LUND UNIVERSITY

65th Scottish Universities Summer School
in Physics: LHC Physics
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Monte Carlo Tools

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1. (Monday) Introduction and Overview; Parton Showers
2. (yesterday) Matching Issues; Multiple Parton Interactions
3. **(today) Hadronization; LHC predictions; Generator News**

Hadronization/Fragmentation models

$\boxed{\text{Perturbative} \longrightarrow \text{nonperturbative} \Longrightarrow \text{not calculable from first principles!}}$

Model building = ideology + “cookbook”

Common approaches:

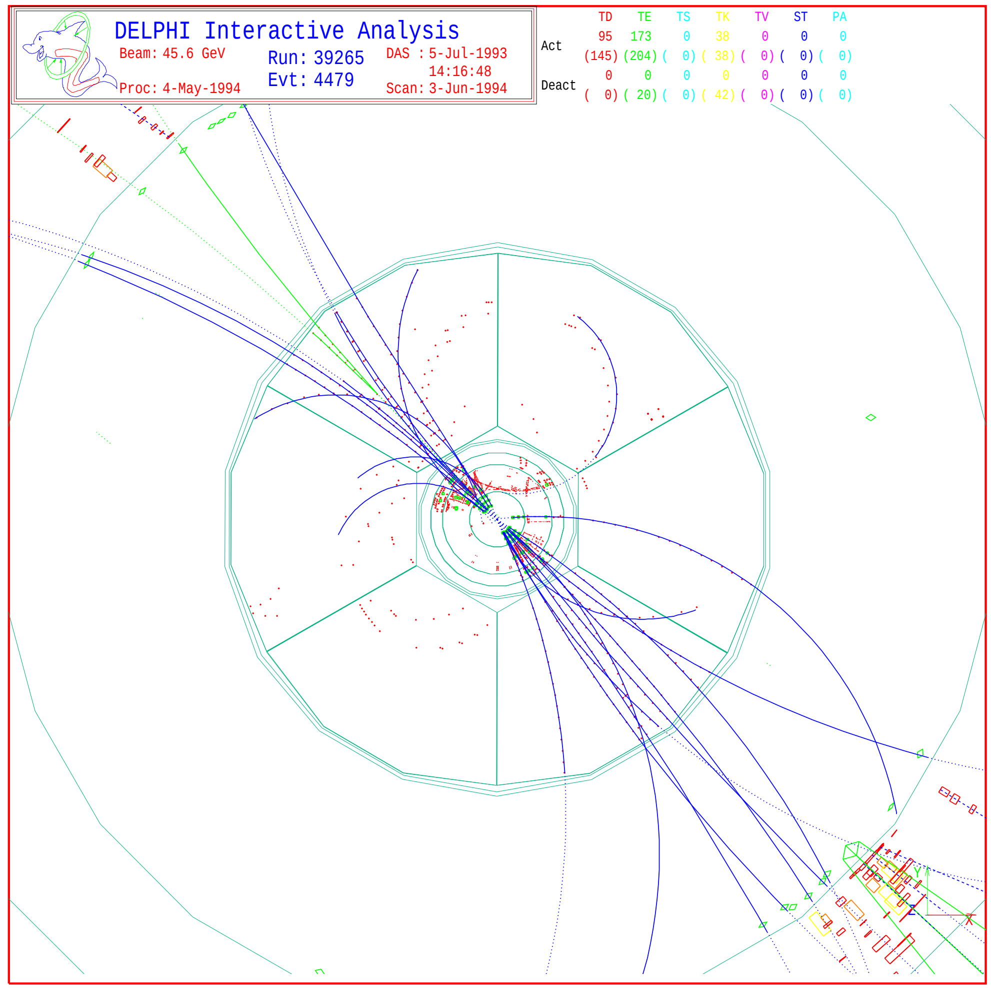
1) **String** Fragmentation
(most ideological)

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

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

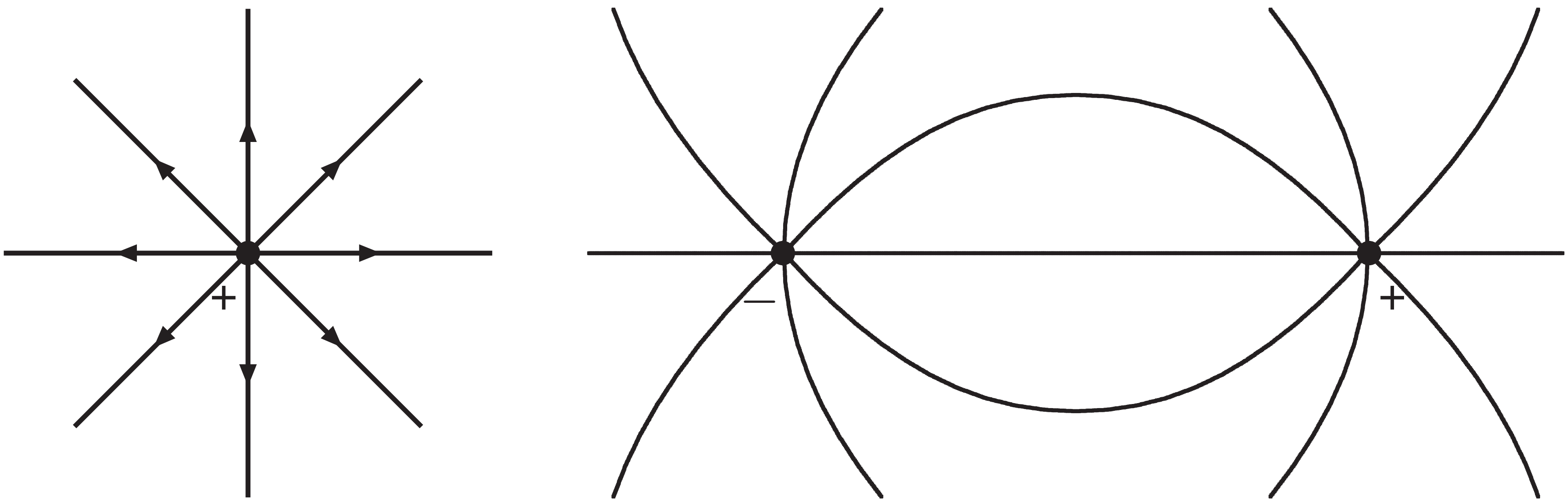
4) Local Parton–Hadron Duality
(limited applicability)

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

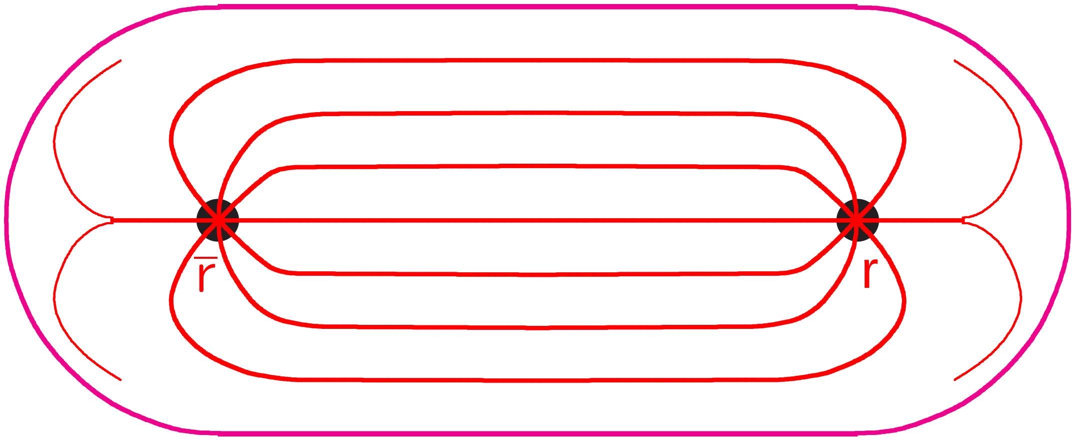


since photons cannot interact with each other.

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”.

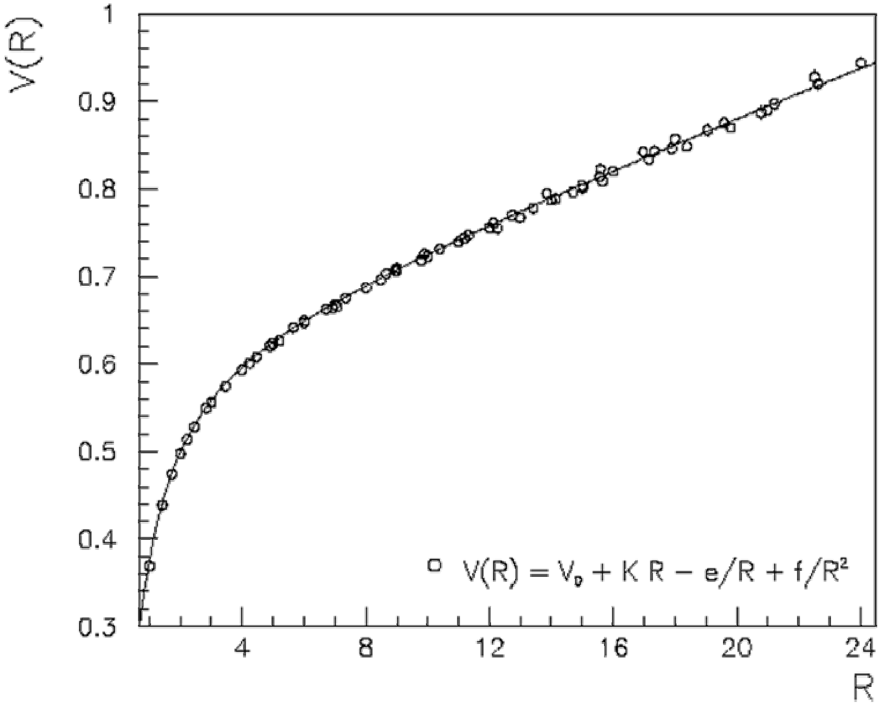
Analogy: vortex lines in type II superconductor)

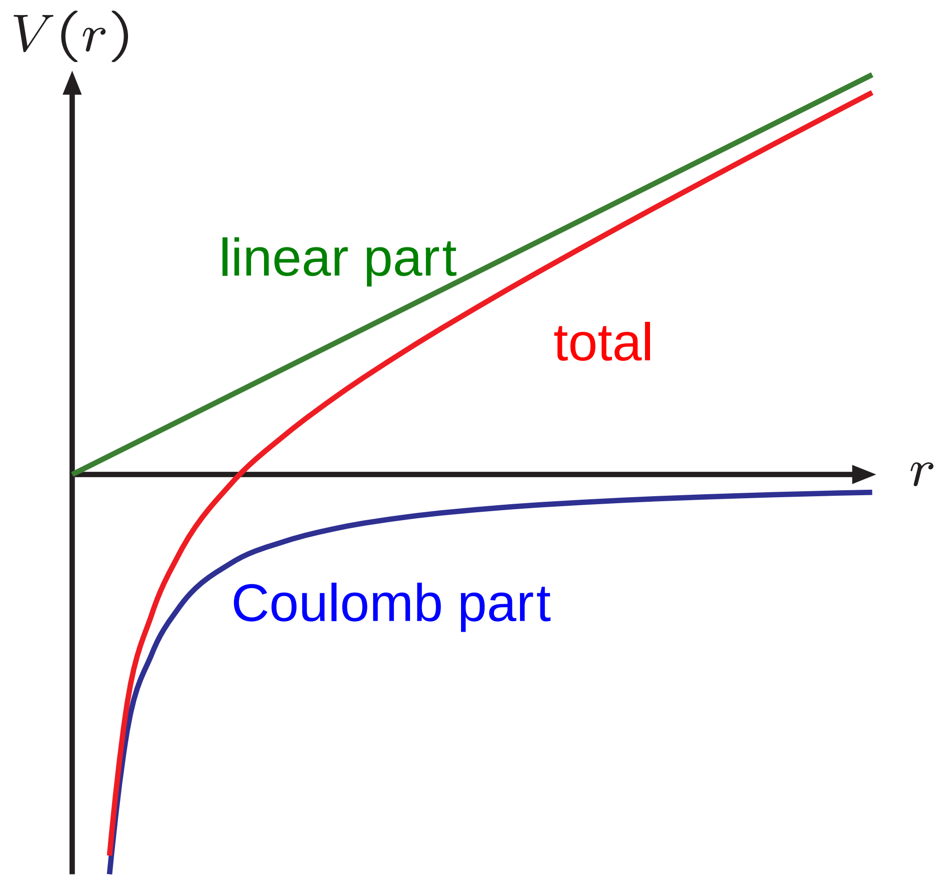
Gives linear confinement with string tension:

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

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

Linear confinement confirmed e.g. by quenched lattice QCD





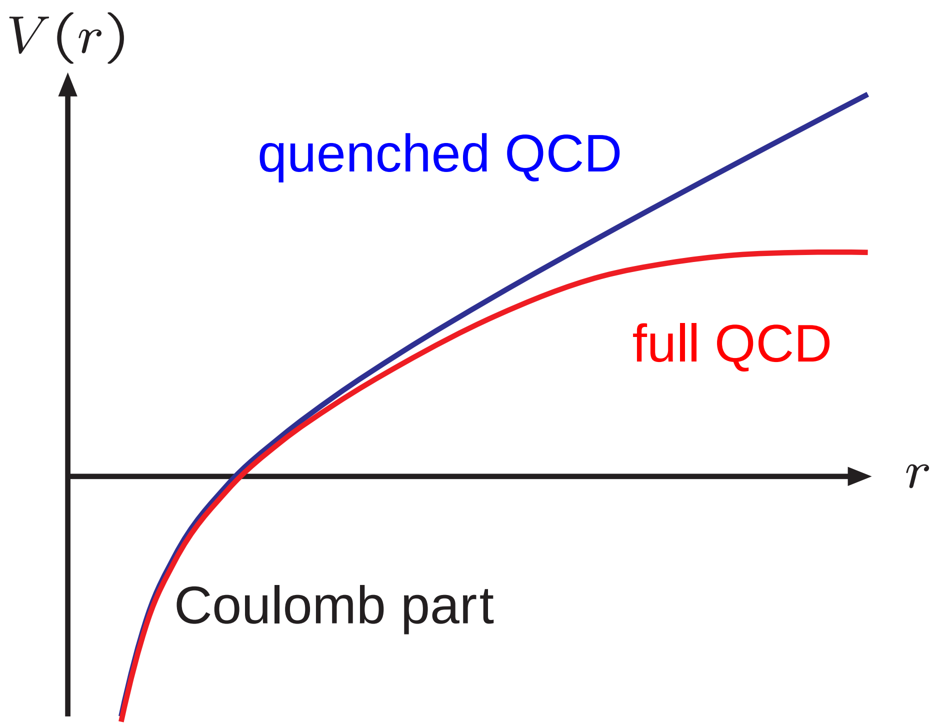
$$V(r) \approx -\frac{4}{3}\frac{\alpha_s}{r} + \kappa r \approx -\frac{0.13}{r} + r$$

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

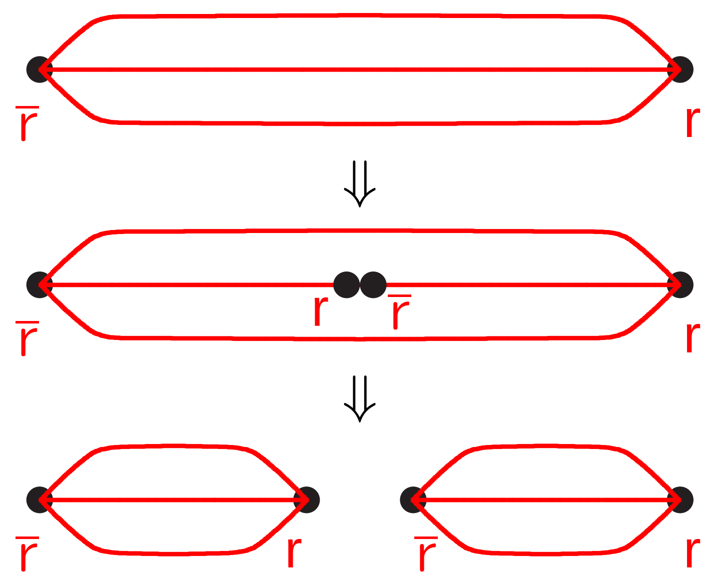
$V(0.4\,\mathrm{fm}) \approx 0$: Coulomb important for internal structure of hadrons, not for particle production (?)

