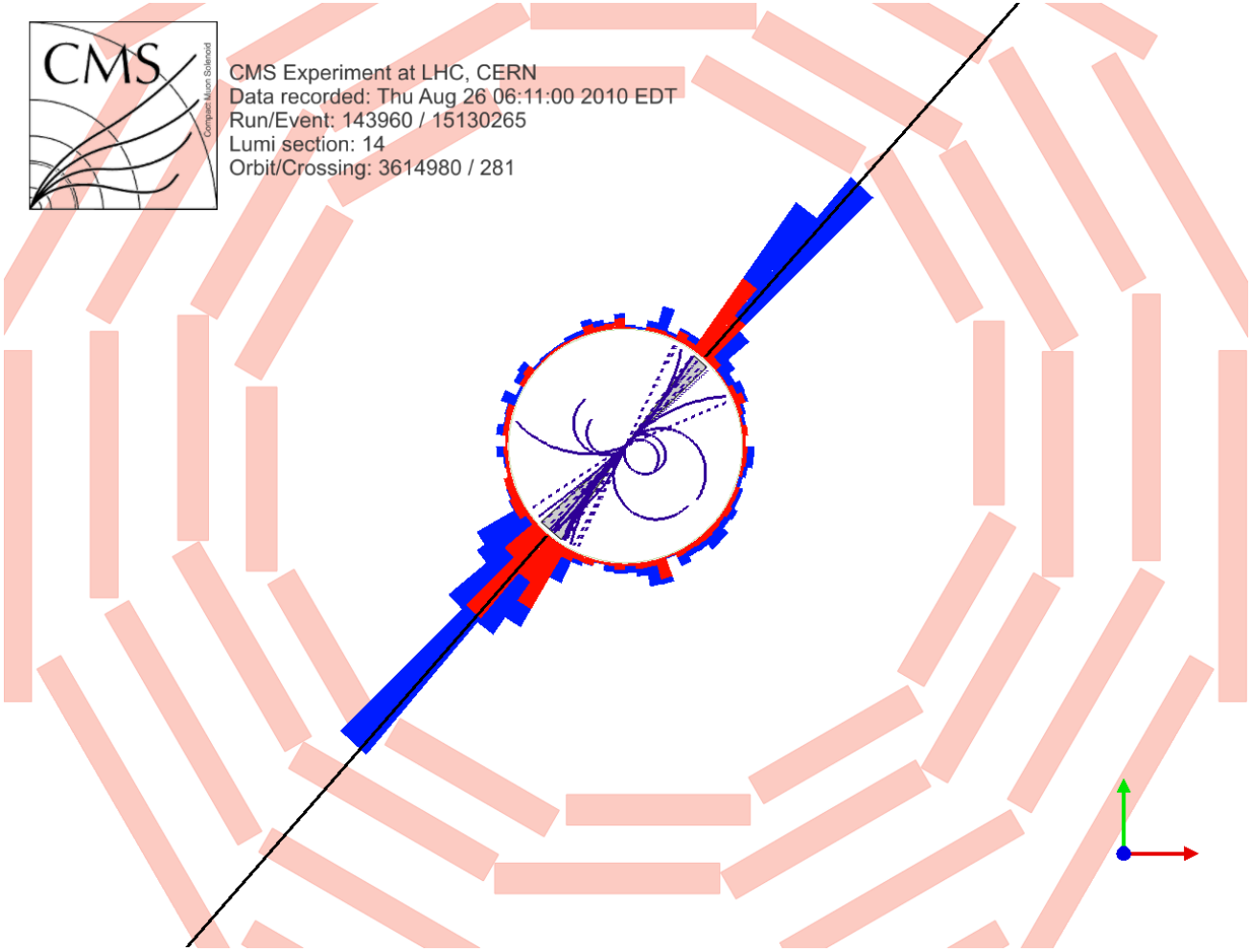
Colliding protons



Colliding protons



Colliding protons



Jets and the LHC

- The LHC has much higher energy than any collider ever
  - More jets
  - Harder (more energetic) jets
  - More jet-like (collimated) jets

- LHC experiments can measure jets really well
  - Better energy resolution than Tevatron
  - Better spatial resolution than Tevatron
  - Can identify individual particles!!

Jet physics is entering a **Golden Era**

Revolution in the last 4 years

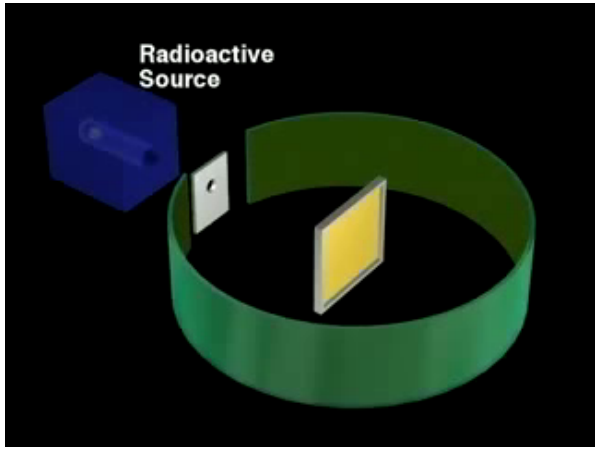
New experimental techniques

New ideas and algorithms

New theoretical methods

BRIEF HISTORY

Nuclear physics begins

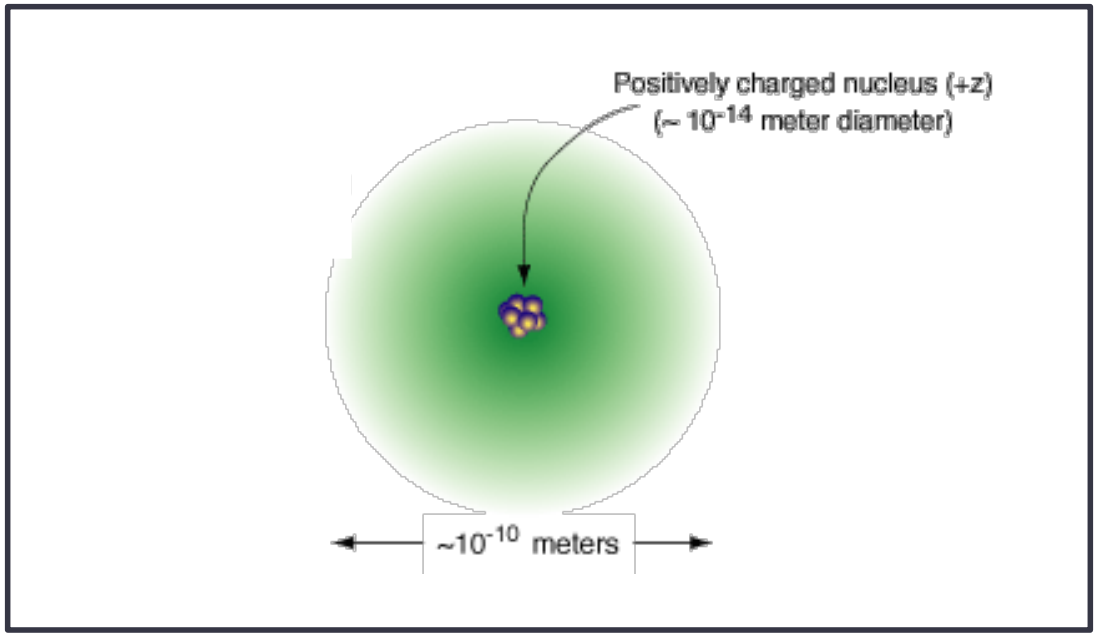


Rutherford's Experiment (1910)

- α particles from ^{214}Po on 0.5 μ thick sheet of gold
- α particle speed = 10^7 m/s

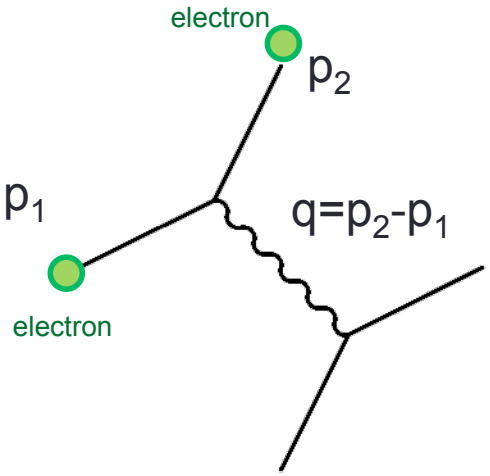
Rutherford concluded:

- Most of the gold foil is empty space
- Mass is concentrated in a hard central nucleus
- Size of nucleus is approximately 3 x10^{-14} m (very close to correct)



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

In general, the cross section depends on the momentum transfer q^2



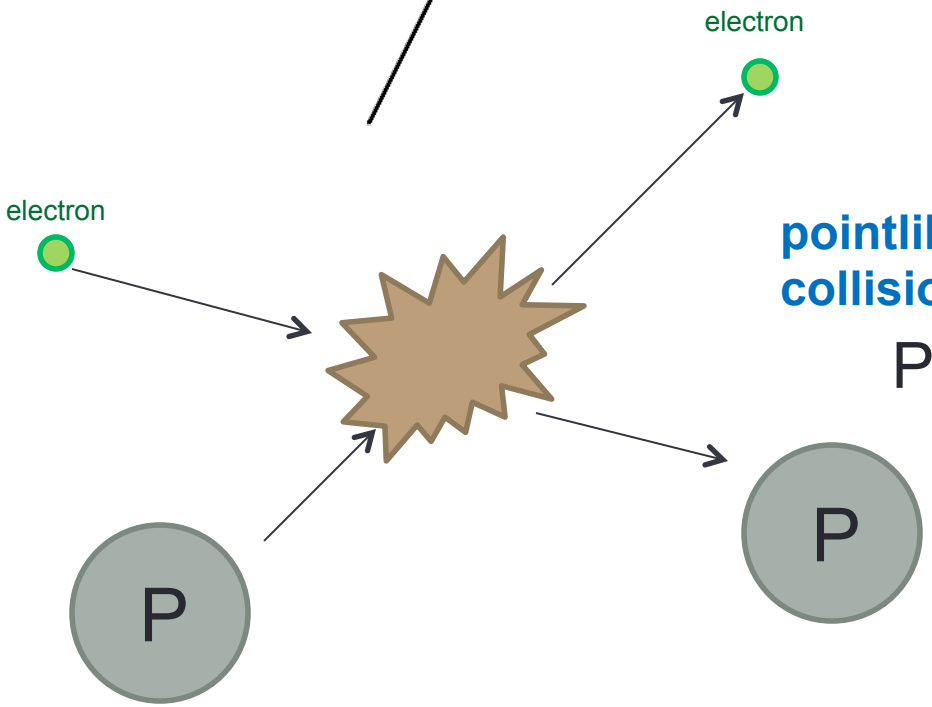
$$d\sigma = d\sigma_{\text{point}} F(q^2)$$

Form factor ~ scattering potential

$$F(q^2) = 1 \quad \leftrightarrow \quad V(r) = \frac{1}{r}$$

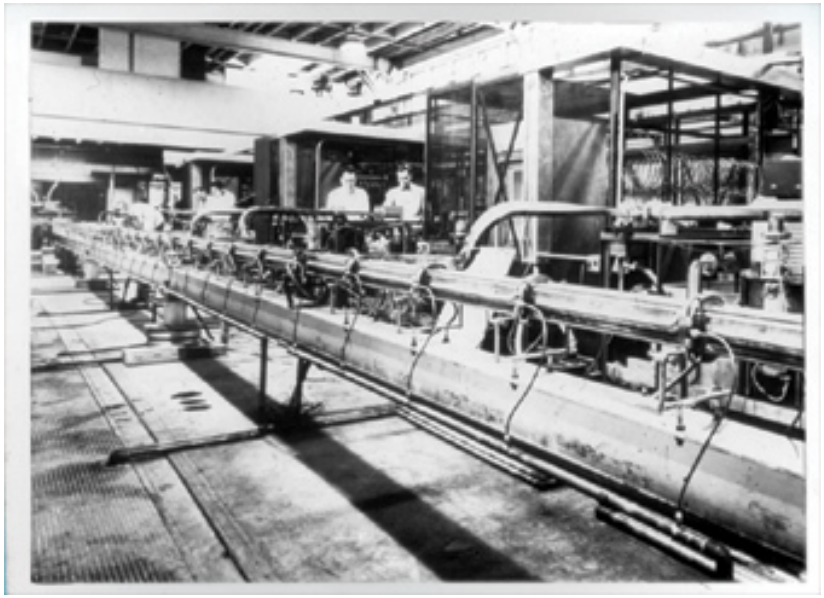
pointlike elastic collisions

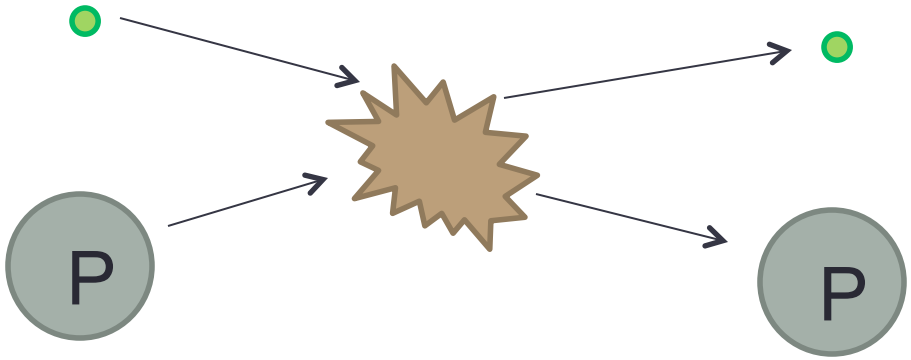
Pure Coulomb potential → no structure

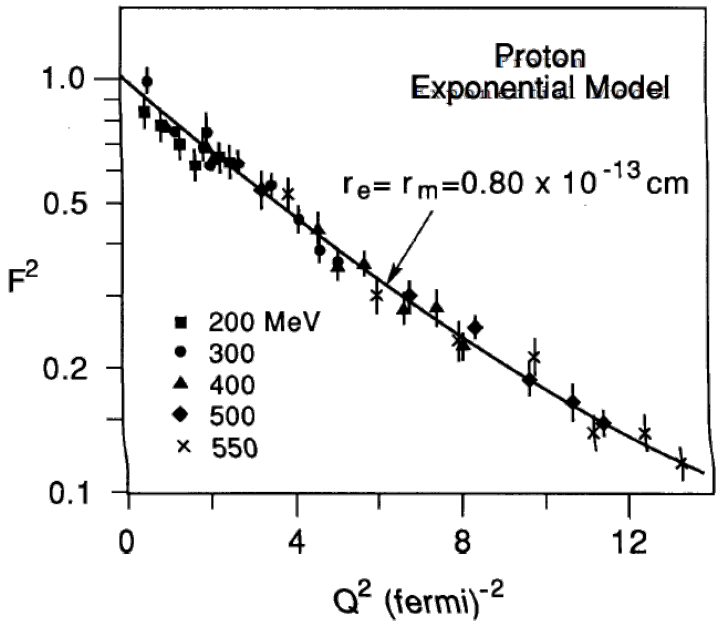


Electron-positron ($e^- P^+$) scattering

1950s at the Mark III linear collider at Stanford
- Energies of order 200-500 MeV







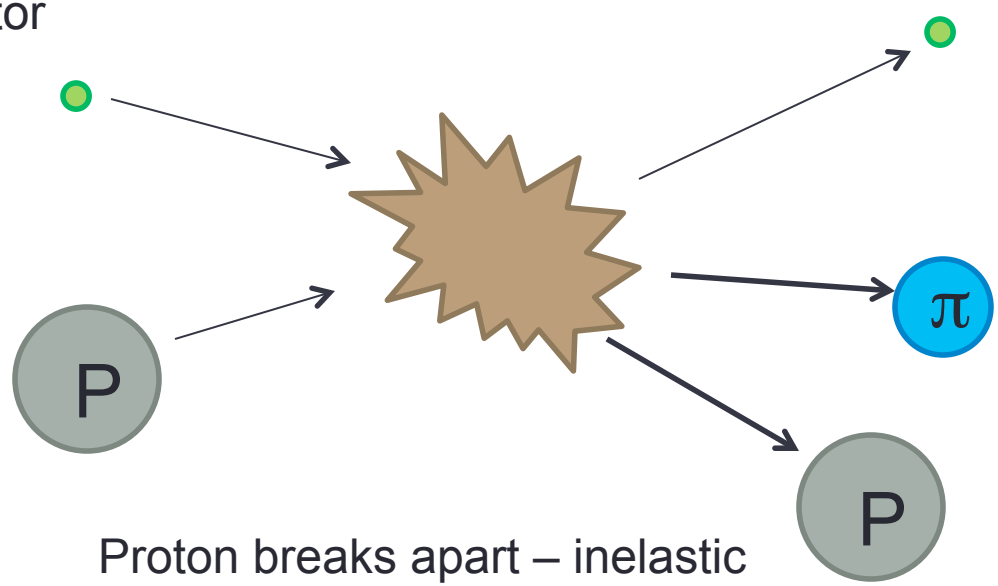
$$F(q^2) \sim \frac{1}{1+\left(\frac{q}{0.71\,\mathrm{GeV}}\right)^2}$$

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

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

Higher energy e^- P^+ scattering

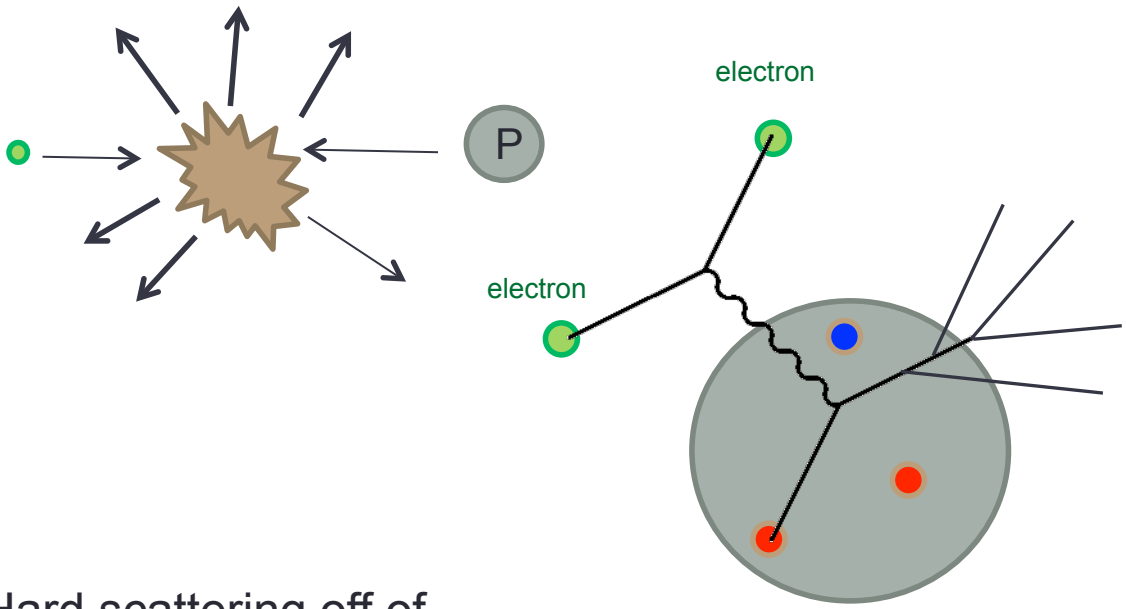
1960s at Stanford Linear Accelerator (SLAC)

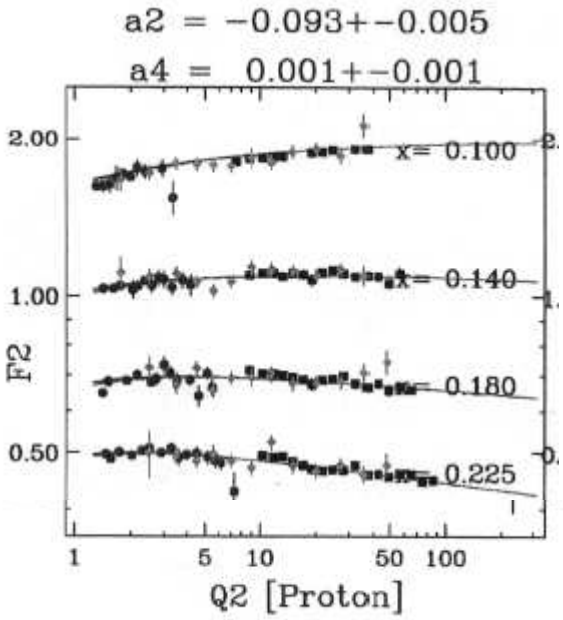


Proton breaks apart – inelastic scattering!

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

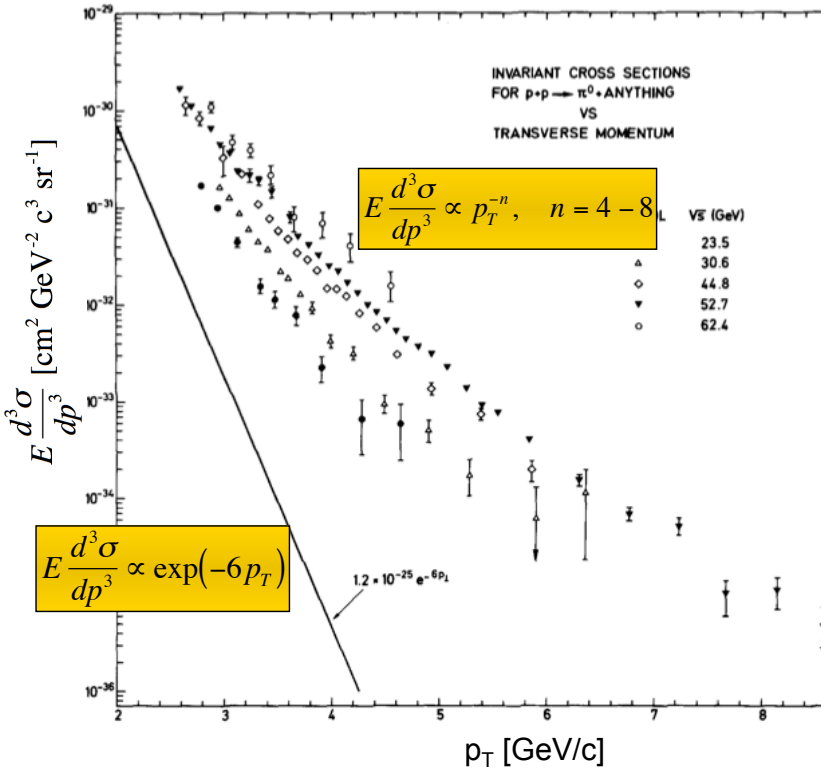
What happens to the proton?

