LUND UNIVERSITY

LNF Spring School "Bruno Touschek"
Entering the LHC Era
Frascati, Italy
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Event Generators for LHC

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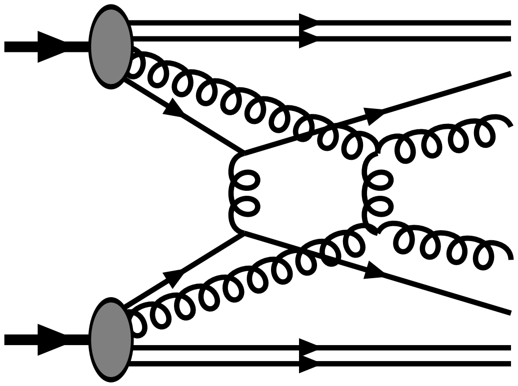
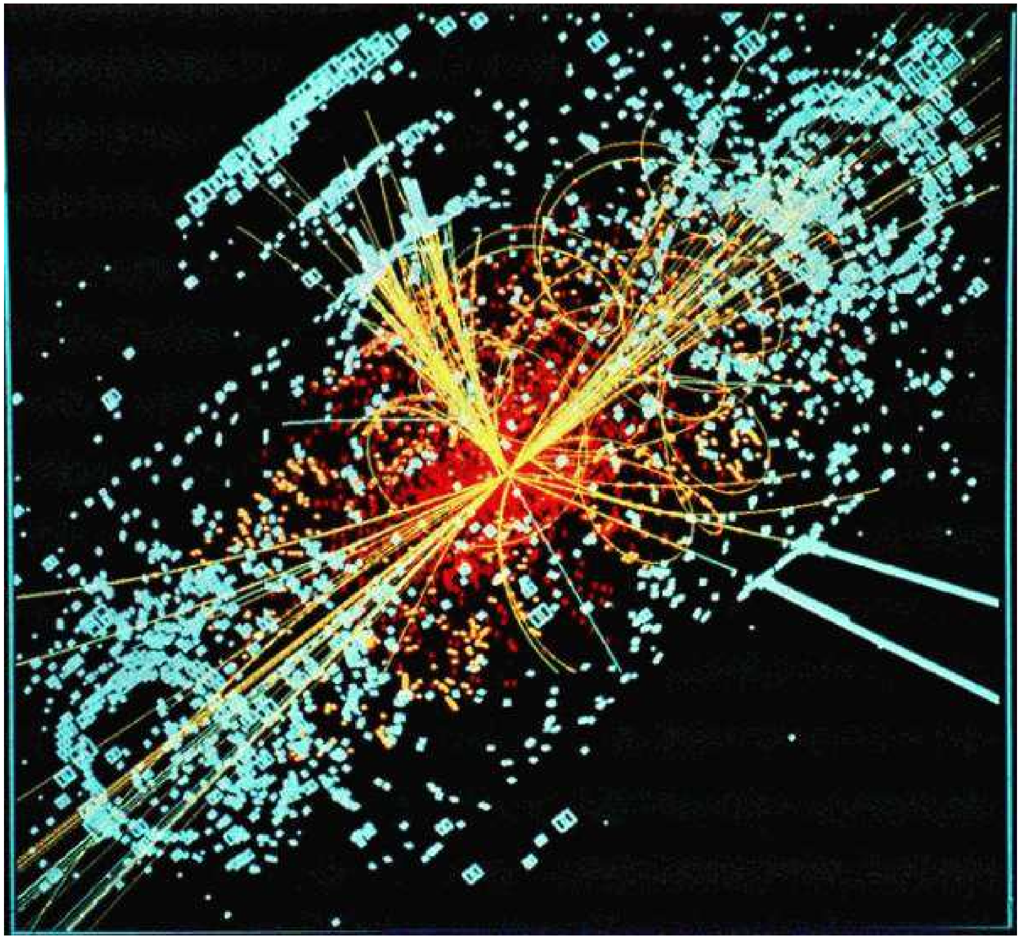
1. (yesterday) Introduction and Overview;
Parton Showers; Matching Issues

2. (today) Multiple Interactions;
Hadronization; Generator News & Conclusions

Multiple Interactions

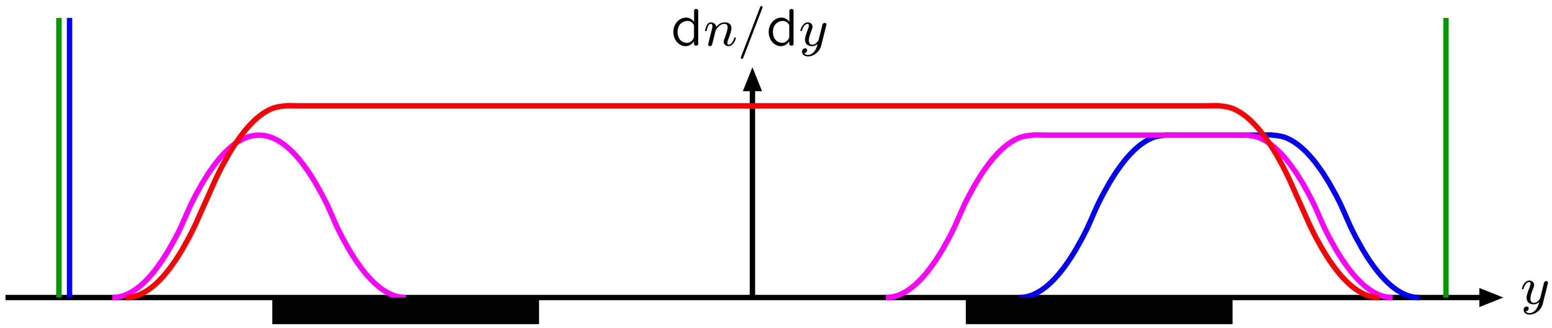




What is minimum bias?

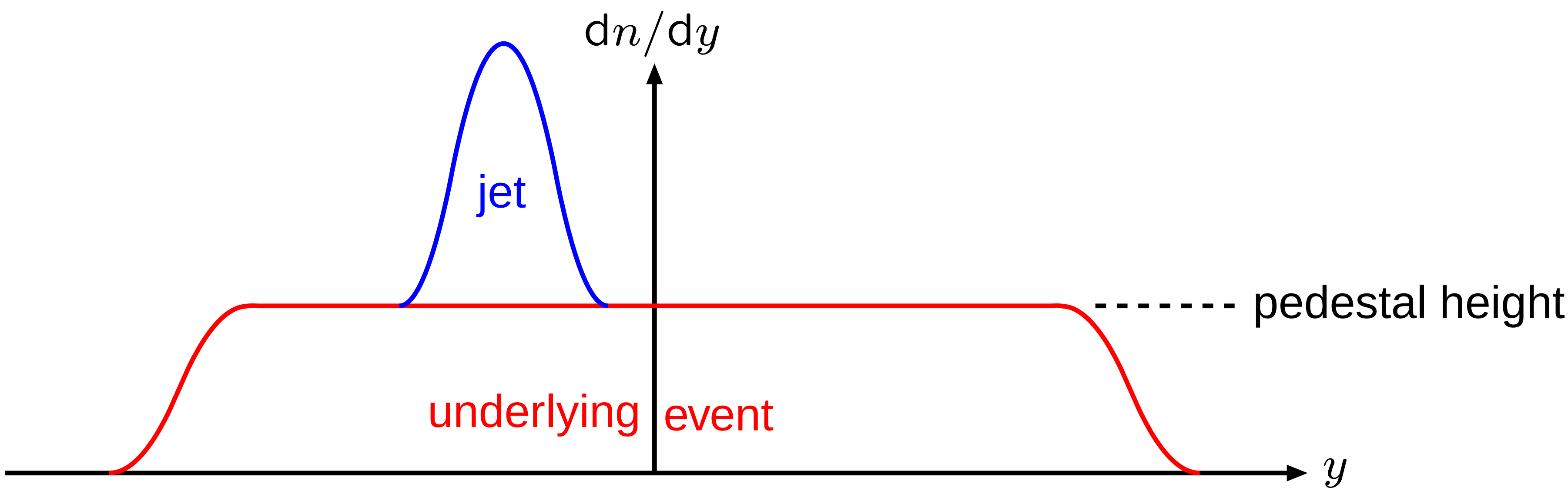
≈ “all events, with no bias from restricted trigger conditions”

$\sigma_{\text{tot}} = \sigma_{\text{elastic}} + \sigma_{\text{single-diffractive}} + \sigma_{\text{double-diffractive}} + \cdots + \sigma_{\text{non-diffractive}}$



reality: $\sigma_{\text{min-bias}} \approx \sigma_{\text{non-diffractive}} + \sigma_{\text{double-diffractive}} \approx 2/3 \times \sigma_{\text{tot}}$

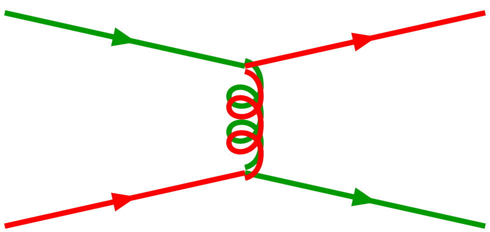
What is underlying event?



What is multiple interactions?

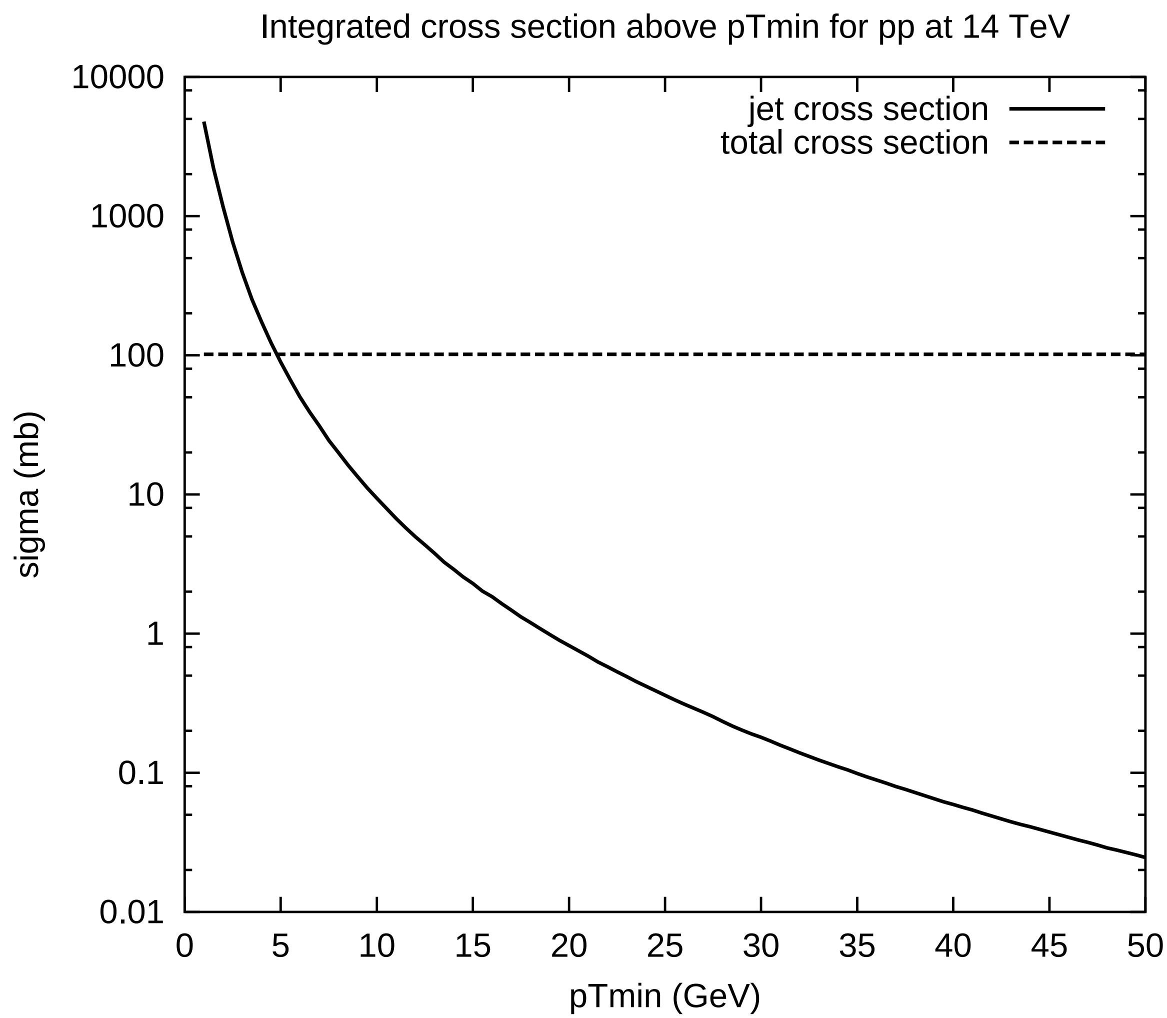
Cross section for $2 \to 2$ interactions is dominated by t-channel gluon exchange, so diverges like $\mathrm{d}\sigma/\mathrm{d}p_\perp^2 \approx 1/p_\perp^4$ for $p_\perp \to 0$.

integrate QCD $2 \to 2$



$\mathrm{qq}' \to \mathrm{qq}'$
$\mathrm{q\overline{q}} \to \mathrm{q}'\overline{\mathrm{q}}'$
$\mathrm{q\overline{q}} \to \mathrm{gg}$
$\mathrm{qg} \to \mathrm{qg}$
$\mathrm{gg} \to \mathrm{gg}$
$\mathrm{gg} \to \mathrm{q\overline{q}}$

with CTEQ 5L PDF's



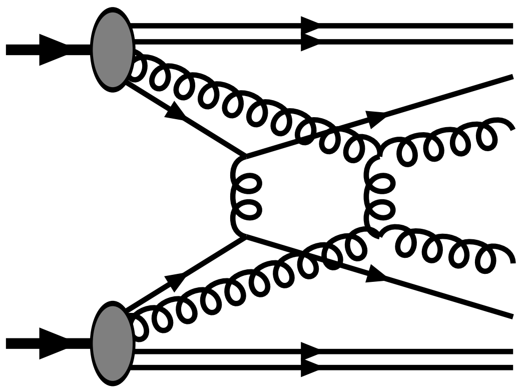
$$\sigma_{\text{int}}(p_{\perp\text{min}}) = \iiint_{p_{\perp\text{min}}} dx_1\, dx_2\, dp_\perp^2\, f_1(x_1, p_\perp^2)\, f_2(x_2, p_\perp^2) \frac{d\hat{\sigma}}{dp_\perp^2}$$

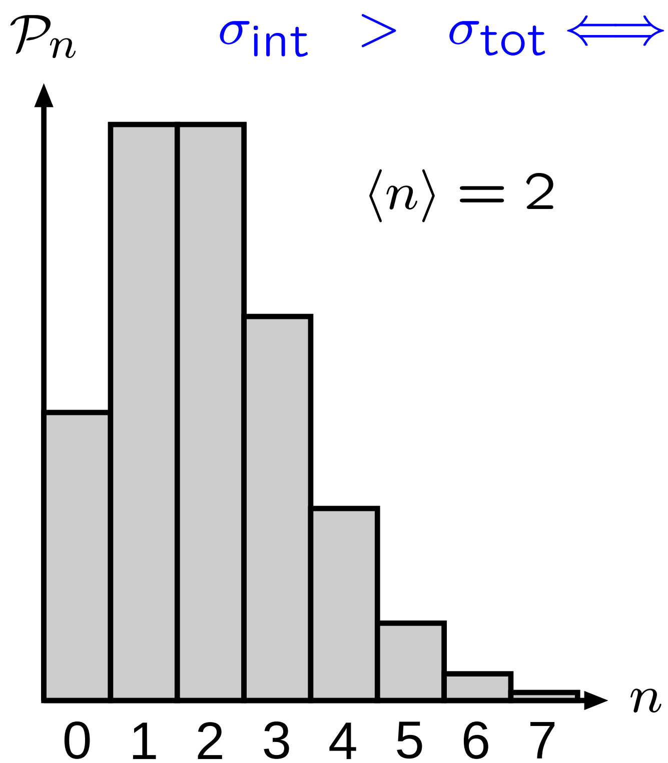
Half a solution to $\sigma_{\text{int}}(p_{\perp\text{min}}) > \sigma_{\text{tot}}$: many interactions per event

$$\sigma_{\text{tot}} = \sum_{n=0}^{\infty} \sigma_n$$

$$\sigma_{\text{int}} = \sum_{n=0}^{\infty} n\,\sigma_n$$

$$\sigma_{\text{int}} > \sigma_{\text{tot}} \iff \langle n \rangle > 1$$





If interactions occur independently
then Poissonian statistics

$$\mathcal{P}_n = \frac{\langle n \rangle^n}{n!} e^{-\langle n \rangle}$$

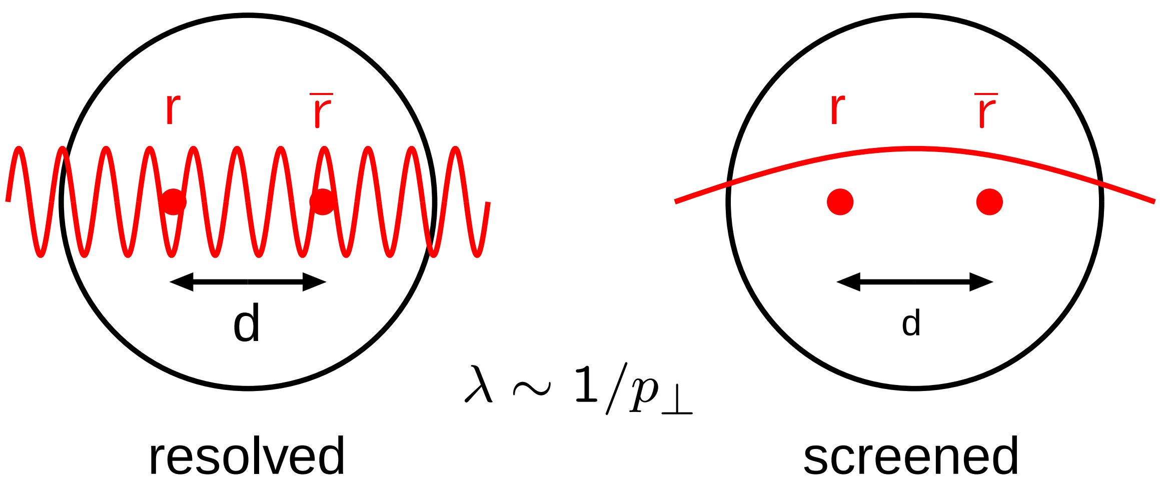
but energy–momentum conservation
$\Rightarrow$ large n suppressed

Other half of solution:
perturbative QCD not valid at small $p_\perp$ since q, g not asymptotic states (confinement!).

Naively breakdown at

$$p_{\perp\mathrm{min}} \simeq \frac{\hbar}{r_\mathrm{p}} \approx \frac{0.2\ \mathrm{GeV}\cdot\mathrm{fm}}{0.7\ \mathrm{fm}} \approx 0.3\ \mathrm{GeV} \simeq \Lambda_\mathrm{QCD}$$

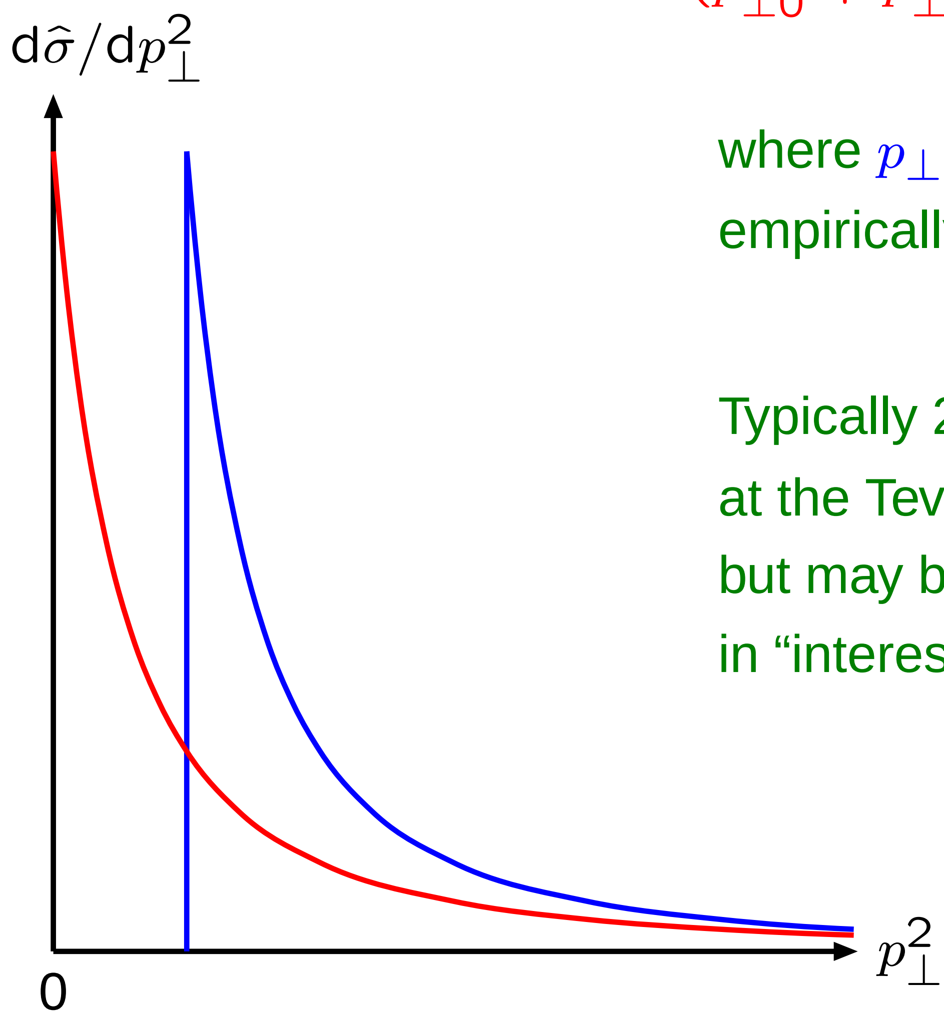
. . . but better replace r_p by (unknown) colour screening length d in hadron



so modify

$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}p_\perp^2} \propto \frac{\alpha_s^2(p_\perp^2)}{p_\perp^4} \rightarrow \frac{\alpha_s^2(p_\perp^2)}{p_\perp^4}\,\theta\,(p_\perp - p_{\perp\mathrm{min}}) \quad \text{(simpler)}$$

$$\text{or} \rightarrow \frac{\alpha_s^2(p_{\perp 0}^2 + p_\perp^2)}{(p_{\perp 0}^2 + p_\perp^2)^2} \quad \text{(more physical)}$$



where $p_{\perp\mathrm{min}}$ or $p_{\perp 0}$ are free parameters, empirically of order **2 GeV**

Typically 2 – 3 interactions/event at the Tevatron, 4 – 5 at the LHC, but may be more in “interesting” high-$p_\perp$ ones.

Modelling multiple interactions

T. Sjöstrand, M. van Zijl, PRD36 (1987) 2019: first models for event properties based on perturbative multiple interactions

(1) Simple scenario:
no longer used (no impact-parameter dependence)

(2) More sophisticated scenario:
still in frequent use (Tune A, Tune DWT, ATLAS tune, . . .)

- Is only a model for nondiffractive events, i.e. for $\sigma_{\text{nd}} \simeq (2/3)\sigma_{\text{tot}}$
- Smooth turn-off at $p_{\perp 0}$ scale
- Require ≥ 1 interaction in an event
- Interactions generated in ordered sequence $p_{\perp 1} > p_{\perp 2} > p_{\perp 3} > \ldots$ by "Sudakov" trick (what happens "first"?)

$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}p_{\perp i}} = \frac{1}{\sigma_{\text{nd}}} \frac{\mathrm{d}\sigma}{\mathrm{d}p_{\perp}} \exp\left[- \int_{p_{\perp}}^{p_{\perp(i-1)}} \frac{1}{\sigma_{\text{nd}}} \frac{\mathrm{d}\sigma}{\mathrm{d}p'_{\perp}} \mathrm{d}p'_{\perp} \right]$$

- After each interaction rescaled new PDF's for momentum conservation
- Leads to n_{int} narrower than Poissonian, except that . . .

