LUND UNIVERSITY

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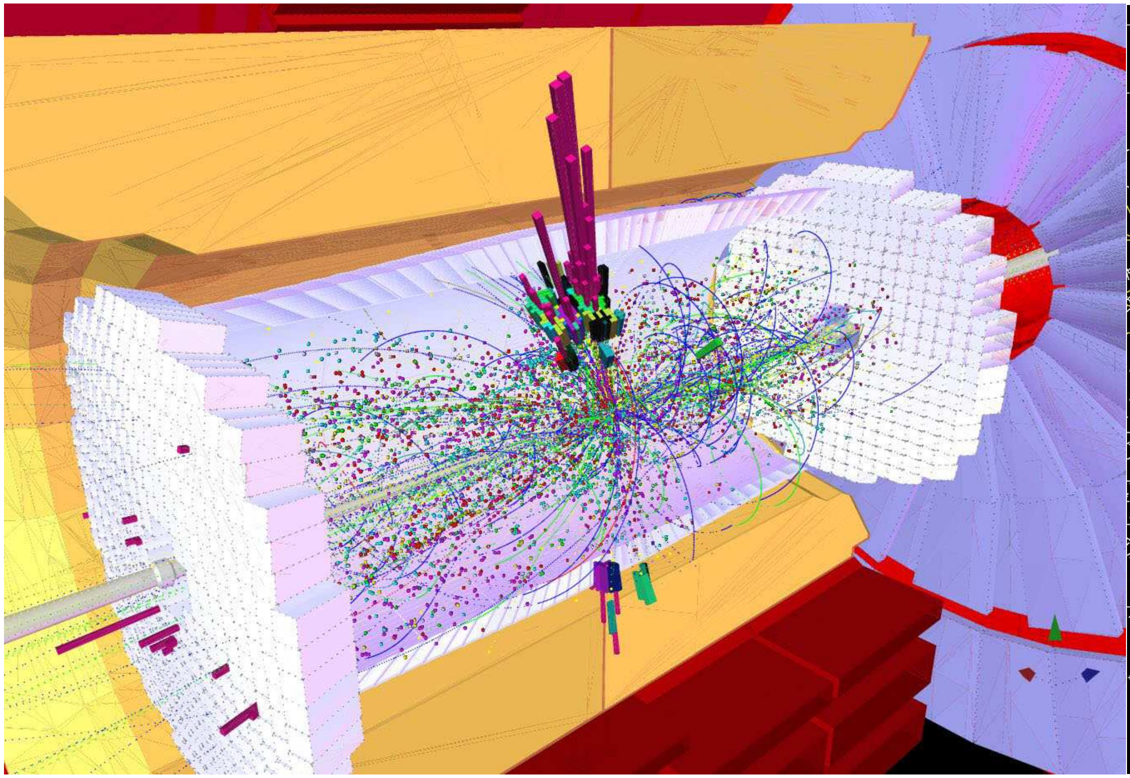
Introduction to Monte Carlo Event Generators

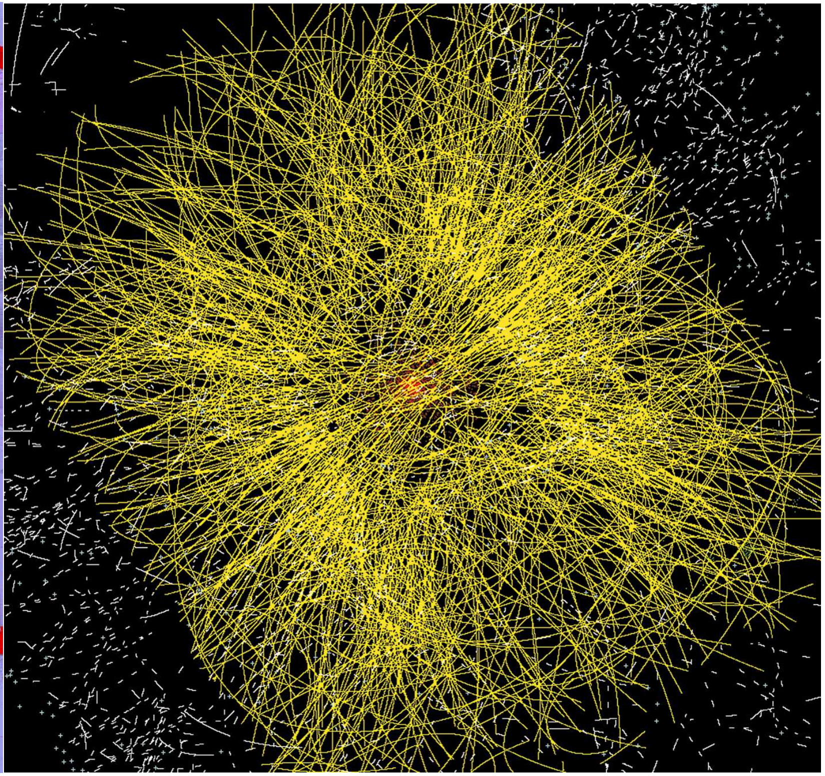
Torbjörn Sjöstrand

Lund University

1. (yesterday) Introduction and Overview; Monte Carlo Techniques
2. (yesterday) Matrix Elements; Parton Showers I
3. (today) Parton Showers II; Matching Issues
4. **(today) Multiple Parton–Parton Interactions**
5. (tomorrow) Hadronization and Decays; Generator Status

Underlying Events and Minimum Bias

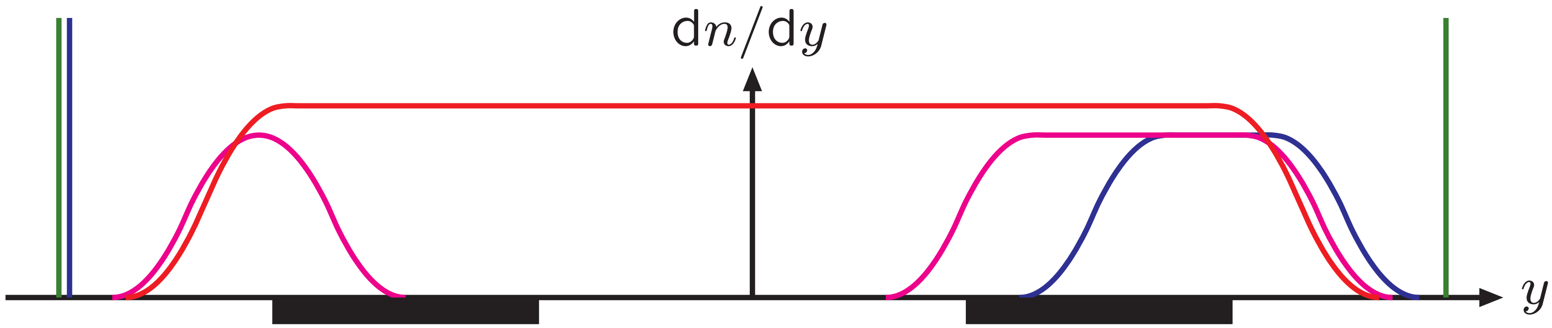




What is minimum bias?

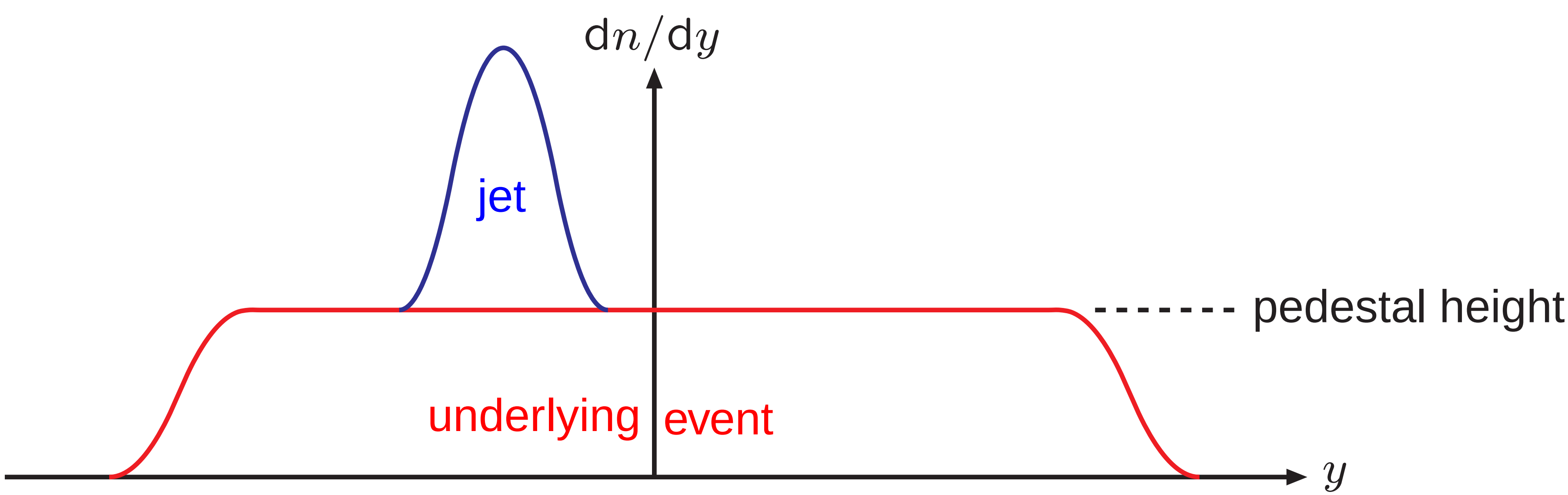
$\approx$ "all events, with no bias from restricted trigger conditions"

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



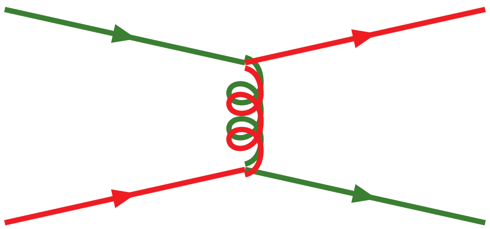
reality: $\sigma_{\text{min-bias}} \approx \sigma_{\text{non-diffractive}} + \sigma_{\text{double-diffractive}} \approx 2/3 \times \sigma_{\text{tot}}$

What is underlying event?



What is multiple (partonic) 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 $2 \to 2$

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

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

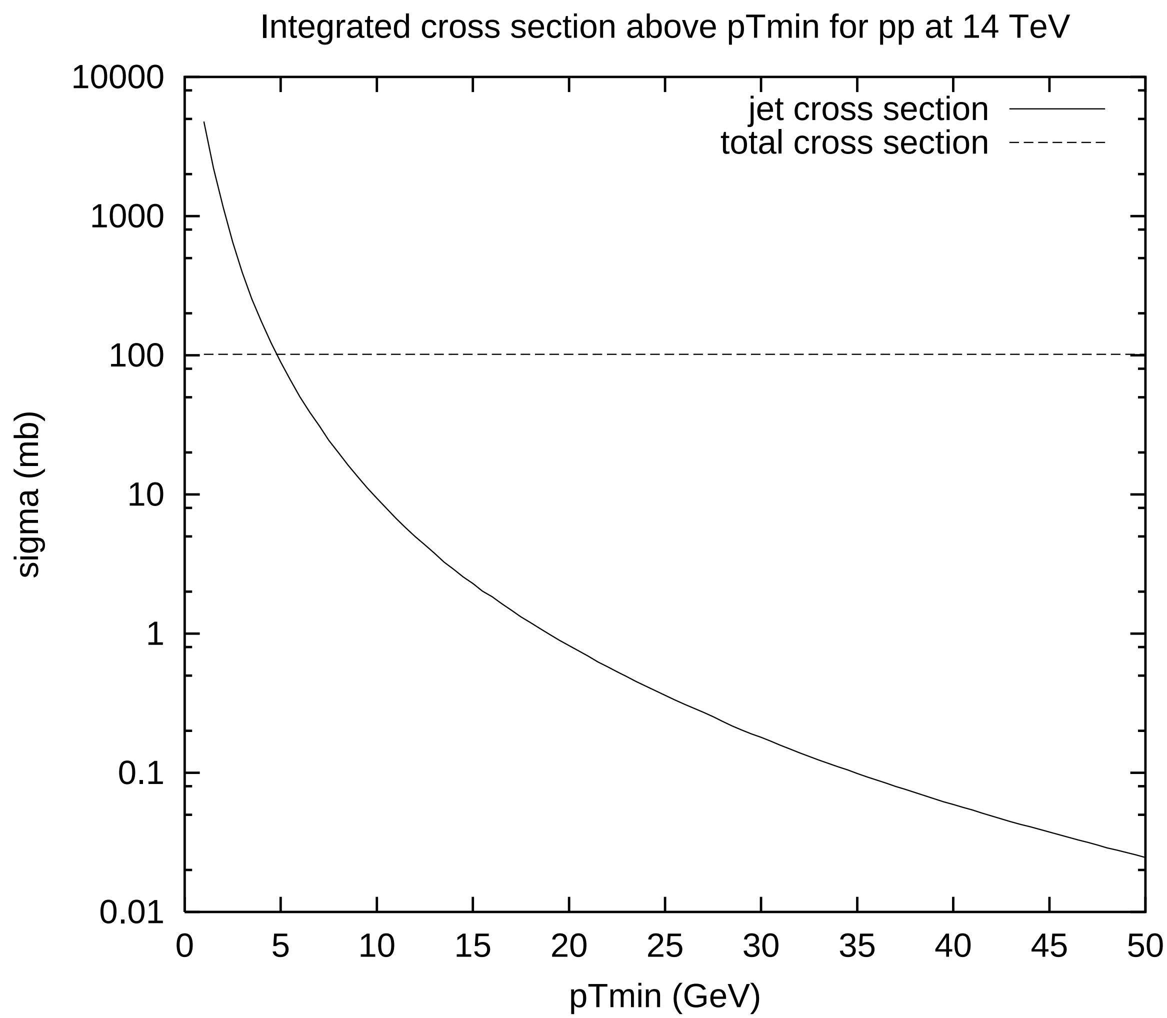
$\mathrm{q\overline{q}} \to \mathrm{gg}$

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

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

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

with CTEQ 5L PDF's



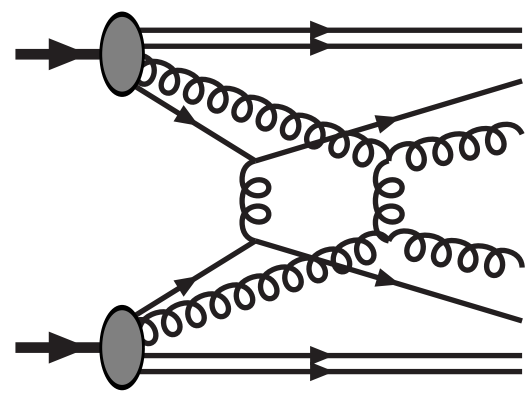
$$\sigma_{\text{int}}(p_{\perp\text{min}}) = \iiint_{p_{\perp\text{min}}} \mathrm{d}x_1\, \mathrm{d}x_2\, \mathrm{d}p_\perp^2\, f_1(x_1, p_\perp^2)\, f_2(x_2, p_\perp^2)\, \frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}p_\perp^2}$$

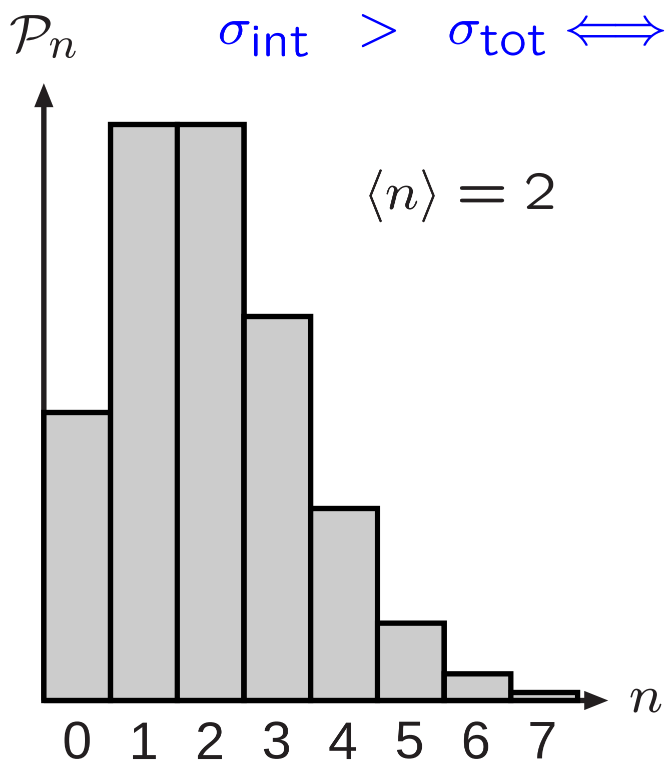
Half a solution to $\sigma_{\text{int}}(p_{\perp\text{min}}) > \sigma_{\text{tot}}$: many interactions per event

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

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

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





If interactions occur independently
then **Poissonian statistics**

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

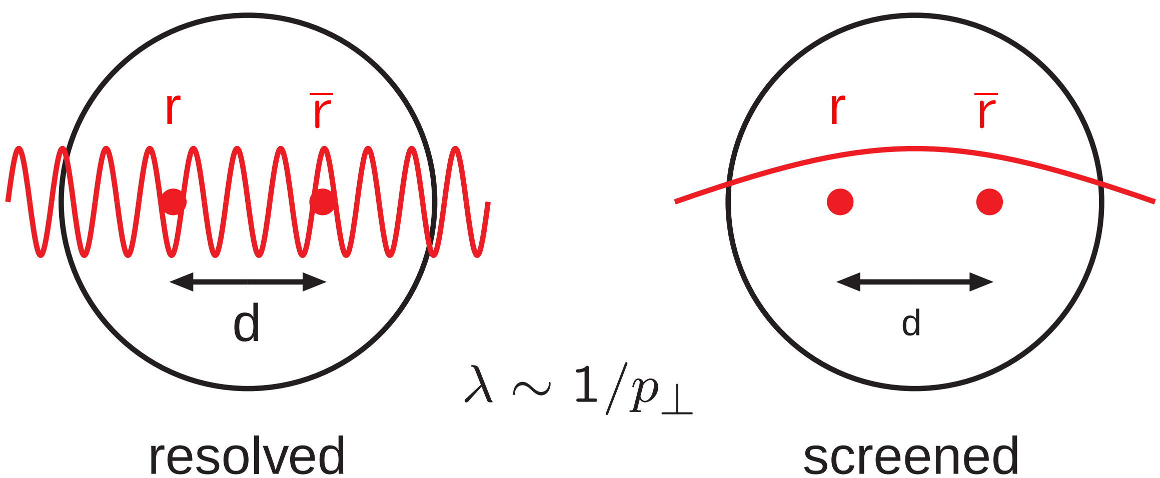
but energy–momentum conservation
$\Rightarrow$ large n suppressed

