BEYOND QUARKS
COLORLESS FORCES IN PARTICLE DIFFRACTION

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Physics Colloquium

Brown University
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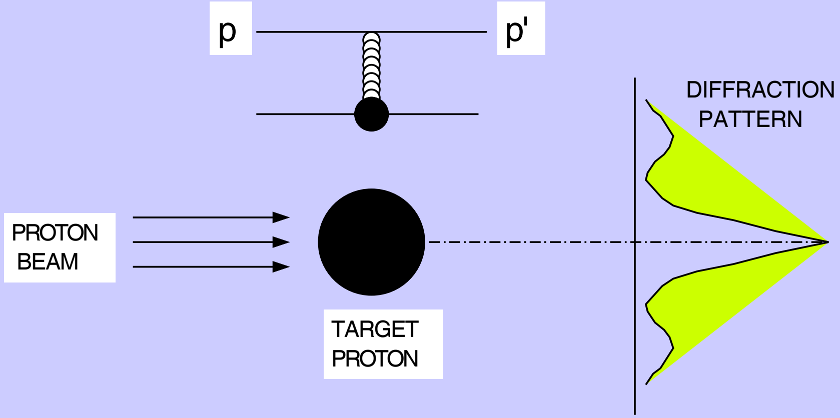
http://physics.rockefeller.edu/dino/my.html

What is
Particle Diffraction?

Elastic Scattering

PROTON-PROTON ELASTIC SCATTERING



p

p'

DIFFRACTION PATTERN

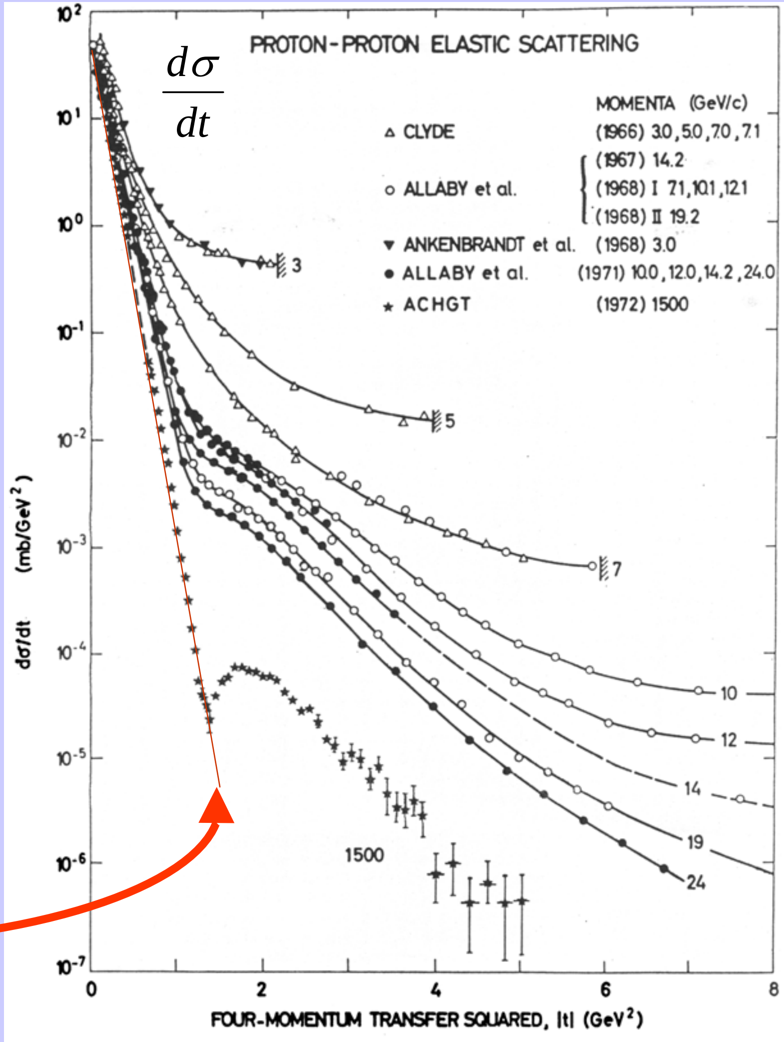
PROTON BEAM

TARGET PROTON

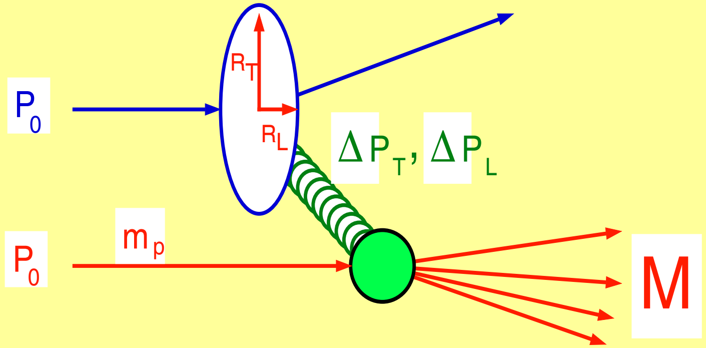
COHERENCE $\Delta p_T \sim \frac{1}{\lambda}$

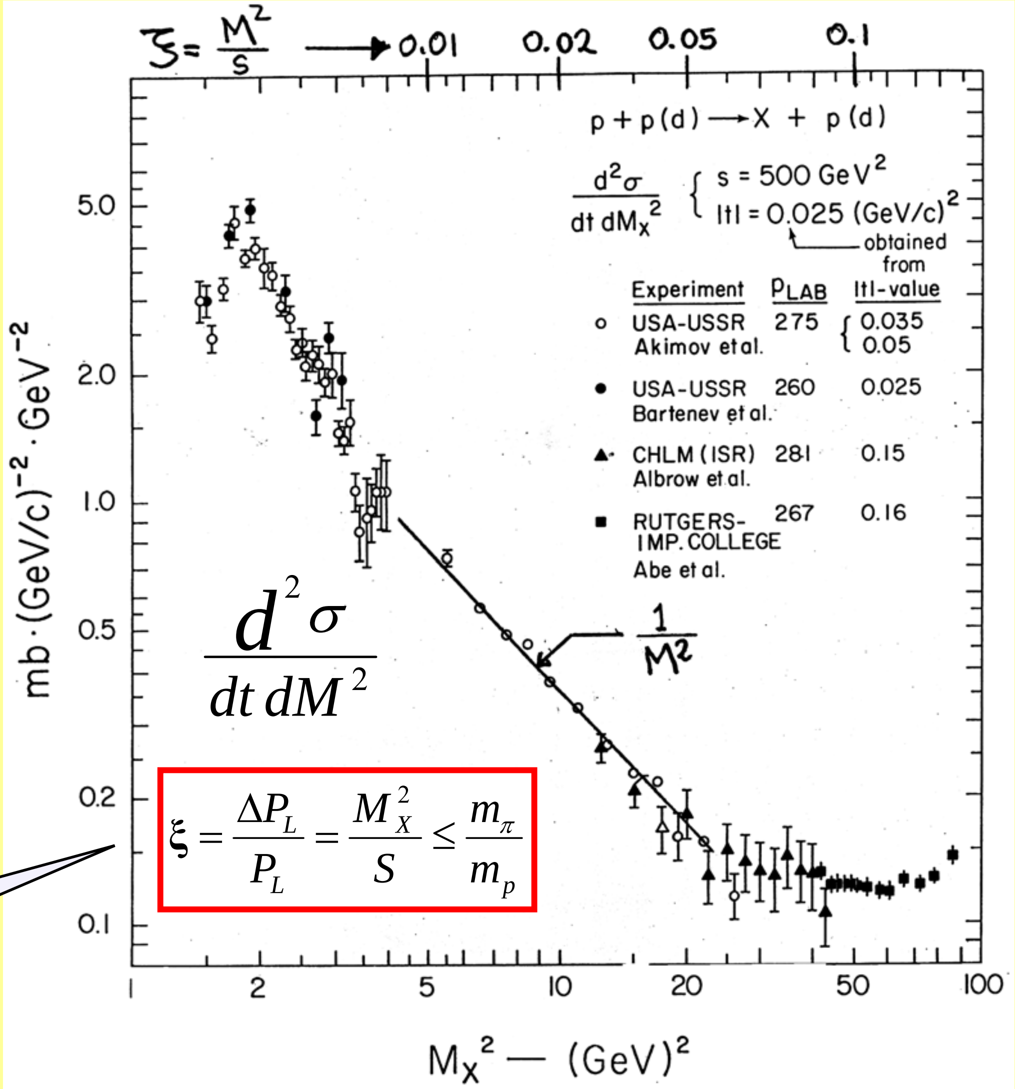
$$\frac{d\sigma}{dt} \sim e^{bt} \sim e^{-\frac{R^2}{4}(p\theta)^2}$$

$$R = \frac{1}{m_\pi} \Rightarrow b \approx 13\left(\frac{\text{GeV}}{c}\right)^{-2}$$



Diffraction Dissociation





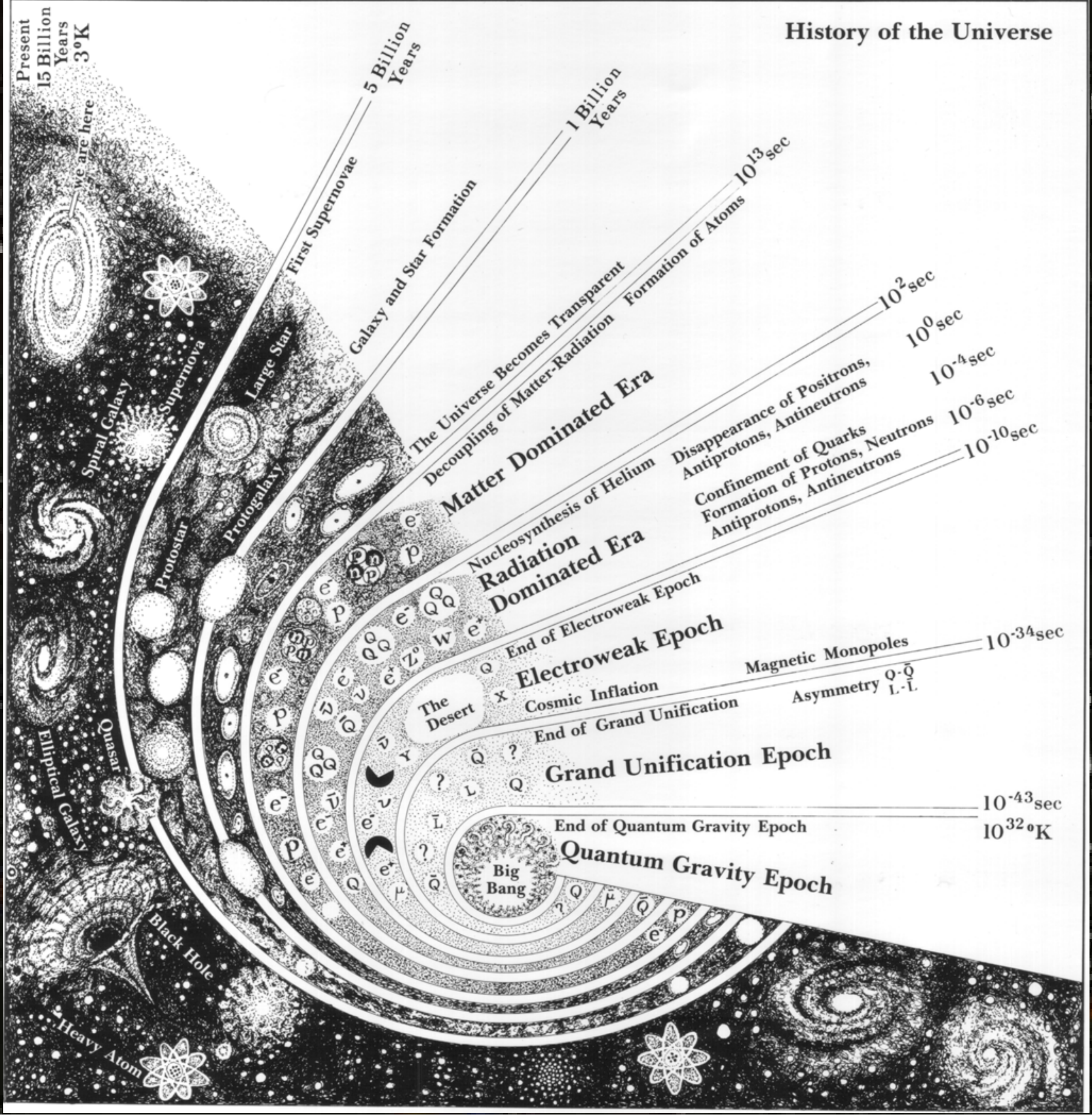
$$\frac{d^2\sigma}{dt\,dM^2}$$

$$\xi = \frac{\Delta P_L}{P_L} = \frac{M_X^2}{S} \leq \frac{m_\pi}{m_p}$$

$$\Delta p_L \sim \frac{1}{\lambda}$$

COHERENCE CONDITION

Why Study Particle Diffraction?


History of the Universe
Present
15 Billion Years
3°K
we are here
5 Billion Years
1 Billion Years
10^{13} sec
10^{2} sec
10^{0} sec
10^{-4} sec
10^{-6} sec
10^{-10} sec
10^{-34} sec
10^{-43} sec
10^{32} °K
First Supernovae
Galaxy and Star Formation
The Universe Becomes Transparent
Decoupling of Matter-Radiation
Formation of Atoms
Matter Dominated Era
Nucleosynthesis of Helium
Disappearance of Positrons, Antiprotons, Antineutrons
Confinement of Quarks
Formation of Protons, Neutrons
Antiprotons, Antineutrons
Radiation Dominated Era
End of Electroweak Epoch
Electroweak Epoch
The Desert
Cosmic Inflation
Magnetic Monopoles
Asymmetry Q-Q̄ L-L̄
End of Grand Unification
Grand Unification Epoch
End of Quantum Gravity Epoch
Quantum Gravity Epoch
Big Bang
Spiral Galaxy
Supernova
Large Star
Protostar
Protogalaxy
Quasar
Elliptical Galaxy
Black Hole
Heavy Atom

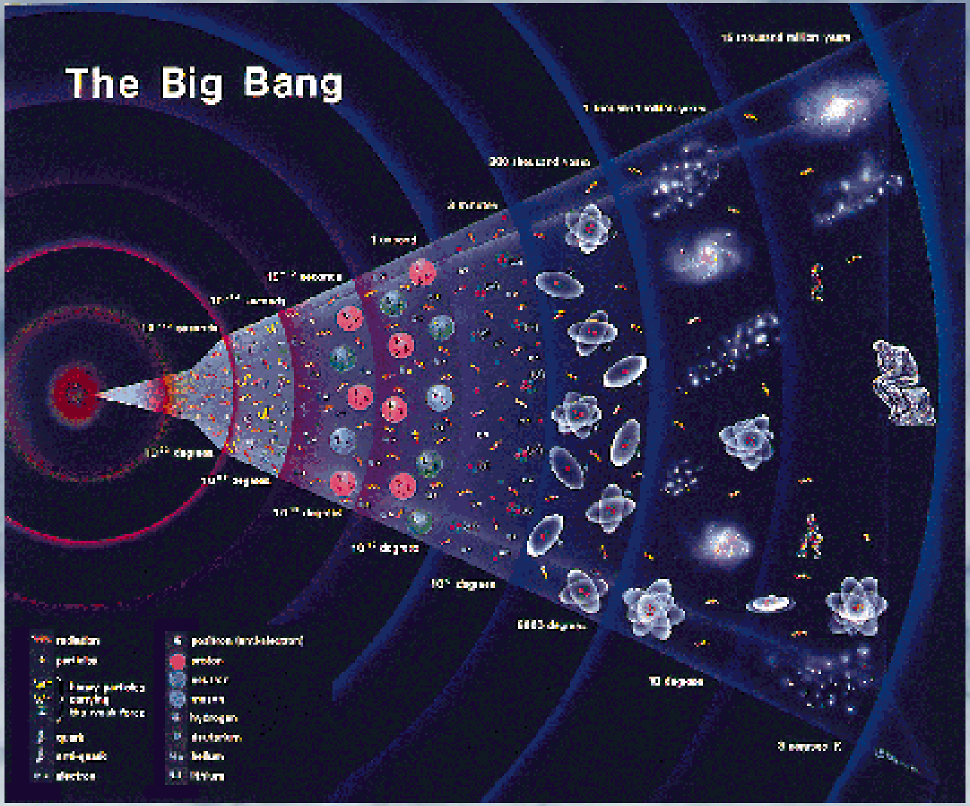
Black Hole Eats Star!

