YETI ’09 – rediscovering the Standard Model and
the prospects for early discovery at the LHC
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Underlying-Event Physics

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with many thanks to. . .

LUND UNIVERSITY

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on QCD Phenomenology
and Monte Carlo Event Generators
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Minimum-Bias and Underlying-Event Physics

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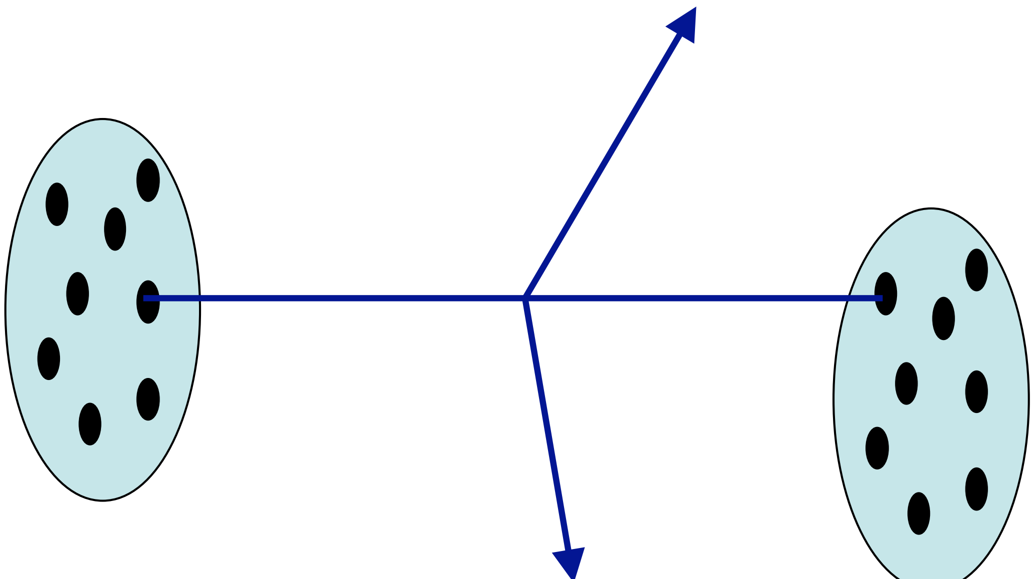
The Underlying Event

- Protons are extended objects
- After a parton has been scattered out of each, what happens to the remnants?



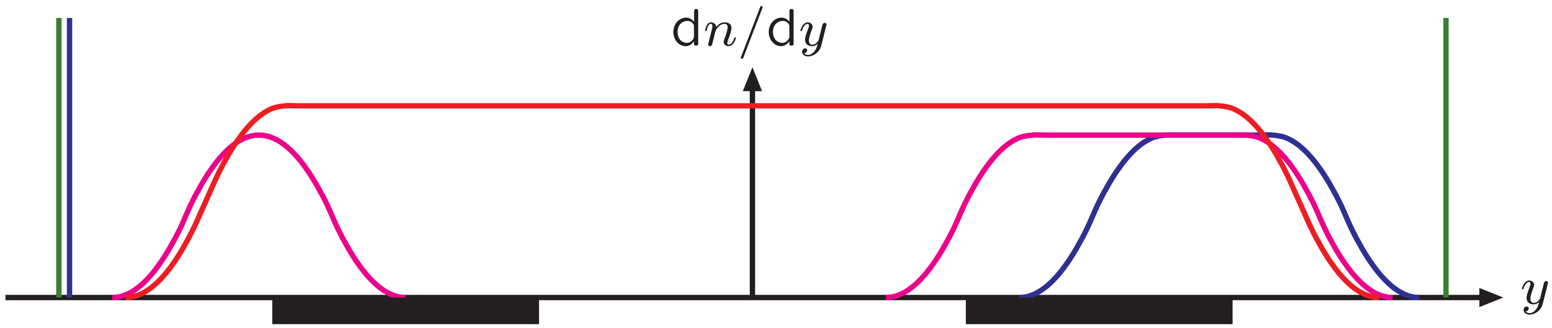
Two models:

- Non-perturbative: Soft parton—parton cross section is so large that the remnants always undergo a soft collision.
- Perturbative: ‘Hard’ parton—parton cross section huge at low p_t, high energy, dominates inelastic cross section and is calculable.

What is minimum bias?

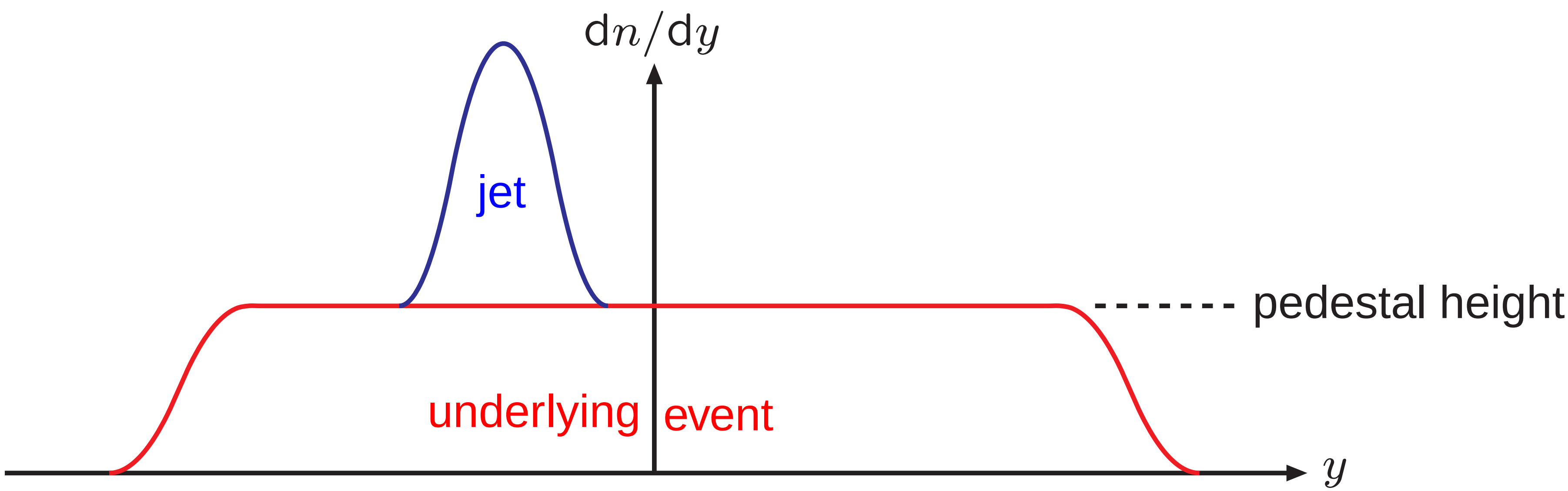
≈ "all events, with no bias from restricted trigger conditions"

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



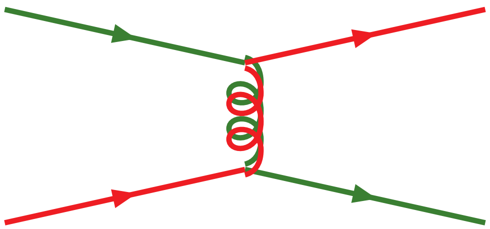
reality: $\sigma_{\rm min-bias} \approx \sigma_{\rm non-diffractive} + \sigma_{\rm double-diffractive} \approx 2/3 \times \sigma_{\rm tot}$

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 $2 \to 2$

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

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

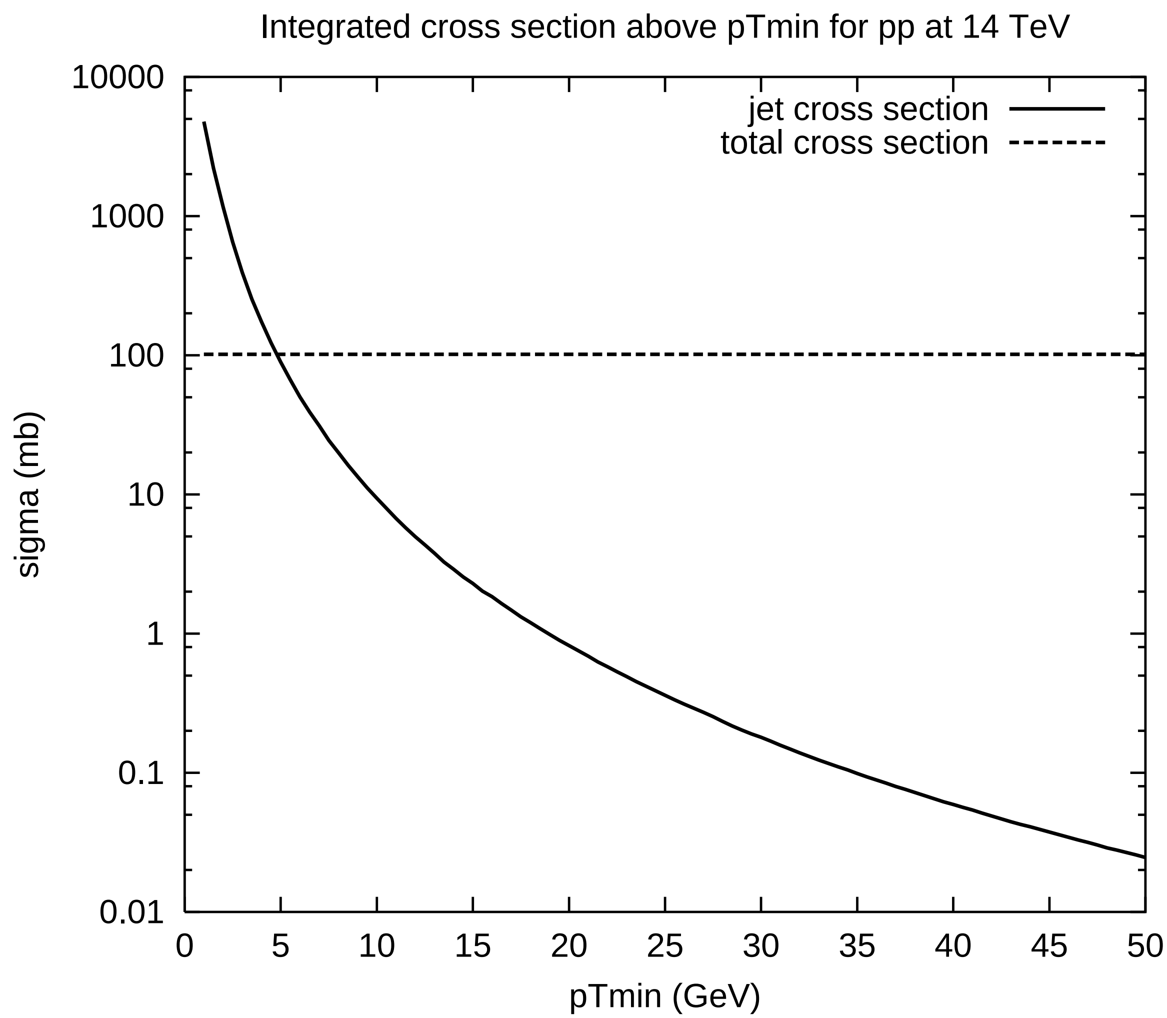
$\mathrm{q\overline{q}} \to \mathrm{gg}$

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

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

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

with CTEQ 5L PDF's



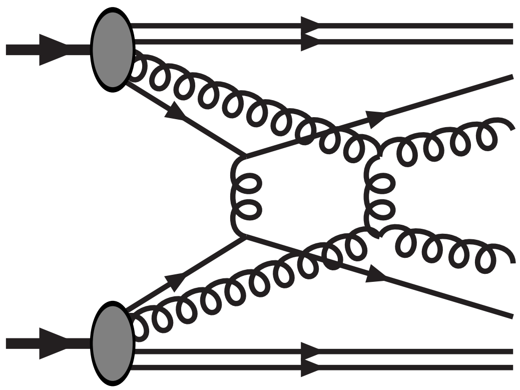
$$\sigma_{\mathrm{int}}(p_{\perp\mathrm{min}}) = \iiint_{p_{\perp\mathrm{min}}} \mathrm{d}x_1\,\mathrm{d}x_2\,\mathrm{d}p_\perp^2\, f_1(x_1,p_\perp^2)\, f_2(x_2,p_\perp^2) \frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}p_\perp^2}$$

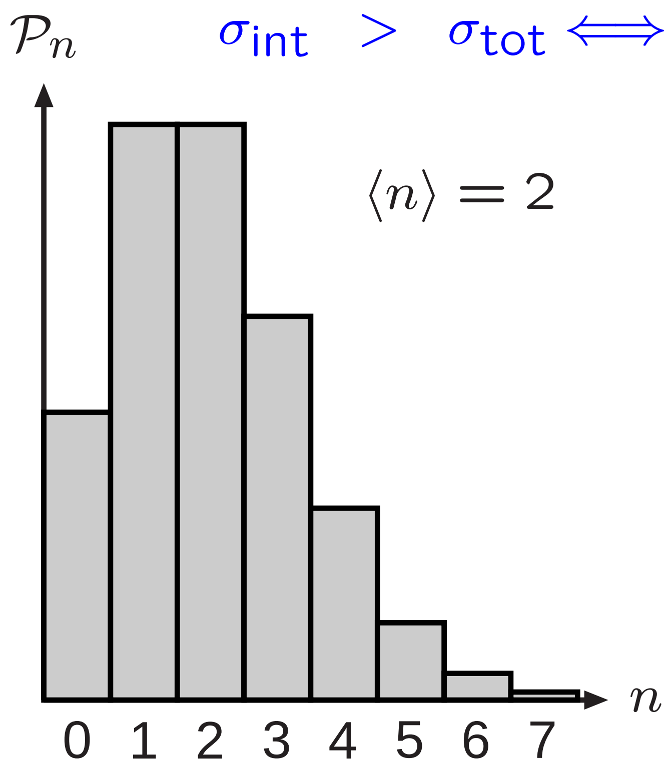
Half a solution to $\sigma_{\mathrm{int}}(p_{\perp\mathrm{min}}) > \sigma_{\mathrm{tot}}$: many interactions per event

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

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

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





If interactions occur independently
then **Poissonian statistics**

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

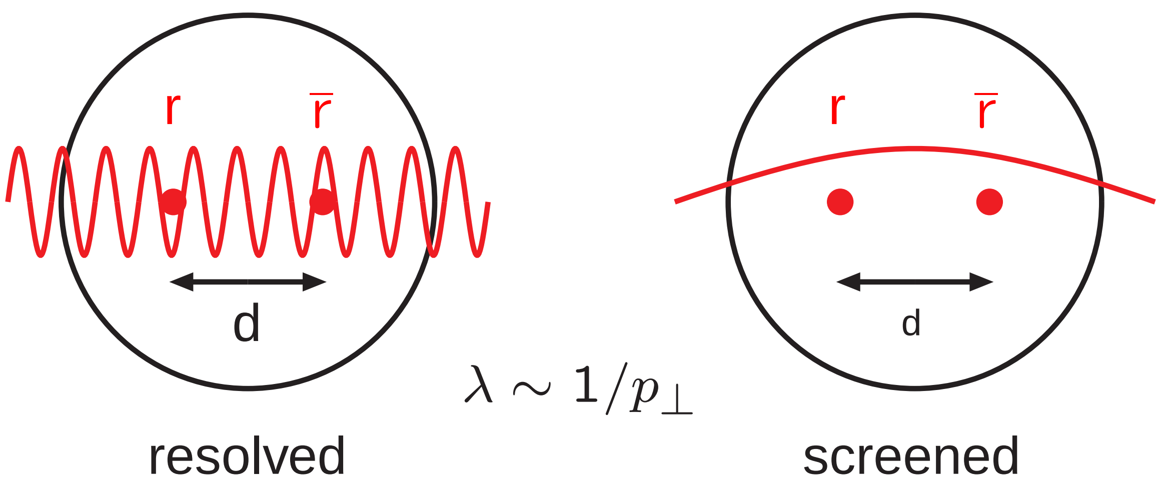
but energy–momentum conservation
$\Rightarrow$ large n suppressed