- Hadrons are extended,
  e.g. double Gaussian (“hot spots”):

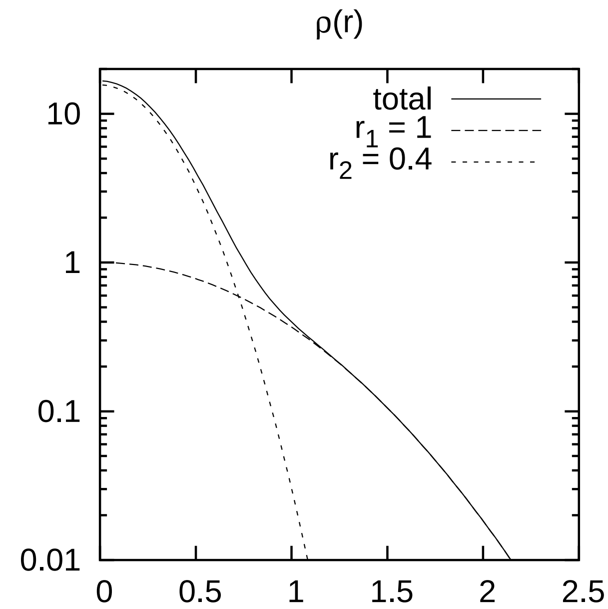
$$\rho_{\mathrm{matter}}(r) = N_1 \exp\left(-\frac{r^2}{r_1^2}\right) + N_2 \exp\left(-\frac{r^2}{r_2^2}\right)$$

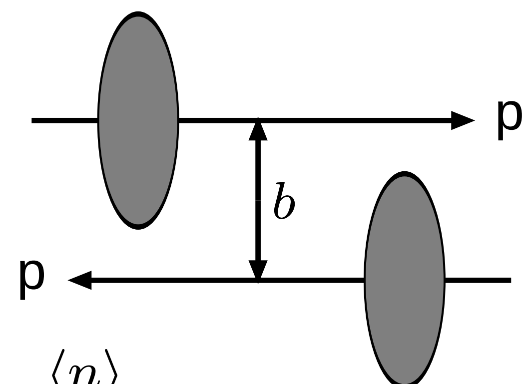
  where $r_2 \neq r_1$ represents “hot spots”
- Events are distributed in impact parameter b
- Overlap of hadrons during collision

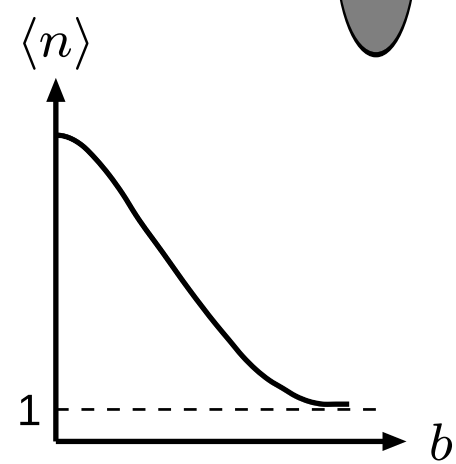
$$\mathcal{O}(b) = \int \mathrm{d}^3\mathbf{x}\,\mathrm{d}t\; \rho_{1,\mathrm{matter}}^{\mathrm{boosted}}(\mathbf{x},t)\rho_{2,\mathrm{matter}}^{\mathrm{boosted}}(\mathbf{x},t)$$

- Average activity at b proportional to $\mathcal{O}(b)$
  $\Rightarrow$ central collisions normally more active
  $\Rightarrow$ $\mathcal{P}_n$ broader than Poissonian

- Time-consuming $(b, p_\perp)$ generation
- Problems if many valence quarks kicked out
  $\Rightarrow$ Simplify after first interaction:
  only gg or $q\overline{q}$ outgoing, no showers, ...

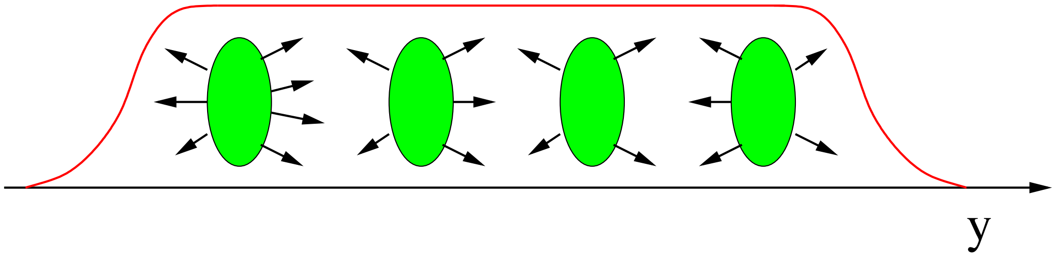






(3) HERWIG

Soft Underlying Event (SUE), based on UA5 Monte Carlo



- Distribute a ($\sim$ negative binomial) number of clusters independently in rapidity and transverse momentum according to parametrization/extrapolation of data
- modify for overall energy/momentum/flavour conservation
- no minijets; correlations only by cluster decays

(4) Jimmy (HERWIG add-on)

- similar to PYTHIA (2) above; but details different
- matter profile by electromagnetic form factor
- no $p_\perp$-ordering of emissions, no rescaling of PDF: abrupt stop when (if) run out of energy

(5) Phojet/DTUjet

- comes from "historical" tradition of soft physics of "cut Pomerons" $\approx p_\perp \to 0$ limit of multiple interactions
- extended also to "hard" interactions similarly to PYTHIA

(6) SHERPA: based on PYTHIA (2), with CKKW added

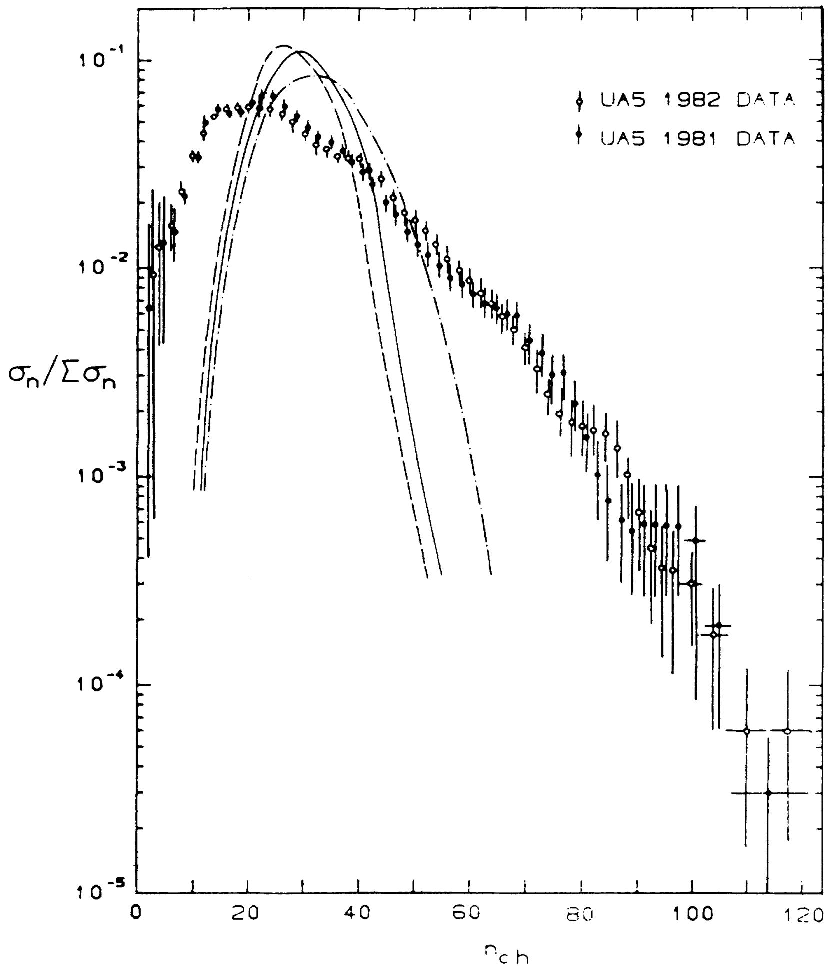


FIG. 3. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs simple models: dashed low p_T only, full including hard scatterings, dash-dotted also including initial- and final-state radiation.

without multiple interactions

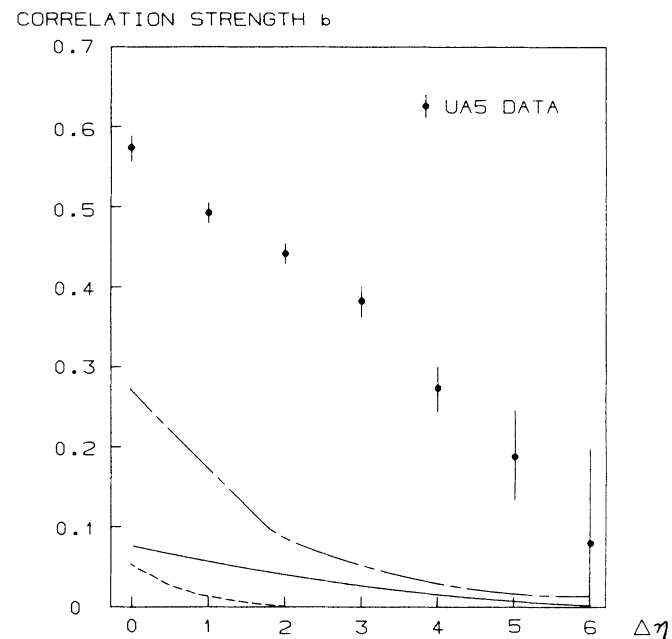


FIG. 4. Forward-backward multiplicity correlation at 540 GeV, UA5 results (Ref. 33) vs simple models; the latter models with notation as in Fig. 3.

with multiple interactions

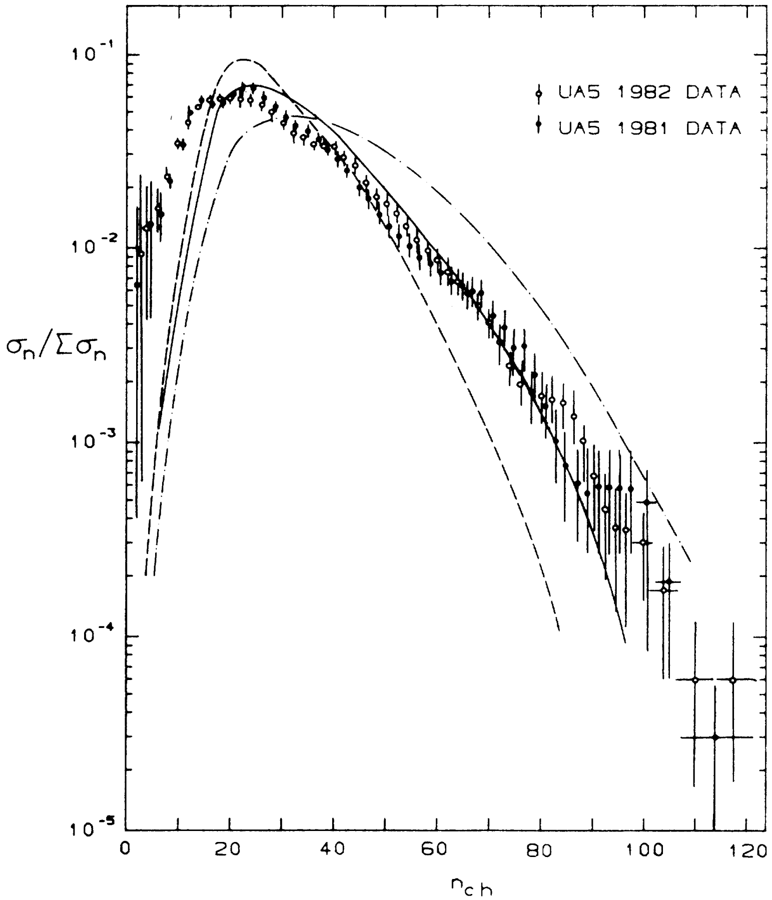


FIG. 5. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs impact-parameter-independent multiple-interaction model: dashed line, $p_{T\min}=2.0$ GeV; solid line, $p_{T\min}=1.6$ GeV; dashed-dotted line, $p_{T\min}=1.2$ GeV.

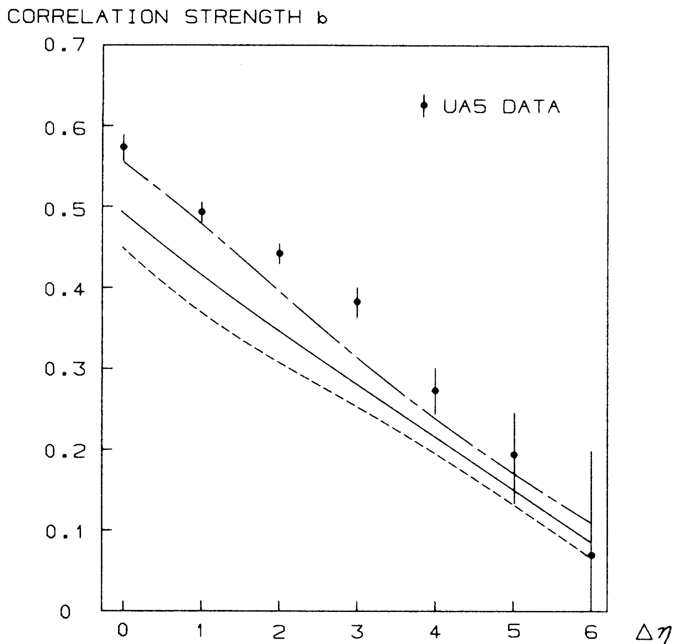


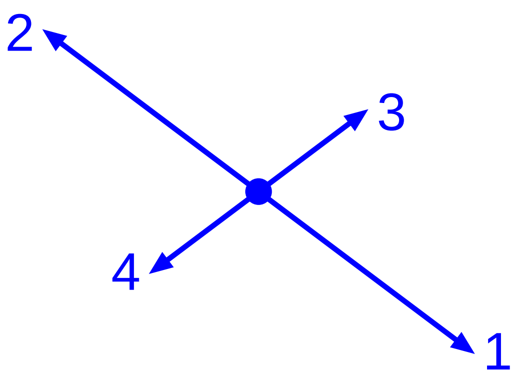
FIG. 6. Forward-backward multiplicity correlation at 540 GeV, UA5 results (Ref. 33) vs impact-parameter-independent multiple-interaction model; the latter with notation as in Fig. 5.

Direct observation of multiple interactions

Four studies: AFS (1987), UA2 (1991), CDF (1993, 1997)

Order 4 jets $\mathbf{p}_{\perp 1} > \mathbf{p}_{\perp 2} > \mathbf{p}_{\perp 3} > \mathbf{p}_{\perp 4}$ and define φ
as angle between $\mathbf{p}_{\perp 1} \mp \mathbf{p}_{\perp 2}$ and $\mathbf{p}_{\perp 3} \mp \mathbf{p}_{\perp 4}$ for AFS/CDF

Double Parton Scattering

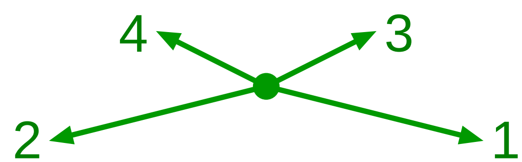


$|\mathbf{p}_{\perp 1} + \mathbf{p}_{\perp 2}| \approx 0$

$|\mathbf{p}_{\perp 3} + \mathbf{p}_{\perp 4}| \approx 0$

$\mathrm{d}\sigma/\mathrm{d}\varphi$ flat

Double BremsStrahlung

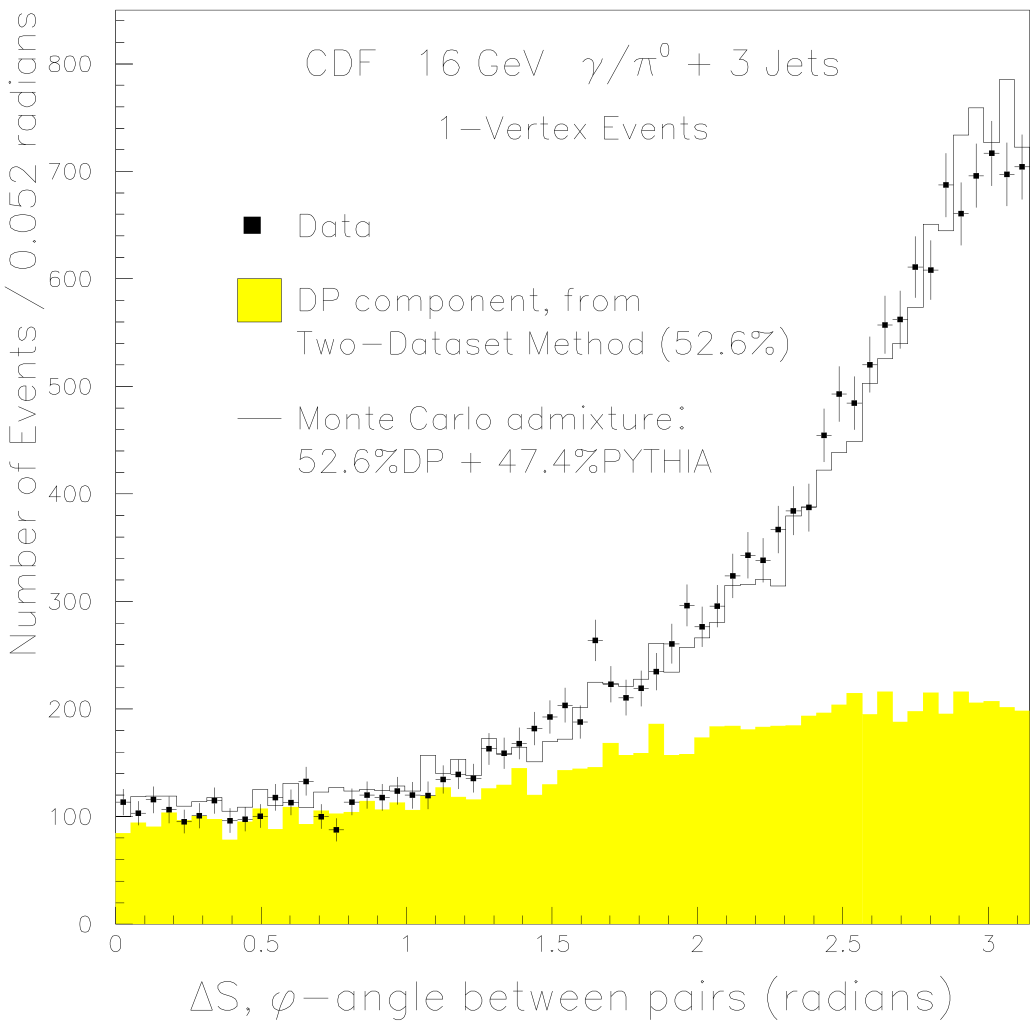


$|\mathbf{p}_{\perp 1} + \mathbf{p}_{\perp 2}| \gg 0$

$|\mathbf{p}_{\perp 3} + \mathbf{p}_{\perp 4}| \gg 0$

$\mathrm{d}\sigma/\mathrm{d}\varphi$ peaked at $\varphi \approx 0/\pi$ for AFS/CDF

AFS 4-jet analysis (pp at 63 GeV): observe 6 times Poissonian prediction,
with impact parameter expect 3.7 times Poissonian,
but big errors $\Rightarrow$ low acceptance, also UA2



CDF 3-jet + prompt photon analysis

Yellow region = double parton scattering (DPS)

The rest = PYTHIA showers

$$\sigma_{\text{DPS}} = \frac{\sigma_A \sigma_B}{\sigma_{\text{eff}}} \quad \text{for } A \neq B \quad \Longrightarrow \sigma_{\text{eff}} = 14.5 \pm 1.7^{+1.7}_{-2.3} \text{ mb}$$

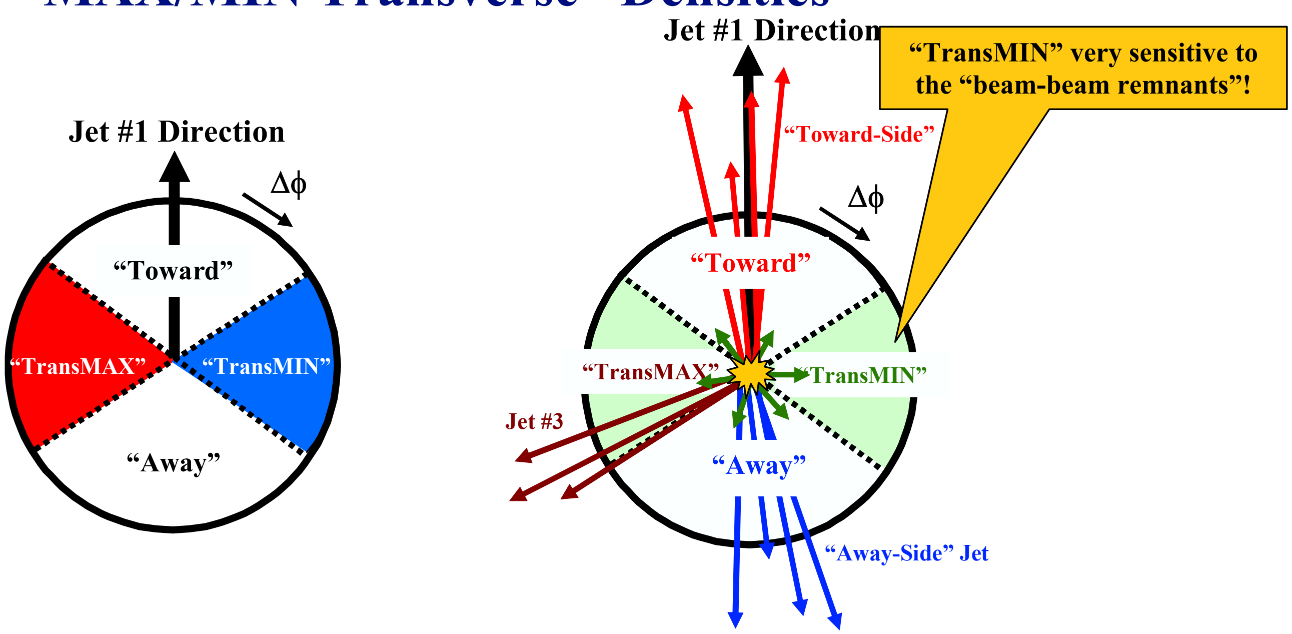
Strong enhancement relative to naive expectations!

Jet pedestal effect

Events with hard scale (jet, W/Z, . . .) have more underlying activity!
Events with n interactions have n chances that one of them is hard,
so “trigger bias”: hard scale $\Rightarrow$ central collision
$\Rightarrow$ more interactions $\Rightarrow$ larger underlying activity.
Centrality effect saturates at $p_{\perp\mathrm{hard}} \sim 10$ GeV.