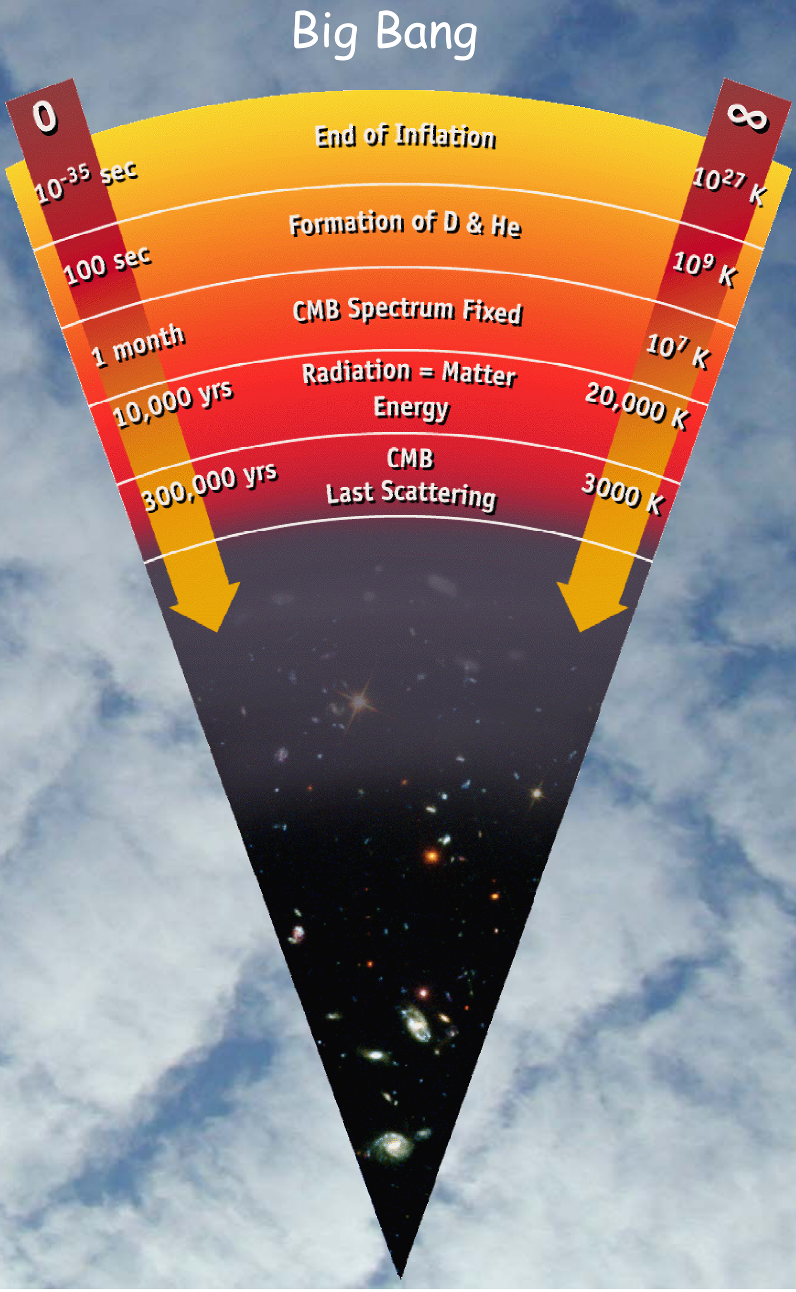
AP Photo

In this illustration, an arrow points to the doomed star. Part of its mass, shown by the white stream, was swallowed by the black hole.

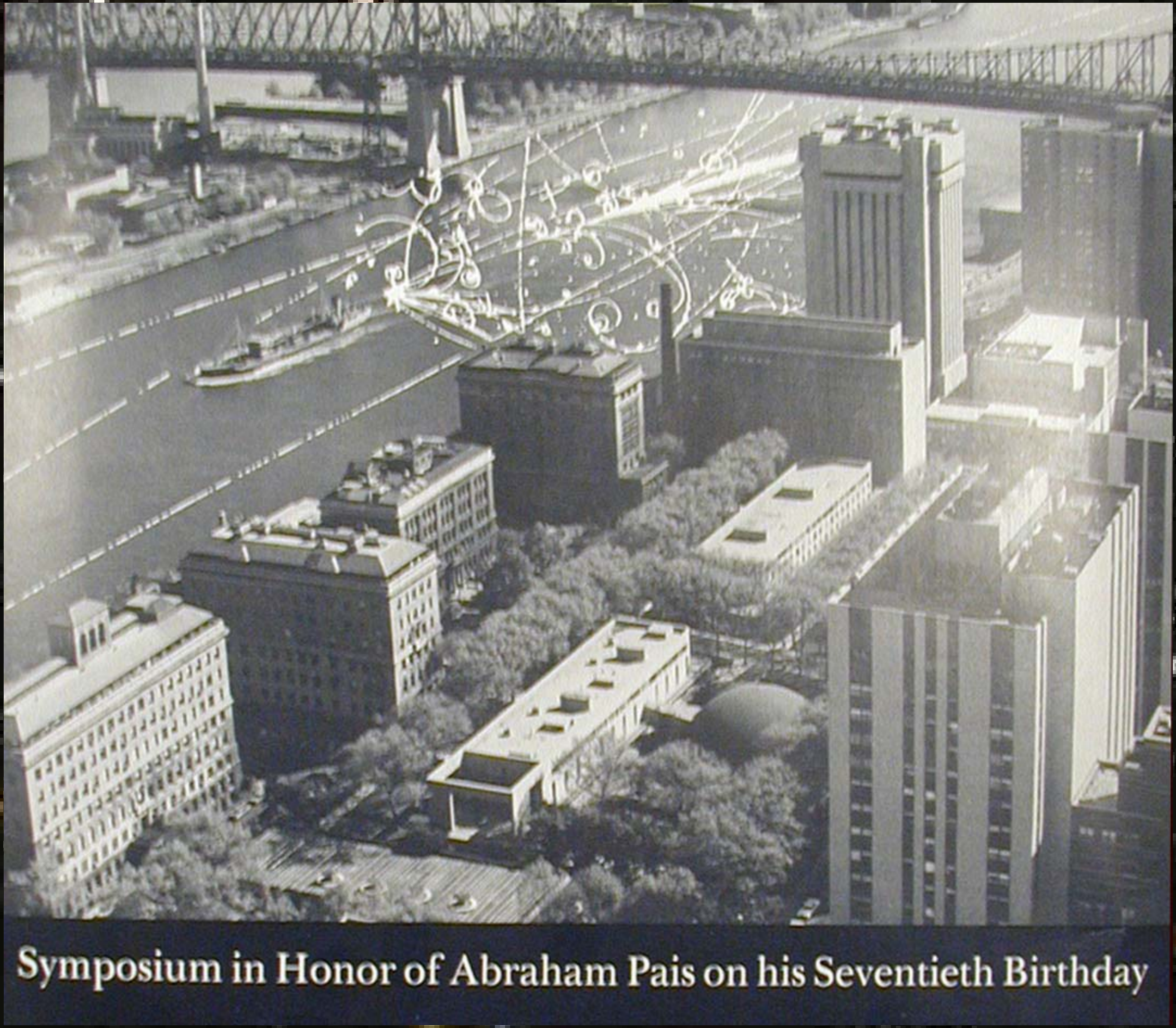
Star No Match for Black Hole

Big bang!


The Big Bang
radiation
particles
heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-electron)
proton
neutron
meson
hydrogen
deuterium
helium
lithium


Big Bang
0
∞
10-35 sec
End of Inflation
1027 K
100 sec
Formation of D & He
109 K
1 month
CMB Spectrum Fixed
107 K
10,000 yrs
Radiation = Matter Energy
20,000 K
300,000 yrs
CMB Last Scattering
3000 K

Big Bang on the East River!

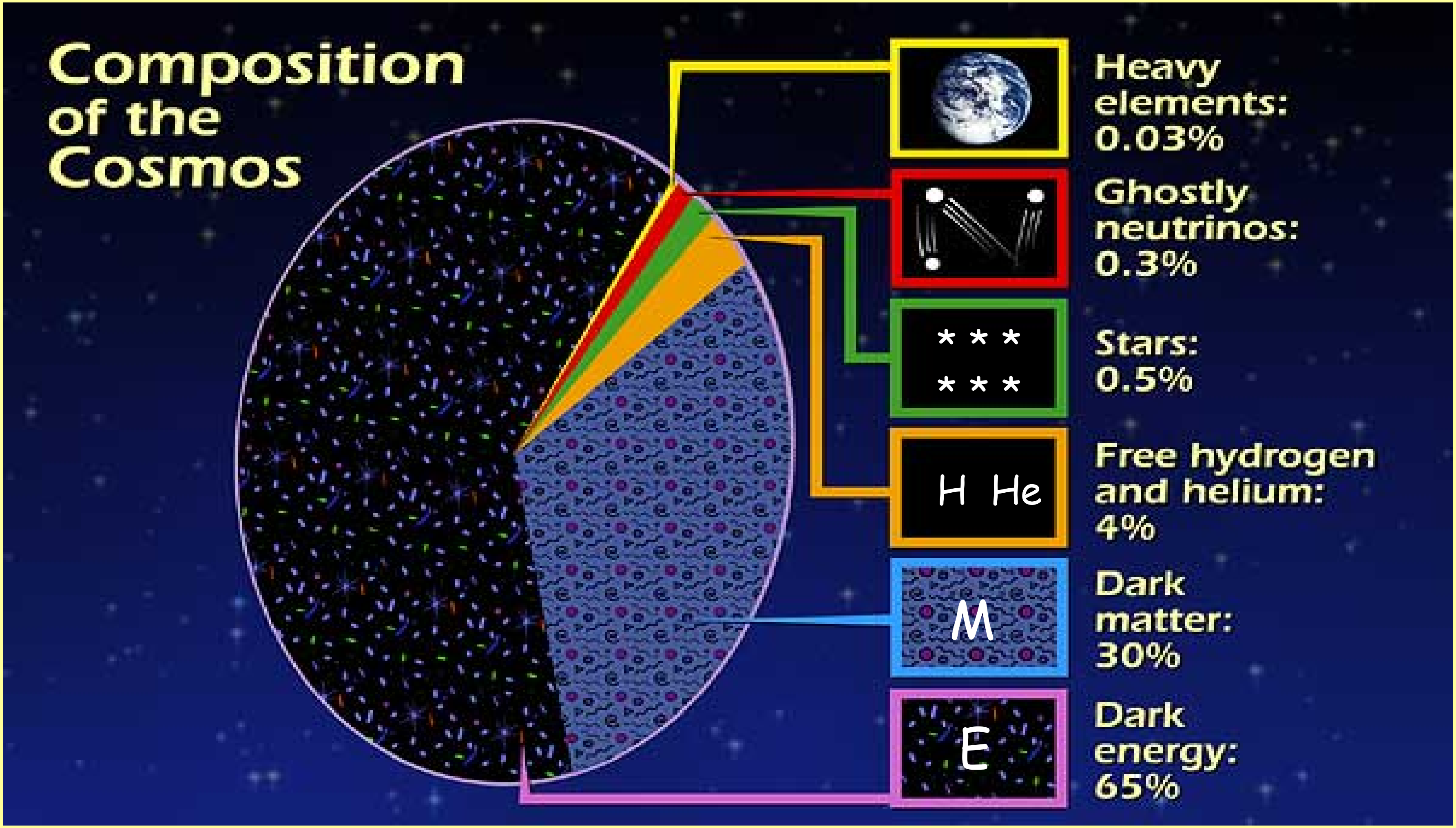


Symposium in Honor of Abraham Pais on his Seventieth Birthday

Blow-hole at Grand Cayman

Why should I care about Particle Diffraction?

What is Dark Energy?