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

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



simplified colour representation:

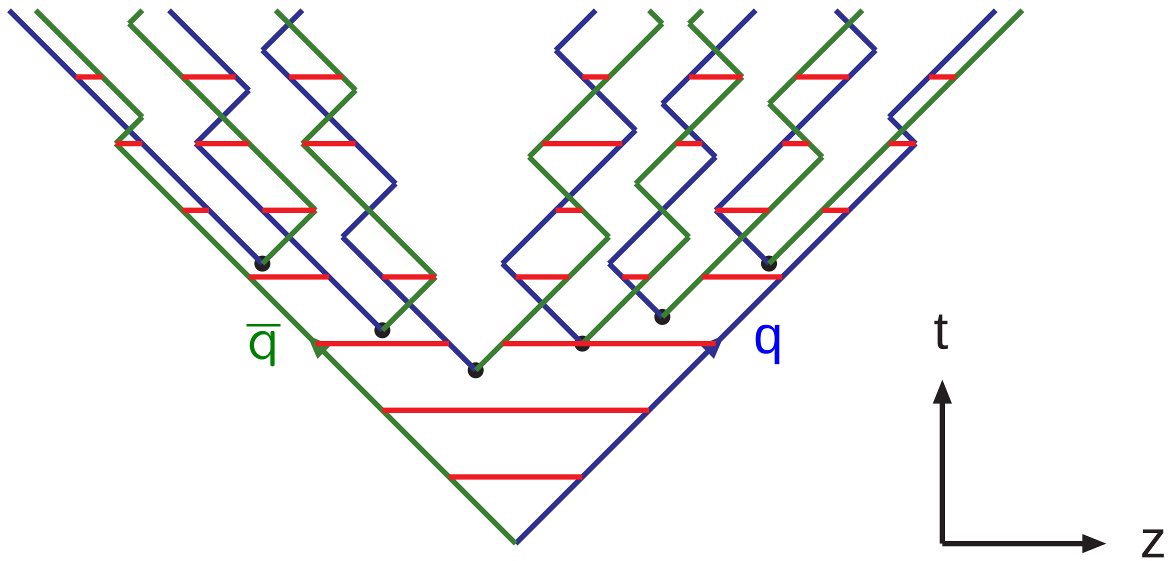


Repeat for large system $\Rightarrow$ *Lund model*

which neglects Coulomb part:

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

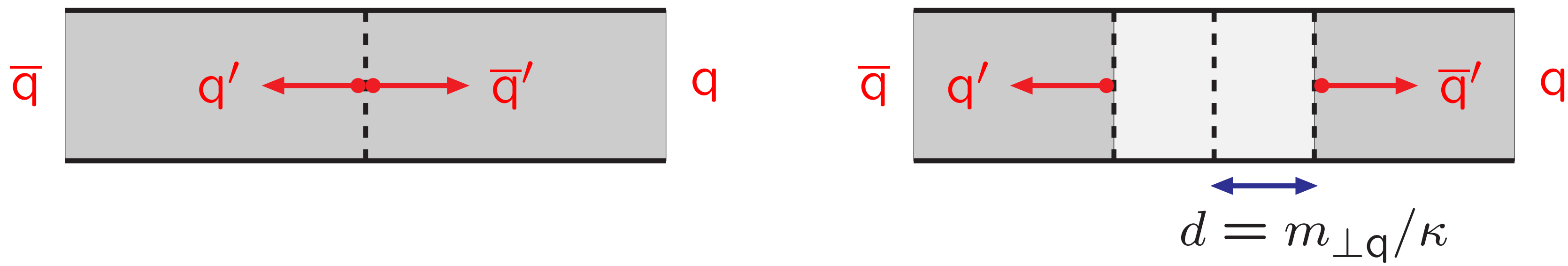
Motion of quarks and antiquarks in a q$\overline{\text{q}}$ system:



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

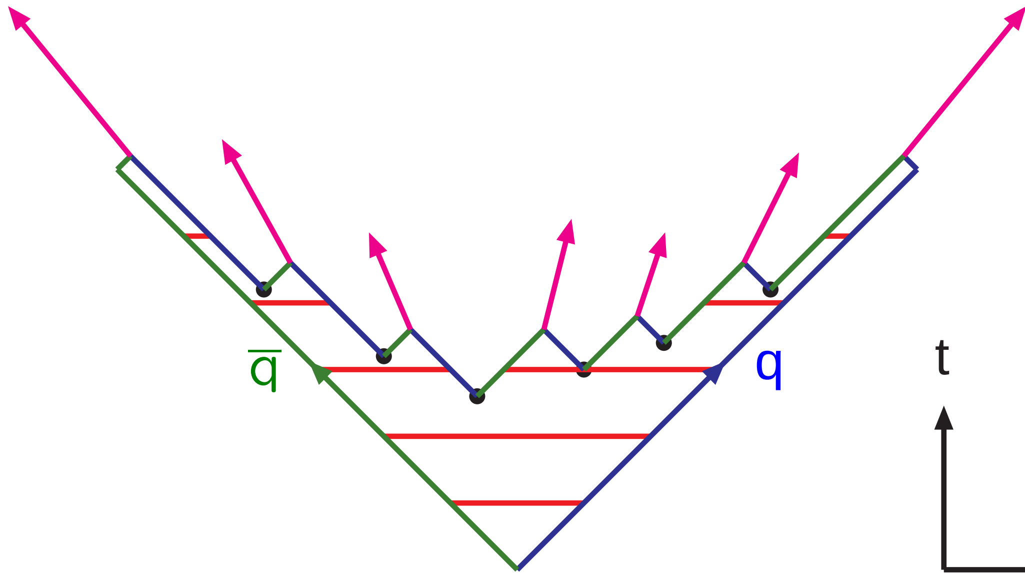
2) suppression of heavy quarks $u\overline{u} : d\overline{d} : s\overline{s} : c\overline{c} \approx 1 : 1 : 0.3 : 10^{-11}$

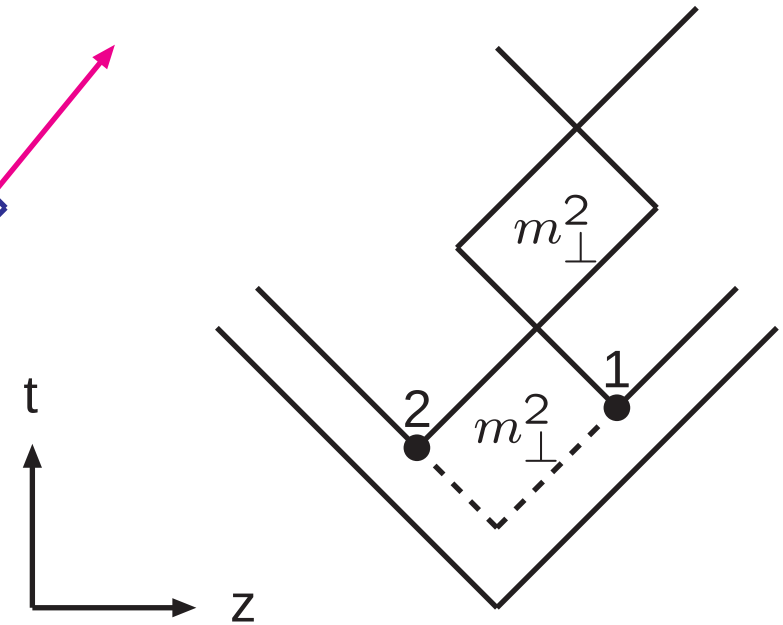
3) diquark $\sim$ antiquark $\Rightarrow$ simple model for baryon production

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

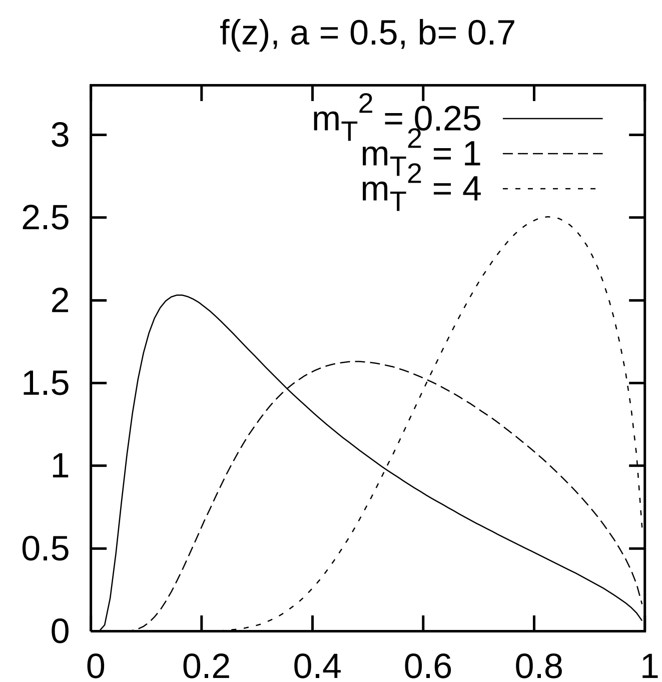
$\Rightarrow$ can proceed in arbitrary order

$\Rightarrow$ *left–right symmetry*

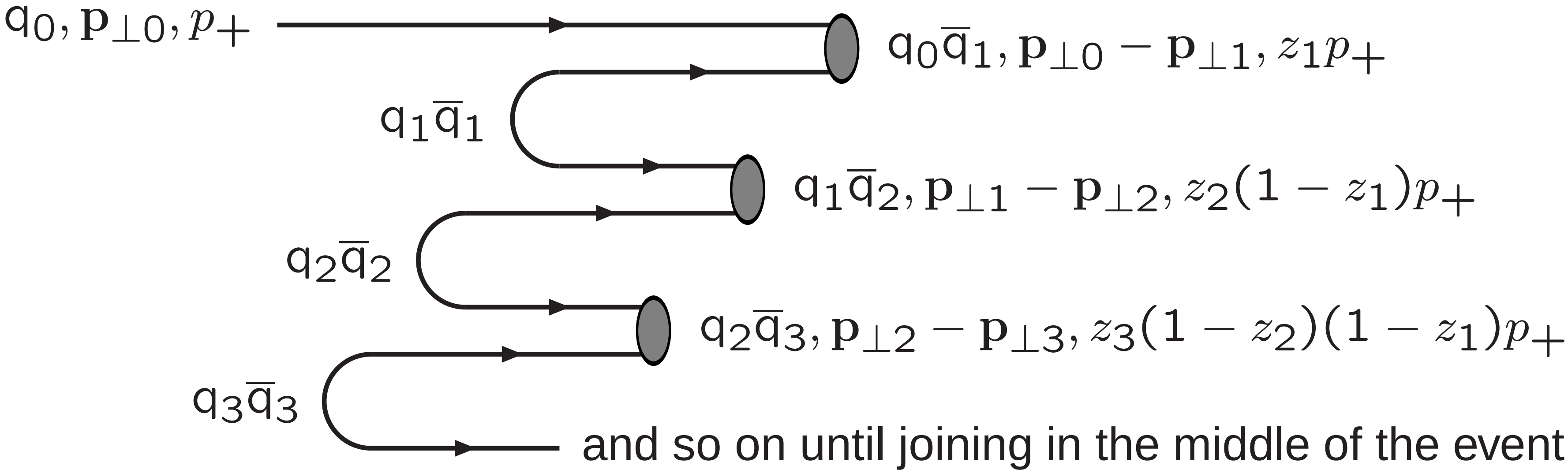
$$\begin{aligned} \mathcal{P}(1,2) &= \mathcal{P}(1) \times \mathcal{P}(1 \to 2) \\ &= \mathcal{P}(2) \times \mathcal{P}(2 \to 1) \end{aligned}$$

$\Rightarrow$ Lund symmetric fragmentation function

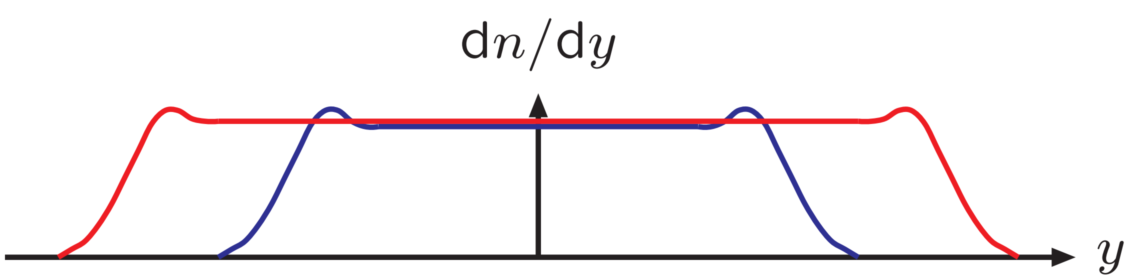
$f(z) \propto (1-z)^a \exp(-bm_\perp^2/z)/z$



The iterative ansatz

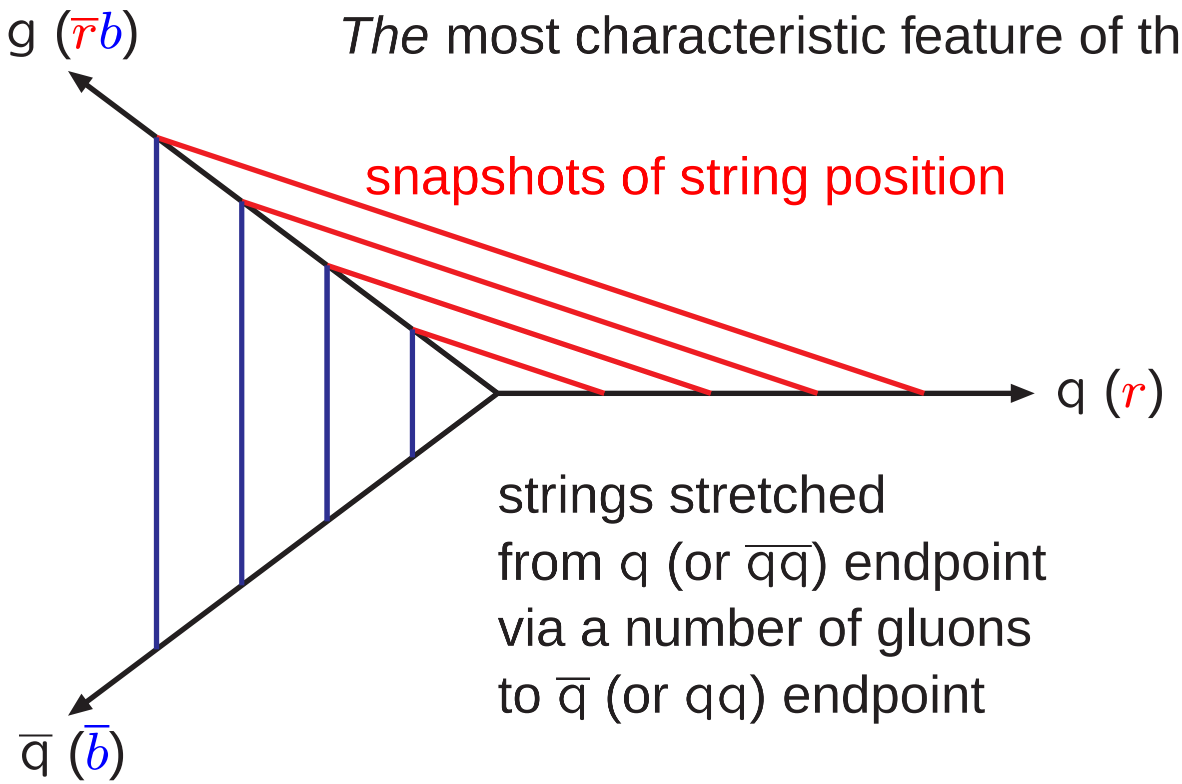


Scaling in lightcone $p_{\pm} = E \pm p_z$ (for $q\overline{q}$ system along z axis)
implies flat central rapidity plateau + some endpoint effects:



$\langle n_{\mathrm{ch}} \rangle \approx c_0 + c_1 \ln E_{\mathrm{cm}}$, $\sim$ 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

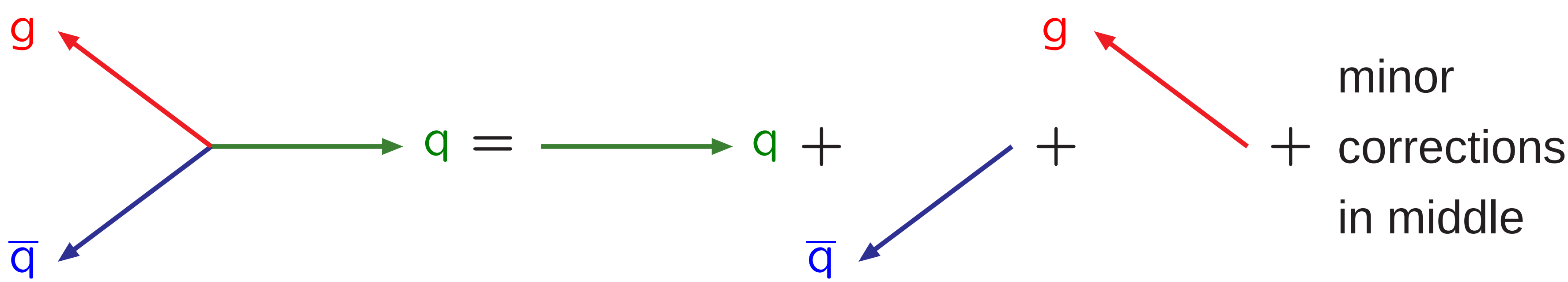
Force ratio gluon/ quark = 2, cf. QCD $N_C/C_F = 9/4$, $\rightarrow$ 2 for $N_C \rightarrow \infty$

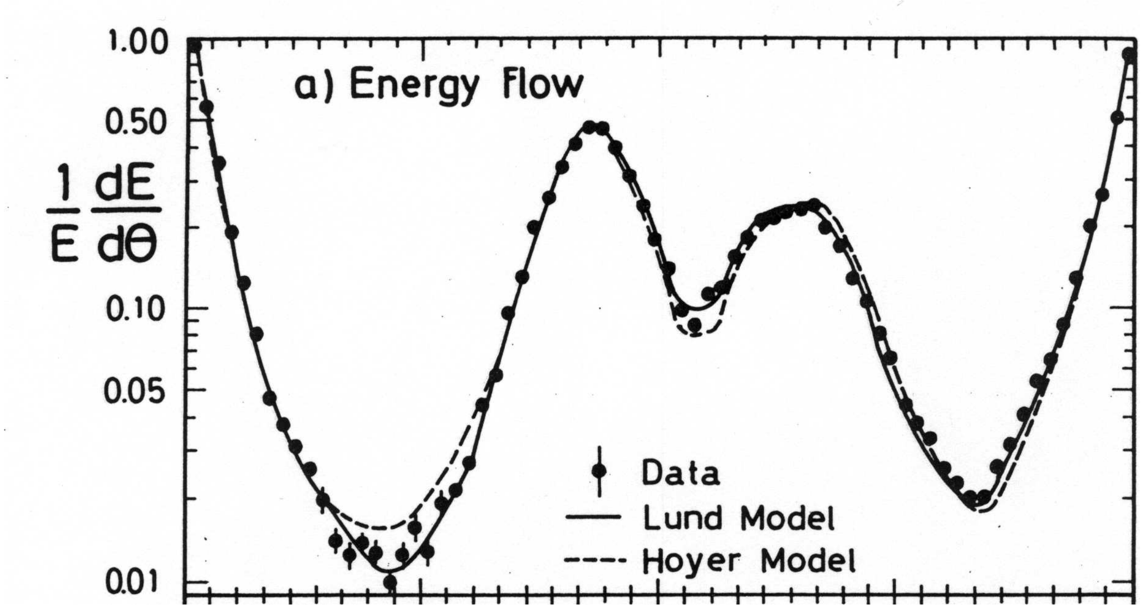
No new parameters introduced for gluon jets!, so:

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

Independent fragmentation

Based on a similar iterative ansatz as string, but





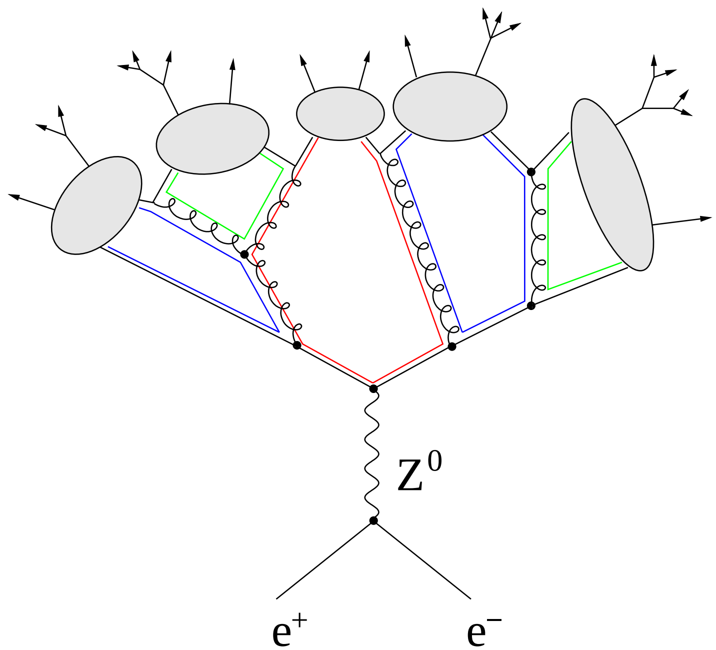
String effect (JADE, 1980) ≈ coherence in nonperturbative context

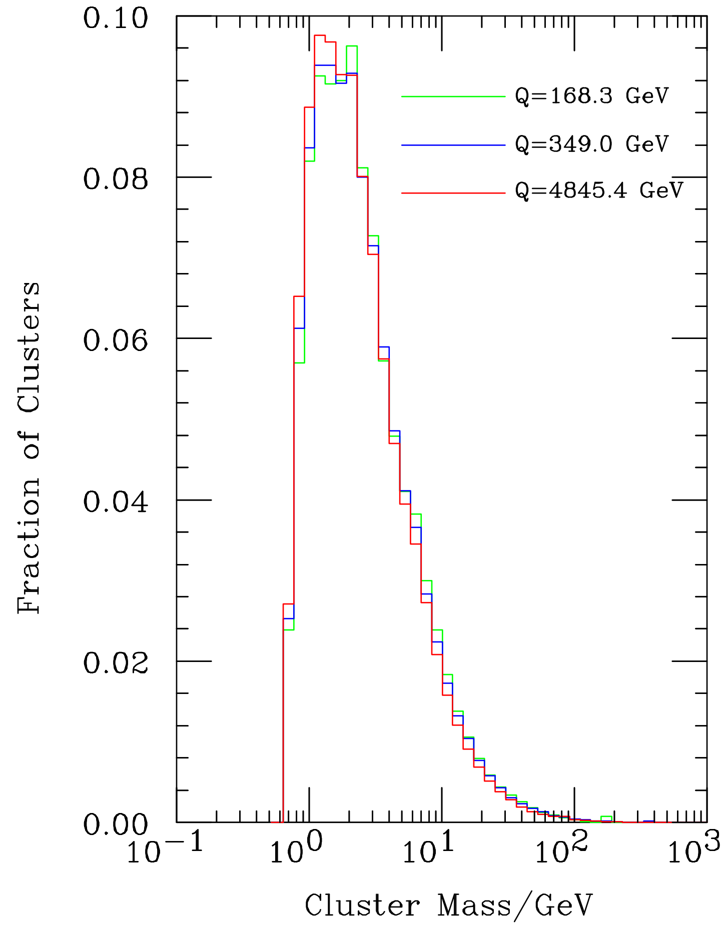
Further numerous and detailed tests at LEP favour string picture . . .

. . . 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 $g \to q\bar{q}$ 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 . . .

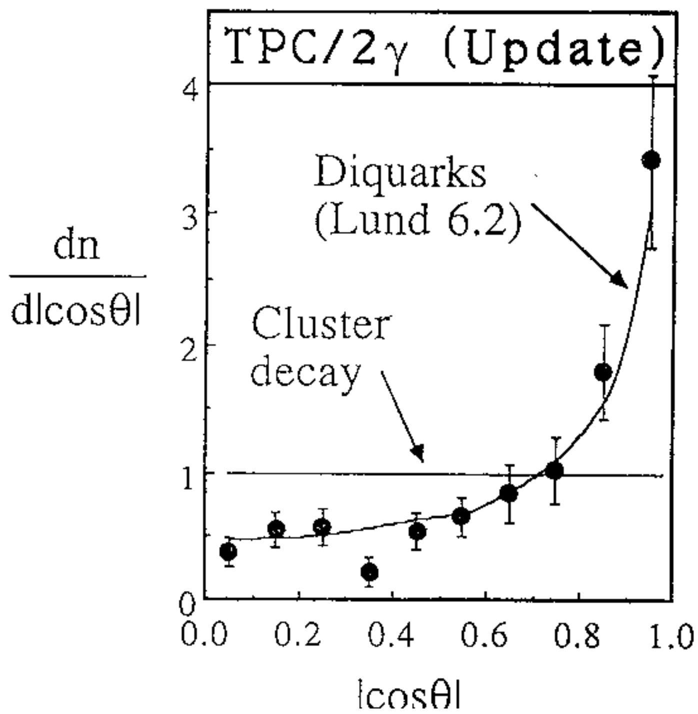
1) Tail to very large-mass clusters (e.g. if no emission in shower);
if large-mass cluster $\rightarrow$ 2 hadrons then
incorrect hadron momentum spectrum, crazy four-jet events
$\Longrightarrow$ split big cluster into 2 smaller along "string" direction;
daughter-mass spectrum $\Rightarrow$ iterate if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

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

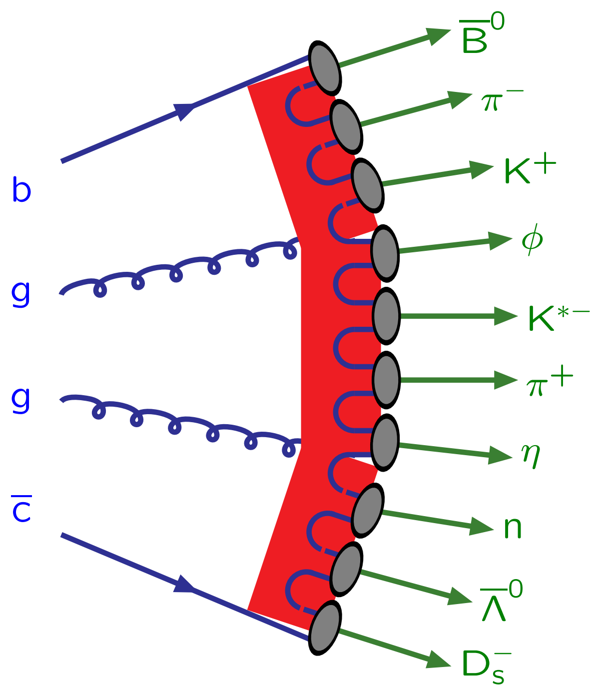
3) Too soft charm/bottom spectra
$\Longrightarrow$ anisotropic leading-cluster decay

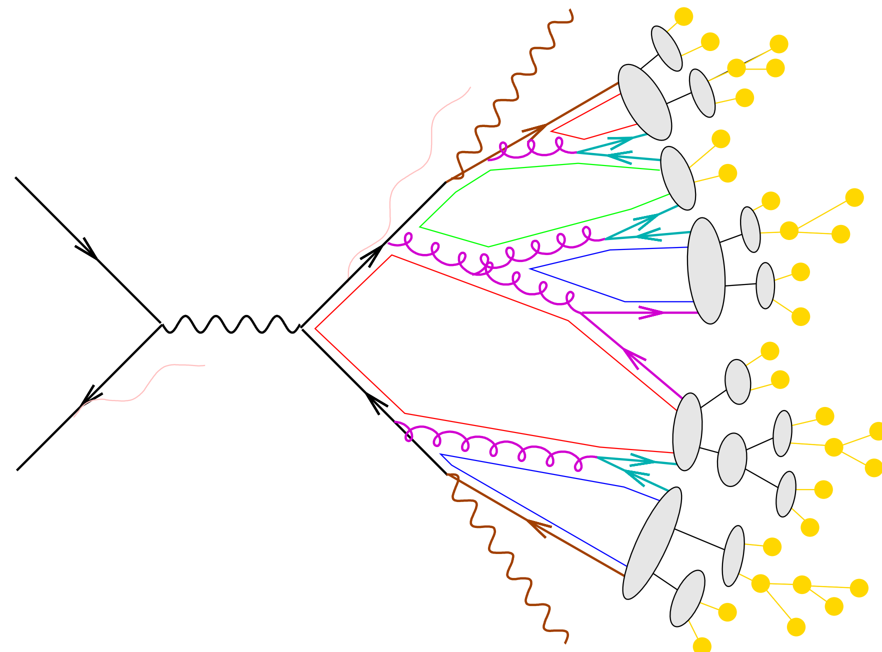
4) Charge correlations still problematic
$\Longrightarrow$ all clusters anisotropic (?)