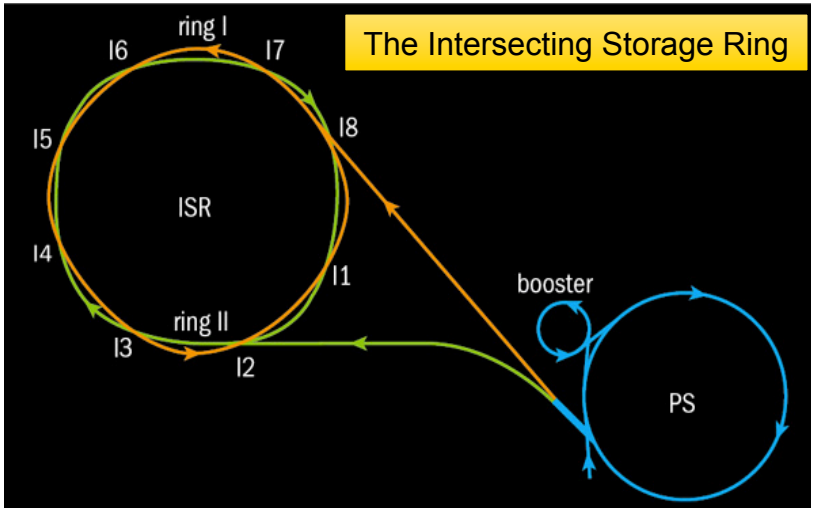
Hard to tell -- DIS experiments of the 50s and 60s were fixed-target experiments
-- not designed to measure the "hadronic" part, just the electron

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

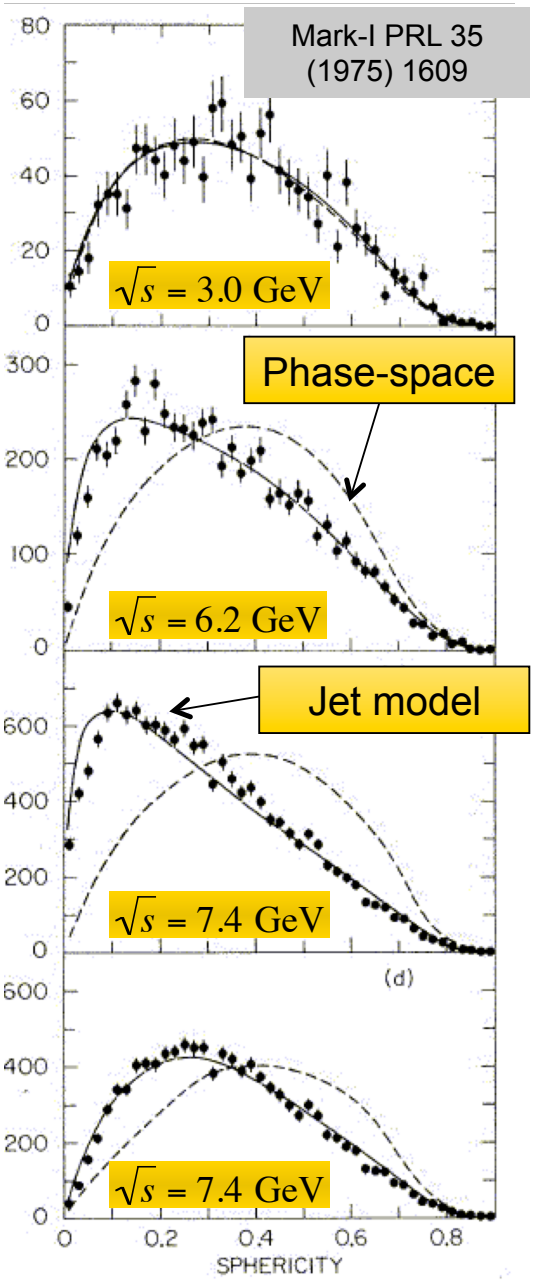
Spear at SLAC

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

- Confirmed jet models with event shapes

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

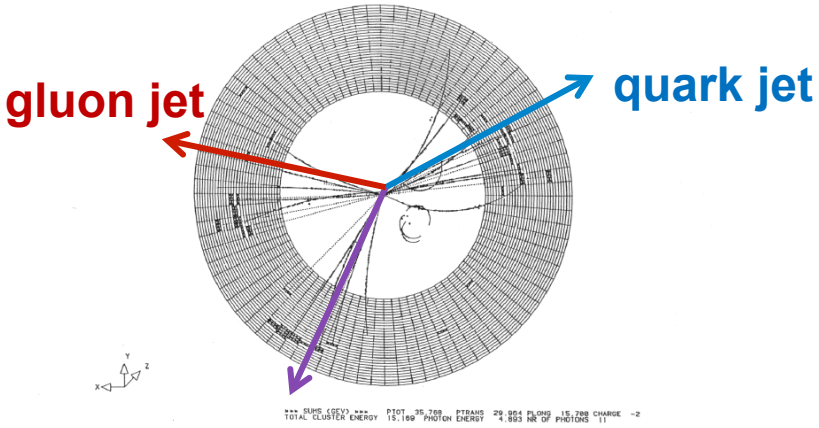
Measured Sphericity (event shape)



From T. Schörner-Sadenius

PETRA at DESY (Hamburg)

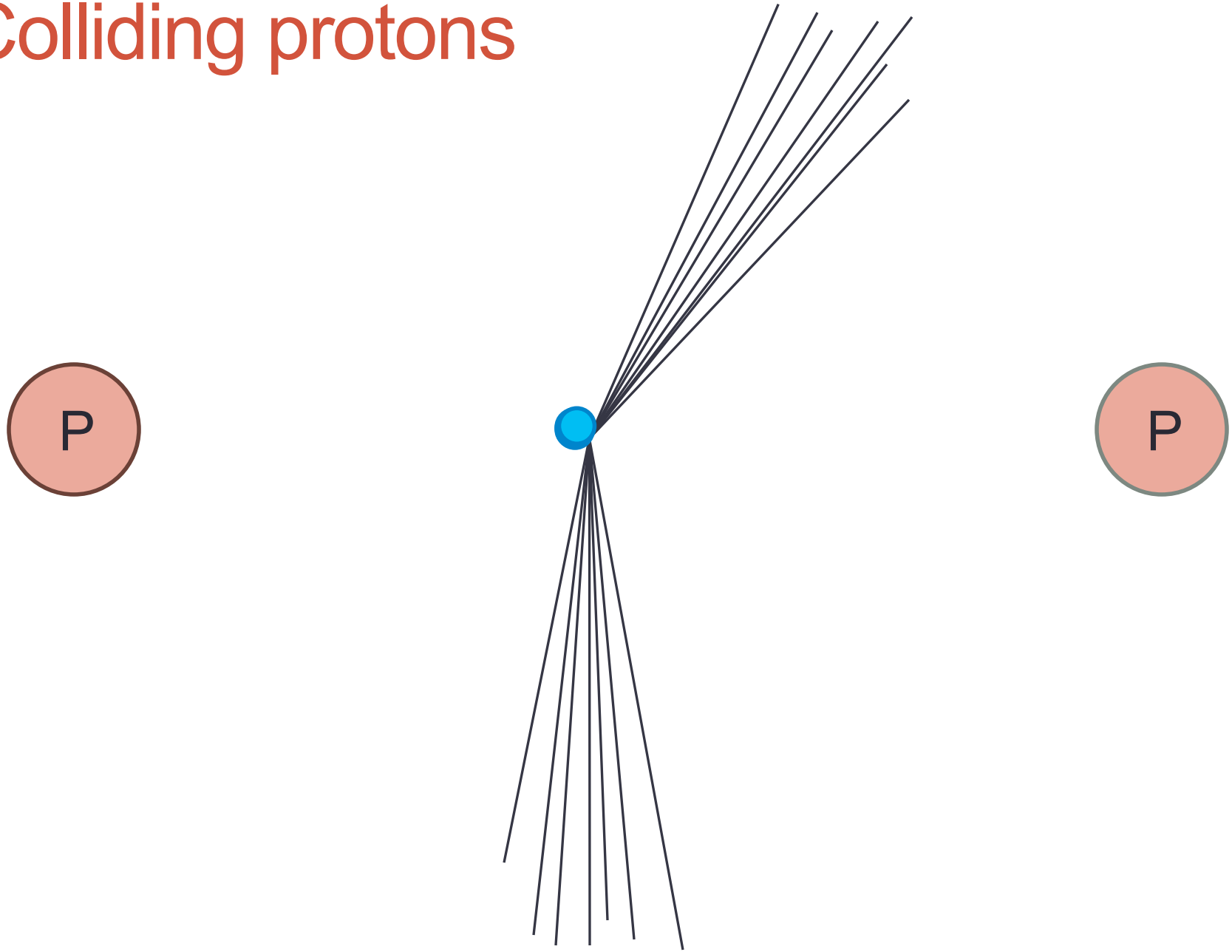
Gluon jets



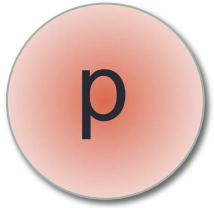
PETRA (DESY) 1979

THE PHYSICS OF JETS

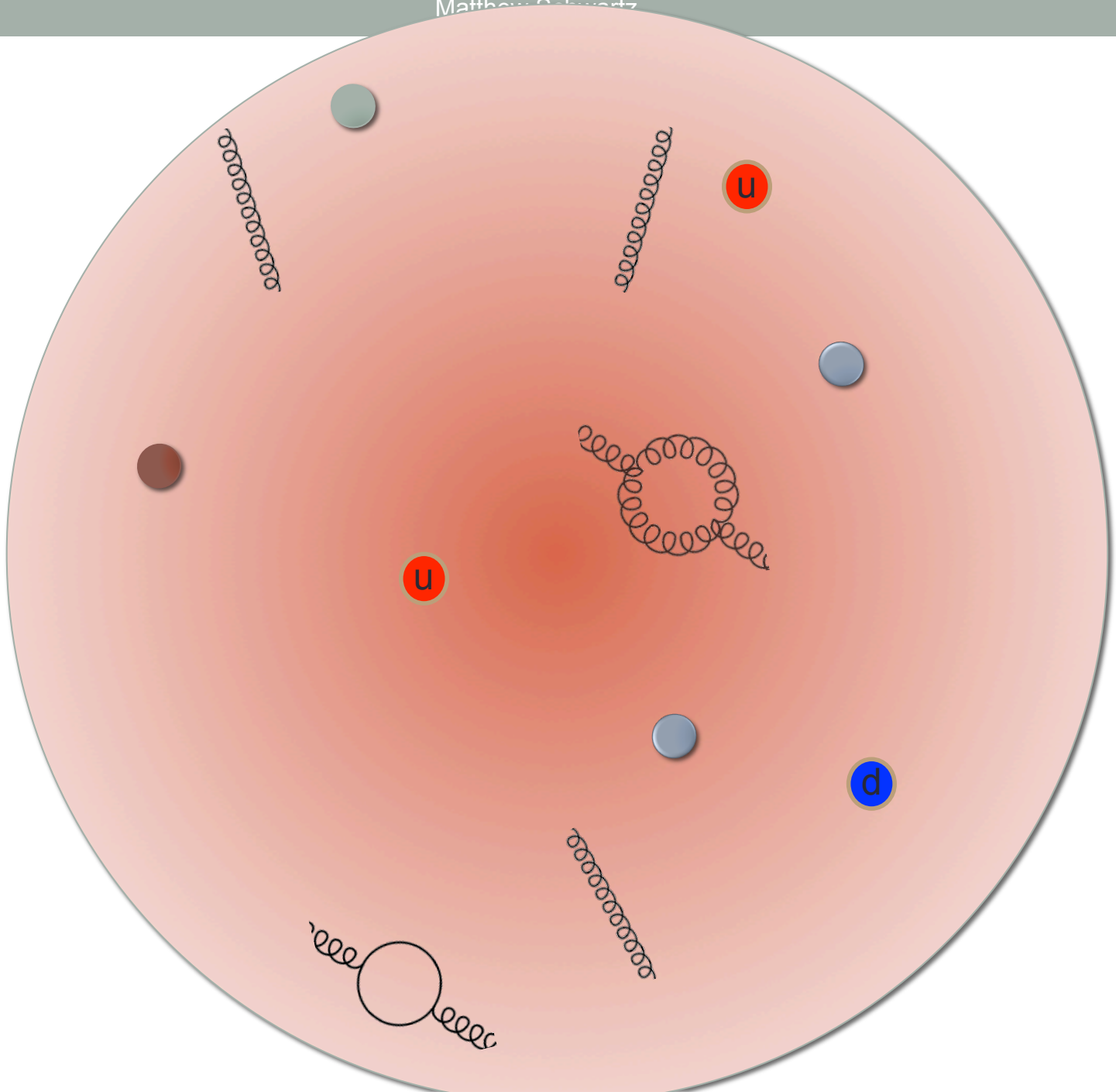
Colliding protons

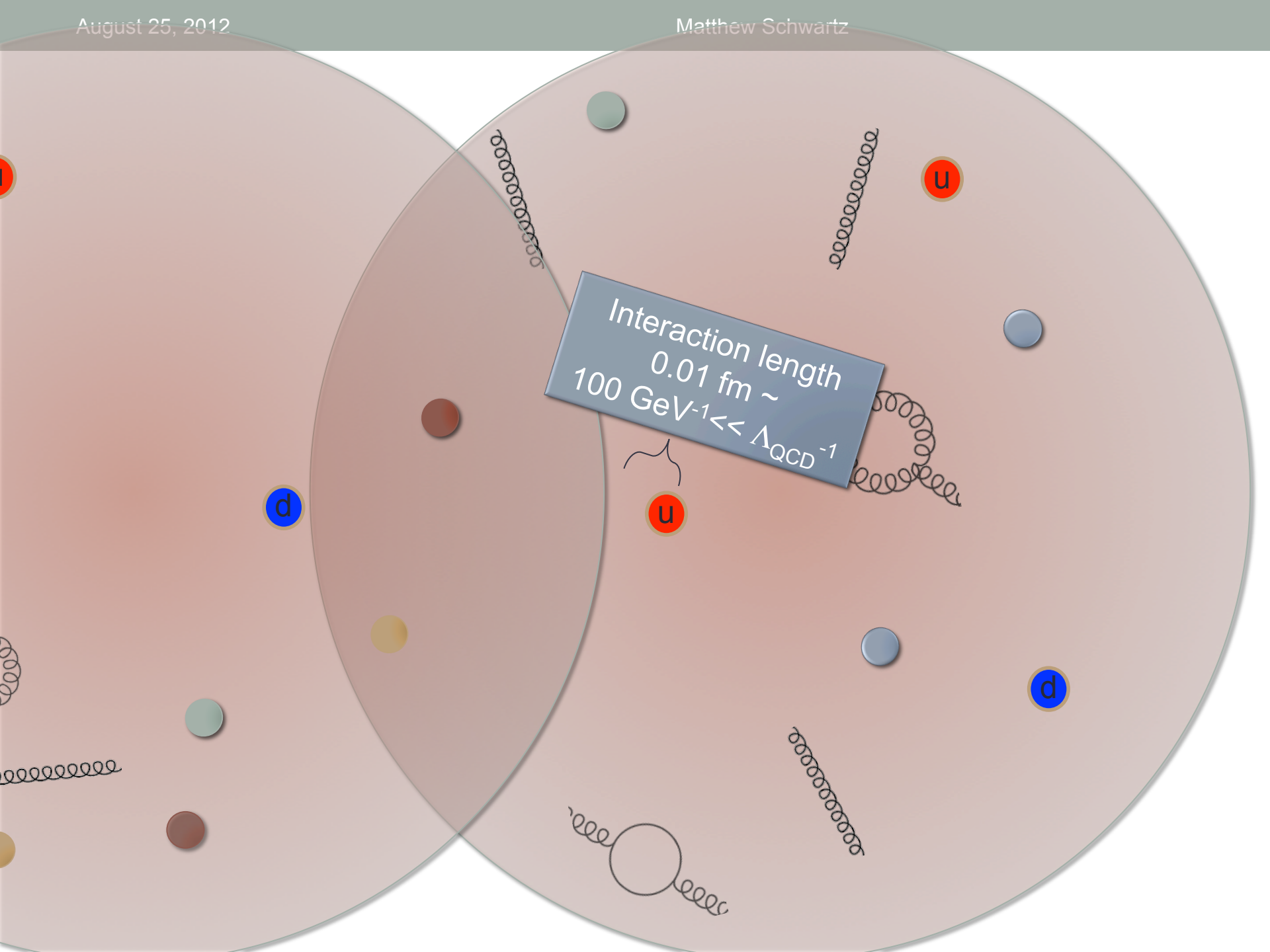


Colliding protons



Size is
1 fm ~ Λ_{QCD}^{-1}

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Interaction length
0.01 fm ~
100 GeV^{-1}<< Λ_{QCD}^{-1}
d
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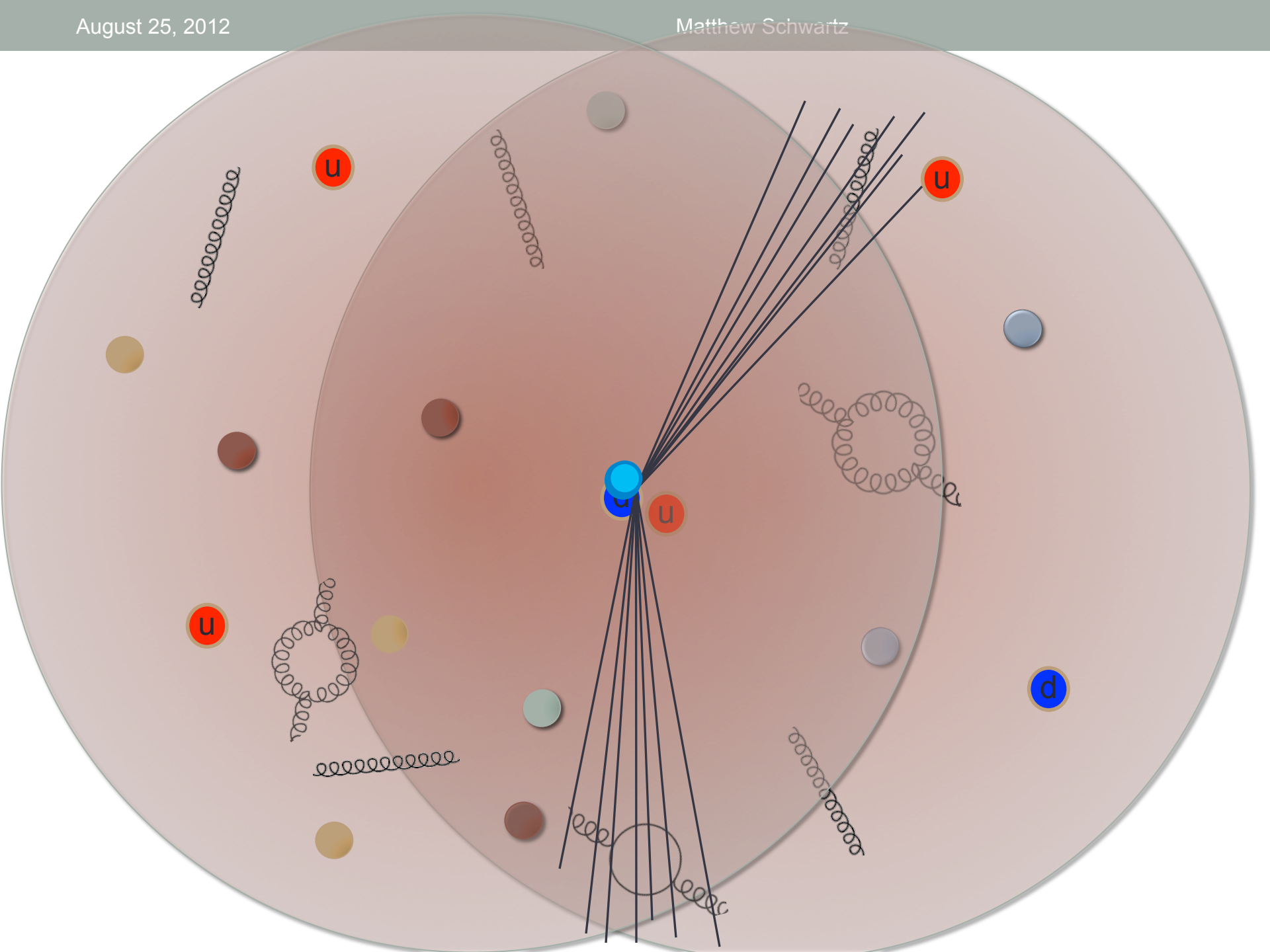
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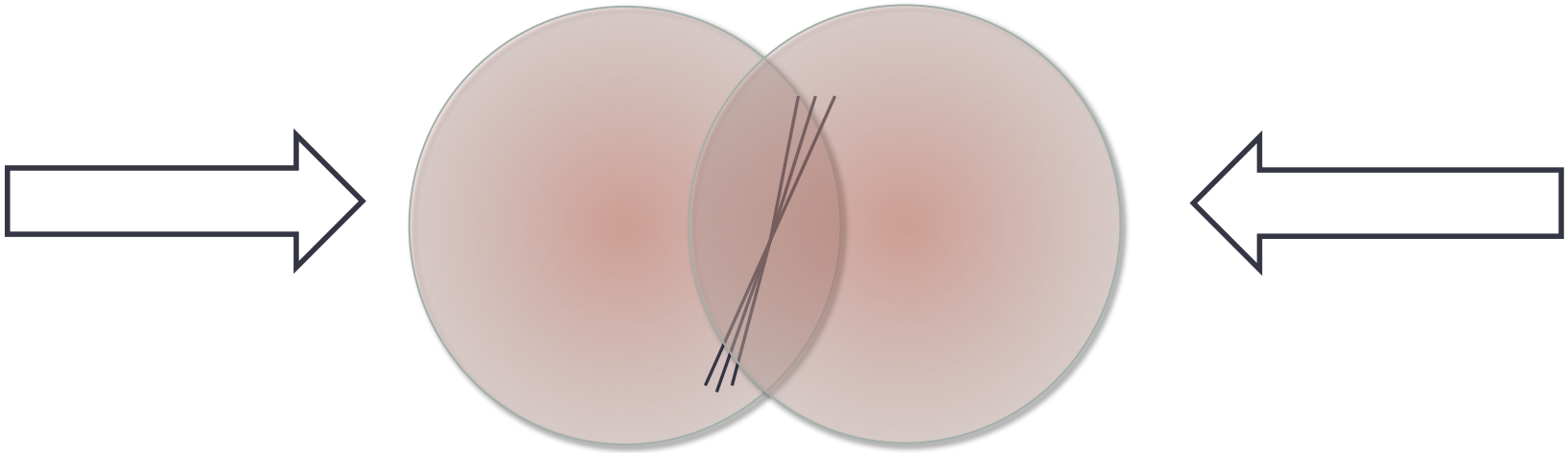
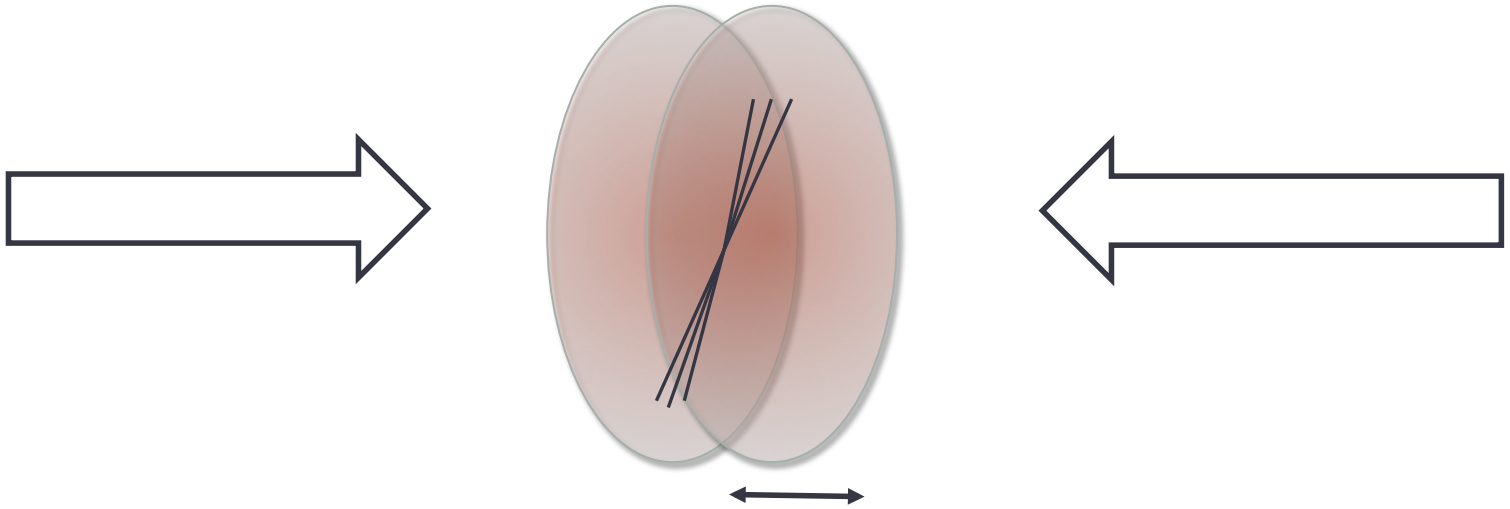
Special relativity