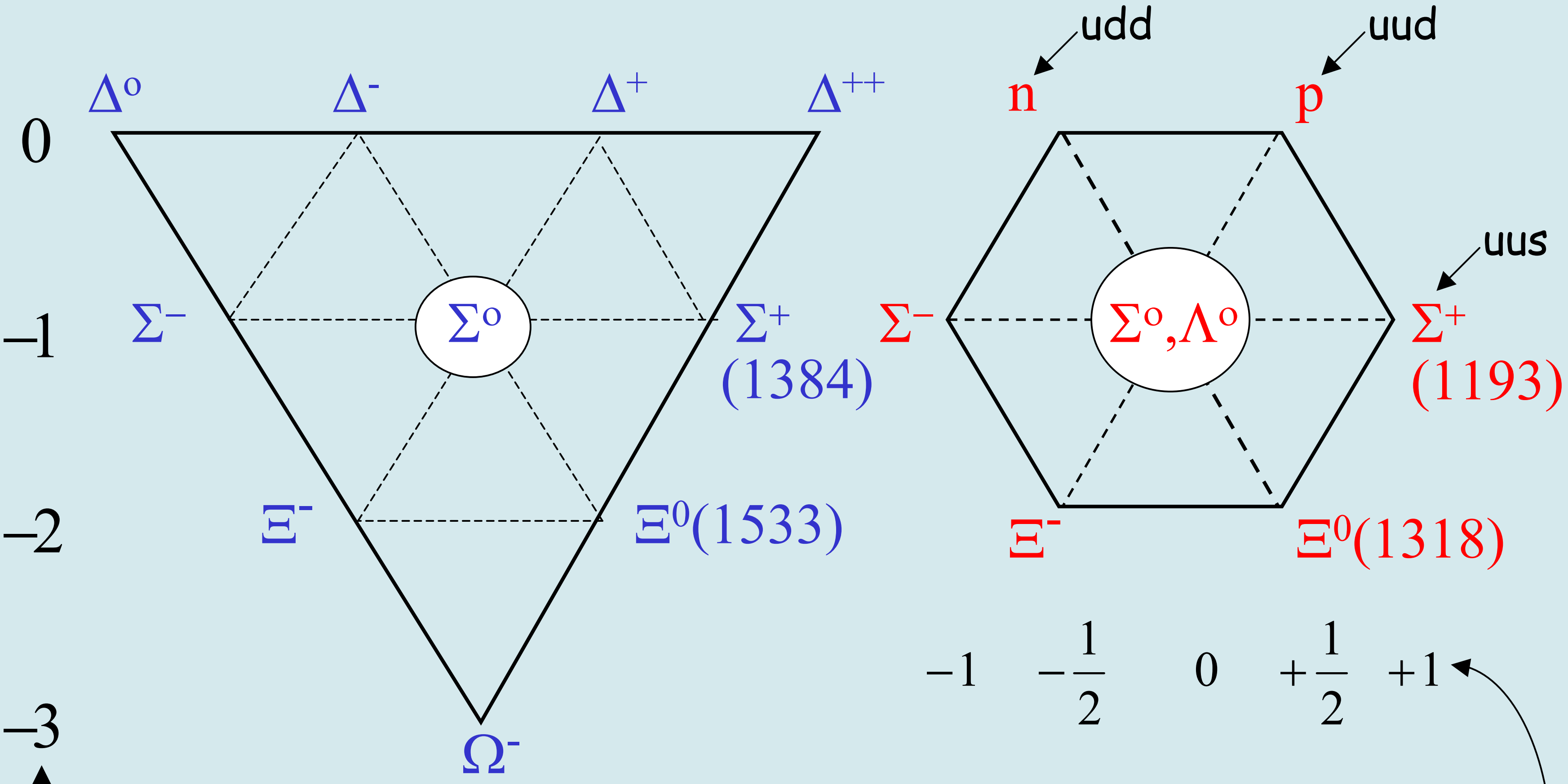


A short tour of particle physics

NYC, 1994 Five Borough Bike Tour
Next tour: May 1, 2005

SU3
The Standard Model
String theory
QCD

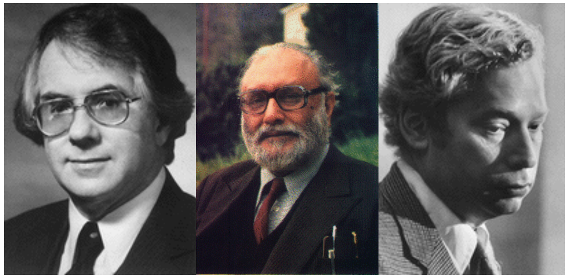
SU3: Law and Order in the Particle Zoo



u : I_3= 1/2 S= 0 Q= 2/3
d : I_3= -1/2 S= 0 Q= -1/3
s : I_3= 0 S=-1 Q= -1/3

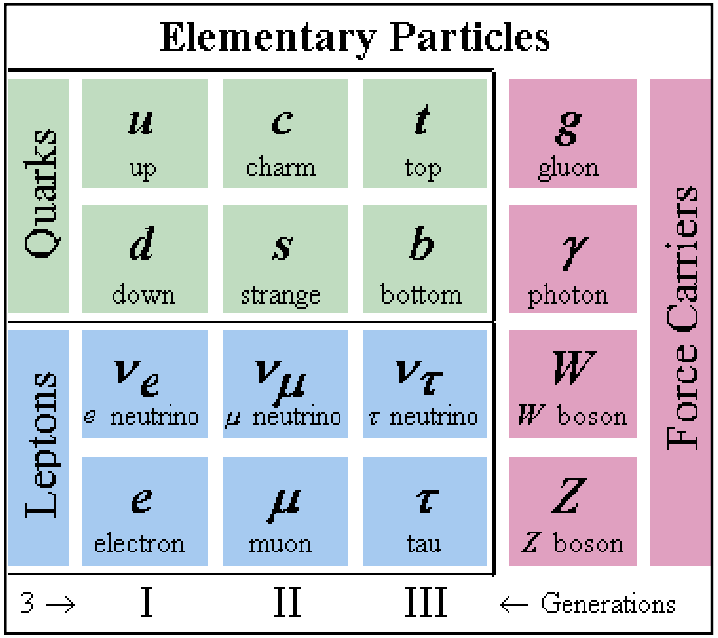
Strangeness: S

Isotopic spin:
I_3=Q-(B+S)/2



The Standard Model

Glashow, Salam, and Weinberg



Elementary Particles

Quarks	u up	c charm	t top	g gluon	Force Carriers
	d down	s strange	b bottom	γ photon	
Leptons	ν_e e neutrino	ν_μ μ neutrino	ν_τ τ neutrino	W W boson	
	e electron	μ muon	τ tau	Z Z boson	
3 →	I	II	III	← Generations	

$$L = -\frac{1}{4}W_{\mu\nu}W^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

$$+\bar{L}\gamma^{\mu}\left(i\partial_{\mu} - g\frac{1}{2}\tau.W_{\mu} - g'\frac{Y}{2}B_{\mu}\right)L$$

$$+\bar{R}\gamma^{\mu}\left(i\partial_{\mu} - g'\frac{Y}{2}B_{\mu}\right)R$$

$$+\left|\left(i\partial_{\mu} - g\frac{1}{2}\tau.W_{\mu} - g'\frac{Y}{2}B_{\mu}\right)\phi\right|^{2} - V(\phi)$$

$$-\left(G_{1}\bar{L}\phi R + G_{2}\bar{L}\phi_{c}R + \text{hermitian conjugate}\right)$$

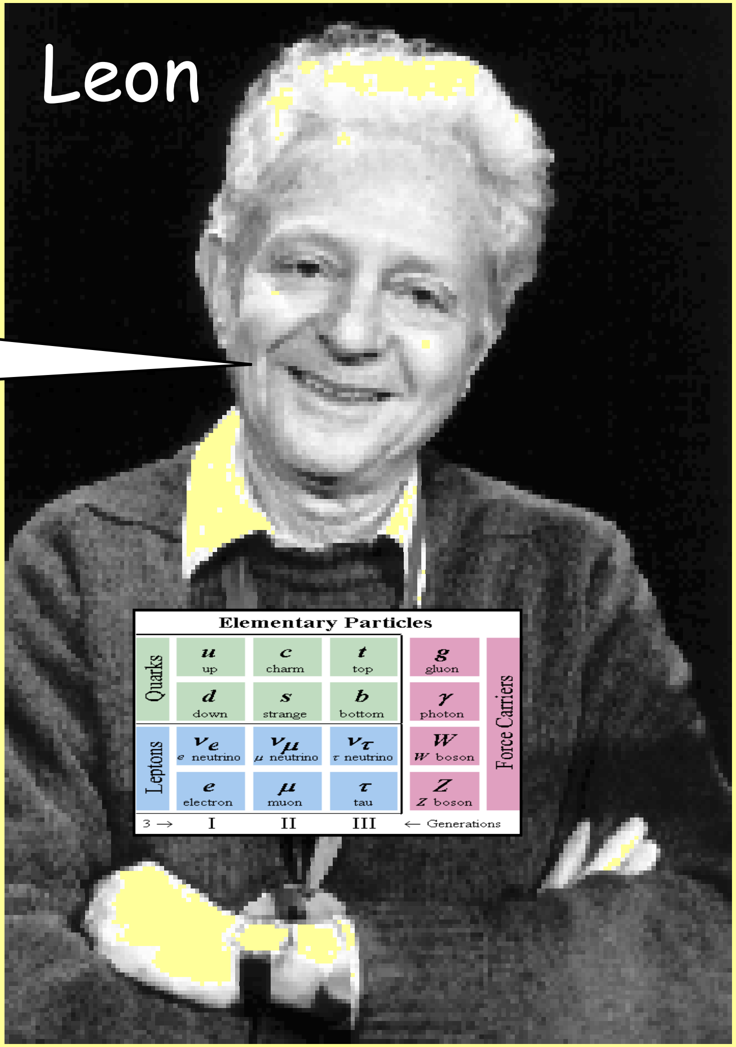
$M_\gamma, g = 0$ $M_{W,Z} \sim 80\ M_p$ $M_{top} \sim M_{gold}$

Higgs field generates Mass !

	Force	Strength
g →	strong	1
γ →	electromagnetic	10^{-2}
W, Z →	weak	10^{-14}

Leon & the SM

A good theory should fit on a T-shirt!



Elementary Particles

Quarks	u up	c charm	t top	g gluon
	d down	s strange	b bottom	γ photon
Leptons	ν_e e neutrino	ν_μ μ neutrino	ν_τ τ neutrino	W W boson
	e electron	μ muon	τ tau	Z Z boson
3 →	I	II	III	← Generations

Force Carriers

But what about interactions?

$$
\begin{aligned}
L = & -\frac{1}{4}\mathrm{W}_{\mu\nu}\mathrm{W}^{\mu\nu} - \frac{1}{4}\mathrm{B}_{\mu\nu}\mathrm{B}^{\mu\nu} \\
& + \overline{\mathrm{L}}\gamma^{\mu}\left(i\partial_{\mu} - g\frac{1}{2}\tau.\mathrm{W}_{\mu} - g'\frac{\mathrm{Y}}{2}\mathrm{B}_{\mu}\right)\mathrm{L} \\
& + \overline{\mathrm{R}}\gamma^{\mu}\left(i\partial_{\mu} - g'\frac{\mathrm{Y}}{2}\mathrm{B}_{\mu}\right)\mathrm{R} \\
& + \left|\left(i\partial_{\mu} - g\frac{1}{2}\tau.\mathrm{W}_{\mu} - g'\frac{\mathrm{Y}}{2}\mathrm{B}_{\mu}\right)\phi\right|^{2} - \mathrm{V}(\phi) \\
& - \left(\mathrm{G}_1\overline{\mathrm{L}}\phi\mathrm{R} + \mathrm{G}_2\overline{\mathrm{L}}\phi_c\mathrm{R} + \text{hermitian conjugate}\right)
\end{aligned}
$$

The Peon

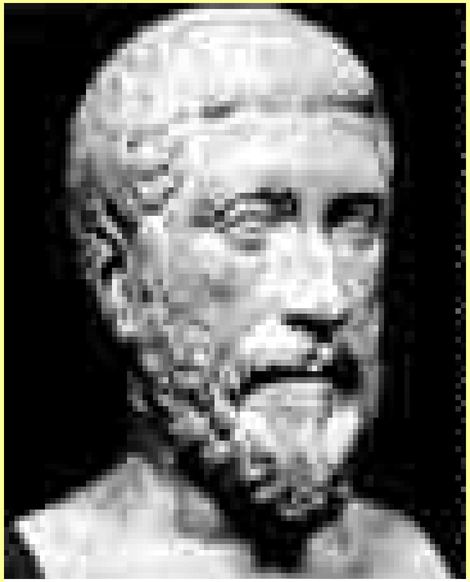
AND WHAT ABOUT GRAVITY?

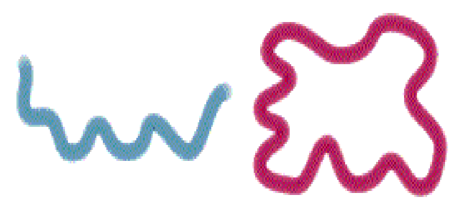
String Theory, then?

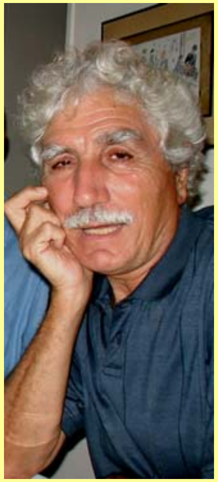
Particles correspond to
the vibration modes of
a string in 10 dimensions

Gravity is included!

Pythagoras
applied it to music
in 400 BC:
1+2+3+4=10





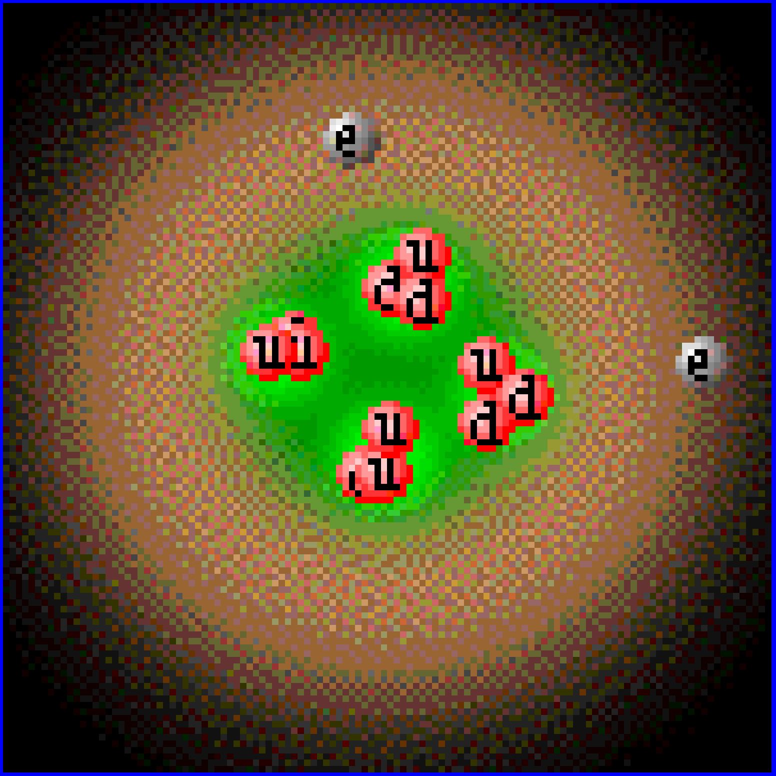


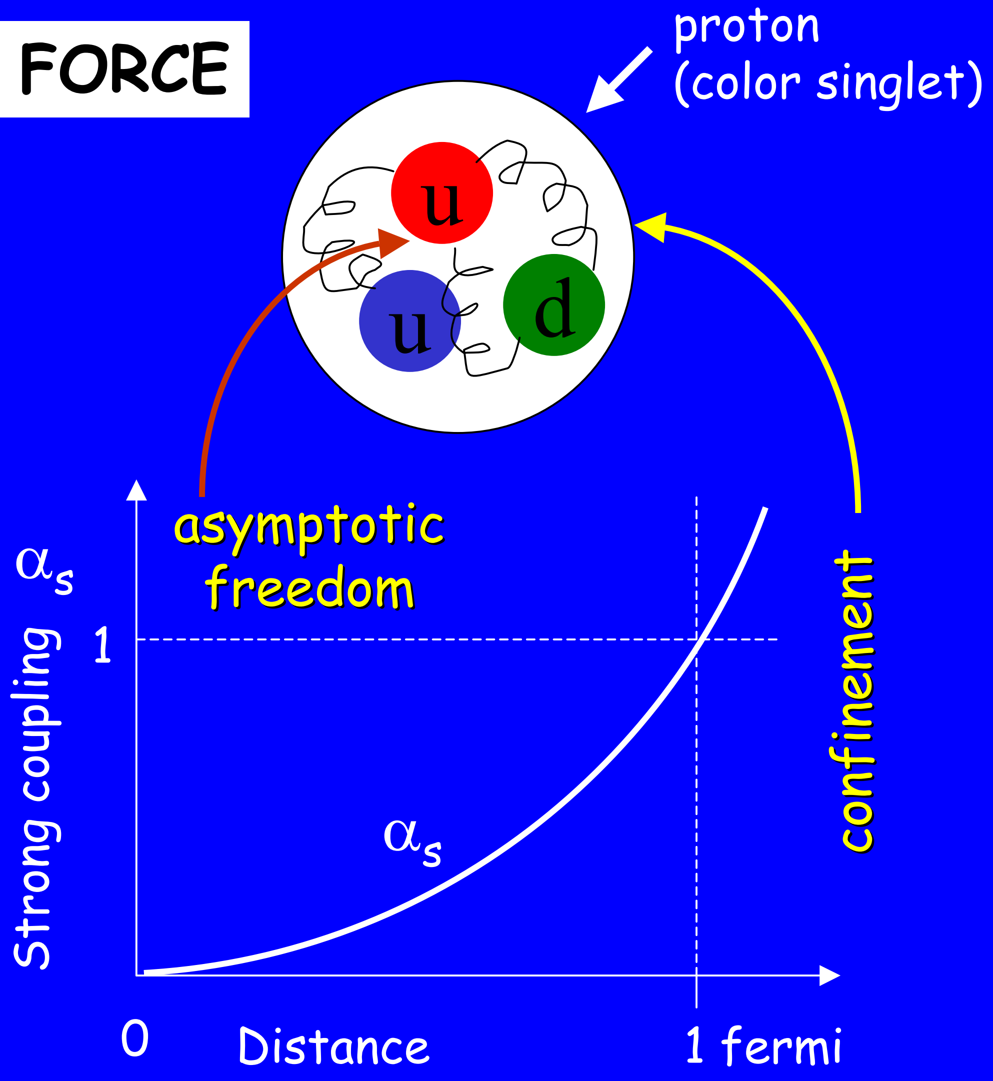
And it surely makes an interesting T-shirt!