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



String vs. Cluster





program	PYTHIA	HERWIG
model	string	cluster
energy–momentum picture	powerful predictive	simple unpredictive
parameters	few	many
flavour composition	messy unpredictive	simple 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 $Q \approx \Lambda_{\text{QCD}}$
(or m_{hadron}, if larger)

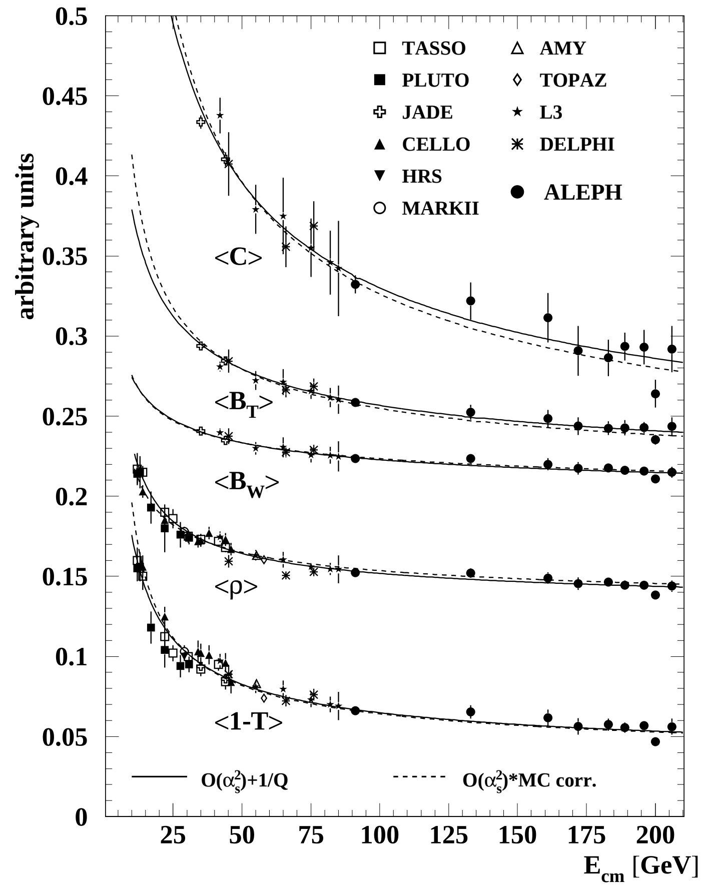
"Hard Line": each parton $\equiv$ one hadron

"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)

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

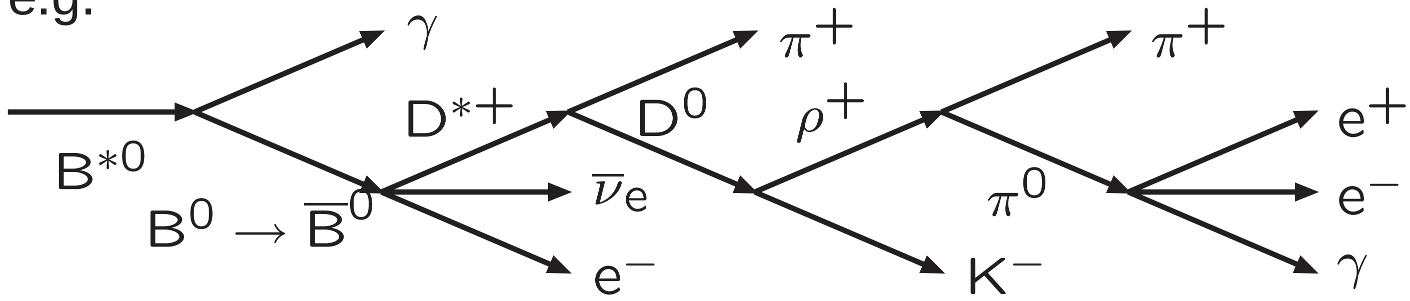


Not Monte Carlo, **not** for arbitrary quantities

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

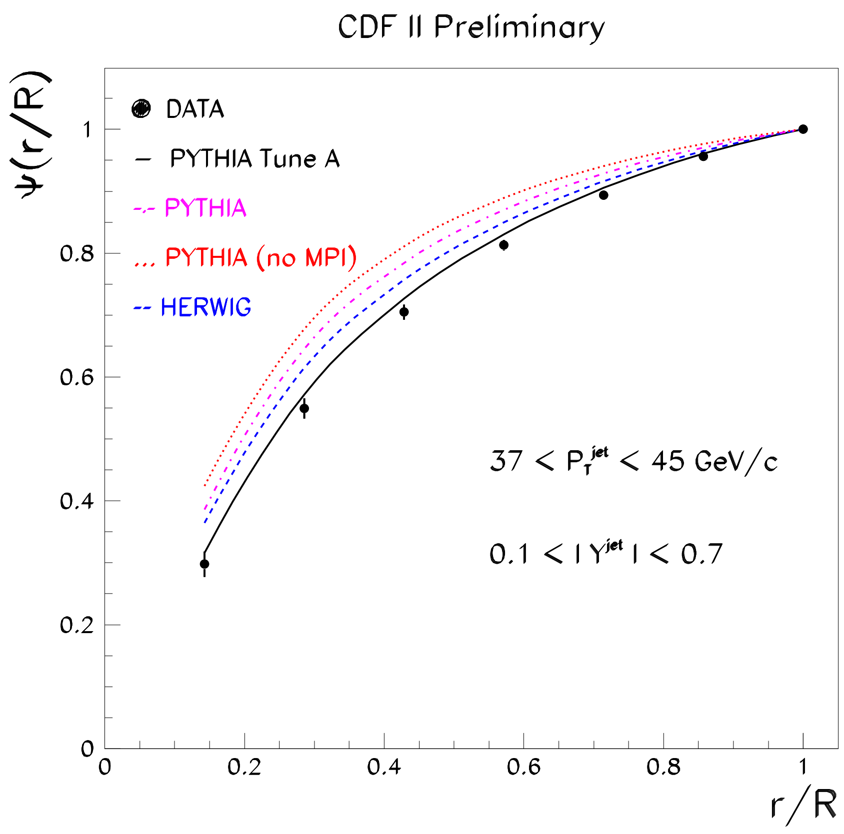
Dedicated programs, with special attention to polarization effects:
- EVTGEN: B decays
- TAUOLA: τ decays

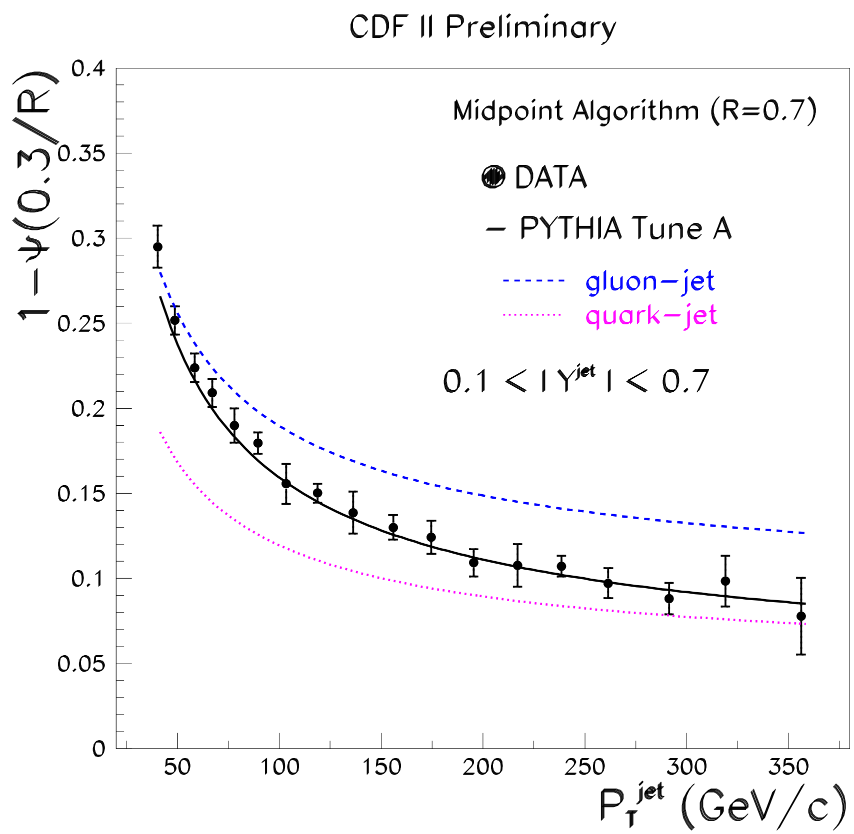
Jet Universality

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.

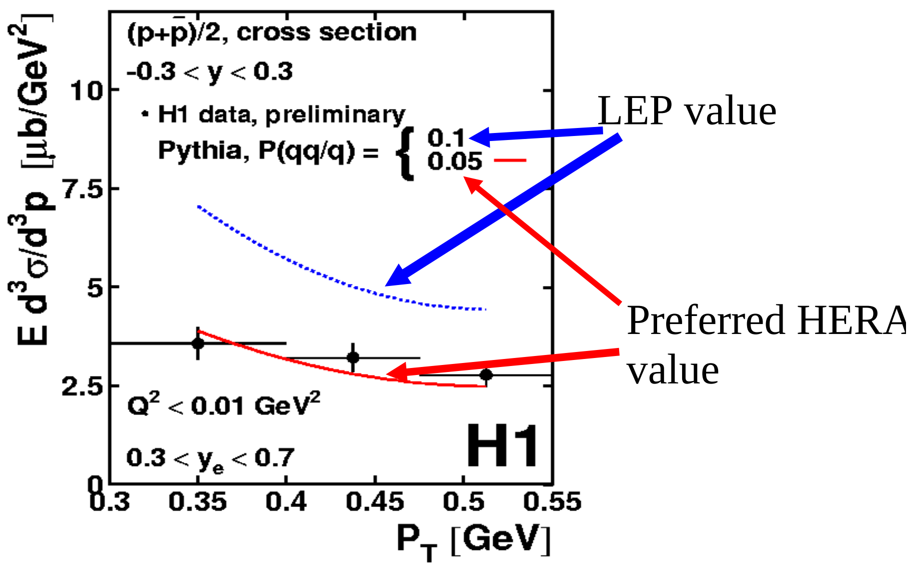
Answer 2: no, perturbative evolution gives calculable differences.

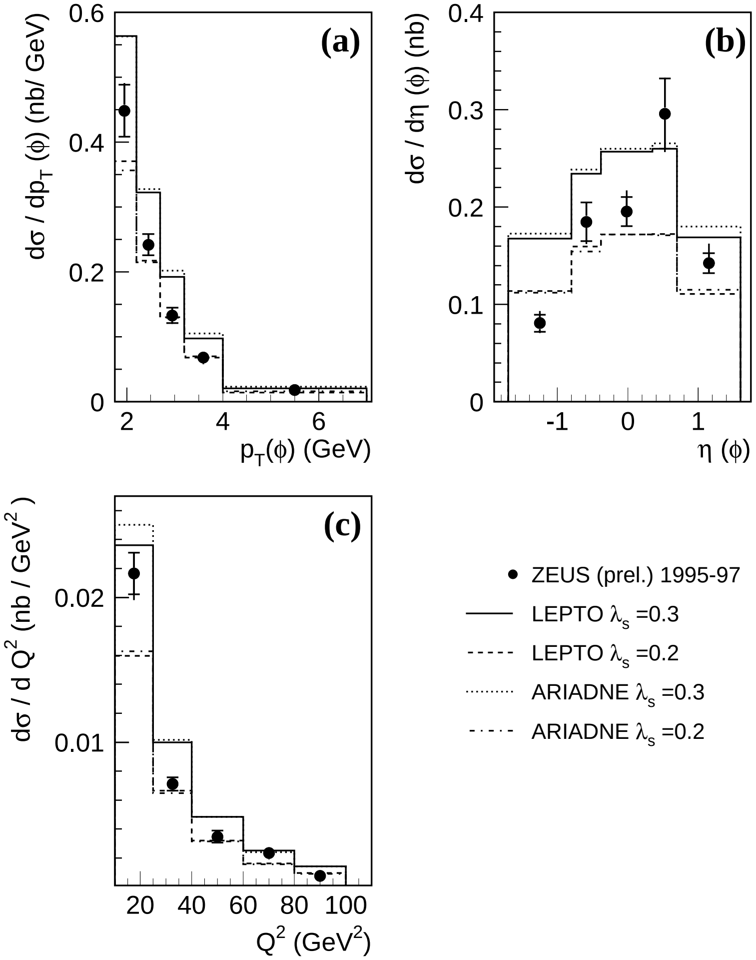




Answer 3: (string) hadronization mechanism assumed universal,
but is not quite.

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



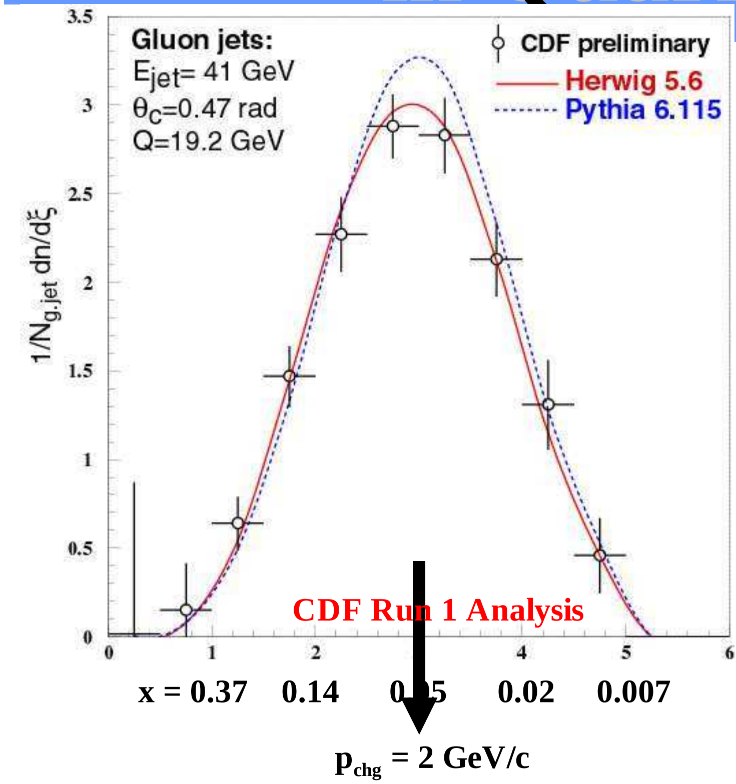


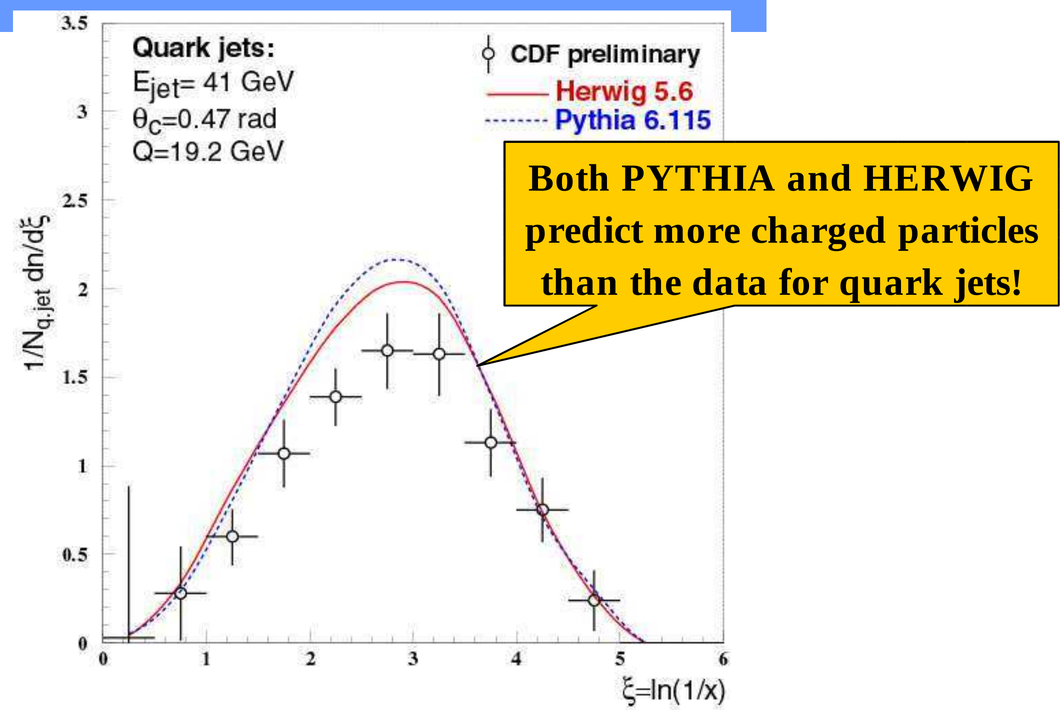
so discrepancies
$$\mathcal{P}_{\mathrm{qq}}/\mathcal{P}_{\mathrm{q}} = 0.1 \text{ at LEP}, \quad = 0.05 \text{ at HERA}$$
$$\mathcal{P}_{\mathrm{s}}/\mathcal{P}_{\mathrm{u}} = 0.3 \text{ at LEP}, \quad = 0.2 \text{ at HERA}$$