Special relativity



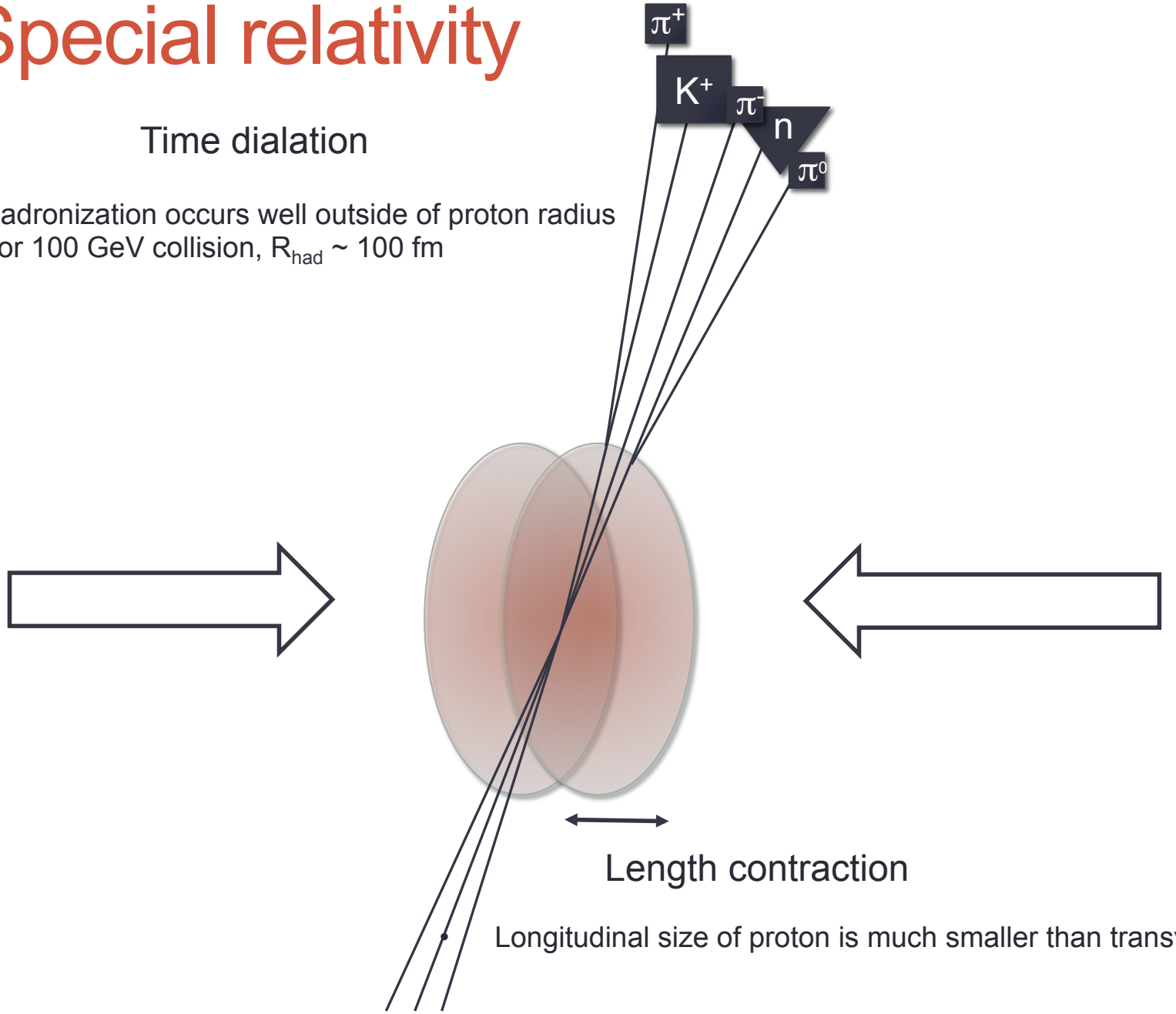
Length contraction

- Longitudinal size of proton is much smaller than transverse size

Special relativity

Time dialation

- Hadronization occurs well outside of proton radius
- For 100 GeV collision, R_{had} ~ 100 fm



Length contraction

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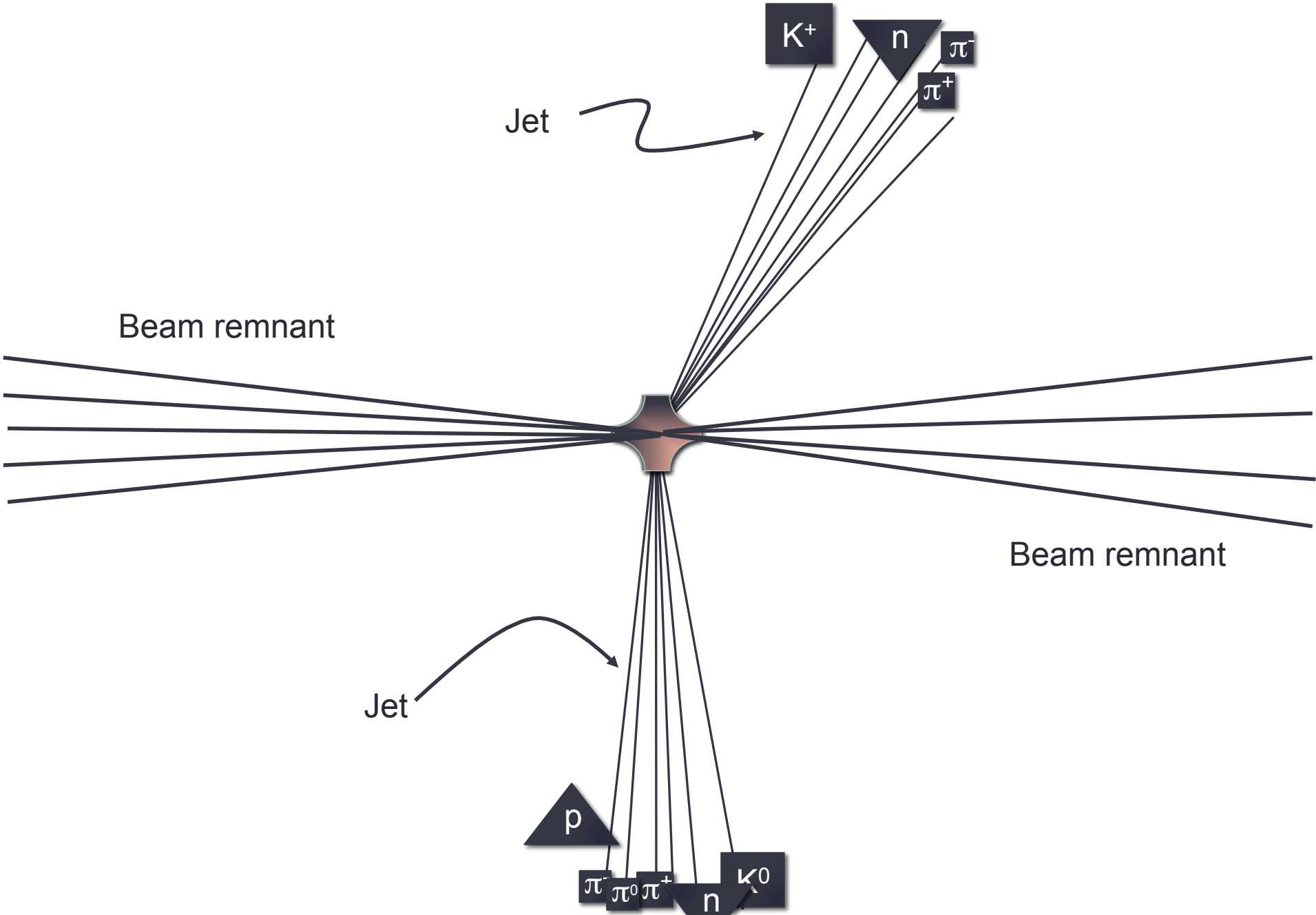
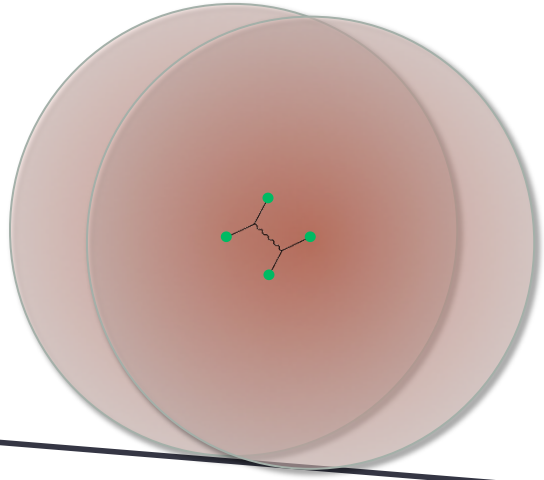
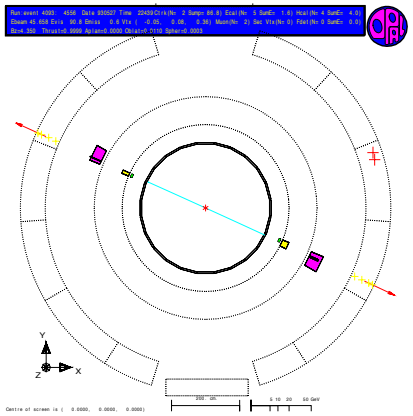

K+
n
π-
π+
Jet
Beam remnant
Beam remnant
Jet
p
π-
π0
π+
n
K0

at **short distances**

QCD is like QED

- Electrons in, electrons out

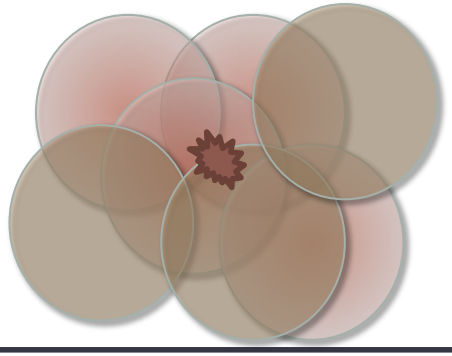


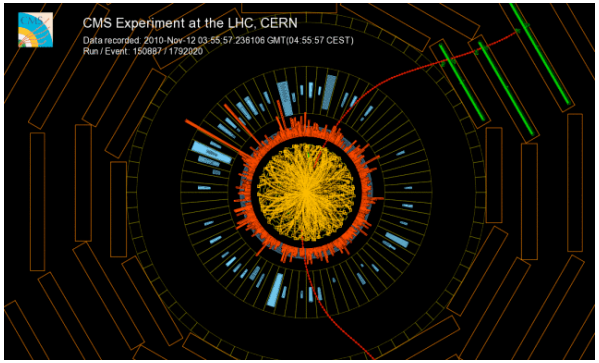


OPAL $e^+e^- \rightarrow \mu^+\mu^-$ event

at **long distances** QCD is a mess

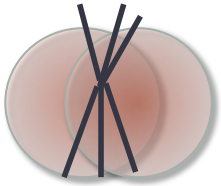
- Nuclei in, hadrons out

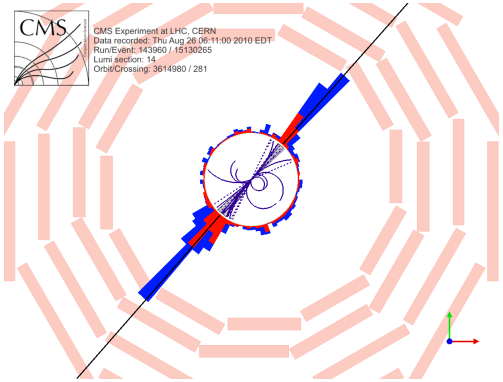




CMS
Heavy ion event

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
   Hadrons leave the proton and
   do not interact strongly until detected → Hadronization

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

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]

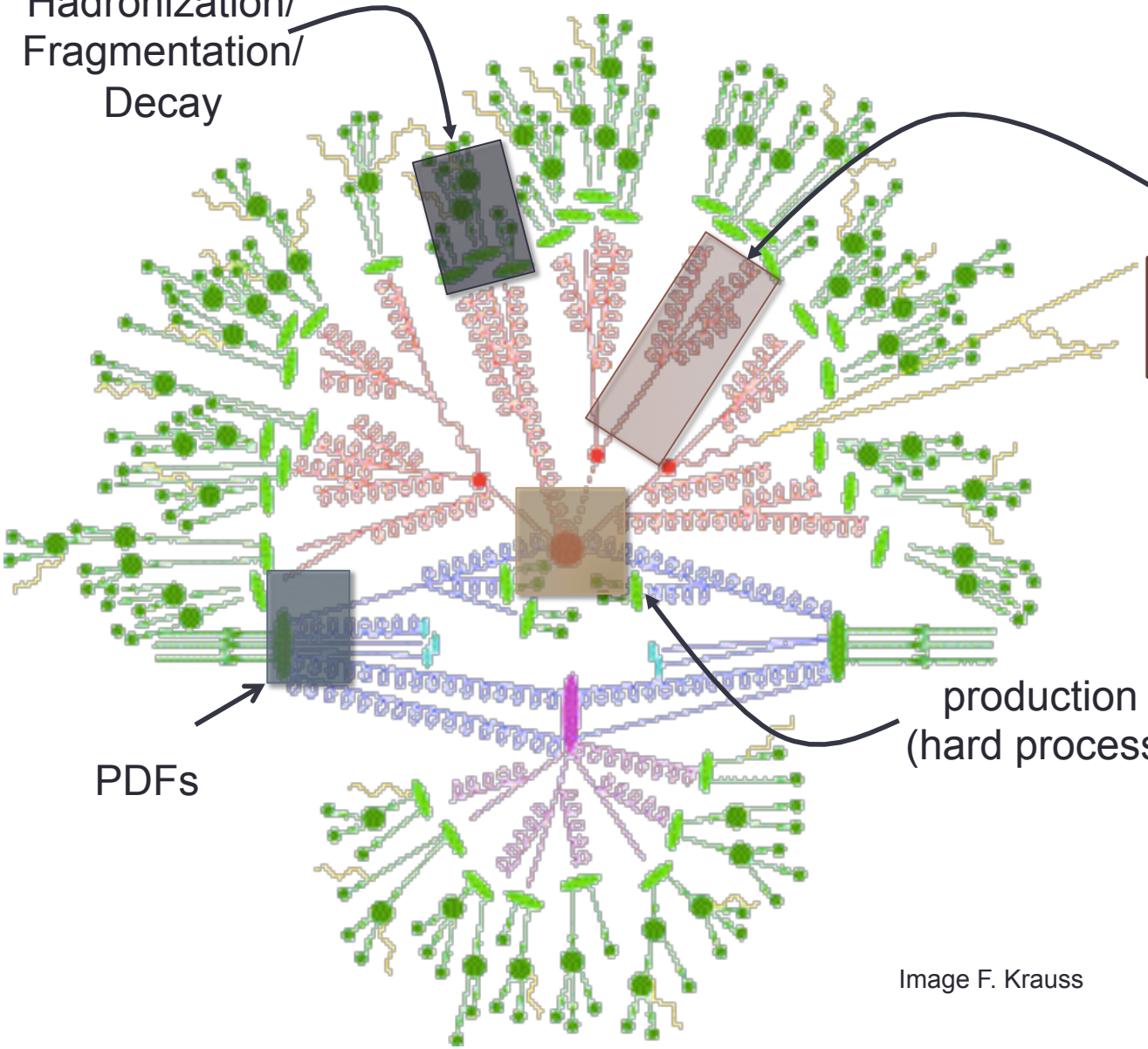
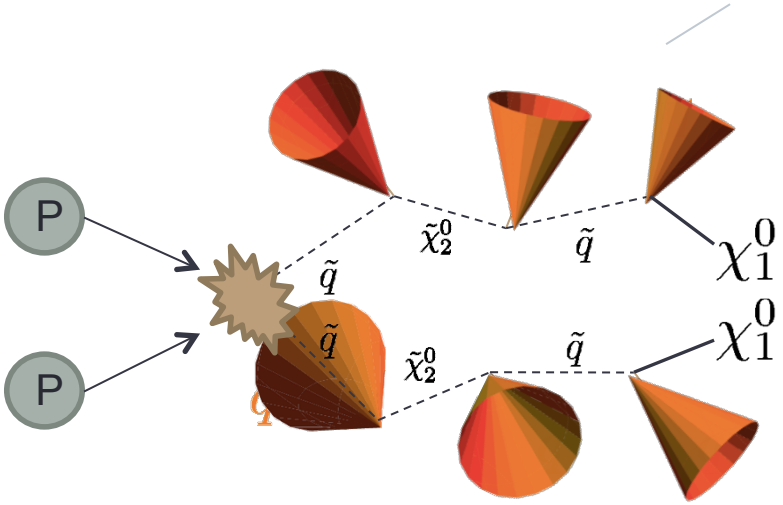


Image F. Krauss

Factorization

- Partons produced at short distances



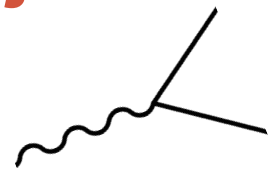
6 Jets

- Radiation and hadronization cannot change parton momentum by much

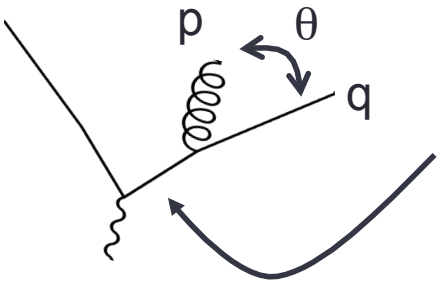
Short distance physics
imprinted on **jets**!

JETS FROM PERTBUATIVE QCD

Why jets?