QCD - Quantum Chromo-Dynamics

The Theory of Strong Interactions

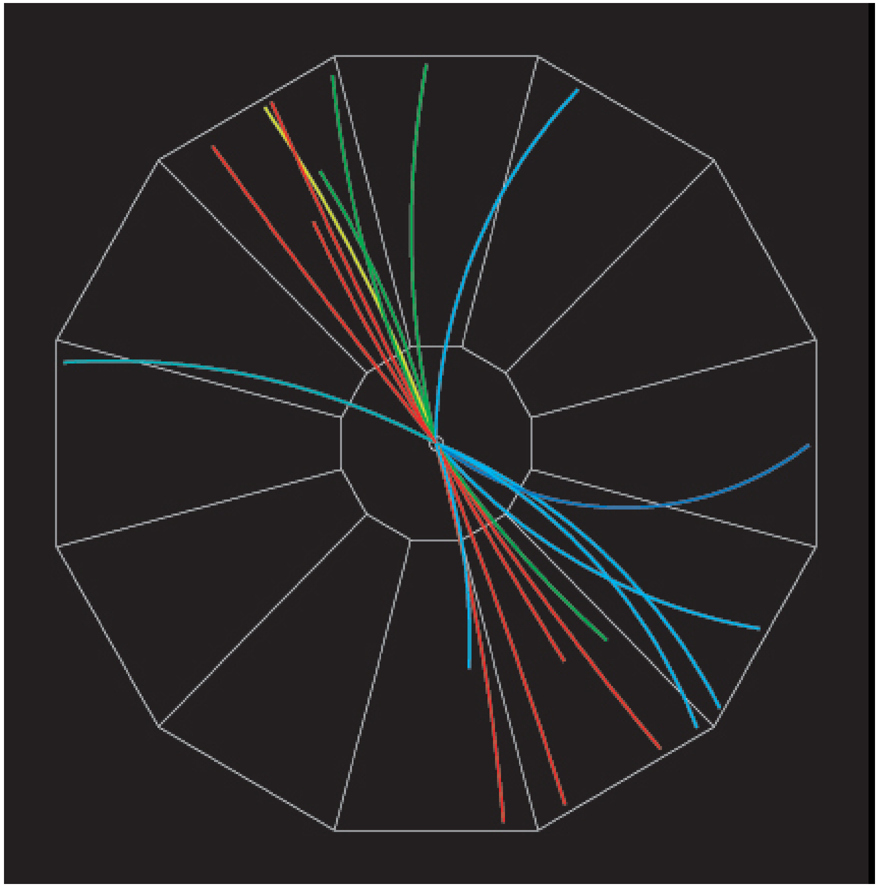
COLOR FORCE





David Politzer

Collisions and Explosions



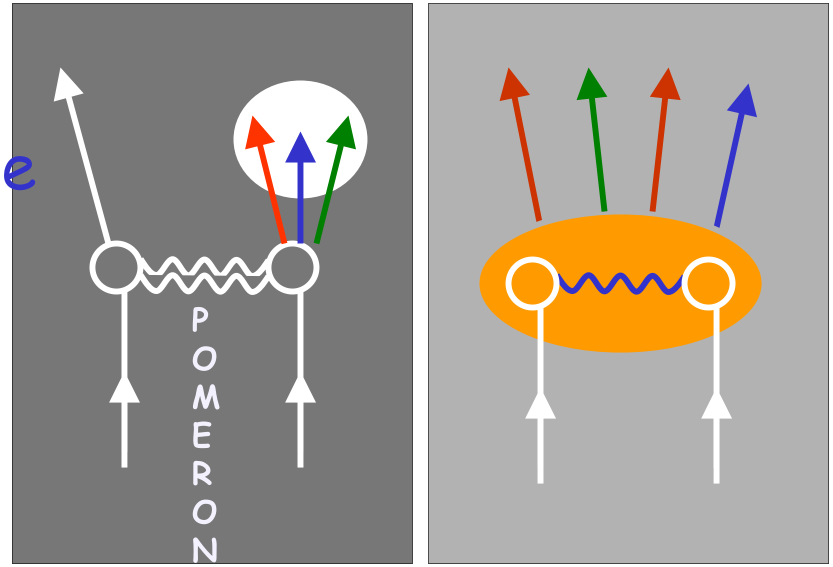
Fireworks - Central Park 2004

Diffractive Interactions


Suren Bagdasarov


Andrei Solodsky


Kenichi Hatakeyama



Diffractive:

colorless exchange

Protons retain their quantum numbers

ENERGY ESCAPES

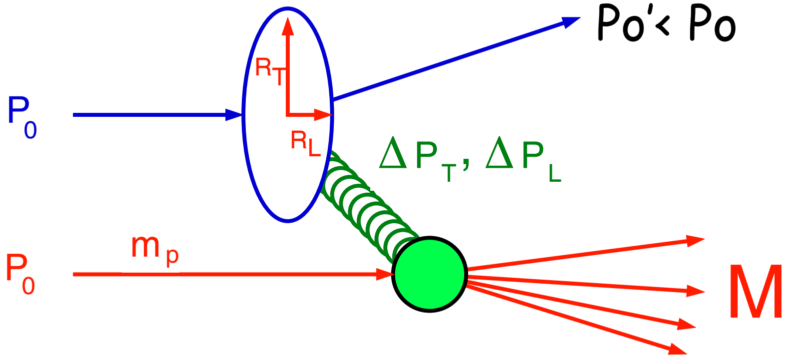
Non-diffractive:

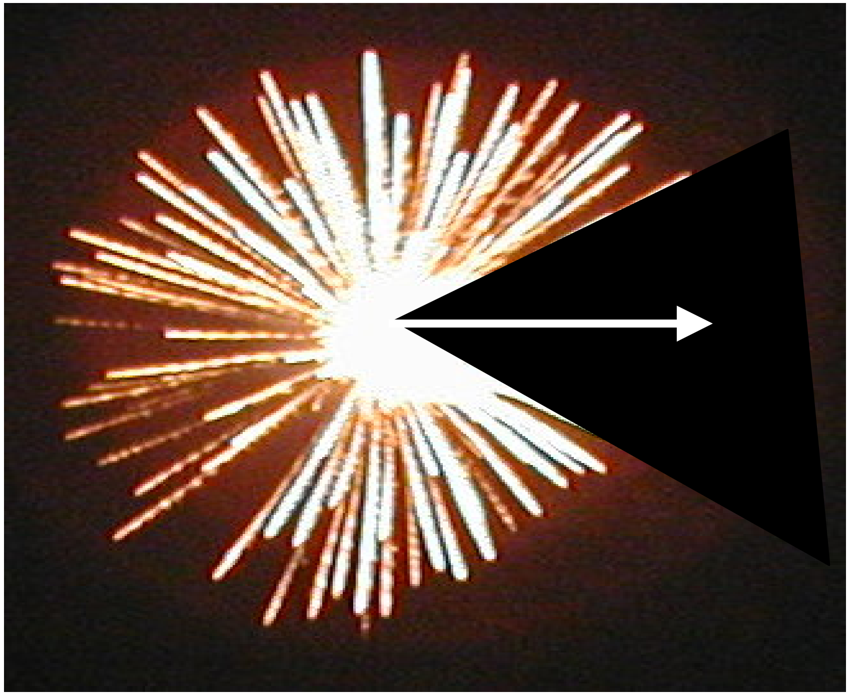
color exchange

Protons acquire color and break apart

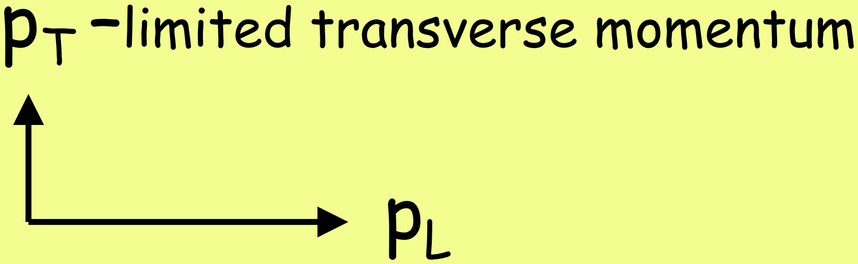
CONFINEMENT

Asymmetric explosion





Rapidity



p_T -limited transverse momentum

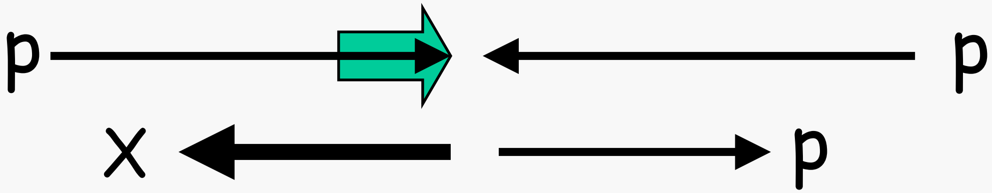
p_L

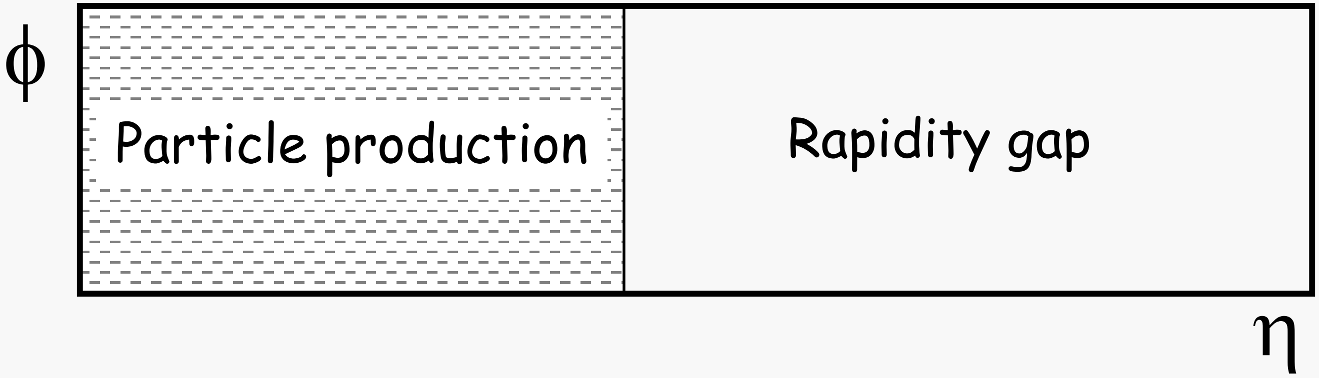
$$\text{rapidity}: \quad y = \frac{1}{2}\ln\frac{E+p_L}{E-p_L} = \frac{E+p_L}{\sqrt{p_T^2+m^2}}$$

$$\text{pseudorapidity}: \quad (m=0) \quad \eta = -\ln\tan\frac{\theta}{2}$$

Rapidity Gaps

Bj, PRD 47 (1993) 101: regions of (pseudo)rapidity devoid of particles





$$\left(\frac{d\sigma}{d\Delta\eta}\right)_{t=0} \approx \text{conctant} \Rightarrow \frac{d\sigma}{dM^2} \sim \frac{1}{M^2}$$

Forty Years of Diffraction

http://physics.rockefeller.edu/dino/my.html

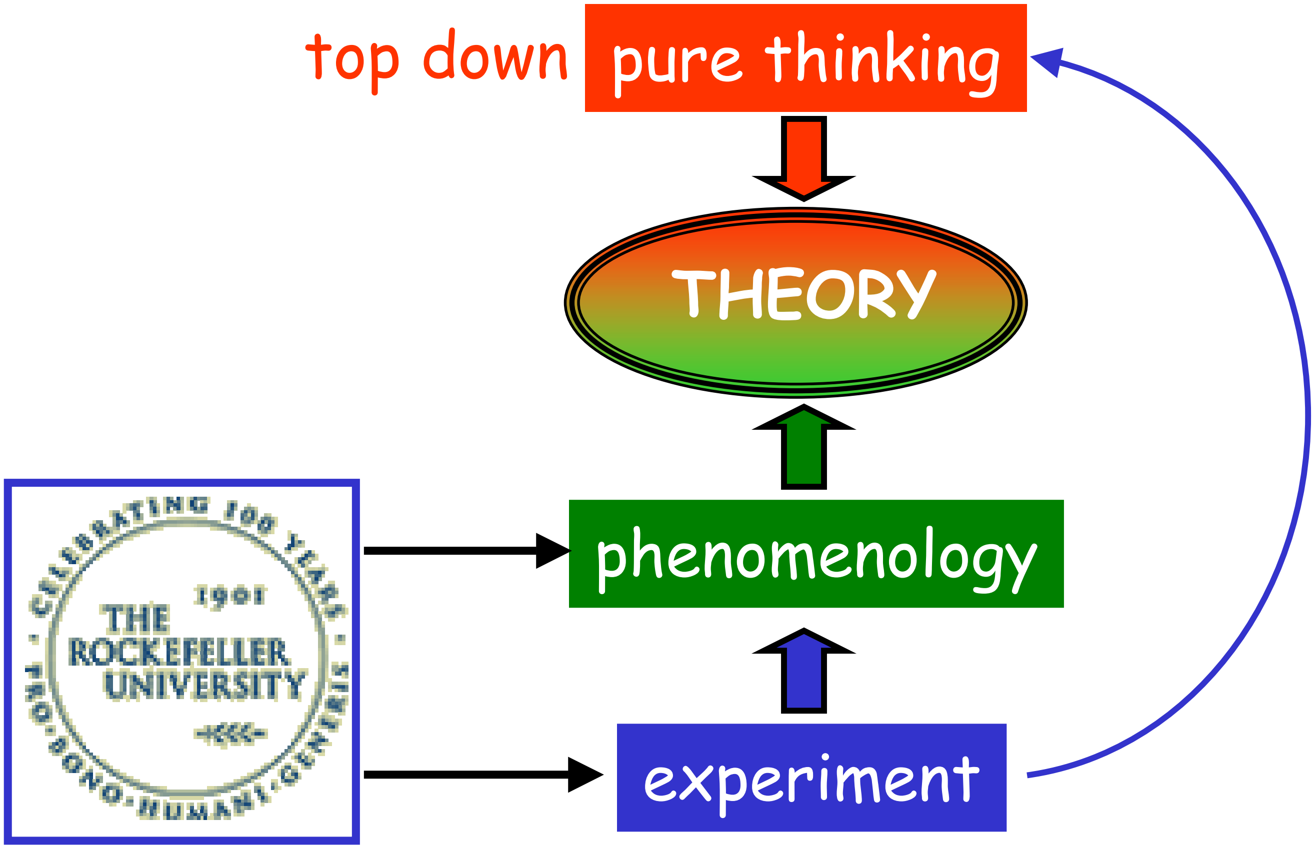
- 1960's BNL: first observation of pp -> pX
- 1970's Fermilab fixed target, ISR, SPS
  → Regge theory & factorization

Review: KG, Phys. Rep. 101 (1983) 169

- 1980's UA8: diffractive dijets ⇨ hard diffraction
- 1990's Tev Run-I: Regge factorization breakdown
  Tev/ HERA: QCD factorization breakdown
- 21st C Multigap diffraction: restoration of factorization
  Ideal for diffractive studies @ LHC

Theory of Diffraction

- Important for understanding hadron structure and quark confinement.
- QCD can only be solved perturbatively for cases in which $\alpha_s \ll 1$.
- Need to develop new mathematical methods to deal with diffraction.



