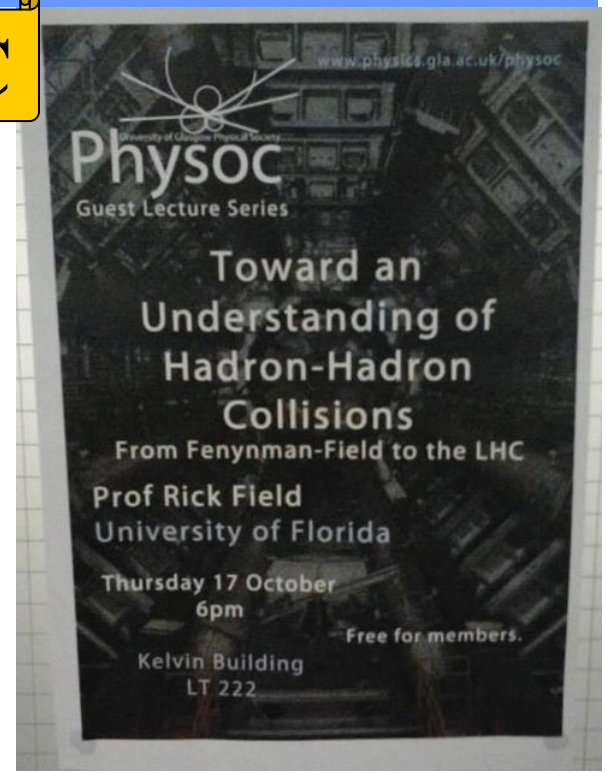
Toward an Understanding of Hadron-Hadron Collisions

From Feynman-Field to the LHC

Rick Field

University of Florida

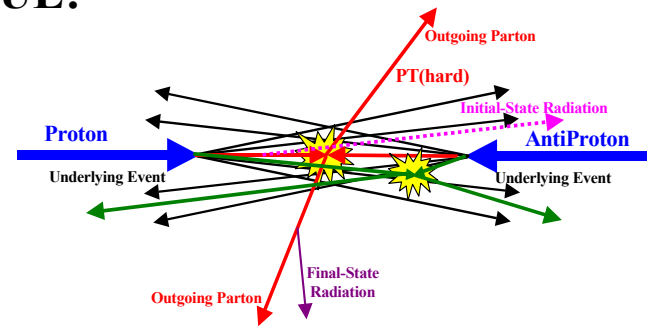
Quantum Chromo-Dynamics



Outline of Talk

- Ricky & Sally.
- The Berkeley Years – Rick & Jimmie.

- The early days of Feynman-Field Phenomenology.
- Mapping out the energy dependence of the UE: Tevatron to the LHC.
- Early LHC UE predictions.
- From 7 GeV/c pions to 1 TeV jets!



Margaret Morlan

Margaret Field in "The Man From Planet X" (1951)

http://www.youtube.com/watch?v=896jnOb1fcI

Ricky Field - Scientist

Sally Field - Actress

- **My mother was born on May 10, 1922, in Houston Texas. She died on Sunday November 6, 2011 in Malibu, California at age 89.**

Margaret Morlan

Margaret Field in "The Man From Planet X" (1951)

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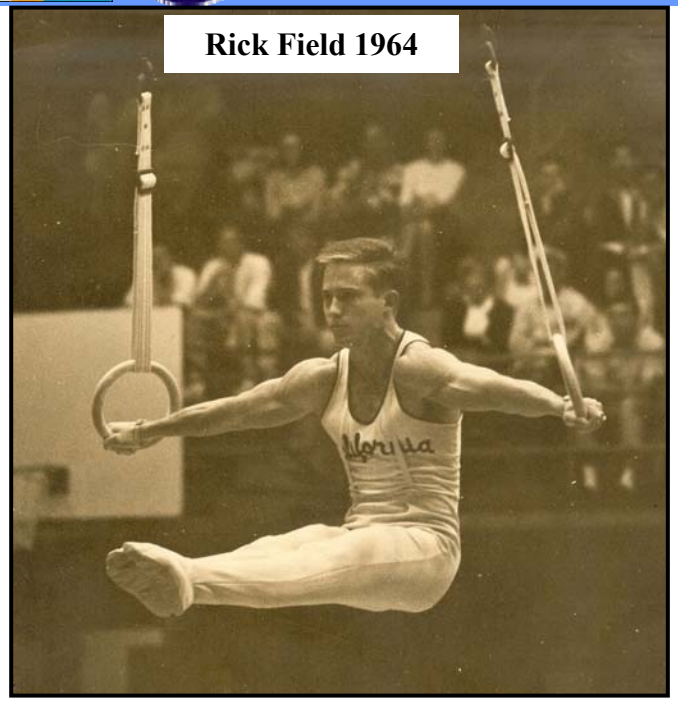
Sally Field - Actress

The Berkeley Years



Rick Field 1964

R. D. Field
University of California, Berkeley, 1962-66 (*undergraduate*)
University of California, Berkeley, 1966-71 (*graduate student*)

Rick & Jimmie 1968

The Berkeley Years

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Volume 31B, number 9 PHYSICS LETTERS 27 April 1970

BACKWARD np SCATTERING WITH A POLARIZED TARGET*

P. R. ROBRISH, O. CHAMBERLAIN, R. D. FIELD Jr., R. Z. FUZESY, W. GORN, C. C. MOREHOUSE
T. POWELL, S. ROCK, S. SHANNON, G. SHAPIRO and H. WEISBERG
University of California, Lawrence Radiation Laboratory, Berkeley, California 94720, *USA*

and

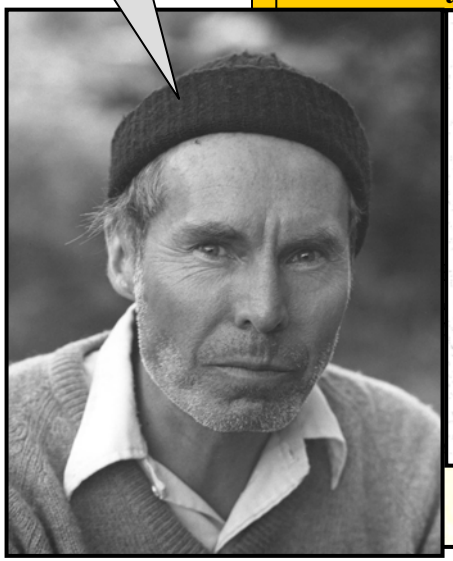
M. J. LONGO
University of Michigan, Ann Arbor, Michigan 48104, *USA*

Received 16 March 1970

The Berkeley Years

My Ph.D. advisor!

R. D. Field
University of California, Berkeley, 1962-66 (*undergraduate*)
University of California, Berkeley, 1966-71 (*graduate student*)



PHYSICAL REVIEW D VOLUME 4, NUMBER 3 1 AUGUST 1971

Evidence on Duality and Exchange Degeneracy from Finite-Energy Sum Rules: $K^-n \to \pi^-\Lambda$ and $\pi^+n \to K^+\Lambda$†

R. D. Field, Jr. and J. D. Jackson
Department of Physics and Lawrence Radiation Laboratory, University of California, Berkeley, California 94720
(Received 5 April 1971)

Using finite-energy sum rules for the reactions $K^-n \to \pi^-\Lambda$ and $\pi^+n \to K^+\Lambda$, we determine the effective "pole" parameters of the K^* and K^{**} Regge trajectories from a knowledge of the low-energy resonances and their couplings. The resonance parameters and the $D/(D+F)$ ratio for the $\frac{1}{2}^+$ baryon octet are varied somewhat to test the sensitivity of the high-energy predictions; $\frac{1}{2}^+$ octet couplings within the range of values found empirically in other reactions are preferred in our solution. We find that the s-channel resonances in $K^-n \to \pi^-\Lambda$ *do* add in such a way as to produce predominantly real amplitudes at high energies as predicted by duality diagrams. We find, however, that these predictions are not satisfied *exactly*.

Received 16 March 1970

The Berkeley Years

My Ph.D. advisor!

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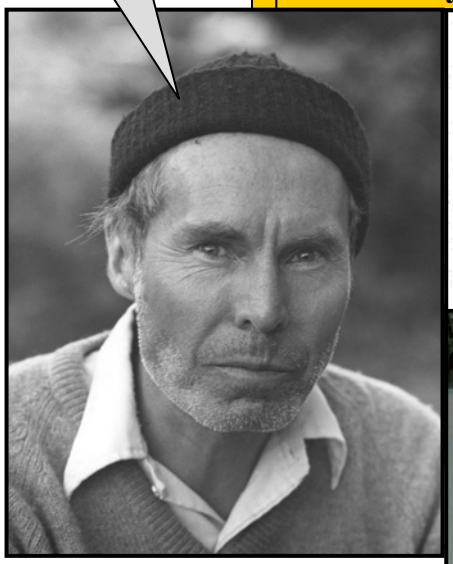

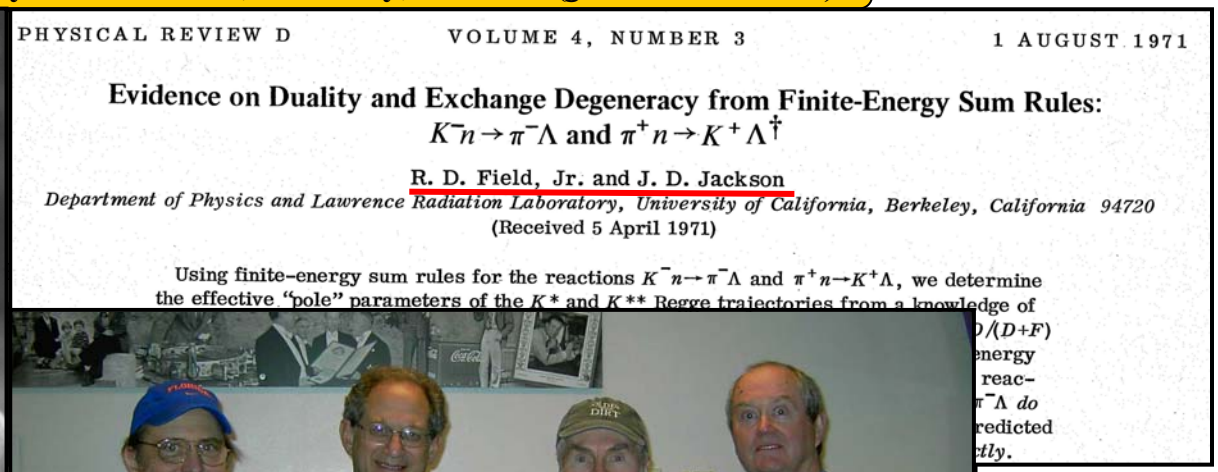

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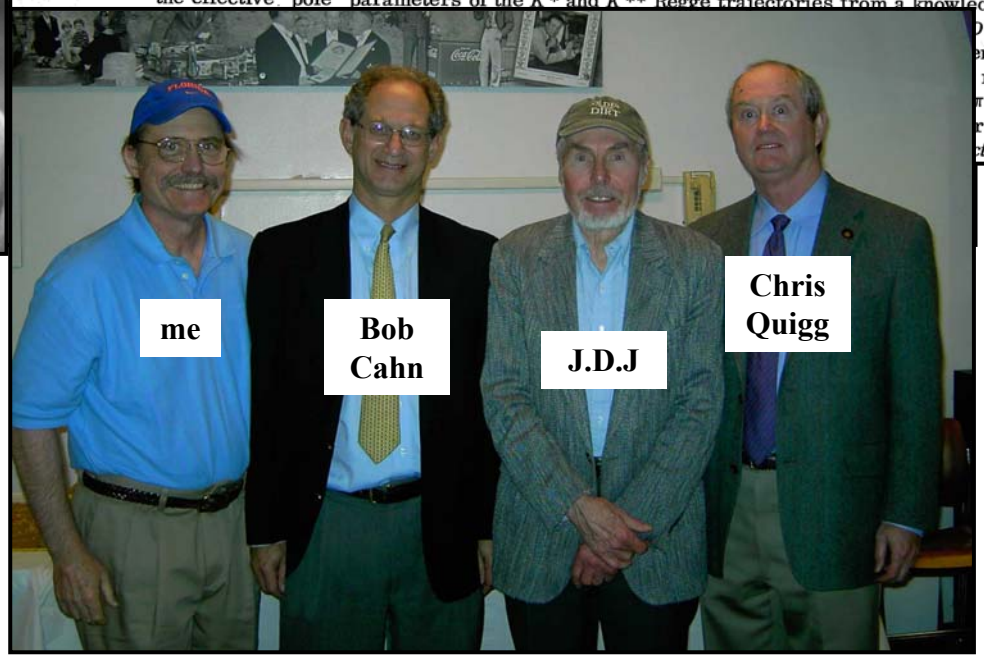


Before Feynman-Field

Rick & Jimmie
1968

Rick & Jimmie
1970

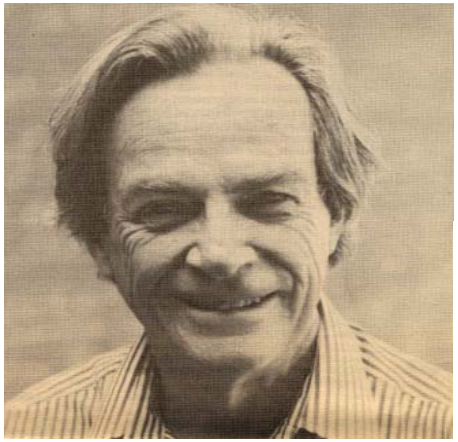
Rick & Jimmie
1972 (*pregnant!*)

Before Feynman-Field

Rick & Jimmie at CALTECH 1973

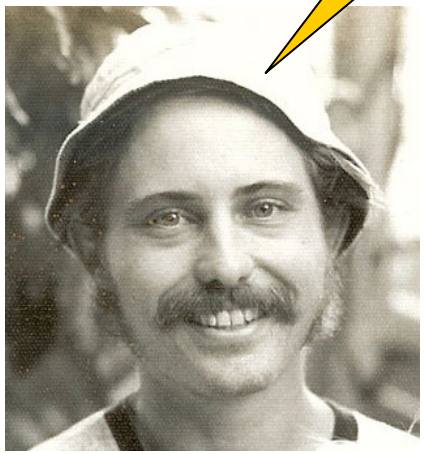
Toward and Understanding of Hadron-Hadron Collisions

Feynman-Field Phenomenology



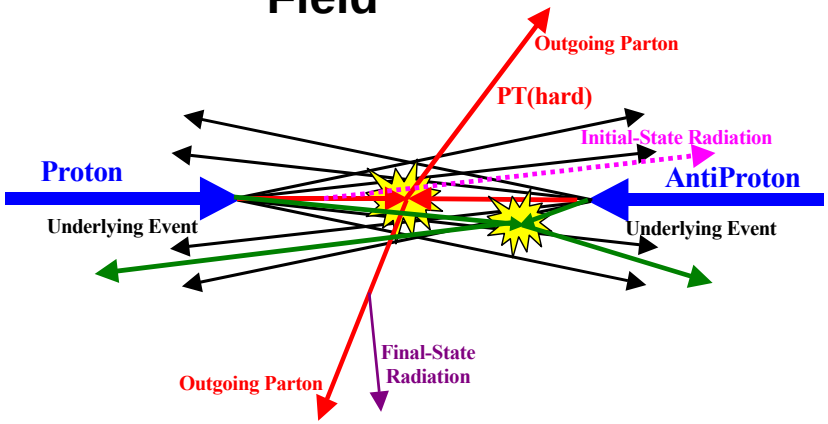
Feynman

and



Field

- **From 7 GeV/c π^0's to 1 TeV Jets. The early days of trying to understand and simulate hadron-hadron collisions.**



The Feynman-Field Days

1973-1983

"Feynman-Field Jet Model"

- **FF1: "Quark Elastic Scattering as a Source of High Transverse Momentum Mesons", R. D. Field and R. P. Feynman, Phys. Rev. D15, 2590-2616 (1977).**
- **FFF1: "Correlations Among Particles and Jets Produced with Large Transverse Momenta", R. P. Feynman, R. D. Field and G. C. Fox, Nucl. Phys. B128, 1-65 (1977).**
- **FF2: "A Parameterization of the properties of Quark Jets", R. D. Field and R. P. Feynman, Nucl. Phys. B136, 1-76 (1978).**
- **F1: "Can Existing High Transverse Momentum Hadron Experiments be Interpreted by Contemporary Quantum Chromodynamics Ideas?", R. D. Field, Phys. Rev. Letters 40, 997-1000 (1978).**
- **FFF2: "A Quantum Chromodynamic Approach for the Large Transverse Momentum Production of Particles and Jets", R. P. Feynman, R. D. Field and G. C. Fox, Phys. Rev. D18, 3320-3343 (1978).**

- **FW1: "A QCD Model for e^+e^- Annihilation", R. D. Field and S. Wolfram, Nucl. Phys. B213, 65-84 (1983).**

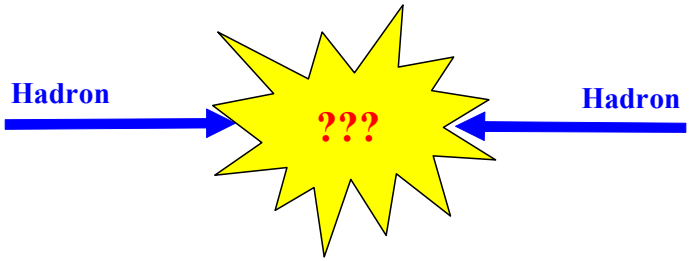
My 1st graduate student!

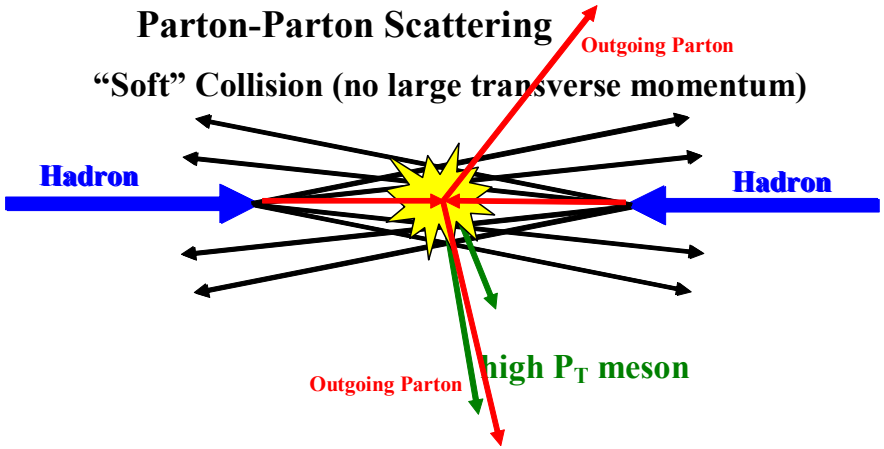
Hadron-Hadron Collisions

FF1 1977

- **What happens when two hadrons collide at high energy?**
- **Most of the time the hadrons ooze through each other and fall apart (*i.e.* no hard scattering). The outgoing particles continue in roughly the same direction as initial proton and antiproton.**
- **Occasionally there will be a large transverse momentum meson. Question: Where did it come from?**
- **We assumed it came from quark-quark elastic scattering, but we did not know how to calculate it!**

"Black-Box Model"





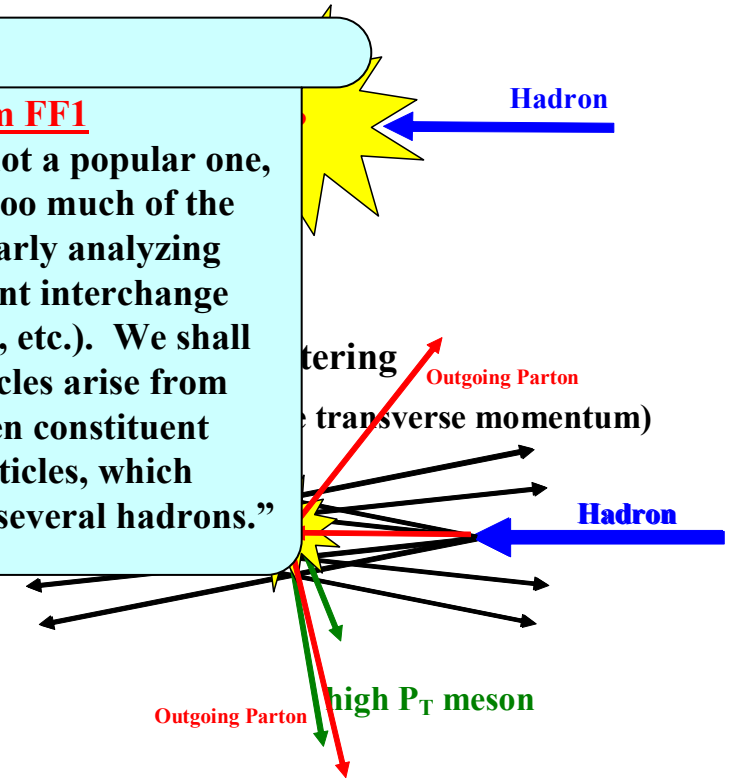
Hadron-Hadron Collisions

FF1 1977

- What happens whe
  collide at high ener
- Most of the time th
  through each other
  no hard scattering)
  particles continue i
  direction as initial p
  antiproton.
- Occasionally the
  transverse momentum meson.
  Question: Where did it come from?
- We assumed it came from quark-quark elastic scattering, but we did not know how to calculate it!

Feynman quote from FF1

"The model we shall choose is not a popular one, so that we will not duplicate too much of the work of others who are similarly analyzing various models (e.g. constituent interchange model, multiperipheral models, etc.). We shall assume that the high P_T particles arise from direct hard collisions between constituent quarks in the incoming particles, which fragment or cascade down into several hadrons."



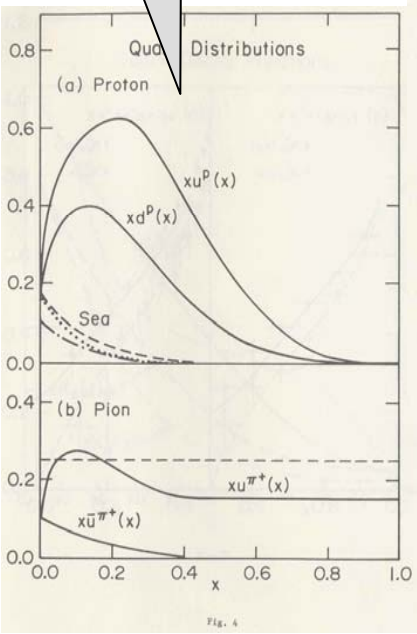
"Black-Box Model"

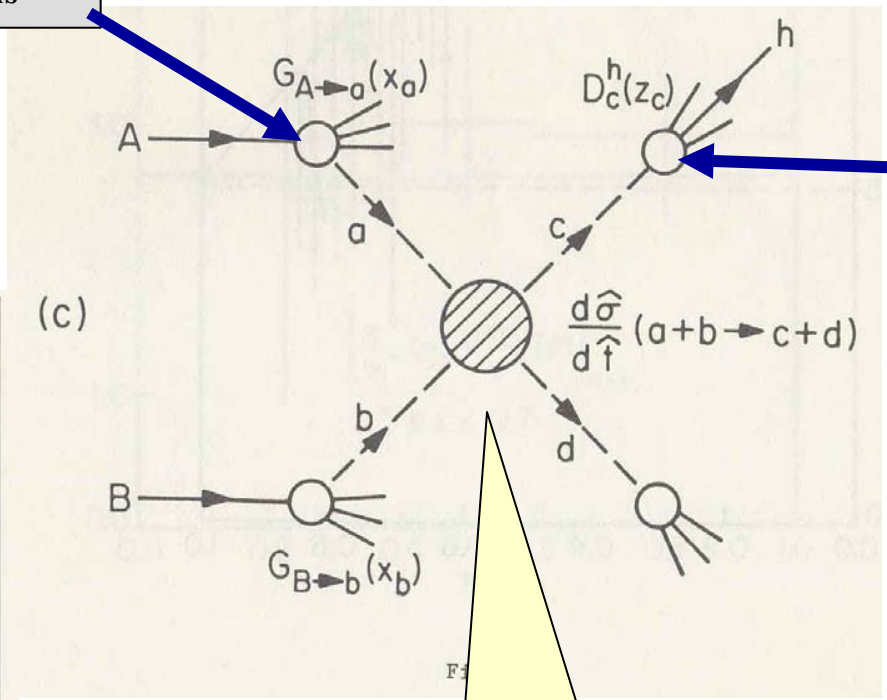
Quark-Quark Black-Box Model

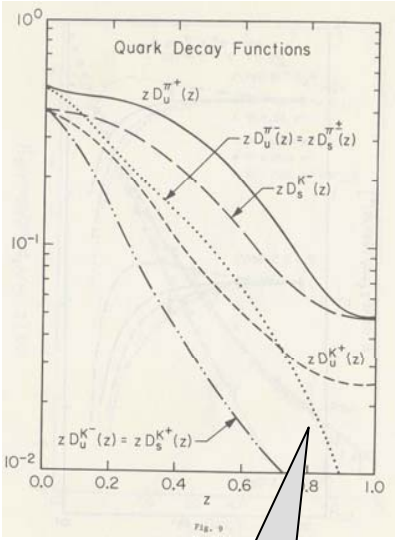
FF1 1977

No gluons!

Quark Distribution Functions
determined from deep-inelastic lepton-hadron collisions







Quark-Quark Cross-Section
Unknown! Deteremined from hadron-hadron collisions.

