LUND UNIVERSITY

Monte Carlo School
Physics at the Terascale
21–24 April 2008
DESY, Hamburg

Minimum-Bias and Underlying-Event Physics in PYTHIA

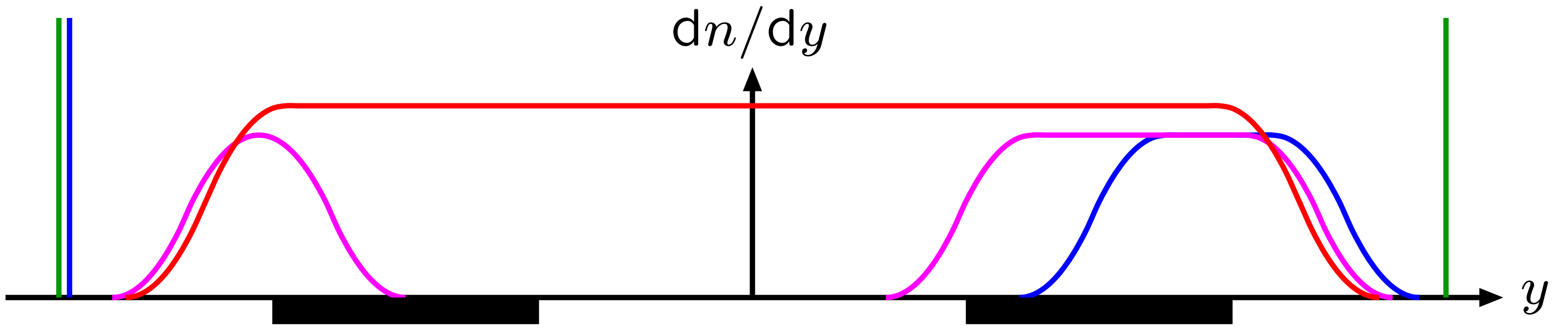
Torbjörn Sjöstrand

Department of Theoretical Physics, Lund University

What is minimum bias?

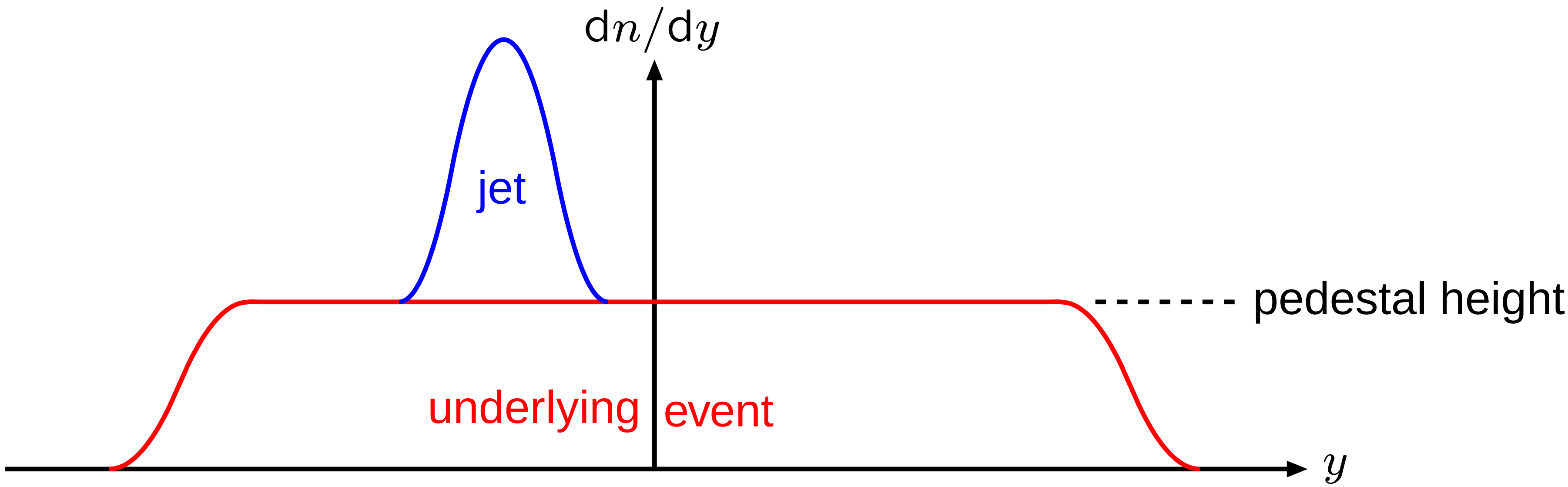
≈ "all events, with no bias from restricted trigger conditions"

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



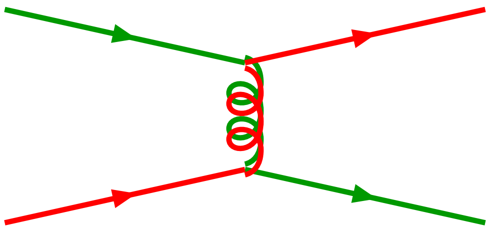
reality: $\sigma_{\mathrm{min-bias}} \approx \sigma_{\mathrm{non-diffractive}} + \sigma_{\mathrm{double-diffractive}} \approx 2/3 \times \sigma_{\mathrm{tot}}$

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 $\mathrm{d}\hat{\sigma}/\mathrm{d}p_\perp^2 \approx 1/p_\perp^4$ for $p_\perp \to 0$.



integrate QCD $2 \to 2$

$\mathrm{qq}' \to \mathrm{qq}'$

$\mathrm{q\overline{q}} \to \mathrm{q}'\overline{\mathrm{q}}'$

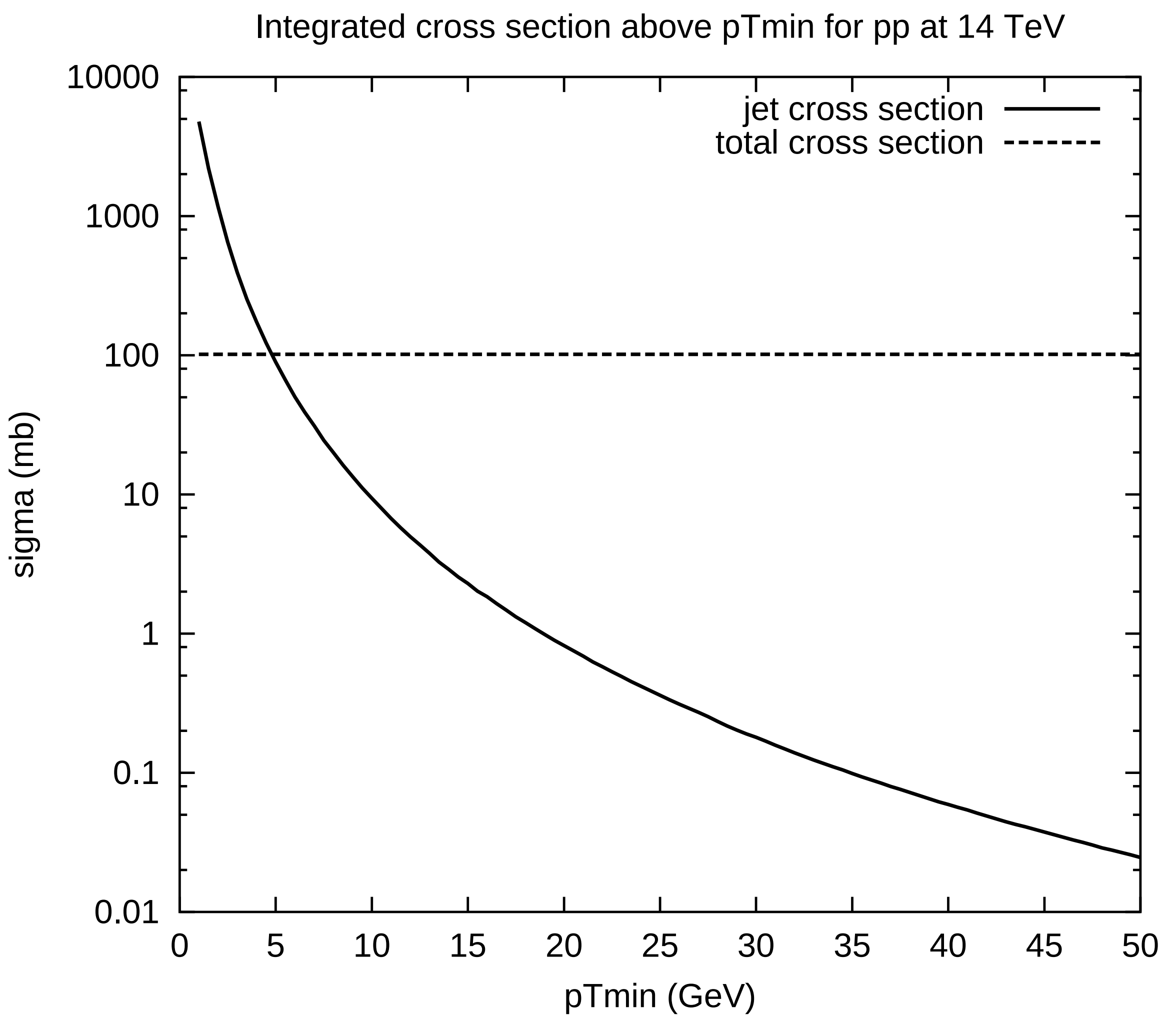
$\mathrm{q\overline{q}} \to \mathrm{gg}$

$\mathrm{qg} \to \mathrm{qg}$

$\mathrm{gg} \to \mathrm{gg}$

$\mathrm{gg} \to \mathrm{q\overline{q}}$

with CTEQ 5L PDF's



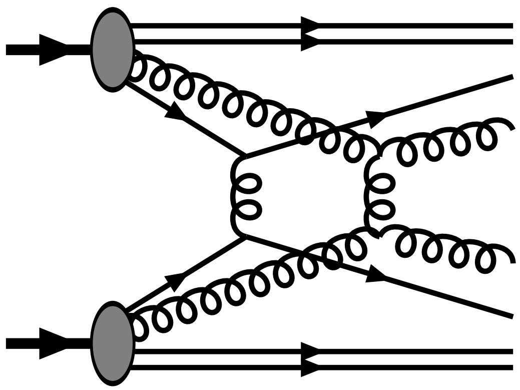
$$\sigma_{\mathrm{int}}(p_{\perp\mathrm{min}}) = \iiint_{p_{\perp\mathrm{min}}} \mathrm{d}x_1\,\mathrm{d}x_2\,\mathrm{d}p_\perp^2\, f_1(x_1,p_\perp^2)\, f_2(x_2,p_\perp^2) \frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}p_\perp^2}$$

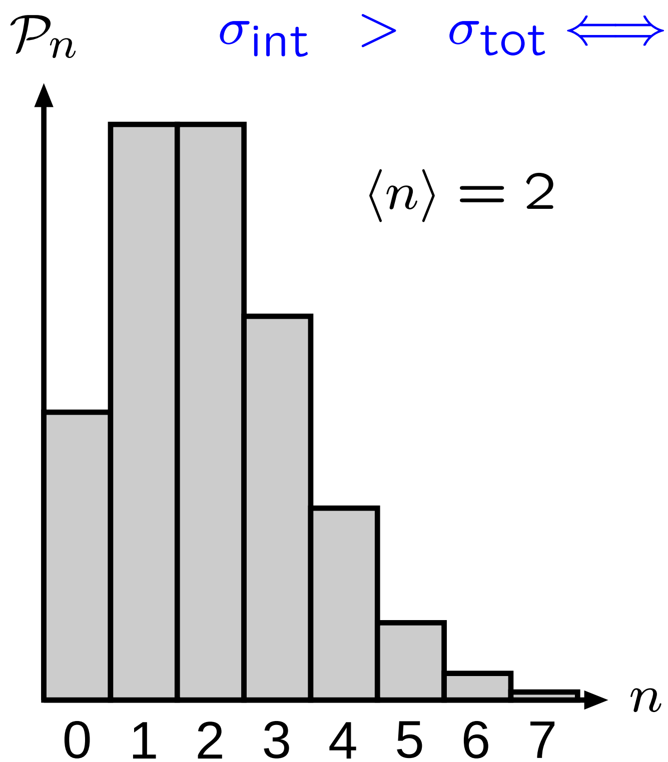
Half a solution to $\sigma_{\mathrm{int}}(p_{\perp\mathrm{min}}) > \sigma_{\mathrm{tot}}$: many interactions per event