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

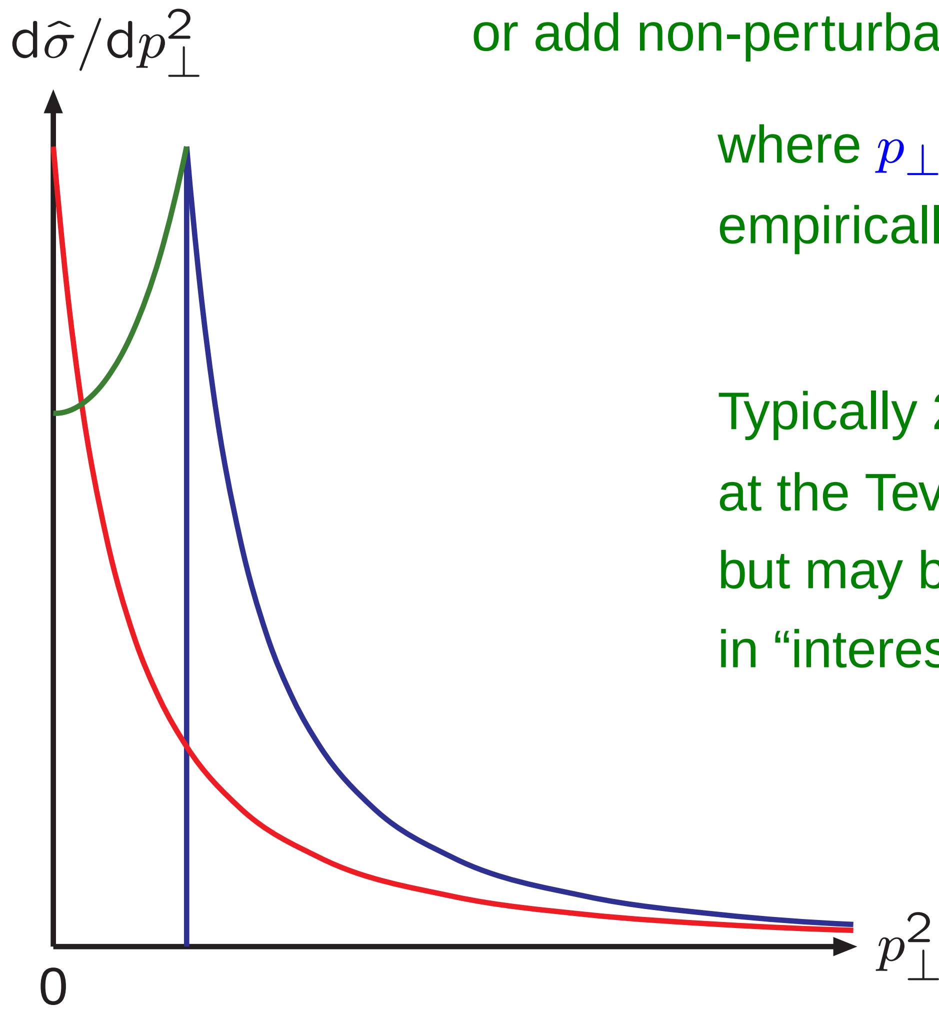


so modify

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

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

or add non-perturbative soft component



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.

Basic generation of multiple interactions

- For now exclude diffractive (and elastic) topologies, i.e. only model nondiffractive events, with $\sigma_{\mathrm{nd}} \simeq 0.6 \times \sigma_{\mathrm{tot}}$
- Differential probability for interaction at $p_\perp$ is

$$\frac{\mathrm{d}P}{\mathrm{d}p_\perp} = \frac{1}{\sigma_{\mathrm{nd}}} \frac{\mathrm{d}\sigma}{\mathrm{d}p_\perp}$$

- Average number of interactions naively

$$\langle n \rangle = \frac{1}{\sigma_{\mathrm{nd}}} \int_0^{E_{\mathrm{cm}}/2} \frac{\mathrm{d}\sigma}{\mathrm{d}p_\perp} \mathrm{d}p_\perp$$

- Require ≥ 1 interaction in an event or else pass through without anything happening

$$P_{\geq 1} = 1 - P_0 = 1 - \exp(-\langle n \rangle)$$

(Alternatively: allow soft nonperturbative interactions even if no perturbative ones.)

Can pick n from Poissonian and then generate n independent interactions according to $\mathrm{d}\sigma/\mathrm{d}p_\perp$ (so long as energy left)

Impact parameter dependence

So far assumed that all collisions have equivalent initial conditions, but hadrons are extended,

e.g. electromagnetic form factor:

$$S_{\mathrm{p}}(\mathbf{b}) = \int \frac{\mathrm{d}^2\mathbf{k}}{(2\pi)^2} \frac{\exp(i\mathbf{k}\cdot\mathbf{b})}{(1+\mathbf{k}^2/\mu^2)^2}$$

where $\mu = 0.71$ GeV (or free parameter);

and overlap of hadrons during collision is

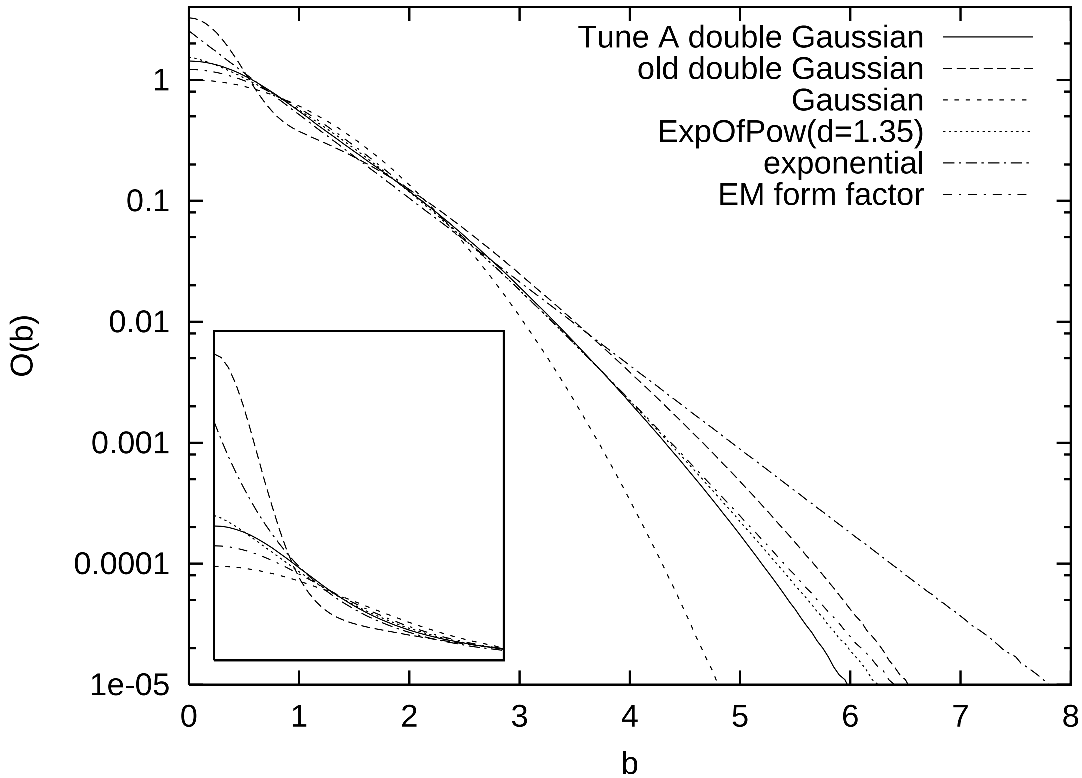
$$\mathcal{O}(b) = \int \mathrm{d}^2\mathbf{b_1}\,\mathrm{d}^2\mathbf{b_2}\,S_{\mathrm{p}}(\mathbf{b_1})\,S_{\mathrm{p}}(\mathbf{b_2})\,\delta^{(2)}(\mathbf{b}-\mathbf{b_1}+\mathbf{b_2})$$

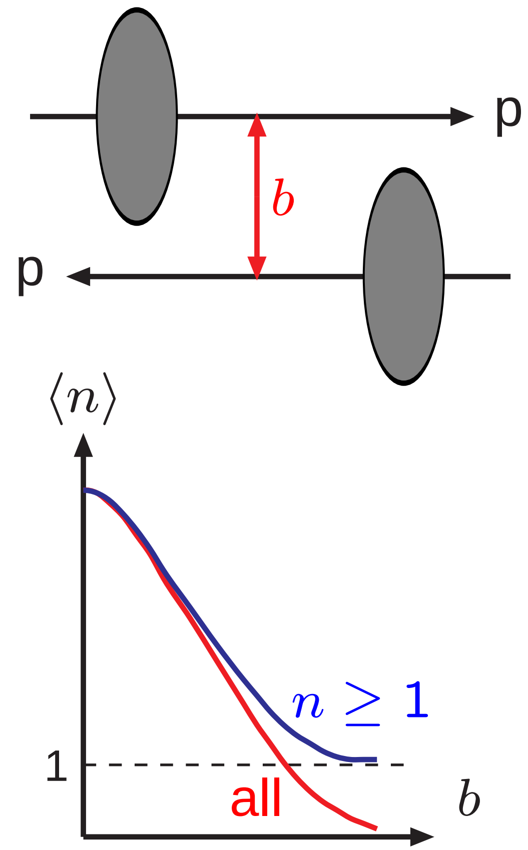
or empirical double Gaussian:

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

where $r_2 \neq r_1$ represents “hot spots”, giving

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





- Events are distributed in impact parameter b
- Average activity at b proportional to $\mathcal{O}(b)$
  - ⋆ central collisions more active $\Rightarrow \mathcal{P}_n$ broader than Poissonian
  - ⋆ peripheral passages normally give no collisions at all $\Rightarrow$ finite σ_{tot}
- Also crucial for *pedestal effect* (more later)

PYTHIA implementations

(1) Simple scenario (1985):

first model for event properties based on perturbative multiple interactions

no longer used (no impact-parameter dependence)

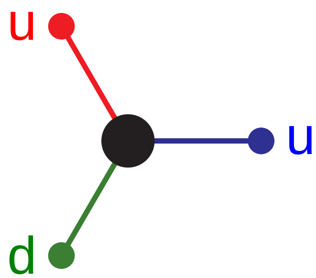
(2) Impact-parameter-dependence (1987):

still in frequent use (Tune A, Tune DWT, ATLAS tune, . . .)

- double Gaussian matter distribution,
- interactions ordered in decreasing $p_{\perp}$,
- PDF's rescaled for momentum conservation,
- *but* no showers for subsequent interactions and simplified flavours

(3) Improved handling of PDFs and beam remnants (2004)

- Trace flavour content of remnant, including baryon number (junction)
- Study colour (re)arrangement among outgoing partons (ongoing!)
- Allow radiation for all interactions

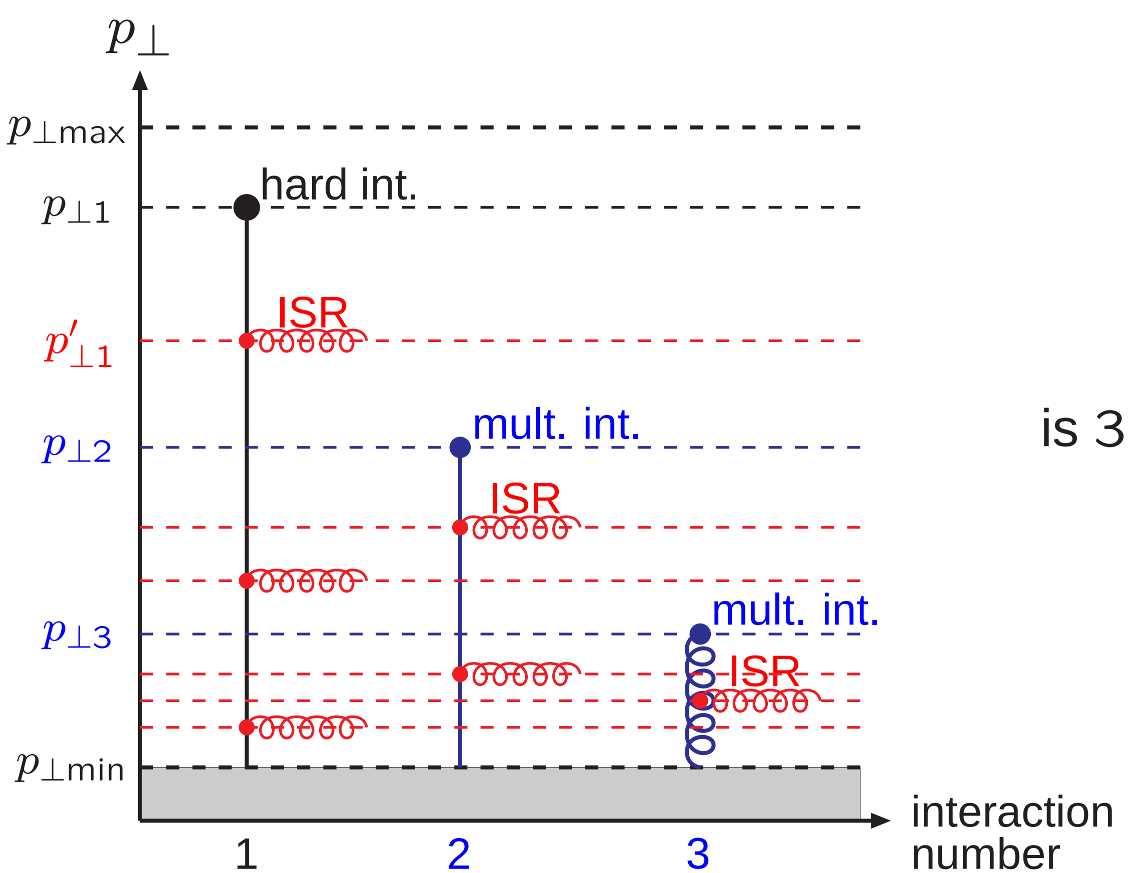


(4) Evolution interleaved with ISR (2004)