Leading order: R=0, Energy = E



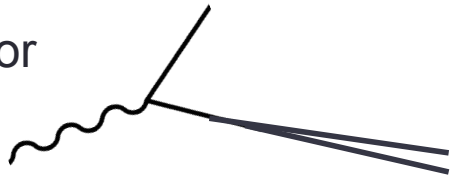
Propagator factor: $\frac{1}{(p+q)^2} = \frac{1}{2p\cdot q} = \frac{1}{E_p E_q(1-\cos\theta)} = \frac{1}{2E_q E_p \sin^2\frac{\theta}{2}}$

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

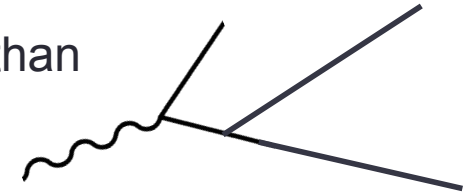
$$d\sigma \sim \alpha_s \int_0^R \frac{\mathrm{d}\theta}{\theta}\frac{\mathrm{d}E}{E} \sim \alpha_s \ln R \ln E$$

Sudakov double logartihms

Rate for

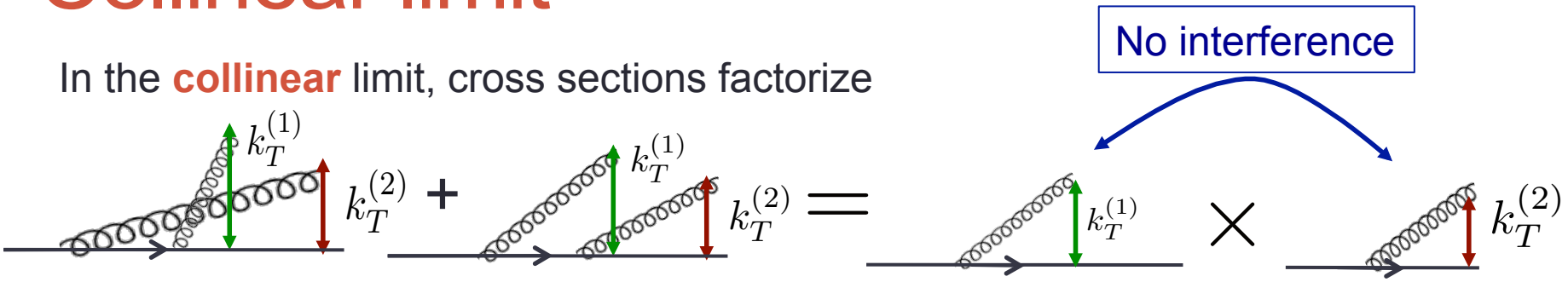


much greater than



Collinear limit

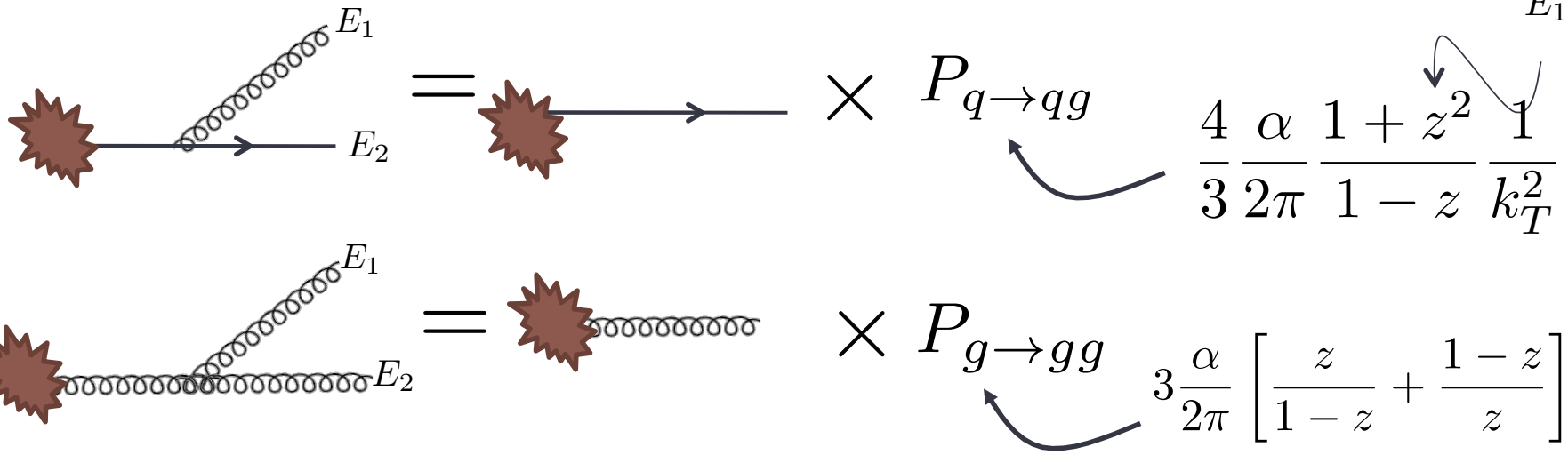
In the **collinear** limit, cross sections factorize



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

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

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

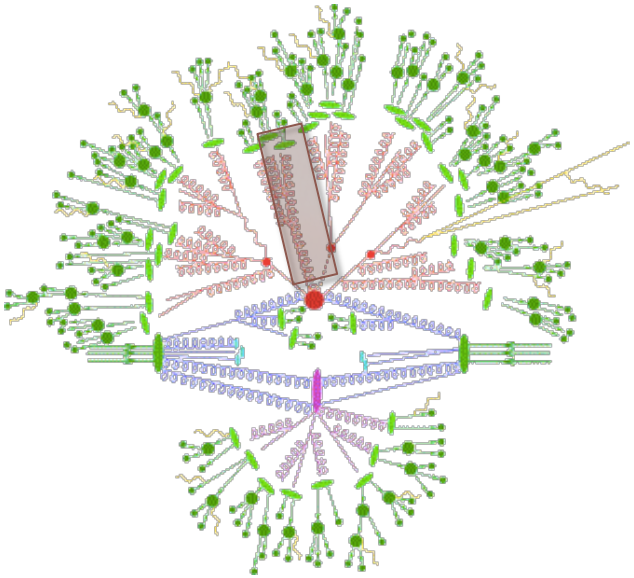


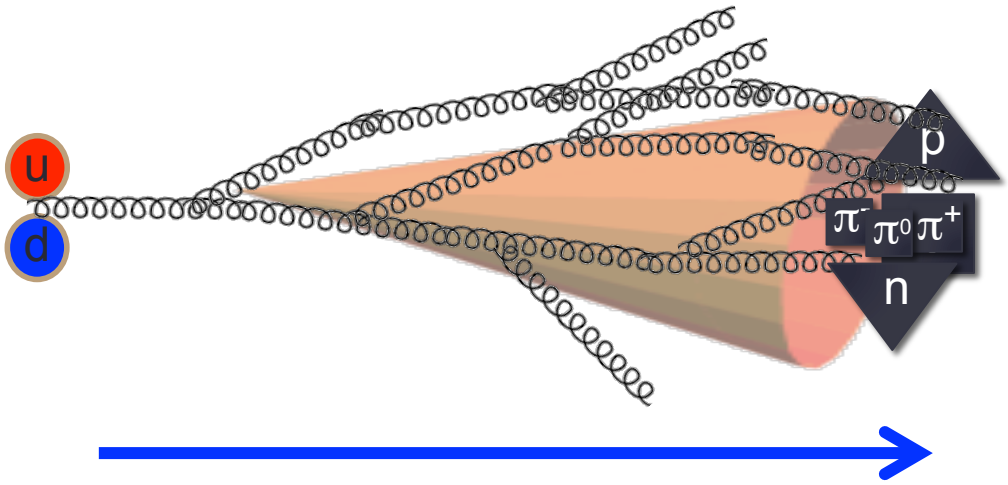
Parton shower

Probability of finding a gluon with energy fraction z and transverse momentum k_T

$$\mathrm{d}P = \frac{4}{3}\frac{\alpha}{2\pi}\frac{1+z^2}{1-z}\frac{1}{k_T^2}\,\mathrm{d}k_T^2\,\mathrm{d}z$$

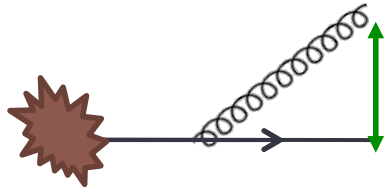
- Start with the largest scale ($k_T \sim Q$)
- Is there an emission?
- If not, try lower scales.





Parton "evolves" from hard scale to Λ_{QCD}

Sudakov factors



$t \sim k_T^2$ ~ invariant mass

$$d\sigma = \frac{\alpha}{2\pi}\frac{1}{t}\frac{1+z^2}{1-z}dt\,dz$$

Probability of finding a gluon with energy fraction z and transverse momentum $t \sim k_T^2$

Integrate over z

$$d\sigma = P(t)dt = C_F\frac{\alpha_s}{2\pi}\frac{1}{t}\left(\ln\frac{t}{Q^2}+\frac{3}{2}\right)$$

Probability of finding a gluon at this t

What is the scale for the hardest gluon?
- Should correspond to scale of the second hardest jet

Sudakov factor $\Delta(t_0,t)$ is the probabilty of finding no gluons between t_0 at t

$$\Delta(t_0,t+\delta t) = \Delta(t_0,t)\left(1-\int_t^{t+\delta t} dt'\,P(t')\right) = \Delta(t_0,t) - P(x)\delta x\Delta(t_0,t)$$

$$\Delta(t_0,t+\delta t) = \Delta(t_0,t) + \delta x\frac{d}{dx}\Delta(t_0,t)$$

$$\Rightarrow \frac{d}{dx}\Delta(t_0,t) = -P(t)\Delta(t_0,t)$$

Thus, $\Delta(t_0,t) = \exp\left(-\int_t^{t_0} P(t')dt'\right) \sim \exp\left[-\frac{2\alpha_s}{3\pi}\left(\ln^2\frac{t}{Q}+\frac{3}{2}\ln\frac{t}{Q}\right)\right]$

And so, the cross section for the hardest gluon is

$$d\sigma = \Delta(Q,t)P(t)dt \approx e^{-\frac{2\alpha_s}{3\pi}\ln^2\frac{t}{Q}}\frac{dt}{t}$$

Sudakov factor
= semi-classical resummation
of the leading Sudakov logarithm

Parton shower

- Probability of emission at some t

$$d\sigma = P(t)dt = C_F \frac{\alpha_s}{2\pi}\frac{1}{t}\left(\ln\frac{t}{Q^2}+\frac{3}{2}\right)$$

Probability that hardest emission is at t

$$d\sigma = \Delta(Q,t)P(t)dt \approx \underbrace{e^{-\frac{2\alpha_s}{3\pi}\ln^2\frac{t}{Q}}}\frac{dt}{t}$$

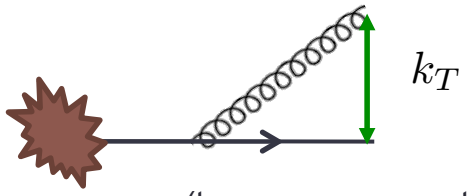
Leading log resummation

- Agrees with cross section for hardest parton in QCD including leading log resummation

$$k_T^2 = tz(1-z) \Longrightarrow \frac{\mathrm{d}k_T^2}{k_T^2} = \frac{\mathrm{d}t}{t}$$

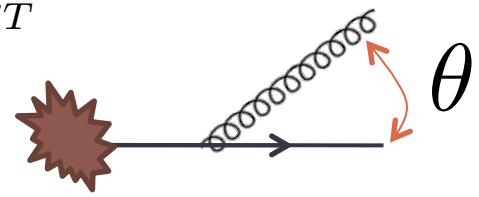
- Formally correct at this order for many scale choices

$$\mathrm{d}\sigma \approx e^{-\frac{2\alpha_s}{3\pi}\ln^2\frac{k_T^2}{Q^2}}\frac{\mathrm{d}k_T^2}{k_T^2}$$



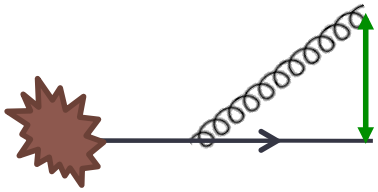
(transverse momentum)

$$\mathrm{d}\sigma \approx e^{-\frac{2\alpha_s}{3\pi}\ln^2\theta}\frac{\mathrm{d}\theta}{\theta}$$



(angle)

$$\mathrm{d}\sigma \approx e^{-\frac{2\alpha_s}{3\pi}\ln^2\frac{t}{Q^2}}\frac{\mathrm{d}t}{t}$$



(invariant mass)

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

Parton shower

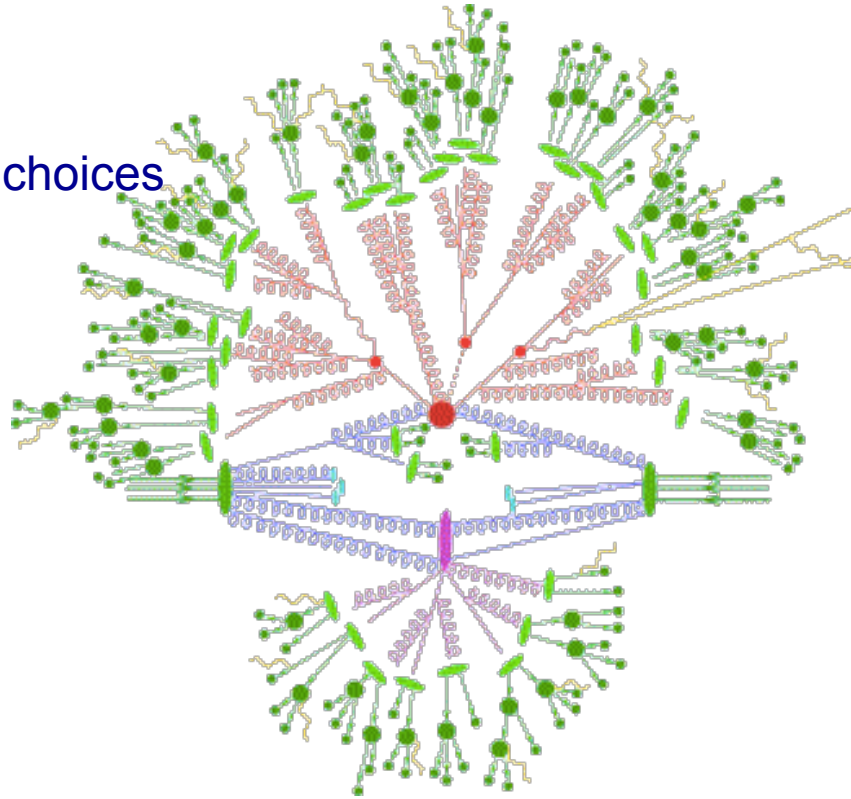
- Semi-classical model which agrees with perturbative QCD in collinear limit at leading-logartihmic level

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

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

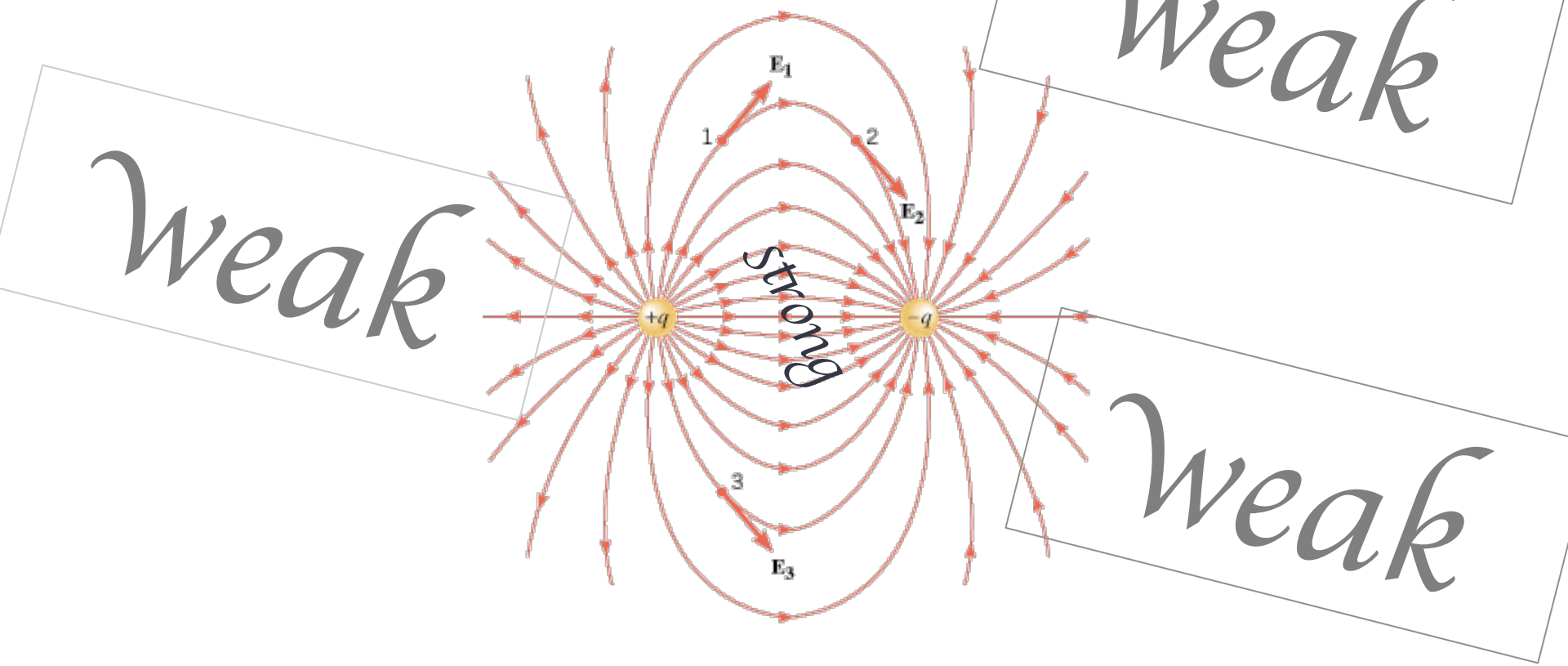
DGLAP splitting functions

- Formally correct at this order for many scale choices
- Common scale choices motivated by **soft physics**



Soft limit

QED dipole

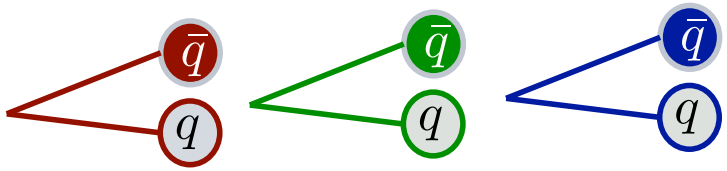


- In soft limit (large distance limit), field from + and – charges cancel
- Coherent destructive **interferece**

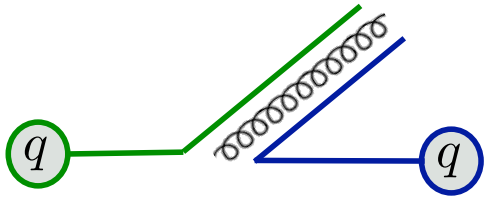
Soft limit

QCD

3 quark color dipoles

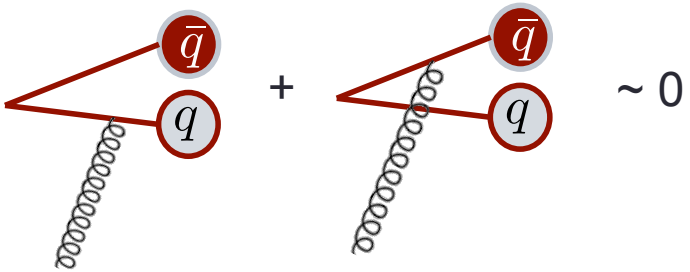


Gluons act like ends of 2 dipoles

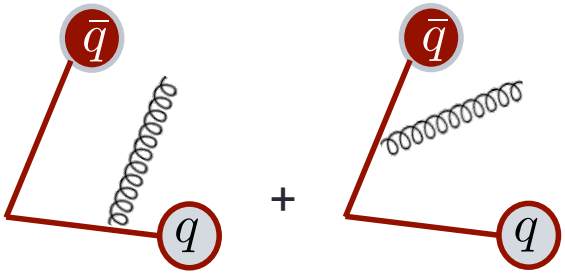


Accurate up to $1/N^2$ ~10% effects

Destructive interference



~ 0

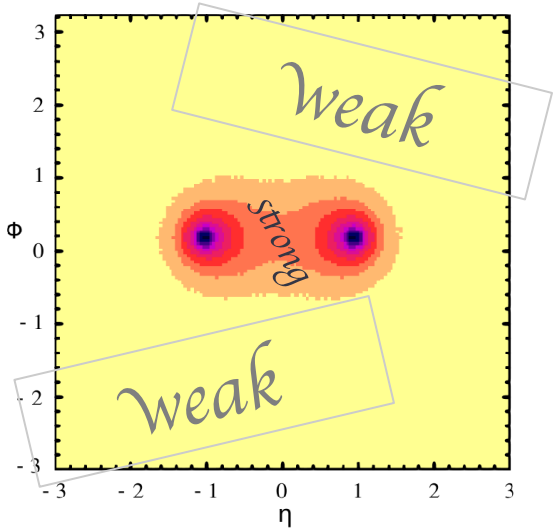


$\neq 0$

Constructive interference

Color coherence

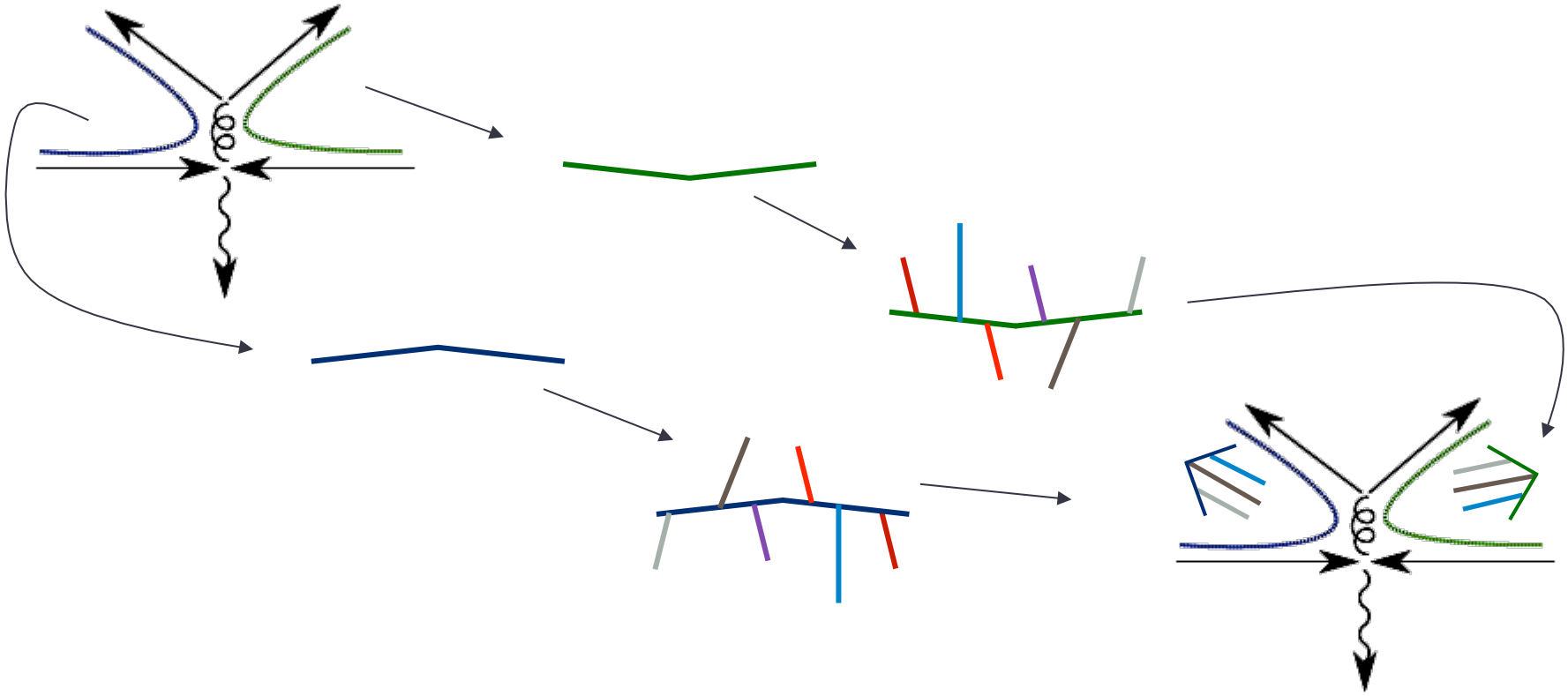
Angular ordering



Pythia simulation

Dipole shower

Dipole showers in its rest frame



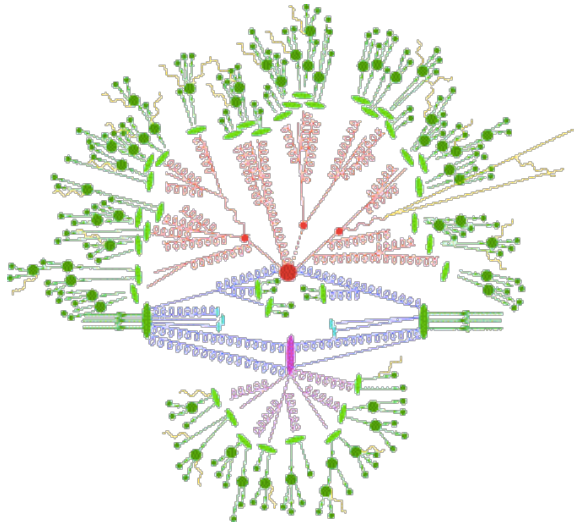
- Boost → **string showers** in **dipole-momentum** direction
- Alternative to angular ordering