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

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

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





If interactions occur independently

then Poissonian statistics

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

but energy–momentum conservation

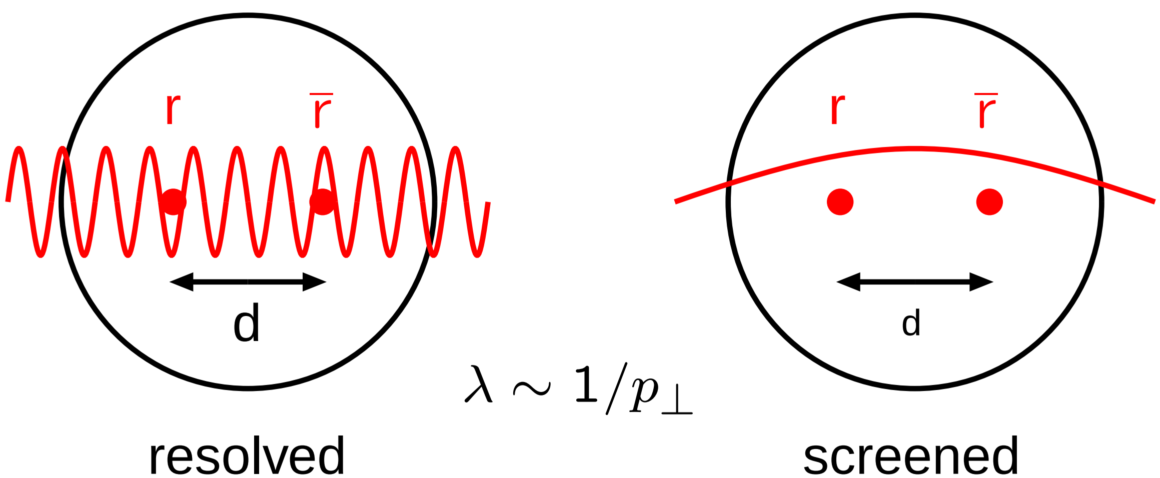
$\Rightarrow$ large n suppressed

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

Naively breakdown at

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

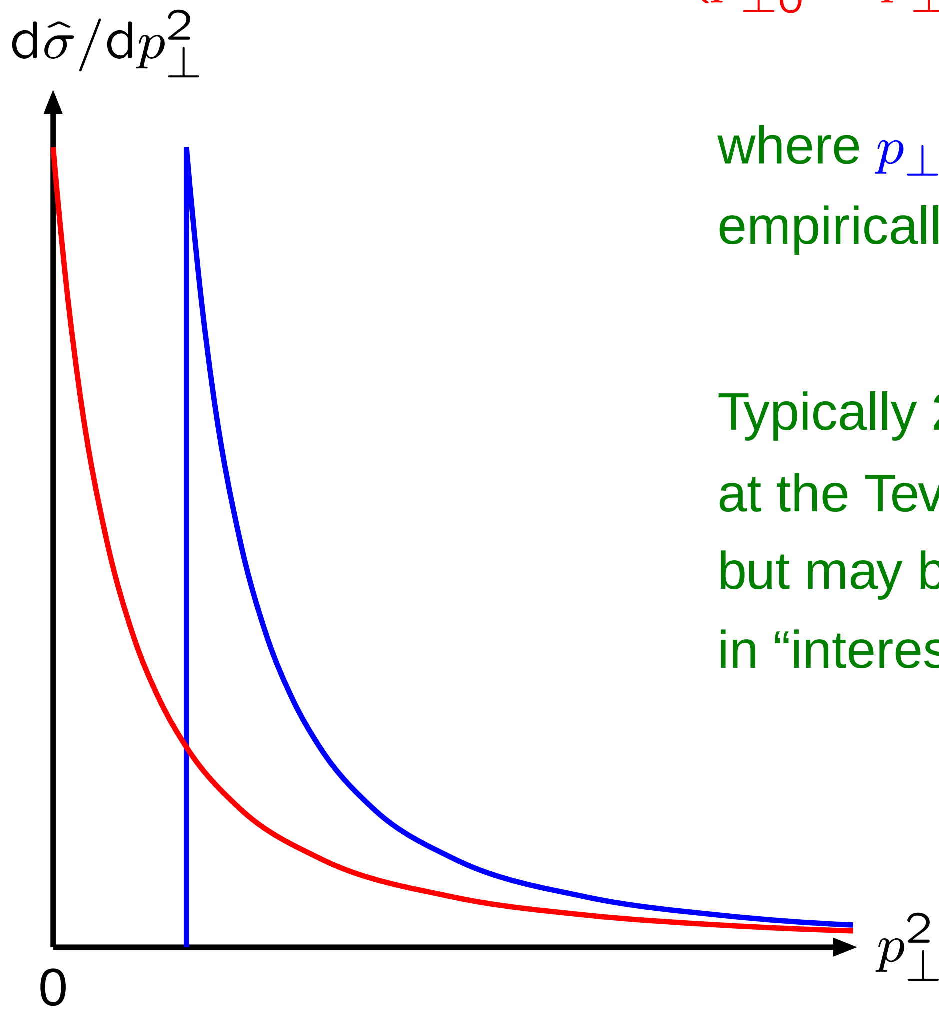
. . . but better replace r_p by (unknown) colour screening length d in hadron



so modify

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

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



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 $\sigma_{\mathrm{nd}} \simeq (2/3)\sigma_{\mathrm{tot}}$
- 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"?)

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

- 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"):

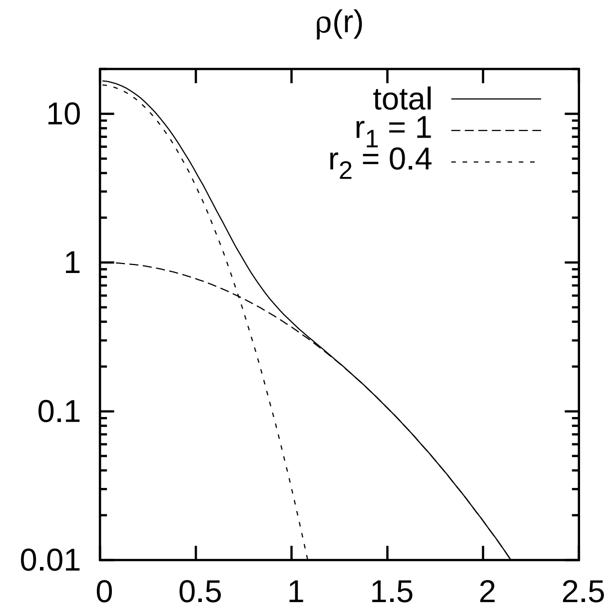
$$\rho_{\text{matter}}(r) = N_1 \exp\left(-\frac{r^2}{r_1^2}\right) + N_2 \exp\left(-\frac{r^2}{r_2^2}\right)$$

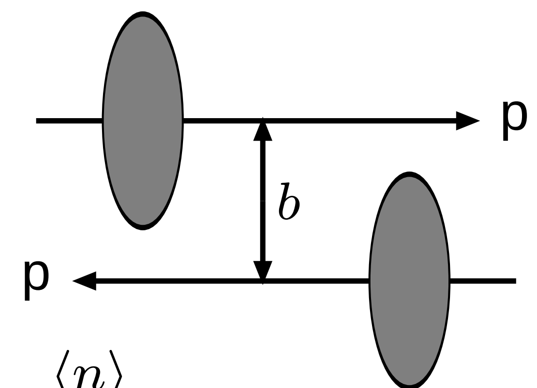
  where $r_2 \neq r_1$ represents "hot spots"
- Events are distributed in impact parameter b
- Overlap of hadrons during collision

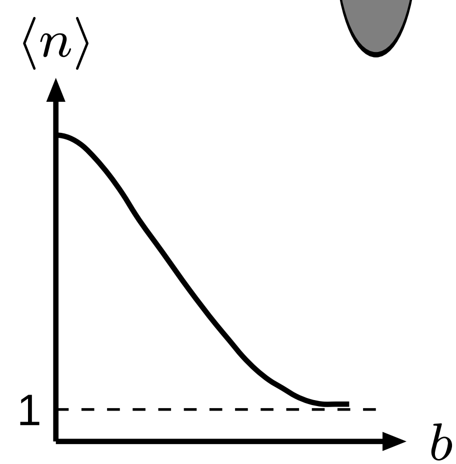
$$\mathcal{O}(b) = \int \mathrm{d}^3\mathbf{x}\,\mathrm{d}t\;\rho_{1,\text{matter}}^{\text{boosted}}(\mathbf{x},t)\,\rho_{2,\text{matter}}^{\text{boosted}}(\mathbf{x},t)$$

- 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, ...

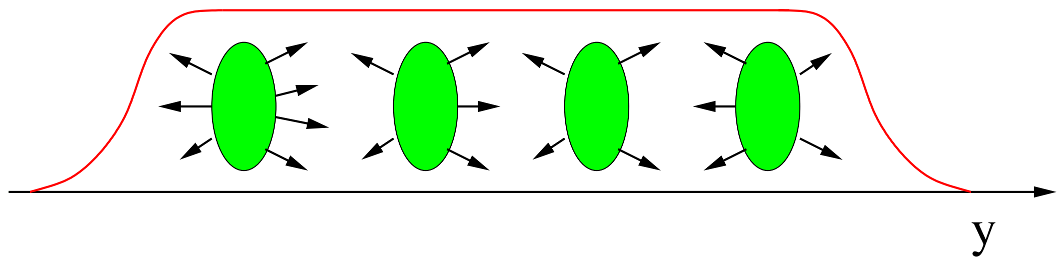






(3) HERWIG

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

without multiple interactions

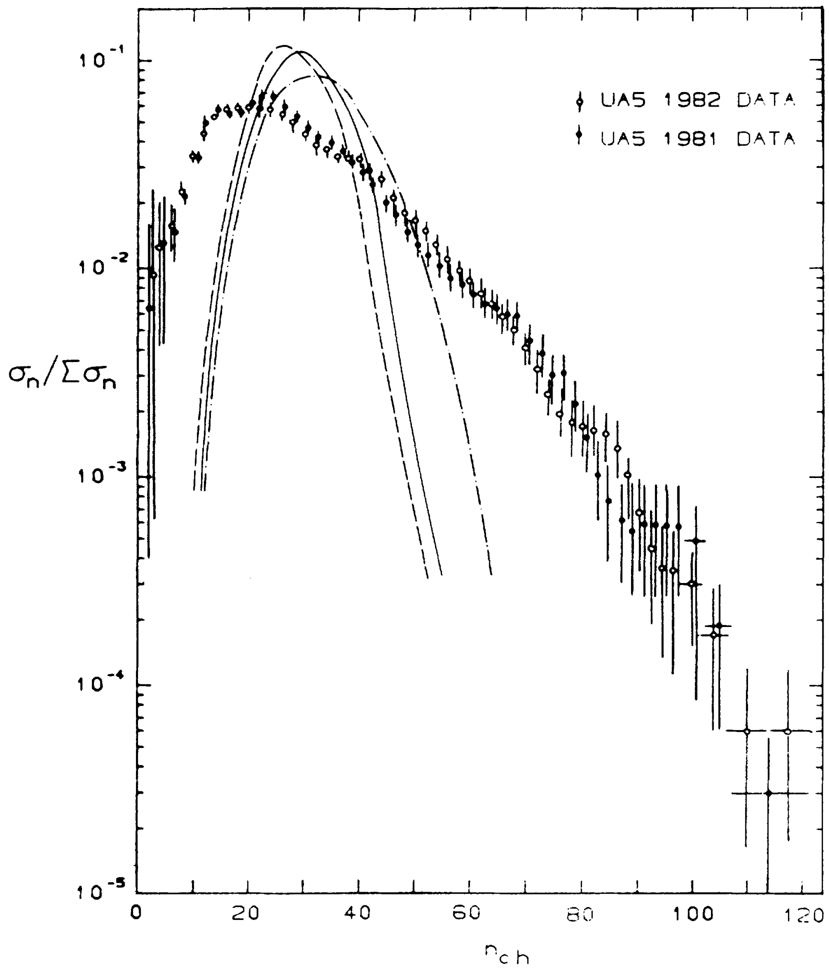


FIG. 3. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs simple models: dashed low p_T only, full including hard scatterings, dash-dotted also including initial- and final-state radiation.