Studied in detail by Rick Field, comparing with CDF data:

“MAX/MIN Transverse” Densities



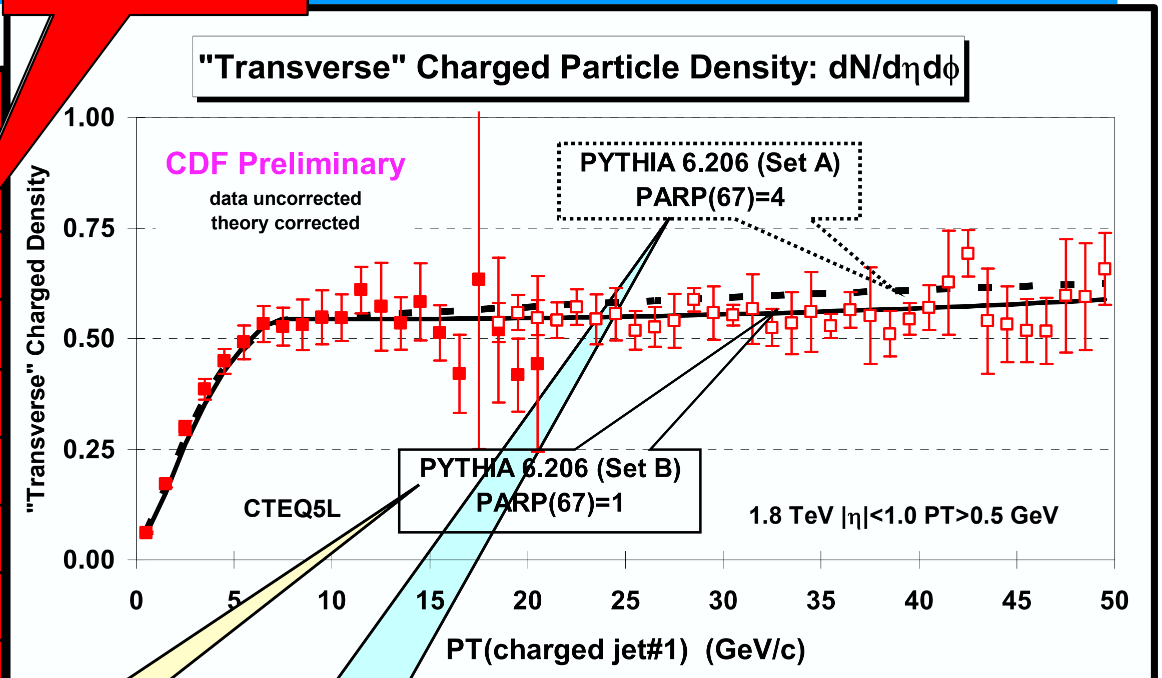
- **Define the MAX and MIN “transverse” regions on an event-by-event basis with MAX (MIN) having the largest (smallest) density.**

Tuned PYTHIA 6.206

Tune A CDF Run 2 Default!

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

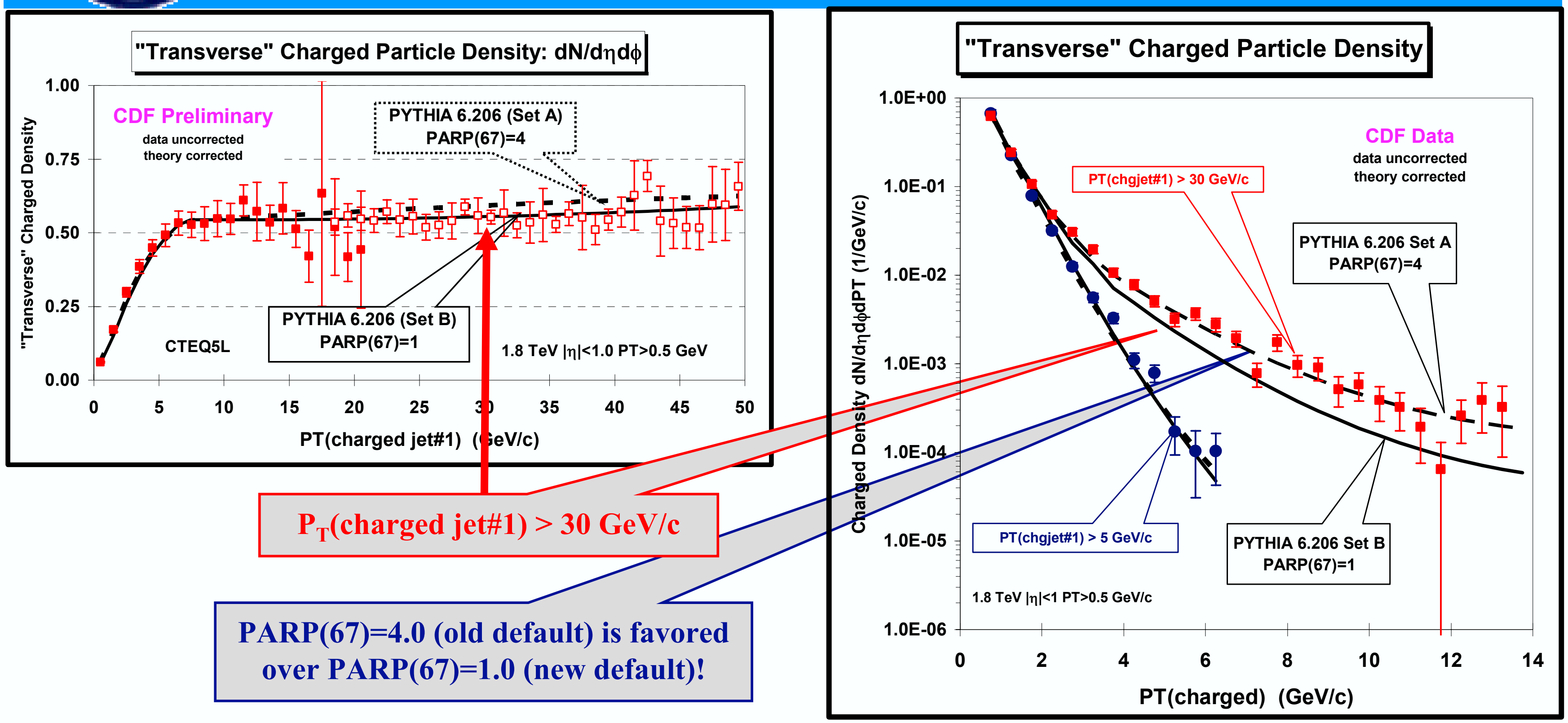


Plot shows the "Transverse" charged particle density versus P_T(chgjet#1) compared to the QCD hard scattering predictions of two tuned versions of PYTHIA 6.206 (CTEQ5L, Set B (PARP(67)=1) and Set A (PARP(67)=4)).

New PYTHIA default (less initial-state radiation)

Old PYTHIA default (more initial-state radiation)

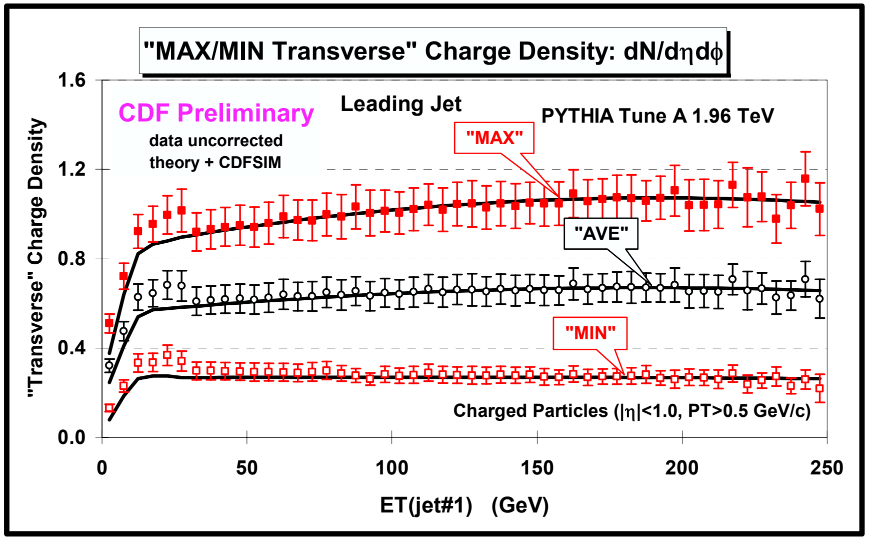
Tuned PYTHIA 6.206 "Transverse" P_T Distribution

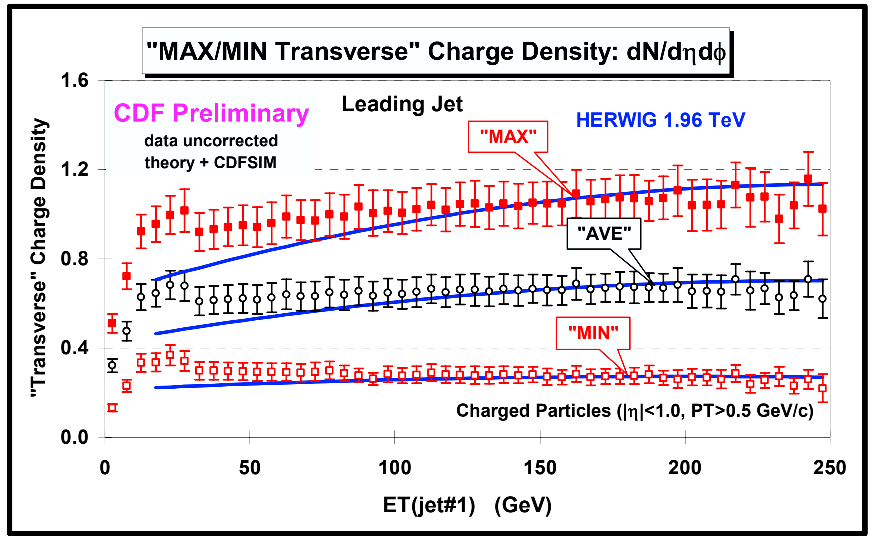


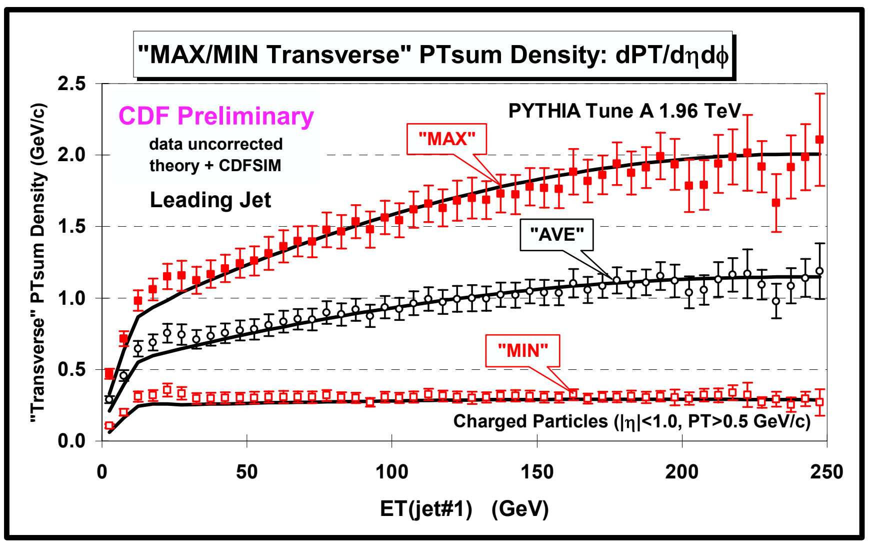
- **Compares the average "transverse" charge particle density (|η|<1, P_T>0.5 GeV) versus P_T(charged jet#1) and the P_T distribution of the "transverse" density, $dN_{chg}/d\eta d\phi dP_T$ with the QCD Monte-Carlo predictions of two tuned versions of PYTHIA 6.206 (P_T(hard) > 0, CTEQ5L, Set B (PARP(67)=1) and Set A (PARP(67)=4)).**

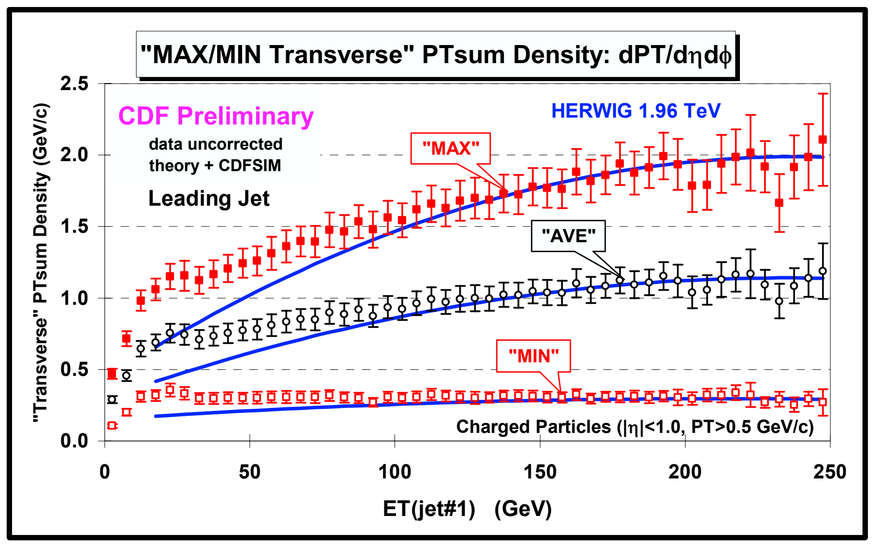
Leading Jet: "MAX & MIN Transverse" Densities

PYTHIA Tune A HERWIG



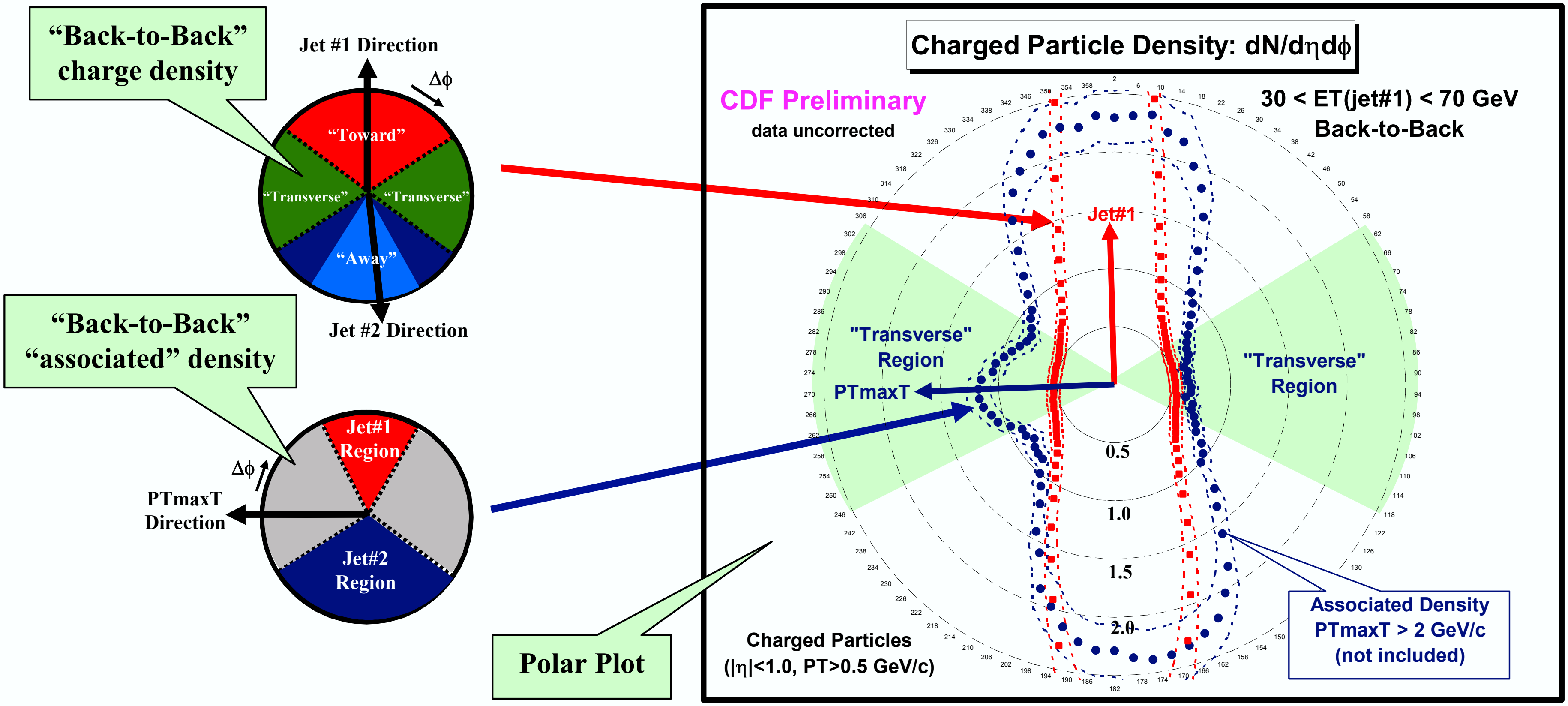






Charged particle density and PTsum density for "leading jet" events versus E_T(jet#1) for PYTHIA Tune A and HERWIG.

Back-to-Back "Associated" Charged Particle Densities

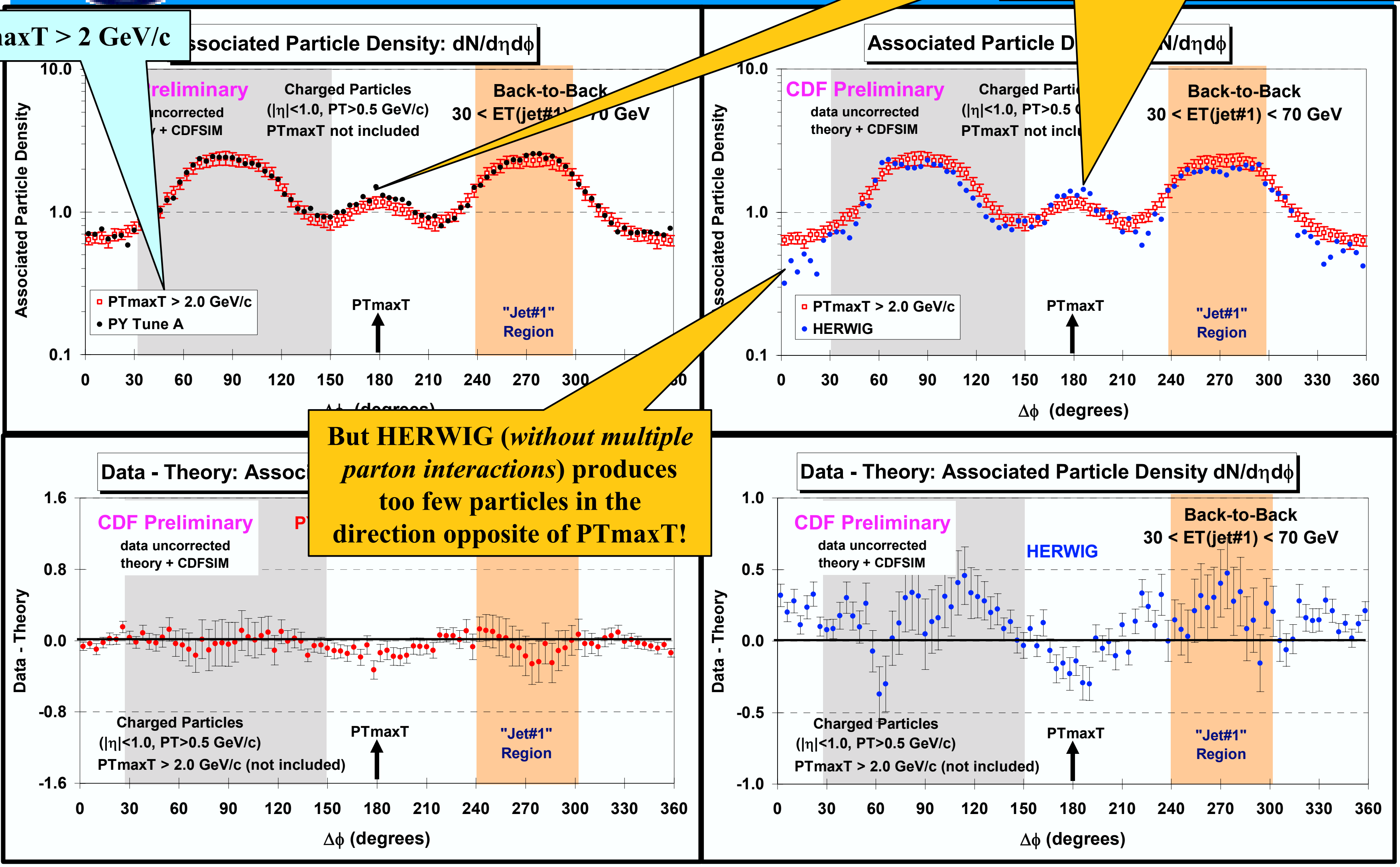


- Shows the **Δφ dependence of the "associated" charged particle density**, $dN_{chg}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$, PTmaxT > 2.0 GeV/c (*not including PTmaxT*) relative to PTmaxT (rotated to 180°) and the charged particle density, $dN_{chg}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$, relative to jet#1 (rotated to 270°) for **"back-to-back events" with $30 < E_T(\text{jet\#1}) < 70$ GeV**.

"Associated" Charge De[...] PYTHIA Tune A vs HE[...]

For PTmaxT > 2.0 GeV both PYTHIA and HERWIG produce slightly too many "associated" particles in the direction of PTmaxT!

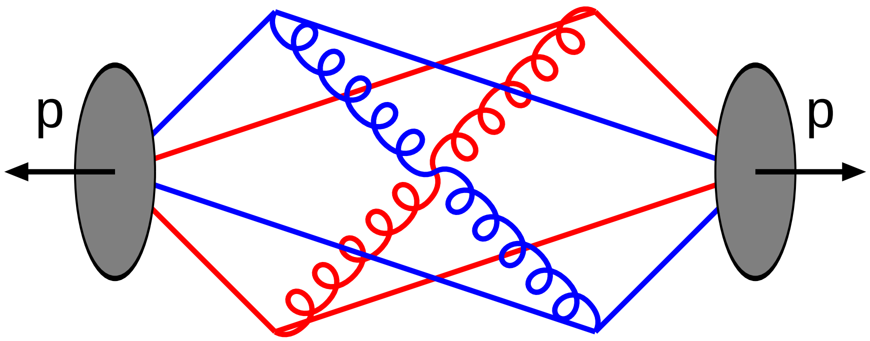
PTmaxT > 2 GeV/c



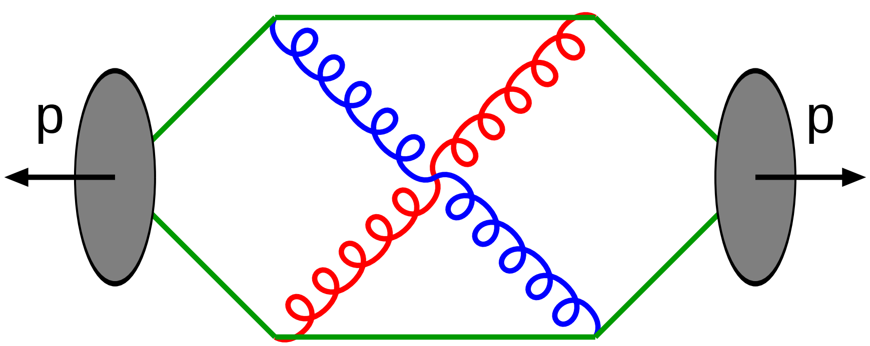
But HERWIG (*without multiple parton interactions*) produces too few particles in the direction opposite of PTmaxT!