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

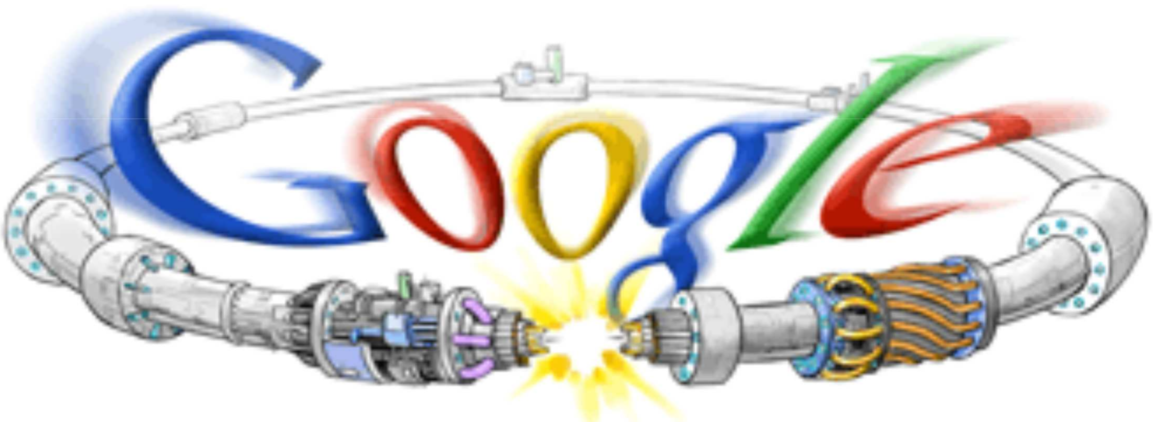




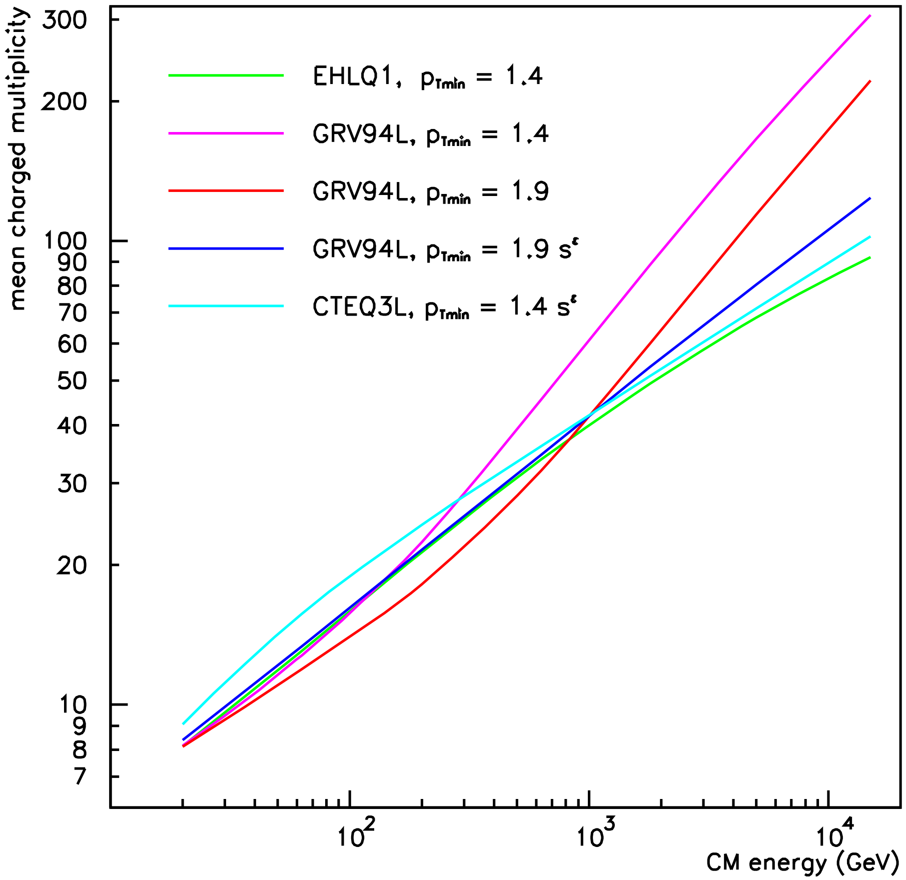
Momentum distribution of charged particles in gluon jets. HERWIG 5.6 predictions are in a good agreement with CDF data. PYTHIA 6.115 produces slightly more particles in the region around the peak of distribution.

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

Extrapolations to LHC



Recall $$\frac{d\sigma}{dp_\perp^2} \propto \frac{1}{p_\perp^4} \to \frac{1}{(p_\perp^2 + p_{\perp 0}^2)^2}$$



Larger collision energy

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

$\Rightarrow$ smaller colour screening length d

$\Rightarrow$ larger $p_{\perp 0}$

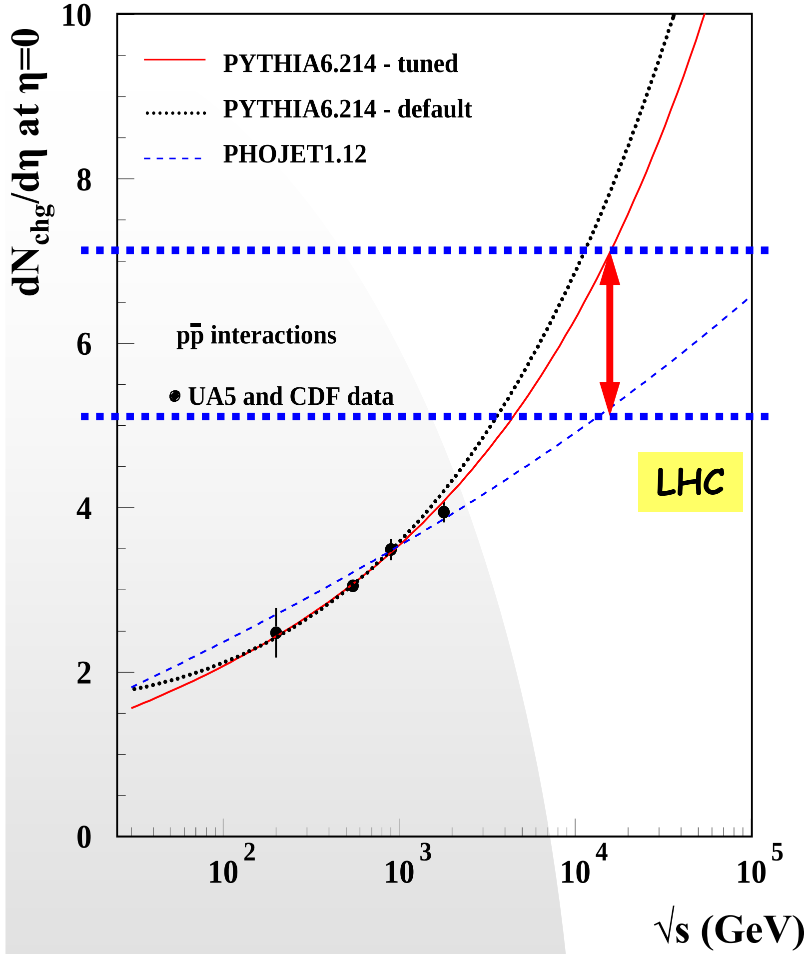
Post-HERA PDF fits steeper at small x

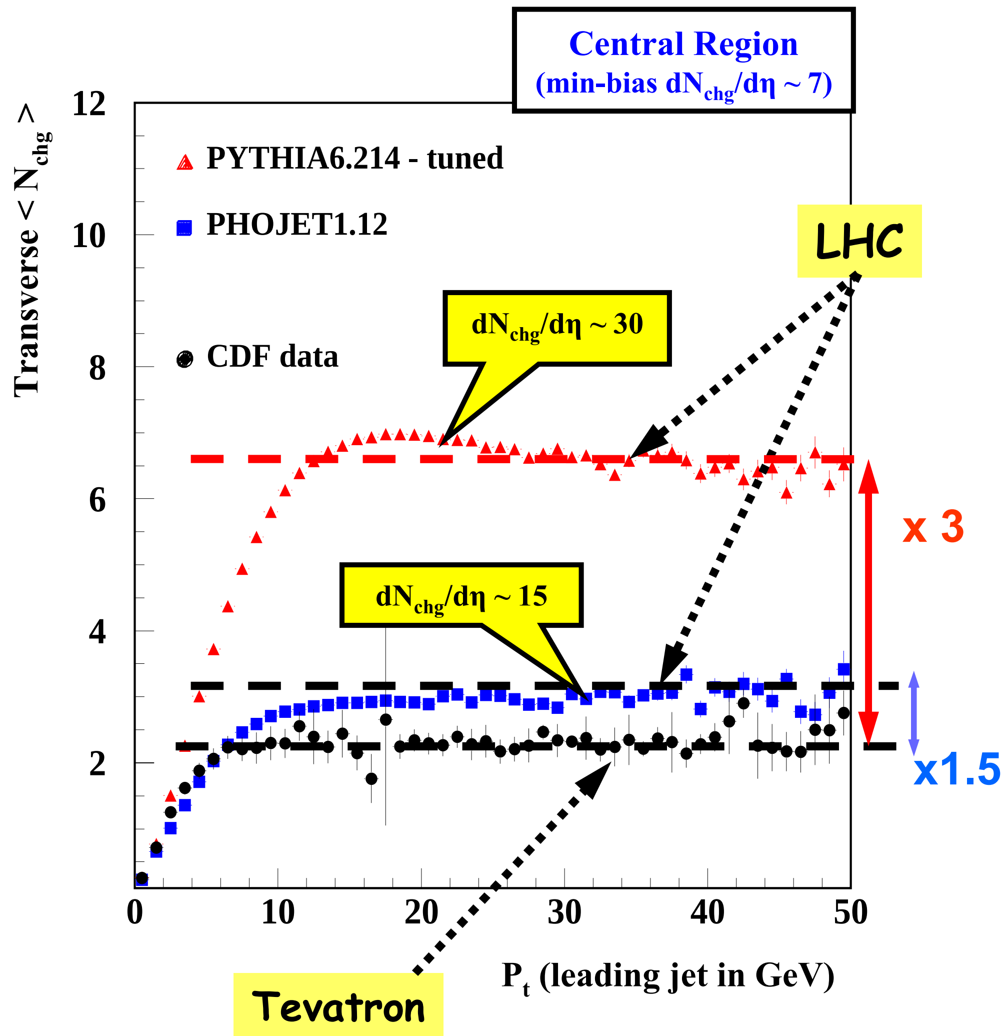
$\Rightarrow$ stronger energy dependence

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

$$p_{\perp 0}(s) = 2.25\ \text{GeV} \left(\frac{E_{\text{cm}}}{1.8\ \text{TeV}} \right)^{0.24}$$

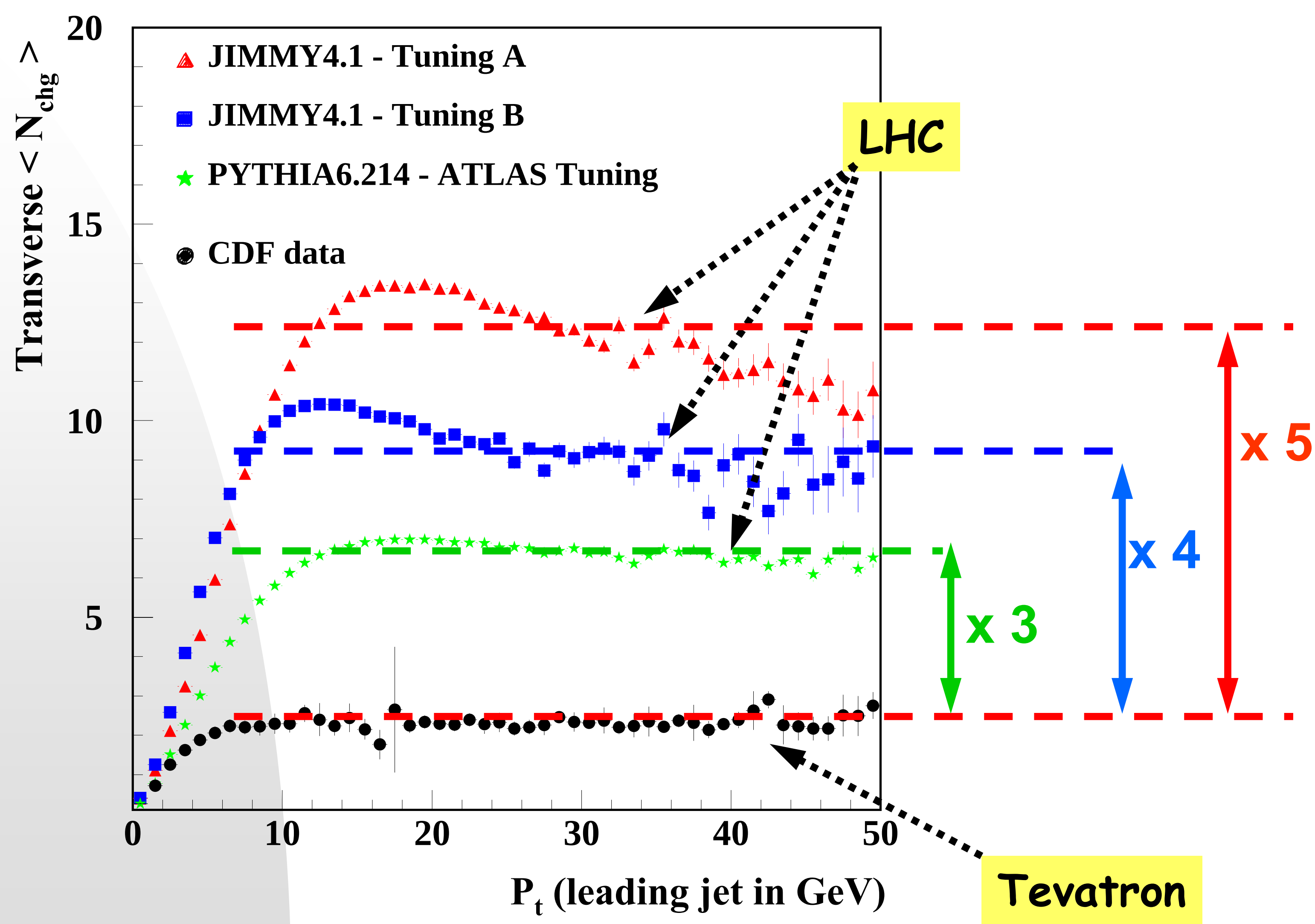
LHC predictions: pp collisions at √s = 14 TeV



