LUND UNIVERSITY

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Monte Carlo Generators

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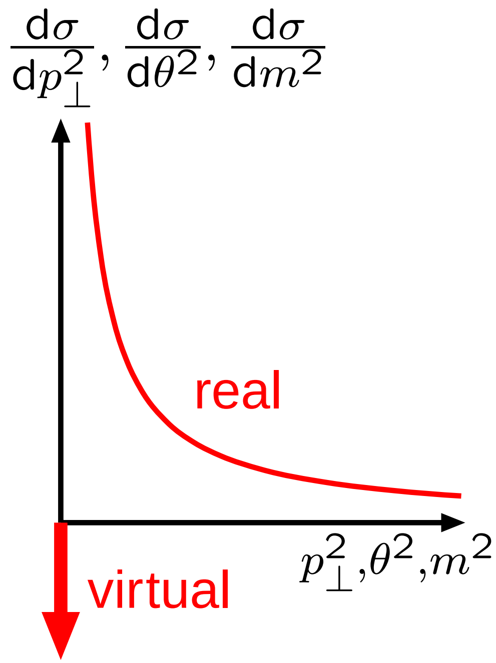
(yesterday) Introduction and Overview;
Matrix Elements; Parton Showers

(today) Matching Issues; Multiple Interactions;
Hadronization and Decays; Summary and Outlook

Matrix Elements vs. Parton Showers

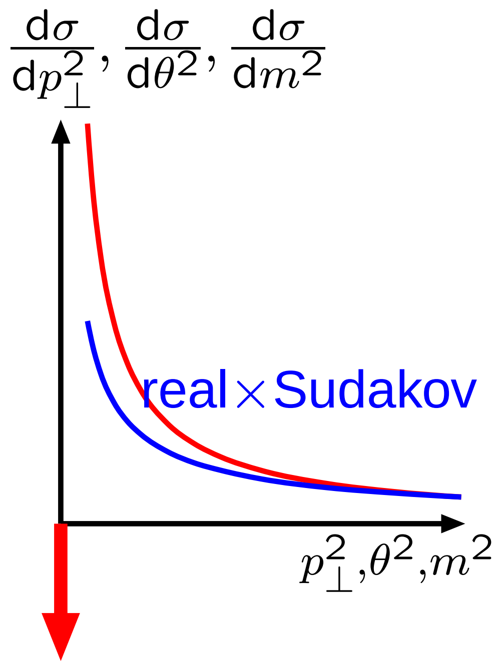
ME : Matrix Elements

+ systematic expansion in α_s (‘*exact*’)
+ powerful for multiparton Born level
+ flexible phase space cuts
− loop calculations very tough
− negative cross section in collinear regions
  $\Rightarrow$ unpredictive jet/event structure
− *no easy match to hadronization*



PS : Parton Showers

− approximate, to LL (or NLL)
− main topology not predetermined
  $\Rightarrow$ inefficient for exclusive states
+ process-generic $\Rightarrow$ simple multiparton
+ Sudakov form factors/resummation
  $\Rightarrow$ sensible jet/event structure
+ *easy to match to hadronization*



Matrix Elements and Parton Showers

Recall complementary strengths:

- ME's good for well separated jets
- PS's good for structure inside jets

Marriage desirable! But how?

Problems:
- gaps in coverage?
- doublecounting of radiation?
- Sudakov?
- NLO consistency?

Much work ongoing $\Longrightarrow$ no established orthodoxy

Three main areas, in ascending order of complication:

1) Match to lowest-order nontrivial process — merging

2) Combine leading-order multiparton process — vetoed parton showers

3) Match to next-to-leading order process — MC@NLO

Merging

= cover full phase space with smooth transition ME/PS

Want to reproduce $W^{\mathrm{ME}} = \frac{1}{\sigma(\mathrm{LO})} \frac{\mathrm{d}\sigma(\mathrm{LO}+\mathrm{g})}{\mathrm{d}(\mathrm{phasespace})}$

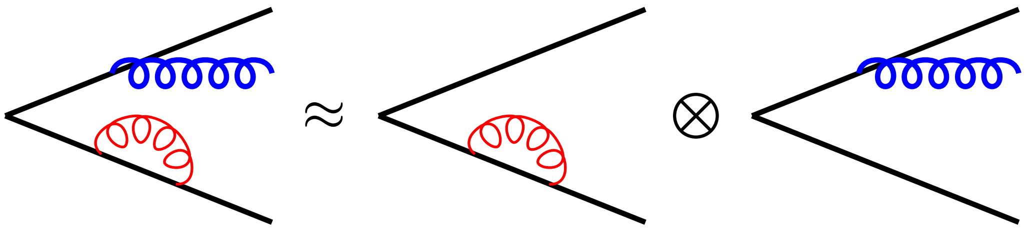
by shower generation + correction procedure

$$\overbrace{W^{\mathrm{ME}}}^{\text{wanted}} = \overbrace{W^{\mathrm{PS}}}^{\text{generated}} \; \overbrace{\frac{W^{\mathrm{ME}}}{W^{\mathrm{PS}}}}^{\text{correction}}$$

- Exponentiate ME correction by shower Sudakov form factor:

$$W^{\mathrm{PS}}_{\mathrm{actual}}(Q^2) = W^{\mathrm{ME}}(Q^2)\,\exp\left(-\int_{Q^2}^{Q^2_{\mathrm{max}}} W^{\mathrm{ME}}(Q'^2)\,\mathrm{d}Q'^2\right)$$

- Do not normalize W^{ME} to $\sigma(\mathrm{NLO})$ (error $\mathcal{O}(\alpha_{\mathrm{s}}^2)$ either way)



$1 + \mathcal{O}(\alpha_{\mathrm{s}})$ $\;\; \int = 1$

$$\mathrm{d}\sigma = K \;\sigma_0 \;\mathrm{d}W^{\mathrm{PS}}$$

- Normally several shower histories $\Rightarrow$ $\sim$equivalent approaches

Final-State Shower Merging

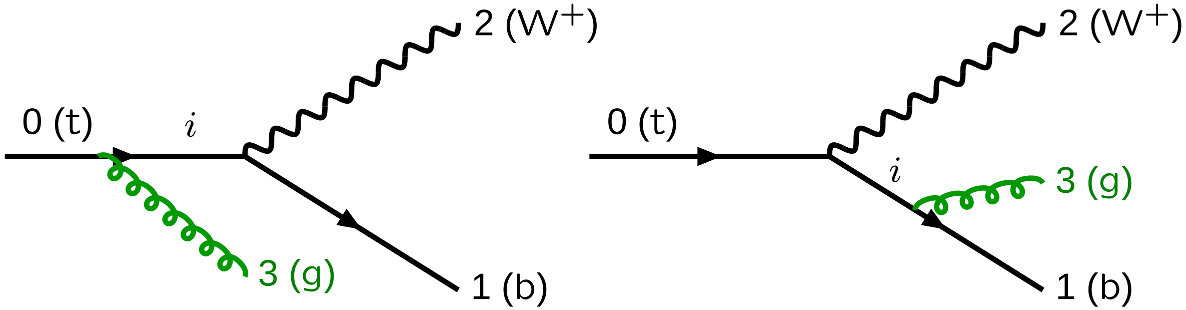
Merging with $\gamma^*/\mathrm{Z}^0 \to \mathrm{q\overline{q}g}$ for $m_{\mathrm{q}} = 0$ since long

(M. Bengtsson & TS, PLB185 (1987) 435, NPB289 (1987) 810)

For $m_{\mathrm{q}} > 0$ pick $Q_i^2 = m_i^2 - m_{i,\mathrm{onshell}}^2$ as evolution variable since

$$W^{\mathrm{ME}} = \frac{(\ldots)}{Q_1^2 Q_2^2} - \frac{(\ldots)}{Q_1^4} - \frac{(\ldots)}{Q_2^4}$$

Coloured decaying particle also radiates:



ME $\frac{1}{Q_0^2 Q_1^2}$

matches

PS $\mathrm{b} \to \mathrm{bg}$

$\Rightarrow$ can merge PS with generic $a \to bc\mathrm{g}$ ME

(E. Norrbin & TS, NPB603 (2001) 297)

Subsequent branchings $\mathrm{q} \to \mathrm{qg}$: also matched to ME, with reduced energy of system

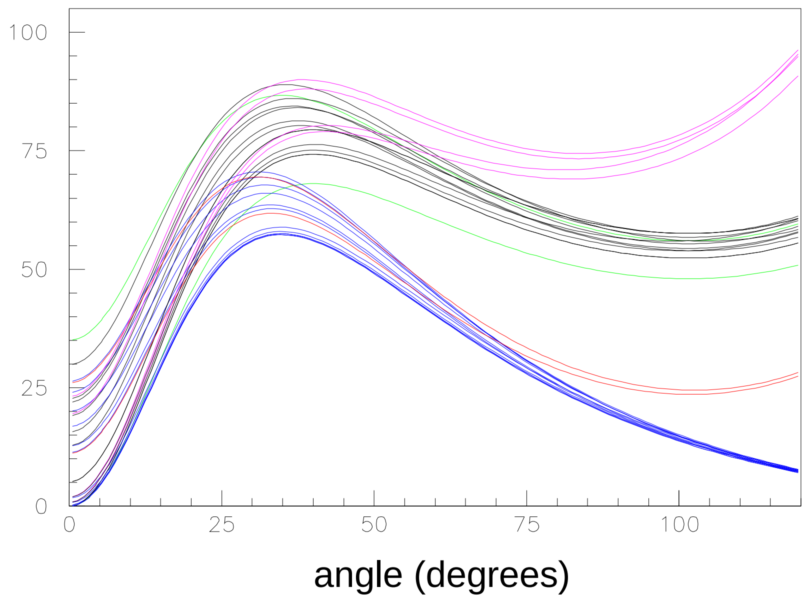
PYTHIA performs merging with generic FSR $a \to bc\mathrm{g}$ ME,

in SM: $\gamma^*/\mathrm{Z}^0/\mathrm{W}^\pm \to \mathrm{q}\overline{\mathrm{q}}$, $\mathrm{t} \to \mathrm{bW}^+$, $\mathrm{H}^0 \to \mathrm{q}\overline{\mathrm{q}}$,

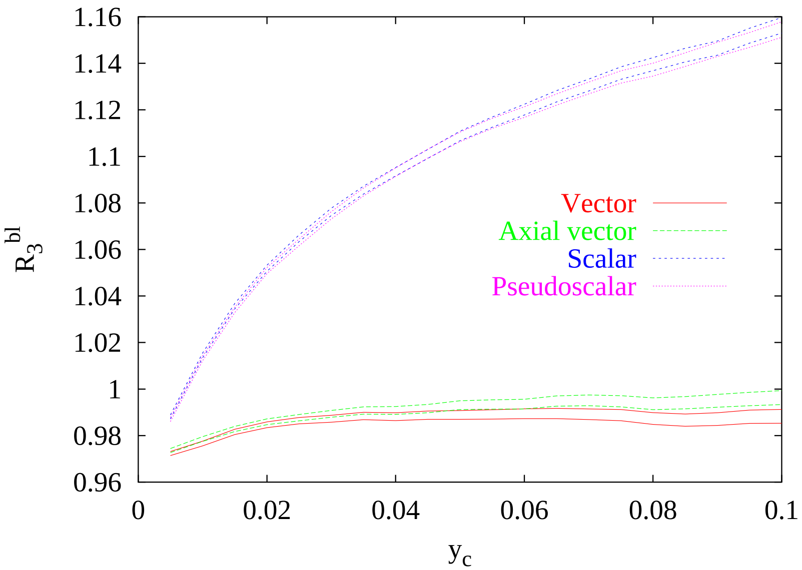
and MSSM: $\mathrm{t} \to \mathrm{bH}^+$, $\mathrm{Z}^0 \to \tilde{\mathrm{q}}\overline{\tilde{\mathrm{q}}}$, $\tilde{\mathrm{q}} \to \tilde{\mathrm{q}}'\mathrm{W}^+$, $\mathrm{H}^0 \to \tilde{\mathrm{q}}\overline{\tilde{\mathrm{q}}}$, $\tilde{\mathrm{q}} \to \tilde{\mathrm{q}}'\mathrm{H}^+$,

$\chi \to \mathrm{q}\overline{\tilde{\mathrm{q}}}$, $\chi \to \mathrm{q}\overline{\tilde{\mathrm{q}}}$, $\tilde{\mathrm{q}} \to \mathrm{q}\chi$, $\mathrm{t} \to \tilde{\mathrm{t}}\chi$, $\tilde{\mathrm{g}} \to \mathrm{q}\overline{\tilde{\mathrm{q}}}$, $\tilde{\mathrm{q}} \to \mathrm{q}\tilde{\mathrm{g}}$, $\mathrm{t} \to \tilde{\mathrm{t}}\tilde{\mathrm{g}}$

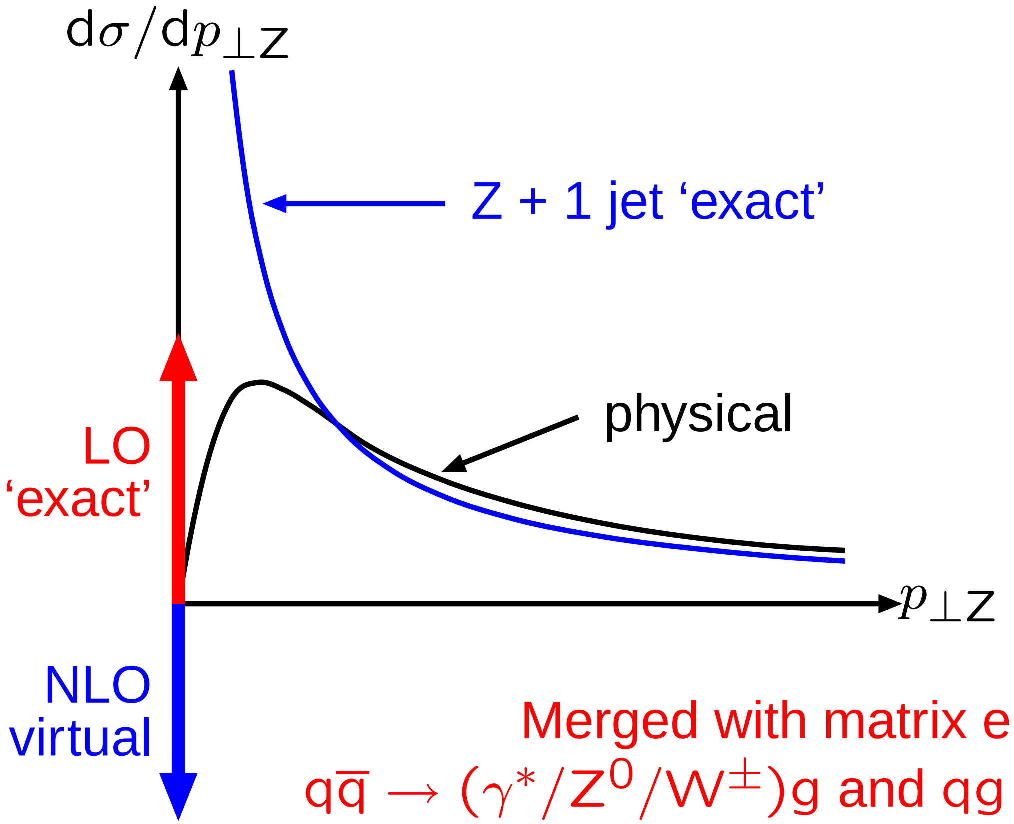
g emission for different colour, spin and parity:



$R_3^{\mathrm{bl}}(y_c)$: mass effects in Higgs decay:



Initial-State Shower Merging



resummation:
physical $p_{\perp Z}$ spectrum

shower: ditto
+ accompanying
jets (exclusive)

Merged with matrix elements for
$q\bar{q} \to (\gamma^*/Z^0/W^\pm)g$ and $qg \to (\gamma^*/Z^0/W^\pm)q'$:
(G. Miu & TS, PLB449 (1999) 313)

$$\left(\frac{W^{ME}}{W^{PS}}\right)_{q\bar{q}'\to gW} = \frac{\hat{t}^2 + \hat{u}^2 + 2m_W^2\hat{s}}{\hat{s}^2 + m_W^4} \leq 1$$

$$\left(\frac{W^{ME}}{W^{PS}}\right)_{qg\to q'W} = \frac{\hat{s}^2 + \hat{u}^2 + 2m_W^2\hat{t}}{(\hat{s} - m_W^2)^2 + m_W^4} < 3$$

with $Q^2 = -m^2$
and $z = m_W^2/\hat{s}$

Merging in HERWIG

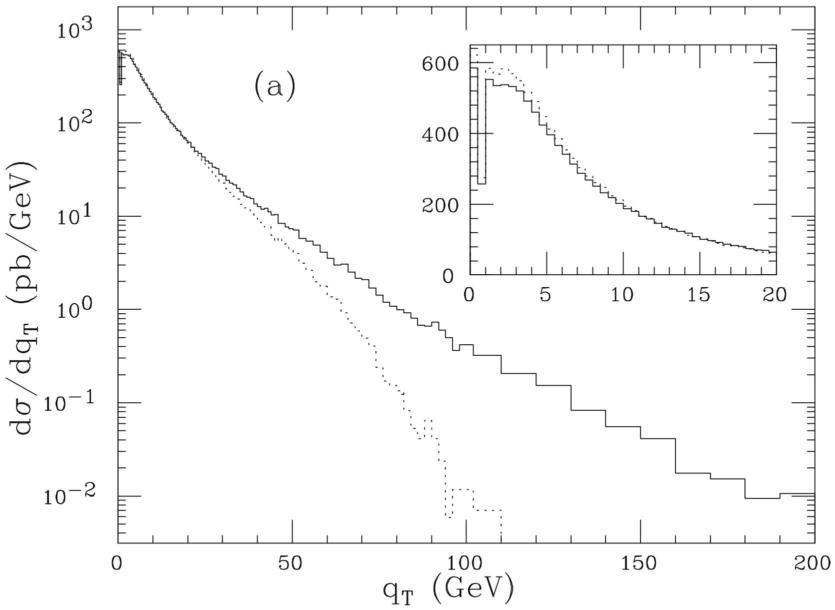
HERWIG also contains merging, for

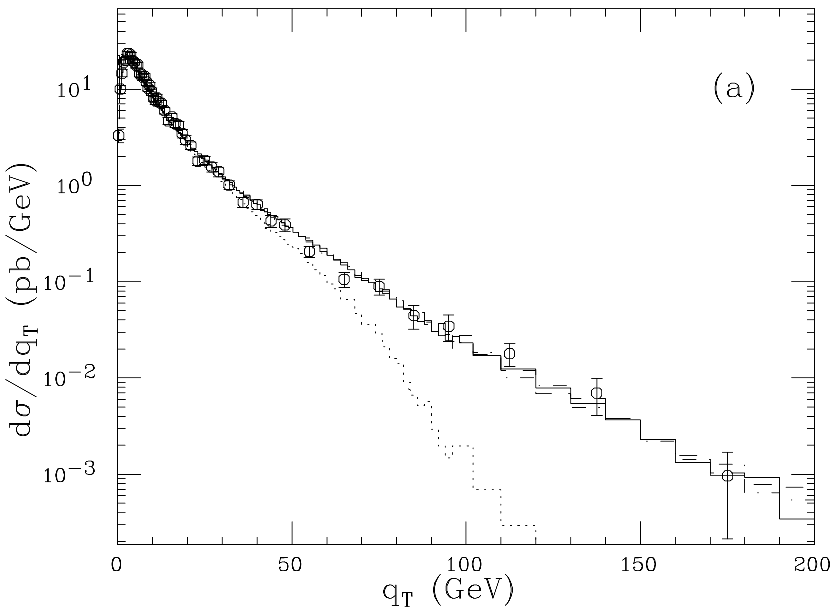
- $Z^0 \to q\bar{q}$
- $t \to bW^+$
- $q\bar{q} \to Z^0$

and some more

Special problem:
angular ordering does not cover full phase space; so
(1) fill in “dead zone” with ME
(2) apply ME correction
in allowed region

Important for agreement with data:





Vetoed Parton Showers

S. Catani, F. Krauss, R. Kuhn, B.R. Webber, JHEP 0111 (2001) 063; L. Lönnblad, JHEP0205 (2002) 046;
F. Krauss, JHEP 0208 (2002) 015; S. Mrenna, P. Richardson, JHEP0405 (2004) 040;
M.L. Mangano, in preparation

Generic method to combine ME's of several different orders to NLL accuracy; will be a 'standard tool' in the future

Basic idea:

- consider (differential) cross sections $\sigma_0, \sigma_1, \sigma_2, \sigma_3, \ldots$, corresponding to a lowest-order process (e.g. W or H production), with more jets added to describe more complicated topologies, in each case to the respective leading order
- σ_i, $i \geq 1$, are divergent in soft/collinear limits
- absent virtual corrections would have ensured "detailed balance", i.e. an emission that adds to σ_{i+1} subtracts from σ_i
- such virtual corrections correspond (approximately) to the Sudakov form factors of parton showers
- so use shower routines to provide missing virtual corrections $\Rightarrow$ rejection of events (especially) in soft/collinear regions

Veto scheme:

1) Pick hard process, mixing according to $\sigma_0 : \sigma_1 : \sigma_2 : \ldots$,
above some ME cutoff, with large fixed $\alpha_{\mathrm{s}0}$

2) Reconstruct imagined shower history (in different ways)

3) Weight $W_\alpha = \prod_{\mathrm{branchings}} (\alpha_{\mathrm{s}}(k_{\perp i}^2)/\alpha_{\mathrm{s}0}) \Rightarrow$ accept/reject

CKKW-L:

4) Sudakov factor for non-emission
on all lines above ME cutoff

$$W_{\mathrm{Sud}} = \prod_{\text{``propagators''}} \mathrm{Sudakov}(k_{\perp \mathrm{beg}}^2, k_{\perp \mathrm{end}}^2)$$

4a) CKKW : use NLL Sudakovs

4b) L: use trial showers

5) $W_{\mathrm{Sud}} \Rightarrow$ accept/reject

6) do shower,
vetoing emissions above cutoff

MLM:

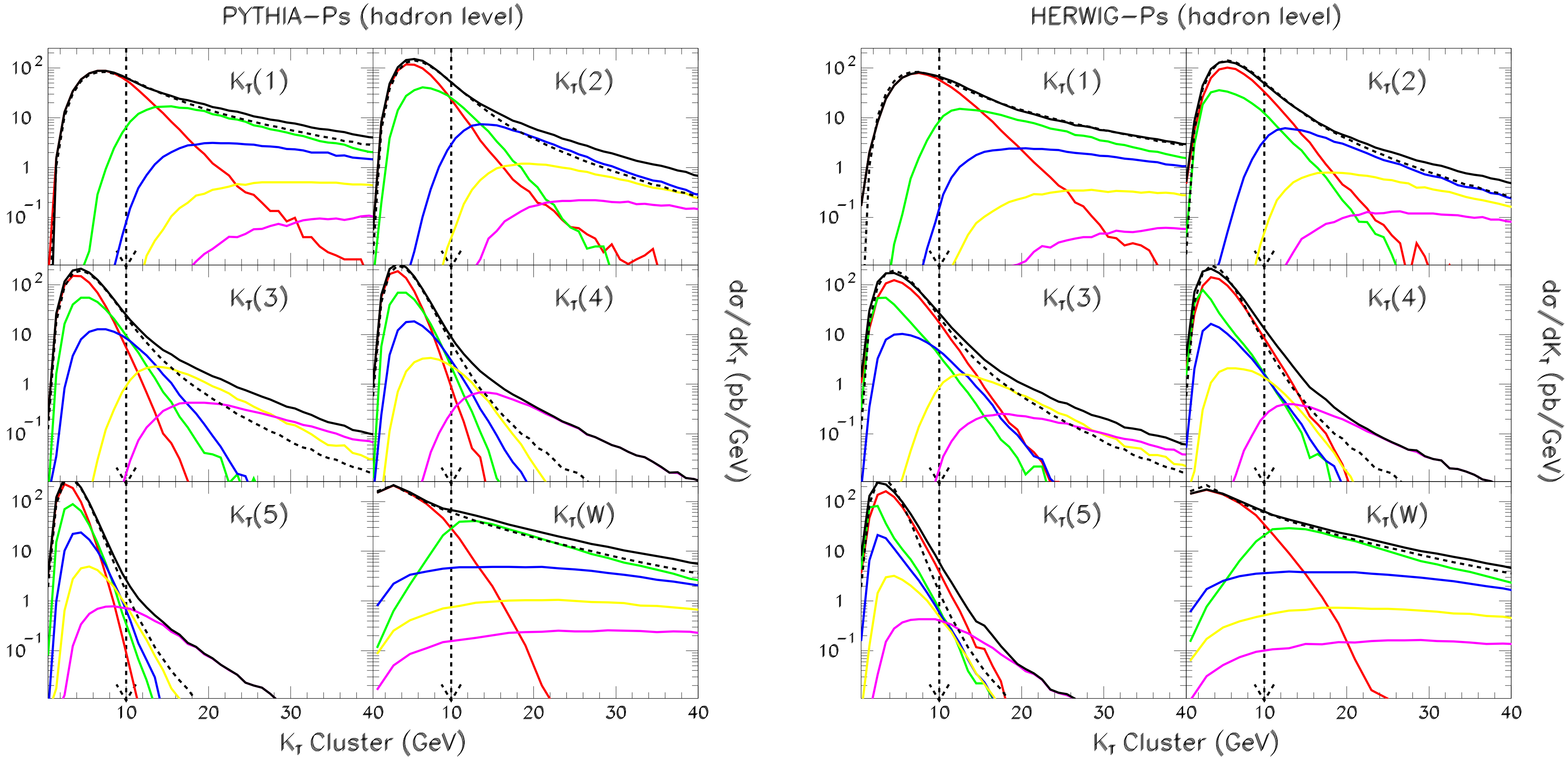
4) do parton showers

5) (cone-)cluster
showered event

6) match partons and jets

7) if all partons are matched,
and $n_{\mathrm{jet}} = n_{\mathrm{parton}}$,
keep the event,
else discard it

CKKW mix of W + (0, 1, 2, 3, 4) partons, hadronized and clustered to jets:



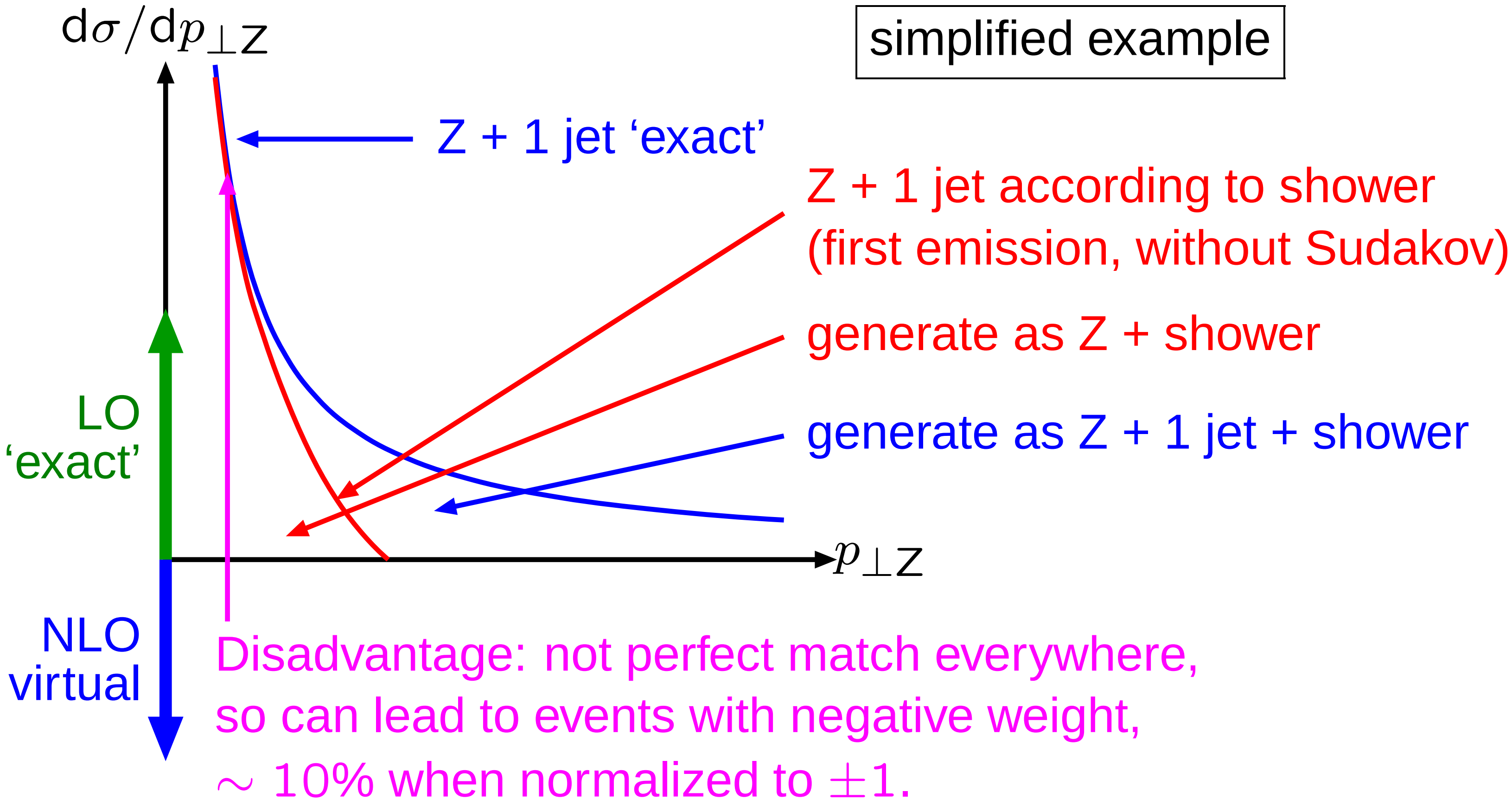
MC@NLO

Objectives:

- Total rate should be accurate to NLO.
- NLO results are obtained for all observables when (formally) expanded in powers of α_S.
- Hard emissions are treated as in the NLO computations.
- Soft/collinear emissions are treated as in shower MC.
- The matching between hard and soft emissions is smooth.
- The outcome is a set of “normal” events, that can be processed further.

Basic scheme (simplified!):

1) Calculate the NLO matrix element corrections to an n-body process (using the subtraction approach).
2) Calculate analytically (no Sudakov!) how the first shower emission off an n-body topology populates $(n + 1)$-body phase space.
3) Subtract the shower expression from the $(n + 1)$ ME to get the “true” $(n + 1)$ events, and consider the rest of σ_{NLO} as n-body.
4) Add showers to both kinds of events.



MC@NLO in comparison:

- Superior with respect to “total” cross sections.
- Equivalent to merging for event shapes (differences higher order).
- Inferior to CKKW–L for multijet topologies.

$\Rightarrow$ pick according to current task and availability.

MC@NLO 2.31 [hep-ph/0402116]

IPROC	Process
–1350–IL	$H_1H_2 \to (Z/\gamma^* \to)l_{\rm IL}\bar{l}_{\rm IL} + X$
–1360–IL	$H_1H_2 \to (Z \to)l_{\rm IL}\bar{l}_{\rm IL} + X$
–1370–IL	$H_1H_2 \to (\gamma^* \to)l_{\rm IL}\bar{l}_{\rm IL} + X$
–1460–IL	$H_1H_2 \to (W^+ \to)l^+_{\rm IL}\nu_{\rm IL} + X$
–1470–IL	$H_1H_2 \to (W^- \to)l^-_{\rm IL}\bar{\nu}_{\rm IL} + X$
–1396	$H_1H_2 \to \gamma^*(\to \sum_i f_i\bar{f}_i) + X$
–1397	$H_1H_2 \to Z^0 + X$
–1497	$H_1H_2 \to W^+ + X$
–1498	$H_1H_2 \to W^- + X$
–1600–ID	$H_1H_2 \to H^0 + X$
–1705	$H_1H_2 \to b\bar{b} + X$
–1706	$H_1H_2 \to t\bar{t} + X$
–2850	$H_1H_2 \to W^+W^- + X$
–2860	$H_1H_2 \to Z^0Z^0 + X$
–2870	$H_1H_2 \to W^+Z^0 + X$
–2880	$H_1H_2 \to W^-Z^0 + X$

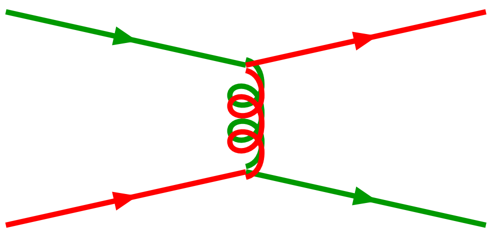
(Frixione, Webber)

- Works identically to HERWIG: the very same analysis routines can be used
- Reads shower initial conditions from an event file (as in ME corrections)
- Exploits Les Houches accord for process information and common blocks
- Features a self contained library of PDFs with old and new sets alike
- LHAPDF will also be implemented

What is multiple interactions?

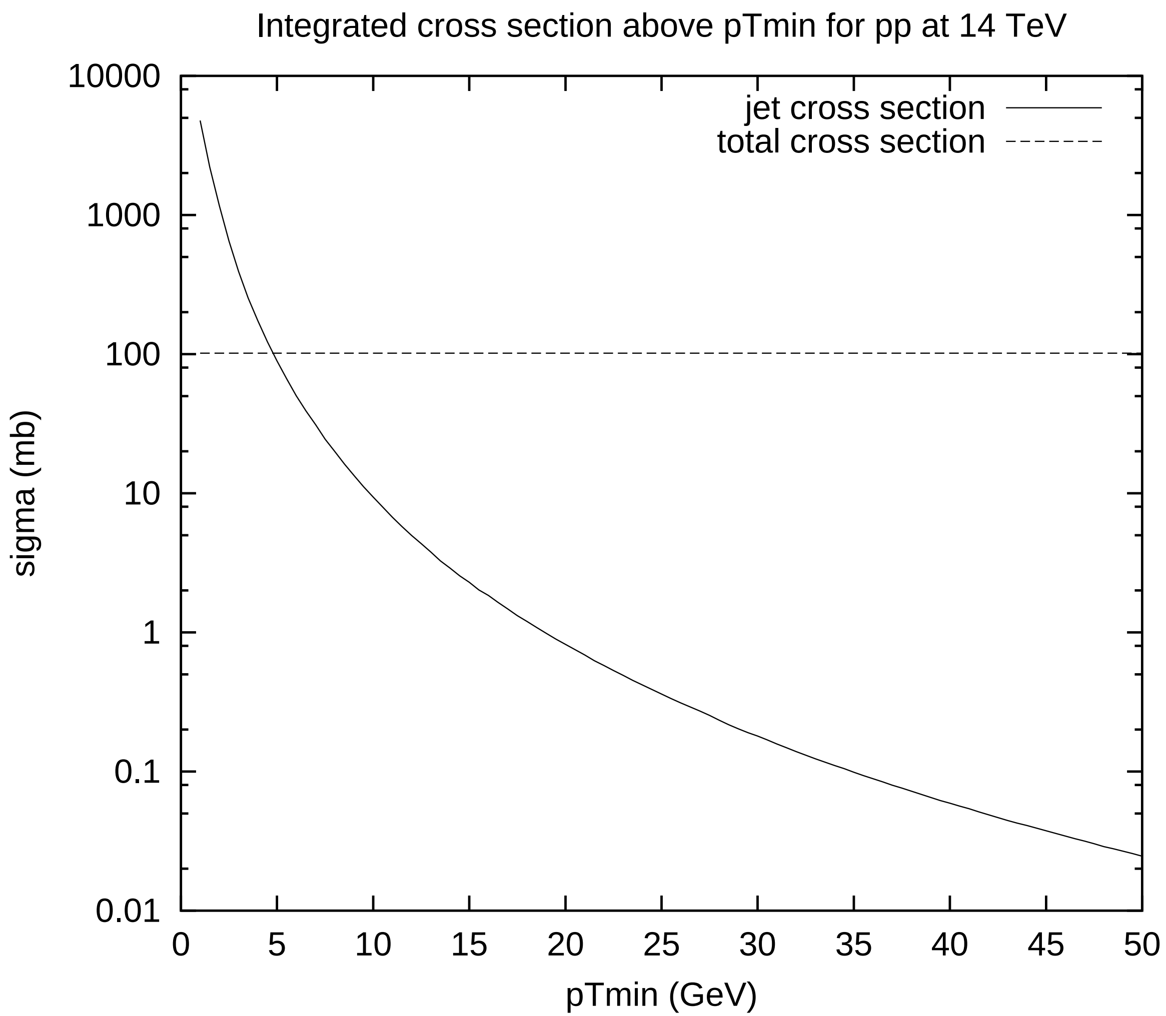
Cross section for $2 \to 2$ interactions is dominated by t-channel gluon exchange, so diverges like $\mathrm{d}\sigma/\mathrm{d}p_\perp^2 \approx 1/p_\perp^4$ for $p_\perp \to 0$.

integrate QCD $2 \to 2$



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

with CTEQ 5L PDF's



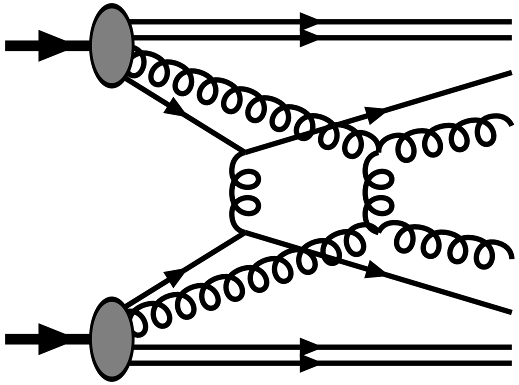
So $\sigma_{\mathrm{int}}(p_{\perp\mathrm{min}}) > \sigma_{\mathrm{tot}}$ for $p_{\perp\mathrm{min}} \lesssim 5$ GeV

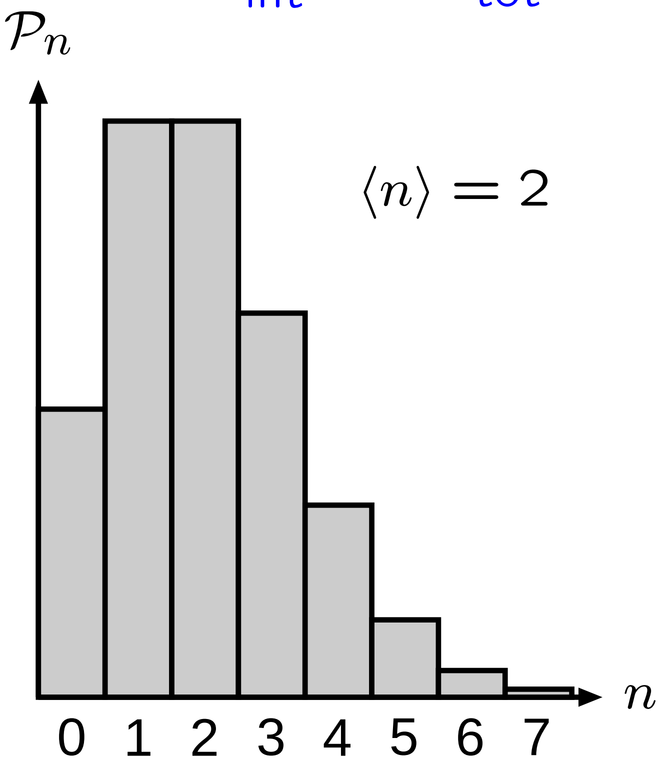
Half a solution: many interactions per event

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

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

$$\sigma_{\mathrm{int}} > \sigma_{\mathrm{tot}} \Longleftrightarrow \langle n \rangle > 1$$





If interactions occur independently
then Poissonian statistics

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

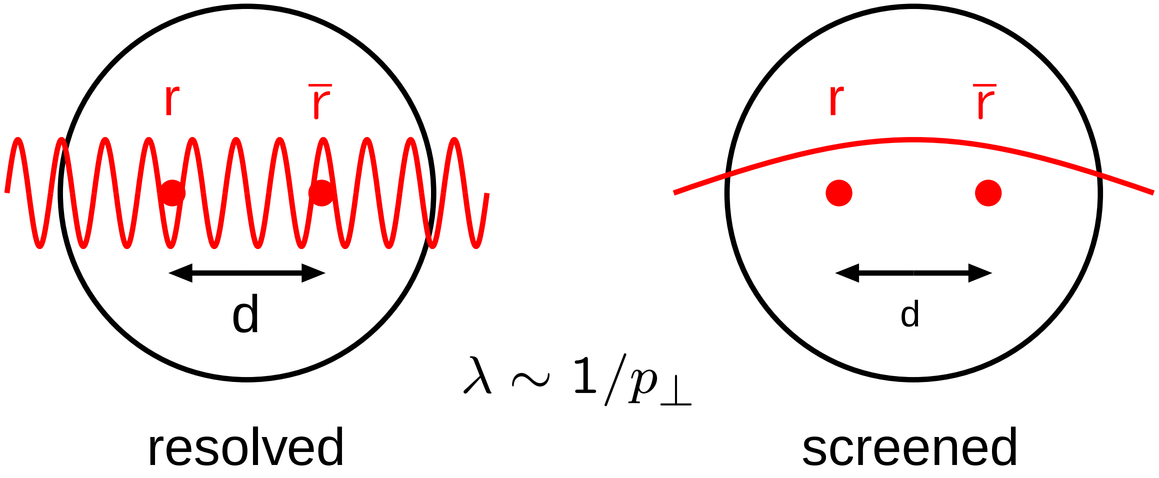
but energy–momentum conservation
$\Rightarrow$ large n suppressed

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

Naively breakdown at

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

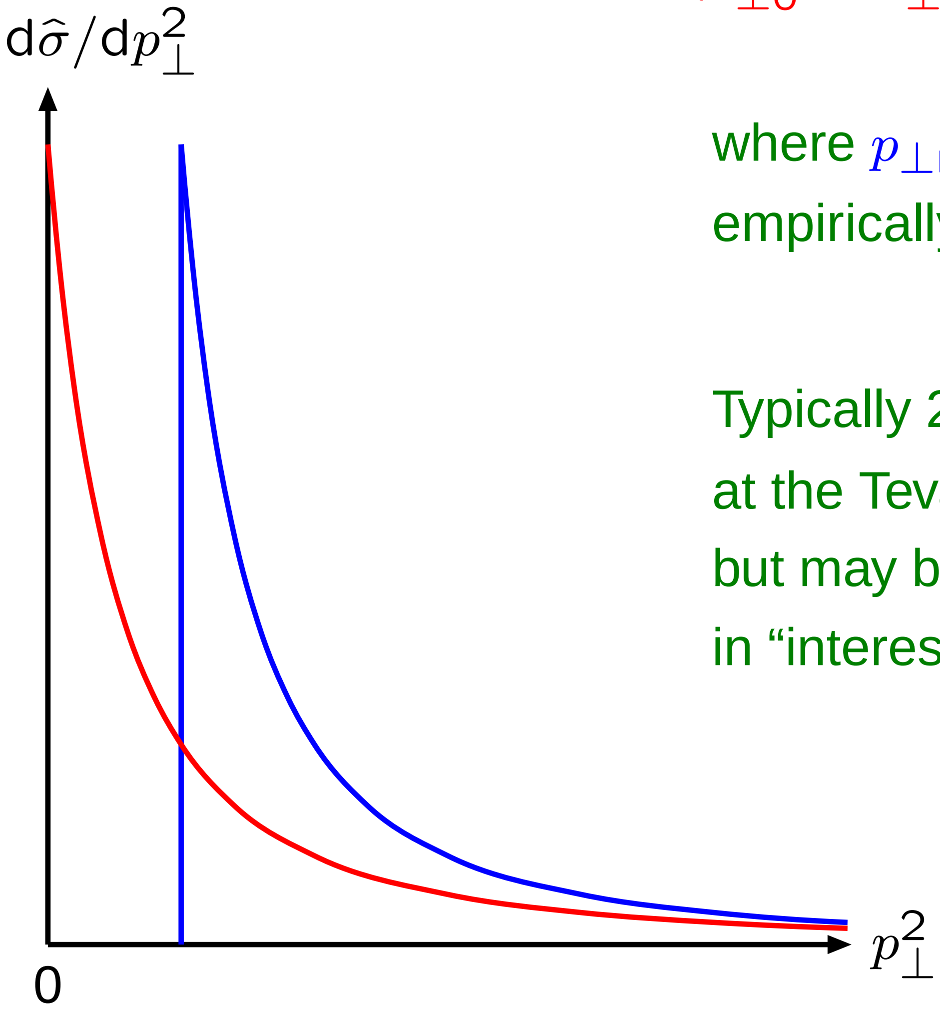
. . . but better replace r_p by (unknown) colour screening length d in hadron



so modify

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

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



where $p_{\perp\min}$ 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 model(s) for event properties based on perturbative multiple interactions

(1) Simple scenario:

- Sharp cut-off at $p_{\perp\mathrm{min}}$ main free parameter
- Is only a model for nondiffractive events, i.e. for $\sigma_{\mathrm{nd}} \simeq (2/3)\sigma_{\mathrm{tot}}$
- Average number of interactions is $\langle n \rangle = \sigma_{\mathrm{int}}(p_{\perp\mathrm{min}})/\sigma_{\mathrm{nd}}$
- Interactions occur almost independently, i.e.
  Poissonian statistics $\mathcal{P}_n = \langle n \rangle^n e^{-\langle n \rangle}/n!$
  with fraction $\mathcal{P}_0 = e^{-\langle n \rangle}$ pure low-$p_\perp$ events
- Interactions generated in ordered sequence $p_{\perp 1} > p_{\perp 2} > p_{\perp 3} > \ldots$
  by "Sudakov" trick (what happens "first"?)