Colour correlations

$\langle p_\perp \rangle (n_{\text{ch}})$ is very sensitive to colour flow



long strings to remnants $\Rightarrow$ much n_{ch}/interaction $\Rightarrow \langle p_\perp \rangle (n_{\text{ch}}) \sim$ flat



short strings (more central) $\Rightarrow$ less n_{ch}/interaction $\Rightarrow \langle p_\perp \rangle (n_{\text{ch}})$ rising

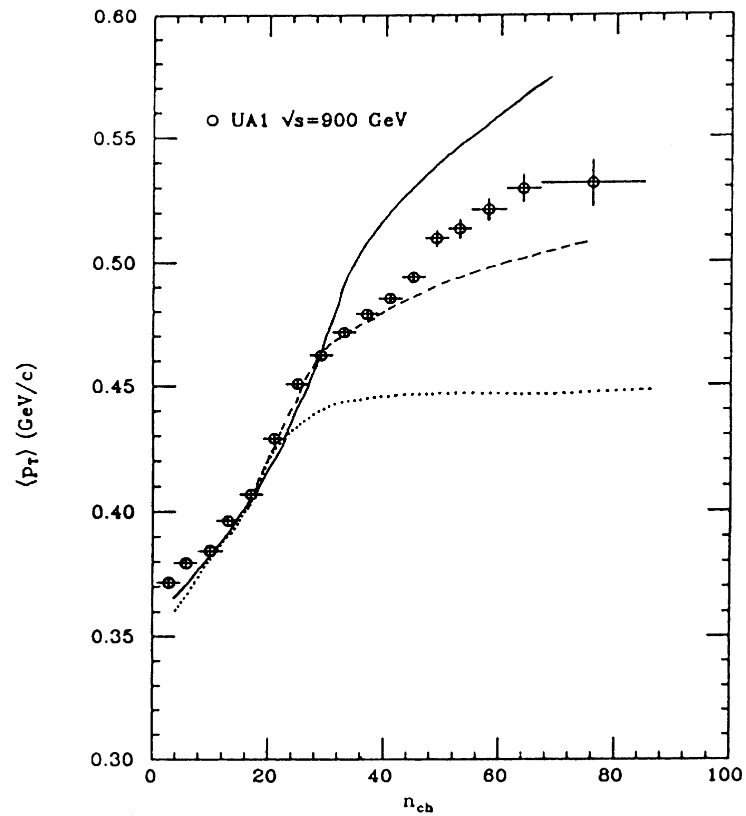
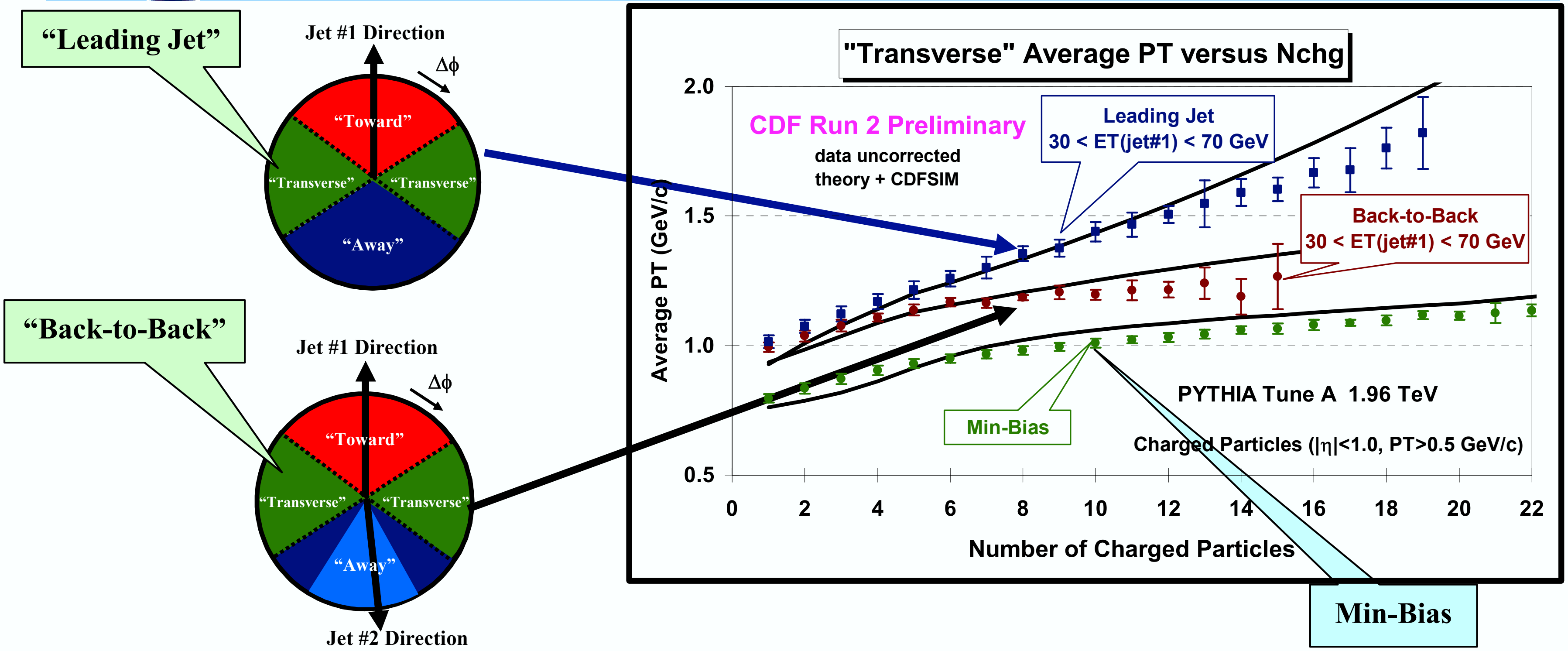


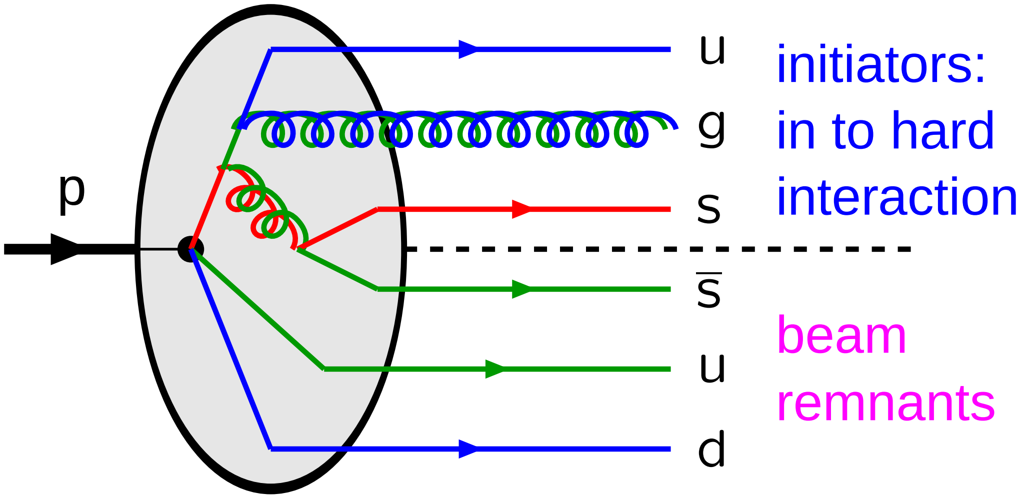
FIG. 27. Average transverse momentum of charged particles in $|\eta| < 2.5$ as a function of the multiplicity. UA1 data points (Ref. 49) at 900 GeV compared with the model for different assumptions about the nature of the subsequent (nonhardest) interactions. Dashed line, assuming $q\bar{q}$ scatterings only; dotted line, gg scatterings with "maximal" string length; solid line gg scatterings with "minimal" string length.

"Transverse" $\langle p_T \rangle$ versus "Transverse" Nchg



- Look at the $\langle p_T \rangle$ of particles in the "transverse" region ($p_T > 0.5$ GeV/c, $|\eta| < 1$) versus the number of particles in the "transverse" region: $\langle p_T \rangle$ vs Nchg.
- Shows $\langle p_T \rangle$ versus Nchg in the "transverse" region ($p_T > 0.5$ GeV/c, $|\eta| < 1$) for "Leading Jet" and "Back-to-Back" events with $30 < E_T(\text{jet\#1}) < 70$ GeV compared with "min-bias" collisions.

Initiators and Remnants



Need to assign:

- correlated flavours
- correlated $x_i = p_{zi}/p_{z\text{tot}}$
- correlated primordial $k_{\perp i}$
- correlated colours
- correlated showers

- **PDF after preceding MI/ISR activity:**

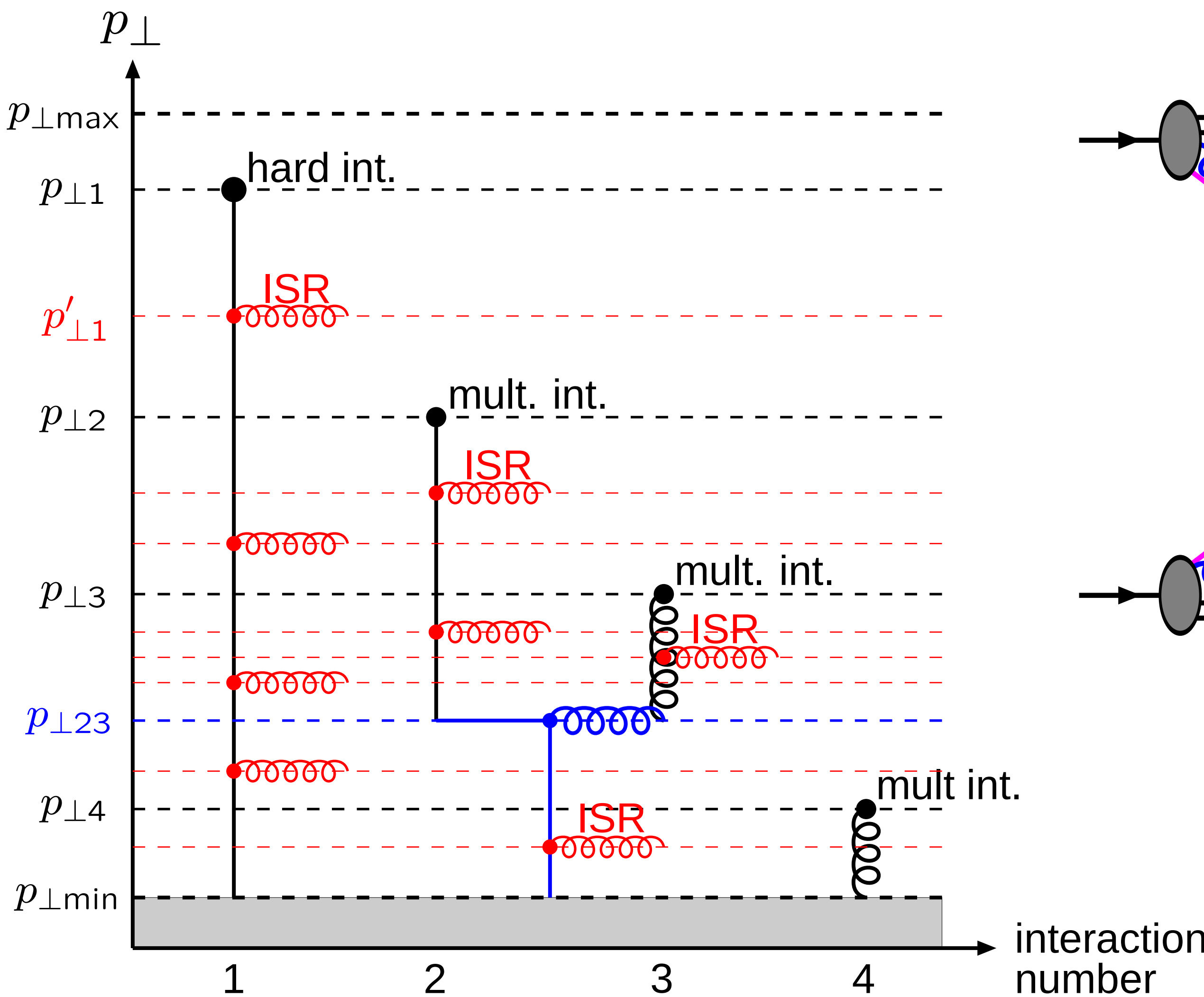
0) Squeeze range $0 < x < 1$ into $0 < x < 1 - \sum x_i$ (ISR: $i \neq i_{\text{current}}$)

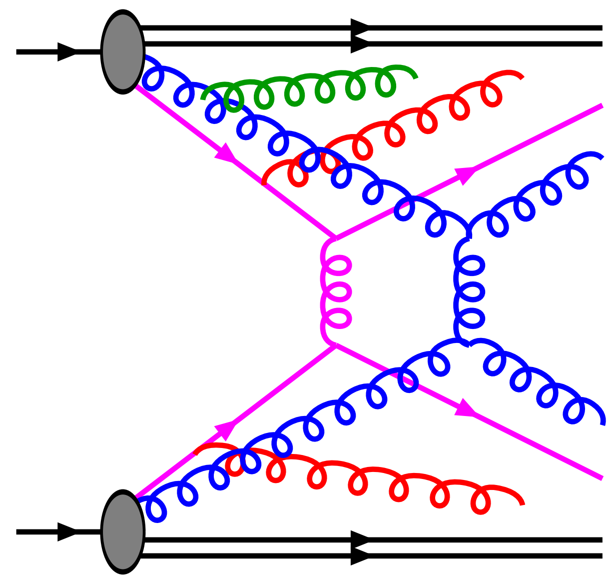
1) Valence quarks: scale down by number already kicked out

2) Introduce companion quark $\mathrm{q}/\overline{\mathrm{q}}$ to each kicked-out sea quark $\overline{\mathrm{q}}/\mathrm{q}$, with x based on assumed $\mathrm{g} \to \mathrm{q}\overline{\mathrm{q}}$ splitting

3) Gluon and other sea: rescale for total momentum conservation

Interleaved Multiple Interactions





Multiple Interactions: A New Evolution Equation

	time	evolution	probability
FSR	forwards	$p_\perp \searrow 0$	normal & local
ISR	backwards	$p_\perp \searrow 0$	conditional
MI	simultaneous	$p_\perp \searrow 0$	conditional

ISR + MI: PDF competition $\Rightarrow$ interleaving (PYTHIA 6.3)

FSR: previously at end, now also interleaved (PYTHIA 8.1):

$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}p_\perp} = \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MI}}}{\mathrm{d}p_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{FSR}}}{\mathrm{d}p_\perp} \right) \times \exp\left(- \int_{p_\perp}^{p_{\perp i-1}} \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MI}}}{\mathrm{d}p'_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p'_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{FSR}}}{\mathrm{d}p'_\perp} \right) \mathrm{d}p'_\perp \right)$$

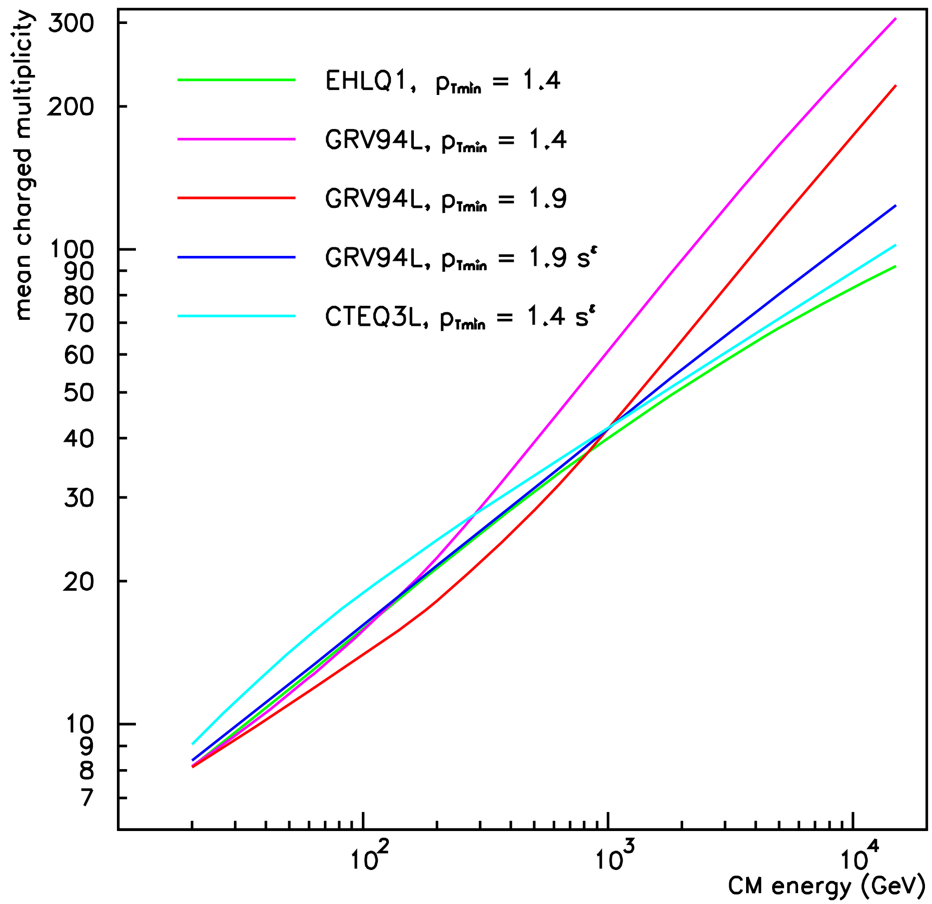
“resolution evolution”

Monte Carlo: winner takes all

+ many other assumptions/models

Extrapolation to LHC

Energy dependence of $p_{\perp\mathrm{min}}$ and $p_{\perp 0}$:



Larger collision energy

$\Rightarrow$ probe parton ($\approx$ gluon) density at smaller x

$\Rightarrow$ smaller colour screening length d

$\Rightarrow$ larger $p_{\perp\mathrm{min}}$ or $p_{\perp 0}$

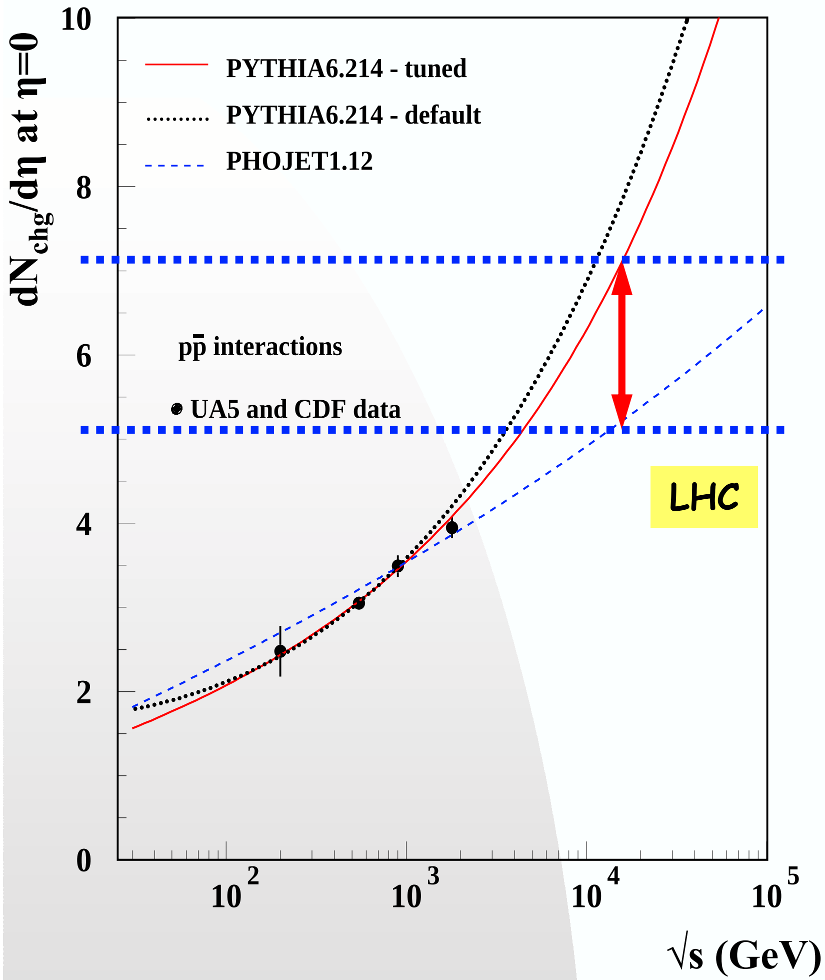
Post-HERA PDF fits steeper at small x

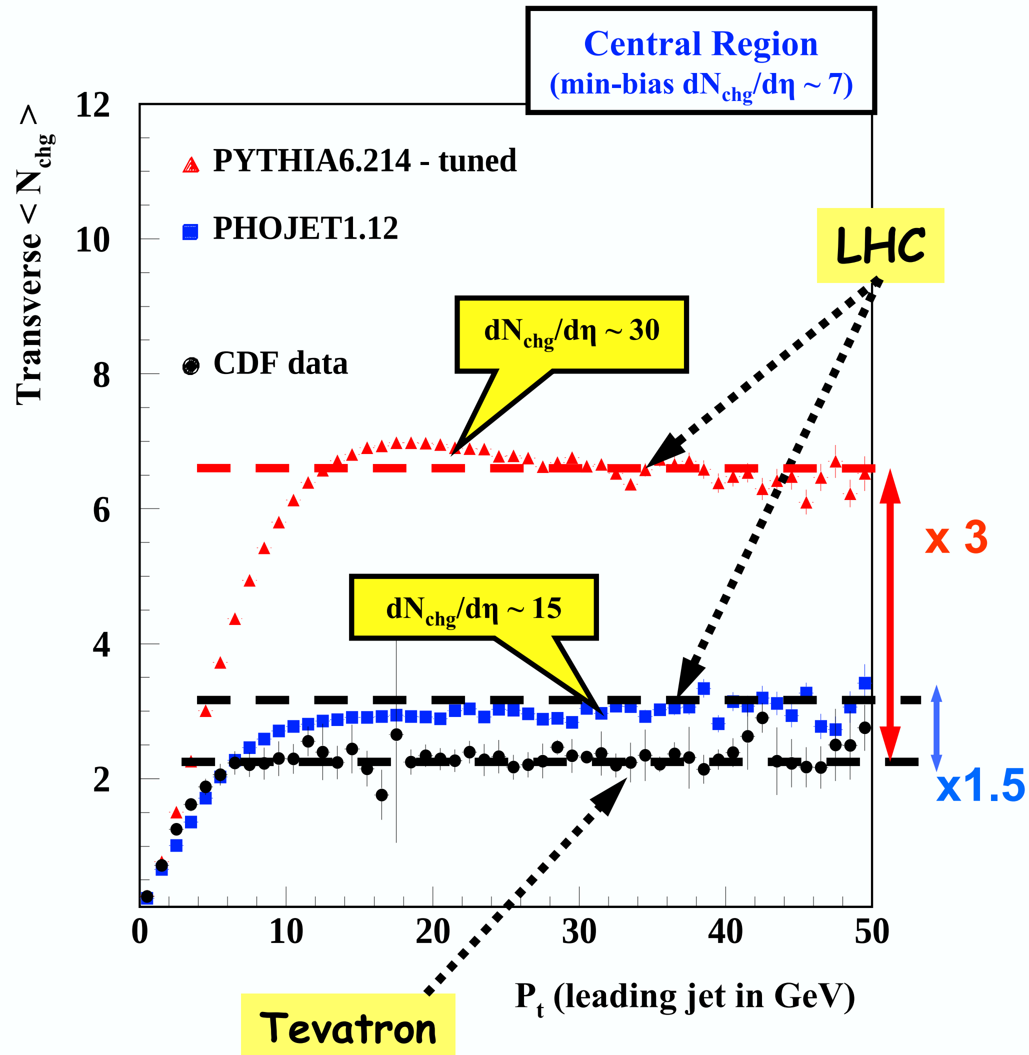
$\Rightarrow$ stronger energy dependence

Current PYTHIA 8 default, tied to CTEQ 5L, is

$$p_{\perp 0}(s) = 2.15\ \mathrm{GeV} \left(\frac{s}{(1.8\ \mathrm{TeV})^2} \right)^{0.08}$$