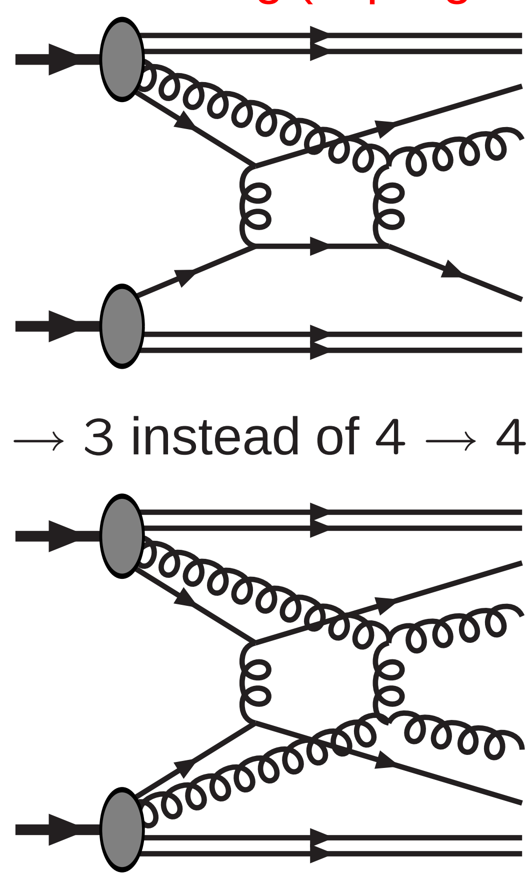
- Transverse-momentum-ordered showers

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

with ISR sum over all previous MI



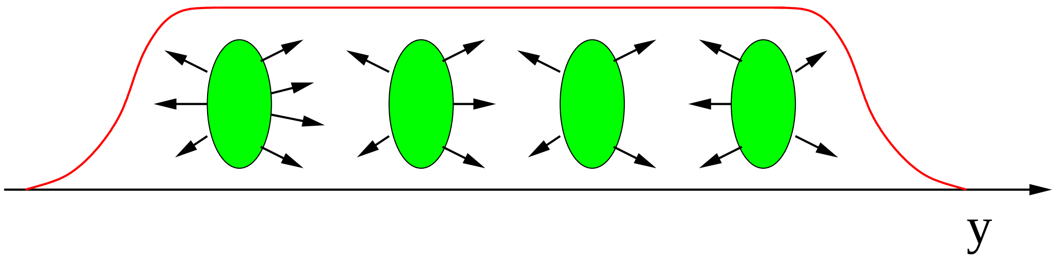
(5) Rescattering (in progress)



is 3 $\to$ 3 instead of 4 $\to$ 4:

HERWIG implementations

(1) Soft Underlying Event (1988), 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

(2) Jimmy (HERWIG add-on 1995; part of Herwig++ 2007)

- only model of underlying event, not of minimum bias
- similar to PYTHIA (2) above; but details different
- matter profile by electromagnetic form factor (with tuned size)
- no $p_\perp$-ordering of emissions, no PDF rescaling for non-valence partons: abrupt stop when (if) run out of energy

(3) Ivan (non-public code 2002; part of Herwig++ 2008)

- also handles minimum bias
- soft and hard multiple interactions together fill whole $p_\perp$ range

SHERPA implementations

(1) Conventional approach (2004)

- Based on formalism of PYTHIA (2) but
- Full showers for all interactions, with CKKW matching

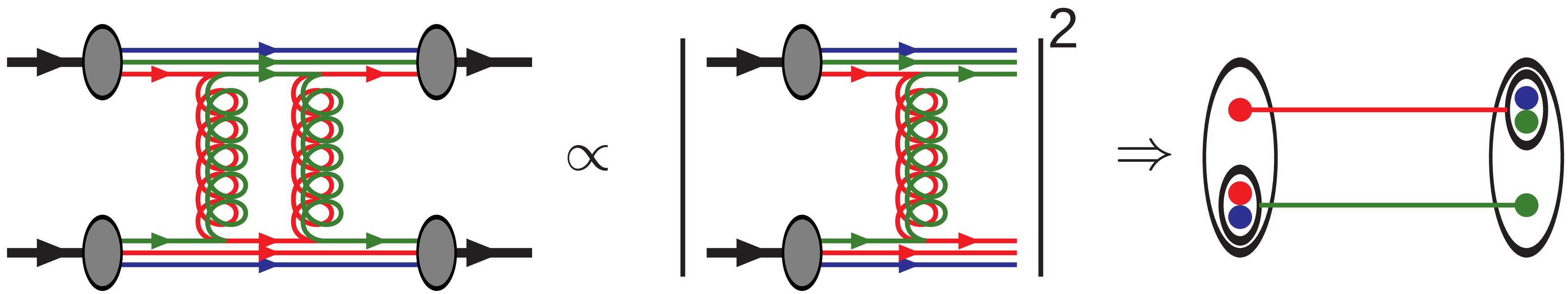
(2) $k_\perp$-factorization-based approach (2007)

- unintegrated PDFs and off-shell matrix elements
- consistent with BFKL evolution (small x)
- combination with multiple interactions in progress

PhoJet (& relatives) implementations

(1) Cut Pomeron ($\sim$ 1980)

- Pomeron predates QCD; nowadays $\sim$ glueball tower
- Optical theorem relates σ_{total} and σ_{elastic}



- Unified framework of nondiffractive and diffractive interactions
- Purely low-$p_{\perp}$: only primordial $k_{\perp}$ fluctuations
- Usually simple Gaussian matter distribution

(2) Extension to large $p_{\perp}$ (1992)

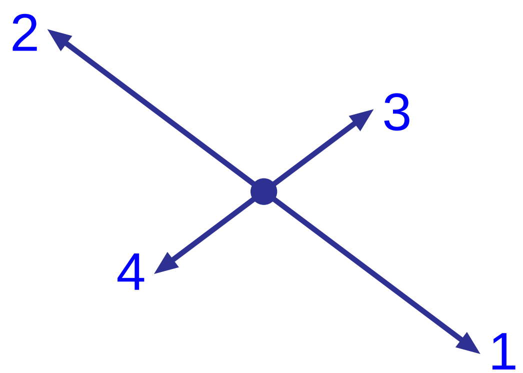
- distinguish soft and hard Pomerons (cf. Ivan):
  soft = nonperturbative, low-$p_{\perp}$, as above
  hard = perturbative, "high"-$p_{\perp}$
- hard based on PYTHIA code, with lower cutoff in $p_{\perp}$

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

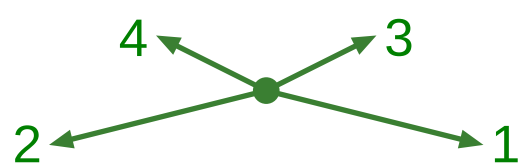


$|\mathbf{p}_{\perp 1} + \mathbf{p}_{\perp 2}| \approx 0$

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

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

Double BremsStrahlung

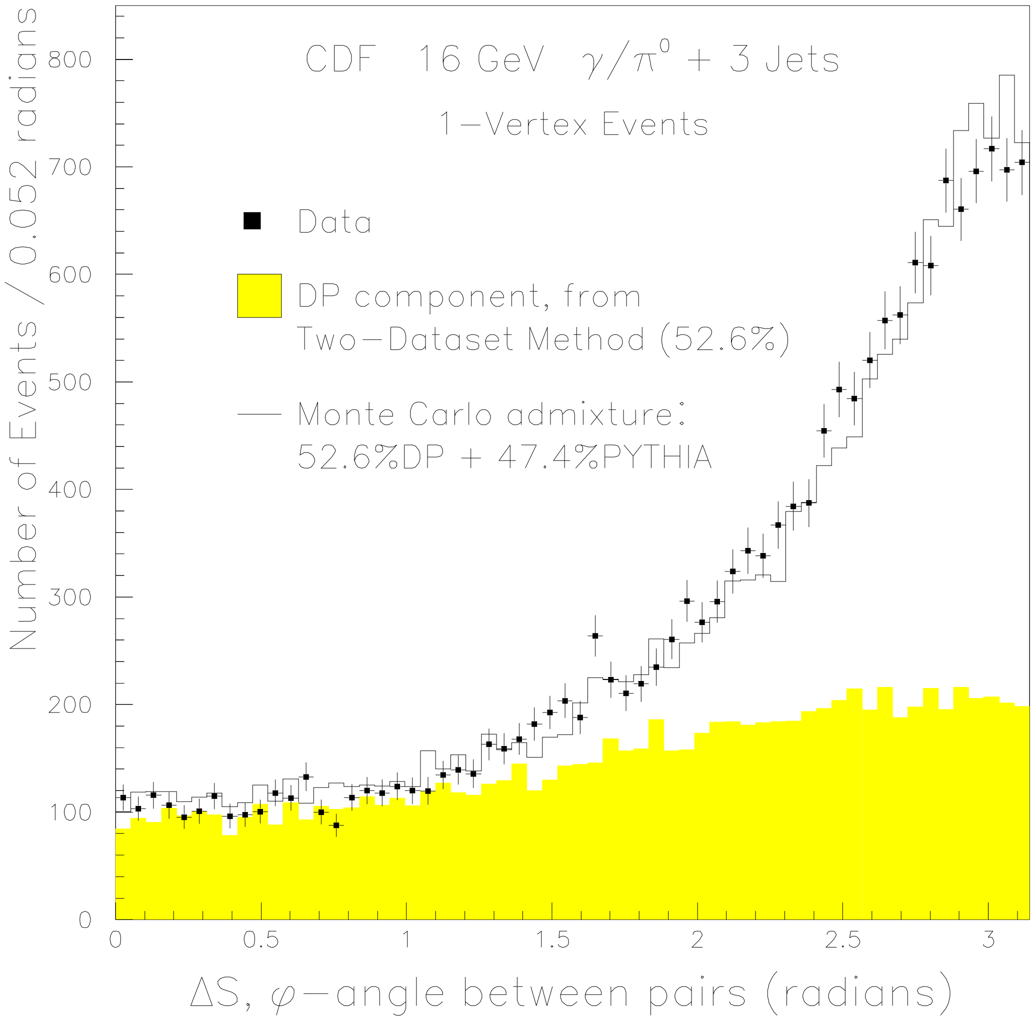


$|\mathbf{p}_{\perp 1} + \mathbf{p}_{\perp 2}| \gg 0$

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

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

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

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,

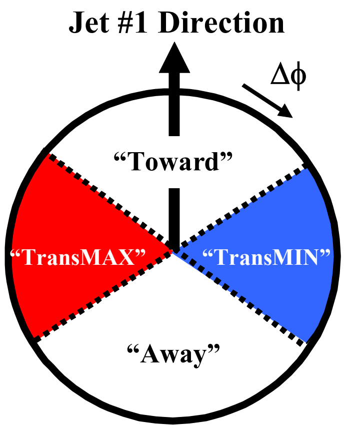
so "trigger bias": hard scale ⇒ central collision

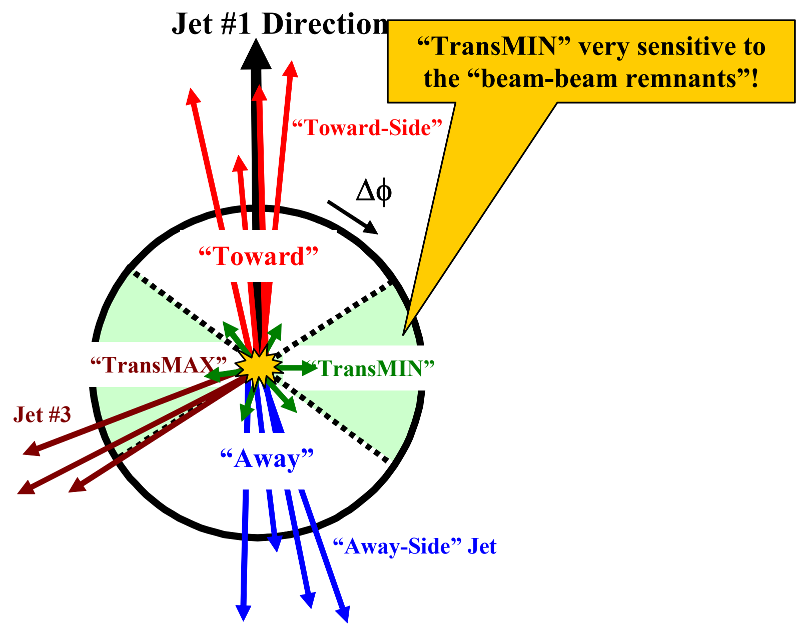
⇒ more interactions ⇒ larger underlying activity.

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

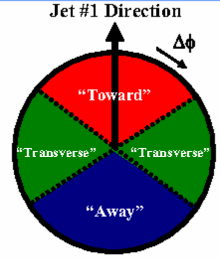


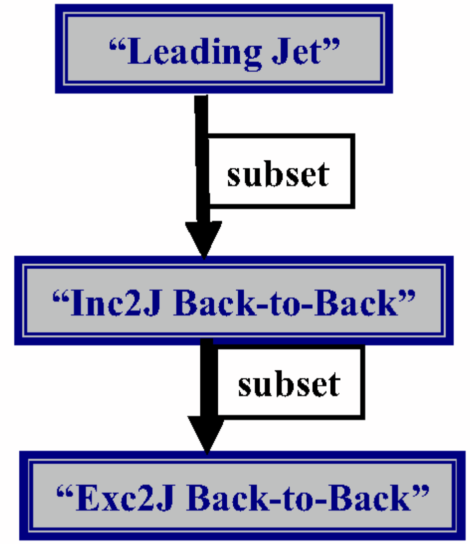


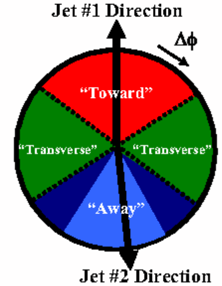
- **Define the MAX and MIN "transverse" regions on an event-by-event basis with MAX (MIN) having the largest (smallest) density.**

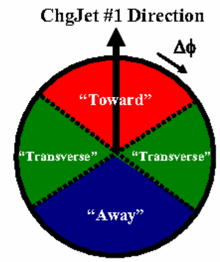
Event Topologies

- **"Leading Jet"** events correspond to the leading calorimeter jet (MidPoint R = 0.7) in the region $|\eta| < 2$ with no other conditions.
- **"Inclusive 2-Jet Back-to-Back"** events are selected to have at least two jets with Jet#1 and Jet#2 nearly "back-to-back" ($\Delta\phi_{12} > 150^o$) with almost equal transverse energies (P_T(jet#2)/P_T(jet#1) > 0.8) with no other conditions .
- **"Exclusive 2-Jet Back-to-Back"** events are selected to have at least two jets with Jet#1 and Jet#2 nearly "back-to-back" ($\Delta\phi_{12} > 150^o$) with almost equal transverse energies (P_T(jet#2)/P_T(jet#1) > 0.8) and P_T(jet#3) < 15 GeV/c.
- **"Leading ChgJet"** events correspond to the leading charged particle jet (R = 0.7) in the region $|\eta| < 1$ with no other conditions.
- **"Z-Boson"** events are Drell-Yan events with 70 < M(lepton-pair) < 110 GeV with no other conditions.

