From Bjorken Scaling to pQCD--- Experimental techniques from p-p collisions of the 1970’s with application to Au+Au collisions at RHIC

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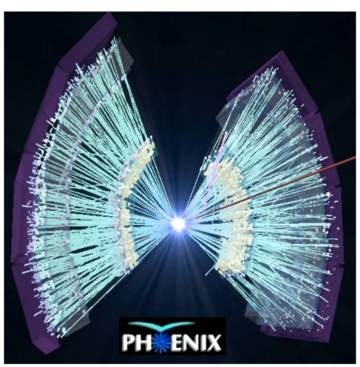


RHIC/AGS Users Meeting
May 11, 2004

Bjorken Scaling in Deeply Inelastic Scattering and the Parton Model---1968

♡ The discovery that the DIS structure function

$$F_2(Q^2, \nu) = F_2(\frac{Q^2}{\nu}) \qquad (1)$$

"SCALED" i.e just depended on the ratio

$$x = \frac{Q^2}{2M\nu} \qquad (2)$$

independently of Q^2 $(\sim 1/r^2)$

♡ as originally suggested by **Bjorken** Phys. Rev. **179**, 1547 (1969)

♡ Led to the concept of a proton composed of point-like **partons**. Phys. Rev. **185**, 1975 (1969)

$$\nu = \frac{Q^2}{2Mx}$$

- The probability for a parton to carry a fraction x of the proton's momentum is measured by $F_2(x)$

BBK 1971

S.M.Berman, J.D.Bjorken and J.B.Kogut, Phys. Rev. **D4**, 3388 (1971)

- BBK calculated for p+p collisions, the inclusive reaction

$$A+B \rightarrow C + X \qquad \text{when particle } C \text{ has } p_T >> 1 \text{ GeV/c}$$

  - The charged partons of DIS **must scatter electromagnetically** *"which may be viewed as a* **lower bound** *on the real cross section at large p_T."*

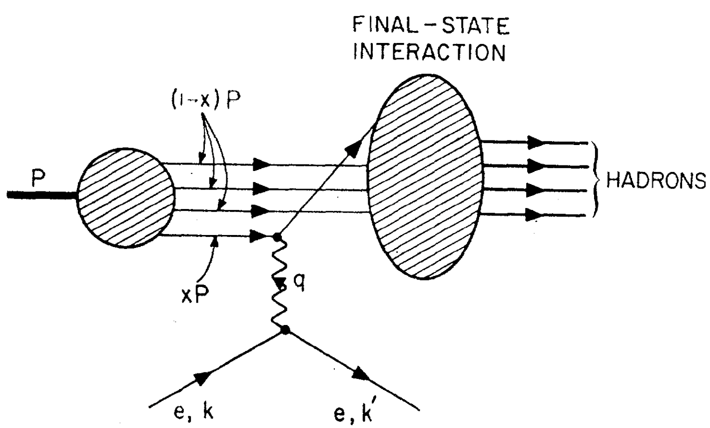
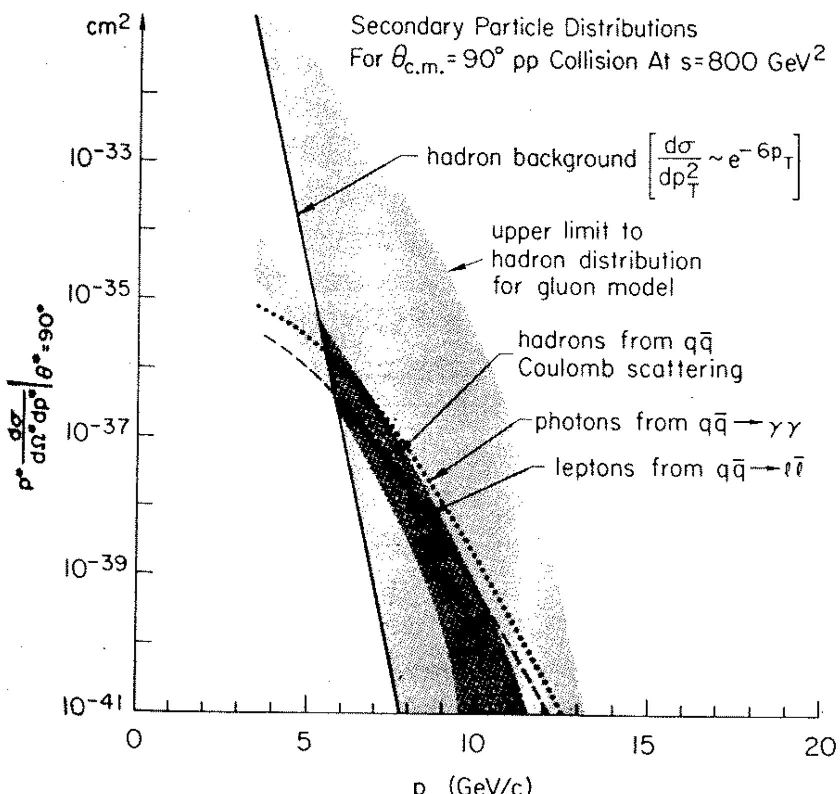


FIG. 1. Kinematics of lepton-nucleon scattering in the parton model.



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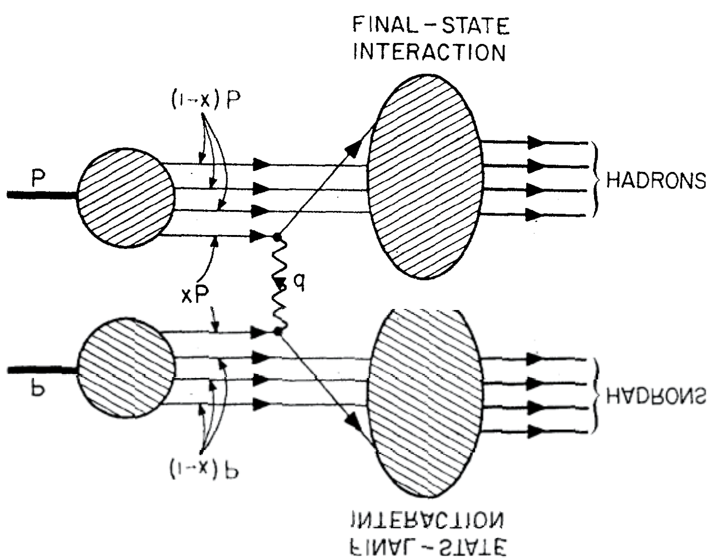
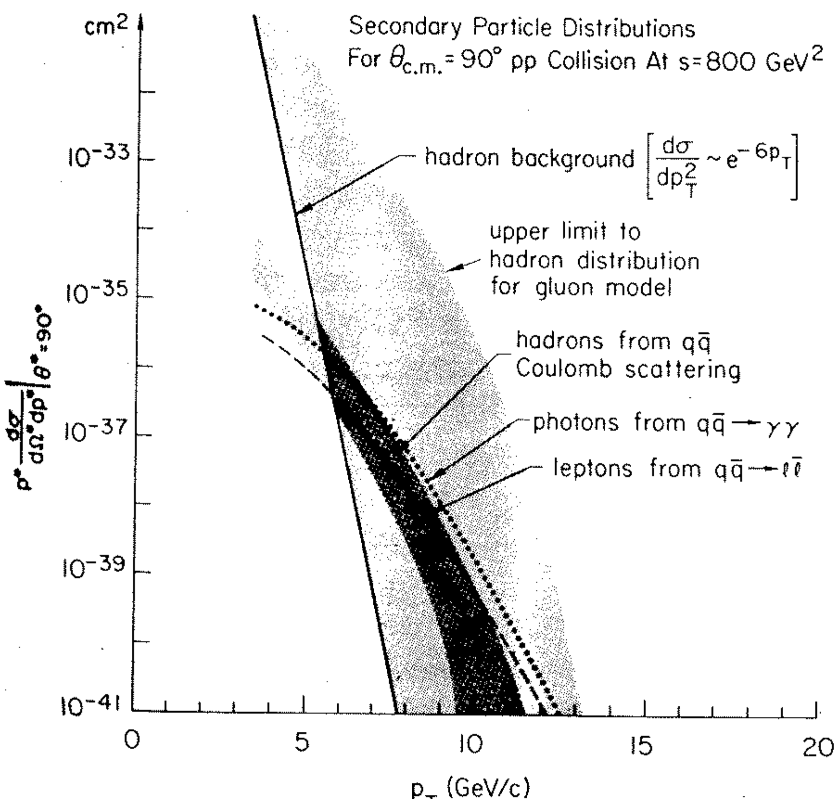
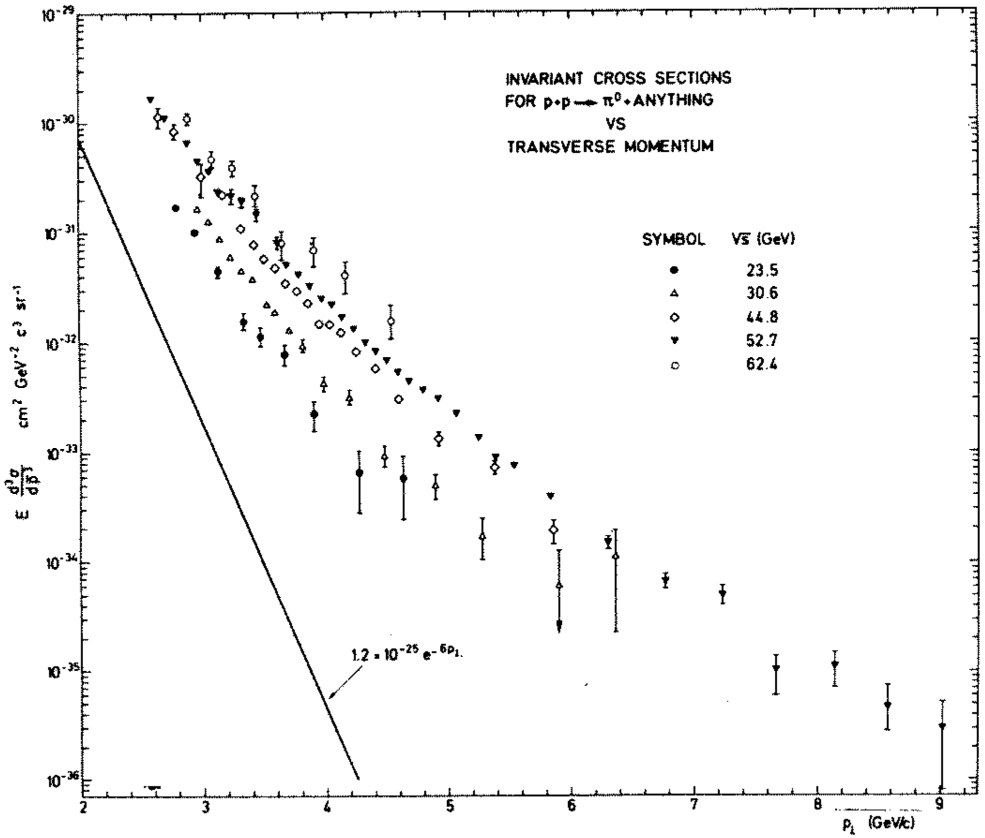