Quark Fragmentation Functions
determined from e^+e^- annihilations

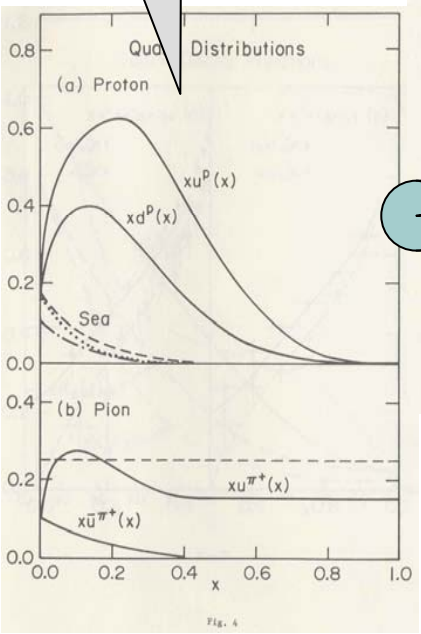
Quark-Quark Black-Box Model

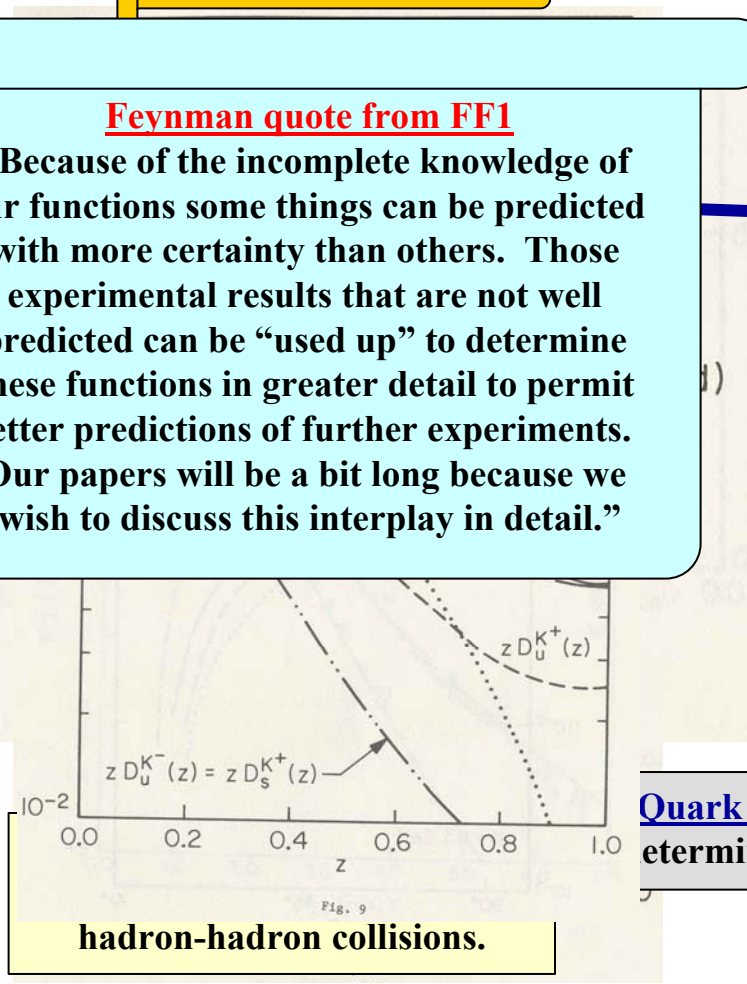
FF1 1977

No gluons!

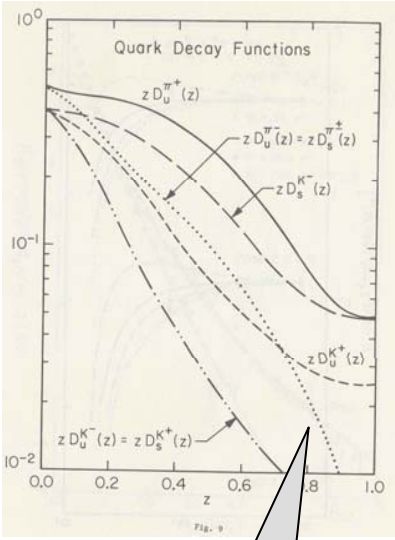
Quark Distribution Functions
determined from deep-inelastic lepton-hadron collisions

Feynman quote from FF1
"Because of the incomplete knowledge of our functions some things can be predicted with more certainty than others. Those experimental results that are not well predicted can be "used up" to determine these functions in greater detail to permit better predictions of further experiments. Our papers will be a bit long because we wish to discuss this interplay in detail."





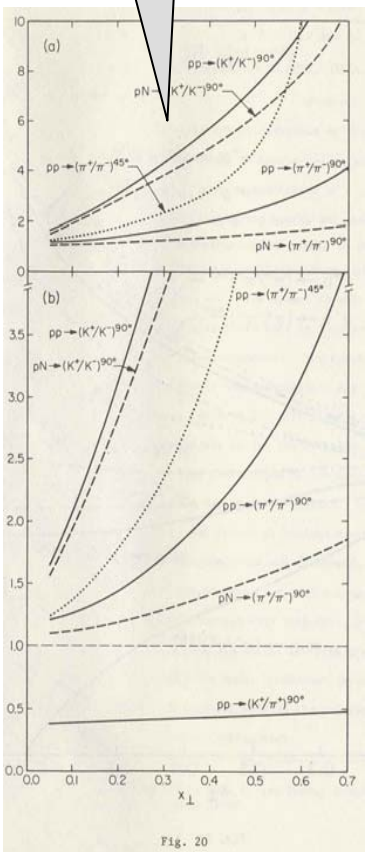
hadron-hadron collisions.



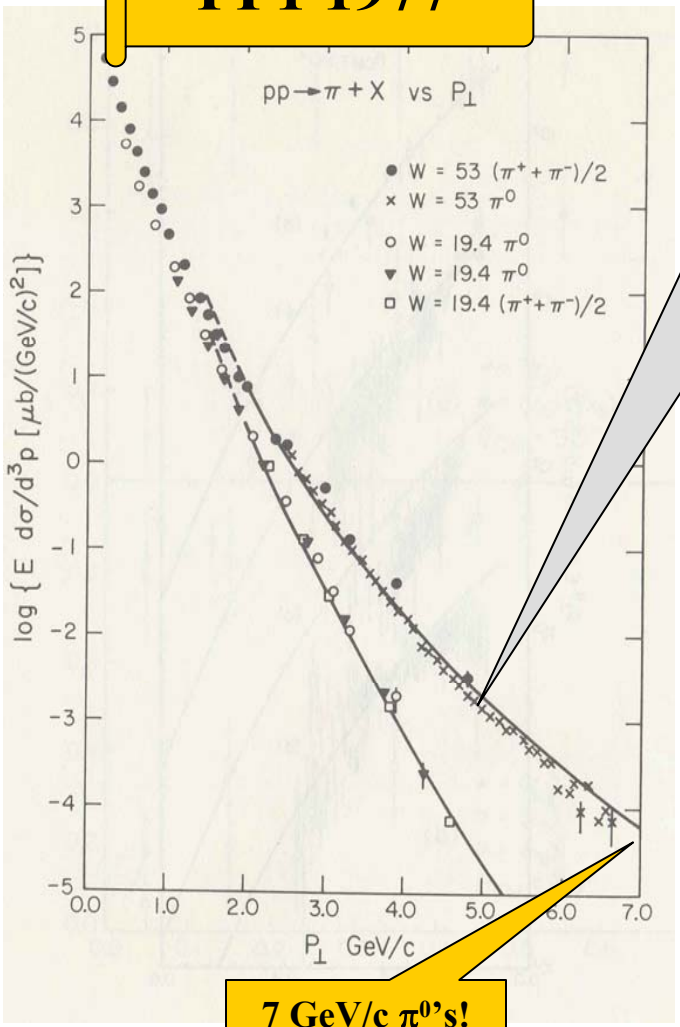
Quark Fragmentation Functions
determined from e^+e^- annihilations

Quark-Quark Black-Box Model

Predict
particle ratios

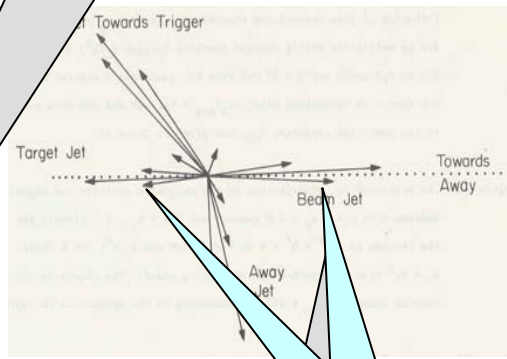


FF1 1977



7 GeV/c π^0's!

Predict
increase with increasing CM energy W



"Beam-Beam Remnants"

Predict
overall event topology (FFF1 paper 1977)

Telagram from Feynman

July 1976

western union

Telefax

ICS IPMIINA IISS

IISS FK WUI 19 0249

PMS PASADENA CA

UWA1871 PSX555 310384W 7290

UWNX CO FRXX OIS

CHAMONIXMONTBLANC

RICK FIELD CALTECH

PASADENA/CALIF

SAW CRONIN AM NOW CONVINCED WERE RIGHT TRACK QUICK WRITE

FEY

NBAM

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FEY

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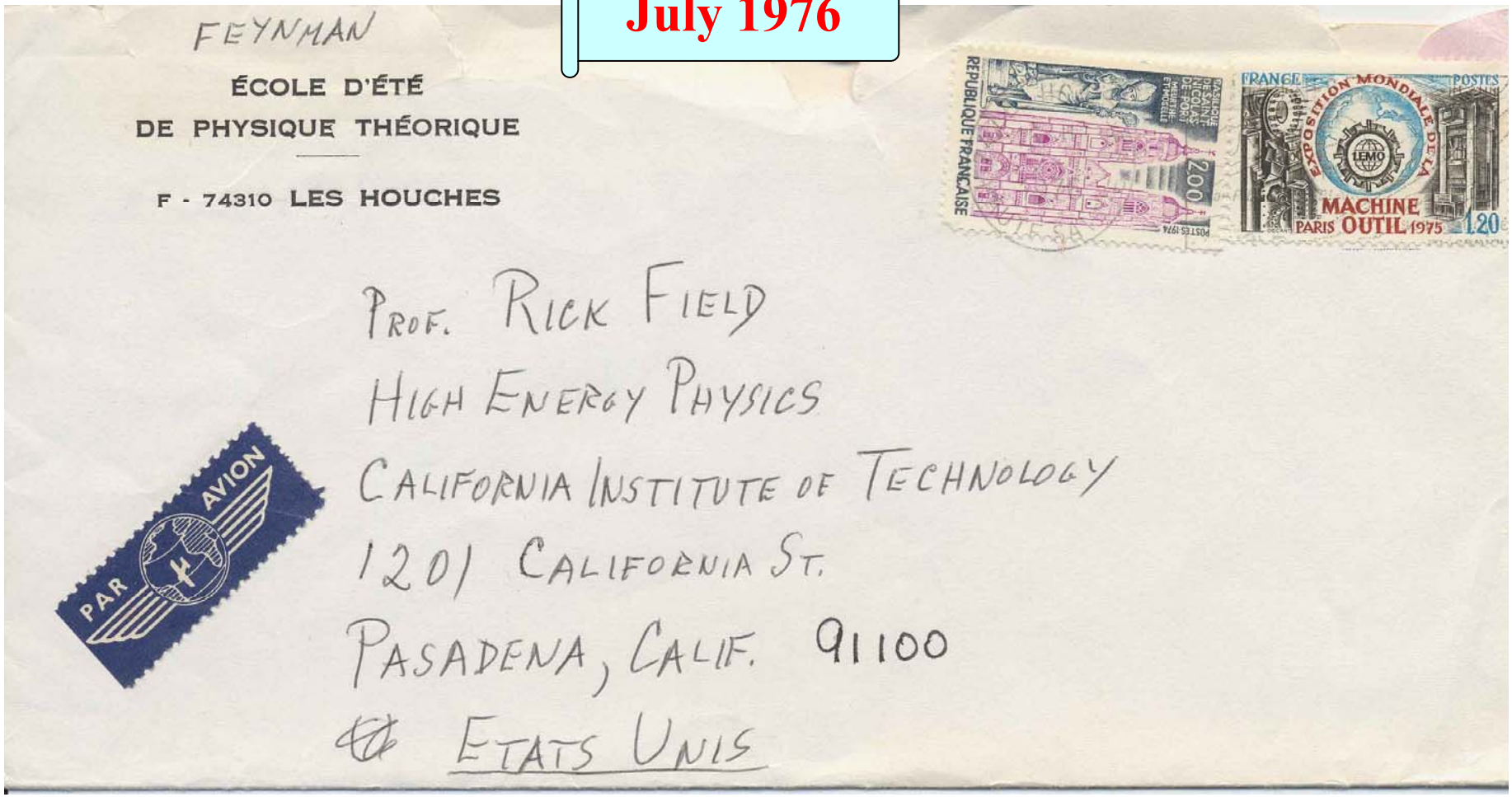
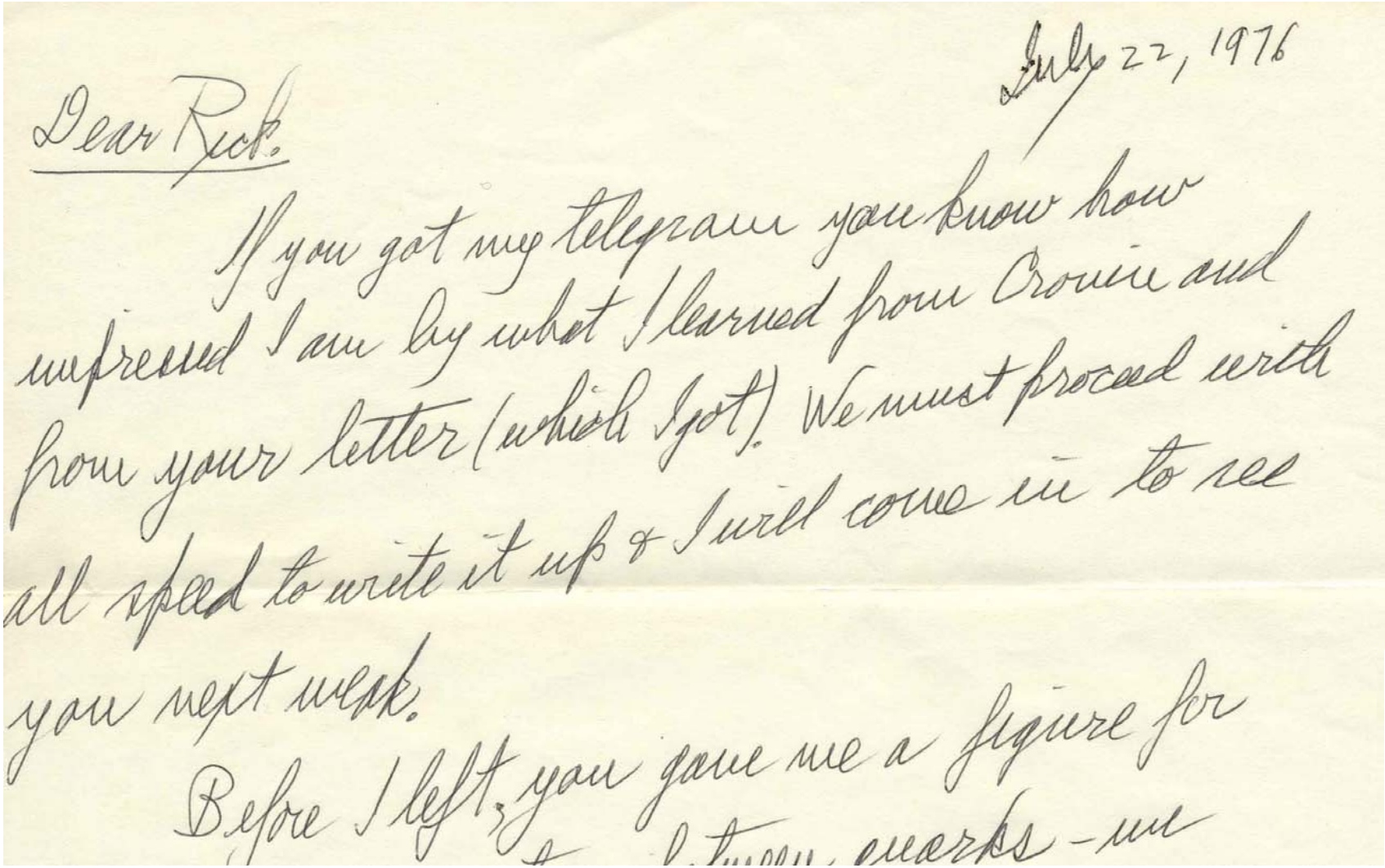
SAW CRONIN AM NOW CONVINCED WERE RIGHT TRACK QUICK WRITE FEYNMAN

Letter from Feynman

July 1976



Letter from Feynman Page 1



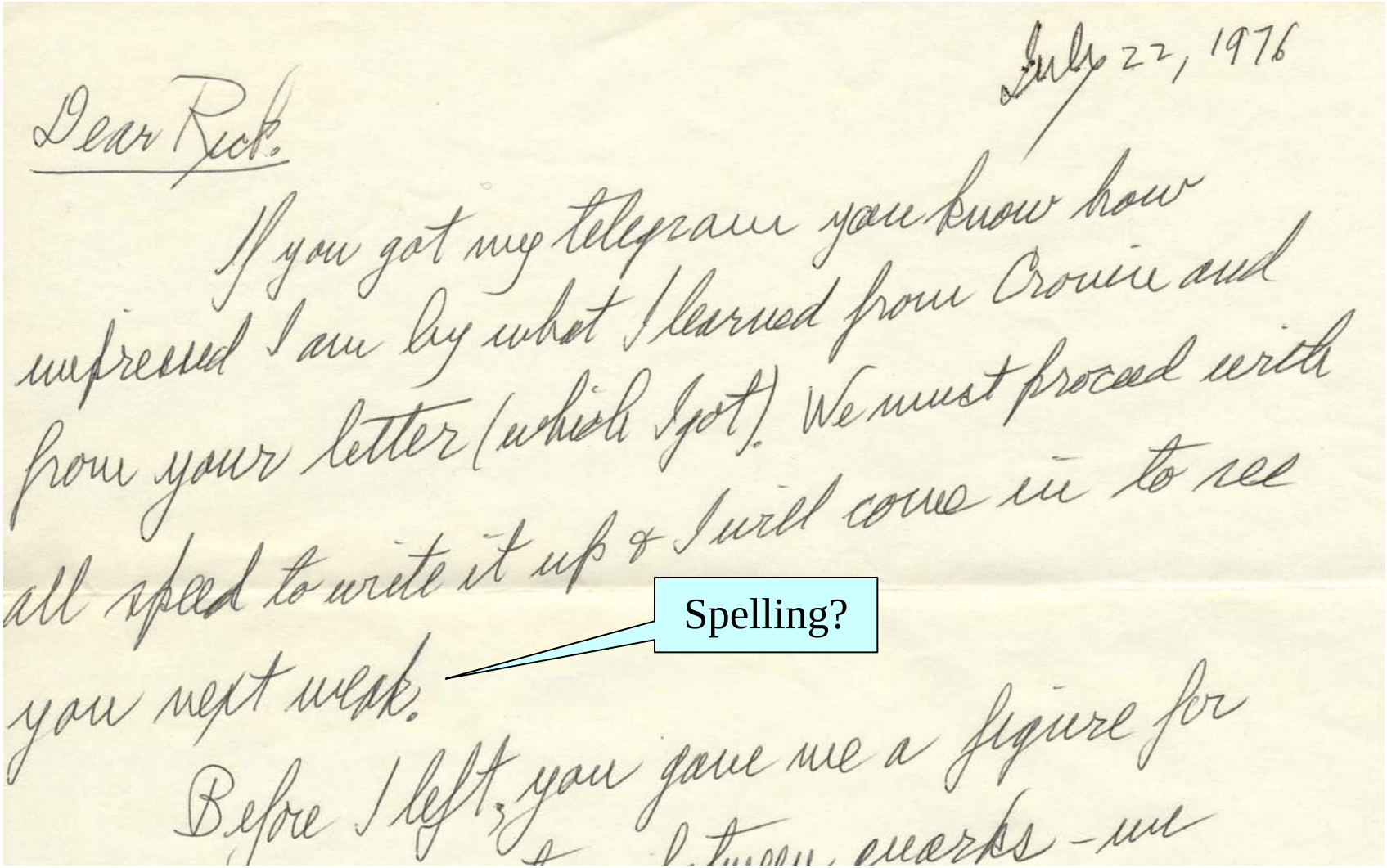
July 22, 1976

Dear Rick.

If you got my telegram you know how impressed I am by what I learned from Cronin and from your letter (which I got). We must proceed with all speed to write it up & I will come in to see you next week.

Before I left, you gave me a figure for [illegible] charm quarks - me

Letter from Feynman Page 1



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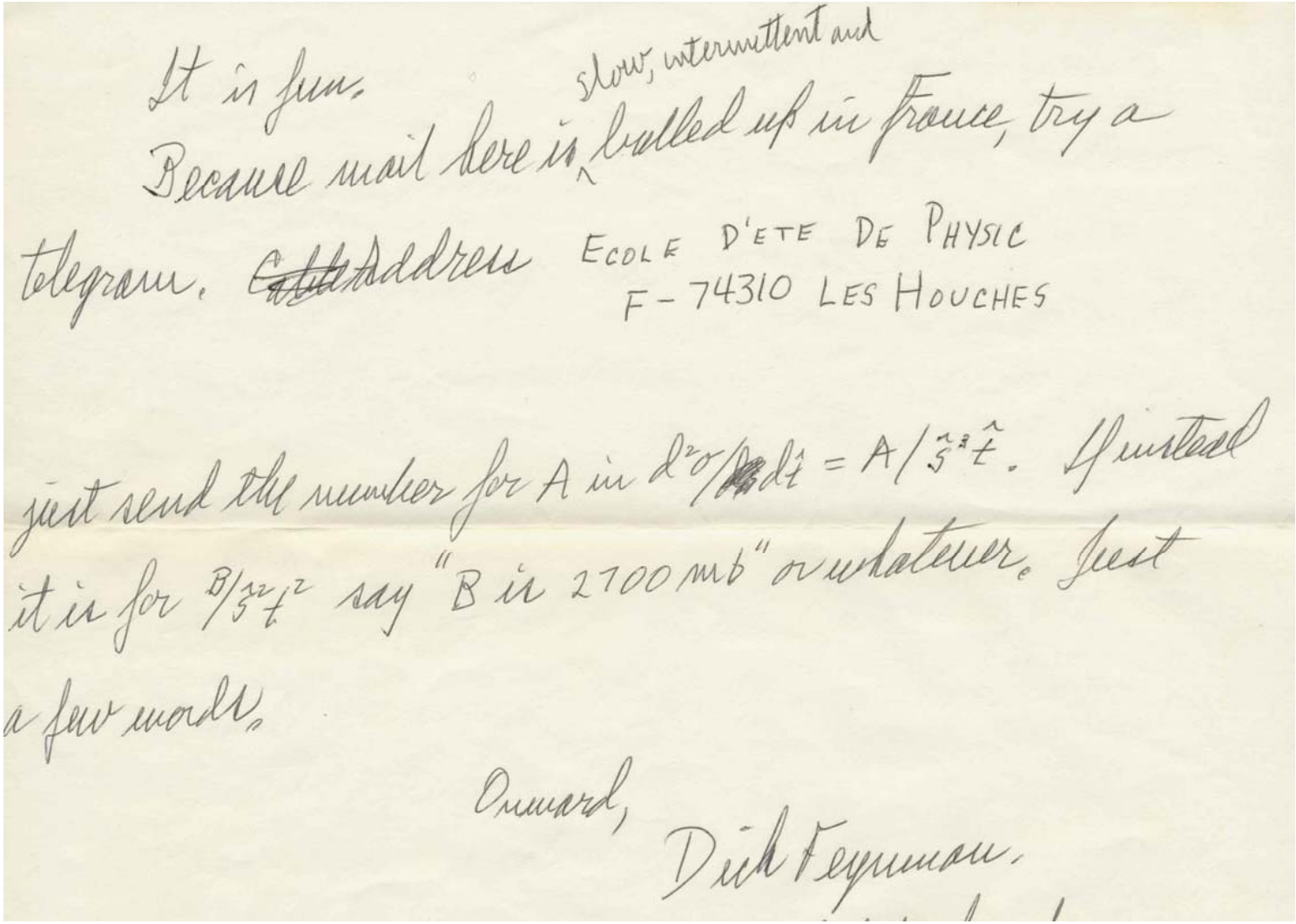
Spelling?

Letter from Feynman Page 3



It is fun.

Because mail here is slow, intermittent and balled up in France, try a telegram. ~~Cable~~ Address ECOLE D'ETE DE PHYSIC
F-74310 LES HOUCHES

just send the number for A in $d^2\sigma/dt = A/s^2 t$. If instead it is for $B/s^2 t^2$ say "B is 2700 mb" or whatever. Just a few words.

Onward,

Dick Feynman.

Letter from Feynman Page 3

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Onward!