top down

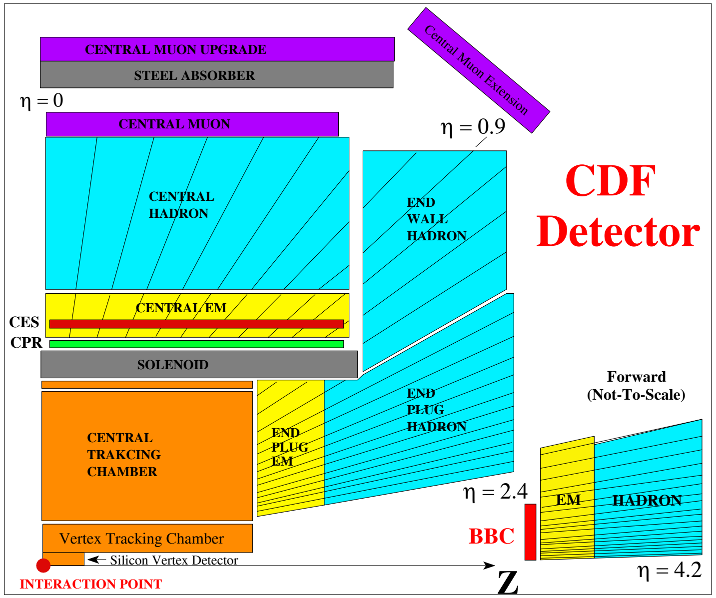
pure thinking

THEORY

phenomenology

experiment

Run-I A,B: Rapidity Gap Studies



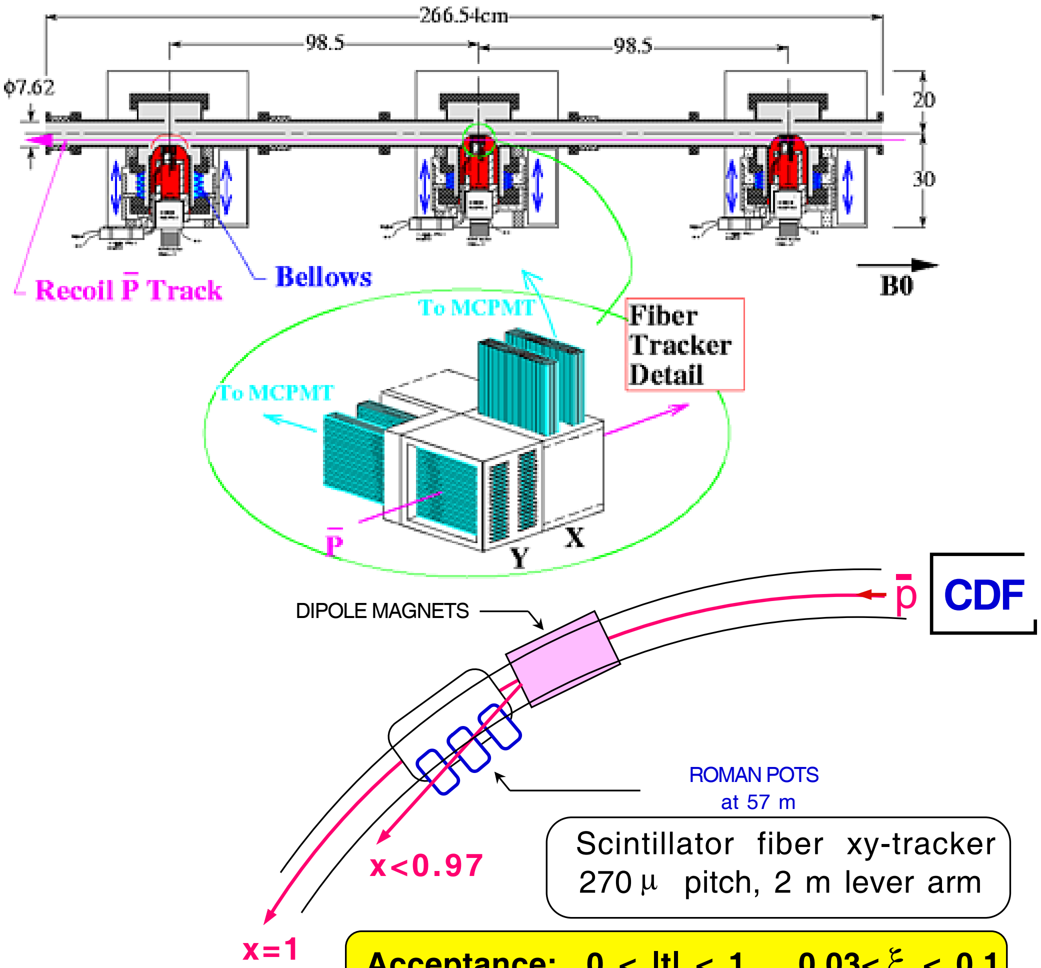
Forward Detectors

BBC $3.2<\eta<5.9$

FCAL $2.4<\eta<4.2$

CDF-IC

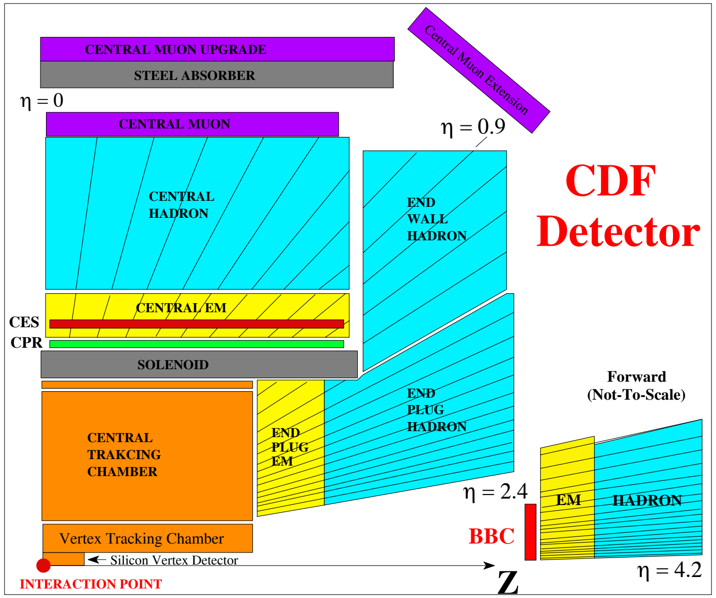
Run-IC



Scintillator fiber xy-tracker
270 µ pitch, 2 m lever arm

Acceptance: $0 < |t| < 1$, $0.03 < \xi < 0.1$

Run-IA,B

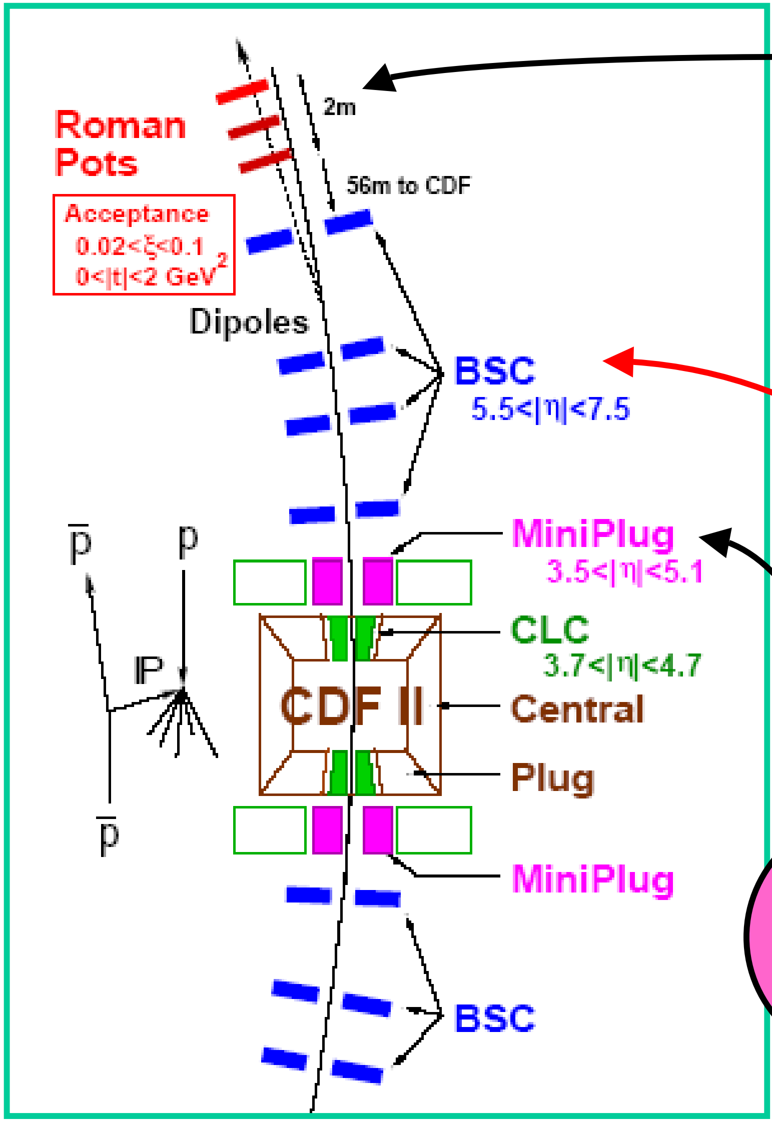


Forward Detectors

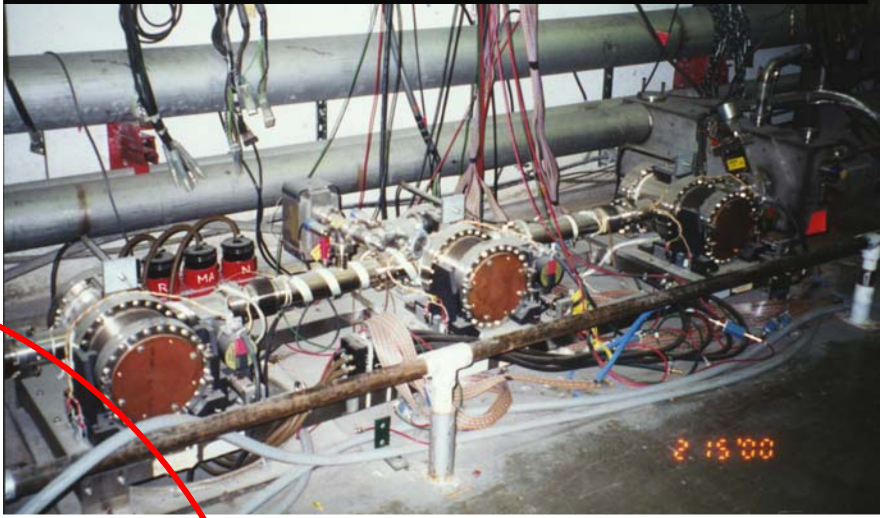
BBC $3.2<\eta<5.9$

FCAL $2.4<\eta<4.2$

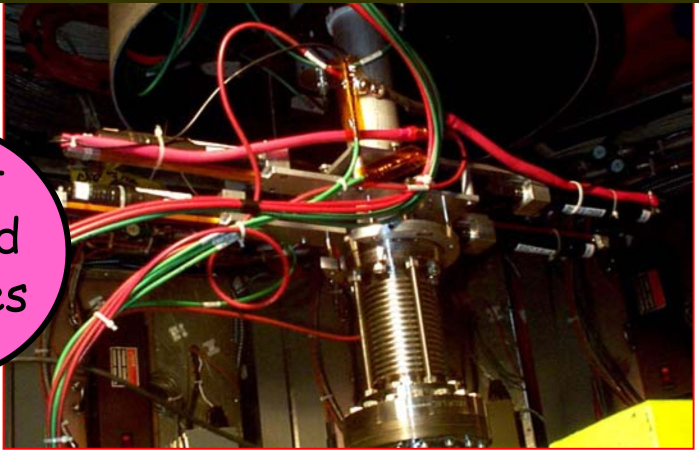
CDF-II



Tag leading p-bar @ 0.02 < ξ< 0.1

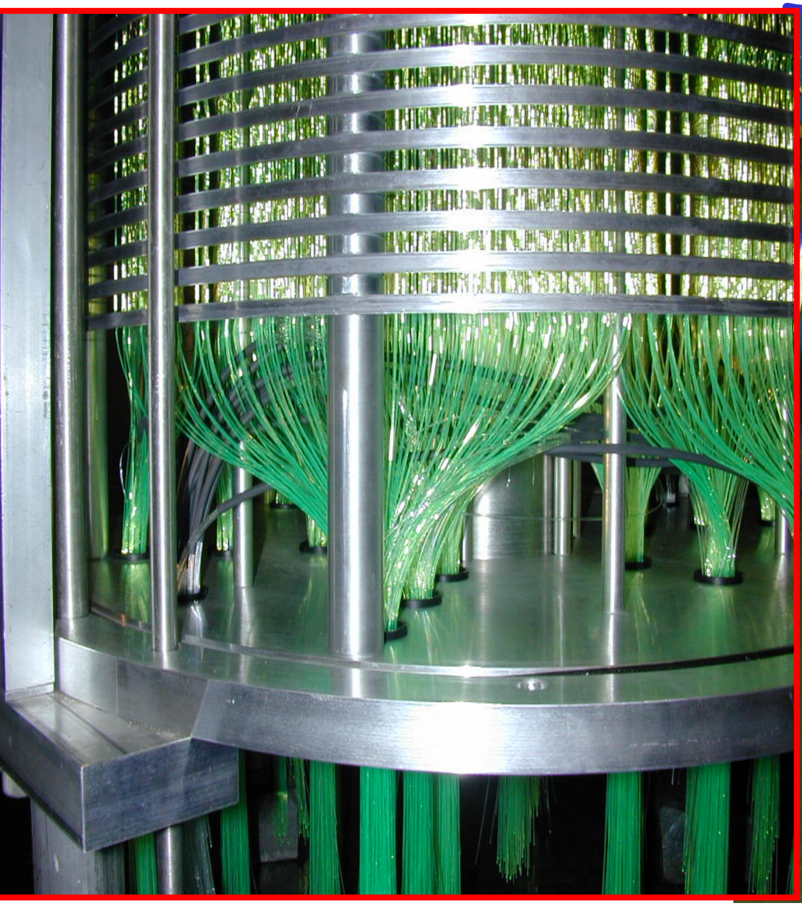


Reject (retain) 95% of ND (SD)events



detect forward particles

MiniPlug Calorimeter



About 1500 wavelength shifting fibers of 1 mm dia. are 'strung' through holes drilled in 36x$\frac{1}{4}$" lead plates sandwiched between reflective Al sheets and guided into bunches to be viewed individually by multi-channel photomultipliers.

Artist's View of MiniPlug

84 towers

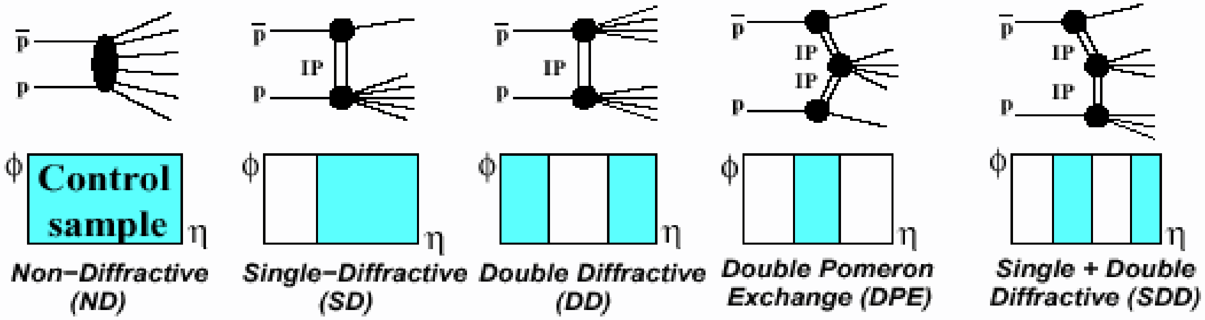
25 in

Diffraction@CDF in Run I

16 papers

- ☐ **Elastic scattering** PRD 50 (1994) 5518
- ☐ **Total cross section** PRD 50 (1994) 5550
- ☐ **Diffraction**