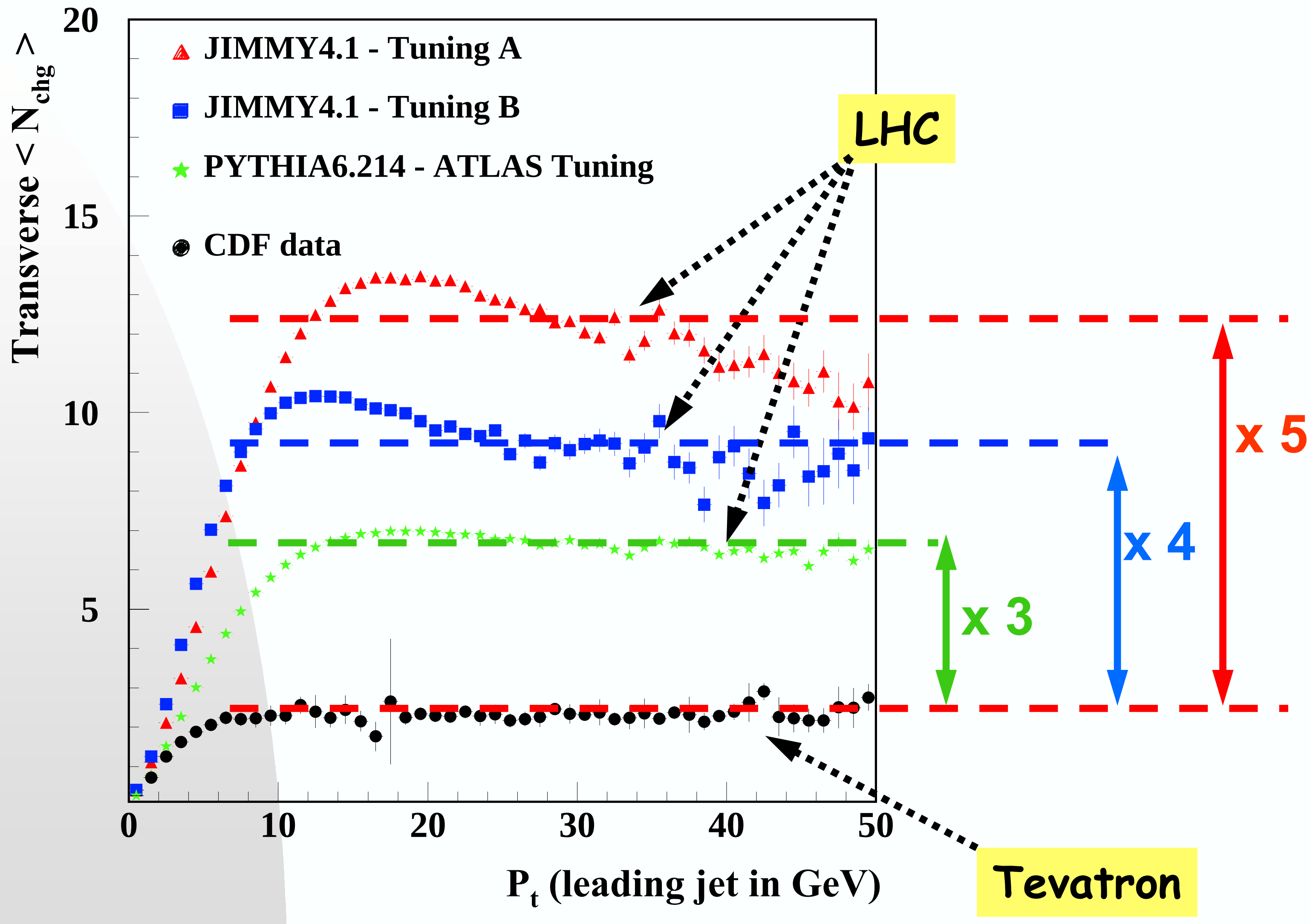
LHC predictions: pp collisions at √s = 14 TeV



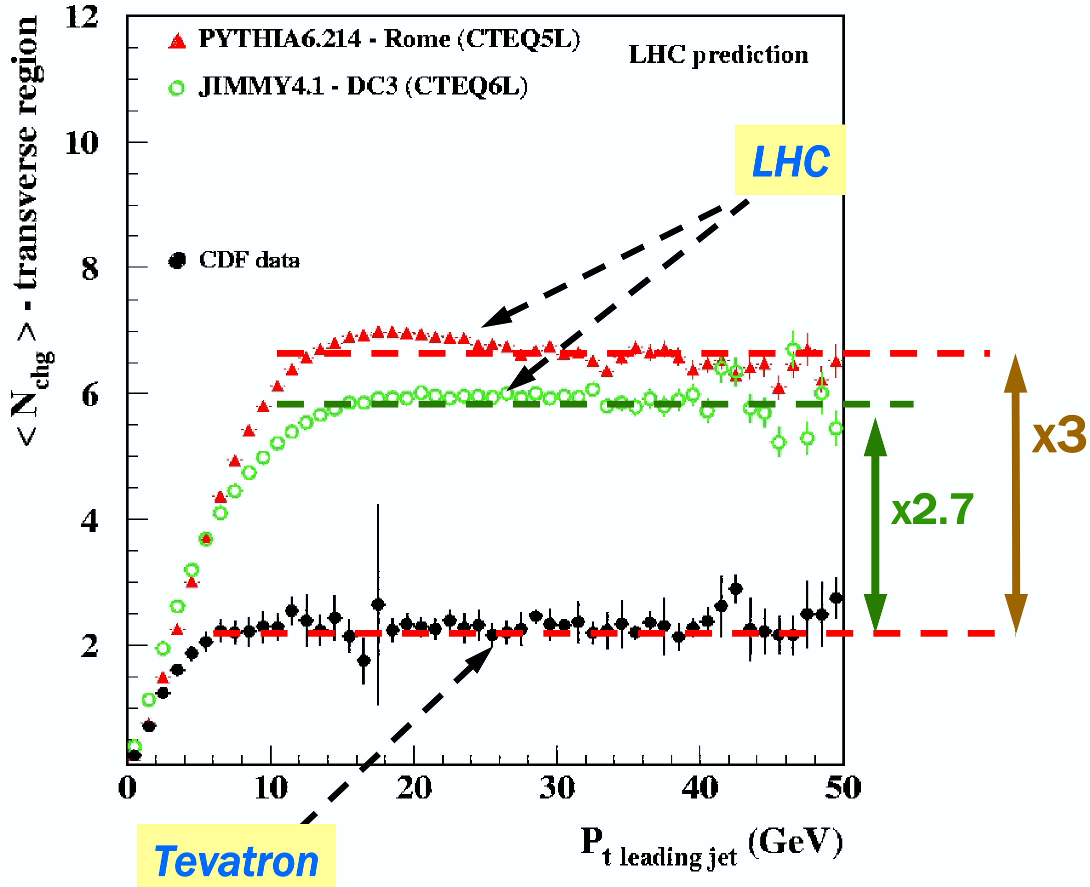


- PYTHIA models favour $\ln^2(s)$;
- PHOJET suggests a ln(s) dependence.

LHC predictions: JIMMY4.1 Tunings A and B vs. PYTHIA6.214 – ATLAS Tuning (DC2)



UE tunings: Pythia vs. Jimmy



PTJIM=4.9

$= 2.8 \times (14 / 1.8)^{0.27}$

- energy dependent PTJIM generates UE predictions similar to the ones generated by PYTHIA6.2 – ATLAS.

Multiple Interactions Outlook

Issues requiring further thought and study:

- Multi-parton PDF's $f_{a_1 a_2 a_3 \cdots}(x_1, Q_1^2, x_2, Q_2^2, x_3, Q_3^2, \ldots)$
- Close-packing in initial state, especially small x
- Impact-parameter picture and (x, b) correlations
  e.g. large-x partons more central!, valence quarks more central?
- Details of colour-screening mechanism
- Rescattering: one parton scattering several times
- Intertwining: one parton splits in two that scatter separately
- Colour sharing: two FS–IS dipoles become one FS–FS one
- Colour reconnection: required for $\langle p_\perp \rangle (n_{\mathrm{charged}})$
- Collective effects (e.g. QGP, cf. Hadronization above)
- Relation to diffraction: eikonalization, multi-gap topologies, . . .

Action items:

- Vigorous experimental program at LHC
- Study energy dependence: RHIC (pp) $\rightarrow$ Tevatron $\rightarrow$ LHC
- Develop new frameworks and refine existing ones

Much work ahead!

Hadronization/Fragmentation models

Perturbative $\longrightarrow$ nonperturbative $\Longrightarrow$ not calculable from first principles!

Model building = ideology + “cookbook”

Common approaches:

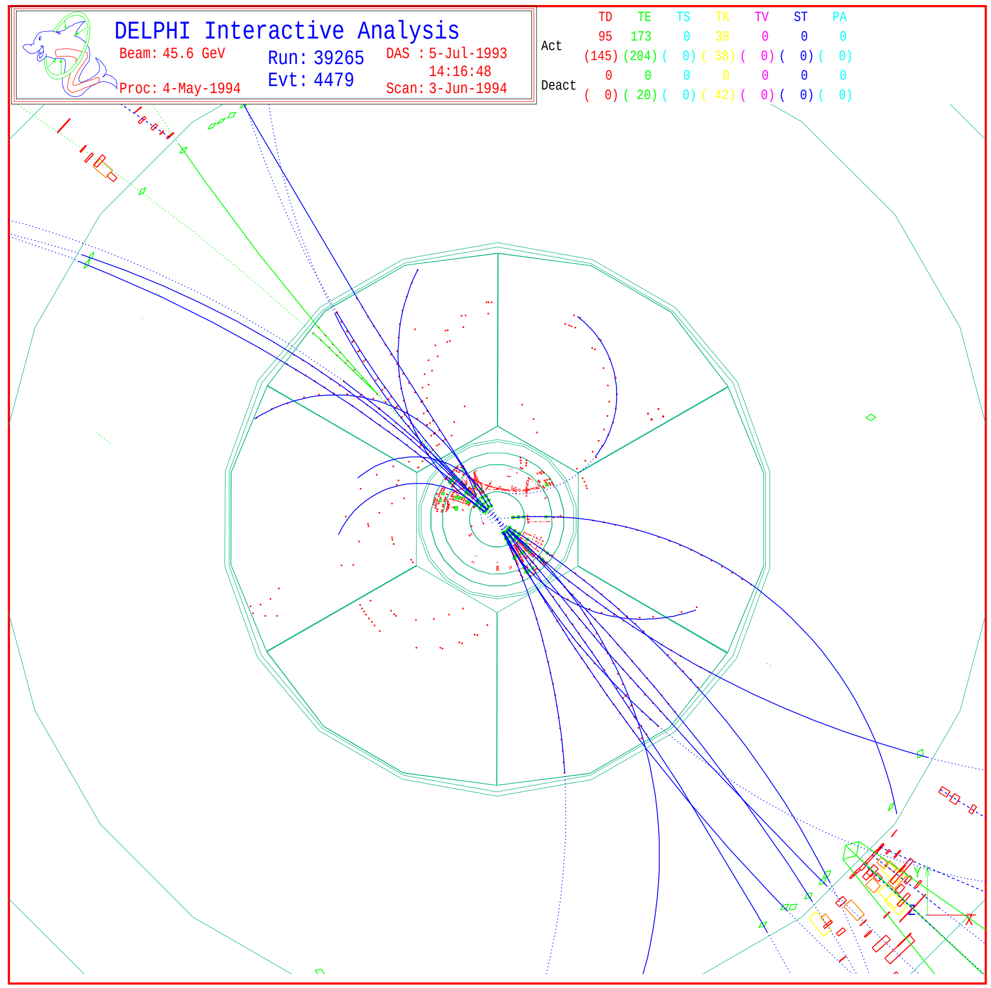
1) **String** Fragmentation
(most ideological)

2) **Cluster** Fragmentation
(simplest?)

3) **Independent** Fragmentation
(most cookbook)

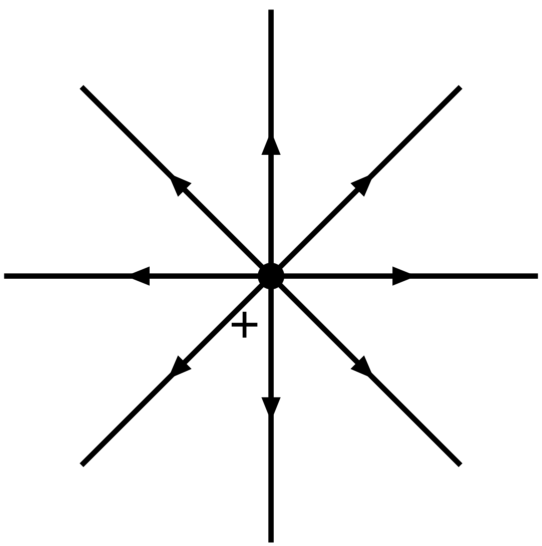
4) Local Parton–Hadron Duality
(limited applicability)

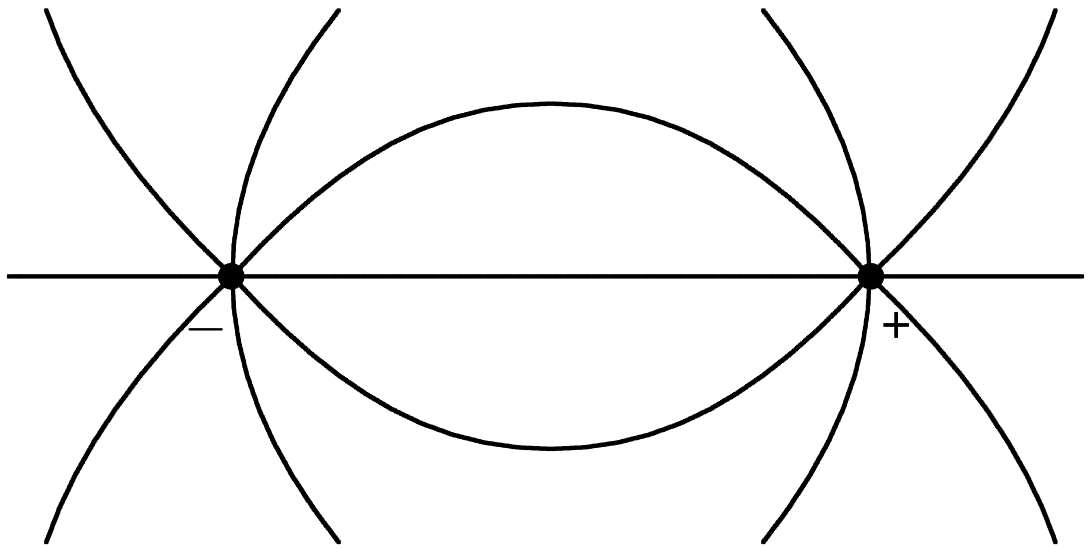
Best studied in
$e^+e^- \to \gamma^*/Z^0 \to q\bar{q}$



The Lund String Model

In QED, field lines go all the way to infinity



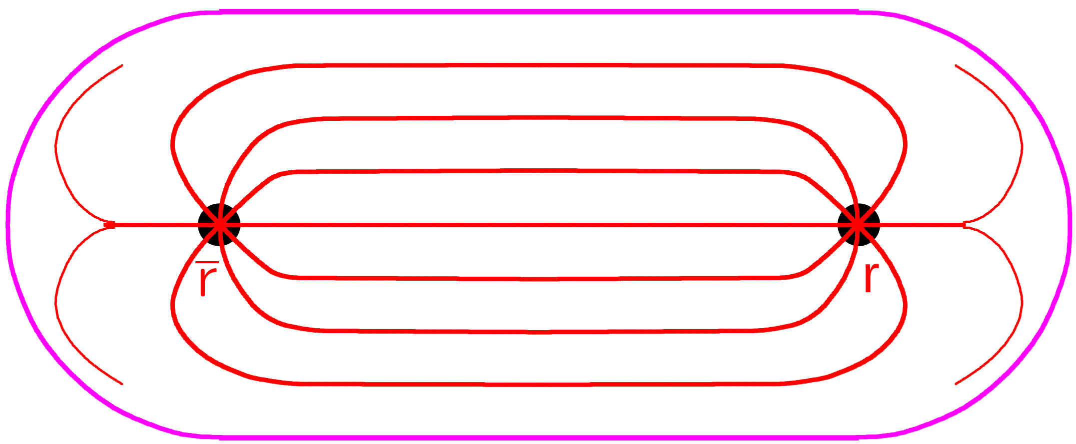


since photons cannot interact with each other.

Potential is simply additive:

$$V(\mathbf{x}) \propto \sum_i \frac{1}{|\mathbf{x} - \mathbf{x}_i|}$$

In QCD, for large charge separation, field lines seem to be compressed to tubelike region(s) $\Rightarrow$ **string(s)**



by self-interactions among soft gluons in the “vacuum”.

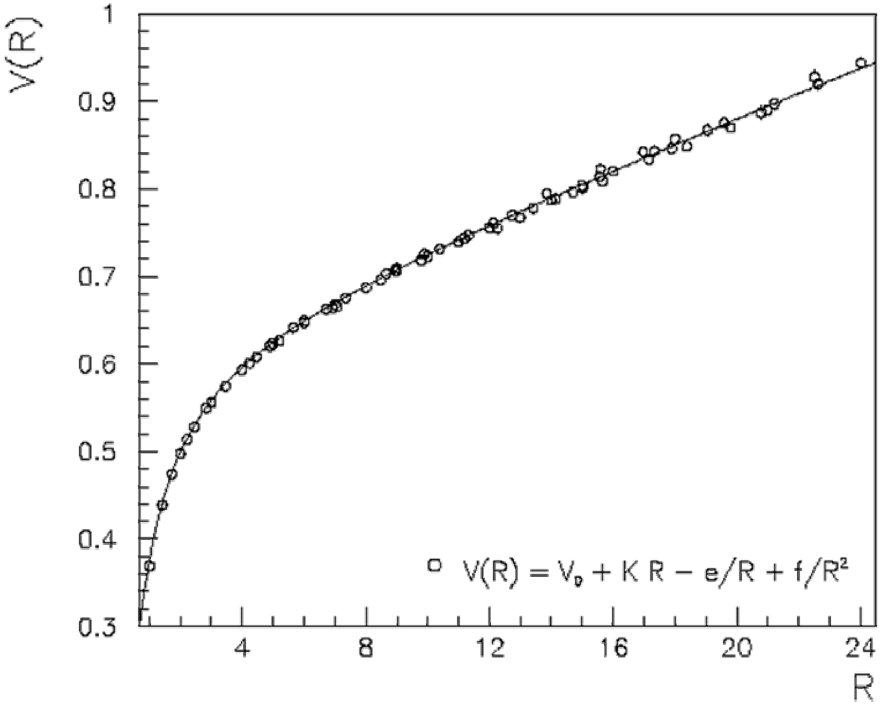
(Non-trivial ground state with quark and gluon “condensates”. Analogy: vortex lines in type II superconductor)

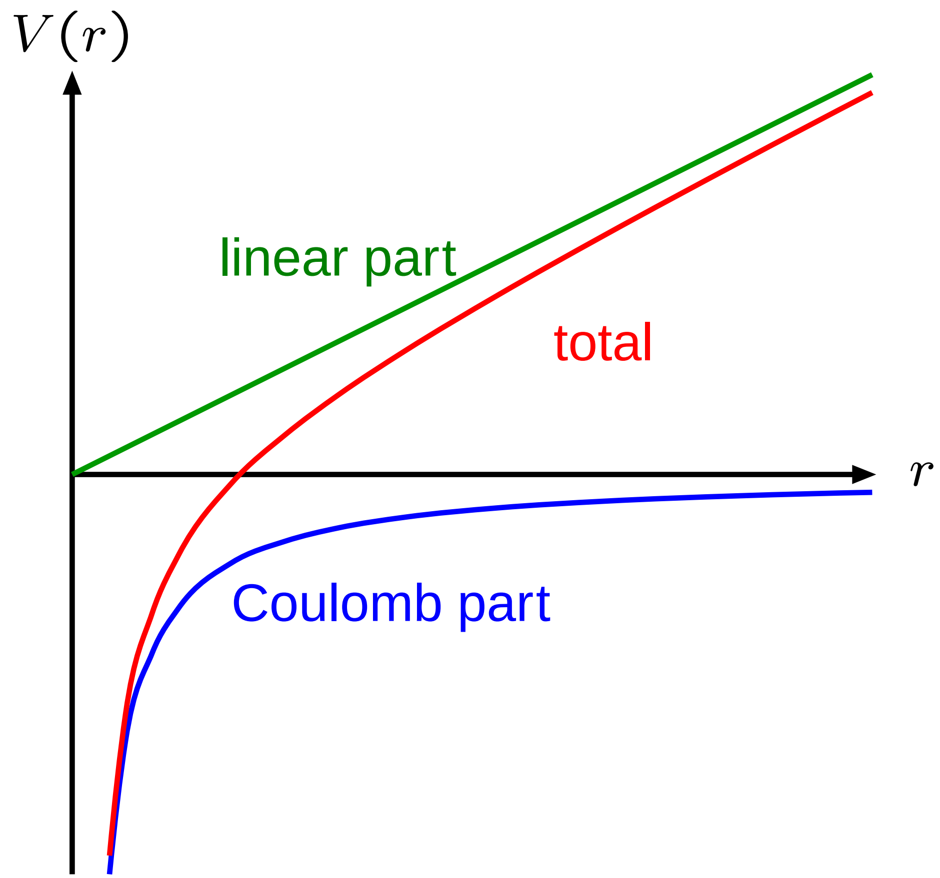
Gives linear confinement with string tension:

$$F(r) \approx \text{const} = \kappa \approx 1\ \text{GeV/fm} \quad \Longleftrightarrow \quad V(r) \approx \kappa r$$

Separation of transverse and longitudinal degrees of freedom $\Rightarrow$ simple description as 1+1-dimensional object – string – with Lorentz invariant formalism

Linear confinenent confirmed e.g. by quenched lattice QCD





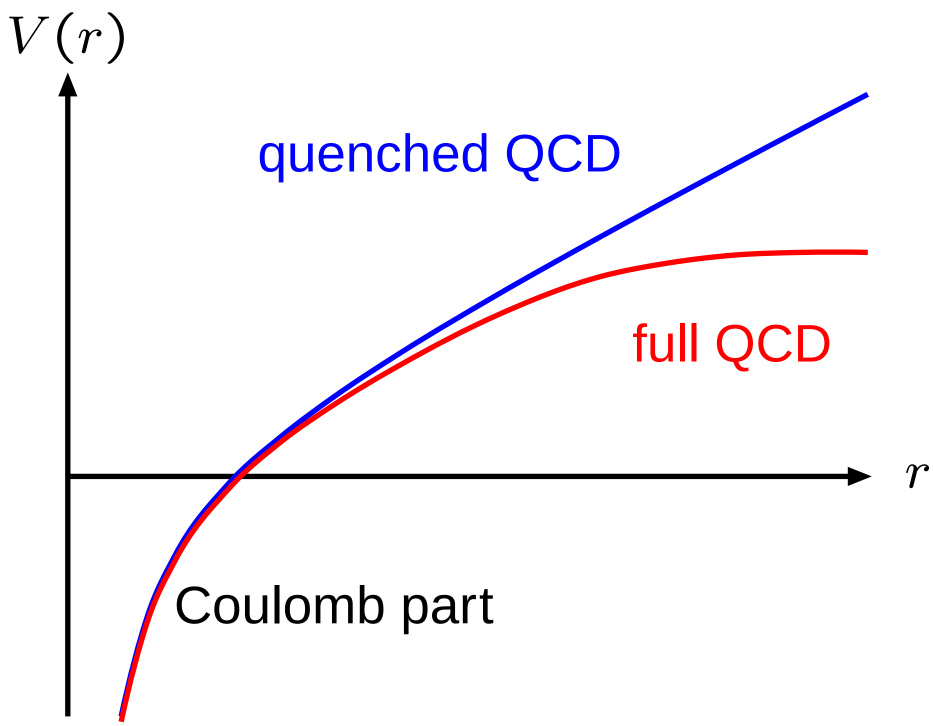
$$V(r) \approx -\frac{4}{3}\frac{\alpha_s}{r} + \kappa r \approx -\frac{0.13}{r} + r$$

(for $\alpha_s \approx 0.5$, r in fm and V in GeV)

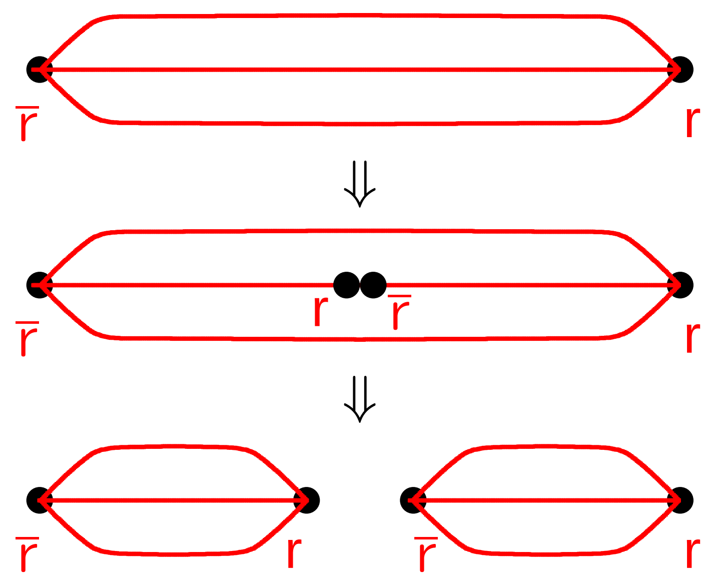
$V(0.4\,\text{fm}) \approx 0$: Coulomb important for internal structure of hadrons, not for particle production (?)