CCR at the CERN-ISR
Discovery of high p_T production in p-p



F.W. Busser, *et al.*,
CERN, Columbia, Rockefeller Collaboration
Phys. Lett. **46B**, 471 (1973)

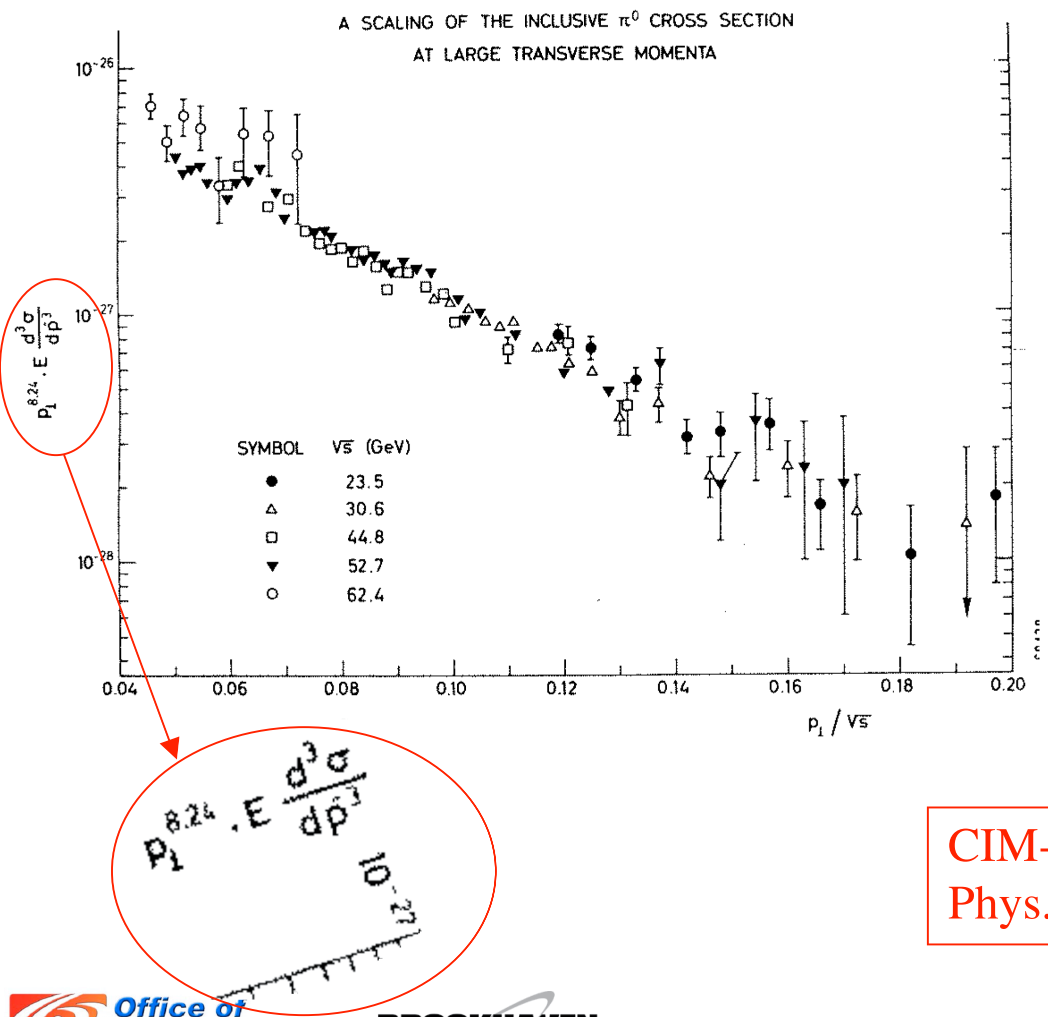
Bj scaling → BBK scaling

$$E\frac{d^3\sigma}{dp^3} = \frac{1}{p_T^n} F\left(\frac{2p_T}{\sqrt{s}}\right)$$

- e^{-6p_T} breaks to a power law at high p_T with characteristic √s dependence
- Large rate indicates that partons interact strongly (>> EM) with other.
- Data follow BBK scaling but with n=8!, not n=4 as expected for QED

BBK scaling with n=8, not 4
Inspires Constituent Interchange Model

Berman, Bjorken, Kogut, PR**D4**,3388(1971)



$$E\frac{d^3\sigma}{dp^3} = \frac{1}{p_T^n} F\left(\frac{2p_T}{\sqrt{s}}\right)$$

$x_T = 2p_T/\sqrt{s}$

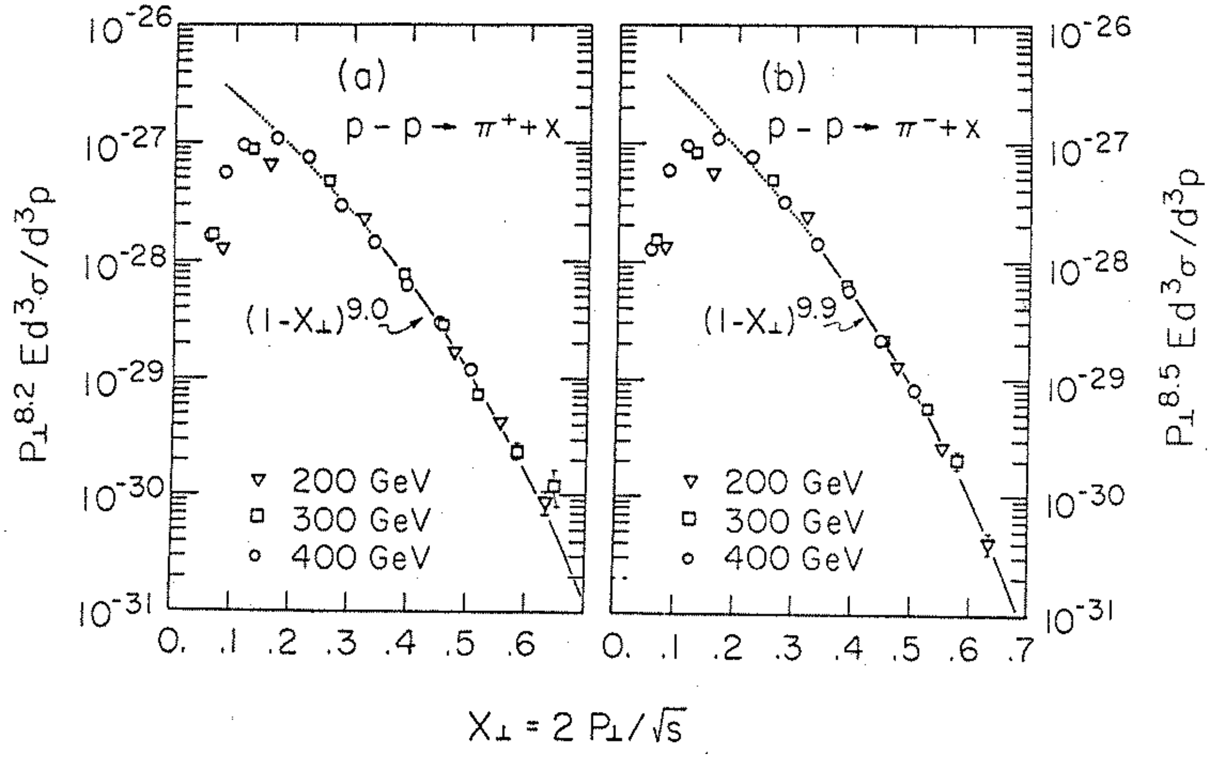
n=4 for QED or vector gluon

n=8 for quark-meson scattering by the exchange of a quark

CIM-Blankenbecler, Brodsky, Gunion, Phys.Lett.**42B**,461(1972)