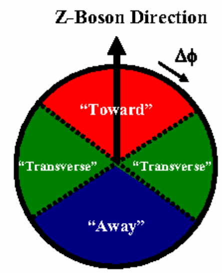






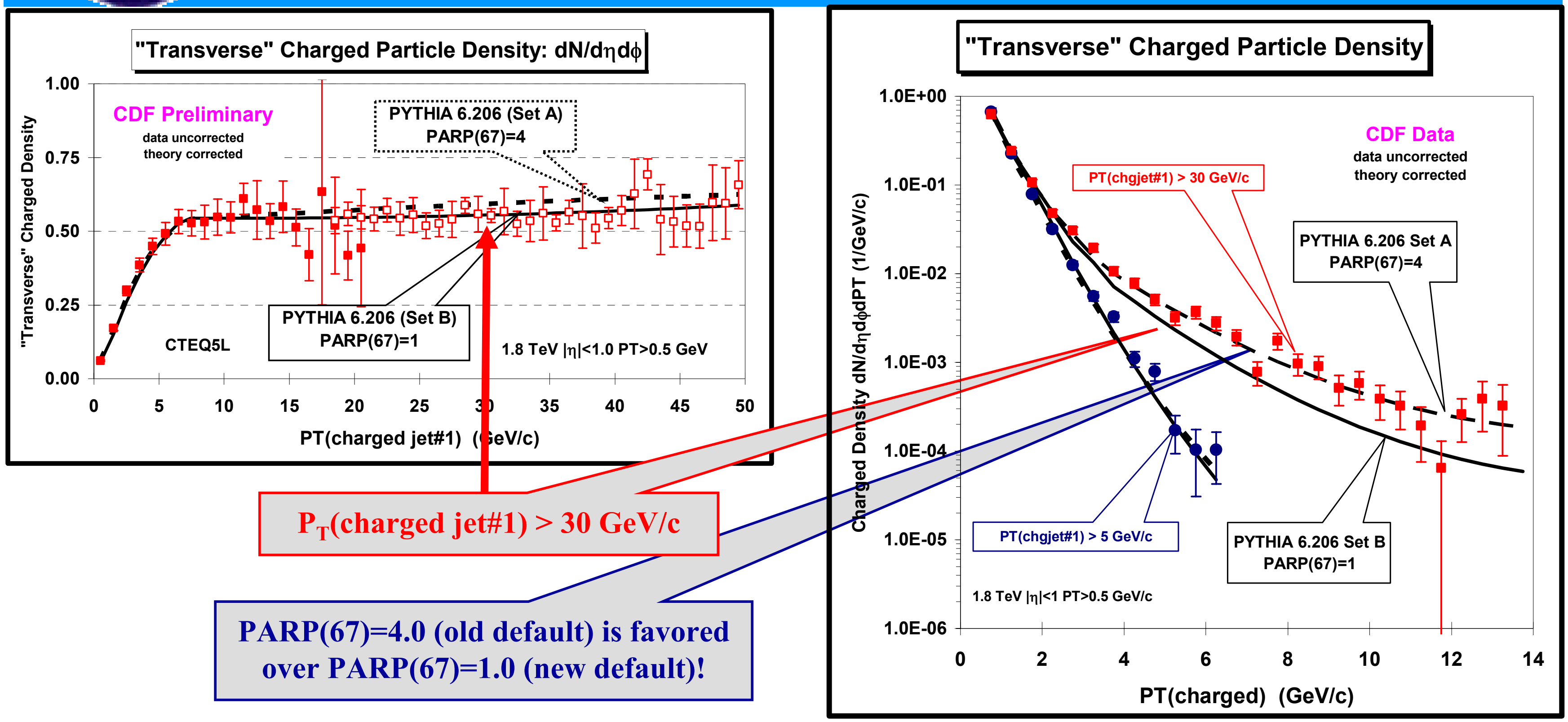


"Charged Jet"



Z-Boson

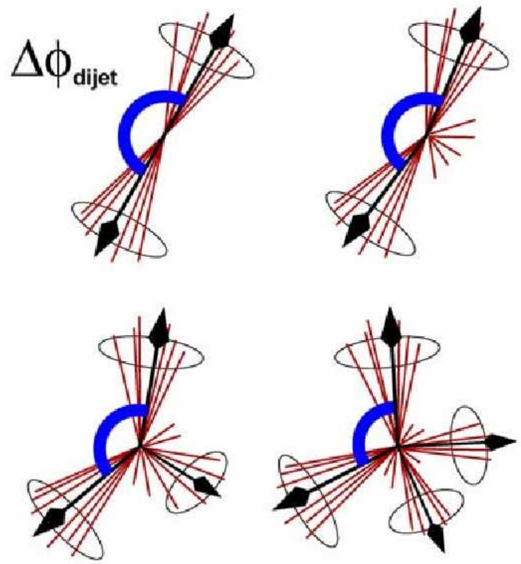
Tuned PYTHIA 6.206 "Transverse" P_T Distribution



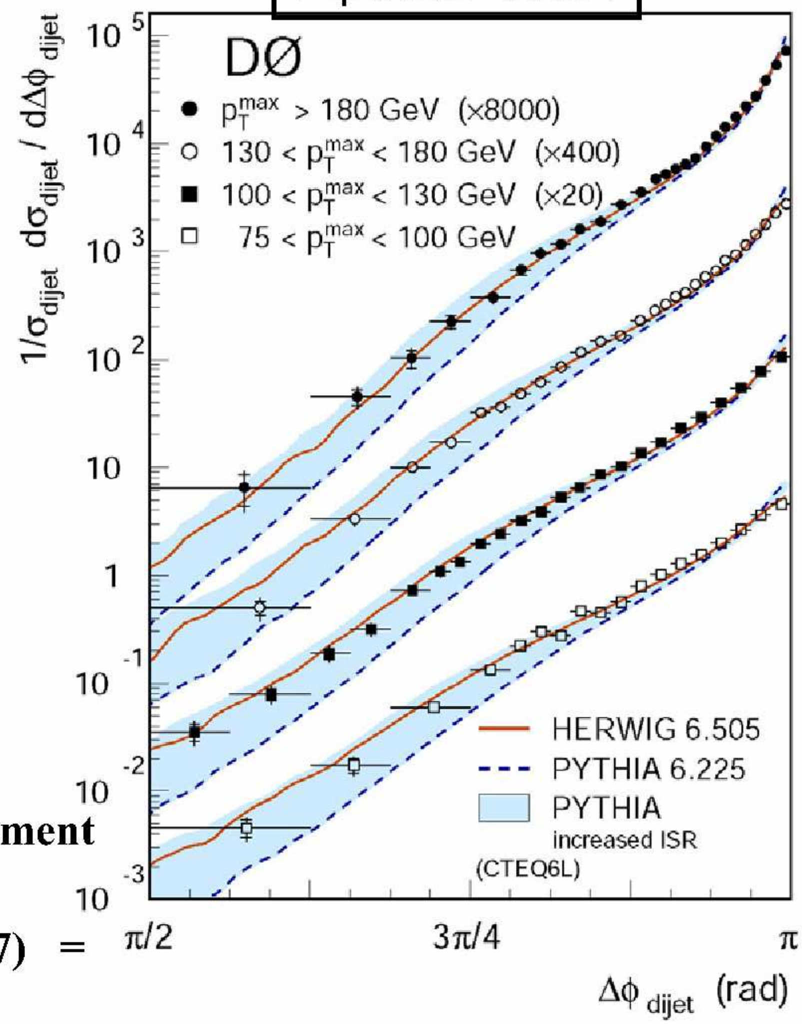
- Compares the average "transverse" charge particle density ($|\eta|<1$, $P_T>0.5$ GeV) versus P_T(charged jet#1) and the P_T distribution of the "transverse" density, $dN_{chg}/d\eta d\phi dP_T$ with the QCD Monte-Carlo predictions of two tuned versions of PYTHIA 6.206 (P_T(hard) > 0, CTEQ5L, Set B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

Jet-Jet Correlations (DØ)

Jet#1-Jet#2 Δφ Distribution



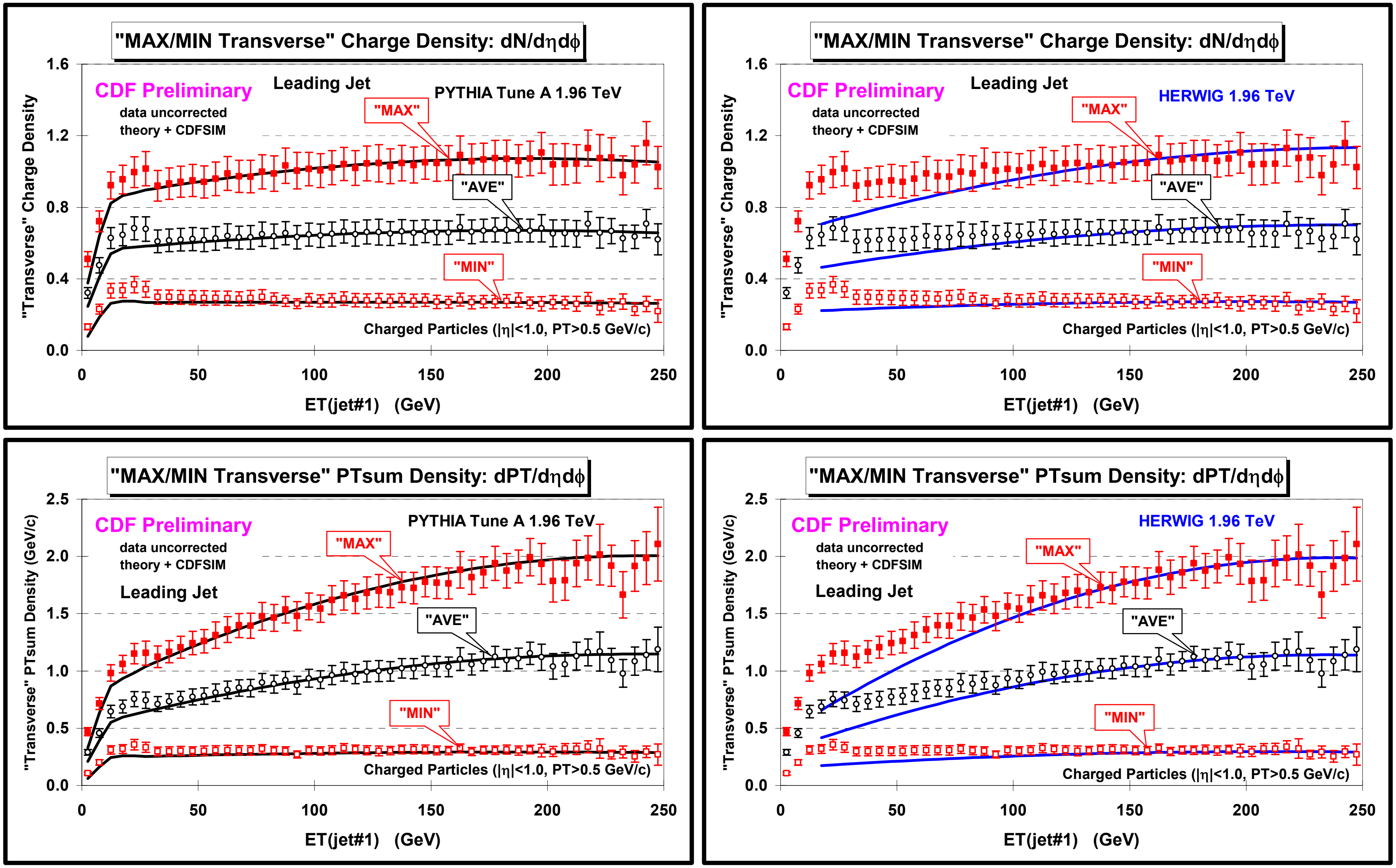
Δφ Jet#1-Jet#2



- MidPoint Cone Algorithm (R = 0.7, f_{merge} = 0.5)
- $\mathcal{L}$ = 150 pb^{-1} (Phys. Rev. Lett. 94 221801 (2005))
- Data/NLO agreement good. Data/HERWIG agreement good.
- Data/PYTHIA agreement good provided PARP(67) = 1.0→4.0 (i.e. like Tune A, best fit 2.5).

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.

CDF Run 1 $P_T(Z)$

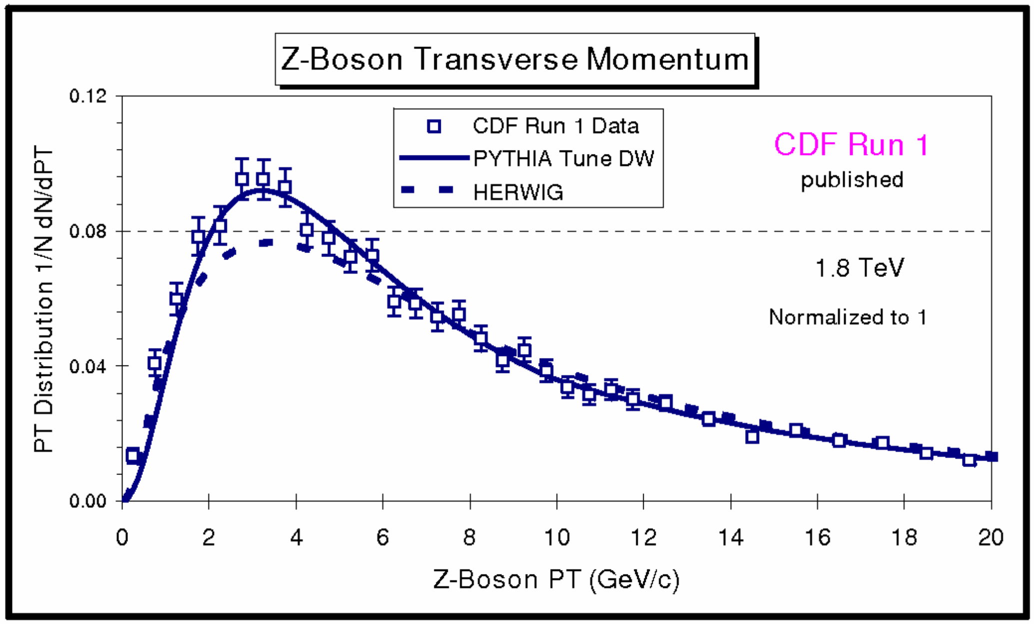
PYTHIA 6.2 CTEQ5L

Parameter	Tune DW	Tune AW
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(62)	1.25	1.25
PARP(64)	0.2	0.2
PARP(67)	2.5	4.0
MSTP(91)	1	1
PARP(91)	2.1	2.1
PARP(93)	15.0	[illegible]

UE Parameters

ISR Parameters

Intrensic KT

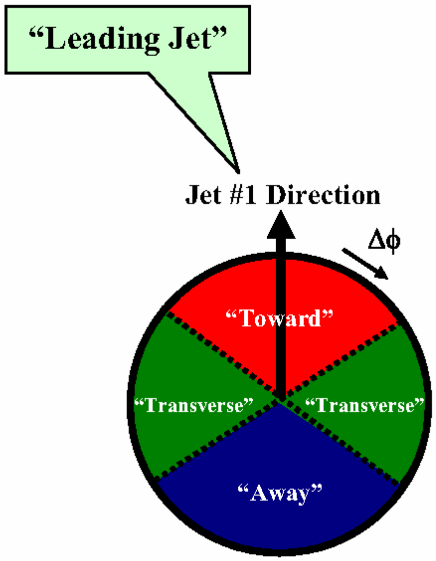


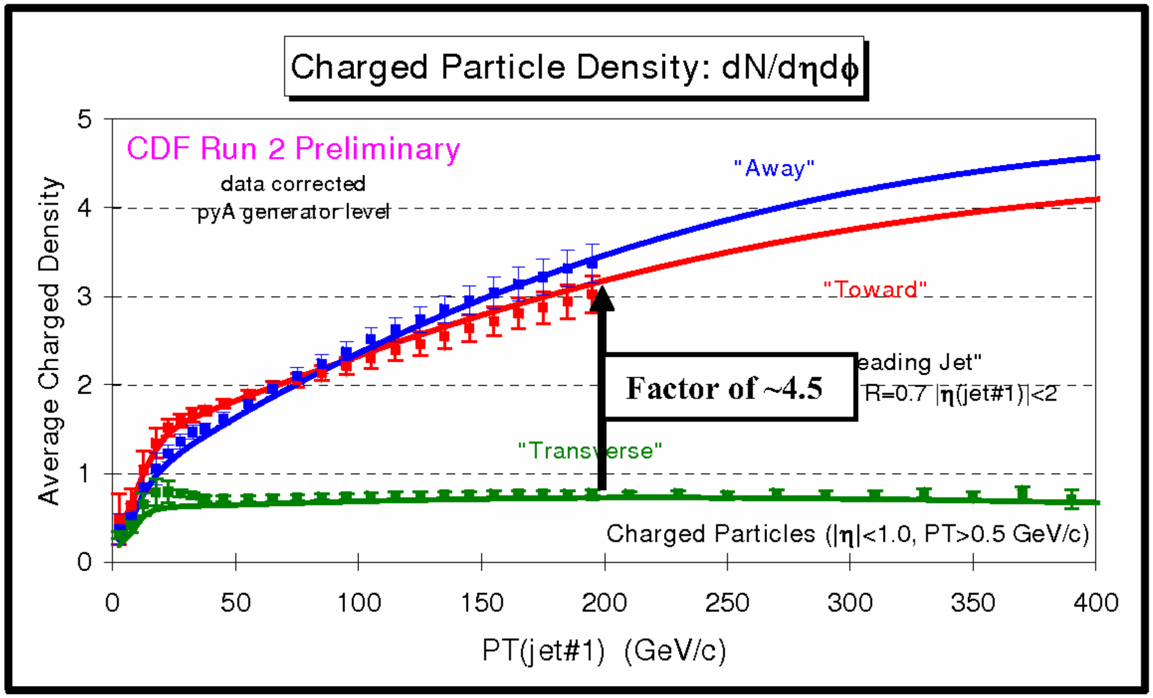
- Shows the Run 1 Z-boson p_T distribution ($<p_T(Z)> \approx 11.5$ GeV/c) compared with PYTHIA Tune DW, and HERWIG.