Parton shower summary

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

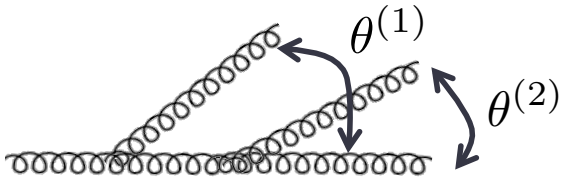
$$\begin{aligned} \mathrm{d}\sigma &\approx e^{-\int \mathrm{d}P} \mathrm{d}P \\ &\approx \underbrace{e^{-\frac{2\alpha_s}{3\pi}\ln^2\frac{\mu^2}{Q^2}}}\frac{\mathrm{d}\mu}{\mu} \end{aligned}$$

Suadkov factor
(leading log resummation)

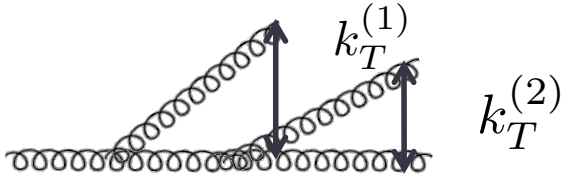


- Formally correct at **leading log** in the **collinear limit**

Herwig uses an angle ordered shower



Pythia uses a k_T ordered dipole shower

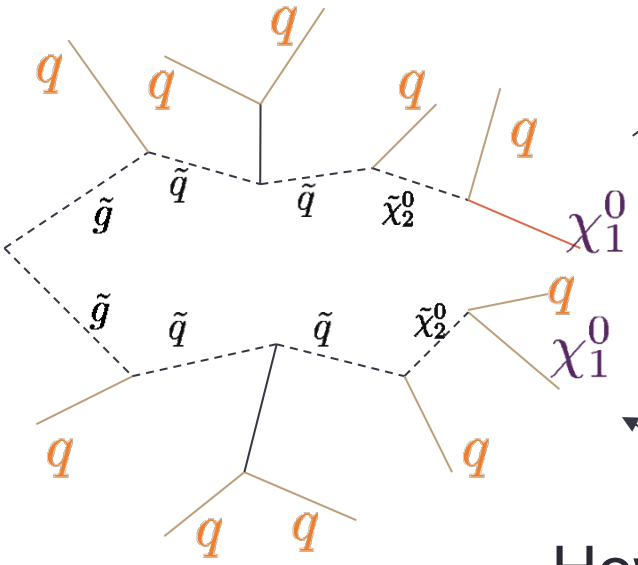


- Both incorporate **color coherence**
- Neither gets soft limit exactly right
- Parton showers give **amazingly accurate** simulations of complicated final states

JET ALGORITHMS

Jet-parton-map

We want to see quarks and gluons:



Parton shower

We observe jets:

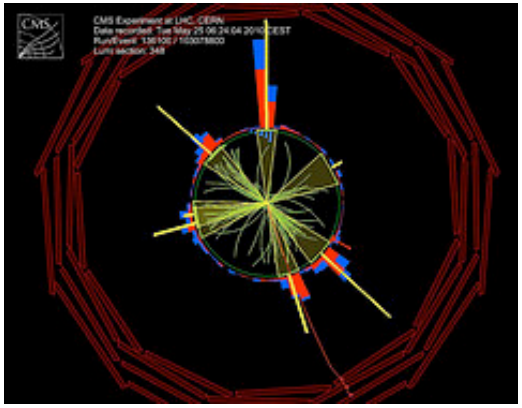
+ missing energy

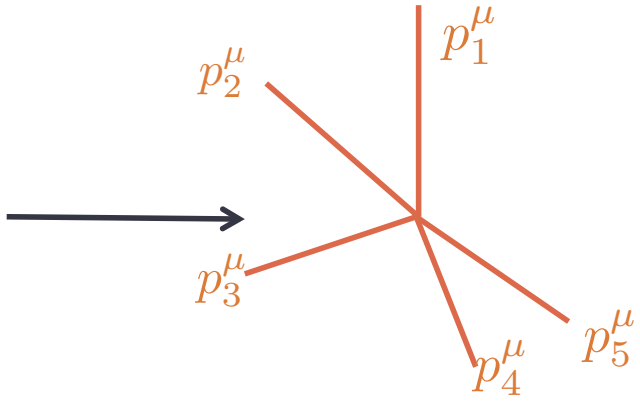
How can we **invert** ?

- 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

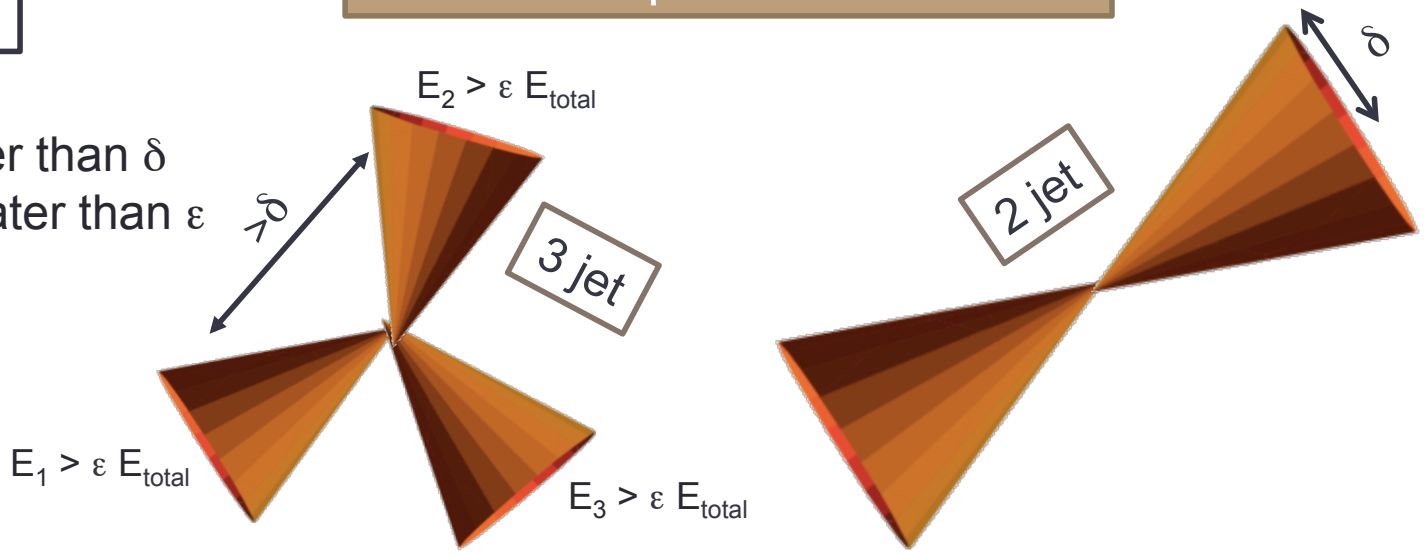
Sterman-Weinberg jets (1977)

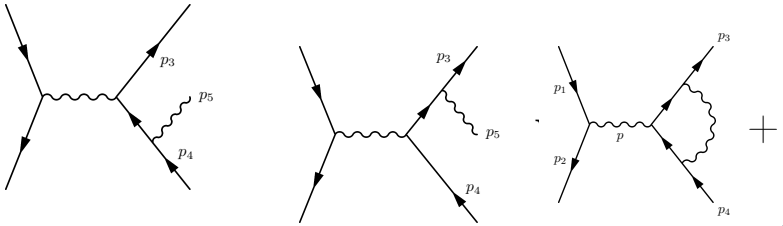
e^+e^- to 2 or 3 jets

Jets from pertubative QCD

3 jets if:

- Angles greater than δ
- Energies greater than ε





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

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

- 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	

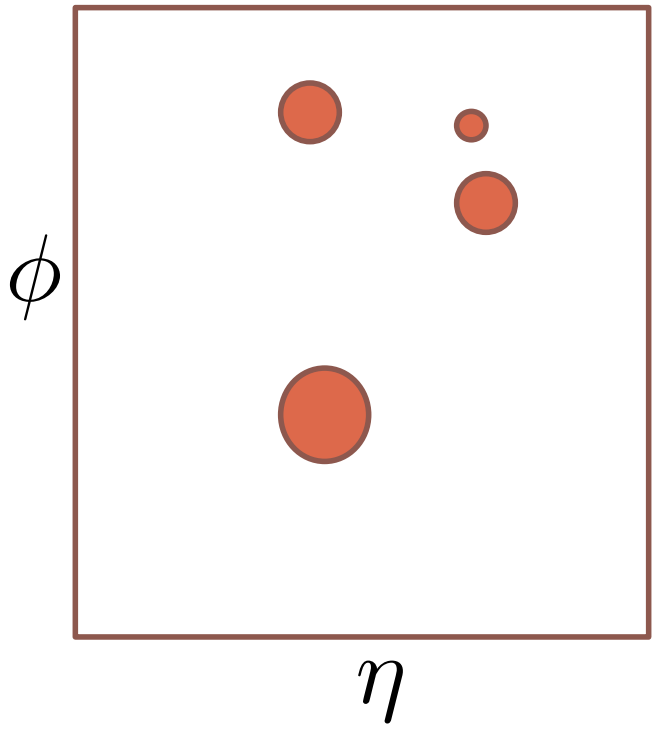
G. Salam

Iterative jet algorithms

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

- **Calculate** the pairwise distances

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



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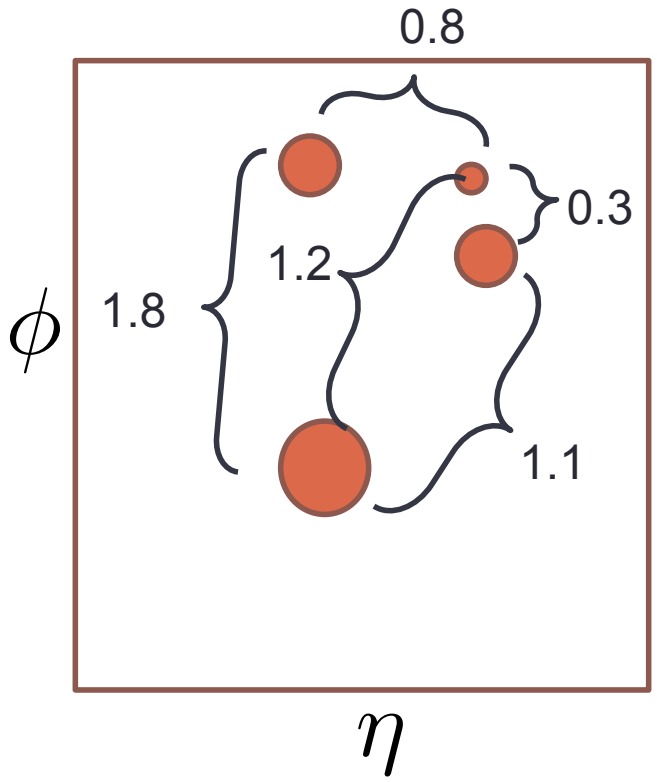
- **Merge** the two closest particles



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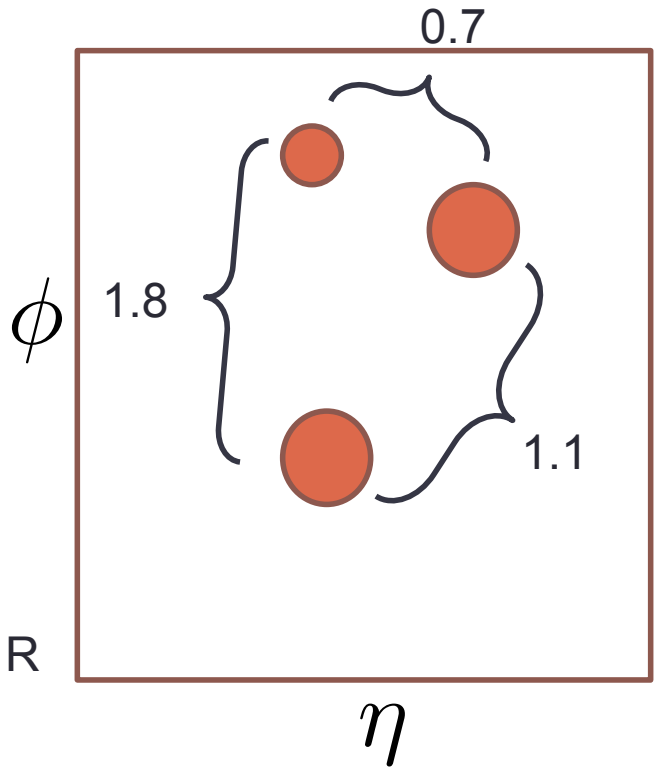
- **Calculate** the pairwise distances

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

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



Iterative jet algorithms

- Start with input 4-vectors
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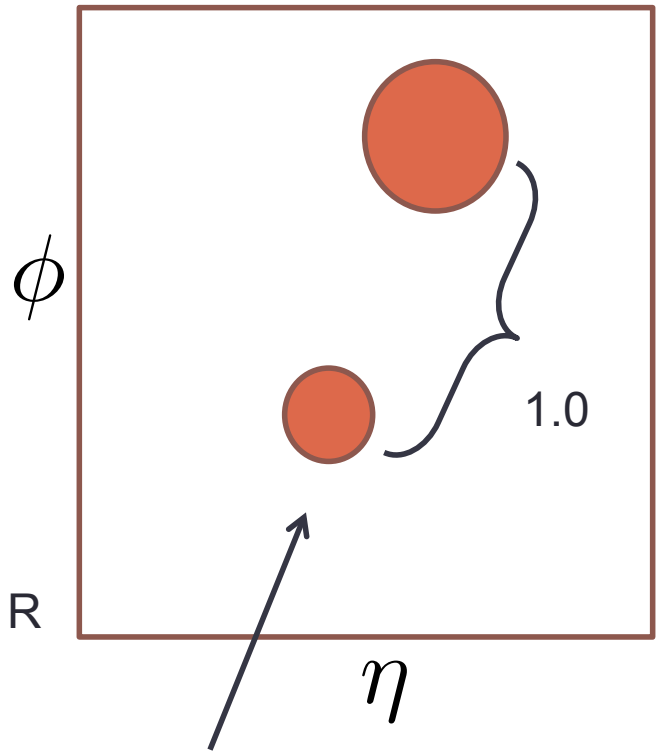
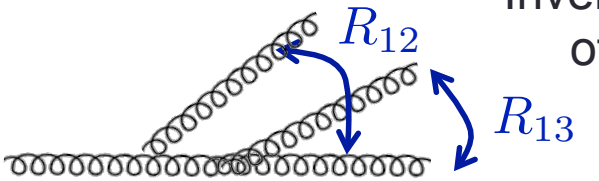


Two R=1.0 Jets

Different distance measures

Cambride/Aachen algorithm

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

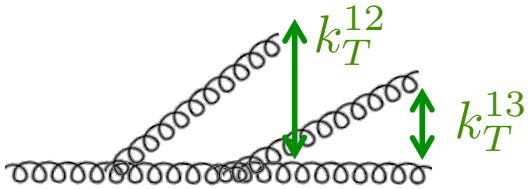


Inversion of **Herwig shower**

- clusters closest radiation first

k_T algorithm

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



Inversion of **Pythia shower**

- clusters hard collinear radiation first

anti k_T algorithm

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

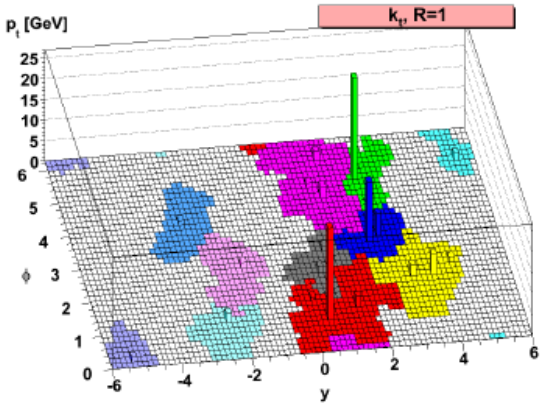
- Clusters farthest first
- No inverse parton-shower interpretation
- Produces round jets
- Almost exclusively used by ATLAS and CMS

Jet algorithms

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

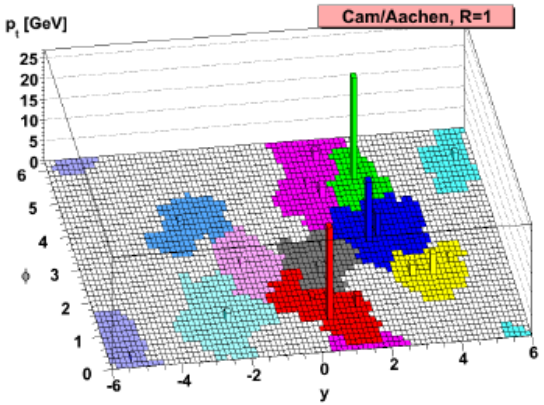
k_T

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

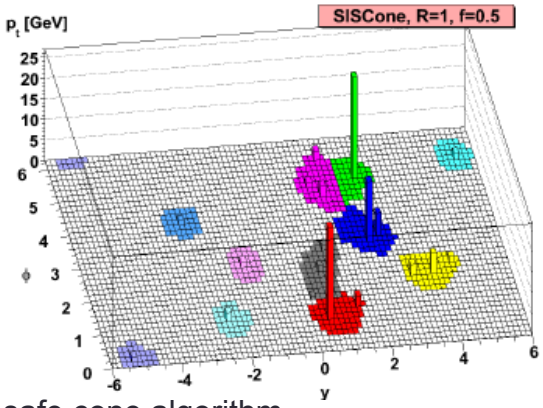


Cambridge/Aachen

- Based on angles
- Closer to cones

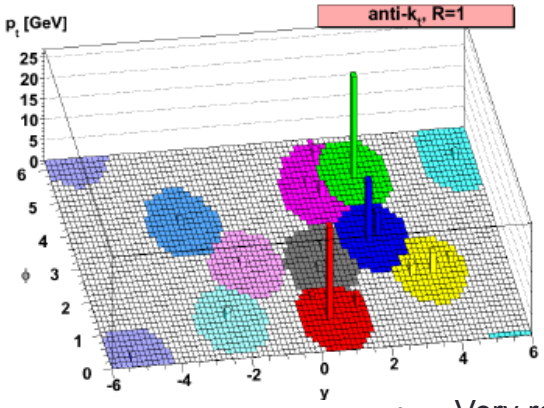


SICcone



- 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)

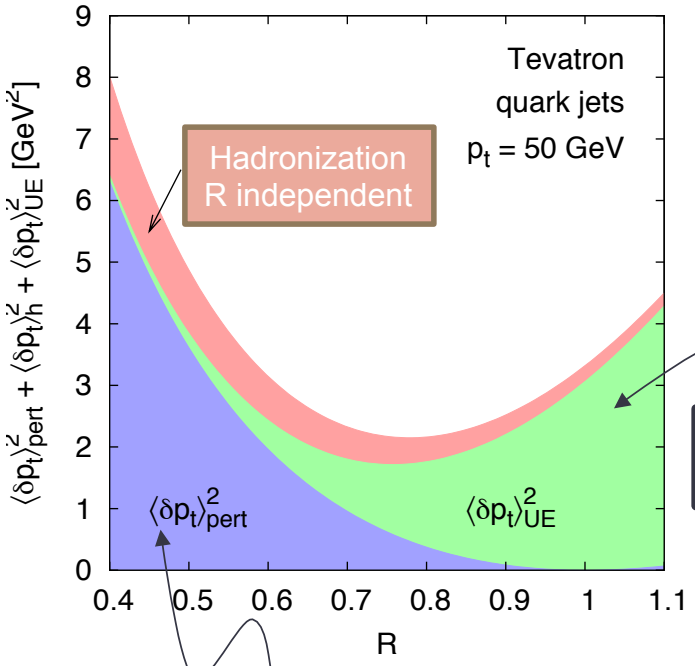
Bigger R

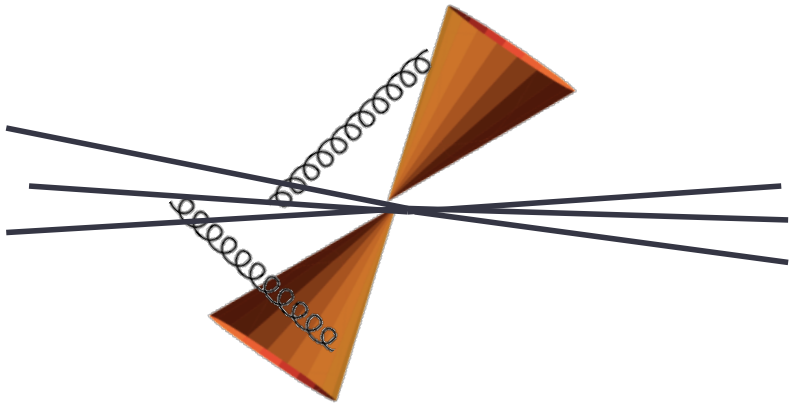
- Include little initial state radiation
- Include little pileup

Smaller R

Jet p_T versus parton p_T

From arXiv:0712.3014





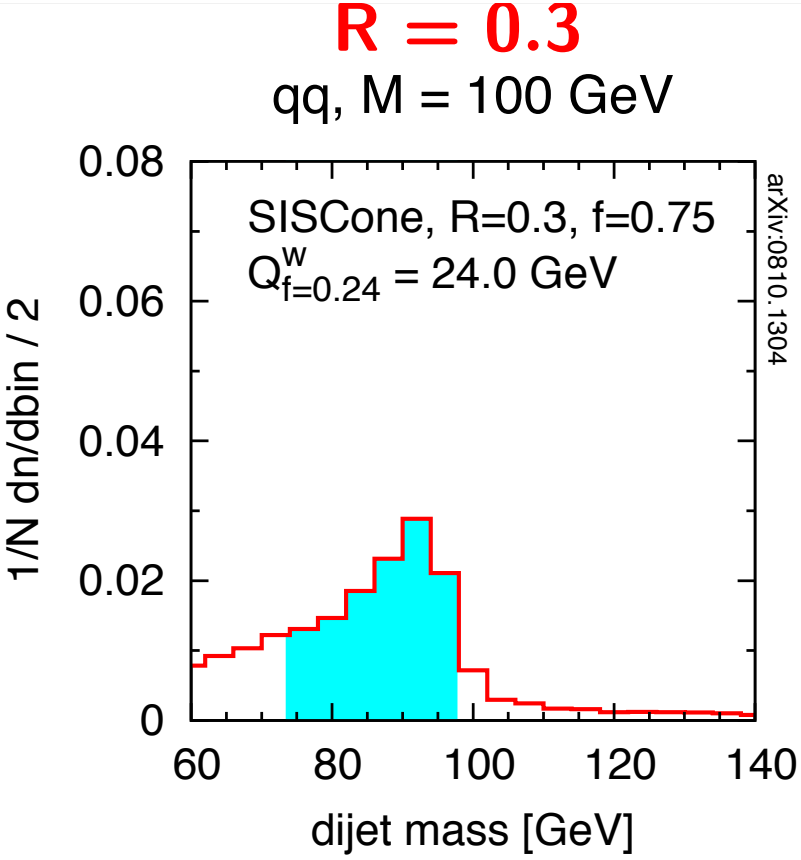
Underlying event (ISR, proton remnants)

