ATLAS week
CERN
17 February 2005

LUND UNIVERSITY

New $p_\perp$-ordered Showers
and
Interleaved Multiple Interactions

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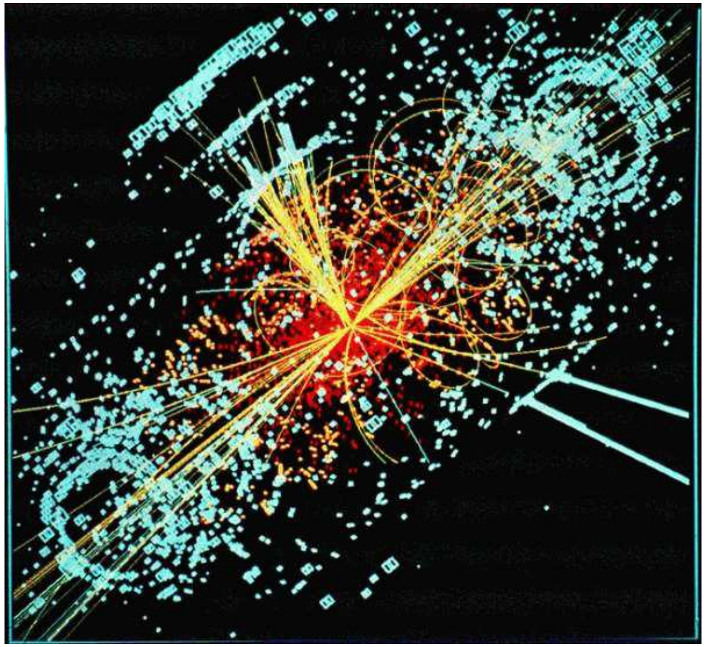
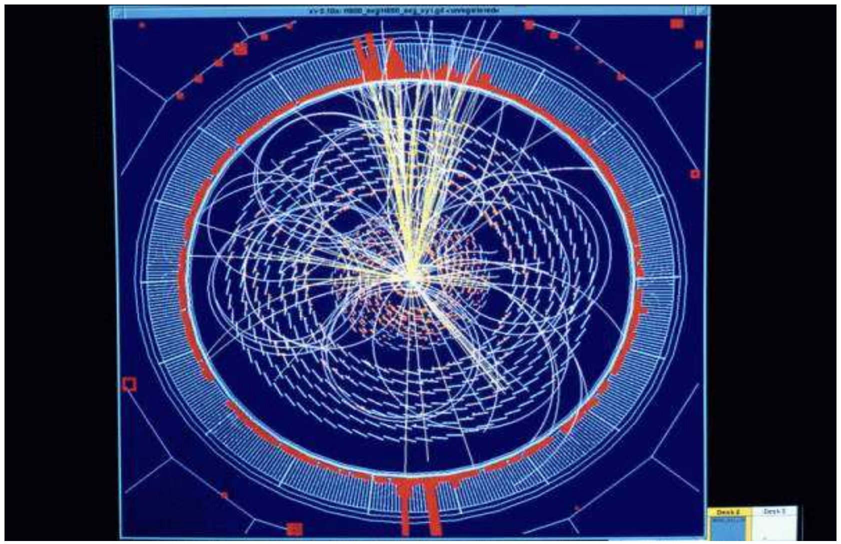
also **JHEP 03 (2004) 053 [hep-ph/0402078]**





The structure of an event

Multiple interactions

The $p_\perp$-based philosophy

$p_\perp$-ordered showers

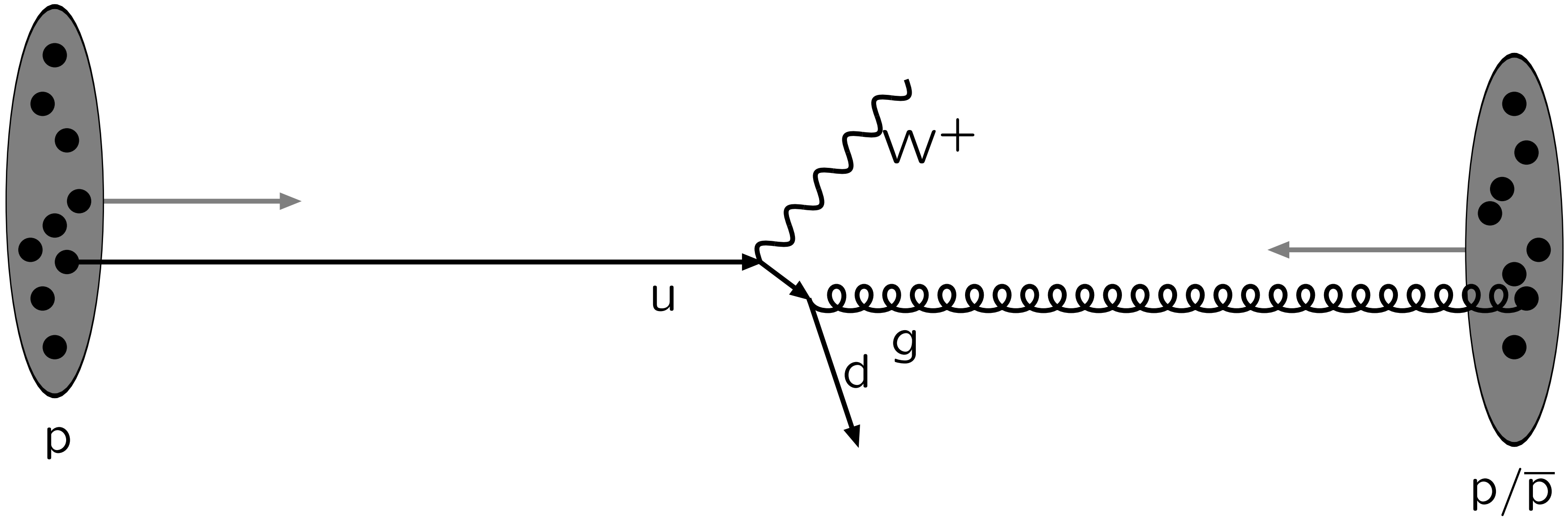
Interleaved interactions

Outlook

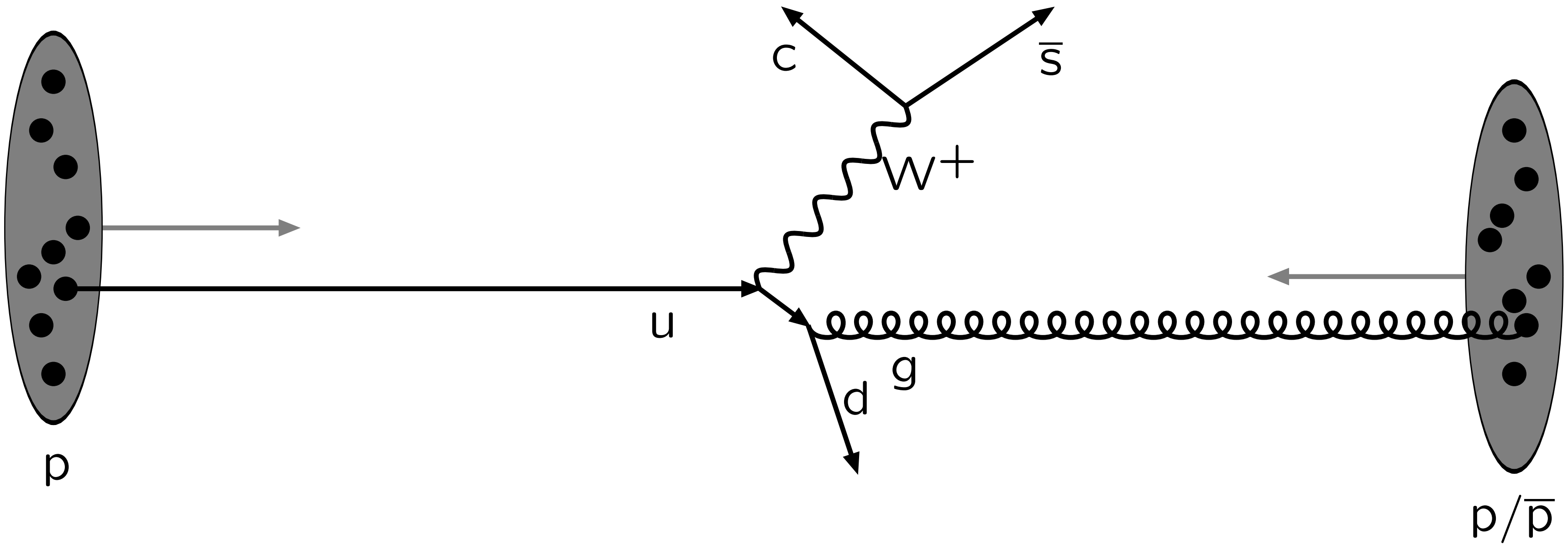
The structure of an event

Warning: schematic only, everything simplified, nothing to scale, . . .

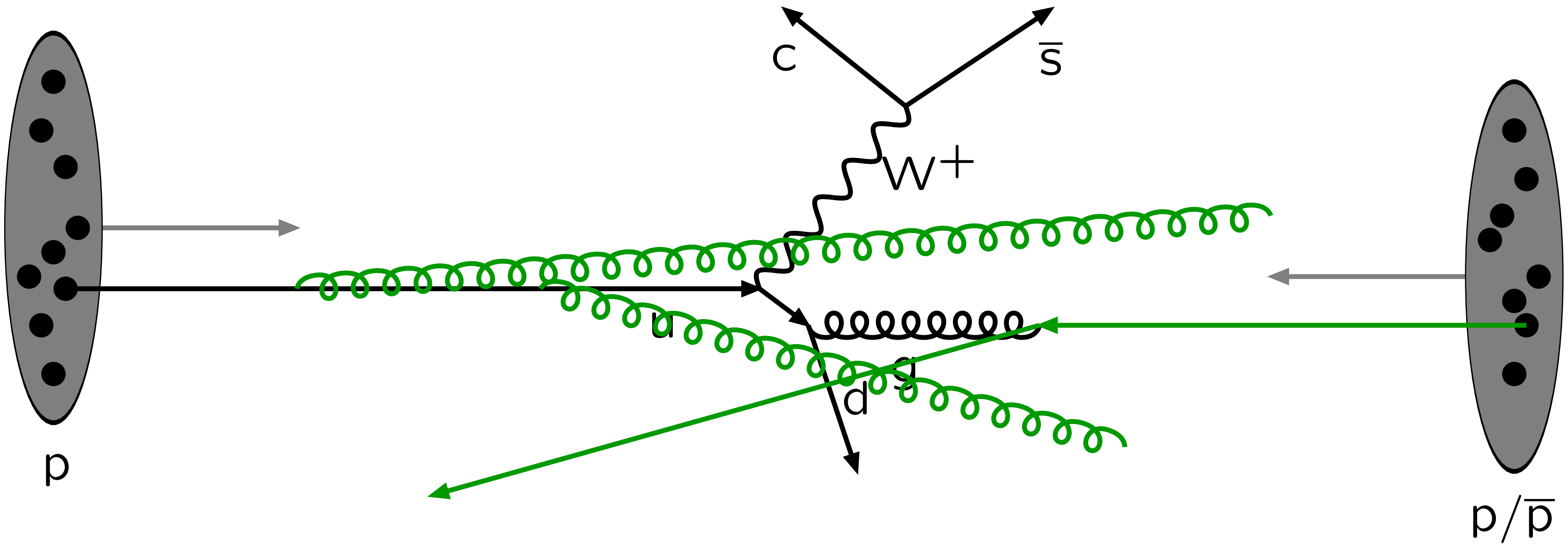
Incoming beams: parton densities



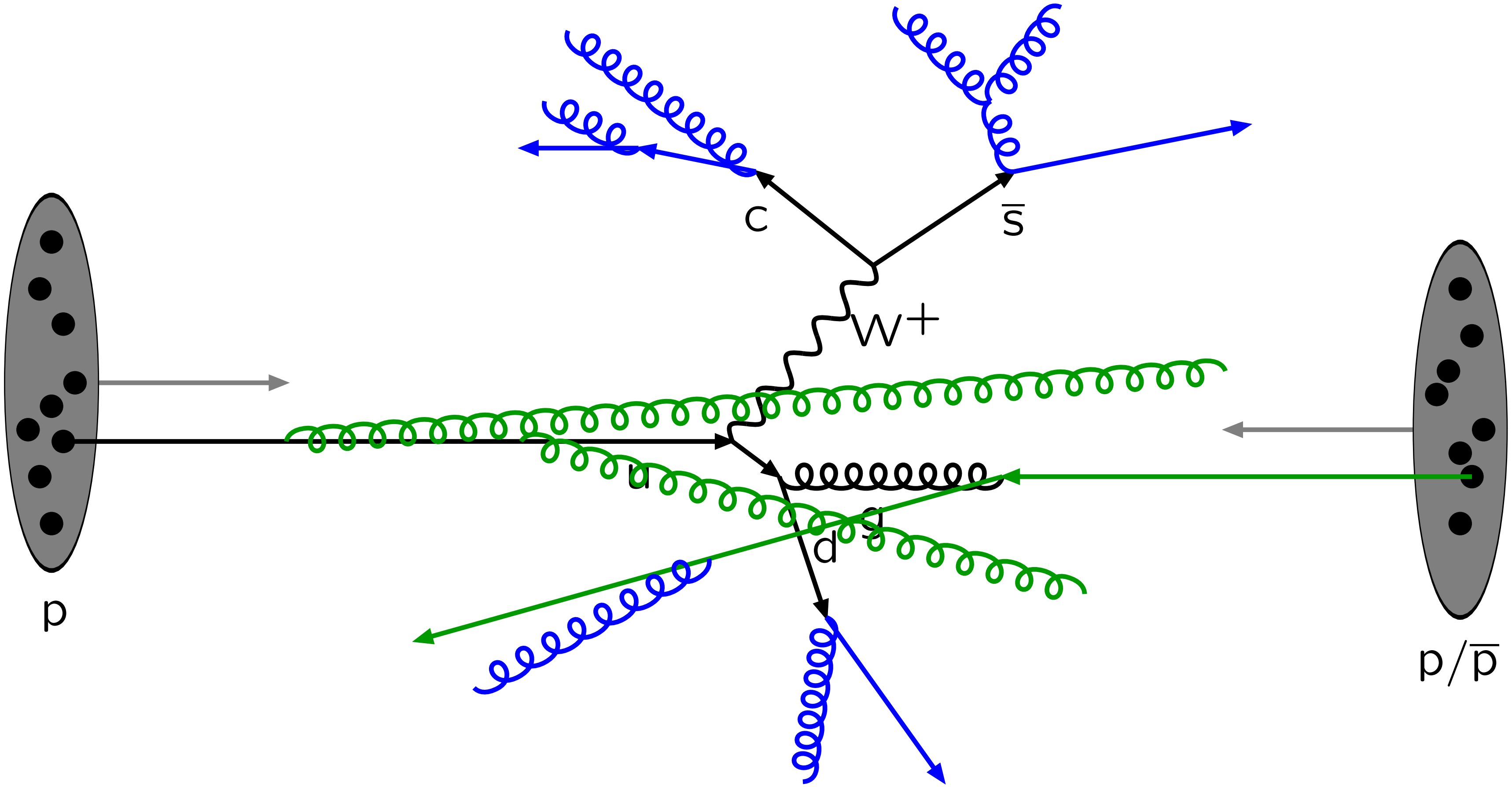
Hard subprocess: described by matrix elements



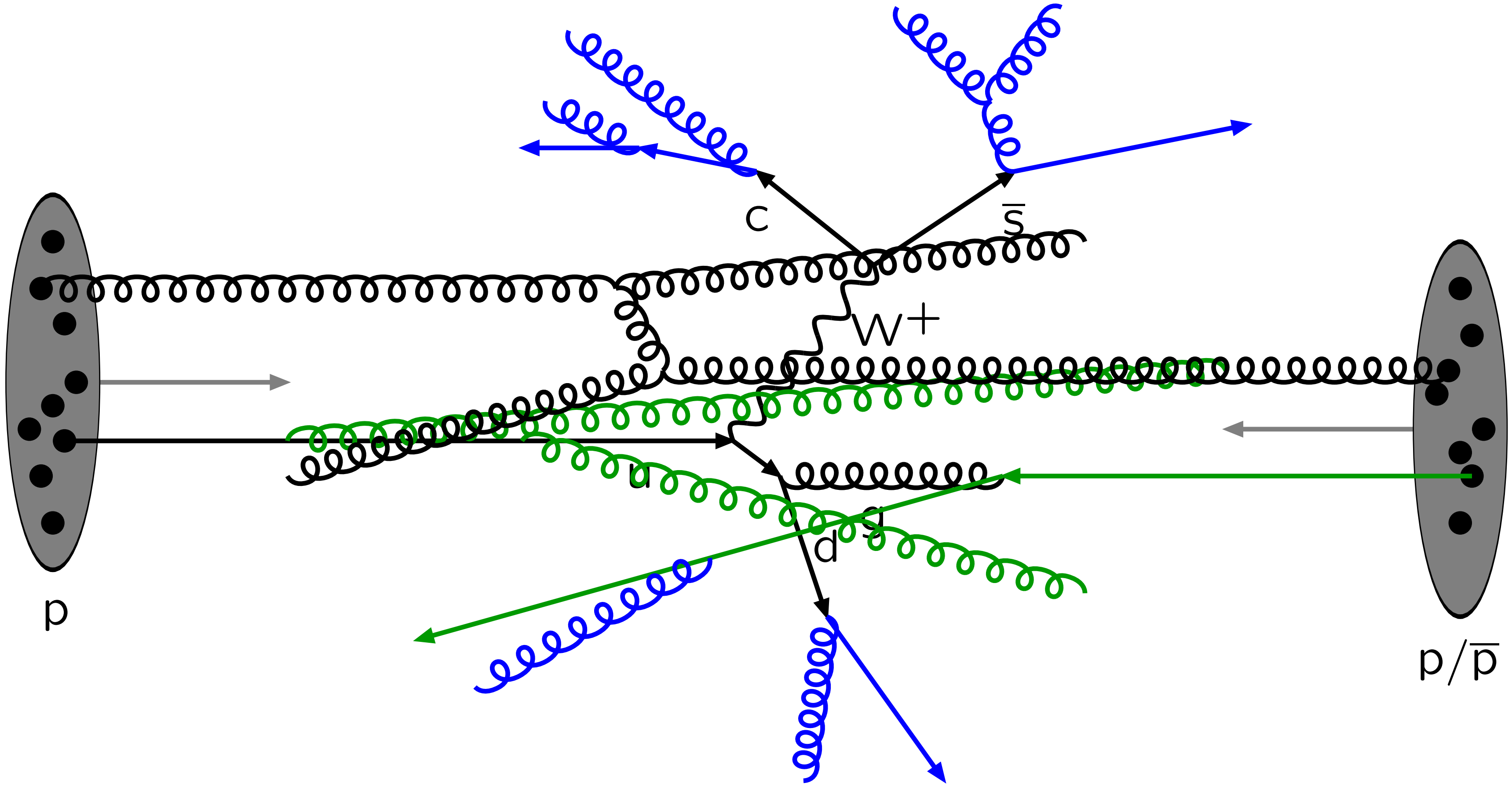
Resonance decays: correlated with hard subprocess



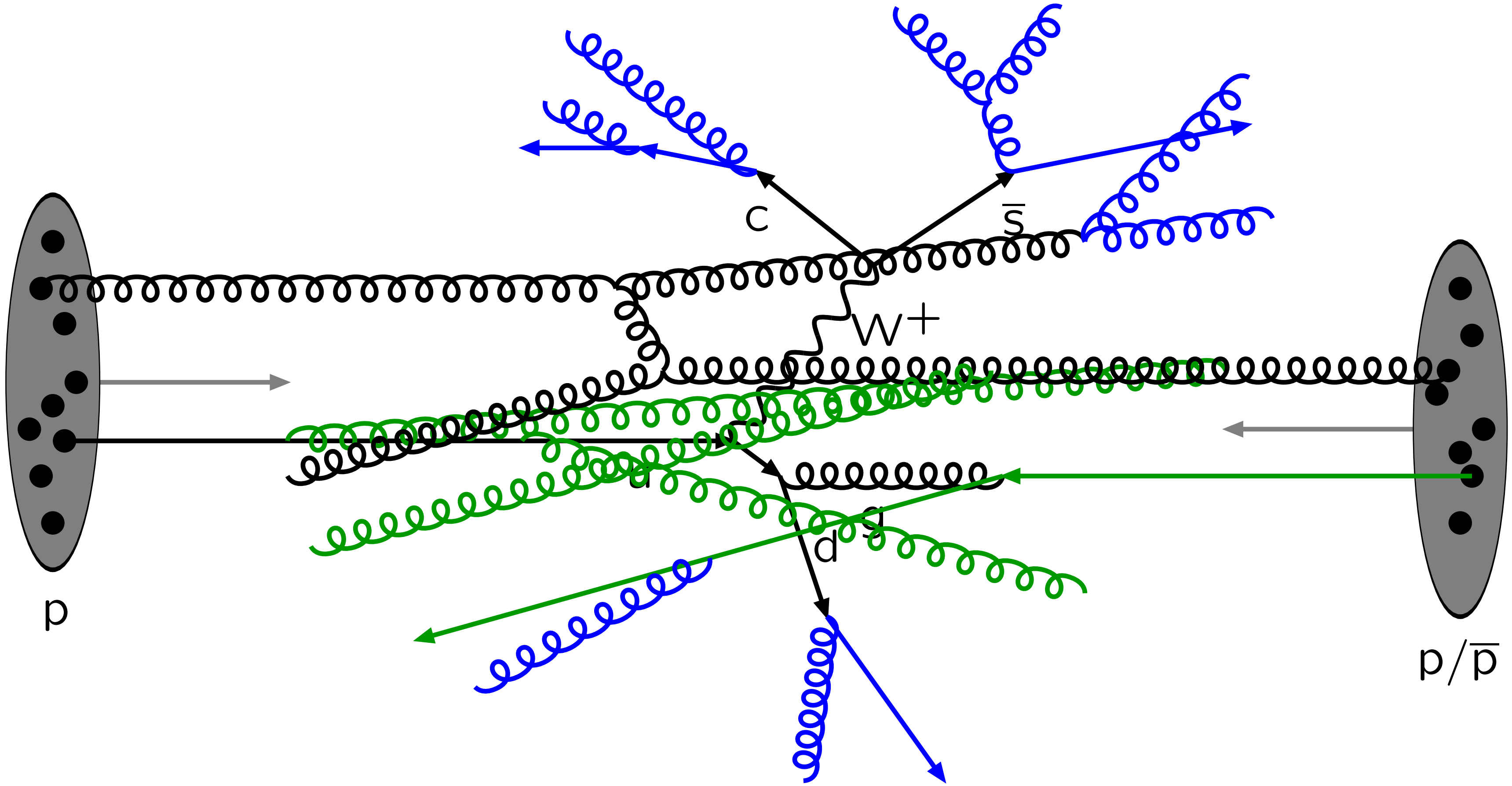
Initial-state radiation: spacelike parton showers