Tune DW uses D0's perfered value of PARP(67)!

Tune DW has a lower value of PARP(67) and slightly more MPI!

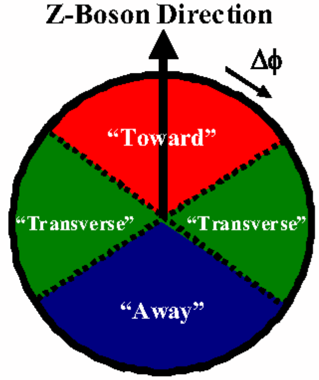
"Towards", "Away", "Transverse"

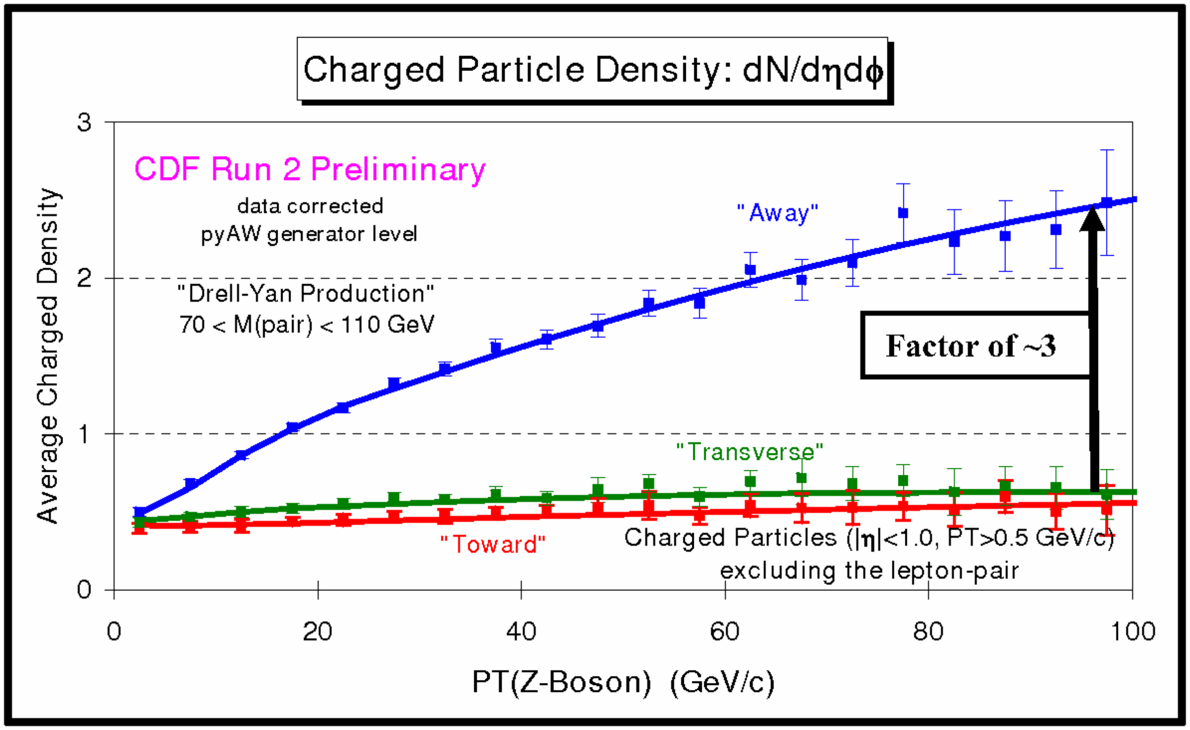




- **Data at 1.96 TeV on the density of charged particles, dN/dηdφ, with p_T > 0.5 GeV/c and |η| < 1 for "leading jet" events as a function of the leading jet p_T for the "toward", "away", and "transverse" regions. The data are corrected to the particle level (*with errors that include both the statistical error and the systematic uncertainty*) and are compared with PYTHIA Tune A at the particle level (*i.e.* generator level).**

"Towards", "Away", "Transverse"

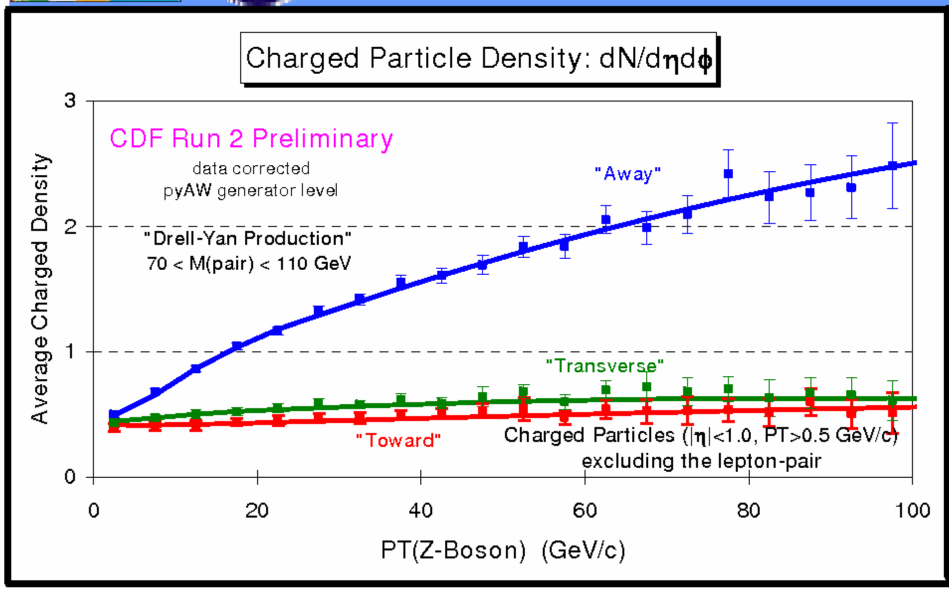


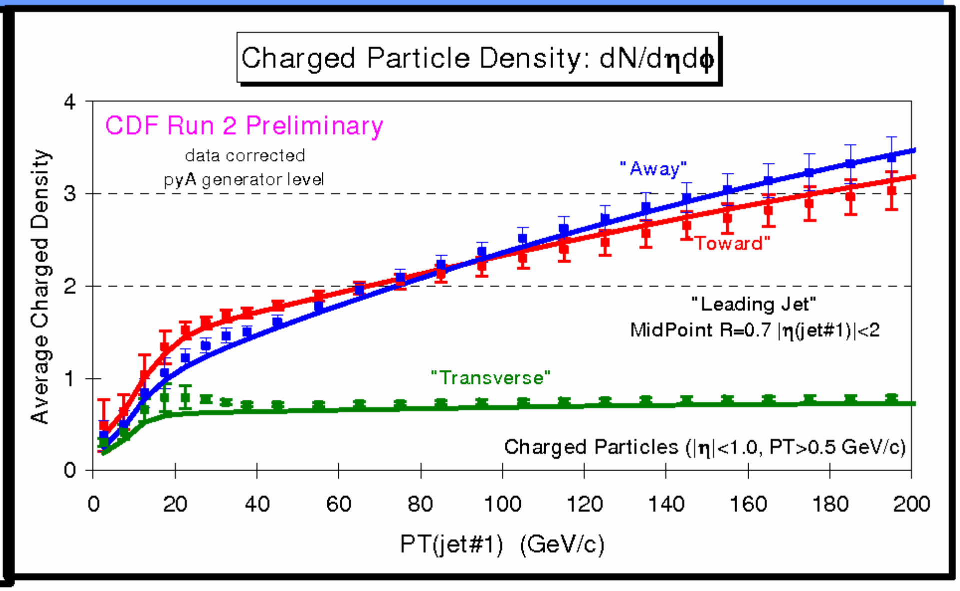


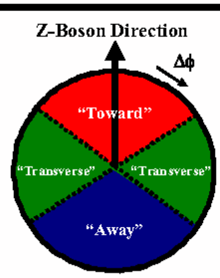
- Data at 1.96 TeV on the density of charged particles, dN/dηdϕ, with $p_T > 0.5$ GeV/c and $|\eta| < 1$ for "Z-Boson" events as a function of the leading jet p_T for the "toward", "away", and "transverse" regions. The data are corrected to the particle level (*with errors that include both the statistical error and the systematic uncertainty*) and are compared with PYTHIA Tune AW at the particle level (*i.e.* generator level).

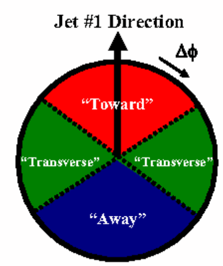
Deepak Kar's Thesis

"Charged Particle Density"



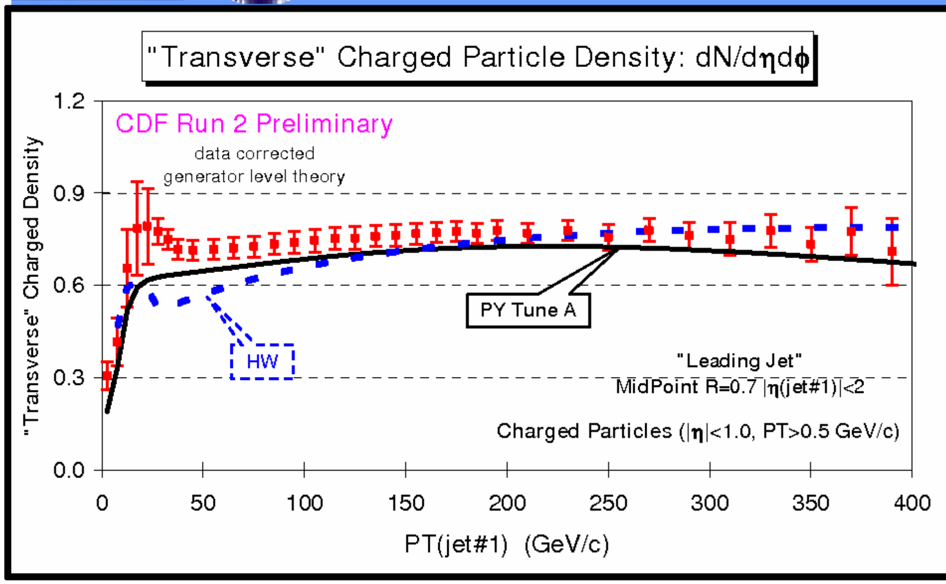


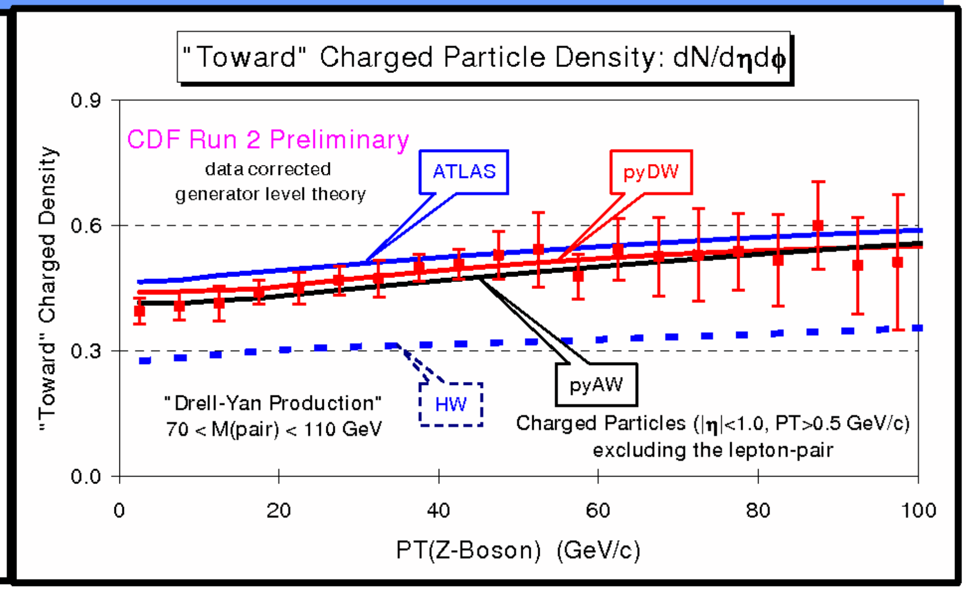


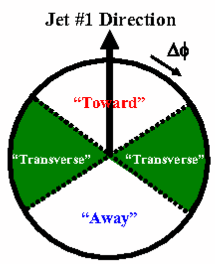


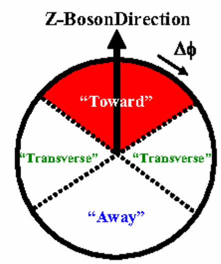
- **Data at 1.96 TeV on the density of charged particles, dN/dηdφ, with $p_T > 0.5$ GeV/c and $|\eta| < 1$ for "Z-Boson" and "Leading Jet" events as a function of the leading jet p_T or $P_T(Z)$ for the "toward", "away", and "transverse" regions. The data are corrected to the particle level (*with errors that include both the statistical error and the systematic uncertainty*) and are compared with PYTHIA Tune AW and Tune A, respectively, at the particle level (*i.e.* generator level).**

“Charged Particle Density”