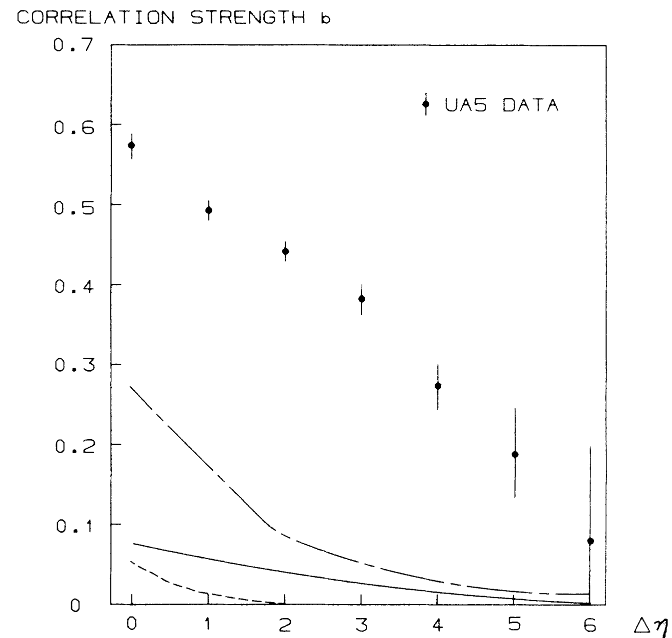


FIG. 4. Forward-backward multiplicity correlation at 540 GeV, UA5 results (Ref. 33) vs simple models; the latter models with notation as in Fig. 3.

with multiple interactions

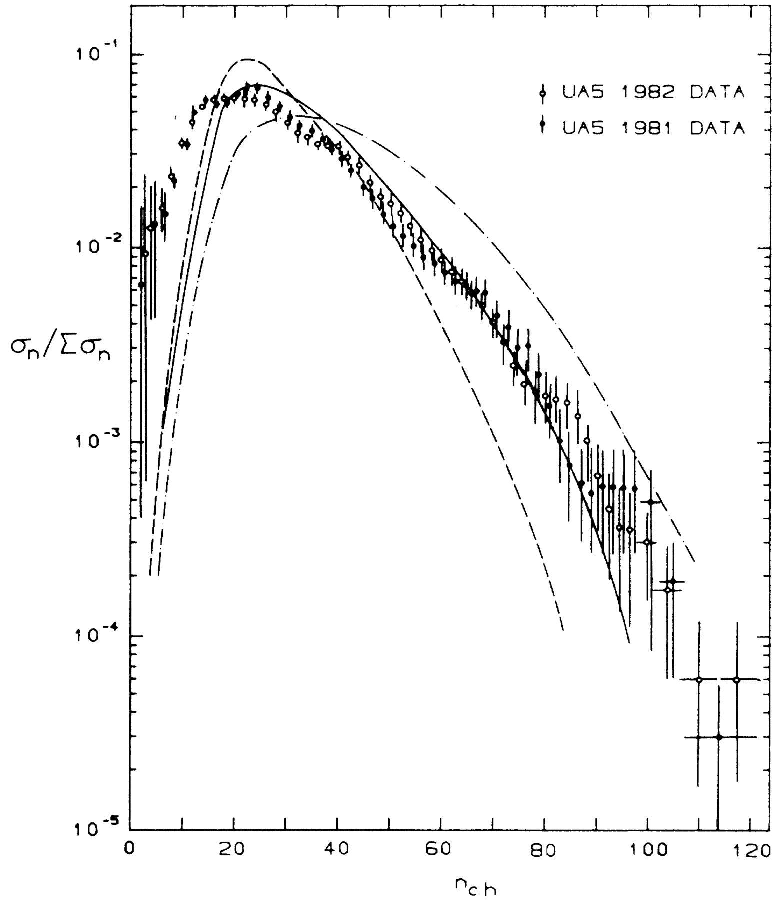


FIG. 5. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs impact-parameter-independent multiple-interaction model: dashed line, $p_{T\min}=2.0$ GeV; solid line, $p_{T\min}=1.6$ GeV; dashed-dotted line, $p_{T\min}=1.2$ GeV.

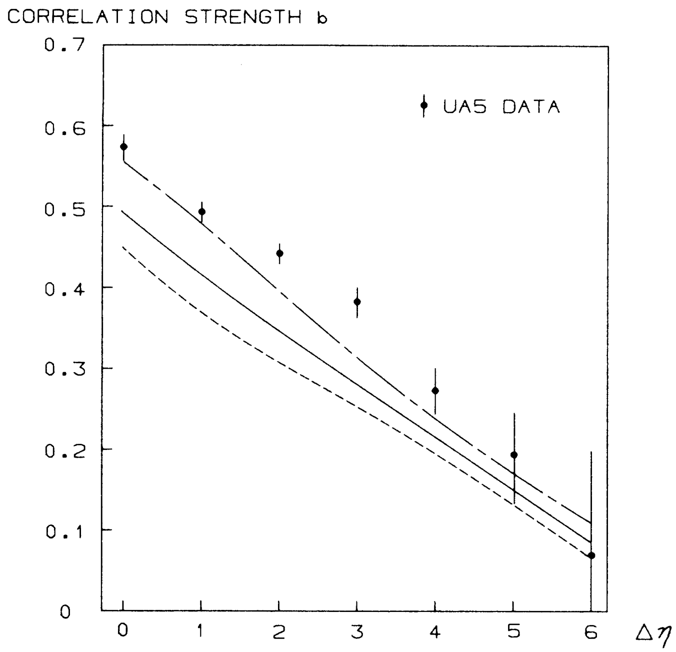


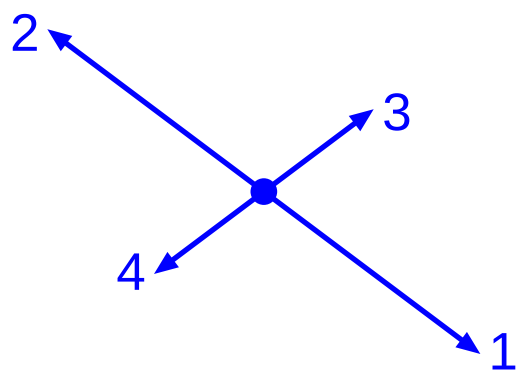
FIG. 6. Forward-backward multiplicity correlation at 540 GeV, UA5 results (Ref. 33) vs impact-parameter-independent multiple-interaction model; the latter with notation as in Fig. 5.