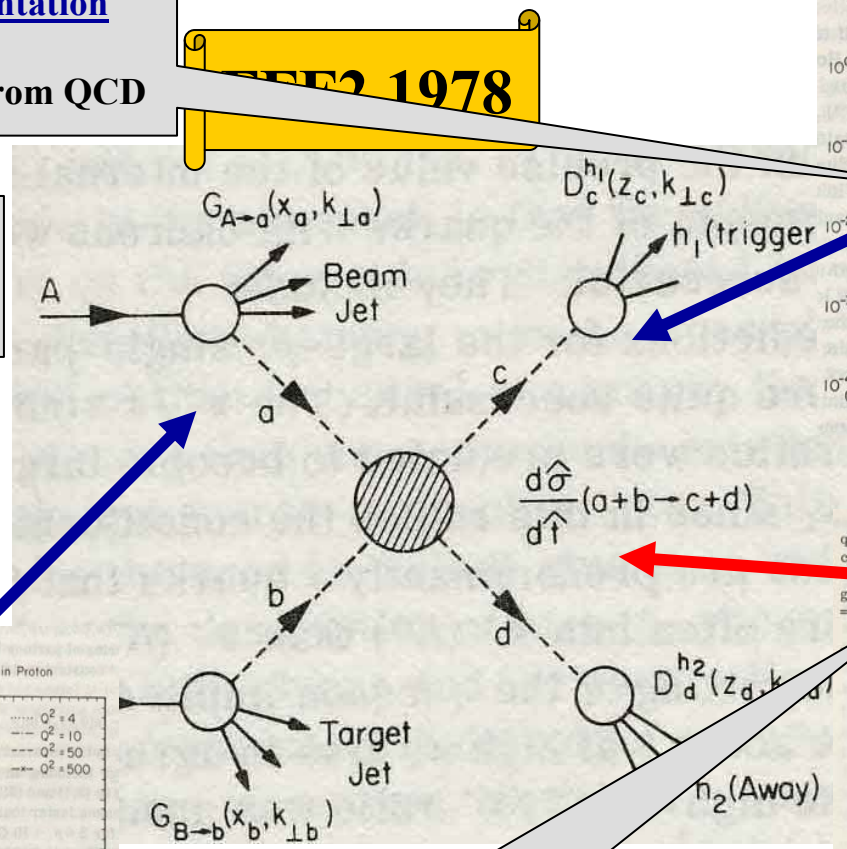
Onward,

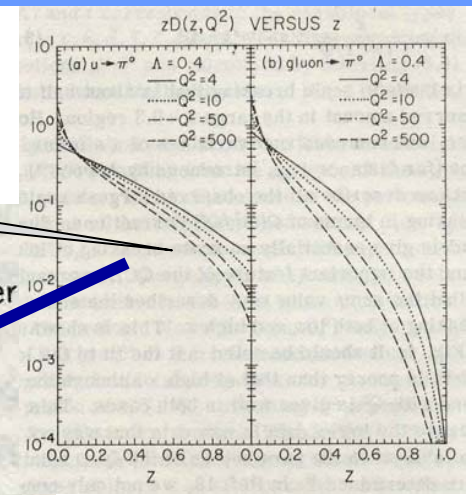
Dick Feynman.

QCD Approach: Quarks & Gluons

Quark & Gluon Fragmentation Functions
Q^2 dependence predicted from QCD

Parton Distribution Functions
Q^2 dependence predicted from QCD





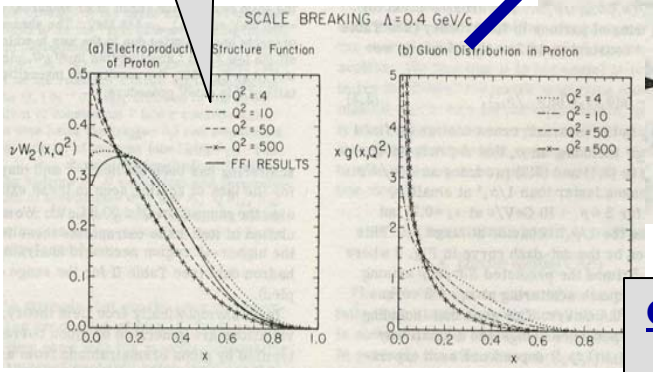


TABLE I. Cross sections for the various constituent quark-quark, quark-gluon, and gluon-gluon subprocesses.[a] The differential cross section is given by $d\hat{\sigma}/d\hat{t} = \alpha_s^2(Q^2)|A|^2/\hat{s}^2$, where $\alpha_s(Q^2)$ is the effective coupling given by Eq. (3.1).

	Subprocess	$\lvert A\rvert^2$
1.	$q_i q_j \to q_i q_j$, $q_i \bar{q}_j \to q_i \bar{q}_j$ $(i \neq j)$	$\frac{4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$
2.	$q_i q_i \to q_i q_i$	$\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}\right)-\frac{8}{27}\frac{\hat{s}^2}{\hat{u}\hat{t}}$
3.	$q_i \bar{q}_i \to q_i \bar{q}_i$	$\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right)-\frac{8}{27}\frac{\hat{u}^2}{\hat{s}\hat{t}}$
4.	$q_i \bar{q}_i \to gg$	$\frac{32}{27}\left(\frac{\hat{u}^2+\hat{t}^2}{\hat{u}\hat{t}}\right)-\frac{8}{3}\left(\frac{\hat{u}^2+\hat{t}^2}{\hat{s}^2}\right)$
5.	$gg \to q_i \bar{q}_i$	$\frac{1}{6}\left(\frac{\hat{u}^2+\hat{t}^2}{\hat{u}\hat{t}}\right)-\frac{3}{8}\left(\frac{\hat{u}^2+\hat{t}^2}{\hat{s}^2}\right)$
6.	$q_i g \to q_i g$	$-\frac{4}{9}\left(\frac{\hat{u}^2+\hat{s}^2}{\hat{u}\hat{s}}\right)+\left(\frac{\hat{u}^2+\hat{s}^2}{\hat{t}^2}\right)$
7.	$gg \to gg$	$\frac{9}{2}\left(3-\frac{\hat{u}\hat{t}}{\hat{s}^2}-\frac{\hat{u}\hat{s}}{\hat{t}^2}-\frac{\hat{s}\hat{t}}{\hat{u}^2}\right)$

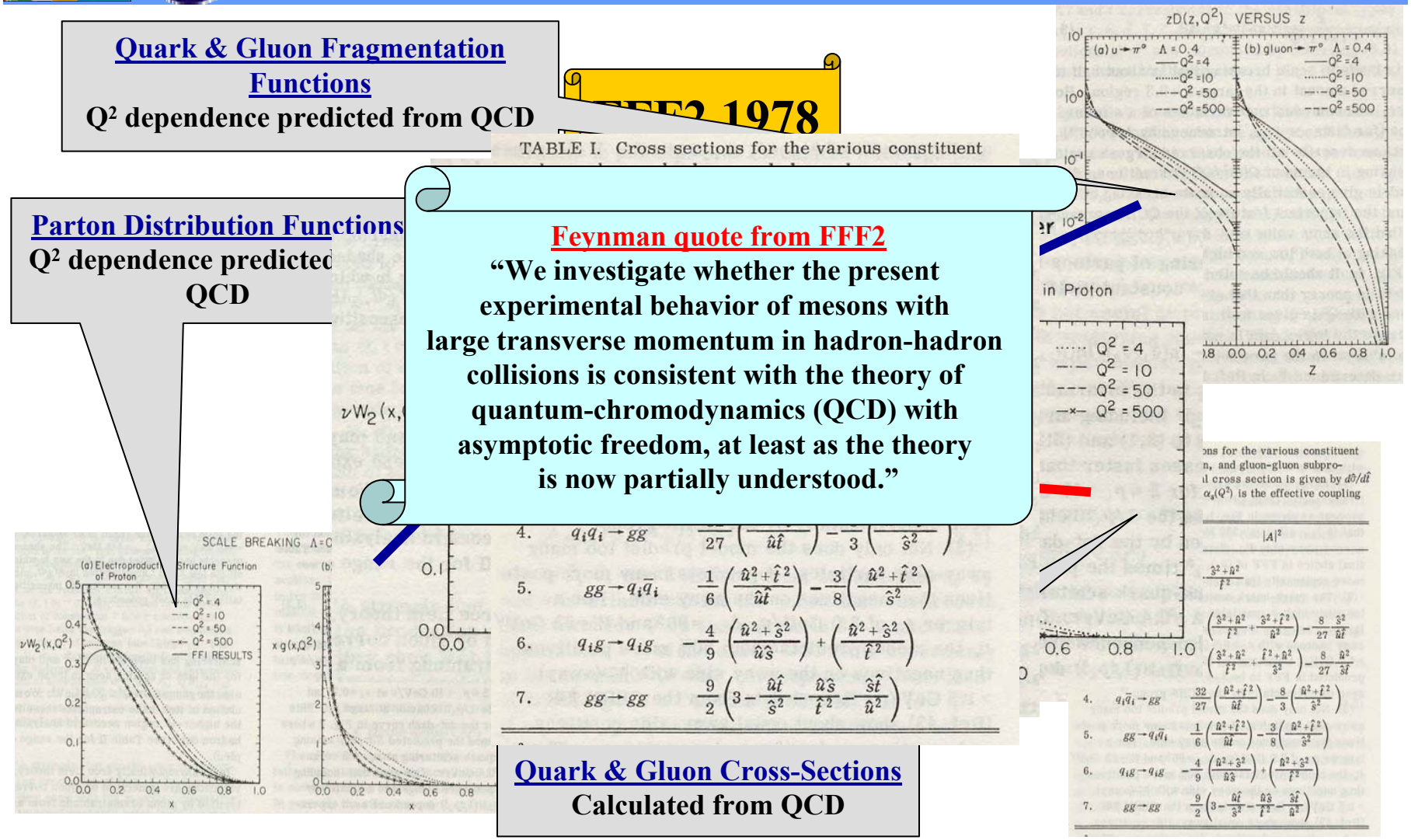
Quark & Gluon Cross-Sections
Calculated from QCD

QCD Approach: Quarks & Gluons

Quark & Gluon Fragmentation Functions
Q^2 dependence predicted from QCD

Parton Distribution Functions
Q^2 dependence predicted QCD

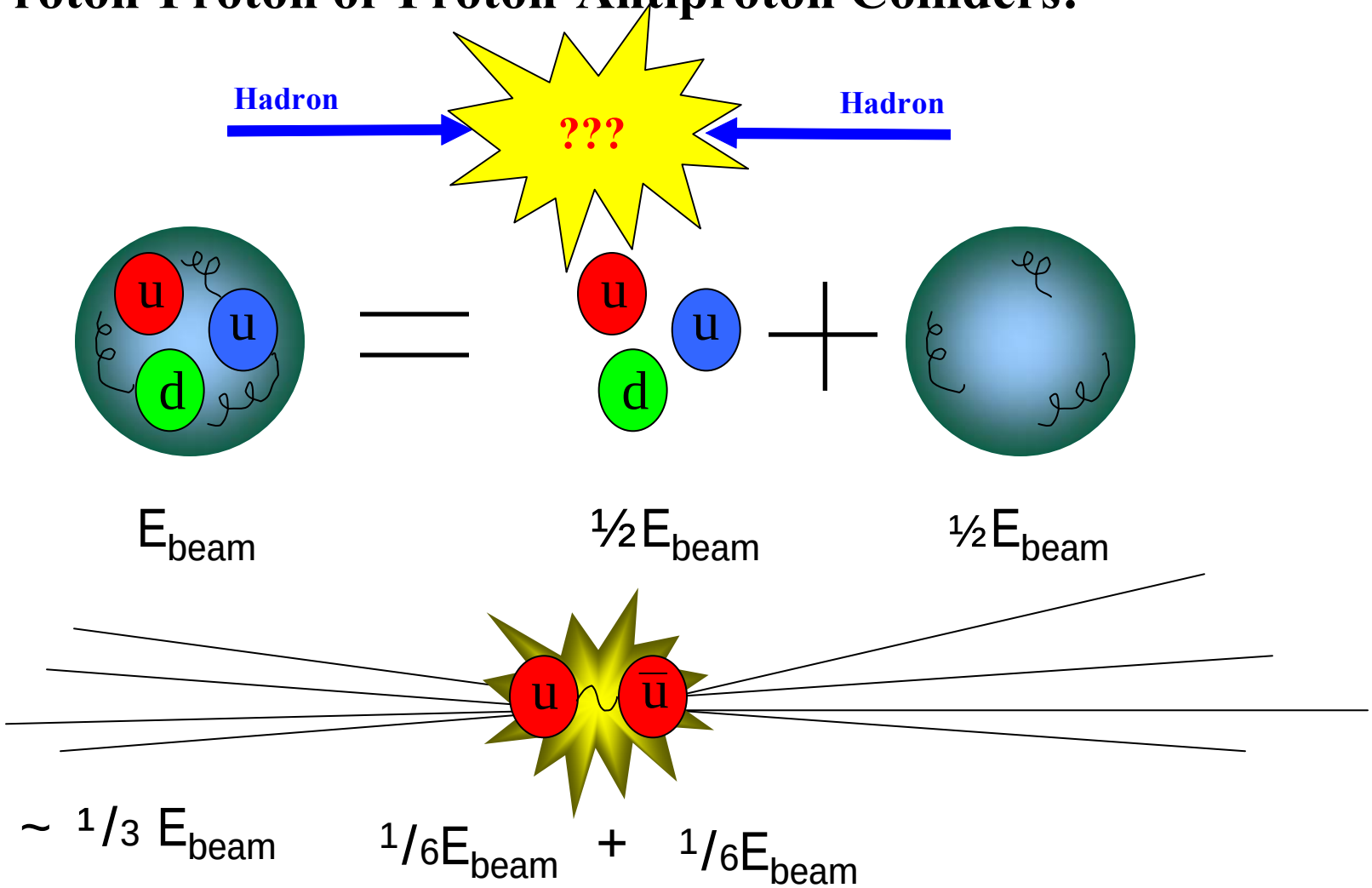
Feynman quote from FFF2
"We investigate whether the present experimental behavior of mesons with large transverse momentum in hadron-hadron collisions is consistent with the theory of quantum-chromodynamics (QCD) with asymptotic freedom, at least as the theory is now partially understood."



Quark & Gluon Cross-Sections
Calculated from QCD

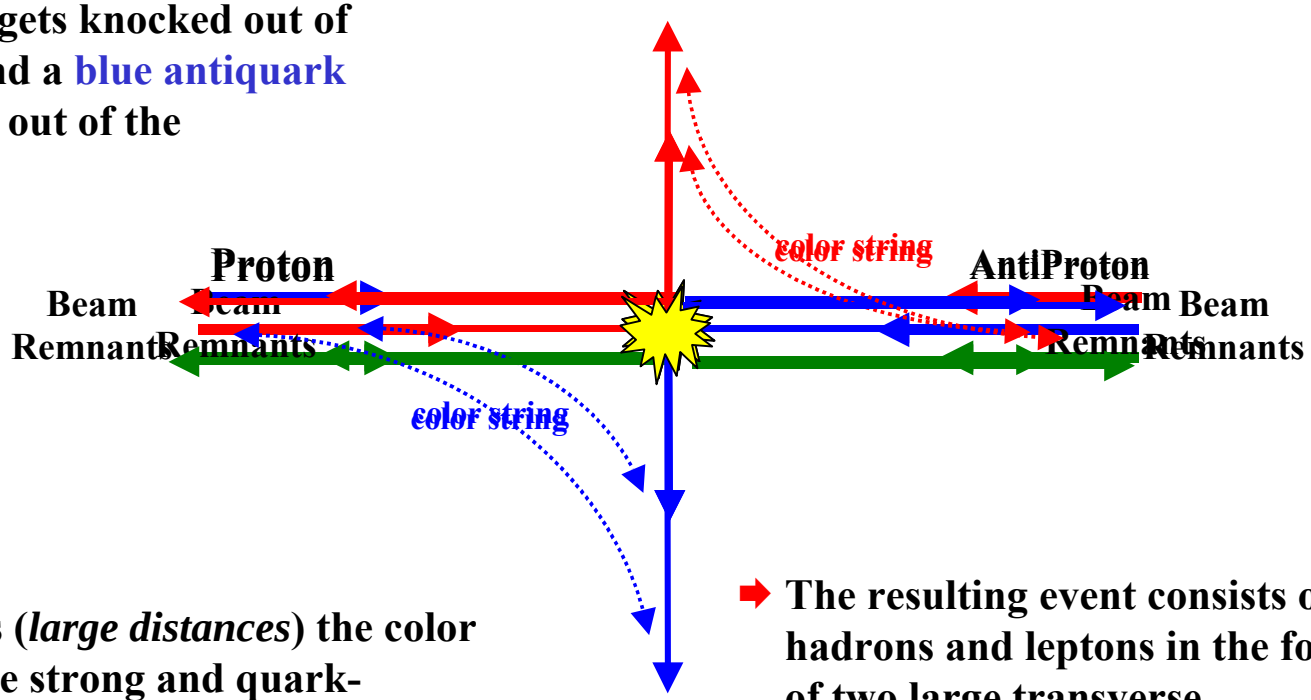
Hadron-Hadron Collisions

- **Proton-Proton or Proton-Antiproton Colliders:**



Monte-Carlo Simulation of Hadron-Hadron Collisions

- Color singlet proton collides with a color singlet antiproton.
- A red quark gets knocked out of the proton and a blue antiquark gets knocked out of the antiproton.
- At short times (*small distances*) the color forces are weak and the outgoing partons move away from the beam-beam remnants.



- At long times (*large distances*) the color forces become strong and quark-antiquark pairs are pulled out of the vacuum and hadrons are formed.
- The resulting event consists of hadrons and leptons in the form of two large transverse momentum outgoing jets plus the beam-beam remnants.

Monte-Carlo Simulation of Hadron-Hadron Collisions

- Color singlet proton collides with a color singlet antiproton.
- A red quark gets knocked out of the proton and a blue antiquark gets knocked out of the antiproton.
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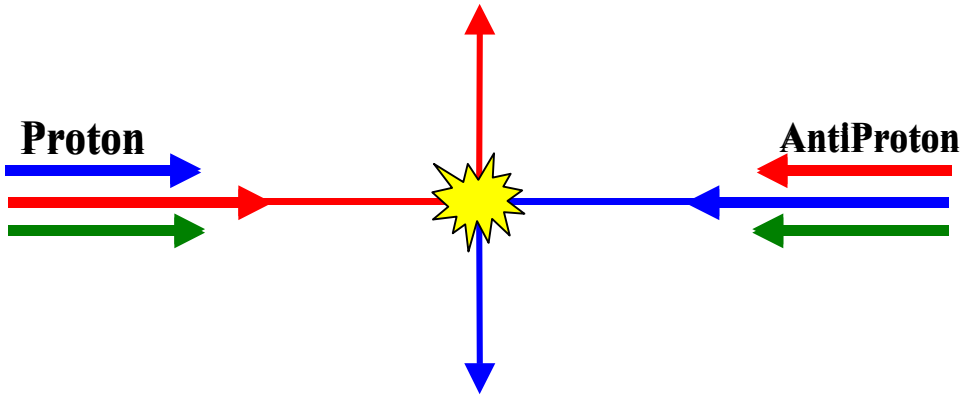

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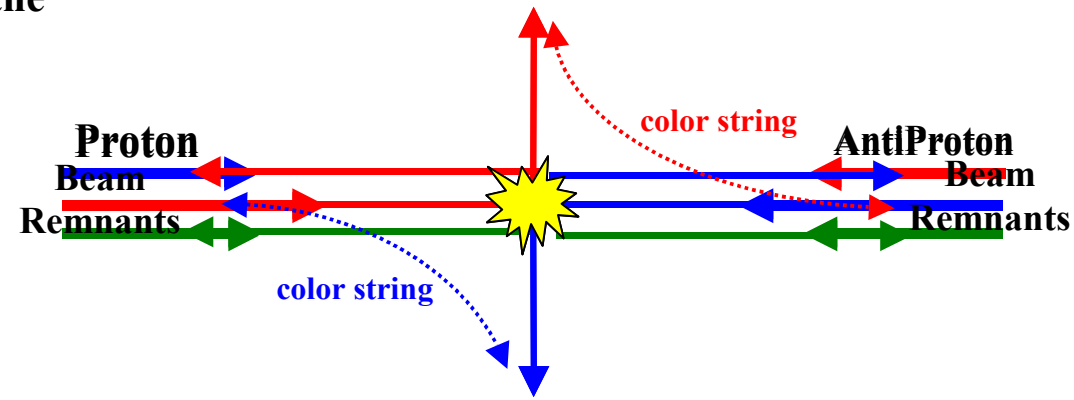

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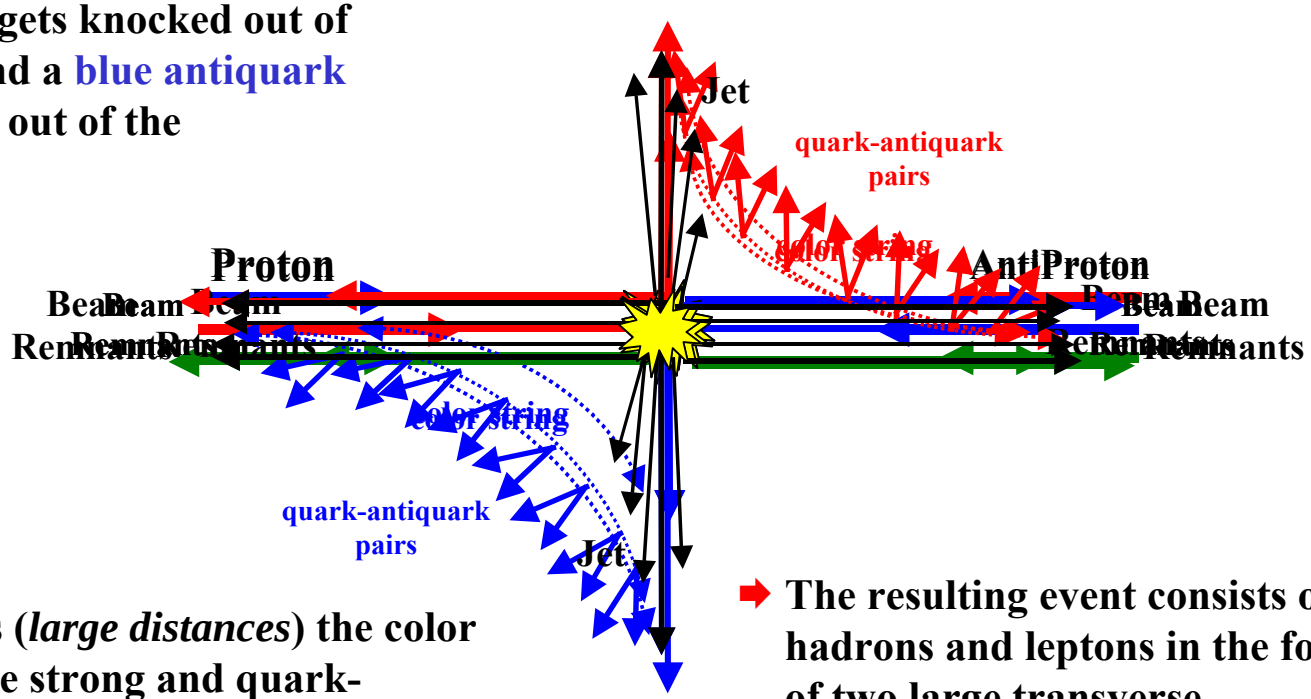

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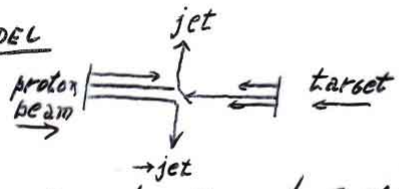
Feynman Talk at Coral Gables
(December 1976)

1st transparency

Field & Feynman CALT-68-565
Fox (Brookhaven APS) CALT-68-573

MODEL



Quark - Quark Collision.
But $P_\perp^{-8}$ Not $P_\perp^{-4}$?

Need: (a) Quark distribution in hadron. (Pion?)
(b) The way quark makes hadron jet.
FROM EXPERIMENTS WITH LEPTONS.
(c) Quark-Quark scattering x-section.

$$\frac{d\hat{\sigma}}{dt} = \frac{2300\ \text{mb}}{s(-t)^3}$$

Try to fit all correlation experiments with no new parameters.

Last transparency

WORK IN PROGRESS

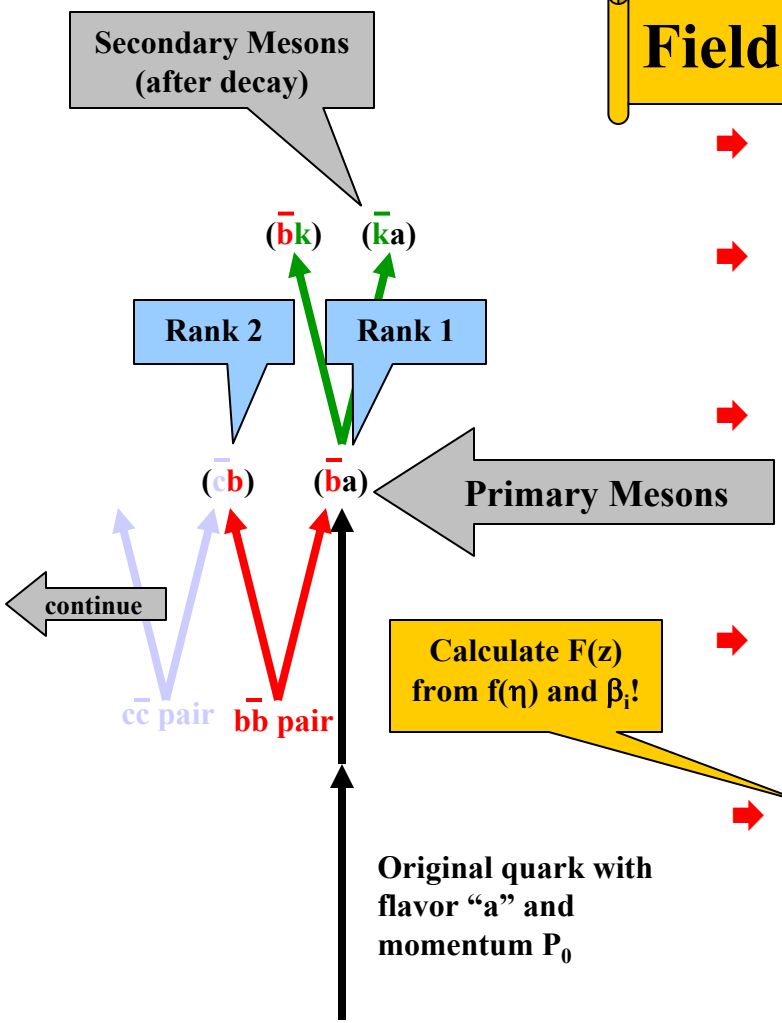
a) More detailed Calculations
b) Theory of $q \to$ hadron cascade

"Feynman-Field Jet Model"

FUTURE.