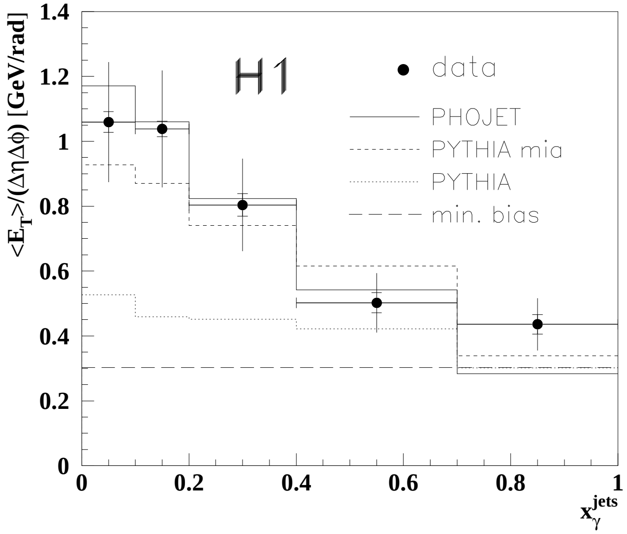




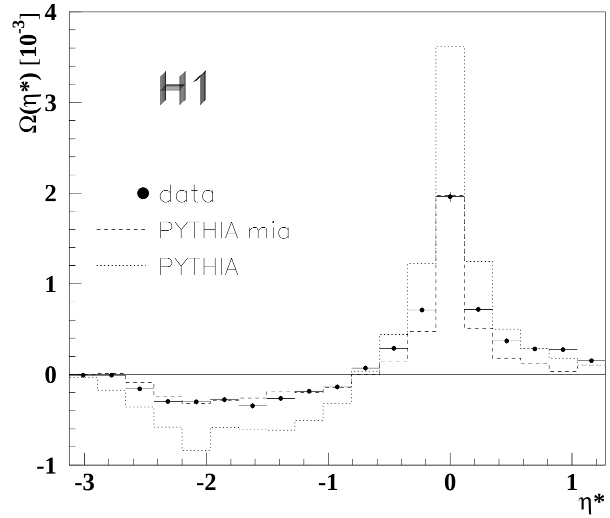
- **Data at 1.96 TeV on the density of charged particles, dN/dηdφ, with $p_T > 0.5$ GeV/c and $|\eta| < 1$ for the “toward” region for “Z-Boson” and the “transverse” region for “Leading Jet” events as a function of the leading jet p_T or $P_T(Z)$. The data are corrected to the particle level (*with errors that include both the statistical error and the systematic uncertainty*) and are compared with PYTHIA Tune AW and Tune A, respectively, at the particle level (*i.e.* generator level). The Z-Boson data are also compared with PYTHIA Tune DW, the ATLAS tune, and HERWIG (without MPI)**

Multiple interactions also preferred by HERA photoproduction data:

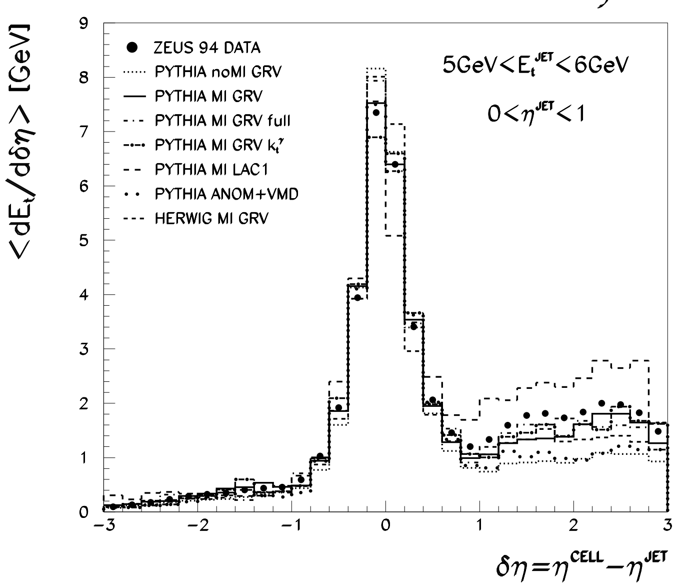
underlying activity in photoproduction vs. DIS



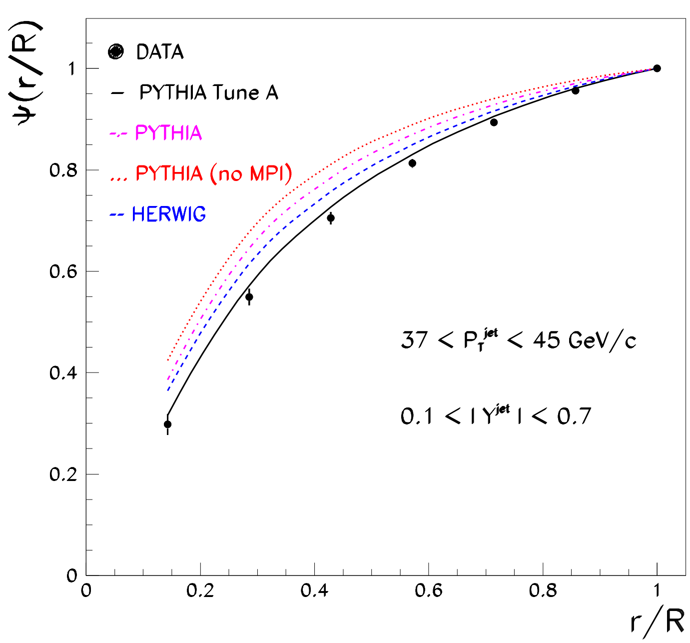
(anti)correlations in energy flow around jet



ZEUS 1994 Preliminary

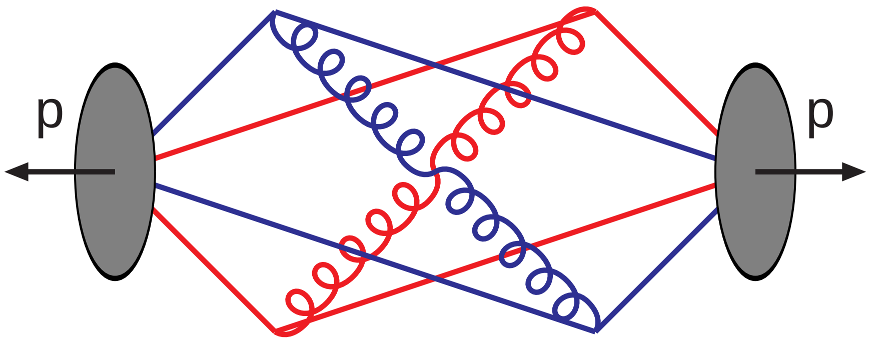


CDF II Preliminary

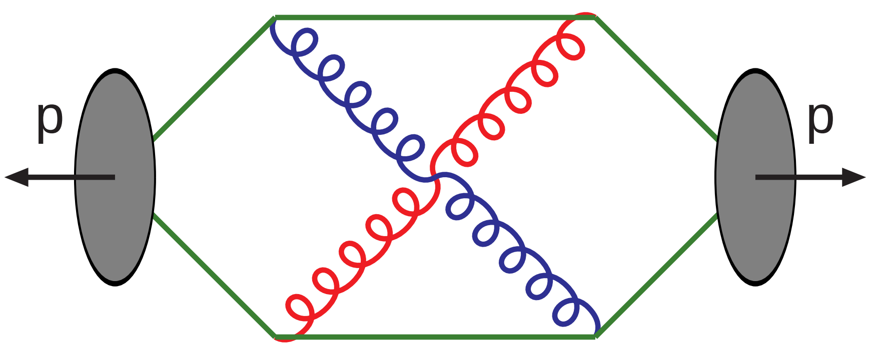


Colour correlations

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

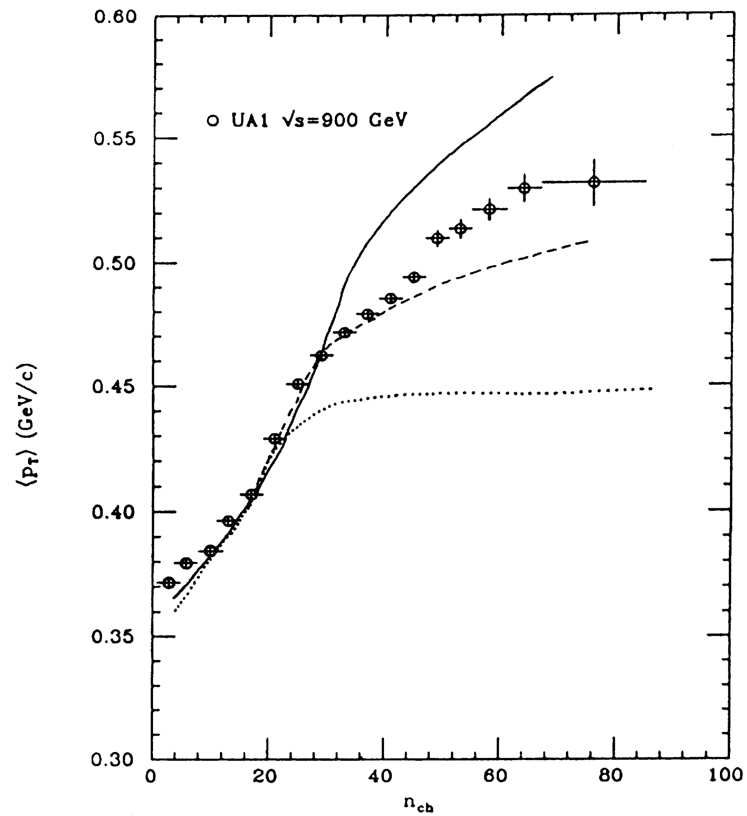
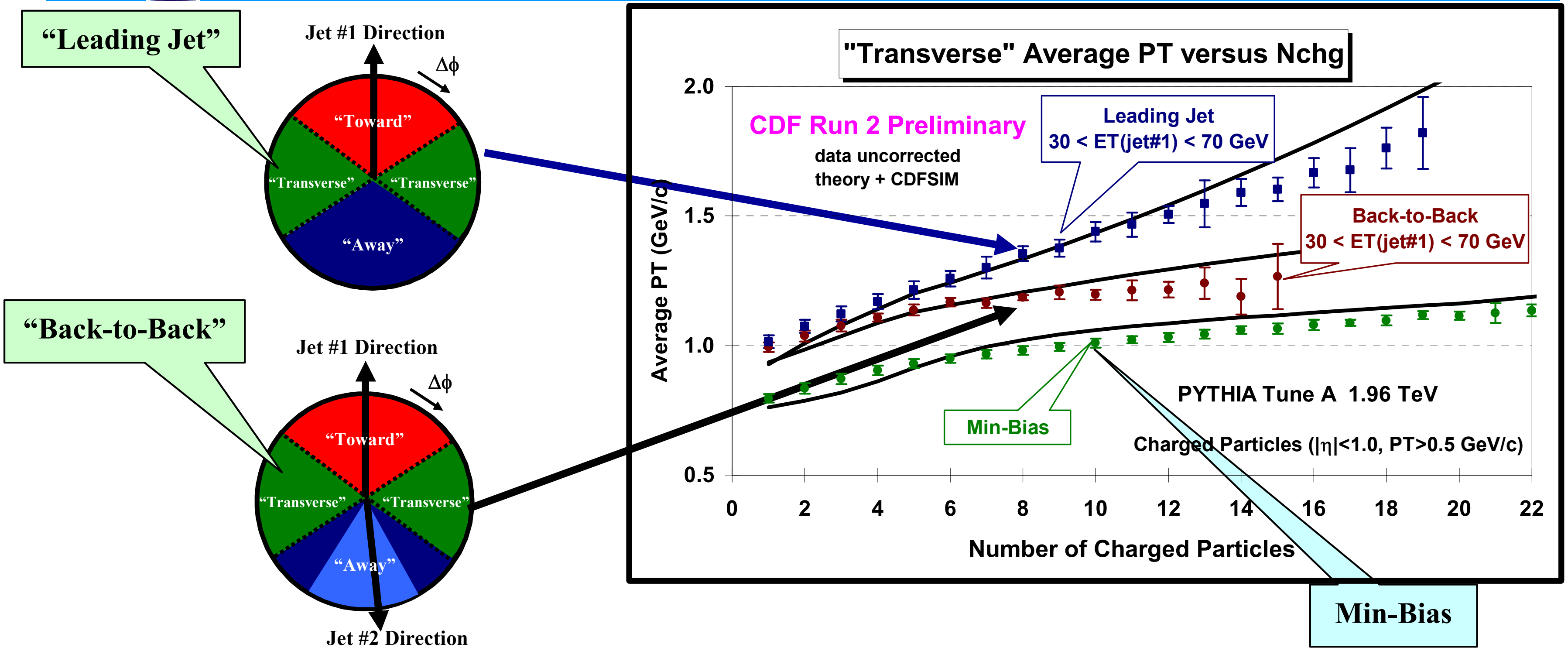


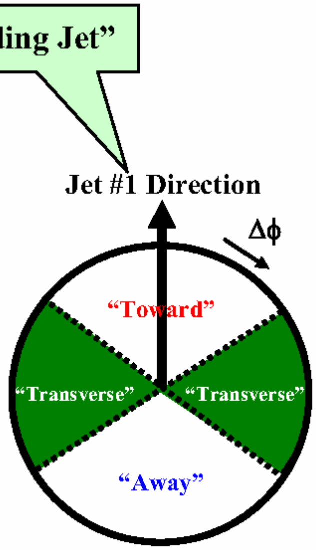
FIG. 27. Average transverse momentum of charged particles in $|\eta| < 2.5$ as a function of the multiplicity. UA1 data points (Ref. 49) at 900 GeV compared with the model for different assumptions about the nature of the subsequent (nonhardest) interactions. Dashed line, assuming $q\bar{q}$ scatterings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

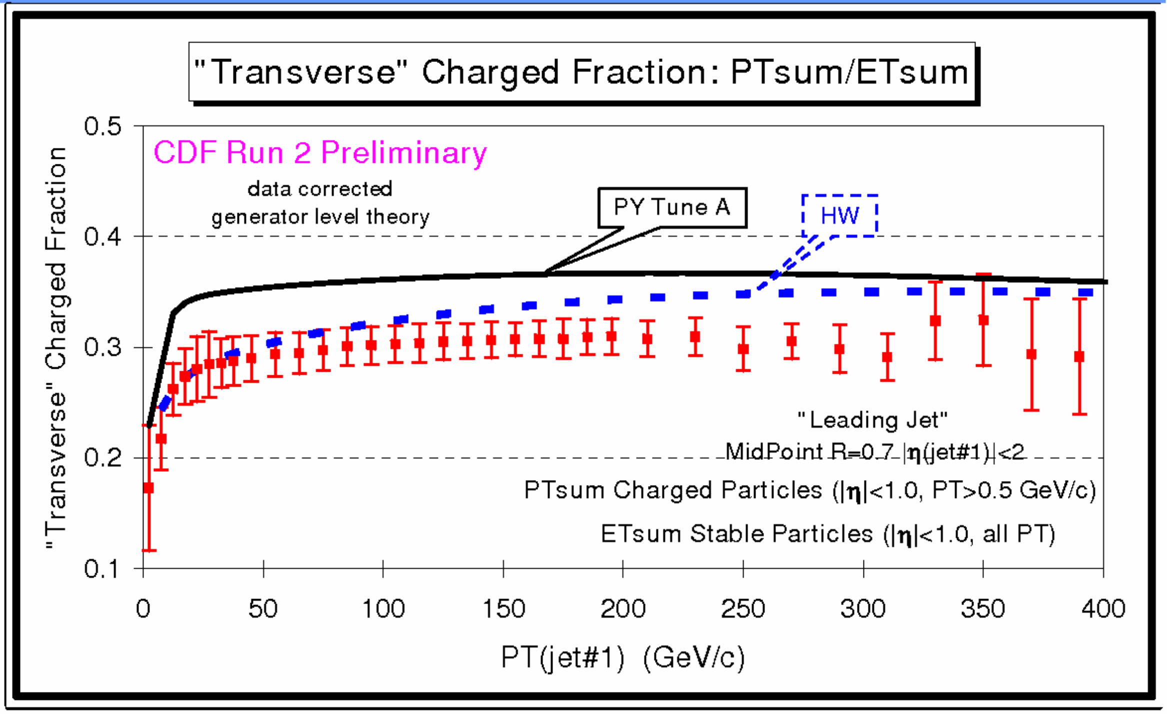
"Transverse" $<p_T>$ versus "Transverse" Nchg



- 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.