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

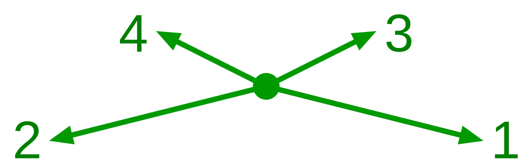


$|\mathbf{p}_{\perp 1} + \mathbf{p}_{\perp 2}| \approx 0$

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

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

Double BremsStrahlung

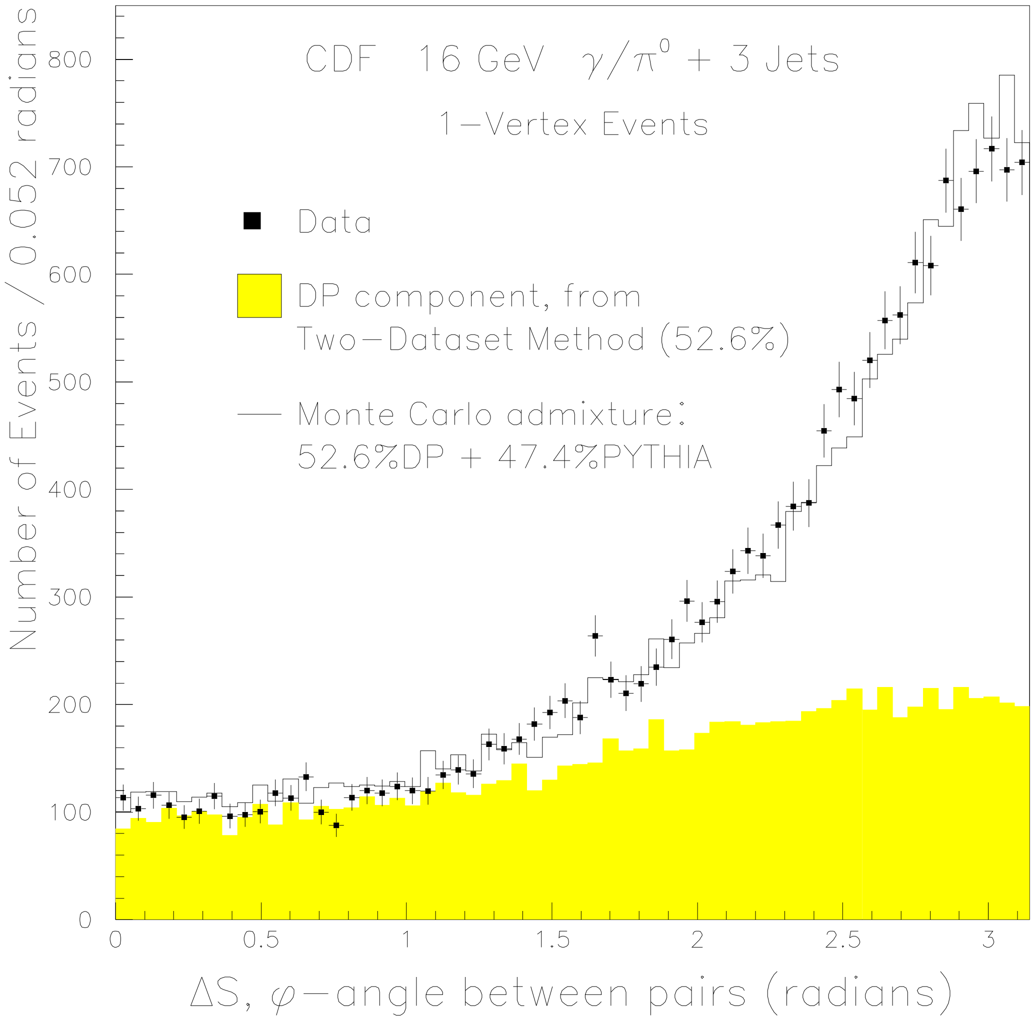


$|\mathbf{p}_{\perp 1} + \mathbf{p}_{\perp 2}| \gg 0$

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

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

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

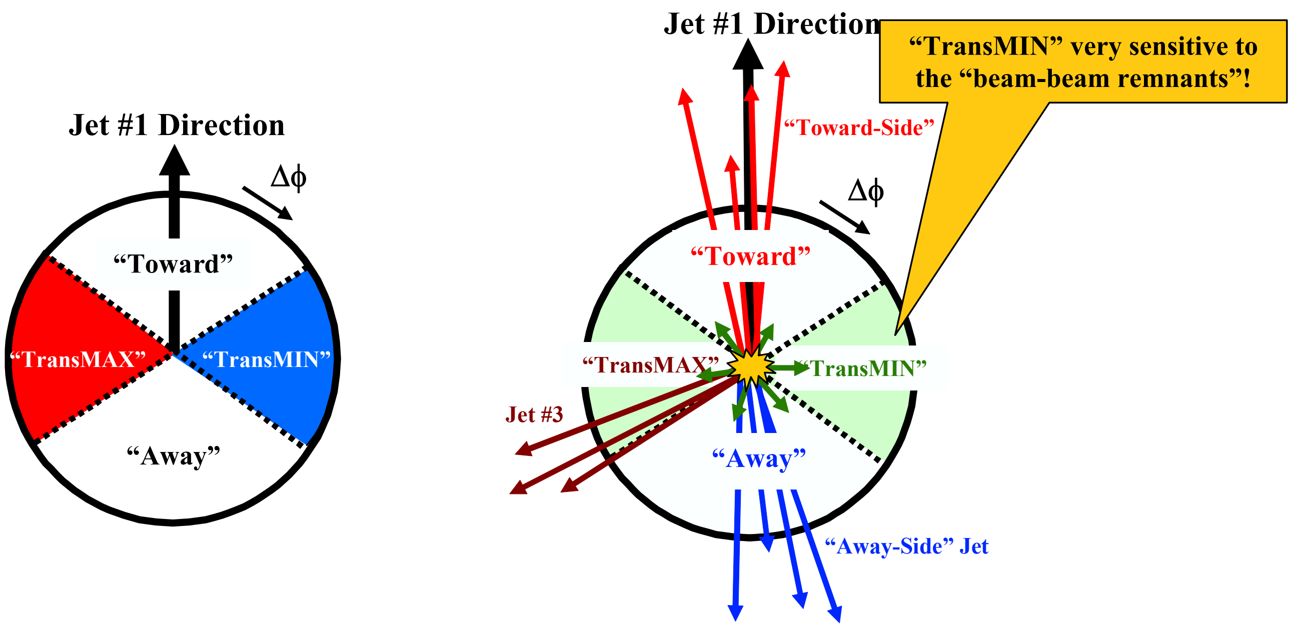
Strong enhancement relative to naive expectations!

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 $p_{\perp\text{hard}} \sim 10$ GeV.

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

"MAX/MIN Transverse" Densities



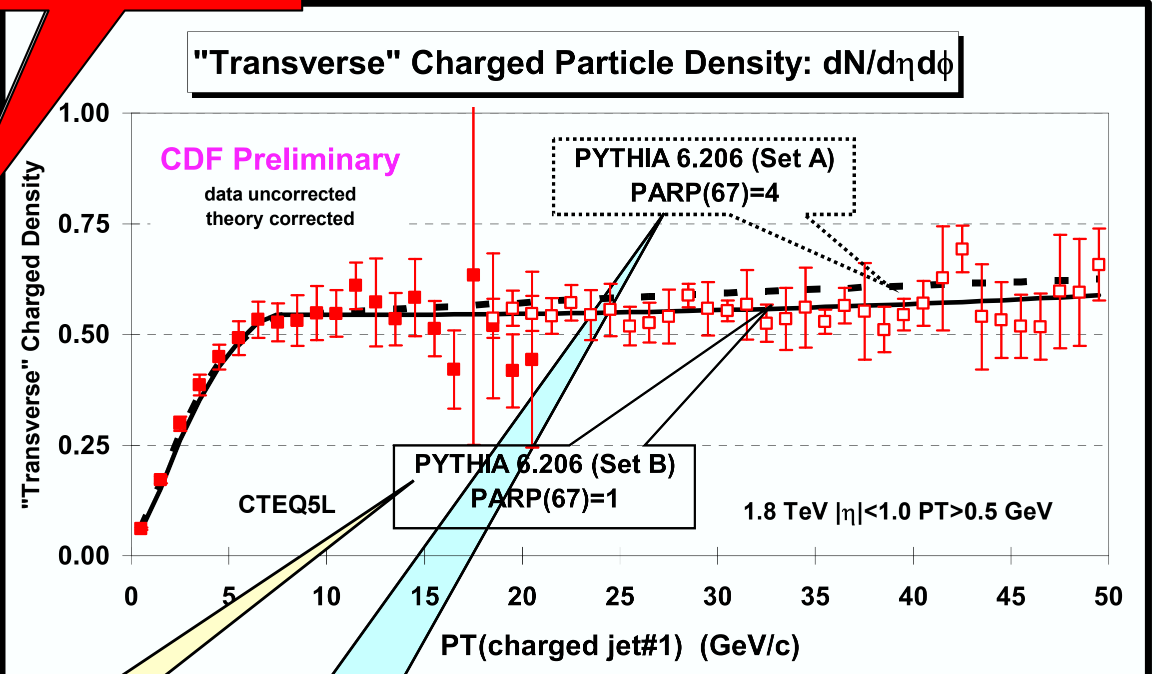
- **Define the MAX and MIN "transverse" regions on an event-by-event basis with MAX (MIN) having the largest (smallest) density.**

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

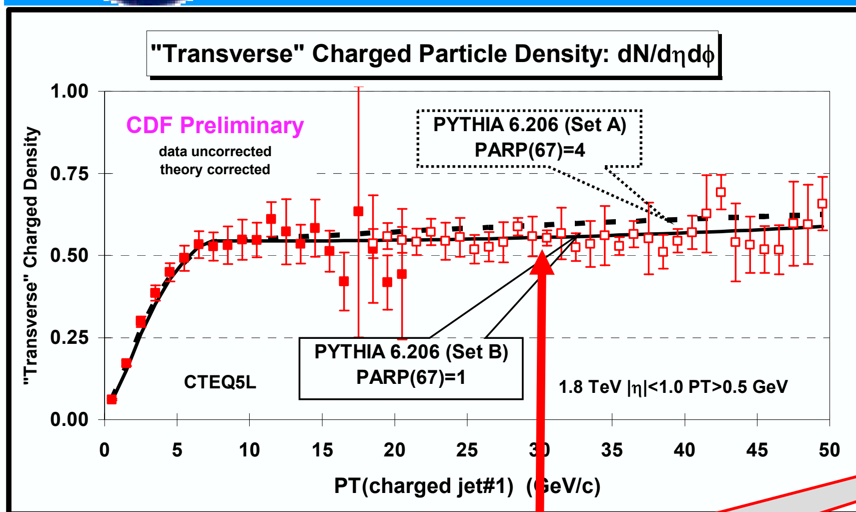


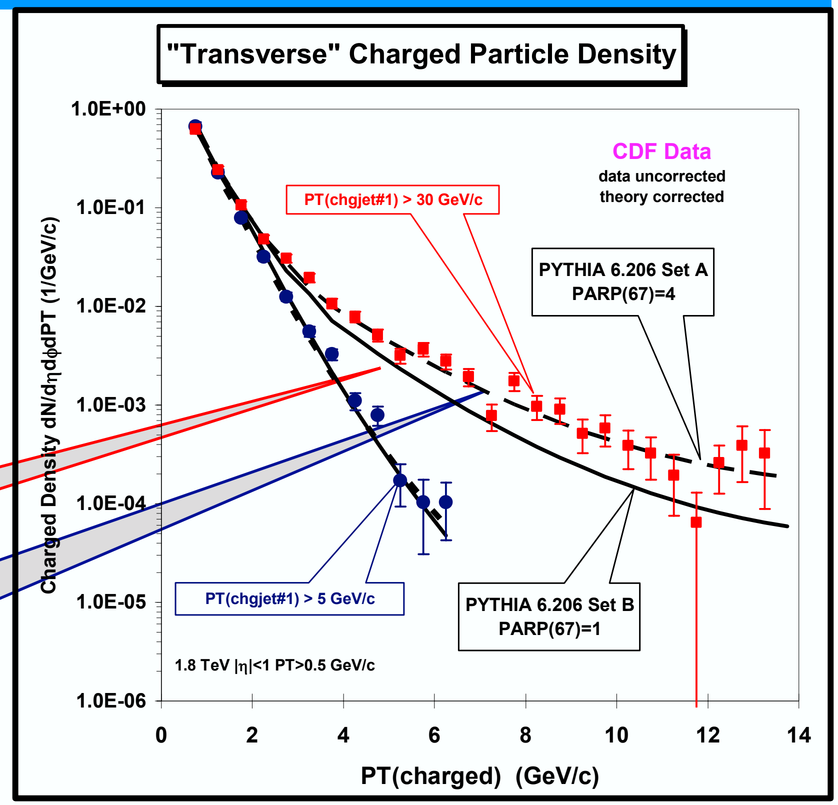
Plot shows the "Transverse" charged particle density versus P_T(chgjet#1) compared to the QCD hard scattering predictions of two tuned versions of PYTHIA 6.206 (CTEQ5L, Set B (PARP(67)=1) and Set A (PARP(67)=4)).

New PYTHIA default (less initial-state radiation)

Old PYTHIA default (more initial-state radiation)