Protons & baryons at high $P_\perp$.
Single γ's at high $P_\perp$.
Nuclear targets.
Are we really in trouble from $P_{transverse}$ of quarks?
Unify theory to that of main collision at low $P_\perp$.

A Parameterization of the Properties of Jets

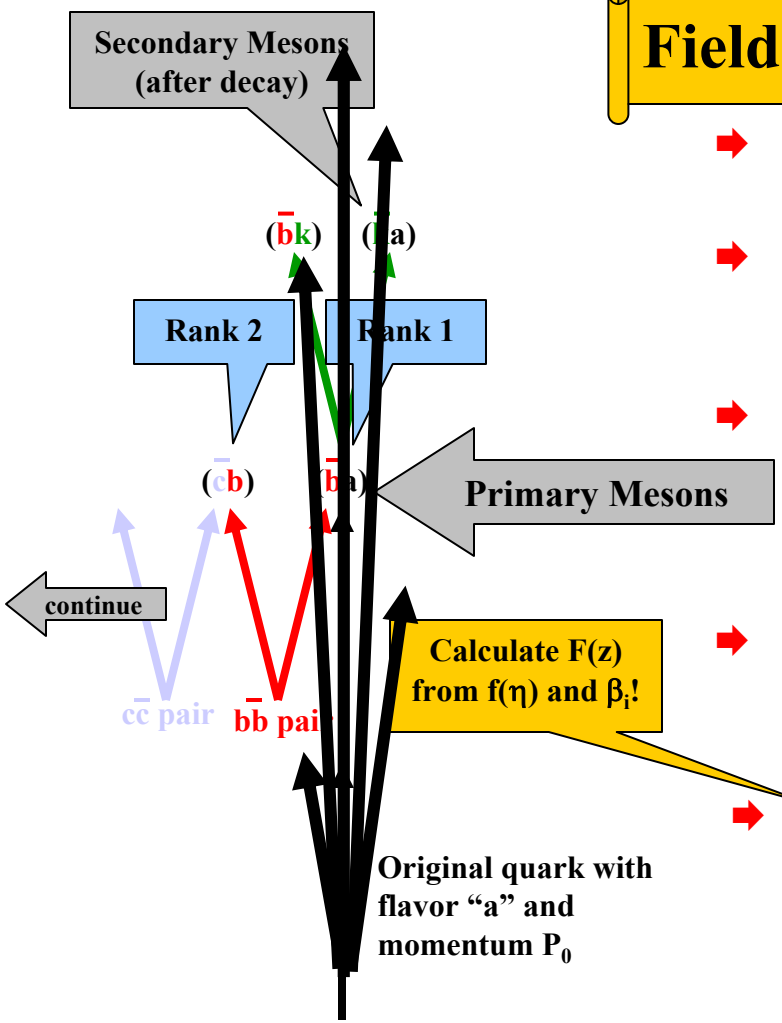


Field-Feynman 1978

- Assumed that jets could be analyzed on a "recursive" principle.
- Let $f(\eta)d\eta$ be the probability that the rank 1 meson *leaves* fractional momentum η to the remaining cascade, leaving quark "b" with momentum $P_1 = \eta_1 P_0$.
- Assume that the mesons originating from quark "b" are distributed in presisely the same way as the mesons which came from quark a (*i.e.* same function $f(\eta)$), leaving quark "c" with momentum $P_2 = \eta_2 P_1 = \eta_2 \eta_1 P_0$.
- Add in flavor dependence by letting β_u = probabliity of producing u-ubar pair, β_d = probability of producing d-dbar pair, etc.
- Let $F(z)dz$ be the probability of finding a meson (*independent of rank*) with fractional mementum z of the original quark "a" within the jet.

Calculate $F(z)$ from $f(\eta)$ and β_i!

A Parameterization of the Properties of Jets



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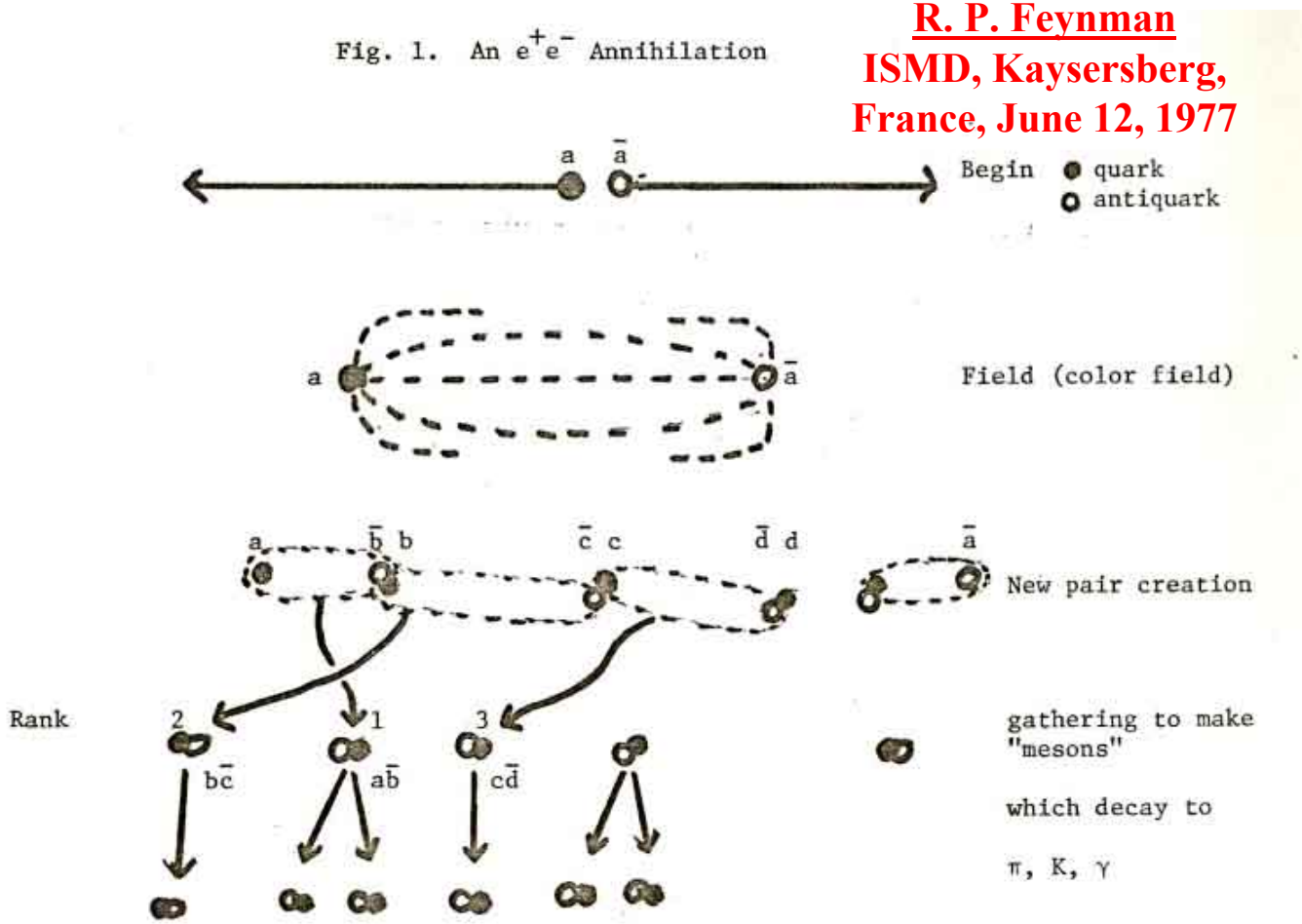
Feynman-Field Jet Model

R. P. Feynman
ISMD, Kaysersberg, France, June 12, 1977



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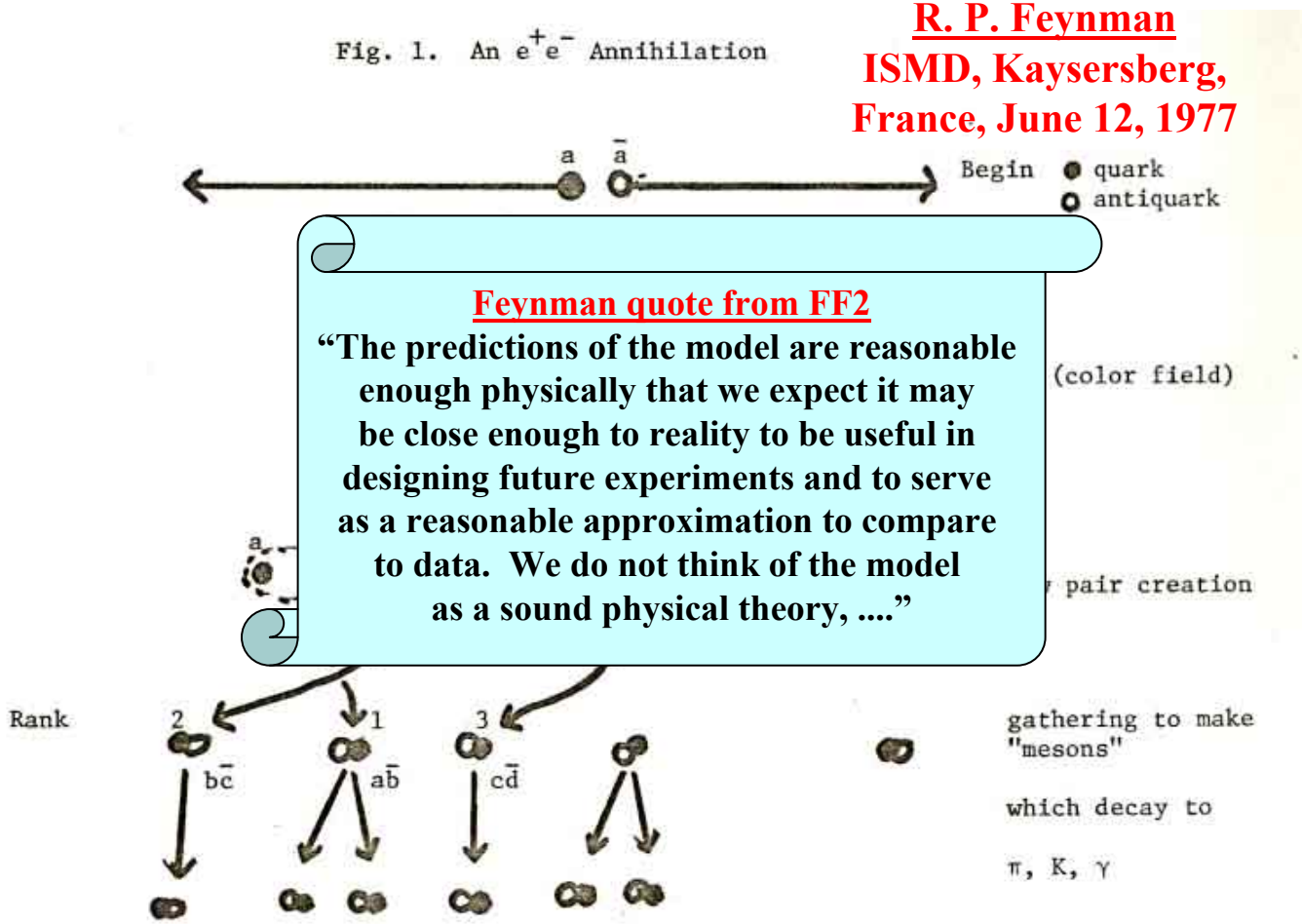


Feynman quote from FF2

"The predictions of the model are reasonable enough physically that we expect it may be close enough to reality to be useful in designing future experiments and to serve as a reasonable approximation to compare to data. We do not think of the model as a sound physical theory, ..."

Monte-Carlo Simulation of Hadron-Hadron Collisions

FF1-FFF1 (1977)
"Black-Box" Model

F1-FFF2 (1978)
QCD Approach

FF2 (1978)
Monte-Carlo simulation of "jets"

FFFW "FieldJet" (1980)
QCD "leading-log order" simulation of hadron-hadron collisions

"FF" or "FW" Fragmentation

the past

---

yesterday

ISAJET ("FF" Fragmentation)

HERWIG ("FW" Fragmentation)

PYTHIA 6.4

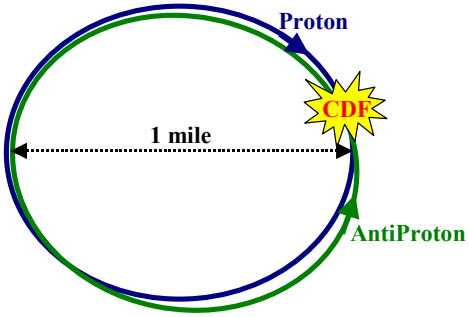
today

SHERPA

PYTHIA 8

HERWIG++

The Fermilab Tevatron



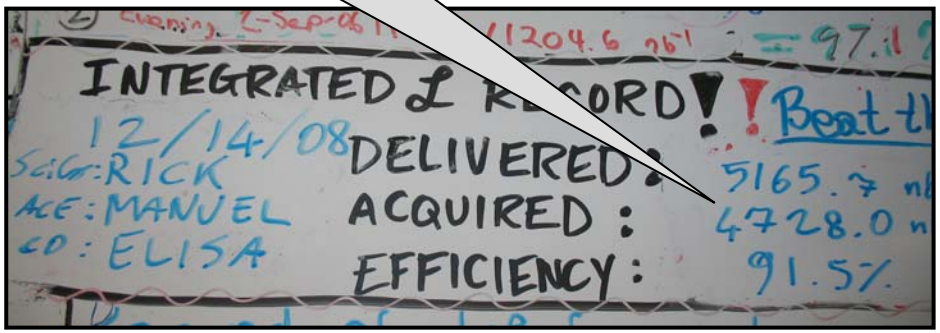
- **I joined CDF in January 1998.**

The Fermilab Tevatron

CDF "SciCo" Shift December 12-19, 2008

My wife Jimmie on shift with me!

Acquired 4728 nb^{-1} during 8 hour "owl" shift!



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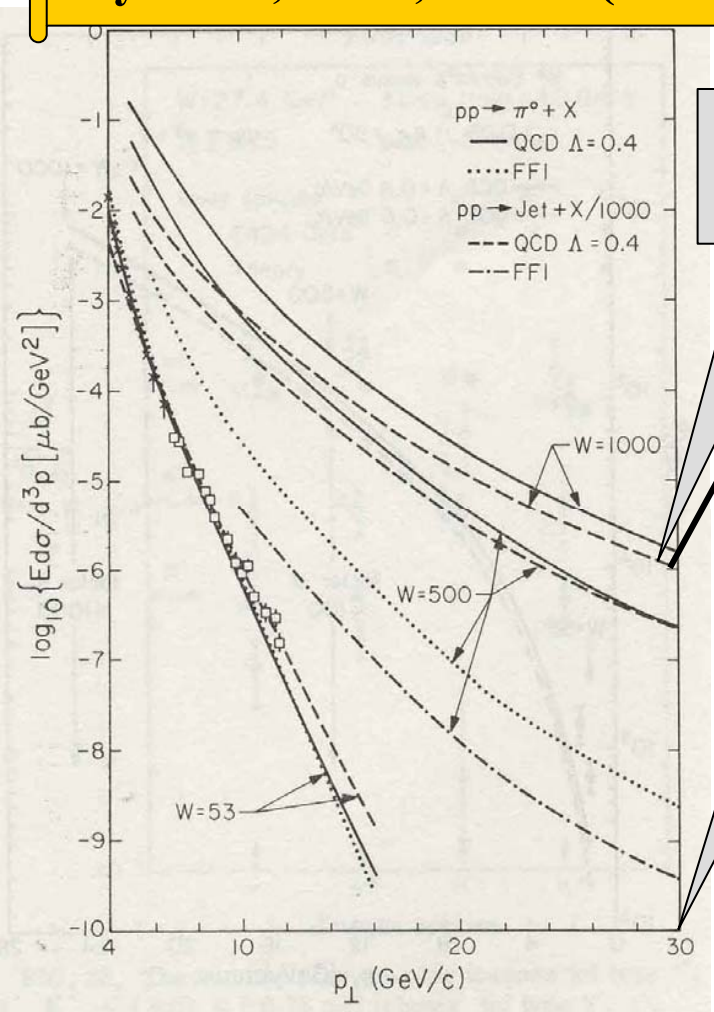
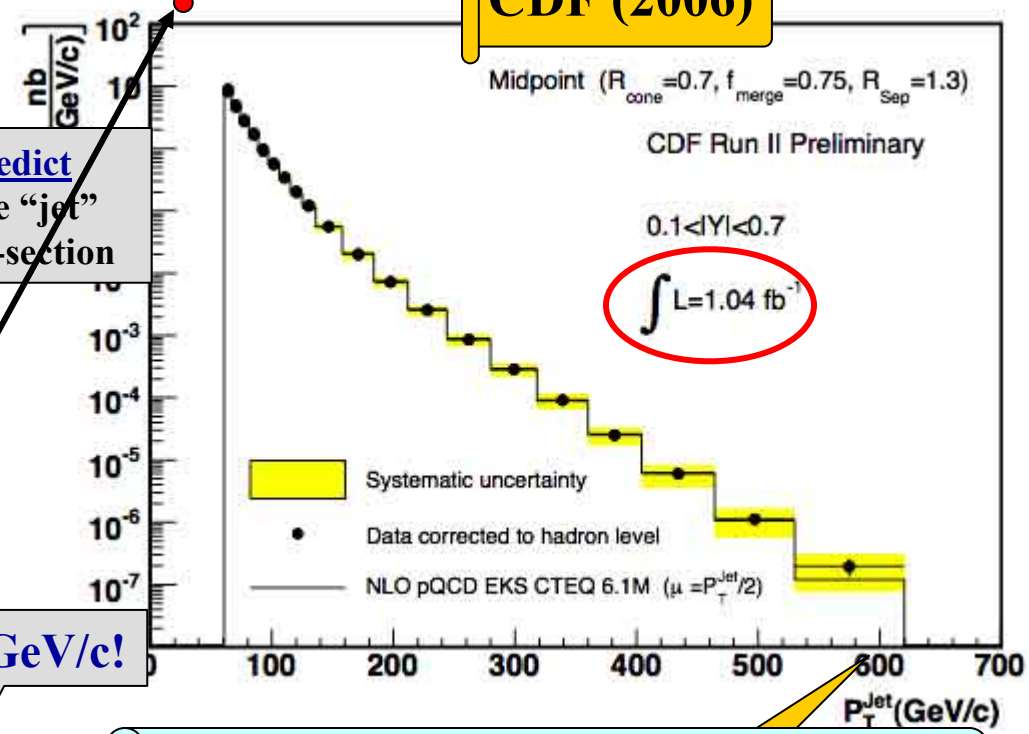
High P_T Jets

Feynman, Field, & Fox (1978)



CDF (2006)



Predict large "jet" cross-section

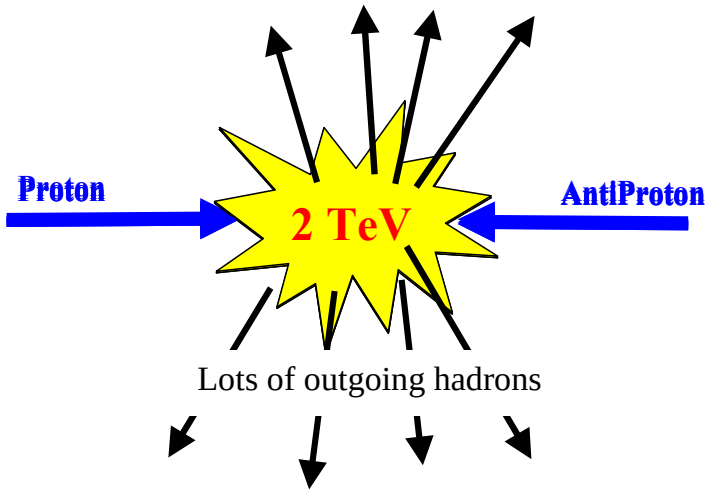
30 GeV/c!

Feynman quote from FFF

"At the time of this writing, there is still no sharp quantitative test of QCD. An important test will come in connection with the phenomena of high P_T discussed here."

High Energy Physics

- **Proton-antiproton collisions at 2 TeV.**
  - **Define E_H to be the amount of energy required to light a 60 Watt light bulb for 1 second (E_H = 60 Joules). 1 TeV = 10^{12} ev = 1.6×10^{-7} Joules and hence E_H = 3.75×10^{8} TeV.**
  - **A proton-antiproton collisions at 2 TeV is equal to about 3.2×10^{-7} Joules which corresponds to about 1/200,000,000 E_H! The energy is not high in every day standards but it is concentrated at a small point (*i.e.* large energy density).**



  - **The mass energy of a proton is about 1 GeV and the mass energy of a pion is about 140 MeV. Hence 2 TeV is equavelent to about 2,000 proton masses or about 14,000 pion masses and lots of hadrons are produced in a typical collision.**

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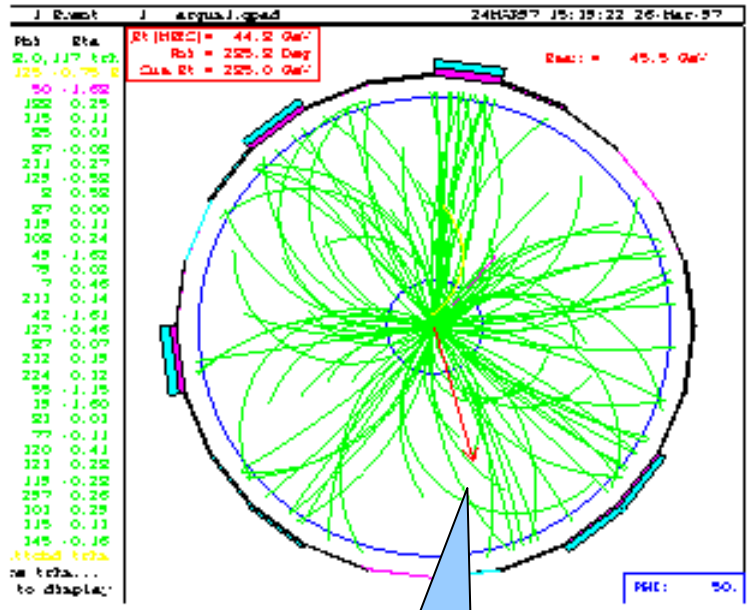
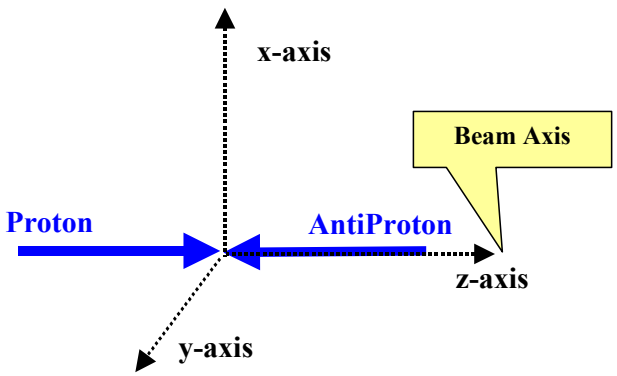
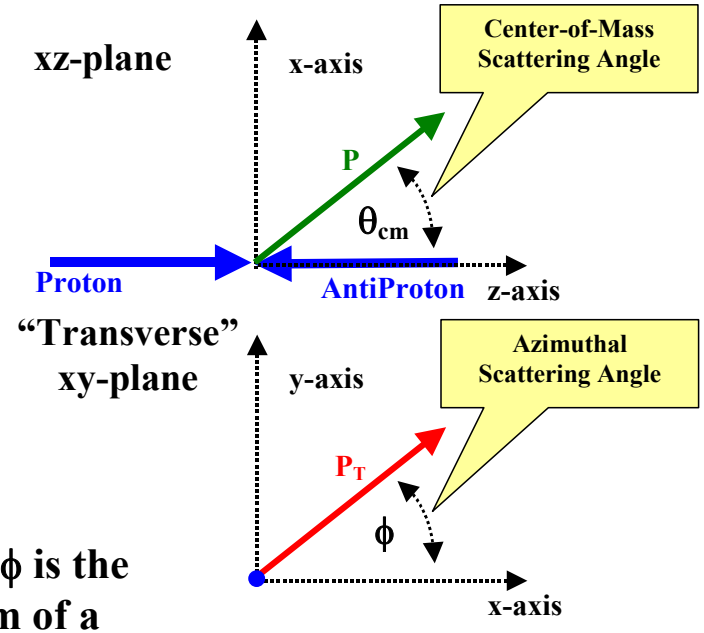


Display of charged particles in the CDF central tracker

Collider Coordinates



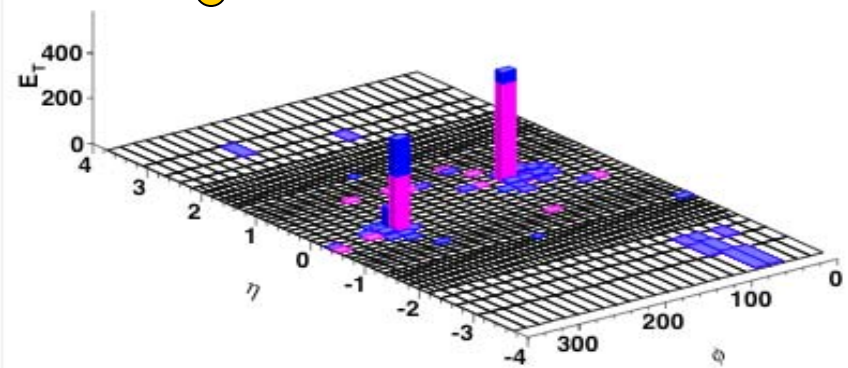


- The z-axis is defined to be the beam axis with the xy-plane being the "transverse" plane.
- θ_{cm} is the center-of-mass scattering angle and ϕ is the azimuthal angle. The "transverse" momentum of a particle is given by $P_T = P \cos(\theta_{cm})$.
- Use η and ϕ to determine the direction of an outgoing particle, where η is the "pseudo-rapidity" defined by $\eta = -\log(\tan(\theta_{cm}/2))$.