The "Transverse" Region

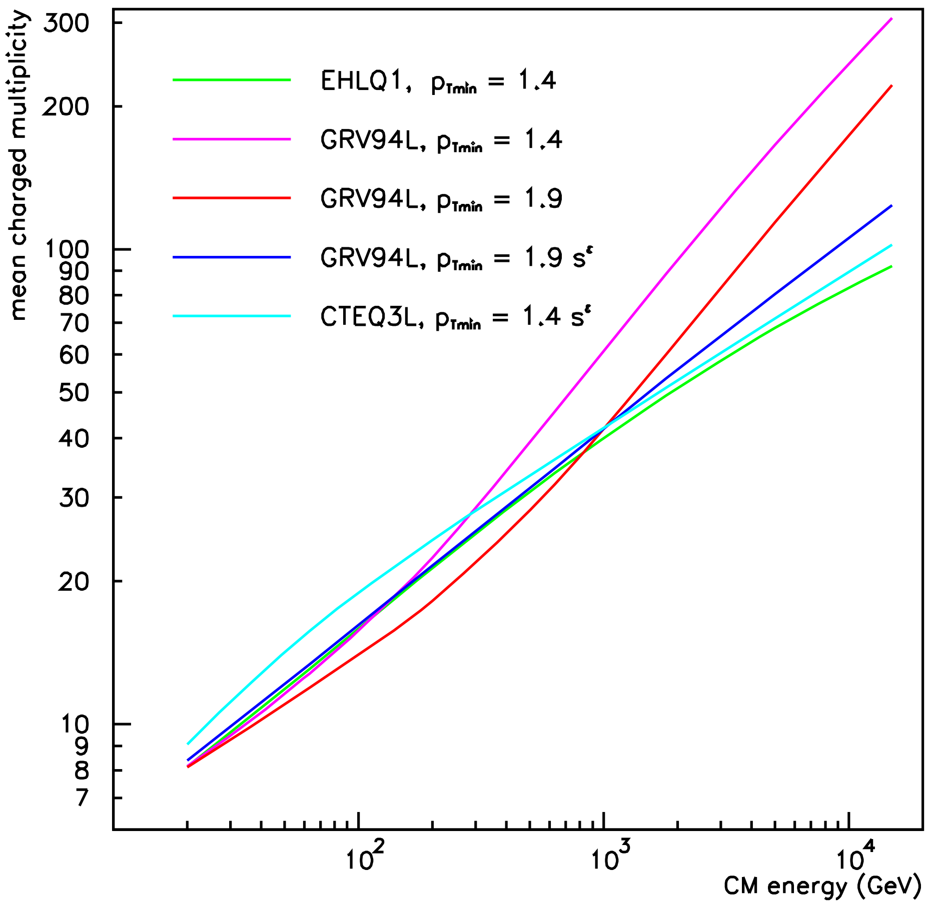




- Data at 1.96 TeV on the charged fraction, PTsum/ETsum, for PTsum ($p_T > 0.5$ GeV/c, $|\eta| < 1$) and ETsum (all p_T, $|\eta| < 1$) for "leading jet" events as a function of the leading jet p_T for the "transverse" region. The data are corrected to the particle level (*with errors that include both the statistical error and the systematic uncertainty*) and are compared with PYTHIA Tune A and HERWIG (without MPI) at the particle level (*i.e.* generator level).

Extrapolation to LHC

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



Larger collision energy

⇒ probe parton (≈ gluon) density at smaller x

⇒ smaller colour screening length d

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

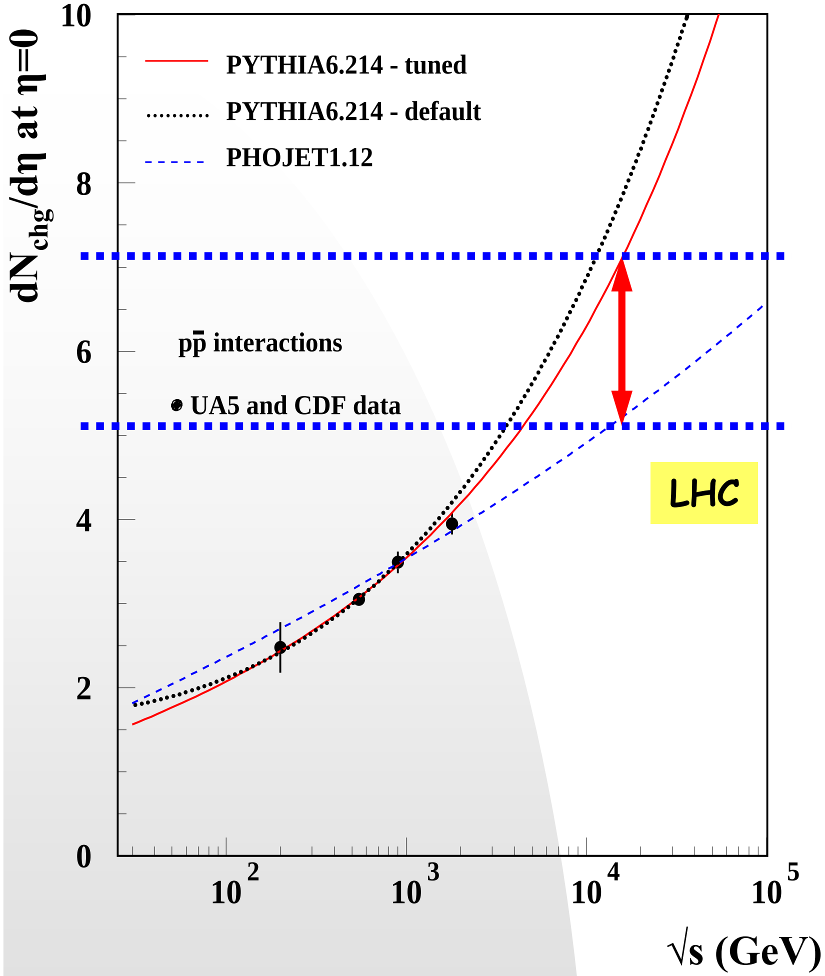
Post-HERA PDF fits steeper at small x

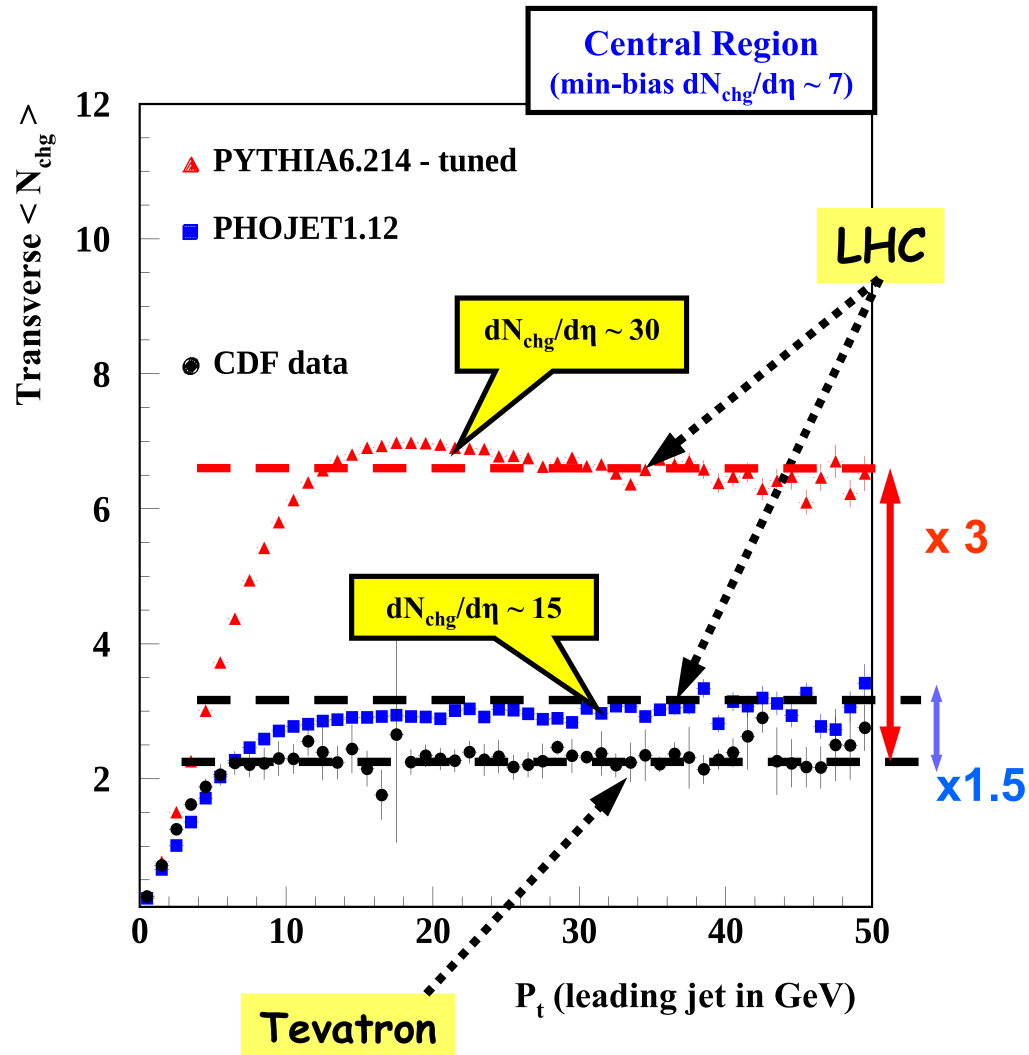
⇒ stronger energy dependence

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

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

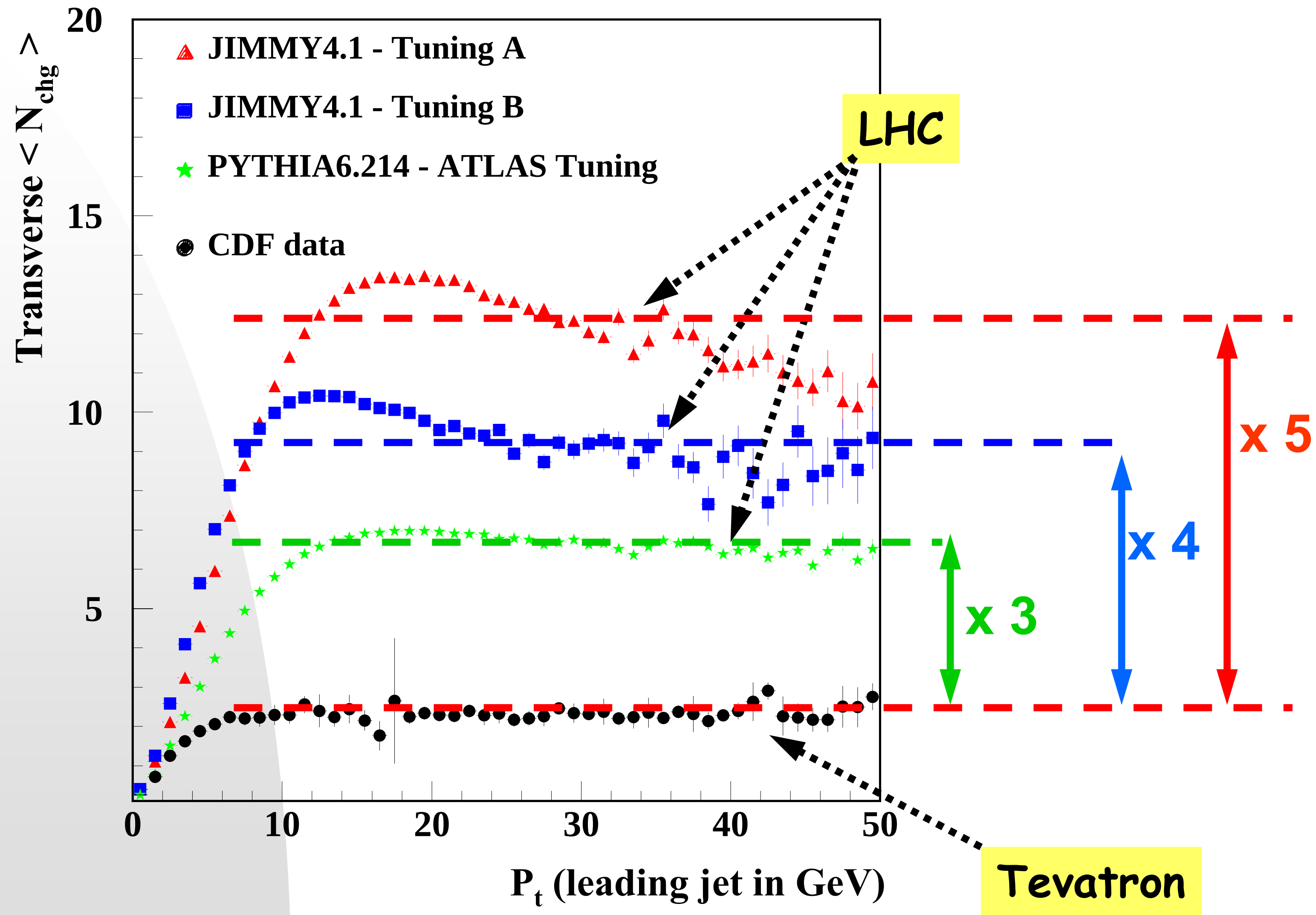
LHC predictions: pp collisions at √s = 14 TeV