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

- Momentum conservation in PDF's $\Rightarrow \mathcal{P}_n$ narrower than Poissonian
- Simplify after first interaction: only gg or $\mathrm{q\overline{q}}$ outgoing, no showers, ...

(2) More sophisticated scenario:

- Smooth turn-off at $p_{\perp 0}$ scale
- Require ≥ 1 interaction in an event
- Hadrons are extended,

  e.g. double Gaussian (“hot spots”):

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

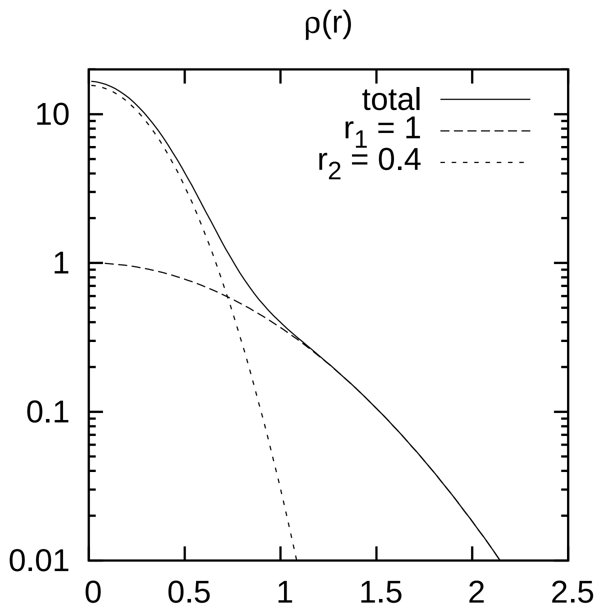
  where $r_2 \neq r_1$ represents “hot spots”
- Events are distributed in impact parameter b
- Overlap of hadrons during collision

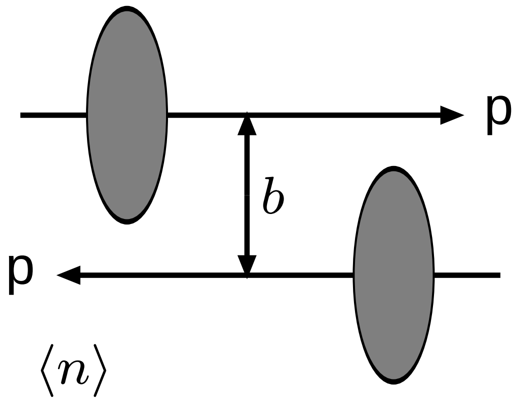
$$\mathcal{O}(b) = \int \mathrm{d}^3\mathbf{x}\,\mathrm{d}t\;\rho_{1,\mathrm{matter}}^{\mathrm{boosted}}(\mathbf{x},t)\,\rho_{2,\mathrm{matter}}^{\mathrm{boosted}}(\mathbf{x},t)$$

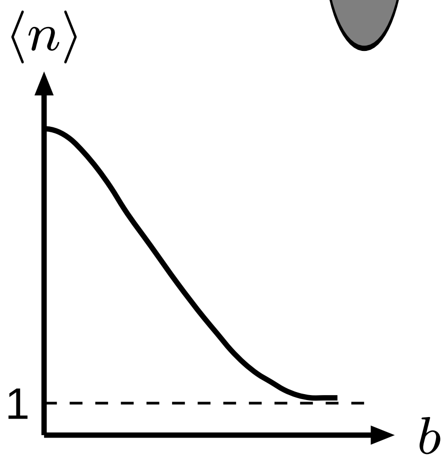
- Average activity at b proportional to $\mathcal{O}(b)$

  $\Rightarrow$ central collisions normally more active

  $\Rightarrow$ $\mathcal{P}_n$ broader than Poissonian
- More time-consuming $(b, p_\perp)$ generation
- Need for simplifications remains

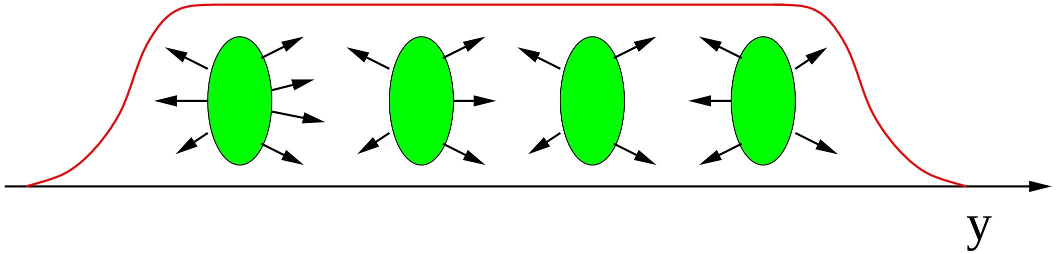






(3) HERWIG

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" $\approx p_\perp \rightarrow 0$ limit of multiple interactions
- extended also to "hard" interactions similarly to PYTHIA

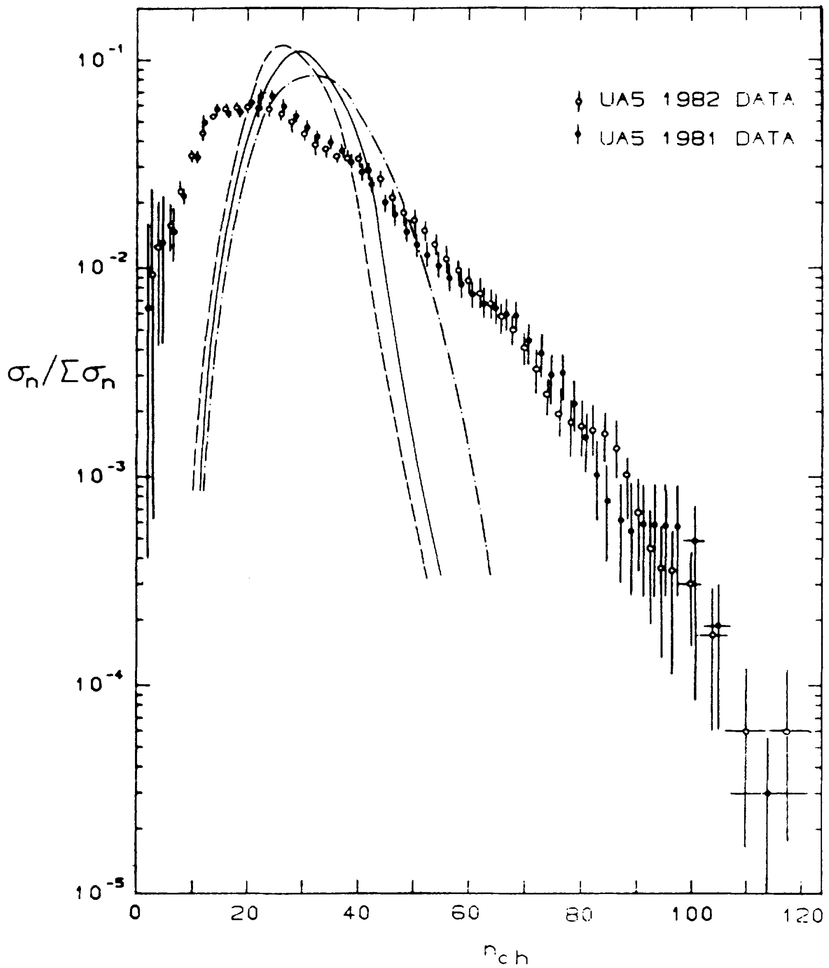


FIG. 3. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs simple models: dashed low p_T only, full including hard scatterings, dash-dotted also including initial- and final-state radiation.

without multiple interactions

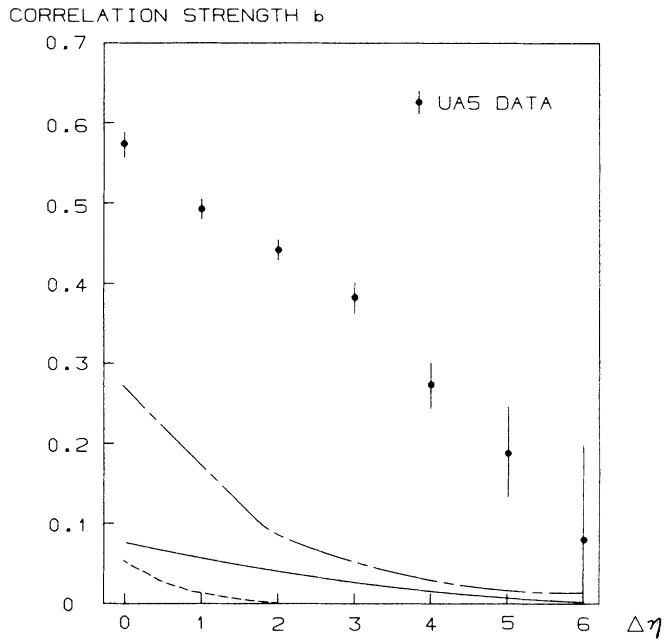


FIG. 4. Forward-backward multiplicity correlation at 540 GeV, UA5 results (Ref. 33) vs simple models; the latter models with notation as in Fig. 3.

with multiple interactions

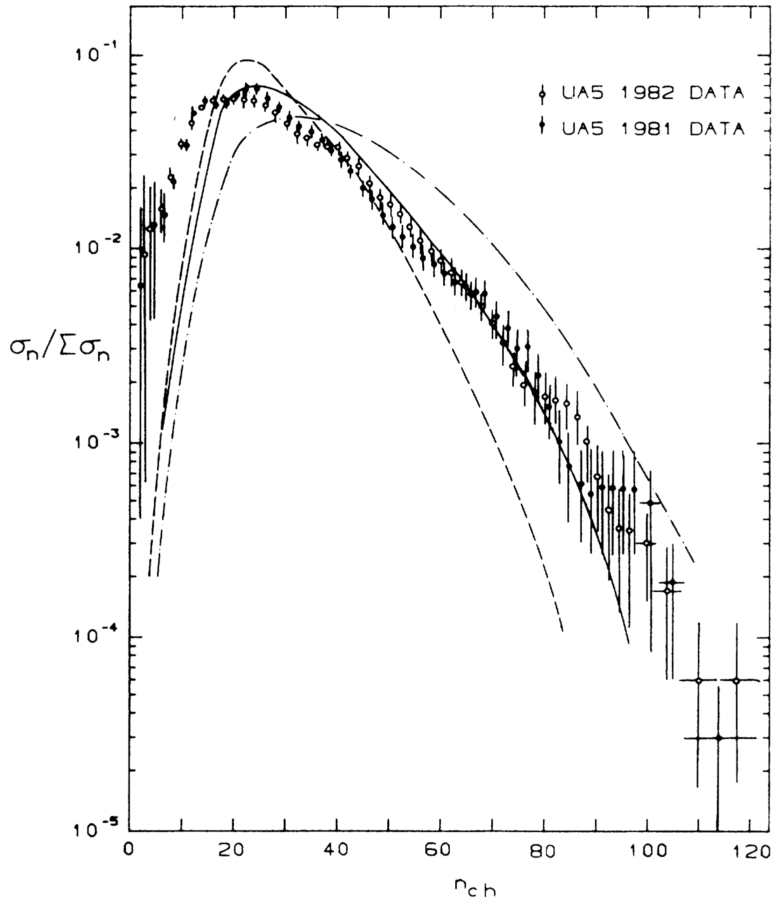


FIG. 5. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs impact-parameter-independent multiple-interaction model: dashed line, $p_{T\min}=2.0$ GeV; solid line, $p_{T\min}=1.6$ GeV; dashed-dotted line, $p_{T\min}=1.2$ GeV.

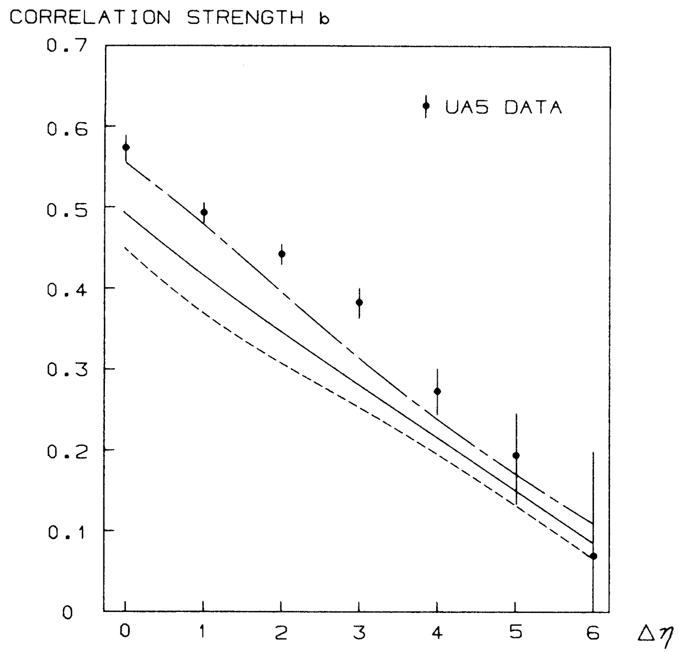
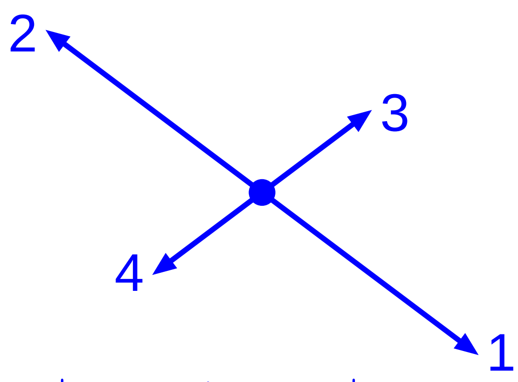


FIG. 6. Forward-backward multiplicity correlation at 540 GeV, UA5 results (Ref. 33) vs impact-parameter-independent multiple-interaction model; the latter with notation as in Fig. 5.

- Direct observation: AFS, (UA2,) CDF

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 $\mathbf{p}_{\perp 1} - \mathbf{p}_{\perp 2}$ and $\mathbf{p}_{\perp 3} - \mathbf{p}_{\perp 4}$

Double Parton Scattering

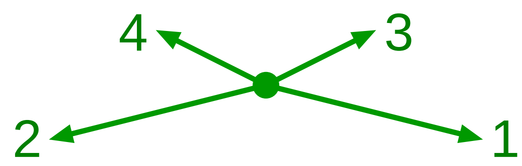


$|\mathbf{p}_{\perp 1} + \mathbf{p}_{\perp 2}| \approx 0$

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

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

Double BremsStrahlung



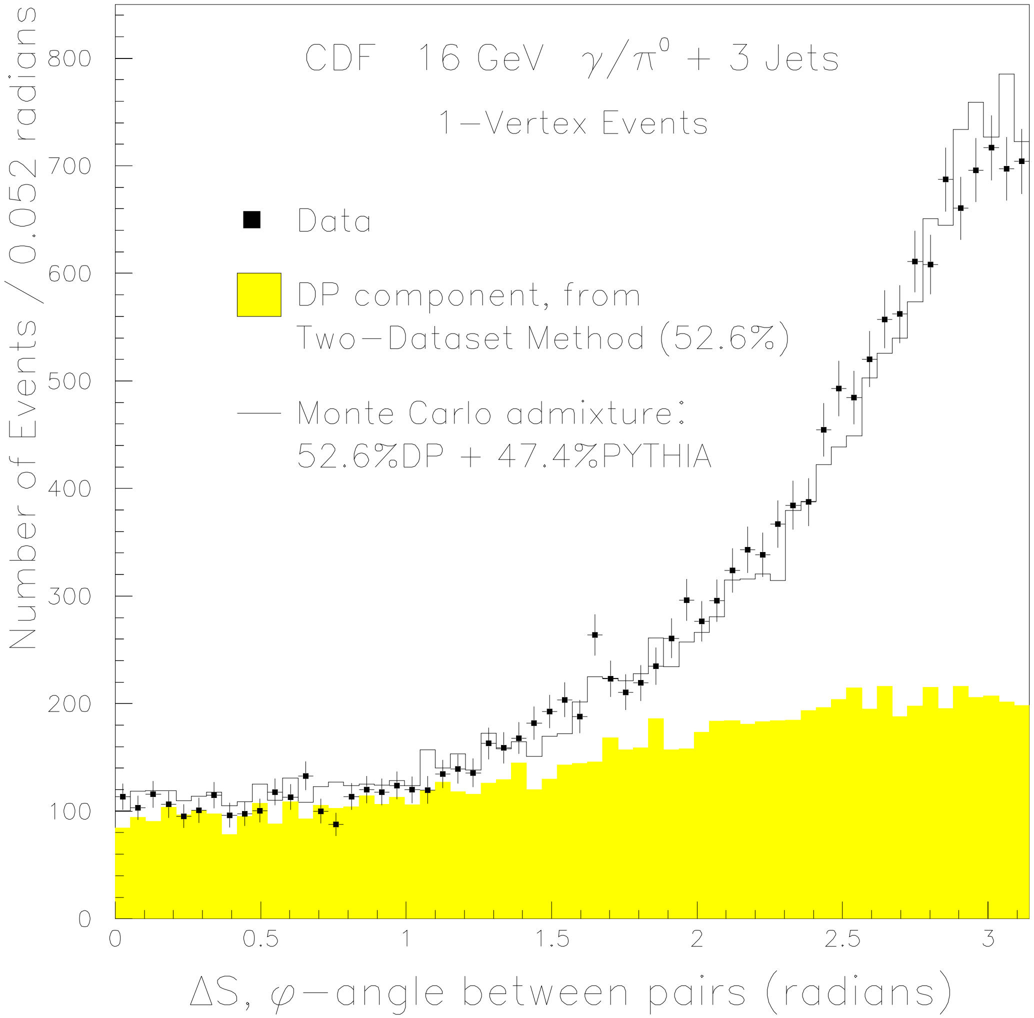
$|\mathbf{p}_{\perp 1} + \mathbf{p}_{\perp 2}| \gg 0$

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

$\mathrm{d}\sigma/\mathrm{d}\varphi$ peaked at $\varphi \approx 0$

AFS 4-jet analysis (pp at 63 GeV);
double bremsstrahlung subtracted:

observed	6	in arbitrary units
no MI	0	
simple MI	1	
double Gaussian	3.7	



CDF 3-jet + prompt photon analysis

Yellow region = double parton scattering (DPS)

The rest = PYTHIA showers

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

Strong enhancement relative to naive expectations!

• Jet pedestal effect: UA1, H1, CDF

Events with hard scale (jet, W/Z, . . .) have more underlying activity!