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

Naively breakdown at

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

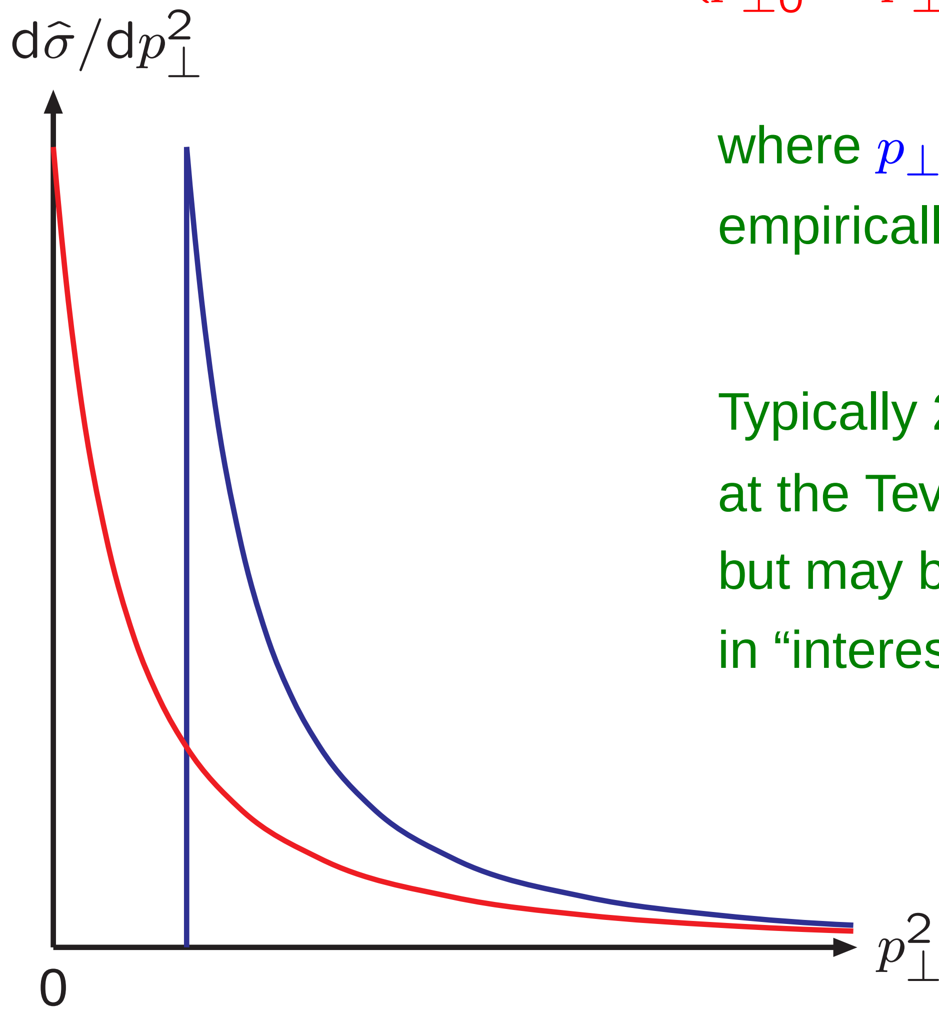
...but better replace r_p by (unknown) colour screening length d in hadron



so modify

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

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



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.

Basic generation of multiple (partonic) 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), or better...

...generate interactions in ordered sequence $p_{\perp 1} > p_{\perp 2} > p_{\perp 3} > \ldots$

- recall "Sudakov" trick used e.g. for parton showers:
  if probability for something to happen at "time" t is $P(t)$
  and happenings are uncorrelated in time (Poissonian statistics)
  then the probability for a *first* happening after 0 at t_1 is

$$\mathcal{P}(t_1) = P(t_1)\ \exp\left(-\int_0^{t_1} P(t)\,\mathrm{d}t\right)$$

  and for an i'th at t_i is

$$\mathcal{P}(t_i) = P(t_i)\ \exp\left(-\int_{t_{i-1}}^{t_i} P(t)\,\mathrm{d}t\right)$$

- Apply to ordered sequence of decreasing $p_\perp$, starting from $E_{\mathrm{cm}}/2$

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

- Use rescaled PDF's taking into account already used momentum
  $\Longrightarrow n_{\mathrm{int}}$ narrower than Poissonian

Impact parameter dependence

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

e.g. 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", and overlap of hadrons during collision is

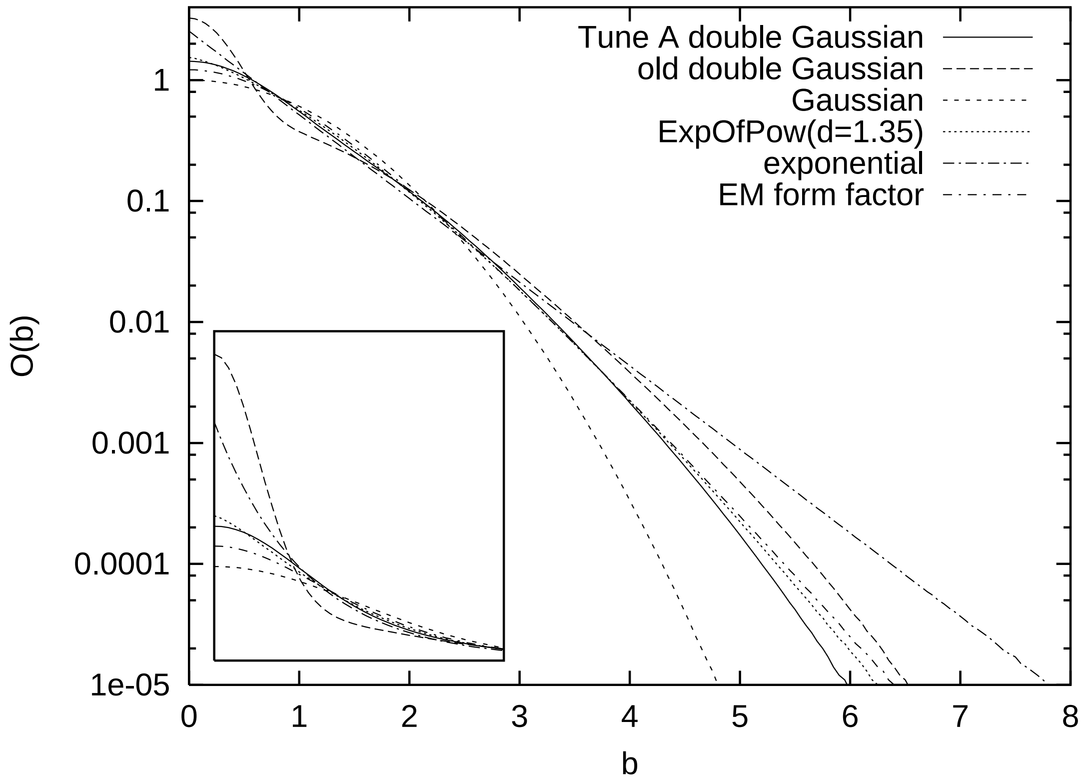
$$\mathcal{O}(b) = \int \mathrm{d}^3\mathbf{x}\,\mathrm{d}t\;\rho_{1,\mathrm{matter}}^{\mathrm{boosted}}(\mathbf{x},t)\rho_{2,\mathrm{matter}}^{\mathrm{boosted}}(\mathbf{x},t)$$

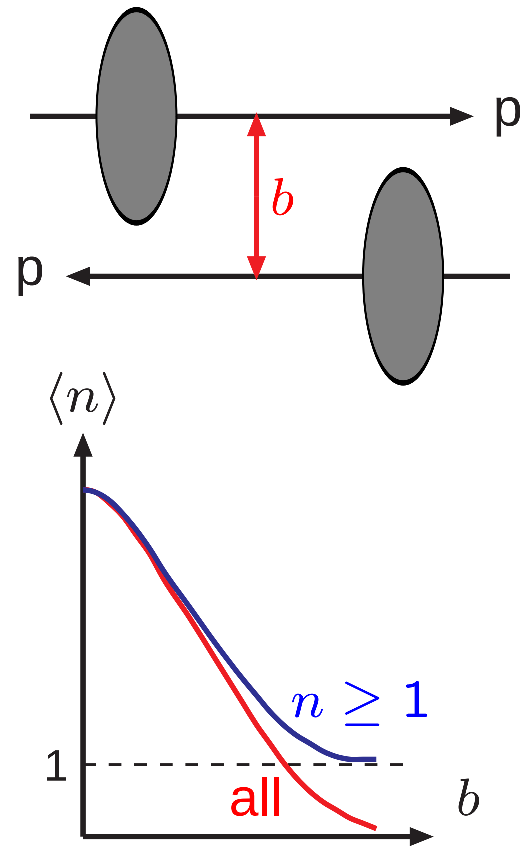
or electromagnetic form factor:

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

where $\mu = 0.71$ GeV $\to$ free parameter, which gives

$$O(b) = \frac{\mu^2}{96\pi}\,(\mu b)^3\,K_3(\mu b)$$





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

PYTHIA implementation

(1) Simple scenario (1985):

first model for event properties based on perturbative multiple interactions

no longer used (no impact-parameter dependence)

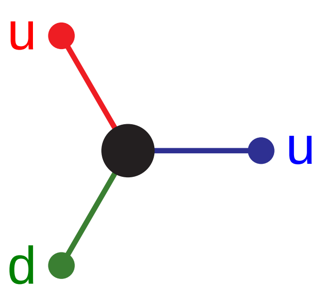
(2) Impact-parameter-dependence (1987):

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

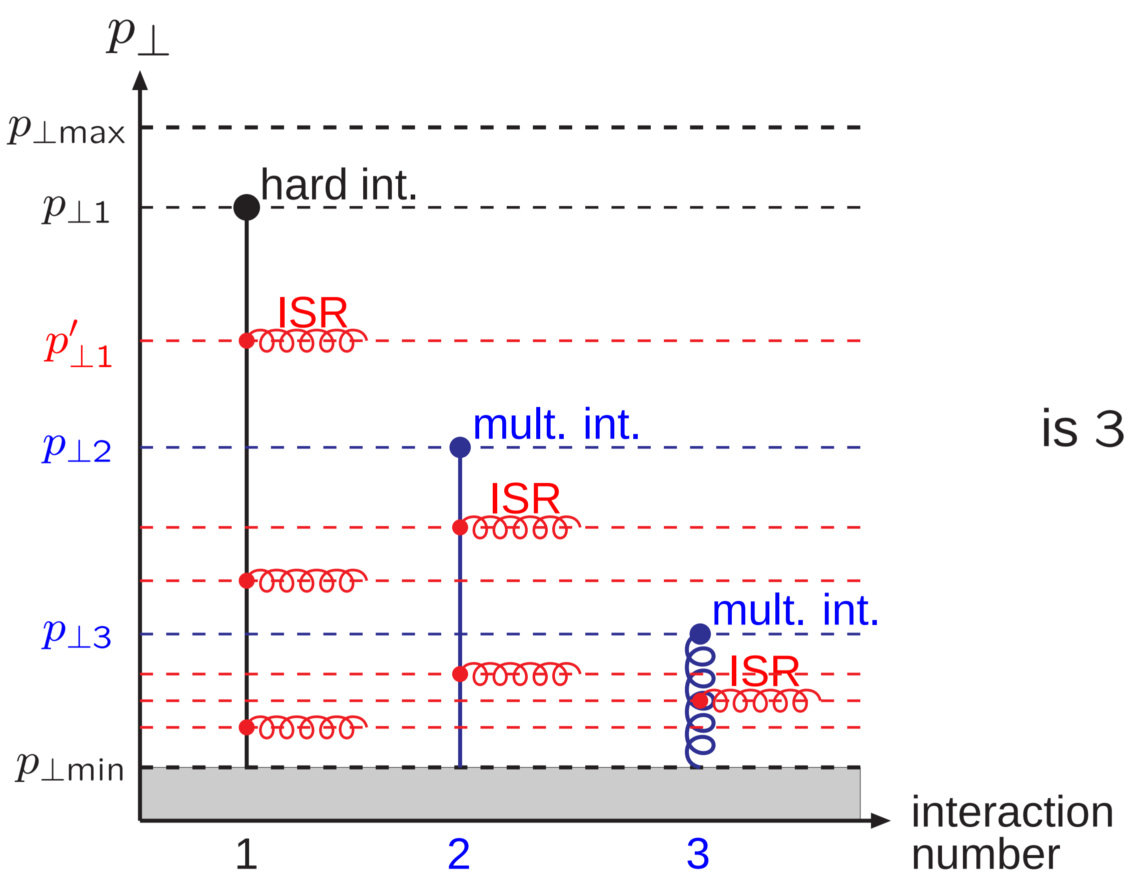


(4) Evolution interleaved with ISR (2004)

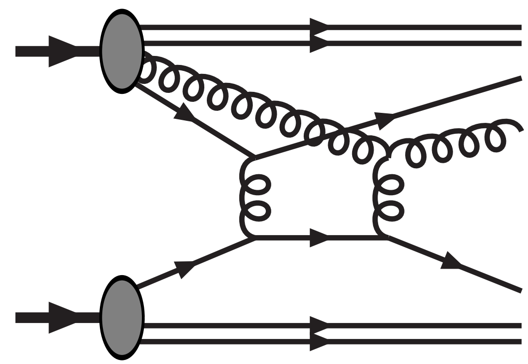
- Transverse-momentum-ordered showers

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

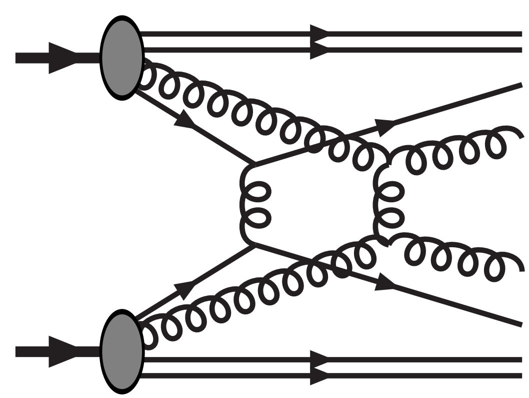
with ISR sum over all previous MI



(5) Rescattering (2009)

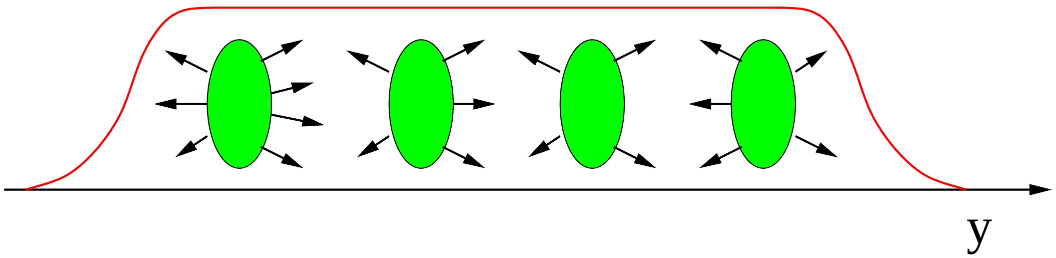


is $3 \to 3$ instead of $4 \to 4$:



HERWIG implementation

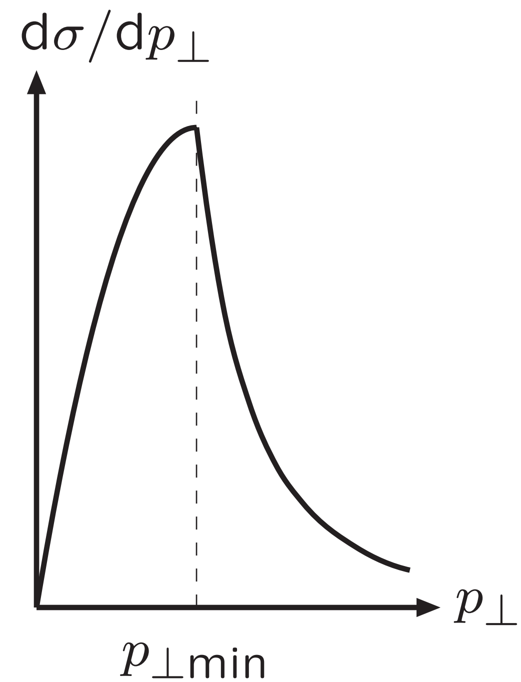
(1) Soft Underlying Event (1988), based on UA5 Monte Carlo



- 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 (1995; HERWIG add-on; part of HERWIG++)

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



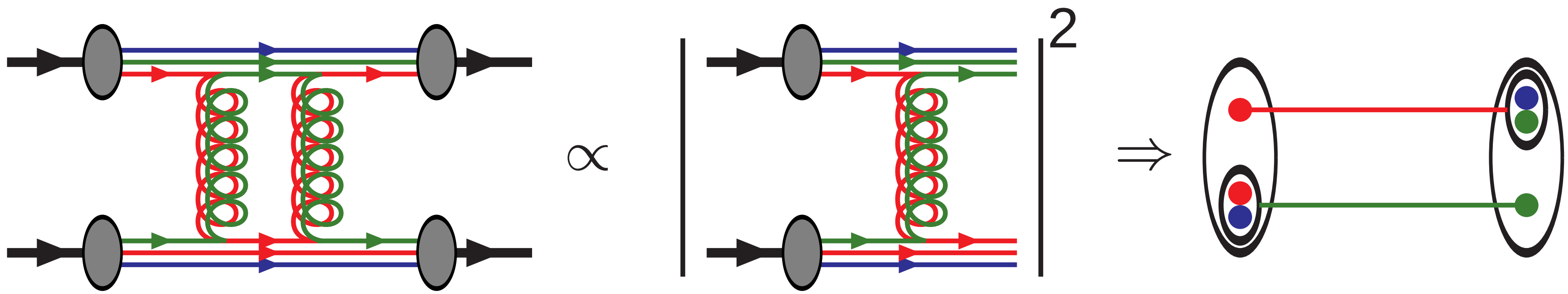
(3) Ivan (2002, code not public; part of HERWIG++)

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

PhoJet (& relatives) implementation

(1) Cut Pomeron (1982)

- 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 $p_\perp$ (1990)

- 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 $p_\perp$

Indirect evidence for multiple interactions

without multiple interactions

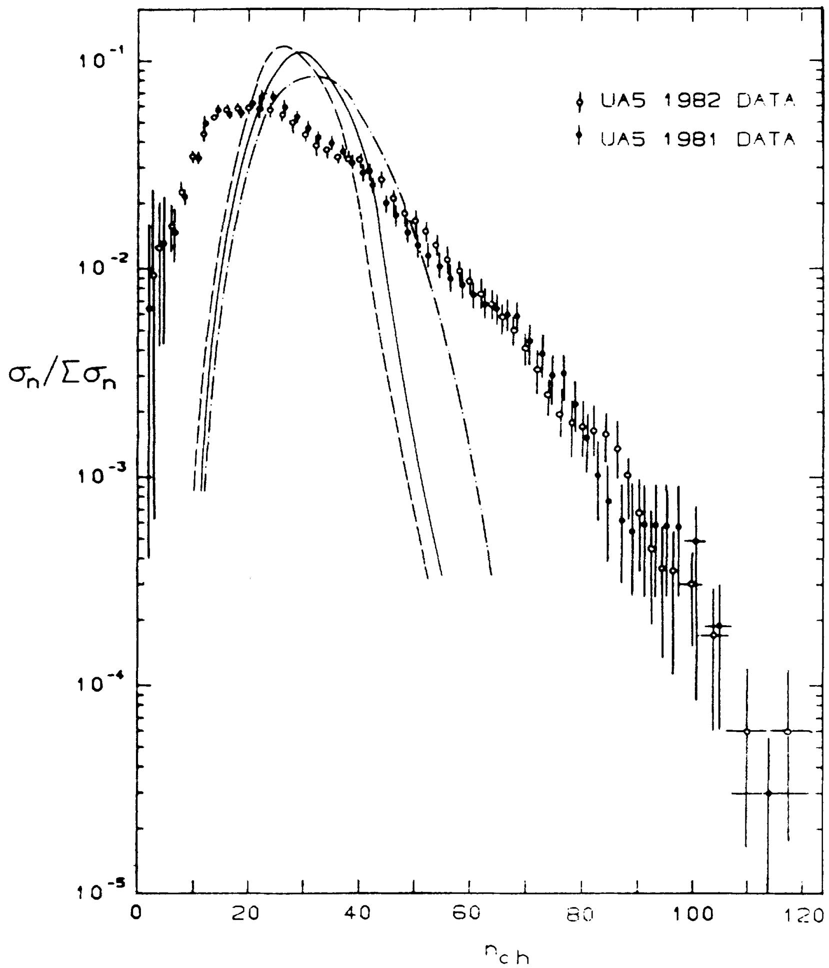


FIG. 3. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs simple models: dashed low p_T only, full including hard scatterings, dash-dotted also including initial- and final-state radiation.