State of the Art
Fermilab 1977

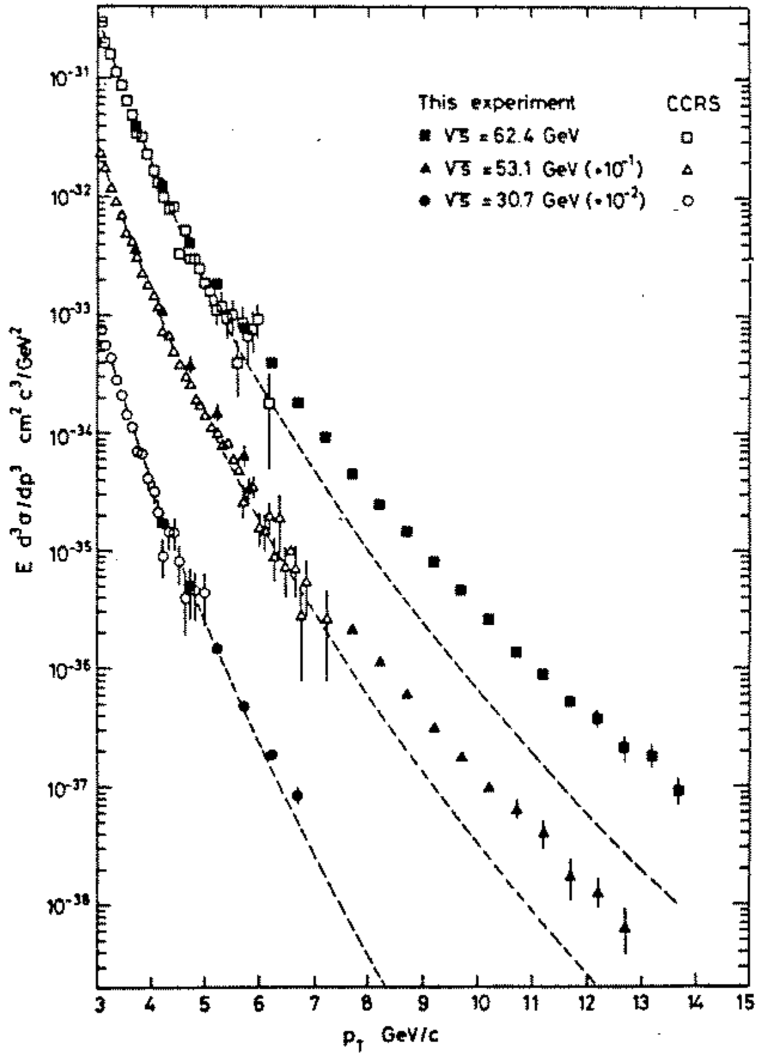
D. Antreasyan, J. Cronin, et al., PRL 38, 112 (1977)



Beautiful x_T scaling at all 3 fixed target energies with n=8

Totally Misleading--Not CIM or QCD but k_T

CCOR 1978---Discovery of "REALLY high p_T>7 GeV/c" at ISR

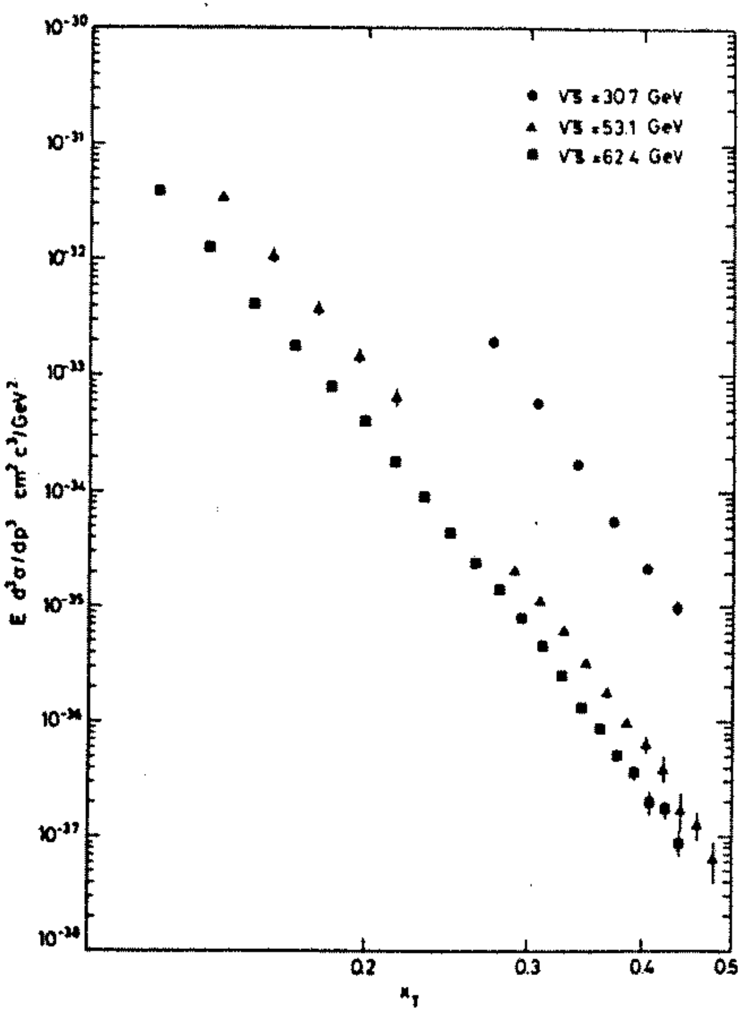


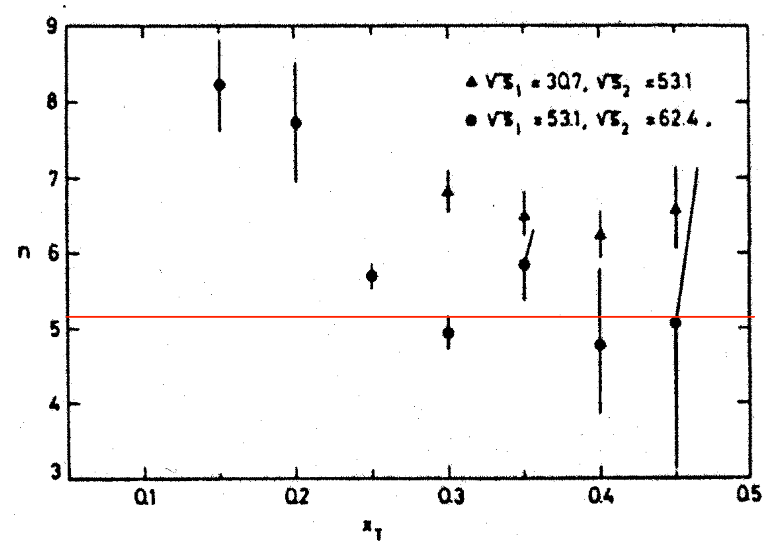
CCOR A.L.S. Angelis, et al, Phys.Lett. **79B**, 505 (1978)
See also A.G. Clark, et al Phys.Lett 74B, 267 (1978)

- Agrees with CCR, CCRS (Busser) data for p_T < 7 GeV/c.
- Disagrees with CCRS fit p_T > 7 GeV/c
- New fit is:

$$Ed^3\sigma/dp^3 \simeq p_T^{-5.1\pm0.4}(1-x_T)^{12.1\pm0.6}$$
$$7.5 \leq p_T \leq 14.0 \text{ GeV/c},$$
$$53.1 \leq \sqrt{s} \leq 62.4 \text{ GeV}$$
(including *all* systematic errors).

$n(x_T, \sqrt{s})$ WORKS $n \to 5 = 4^{++}$





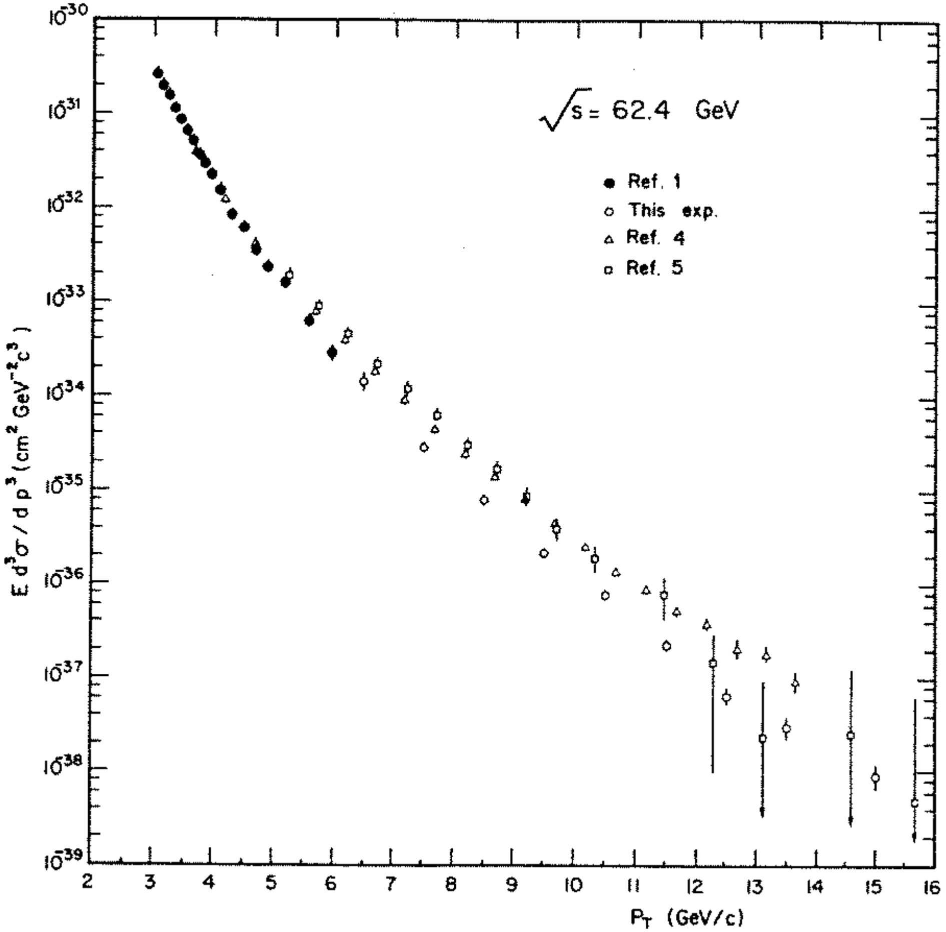
QCD: Cahalan, Geer, Kogut, Susskind, PR**D11**, 1199 (1975)