SOFT diffraction



PRD 50 (1994) 5535

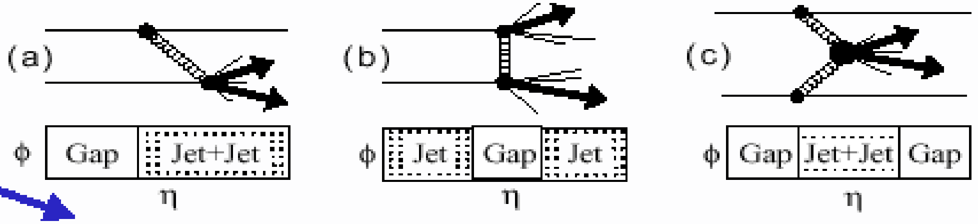
PRL 87 (2001)141802

PRL 93(2004)141601

PRL 91(2003)011802

HARD diffraction

PRL references



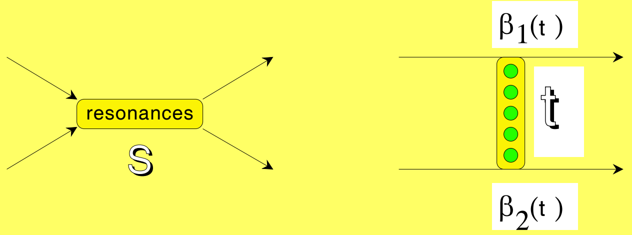
with roman pots

JJ	84 (2000) 5043
JJ	88 (2002) 151802

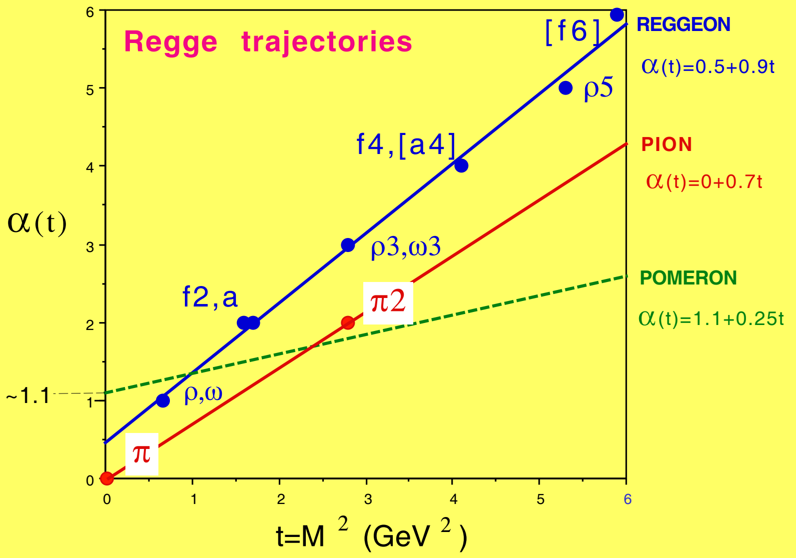
W 78 (1997) 2698	JJ 74 (1995) 855	JJ 85 (2000) 4217
JJ 79 (1997) 2636	JJ 80 (1998) 1156	
b-quark 84 (2000) 232	JJ 81 (1998) 5278	
J/ψ 87 (2001) 241802		

Elastic & Total Cross Sections

REGGE THEORY



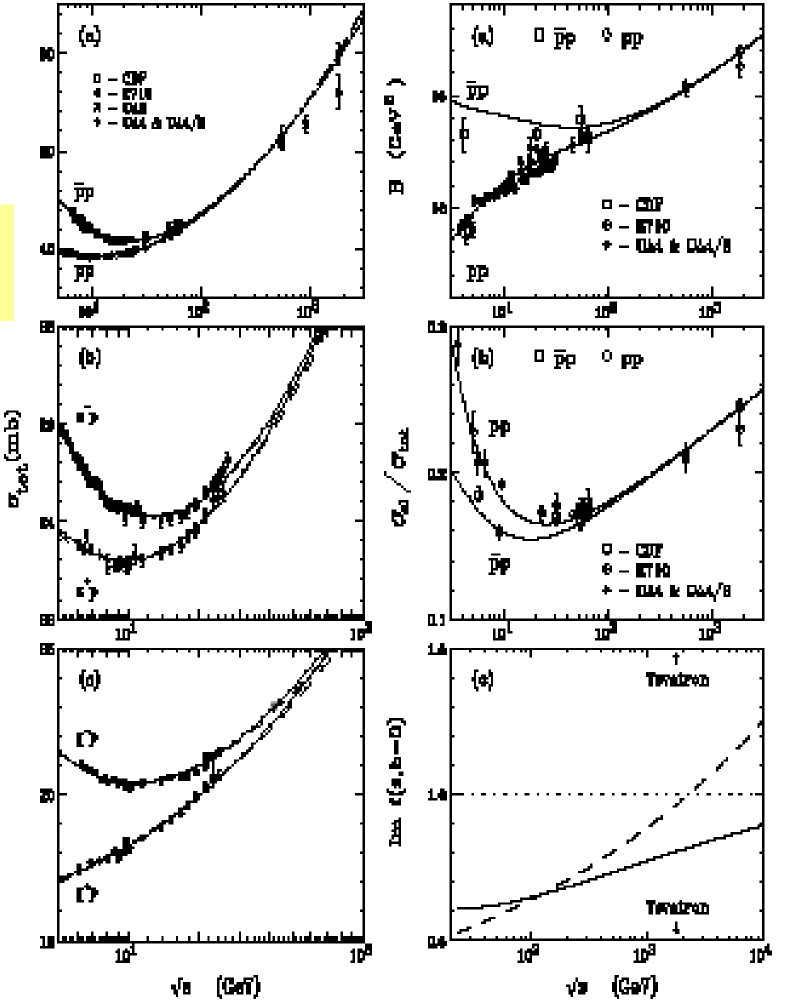
$$T(s,t) = \frac{1}{s}\beta_1(t)\,\beta_2(t)\,s^{\alpha(t)}\,\phi_{a(t)} \qquad \sigma_T = \beta^2(0)\,s^{\alpha(0)-1} \sim s^{\varepsilon}$$



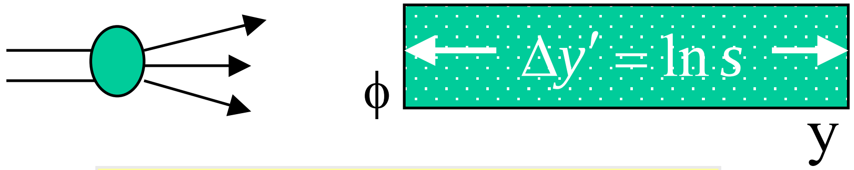
Total and Elastic Cross Sections

Covolan, Montanha and Goulianos, Phys. Lett. B 389 (1996) 176

$\alpha_{I\!P} = 1 + \epsilon(\Rightarrow 0.104) + 0.25t \quad \alpha_{f/a} = 0.68 + 0.82t \quad \alpha_{\omega/\rho} = 0.46 + 0.92t$



The QCD Connection

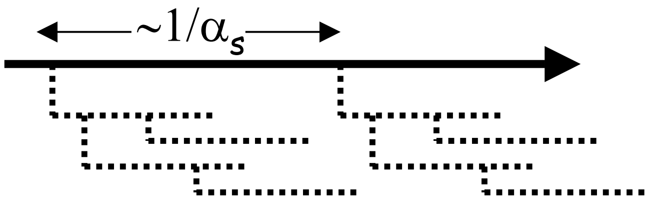


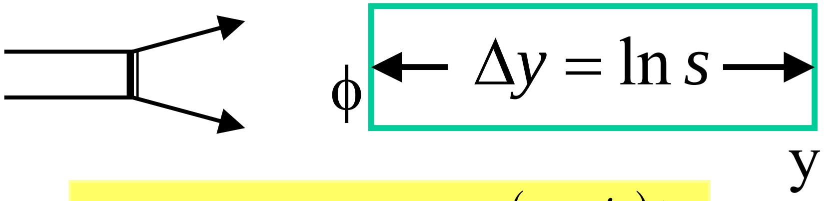
$$\sigma_T(s) = \sigma_o\, s^{\varepsilon} = \sigma_o\, e^{\varepsilon \Delta y'}$$

The exponential rise of $\sigma_T(\Delta y')$ is due to the increase of wee partons with $\Delta y'$

(see E. Levin, An Introduction to Pomerons, Preprint DESY 98-120)

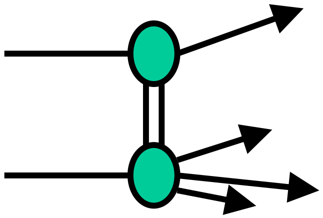
Total cross section:
power law rise with energy





$$\text{Im}\ f_{el}(s,t) \propto e^{(\varepsilon + \alpha' t)\Delta y}$$

Elastic cross section
forward scattering amplitude



Single Diffraction

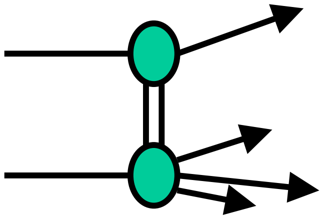
$$\frac{d^2\sigma_{SD}}{dt\,d\xi} = f_{IP/p}(t,\xi) \bullet \sigma_{IP-\bar{p}}(M_X^2)$$

Pomeron flux

Pomeron-proton
total x-section

$$\boxed{\sigma_{SD} \sim s^{2\varepsilon}}$$

Grows faster than $\sigma_T \sim s^{\varepsilon}$



Renormalization

$$\frac{d^2\sigma_{SD}}{dt\,d\xi} = f_{IP/p}(t,\xi)\bullet\sigma_{IP-\bar{p}}(M_X^2)$$

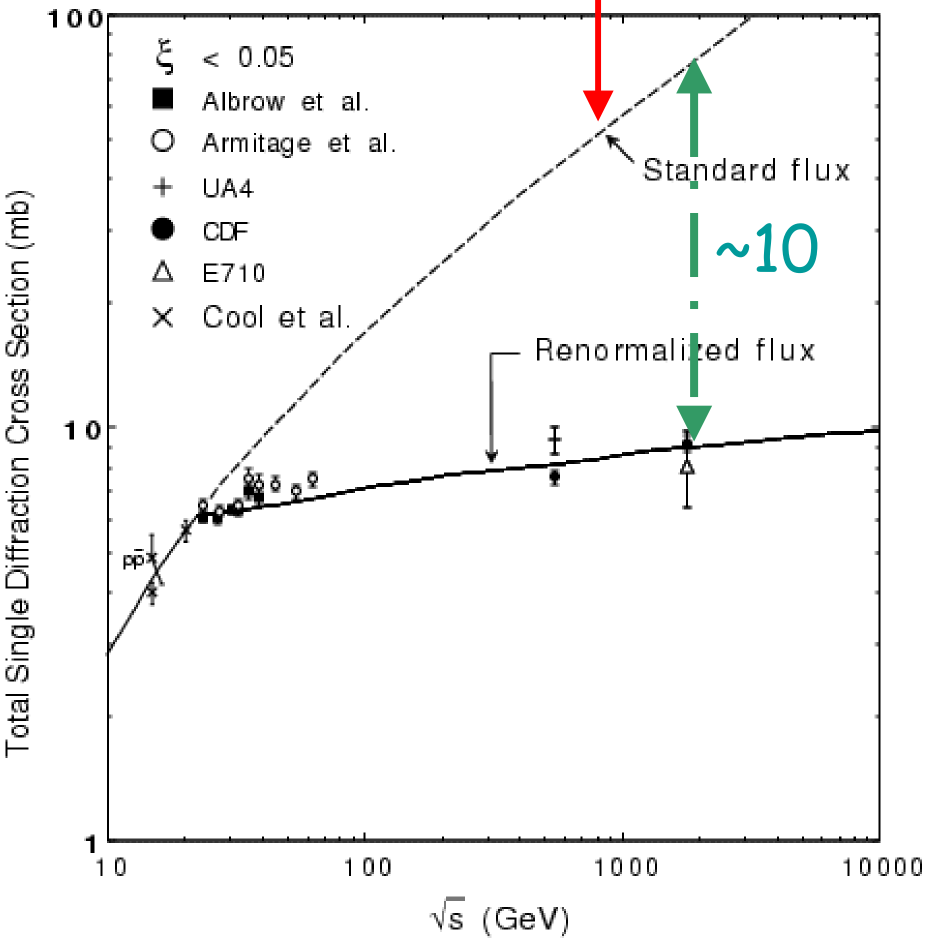
$$\sigma_{SD} \sim s^{2\varepsilon}$$

- **Unitarity problem:**
  With factorization and std pomeron flux σ_{SD} exceeds σ_T at $\sqrt{s} \approx 2\ \mathrm{TeV}$.

- **Renormalization:**
  normalize the pomeron flux to unity

KG, PLB 358 (1995) 379

$$\int_{\xi_{min}}^{0.1}\int_{t=-\infty}^{0} f_{IP/p}(t,\xi)\,d\xi\,dt = 1$$



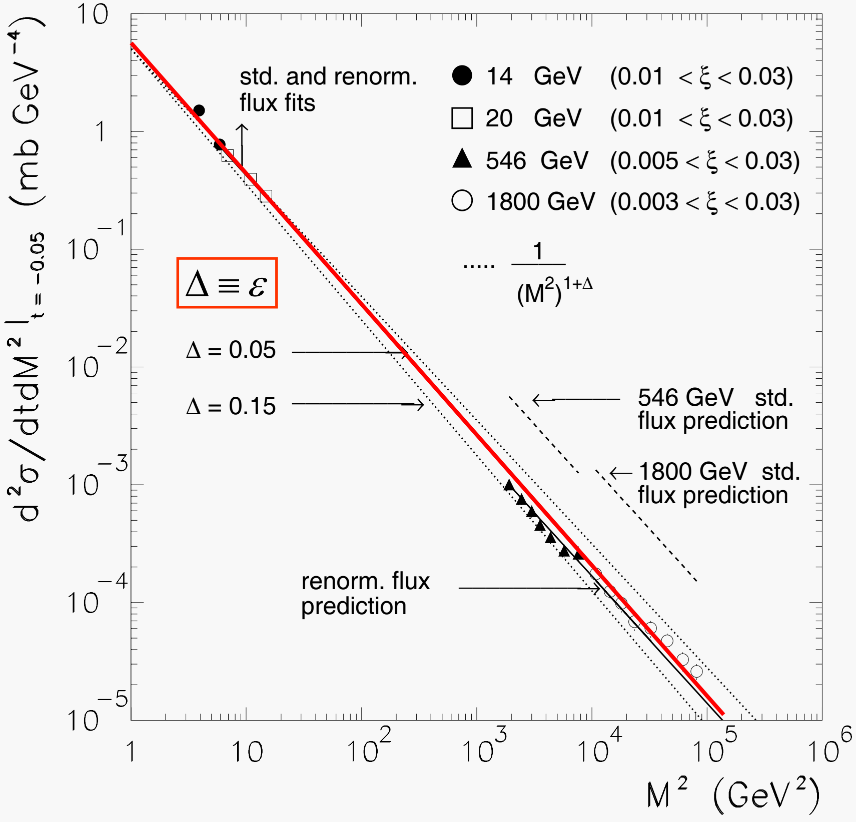
A Scaling Law in Diffraction

Factorization breaks down in favor of M^2-scaling

renormalization

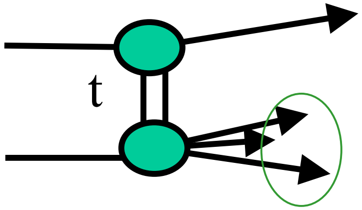
$$\frac{d\sigma}{dM^2} \propto \frac{s^{2\varepsilon} \rightarrow 1}{(M^2)^{1+\varepsilon}}$$

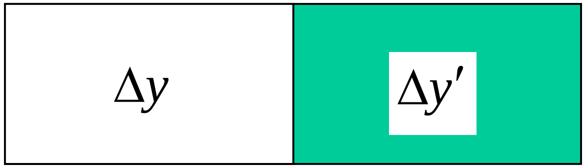
KG&JM, PRD 59 (1999) 114017



QCD Basis of Renormalization

(KG, hep-ph/0205141)