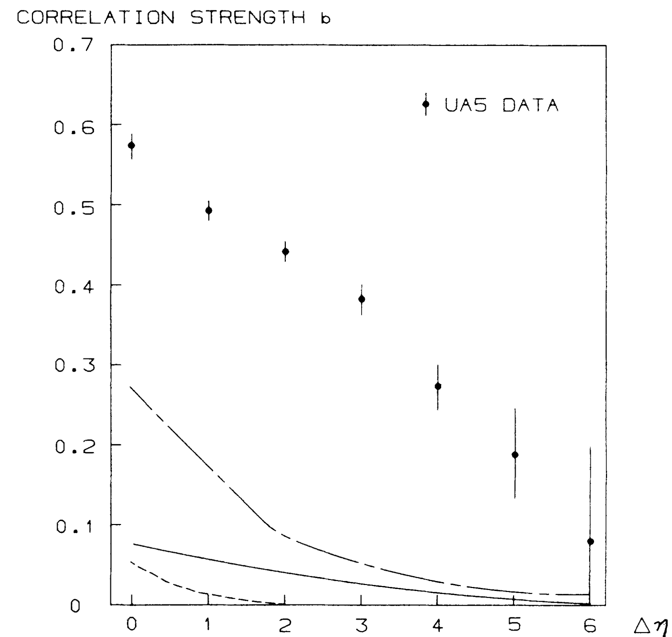


FIG. 4. Forward-backward multiplicity correlation at 540 GeV, UA5 results (Ref. 33) vs simple models; the latter models with notation as in Fig. 3.

with multiple interactions

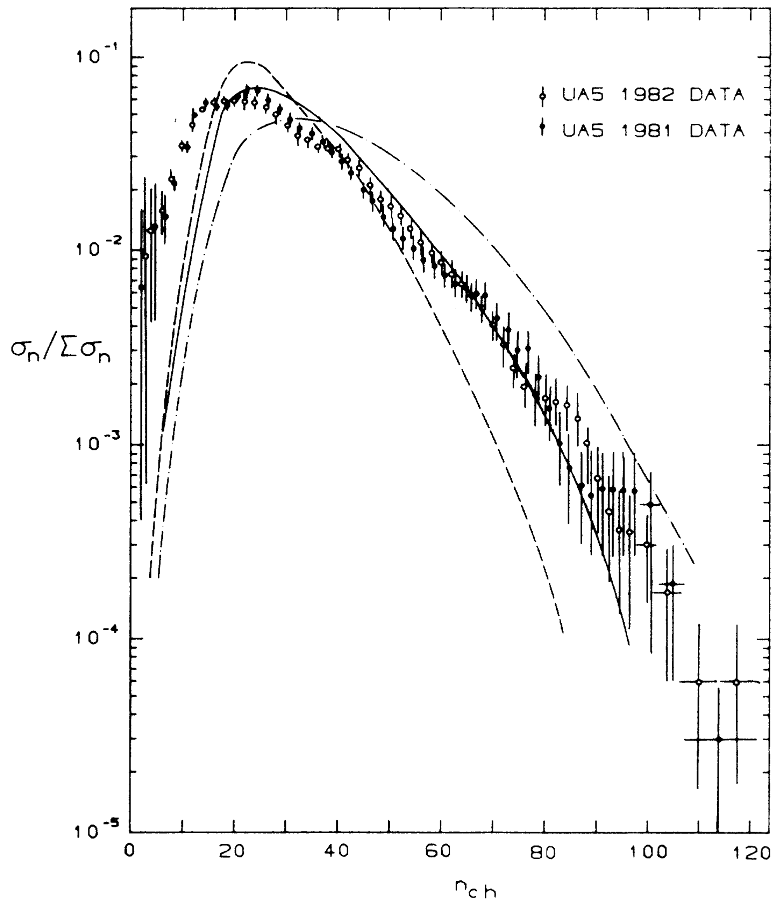


FIG. 5. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs impact-parameter-independent multiple-interaction model: dashed line, $p_{T\min}=2.0$ GeV; solid line, $p_{T\min}=1.6$ GeV; dashed-dotted line, $p_{T\min}=1.2$ GeV.

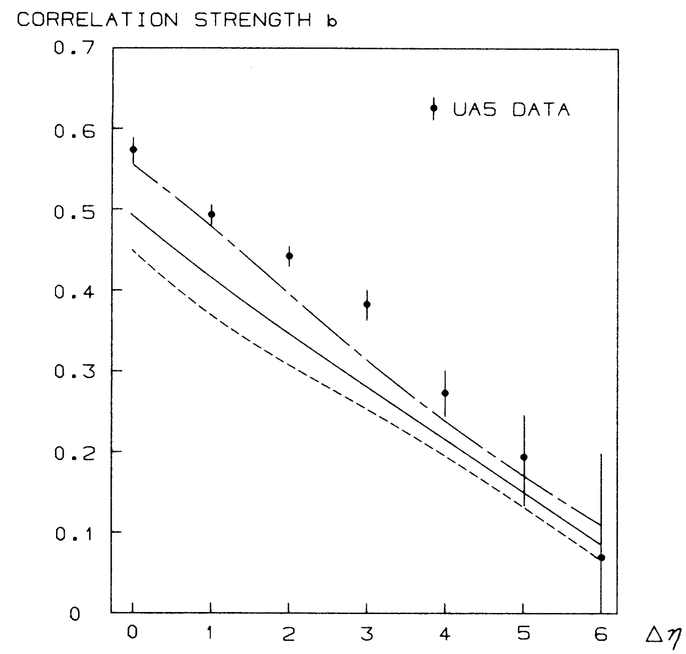


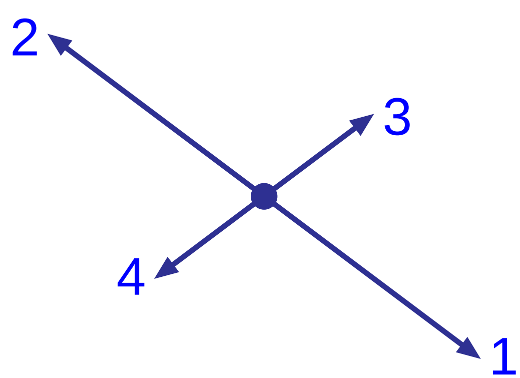
FIG. 6. Forward-backward multiplicity correlation at 540 GeV, UA5 results (Ref. 33) vs impact-parameter-independent multiple-interaction model; the latter with notation as in Fig. 5.

Direct observation of multiple interactions

Five studies: AFS (1987), UA2 (1991), CDF (1993, 1997), D0 (2009)

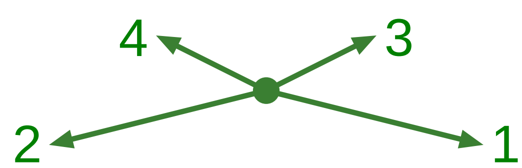
Order 4 jets $\mathbf{p}_{\perp 1} > \mathbf{p}_{\perp 2} > \mathbf{p}_{\perp 3} > \mathbf{p}_{\perp 4}$ and define φ
as angle between $\mathbf{p}_{\perp 1} \mp \mathbf{p}_{\perp 2}$ and $\mathbf{p}_{\perp 3} \mp \mathbf{p}_{\perp 4}$ for AFS/CDF

Double Parton Scattering



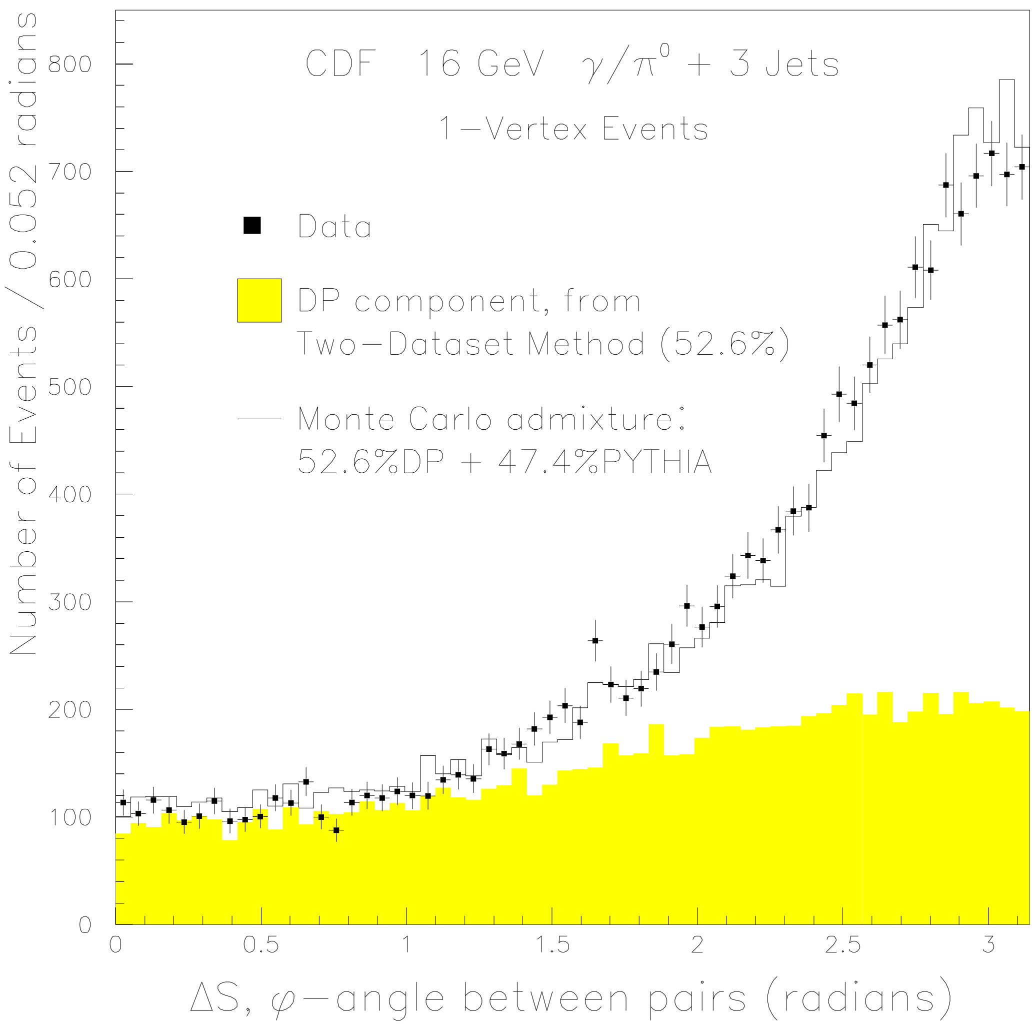
$|\mathbf{p}_{\perp 1} + \mathbf{p}_{\perp 2}| \approx 0$
$|\mathbf{p}_{\perp 3} + \mathbf{p}_{\perp 4}| \approx 0$
$\mathrm{d}\sigma/\mathrm{d}\varphi$ flat

Double BremsStrahlung



$|\mathbf{p}_{\perp 1} + \mathbf{p}_{\perp 2}| \gg 0$
$|\mathbf{p}_{\perp 3} + \mathbf{p}_{\perp 4}| \gg 0$
$\mathrm{d}\sigma/\mathrm{d}\varphi$ peaked at $\varphi \approx 0/\pi$ for AFS/CDF

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



CDF 3-jet + prompt photon analysis

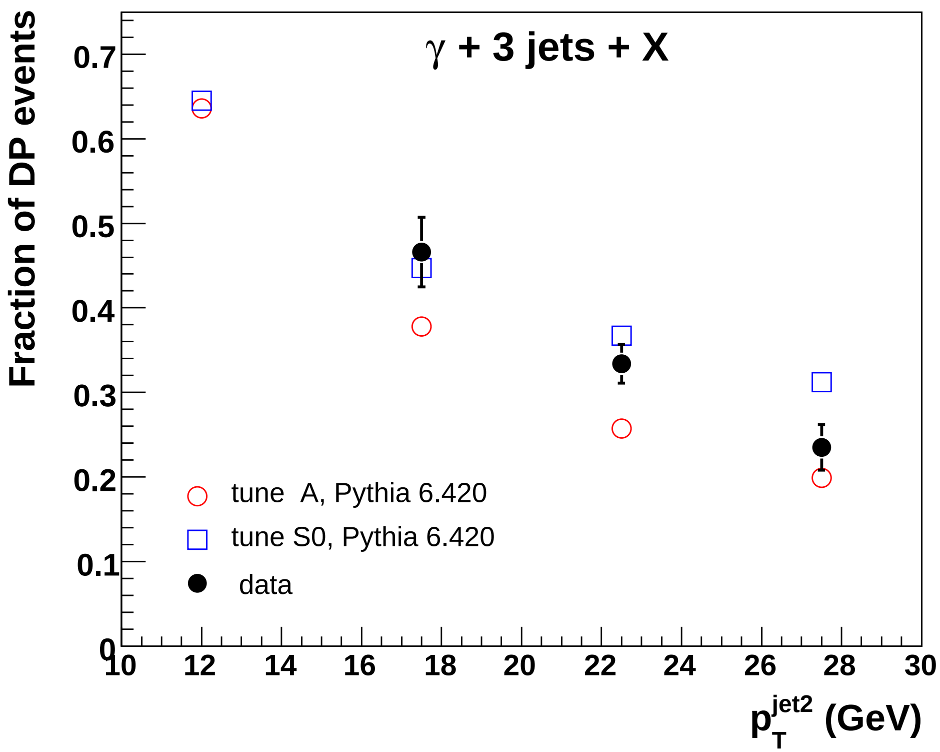
Yellow region = double parton scattering (DPS)

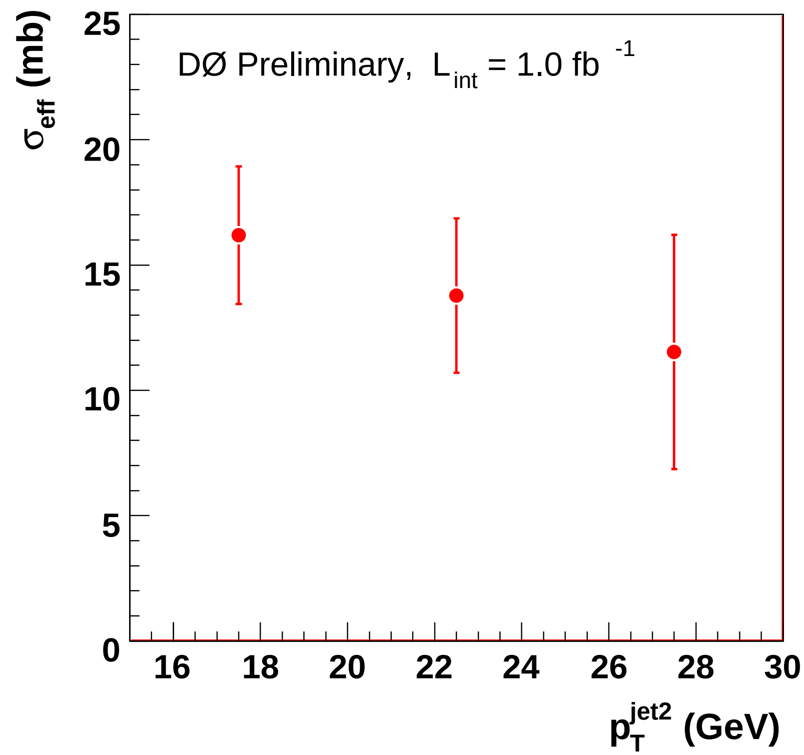
The rest = PYTHIA showers

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

Strong enhancement relative to naive expectations!