$$E\frac{d^3\sigma}{dp^3} = \frac{1}{\sqrt{s}^{\,n(x_T,\sqrt{s})}}\,G(x_T)$$

$$\left(\frac{\sqrt{s_1}}{\sqrt{s_2}}\right)^{n(x_T,\sqrt{s})} = \frac{\frac{Ed^3\sigma}{dp^3}(x_T,\sqrt{s_2})}{\frac{Ed^3\sigma}{dp^3}(x_T,\sqrt{s_1})}$$

Same data $E\, d^3\sigma/dp^3(x_T)$ ln-ln plot

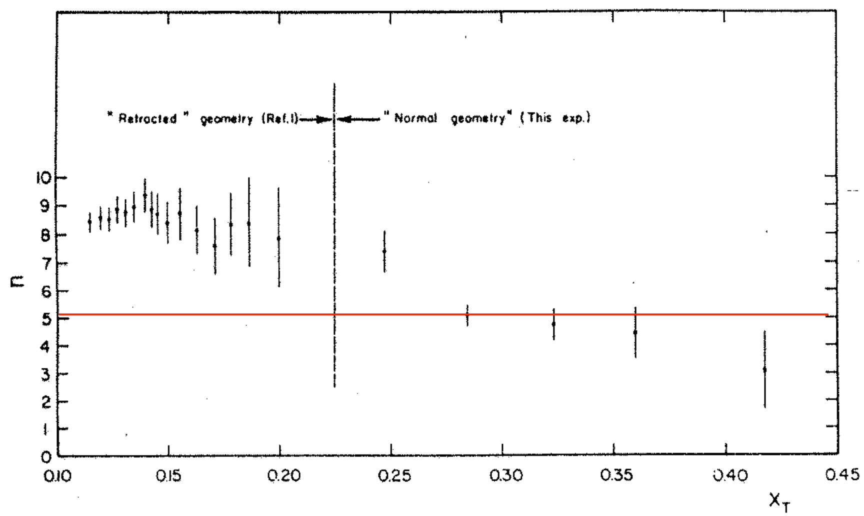
ISR Expt's more interested in n(x_T,√s) than absolute cross section



cross sections vary by factor of 2

Athens BNL CERN Syracuse Collaboration, C.Kourkoumelis, et al Phys.Lett. **84B**, 279 (1979)

but n(x_T,√s) agrees



Status of ISR single particle measurements 1978

♡ Hard-scattering was visible both at ISR and FNAL (Fixed Target) energies by single particle inclusive at large $p_T \geq$ 2-3 GeV/c.

♡ Scaling and dimensional arguments for plotting data revealed the systematics and underlying physics.

♡ The theorists had the basic underlying physics correct; but many (inconvenient) details remained to be worked out, several by experiment.

♡ k_T, the transverse momentum imbalance of outgoing partons (due to initial state radiation), was discovered by experiment.

k_T is what made $n=4^{++} \rightarrow n=8$

Status of QCD Theory in 1978

♡ The first modern QCD calculations and predictions for high p_T single particle inclusive cross sections, including non-scaling and initial state radiation was done in 1978, by Jeff Owens.

J. F. Owens, E. Reya, M. Glück
Phys. Rev. **D18**, 1501 (1978)
Detailed quantum-chromodynamic predictions for high-p_T processes

J. F. Owens and J. D. Kimel
Phys. Rev. **D18**, 3313 (1978)
Parton-transverse-momentum effects and the quantum-chromodynamic description of high-p_T processes

♡ Jets in 4π Calorimeters at ISR energies or lower invisible below $\sqrt{\hat{s}} \sim E_T \leq 25$ GeV.

♡ A 'phase change' in belief in Jets with UA2 event at 1982 ICHEP in Paris.

LO-QCD in 1 slide

Cross Section in p-p collisions c.m. energy $\sqrt{s}$

The overall p-p reaction cross section
is the sum over constituent reactions

$$a + b \to c + d$$

$a(x_1)$, $b(x_2)$, are structure functions, the differential probabilities for constituents a and b to carry momentum fractions x_1 and x_2 of their respective protons, e.g. $u(x_1)$,

$$\frac{d^3\sigma}{dx_1 dx_2 d\cos\theta^*} = \frac{1}{s}\sum_{ab} a(x_1) b(x_2) \frac{\pi\alpha_s^2(Q^2)}{2x_1x_2}\Sigma^{ab}(\cos\theta^*)$$

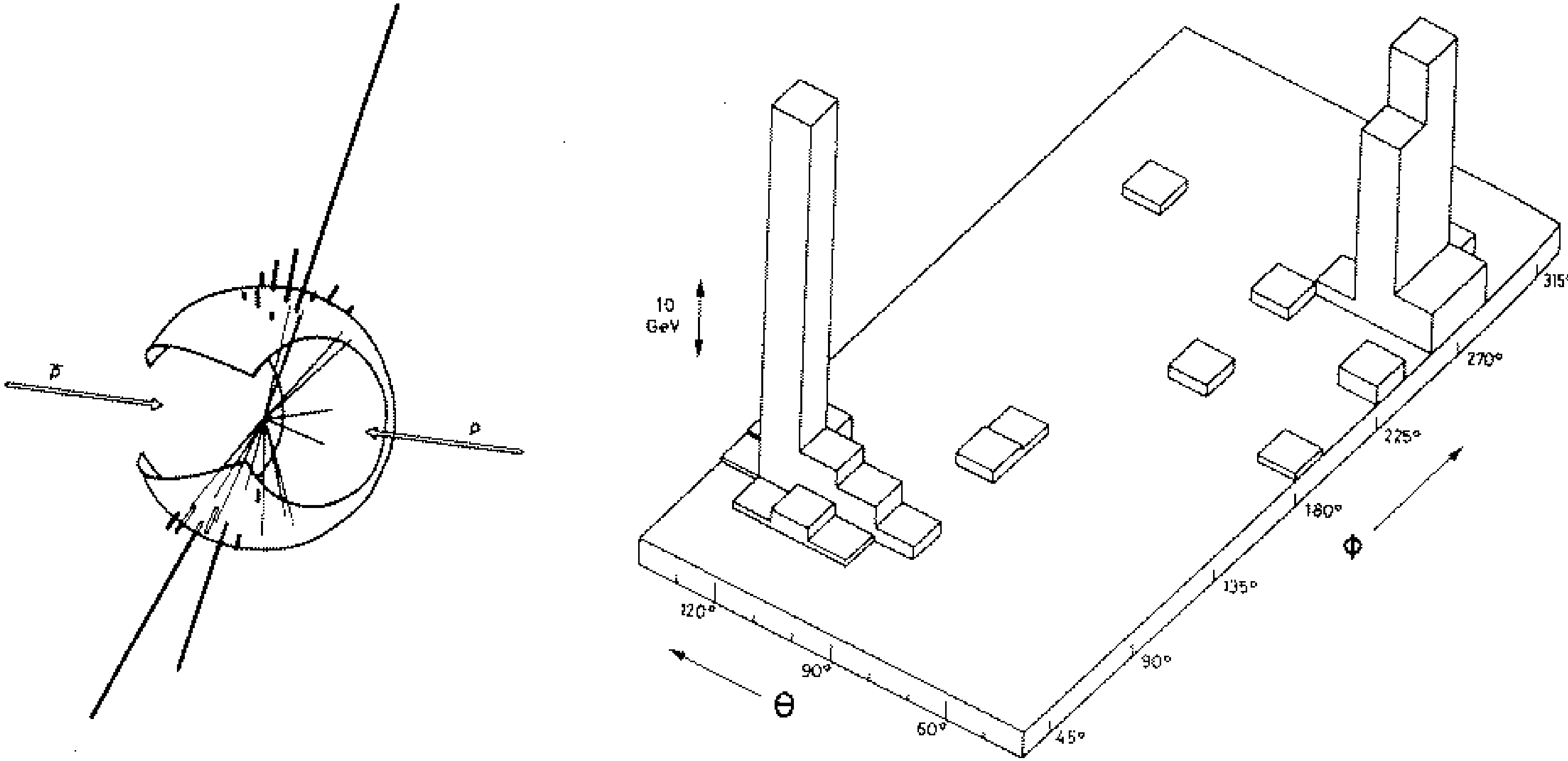
$\Sigma^{ab}(\cos\theta^*)$, the characteristic subprocess angular distributions and $\alpha_s(Q^2) = \frac{12\pi}{25}\ln(Q^2/\Lambda^2)$ are predicted by QCD