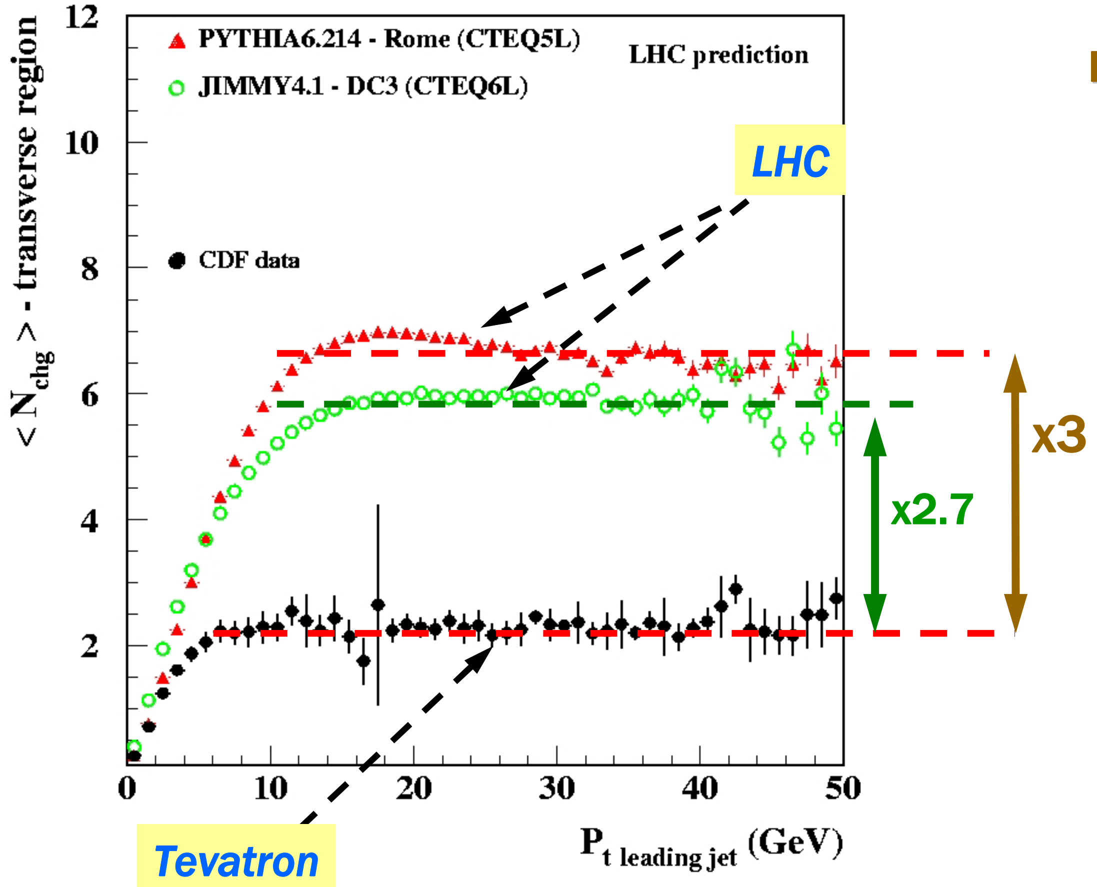


- **PYTHIA** models favour $\ln^2(s)$;
- **PHOJET** suggests a $\ln(s)$ dependence.

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



UE tunings: Pythia vs. Jimmy



PTJIM=4.9

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

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

Connection with total cross section

M. Bähr, J.M. Butterworth, MHS, arXiv:0806.2949 $\longrightarrow$ JHEP

Recall Poisson statistics for independent scatters:

$$\sigma_{n\ \text{scatters}} = \int \mathrm{d}^2 b \, \frac{1}{n!} \left(\mathcal{O}(b)\sigma^{inc} \right)^n \mathrm{e}^{-\mathcal{O}(b)\sigma^{inc}},$$

$$\Rightarrow \sigma_{\text{inelastic}} = \int \mathrm{d}^2 b \left(1 - \mathrm{e}^{-\mathcal{O}(b)\sigma^{inc}} \right),$$

Optical theorem:

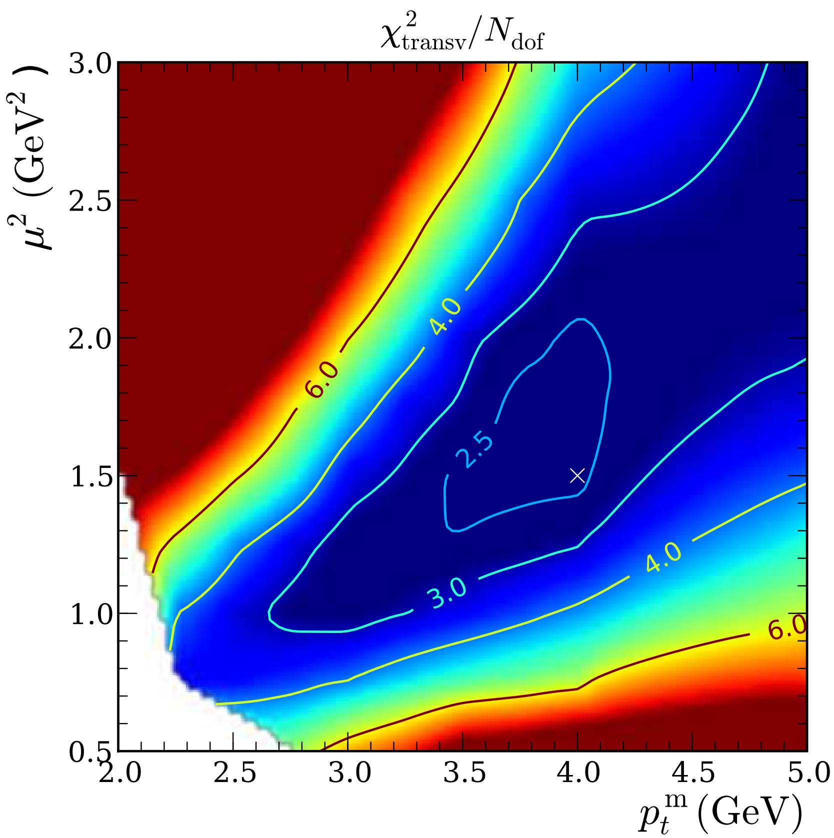
$$\sigma_{\text{total}} = 2 \int \mathrm{d}^2 b \left(1 - \mathrm{e}^{-\frac{1}{2}\mathcal{O}(b)\sigma^{inc}} \right).$$

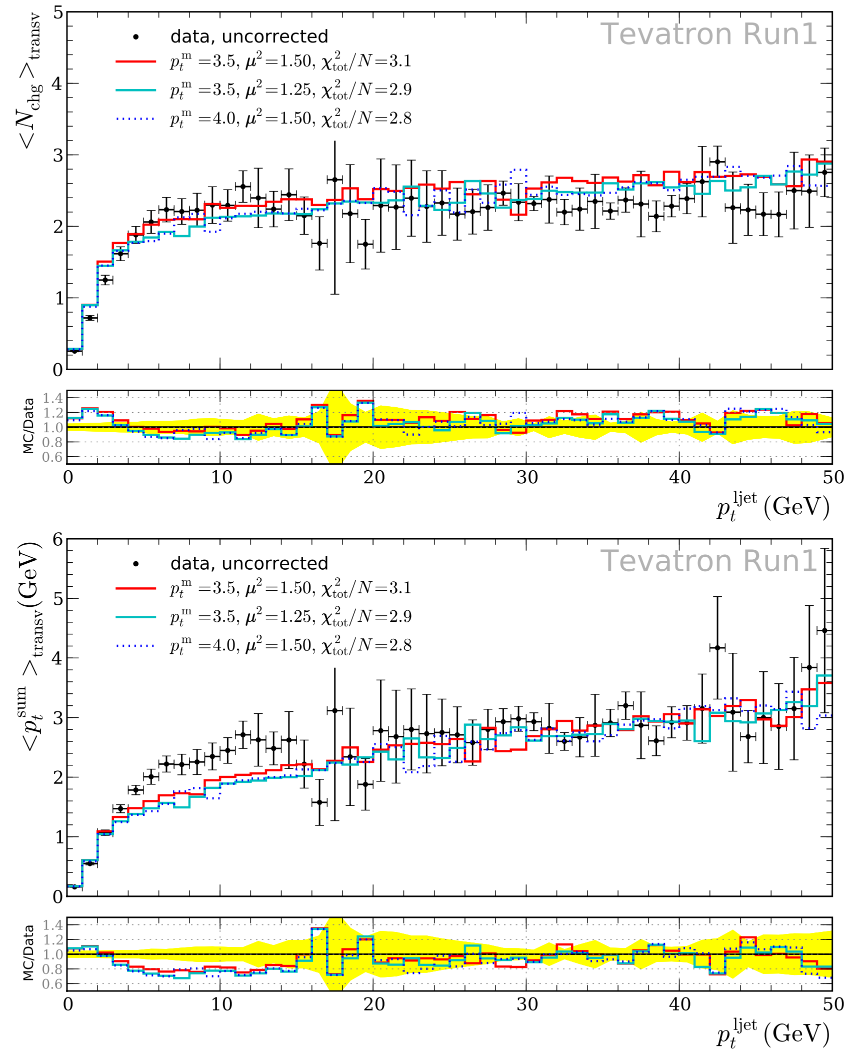
1. Choose matter distribution
2. Choose $p_{\perp\text{min}} \longrightarrow \sigma^{inc}_{P.T.}$
3. Measure $\sigma_{\text{total}} \longrightarrow \sigma^{inc}$
4. $\Rightarrow \sigma^{inc}_{N.P.}$ for Ivan model

$\sigma^{inc}_{N.P.} > 0$ gives theoretical constraint on allowed parameters.

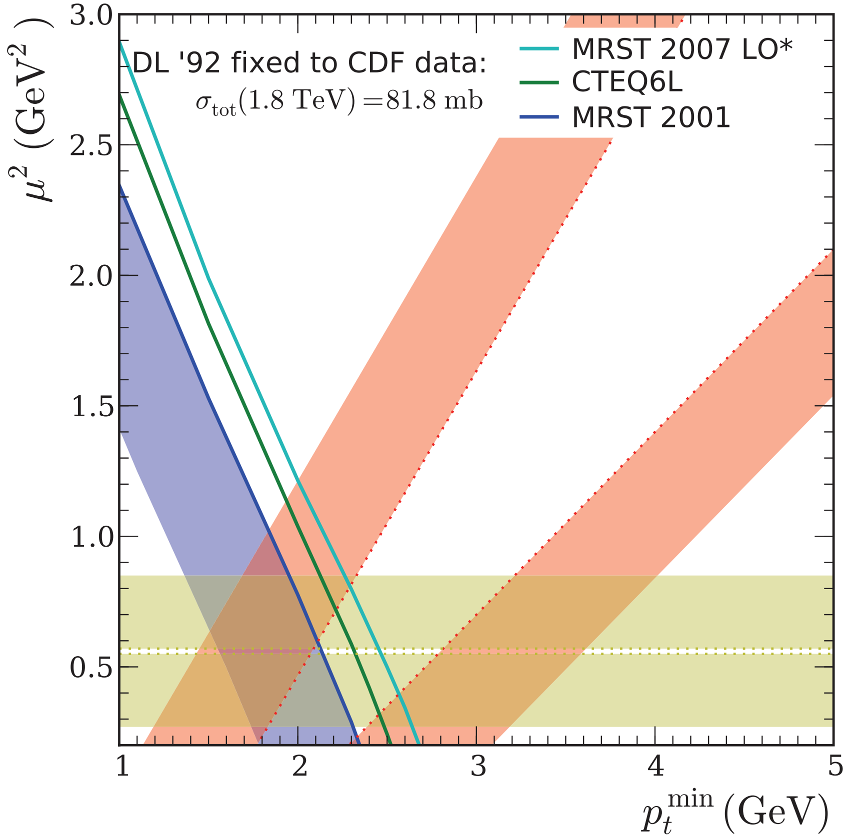
M. Bähr et al., Herwig++ 2.3 Release Note, arXiv:0812.0529

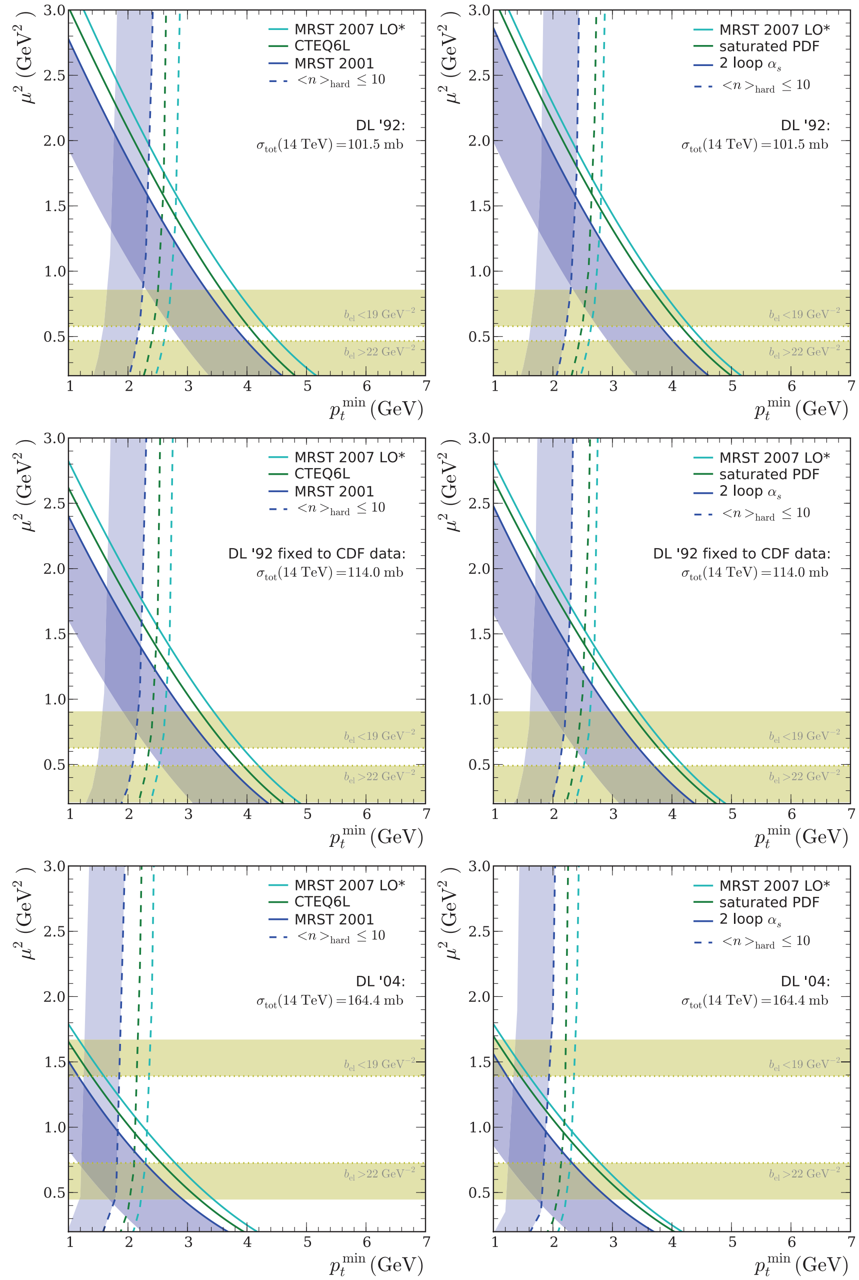
→ reasonable description of Tevatron minimum bias data





M. Bähr, J.M. Butterworth, MHS, arXiv:0806.2949 → JHEP





→ Very early LHC data (total and elastic cross sections) will indicate whether consistent parameter sets possible or energy evolution is mandatory

Summary

- Underlying event/minimum bias collisions least understood aspect of hadron collider physics
- Multiparton collisions an essential component
- Enormous amount of Tevatron data now, more coming
- Some improvements in understanding
- but still quite different models describe the data quite well
- Huge spread in extrapolations to LHC

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) $\longrightarrow$ Tevatron $\longrightarrow$ LHC
- Develop new frameworks and refine existing ones

Much work ahead!