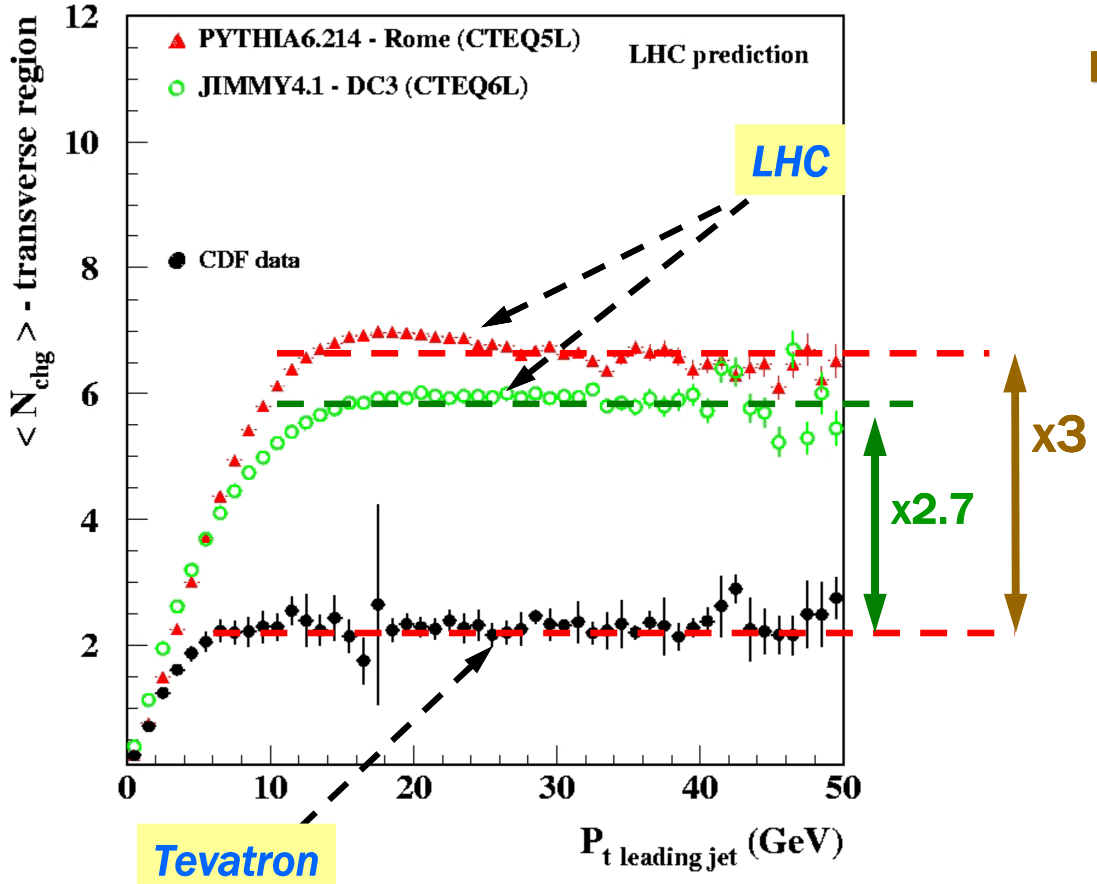


- PYTHIA models favour $\ln^2(s)$;
- PHOJET suggests a $\ln(s)$ dependence.

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



UE tunings: Pythia vs. Jimmy

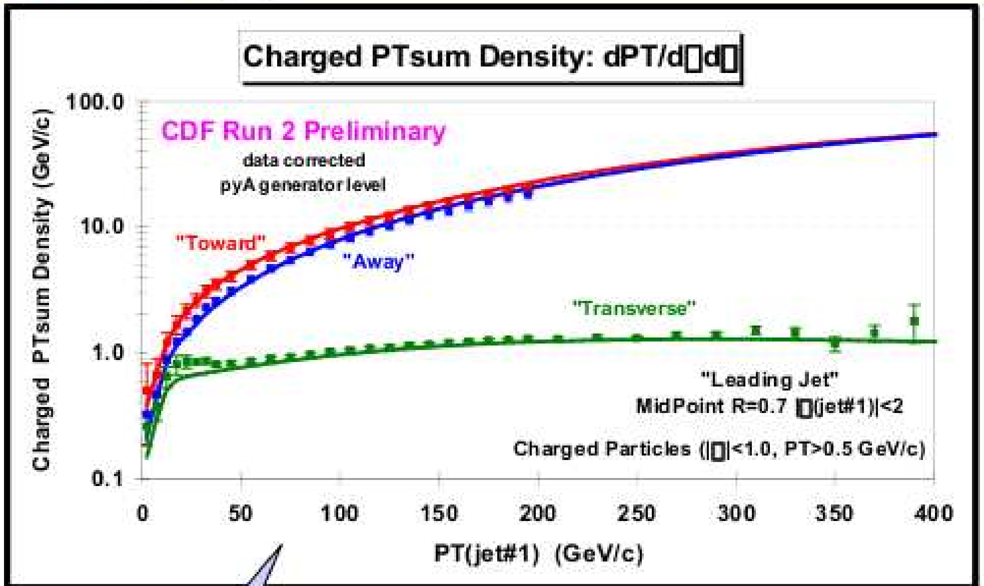


PTJIM=4.9

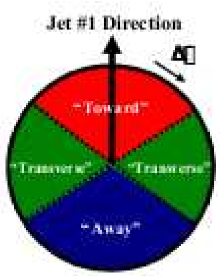
$= 2.8 \times (14 / 1.8)^{0.27}$

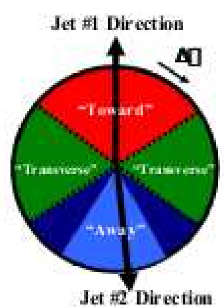
- **energy dependent PTJIM generates UE predictions similar to the ones generated by PYTHIA6.2 – ATLAS.**

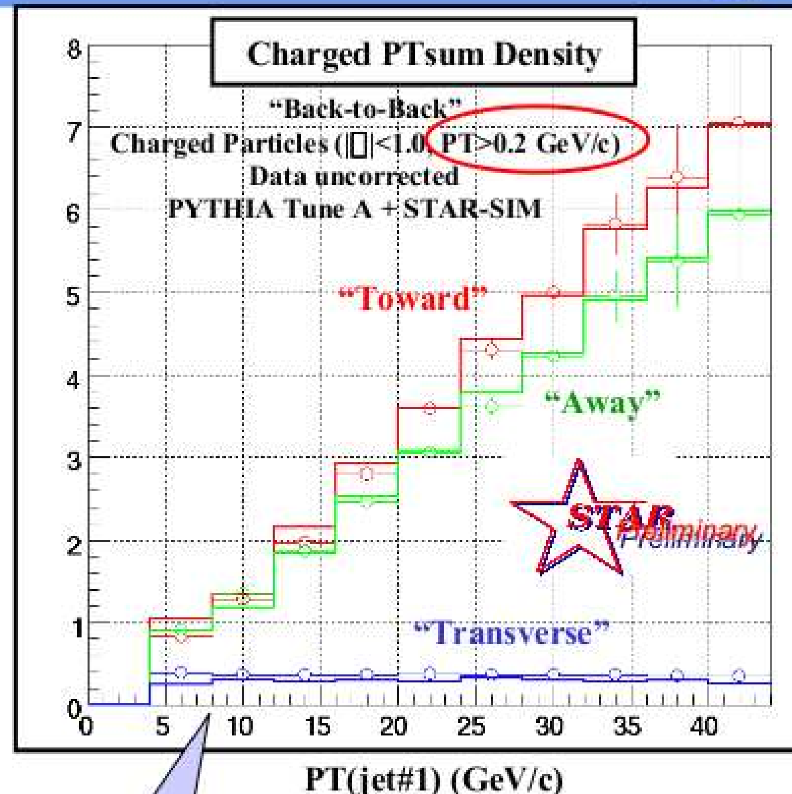
The "Underlying Event" at STAR



"Leading Jet"





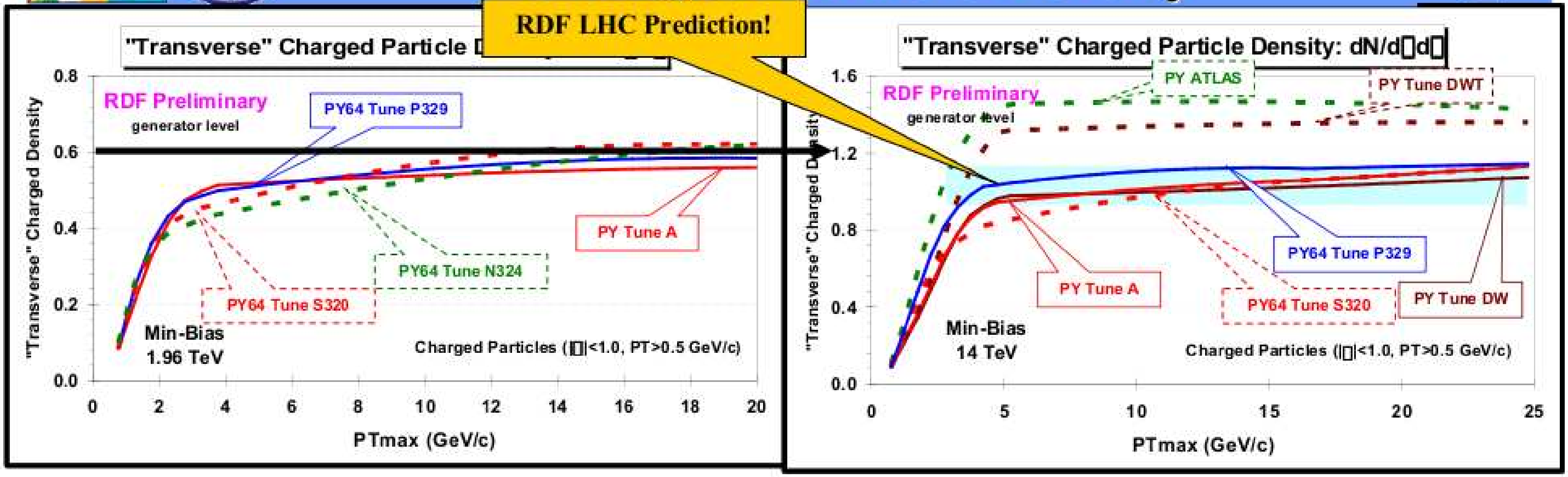


"Back-to-Back"

- Data on the charged particle *scalar* p_T sum density, dPT/dηdϕ, as a function of the leading jet p_T for the "toward", "away", and "transverse" regions compared with PYTHIA Tune A.

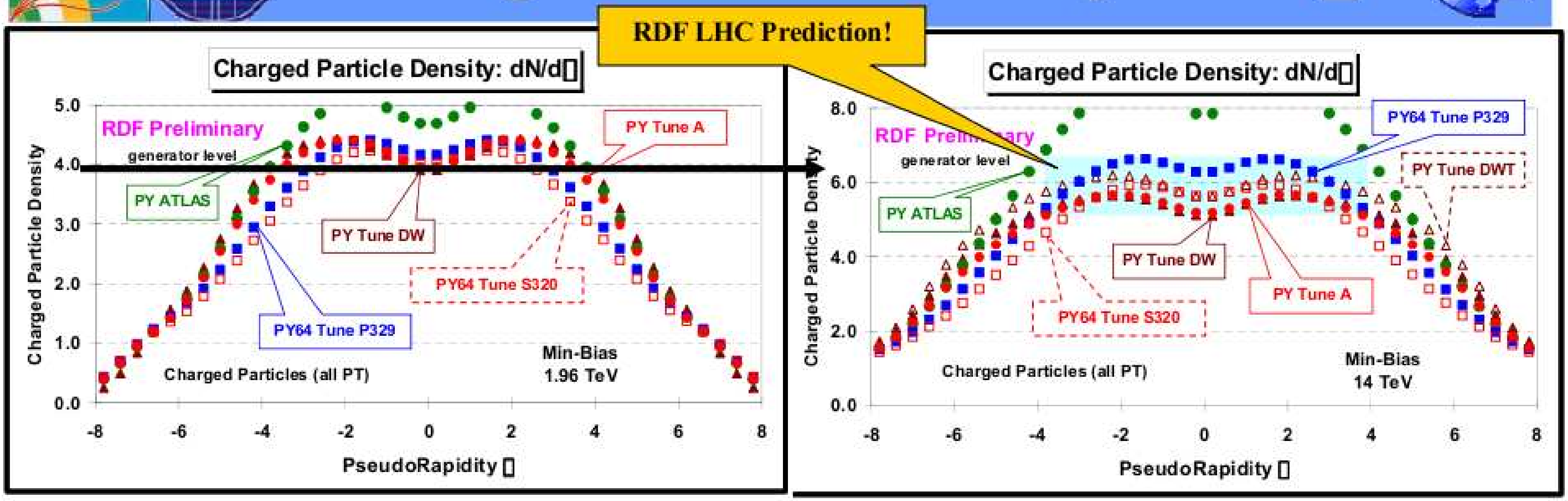
Min-Bias "Associated" Charged Particle Density

RDF LHC Prediction!



- **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 1.96 TeV from PYTHIA Tune A, Tune S320, Tune N324, and Tune P329 at the particle level (*i.e.* generator level).**
- **Extrapolations of PYTHIA Tune A, Tune DW, Tune DWT, Tune S320, Tune P329, and pyATLAS to the LHC.**

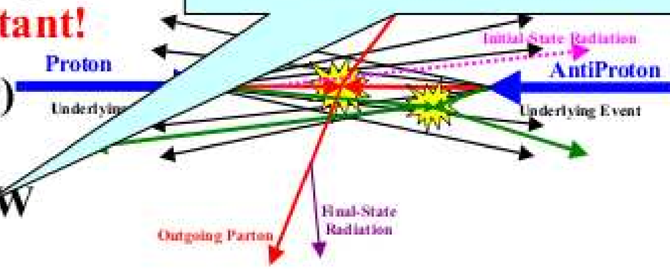
Charged Particle Density: dN/dη



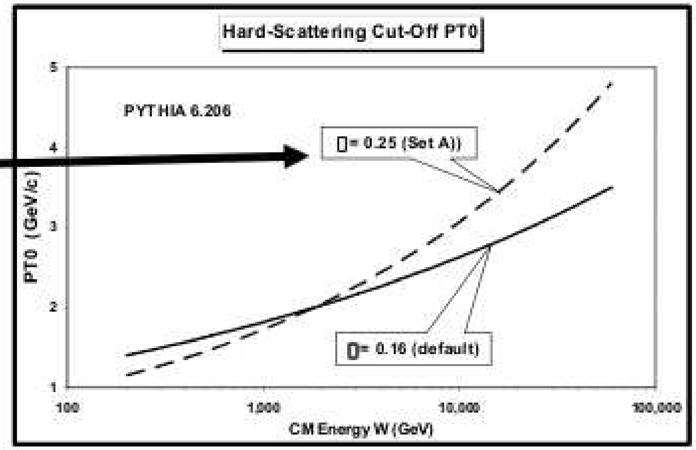
- Charged particle (all p_T) pseudo-rapidity distribution, $dN_{chg}/d\eta d\phi$, at 1.96 TeV for inelastic non-diffractive collisions from PYTHIA Tune A, Tune DW, Tune S320, and Tune P324.
- Extrapolations (all pT) of PYTHIA Tune A, Tune DW, Tune S320, Tune P324. and ATLAS to the LHC.