QCD and Jets are now a cornerstone of the standard model

- Incredibly at the famous Snowmass conference in July 1982, many if not most people were skeptical
- The International HEP conference in Paris, three weeks later, changed everything

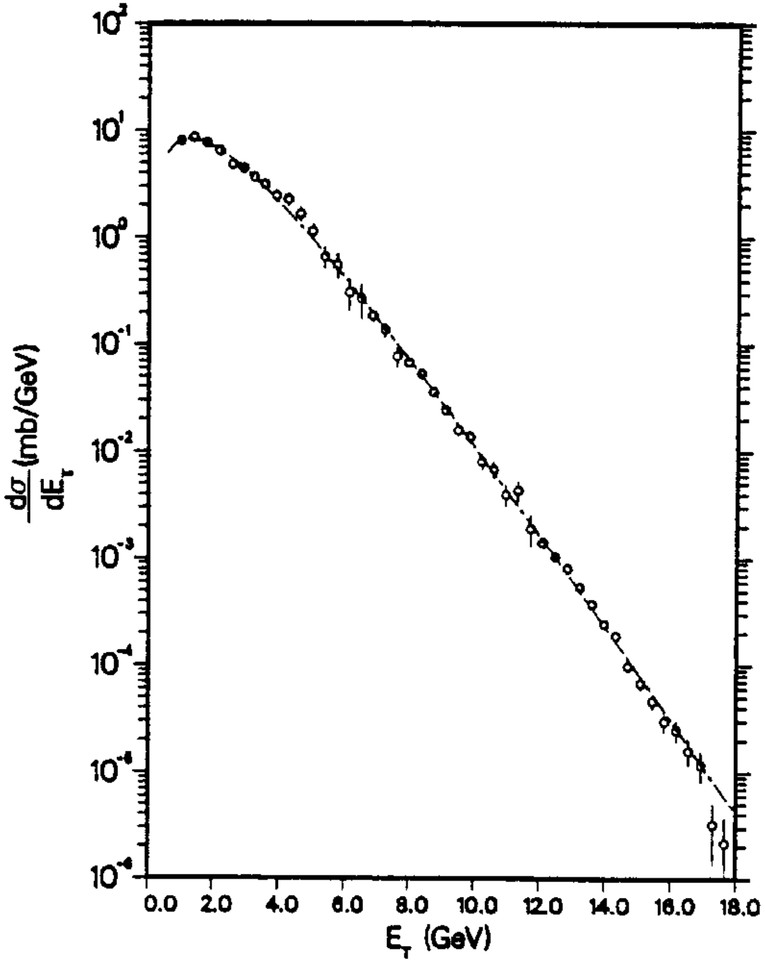
THE UA2 Jet-Paris 1982

From 1980--1982 most high energy physicists doubted jets existed because of the famous NA5 E_T spectrum which showed NO JETS
This one event changed everybody's opinion.

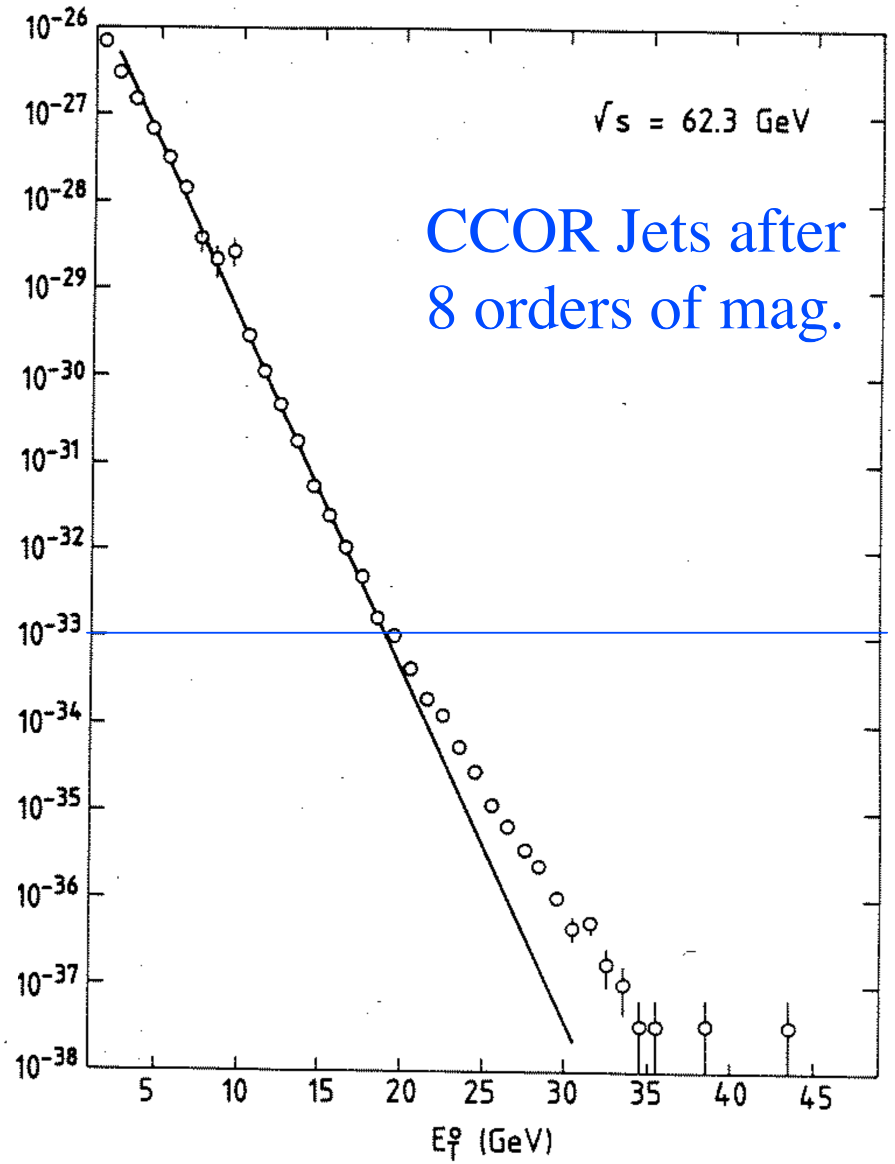


(a) (b)

Also Paris 1982-Jets in E_T distribution



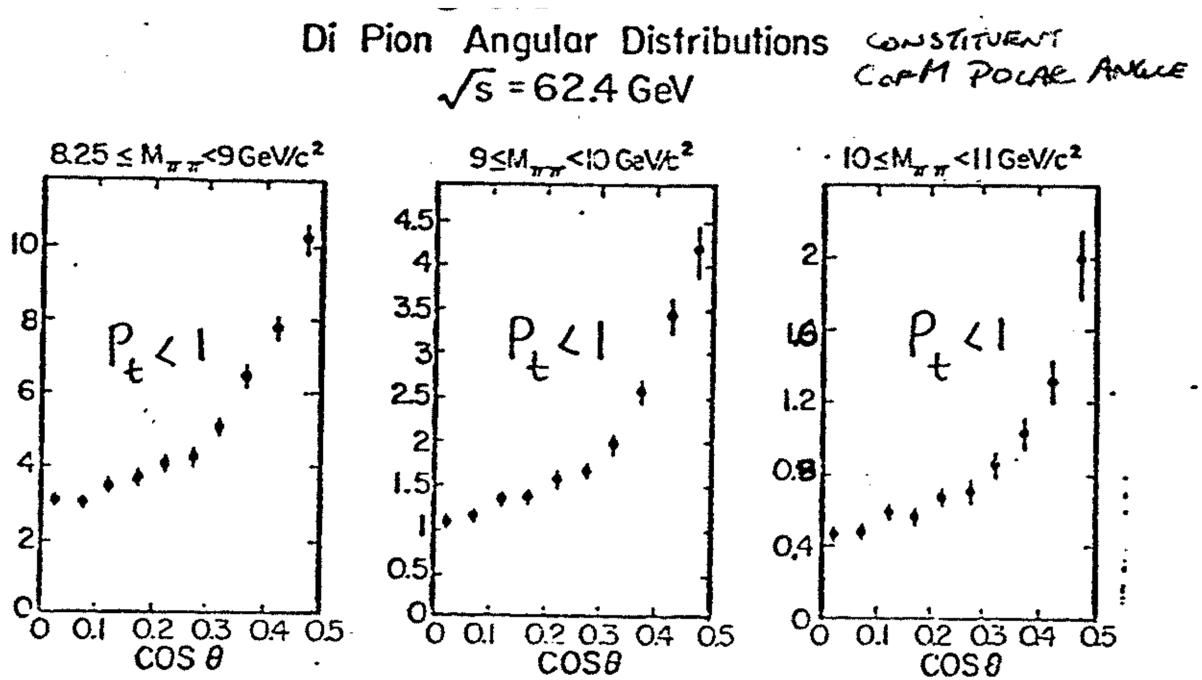
NA5-No Jets 1980 ICHEP
7 orders of magnitude



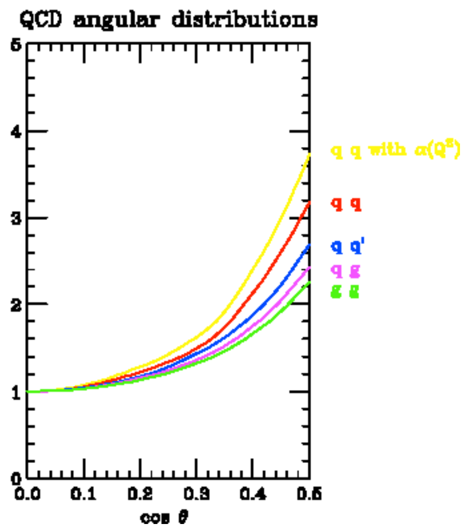
CCOR Jets after
8 orders of mag.