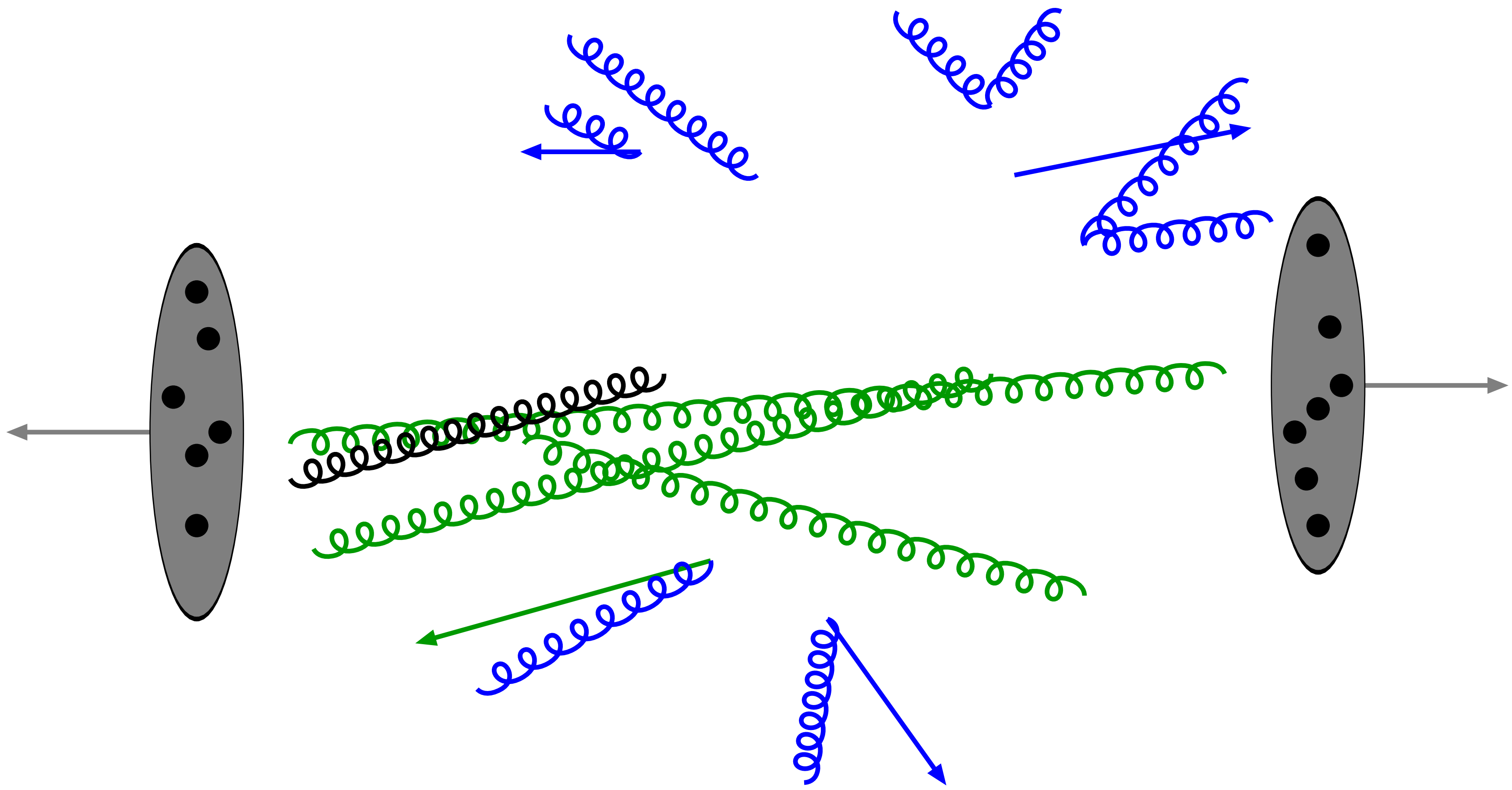
Final-state radiation: timelike parton showers



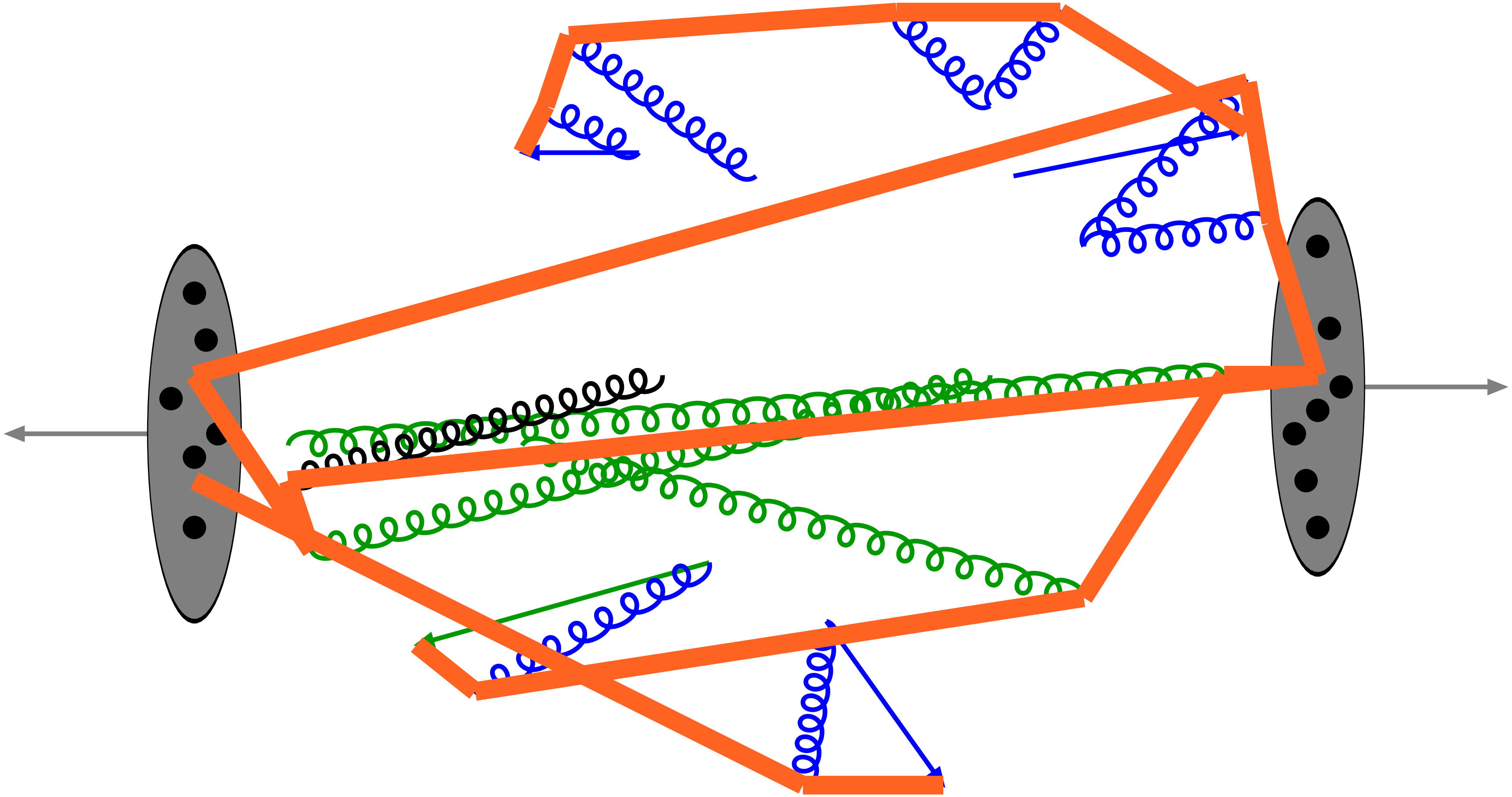
Multiple parton–parton interactions . . .



...with its initial- and final-state radiation

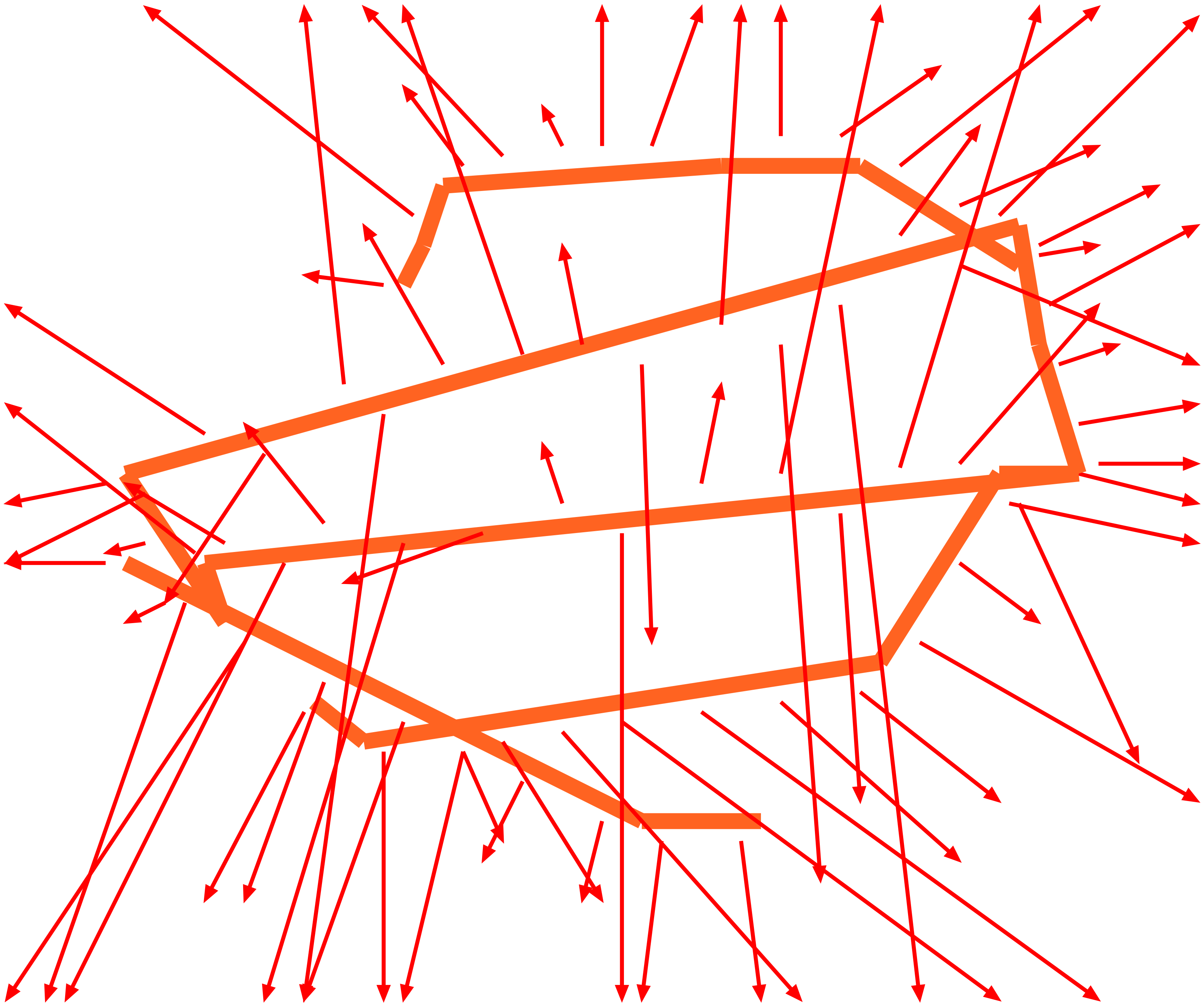


Beam remnants and other outgoing partons

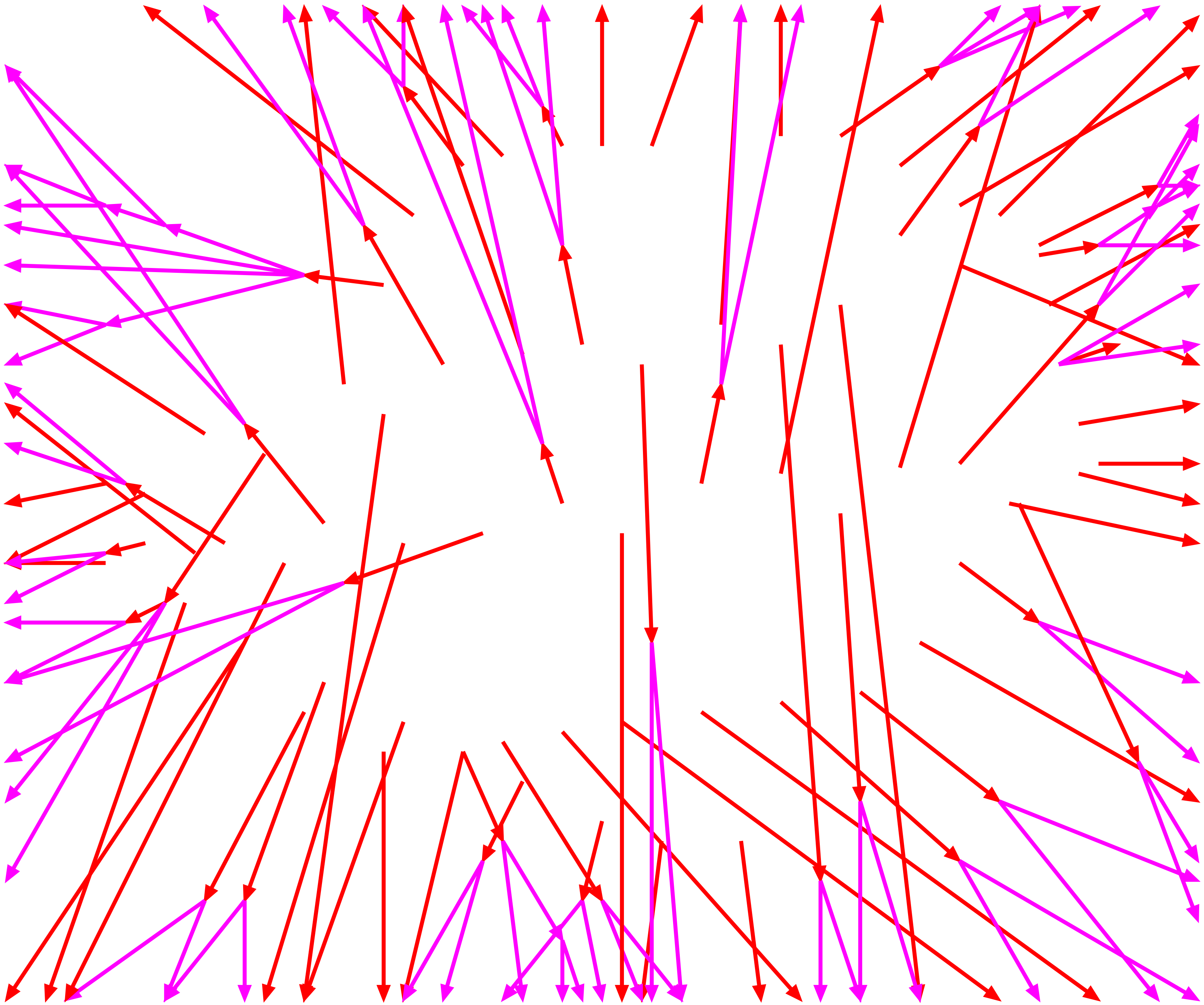


Everything is connected by colour confinement strings

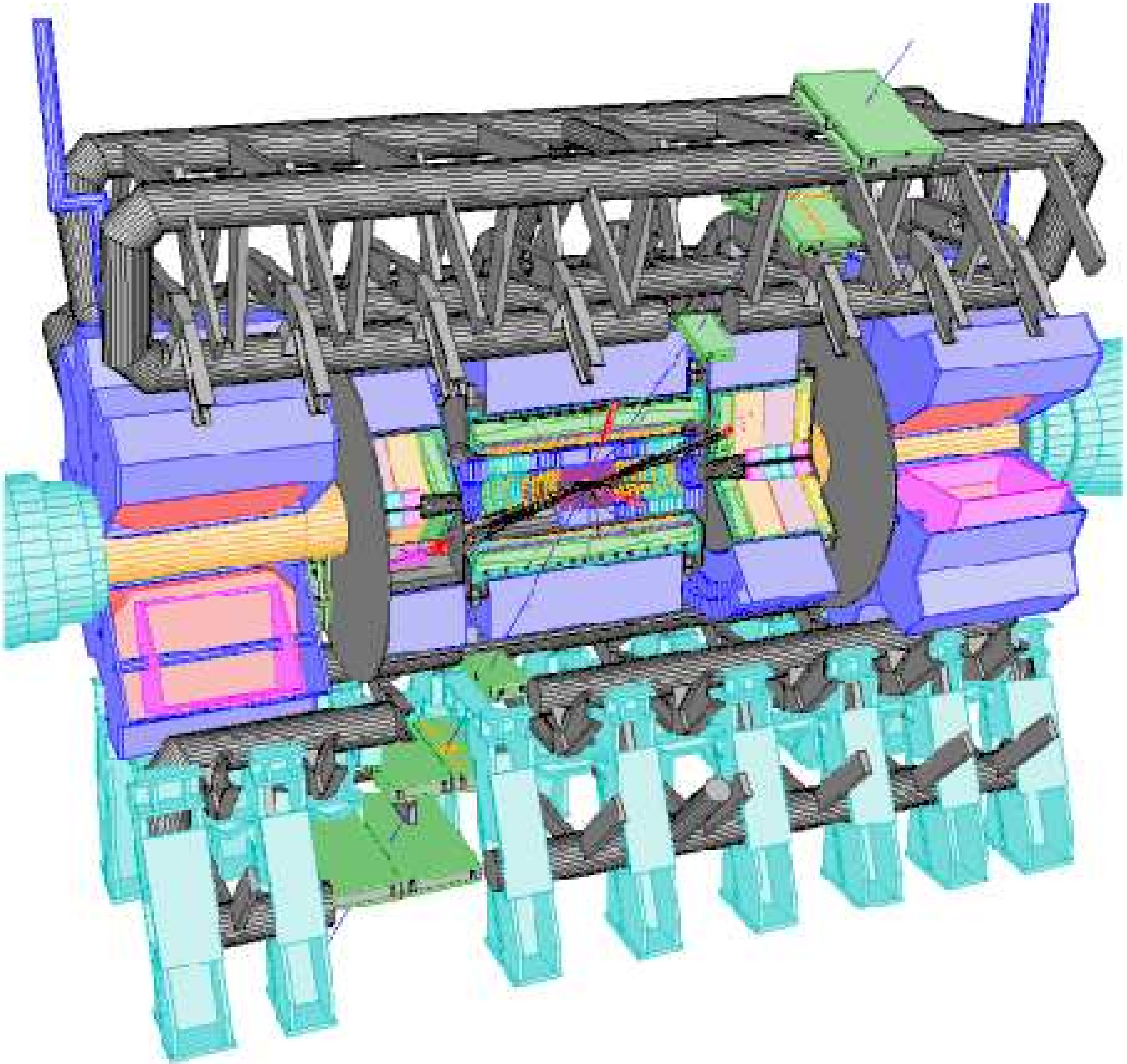
Recall! Not to scale: strings are of hadronic widths



The strings fragment to produce primary hadrons



Many hadrons are unstable and decay further



These are the particles that hit the detector

LHC events are messy! Why care to understand?

Parton showers and multiple interactions contain many interesting and unsolved QCD issues in their own right.

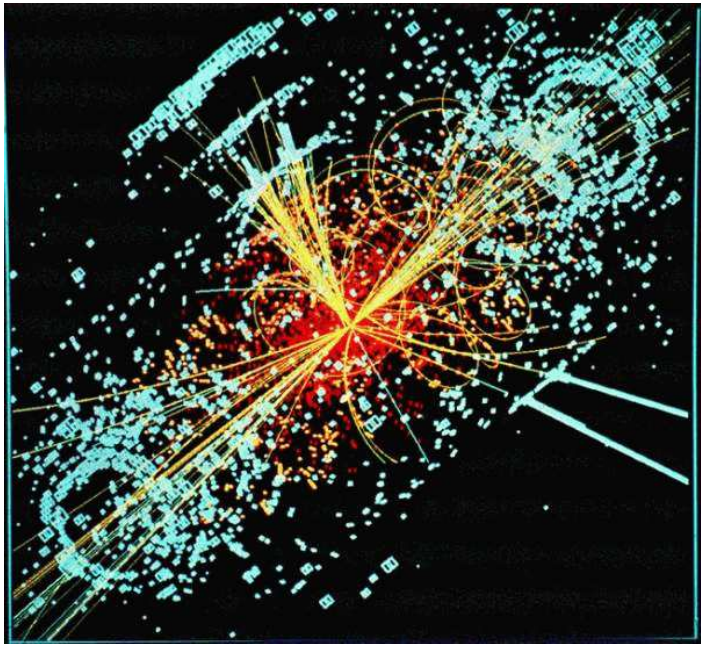
They are also needed to understand signals of and backgrounds to other physics, if these invove jets (= hadrons, photons) or could be affected by the underlying event.

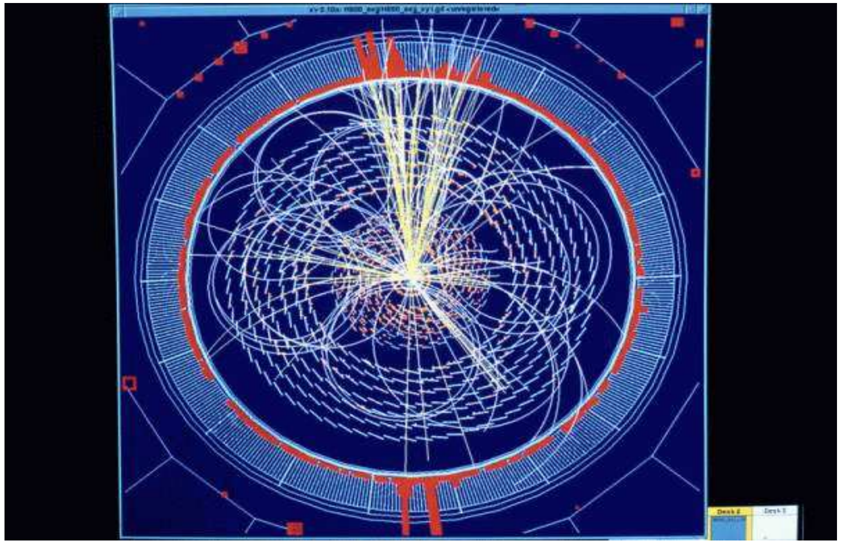
Parton showers are responsible for:

- creation of multijet topologies
- broadening of jet profiles
- shifts in jet energy scale
- nontrival $p_\perp$ correlations
- (non-)isolation of ℓ, γ

Multiple interactions are responsible for:

- large fraction of total multiplicity
- fluctuations to large multiplicities
- rapidity correlations in activity
- multiple (mini)jet production
- jet profile and jet pedestal
- shifts in jet energy scale
- (non-)isolation of ℓ, γ





The structure of an event

Multiple interactions

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$p_\perp$-ordered showers

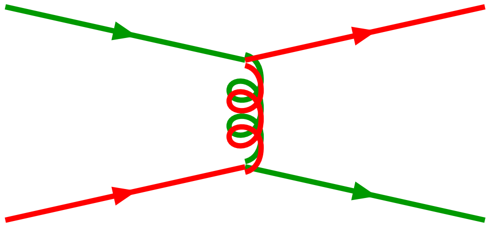
Interleaved interactions

Outlook

What is multiple interactions?