Tuned PYTHIA 6.206 "Transverse" P_T Distribution





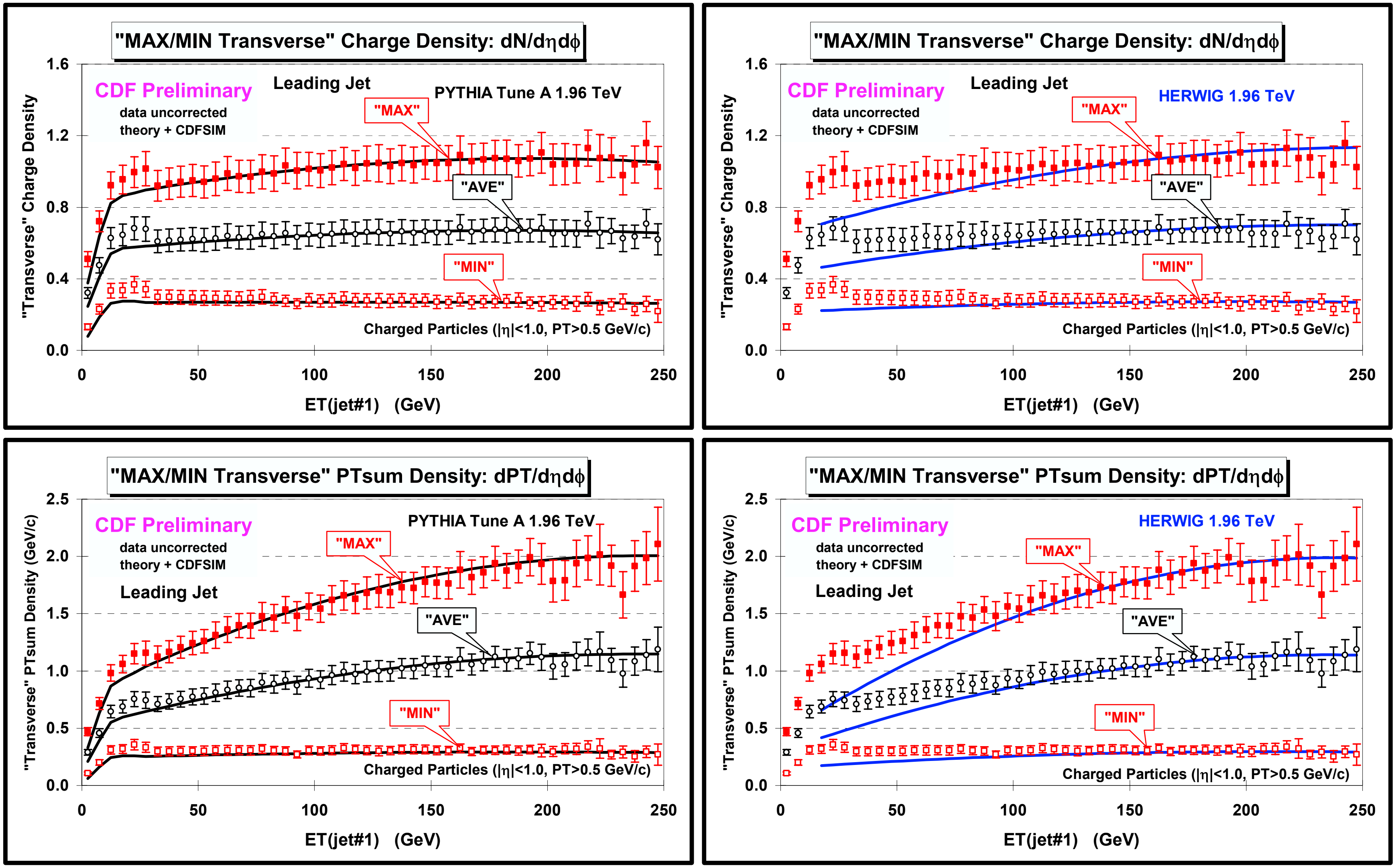
P_T(charged jet#1) > 30 GeV/c

PARP(67)=4.0 (old default) is favored over PARP(67)=1.0 (new default)!

- 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)).

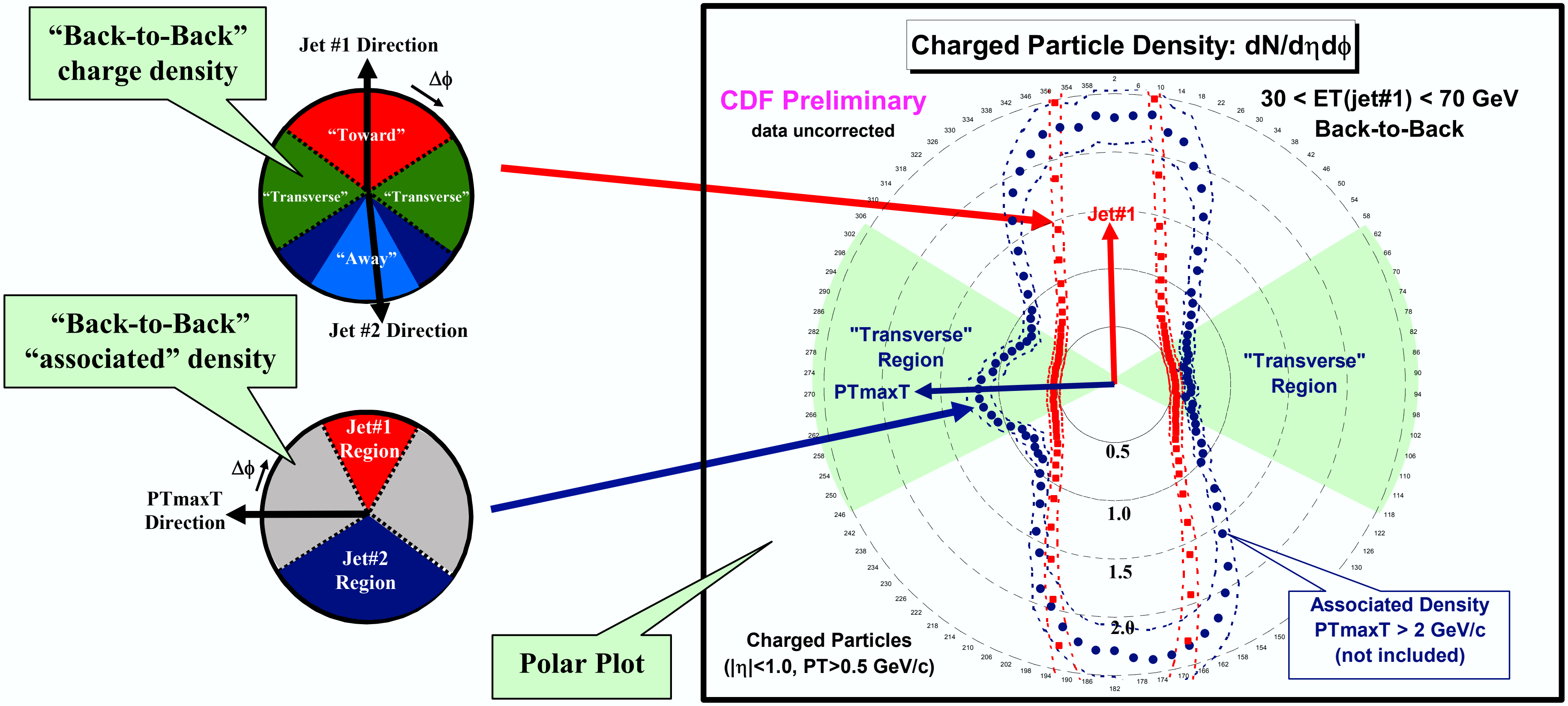
Leading Jet: “MAX & MIN Transverse” Densities

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



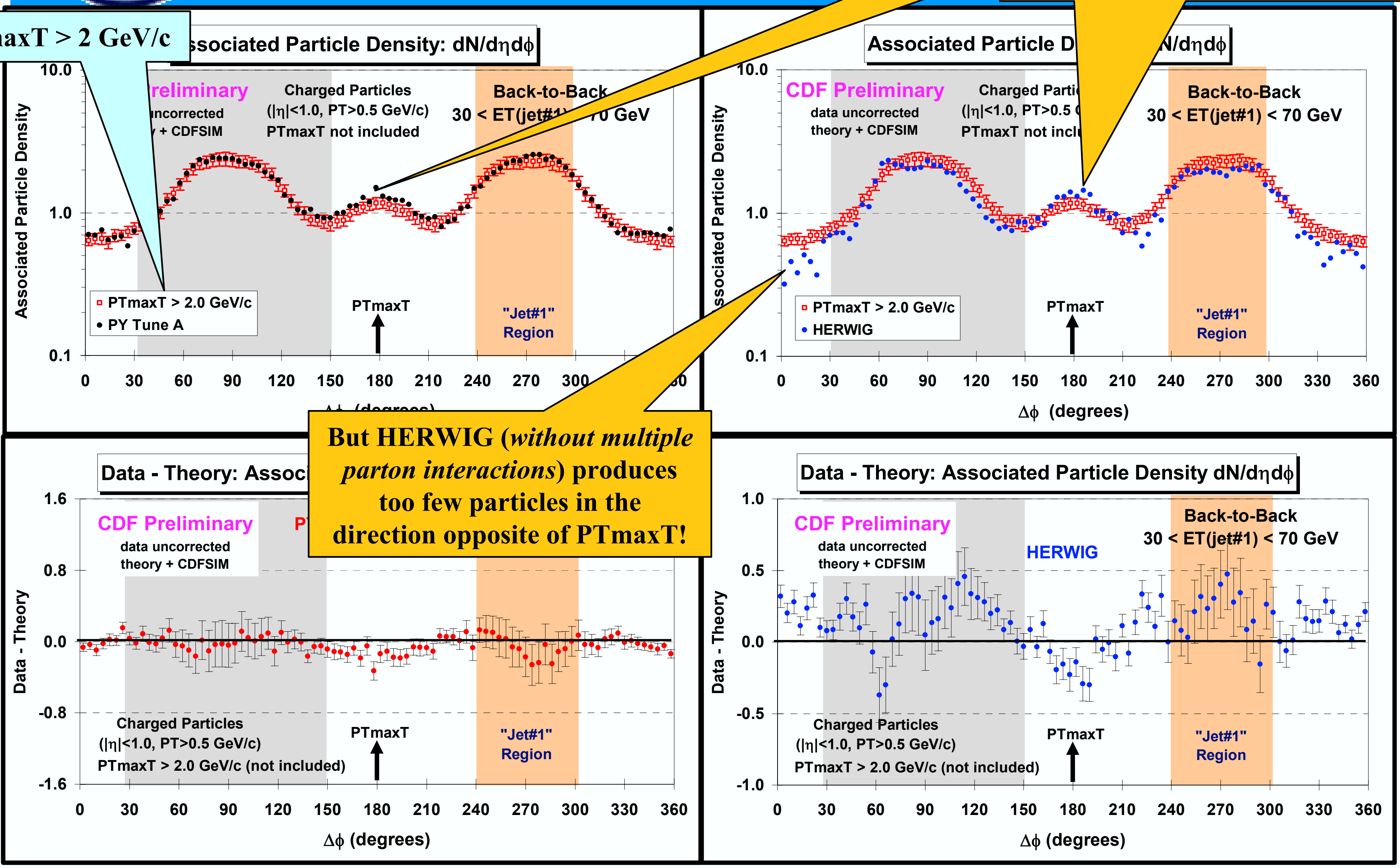
- Shows the **Δφ dependence of the "associated" charged particle density**, $dN_{chg}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$, PTmaxT > 2.0 GeV/c (*not including PTmaxT*) relative to PTmaxT (rotated to 180°) and the charged particle density, $dN_{chg}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| <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

"Associated" Charge De[nsity]
PYTHIA Tune A vs HE[RWIG]

PTmaxT > 2 GeV/c

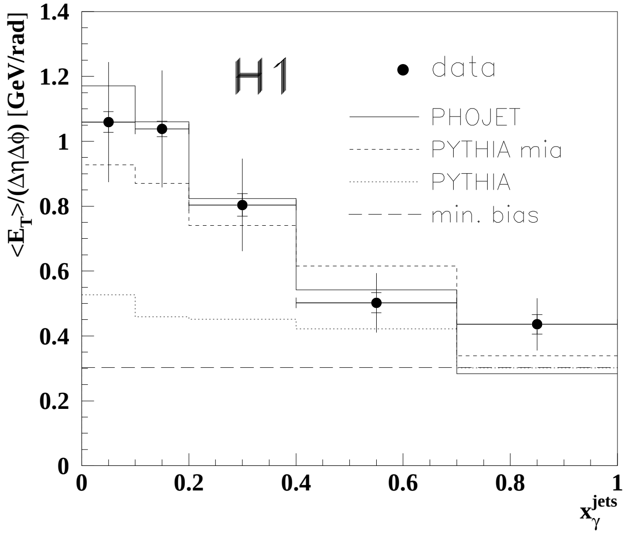
For PTmaxT > 2.0 GeV both PYTHIA and HERWIG produce slightly too many "associated" particles in the direction of PTmaxT!