Summary & Conclus

However, I believe that the better fits to the LEP fragmentation data at high z will lead to small improvements of Tune A at the Tevatron!



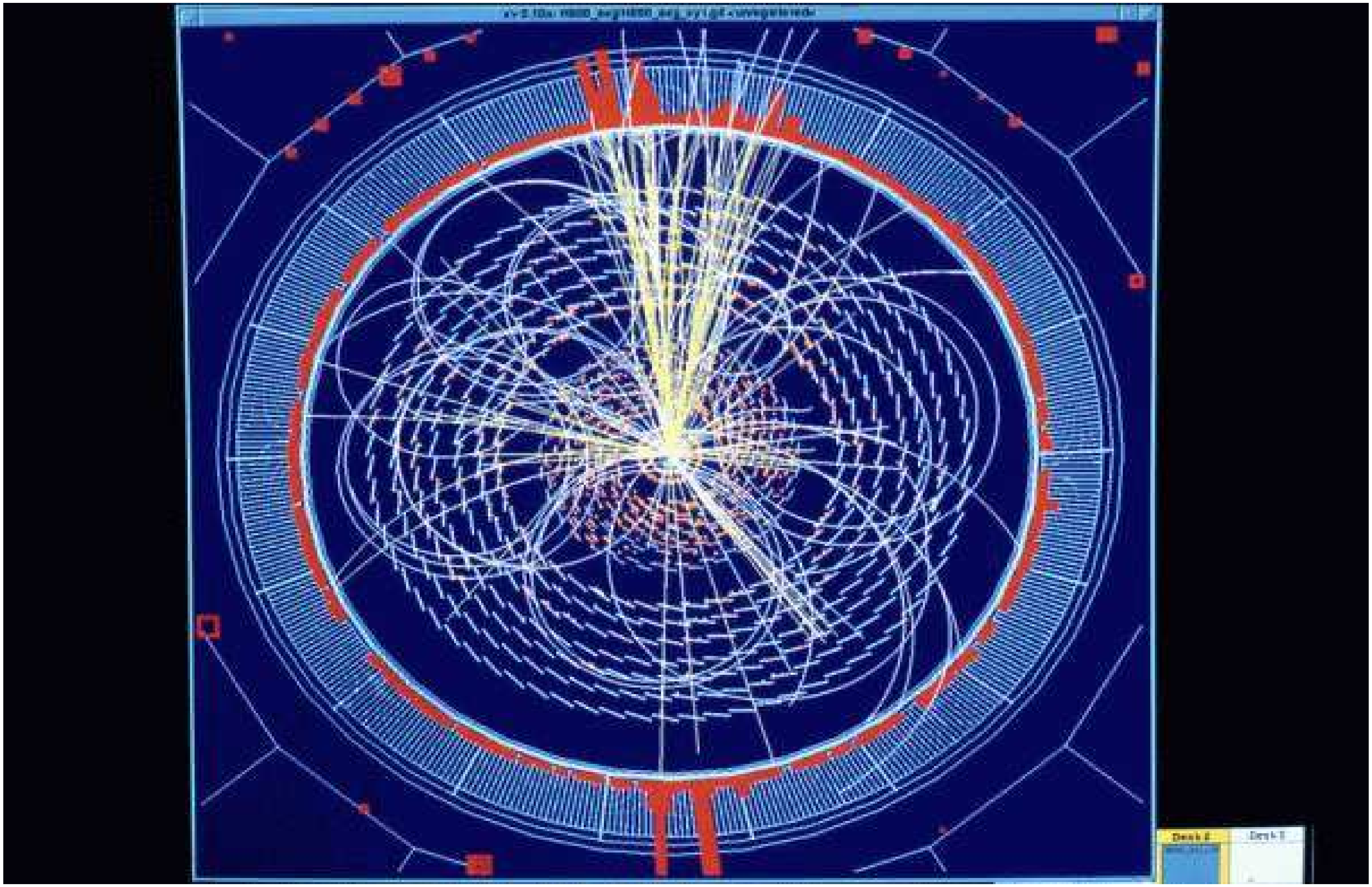
- We are making good progress in understanding and modeling the "underlying event". RHIC data at 200 GeV are very important!
- The new Pythia p_T ordered tunes (py64 S320 and py64 P329) are very similar to Tune A, Tune AW, and Tune DW. At present the new tunes do not fit the data better than Tune AW 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.



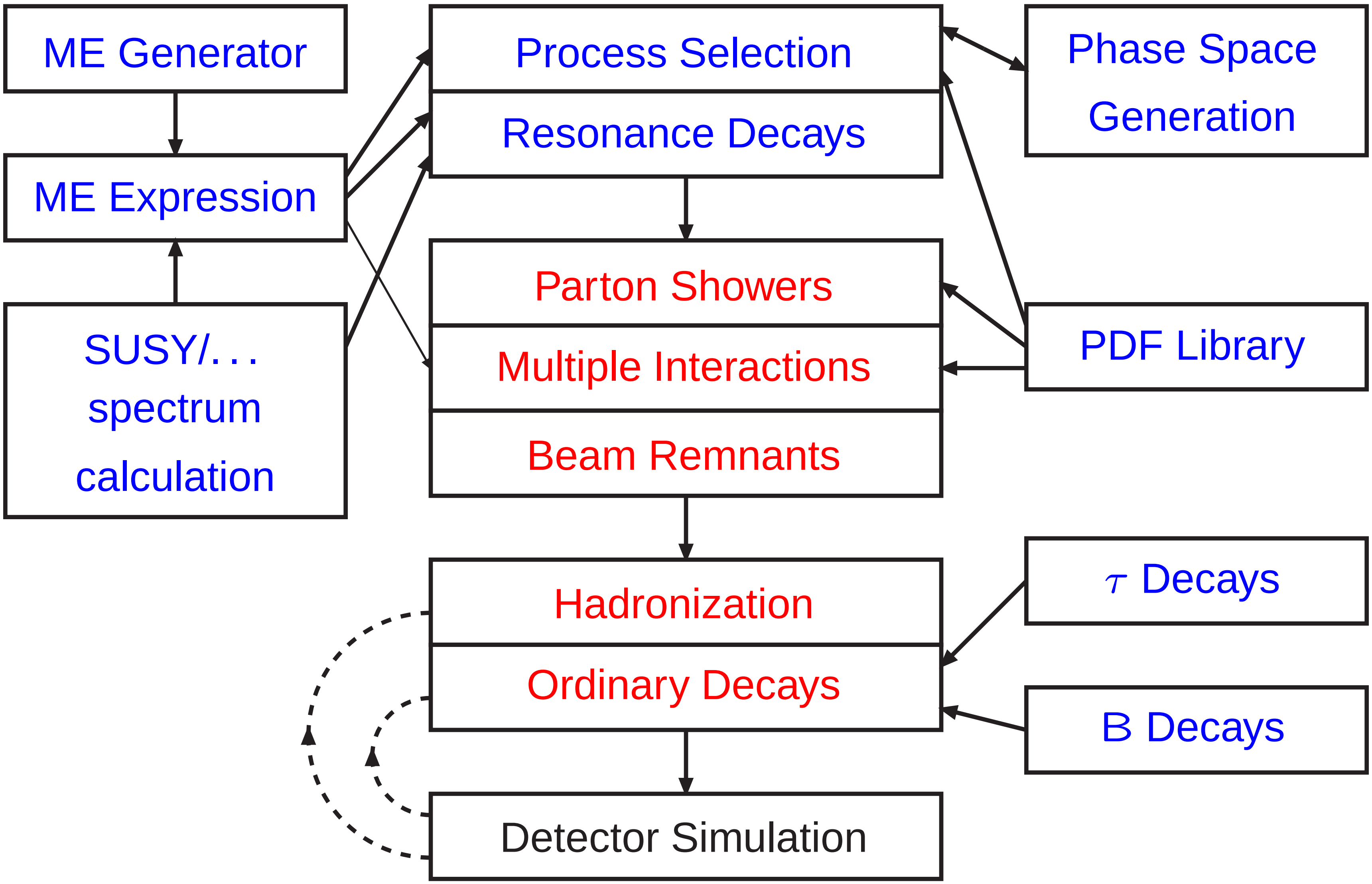
- The new and old PYTHIA tunes are beginning to converge and I believe we are finally in a position to make some legitimate predictions at the LHC!
- All tunes with the default value PARP(90) = 0.16 are wrong and are overestimating the activity of min-bias and the underlying event at the LHC! This includes all my "T" tunes and the 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

Event Generator Developments



The Bigger Picture



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

PDG Particle Codes

A. Fundamental objects

1	d	11	e^-	21	g				
2	u	12	ν_e	22	γ	32	Z'^0		
3	s	13	μ^-	23	Z^0	33	Z''^0		
4	c	14	ν_μ	24	W^+	34	W'^+		
5	b	15	τ^-	25	h^0	35	H^0	37	H^+
6	t	16	ν_τ			36	A^0	39	Graviton

add $-$ sign for antiparticle, where appropriate

+ diquarks, SUSY, technicolor, . . .

B. Mesons

$100\,|q_1| + 10\,|q_2| + (2s+1)$ with $|q_1| \geq |q_2|$

particle if heaviest quark u, $\bar{\mathrm{s}}$, c, $\bar{\mathrm{b}}$; else antiparticle

111	π^0	311	K^0	130	K^0_L	221	η^0	411	D^+	431	D_s^+
211	π^+	321	K^+	310	K^0_S	331	η'^0	421	D^0	443	J/ψ

C. Baryons

$1000\,q_1 + 100\,q_2 + 10\,q_3 + (2s+1)$

with $q_1 \geq q_2 \geq q_3$, or Λ-like $q_1 \geq q_3 \geq q_2$

2112	n	3122	Λ^0	2224	Δ^{++}	3214	Σ^{*0}
2212	p	3212	Σ^0	1114	Δ^-	3334	Ω^-

The workhorses: what are the differences?

HERWIG, PYTHIA and SHERPA intend to offer a convenient framework for LHC physics studies, but with slightly different emphasis:

PYTHIA (successor to JETSET, begun in 1978):

- originated in hadronization studies: the Lund string
- leading in development of multiple parton interactions
- pragmatic attitude to showers & matching
- the first multipurpose generator: machines & processes

HERWIG (successor to EARWIG, begun in 1984):

- originated in coherent-shower studies (angular ordering)
- cluster hadronization & underlying event pragmatic add-on
- large process library with spin correlations in decays

SHERPA (APACIC++/AMEGIC++, begun in 2000):

- own matrix-element calculator/generator
- extensive machinery for CKKW matching to showers
- leans on PYTHIA for MPI and hadronization

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++ Main Players

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

SHERPA: new program, written from scratch
operational since ~2006 (now 1.1.3)
(F. Krauss; T. Gleisberg, S. Hoeche, M. Schoenherr, S. Schumann,
F. Siegert, J. Winter, JHEP 0902 (2009) 007)

HERWIG++: complete reimplementation
November 2007: first full-fledged version (2.1; now 2.3.2)
(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, Eur. Phys. J. C58 (2008) 639)

PYTHIA 8: complete reimplementation
October 2007: first full-fledged version (8.100; now 8.125)
(T. Sjöstrand, S. Mrenna, P. Skands, Comp.Phys.Comm. 178 (2008) 852)

MCnet

• Funded by EU Marie Curie training network •

• Approved for four years starting 1 Jan 2007 •

• Collects HERWIG, SHERPA and PYTHIA •

• Also ThePEG, ARIADNE, VINCIA, . . . •

• Also generator validation (RIVET) and tuning (PROFESSOR) •

(CERN, Durham, Lund, Karlsruhe, UC London; leader: Mike Seymour)

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

• Annual Monte Carlo school: •

Durham, UK, 18 – 20 April 2007

CTEQ – MCnet, Debrecen, Hungary, 8 – 16 August 2008

Lund, Sweden, 1 – 4 July 2009

CTEQ – MCnet, Karlsruhe, Germany, July – August 2010

• Support for other such schools, e.g. •

Physics at the Terascale Monte Carlo Schools, Germany

Short-term studentships:

for Ph.D. students
in theory or experiment,
33 @ 4 months each

formulate your project,
related to your Ph.D. thesis

applications processed
every three months;
next deadline 7 September

must move to another country;
non-EU participation allowed

Some 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
- some processes, especially Technicolor

New features, not found in 6.4:
- some new processes, e.g. for extra dimensions & unparticles
- possibility to use one PDF set for hard process and another for rest
- 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
- rescattering in MPI (preliminary)
- diffraction as Pomeron-proton collisions with MPI
- elastic scattering with Coulomb term (optional)
- updated decay data
- plan to have built-in CKKW-L and NLO matching

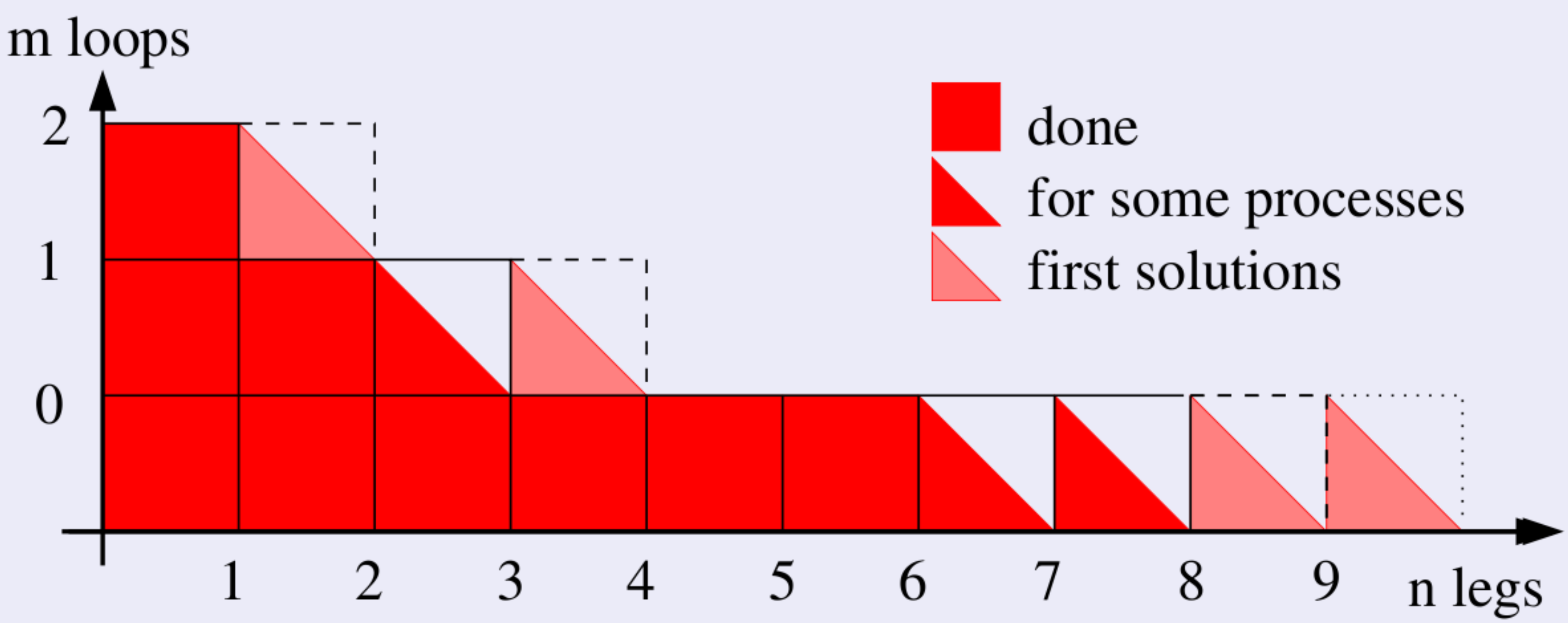
Trying Out PYTHIA 8.1

For subversion `xx` (currently `25`)

- 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, FastJet)
- `make` will compile in $\sim$ 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

Availability of exact calculations (hadron colliders)

- Fixed order matrix elements ("parton level") are exact to a given perturbative order. (and often quite a pain!)
- Important to understand limitations:
  Only tree-level fully automated, 1-loop-level ongoing.