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

integrate QCD $2 \to 2$



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

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

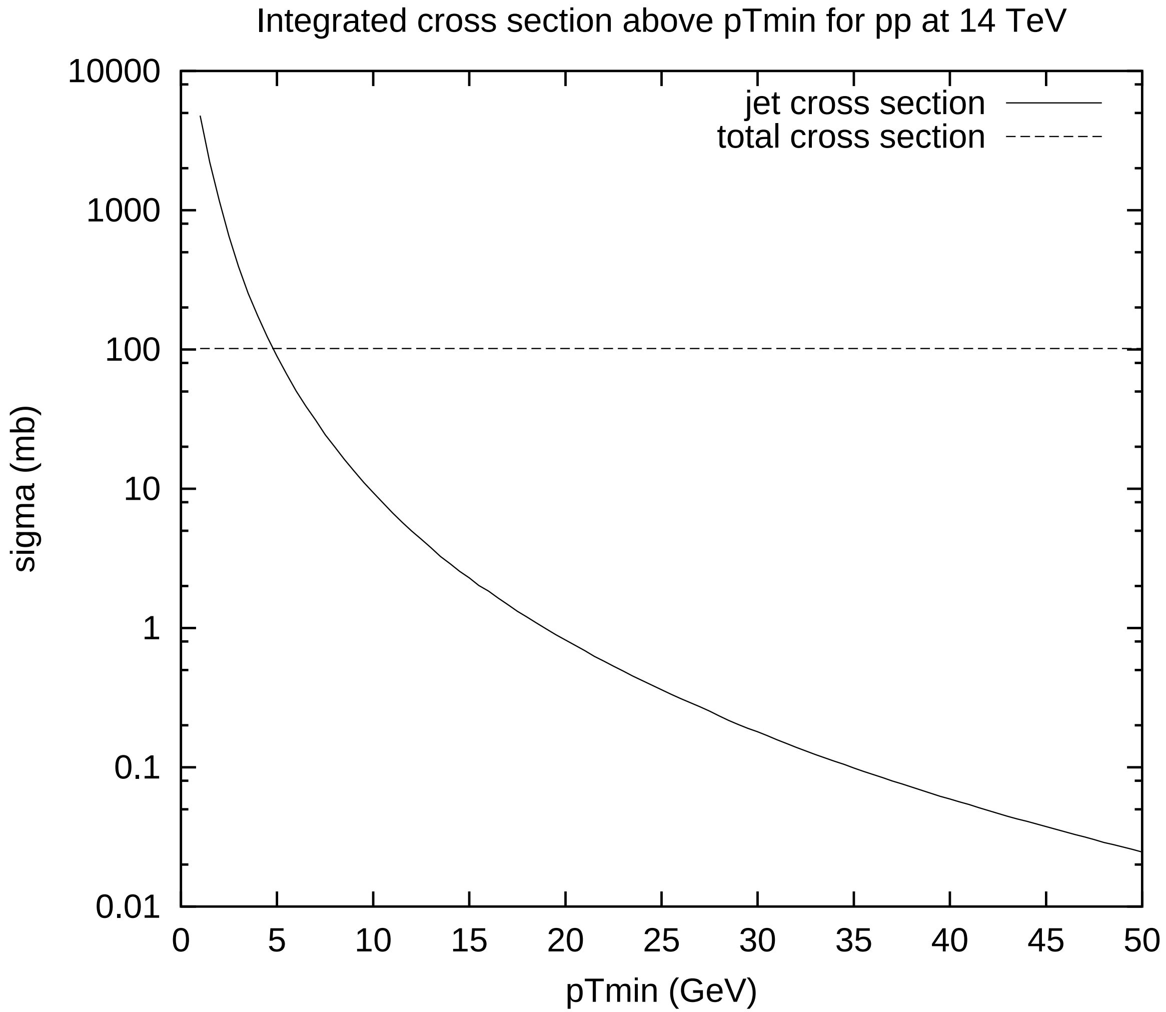
$\mathrm{q\overline{q}} \to \mathrm{gg}$

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

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

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

with CTEQ 5L PDF's



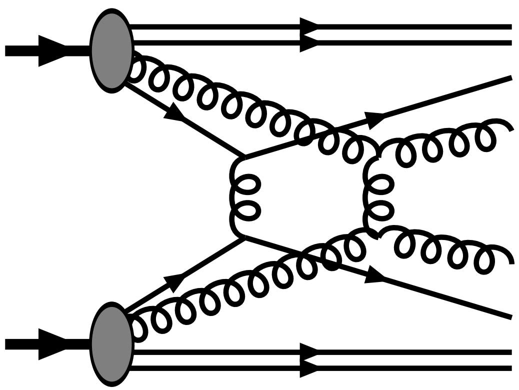
So $\sigma_{\mathrm{int}}(p_{\perp\mathrm{min}}) > \sigma_{\mathrm{tot}}$ for $p_{\perp\mathrm{min}} \lesssim 5$ GeV

Half a solution: many interactions per event

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

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

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



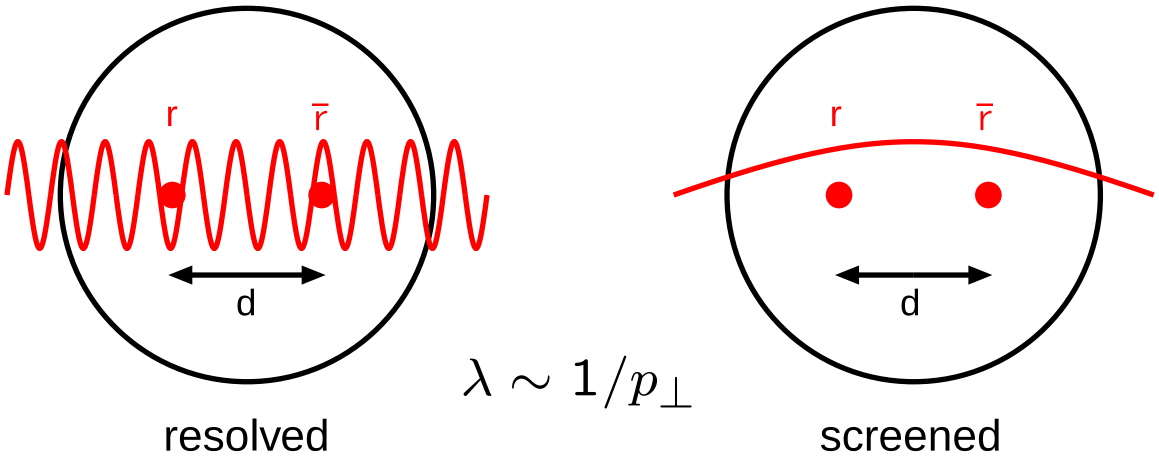
Other half of solution:

perturbative QCD not valid at small $p_{\perp}$ since q, g not asymptotic states.

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

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

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

where $p_{\perp\min}$ or $p_{\perp 0}$ are free parameters, empirically of order **2 GeV**

Typically 2 – 3 interactions/event at the Tevatron, 4 – 5 at the LHC, but may be more in “interesting” high-$p_\perp$ ones.

Modelling multiple interactions

T. Sjöstrand, M. van Zijl, PRD36 (1987) 2019: first model(s) for event properties based on perturbative multiple interactions

(1) Simple scenario:

- Sharp cut-off at $p_{\perp\mathrm{min}}$ main free parameter
- Is only a model for nondiffractive events, i.e. for $\sigma_{\mathrm{nd}} \simeq (2/3)\sigma_{\mathrm{tot}}$
- Average number of interactions is $\langle n \rangle = \sigma_{\mathrm{int}}(p_{\perp\mathrm{min}})/\sigma_{\mathrm{nd}}$
- Interactions occur independently

$$\Rightarrow \text{ Poissonian statistics } \mathcal{P}_n = \langle n \rangle^n e^{-\langle n \rangle}/n!$$

with fraction $\mathcal{P}_0 = e^{-\langle n \rangle}$ pure low-$p_\perp$ events

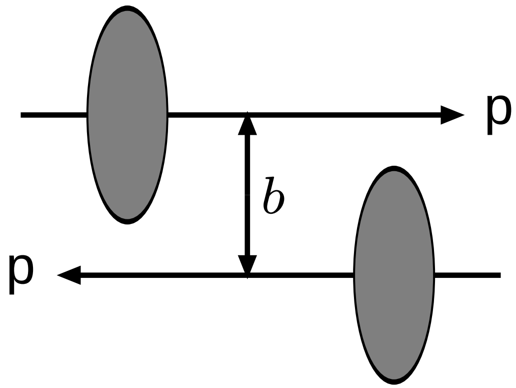
- Interactions generated in ordered sequence $p_{\perp 1} > p_{\perp 2} > p_{\perp 3} > \ldots$ by "Sudakov" trick

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

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

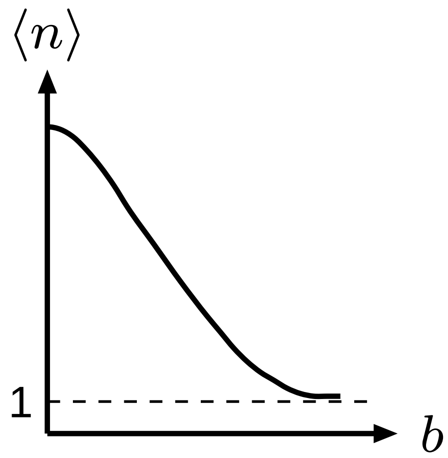
(2) More sophisticated scenario:

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



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

where $r_2/r_1 \neq 1$ represents "hot spots"



- Events are distributed in impact parameter b
- Central collisions normally are more active
  $\Rightarrow \mathcal{P}_n$ broader than Poissonian
- More time-consuming $(b, p_\perp)$ generation
- Need for simplifications remains

(3) HERWIG $\rightarrow$ Jimmy

- similar to (2) above; but details different
- no $p_\perp$-ordering of emissions, no rescaling of PDF:
  abrupt stop when (if) run out of energy

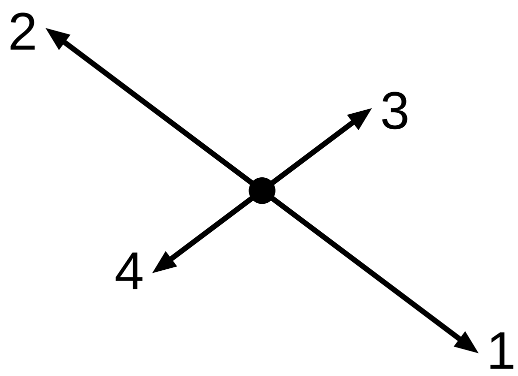
Evidence for multiple interactions

- Width of multiplicity distribution: UA5, E735
- Forward–backward correlations: UA5
- Minijet rates: UA1

- Direct observation: AFS, (UA2,) CDF

Order 4 jets $\mathbf{p}_{\perp 1} > \mathbf{p}_{\perp 2} > \mathbf{p}_{\perp 3} > \mathbf{p}_{\perp 4}$ and define φ as angle between $\mathbf{p}_{\perp 1} - \mathbf{p}_{\perp 2}$ and $\mathbf{p}_{\perp 3} - \mathbf{p}_{\perp 4}$

Double Parton Scattering

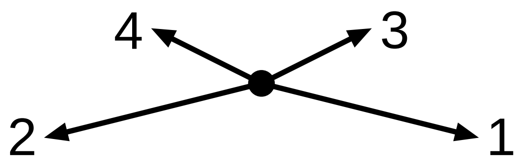


$|\mathbf{p}_{\perp 1} + \mathbf{p}_{\perp 2}| \approx 0$

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

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

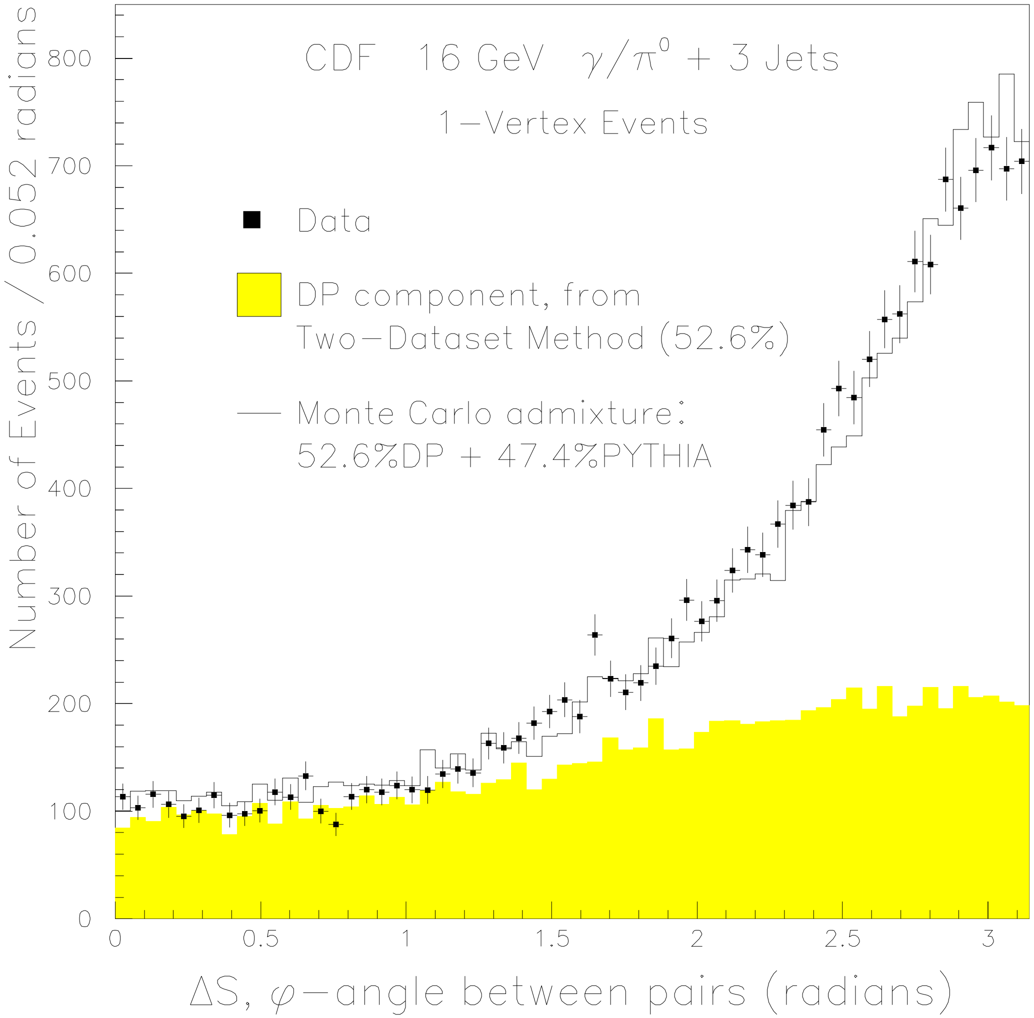
Double BremsStrahlung



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

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

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



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: UA1, H1, CDF

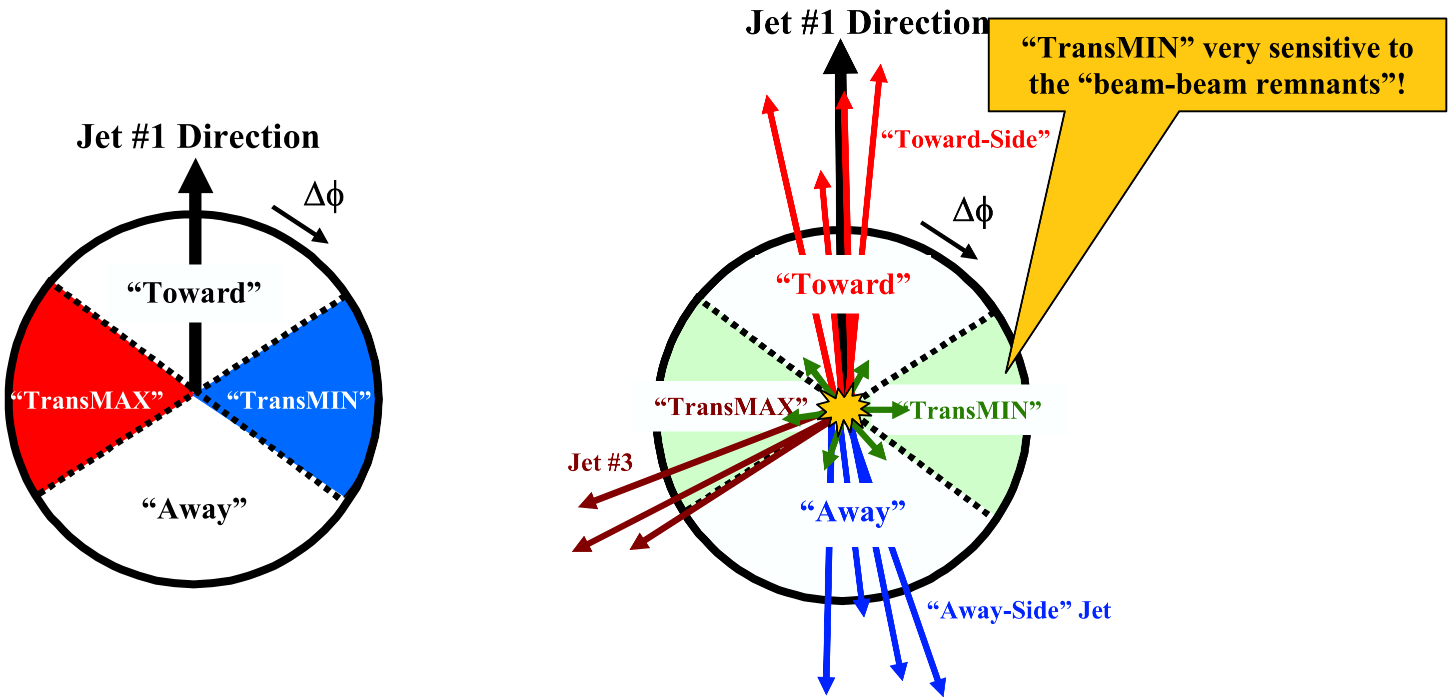
Events with hard scale (jet, W/Z, . . .) have more underlying activity!

Events with n interactions have n chances that one of them is hard, so "trigger bias": hard scale $\Rightarrow$ central collision $\Rightarrow$ more interactions $\Rightarrow$ larger underlying activity.

Centrality effect saturates at $p_{\perp \mathrm{hard}} \sim 10$ GeV.

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

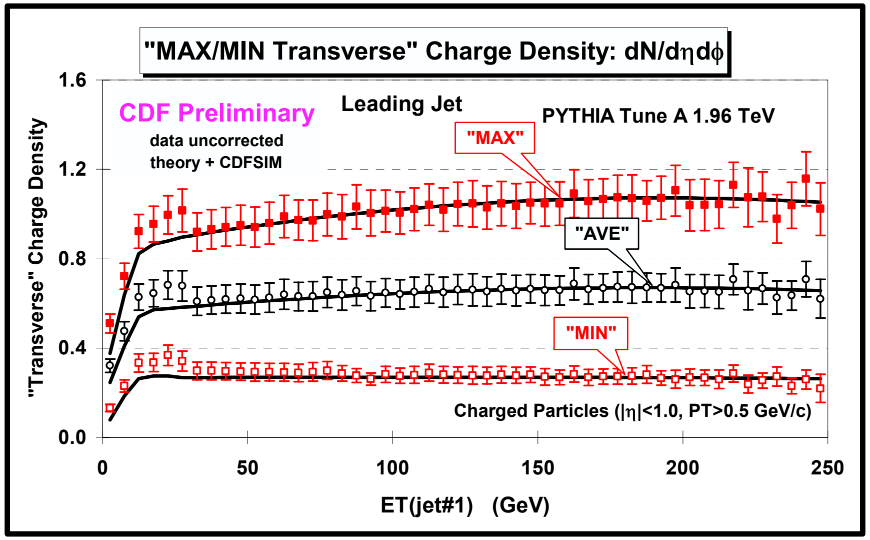
"MAX/MIN Transverse" Densities

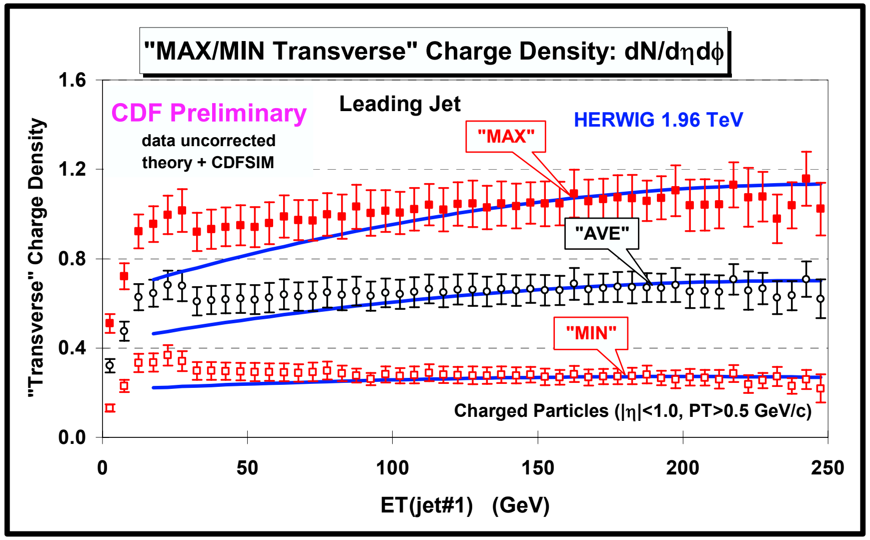


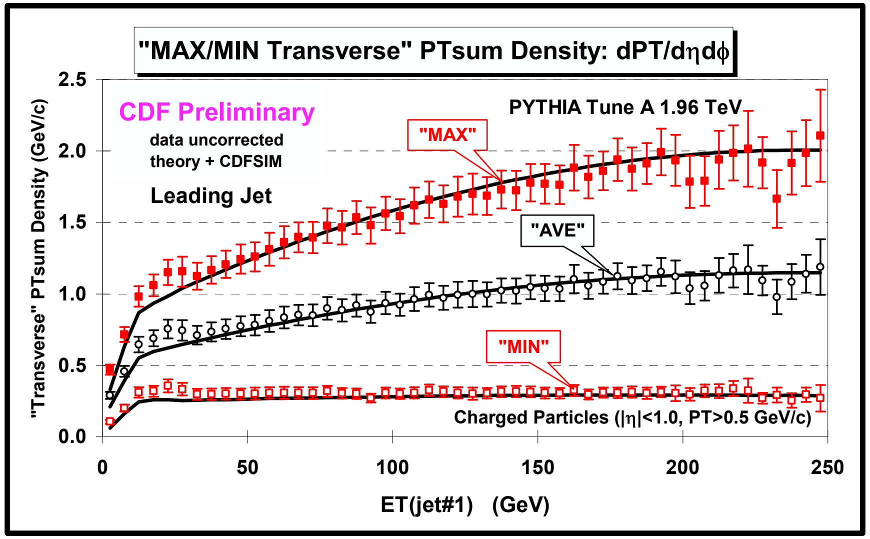
- **Define the MAX and MIN "transverse" regions on an event-by-event basis with MAX (MIN) having the largest (smallest) density.**

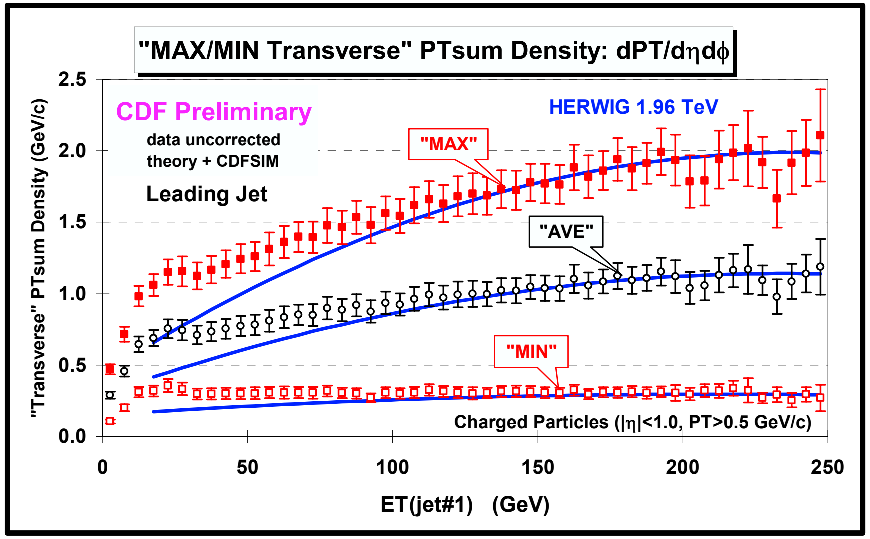
Leading Jet: "MAX & MIN Transverse" Densities

PYTHIA Tune A HERWIG



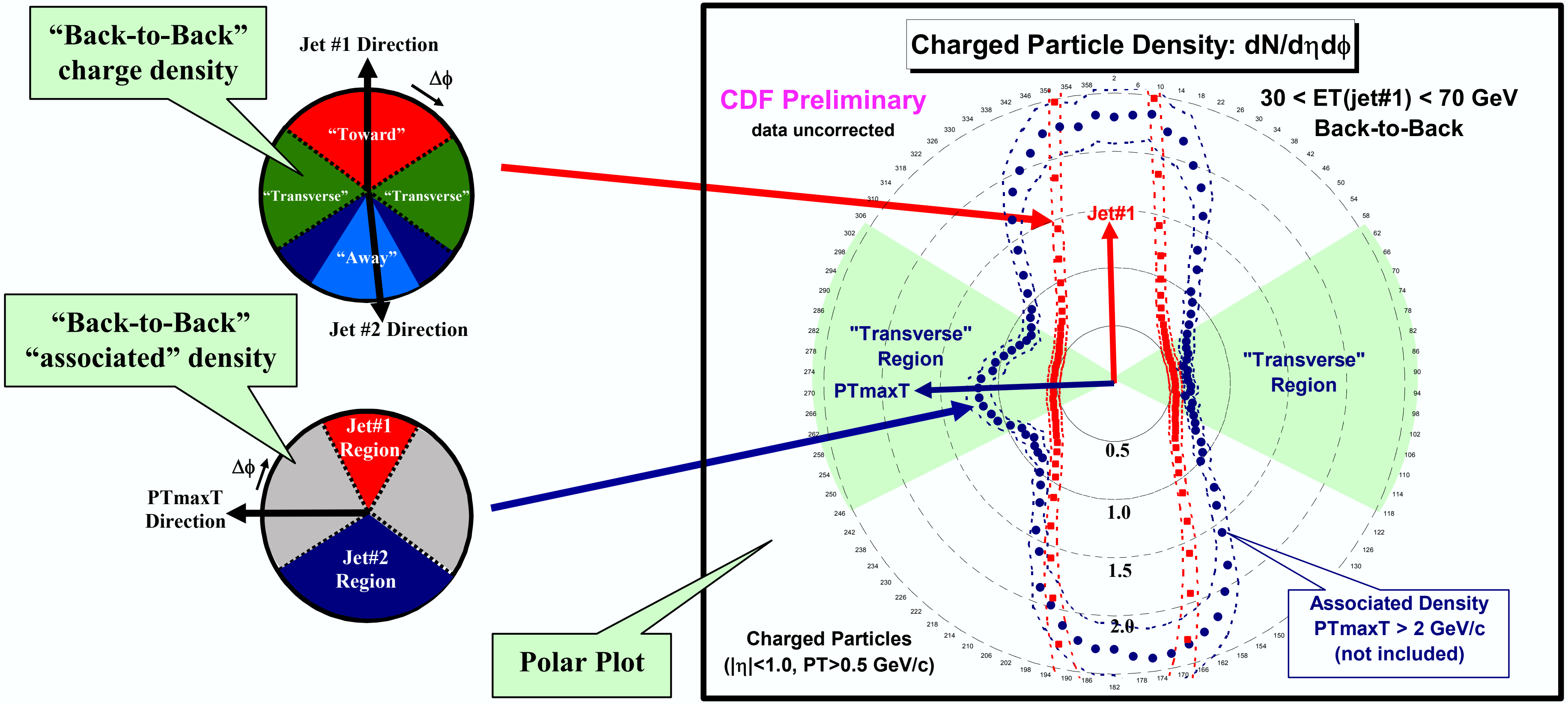






Charged particle density and PTsum density for "leading jet" events versus E_T(jet#1) for PYTHIA Tune A and HERWIG.