Events with n interactions have n chances that one of them is hard,

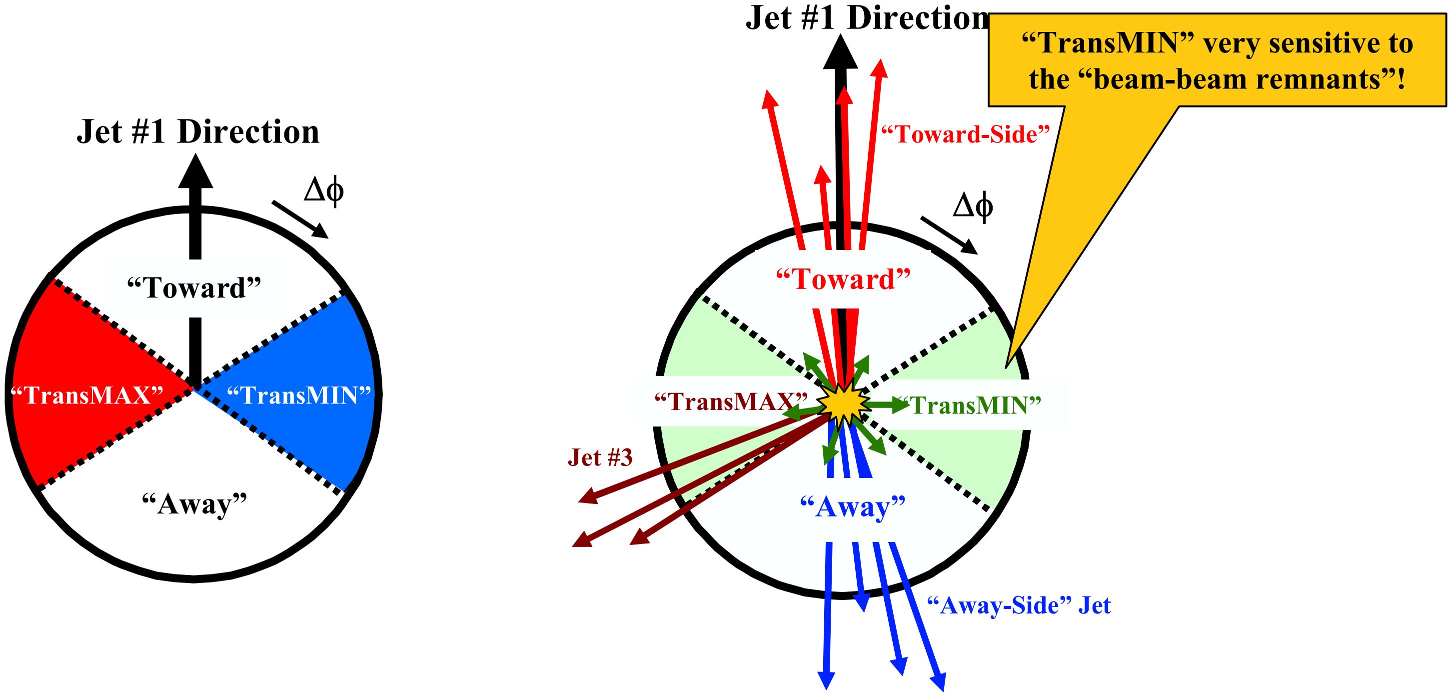
so "trigger bias": hard scale $\Rightarrow$ central collision

$\Rightarrow$ 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:

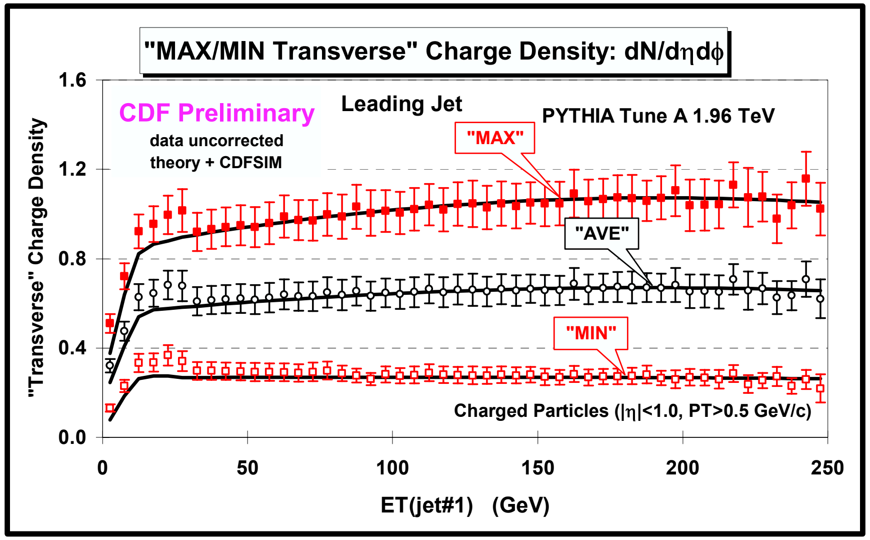
"MAX/MIN Transverse" Densities

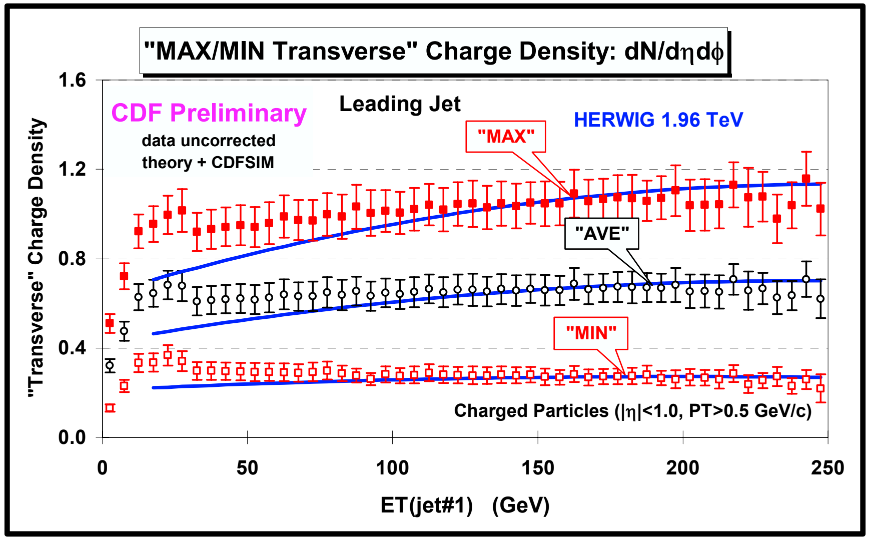


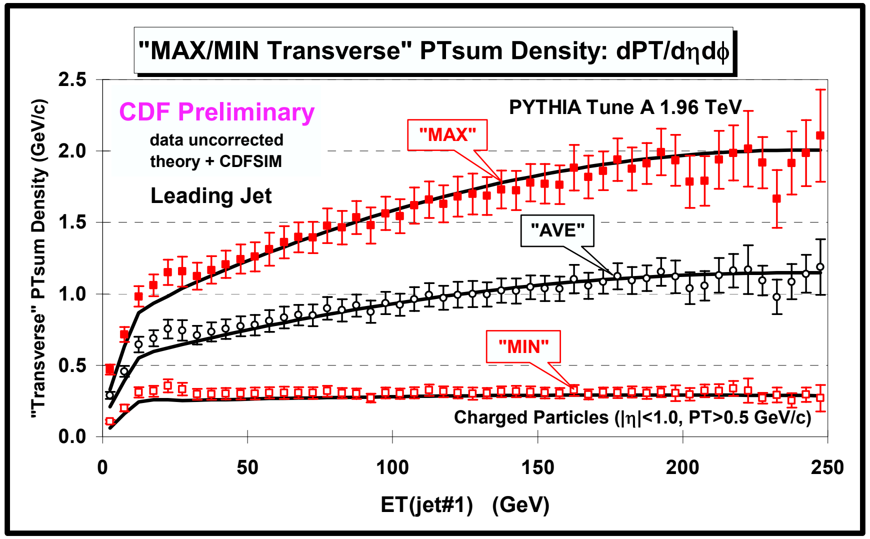
- **Define the MAX and MIN "transverse" regions on an event-by-event basis with MAX (MIN) having the largest (smallest) density.**

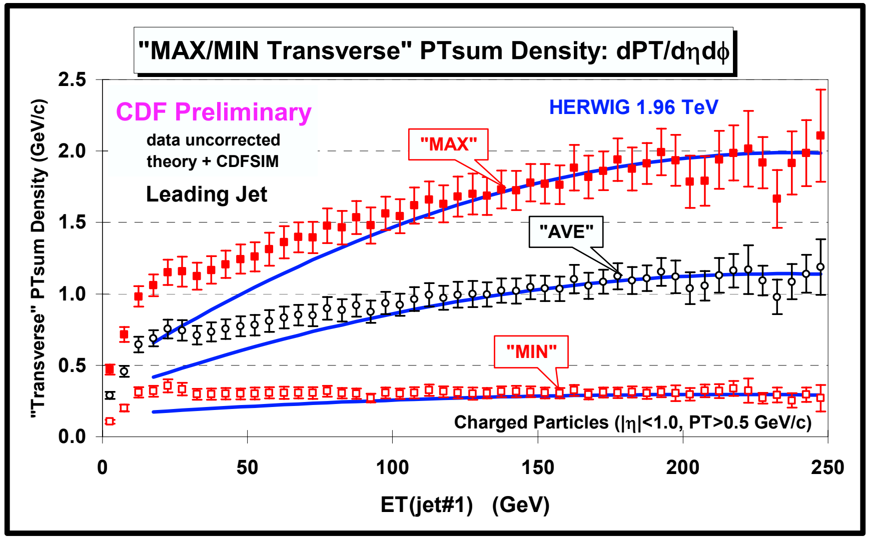
Leading Jet: “MAX & MIN Transverse” Densities

PYTHIA Tune A HERWIG



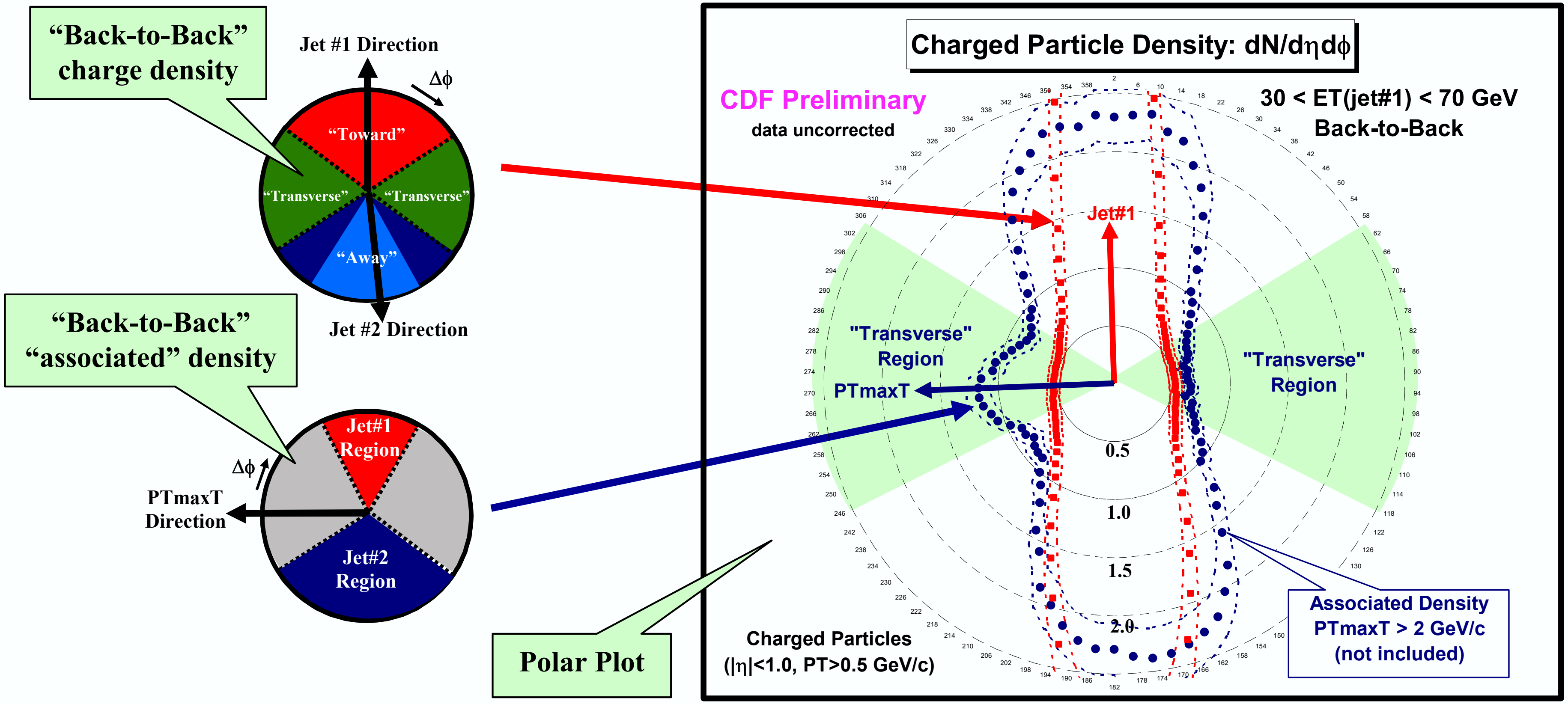






Charged particle density and PTsum density for “leading jet” events versus E_T(jet#1) for PYTHIA Tune A and HERWIG.

Back-to-Back "Associated" Charged Particle Densities



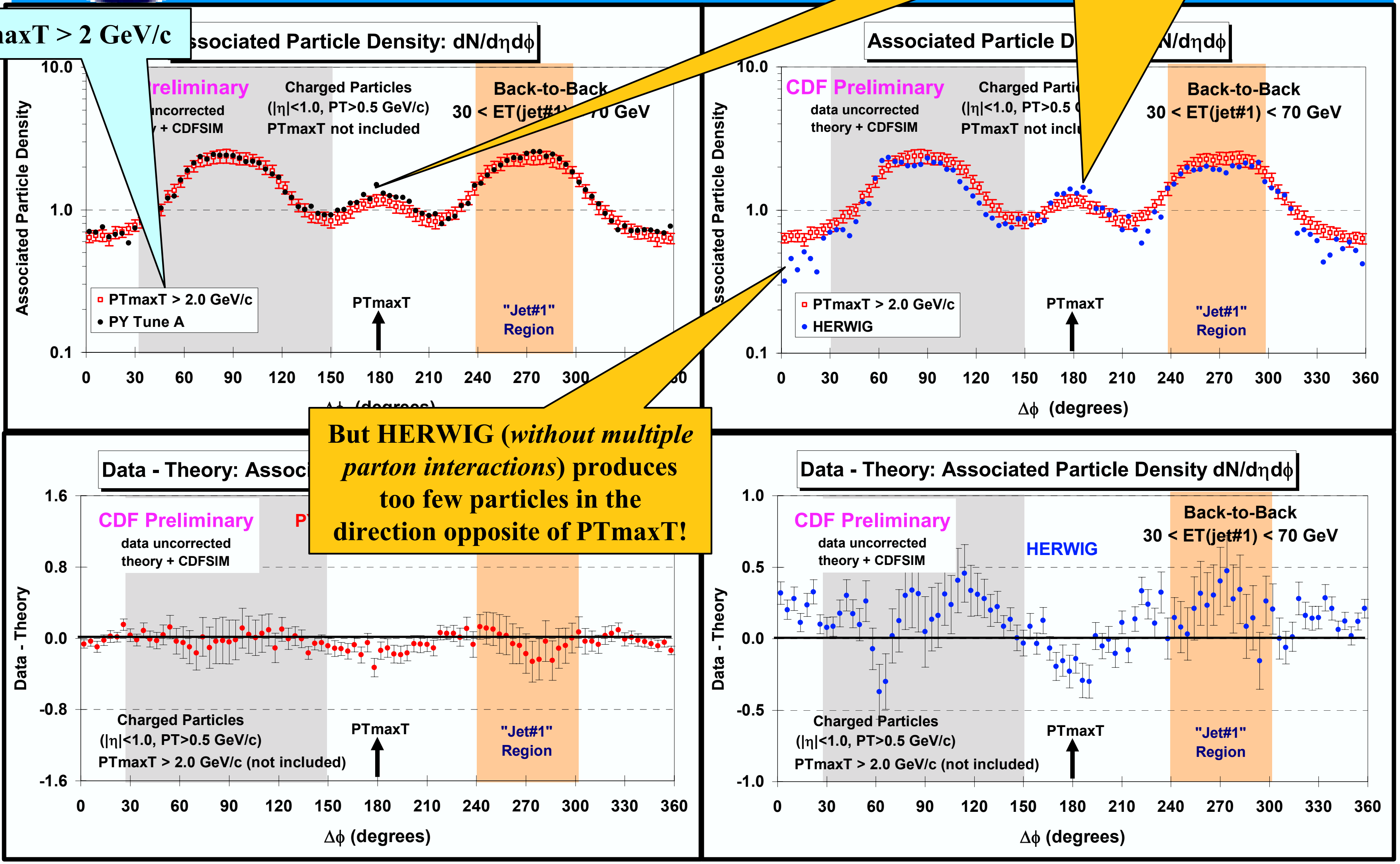
- Shows the **Δϕ dependence of the "associated" charged particle density**, $dN_{chg}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$, PTmaxT > 2.0 GeV/c (*not including PTmaxT*) relative to PTmaxT (rotated to 180°) and the charged particle density, $dN_{chg}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$, 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…

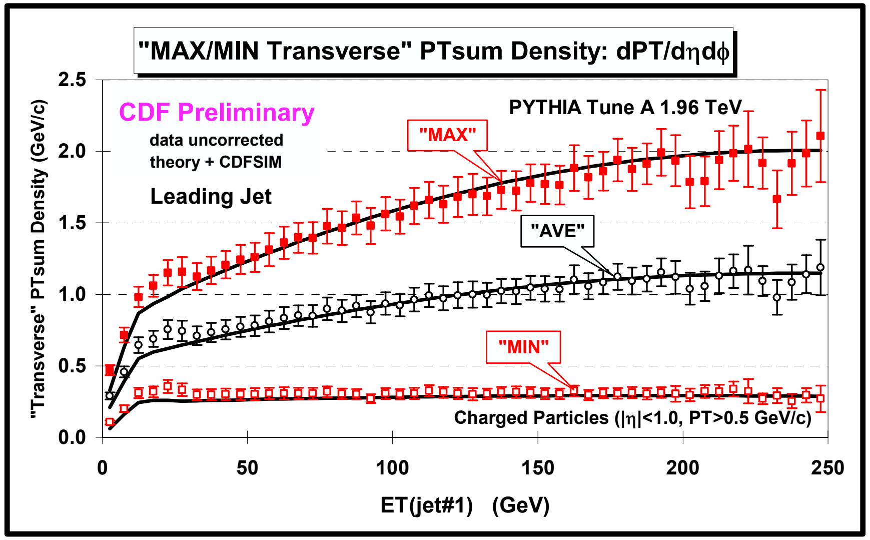
For PTmaxT > 2.0 GeV both PYTHIA and HERWIG produce slightly too many "associated" particles in the direction of PTmaxT!