2 independent variables: $t, \Delta y$

color factor

$$\kappa = \frac{g_{IP-IP-IP}(t)}{\beta_{IP-p-p}(0)} \approx 0.17$$

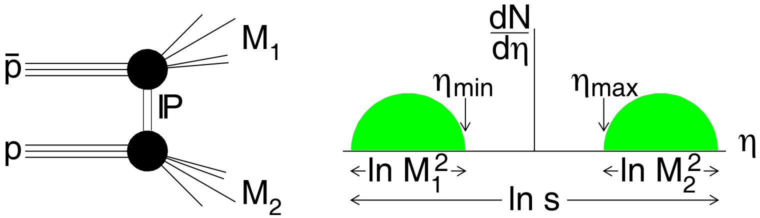
$$\frac{d^2\sigma}{dt\, d\Delta y} = \underbrace{C \bullet F_p^2(t) \bullet \left\{e^{(\varepsilon+\alpha' t)\Delta y}\right\}^2}_{\text{Gap probability}} \bullet \kappa \bullet \underbrace{\left\{\sigma_o\, e^{\varepsilon\, \Delta y'}\right\}}$$

$$\downarrow$$

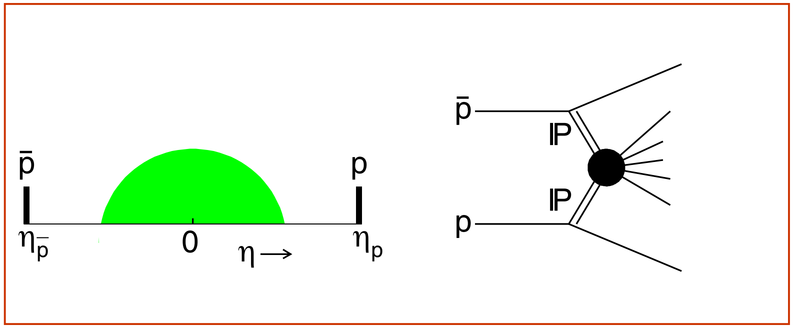
$$\sim e^{2\varepsilon\Delta y} \longrightarrow \boxed{\int_{\Delta y_{\min}}^{\Delta y=\ln s} s^{2\varepsilon\,\Delta y} \approx s^{2\varepsilon}}$$

Renormalization removes the s-dependence → SCALING

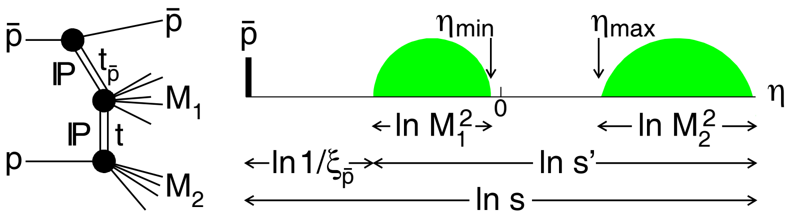
Central and Double Gaps



- ❑ **Double Diffraction Dissociation**
  - ➢ **One central gap**



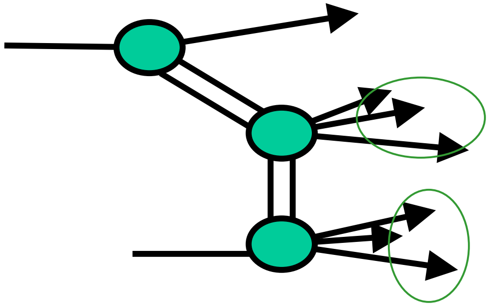
- ❑ **Double Pomeron Exchange**
  - ➢ **Two forward gaps**

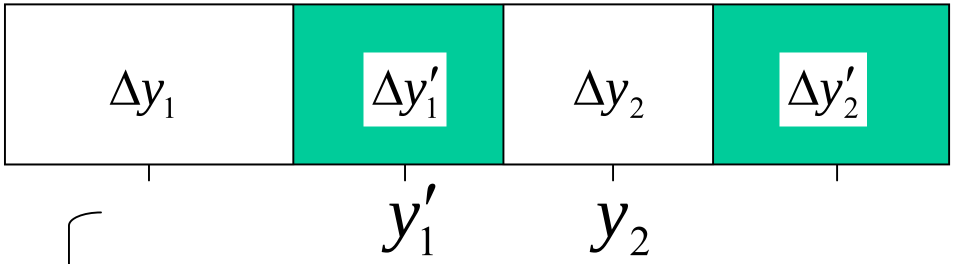


- ❑ **SDD: Single+Double Diffraction**
  - ➢ **One forward + one central gap**

Multigap Renormalization

(KG, hep-ph/0205141)





5 independent variables $\left\{ \begin{array}{l} y_1' \quad y_2 \\ t_1 \quad \Delta y = \Delta y_1 + \Delta y_2 \quad t_2 \end{array} \right.$

color factors

$$\frac{d^5\sigma}{\prod_{i=1-5} dV_i} = \underbrace{C\times F_p^2(t_1)\prod_{i=1-2}\left\{e^{(\varepsilon+\alpha' t_i)\Delta y_i}\right\}^2}_{\text{Gap probability}} \times \kappa^2 \underbrace{\left\{\sigma_o\, e^{\varepsilon(\Delta y_1'+\Delta y_2')}\right\}}_{\text{Sub-energy cross section (for regions with particles)}}$$

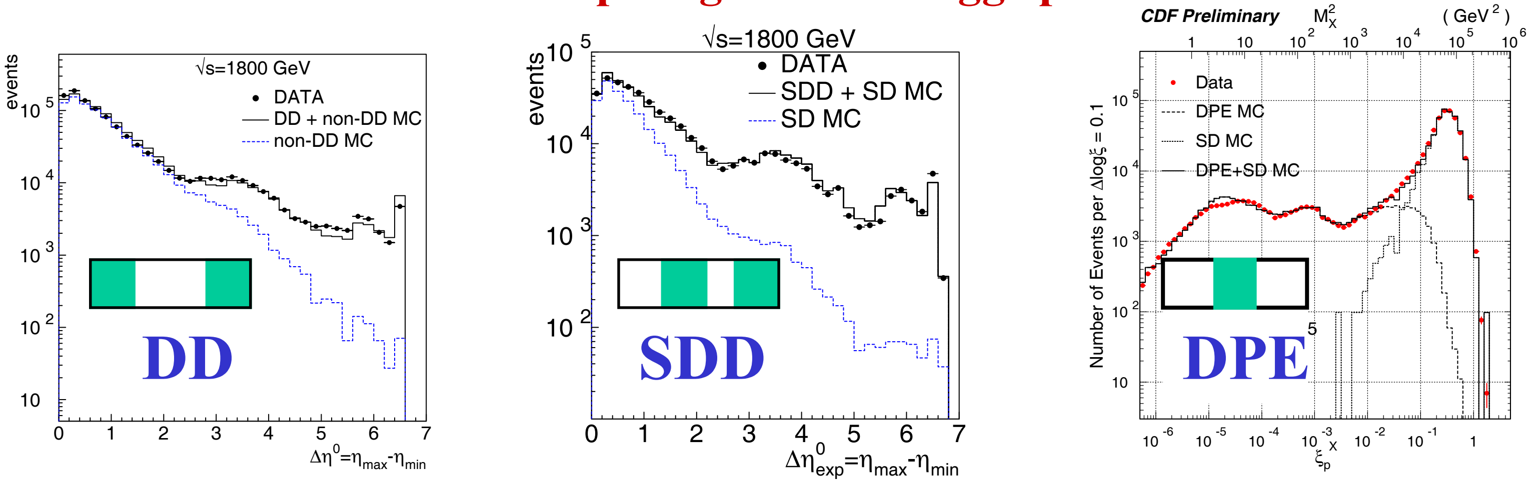
$$\sim e^{2\varepsilon\Delta y}$$

$$\boxed{\int_{\Delta y_{\min}}^{\Delta y=\ln s} s^{2\varepsilon\,\Delta y} \approx s^{2\varepsilon}}$$

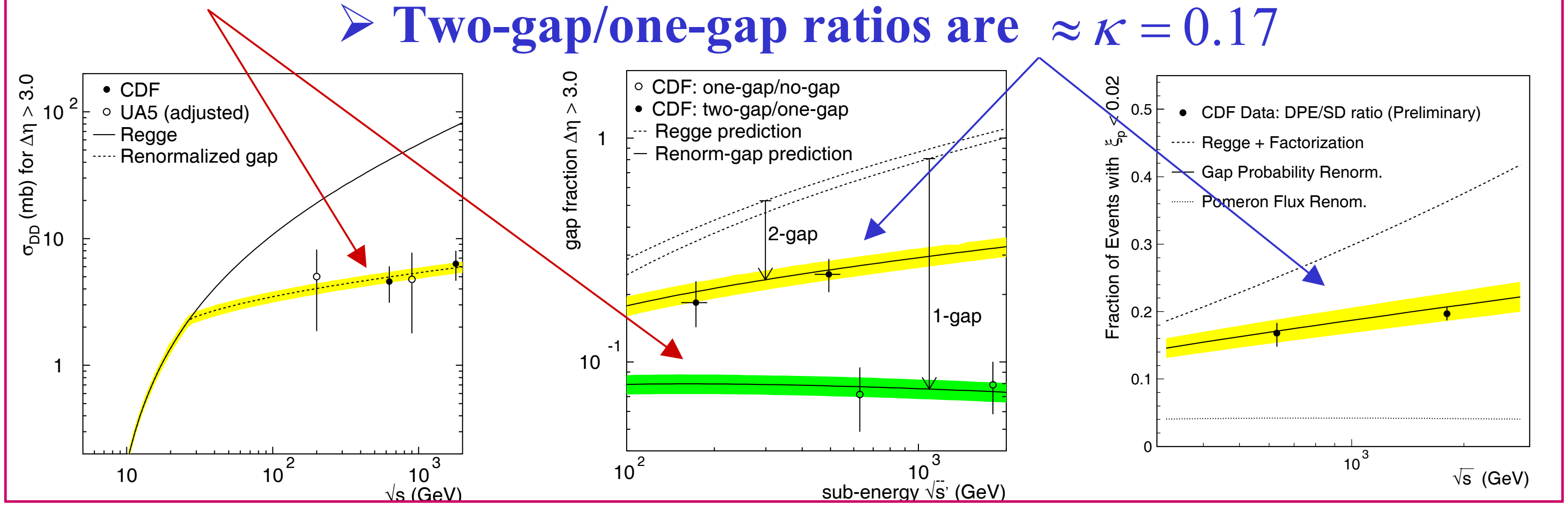
Same suppression as for single gap!

Central & Double-Gap CDF Results

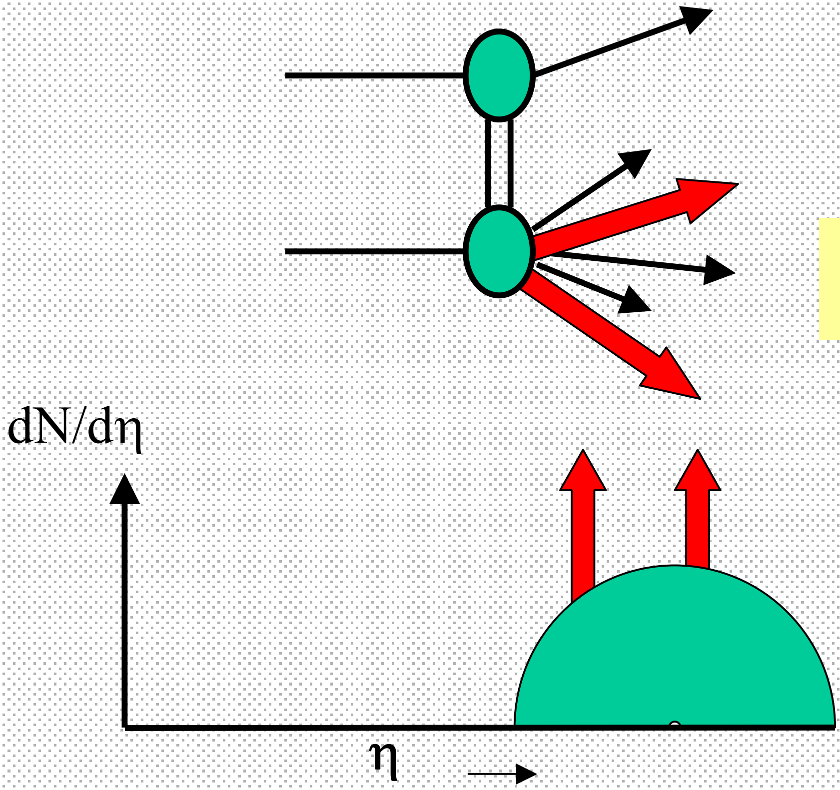
Differential shapes agree with Regge predictions



- **One-gap cross sections are suppressed**
  - **Two-gap/one-gap ratios are** $\approx \kappa = 0.17$



Hard Diffraction @ CDF



JJ, W, b, J/ψ

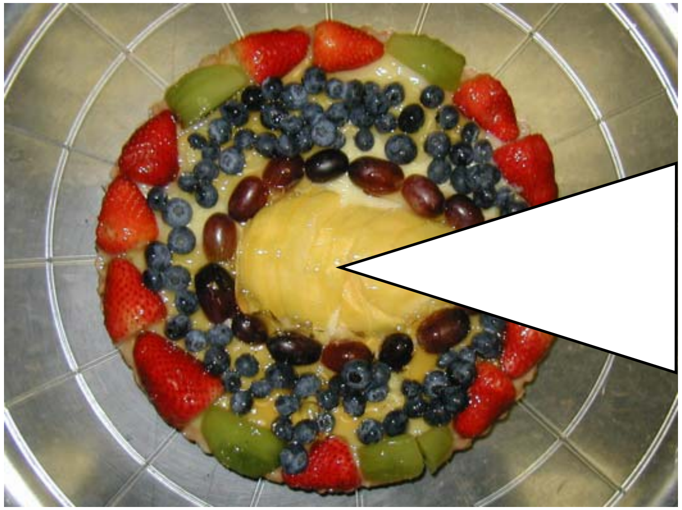
Diffractive Fractions @ CDF

$$\bar{p}p \rightarrow (Hd + X) + \text{gap}$$

SD/ND ratio at 1800 GeV

Hd	Fraction(%)
W	1.15 (0.55)
JJ	0.75 (0.10)
b	0.62 (0.25)
J/ψ	1.45 (0.25)

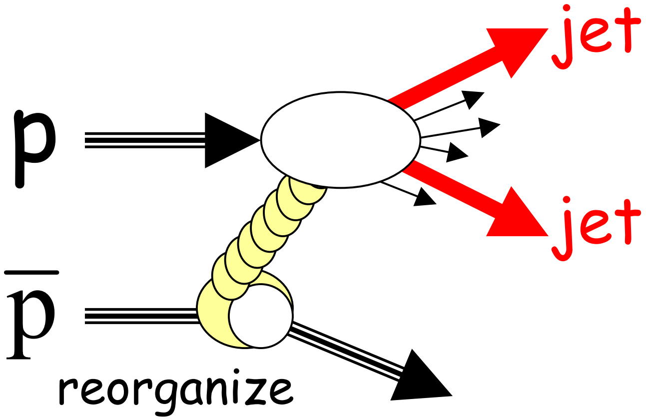
All ratios ~ 1%
➔~ uniform suppression
~ FACTORIZATION



Did the person who ate the missing piece of pie remove any fruit from the rest of the pie!

Diffractive Dijets @ Tevatron

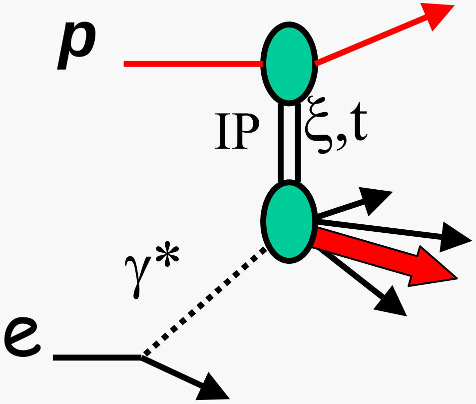
Factorization breaks down: but how?