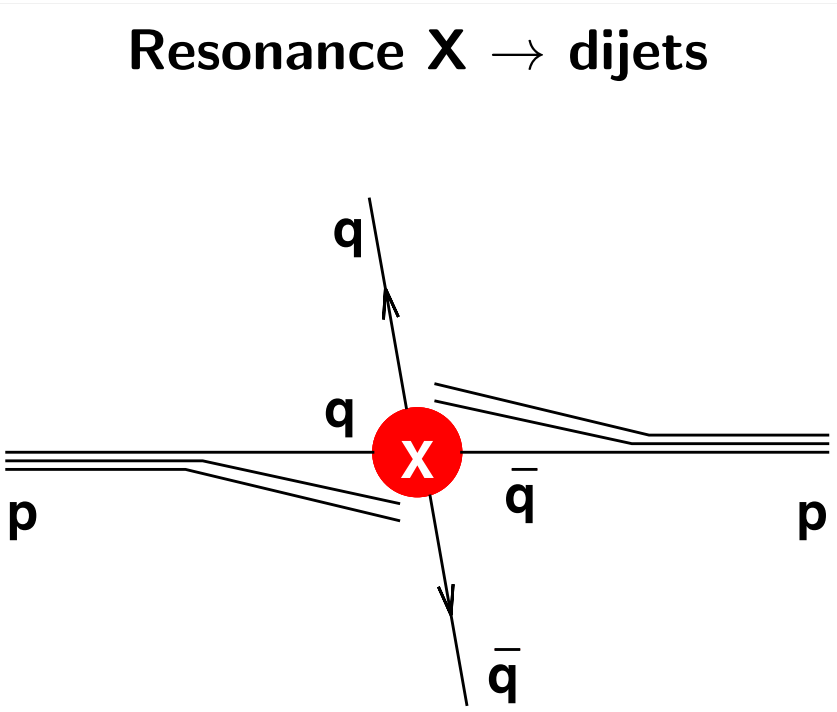
Pertubative part (FSR)

In practice

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

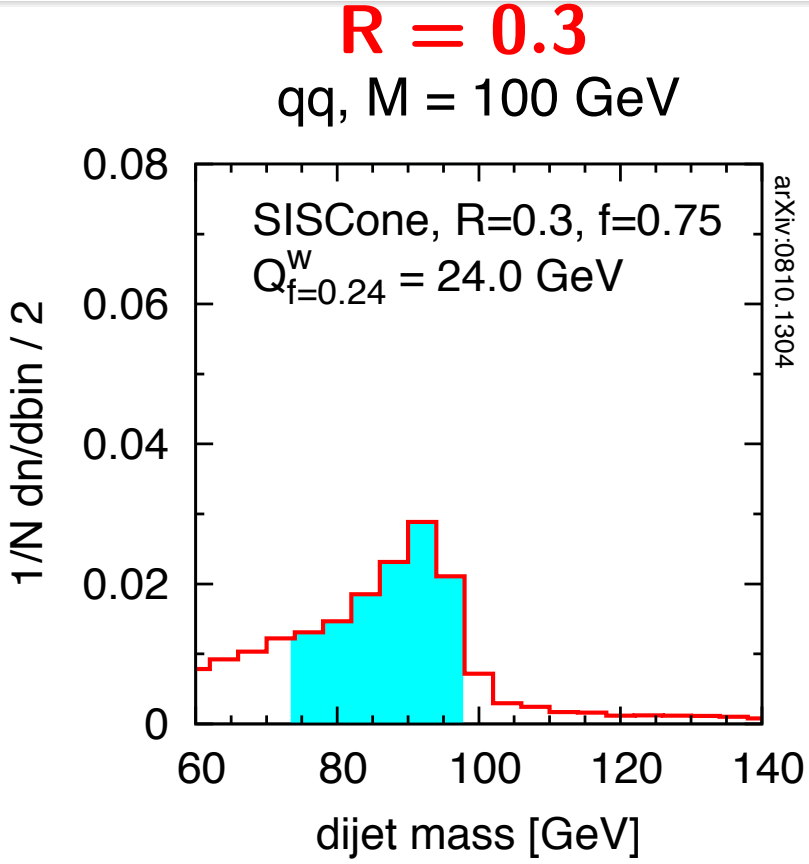
Resonance peak various R

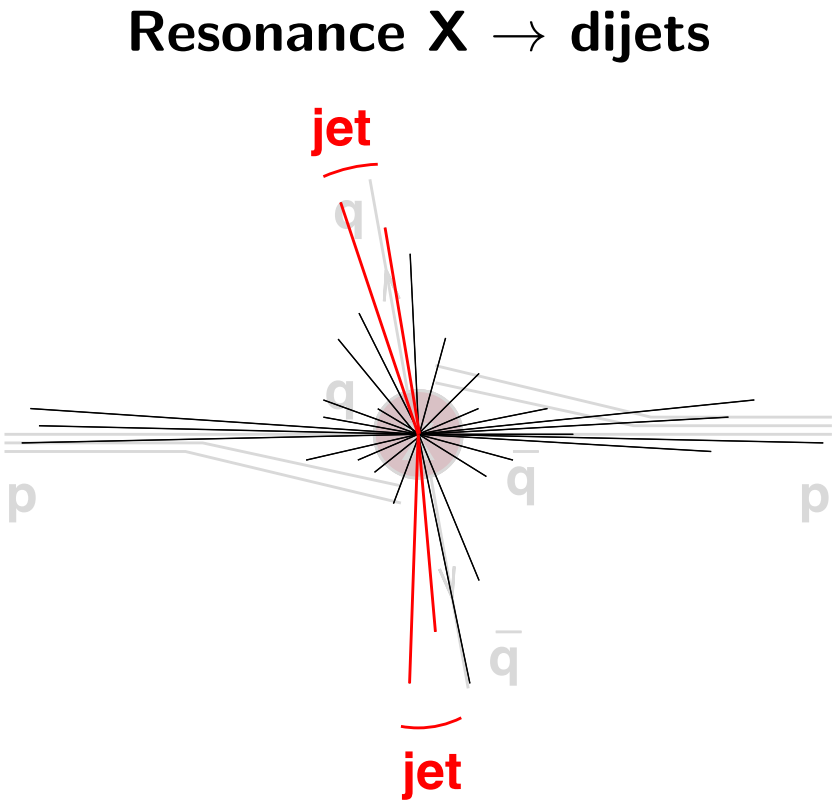




from G. Salam
http://www.lpthe.jussieu.fr/~salam/jet-quality/

Resonance peak various R





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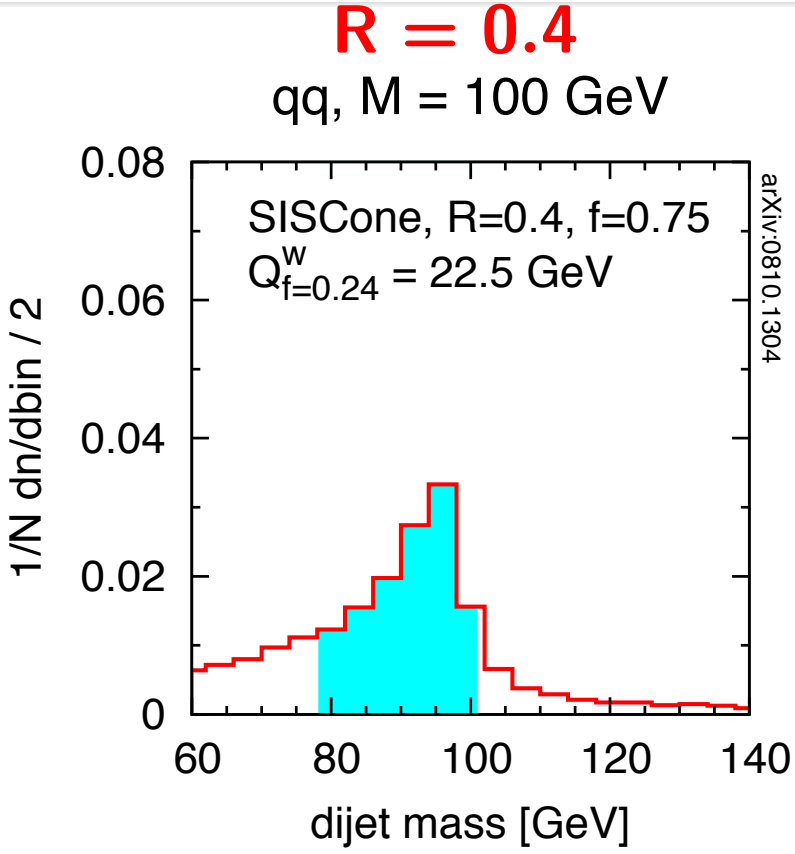
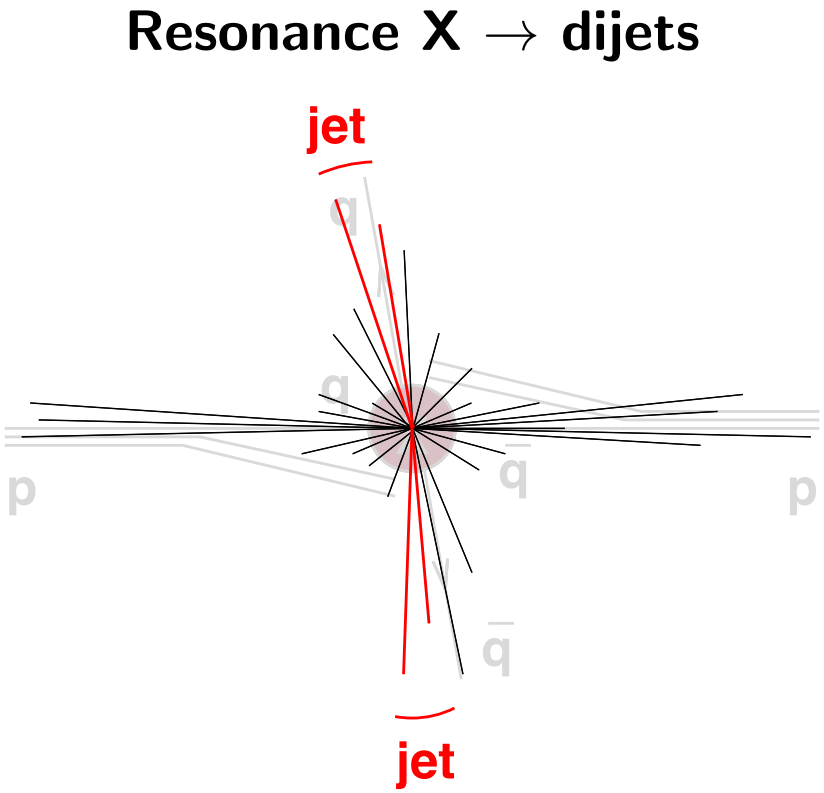
Resonance peak various R





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

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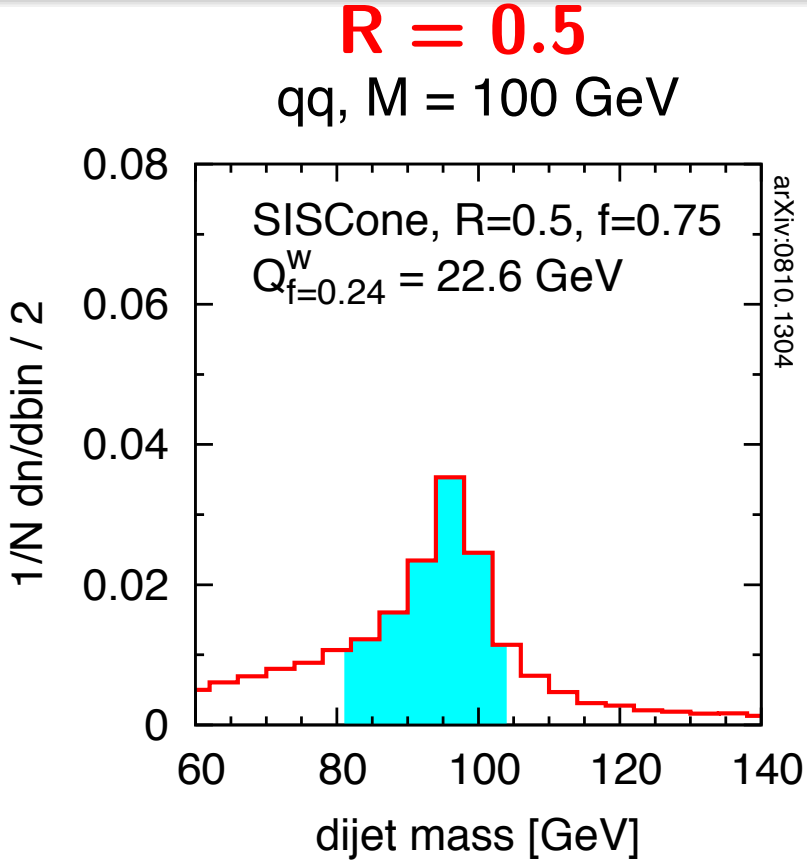

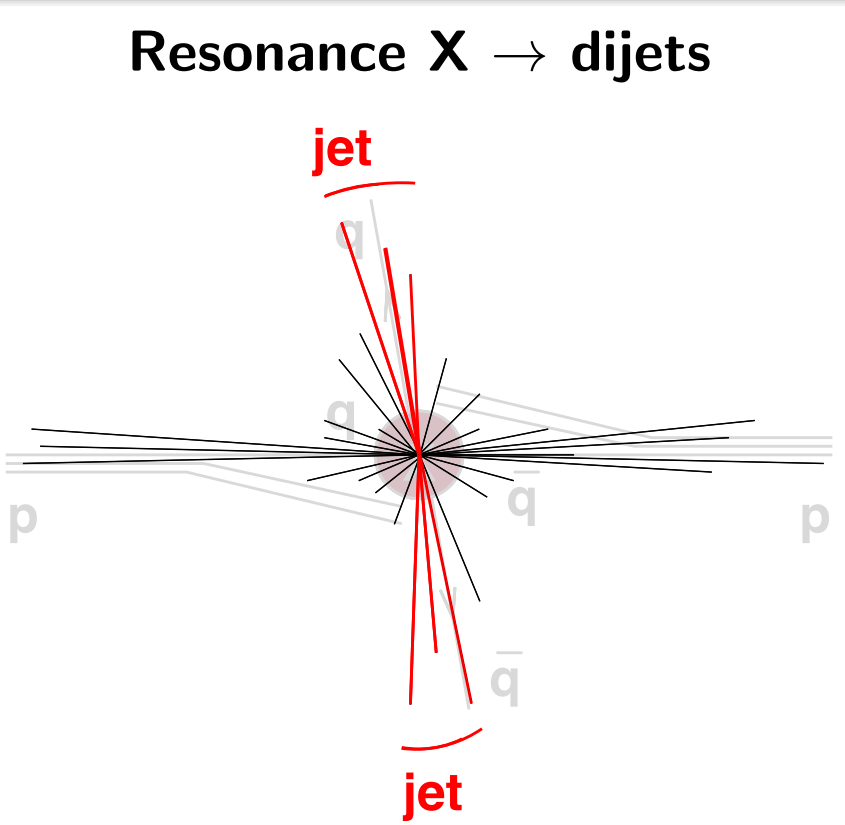

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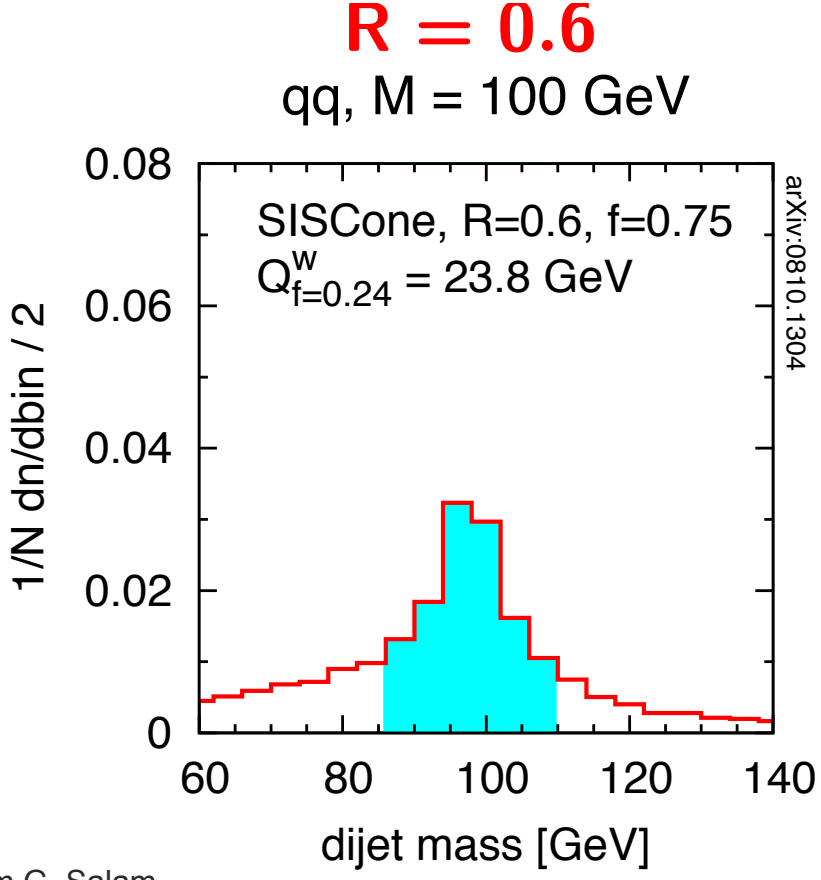

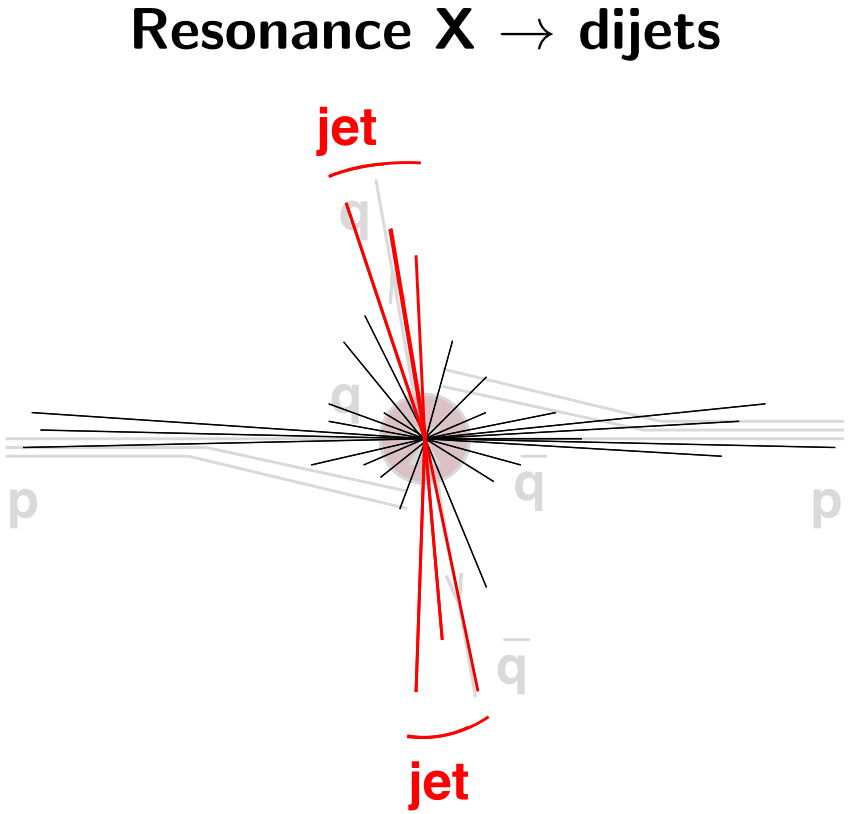

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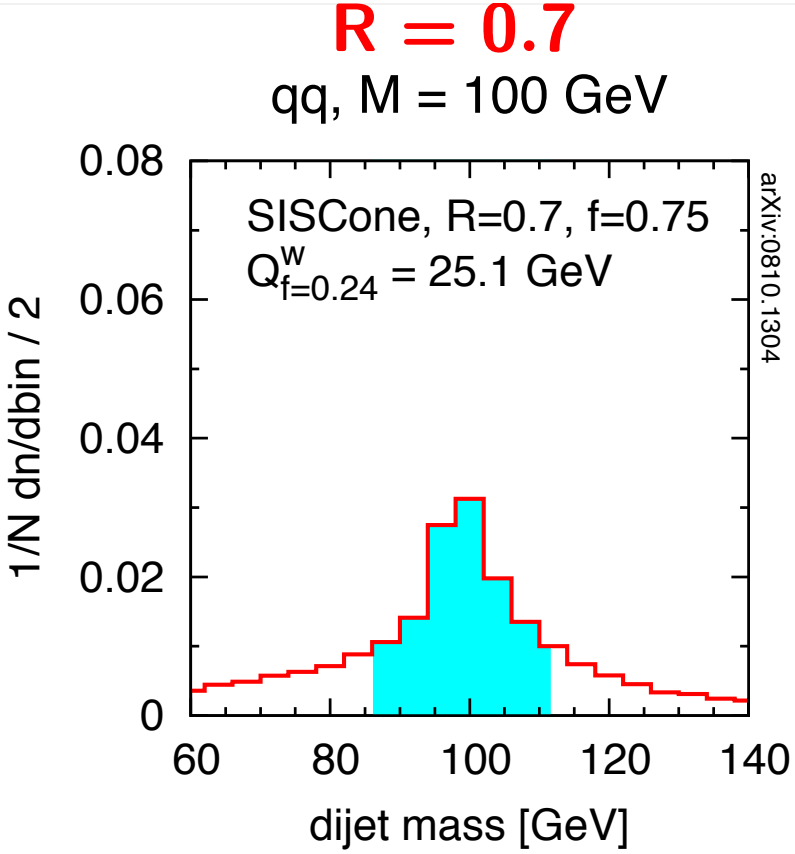