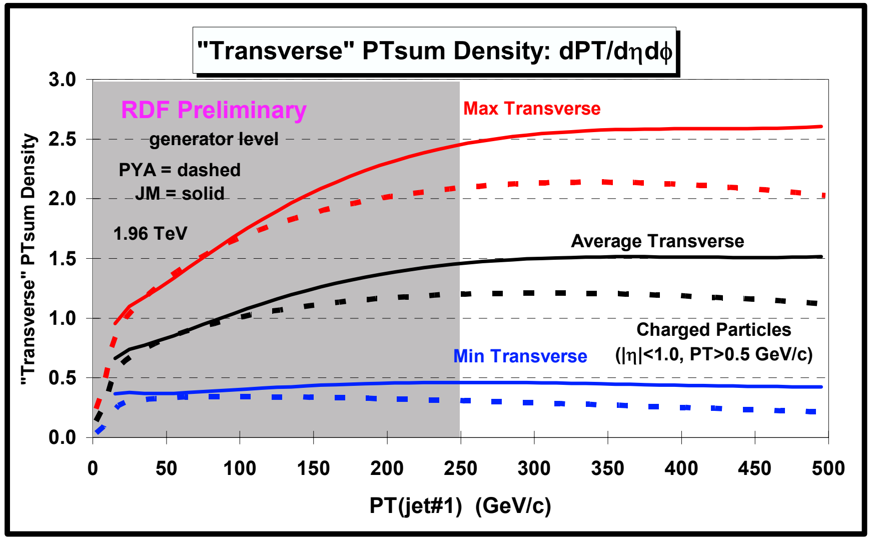
PTmaxT > 2 GeV/c

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



PYTHIA Tune A vs JIMMY: "Transverse Region"

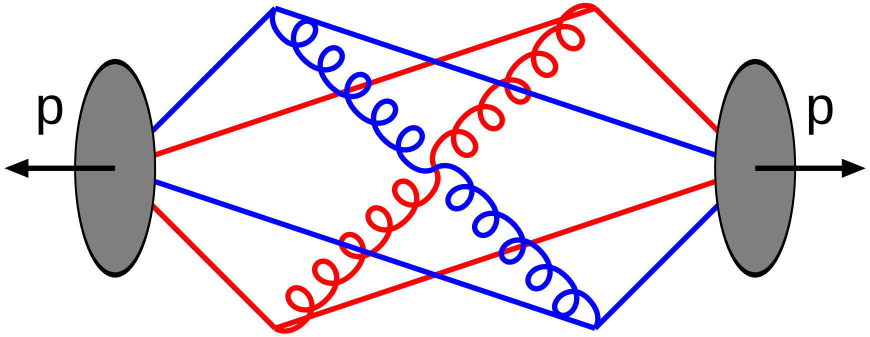




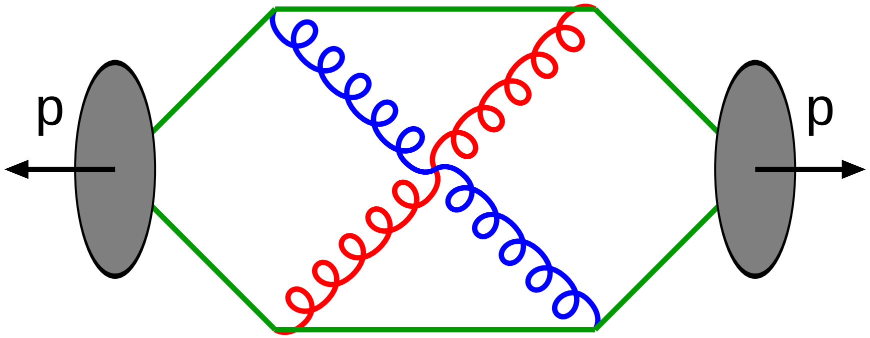
- **(*left*) Run 2 data for charged *scalar* PTsum density (|η|<1, p_T>0.5 GeV/c) in the MAX/MIN/AVE "transverse" region versus P_T(jet#1) compared with PYTHIA Tune A (*after CDFSIM*).**
- **(*right*) Shows the generator level predictions of PYTHIA Tune A (*dashed*) and JIMMY ($P_T$min=1.8 GeV/c) for charged *scalar* PTsum density (|η|<1, p_T>0.5 GeV/c) in the MAX/MIN/AVE "transverse" region versus P_T(jet#1).**
- **The tuned JIMMY now agrees with PYTHIA for P_T(jet#1) < 100 GeV but produces much more activity than PYTHIA Tune A (and the data?) in the "transverse" region for P_T(jet#1) > 100 GeV!**

Colour correlations

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



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



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

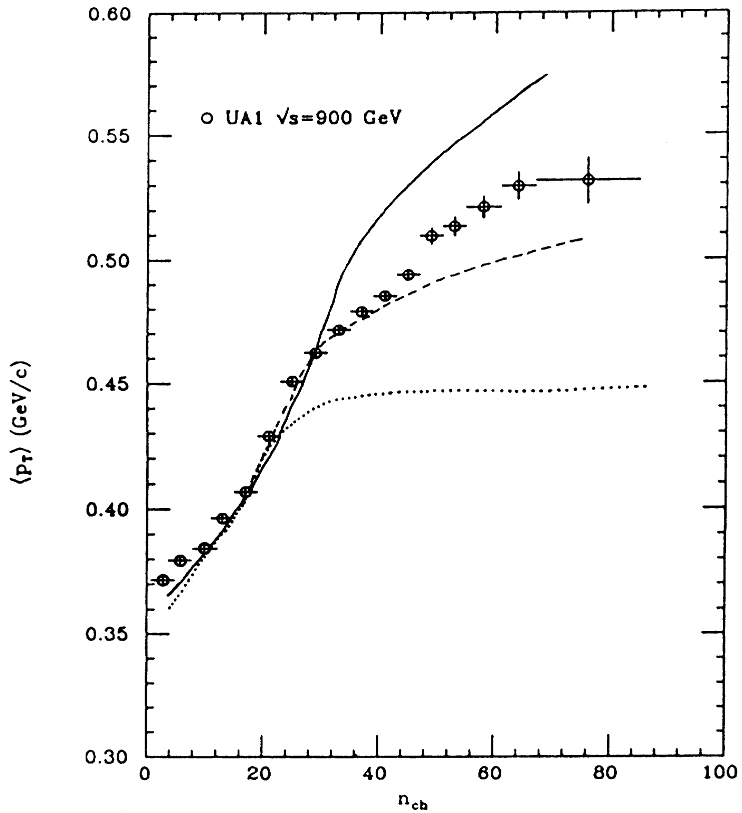
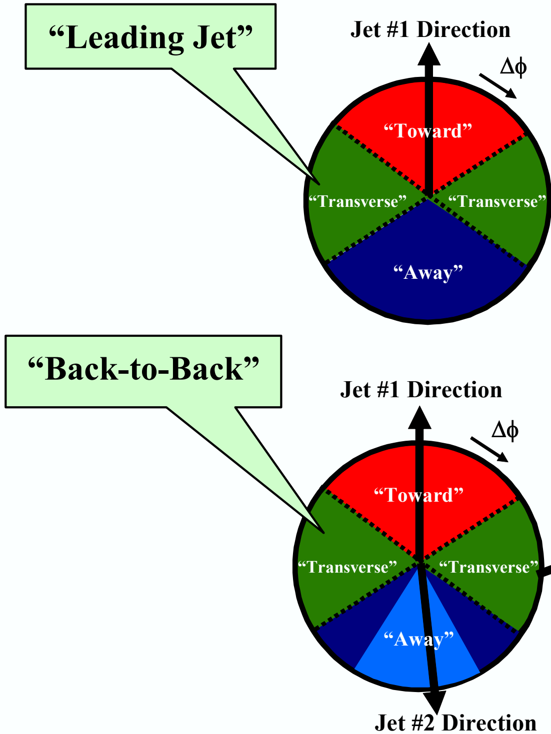
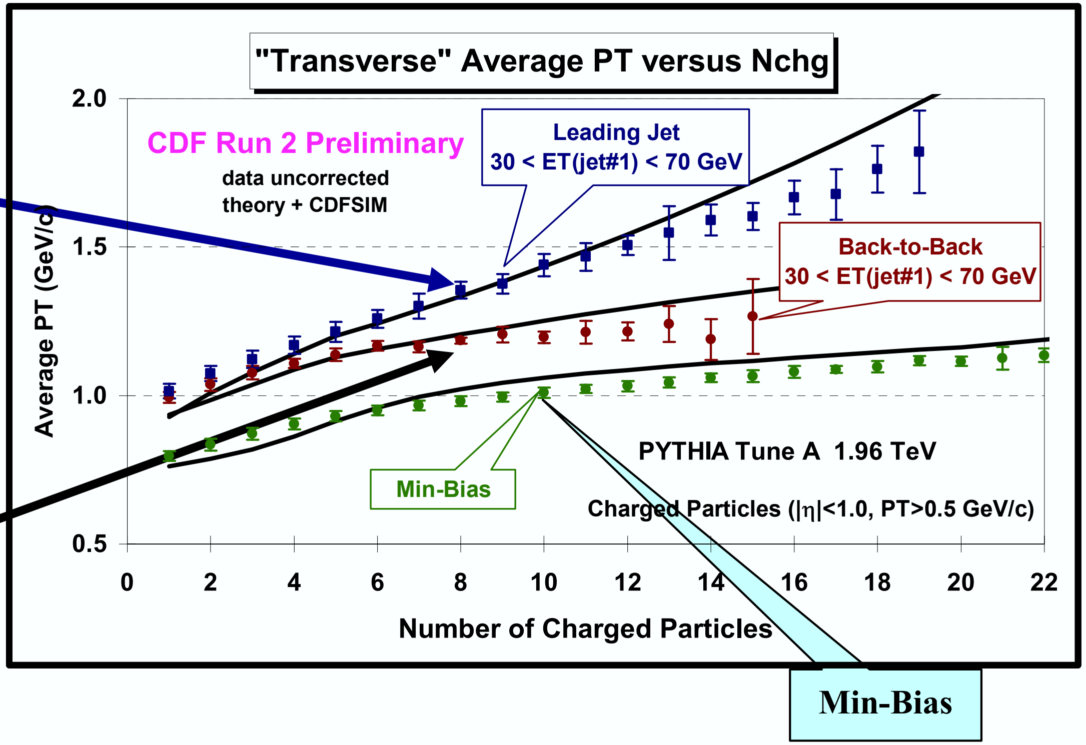


FIG. 27. Average transverse momentum of charged particles in $|\eta| < 2.5$ as a function of the multiplicity. UA1 data points (Ref. 49) at 900 GeV compared with the model for different assumptions about the nature of the subsequent (nonhardest) interactions. Dashed line, assuming $q\bar{q}$ scatterings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

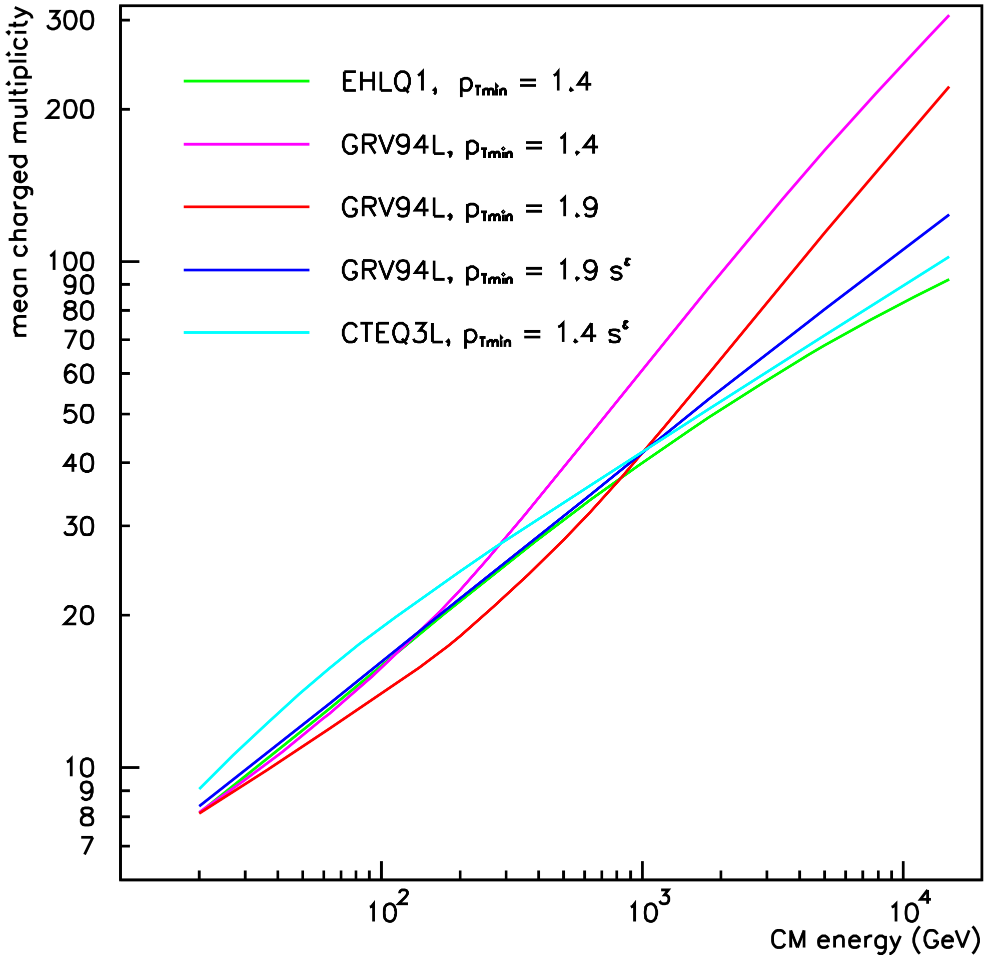
"Transverse" $<p_T>$ versus "Transverse" Nchg





- Look at the $<p_T>$ of particles in the "transverse" region ($p_T > 0.5$ GeV/c, $|\eta| < 1$) versus the number of particles in the "transverse" region: $<p_T>$ vs Nchg.
- Shows $<p_T>$ 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(jet#1) < 70 GeV compared with "min-bias" collisions.

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 $p_{\perp 0}$

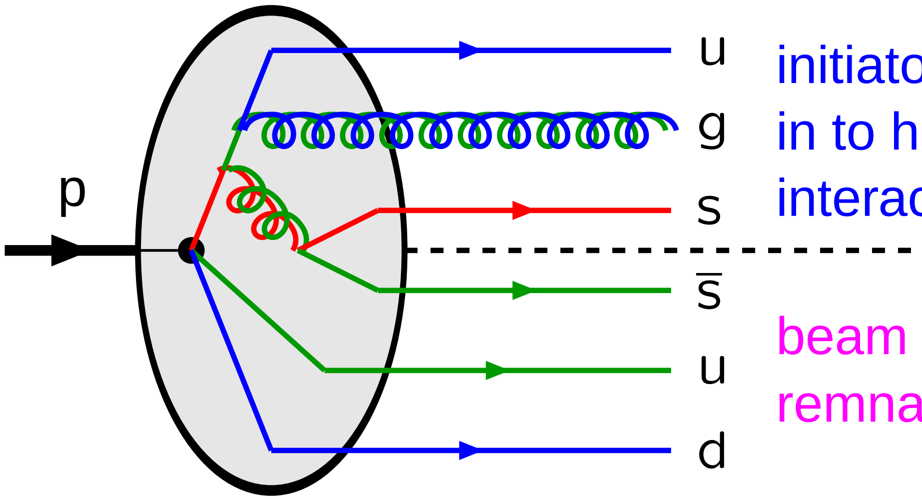
Post-HERA PDF fits steeper at small x

$\Rightarrow$ stronger energy dependence

Current PYTHIA default (Tune A, old model), tied to CTEQ 5L, is

$$p_{\perp\mathrm{min}}(s) = 2.0\ \mathrm{GeV}\left(\frac{s}{(1.8\ \mathrm{TeV})^2}\right)^{0.08}$$

Initiators and Remnants



Need to assign:

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

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

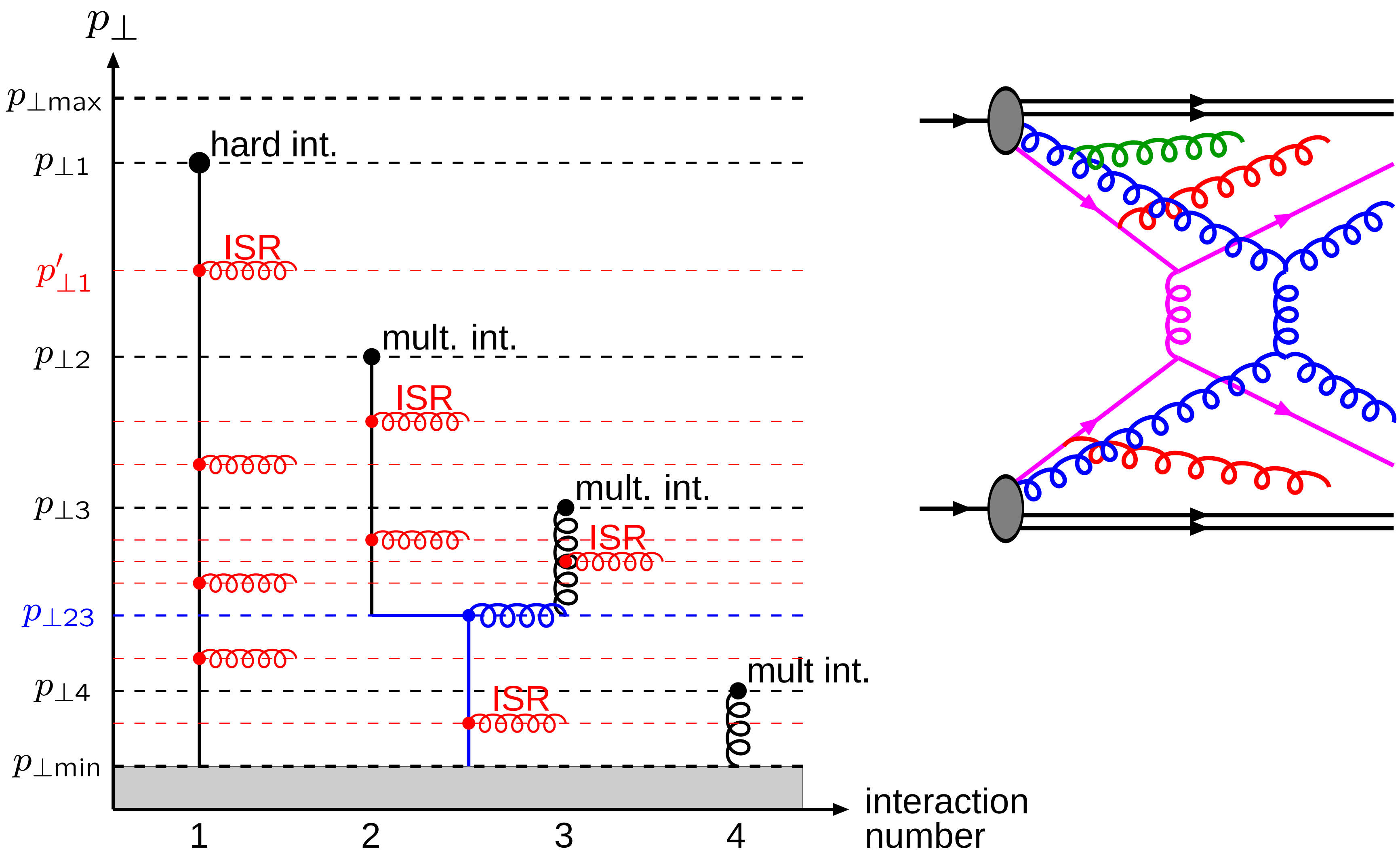
0) Squeeze range $0 < x < 1$ into $0 < x < 1 - \sum x_i$ (ISR: $i \neq i_{\mathrm{current}}$)

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

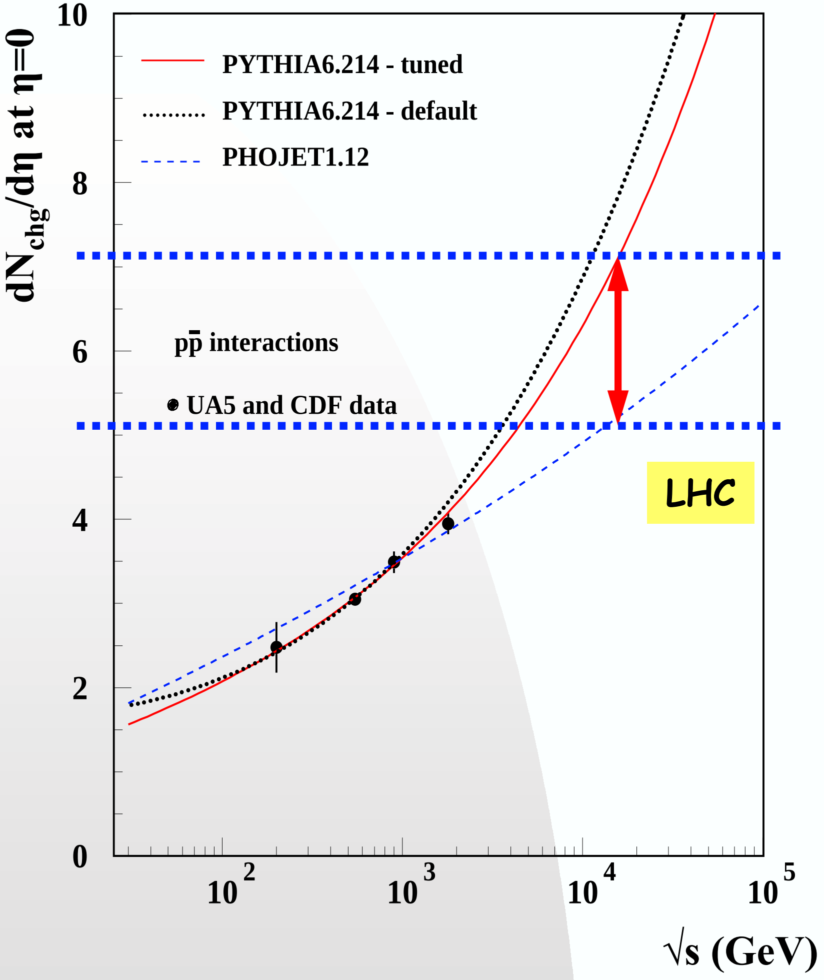
2) Introduce companion quark $\mathrm{q}/\overline{\mathrm{q}}$ to each kicked-out sea quark $\overline{\mathrm{q}}/\mathrm{q}$, with x based on assumed $\mathrm{g} \to \mathrm{q}\overline{\mathrm{q}}$ splitting

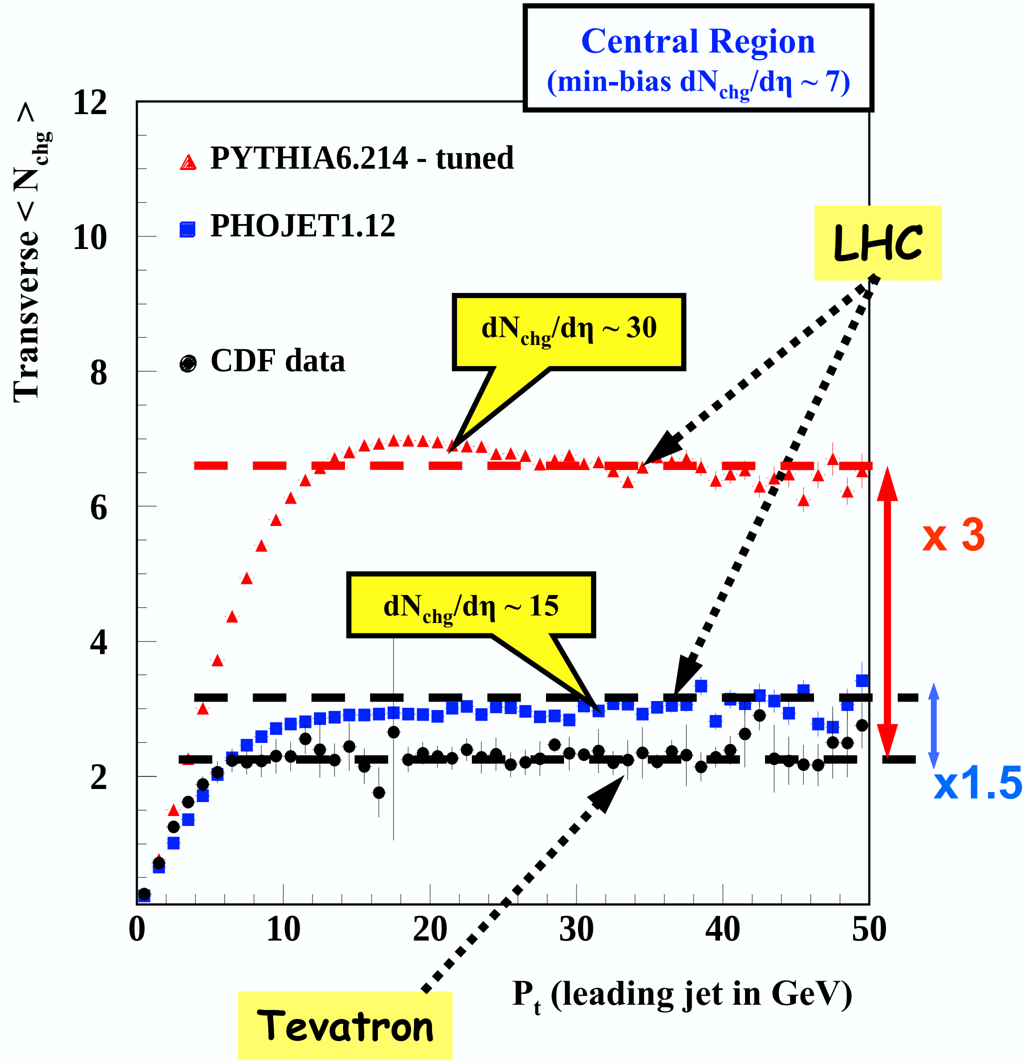
3) Gluon and other sea: rescale for total momentum conservation