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

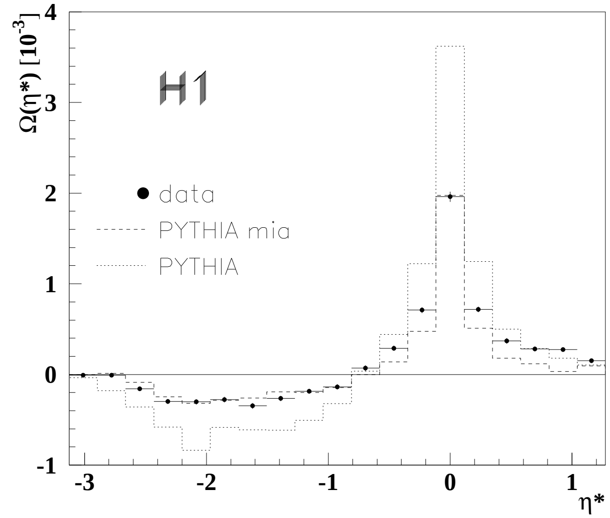


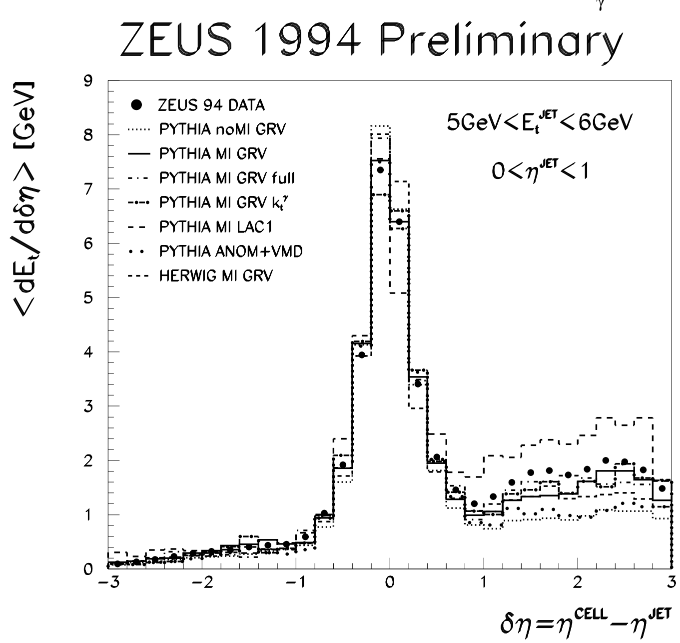
Multiple interactions also preferred by HERA photoproduction data:

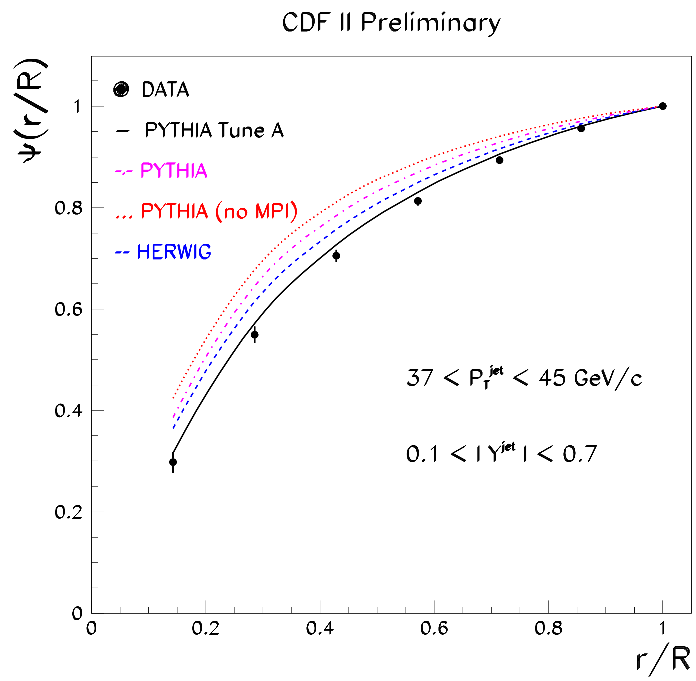
underlying activity in photoproduction vs. DIS



(anti)correlations in energy flow around jet

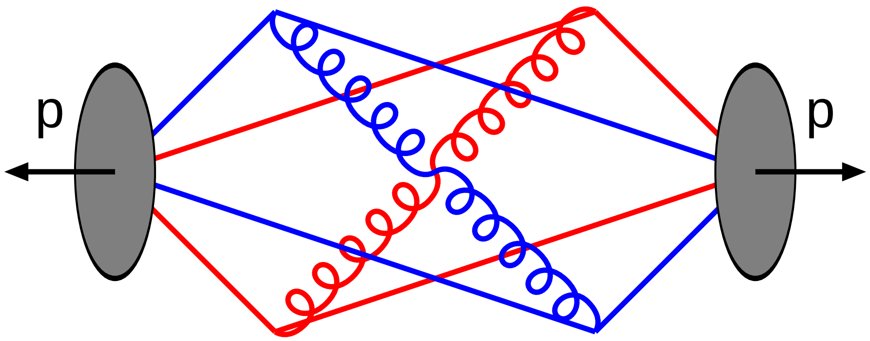




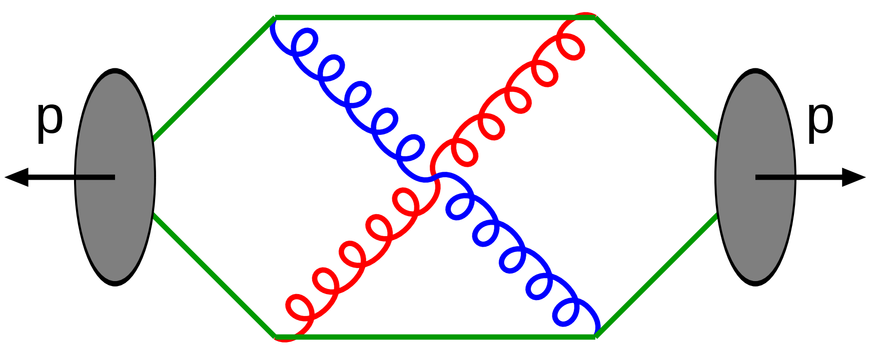


Colour correlations

$\langle p_\perp \rangle (n_{\text{ch}})$ 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

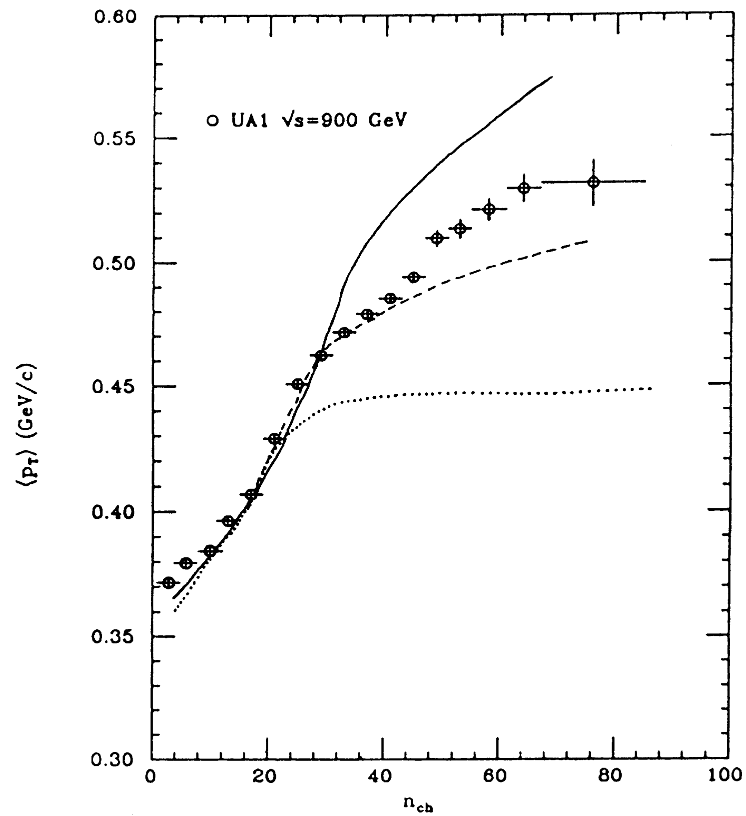
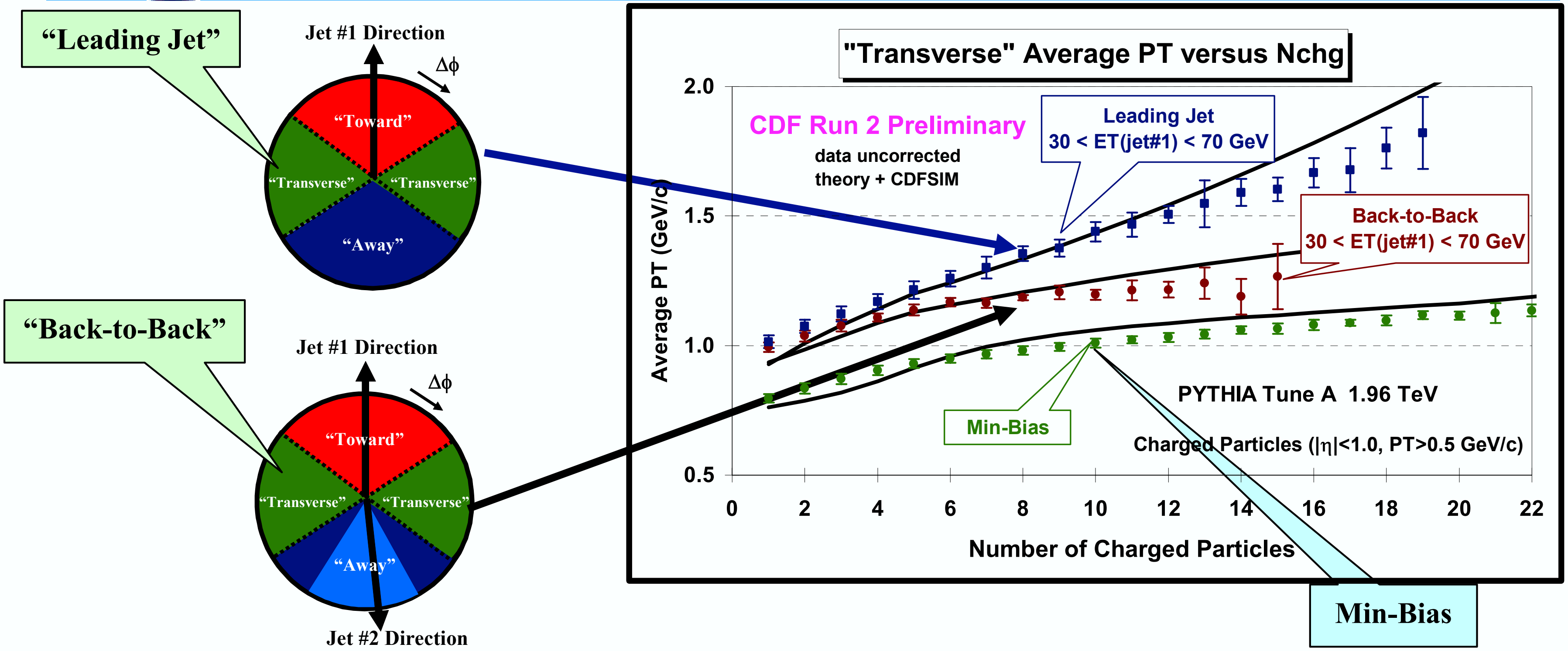