Real world (??, or at least unquenched lattice QCD)

$\Longrightarrow$ nonperturbative string breakings $gg\ldots \to q\bar{q}$



simplified colour representation:

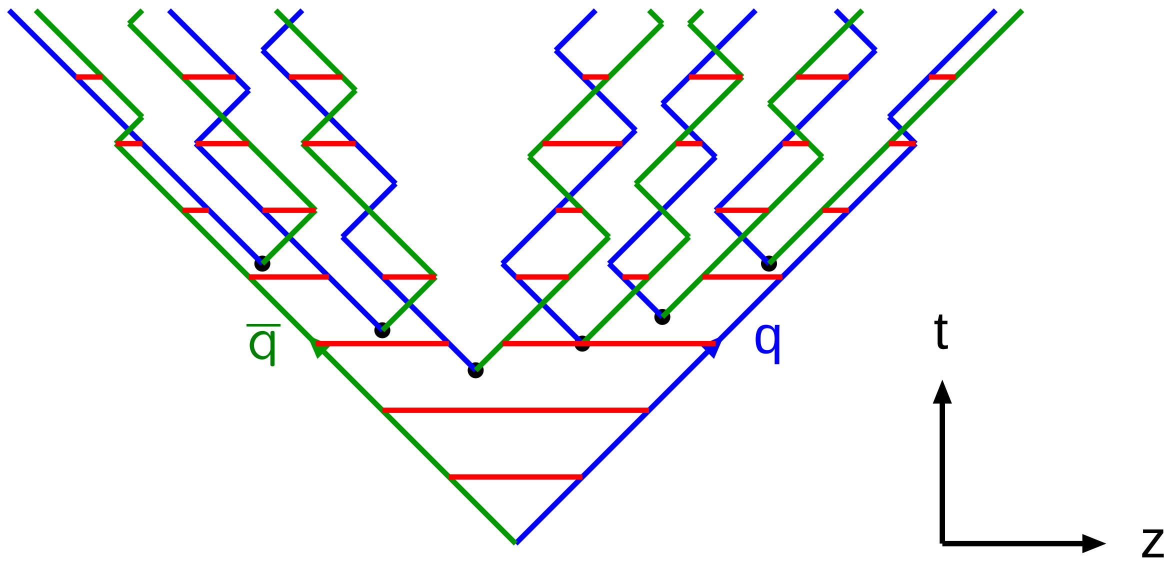


Repeat for large system ⇒ *Lund model*

which neglects Coulomb part:

$$\left|\frac{\mathrm{d}E}{\mathrm{d}z}\right| = \left|\frac{\mathrm{d}p_z}{\mathrm{d}z}\right| = \left|\frac{\mathrm{d}E}{\mathrm{d}t}\right| = \left|\frac{\mathrm{d}p_z}{\mathrm{d}t}\right| = \kappa$$

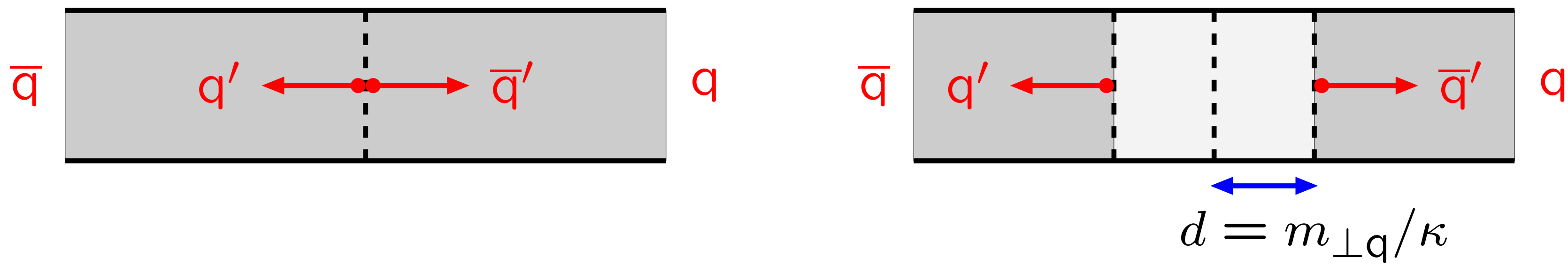
Motion of quarks and antiquarks in a $q\overline{q}$ system:



gives simple but powerful picture of hadron production

(with extensions to massive quarks, baryons, . . .)

How does the string break?



$m_{\perp q'} = 0$ $\qquad$ $m_{\perp q'} > 0$

String breaking modelled by tunneling:

$$\mathcal{P} \propto \exp\left(-\frac{\pi m_{\perp q}^2}{\kappa}\right) = \exp\left(-\frac{\pi p_{\perp q}^2}{\kappa}\right) \exp\left(-\frac{\pi m_q^2}{\kappa}\right)$$

1) common Gaussian $p_\perp$ spectrum

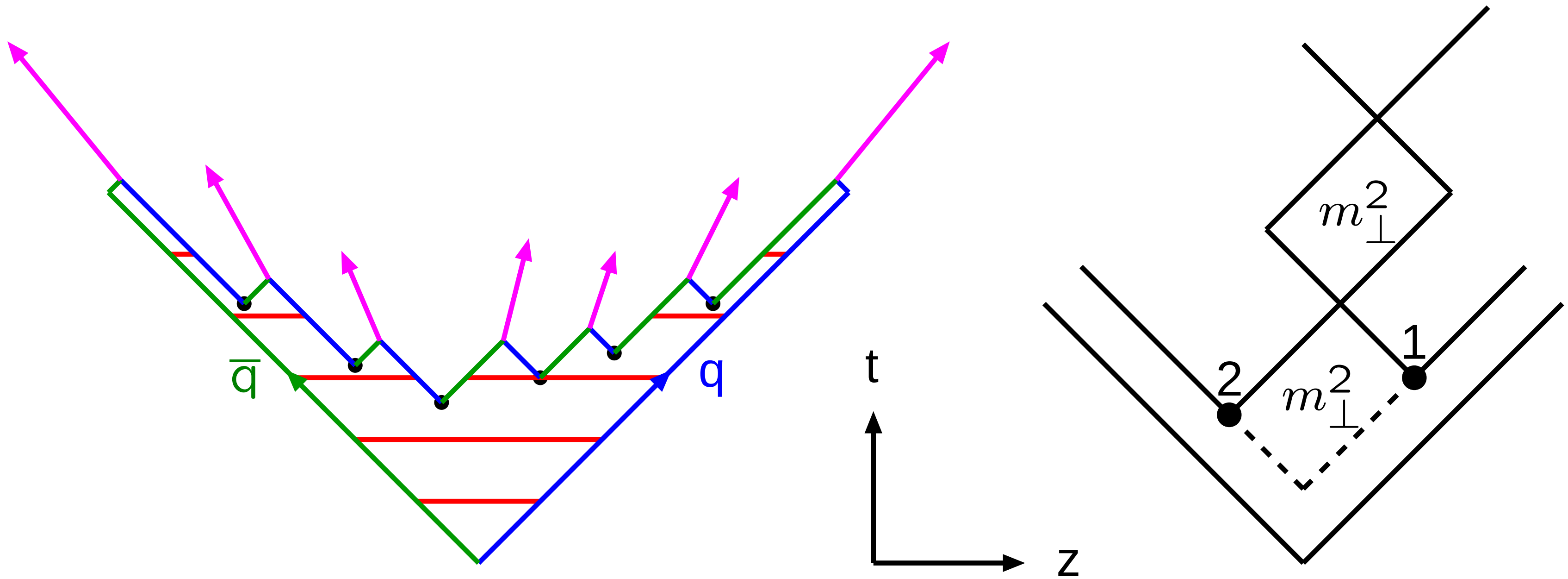
2) suppression of heavy quarks $u\overline{u} : d\overline{d} : s\overline{s} : c\overline{c} \approx 1 : 1 : 0.3 : 10^{-11}$

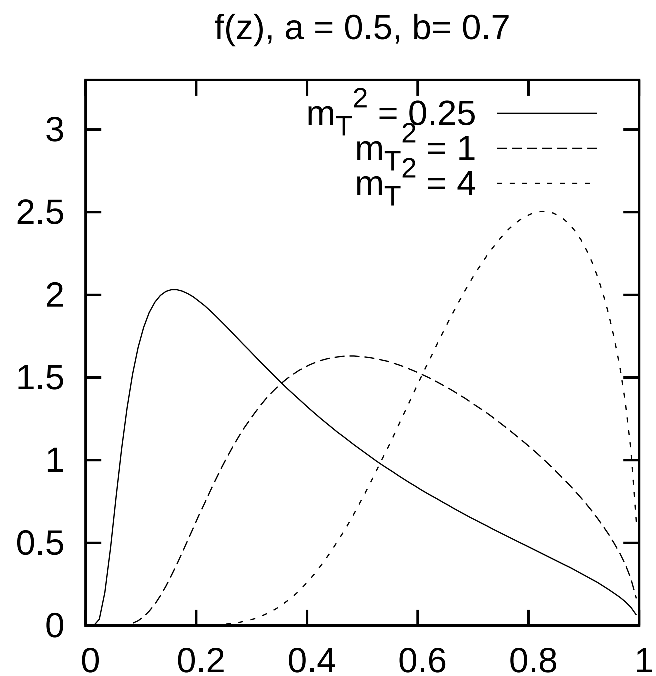
3) diquark $\sim$ antiquark $\Rightarrow$ simple model for baryon production

Hadron composition also depends on spin probabilities, hadronic wave functions, phase space, more complicated baryon production, ...

$\Rightarrow$ “moderate” predictivity (many parameters!)

Fragmentation starts in the middle and spreads outwards:





but breakup vertices causally disconnected

$\Rightarrow$ can proceed in arbitrary order

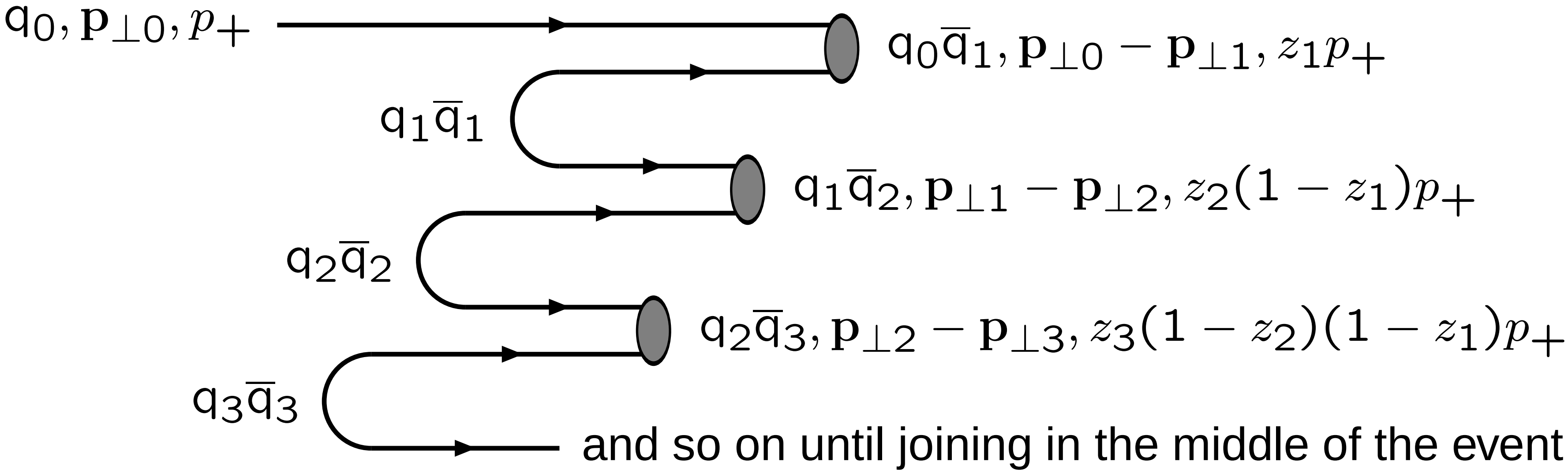
$\Rightarrow$ *left–right symmetry*

$$\begin{aligned} \mathcal{P}(1,2) &= \mathcal{P}(1) \times \mathcal{P}(1 \to 2) \\ &= \mathcal{P}(2) \times \mathcal{P}(2 \to 1) \end{aligned}$$

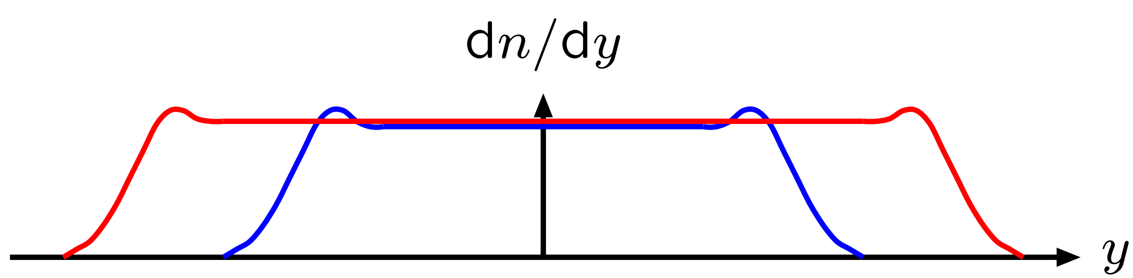
$\Rightarrow$ Lund symmetric fragmentation function

$f(z) \propto (1-z)^a \exp(-bm_\perp^2/z)/z$

The iterative ansatz



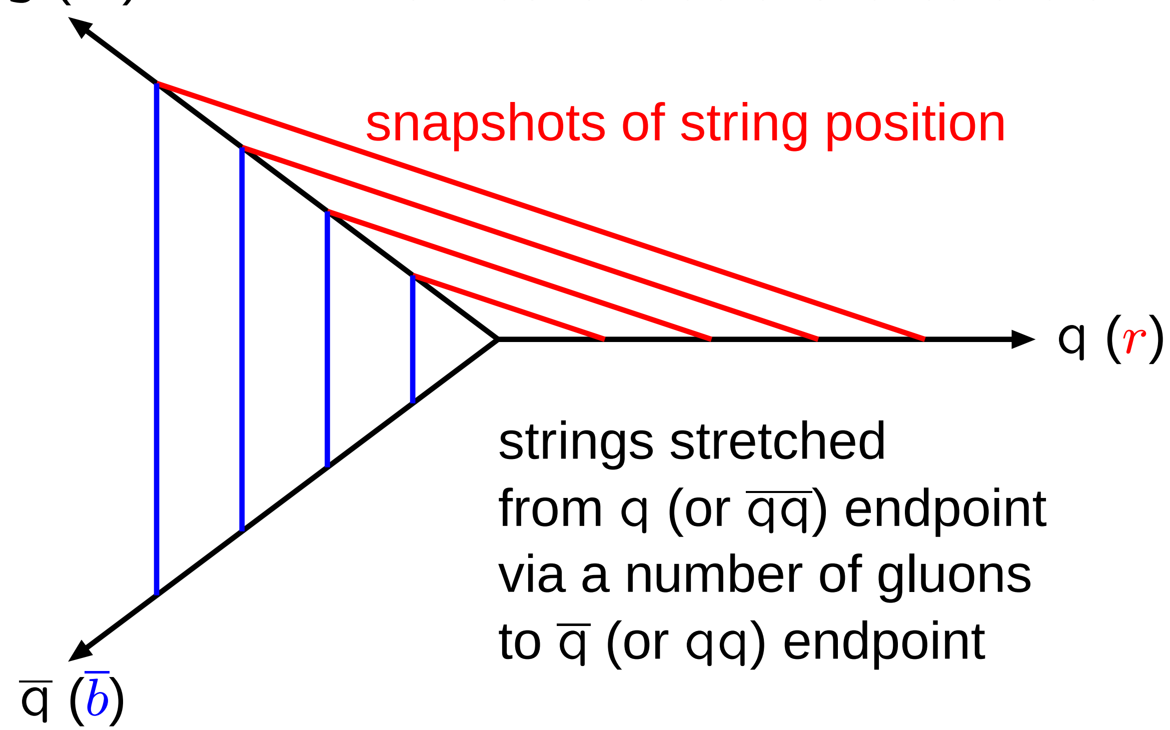
Scaling in lightcone $p_\pm = E \pm p_z$ (for $q\overline{q}$ system along z axis) implies flat central rapidity plateau + some endpoint effects:



$\langle n_{\text{ch}} \rangle \approx c_0 + c_1 \ln E_{\text{cm}}$, $\sim$ Poissonian multiplicity distribution

The Lund gluon picture

The most characteristic feature of the Lund model



strings stretched
from q (or $\overline{\text{qq}}$) endpoint
via a number of gluons
to $\overline{\text{q}}$ (or qq) endpoint

Gluon = kink on string, carrying energy and momentum

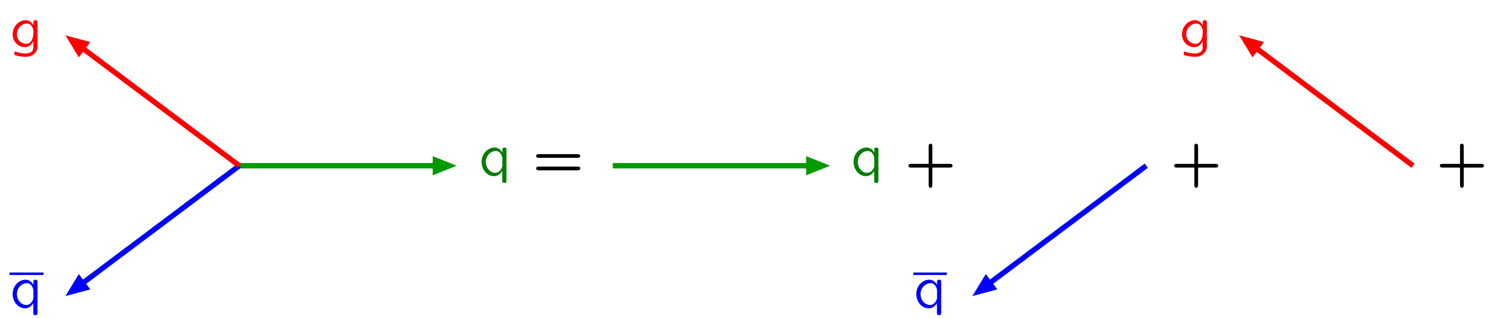
Force ratio gluon/ quark = 2, cf. QCD $N_C/C_F = 9/4$, $\to$ 2 for $N_C \to \infty$

No new parameters introduced for gluon jets!, so:

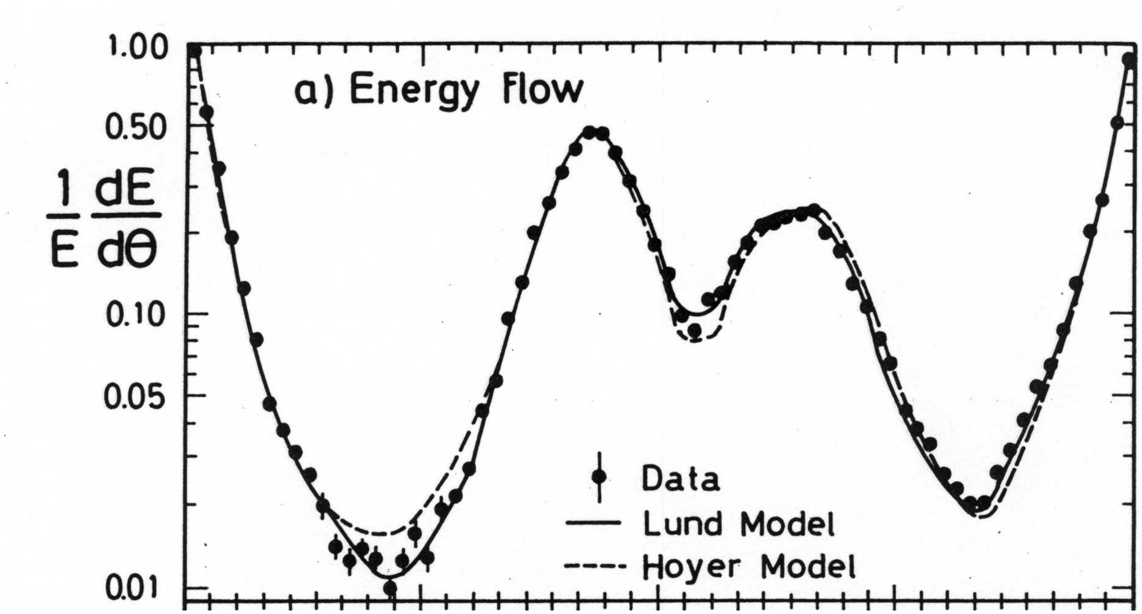
- Few parameters to describe energy-momentum structure!
- Many parameters to describe flavour composition!

Independent fragmentation

Based on a similar iterative ansatz as string, but



minor corrections in middle



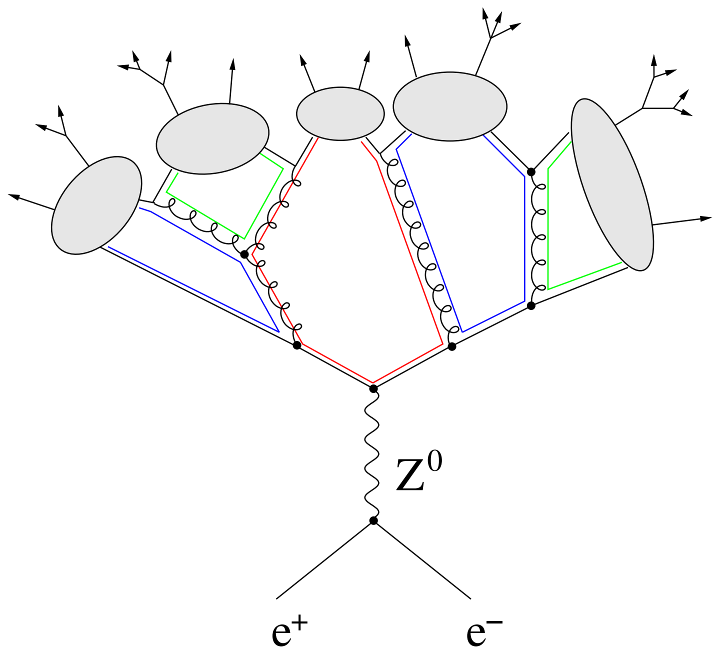
String effect (JADE, 1980) ≈ coherence in nonperturbative context

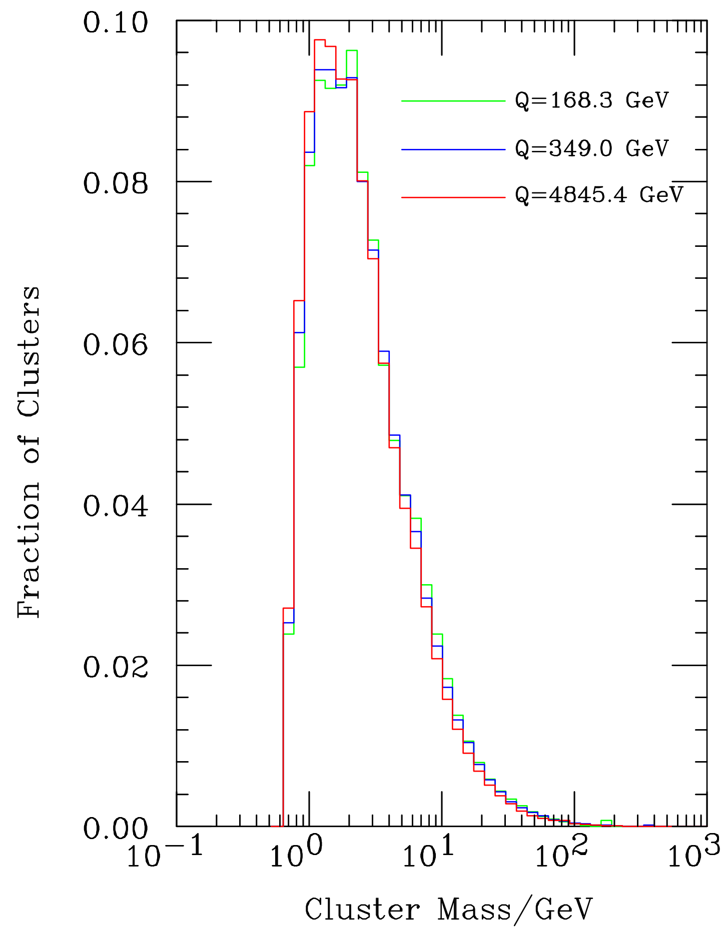
Further numerous and detailed tests at LEP favour string picture . . .