Interleaved Multiple Interactions



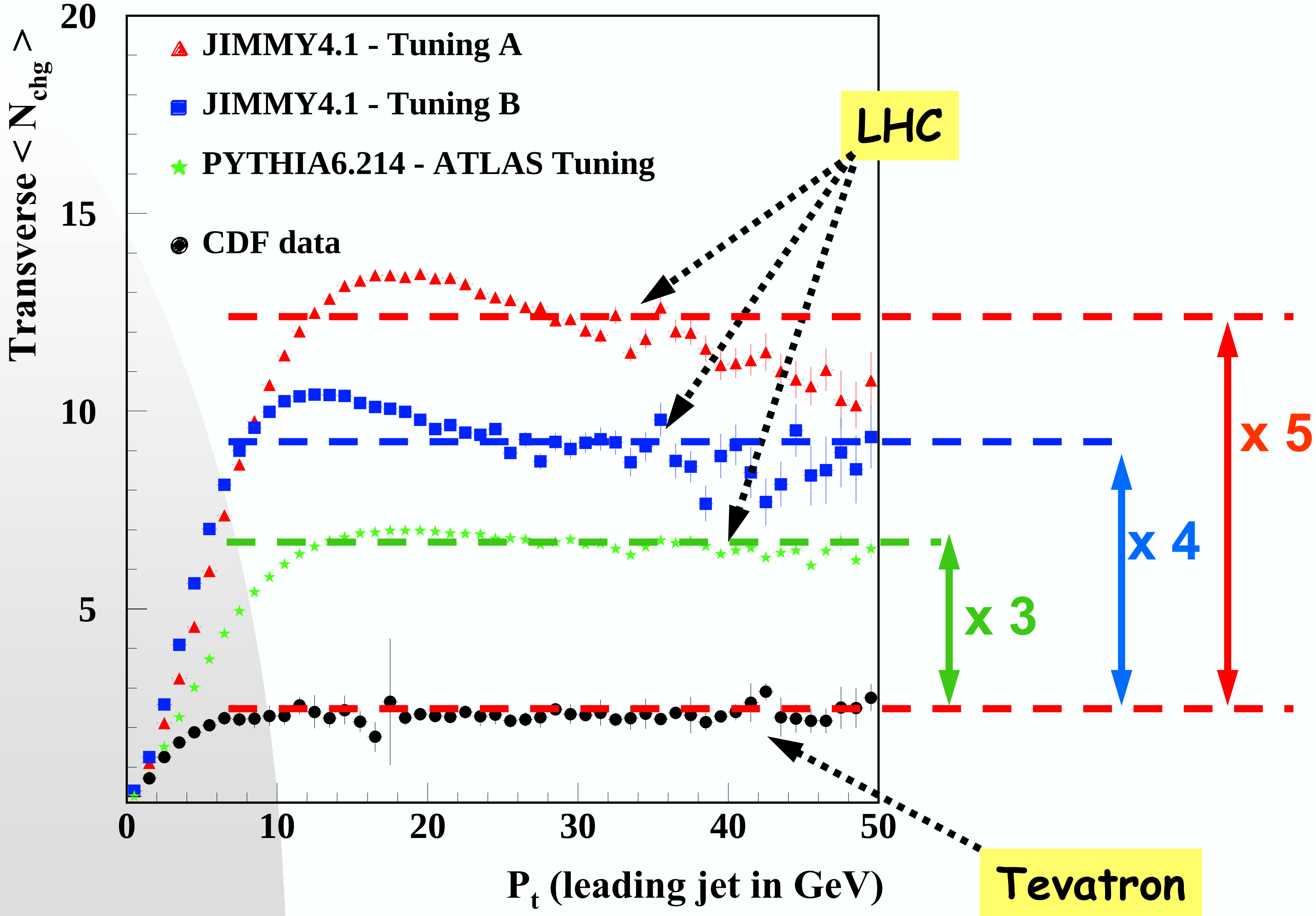
LHC predictions: pp collisions at √s = 14 TeV





- 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)



Hadronization/Fragmentation models

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

Model building = ideology + “cookbook”

Common approaches:

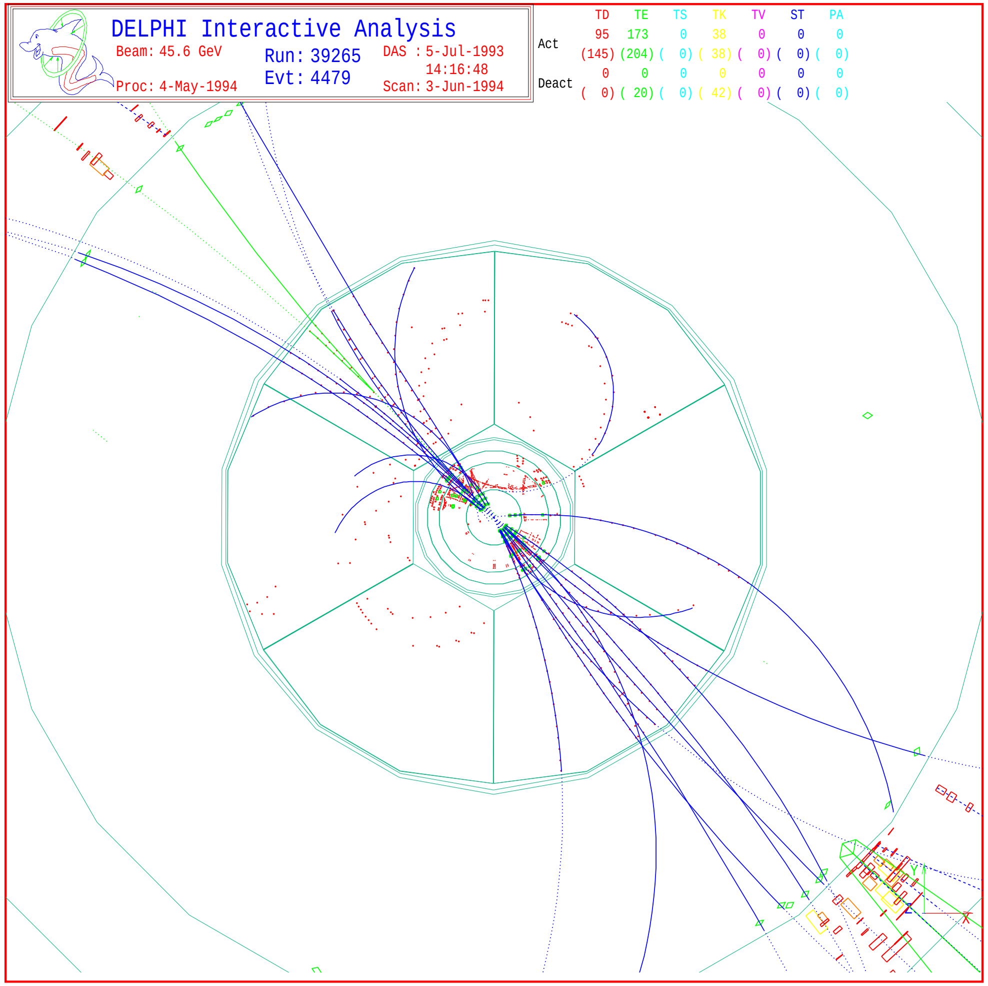
1) **String** Fragmentation
(most ideological)

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

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

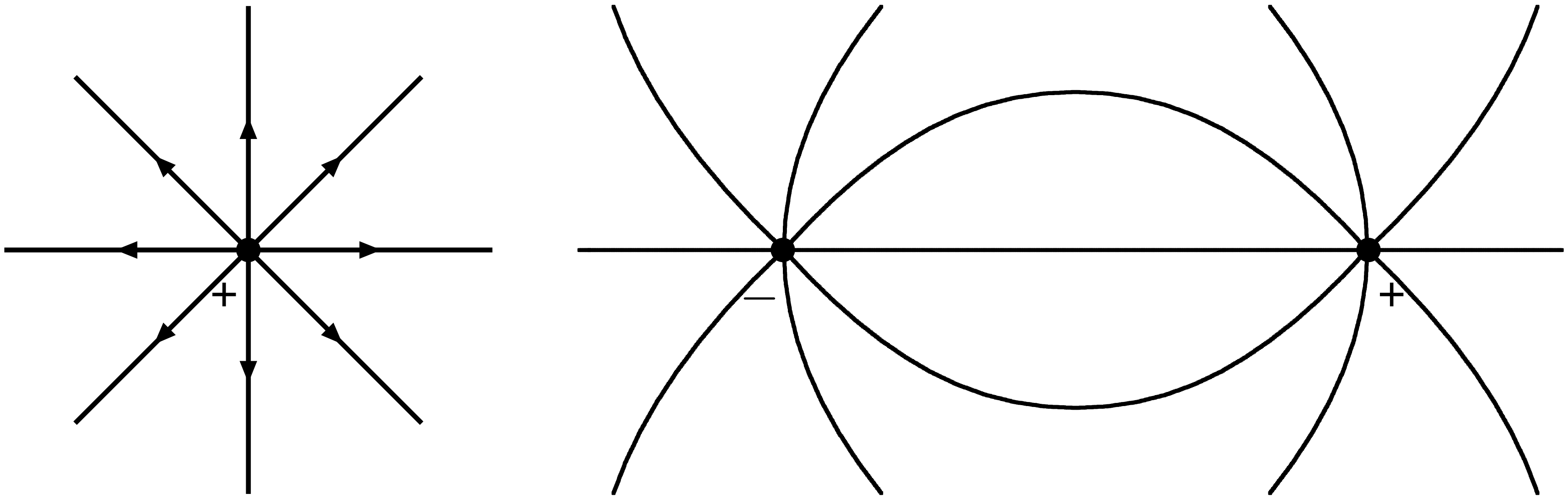
4) Local Parton–Hadron Duality
(limited applicability)

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



The Lund String Model

In QED, field lines go all the way to infinity

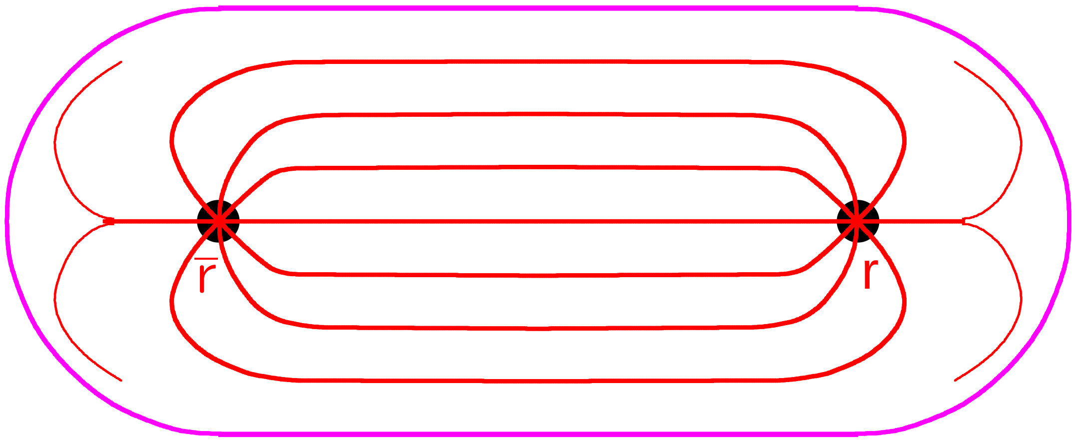


since photons cannot interact with each other.

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".

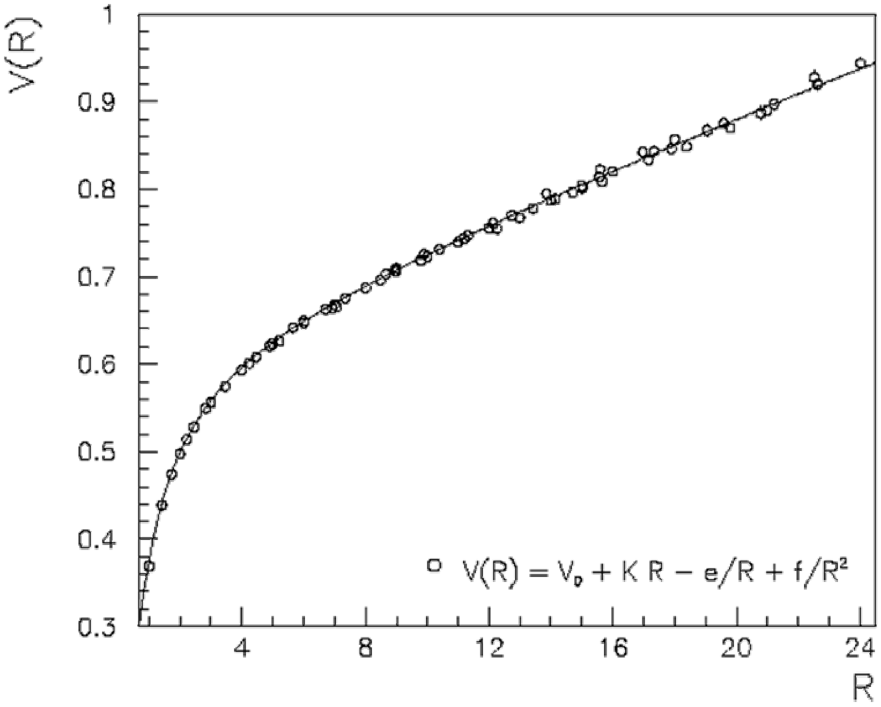
(Non-trivial ground state with quark and gluon "condensates".
Analogy: vortex lines in type II superconductor)

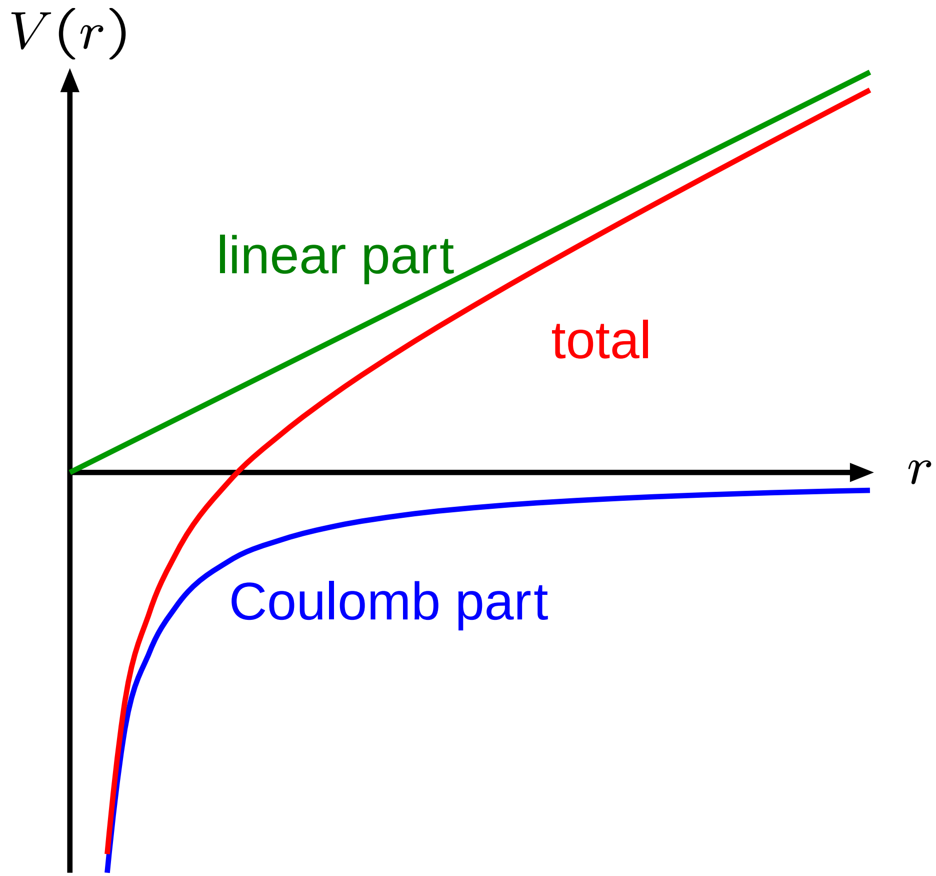
Gives linear confinement with string tension:

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

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

Linear confimenent confirmed e.g. by quenched lattice QCD





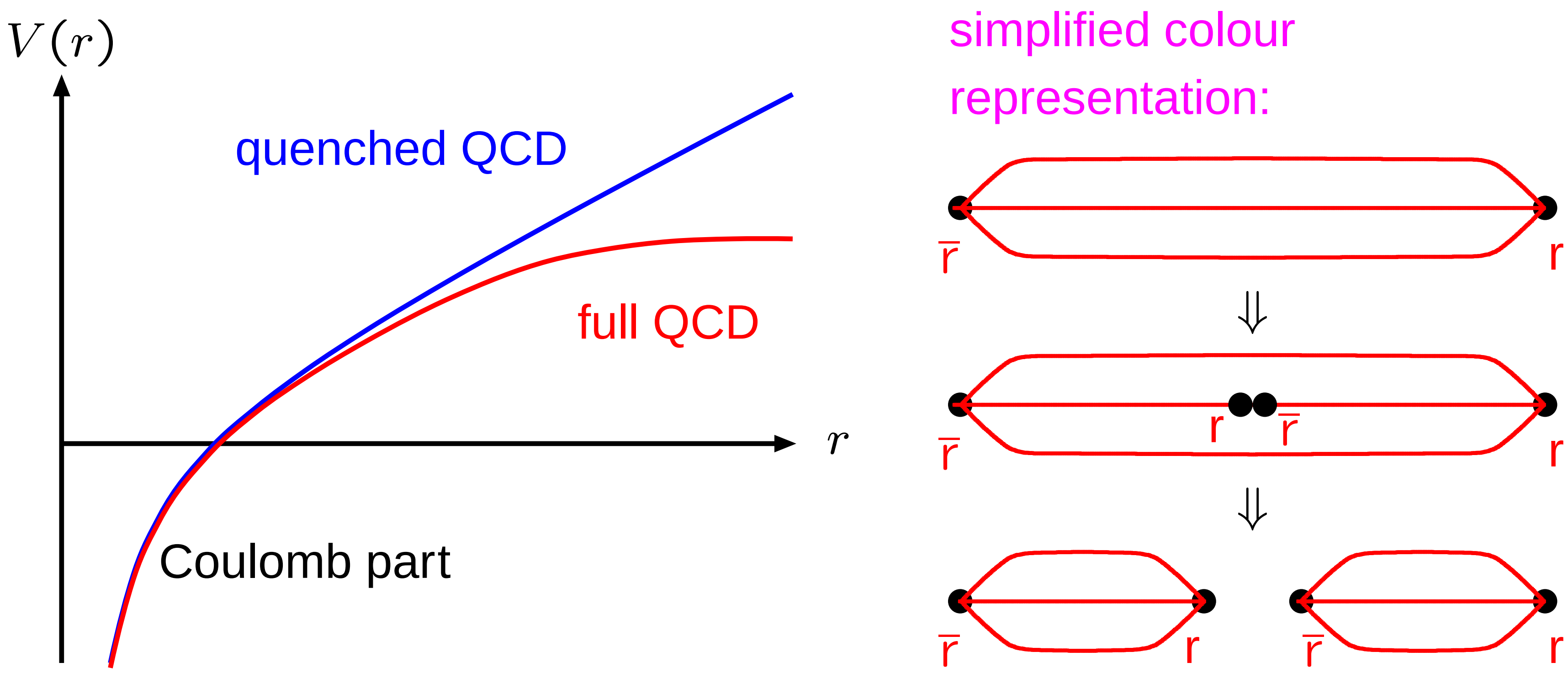
$$V(r) \approx -\frac{4}{3}\frac{\alpha_s}{r} + \kappa r \approx -\frac{0.13}{r} + r$$

(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 $gg\ldots \rightarrow q\overline{q}$