D0 results:





$$\sigma_{\text{eff}} = 15.1 \pm 1.9 \text{ mb}$$

agreement and precision “too good to be true”;

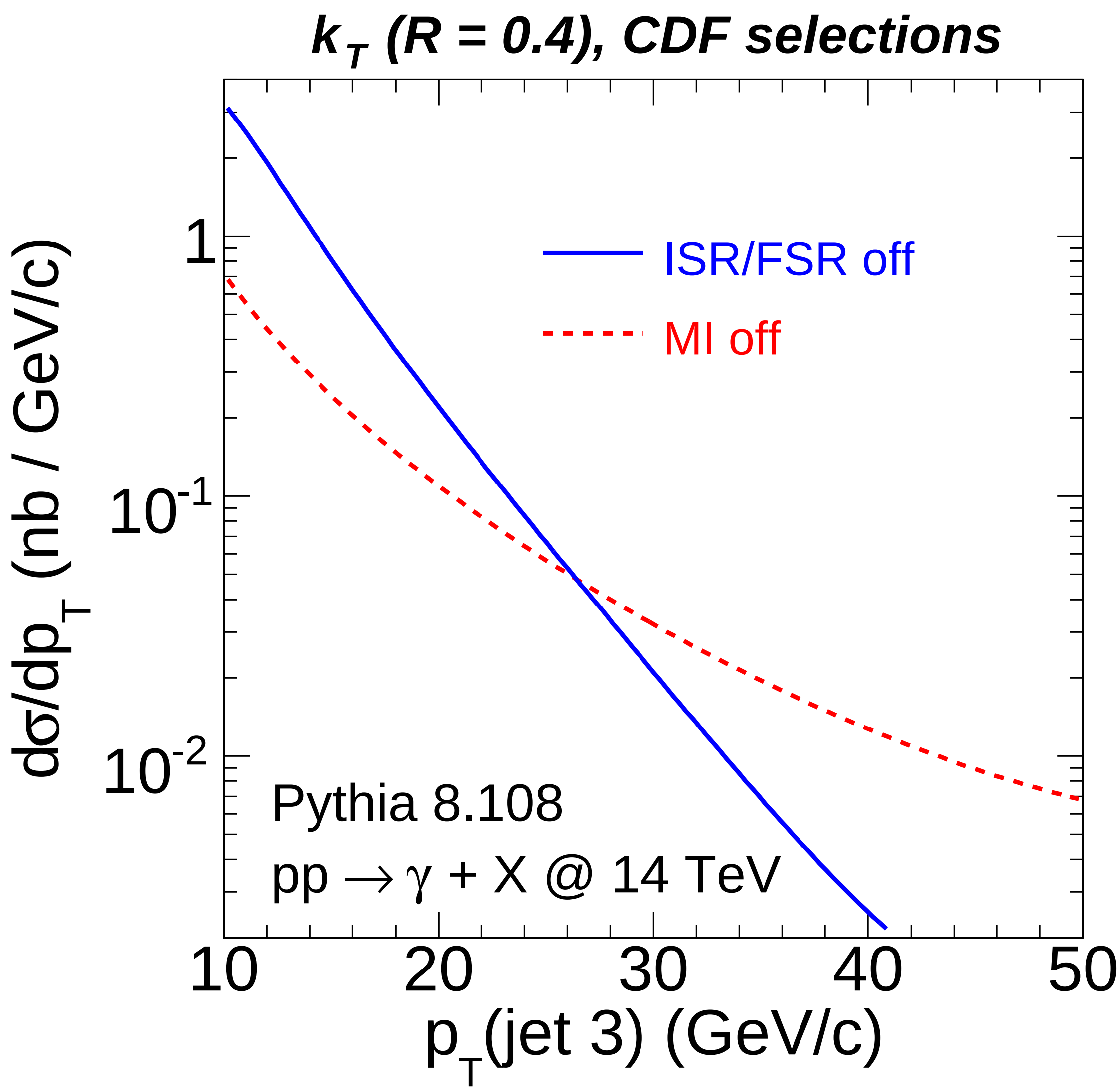
tunes 7 and 3 years old, respectively, and not to this kind of data

Same study also planned for LHC

Selection for DPS delicate balance:

showers dominate at large $p_\perp$ $\Rightarrow$ too large background

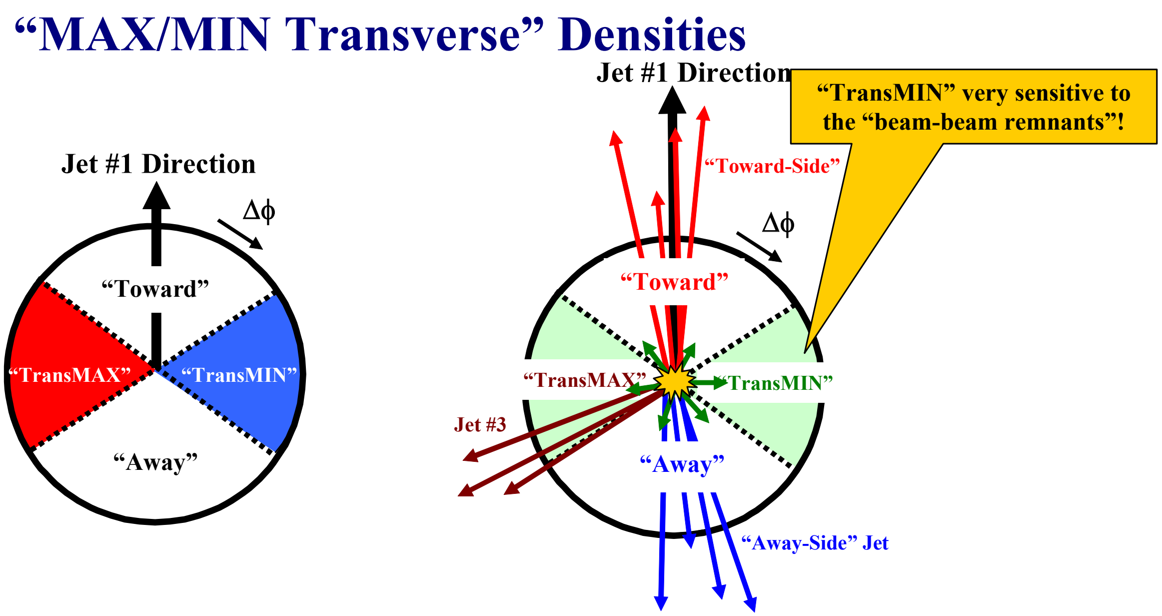
multiple interactions dominate at small $p_\perp$, but there jet identification difficult



Jet pedestal effect

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

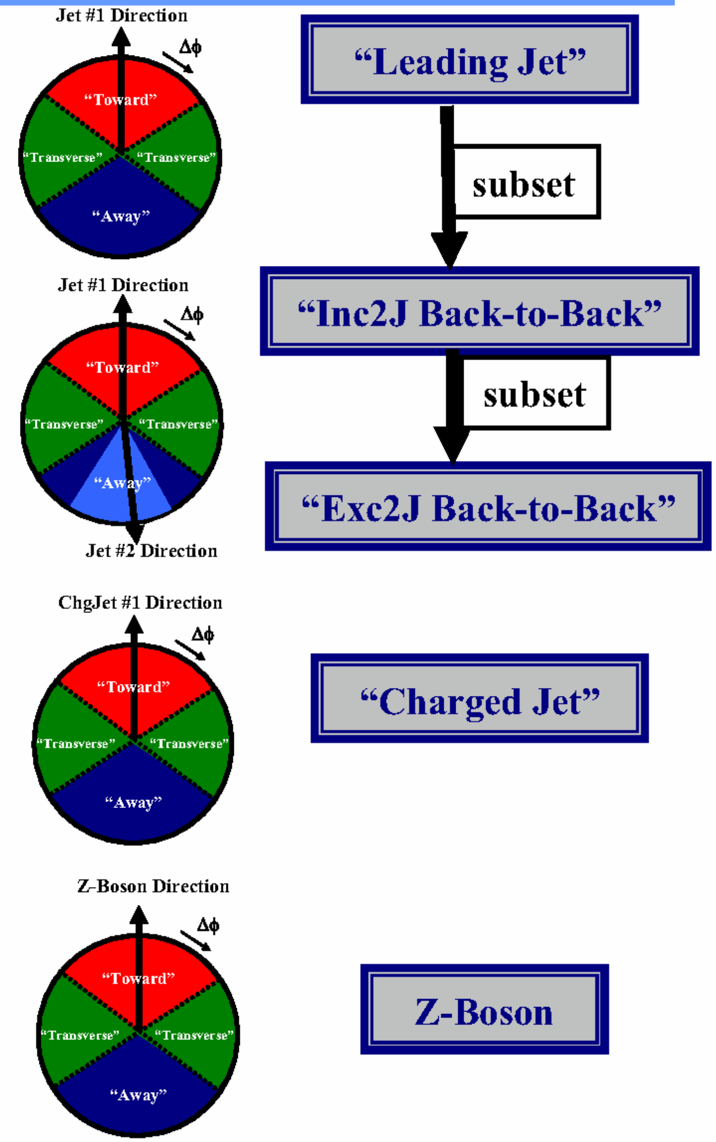
Studied in detail by Rick Field, comparing with CDF data:
(see `http://www.phys.ufl.edu/~rfield/cdf/rdf_talks.html`)



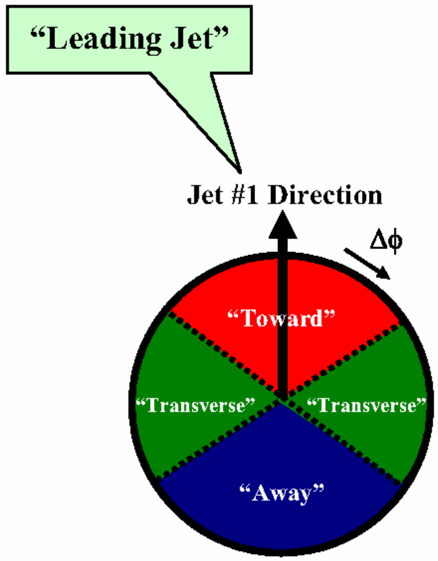
- **Define the MAX and MIN "transverse" regions on an event-by-event basis with MAX (MIN) having the largest (smallest) density.**

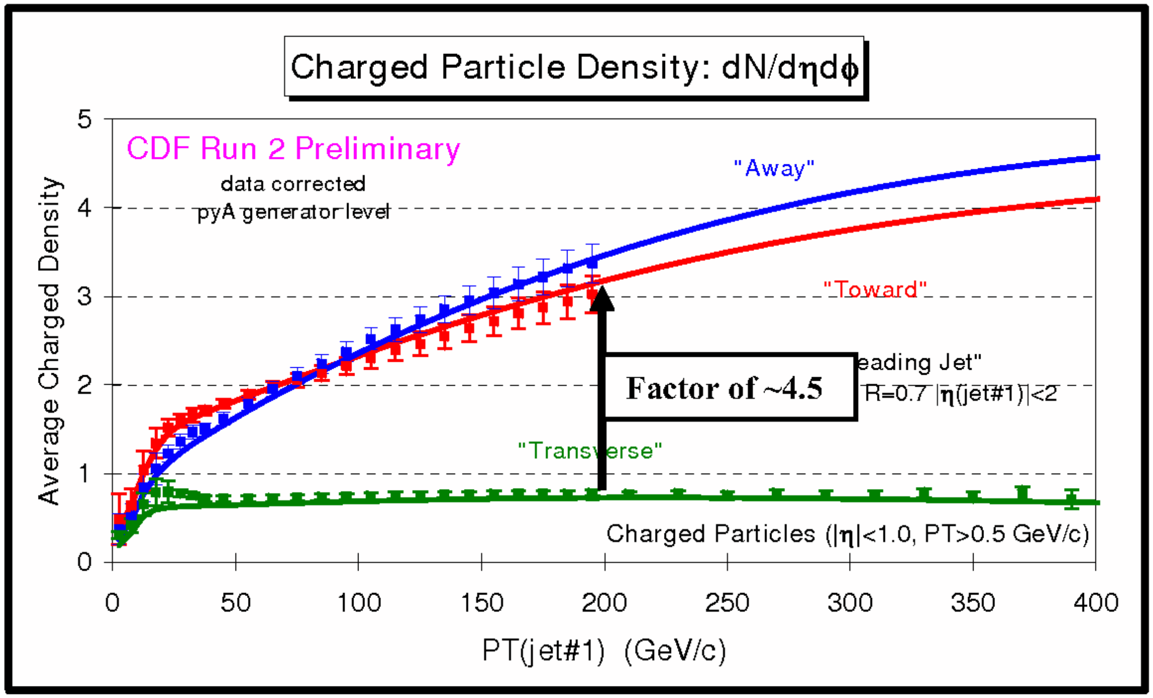
Event Topologies

- **"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.



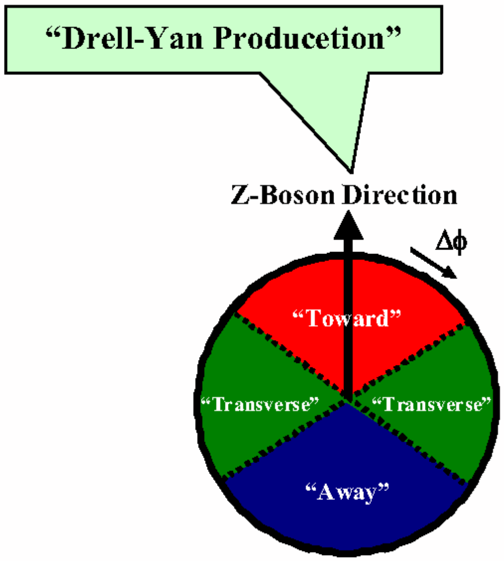
“Towards”, “Away”, “Transverse”

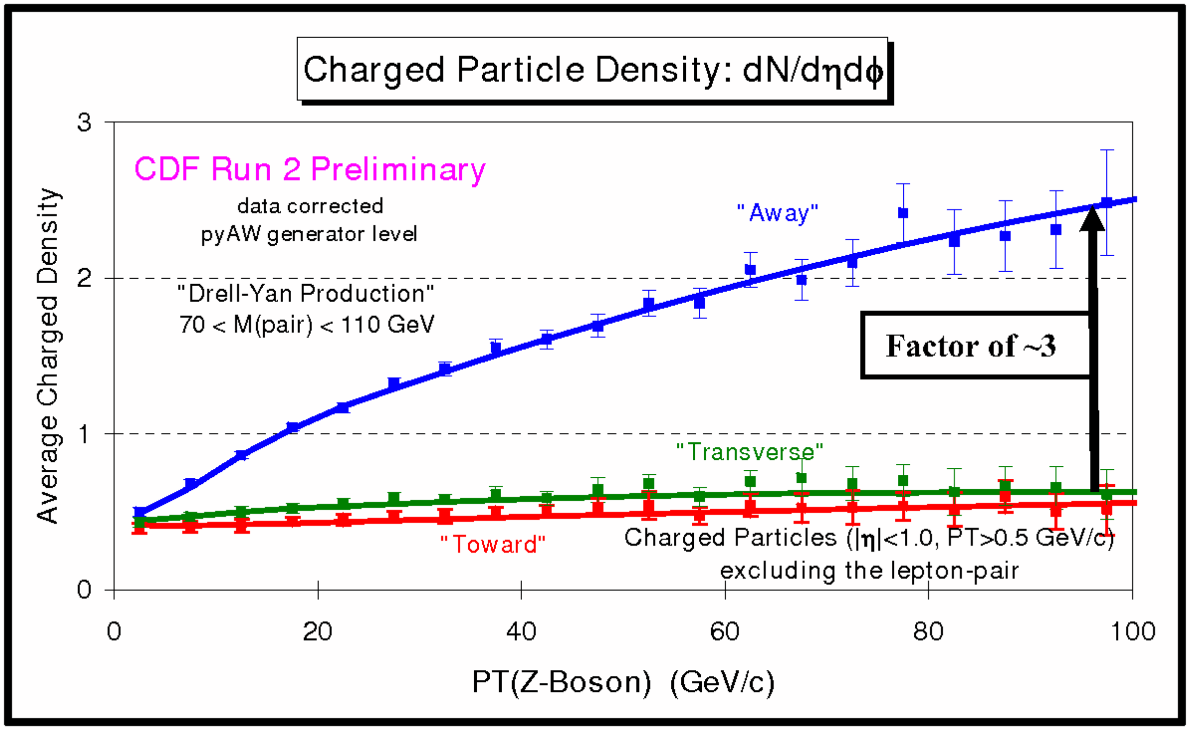




- **Data at 1.96 TeV on the density of charged particles, dN/dηdϕ, with p_T > 0.5 GeV/c and |η| < 1 for “leading jet” events as a function of the leading jet p_T for the “toward”, “away”, and “transverse” regions. The data are corrected to the particle level (***with errors that include both the statistical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

"Towards", "Away", "Transverse"

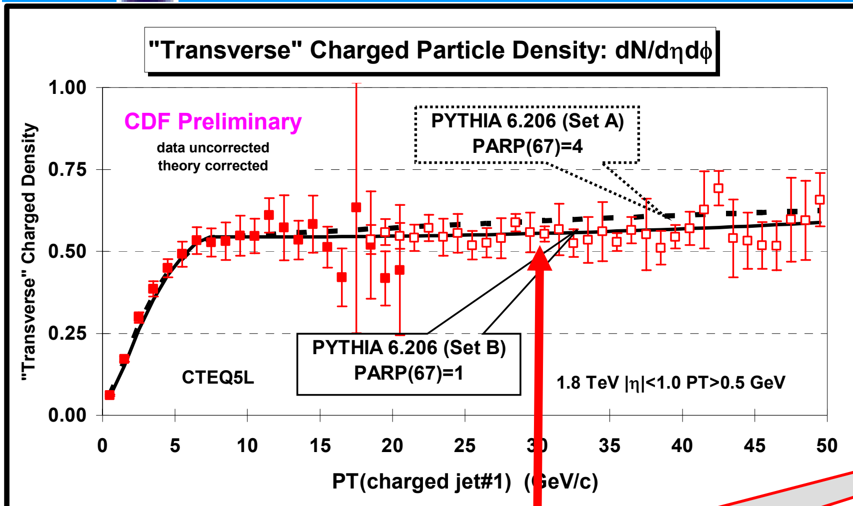


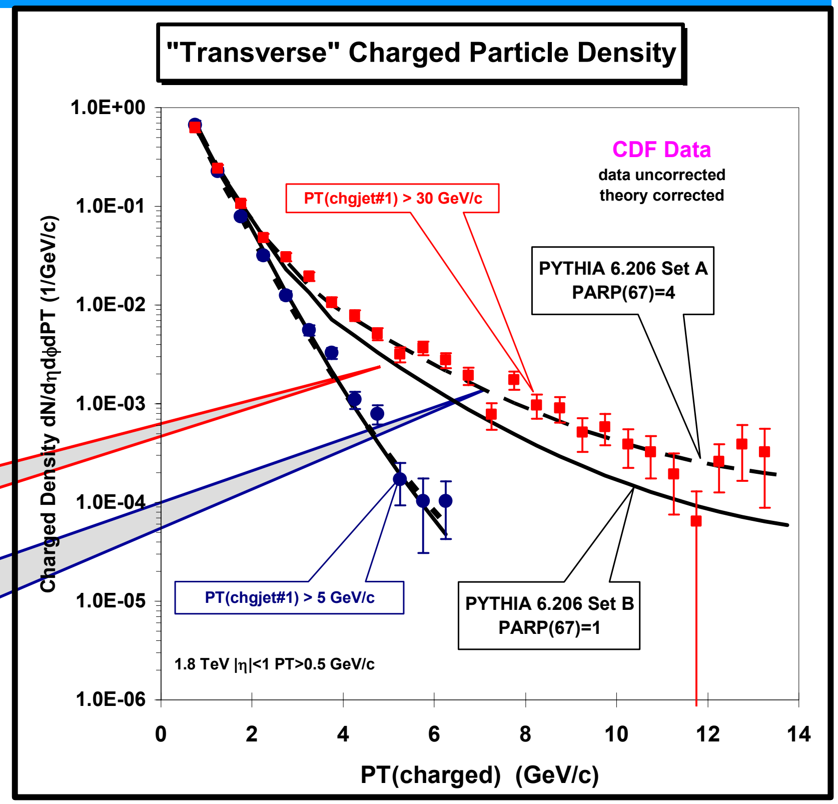


- **Data at 1.96 TeV on the density of charged particles, dN/dηdϕ, with $p_T > 0.5$ GeV/c and $|\eta| < 1$ for "Z-Boson" events as a function of the leading jet p_T for the "toward", "away", and "transverse" regions. The data are corrected to the particle level (*with errors that include both the statistical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