Back-to-Back "Associated" Charged Particle Densities

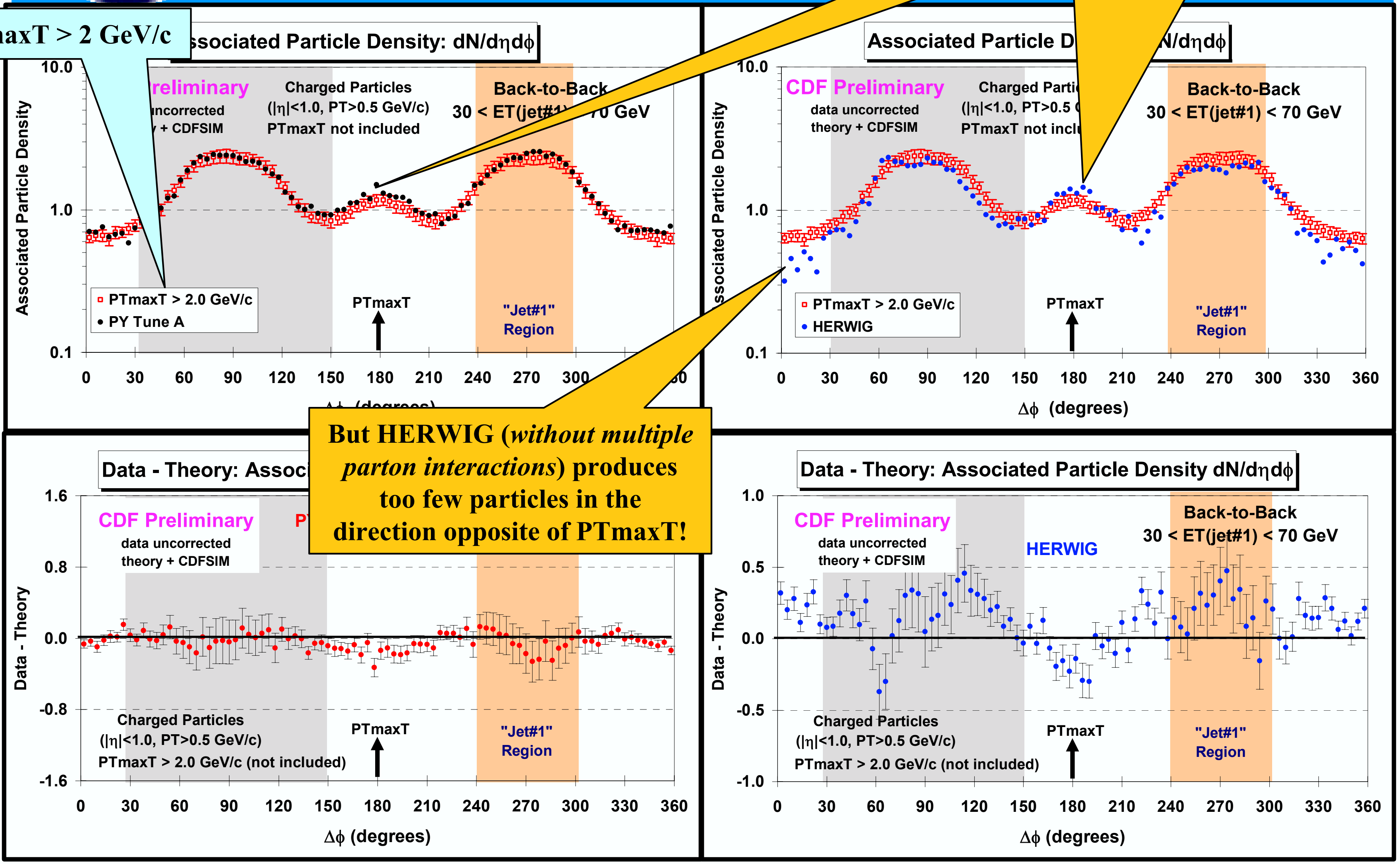


- Shows the Δϕ dependence of the "associated" charged particle density, dNchg/dηdϕ, $p_T > 0.5$ GeV/c, $|\eta| < 1$, PTmaxT > 2.0 GeV/c (*not including PTmaxT*) relative to PTmaxT (rotated to 180°) and the charged particle density, dNchg/dηdϕ, $p_T > 0.5$ GeV/c, $|\eta| < 1$, relative to jet#1 (rotated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

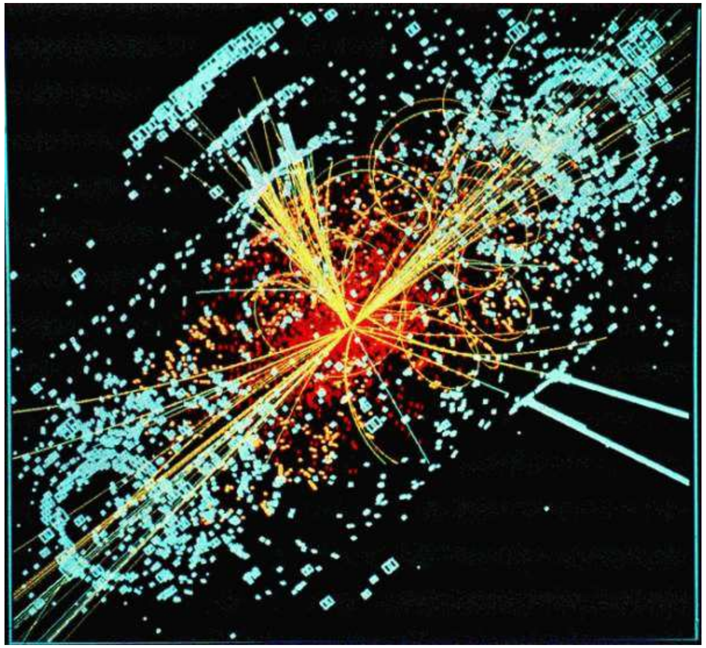
“Associated” Charge De
PYTHIA Tune A vs HEF

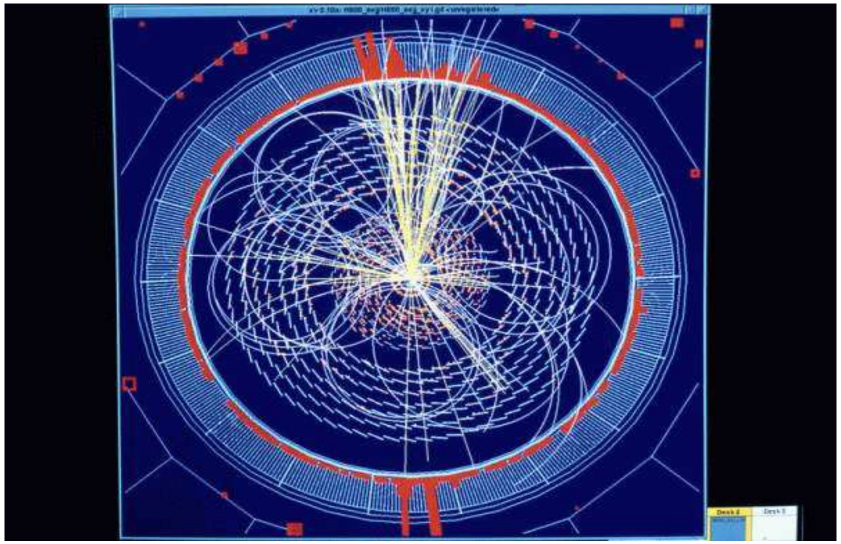
For PTmaxT > 2.0 GeV both PYTHIA and HERWIG produce slightly too many “associated” particles in the direction of PTmaxT!

PTmaxT > 2 GeV/c



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





The structure of an event

Multiple interactions

Backup

multiple interactions

The $p_\perp$-based philosophy

$p_\perp$-ordered showers

Interleaved interactions

Outlook

Further evidence for multiple interactions

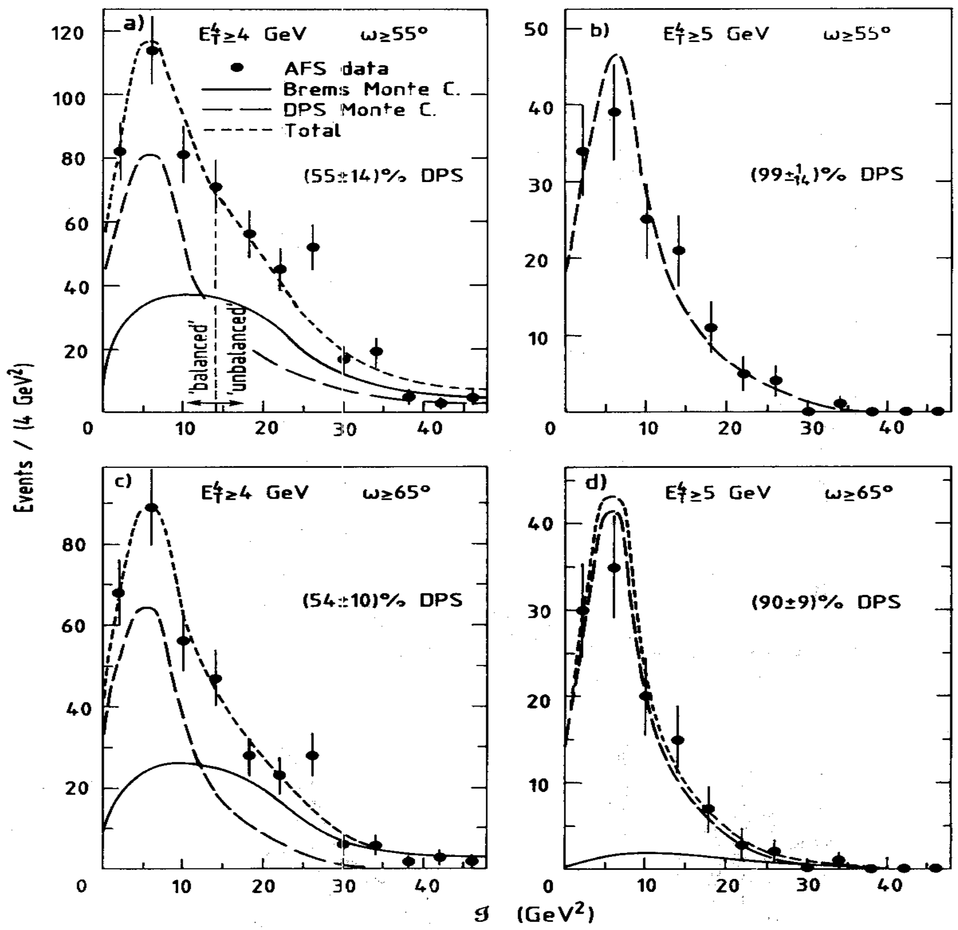


Fig. 3

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

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

UA1 minijet rates

No. jets	UA1 (%)	no MI	simple	double Gaussian
1	9.96	14.30	11.51	8.88
2	3.45	2.45	2.45	2.67
3	1.12	0.22	0.32	0.74
4	0.22	0.01	0.04	0.25
5	0.05	0.00	0.00	0.07

UA2 4-jet analysis (at 630 GeV):

with ansatz $\sigma_{\mathrm{DPS}} = \frac{1}{2}\frac{\sigma_{\mathrm{2jet}}^2}{\sigma_{\mathrm{eff}}}$

limit $\sigma_{\mathrm{eff}} > 8.3$ mb at 95% CL

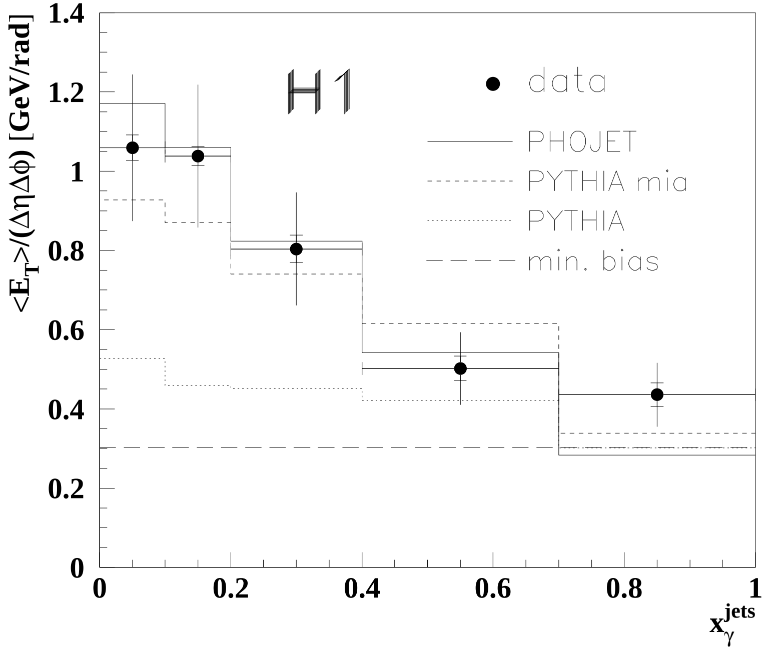
i.e. $\sigma_{\mathrm{DPS}} < 4.5$ in 'AFS units'

$\ldots$but best value 2.5 ± 1

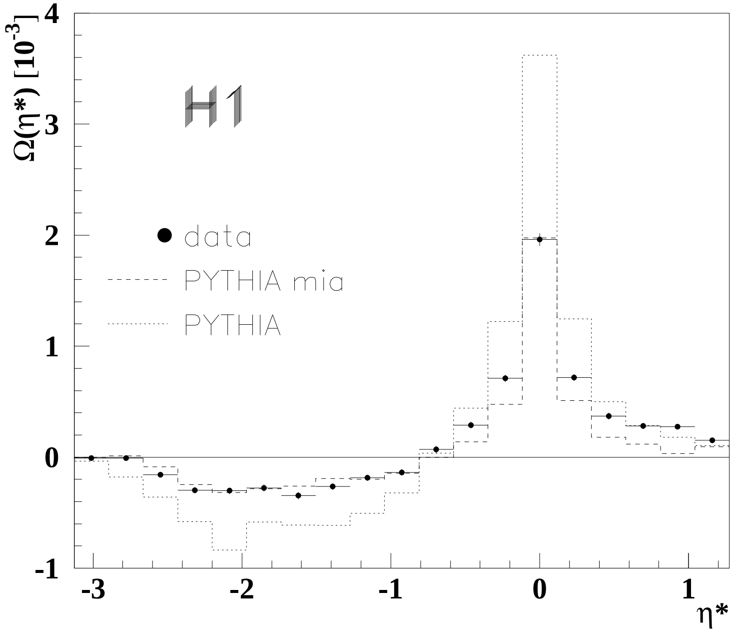
CDF 4-jet analysis (at 1800 GeV):

$$\sigma_{\rm eff} = 12.1^{+10.7}_{-5.4} \text{ mb}$$

H1 event properties:

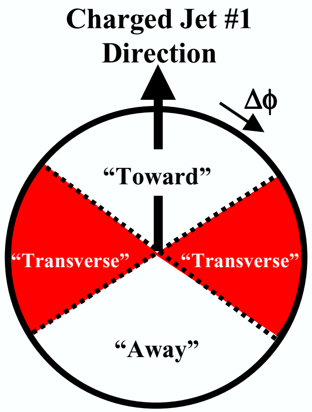


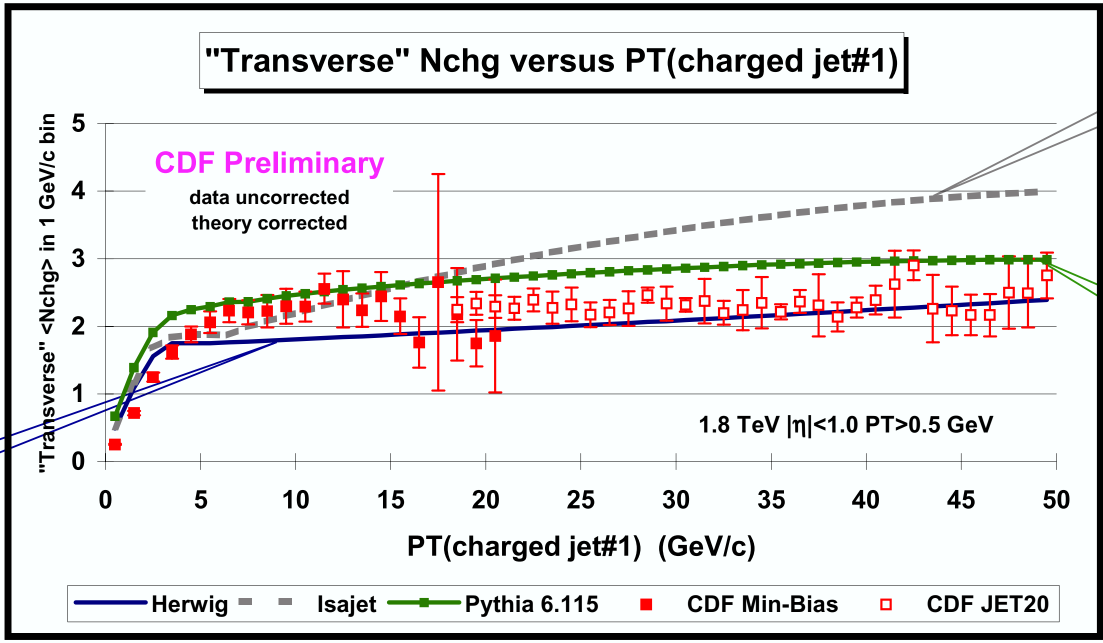
underlying activity in photoproduction vs. DIS



(anti)correlations in energy flow around jet

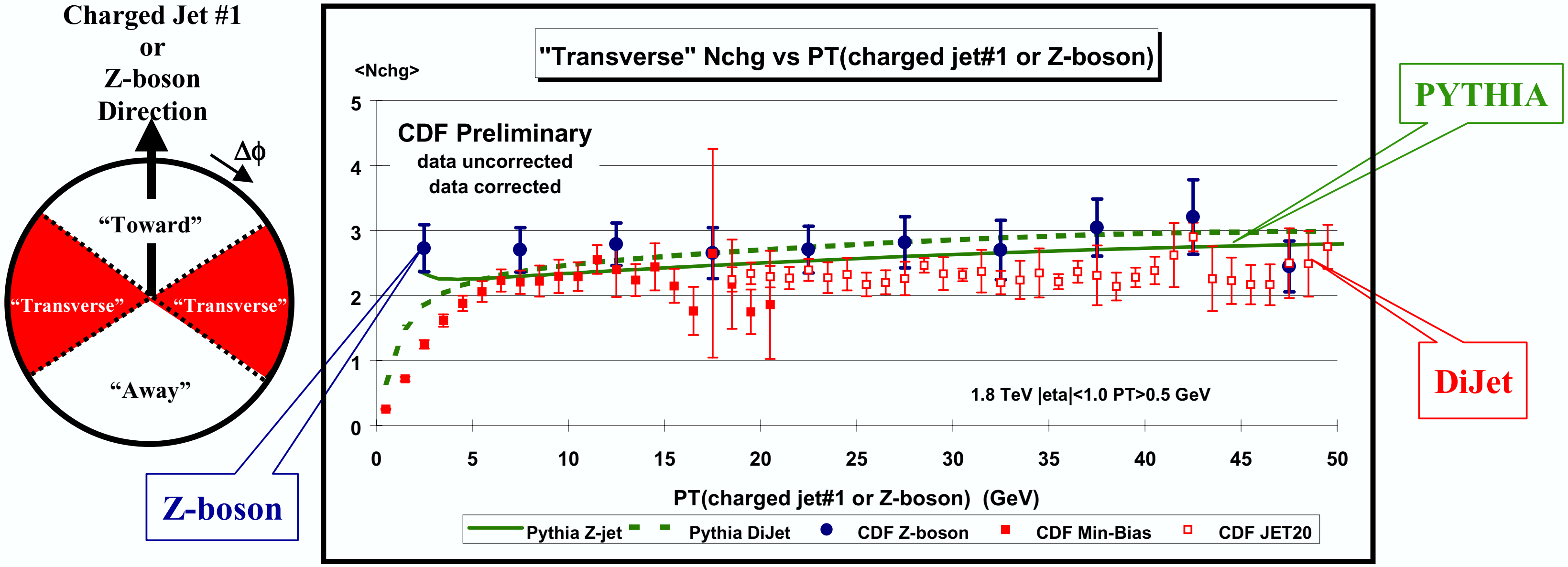
“Transverse” Nchg versus P_T(chgjet#1)





- Plot shows the “Transverse” <Nchg> versus P_T(chgjet#1) compared to the the QCD hard scattering predictions of Herwig 5.9, Isajet 7.32, and Pythia 6.115 (default parameters with P_T(hard)>3 GeV/c).
- Only charged particles with $|\eta| < 1$ and $P_T > 0.5$ GeV are included and the QCD Monte-Carlo predictions have been corrected for efficiency.