Also Paris-1982 first measurement of QCD subprocess angular distribution using π^0-π^0correlations

DATA: CCOR NPB **209**, 284 (1982)



QCD



$$\frac{d^3\sigma}{dx_1 dx_2 d\cos\theta^*} = \frac{1}{s}\sum_{ab} a(x_1)b(x_2)\frac{\pi\alpha_s^2(Q^2)}{2x_1x_2}\Sigma^{ab}(\cos\theta^*)$$

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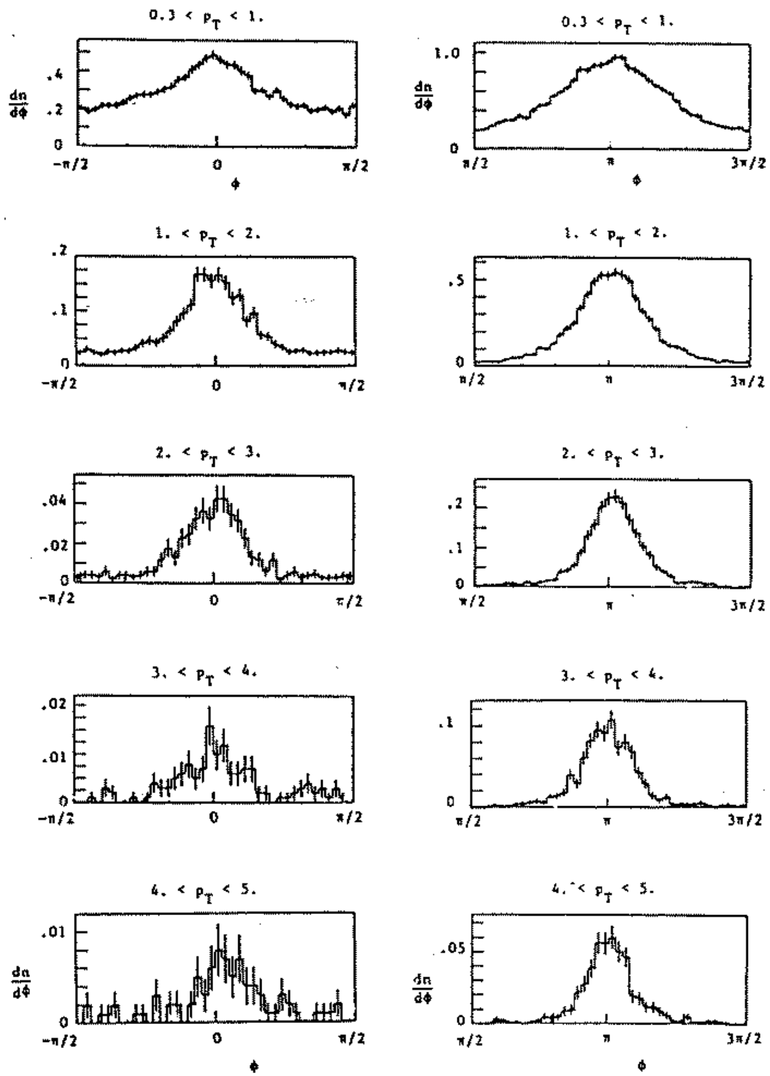
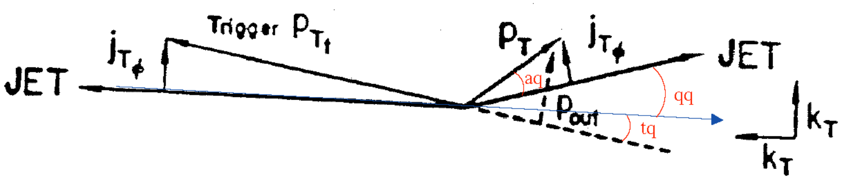
How everything you want to know about JETS was measured with 2-particle correlations



CCOR, A.L.S.Angelis, et al
PL **97B**, 163 (1980)
PhysicaScripta **19**, 116 (1979)



$p_{Tt} > 7$ GeV/c vs. p_T

k_T is not a paramater it can be measured

- In leading order QCD or the Quark-Parton model, the net transverse momentum $\langle p_T \rangle_{\rm pair} = \sqrt{2} \times \langle k_T \rangle$, of a hard-scattering jet-pair, or a Drell-Yan pair, or a pair of high p_T photons, or the $\gamma +$ Jet pair for direct photon production is zero. All the above pairs should be coplanar with the incident beam axis.
- However, early Drell-Yan and inclusive high p_T particle studies showed that k_T was measurable and non-zero.

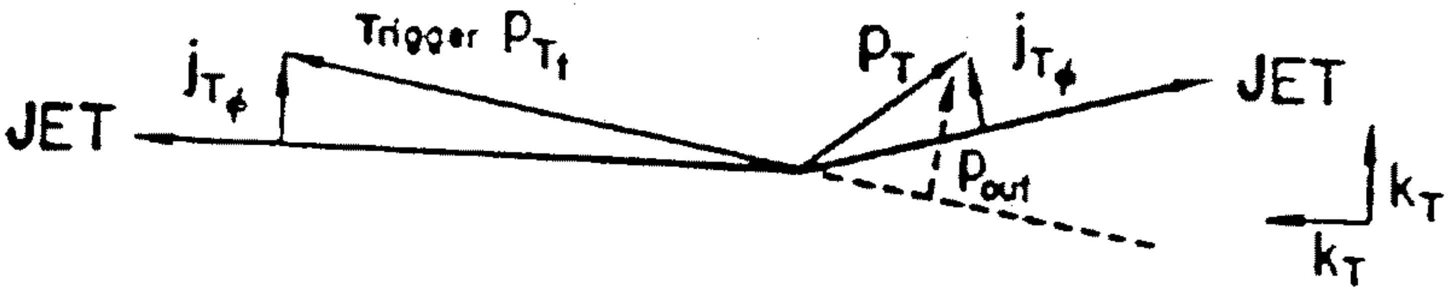
♡ The history of k_T is worth reviewing as k_T was predicted to be zero by theorists, but was discovered to be non-zero by experimentalists. The CCHK experiment [M. Della Negra, et al., Nucl. Phys. **B127**, 1 (1977)] discovered that back-to-back jets had considerable out of plane transverse momentum $p_{\rm out}$, and proposed that this was due to transverse momentum of partons inside a proton.

Feynman Field & Fox to the rescue

♡ This was elaborated by Feynman, Field and Fox, [Nucl. Phys. **B128**, 1, (1997), Phys Rev. **D18**, 3320 (1978)] who introduced the k_T phenomenology of a parton in a proton, which they discussed in terms of 'intrinsic transverse momentum' from confinement which would be constant as a function of x and Q^2, and NLO effects due to hard gluon emission which would vary with x and Q^2, but they used an constant 'effective' k_T to 'explain' the available measurements.

♡ A subsequent ISR experiment, CCOR, showed that k_T for jet-pairs was roughly the same as for Drell-Yan and increased similarly with $\sqrt{s}$ (and p_T) i.e. was not constant. See Fig. 1 in [Ap1].

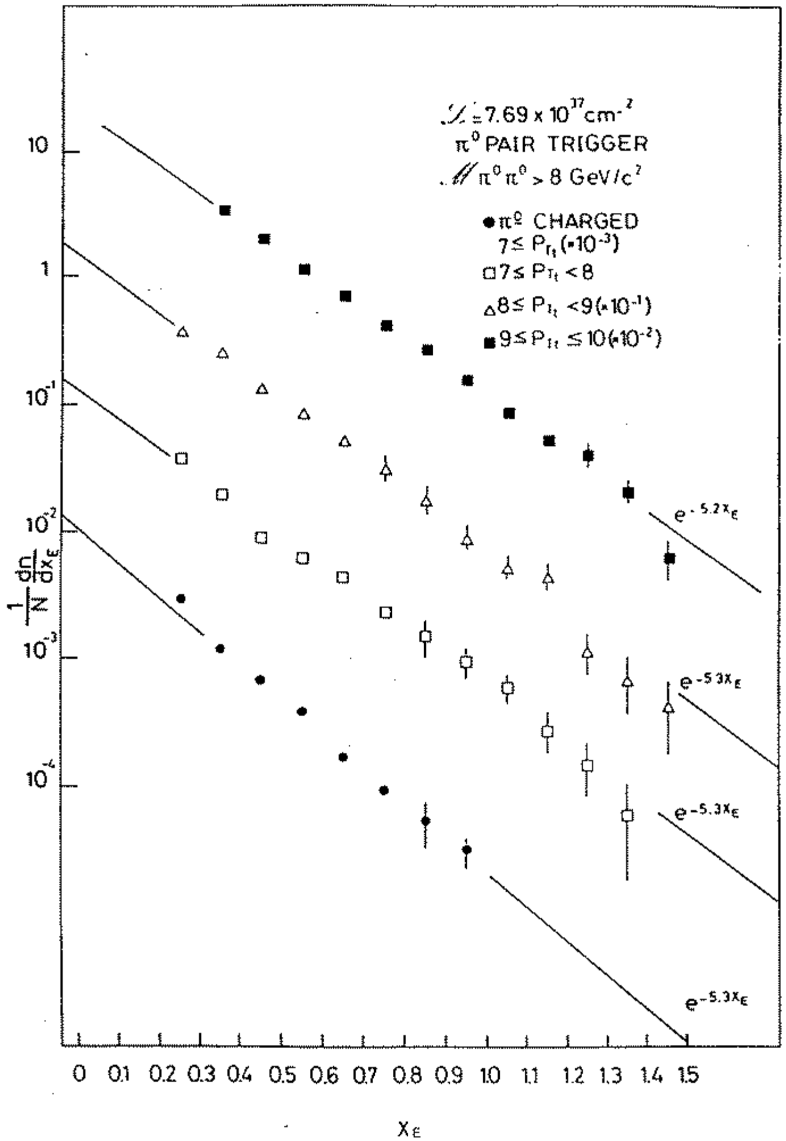
j_T, k_T, x_E, p_{out} definitions all in plane transverse to beam direction



$$\langle|p_{out}|\rangle^2 = x_E^2[2\langle|k_{Ty}|\rangle^2 + \langle|j_{Ty}|\rangle^2] + \langle|j_{Ty}|\rangle^2$$