Deepak Kar's Thesis

Tuned PYTHIA 6.206 "Transverse" P_T Distribution



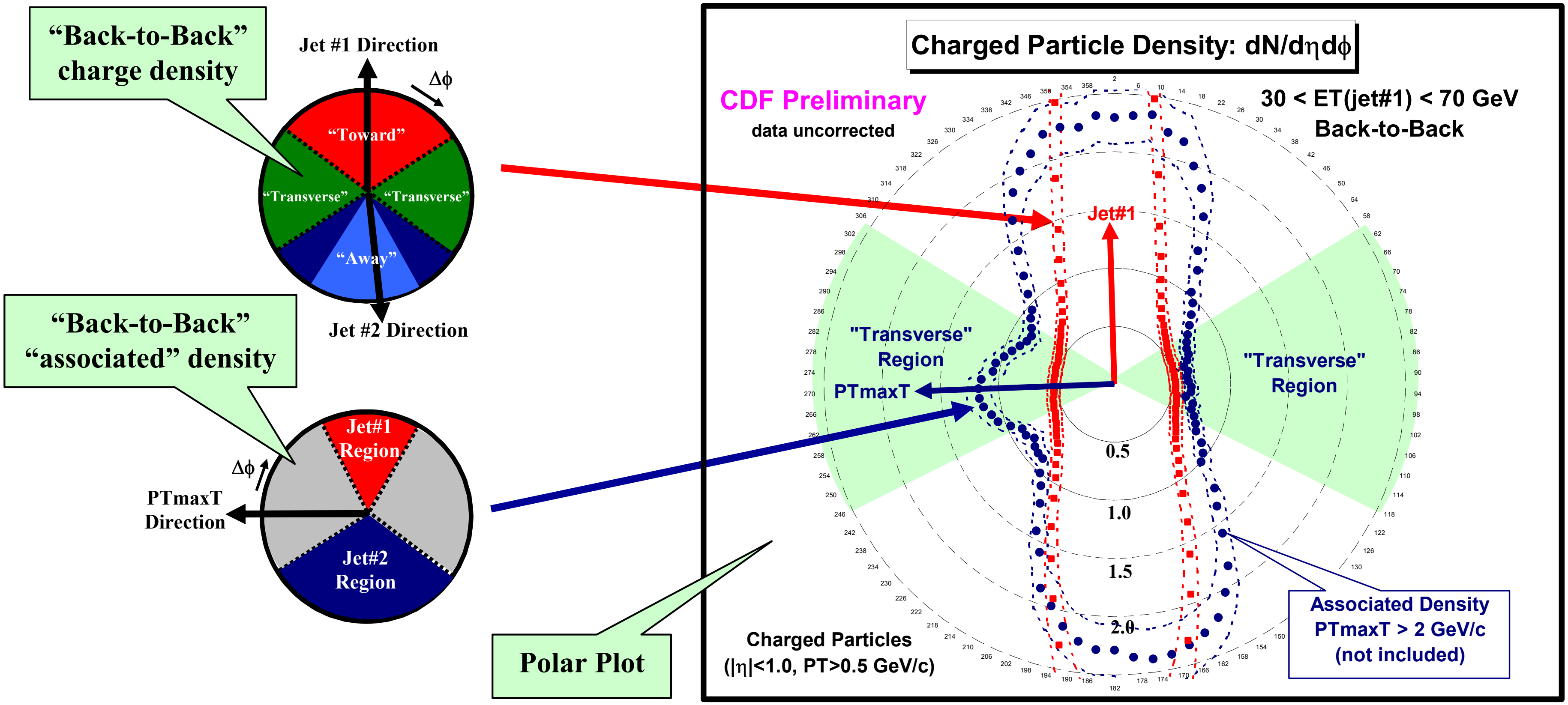


P_T(charged jet#1) > 30 GeV/c

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

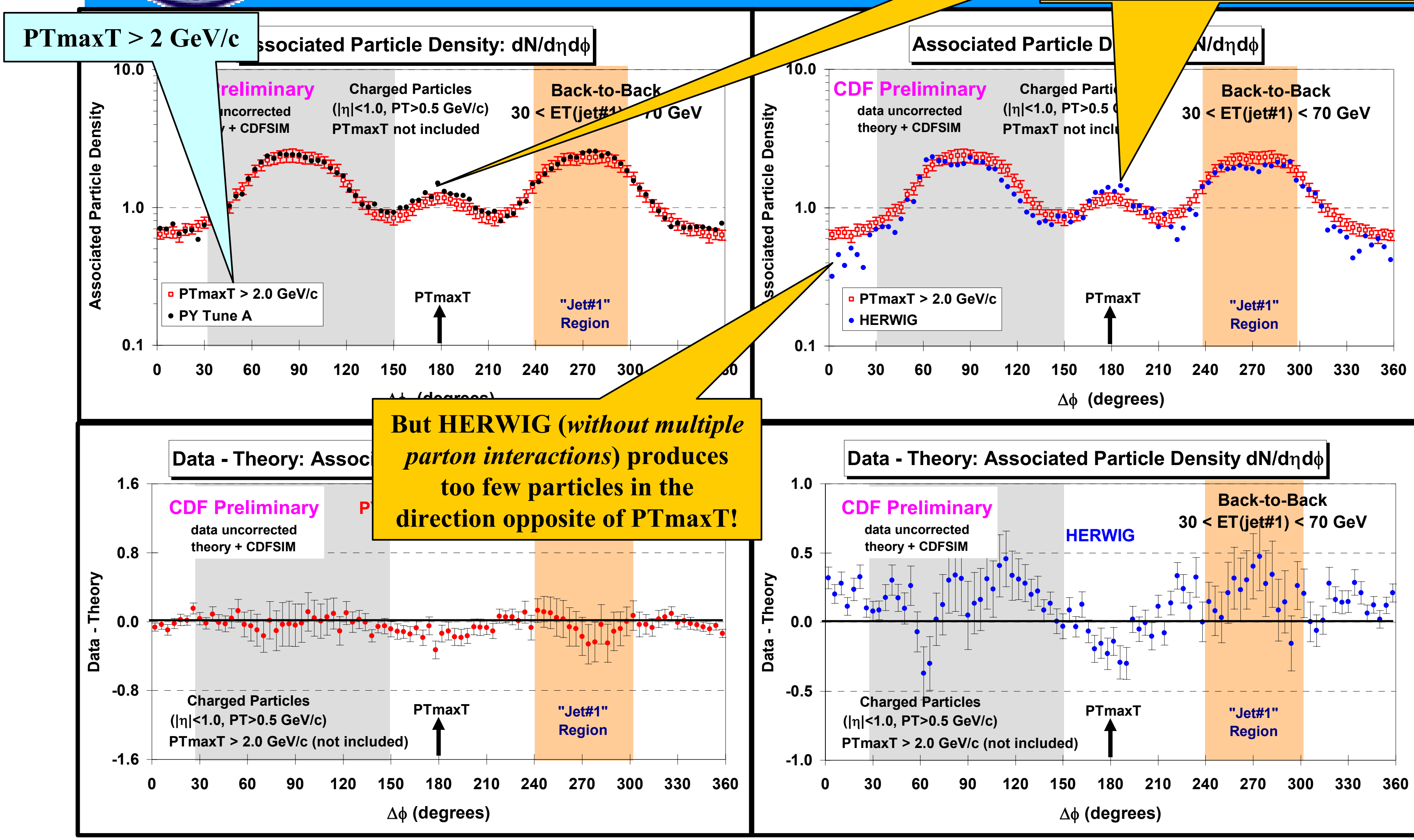
- Compares the average "transverse" charge particle density ($|\eta|<1$, $P_T>0.5$ GeV) versus P_T(charged jet#1) and the P_T distribution of the "transverse" density, $dN_{chg}/d\eta d\phi dP_T$ with the QCD Monte-Carlo predictions of two tuned versions of PYTHIA 6.206 (P_T(hard) > 0, CTEQ5L, Set B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

Back-to-Back "Associated" Charged Particle Densities



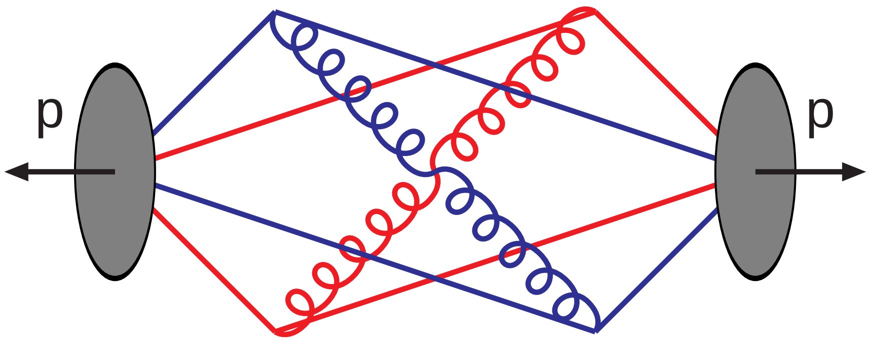
- Shows the $\Delta\phi$ dependence of the "associated" charged particle density, $dN_{chg}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$, PTmaxT > 2.0 GeV/c (*not including PTmaxT*) relative to PTmaxT (rotated to 180°) and the charged particle density, $dN_{chg}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta|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

"Associated" Charge Density PYTHIA Tune A vs HERWIG

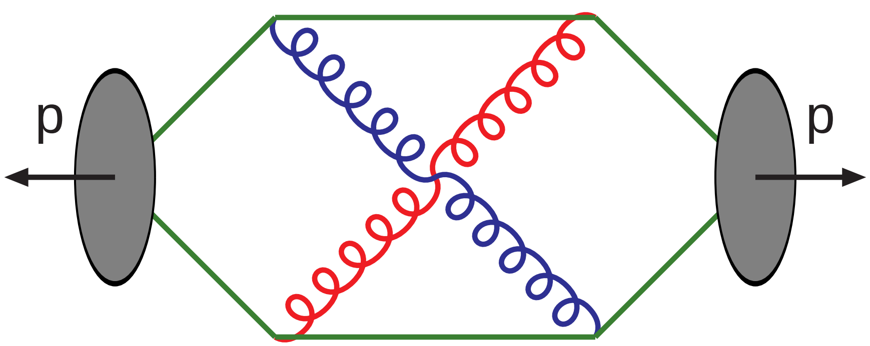


Colour correlations

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



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



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

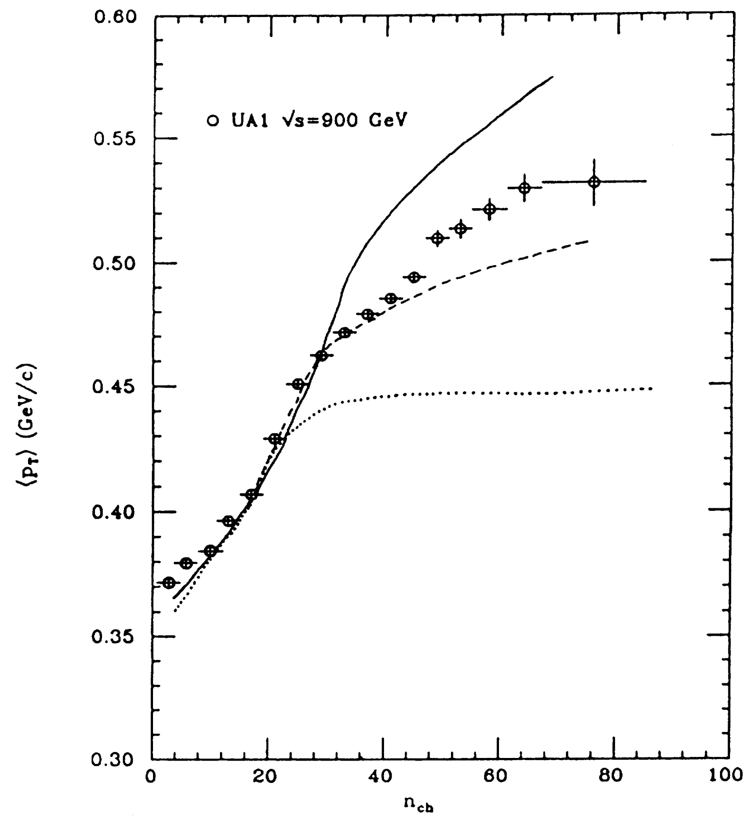
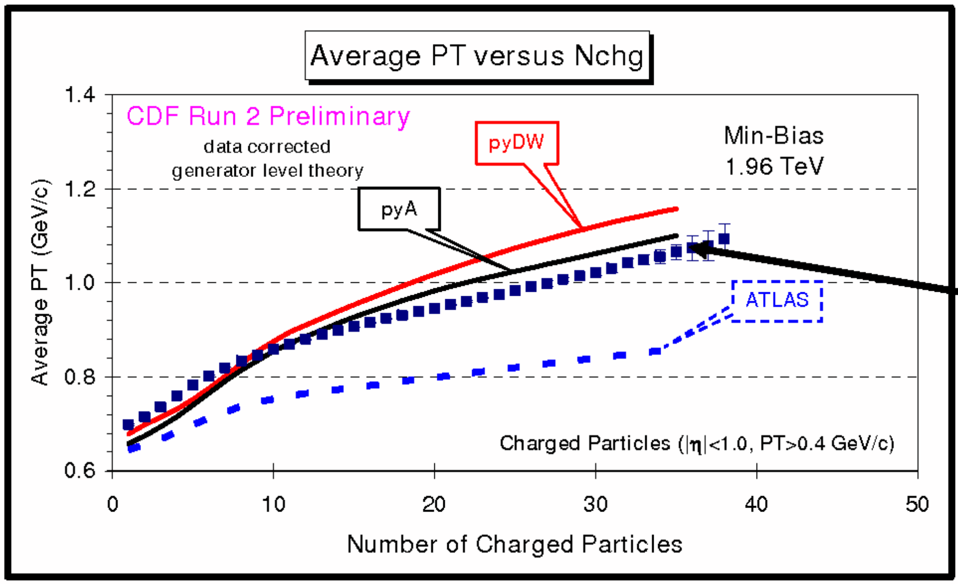
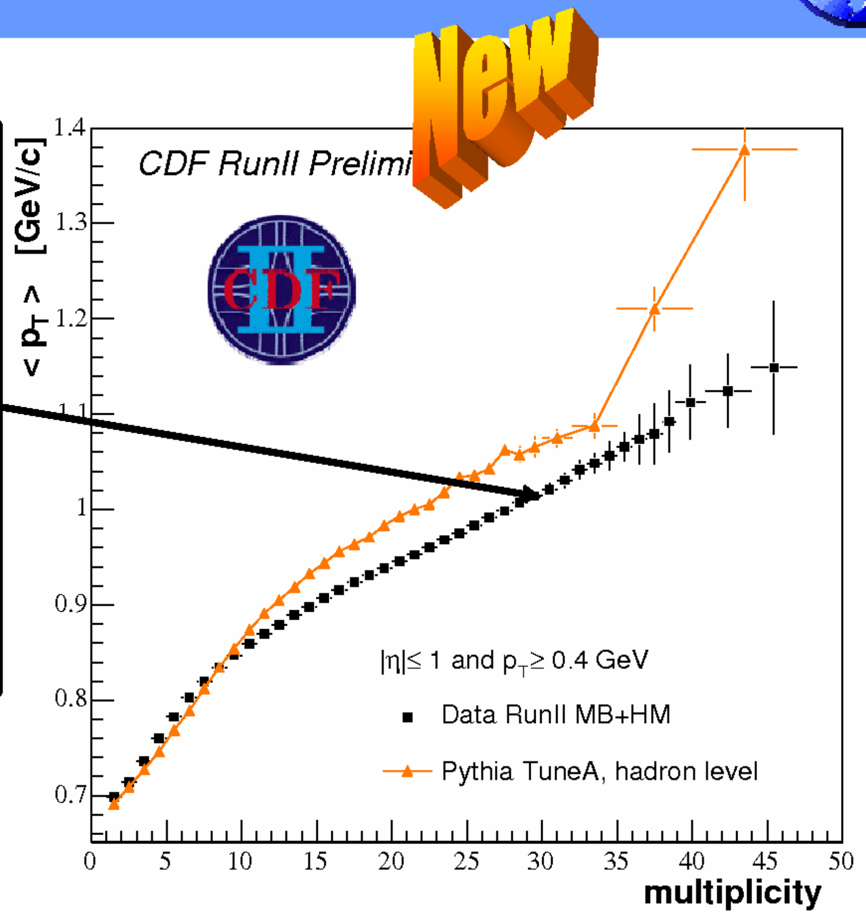


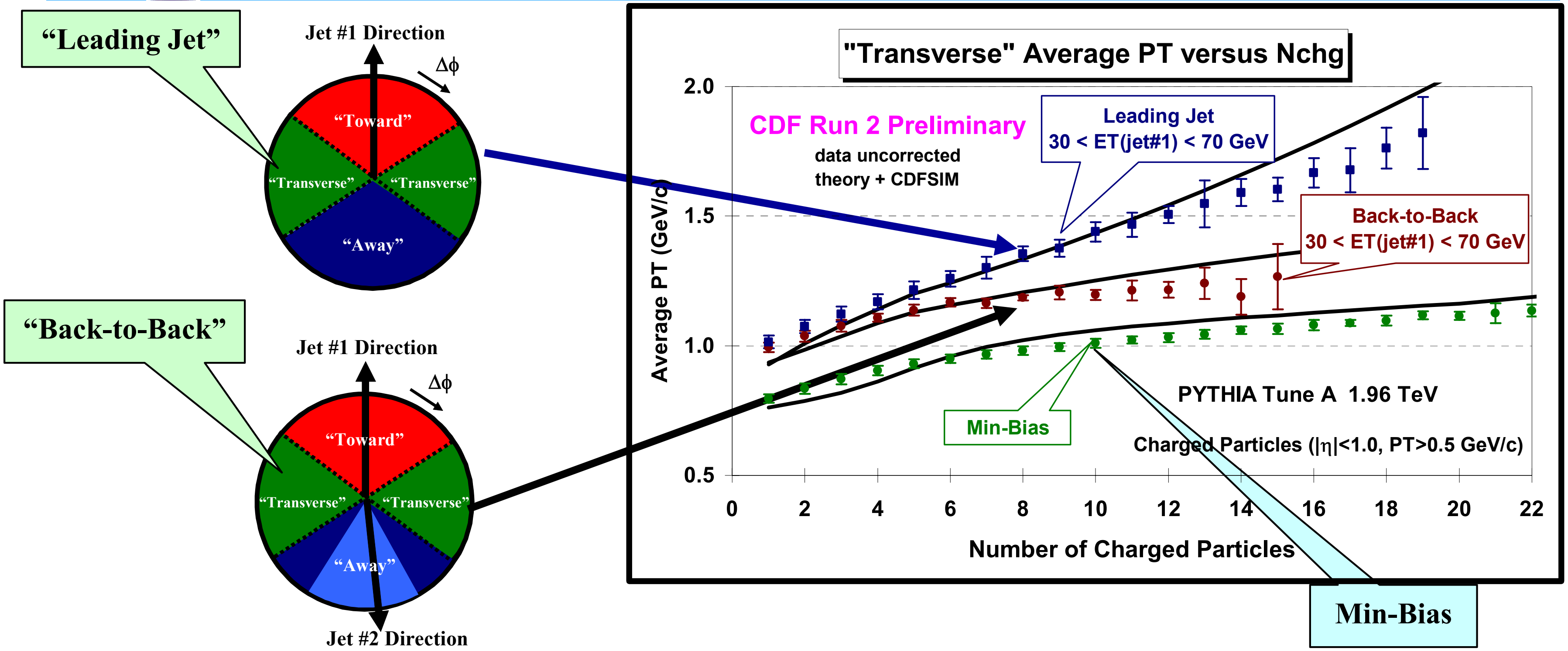
FIG. 27. Average transverse momentum of charged particles in $|\eta| < 2.5$ as a function of the multiplicity. UA1 data points (Ref. 49) at 900 GeV compared with the model for different assumptions about the nature of the subsequent (nonhardest) interactions. Dashed line, assuming $q\bar{q}$ scatterings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