DiJet vs Z-Jet "Transverse" Nchg



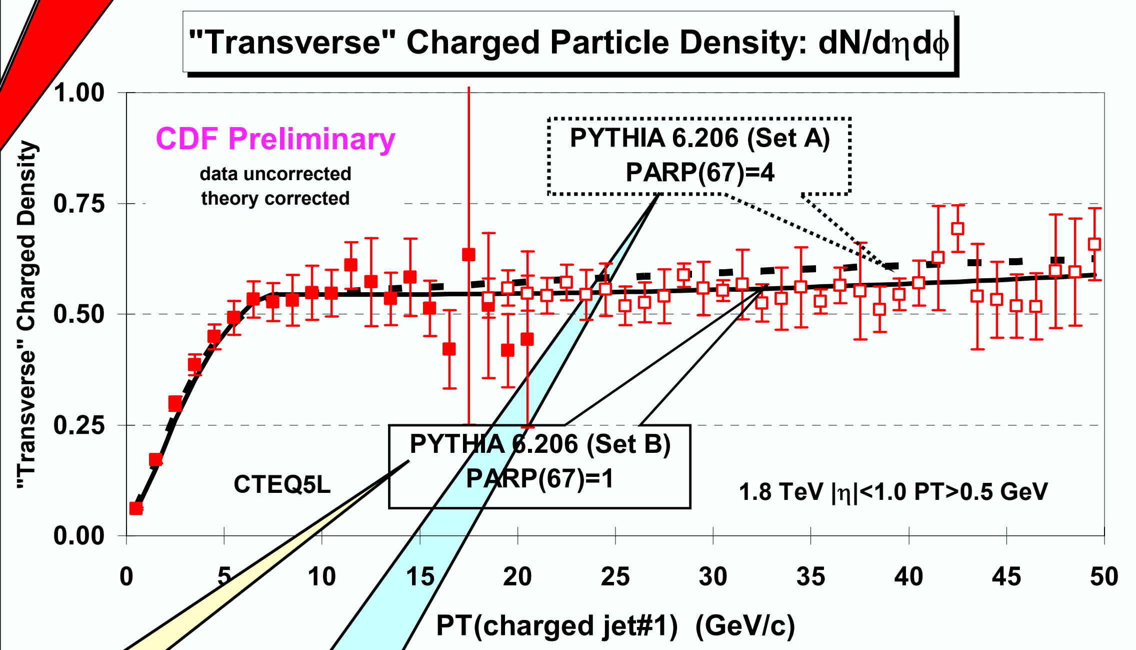
- Comparison of the dijet and the Z-boson data on the average number of charged particles (P_T > 0.5 GeV, $|\eta|$ <1) for the "transverse" region.
- The plot shows the QCD Monte-Carlo predictions of PYTHIA 6.115 (default parameters with P_T(hard)>3 GeV/c) for dijet (dashed) and "Z-jet" (solid) production.

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

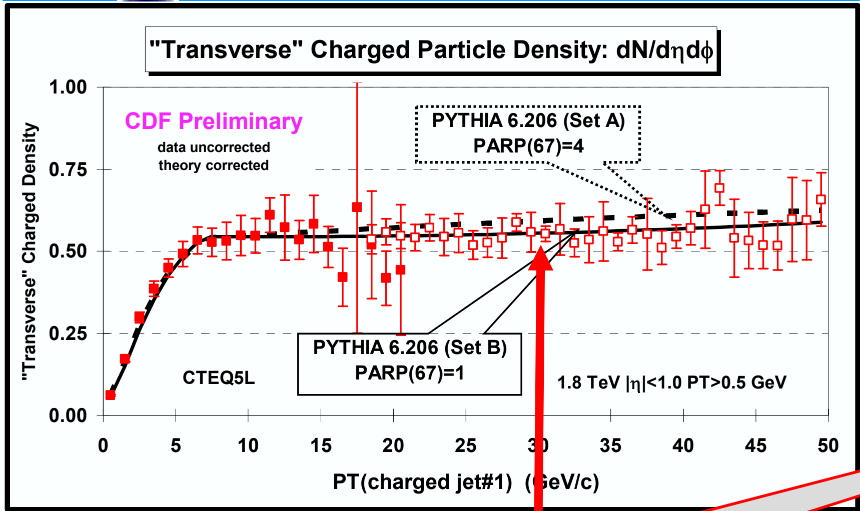


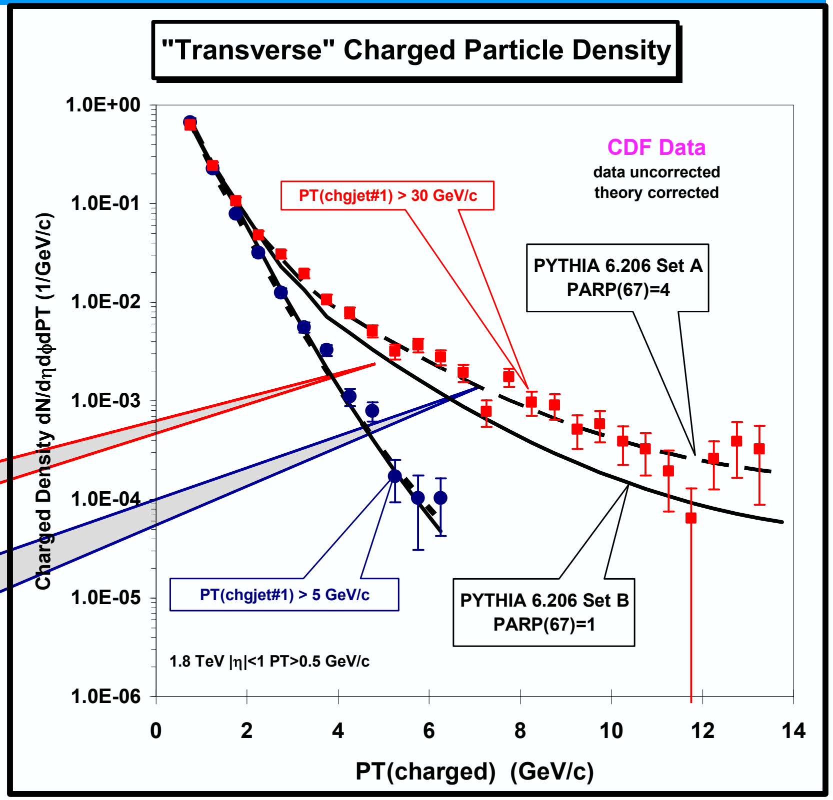
Plot shows the "Transverse" charged particle density versus P_T(chgjet#1) compared to the QCD hard scattering predictions of two tuned versions of PYTHIA 6.206 (CTEQ5L, Set B (PARP(67)=1) and Set A (PARP(67)=4)).

New PYTHIA default
(less initial-state radiation)

Old PYTHIA default
(more initial-state radiation)

Tuned PYTHIA 6.206 "Transverse" P_T Distribution



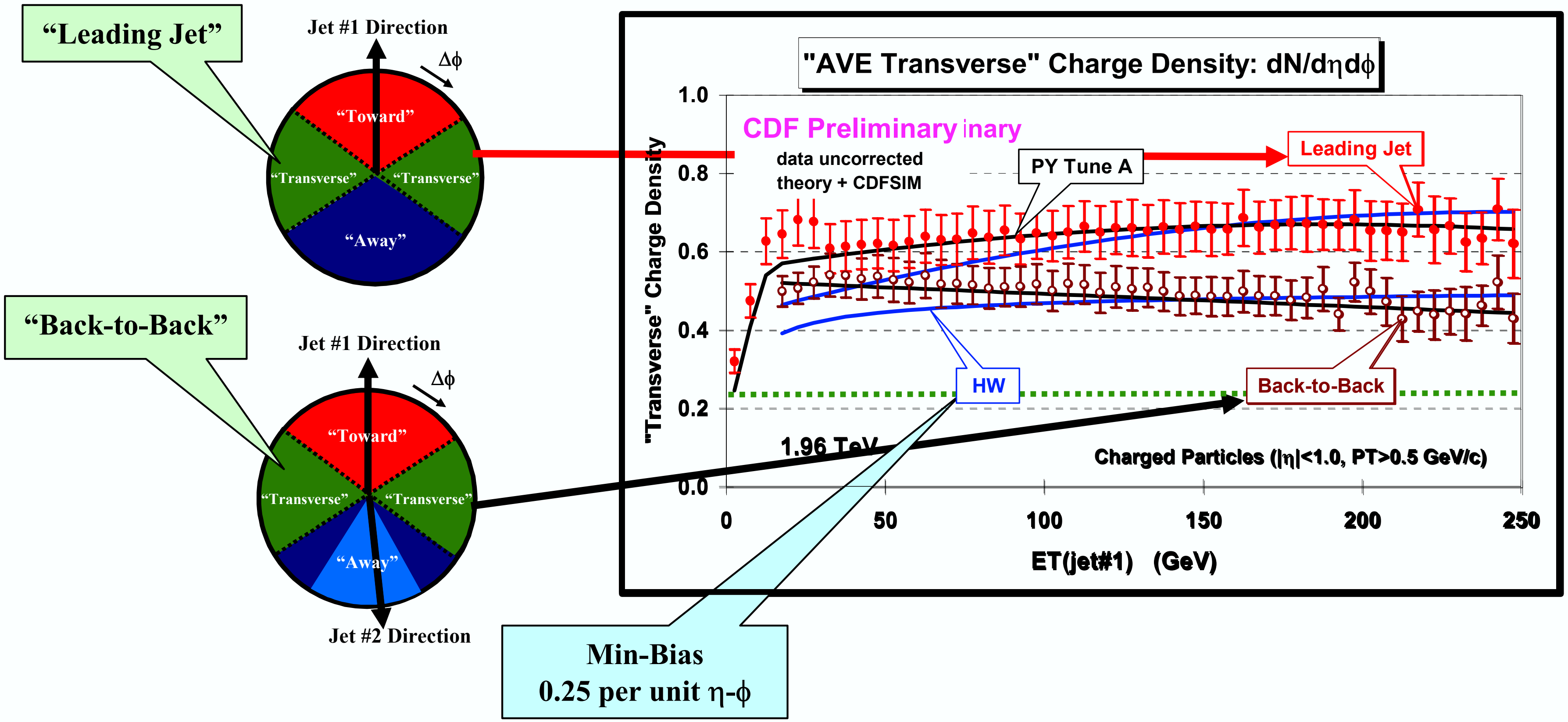


P_T(charged jet#1) > 30 GeV/c

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)).**

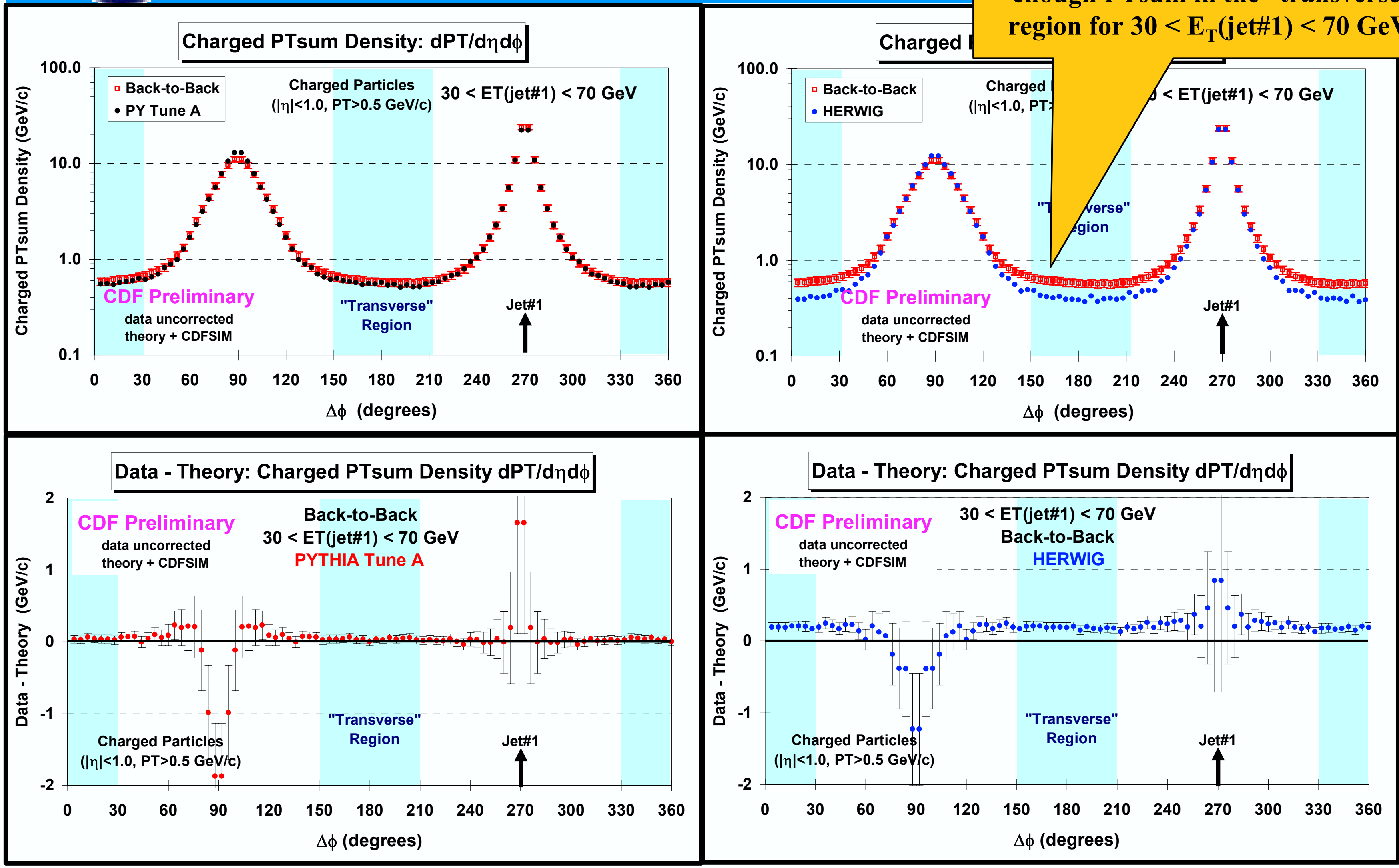
“Transverse” Charge Density versus E_T(jet#1)



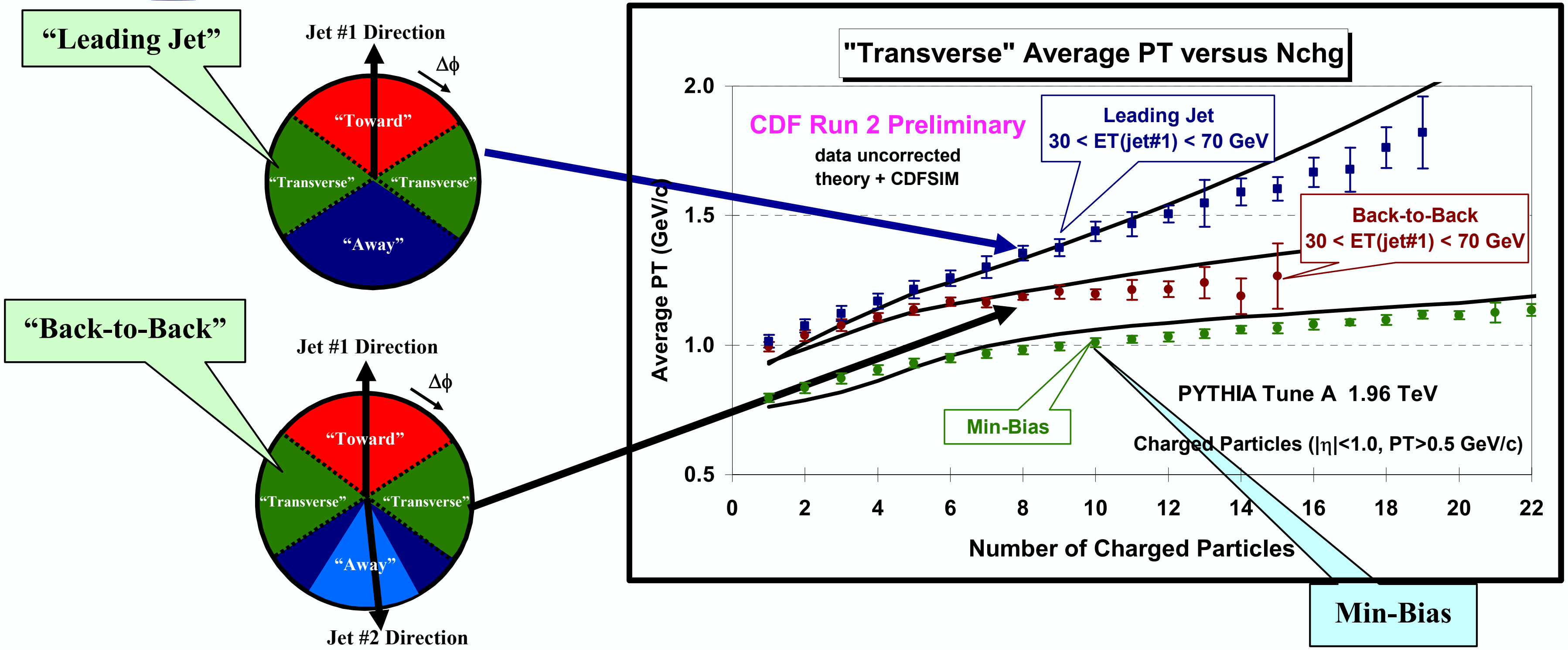
- Shows the **average charged particle density**, $dN_{chg}/d\eta d\phi$, in the **“transverse” region** (p_T > 0.5 GeV/c, $|\eta|$ < 1) versus E_T(jet#1) for **“Leading Jet”** and **“Back-to-Back”** events.
- Compares the (*uncorrected*) data with **PYTHIA Tune A** and **HERWIG** after CDFSIM.

Charged PTsum Density
PYTHIA Tune A vs HE

HERWIG (*without multiple parton interactions*) does not produces enough PTsum in the "transverse" region for $30 < E_T(\text{jet\#1}) < 70$ GeV!

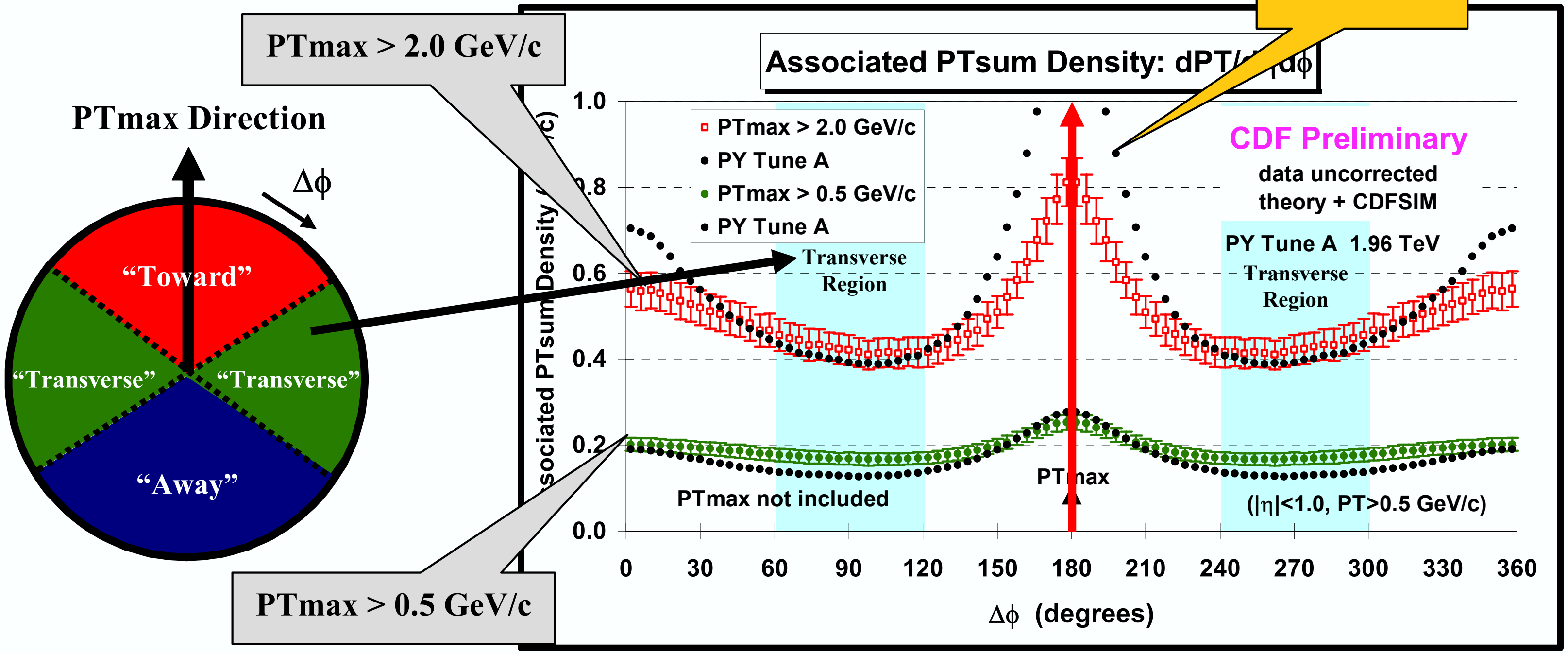


"Transverse" $\langle p_T \rangle$ versus "Transverse" Nchg



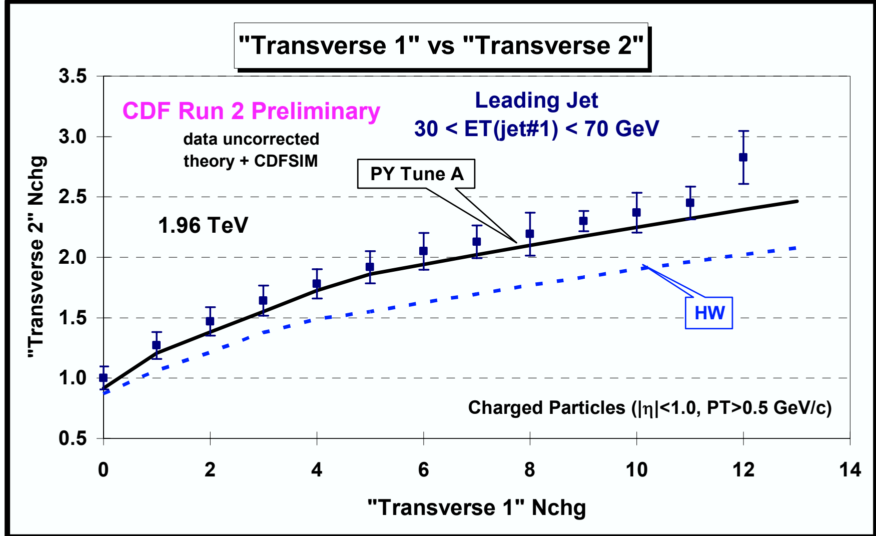
- Look at the $\langle p_T \rangle$ of particles in the "transverse" region ($p_T > 0.5$ GeV/c, $|\eta| < 1$) versus the number of particles in the "transverse" region: $\langle p_T \rangle$ vs Nchg.
- Shows $\langle p_T \rangle$ versus Nchg in the "transverse" region ($p_T > 0.5$ GeV/c, $|\eta| < 1$) for "Leading Jet" and "Back-to-Back" events with 30 < E_T(jet#1) < 70 GeV compared with "min-bias" collisions.