(Next few slides stolen from Frank Krauss, with permission)

Parton-Level Simulations

Stating the problem(s)

- Multi-particle final states for signals & backgrounds.
- Need to evaluate $\mathrm{d}\sigma_N$:

$$\int_{\text{cuts}} \left[\prod_{i=1}^{N} \frac{\mathrm{d}^3 q_i}{(2\pi)^3 2E_i}\right] \delta^4\left(p_1 + p_2 - \sum_i q_i\right) \left|\mathcal{M}_{p_1 p_2 \to N}\right|^2 .$$

- Problem 1: Factorial growth of number of amplitudes.
- Problem 2: Complicated phase-space structure.
- Solutions: Numerical methods.

Basic ideas of efficient ME calculation

Need to evaluate $|\mathcal{M}|^2 = \left|\sum_i \mathcal{M}_i\right|^2$

- Obvious: Traditional textbook methods (squaring, completeness relations, traces) fail
  $\Longrightarrow$ result in proliferation of terms $(\mathcal{M}_i \mathcal{M}_j^*)$
  $\Longrightarrow$ Better: Amplitudes are complex numbers,
  $\Longrightarrow$ add them before squaring!
- Remember: spinors, gamma matrices have explicit form could be evaluated numerically (brute force)
  But: Rough method, lack of elegance, CPU-expensive

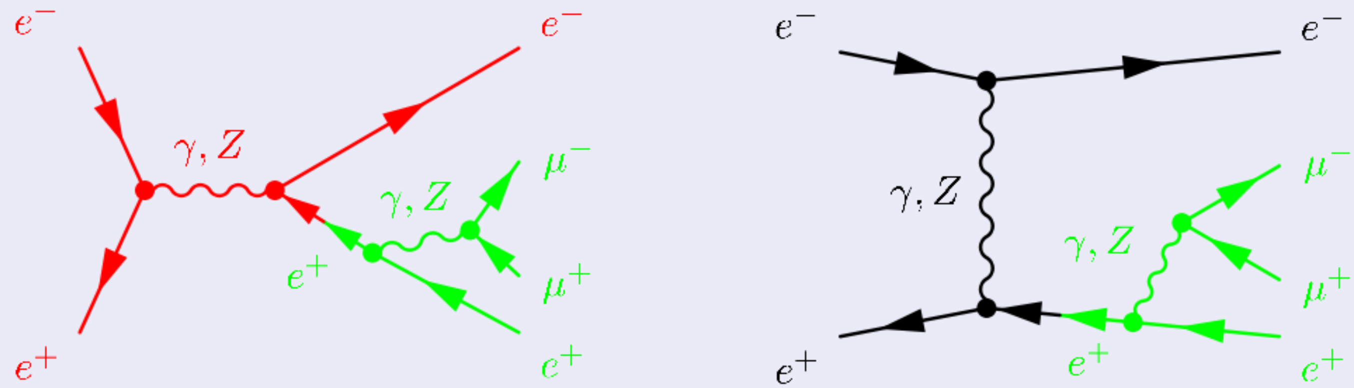
Helicity method

- Introduce basic helicity spinors (needs to "gauge"-vectors)
- Write everything as spinor products, e.g.
  $$\bar{u}(p_1,\, h_1)u(p_2,\, h_2) = \text{complex numbers.}$$
  Completeness rel'n: $(\not{p} + m) \Longrightarrow \frac{1}{2}\sum_h \left[\left(1 + \frac{m^2}{p^2}\right)\bar{u}(p,\, h)u(p,\, h) + \left(1 - \frac{m^2}{p^2}\right)\bar{v}(p,\, h)v(p,\, h)\right]$
- There are other genuine expressions ...
- Translate Feynman diagrams into "helicity amplitudes": complex-valued functions of momenta & helicities.
- Spin-correlations etc. nearly come for free.

Taming the factorial growth

- In the helicity method
  - Reusing pieces: Calculate only once!
  - Factoring out: Reduce number of multiplications!

  Implemented as a-posteriori manipulations of amplitudes.



- Better method: Recursion relations (recycling built in).
  Best candidate so far: Off-shell recursions

(Dyson-Schwinger, Berends-Giele etc.)

Colour-dressing: Fighting factorial growth in colour

- In principle: sampling over colours improves situation.

(But still, e.g. naively $\simeq (n-1)!$ permutations/colour-ordering for n external gluons).

- Improved scheme: colour dressing.

F.Maltoni, K.Paul, T.Stelzer & S.Willenbrock Phys. Rev. **D67** (2003) 014026

- Works very well with Berends-Giele recursions:

C.Duhr, S.Hoche & F.Maltoni, JHEP **0608** (2006) 062

Final State	BG		BCF		CSW	
	CO	CD	CO	CD	CO	CD
$2g$	0.24	0.28	0.28	0.33	0.31	0.26
$3g$	0.45	0.48	0.42	0.51	0.57	0.55
$4g$	1.20	1.04	0.84	1.32	1.63	1.75
$5g$	3.78	2.69	2.59	7.26	5.95	5.96
$6g$	14.2	7.19	11.9	59.1	27.8	30.6
$7g$	58.5	23.7	73.6	646	146	195
$8g$	276	82.1	597	8690	919	1890
$9g$	1450	270	5900	127000	6310	29700
$10g$	7960	864	64000	-	48900	-

Time [s] for the evaluation of 10^4 phase space points, sampled over helicities & colour.

Efficient phase space integration

("Amateurs study strategy, professionals study logistics")

- Democratic, process-blind integration methods:
  - Rambo/Mambo: Flat & isotropic

    R.Kleiss, W.J.Stirling & S.D.Ellis, Comput. Phys. Commun. **40** (1986) 359;
  - HAAG/Sarge: Follows QCD antenna pattern

    A.van Hameren & C.G.Papadopoulos, Eur. Phys. J. C **25** (2002) 563.
- Multi-channeling: Each Feynman diagram related to a phase space mapping (= "channel"), optimise their relative weights. R.Kleiss & R.Pittau, Comput. Phys. Commun. **83** (1994) 141.
- Main problem: practical only up to $\mathcal{O}(10\mathrm{k})$ channels.
- Some improvement by building phase space mappings recursively: More channels feasible, efficiency drops a bit.

Best answer at the moment: COMIX (personal bias)

T.Gleisberg & S.Hoeche, JHEP **0812** (2008) 039

- Colour-dressed Berends-Giele amplitudes in the SM.
- Fully recursive phase space generation.
- Example results (cross sections):

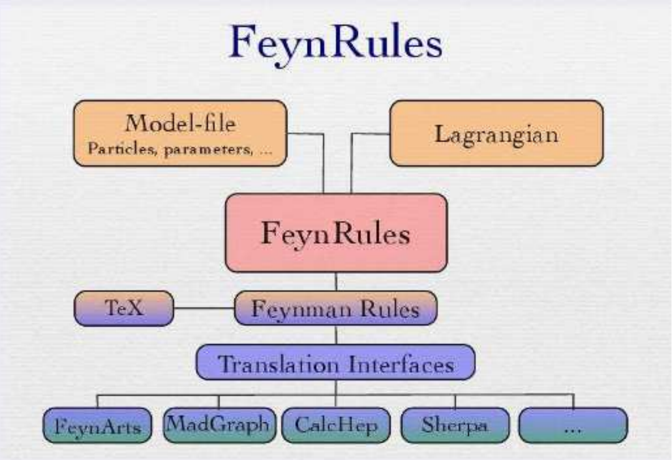
$gg \to ng$	Cross section [pb]				
n $\sqrt{s}$ [GeV]	8 1500	9 2000	10 2500	11 3500	12 5000
COMIX	0.755(3)	0.305(2)	0.101(7)	0.057(5)	0.019(2)
Maltoni (2002)	0.70(4)	0.30(2)	0.097(6)		
ALPGEN	0.719(19)				

σ [μb]	Number of jets						
$b\bar{b}$ + QCD jets	0	1	2	3	4	5	6
COMIX	470.8(5)	8.83(2)	1.826(8)	0.459(2)	0.1500(8)	0.0544(6)	0.023(2)
ALPGEN	470.6(6)	8.83(1)	1.822(9)	0.459(2)	0.150(2)	0.053(1)	0.0215(8)
AMEGIC++	470.3(4)	8.84(2)	1.817(6)				

FeynRules: implementing new models

Aim

- Portable, transparent & reproducible implementation of (nearly arbitrary) new physics models.
- In most codes: New models given by new particles, their properties & interactions.
- Output to standard ME generators enabled (MADGRAPH, SHERPA, ...)



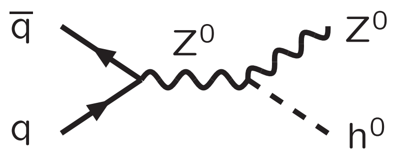
- Various models already implemented & validated for a list: http://feynrules.phys.ucl.ac.be

Event Physics Overview

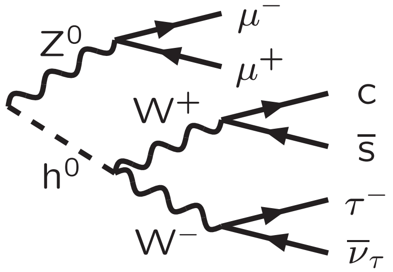
Repetition: from the “simple” to the “complex”,
or from “calculable” at large virtualities to “modelled” at small

Matrix elements (ME):

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

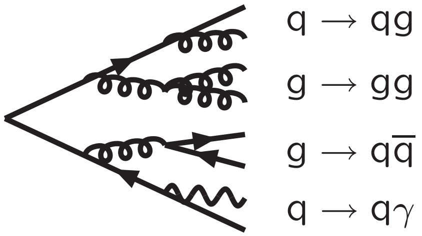


2) Resonance decays:
includes correlations.

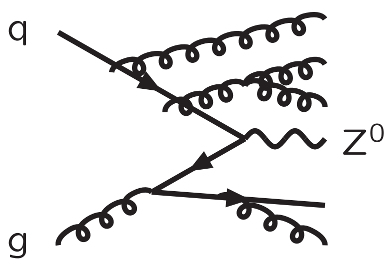


Parton Showers (PS):

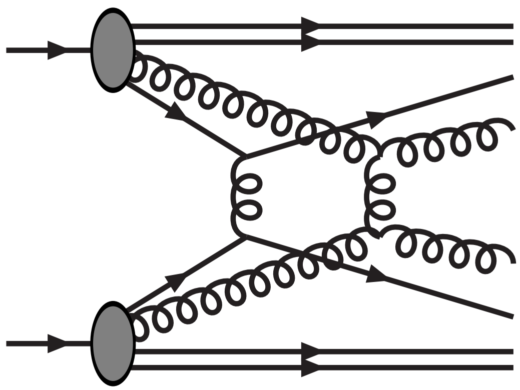
3) Final-state parton showers.



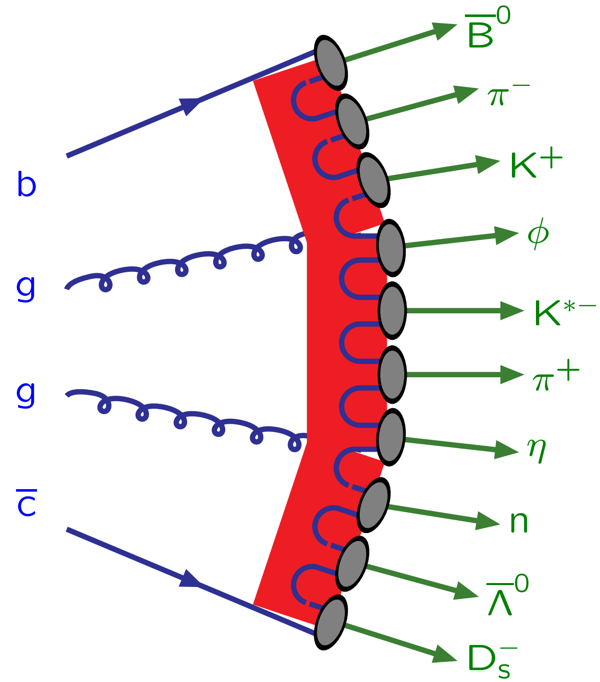
4) Initial-state parton showers.



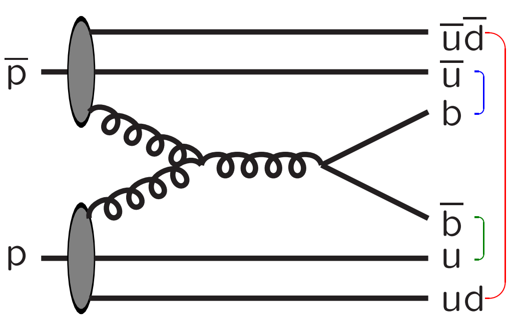
5) Multiple parton–parton interactions.



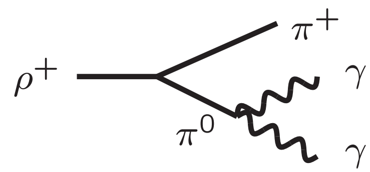
7) Hadronization



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"

Many presentations at the MCnet Summer School, Lund, July 2009:
http://conference.ippp.dur.ac.uk/conferenceOtherViews.py?view=ippp&confId=264#2009-07-01

Many presentations at the CTEQ–MCnet Summer School, Aug 2008:
http://conference.ippp.dur.ac.uk/conferenceOtherViews.py?view=ippp&confId=156

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

The "Les Houches Guidebook to Monte Carlo Generators
for Hadron Collider Physics", hep-ph/0403045
http://arxiv.org/pdf/hep-ph/0403045

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?

Final words

“Good,” said the First Speaker. “And tell me, what do you think of all this. A finished work of art, is it not?”
“Definitely!”
“Wrong! It is not.” This, with sharpness. “It is the first lesson you must unlearn. The Seldon Plan is neither complete nor correct. Instead it is merely the best that could be done at the time.”

— And Now You Don’t (Second Foundation), Isaac Asimov, 1949

But it often happens that the physics simulations provided by the Monte Carlo generators carry the authority of data itself. They look like data and feel like data, and if one is not careful they are accepted as if they were data.

J.D. Bjorken

from a talk given at the 75th anniversary celebration of the Max-Planck Institute of Physics, Munich, Germany, December 10th, 1992. As quoted in: Beam Line, Winter 1992, Vol. 22, No. 4