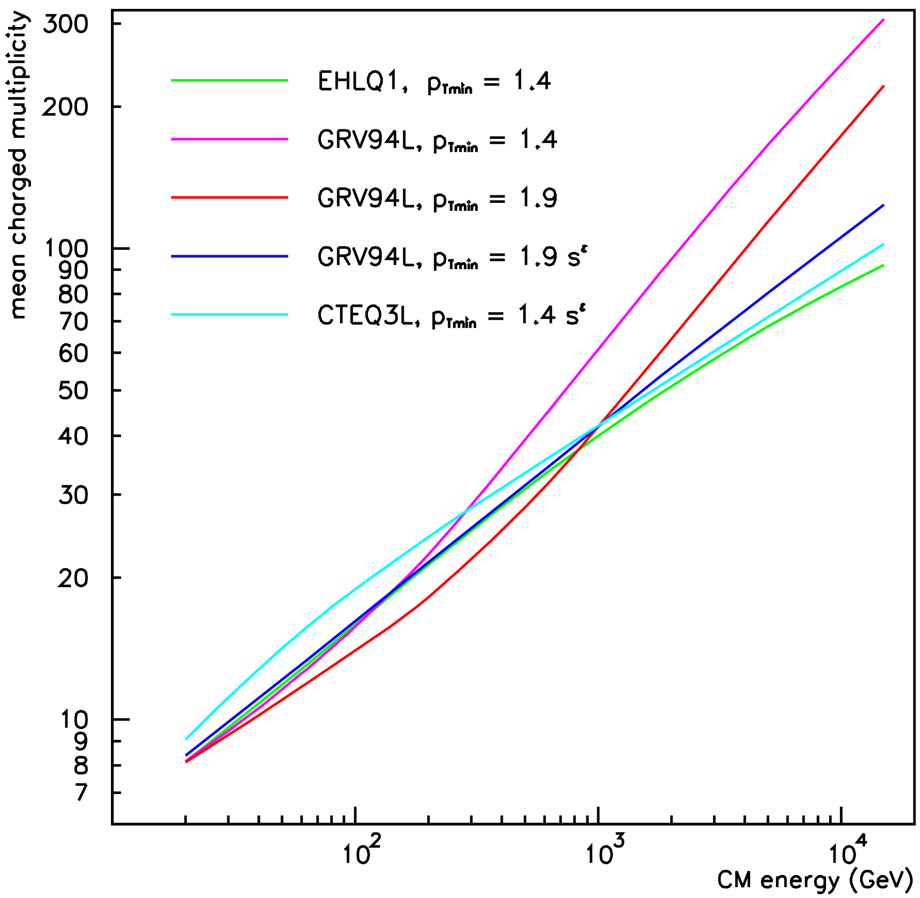
- Data at 1.96 TeV on the average p_T of charged particles versus the number of charged particles (p_T > 0.4 GeV/c, $|\eta| < 1$) for "min-bias" collisions at CDF Run 2. The data are corrected to the particle level and are compared with PYTHIA Tune A at the particle level (*i.e.* generator level).

"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 $30 < E_T(\text{jet\#1}) < 70$ 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

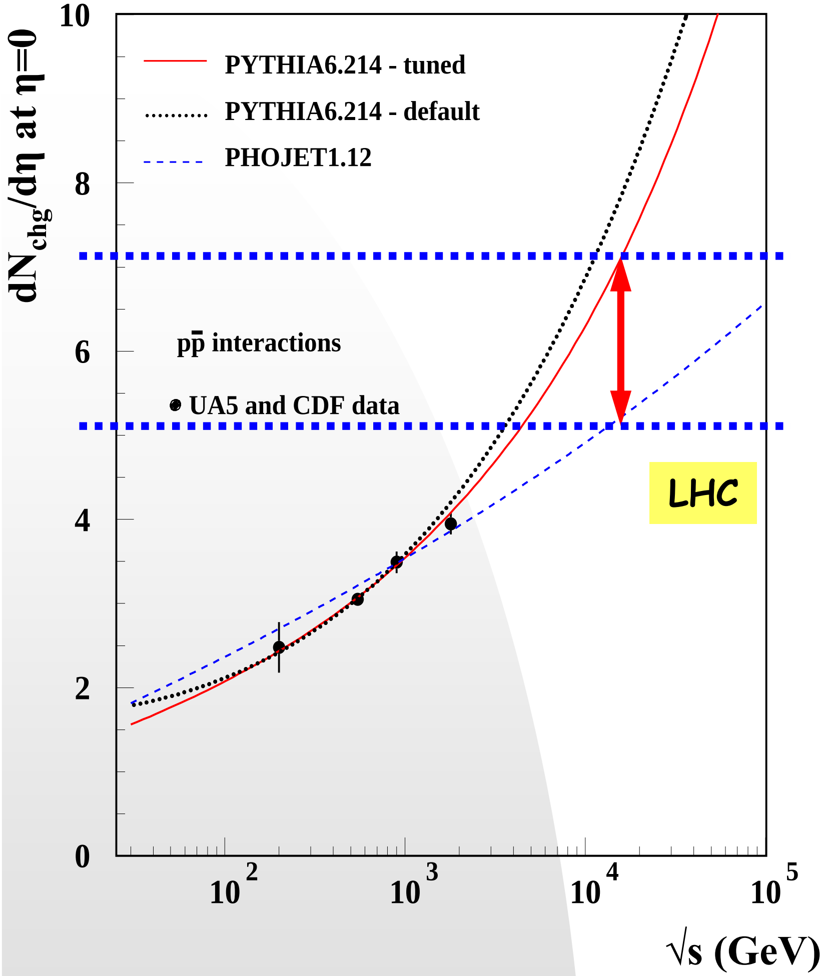
$\Rightarrow$ stronger energy dependence

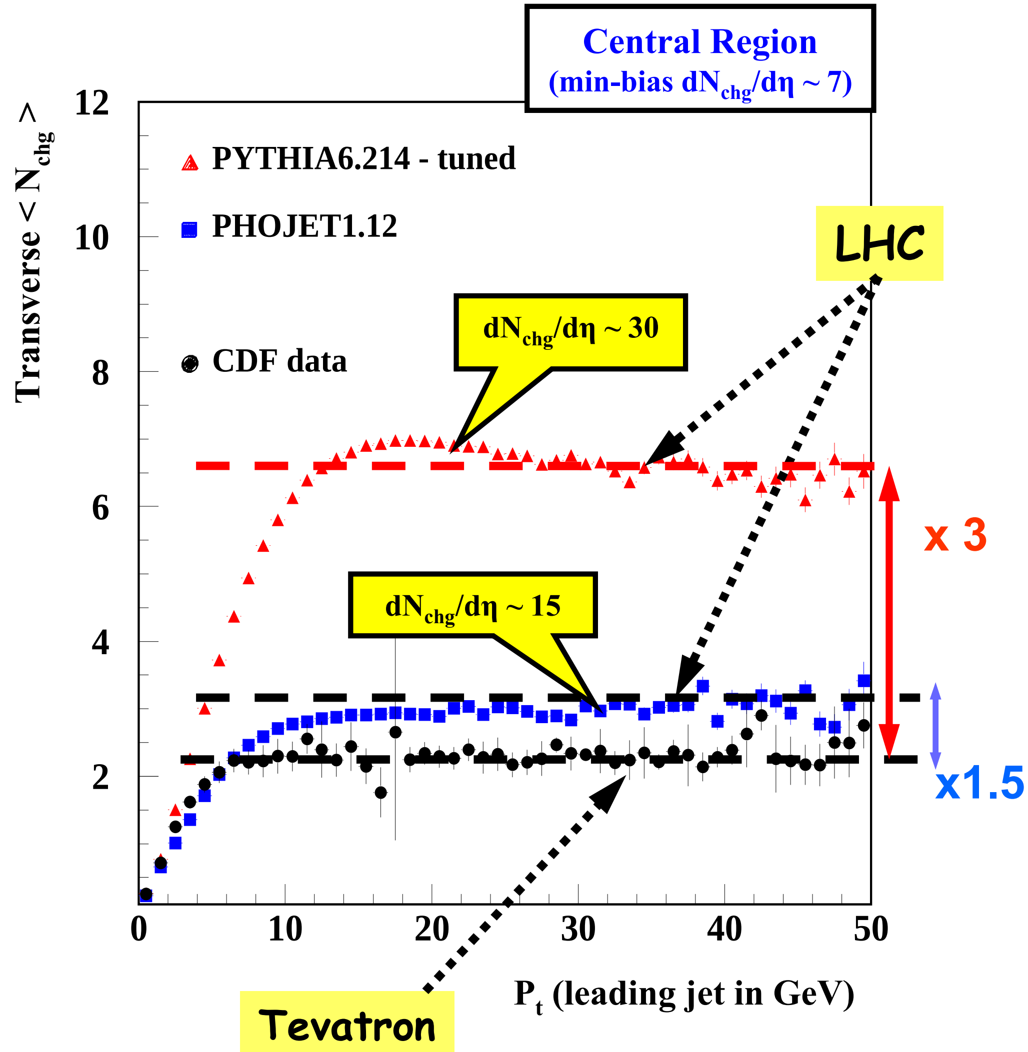
For a long time PYTHIA default (Tune A, old model), tied to CTEQ 5L, was

$$p_{\perp\mathrm{min}}(s) = 2.0\ \mathrm{GeV}\left(\frac{E_{\mathrm{CM}}}{1.8\ \mathrm{TeV}}\right)^{0.16}$$

In recent years debate in the range 0.20 – 0.30 $\Rightarrow$ slower increase

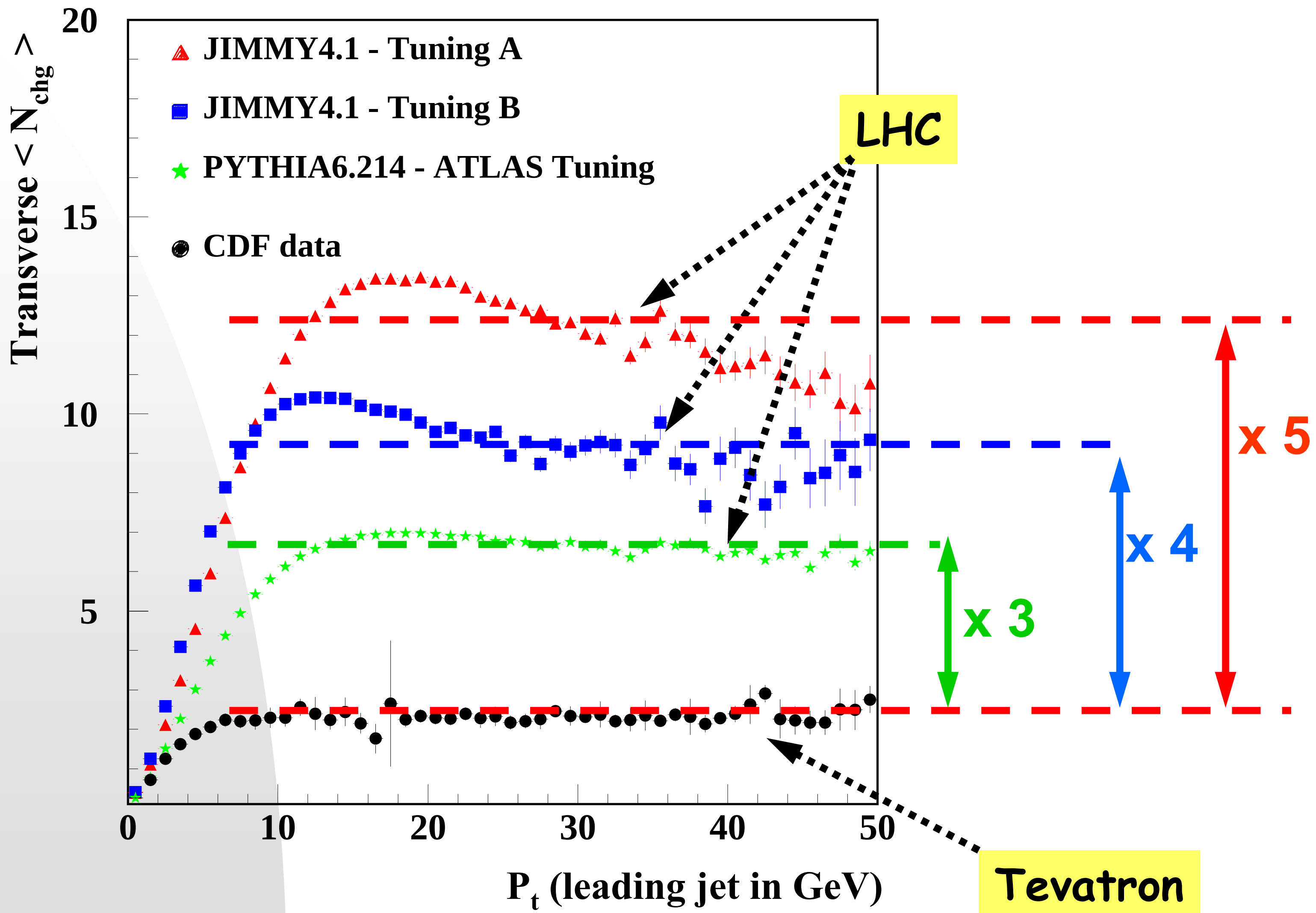
LHC predictions: pp collisions at $\sqrt{s}$ = 14 TeV





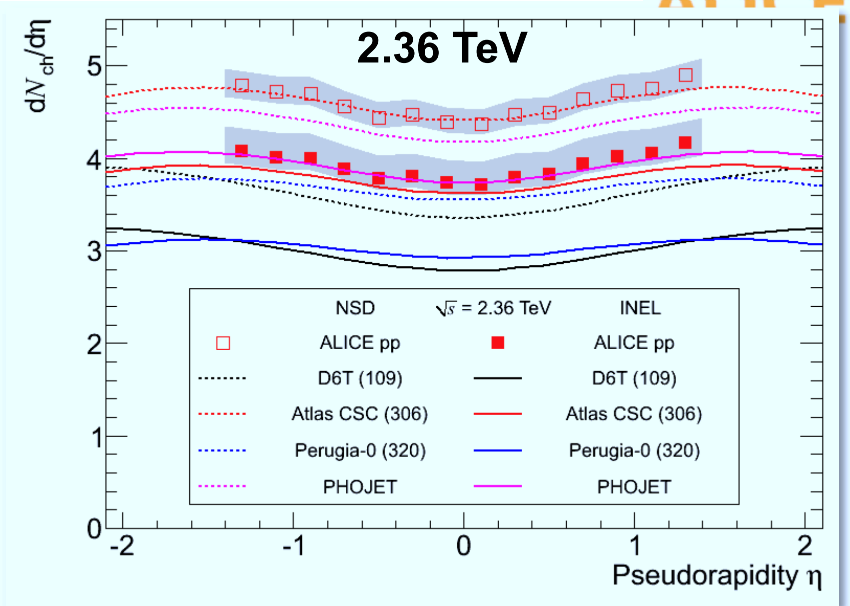
- PYTHIA models favour $\ln^2(s)$;
- PHOJET suggests a $\ln(s)$ dependence.