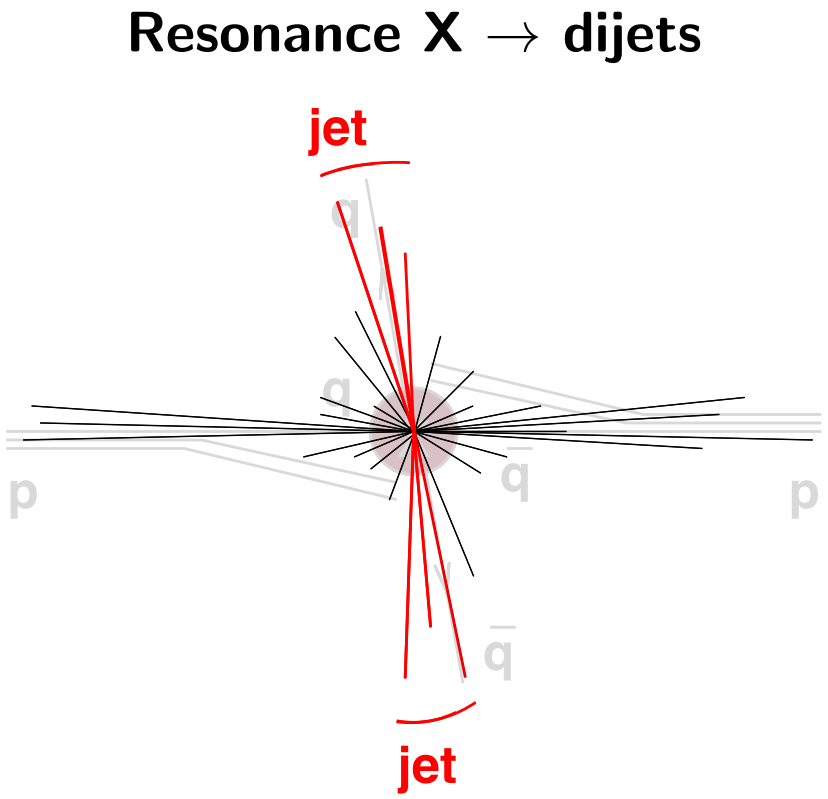

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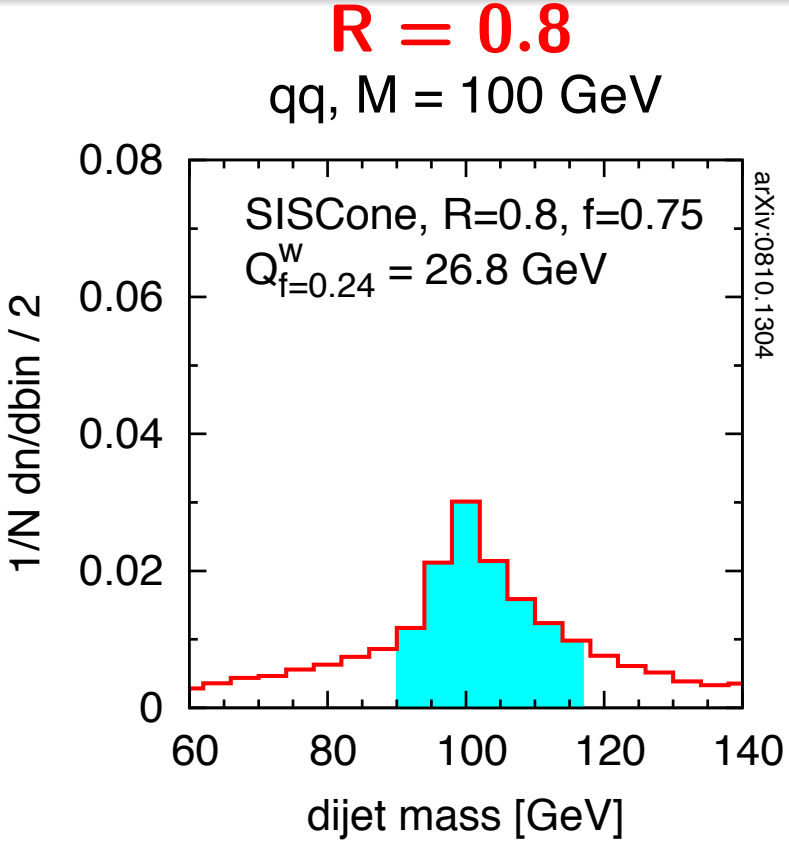

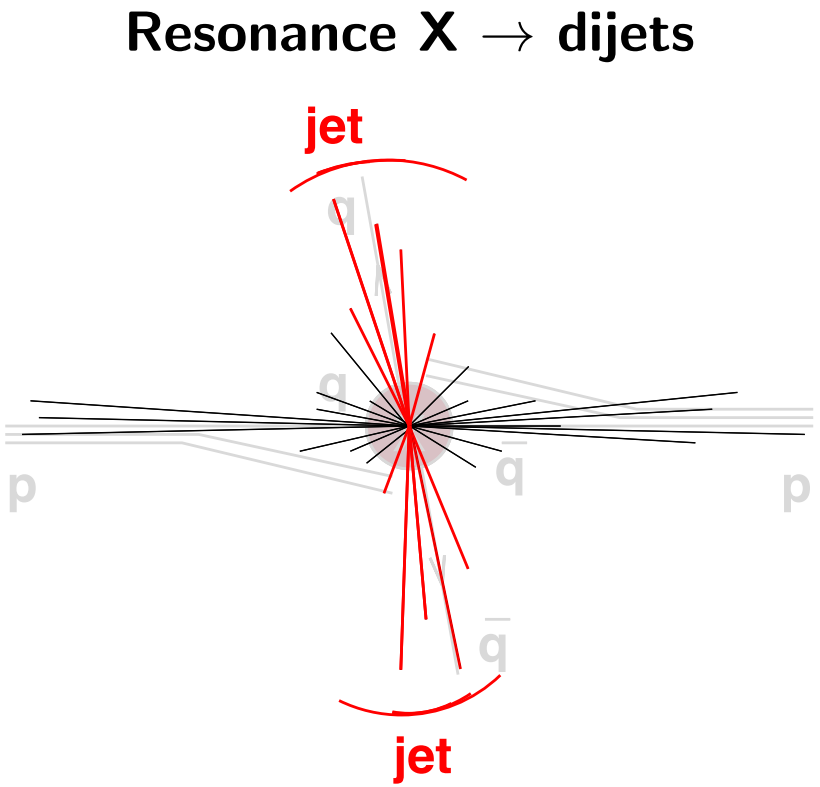

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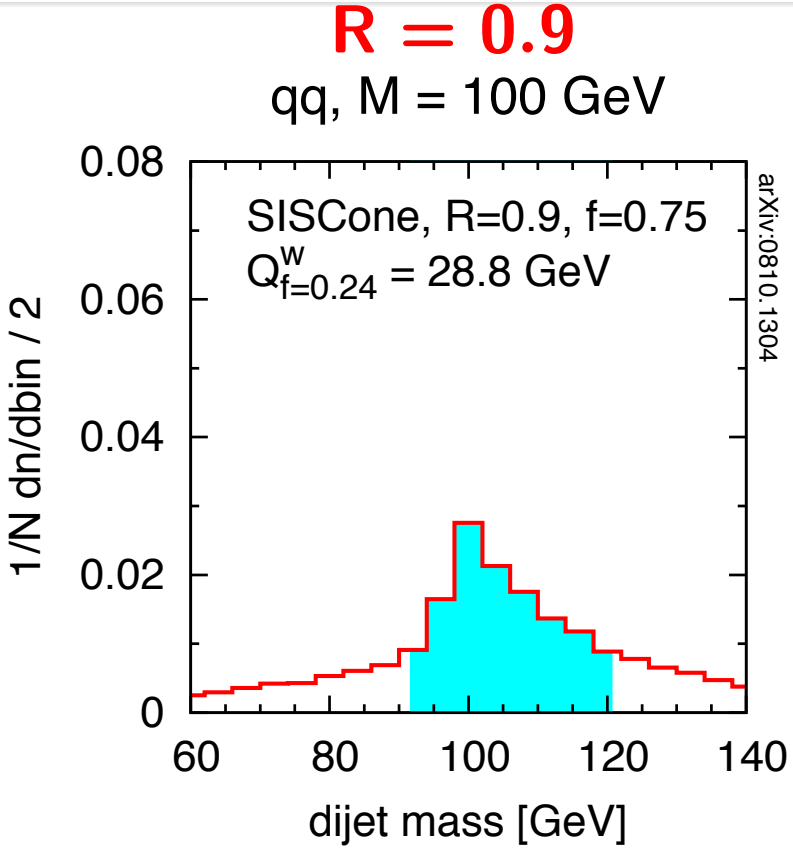

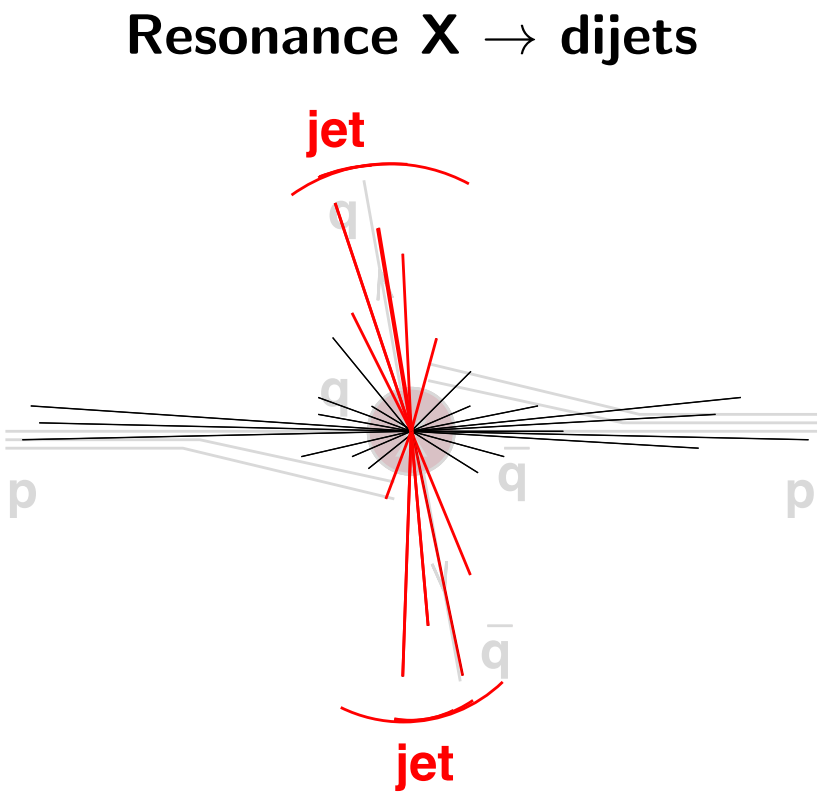

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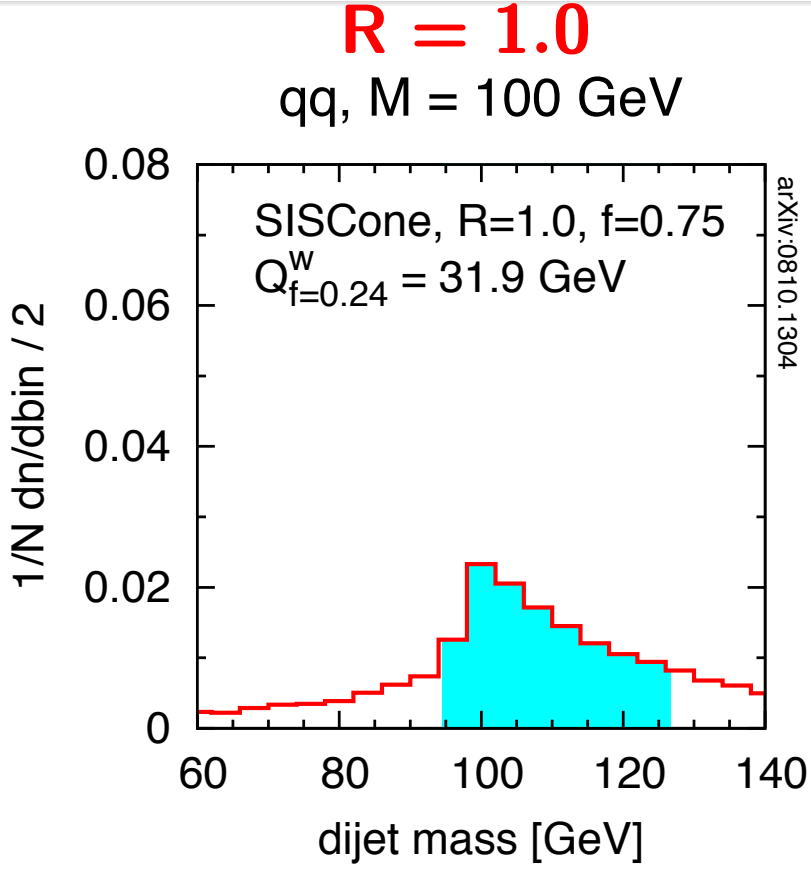

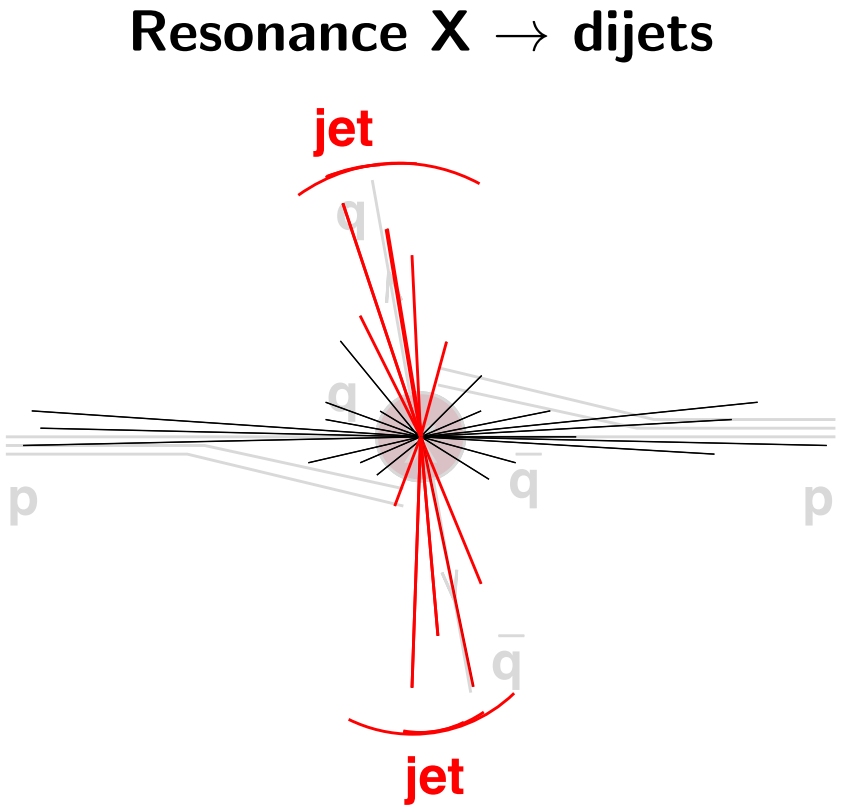

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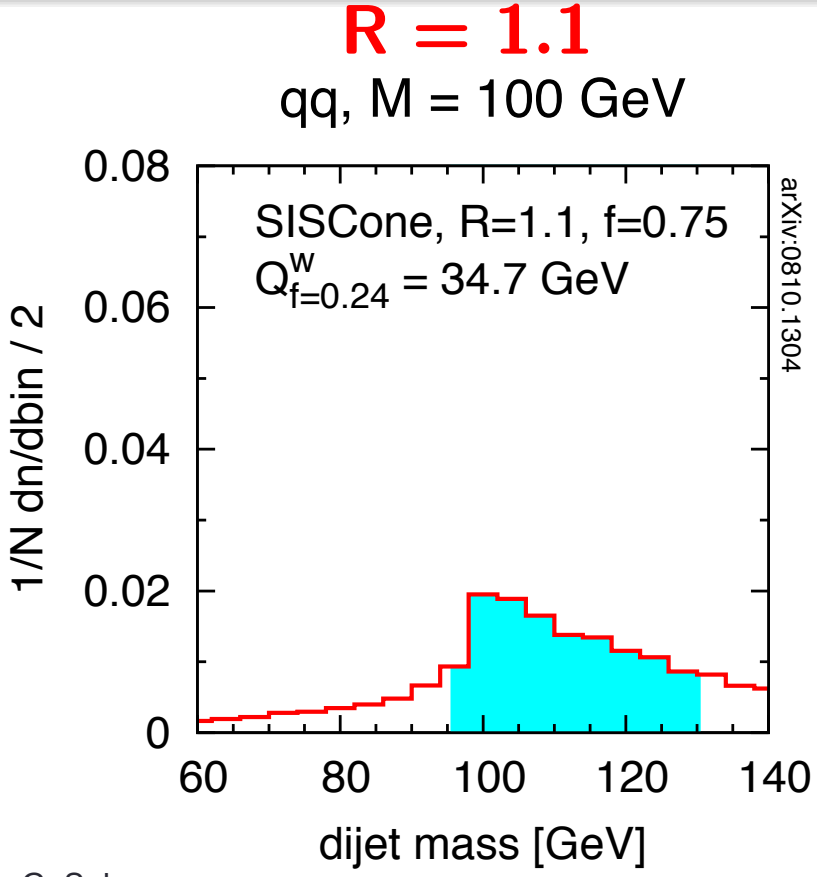

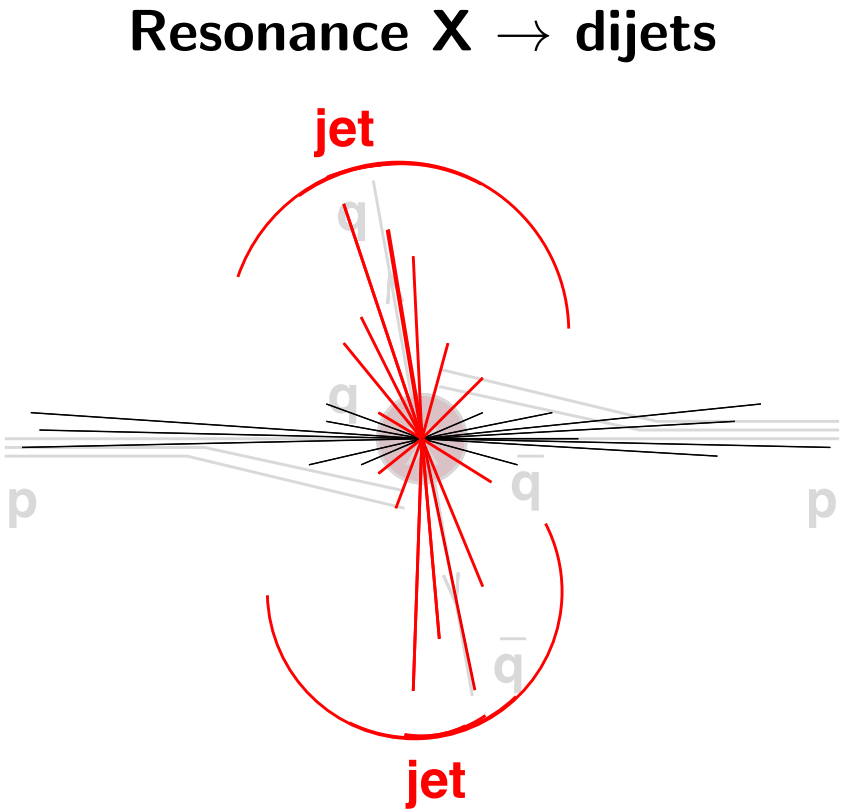

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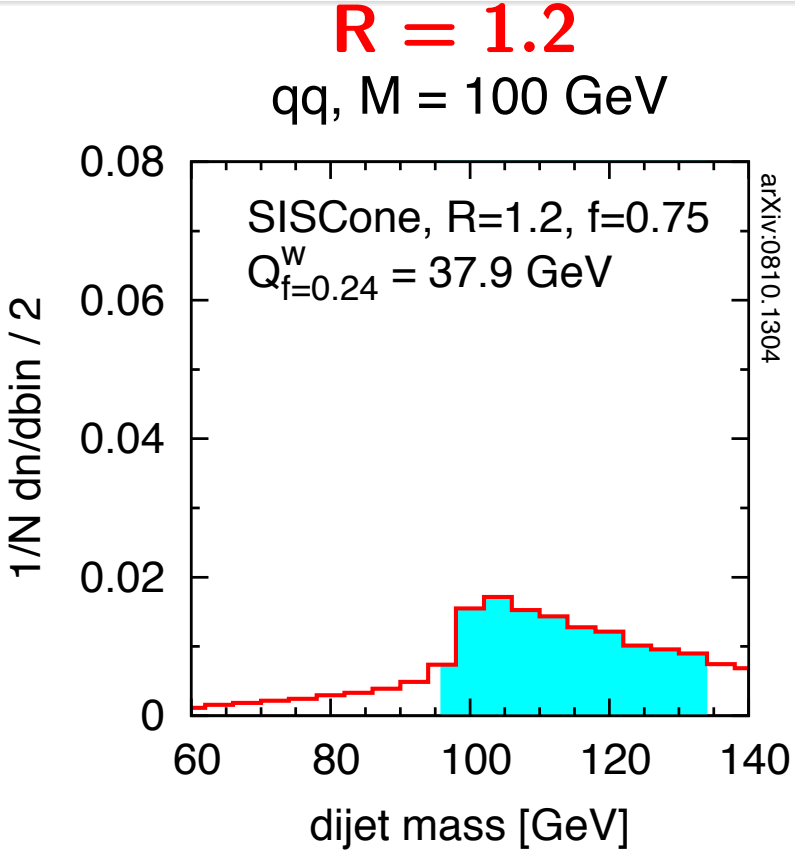