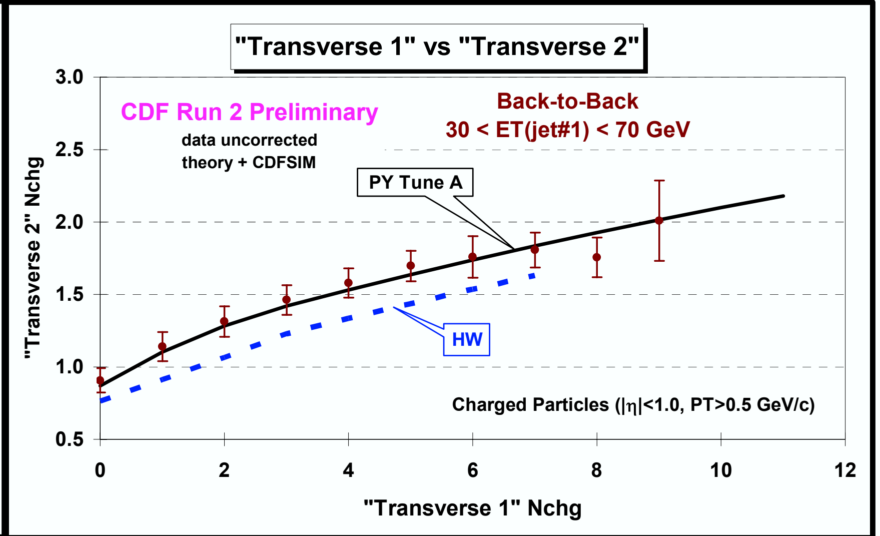
Min-Bias "Associated" Charged PTsum Density

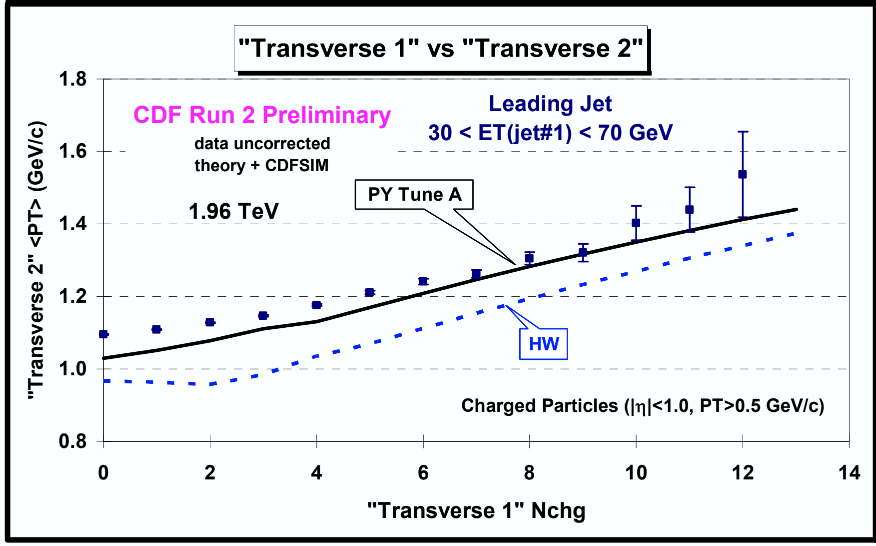


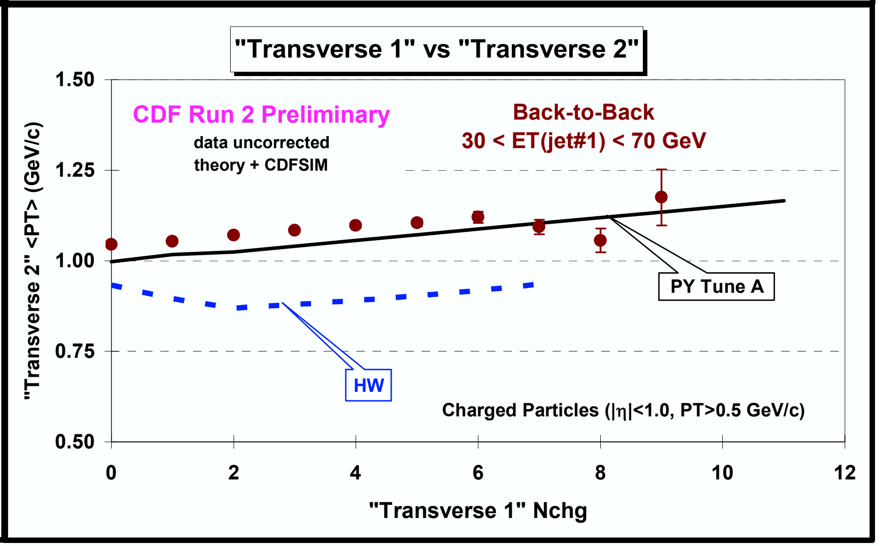
- Shows the data on the Δφ dependence of the "associated" charged PTsum density, dPTsum/dηdφ, for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmax*) relative to PTmax (rotated to 180°) for "min-bias" events with PTmax > 0.5 GeV/c and PTmax > 2.0 GeV/c compared with PYTHIA Tune A (after CDFSIM).
- PYTHIA Tune A predicts a larger correlation than is seen in the "min-bias" data (*i.e.* Tune A "min-bias" is a bit too "jetty").

"Transverse 1" Region vs "Transverse 2" Region

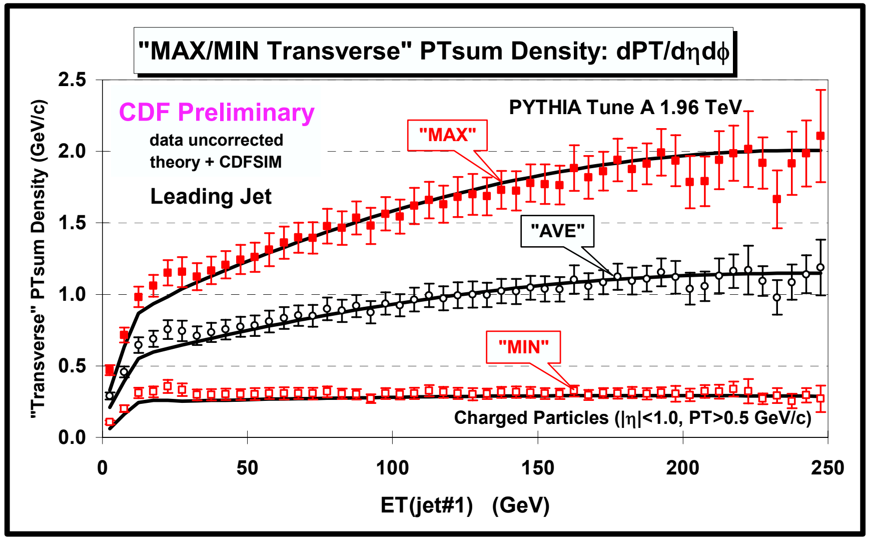


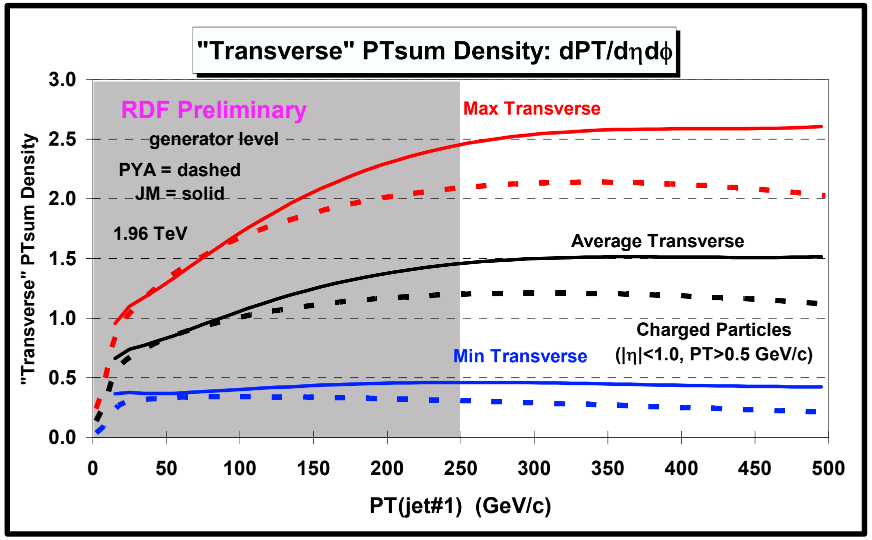






PYTHIA Tune A vs JIMMY: "Transverse Region"

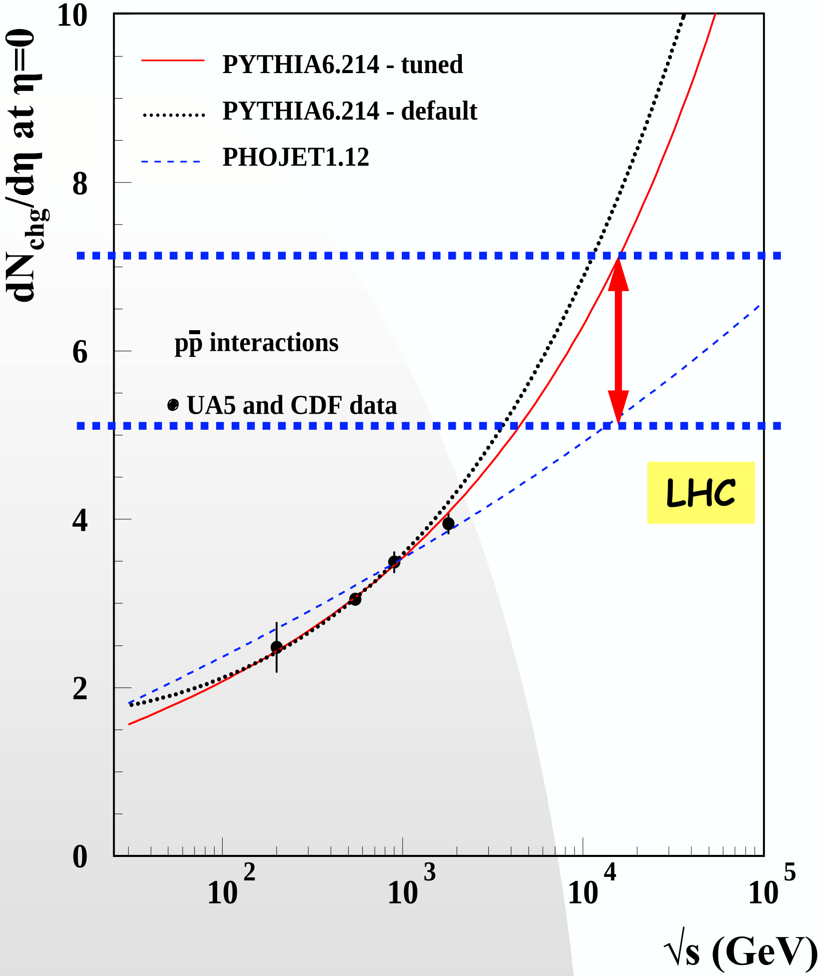


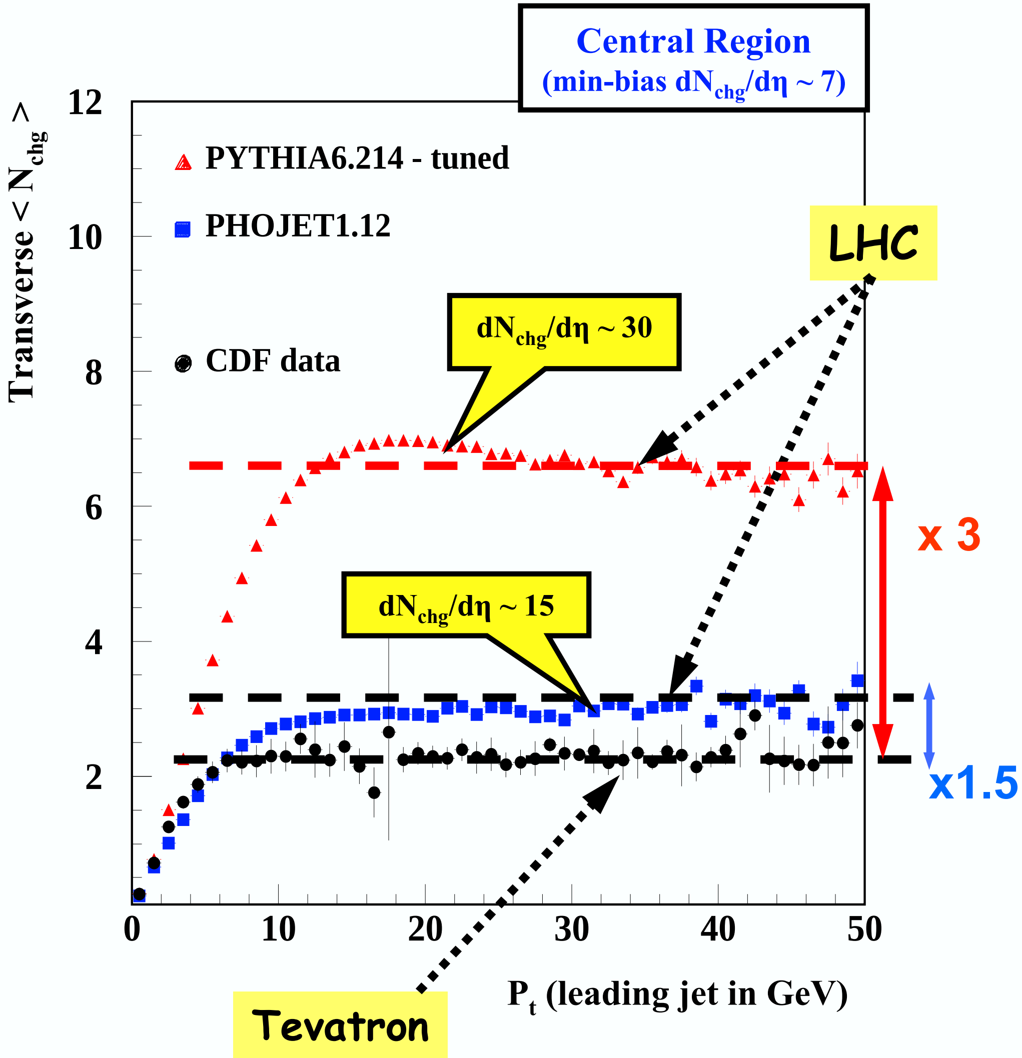


- (*left*) Run 2 data for charged *scalar* PTsum density (|η|<1, p_T>0.5 GeV/c) in the MAX/MIN/AVE "transverse" region versus P_T(jet#1) compared with PYTHIA Tune A (*after CDFSIM*).
- (*right*) Shows the generator level predictions of PYTHIA Tune A (*dashed*) and JIMMY ($P_T$min=1.8 GeV/c) for charged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

Comments	PYTHIA6.2 - Default	ATLAS – TDR (PYTHIA5.7)	CDF – Tune A (PYTHIA6.206)	PYTHIA6.214 - Tuned
Generated processes (QCD + low-pT)	Non-diffractive inelastic (MSEL=1)	Non-diffractive inelastic (MSEL=1)	Non-diffractive inelastic + double diffraction (MSEL=0, ISUB 94 and 95)	**Non-diffractive + double diffraction (MSEL=0, ISUB 94 and 95)**
p.d.f.	CTEQ 5L (MSTP(51)=7)	CTEQ 2L (MSTP(51)=9)	CTEQ 5L (MSTP(51)=7)	**CTEQ 5L (MSTP(51)=7)**
Multiple interactions models	MSTP(81) = 1 MSTP(82) = 1	MSTP(81) = 1 MSTP(82) = 4	MSTP(81) = 1 MSTP(82) = 4	**MSTP(81) = 1 MSTP(82) = 4**
pT min	PARP(82) = 1.9 PARP(89) = 1 TeV PARP(90) = 0.16	PARP(82) = 1.55 no energy depend.	PARP(82) = 2.0 PARP(89) = 1.8 TeV PARP(90) = 0.25	**PARP(82) = 1.8 PARP(89) = 1 TeV PARP(90) = 0.16**
Core radius	20% of the hadron radius (PARP(84) = 0.2)	20% of the hadron radius (PARP(84) = 0.2)	40% of the hadron radius (PARP(84) = 0.4)	**50% of the hadron radius (PARP(84) = 0.5)**
Gluon production mechanism	PARP(85) = 0.33 PARP(86) = 0.66	PARP(85) = 0.33 PARP(86) = 0.66	PARP(85) = 0.9 PARP(86) = 0.95	**PARP(85) = 0.33 PARP(86) = 0.66**
α_s and K-factors	MSTP(2) = 1 MSTP(33) = 0	MSTP(2) = 2 MSTP(33) = 3	MSTP(2) = 1 MSTP(33) = 0	**MSTP(2) = 1 MSTP(33) = 0**
Regulating initial state radiation	PARP(67) = 1	PARP(67) = 4	PARP(67) = 4	**PARP(67) = 1**

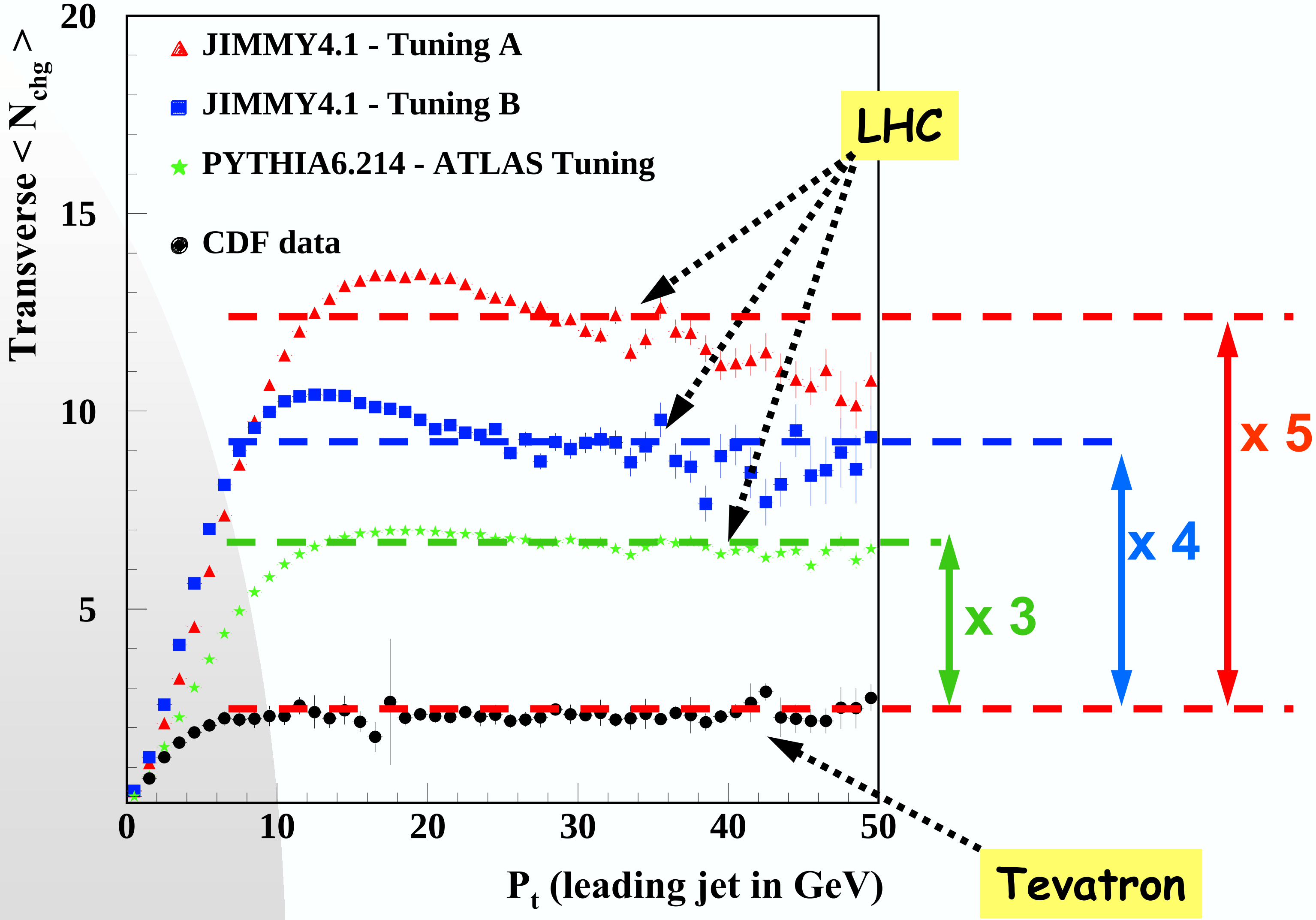
LHC predictions: pp collisions at √s = 14 TeV

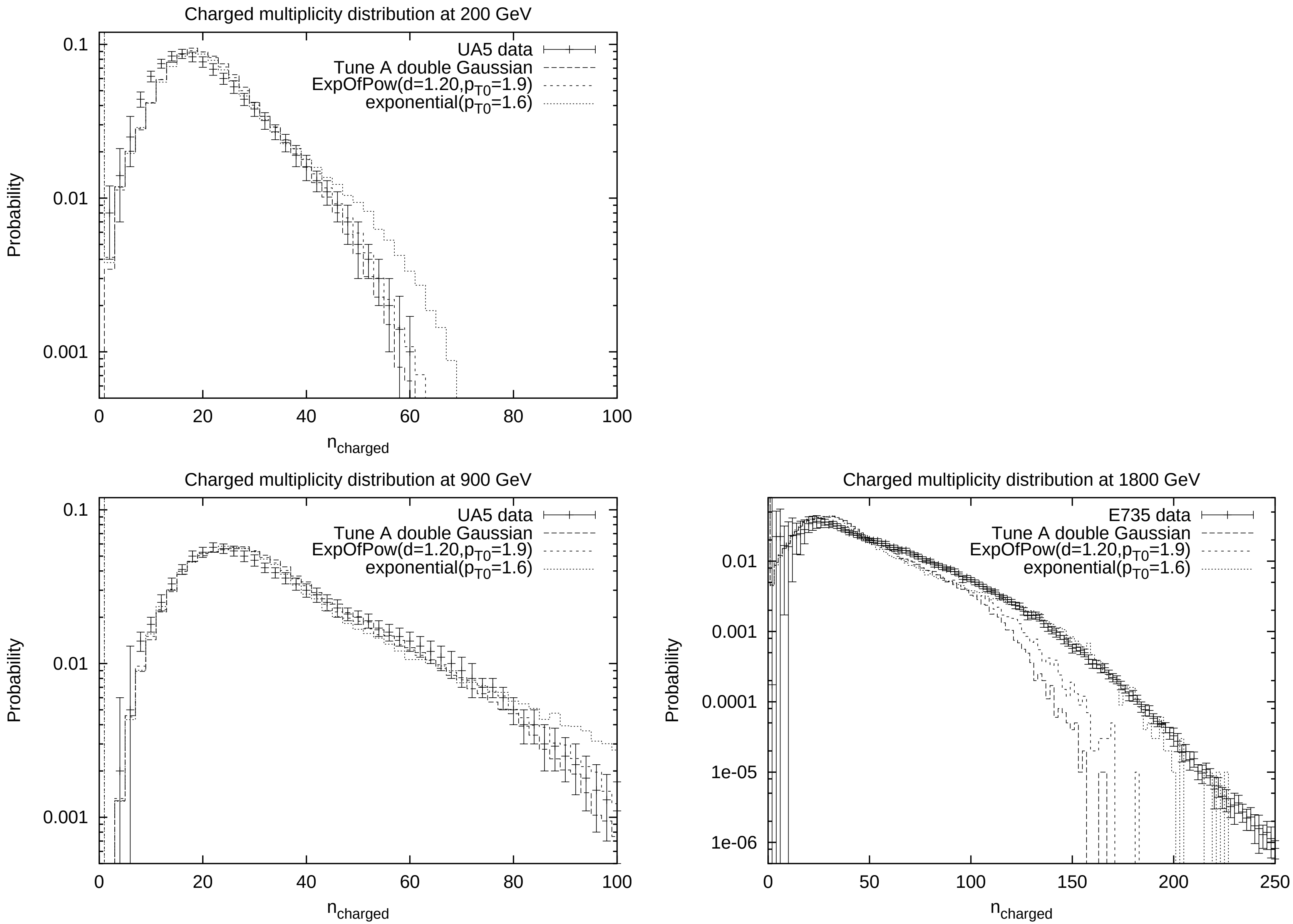


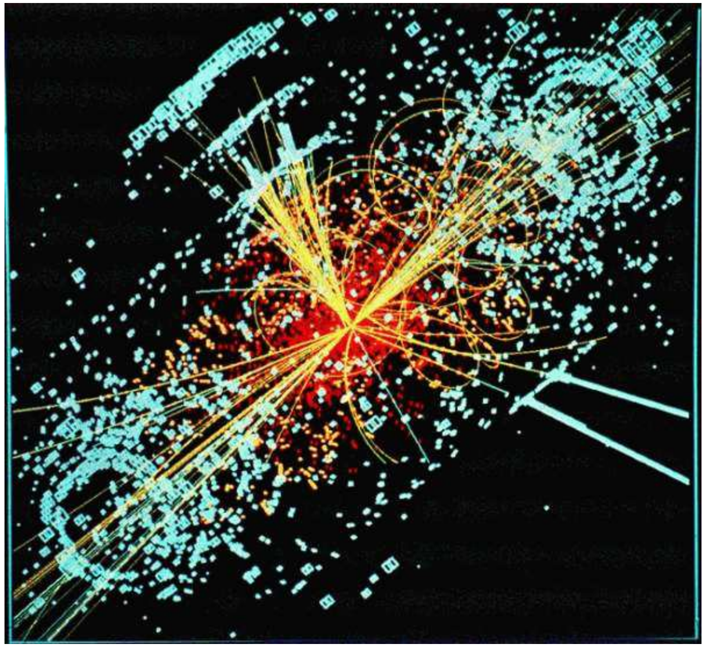


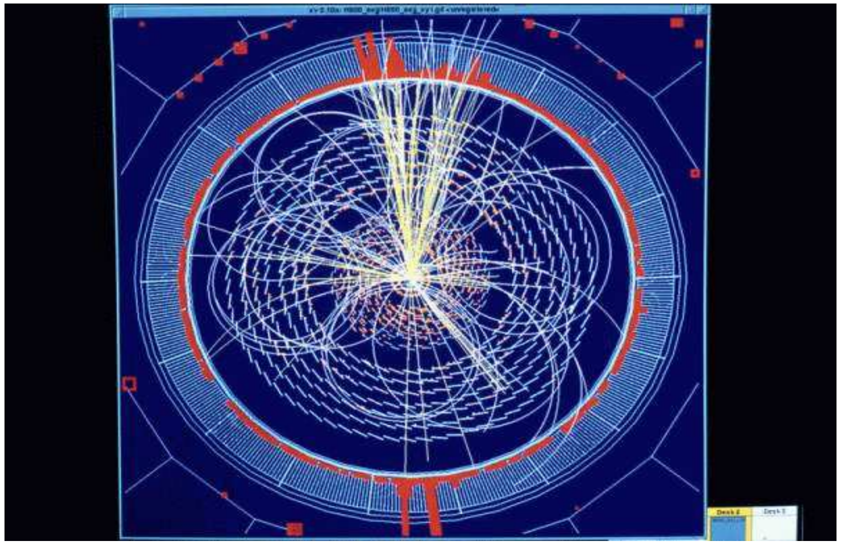
- **PYTHIA** models favour $\ln^2(s)$;
- **PHOJET** suggests a $\ln(s)$ dependence.