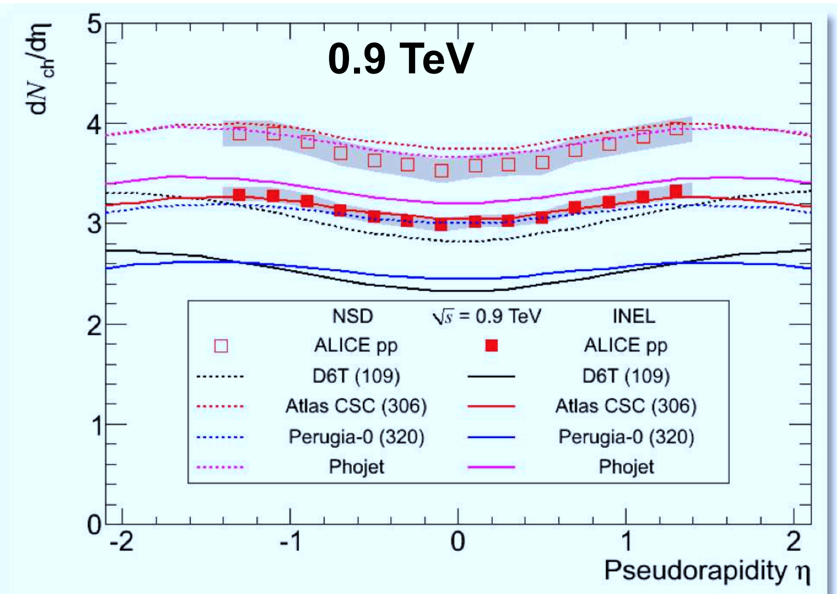
LHC predictions: JIMMY4.1 Tunings A and B vs. PYTHIA6.214 – ATLAS Tuning (DC2)

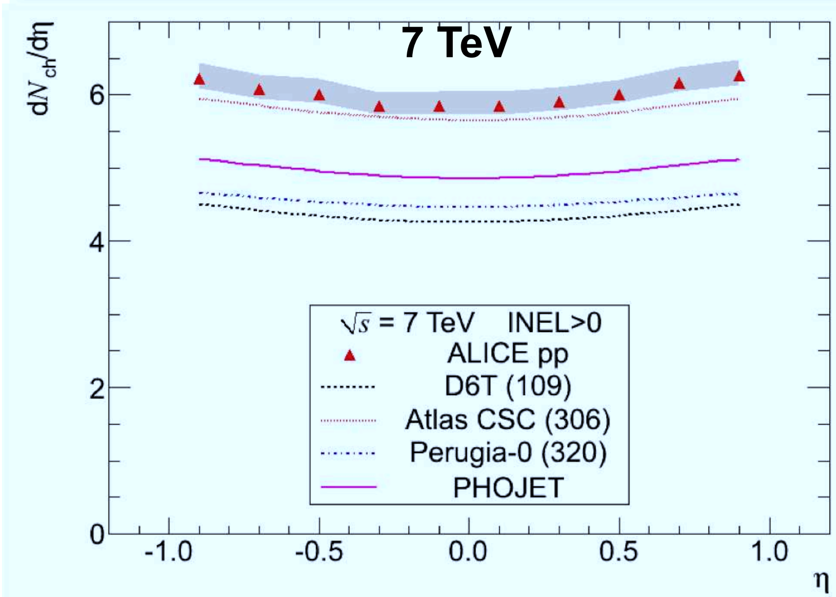


$dN_{ch}/d\eta$ vs. Monte Carlo

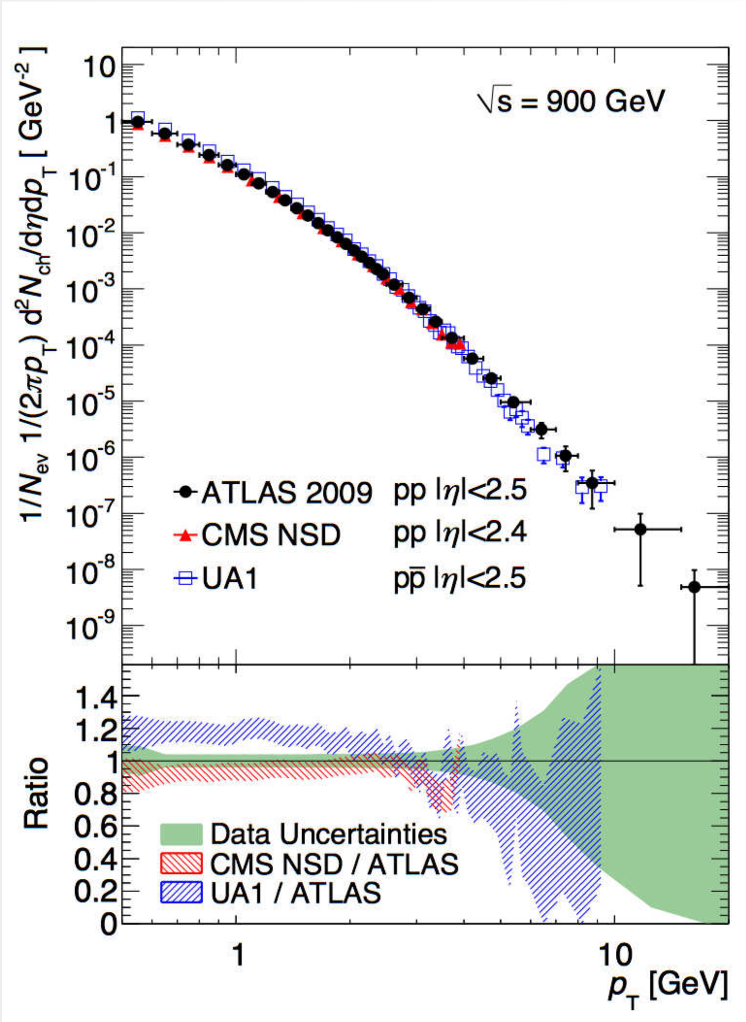
- Pythia D6T and Perugia-0 match neither INEL, NSD or INEL>0 at any energy
- Pythia ATLAS-CSC and Phojet reasonably close with some deviations at 0.9 and 2.36 TeV
- Only ATLAS-CSC close at 7 TeV

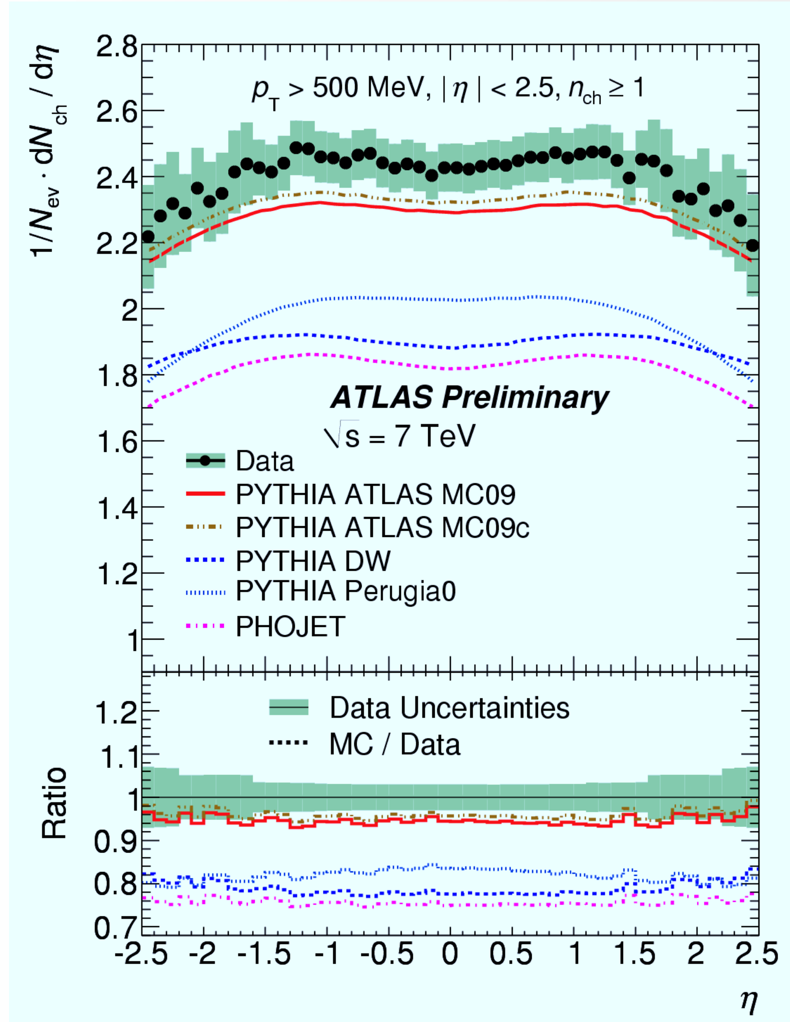






Charged Particle Multiplicities at √s=0.9, 7 TeV

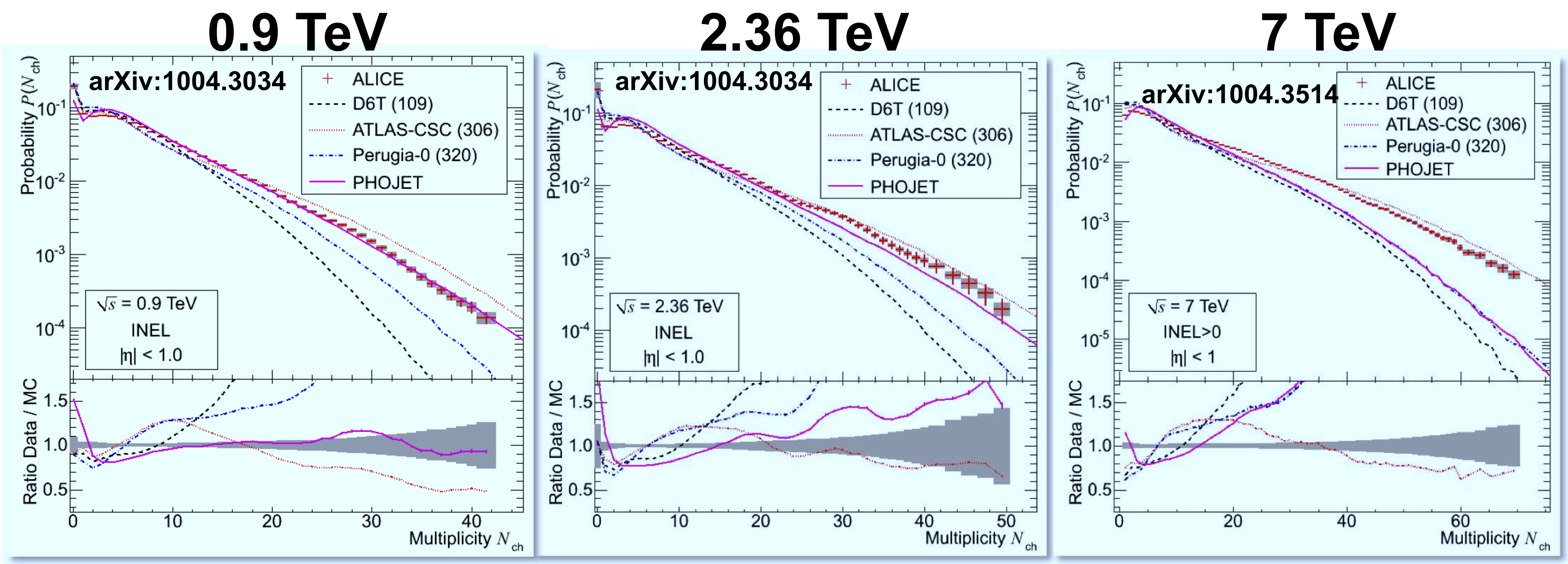




Monte Carlo underestimates the track multiplicity seen in ATLAS

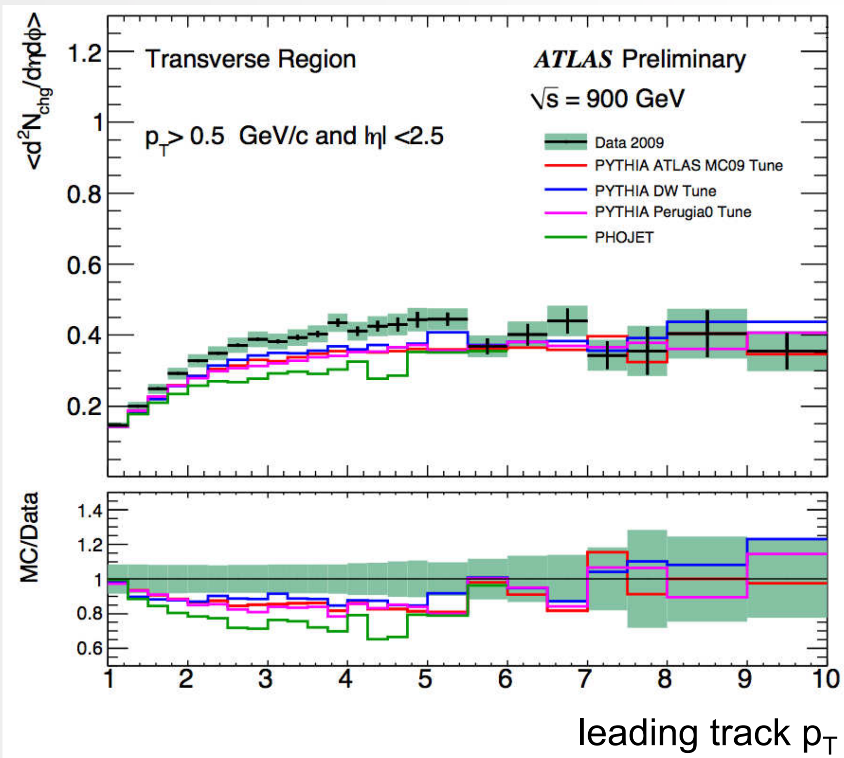
dN/dN$_{ch}$: vs. Monte Carlo

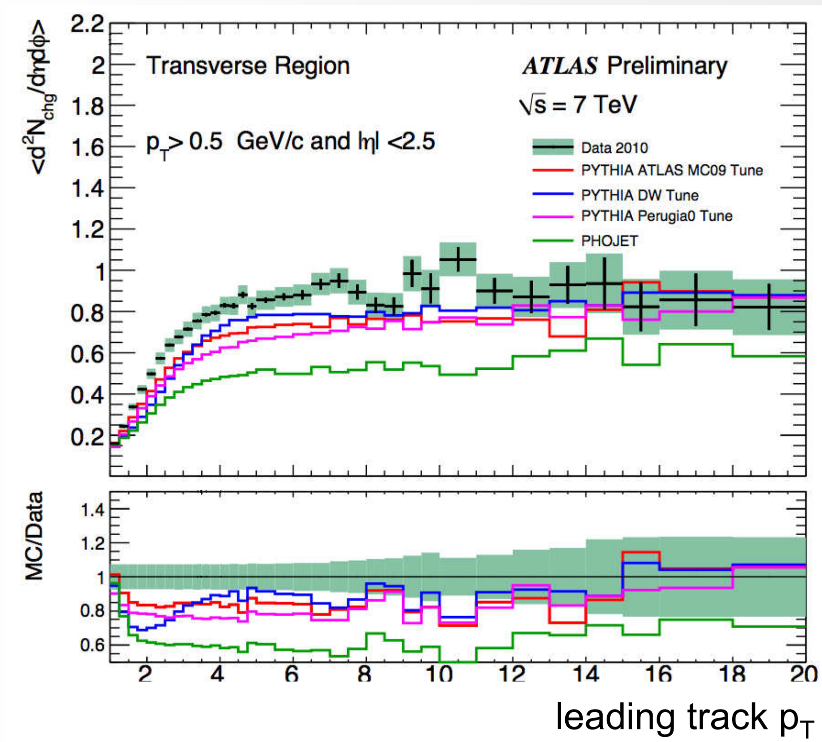
- Phojet
  - provides a good description at 900 GeV
  - fails at 2.36 and 7 TeV
- Pythia Atlas CSC
  - fails at 0.9 TeV
  - reasonably close at 2.36 and 7 TeV but deviations around 10-20
- Pythia D6T and Perugia-0 far from the distribution at all energies



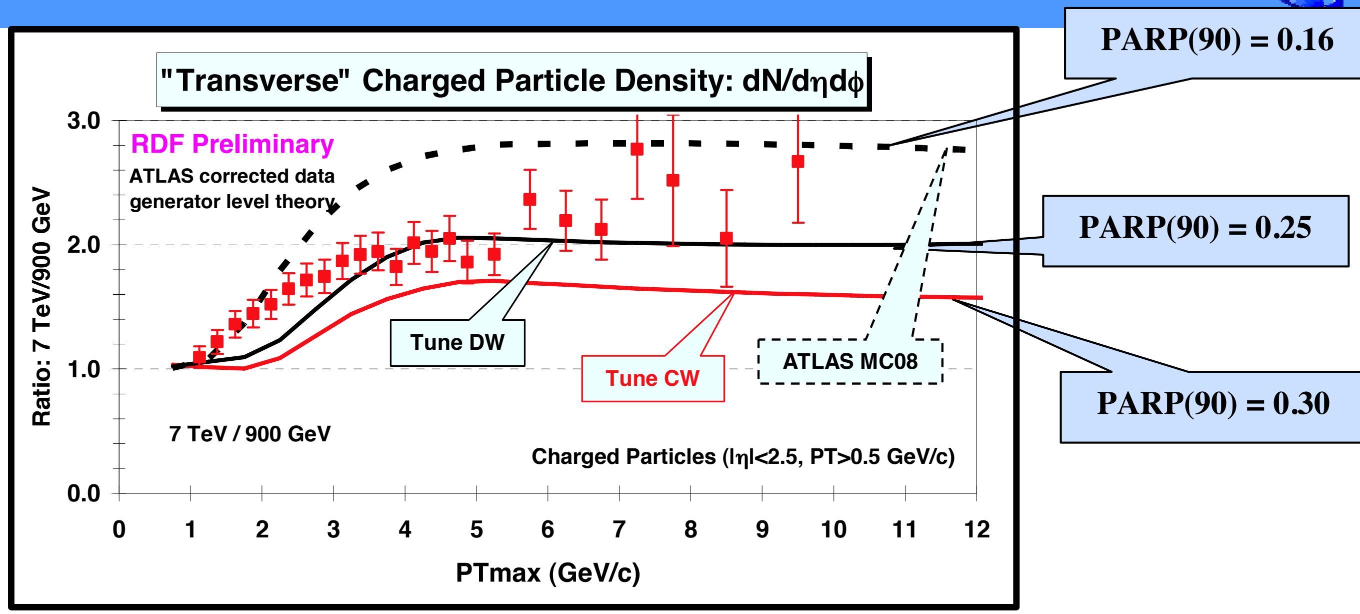
Underlying Event (2)

- All MC tunes underestimate activity by 10-15% in plateau of transverse region
  Observed both for particle density and sum of track p_T
- Increase of factor two in UE activity from 900 GeV to 7 TeV, comparable to MC prediction
- Plateau at p_T^{lead}> 3 GeV at 900GeV and p_T^{lead}>5 GeV at 7 TeV
- From plateau region ~2.5 charged particles per unit of η at 900 GeV and 5 particles at 7 TeV.

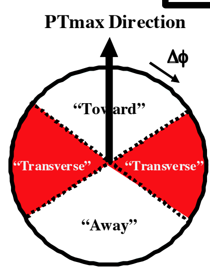




"Transverse" Charge Density



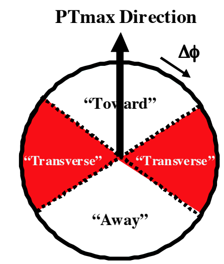
LHC
900 GeV



900 GeV → 7 TeV
(UE increase ~ factor of 2)

~0.4 → ~0.8

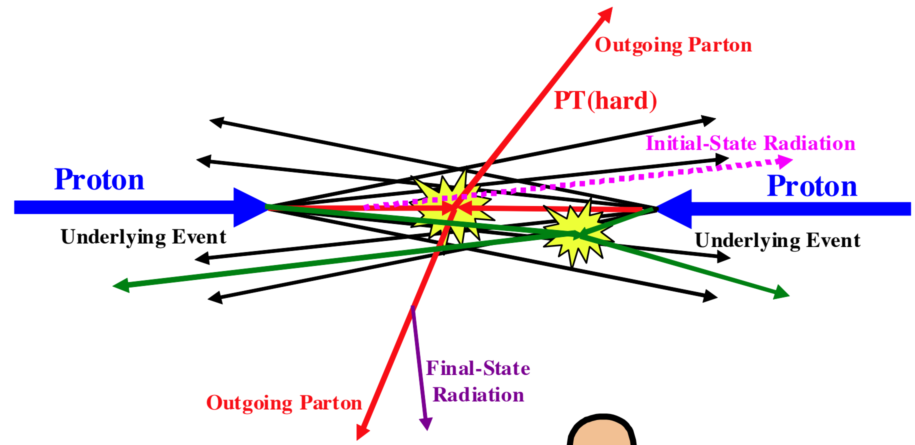
LHC
7 TeV



- Ratio of the ATLAS preliminary data on the charged particle density in the "transverse" region for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 2.5$) at 900 GeV and 7 TeV as defined by PTmax compared with PYTHIA Tune CW, DW, and ATLAS MC08.