. . . but much is still uncertain when moving to hadron colliders.

The HERWIG Cluster Model

"Preconfinement":
colour flow is local
in coherent shower evolution





1) Introduce forced $g \rightarrow q\bar{q}$ branchings
2) Form colour singlet clusters
3) Clusters decay isotropically to 2 hadrons according to phase space weight $\sim (2s_1+1)(2s_2+1)(2p^*/m)$

simple and clean, but . . .

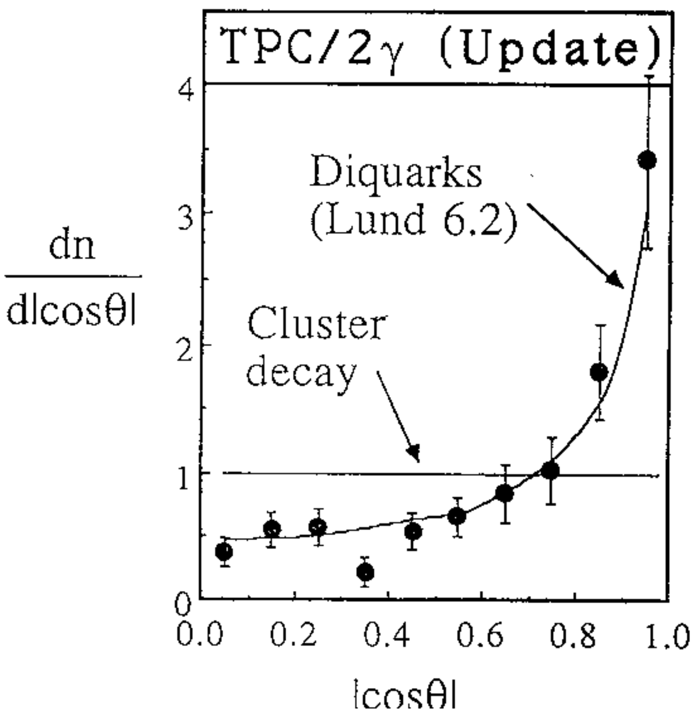
1) Tail to very large-mass clusters (e.g. if no emission in shower);
if large-mass cluster $\rightarrow$ 2 hadrons then
incorrect hadron momentum spectrum, crazy four-jet events
$\Longrightarrow$ split big cluster into 2 smaller along “string” direction;
daughter-mass spectrum $\Rightarrow$ iterate if required;
$\sim$ 15% of primary clusters are split, but give $\sim$ 50% of final hadrons

2) Isotropic baryon decay inside cluster
$\Longrightarrow$ splittings $g \rightarrow qq + \overline{qq}$

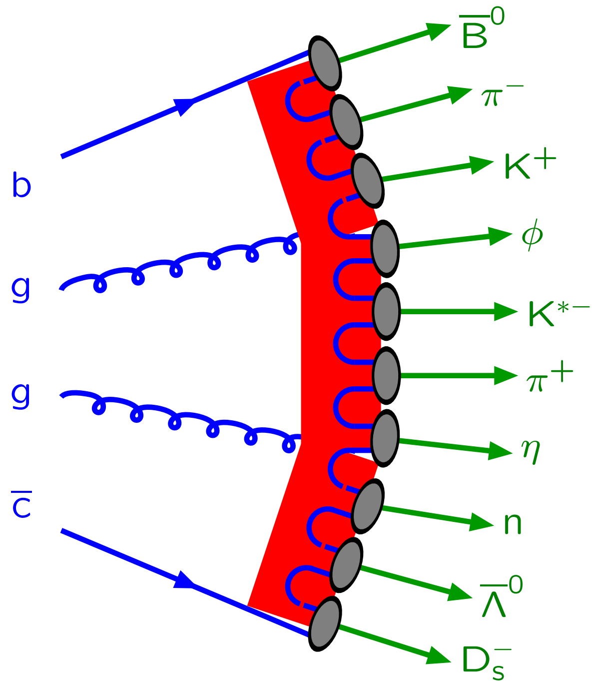
3) Too soft charm/bottom spectra
$\Longrightarrow$ anisotropic leading-cluster decay

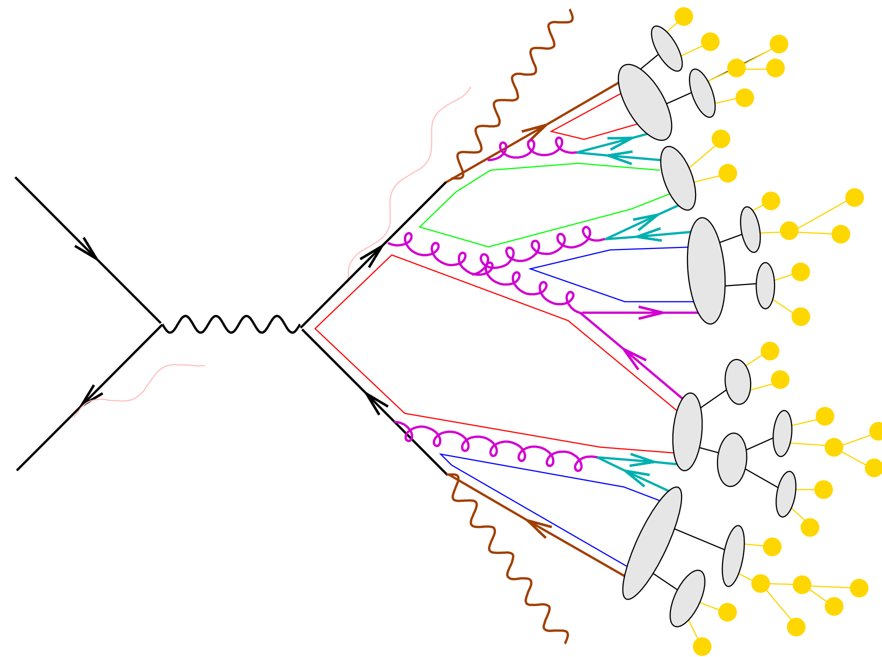
4) Charge correlations still problematic
$\Longrightarrow$ all clusters anisotropic (?)

5) Sensitivity to particle content
$\Longrightarrow$ only include complete multiplets



String vs. Cluster





program	PYTHIA	HERWIG
model	string	cluster
energy–momentum picture	powerful	simple
	predictive	unpredictive
parameters	few	many
flavour composition	messy	simple
	unpredictive	in-between
parameters	many	few

“There ain’t no such thing as a parameter-free *good* description”

Local Parton–Hadron Duality

Analytic approach:

Run shower down to to $Q \approx \Lambda_{\mathrm{QCD}}$

(or m_{hadron}, if larger)

"Hard Line": each parton $\equiv$ one hadron

"Soft Line": local hadron density

$\propto$ parton density

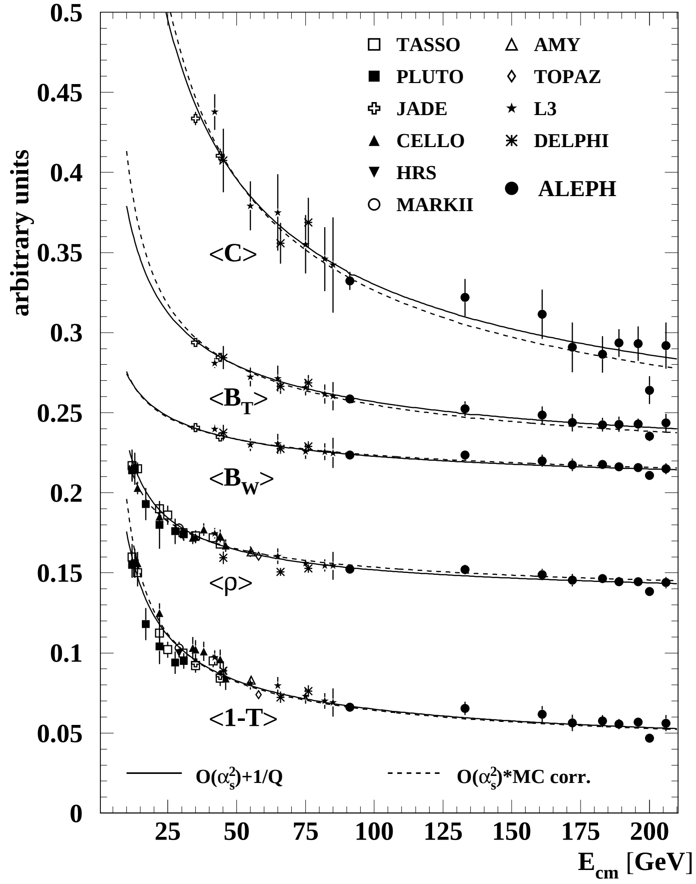
describes momentum spectra $\mathrm{d}n/\mathrm{d}x_p$

and semi-inclusive particle flow,

but fails for identified particles

+ "renormalons" (power corrections)

$$\langle 1 - T \rangle = a\, \alpha_{\mathrm{s}}(E_{\mathrm{cm}}) + b\, \alpha_{\mathrm{s}}^2(E_{\mathrm{cm}}) + c/E_{\mathrm{cm}}$$

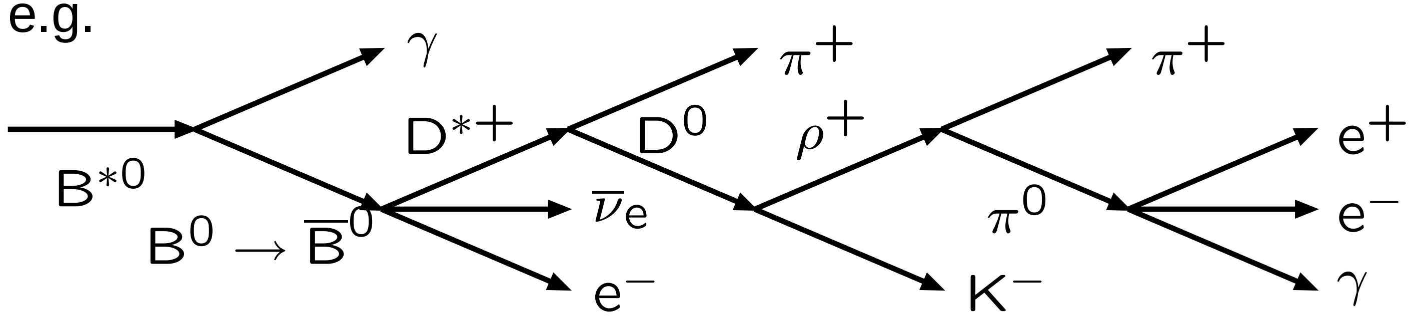


Not Monte Carlo, **not** for arbitrary quantities

Decays

Unspectacular/ungrateful but necessary:
this is where most of the final-state particles are produced!
Involves hundreds of particle kinds and thousands of decay modes.

e.g.



- $B^{*0} \to B^0\gamma$: electromagnetic decay
- $B^0 \to \overline{B}^0$ mixing (weak)
- $\overline{B}^0 \to D^{*+}\overline{\nu}_e e^-$: weak decay, displaced vertex, $|\mathcal{M}|^2 \propto (p_{\overline{B}}p_{\overline{\nu}})(p_e p_{D^*})$
- $D^{*+} \to D^0\pi^+$: strong decay
- $D^0 \to \rho^+ K^-$: weak decay, displaced vertex, ρ mass smeared
- $\rho^+ \to \pi^+\pi^0$: ρ polarized, $|\mathcal{M}|^2 \propto \cos^2\theta$ in ρ rest frame
- $\pi^0 \to e^+e^-\gamma$: Dalitz decay, $m(e^+e^-)$ peaked

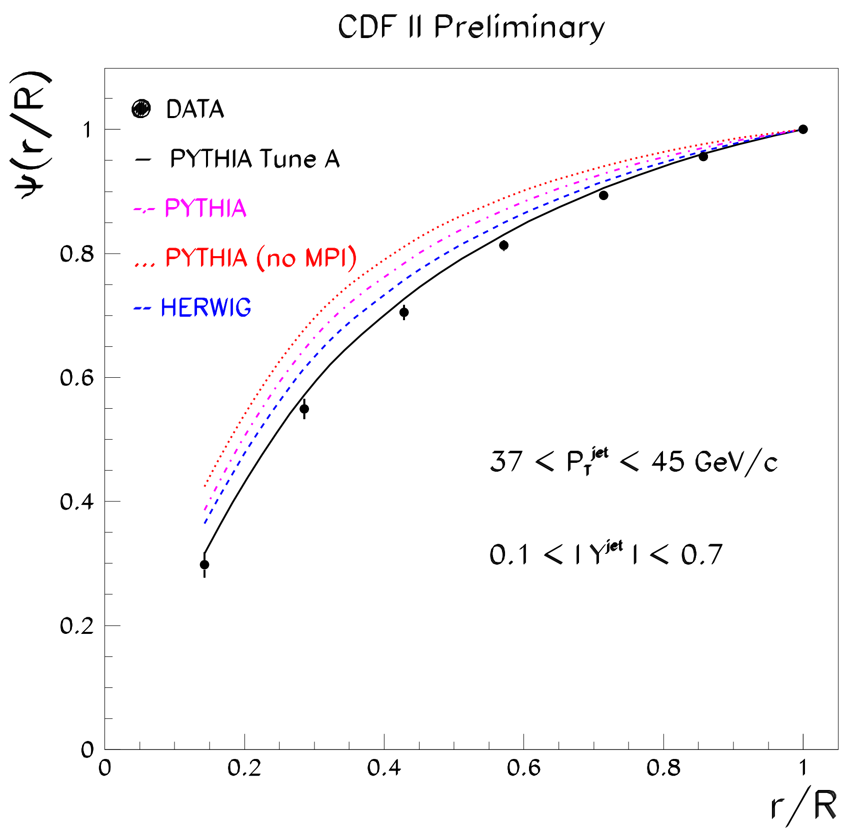
Dedicated programs, with special attention to polarization effects:
- EVTGEN: B decays
- TAUOLA: τ decays

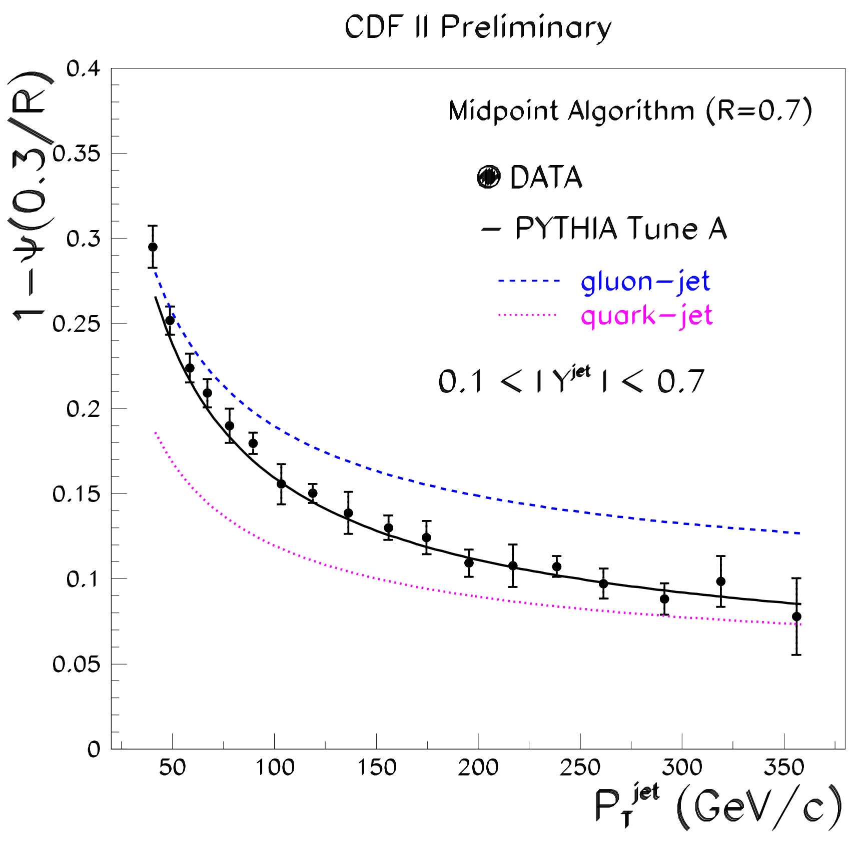
Jet Universality

Question: are jets the same in all processes?

Answer 1: no, at LEP mainly quarks jets, often b/c,
at LHC mainly gluons, if quarks then mainly u/d.

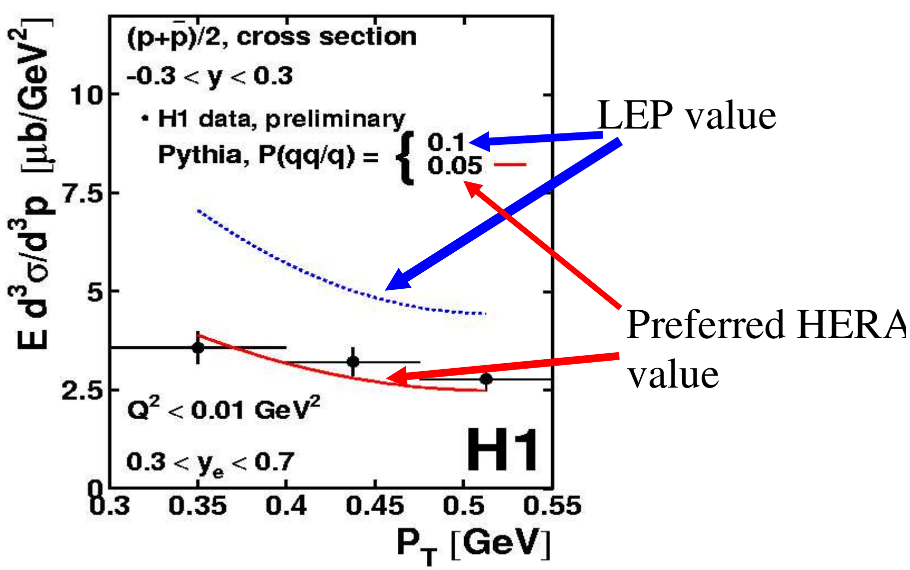
Answer 2: no, perturbative evolution gives calculable differences.

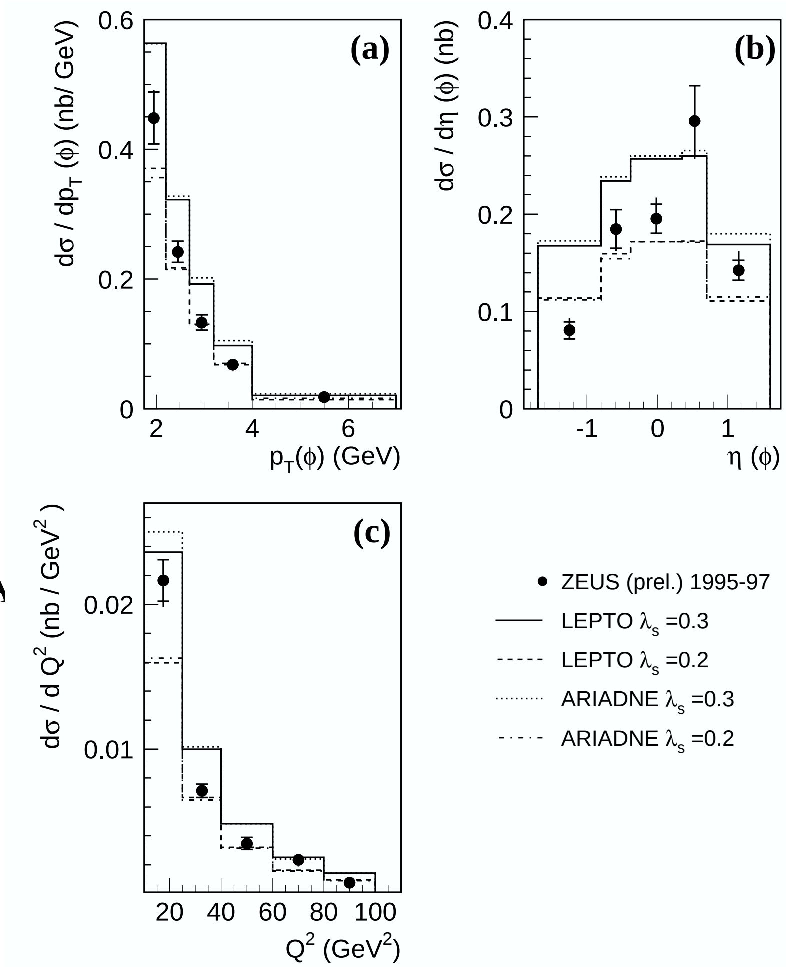




Answer 3: (string) hadronization mechanism assumed universal, but is not quite.

E $d^3\sigma/d^3p$: Dependence on proton P_T





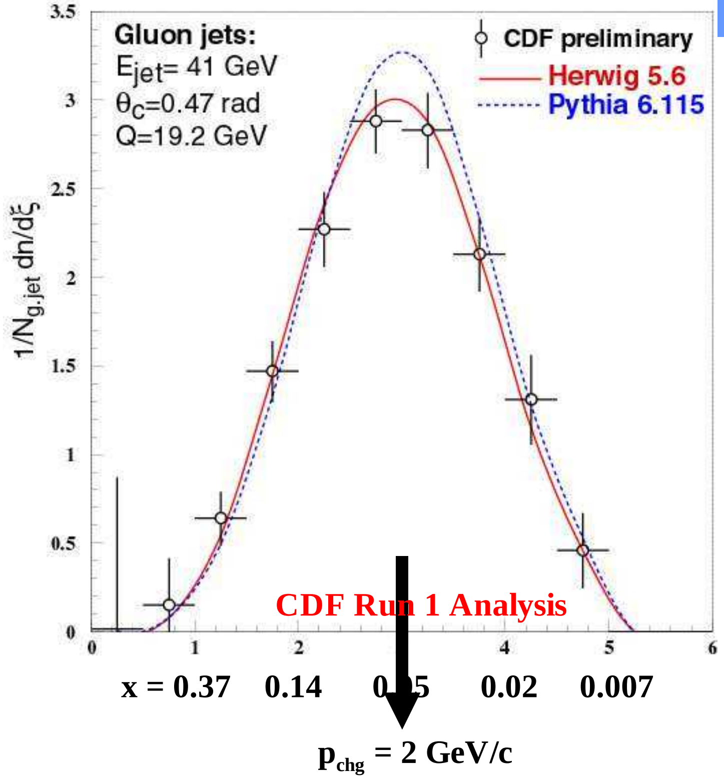
so discrepancies

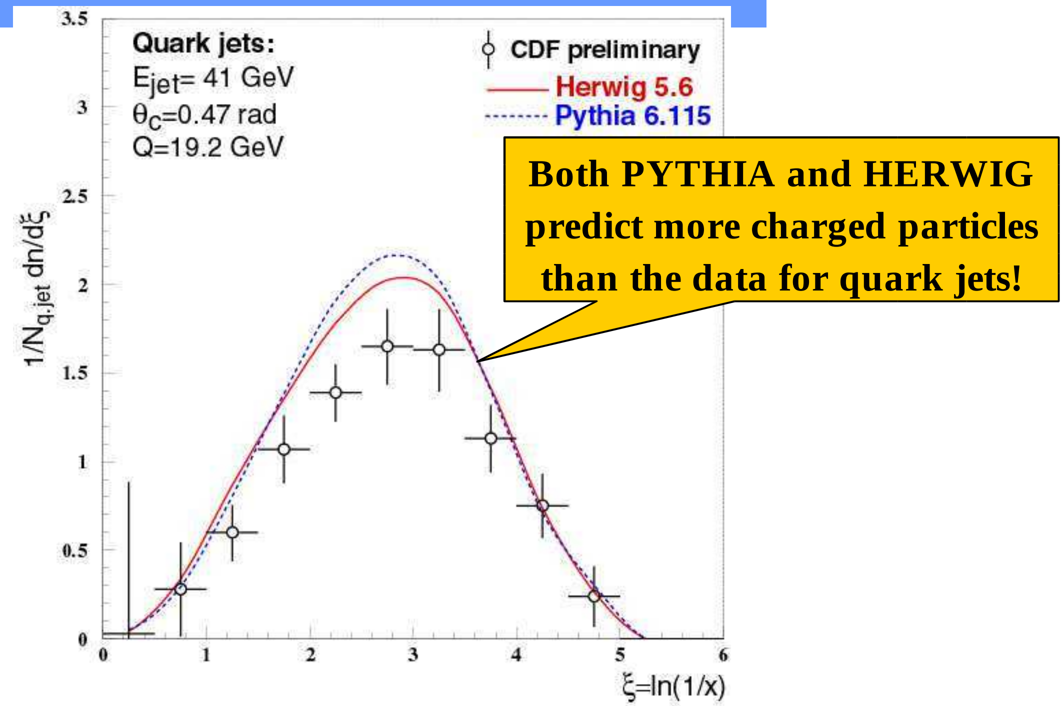
$$\mathcal{P}_{qq}/\mathcal{P}_q = 0.1 \text{ at LEP}, \quad = 0.05 \text{ at HERA}$$
$$\mathcal{P}_s/\mathcal{P}_u = 0.3 \text{ at LEP}, \quad = 0.2 \text{ at HERA}$$

Reasons? HERA dominated by “beam jets”, so

- Less perturbative evolution $\Rightarrow$ strings less “wrinkled”?
- Many overlapping strings $\Rightarrow$ collective phenomena?