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




Charged multiplicity distribution at 200 GeV
UA5 data
Tune A double Gaussian
ExpOfPow(d=1.20,p$_{T0}$=1.9)
exponential(p$_{T0}$=1.6)
Probability
0.1
0.01
0.001
0
20
40
60
80
100
n$_{charged}$
Charged multiplicity distribution at 900 GeV
UA5 data
Tune A double Gaussian
ExpOfPow(d=1.20,p$_{T0}$=1.9)
exponential(p$_{T0}$=1.6)
Probability
0.1
0.01
0.001
0
20
40
60
80
100
n$_{charged}$
Charged multiplicity distribution at 1800 GeV
E735 data
Tune A double Gaussian
ExpOfPow(d=1.20,p$_{T0}$=1.9)
exponential(p$_{T0}$=1.6)
Probability
0.01
0.001
0.0001
1e-05
1e-06
0
50
100
150
200
250
n$_{charged}$





The structure of an event

Multiple interactions

The $p_{\perp}$-based philosophy

$p_{\perp}$-ordered showers

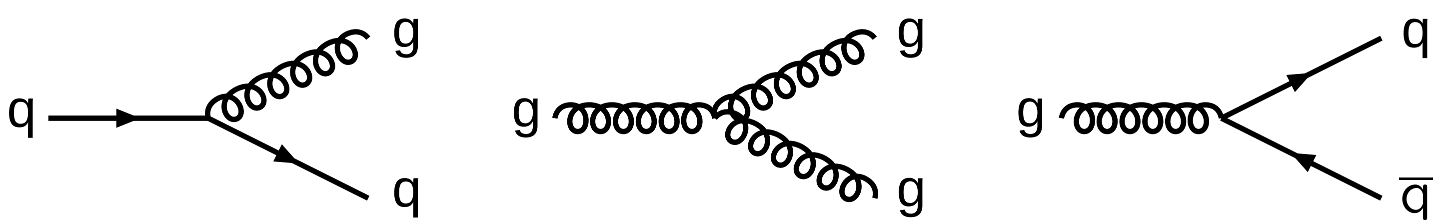
Interleaved interactions

Outlook

The need for an ordering variable

Structure of incoming hadrons is Q^2 dependent — the DGLAP equations:

$$\mathrm{d}f_b(x,Q^2) = \frac{\mathrm{d}Q^2}{Q^2} \sum_a \int_x^1 \frac{\mathrm{d}z}{z} f_a\left(\frac{x}{z}, Q^2\right) \frac{\alpha_\mathrm{s}}{2\pi} P_{a\to bc}(z)$$



Structure at Q is resolved at a time $t \sim 1/Q$ *before* collision

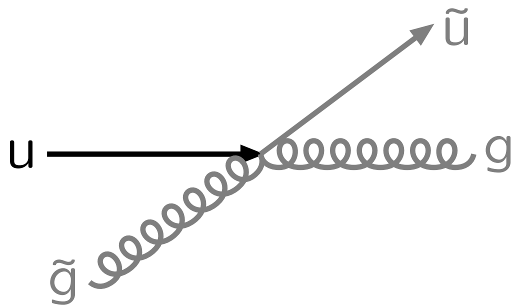
Normal DGLAP is defined for $f_i(x,Q^2)$ of *single* parton;
for multiple interactions we need $f_{i_1 i_2 \ldots}(x_1, Q_1^2; x_2 Q_2^2; \ldots)$

Could be addressed by forwards evolution:
pick a complete partonic set at low Q_0 and evolve, see what happens.
Inefficient:
1) have to evolve and check for *all* potential collisions, but 99.9...% inert
2) impossible to steer the production e.g. of a narrow resonance (Higgs)

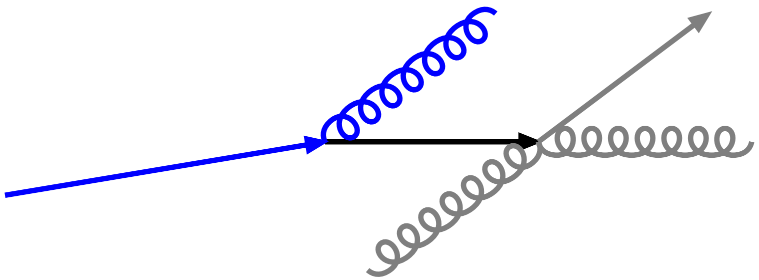
Backwards evolution

— start at hard interaction and trace what happened “before” —

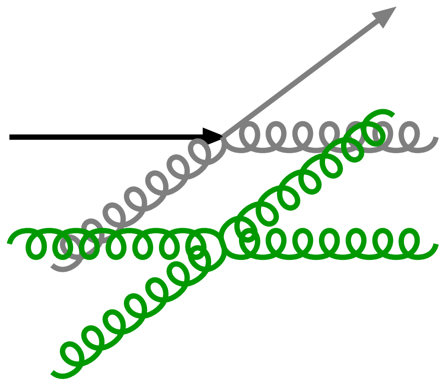
viable and ∼equivalent *but* now **competition**:



at smaller Q^2 can reconstruct back to either of



and

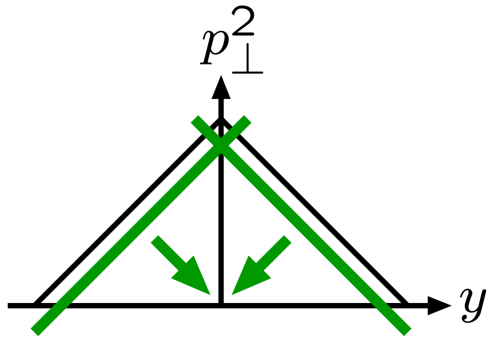


$\Longrightarrow$

Need to agree on common definition of ordering (“time”) variable!

Ordering variables in final-state radiation

PYTHIA: $Q^2 = m^2$



large mass first

$\Rightarrow$ "hardness" ordered

coherence brute force

covers phase space

ME merging simple

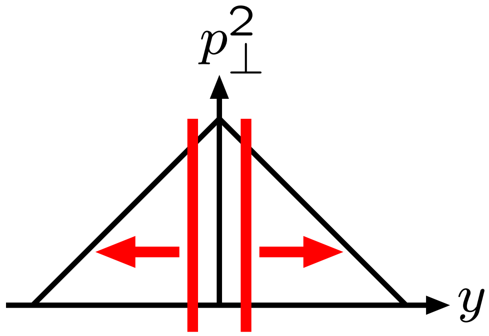
g $\rightarrow$ q$\overline{\text{q}}$ simple

not Lorentz invariant

no stop/restart

ISR: $m^2 \rightarrow -m^2$

HERWIG: $Q^2 \sim E^2\theta^2$



large angle first

$\Rightarrow$ **hardness not ordered**

coherence inherent

gaps in coverage

ME merging messy

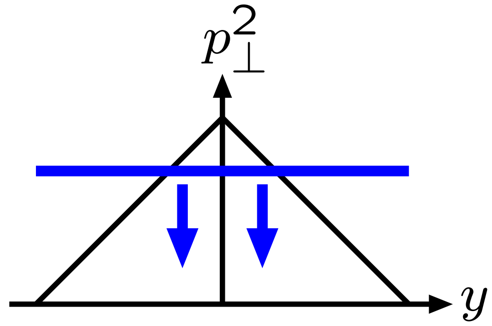
g $\rightarrow$ q$\overline{\text{q}}$ simple

not Lorentz invariant

no stop/restart

ISR: $\theta \rightarrow \theta$

ARIADNE: $Q^2 = p_\perp^2$



large $p_\perp$ first

$\Rightarrow$ "hardness" ordered

coherence inherent

covers phase space

ME merging simple

g $\rightarrow$ q$\overline{\text{q}}$ messy

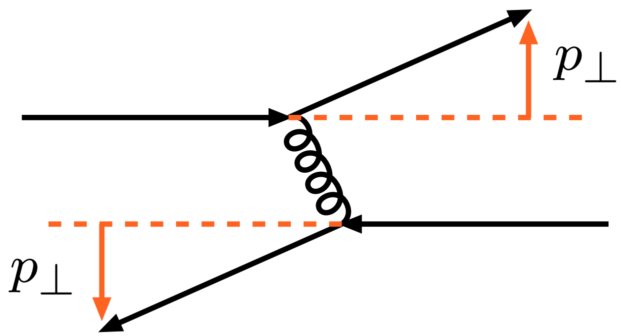
Lorentz invariant

can stop/restart

ISR: more messy

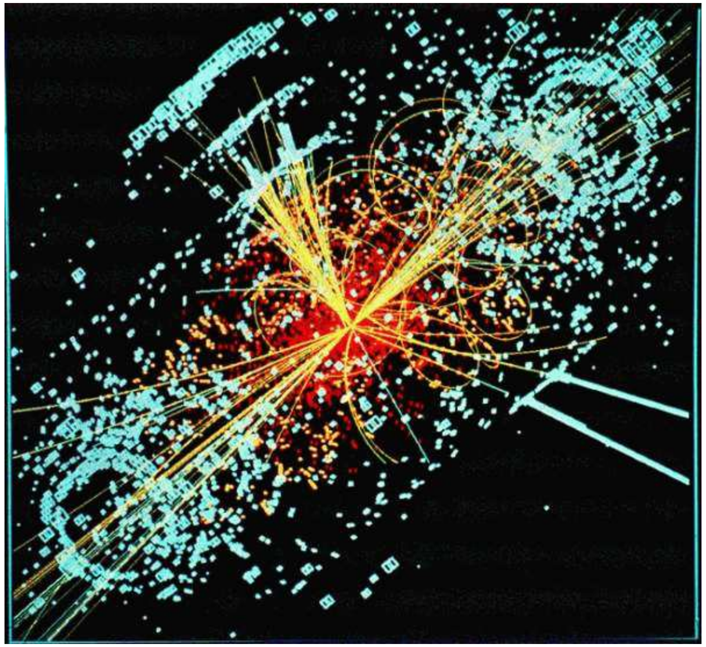
Why is transverse momentum a good choice?

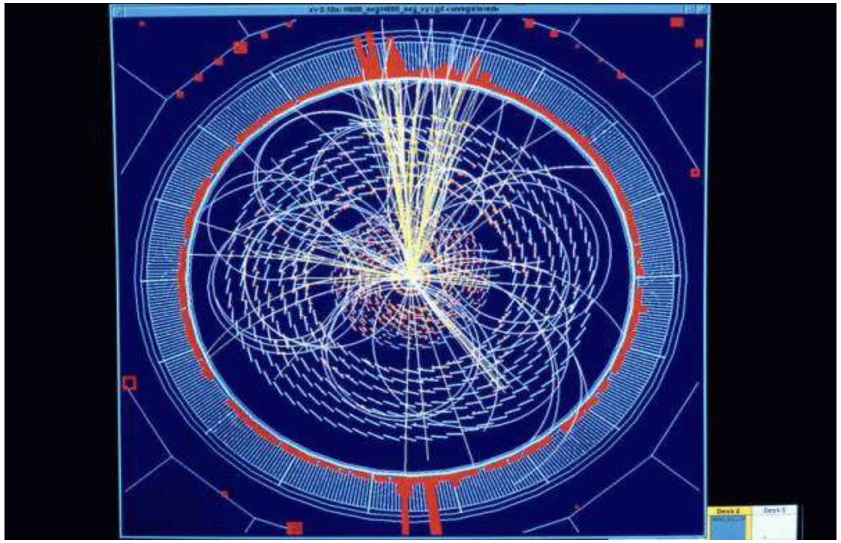
- *The* natural scale for $2 \to 2$ QCD processes



$$p_\perp^2 = \frac{\hat{t}\hat{u}}{\hat{s}} \longmapsto \begin{cases} |\hat{t}| & \text{for } \hat{t} \to 0 \\ |\hat{u}| & \text{for } \hat{u} \to 0 \\ \frac{\hat{s}}{4} & \text{at } 90^\circ \end{cases}$$

- Screening inside incoming hadrons $\Rightarrow p_\perp$ cutoff
- Allowed, reasonable choice for FSR and ISR
- Coherence in FSR, partly also in ISR
- Scale choice $\alpha_s(p_\perp^2)$ for ISR/FSR is optimal
  (absorbs singular $\ln z$, $\ln(1-z)$ terms in NLO splitting kernels)
  $\Rightarrow$ lower cutoff of showers is in $p_\perp$
- Formation time for radiation $\Delta t \sim \frac{E}{p_\perp^2} \sim \frac{\gamma}{p_\perp} \gtrsim 1/p_\perp$
- No alternative??





The structure of an event

Multiple interactions

The $p_\perp$-based philosophy

$p_\perp$-ordered showers

Interleaved interactions

Outlook

Objective

Incorporate several of the good points of the dipole formalism (like ARIADNE) within the shower approach ($\Rightarrow$ hybrid)

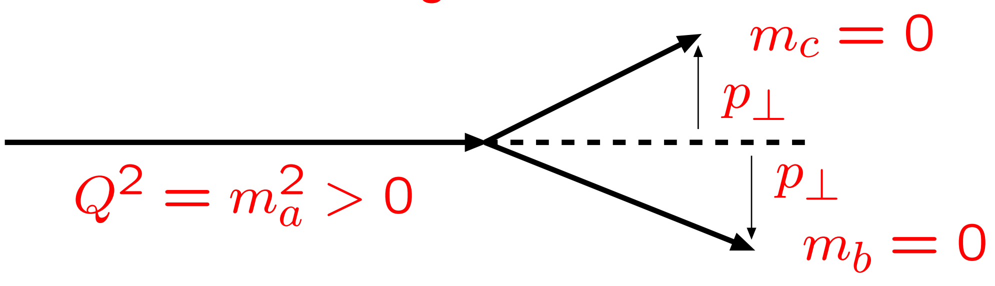
$\pm$ explore alternative $p_\perp$ definitions
$+$ $p_\perp$ ordering $\Rightarrow$ coherence inherent
$+$ ME merging works as before (unique $p_\perp^2 \leftrightarrow Q^2$ mapping; same z)
$+$ g $\rightarrow$ q$\overline{\text{q}}$ natural
$+$ kinematics constructed after each branching
(partons explicitly on-shell until they branch)
$+$ showers can be stopped and restarted at given $p_\perp$ scale
(not yet worked-out for ISR+FSR)
$+$ $\Rightarrow$ well suited for ME/PS matching (L-CKKW, real+fictitious showers)
$+$ $\Rightarrow$ well suited for simple match with $2 \rightarrow 2$ hard processes
$++$ well suited for *interleaved multiple interactions*

Simple kinematics

Consider branching $a \to bc$ in lightcone coordinates $p^{\pm} = E \pm p_z$

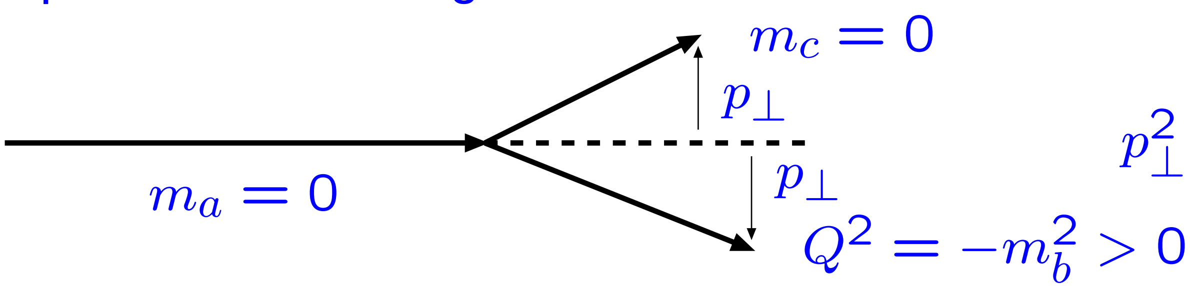
$$\left.\begin{array}{l} p_b^+ = z p_a^+ \\ p_c^+ = (1-z) p_a^+ \\ p^- \text{ conservation} \end{array}\right\} \Longrightarrow m_a^2 = \frac{m_b^2 + p_\perp^2}{z} + \frac{m_c^2 + p_\perp^2}{1-z}$$

Timelike branching:



$$p_\perp^2 = z(1-z)Q^2$$

Spacelike branching:



$$p_\perp^2 = (1-z)Q^2$$

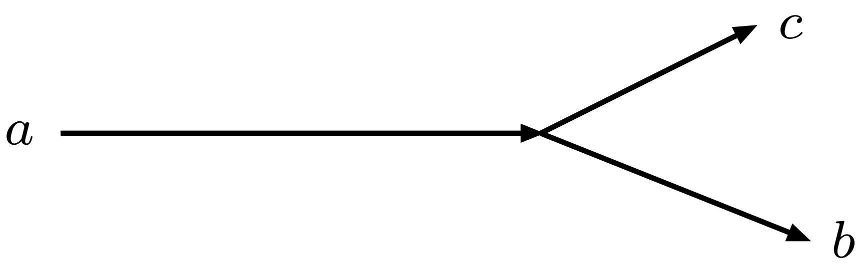
Guideline, not final $p_\perp$!

General Strategy (1)

1) *Define* $\mathrm{p}_{\perp\mathrm{evol}}^2 = z(1-z)Q^2 = z(1-z)m^2$ for FSR
$\mathrm{p}_{\perp\mathrm{evol}}^2 = (1-z)Q^2 = (1-z)(-m^2)$ for ISR

2) Find list of *radiators* = partons that can radiate.
Evolve them all *downwards* in $\mathrm{p}_{\perp\mathrm{evol}}$ from common $p_{\perp\mathrm{max}}$

$$\mathrm{d}\mathcal{P}_a = \frac{\mathrm{dp}_{\perp\mathrm{evol}}^2}{\mathrm{p}_{\perp\mathrm{evol}}^2} \frac{\alpha_\mathrm{s}(\mathrm{p}_{\perp\mathrm{evol}}^2)}{2\pi} P_{a\to bc}(z)\,\mathrm{d}z\ \exp\left(-\int_{\mathrm{p}_{\perp\mathrm{evol}}^2}^{p_{\perp\mathrm{max}}^2}\cdots\right)$$



$$\mathrm{d}\mathcal{P}_b = \frac{\mathrm{dp}_{\perp\mathrm{evol}}^2}{\mathrm{p}_{\perp\mathrm{evol}}^2} \frac{\alpha_\mathrm{s}(\mathrm{p}_{\perp\mathrm{evol}}^2)}{2\pi} \frac{x' f_a(x', \mathrm{p}_{\perp\mathrm{evol}}^2)}{x f_b(x, \mathrm{p}_{\perp\mathrm{evol}}^2)} P_{a\to bc}(z)\,\mathrm{d}z\ \exp(-\cdots)$$

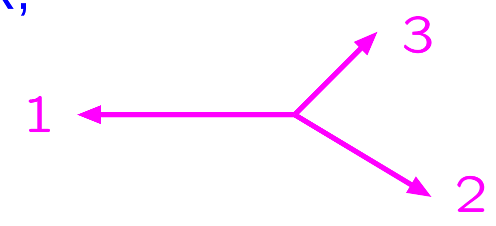
Pick the one with *largest* $\mathrm{p}_{\perp\mathrm{evol}}$ to undergo branching; also gives z.

3) *Derive* $Q^2 = \mathrm{p}_{\perp\mathrm{evol}}^2/z(1-z)$ for FSR
$Q^2 = \mathrm{p}_{\perp\mathrm{evol}}^2/(1-z)$ for ISR

General Strategy (2)

4) Find *recoiler* = parton to take recoil when radiator is pushed off-shell
usually nearest colour neighbour for FSR
incoming parton on other side of event for ISR

5) Interpret z as *energy fraction* (not lightcone)
in radiator+recoiler rest frame for FSR,
in mother-of-radiator+recoiler rest frame for ISR,
so that *Lorentz invariant*
$(2E_i/E_{\mathrm{cm}} = 1 - m_{jk}^2/E_{\mathrm{cm}}^2)$
and straightforward match to matrix elements

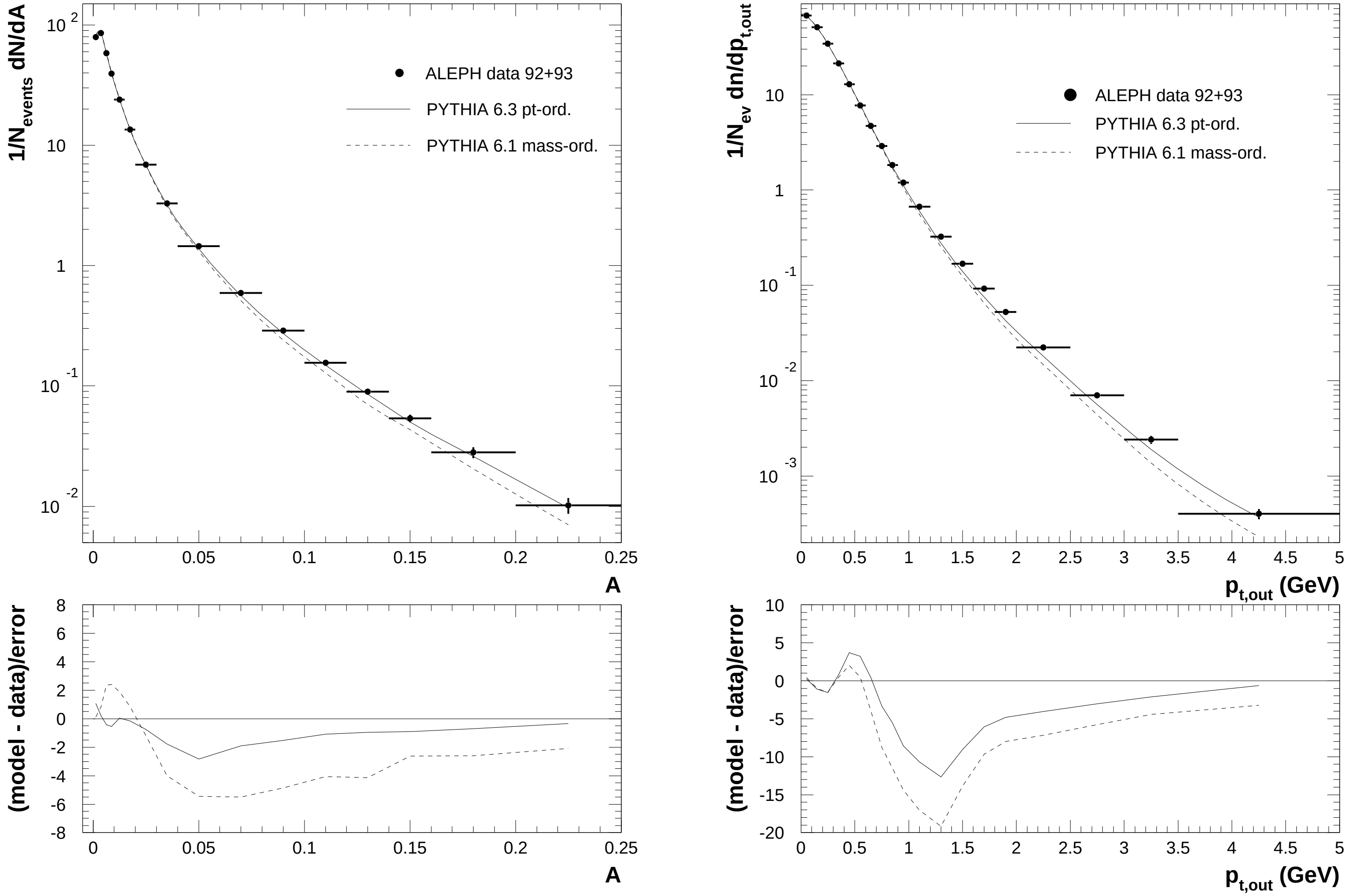


6) Do *kinematics* based on Q^2 and z,
a) assuming yet unbranched partons on-shell
b) shuffling energy–momentum from recoiler as required

7) Continue evolution of all radiators from recently picked $p_{\perp\mathrm{evol}}$.
Iterate until no branching above $p_{\perp\mathrm{min}}$.
$\Rightarrow$ One combined sequence $p_{\perp\mathrm{max}} > p_{\perp 1} > p_{\perp 2} > \ldots > p_{\perp\mathrm{min}}$.