η	θ_{cm}
0	90°
1	40°
2	15°
3	6°
4	2°

CDF DiJet Event: M(jj) ≈ 1.4 TeV

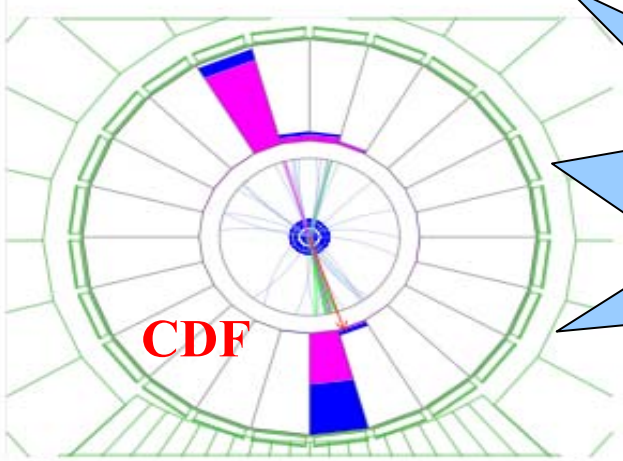
E_T^{jet1} = 666 GeV E_T^{jet2} = 633 GeV
E_{sum} = 1,299 GeV M(jj) = 1,364 GeV



CDF Run II Preliminary

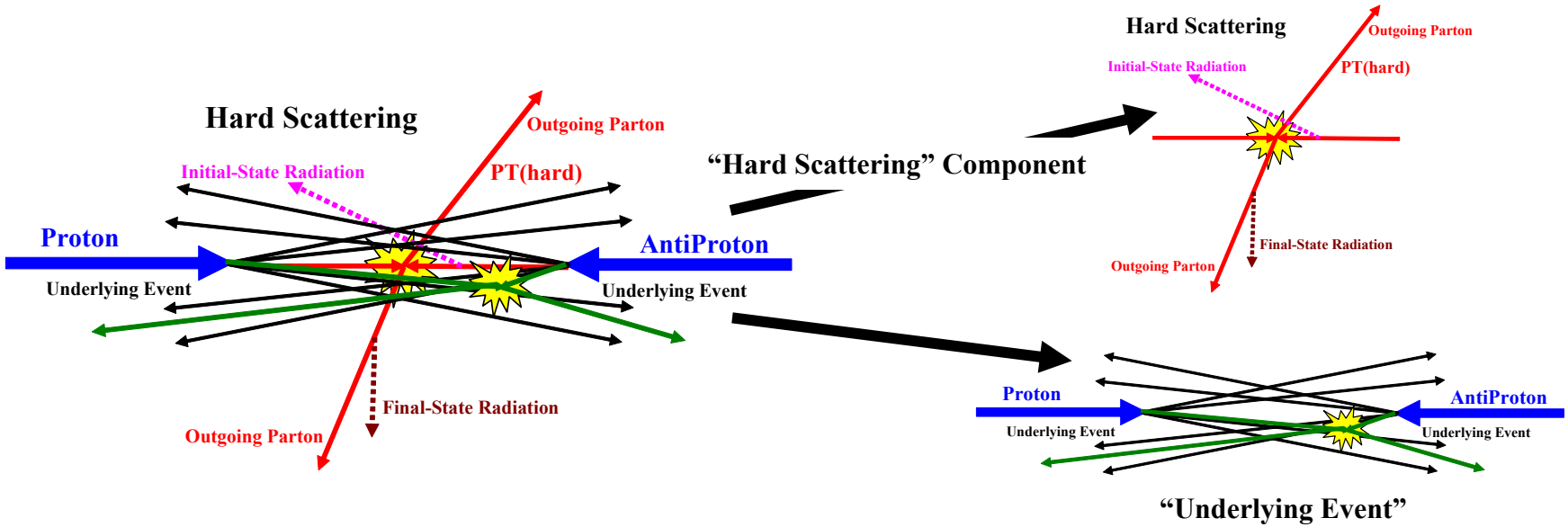
```
Jet Et1 = 666 GeV (corr)
          583 GeV (raw)
eta1    = 0.31 (detector)
          0.43 (corr z)

Jet Et2 = 633 GeV (corr)
          546 GeV (raw)
eta2    = -0.30 (detector)
          -0.19 (corr z)
```

Proton-Antiproton Collisions at 1.96 TeV



$M(jj)/E_{cm} \approx 70\%$!!

QCD Monte-Carlo Models: High Transverse Momentum Jets



- Start with the perturbative 2-to-2 (or sometimes 2-to-3) parton-parton scattering and add initial and final-state gluon radiation (in the leading log approximation or modified leading log approximation).
- The "underlying event" consists of the "beam-beam remnants" and from particles arising from soft or semi-soft multiple parton interactions (MPI).
- Of course the outgoing colored partons fragment into hadron "jet" and inevitably "underlying event" observables receive contributions from initial and final-state radiation.

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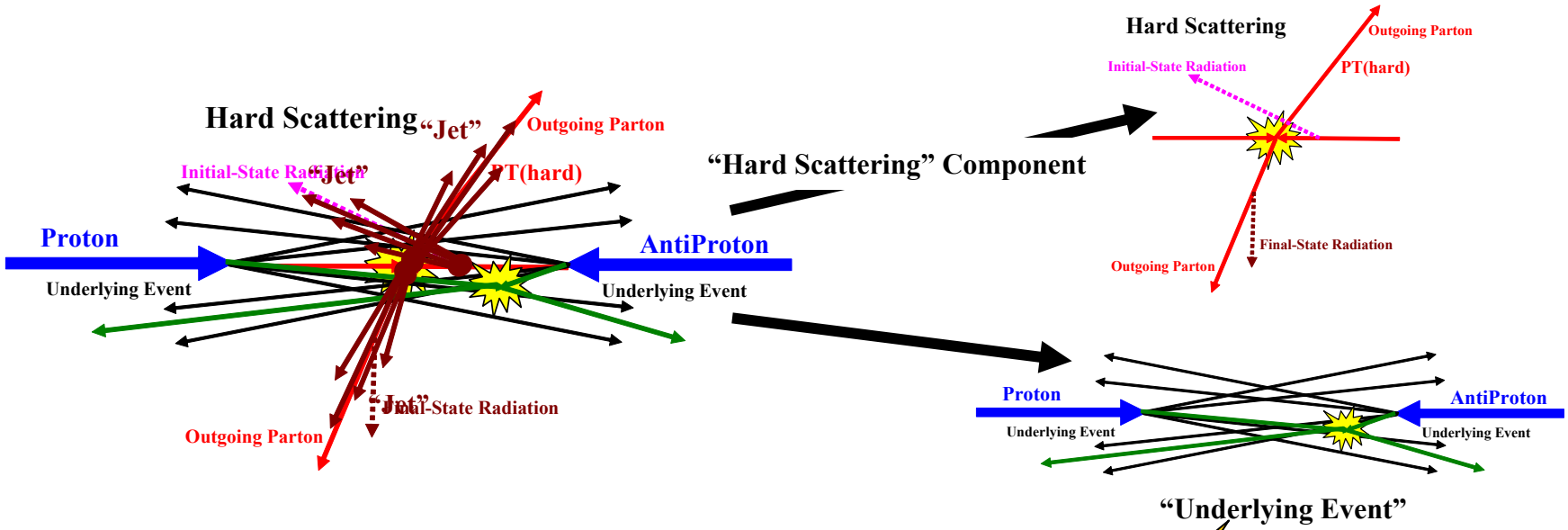

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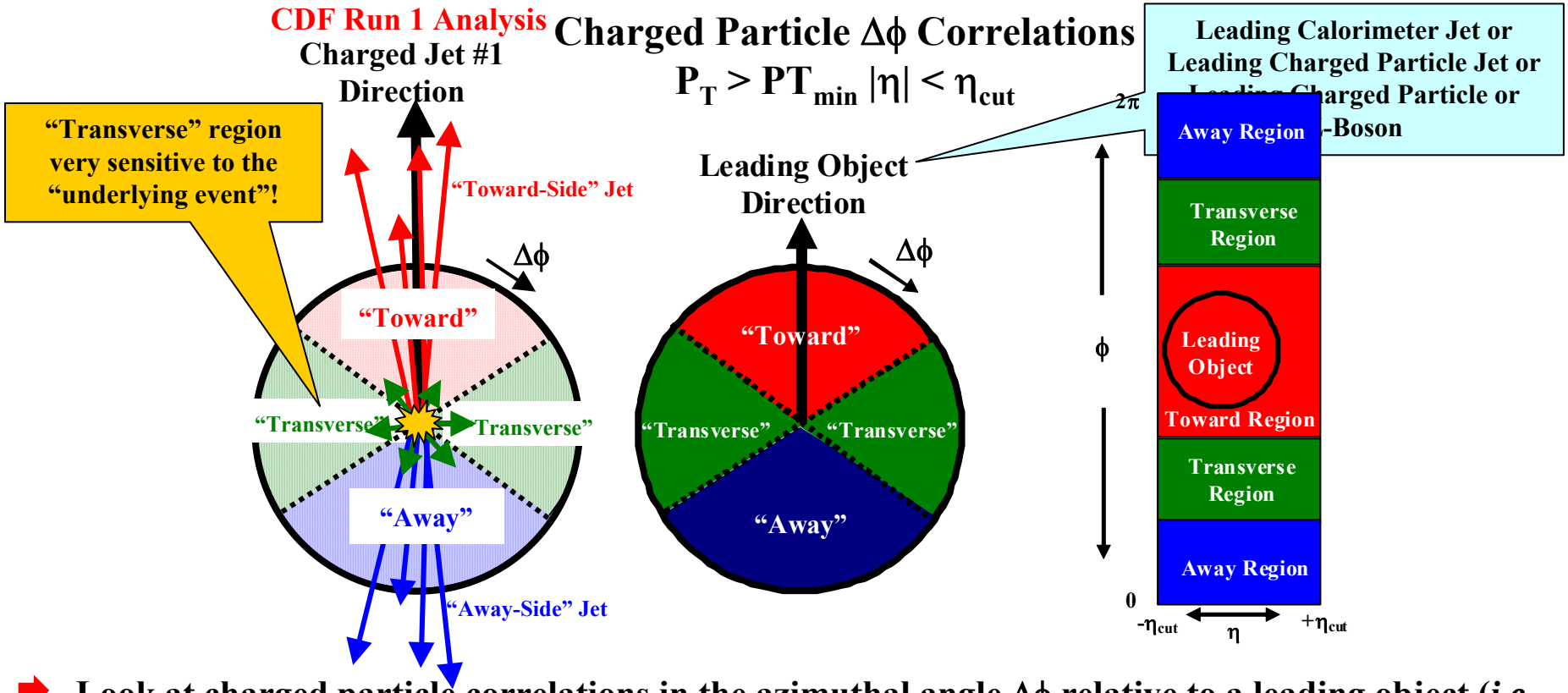
- Of course the outgoing colored parton ly "underlying event" observables receive contributions fron

The "underlying event" is an unavoidable background to most collider observables and having good understand of it leads to more precise collider measurements!

Traditional Approach



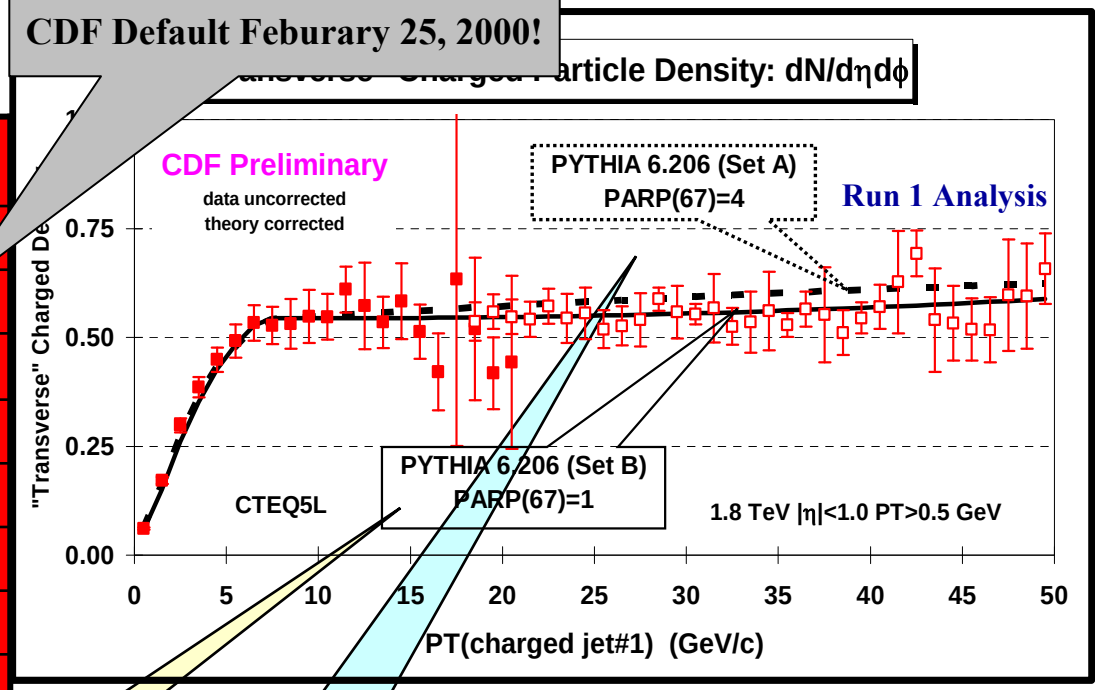
- Look at charged particle correlations in the azimuthal angle Δϕ relative to a leading object (*i.e.* CaloJet#1, ChgJet#1, PTmax, Z-boson). For CDF PTmin = 0.5 GeV/c $\eta_{cut} = 1$.
- Define $|\Delta\phi| < 60^o$ as "Toward", $60^o < |\Delta\phi| < 120^o$ as "Transverse", and $|\Delta\phi| > 120^o$ as "Away".
- All three regions have the same area in η-ϕ space, $\Delta\eta\times\Delta\phi = 2\eta_{cut}\times 120^o = 2\eta_{cut}\times 2\pi/3$. Construct densities by dividing by the area in η-ϕ space.

Run 1 PYTHIA Tune A

PYTHIA 6.206 CTEQ5L

Parameter	Tune B	Tune A
MSTP(81)	1	1
MSTP(82)	4	4
PARP(82)	1.9 GeV	2.0 GeV
PARP(83)	0.5	0.5
PARP(84)	0.4	0.4
PARP(85)	1.0	0.9
PARP(86)	1.0	0.95
PARP(89)	1.8 TeV	1.8 TeV
PARP(90)	0.25	0.25
PARP(67)	1.0	4.0

CDF Default Feburary 25, 2000!

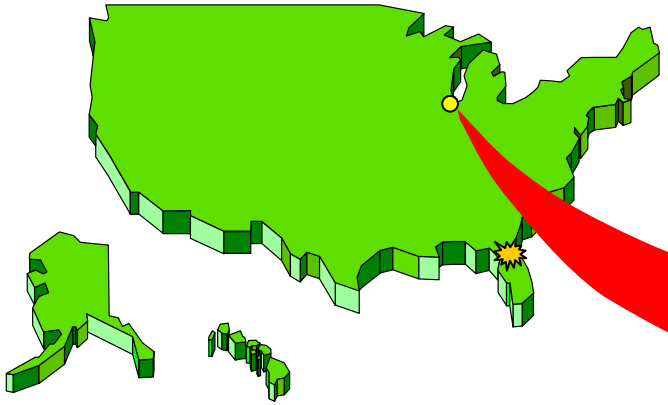


Plot shows the "transverse" charged particle density versus P_T(chgjet#1) compared to the QCD hard scattering predictions of two tuned versions of PYTHIA 6.206 (CTEQ5L, Set B (PARP(67)=1) and Set A (PARP(67)=4)).

New PYTHIA default (less initial-state radiation)

Old PYTHIA default (more initial-state radiation)

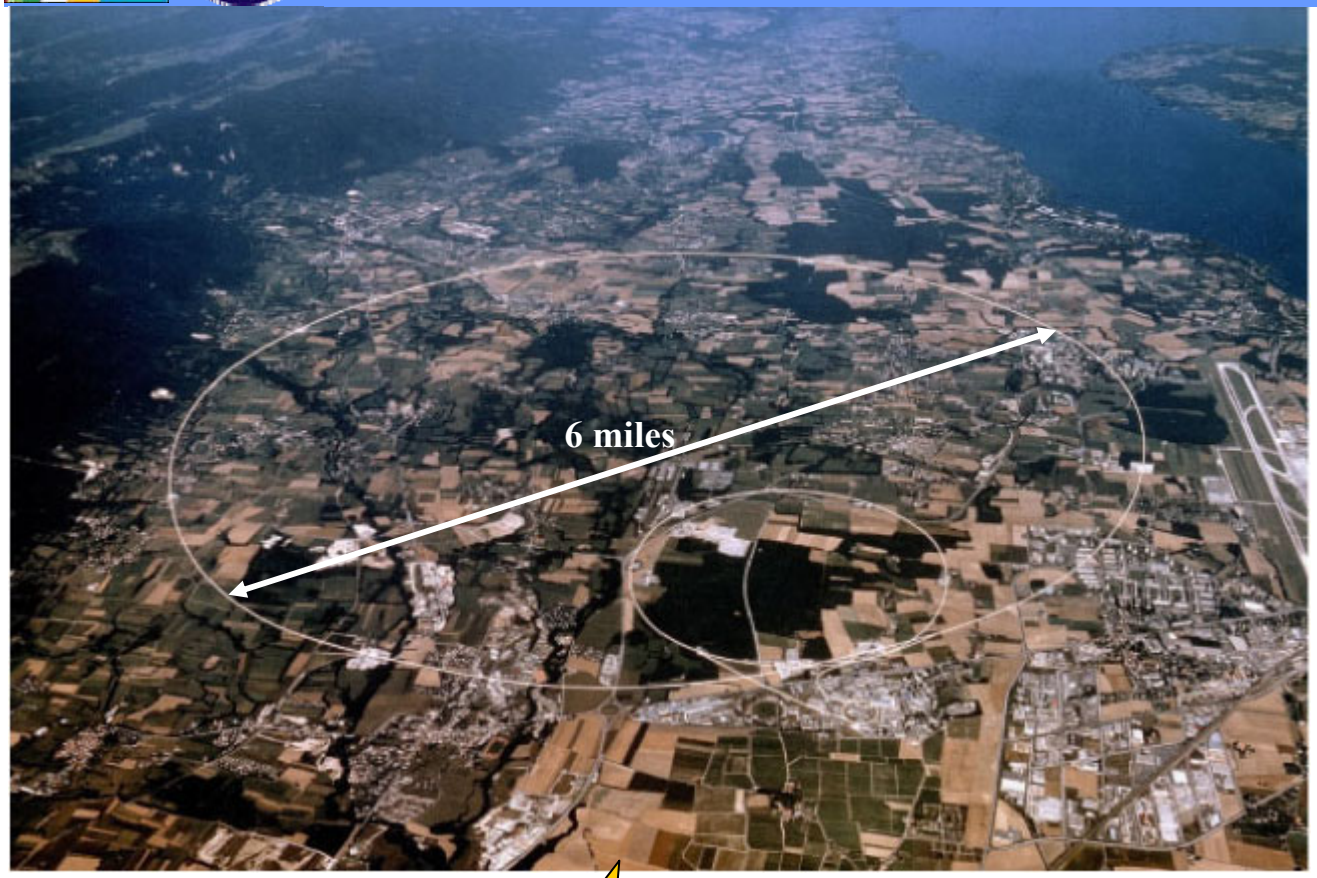
The New Forefront



- The forefront of science is moving from the US to CERN (Geneva, Switzerland).

- The LHC is designed to collide protons with protons at a center-of-mass energy of 14 TeV (seven times greater energy than Fermilab)!

The LHC at CERN



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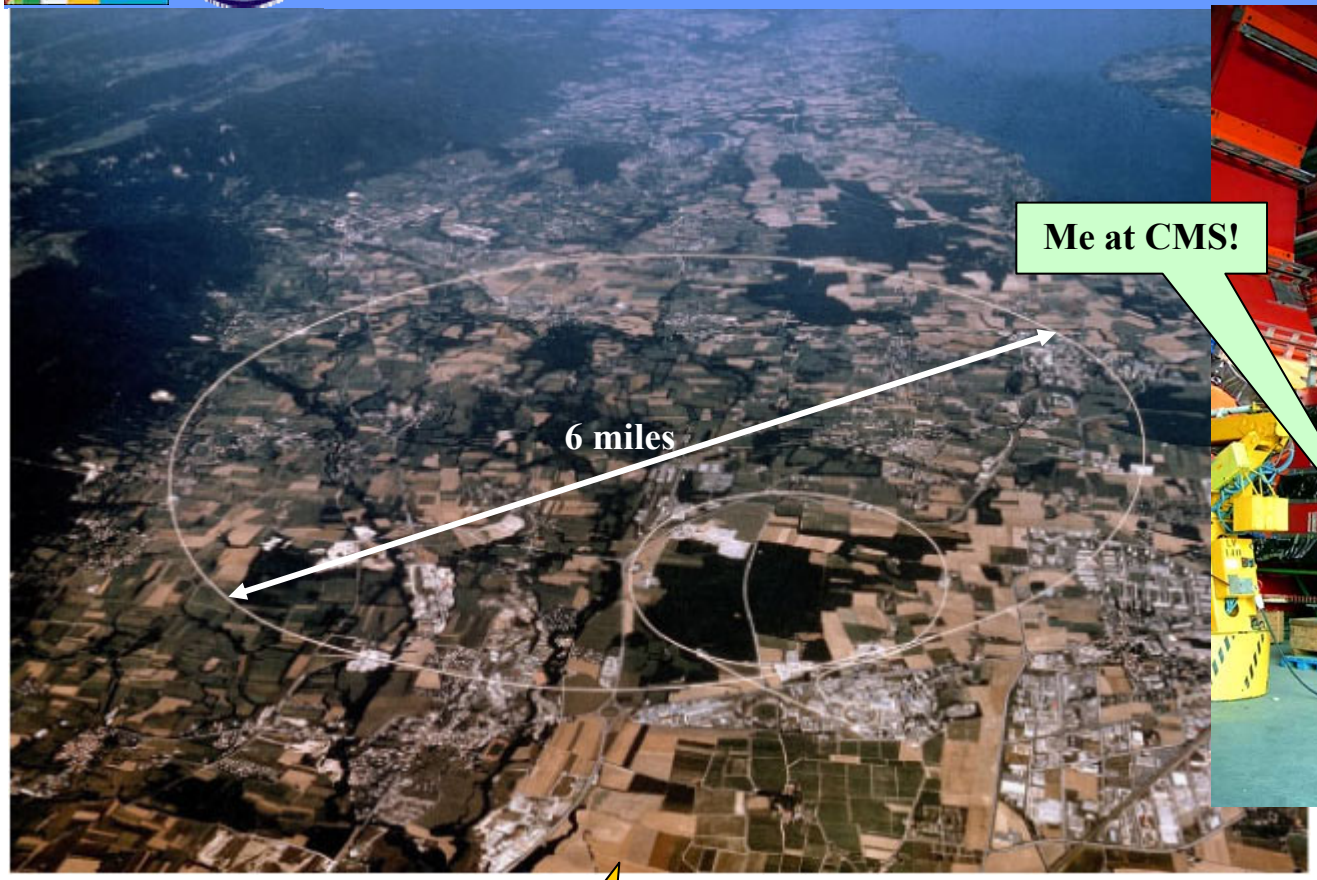
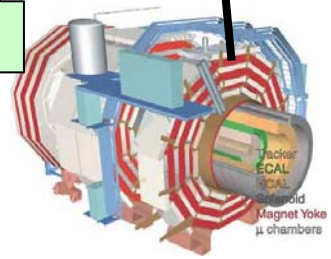
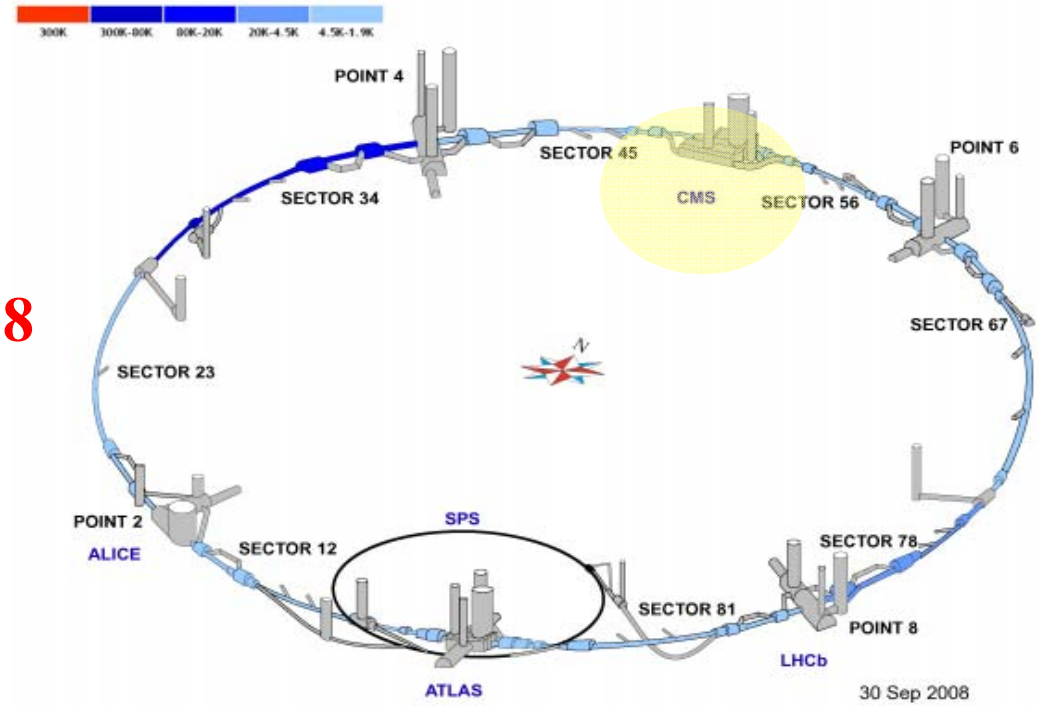