- j_T is parton fragmentation transverse momentum
- k_T is transverse momentum of a parton in a proton (2 protons)
- $x_E = -p_T \bullet p_{Tt}/|p_{Tt}|^2$ represents away jet fragmentation z
- p_{out} is component of away p_T perpendicular to trigger p_{Tt}

x_E distribution measures fragmentation fn.

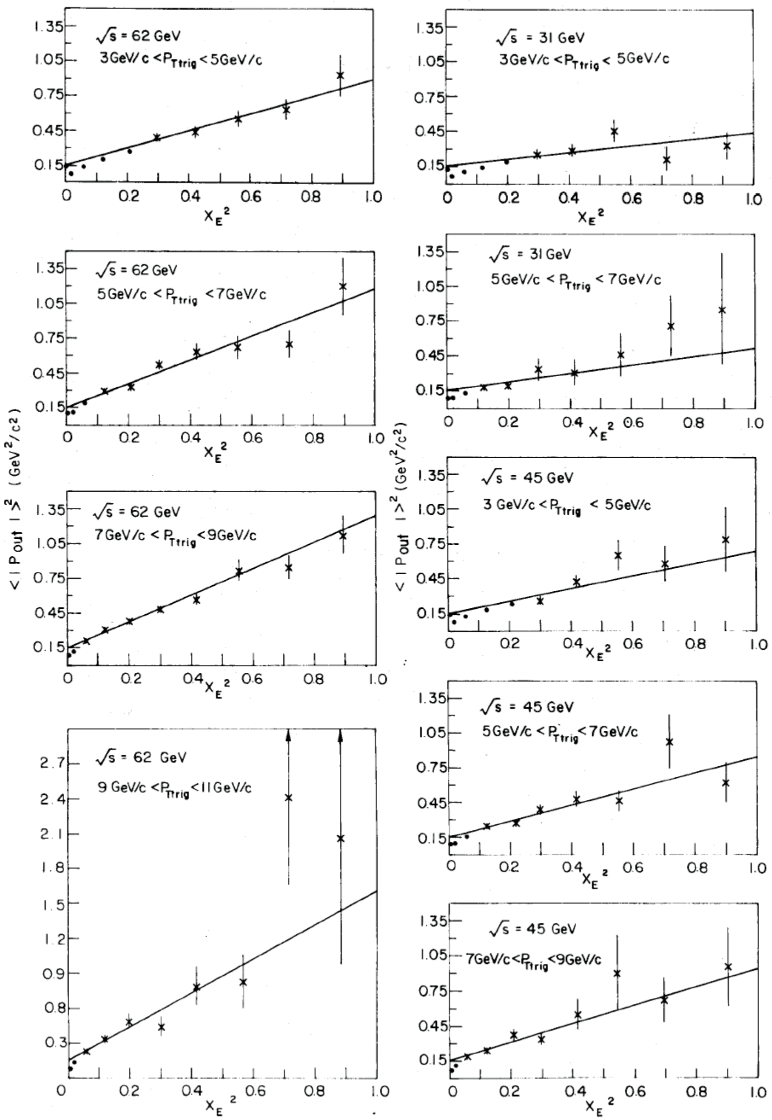


$x_E \sim z/\langle z_{trig} \rangle$

$\Rightarrow e^{-6z}$

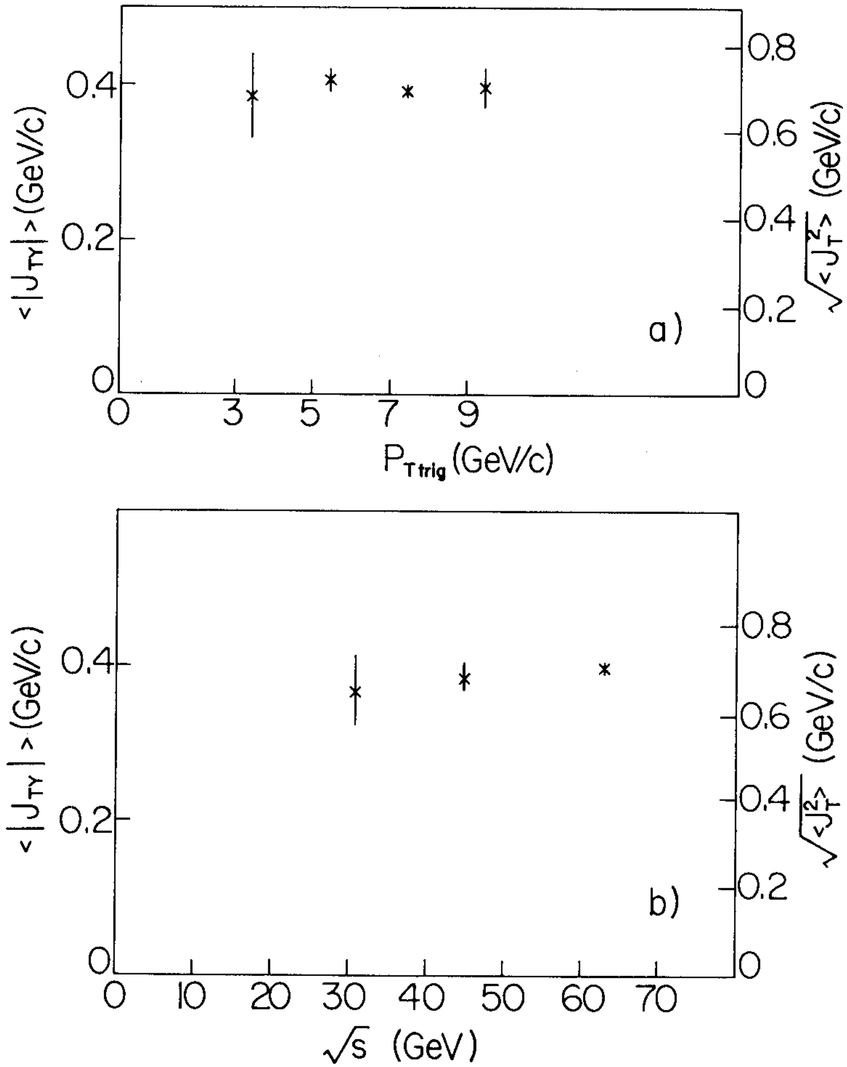
- independent of p_{Tt}

CCOR $\langle|p_{out}|\rangle^2$ vs x^2_E



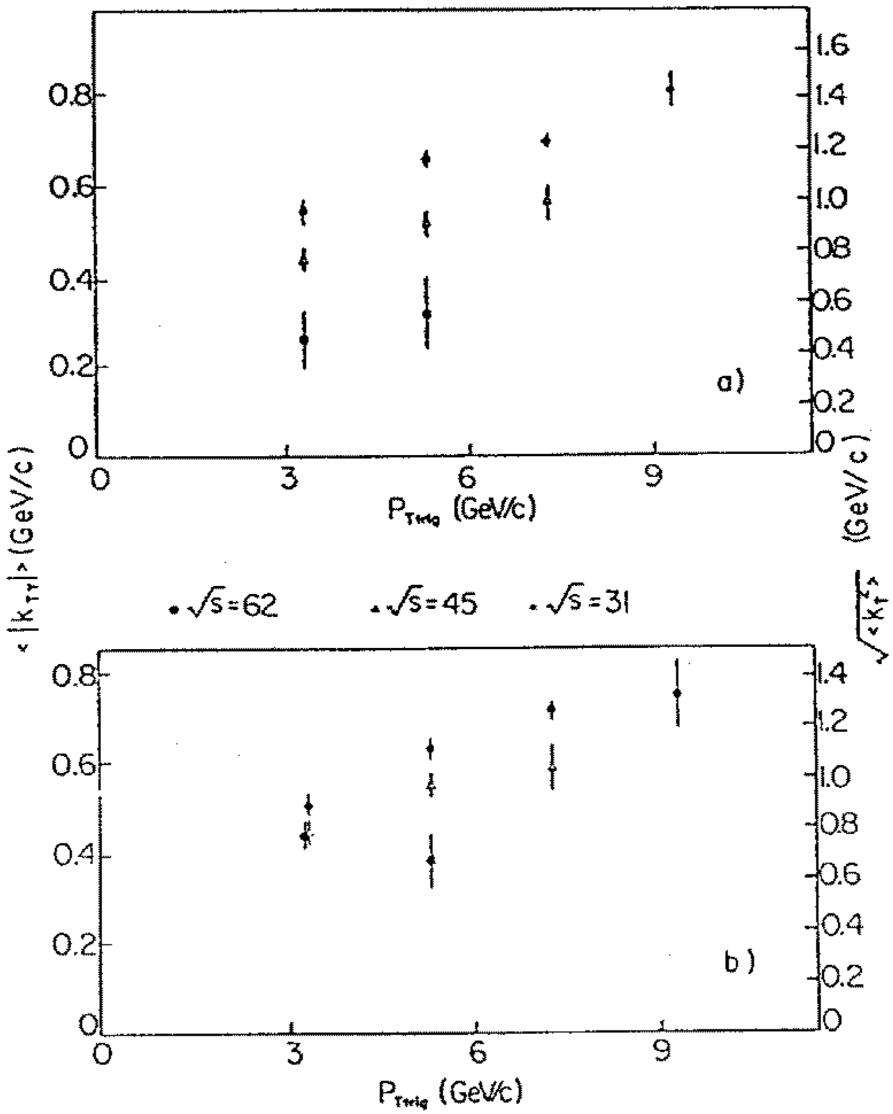
$$\langle|p_{out}|\rangle^2 = x_E^2[2\langle|k_{Ty}|\rangle^2 + \langle|j_{Ty}|\rangle^2] + \langle|j_{Ty}|\rangle^2$$