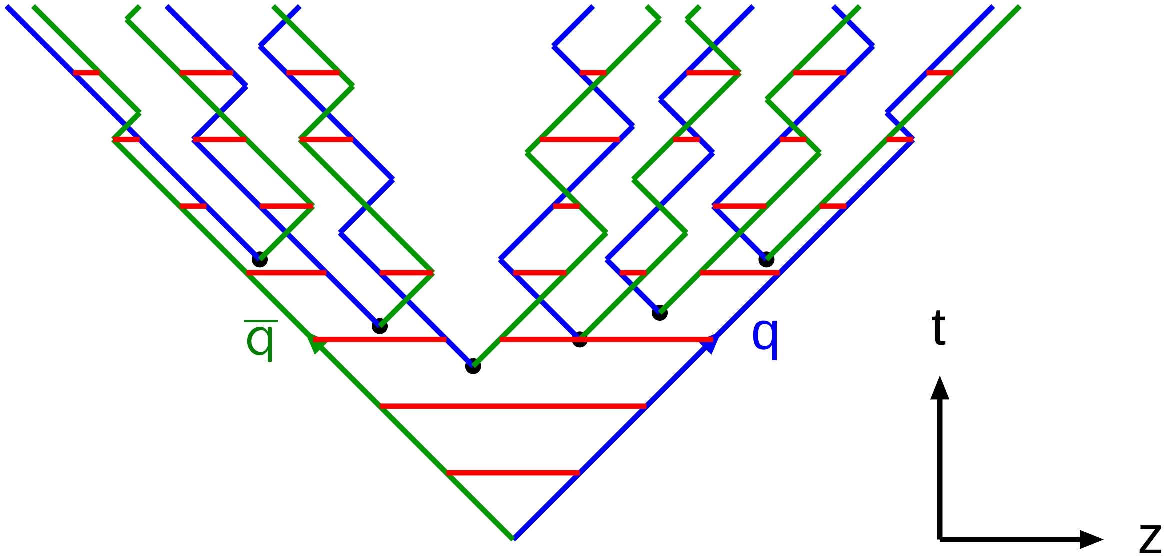


Repeat for large system ⇒ *Lund model*

which neglects Coulomb part:

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

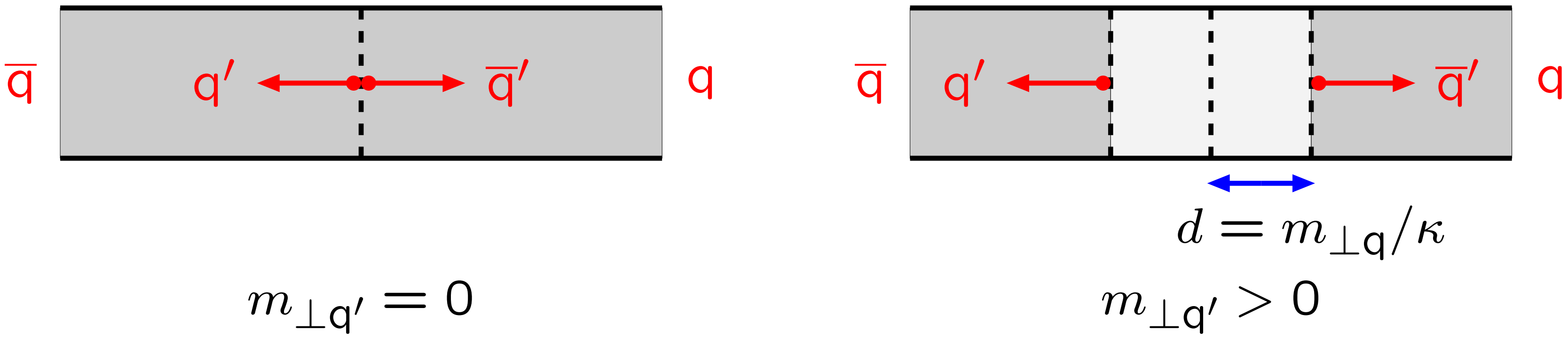
Motion of quarks and antiquarks in a $\mathrm{q\overline{q}}$ system:



gives simple but powerful picture of hadron production

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

How does the string break?



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

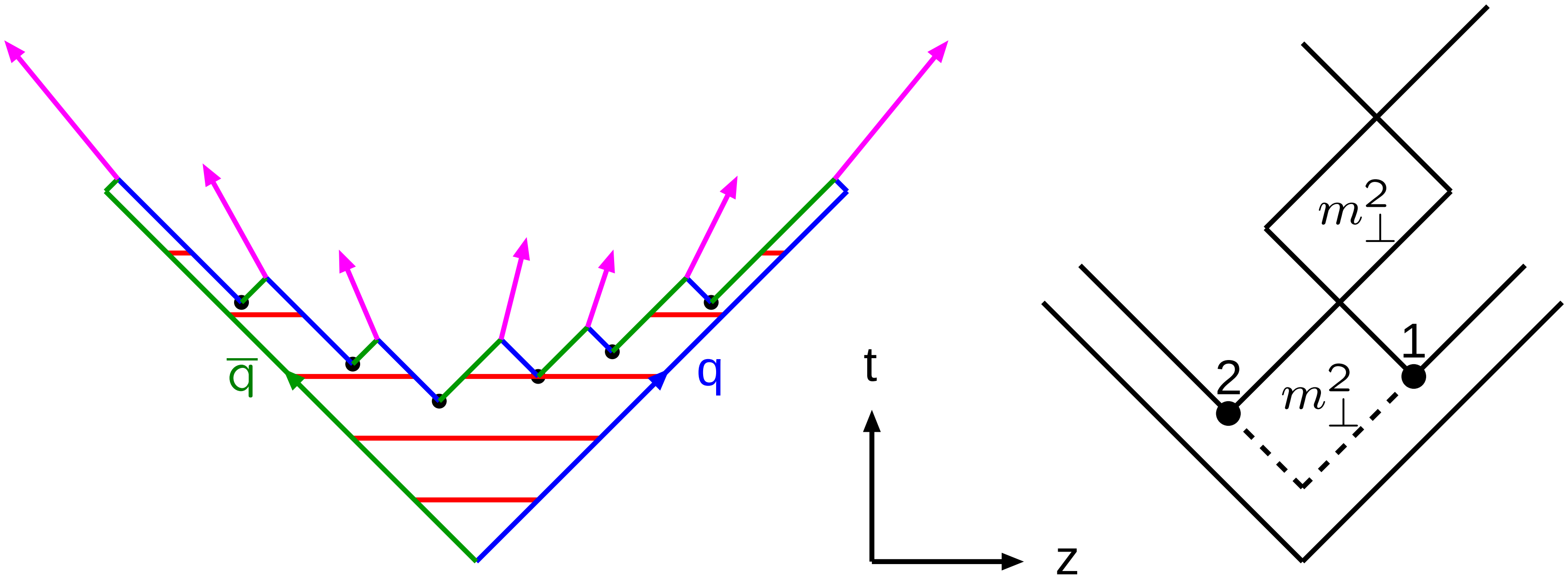
2) suppression of heavy quarks $u\overline{u} : d\overline{d} : s\overline{s} : c\overline{c} \approx 1 : 1 : 0.3 : 10^{-11}$

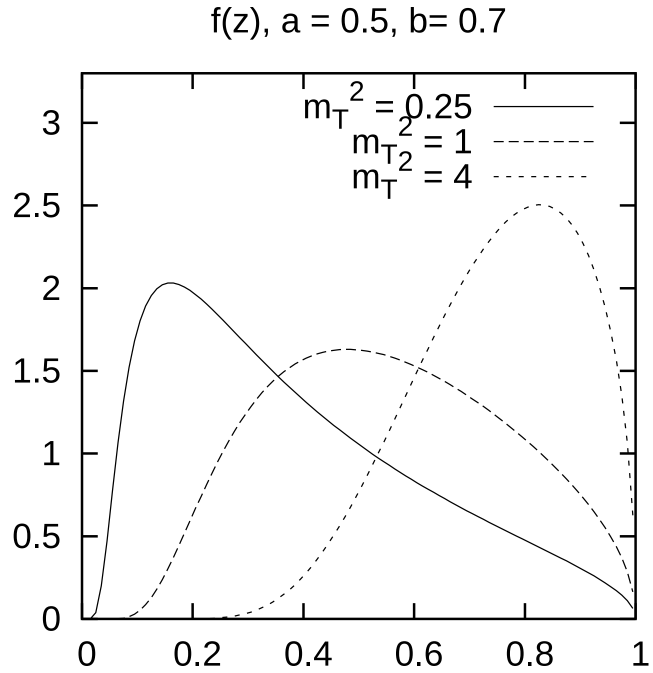
3) diquark $\sim$ antiquark $\Rightarrow$ simple model for baryon production

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*

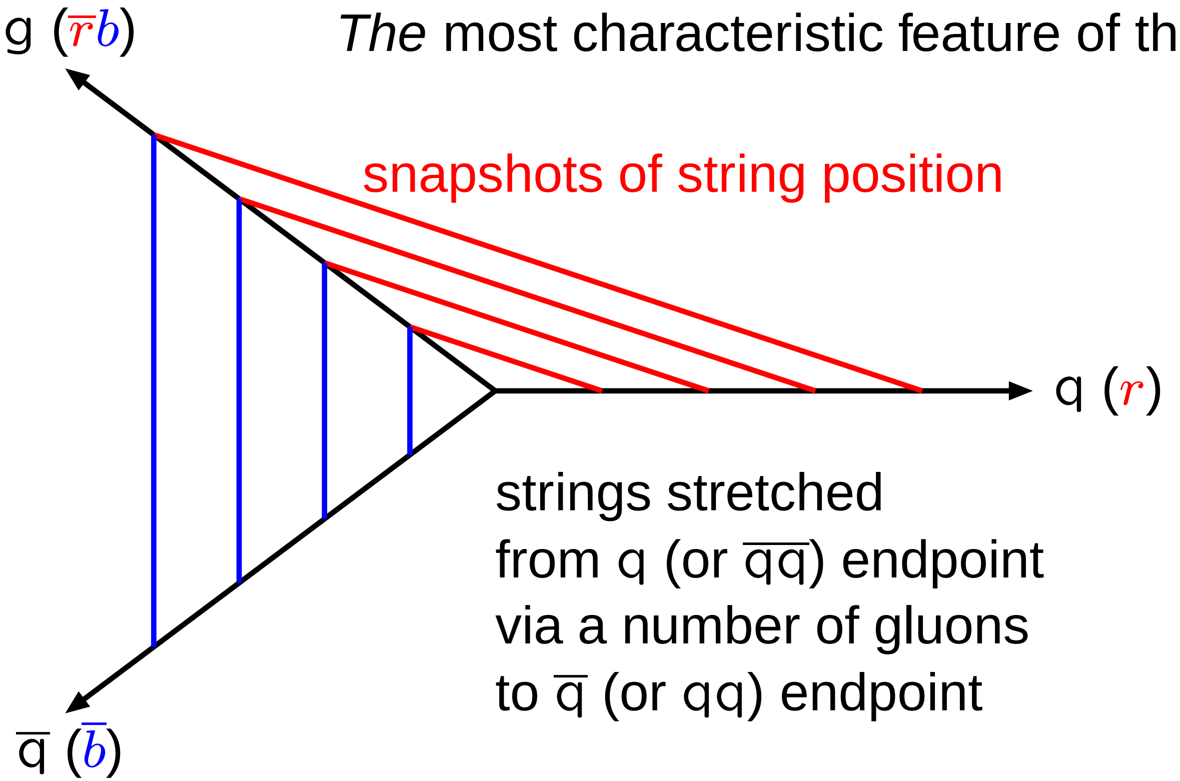
$$\mathcal{P}(1,2) = \mathcal{P}(1) \times \mathcal{P}(1 \to 2)$$
$$= \mathcal{P}(2) \times \mathcal{P}(2 \to 1)$$

$\Rightarrow$ Lund symmetric fragmentation function

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

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

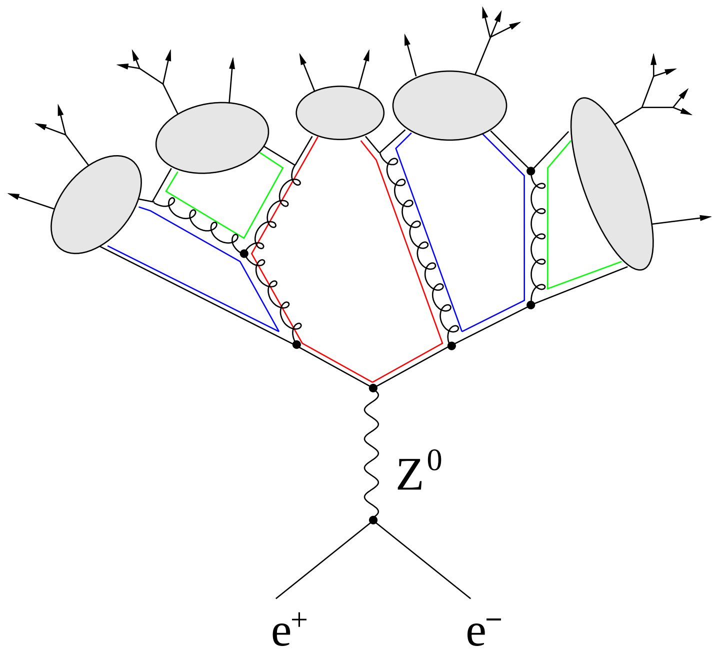
Force ratio gluon/ quark = 2, cf. QCD $N_C/C_F = 9/4$, $\to$ 2 for $N_C \to \infty$

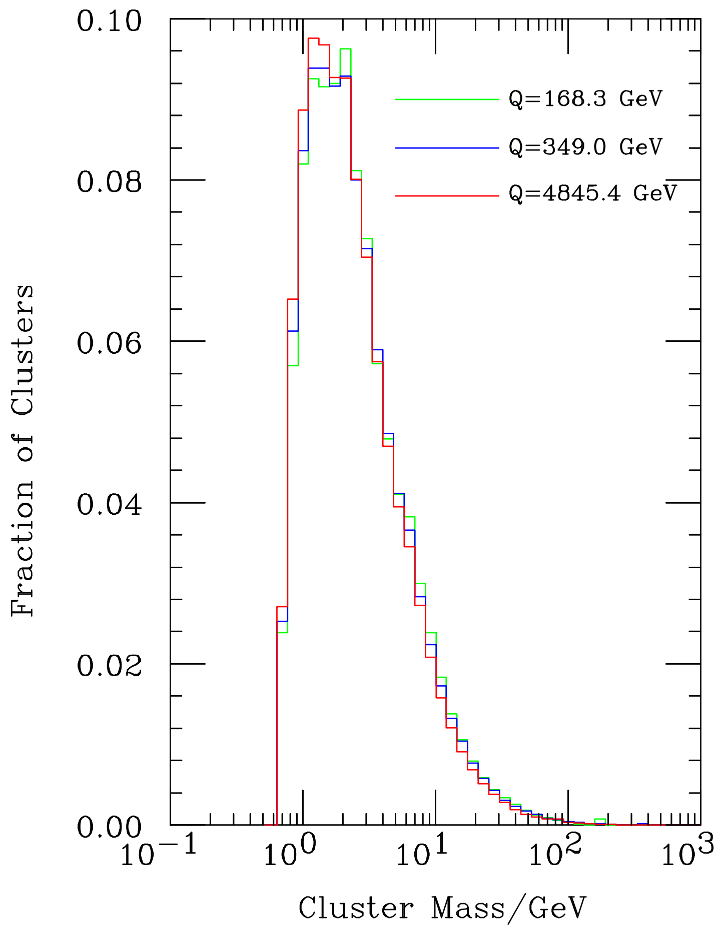
No new parameters introduced for gluon jets!, so:

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

The HERWIG Cluster Model

“Preconfinement”:
colour flow is local
in coherent shower evolution





1) Introduce forced $g \to q\overline{q}$ 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 . . .

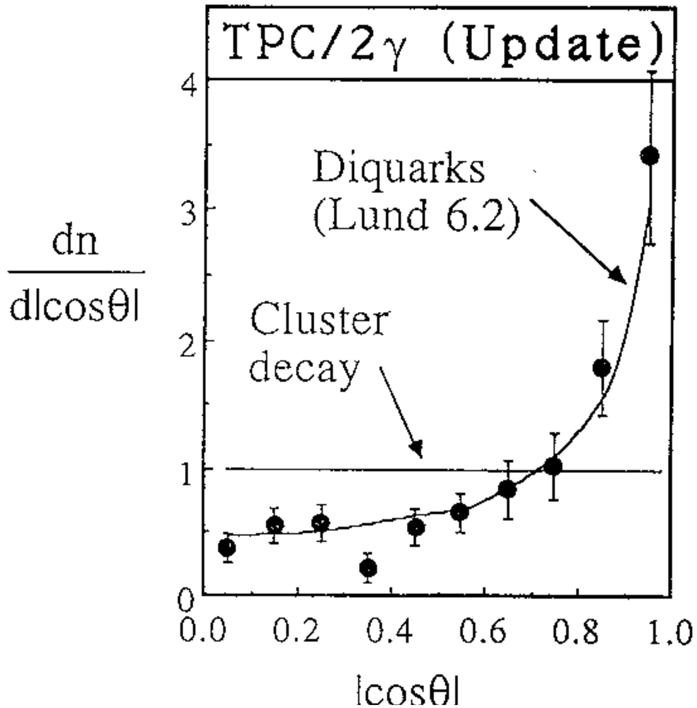
1) Tail to very large-mass clusters (e.g. if no emission in shower);
if large-mass cluster $\rightarrow$ 2 hadrons then
incorrect hadron momentum spectrum, crazy four-jet events
$\Longrightarrow$ split big cluster into 2 smaller along "string" direction;
daughter-mass spectrum $\Rightarrow$ iterate if 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 $+$ $\overline{\text{qq}}$

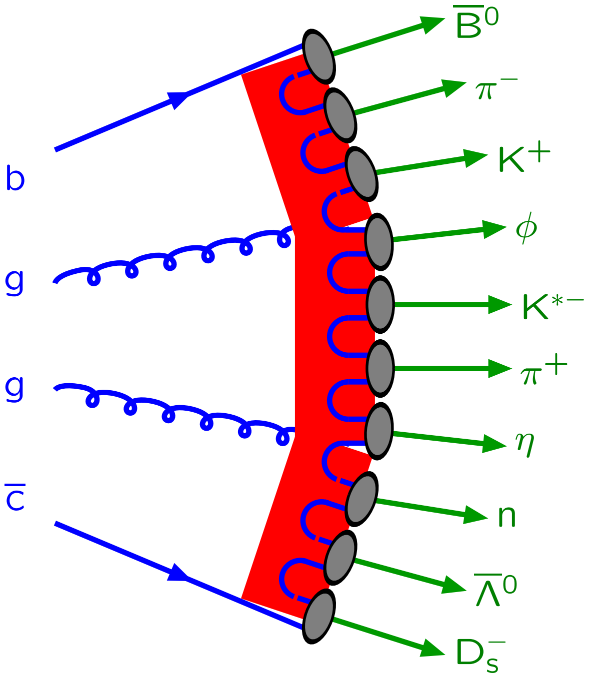
3) Too soft charm/bottom spectra
$\Longrightarrow$ anisotropic leading-cluster decay

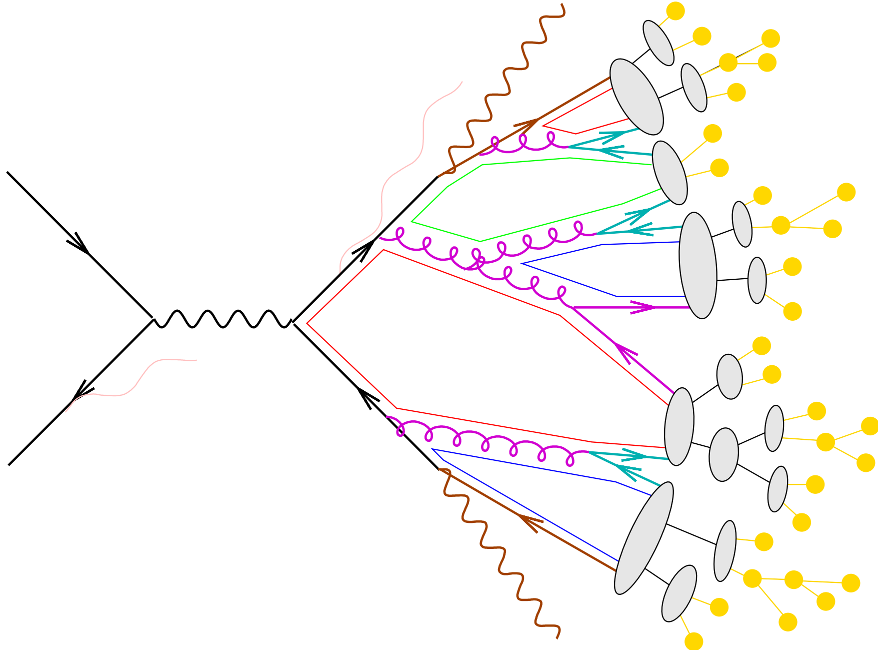
4) Charge correlations still problematic
$\Longrightarrow$ all clusters anisotropic (?)