CMS at the LHC



The LHC

- **7 TeV on 7 TeV proton-proton collider, 27km ring**
  - 7 times higher energy than the Tevatron at Fermilab
    - Aim for 5 TeV for 2008
  - 100 times higher design luminosity than Tevatron ($L=10^{34}cm^{-2}s^{-1}$)
- **1232 superconducting 8.4T dipole magnets @ T=1.9ºK**
  - Largest cryogenic structure, 40 ktons of mass to cool
- **4 experiments**
- **Start Date:**
  September 10, 2008

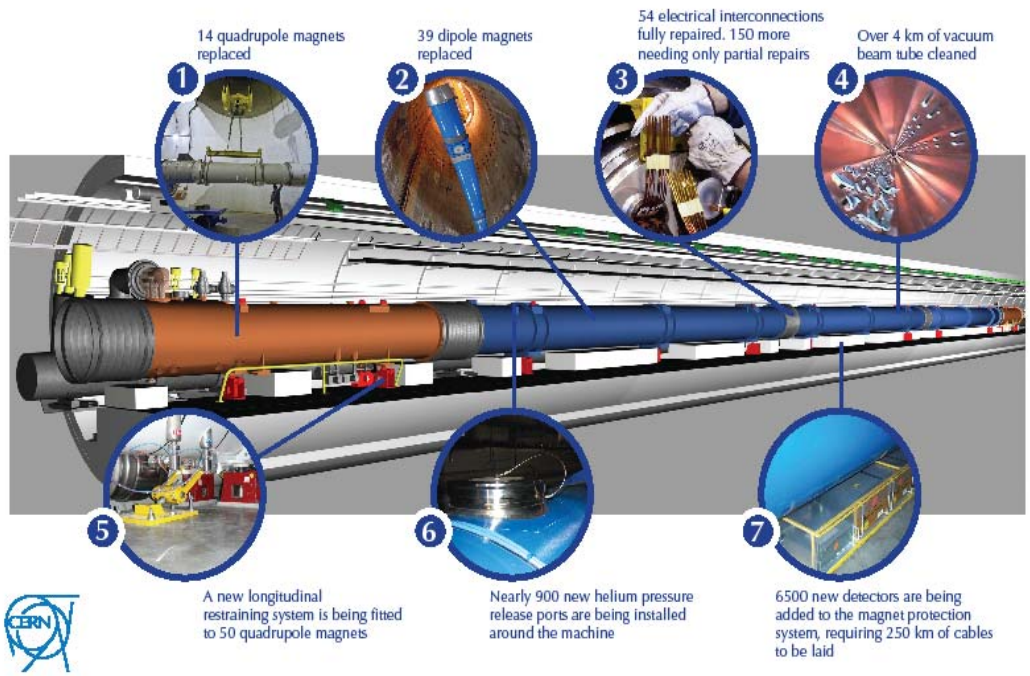


Incident of September 19th 2008

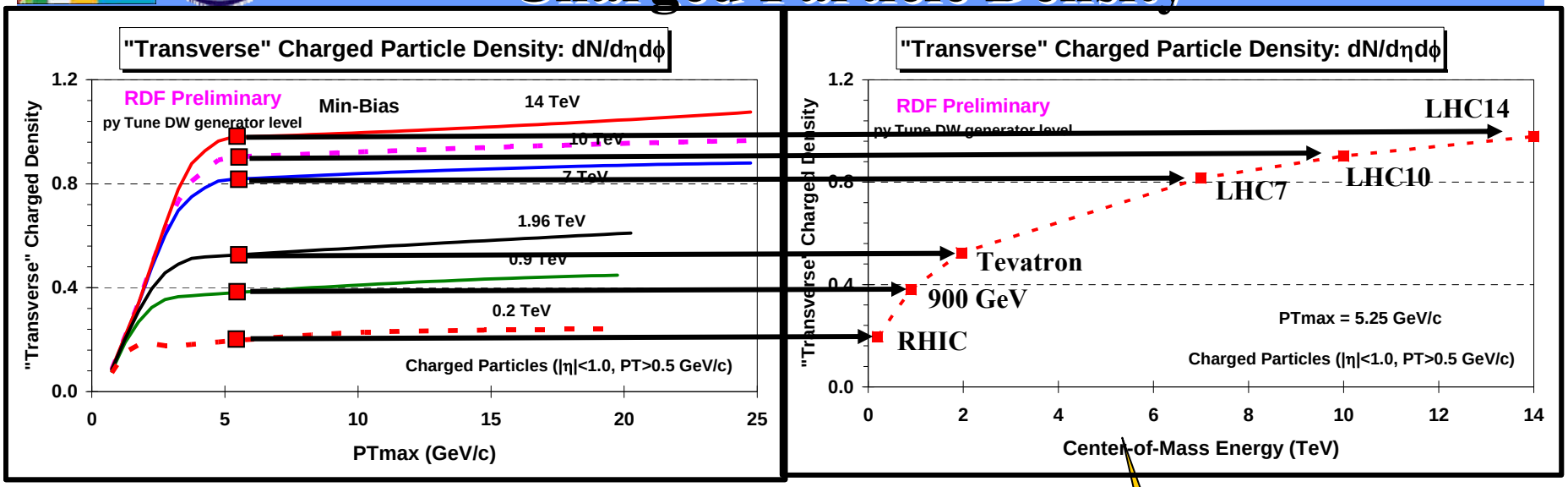
- Very impressive start-up with beam on September 10, 2008!

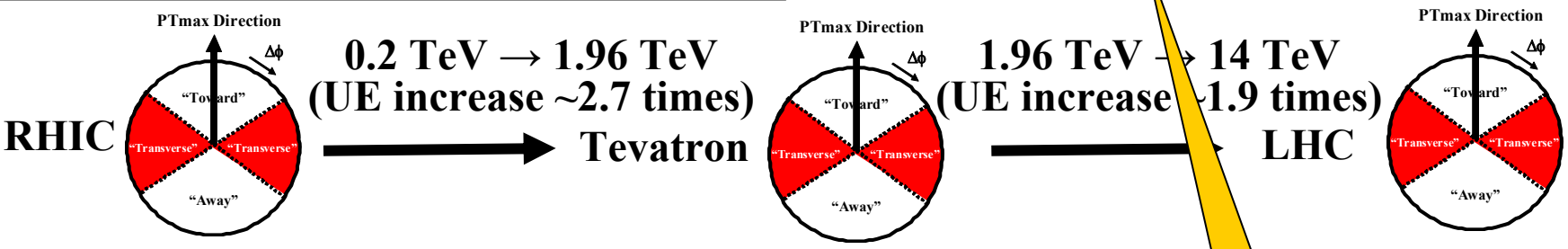
- While making the last step of the dipole circuit in sector 34, to 9.3kA. At 8.7kA, development of resistive zone in the dipole bus bar splice between Q24 R3 and the neighboring dipole. Electrical arc developed which punctured the helium encl

14 months of repair!



Min-Bias "Associated" Charged Particle Density

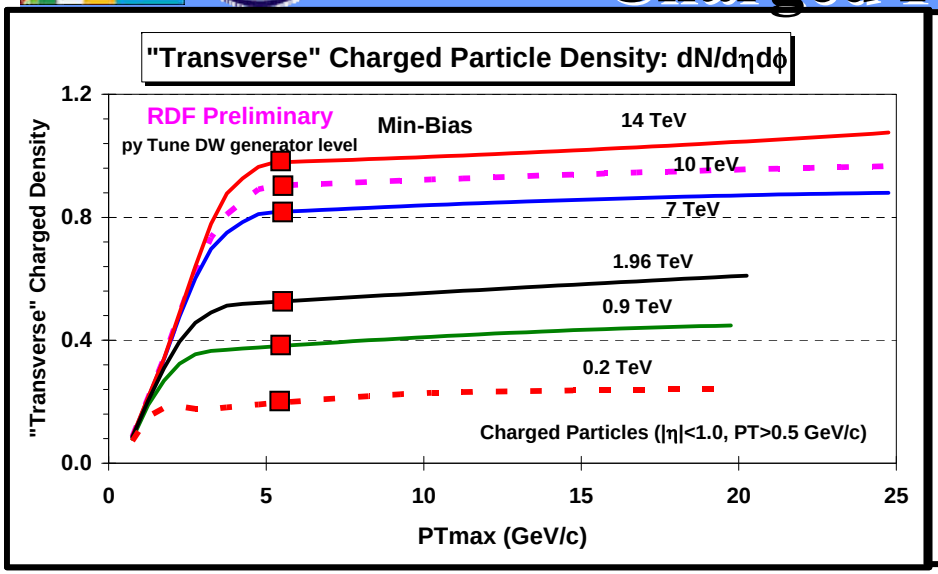


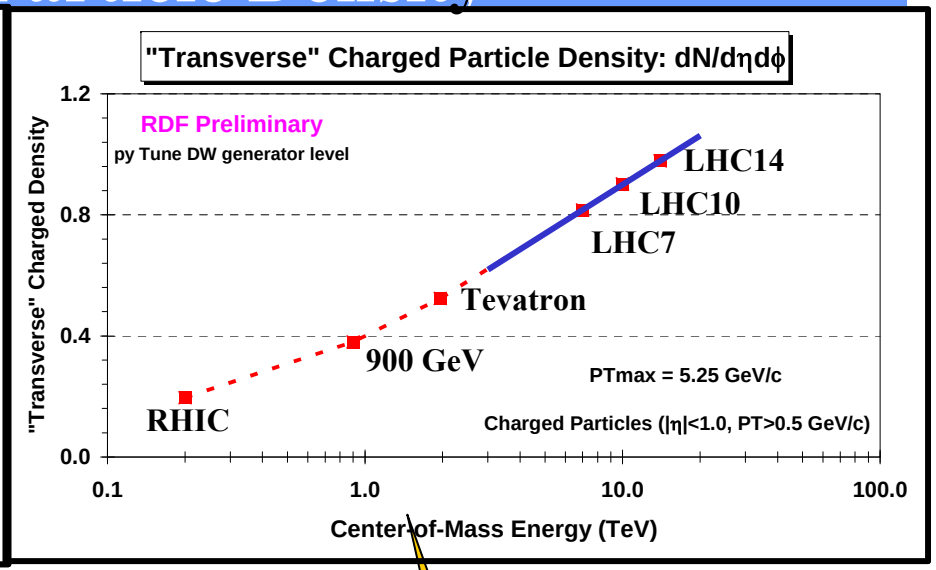


Linear scale!

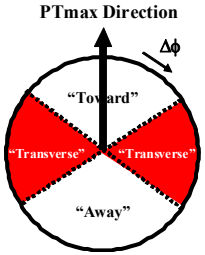
- Shows the "associated" charged particle density in the "transverse" region as a function of PTmax for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, *not including PTmax*) in "min-bias" events at 0.2 TeV, 0.9 TeV, 1.96 TeV, 7 TeV, 10 TeV, 14 TeV predicted by PYTHIA Tune DW at the particle level (*i.e.* generator level).

Min-Bias "Associated" Charged Particle Density





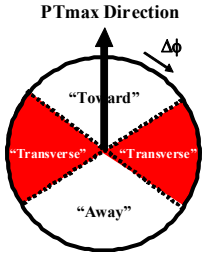
LHC7



7 TeV → 14 TeV
(UE increase ~20%)

Linear on a log plot!

LHC14

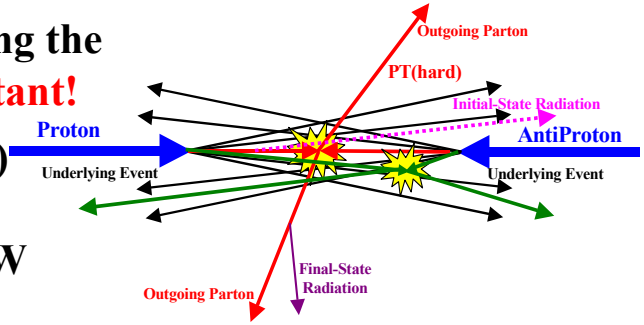


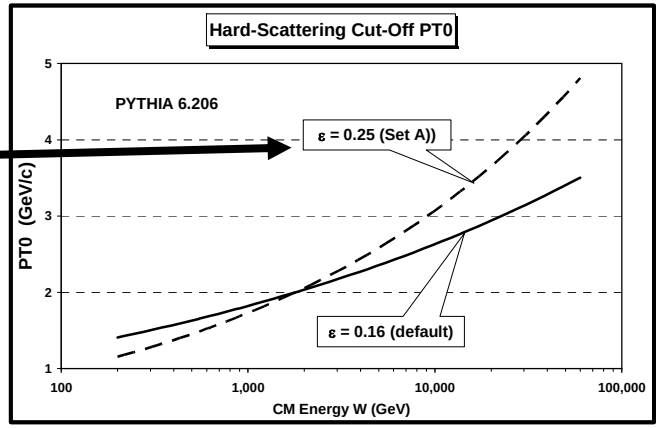
Log scale!

- **Shows the "associated" charged particle density in the "transverse" region as a function of PTmax for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmax*) for "min-bias" events at 0.2 TeV, 0.9 TeV, 1.96 TeV, 7 TeV, 10 TeV, 14 TeV predicted by PYTHIA py Tune DW at the particle level (*i.e.* generator level).**

Conclusions November 2009

- We are making good progress in understanding and modeling the "underlying event". RHIC data at 200 GeV are very important!
- The new Pythia p_T ordered tunes (py64 S320 and py64 P329) are very similar to Tune A, Tune AW, and Tune DW. At present the new tunes do not fit the data better than Tune AW and Tune DW. However, the new tune are theoretically preferred!
- It is clear now that the default value PARP(90) = 0.16 is not correct and the value should be closer to the Tune A value of 0.25.
- The new and old PYTHIA tunes are beginning to converge and I believe we are finally in a position to make some legitimate predictions at the LHC!
- All tunes with the default value PARP(90) = 0.16 are wrong and are overestimating the activity of min-bias and the underlying event at the LHC! This includes all my "T" tunes and the (old) ATLAS tunes!
- Need to measure "Min-Bias" and the "underlying event" at the LHC as soon as possible to see if there is new QCD physics to be learned!



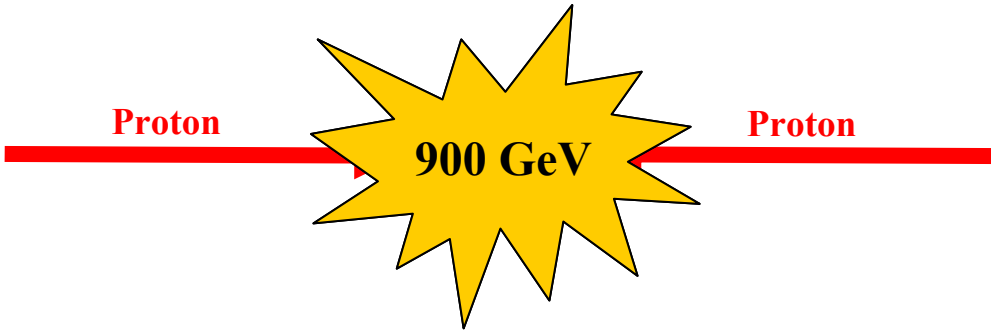


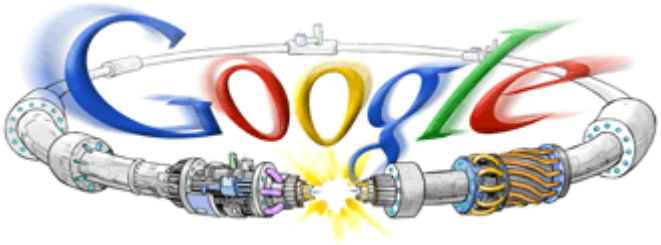
UE&MB@CMS

LHC 2009 Summary

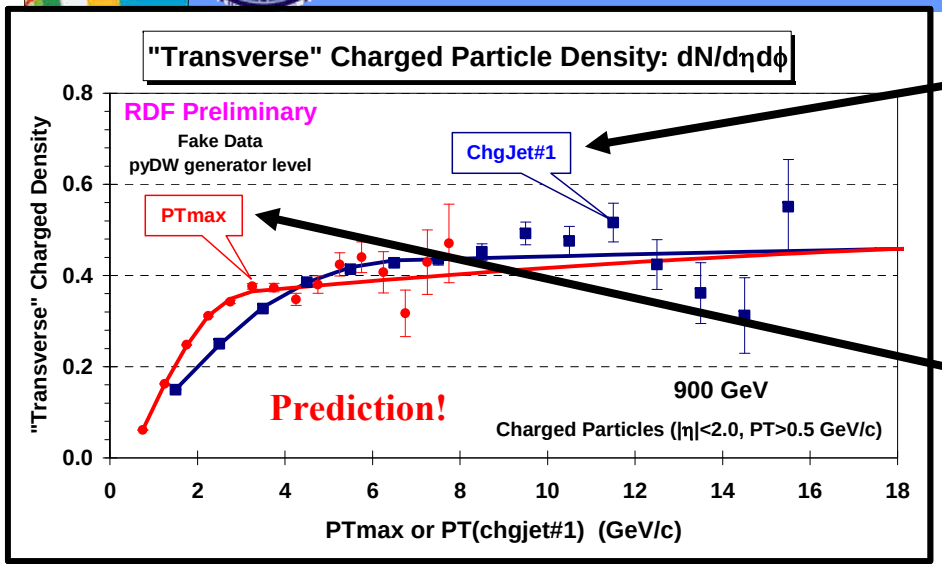
- *November 20th 2009*
  - **First beams around again**
- *November 29th 2009*
  - **Both beams accelerated to 1.18 TeV simultaneously**
- *December 8th 2009*
  - **2x2 accelerated to 1.18 TeV**
  - **First collisions at E_{cm} = 2.36 TeV!**
- *December 14th 2009*
  - **Stable 2x2 at 1.18 TeV**
  - **Collisions in all four experiments**

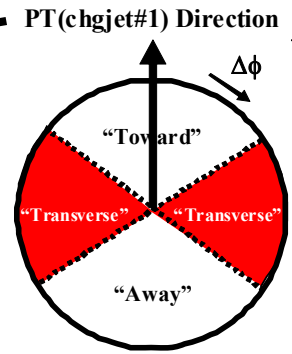
LHC - highest energy collider



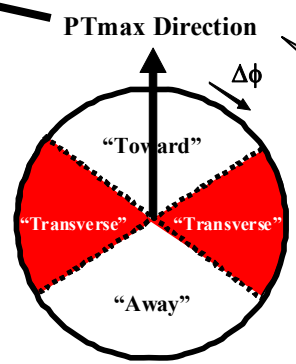


"Transverse" Charged Particle Density





Leading Charged Particle Jet, chgjet#1.

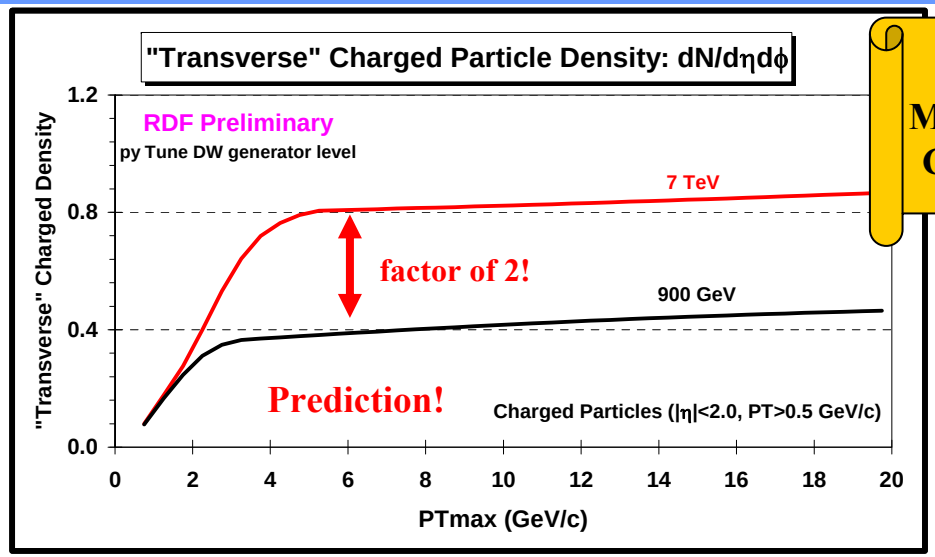


Leading Charged Particle, PTmax.

- **Fake data (from MC) at 900 GeV on the "transverse" charged particle density, dN/dηdϕ, as defined by the leading charged particle (PTmax) and the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2$. The fake data (from PYTHIA Tune DW) are generated at the particle level (*i.e.* generator level) assuming 0.5 M min-bias events at 900 GeV (361,595 events in the plot).**

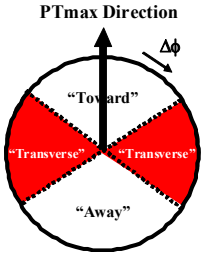
Rick Field
MB&UE@CMS Workshop
CERN, November 6, 2009

"Transverse" Charge Density



Rick Field
MB&UE@CMS Workshop
CERN, November 6, 2009

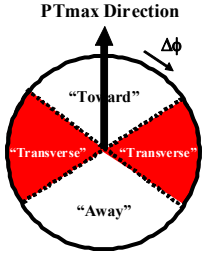
LHC 900 GeV



900 GeV → 7 TeV
(UE increase ~ factor of 2)

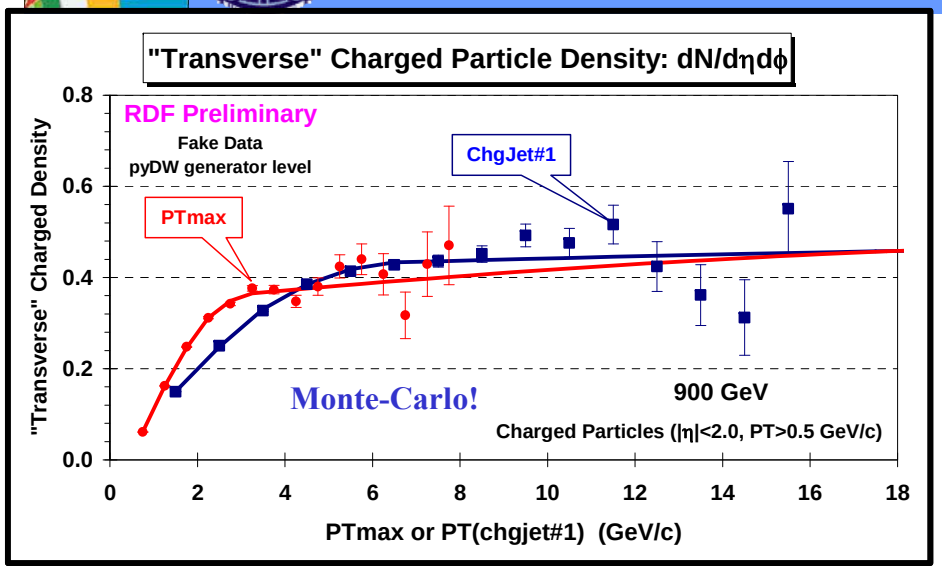
~0.4 → ~0.8

LHC 7 TeV



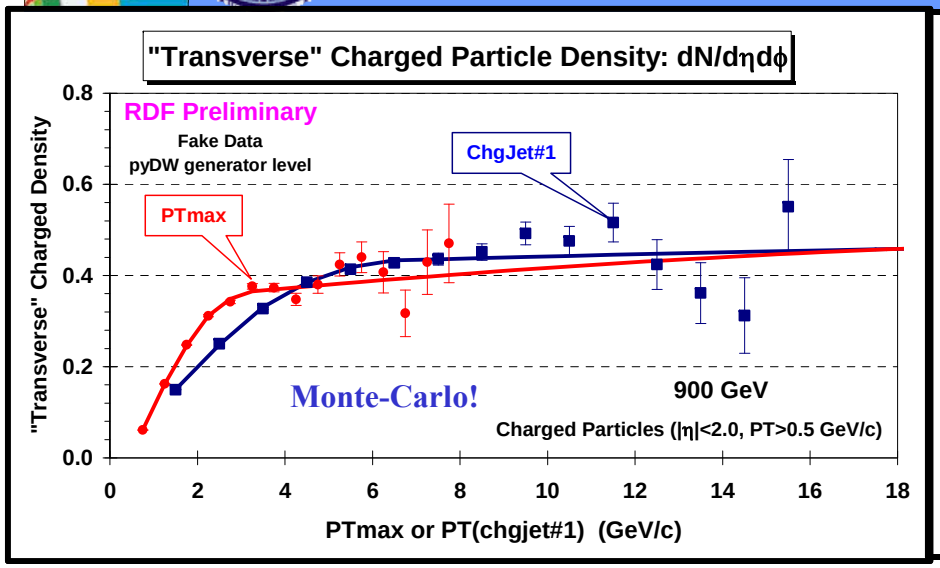
- **Shows the charged particle density in the "transverse" region for charged particles (p_T > 0.5 GeV/c, |η| < 2) at 900 GeV and 7 TeV as defined by PTmax from PYTHIA Tune DW and at the particle level (*i.e.* generator level).**