j_T is constant-independent of p_{Tt} and $\sqrt{s}$ Characteristic of jet fragmentation



- it took the $e^+ e^-$ people several more years to get this correct because they didn't understand the seagull effect.

k_T varies with p_{Tt} and $\sqrt{s}$--not intrinsic



k_T Phenomenology-I

- k_T denotes the magnitude of the effective transverse momentum vector $\vec{k}_T$ of each of the 2 colliding partons.
- The net p_T of the constituent c.m. system of the two colliding partons is

$$\vec{p}_T = \vec{k}_{T_1} + \vec{k}_{T_2} \tag{3}$$

Or, more accurately

$$p_T^2 = k_{T_1}^2 + k_{T_2}^2 = 2k_T^2 \tag{4}$$

- It is assumed that the two k_T act incoherently, or equivalently that one $\vec{k}_T$ acts in the scattering plane to make the energies of the two final state partons unequal, and one $\vec{k}_T$ acts perpendicular to the scattering plane to make the outgoing partons acoplanar with the direction of the colliding protons.

k_T Phenomenology-II

◇ This simple concept leads to confusion since k_T is the magnitude of a vector, which is always positive like a radius, whereas the **components** of the vectors $\vec{p}_T$, $\vec{k}_T$, which act parallel or perpendicular to the scattering plane are more correctly written:

$$\langle p_{Tx}^2 \rangle = \langle k_{T1x}^2 \rangle + \langle k_{T2x}^2 \rangle \quad (5)$$

$$\langle p_{Tx}^2 \rangle = 2 \times \langle k_{Tx}^2 \rangle \quad (6)$$

$$\langle p_{Tx} \rangle = \sqrt{2} \times \langle k_{Tx} \rangle = 0 \quad (7)$$

where $k_T = k_{T_1} = k_{T_2}$.

◇ The components k_{Tx} and k_{Ty} of the vector $\vec{k}_T$ are taken as gaussian, and following the notation of [Ap1]

$$k_{Tx} = \sigma_{\rm 1parton,1d} \quad (8)$$

$$k_{Ty} = \sigma_{\rm 1parton,1d} \quad (9)$$

$$k_T = \sqrt{k_{Tx}^2 + k_{Ty}^2} = \sigma_{\rm 1parton,2d} \quad (10)$$

Early theoretical attempt to understand k_T

♡ Altarelli, et al., predicted (in 1985) the value of $\langle p_T \rangle_{\rm pair}$ (which they called $\langle q_T \rangle$) for Drell-Yan pairs, which we have seen is the same as for di-hadrons. Interestingly, their predictions go to 200 GeV where the predicted $\langle q_T \rangle = \sigma_{\rm 2partons,2d} = 3.5 \pm 0.2$ GeV/c.

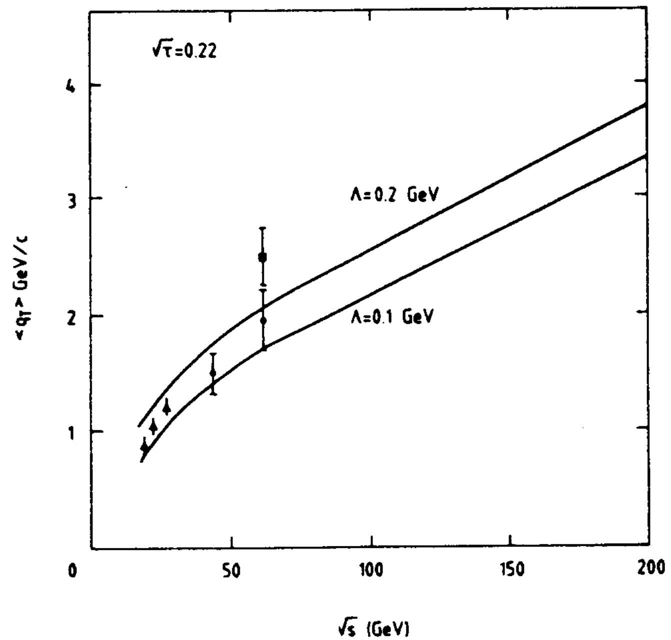


Figure 36: $\langle q_T \rangle$ vs $\sqrt{s}$ at fixed $\sqrt{\tau} = x_1 x_2 = 0.22$. Data shown are ISR and FNAL Drell-Yan. The curves are the theoretical predictions obtained using $\Lambda = 0.1 - 0.2$ GeV. No intrinsic q_T is included. At large values of $\sqrt{s}$, $\langle q_T \rangle$ increases linearly with $\sqrt{s}$. At smaller values, deviations from the linear law are visible, which are due to soft gluon and scaling violation pre-asymptotic effects

Gaussian Integrals-I

- Recall how a the integral of a 1d Gaussian is obtained: take x to represent k_{Tx}, take y to represent k_{Ty}, and $r = \sqrt{x^2+y^2}$ to represent k_T; and in 2d, $dx\,dy = r\,dr\,d\phi$

$$\mathrm{Prob}(x)\,dx = \frac{1}{\sqrt{2\pi\sigma^2}} \exp -\frac{x^2}{2\sigma^2}\,dx \quad (11)$$

$$\mathrm{Prob}(y)\,dy = \frac{1}{\sqrt{2\pi\sigma^2}} \exp -\frac{y^2}{2\sigma^2}\,dy \quad (12)$$

$$\mathrm{Prob}(x,y)\,dx\,dy = \frac{1}{2\pi\sigma^2} \exp -\frac{x^2+y^2}{2\sigma^2}\,dx\,dy \quad (13)$$

$$= \frac{1}{2\sigma^2} \exp -\frac{r^2}{2\sigma^2}\,dr^2 \quad (14)$$

◇ This is just Eq. 4 of [Ap1] and shows that the distribution of k_T^2 is exponential with mean value $\langle k_T^2 \rangle = 2\sigma^2 \equiv 2\sigma_{1\mathrm{d}}^2 = \sigma_{2\mathrm{d}}^2$.

Gaussian Integrals-II

- A few more 1d and 2d Gaussian identities can be derived but are just stated here (to understand why $\sqrt{\langle k_T^2\rangle} = \langle k_T\rangle \times 2/\sqrt{\pi}$)

$$\langle r^2\rangle = 2\sigma_{1\mathrm{d}}^2 = \sigma_{2\mathrm{d}}^2 \qquad (15)$$

$$\langle x^2\rangle = \langle y^2\rangle = \sigma_{1\mathrm{d}}^2 = \frac{\langle r^2\rangle}{2} \qquad (16)$$

$$\langle x\rangle = \langle y\rangle = 0 \qquad (17)$$

$$\langle |x|\rangle = \langle |y|\rangle = \sqrt{\frac{2}{\pi}}\sigma_{1\mathrm{d}} = \sqrt{\frac{\langle r^2\rangle}{\pi}} \qquad (18)$$

$$\langle r\rangle^2 = \frac{\pi}{4}\sigma_{2\mathrm{d}}^2 = \frac{\pi}{4}\langle r^2\rangle \qquad (19)$$

- Finally a point made very clearly by [Ap1]. k_T (really p_{Tx}) is the net momentum in the plane of the $\gamma +$ Jet pair. Thus the γ is smeared in momentum **by half this value**, i.e.

$$\sigma_{\gamma,1\mathrm{d}} = k_T/2 = \sigma_{1\mathrm{parton},2\mathrm{d}}/2 \qquad (20)$$

Conclusions from ISR

- Hard Scattering in p-p collisions was discovered at the CERN ISR in 1972 by the method of leading particles.
- A very large flux of high p_T pions was observed with a power-law tail which varied systematically with $\sqrt{s}$, the c.m. energy of the collision.
- The huge flux of high p_T particles proved that the partons of DIS strongly interacted with each other.
- Scaling arguments allowed the form of the force law between 'partons' to be determined but there was some early confusion caused by initial transverse momentum k_T which distorted the spectra.
- Further ISR measurements utilizing inclusive single or pairs of hadrons established that high transverse momentum particles are produced from states with two roughly back-to-back jets which are the result of scattering of constituents of the nucleons as described by Quantum Chromodynamics.