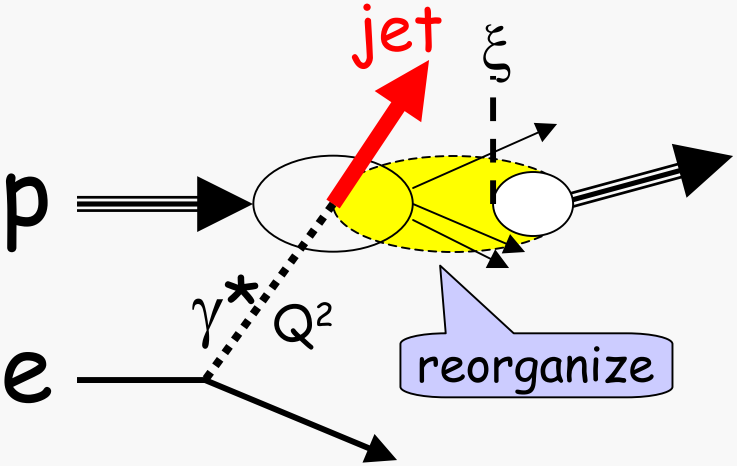
$$F^{D}(\xi,x,Q^2)\propto\frac{1}{\xi^{1+2\varepsilon}}\cdot F(x/\xi,Q^2)$$

Diffractive DIS @ HERA

Pomeron exchange



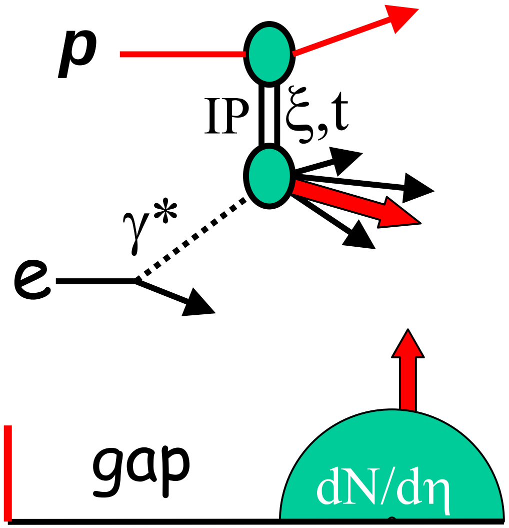
Color reorganization

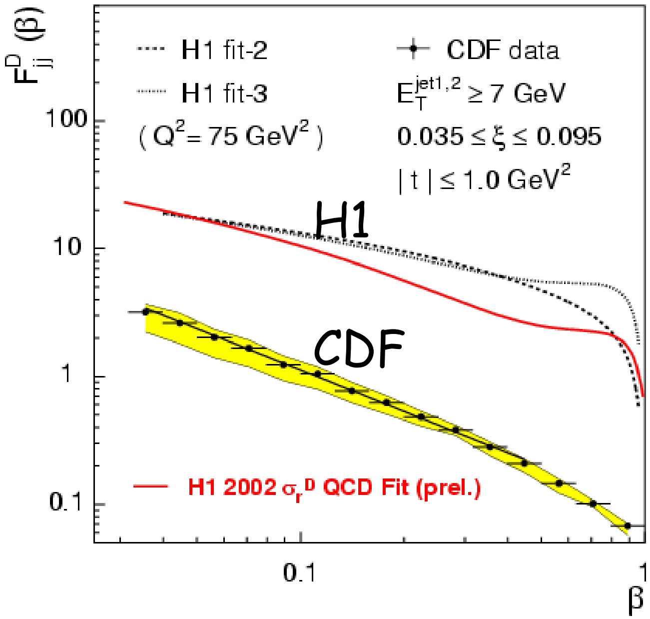


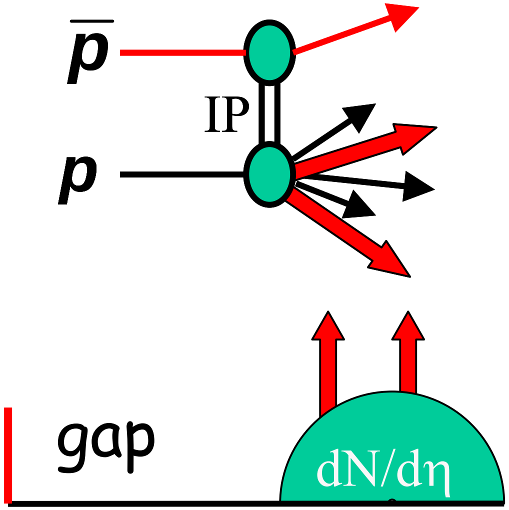
Factorization holds
(John Collins)

Tevatron vs HERA: Factorization Breakdown

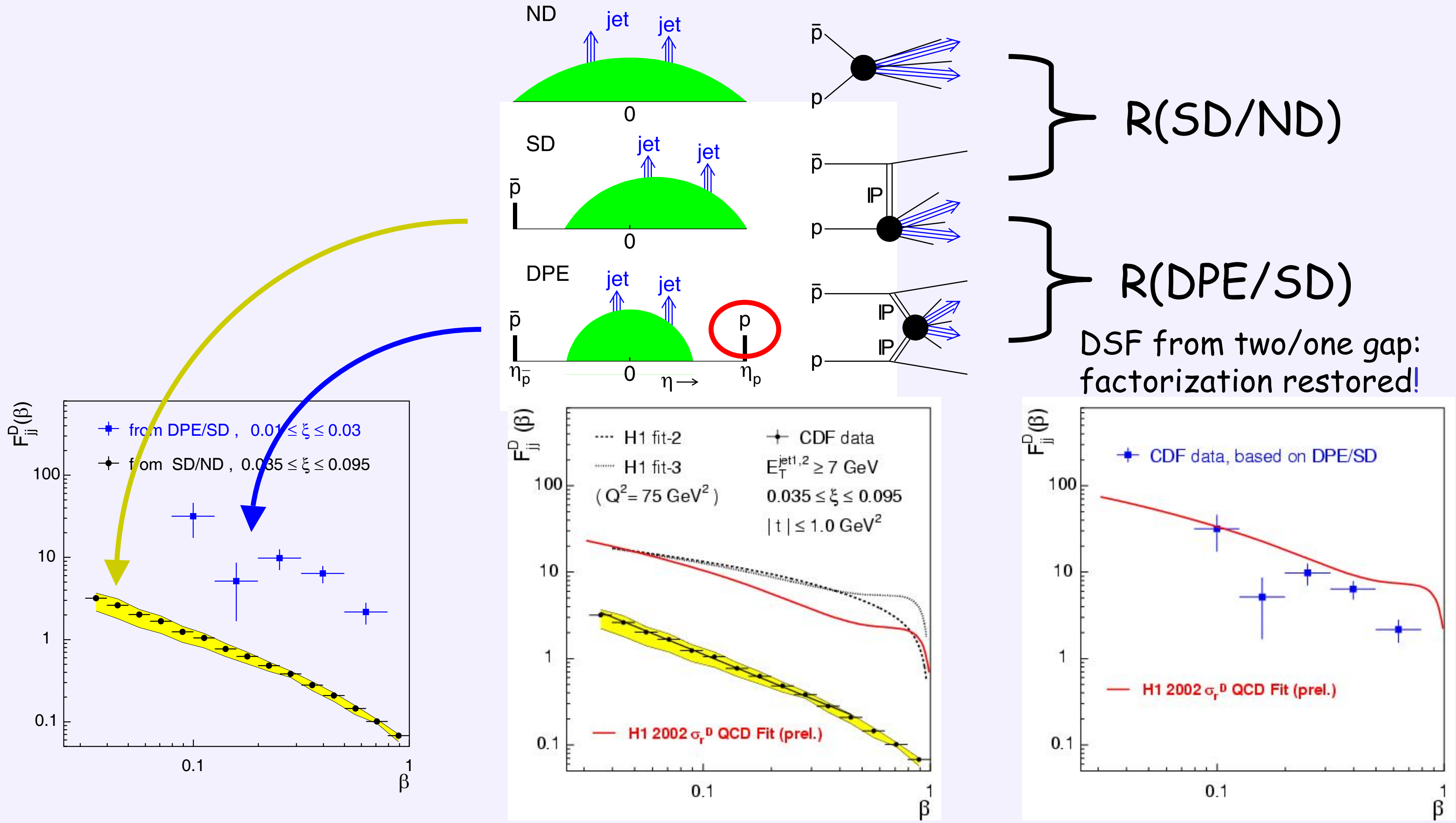
Predicted in KG, PLB 358 (1995) 379







Restoring Factorization



R(SD/ND)

R(DPE/SD)

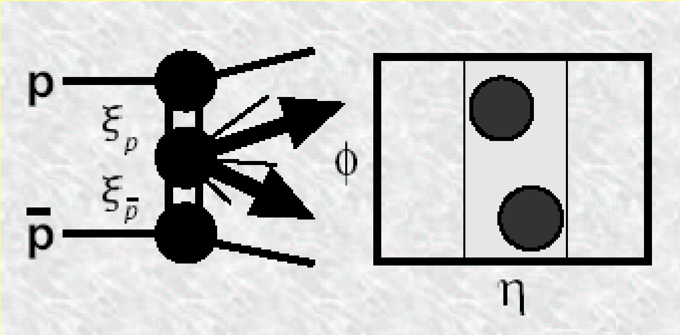
DSF from two/one gap:
factorization restored!

Diffractive Higgs Production

Interest in diffractive Higgs production

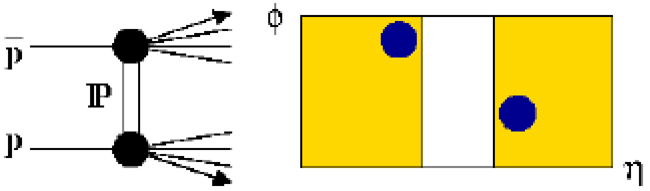
Khoze, Martin, Ryskin
Eur. Phys. J.
C23, 311 (2001),
C26, 229 (2002)

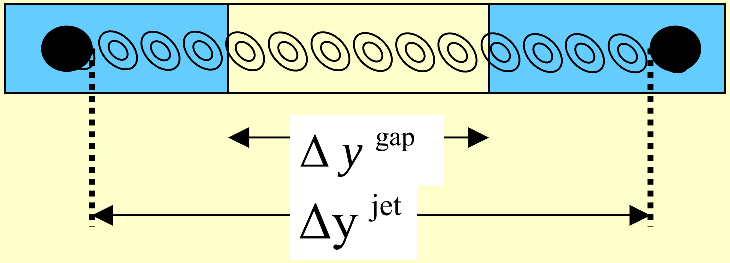
Calibrate on exclusive dijets



Gap Between Jets

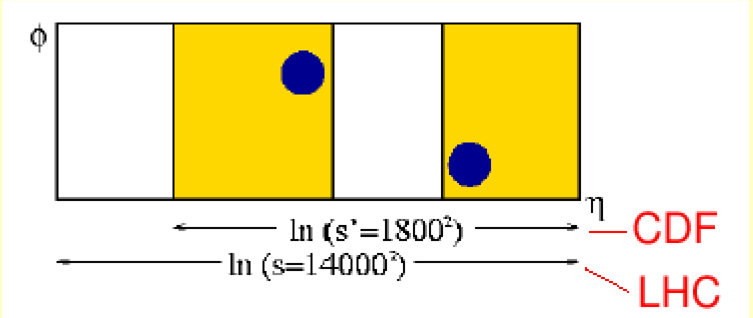
$$\bar{p} + p \to \text{Jet} + \text{Gap} + \text{Jet}$$



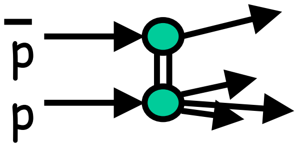


Question

$$\Delta y^{gap} \xleftrightarrow{???} \Delta y^{jet}$$

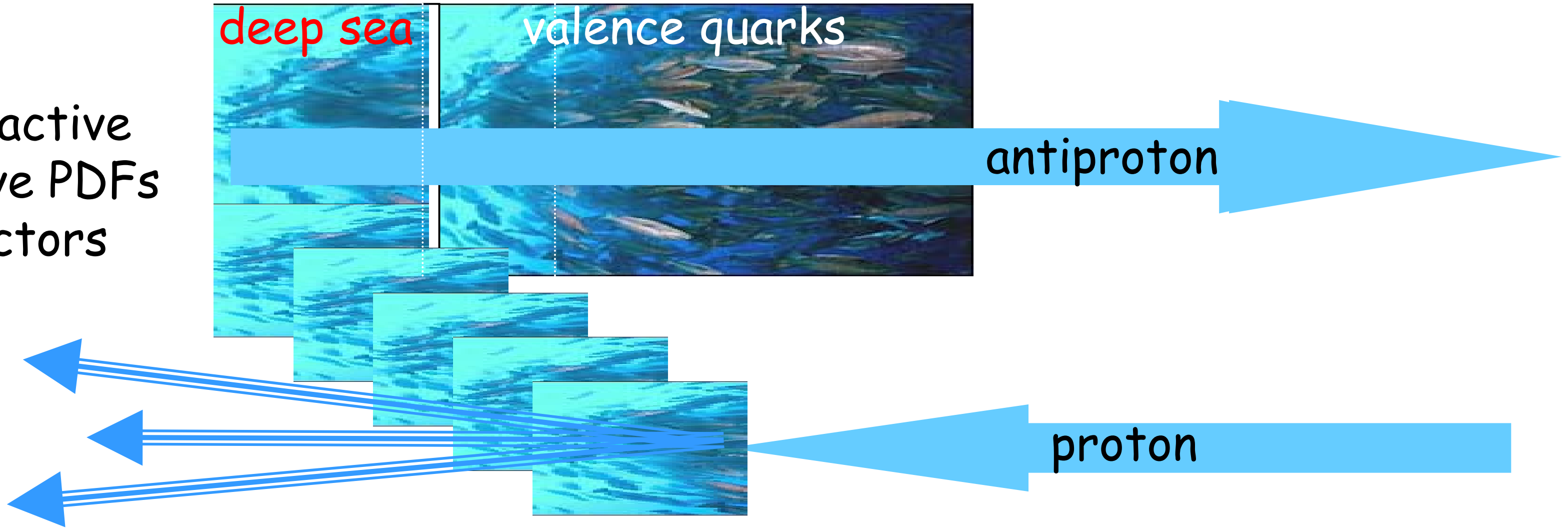


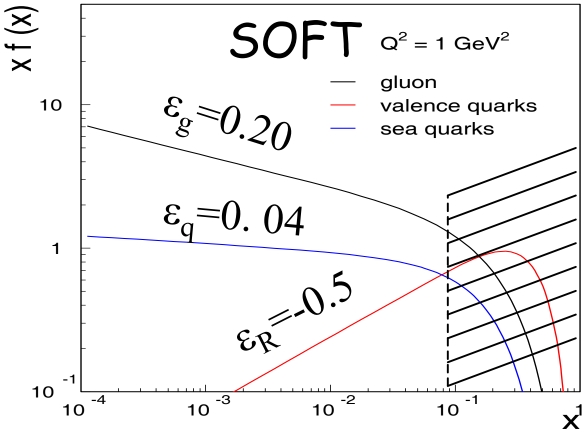
$$R_{LHC}^{J-G-J}(s') = R_{TEV}^{J-G-J}/S \approx 1\%/0.2 \approx 5\%$$



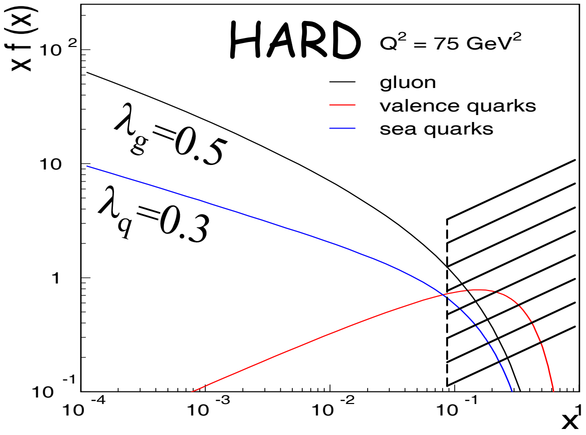
Diffraction in QCD

Derive diffractive from inclusive PDFs and color factors





$$x \cdot f(x) = \frac{1}{x^{\varepsilon\,(\text{or}\,\lambda)}}$$



The Rockefeller Experimental HEP Group


Anwar


Luc


Stefano


Michele

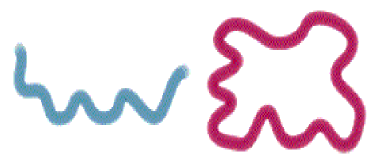

Mary

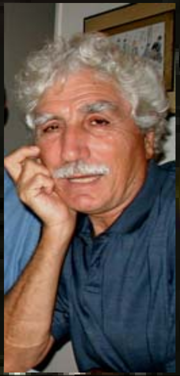

Koji


Christina


Andrea


Ken





It surely makes an interesting T-shirt!