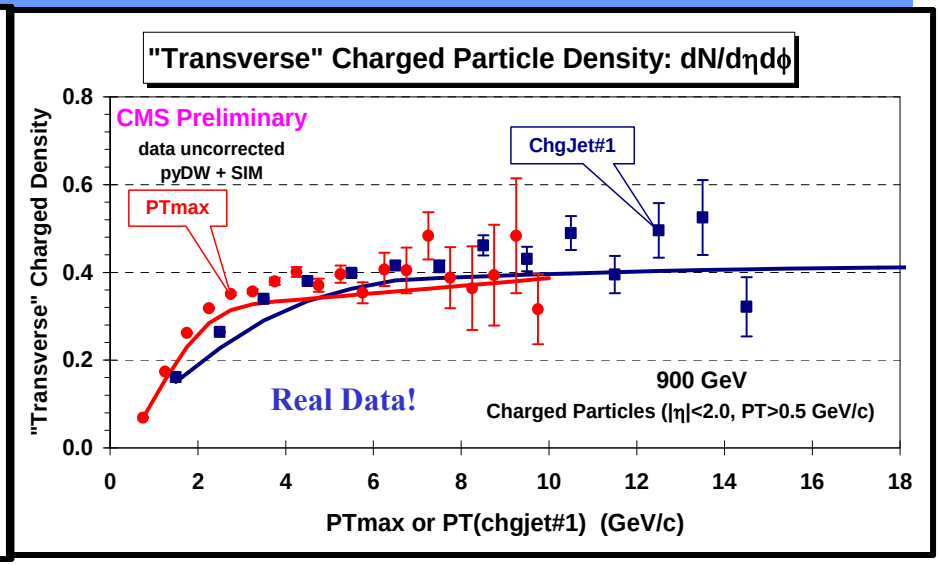
"Transverse" Charged Particle Density



- **Fake data (from MC) at 900 GeV on the "transverse" charged particle density, dN/dηdϕ, as defined by the leading charged particle (PTmax) and the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2$. The fake data (from PYTHIA Tune DW) are generated at the particle level (*i.e.* generator level) assuming 0.5 M min-bias events at 900 GeV (361,595 events in the plot).**

"Transverse" Charged Particle Density



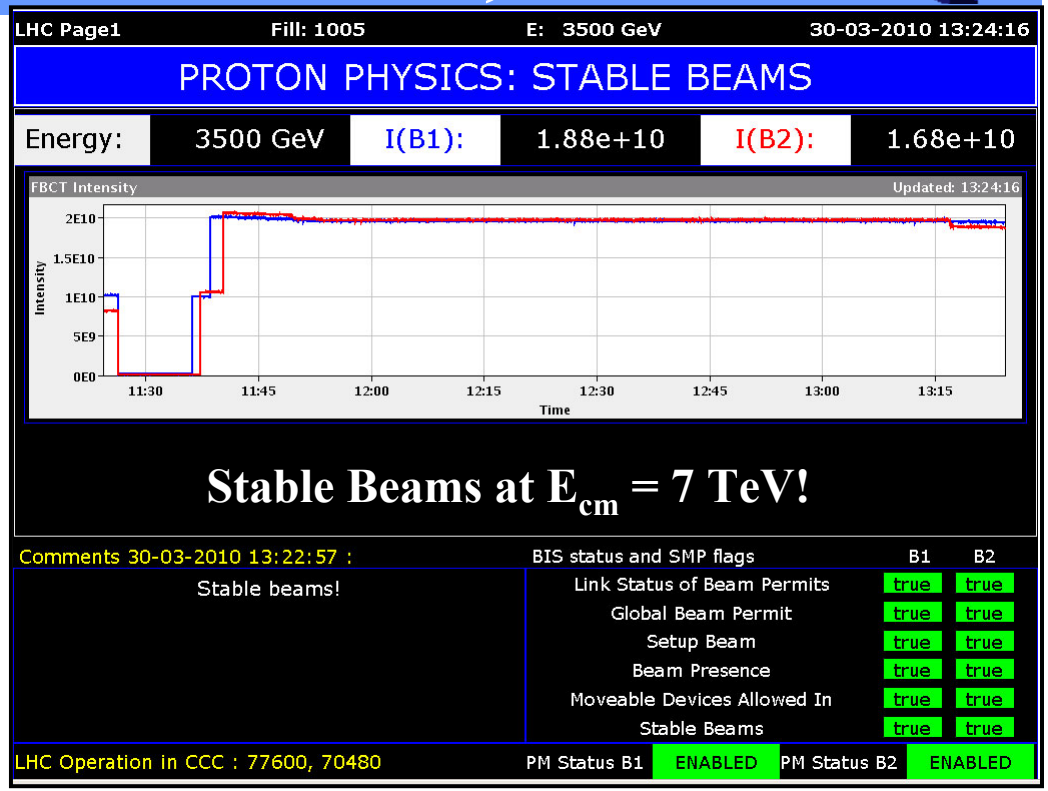


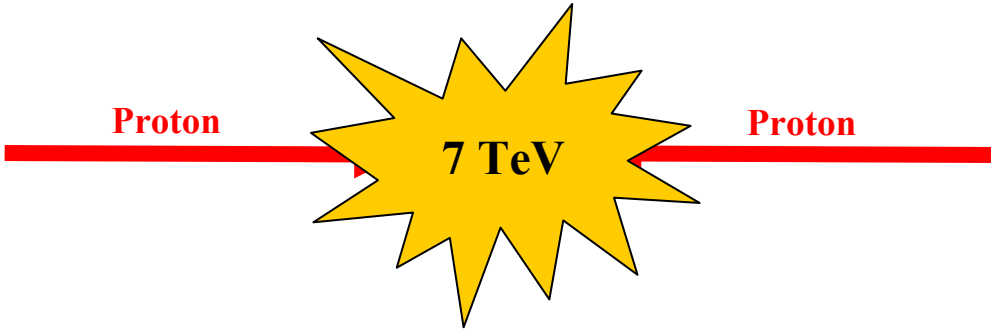
- **Fake data (from MC) at 900 GeV on the "transverse" charged particle density, dN/dηdϕ, as defined by the leading charged particle (PTmax) and the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2$. The fake data (from PYTHIA Tune DW) are generated at the particle level (*i.e.* generator level) assuming 0.5 M min-bias events at 900 GeV (361,595 events in the plot).**

- **CMS preliminary data at 900 GeV on the "transverse" charged particle density, dN/dηdϕ, as defined by the leading charged particle (PTmax) and the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2$. The data are uncorrected and compared with PYTHIA Tune DW after detector simulation (216,215 events in the plot).**

LHC: March 30, 2010

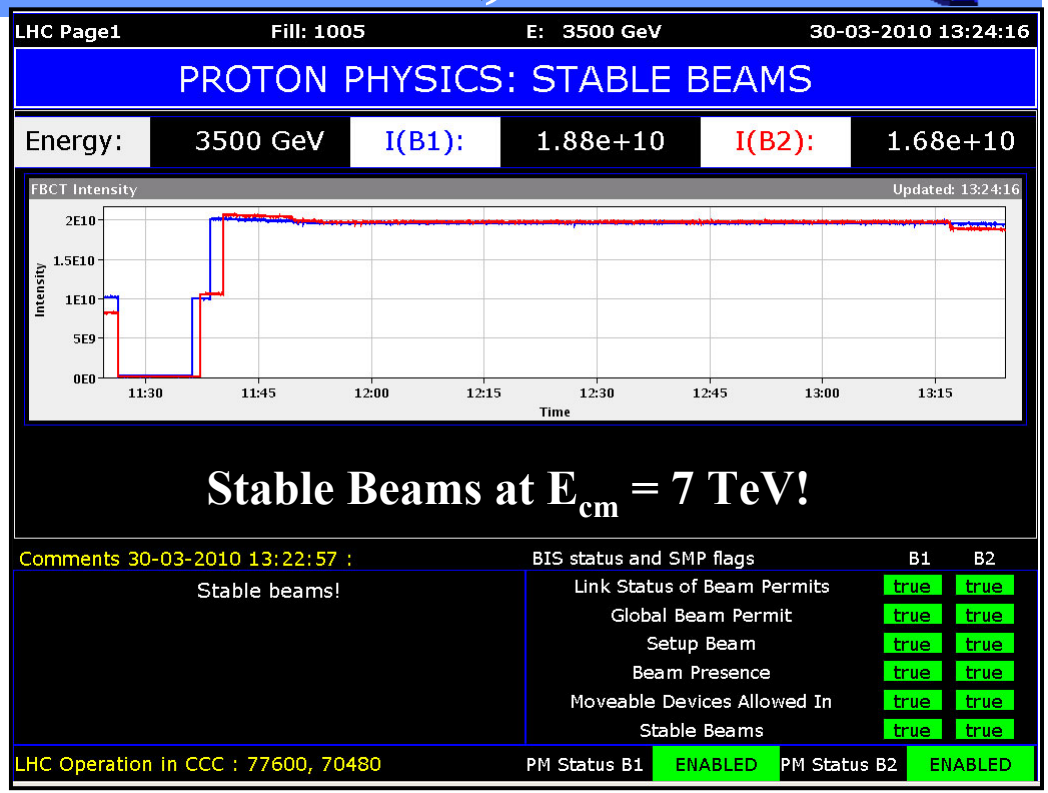
- **First collisions with beam energies of 3.5 TeV (E_{cm} = 7 TeV)! Factor of 4.5 higher energy than the Tevatron.**

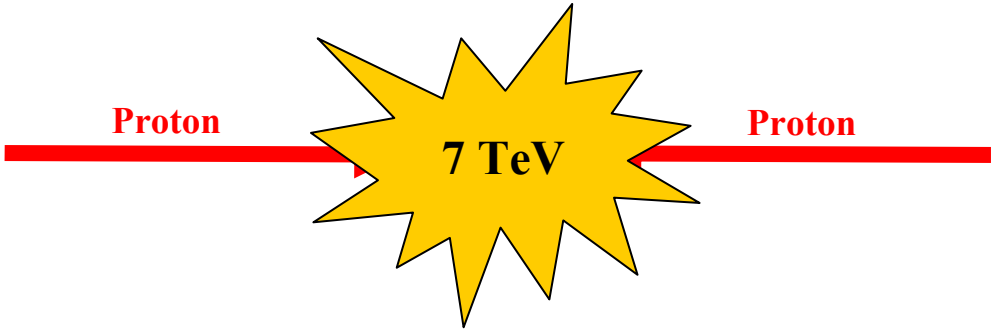




LHC: March 30, 2010

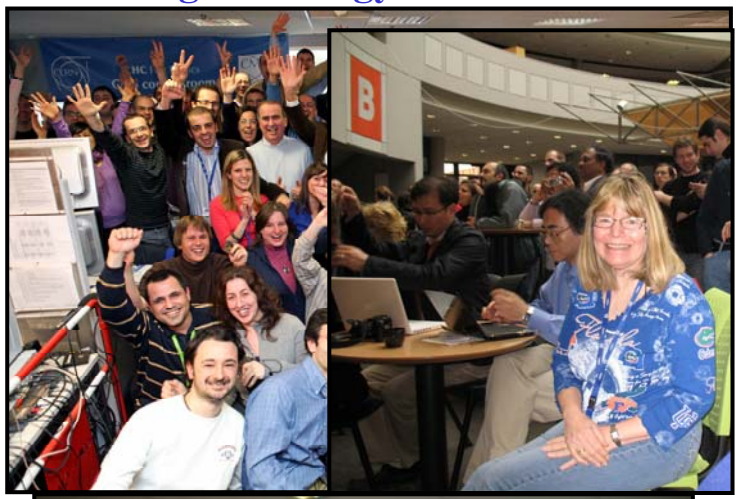
- First collisions with beam energies of 3.5 TeV (E_{cm} = 7 TeV)! Factor of 4.5 higher energy than the

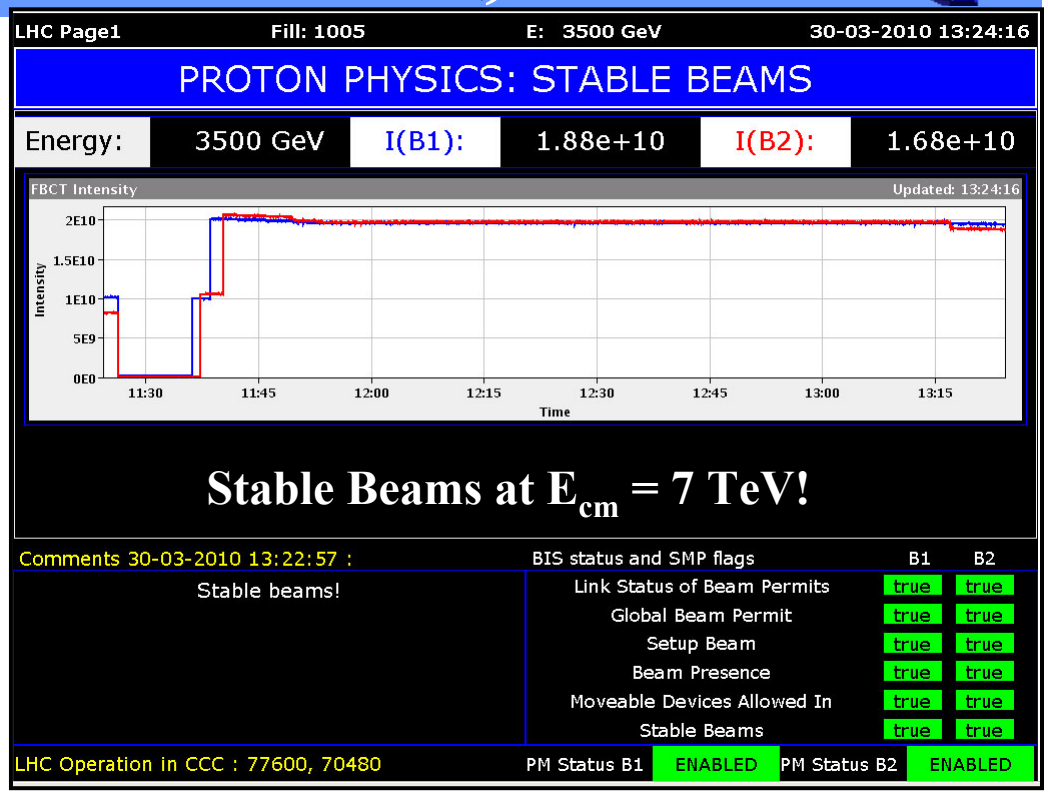


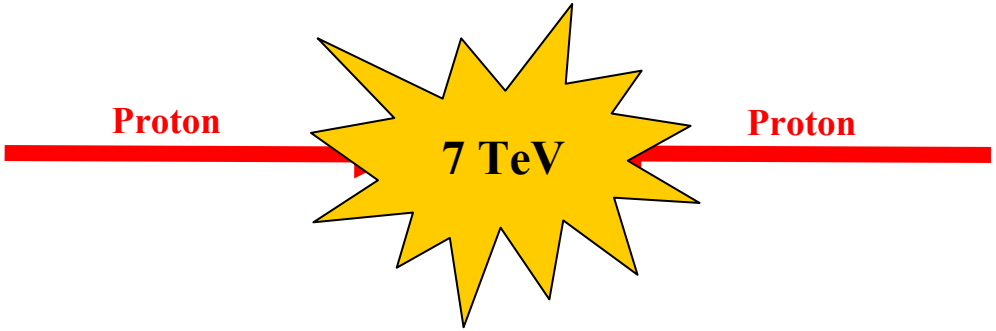


LHC: March 30, 2010

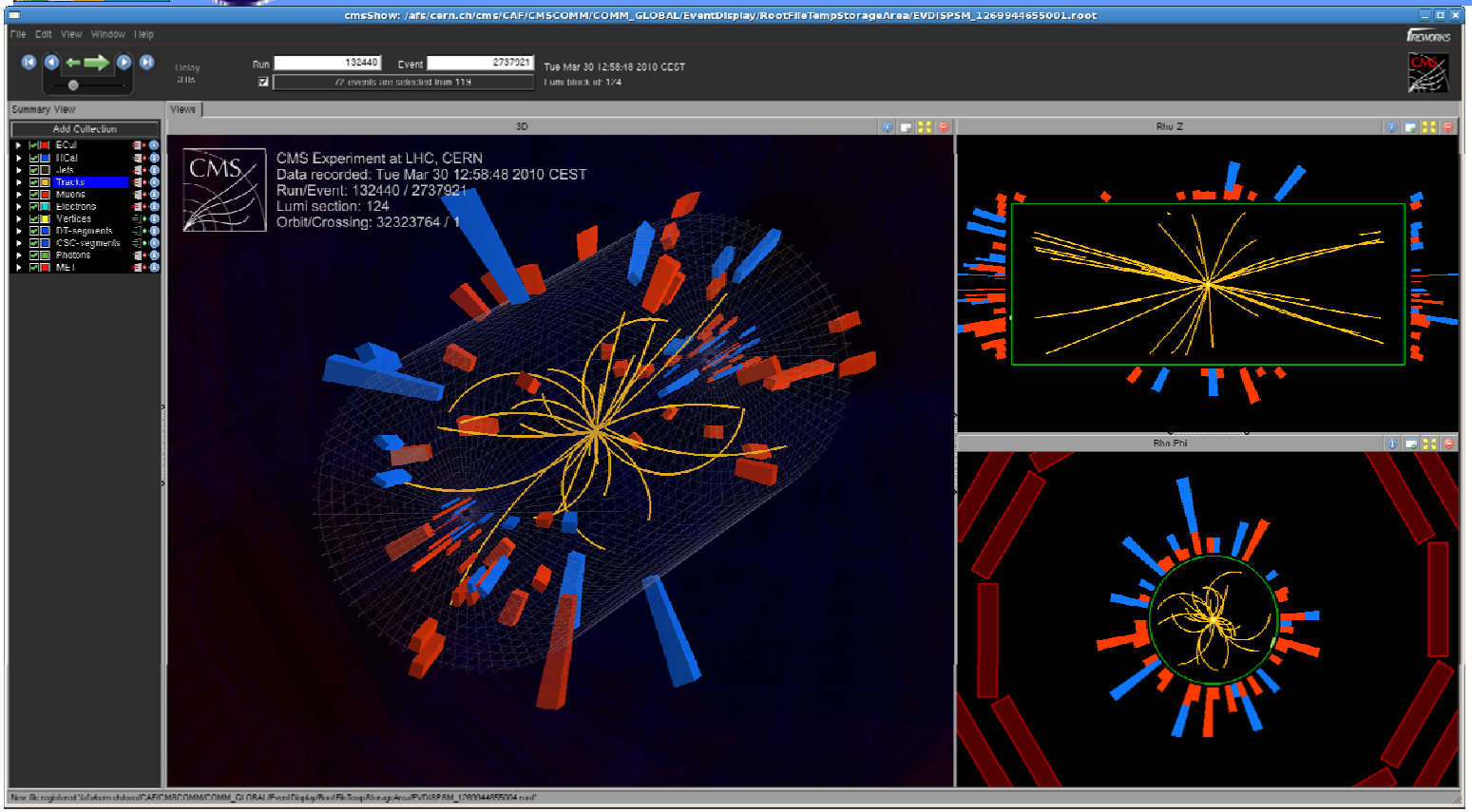
- **First collisions with beam energies of 3.5 TeV (E_{cm} = 7 TeV)! Factor of 4.5 higher energy than the**





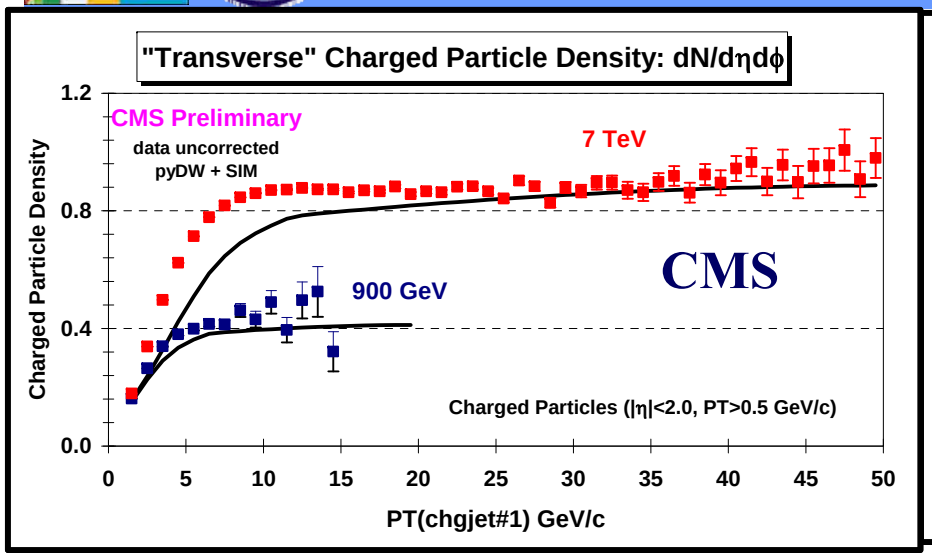


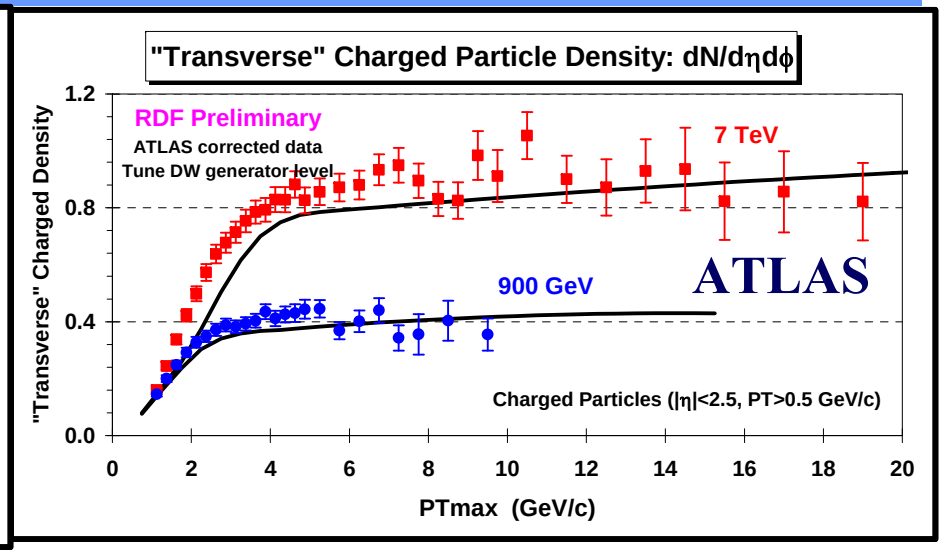
CMS: March 30, 2010



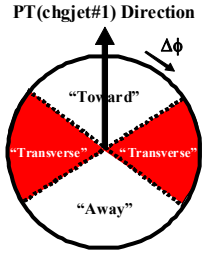
CMS: March 30, 2010

PYTHIA Tune DW

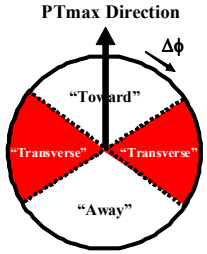




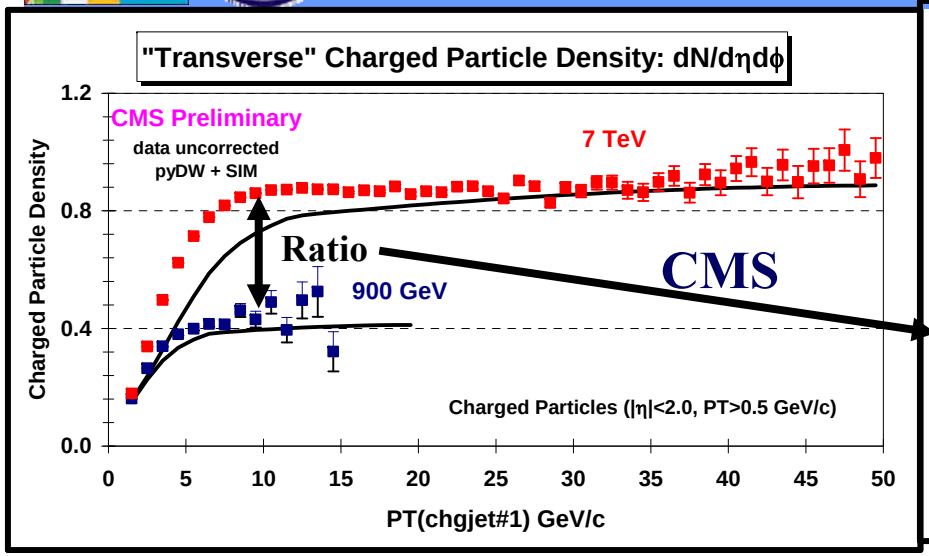
➡ **CMS preliminary data at 900 GeV and 7 TeV on the "transverse" charged particle density, dN/dηdϕ, as defined by the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2$. The data are uncorrected and compared with PYTHIA Tune DW after detector simulation.**

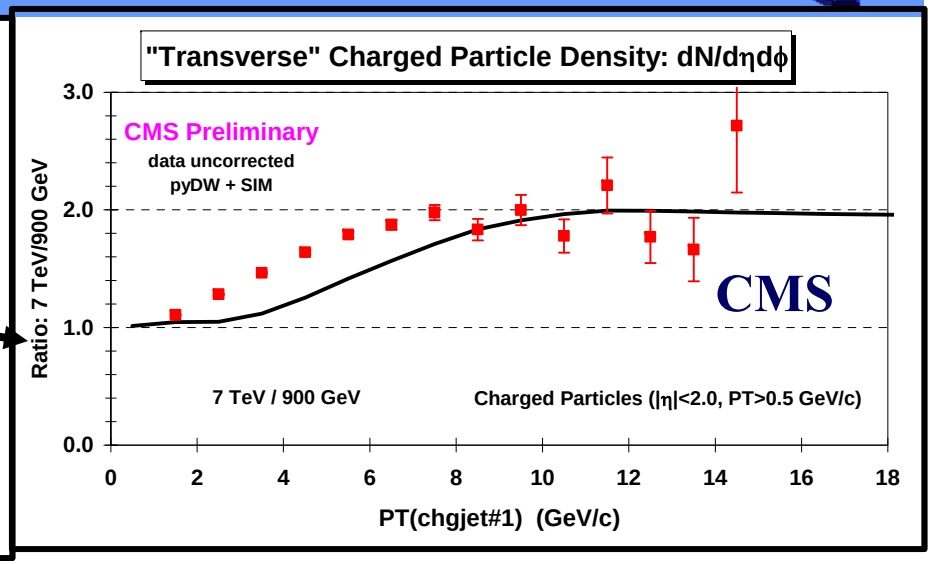


➡ **ATLAS preliminary data at 900 GeV and 7 TeV on the "transverse" charged particle density, dN/dηdϕ, as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2.5$. The data are corrected and compared with PYTHIA Tune DW at the generator level.**