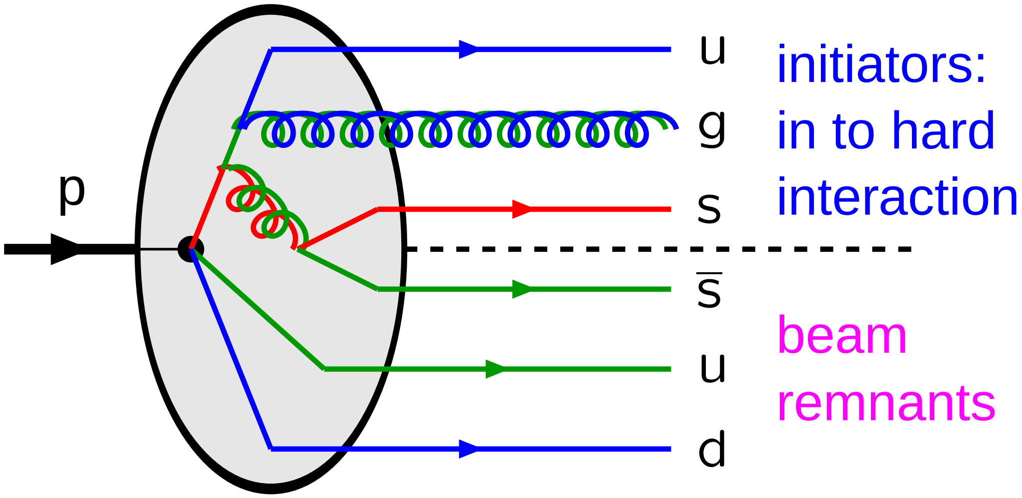
FIG. 27. Average transverse momentum of charged particles in $|\eta| < 2.5$ as a function of the multiplicity. UA1 data points (Ref. 49) at 900 GeV compared with the model for different assumptions about the nature of the subsequent (nonhardest) interactions. Dashed line, assuming $q\bar{q}$ scatterings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

“Transverse” <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.

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:**

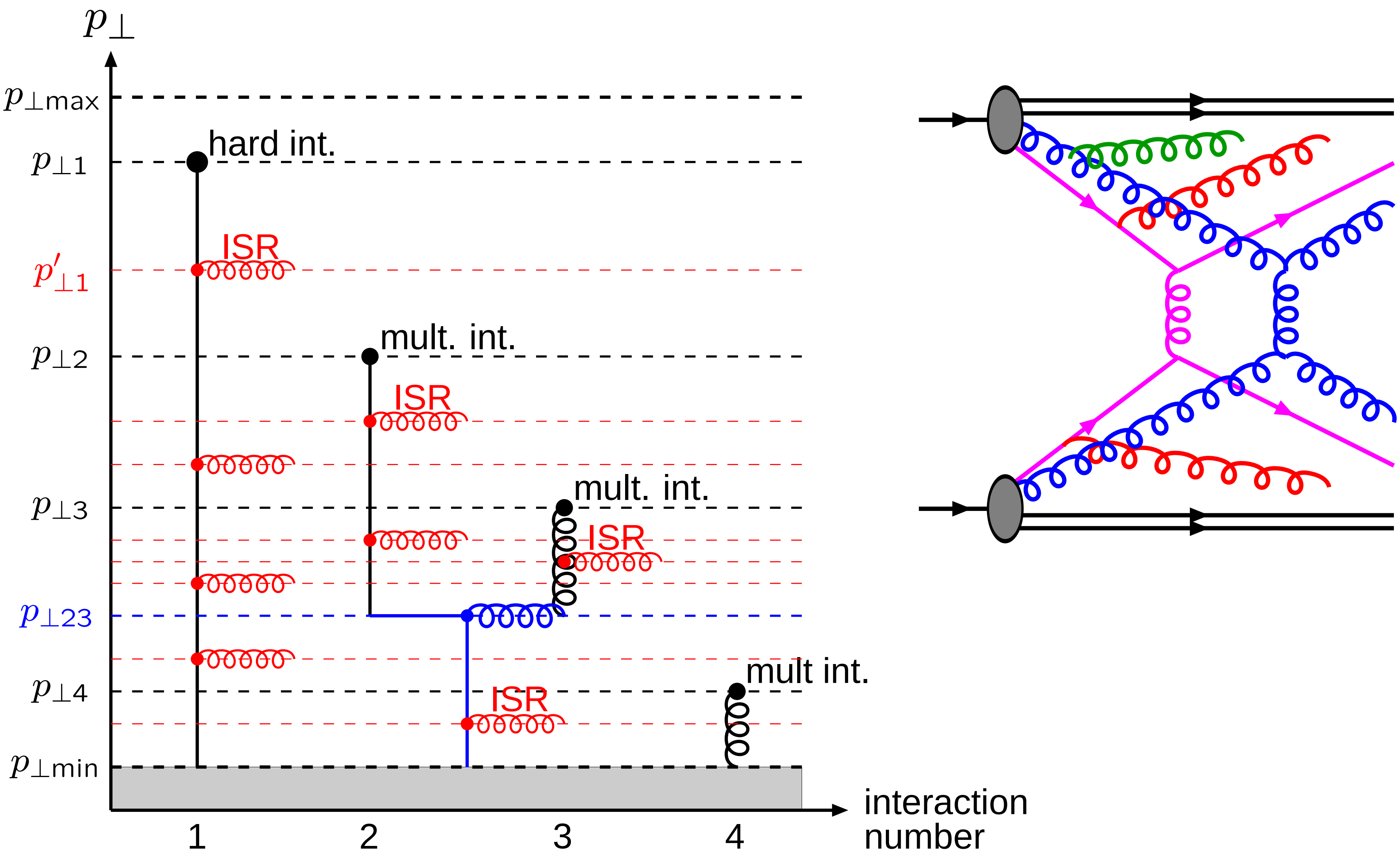
0) Squeeze range $0 < x < 1$ into $0 < x < 1 - \sum x_i$ (ISR: $i \neq i_{\text{current}}$)

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

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

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

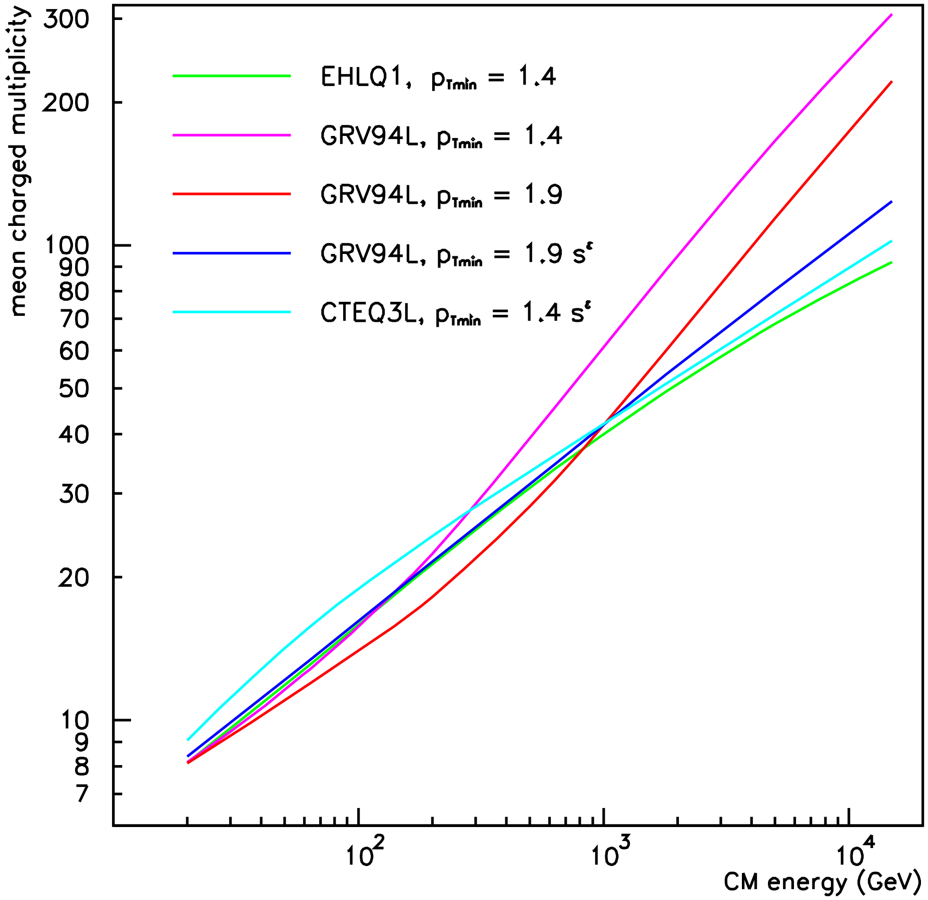
“resolution evolution”