Distribution of Particles in Quark and Gluon Jets

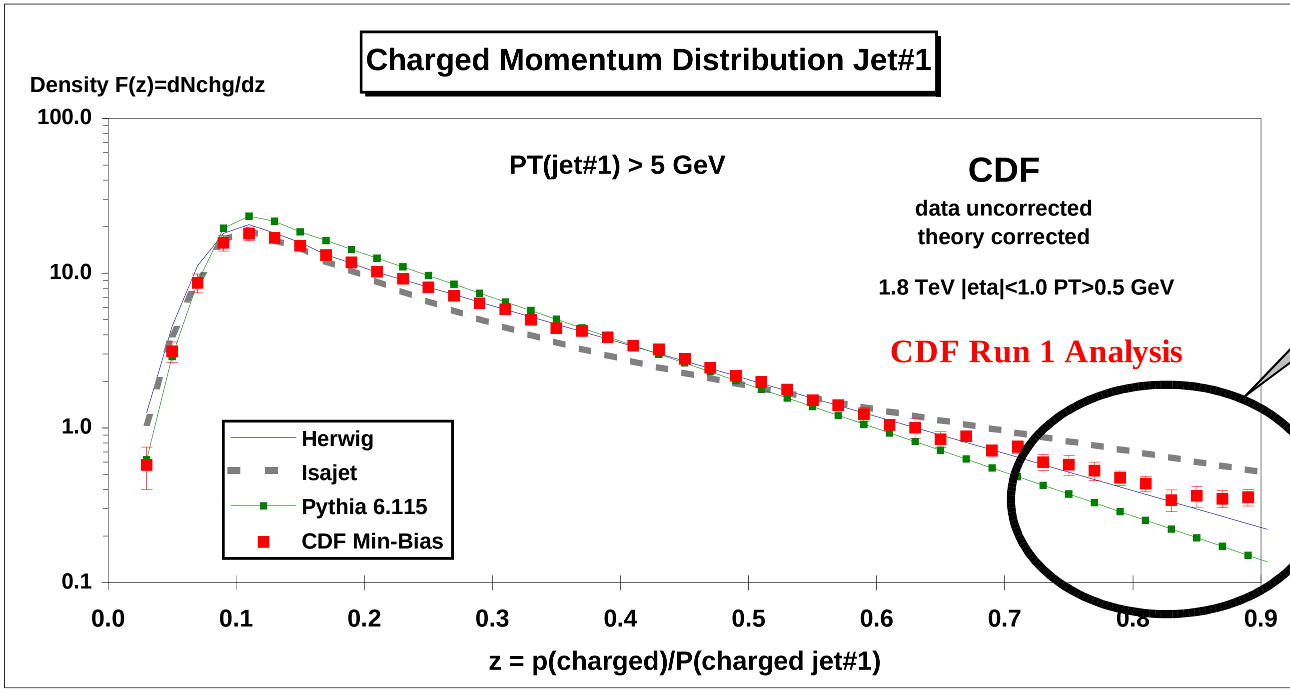




Momentum distribution of charged particles in gluon jets. HERWIG 5.6 predictions are in a good agreement with CDF data. PYTHIA 6.115 produces slightly more particles in the region around the peak of distribution.

Momentum distribution of charged particles in quark jets. Both HERWIG and PYTHIA produce more particles in the central region of distribution.

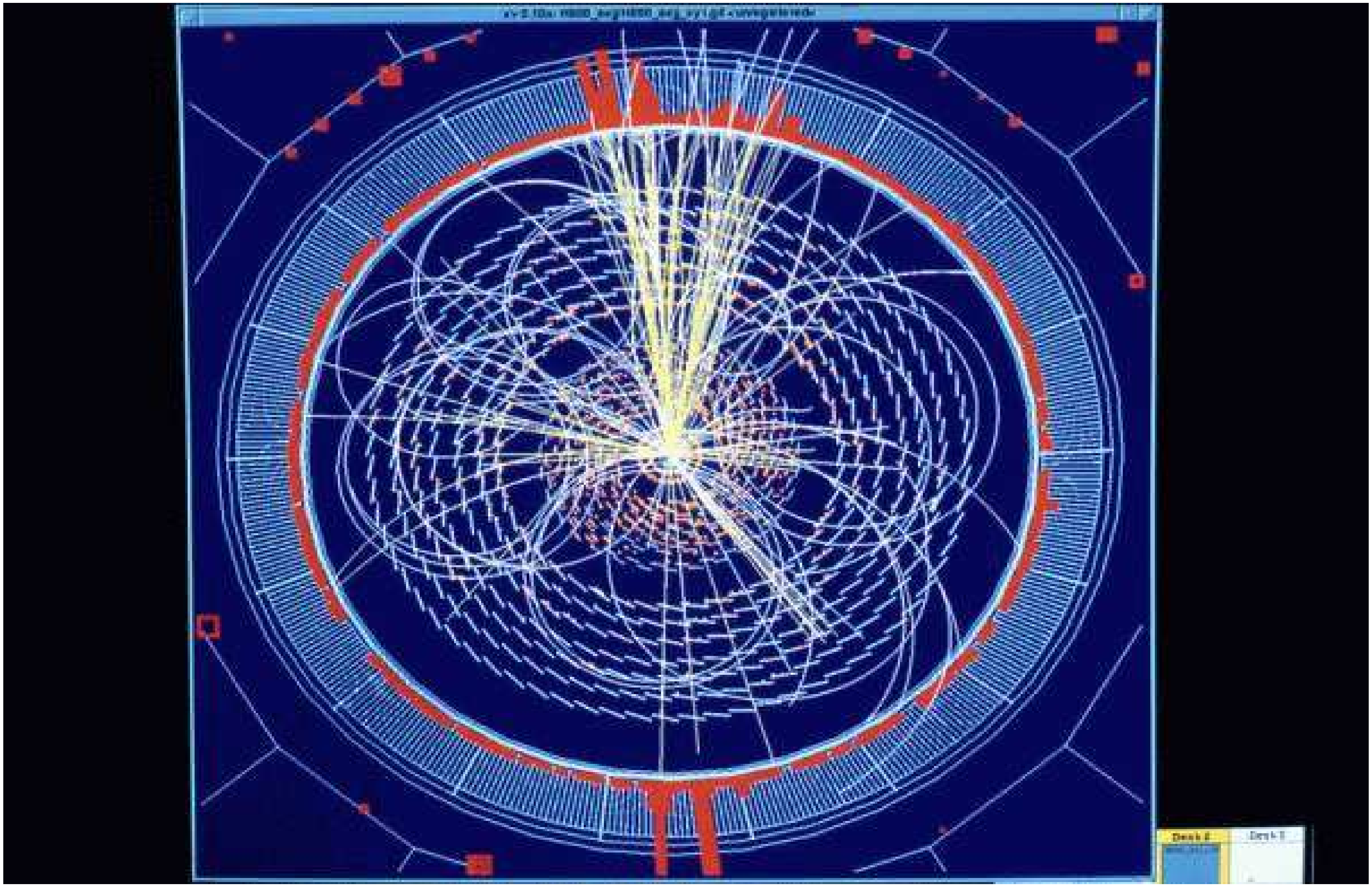
Run 1 Fragmentation Function



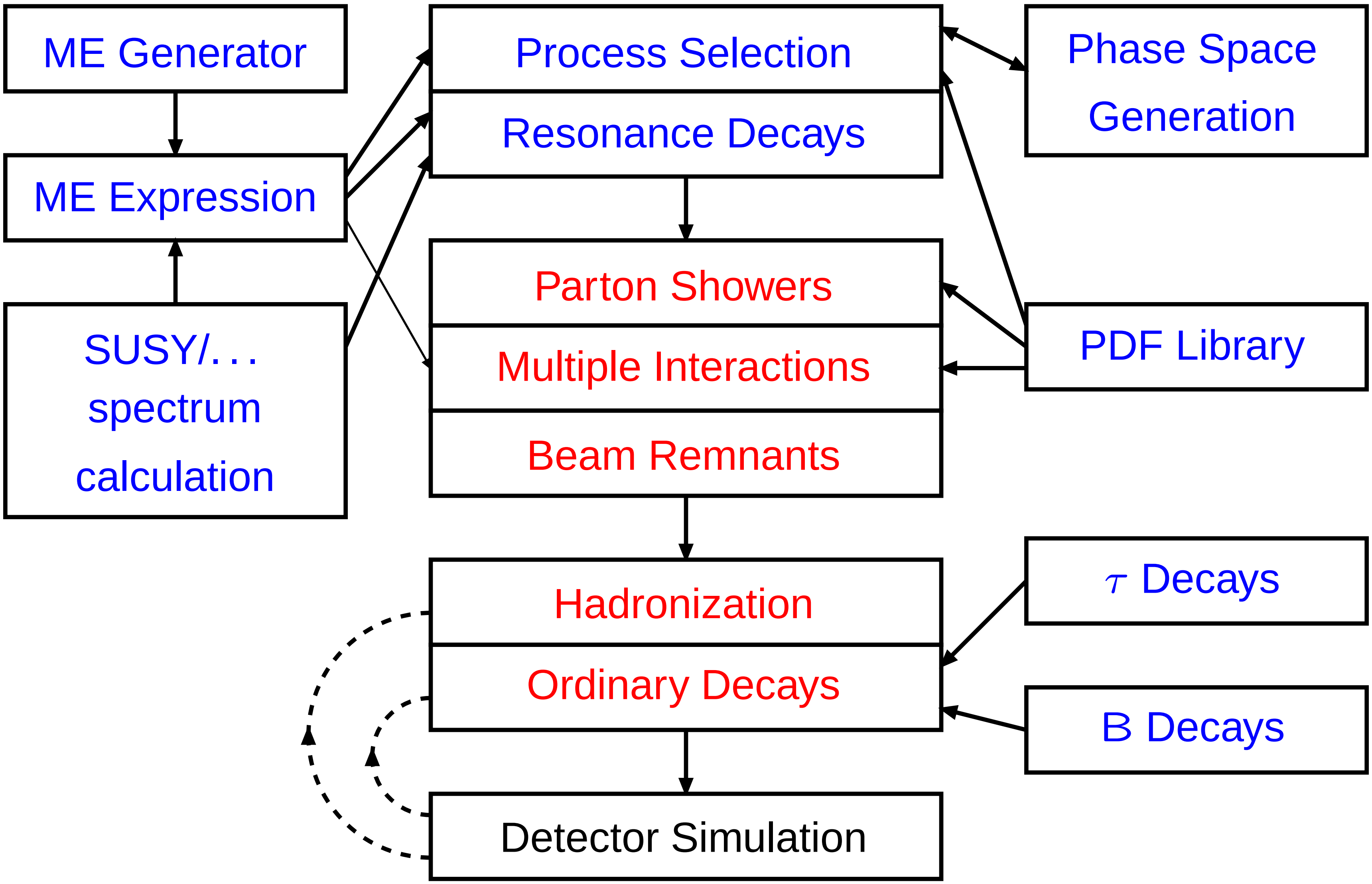
PYTHIA does not agree at high z!

CDF Run 1 data from on the momentum distribution of charged particles (p_T > 0.5 GeV and $|\eta|$ < 1) within chgjet#1 (*leading charged jet*) for P_T(chgjet#1) > 5 GeV compared with the QCD "hard scattering" Monte-Carlo predictions of HERWIG, ISAJET, and PYTHIA. The points are the charged number density, $F(z) = dN_{chg}/dz$, where z = p_{chg}/P(chgjet#1) is the ratio of the charged particle momentum to the charged momentum of chgjet#1.

Event Generator Developments



The Bigger Picture



need standardized interfaces (LHA/LHEF, LHAPDF, SUSY LHA, HepMC, . . .)

On To C++

Currently HERWIG and PYTHIA are successfully being used,
also in new LHC environments, using C++ wrappers

Q: Why rewrite?
A1: Need to clean up!
A2: Fortran 77 is limiting

Q: Why C++?
A1: All the reasons for ROOT, Geant4, . . .
(“a better language”, industrial standard, . . .)
A2: Young experimentalists will expect C++
(educational and professional continuity)
A3: Only game in town! Fortran 90

So far mixed experience:

- Conversion effort: everything takes longer and costs more
(as for LHC machine, detectors and software)
- The physics hurdle is as steep as the C++ learning curve

C++ Players

PYTHIA 7 project $\Longrightarrow$ **ThePEG**
Toolkit for High Energy Physics Event Generation
(L. Lönnblad; S. Gieseke, A. Ribon, P. Richardson)

ARIADNE/LDC: to do ISR/FSR showers, multiple interactions
(L. Lönnblad; N. Lavesson)

HERWIG++: complete reimplementation
November 2007: first full-fledged version (2.1; now 2.2.0)
(P. Richardson; M. Bähr, S. Gieseke, M. Gigg, D. Grellscheid,
K. Hamilton, O. Latunde-Dada, S. Plätzer, M.H. Seymour,
A. Sherstnev, B.R. Webber, arXiv:0803:0883)

SHERPA: new program, written from scratch
operational since $\sim$2006 (now 1.1.0)
(F. Krauss; T. Gleisberg, S. Hoeche, R. Matyszkiewicz,
S. Schumann, F. Siegert, J. Winter)

PYTHIA 8: complete reimplementation
October 2007: first full-fledged version (8.100; now 8.108)
(T. Sjöstrand, S. Mrenna, P. Skands, arXiv:0710.3820 $\rightarrow$ CPC)

MCnet

• EU Marie Curie training network •

• Approved for four years starting 1 Jan 2007 •

• Involves THEPEG/ARIADNE, HERWIG, SHERPA and PYTHIA •
(CERN, Durham, Lund, Karlsruhe, UC London; leader: Mike Seymour)

• 4 postdocs & 2 graduate students: generator development and tuning •

• short-term studentships: 33 @ 4 months each •
(applications processed every three months; next deadline 30 June)
theory or experiment

• Annual Monte Carlo school: •
Durham, UK, 18 – 20 April 2007
CTEQ – MCnet, Debrecen, Hungary, 8 – 16 August 2008
Lund 2009

• Support for other such schools: •
Physics at the Terascale Monte Carlo School, DESY, 21 – 24 April 2008

• non-EU participation up to 30% •

Key differences between PYTHIA 6.4 and 8.1

Old features definitely removed include, among others:

- independent fragmentation
- mass-ordered showers

Features omitted so far include, among others:

- ep, γp and $\gamma\gamma$ beam configurations
- several processes, especially SUSY & Technicolor

New features, not found in 6.4:

- interleaved $p_{\perp}$-ordered MI + ISR + FSR evolution
- richer mix of underlying-event processes (γ, J/ψ, DY, . . .)
- possibility for two selected hard interactions in same event
- possibility to use one PDF set for hard process and another for rest
- elastic scattering with Coulomb term (optional)
- updated decay data

Preliminary plans for the future:

- rescattering in multiple interactions
- NLO and CKKW-L matching

Trying Out PYTHIA 8.1

For subversion `xx` (currently `08`)

- Download `pythia81xx.tgz` from
  `http://home.thep.lu.se/~torbjorn/Pythia.html`
- `tar xvfz pythia81xx.tgz` to unzip and expand
- `cd pythia81xx` to move to new directory
- `./configure ...` needed for external libraries + debug/shared
  (see `README`, libraries: HepMC, LHAPDF, PYTHIA 6)
- `make` will compile in ∼ 3 minutes
  (for archive library, same amount extra for shared)
- The `htmldoc/pythia8100.pdf` file contains A Brief Introduction
- Open `htmldoc/Welcome.html` in a web browser for the full manual
- Install the `phpdoc/` directory on a webserver and open
  `phpdoc/Welcome.html` in a web browser for an interactive manual
- The `examples` subdirectory contains > 30 sample main programs:
  standalone, link to libraries, semi-internal processes, . . .
  (`make mainNN` and then `./mainNN.exe > outfile`)
- A `Worksheet` (on the web pages) contains step-by-step
  instructions and exercises how to write and run a main program

Outlook

Generators in state of continuous development:

$\star$ better & more user-friendly general-purpose
matrix element calculators+integrators $\star$

$\star$ new libraries of physics processes, also to NLO $\star$

$\star$ more precise parton showers $\star$

$\star$ better matching matrix elements $\Leftrightarrow$ showers $\star$

$\star$ improved models for underlying events / minimum bias $\star$

$\star$ upgrades of hadronization and decays $\star$

$\star$ moving to C++ $\star$

$\Rightarrow$ always better, but never enough

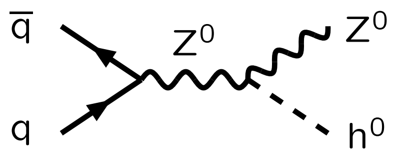
But what are the alternatives, when event structures are complicated
and analytical methods inadequate?

Event Physics Overview

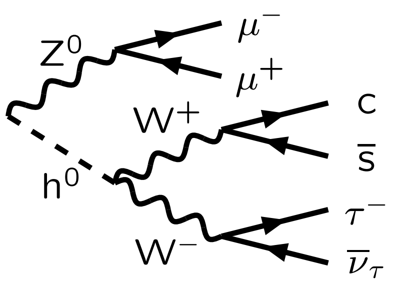
Repetition: from the "simple" to the "complex",
or from "calculable" at large virtualities to "modelled" at small

Matrix elements (ME):

1) Hard subprocess:
$|\mathcal{M}|^2$, Breit-Wigners,
parton densities.

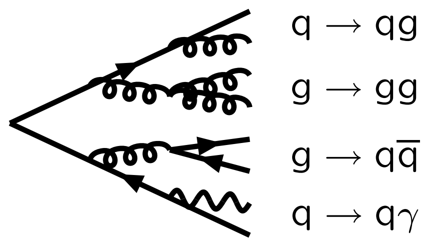


2) Resonance decays:
includes correlations.

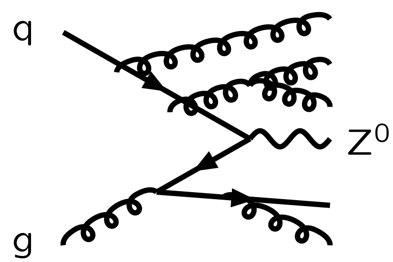


Parton Showers (PS):

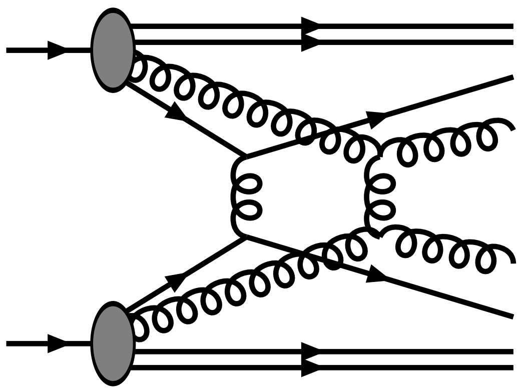
3) Final-state parton showers.



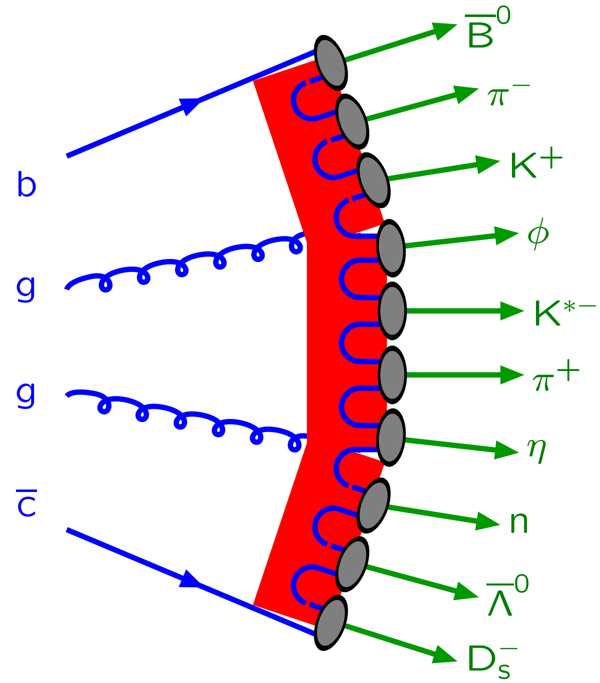
4) Initial-state parton showers.



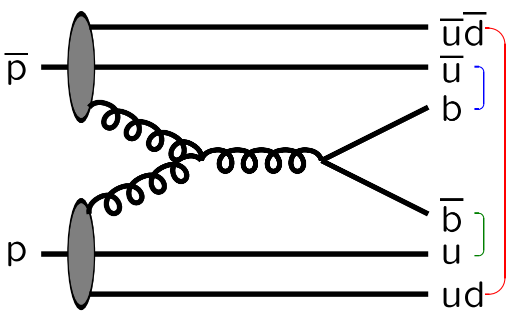
5) Multiple parton–parton interactions.



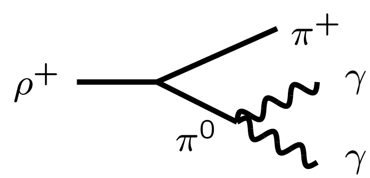
7) Hadronization



6) Beam remnants, with colour connections.



8) Ordinary decays: hadronic, τ, charm, . . .



5) + 6) = Underlying Event

Read More

These lectures (and more):
http://home.thep.lu.se/~torbjorn/ and click on "Talks"

Frank Krauss, CERN–Fermilab Hadron Collider lectures, June 2007:
http://indico.cern.ch/conferenceOtherViews.py?view=cdsagenda&confId=6238

Bryan Webber, MCnet school, Durham, April 2007:
http://www.hep.phy.cam.ac.uk/theory/webber/

Peter Richardson, CTEQ Summer School lectures, July 2006:
http://www.ippp.dur.ac.uk/~richardn/talks/

Steve Mrenna, CTEQ Summer School lectures, June 2004:
http://www.phys.psu.edu/~cteq/schools/summer04/mrenna/mrenna.pdf

Mike Seymour, Academic Training lectures July 2003:
http://seymour.home.cern.ch/seymour/slides/CERNlectures.html

The "Les Houches Guidebook to Monte Carlo Generators
for Hadron Collider Physics", hep-ph/0403045
http://arxiv.org/pdf/hep-ph/0403045
(update in preparation for Les Houches 2007 proceedings)