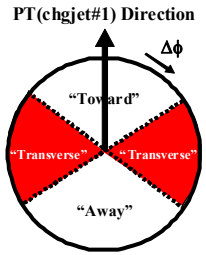


PYTHIA Tune DW



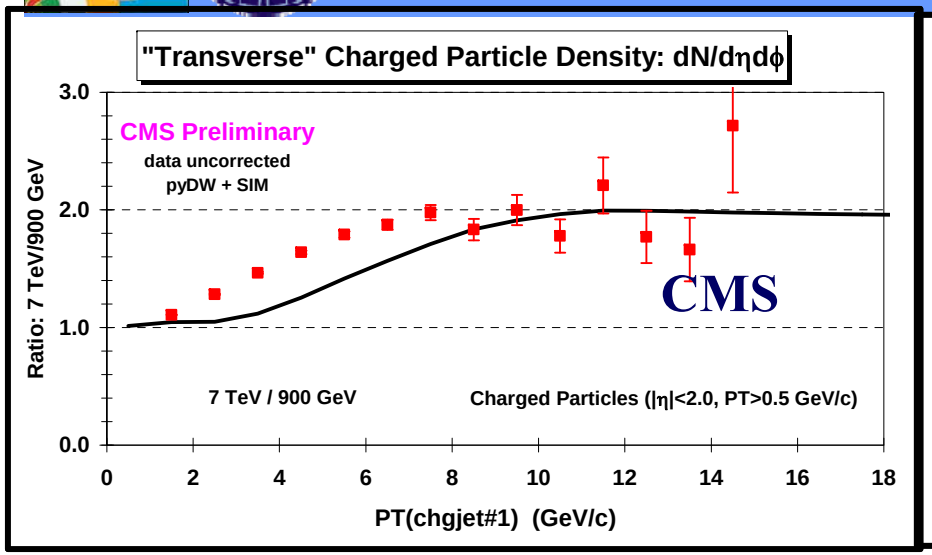


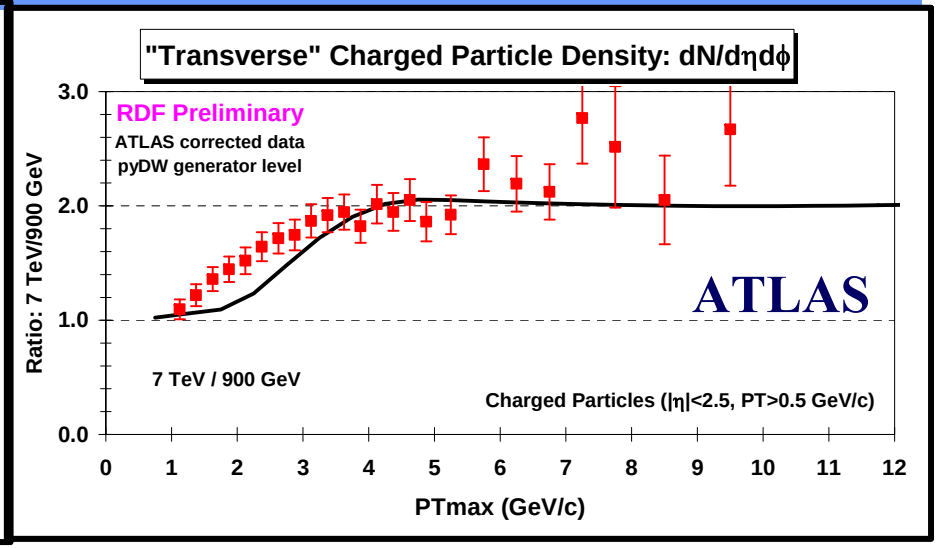
- **CMS preliminary data at 900 GeV and 7 TeV on the "transverse" charged particle density, dN/dηdϕ, as defined by the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2$. The data are uncorrected and compared with PYTHIA Tune DW after detector simulation.**



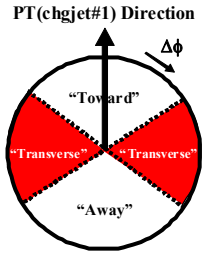
- **Ratio of CMS preliminary data at 900 GeV and 7 TeV on the "transverse" charged particle density, dN/dηdϕ, as defined by the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2$. The data are uncorrected and compared with PYTHIA Tune DW after detector simulation.**

PYTHIA Tune DW

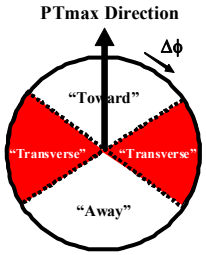




- **Ratio of CMS preliminary data at 900 GeV and 7 TeV on the "transverse" charged particle density, dN/dηdϕ, as defined by the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2$. The data are uncorrected and compared with PYTHIA Tune DW after detector simulation.**

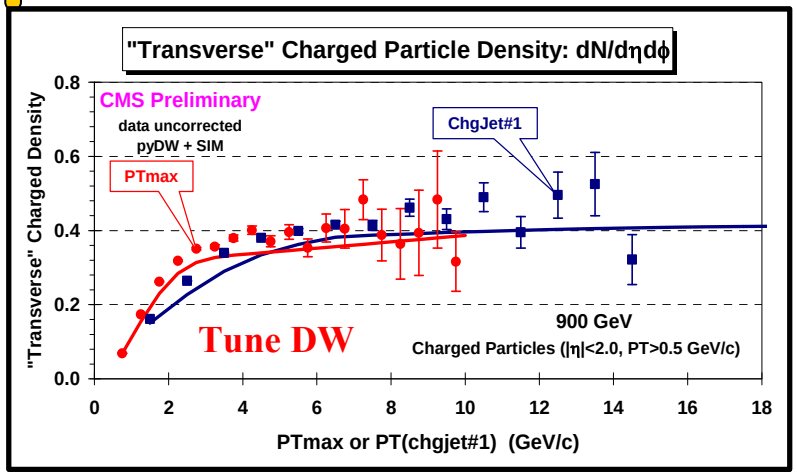


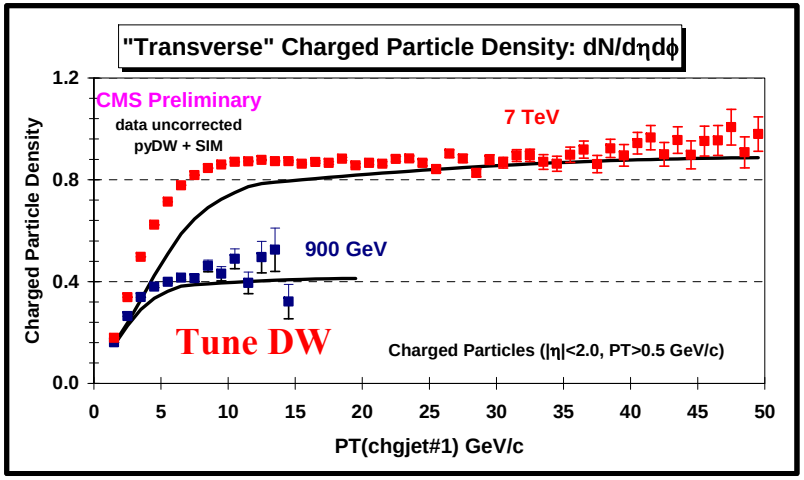
- **Ratio of the ATLAS preliminary data at 900 GeV and 7 TeV on the "transverse" charged particle density, dN/dηdϕ, as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2.5$. The data are corrected and compared with PYTHIA Tune DW at the generator level.**



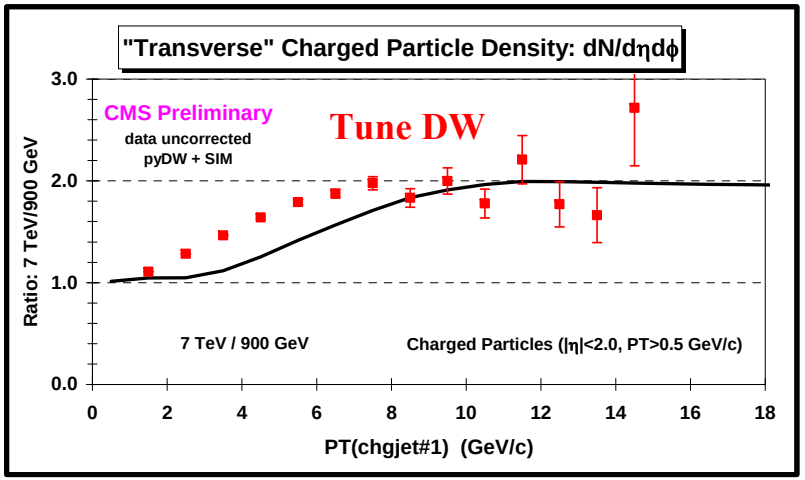
PYTHIA Tune DW

How well did we do at predicting the "underlying event" at 900 GeV and 7 TeV?



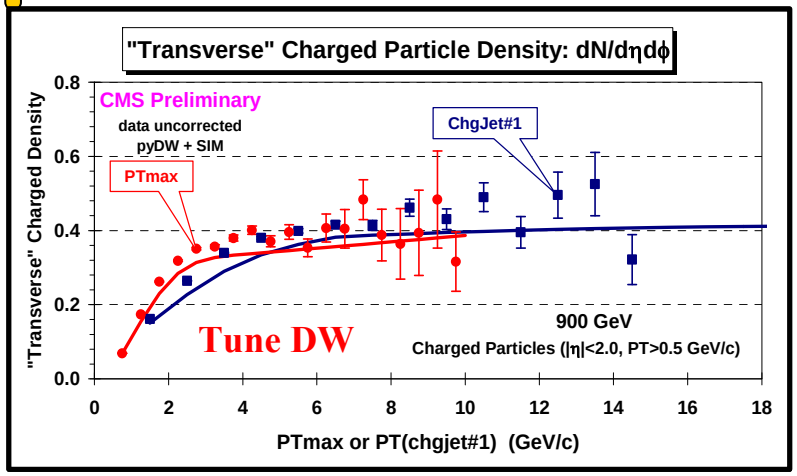


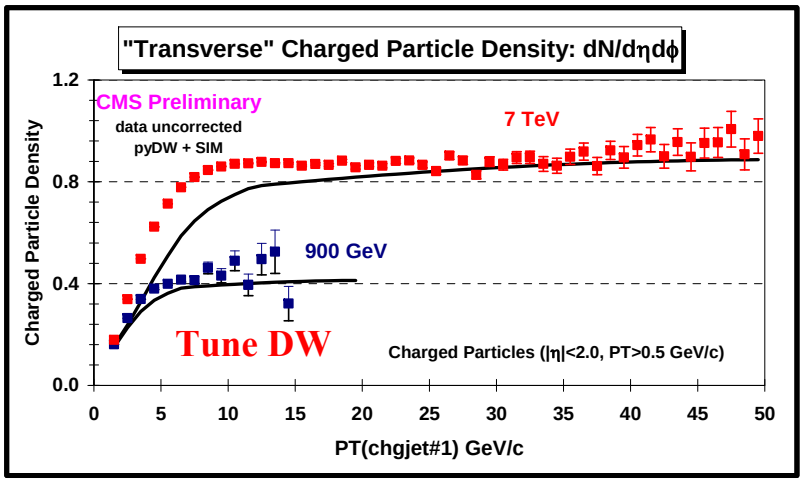
- **I am surprised that the Tunes did not do a better job of predicting the behavior of the "underlying event" at 900 GeV and 7 TeV!**



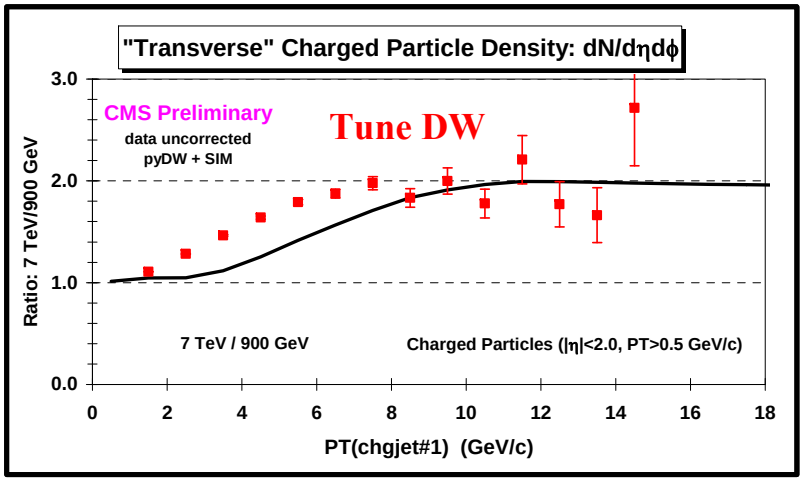
PYTHIA Tune DW

How well did we do at predicting the "underlying event" at 900 GeV and 7 TeV?





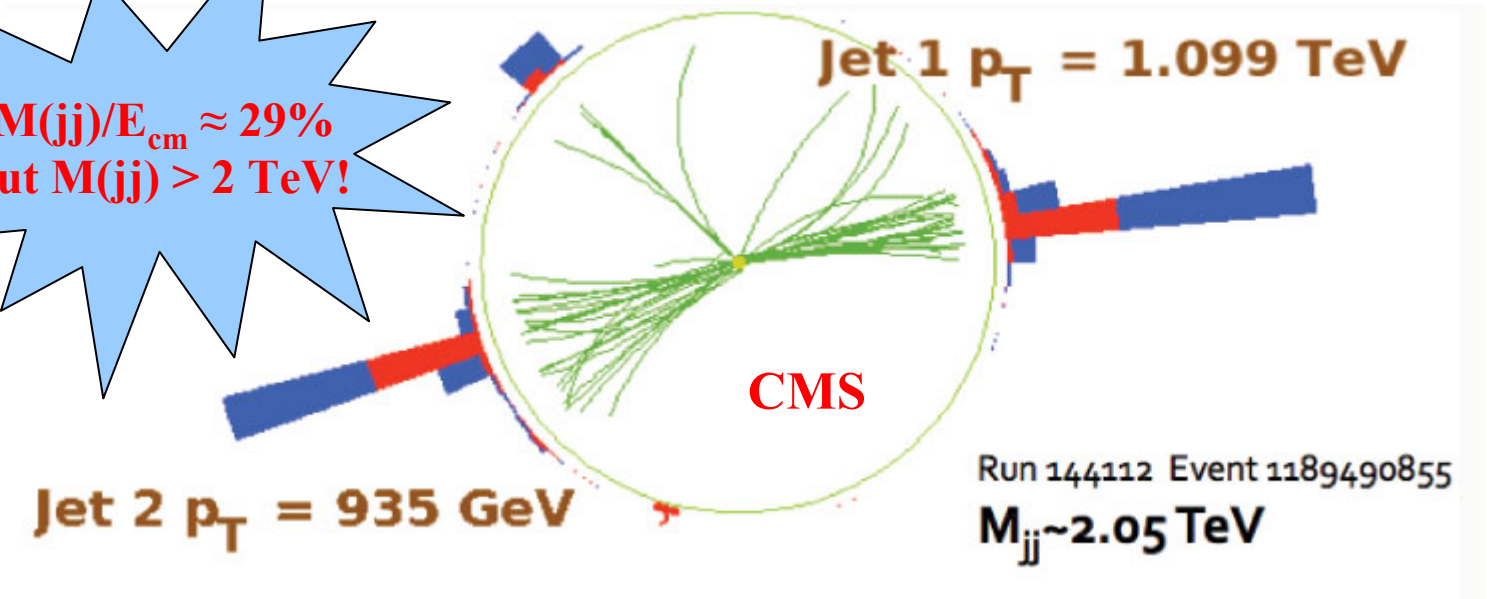
➡ **I am surprised that the Tunes did as well as they did at predicting the behavior of the "underlying event" at 900 GeV and 7 TeV!**



CMS DiJet Event: M(jj) ≈ 2 TeV

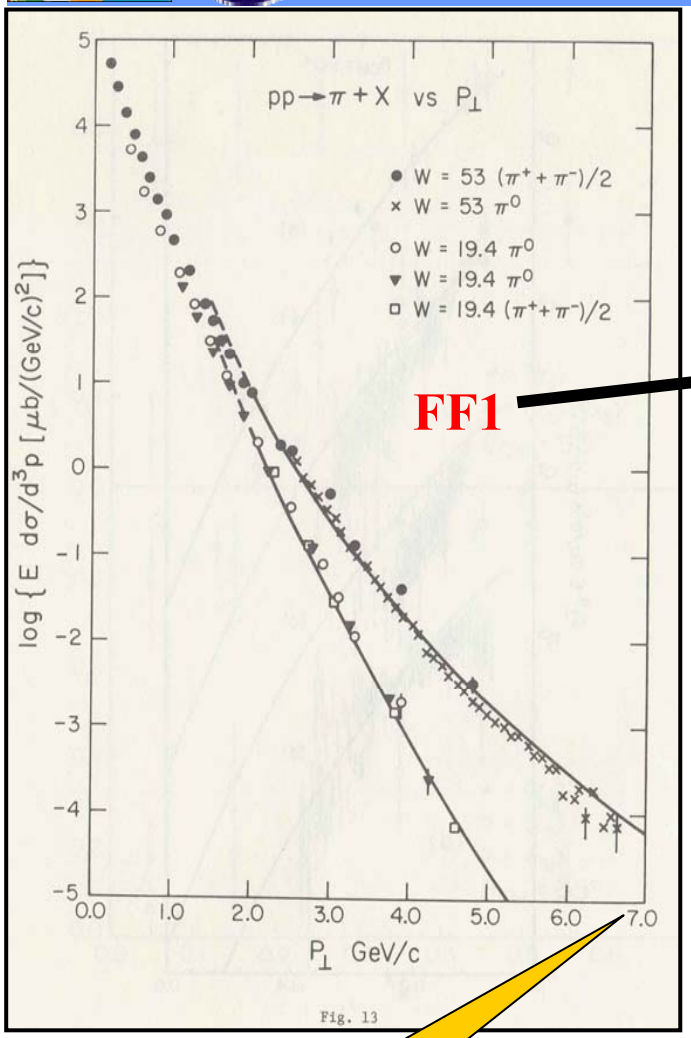
E_T^{jet1} = 1.099 TeV E_T^{jet2} = 935 GeV
M(jj) = 2.05 TeV

$M(jj)/E_{cm} \approx 29\%$
But M(jj) > 2 TeV!

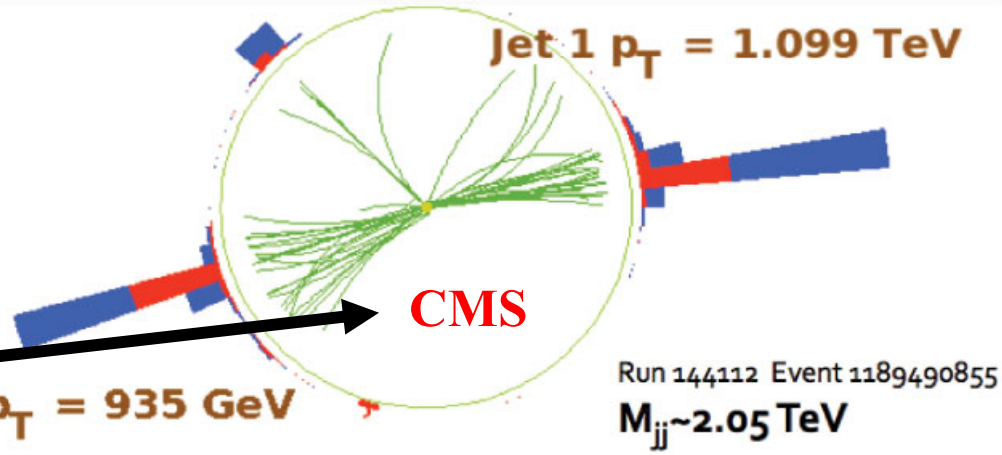


Proton-Proton Collisions at 7 TeV

7 GeV π^0's → 1 TeV Jets



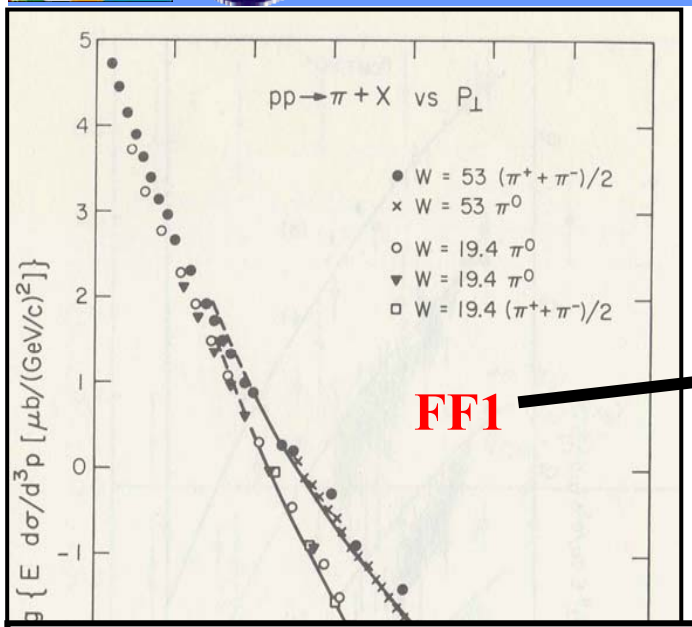
FF1



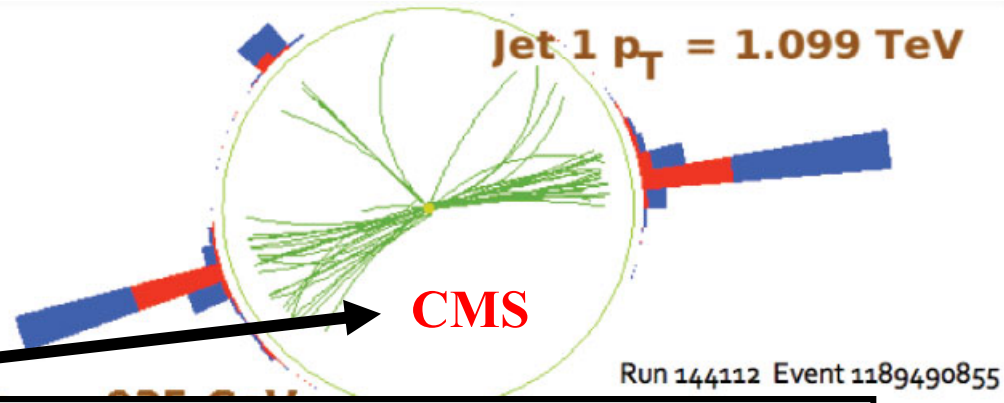
CMS

7 GeV/c π^0's!

7 GeV π^0's → 1 TeV Jets



FF1



CMS

Rick & Jimmie CALTECH 1973

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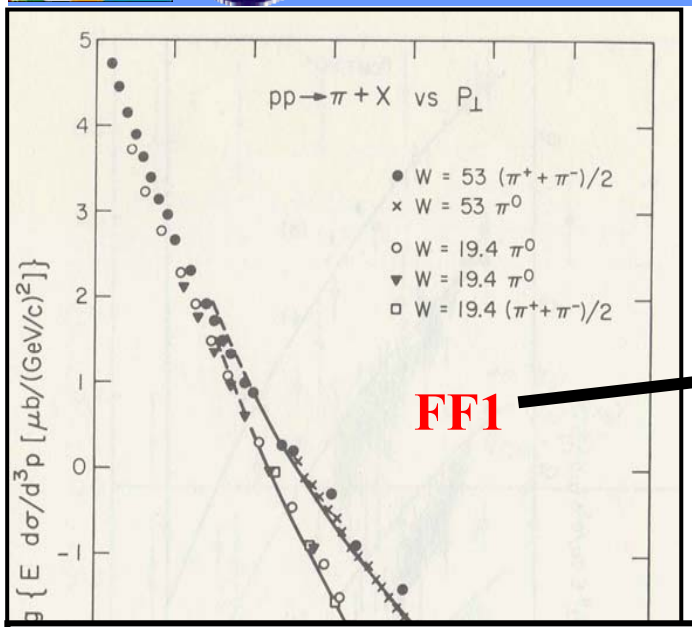
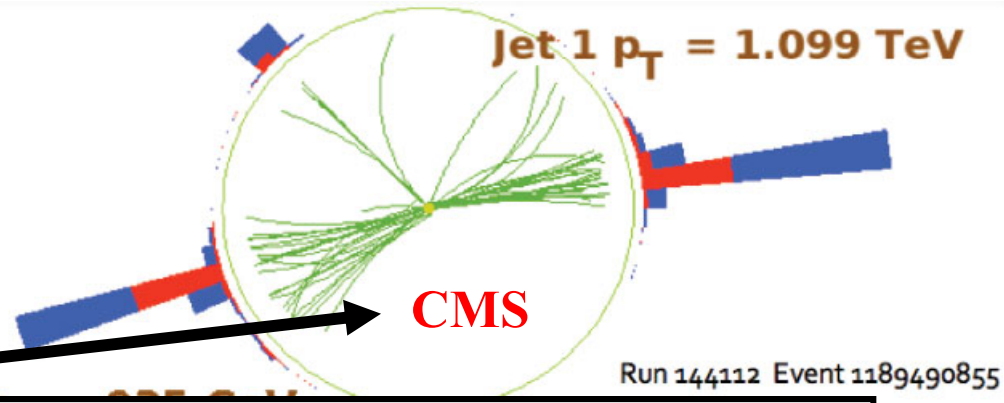
7 GeV π^0's → 1 TeV Jets



FF1



CMS

Rick & Jimmie CALTECH 1973

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