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 $p_{\perp 0}$

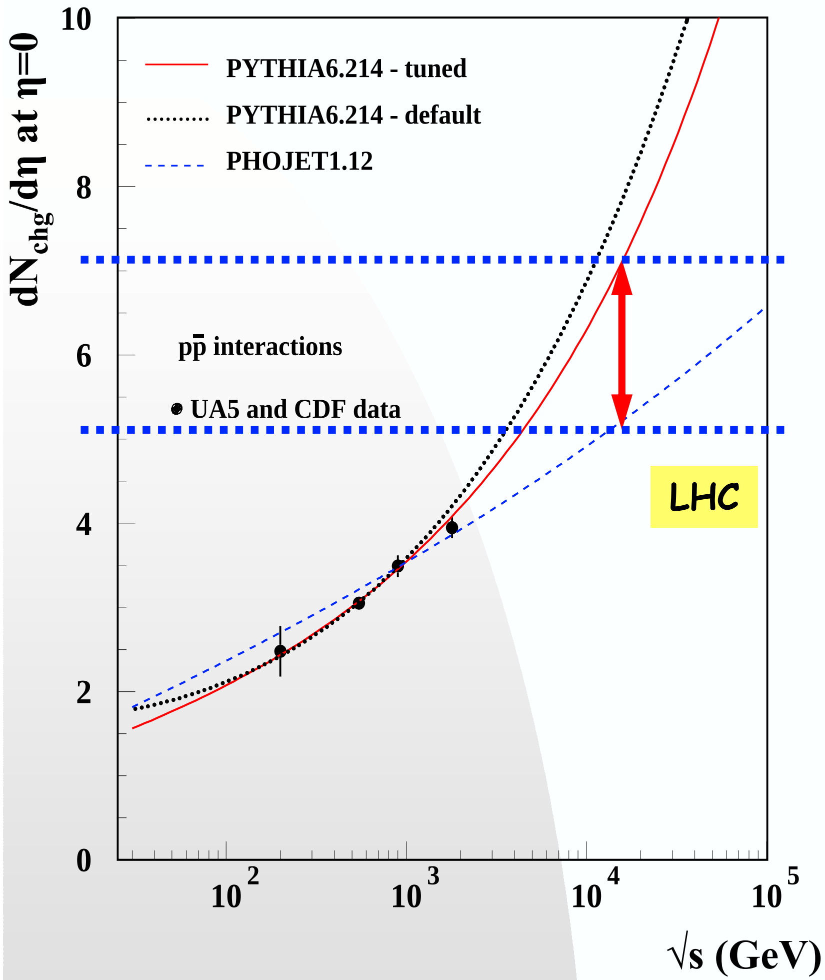
Post-HERA PDF fits steeper at small x

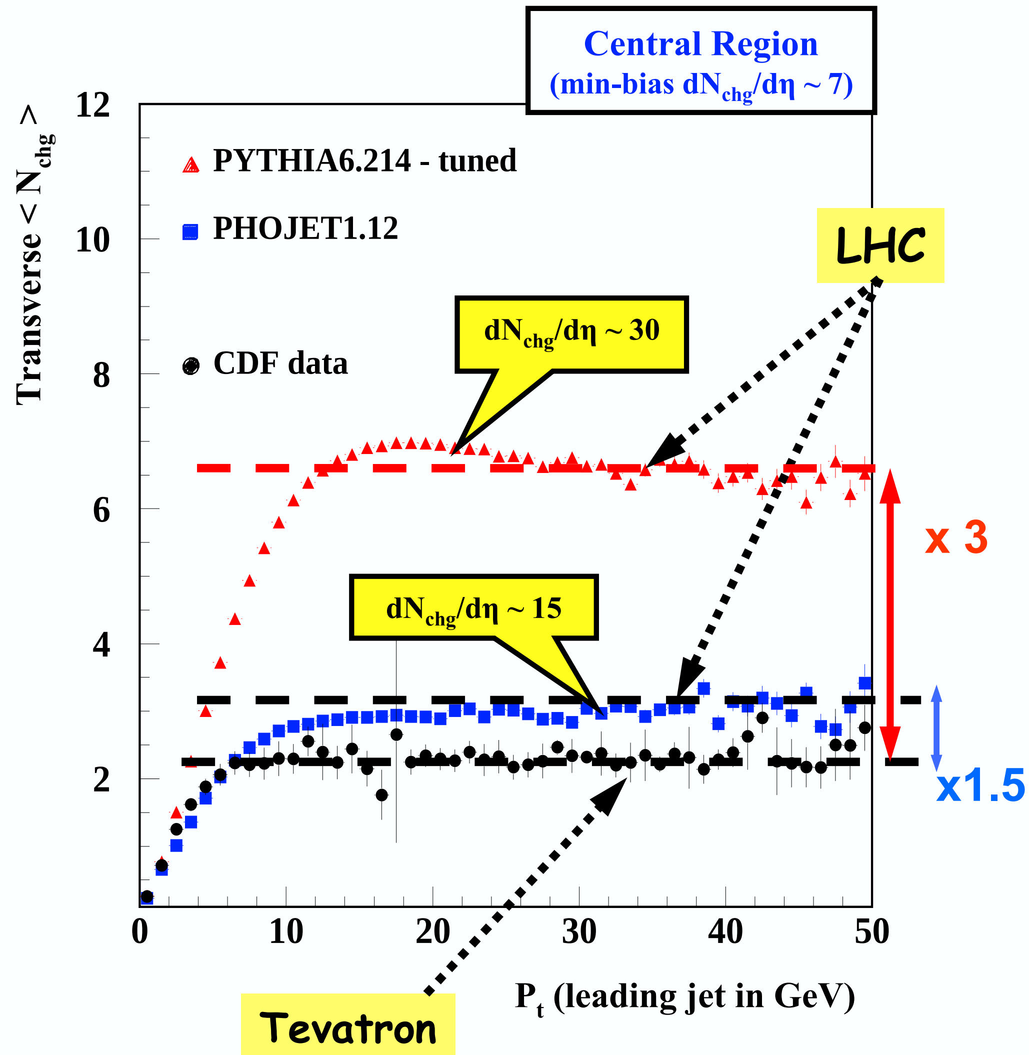
$\Rightarrow$ stronger energy dependence

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

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

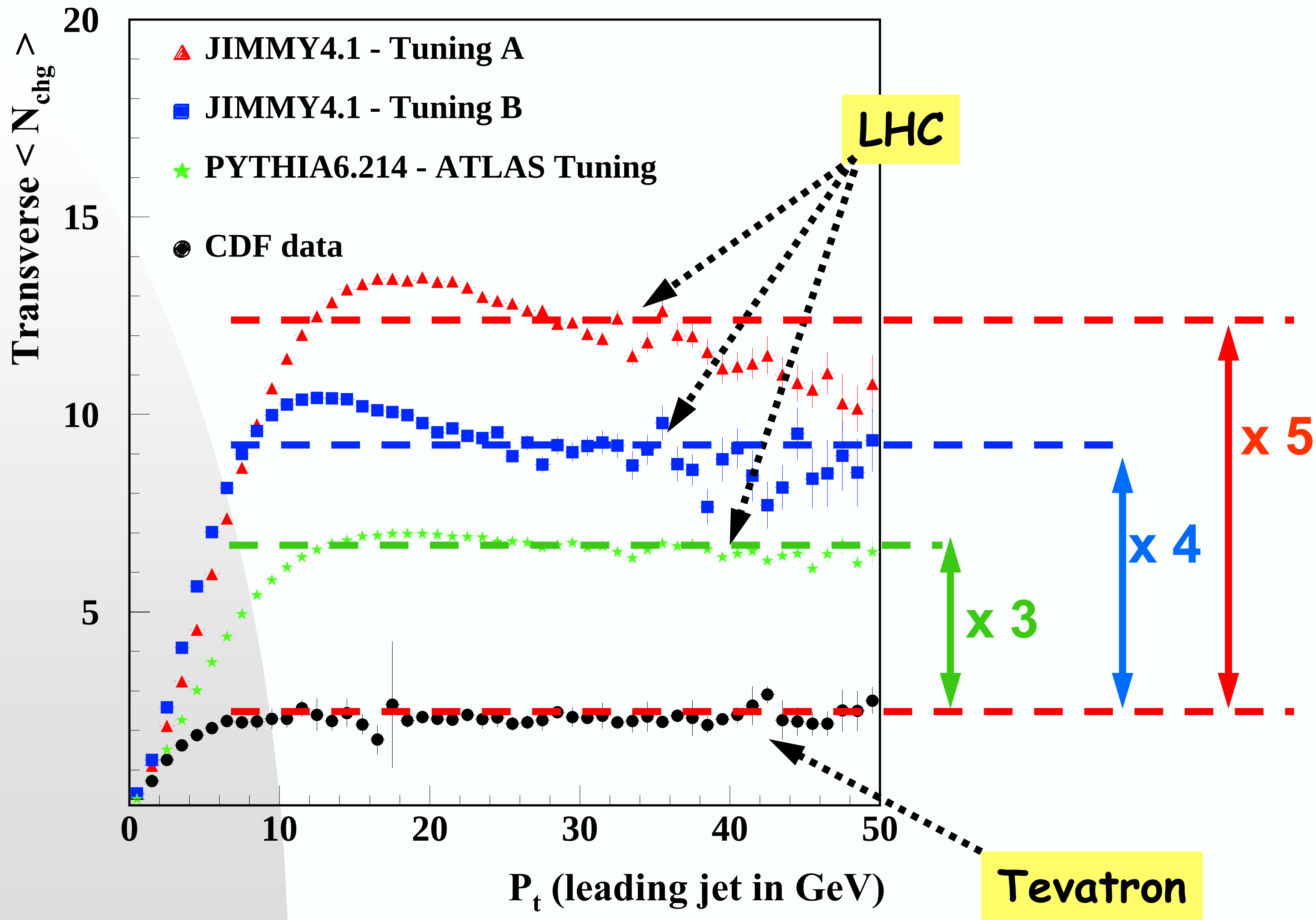
LHC predictions: pp collisions at √s = 14 TeV



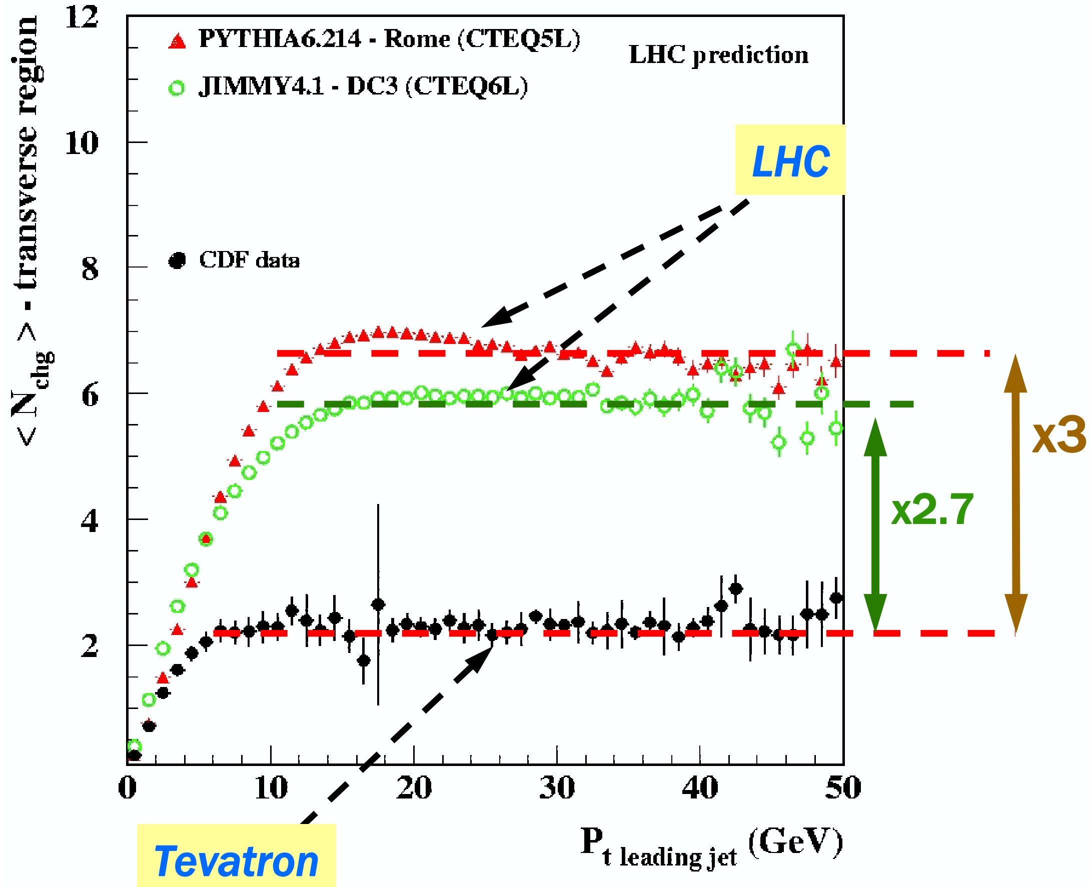


- PYTHIA models favour $\ln^2(s)$;
- PHOJET suggests a $\ln(s)$ dependence.

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!

Perugia, Italy,
27– 31 October,
2008

Home Programme Registration Registered Partecipants Organizing Committee
Accomodation Guidelines & Travelling Contacts Bullettin & Poster Instructions for Authors

News & Announce

22/03/08 – Firts Bulletin available

Courtesy of David Roberts
for
"ElementalParticles"

Welcome to the first International Workshop on Multiple Partonic Interactions at the LHC "1st MPI@LHC".

The objective of this first workshop on Multiple Partonic Interactions (MPI) at the LHC is to raise the profile of MPI studies, summarizing the legacy from the older phenomenology at hadronic colliders and favouring further specific contacts between the theory and experimental communities. The MPI are experiencing a growing popularity and are currently widely invoked to account for observations that would not be explained otherwise: the activity of the Underlying Event, the cross sections for multiple heavy flavour production, the survival probability of large rapidity gaps in hard diffraction, etc. At the same time, the implementation of the MPI effects in the Monte Carlo models is quickly proceeding through an increasing level of sophistication and complexity that in perspective achieves deep general implications for the LHC physics. The ultimate ambition of this workshop is to promote the MPI as unification concept between seemingly heterogeneous research lines and to profit of the complete experimental picture in order to constrain their implementation in the models, evaluating the spin offs on the LHC physics program.