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 $Q \approx \Lambda_{\text{QCD}}$
(or m_{hadron}, if larger)

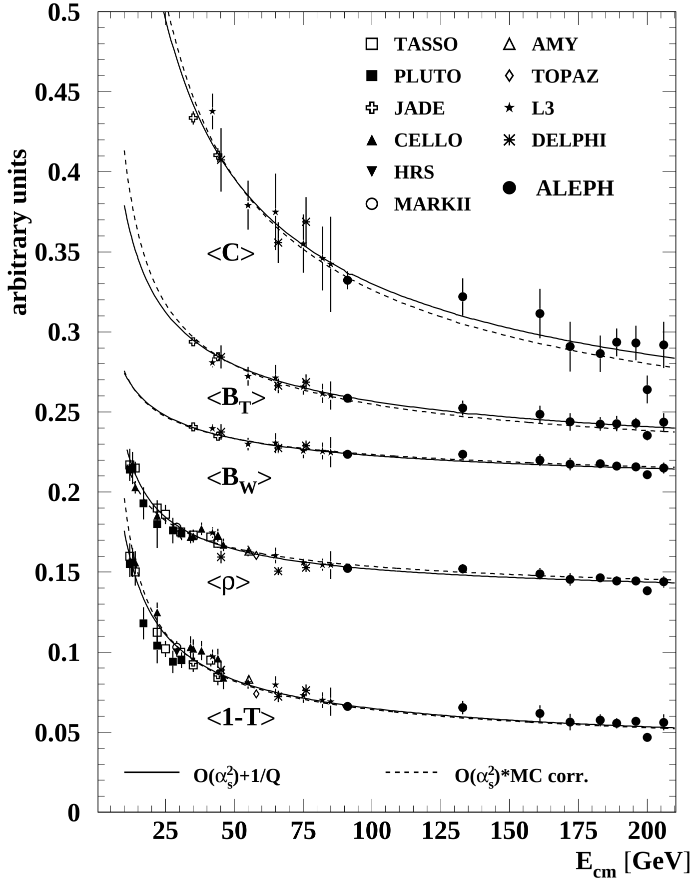
"Hard Line": each parton $\equiv$ one hadron

"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)

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

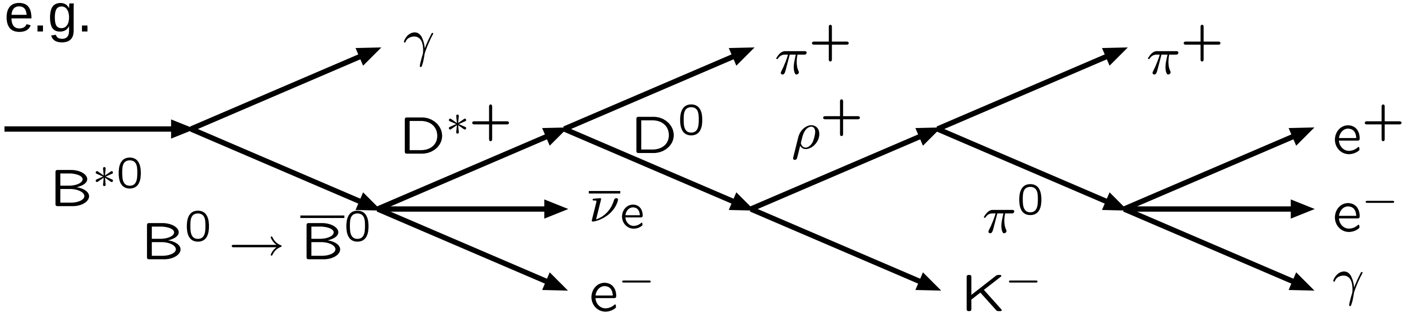


Not Monte Carlo, **not** for arbitrary quantities

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.



- $\mathrm{B}^{*0} \to \mathrm{B}^0\gamma$: electromagnetic decay
- $\mathrm{B}^0 \to \overline{\mathrm{B}}^0$ mixing (weak)
- $\overline{\mathrm{B}}^0 \to \mathrm{D}^{*+}\overline{\nu}_\mathrm{e}\mathrm{e}^-$: weak decay, displaced vertex, $|\mathcal{M}|^2 \propto (p_{\overline{\mathrm{B}}}p_{\overline{\nu}})(p_\mathrm{e}p_{\mathrm{D}^*})$
- $\mathrm{D}^{*+} \to \mathrm{D}^0\pi^+$: strong decay
- $\mathrm{D}^0 \to \rho^+\mathrm{K}^-$: 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
- $\pi^0 \to \mathrm{e}^+\mathrm{e}^-\gamma$: Dalitz decay, $m(\mathrm{e}^+\mathrm{e}^-)$ peaked

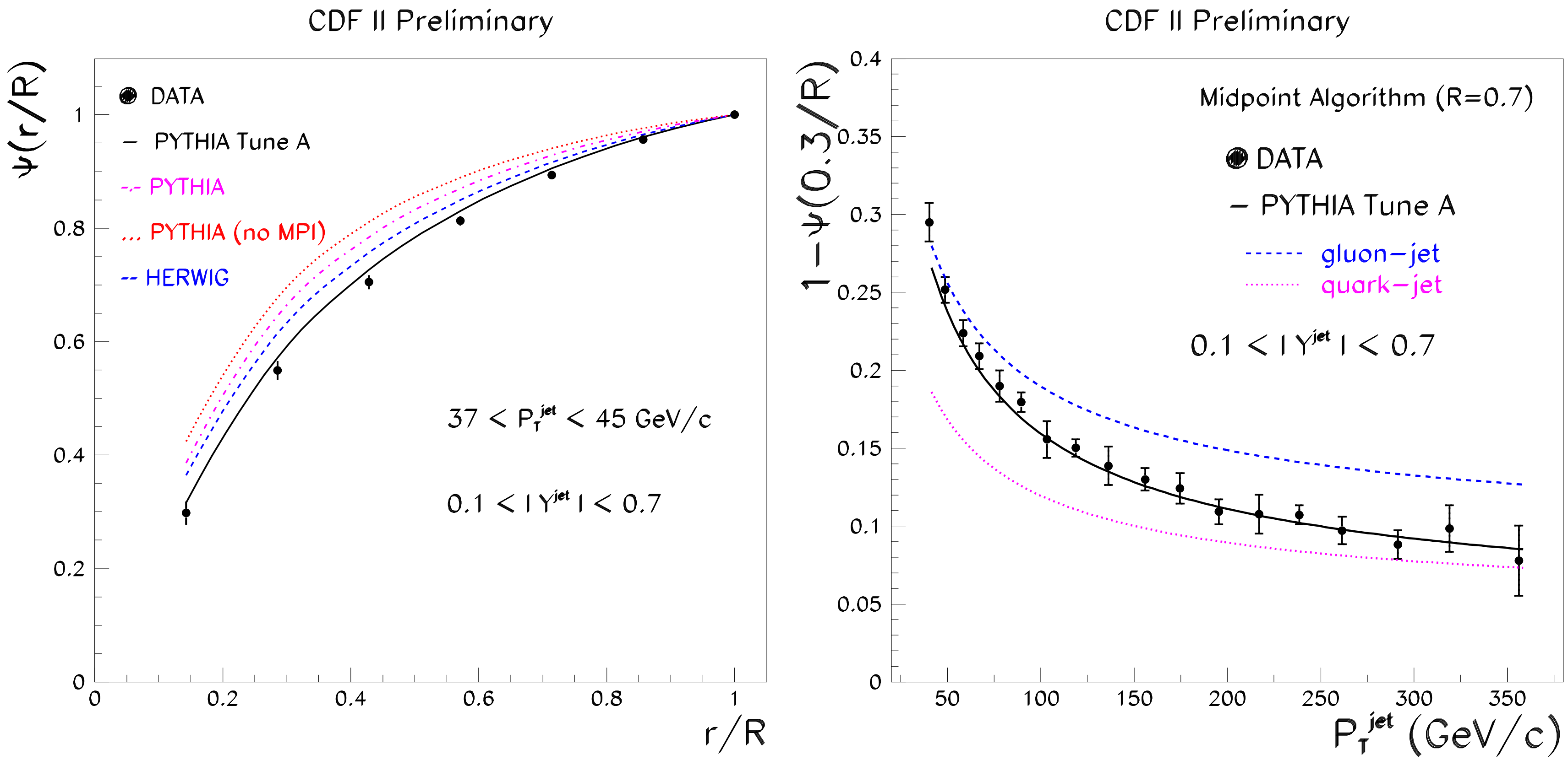
Dedicated programs, with special attention to polarization effects:
- EVTGEN: B decays
- TAUOLA: τ decays

Jet Universality

Question: are jets the same in all processes?

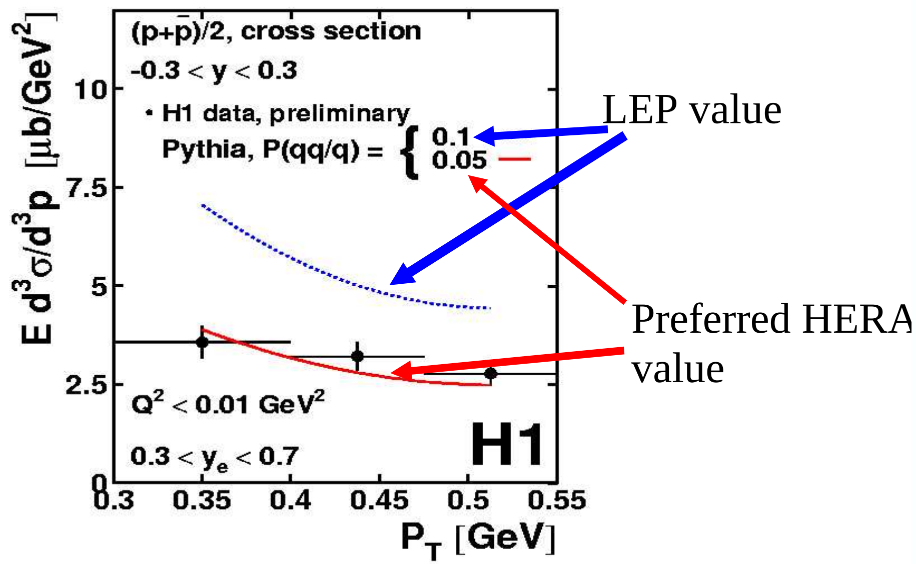
Answer 1: no, at LEP mainly quarks jets, often b/c,
at LHC mainly gluons, if quarks then mainly u/d.

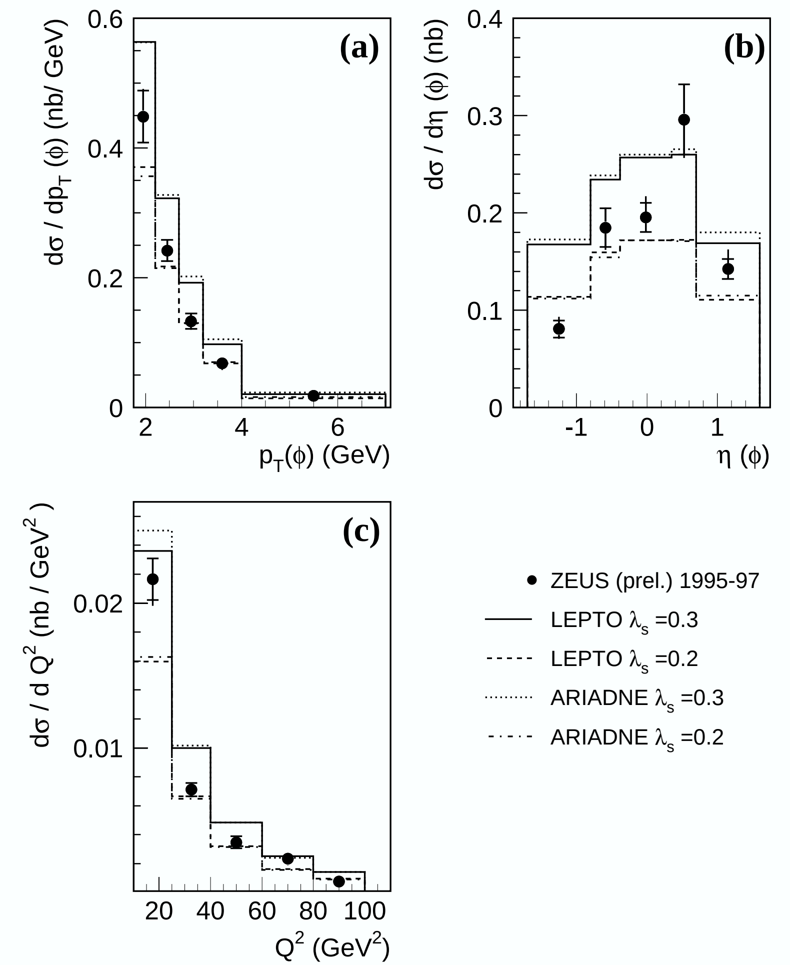
Answer 2: no, perturbative evolution gives calculable differences.



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

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





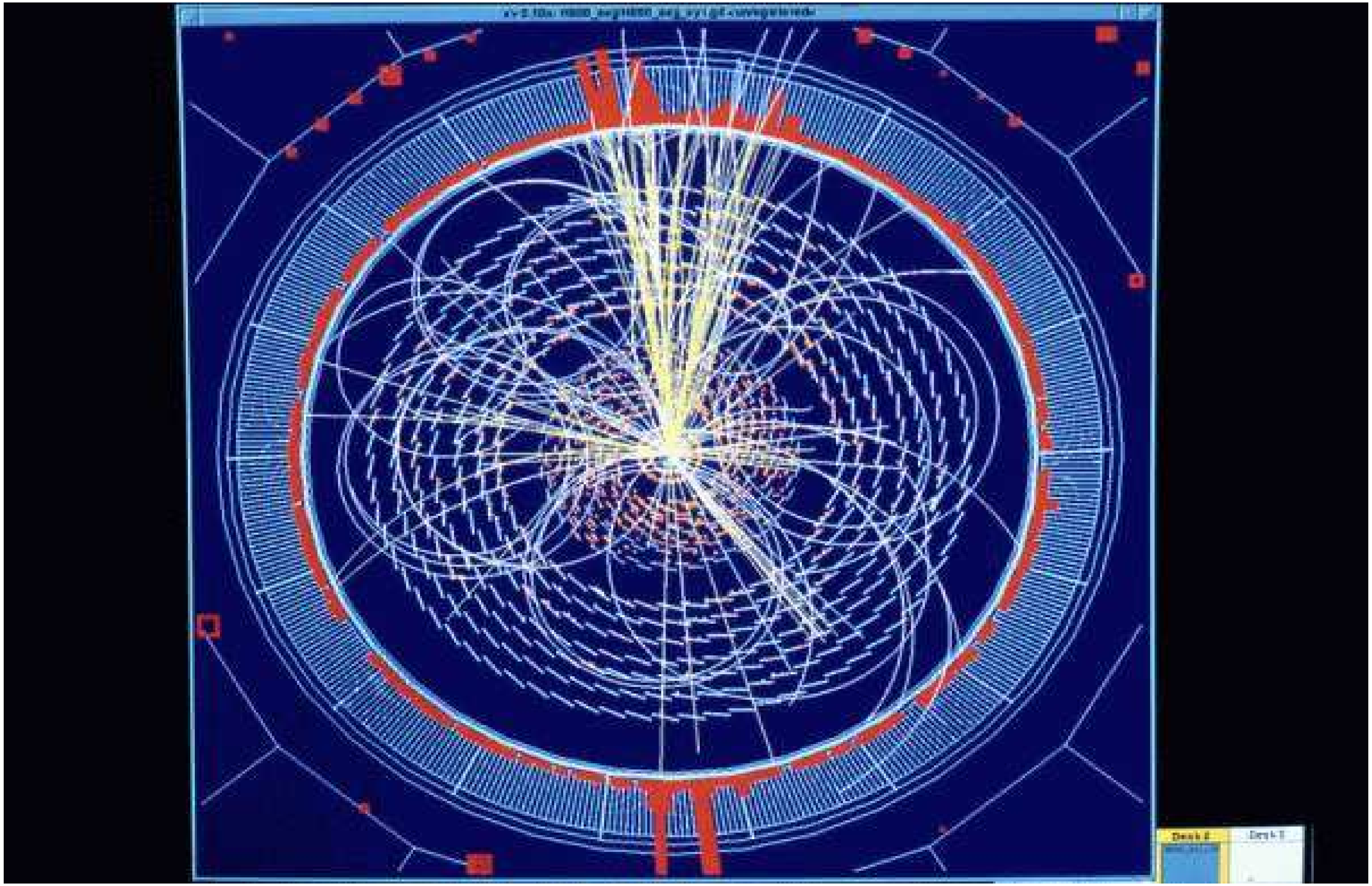
so discrepancies

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

Reasons? HERA dominated by “beam jets”, so

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

Summary and Outlook

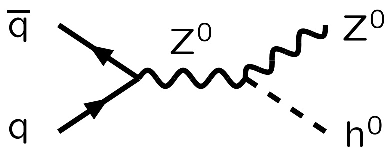


Event Physics Overview

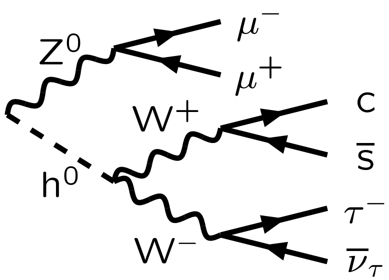
Repetition: from the “simple” to the “complex”,
or from “calculable” at large virtualities to “modelled” at small

Matrix elements (ME):

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

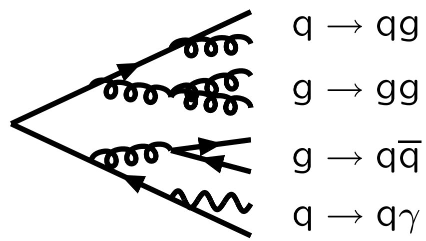


2) Resonance decays:
includes correlations.

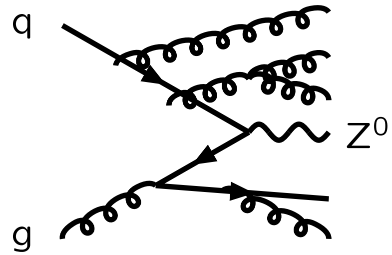


Parton Showers (PS):

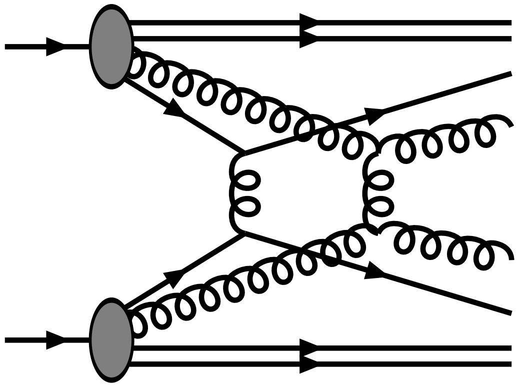
3) Final-state parton showers.



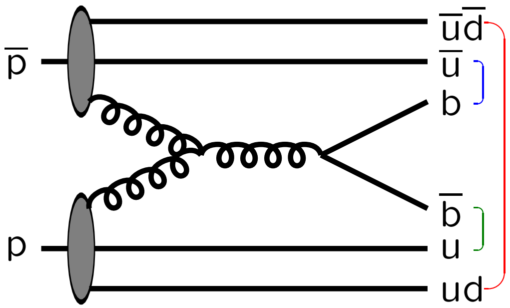
4) Initial-state parton showers.



5) **Multiple parton–parton interactions**

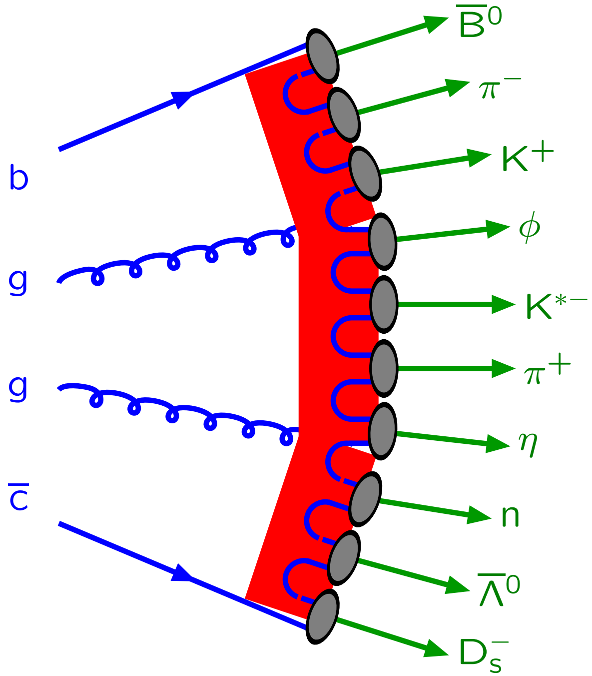


6) **Beam remnants, with colour connections**



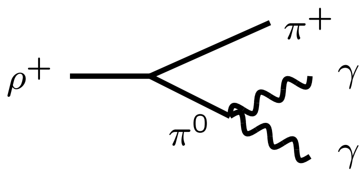
5) + 6) = Underlying Event

7) **Hadronization**



8) **Ordinary decays:**

hadronic, τ, charm, . . .



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

PYTHIA7 project $\Longrightarrow$ **ThePEG**

Toolkit for High Energy Physics Event Generation

(L. Lönnblad; S. Gieseke, A. Ribon, P. Richardson)

HERWIG++: complete reimplementation

(B.R. Webber; S. Gieseke, D. Grellscheid, A. Ribon,

P. Richardson, M. Seymour, P. Stephens, . . .)

ARIADNE/LDC: to do ISR/FSR showers, multiple interactions

(L. Lönnblad; N. Lavesson)

SHERPA: partly wrappers to PYTHIA Fortran; has CKKW

(F. Krauss; T. Fischer, T. Gleisberg, S. Hoeche, T. Laubrich,

A. Schaelicke, S. Schumann, C. Semmling, J. Winter)

PYTHIA8: restart to write complete event generator

(T. Sjöstrand, (S. Mrenna?, P. Skands?))

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 of Warning

[. . .] The Monte Carlo simulation has become the major means of visualization of not only detector performance but also of physics phenomena. So far so good. 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.

[. . .] I am prepared to believe that the computer-literate generation (of which I am a little too old to be a member) is in principle no less competent and in fact benefits relative to us in the older generation by having these marvelous tools. They do allow one to look at, indeed visualize, the problems in new ways. But I also fear a kind of "terminal illness", perhaps traceable to the influence of television at an early age. There the way one learns is simply to passively stare into a screen and wait for the truth to be delivered. A number of physicists nowadays seem to do just this.

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