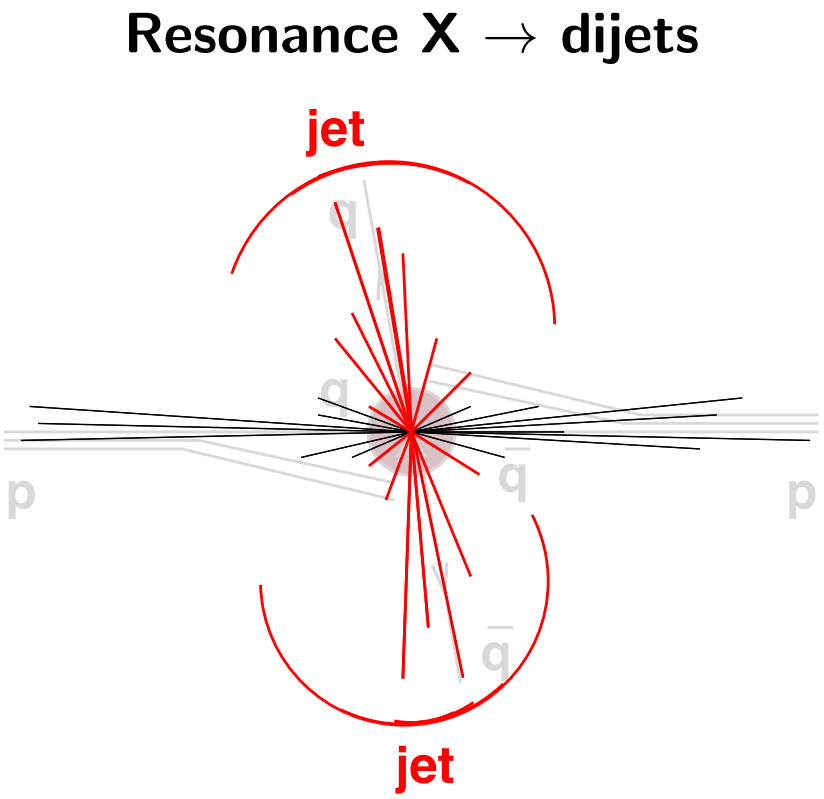

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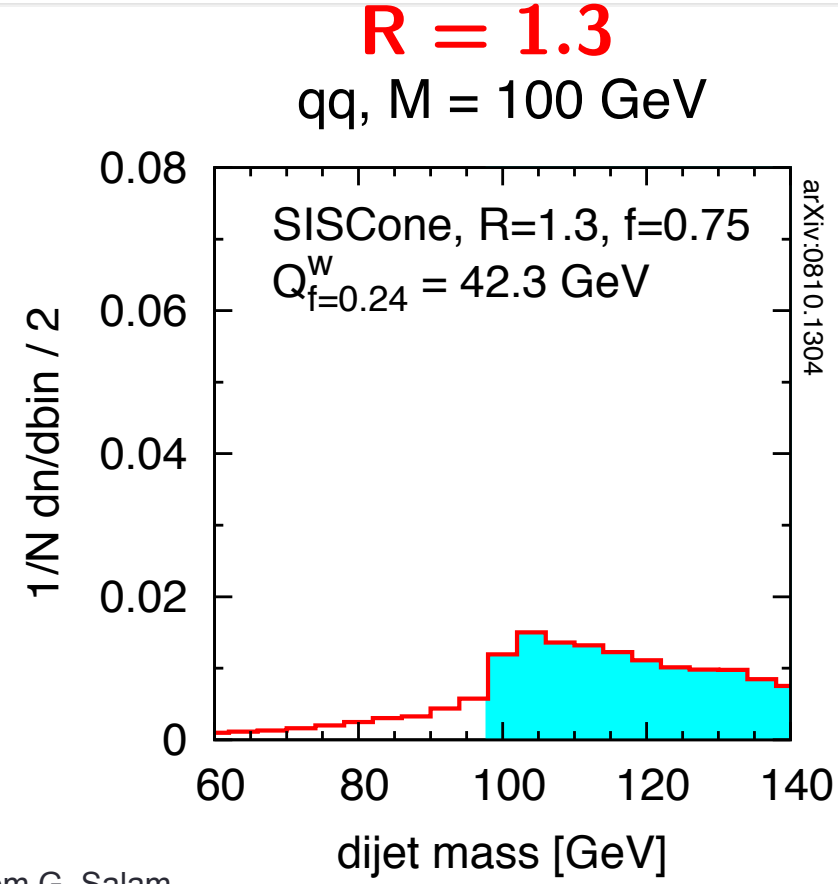

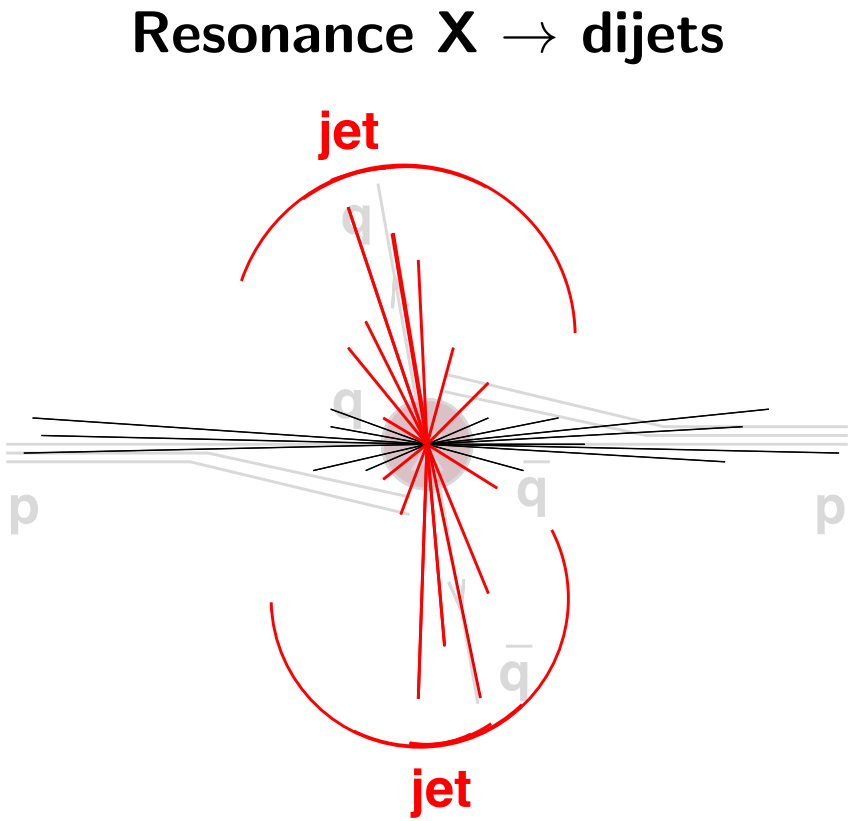

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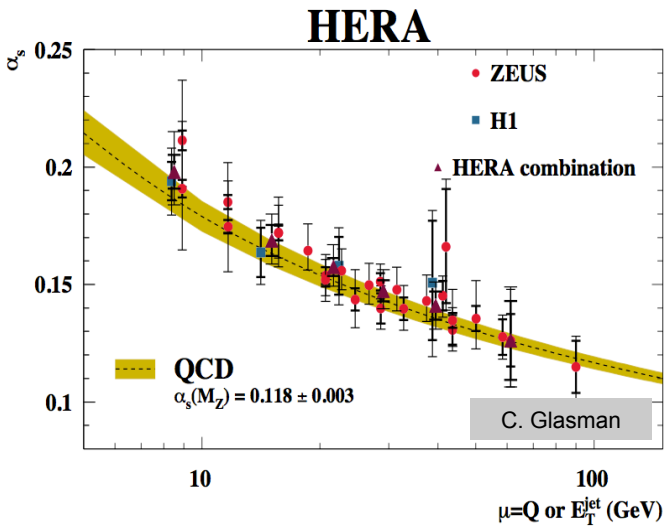
DATA

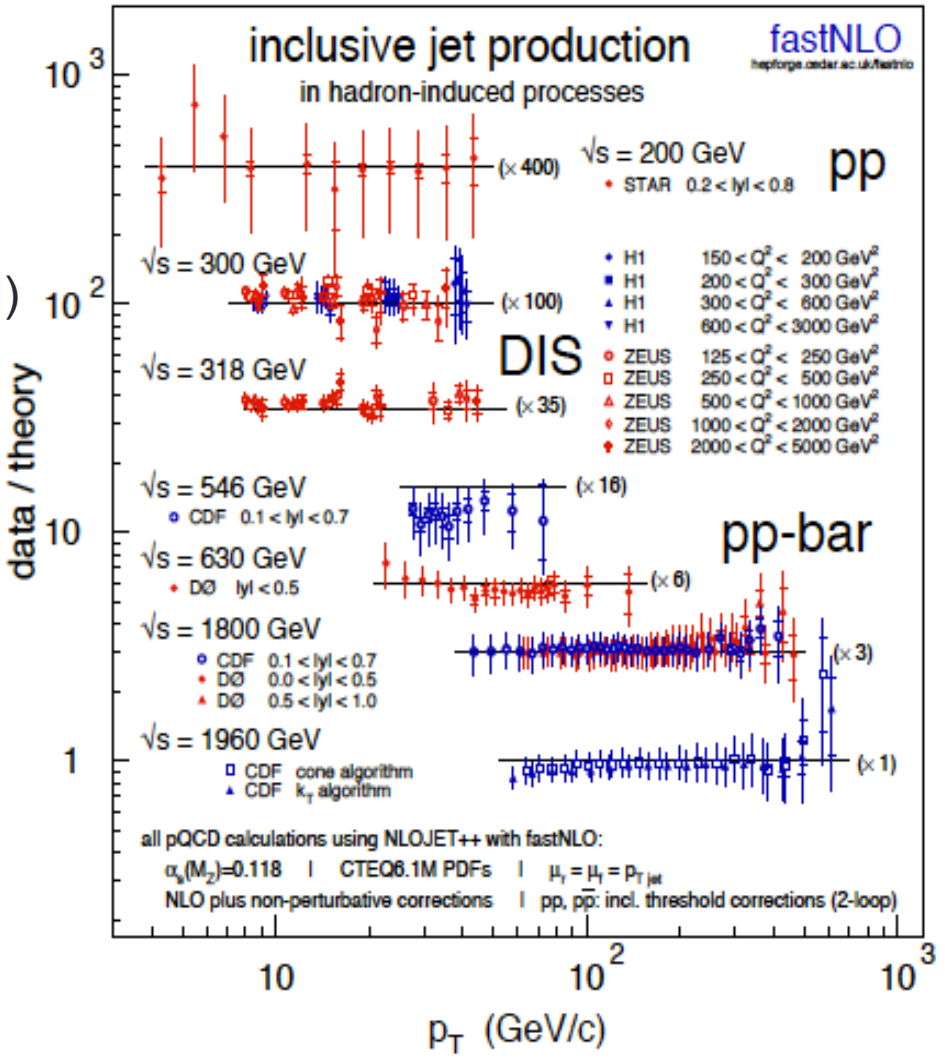
RHIC, Hera and Tevatron

- Excellent agreement between NLO theory and data (10% level)

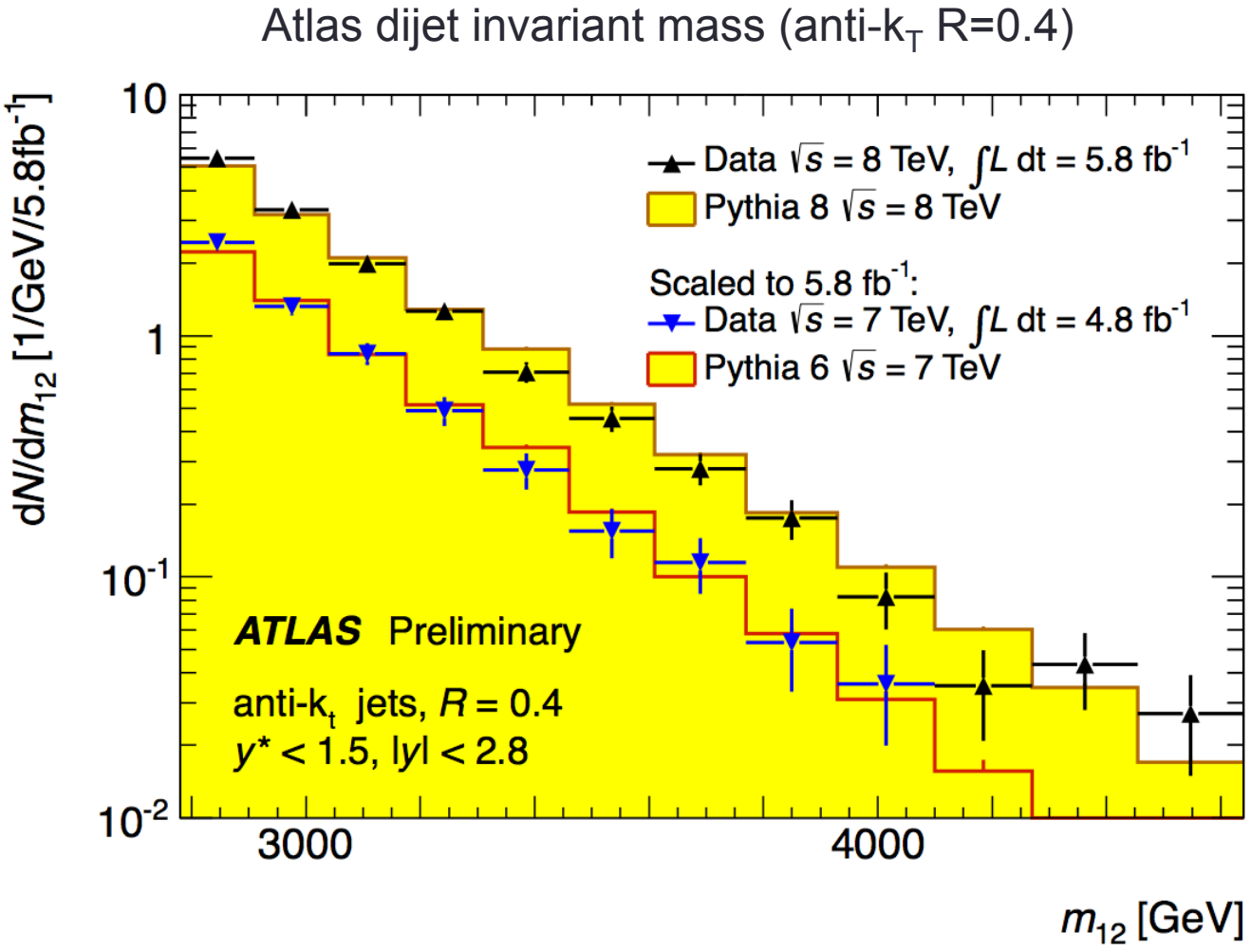
- Using same PDF set (CTEQ6.1M) and same

$$\alpha_s(m_Z) = 0.118$$

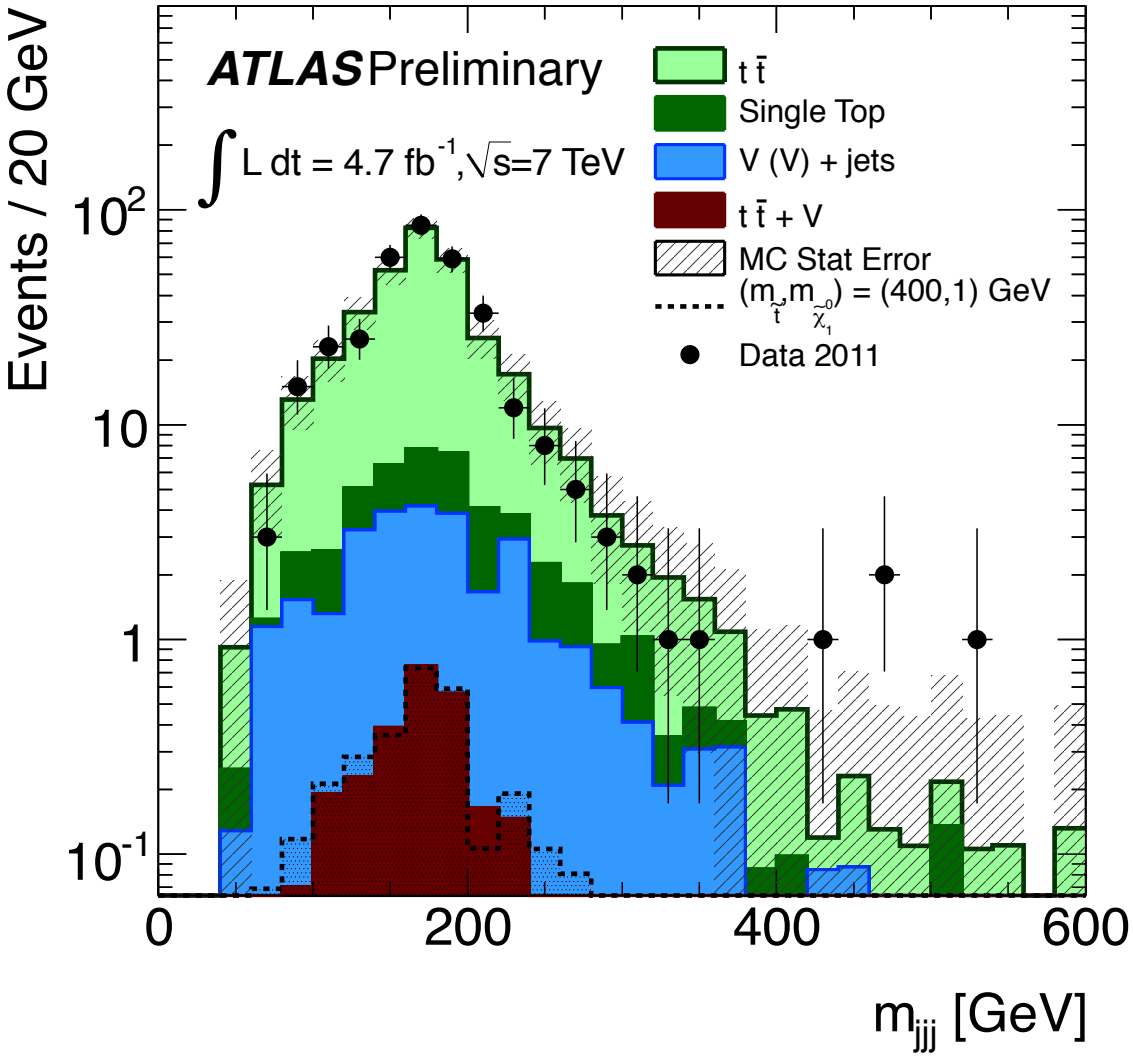




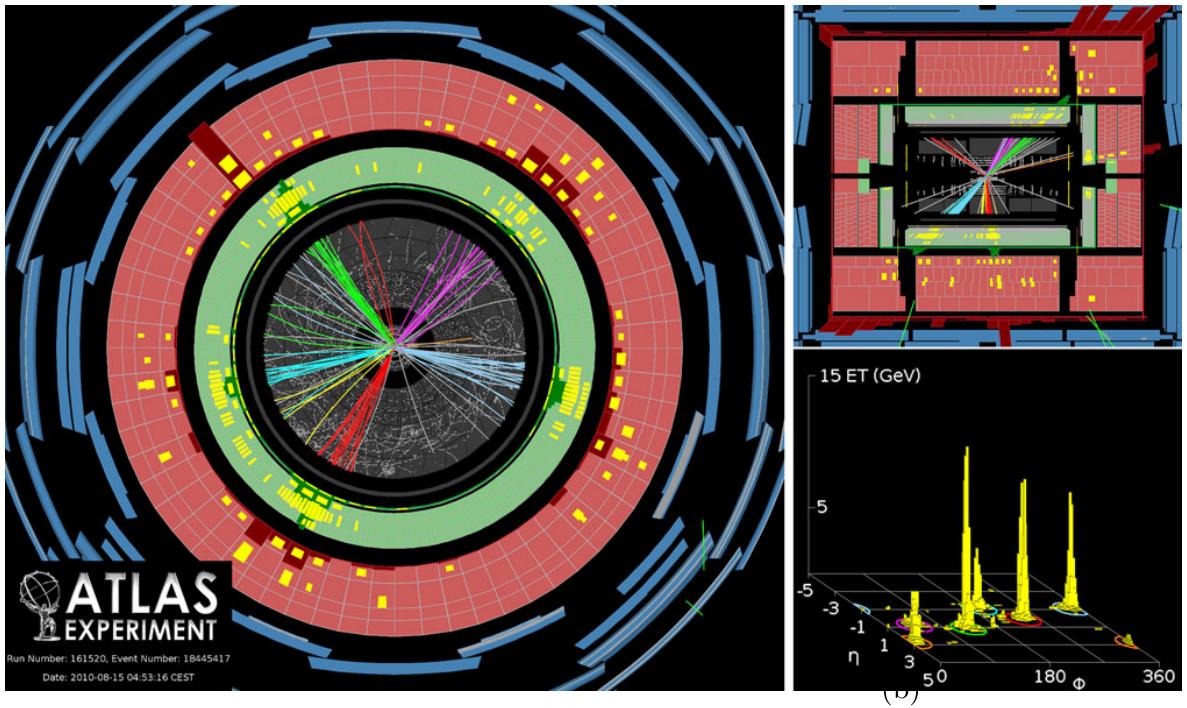
LHC data: dijet invariant mass



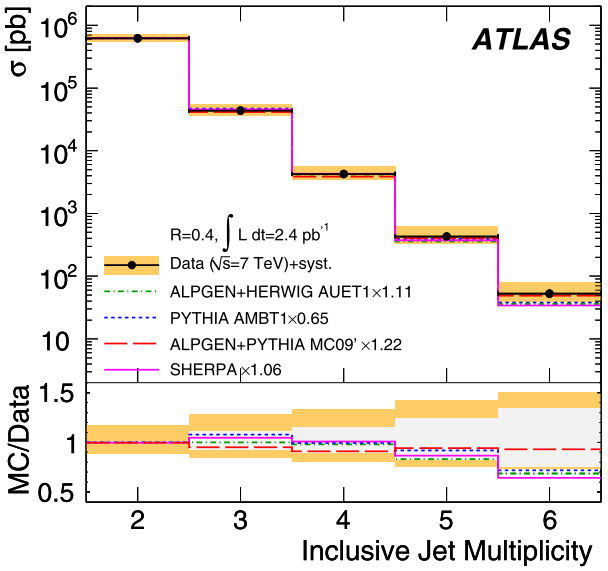
Tri-jet invariant mass

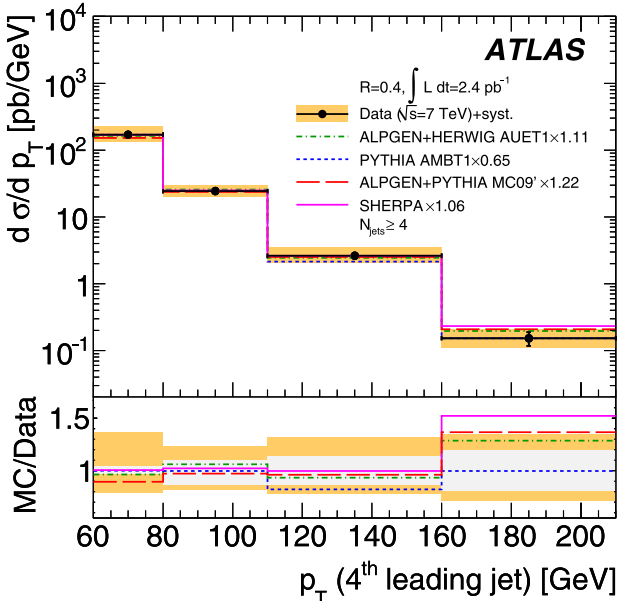


Multijets



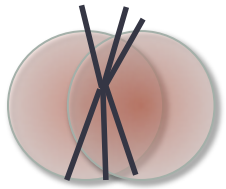
Multijet data
Agrees very well
with theory



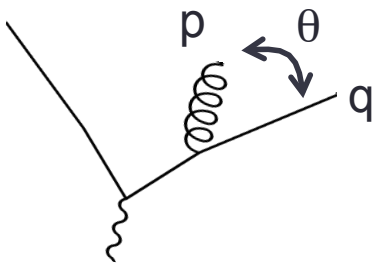


Summary

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



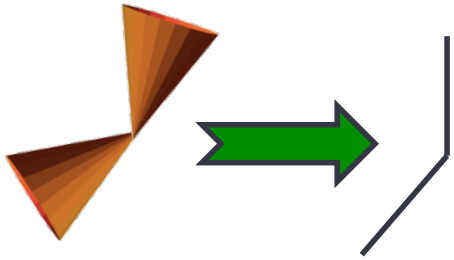
- Collinear and soft regions dominate cross sections



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

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

- 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