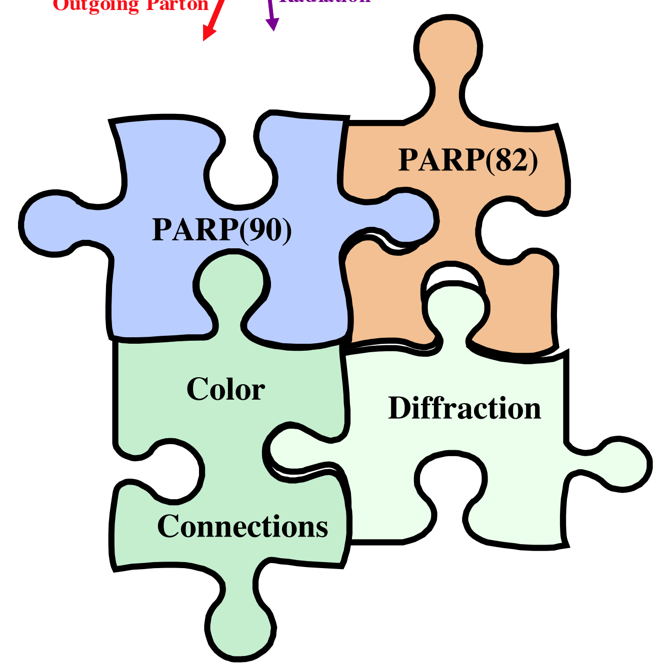
UE Summary

- The "underlying event" at 7 TeV and 900 GeV is almost what we expected! I expect that a PYTHIA 6 tune just slightly different than Tune DW will fit the UE data perfectly including the energy dependence (Tune X1 is not bad!). I also expect to see good PYTHIA 8 tune soon!



- "Min-Bias" is a whole different story! Much more complicated due to diffraction!

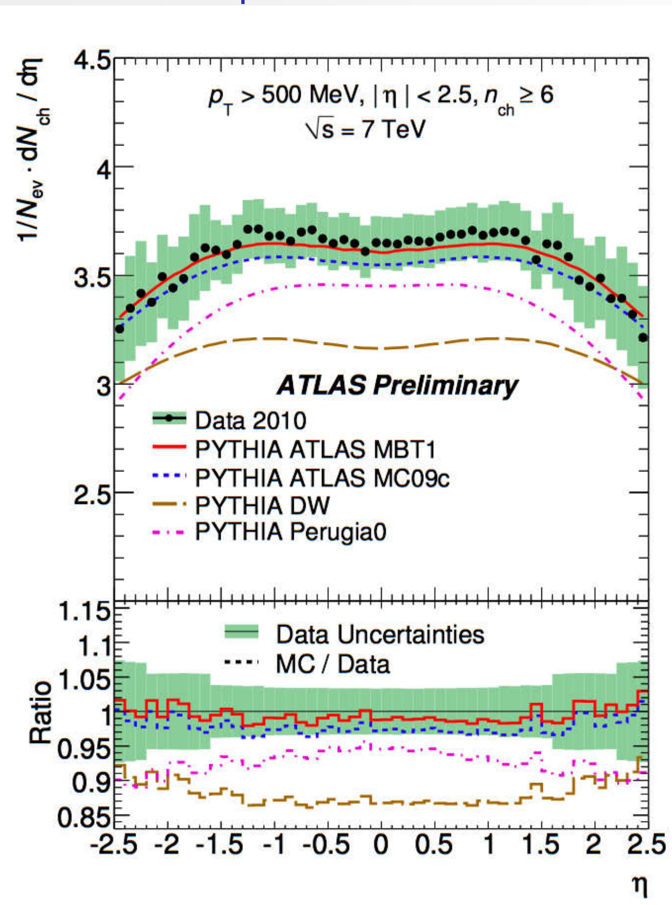
- I will quickly show you some of my attempts (all failures) to fit the LHC "min-bias" data.

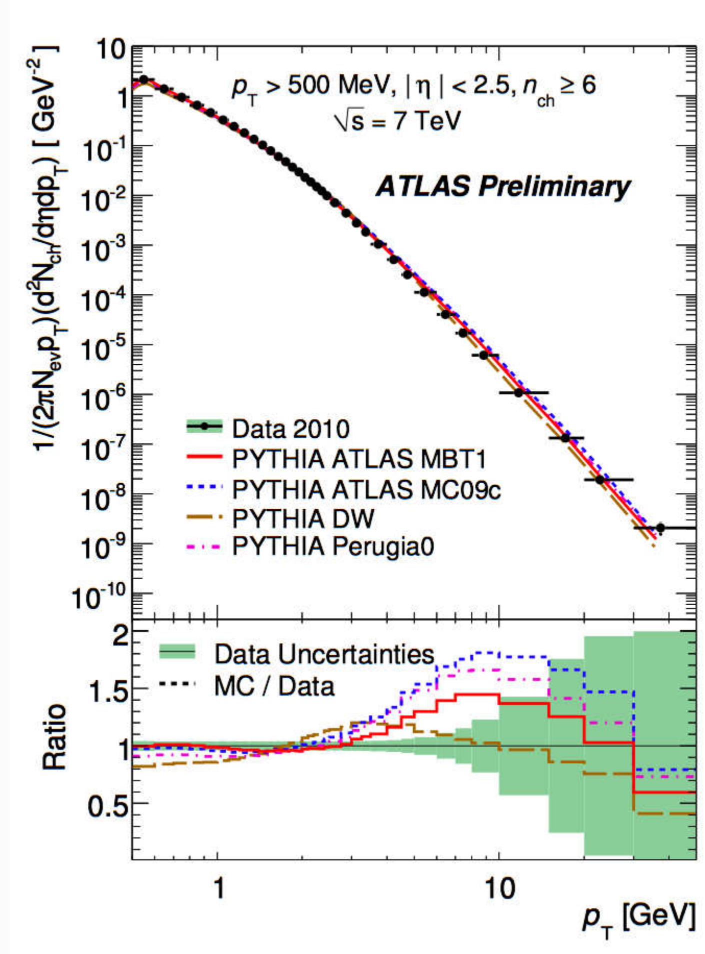


Pythia Tune to ATLAS MinBias and Underlying Event

Used for the tune

ATLAS UE data at 0.9 and 7 TeV
ATLAS charged particle densitites at 0.9 and 7 TeV
CDF Run I underlying event analysis (leading jet)
CDF Run I underlying event "Min-Max" analysis
D0 Run II dijet angular correlations
CDF Run II Min bias
CDF Run I Z pT





Result

This tune describes most of the MinBias and the UE data
Significant improvement compared to pre-LHC tunes
Biggest remaining deviation in $\frac{1}{N_{\mathrm{ev}}} \cdot \frac{1}{2\pi p_{\mathrm{T}}} \cdot \frac{\mathrm{d}^2 N_{\mathrm{ch}}}{\mathrm{d}\eta \mathrm{d}p_{\mathrm{T}}}$
These deviations could not be removed
Needs further investigtions

Diffraction

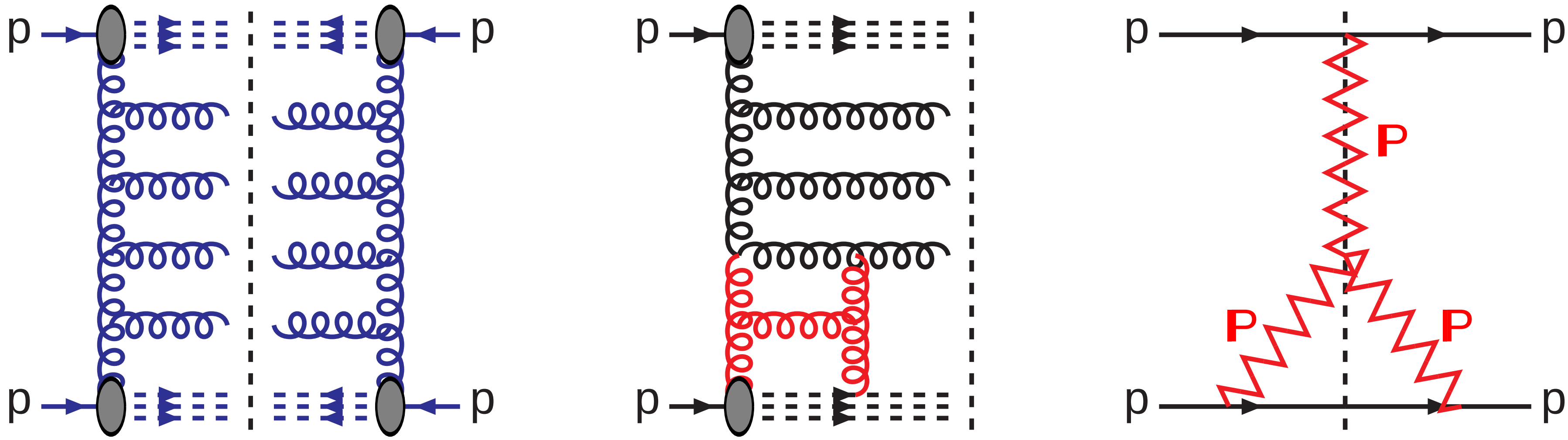
QM: diffraction is shadow of inelastic interactions (disturbed p wavefn).

Predominantly edge phenomenon $\Leftrightarrow$ large impact parameter.

Regge theory: scattering by resonance exchange, predates QCD.

Pomeron: Regge trajectory of states with vacuum quantum numbers.

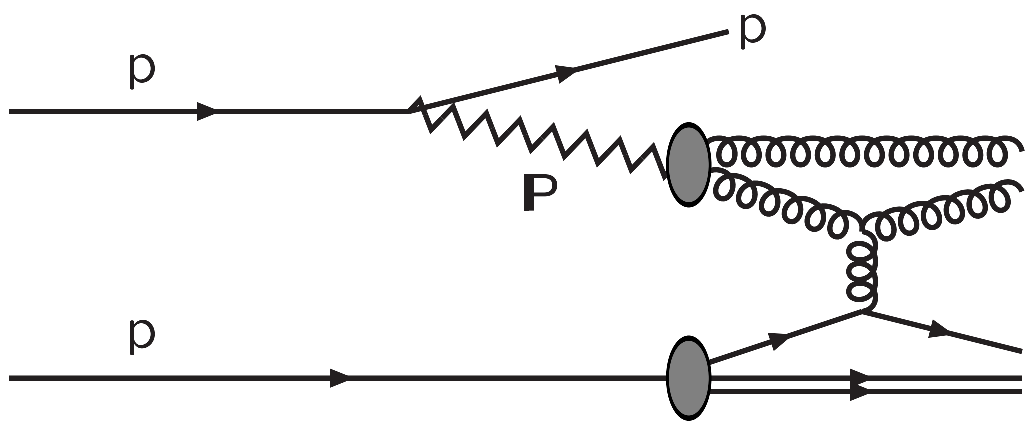
QCD interpretation: glueball state/ladder.



Regge theory predicts/parametrizes rate of diffractive interactions,
but does not tell what diffractive events look like.

(. . . and actually the predicted rate rises too fast $\Rightarrow$ eikonalization . . .)

Ingelman-Schlein (1984): Pomeron as hadron with partonic content
Diffractive event = (Pomeron flux) $\times$ ($\mathbb{P}$p collision)



pp $\to$ pX

Diffractive events can contain high-$p_\perp$ jets:

$$\sigma \sim \int f_{\mathbb{P}/\mathrm{p}}(x_{\mathbb{P}}, t) \int f_{i/\mathbb{P}}(x_i, Q^2) \int f_{j/\mathrm{p}}(x_j, Q^2) \int \mathrm{d}\hat{\sigma}_{ij}$$

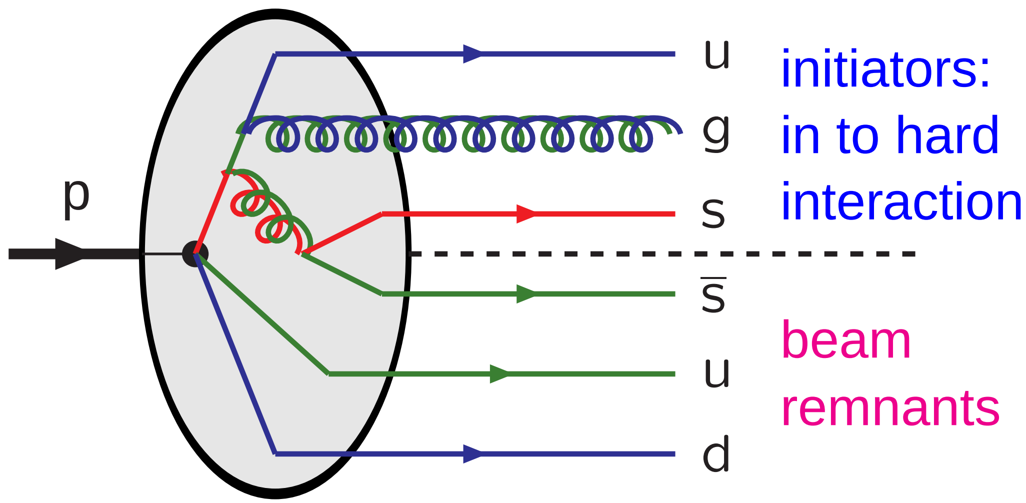
with $M_X^2 = x_{\mathbb{P}} s$ and $\hat{s} = x_i x_j M_X^2$.

$$f_{\mathbb{P}/\mathrm{p}}(x_{\mathbb{P}}, t) \sim \frac{1}{x_{\mathbb{P}}} \quad \Rightarrow \quad \frac{\mathrm{d}\sigma}{\mathrm{d}M_X^2} \sim \frac{1}{M_X^2} \quad \Rightarrow \quad \frac{\mathrm{d}\sigma}{\mathrm{d}y_{\mathrm{gap}}} \sim \mathrm{constant}$$

Many issues, e.g.:

1) imperfect factorization $f_{i/\mathrm{p}}(x_{\mathbb{P}}, t, x_i, Q^2) = f_{\mathbb{P}/\mathrm{p}}(x_{\mathbb{P}}, t)\, f_{i/\mathbb{P}}(x_i, Q^2)$
2) poor knowledge of $f_{\mathbb{P}/\mathrm{p}}(x_{\mathbb{P}}, t)$ and $f_{i/\mathbb{P}}(x_i, Q^2)$
3) parameters of multiple interactions framework
4) multipomeron topologies, . . .

Initiators and Remnants



Need to assign:

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

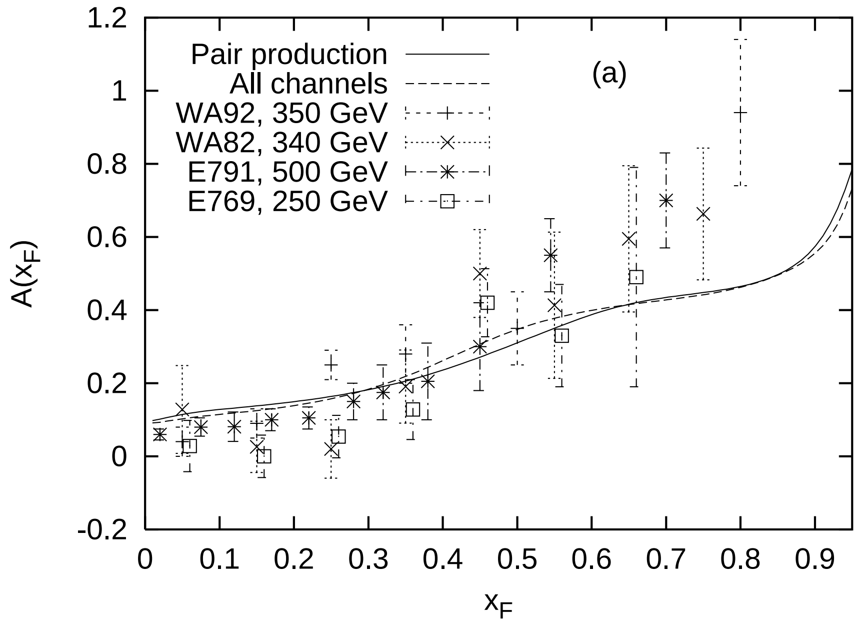
- **PDF after preceding MI/ISR activity:**

0) Squeeze range $0 < x < 1$ into $0 < x < 1 - \sum x_i$ (ISR: $i \neq i_{\text{current}}$)
1) Valence quarks: scale down by number already kicked out
2) Introduce companion quark $\mathrm{q}/\overline{\mathrm{q}}$ to each kicked-out sea quark $\overline{\mathrm{q}}/\mathrm{q}$, with x based on assumed $\mathrm{g} \to \mathrm{q}\overline{\mathrm{q}}$ splitting
3) Gluon and other sea: rescale for total momentum conservation

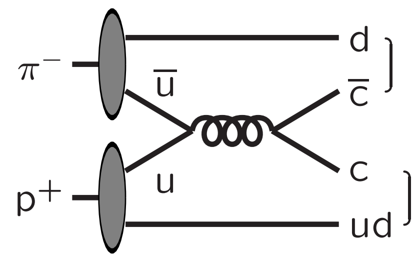
Beam remnant physics

Colour flow connects hard scattering to beam remnants.
Can have consequences, e.g. in $\pi^- p$

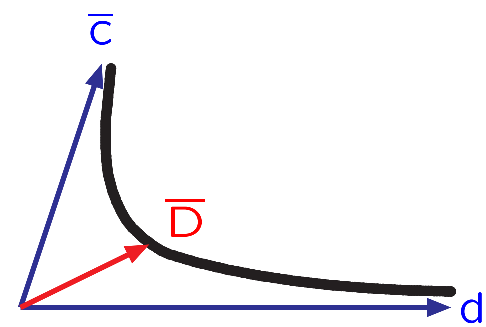
$$A(x_F) = \frac{\#D^- - \#D^+}{\#D^- + \#D^+}$$



(also B asymmetries at LHC, but small)



If low-mass string e.g.:
$\overline{c}d$: D^-, D^{*-}
cud: Λ_c^+, Σ_c^+, Σ_c^{*+}
$\Rightarrow$ flavour asymmetries



Can give D 'drag' to larger x_F than c quark for any string mass

Summary Lecture 4

• Multiple interactions concept compelling; it *has to* exist at some level. •

$\star$ By now, **strong** direct evidence, **overwhelming** indirect evidence $\star$

• Understanding of multiple interactions
crucial for LHC precision physics •

• Many details uncertain •

$\star$ $p_{\perp \mathrm{min}}/p_{\perp 0}$ cut-off $\star$

$\star$ impact parameter picture $\star$

$\star$ energy dependence $\star$

$\star$ multiparton densities in incoming hadron $\star$

$\star$ colour correlations between scatterings $\star$

$\star$ interferences between showers $\star$

$\star \ldots \star$

• Above physics aspects must all be present, and more? •

If a model is simple, it is wrong!

• So stay tuned for even more complicated models in the future. . . . •