Testing the FSR algorithm

Tune performed by Gerald Rudolph (Innsbruck)
based on ALEPH 1992+93 data:



Quality of fit

Distribution of	nb.of interv.	$\sum \chi^2$ of model PY6.3 $p_\perp$-ord.	PY6.1 mass-ord.
Sphericity	23	25	16
Aplanarity	16	23	168
1−Thrust	21	60	8
$\text{Thrust}_{\text{minor}}$	18	26	139
jet res. y_3(D)	20	10	22
$x = 2p/E_{\text{cm}}$	46	207	151
$p_{\perp\text{in}}$	25	99	170
$p_{\perp\text{out}} < 0.7$ GeV	7	29	24
$p_{\perp\text{out}}$	(19)	(590)	(1560)
x(B)	19	20	68
sum $N_{\text{dof}} =$	190	497	765

Generator is not assumed to be perfect, so
add fraction p of value in quadrature to the definition of the error:

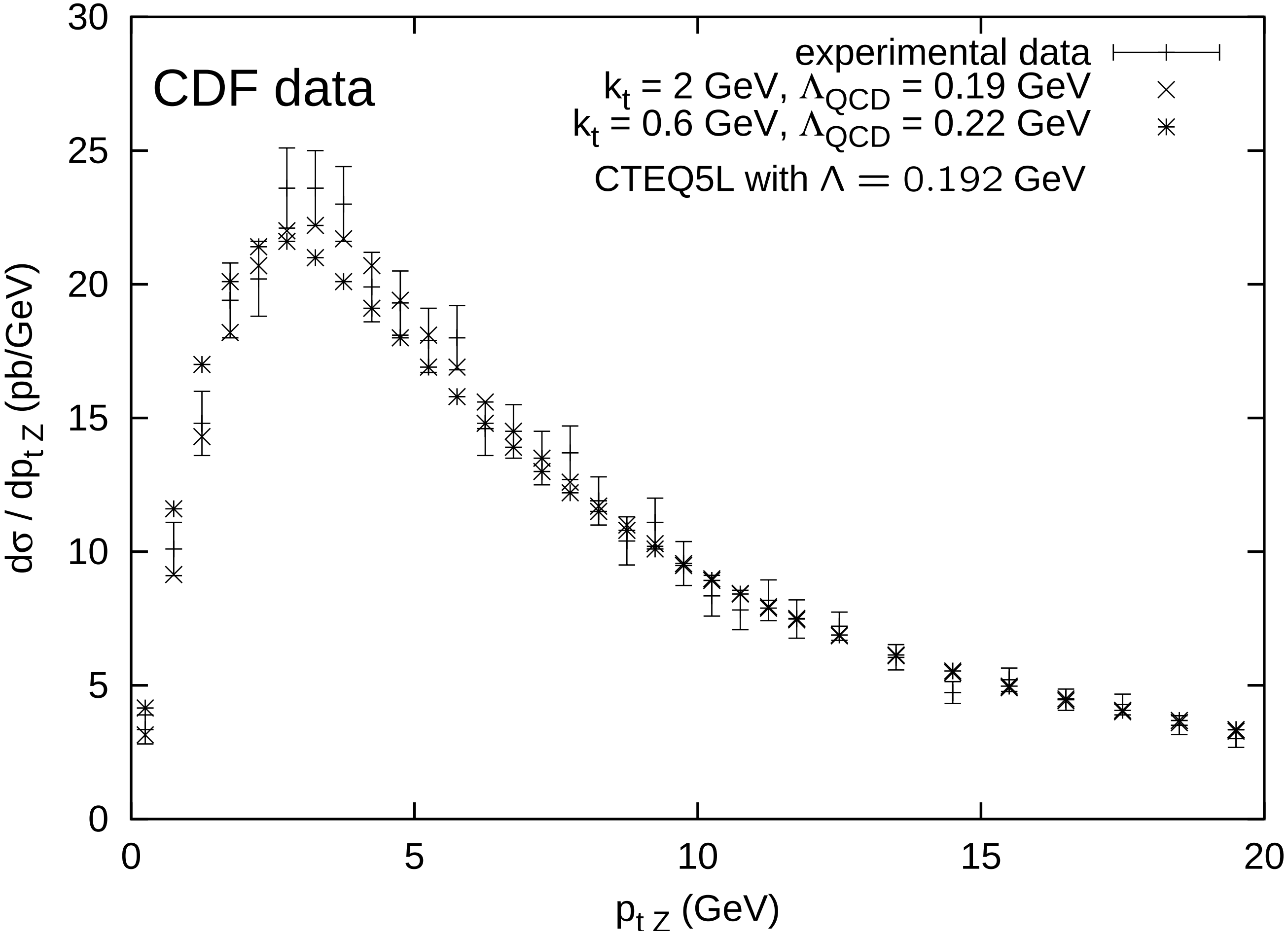
p	0%	0.5%	1%
$\sum \chi^2$	523	364	234

for $N_{\text{dof}} = 196 \Rightarrow$ generator is 'correct' to ~1%

except $p_{\perp\text{out}} > 0.7$ GeV (10%–20% error)

Testing the ISR algorithm

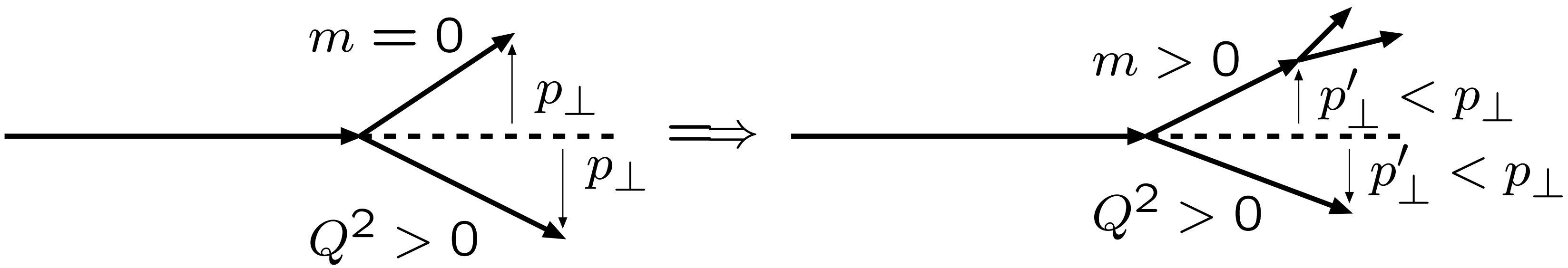
Still only begun. . .

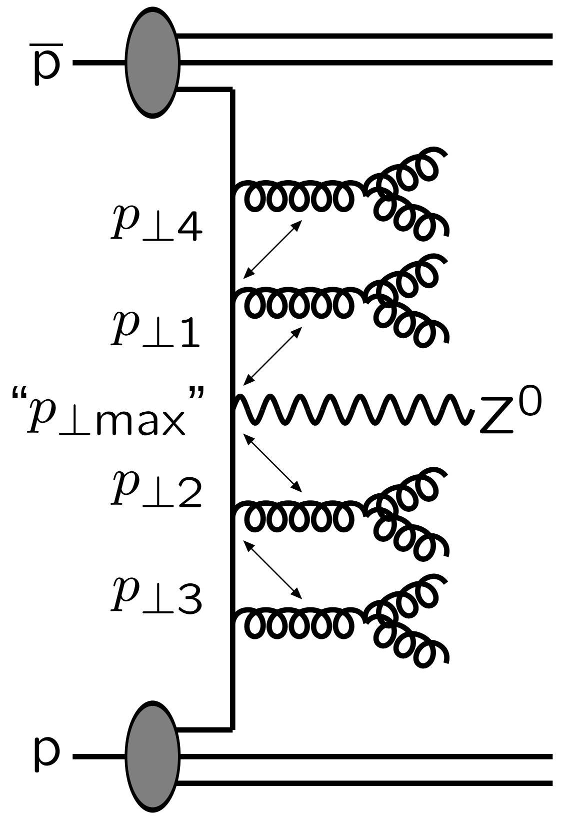


. . . but so far no showstoppers

Combining FSR with ISR

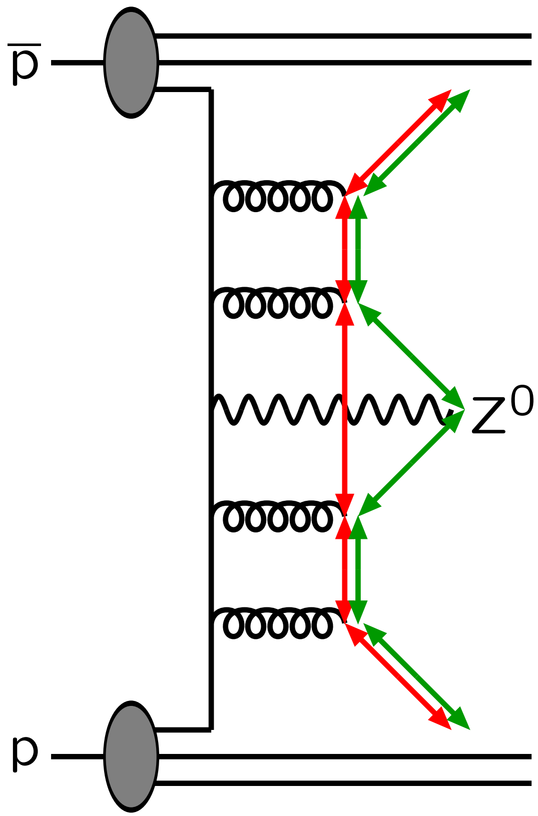
Evolution of timelike sidebranch cascades can reduce $p_\perp$:





Old:

Z^0 takes recoil

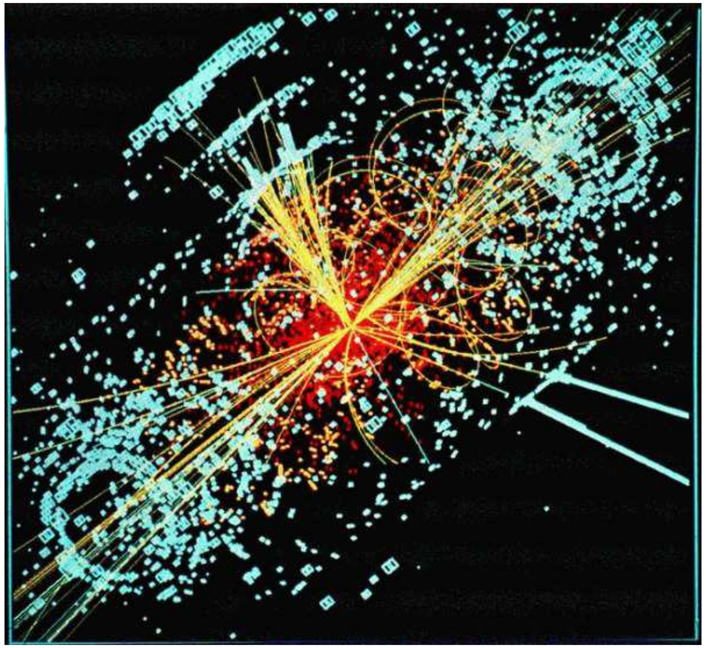


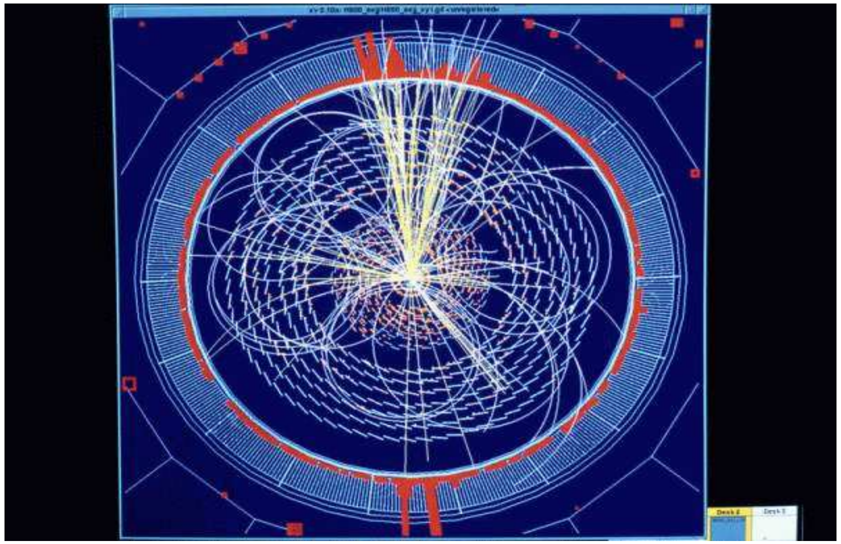
New:

Z^0 takes recoil

or

Z^0 unaffected by FSR (latter later)





The structure of an event

Multiple interactions

The $p_\perp$-based philosophy

$p_\perp$-ordered showers

Backup

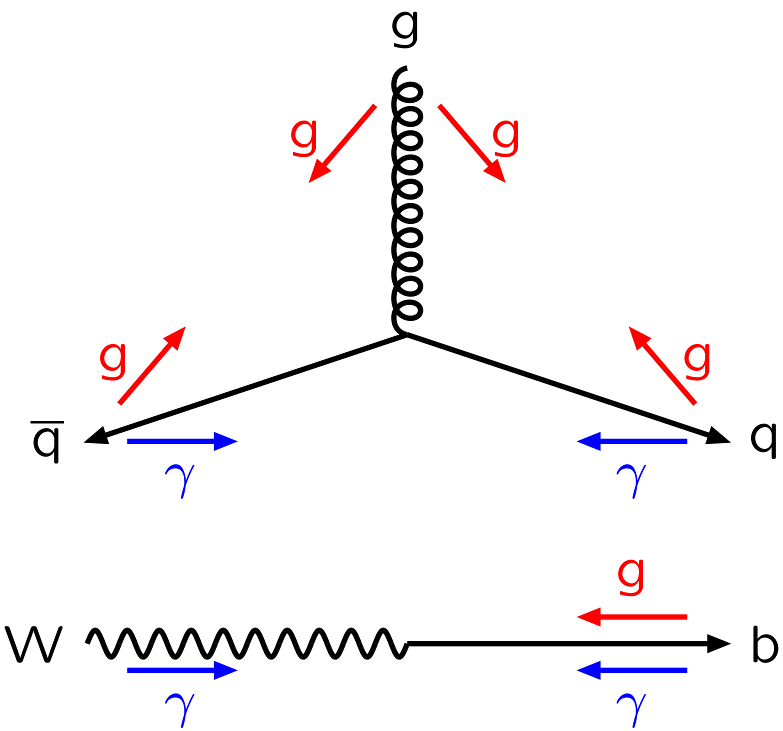
$p_\perp$-ordered showers

Interleaved interactions

Outlook

The FSR algorithm

1) Find radiators and recoilers from initial list of on-shell partons



g: counts twice,
half for each recoiler;
both g $\to$ gg and g $\to$ q$\overline{\text{q}}$

q: one recoiler for q $\to$ qg,
another recoiler for q $\to$ qγ

top decay (e.g.)
colour recoiler $\neq$ colour partner
(should not change top mass)

2) Evolve all radiators downwards from common $p_{\perp\text{max}}$.
Pick the one that branches at the largest actual $p_{\perp\text{evol}}$.

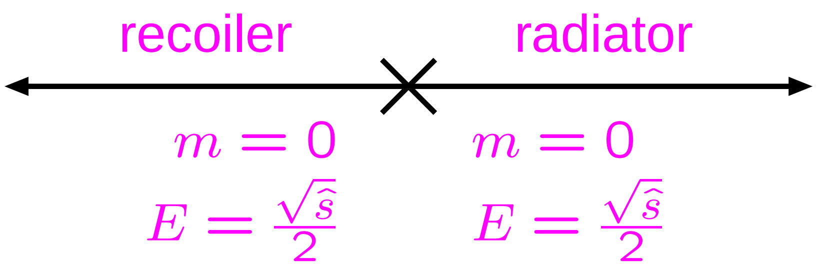
a) Massive quarks: $p^2_{\perp\text{evol}} = z(1-z)(m^2 - m_0^2)$.

b) $z_{\text{min}}(p^2_{\perp\text{evol}}, \hat{s}) < z < z_{\text{max}}(p^2_{\perp\text{evol}}, \hat{s})$ with $\hat{s} = (p_{\text{rad}} + p_{\text{rec}})^2$.

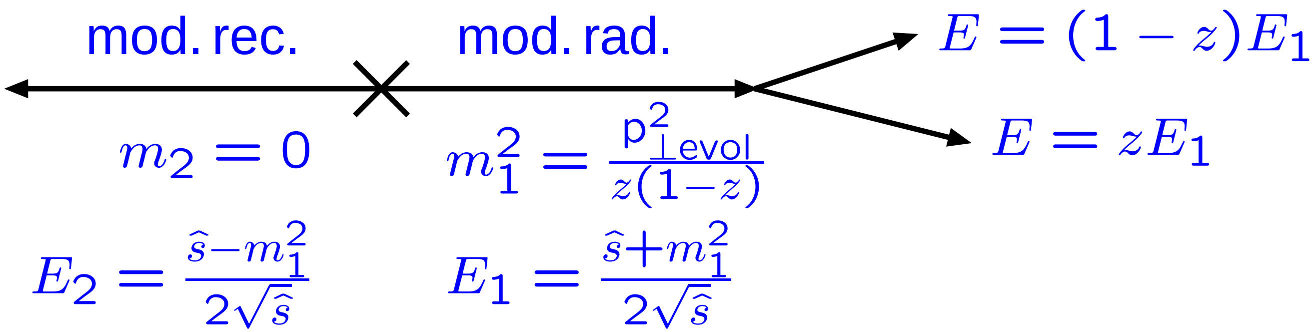
c) Matrix-element merging by veto for many SM+MSSM decays.

3) Construct kinematics of branching:

a) Boost radiator+recoiler
to their rest frame;
radiator along $+z$ axis



b) Replace
by



Actual $p_\perp^2 = m^2 \frac{z(1-z)(\hat{s}+m_1^2)^2 - \hat{s}m_1^2}{(\hat{s}-m_1^2)^2} < \mathrm{p}_{\perp\mathrm{evol}}^2$

since now z energy fraction, not lightcone
(so that simpler merging matrix elements).

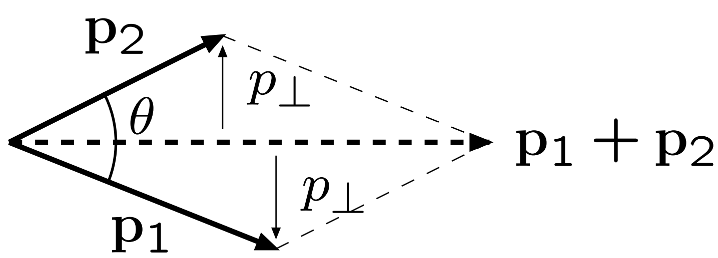
c) φ angle nonisotropic by g polarization.

d) Rotate and boost back.

4) Continue evolution of all radiators from recently picked $\mathrm{p}_{\perp\mathrm{evol}}$.
Iterate until no branching above $p_{\perp\mathrm{min}}$.
$\Rightarrow$ One combined sequence $p_{\perp\mathrm{max}} > p_{\perp 1} > p_{\perp 2} > \ldots > p_{\perp\mathrm{min}}$.

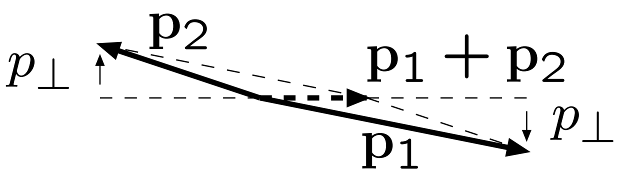
Transverse momentum definition(s)

Consider two massless particles, $E_1 = |\mathbf{p}_1|$ and $E_2 = |\mathbf{p}_2|$:



$$p_\perp = \frac{|\mathbf{p}_1 \times \mathbf{p}_2|}{|\mathbf{p}_1 + \mathbf{p}_2|} = \frac{E_1 E_2 \sin\theta}{\sqrt{E_1^2 + E_2^2 + 2E_1E_2\cos\theta}}$$

but $p_\perp \to 0$ for $\theta \to \pi$ (unless $E_1 = E_2$)



even though m^2 large, so ought to be early, with small α_s

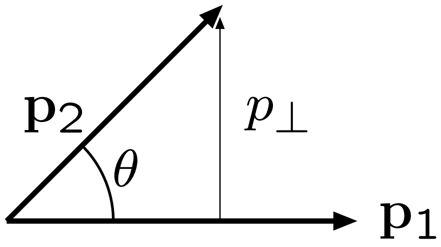
$$\texttt{LUCLUS/PYCLUS}\ (1981):\ \text{if } \theta \to 0 \text{ then } \begin{cases} \sin\theta \approx 2\sin(\theta/2) \\ |\mathbf{p}_1 + \mathbf{p}_2| \approx E_1 + E_2 \end{cases}$$

$$\Longrightarrow p_\perp = \frac{|\mathbf{p}_1 \times \mathbf{p}_2|}{|\mathbf{p}_1 + \mathbf{p}_2|} \approx \frac{E_1 E_2 2\sin(\theta/2)}{E_1 + E_2} \equiv p_{\perp\mathrm{L}}$$

$$p_{\perp\mathrm{L}}^2 = \frac{E_1}{E_1+E_2}\frac{E_2}{E_1+E_2} 2E_1E_2(1-\cos\theta) = z(1-z)m^2 = \mathrm{p}_{\perp\mathrm{evol}}^2$$

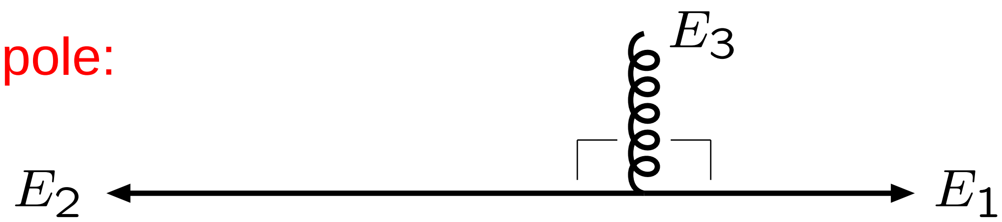
(in rest frame of dipole; not normally the case in LUCLUS/PYCLUS)

Durham clustering algorithm:



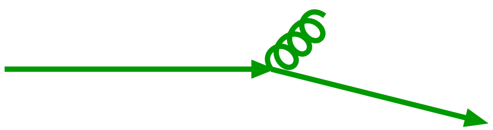
$$\begin{aligned} p_\perp &= \min(E_1, E_2)\sin\theta \\ &\approx \min(E_1, E_2) 2\sin(\theta/2) \equiv p_{\perp\mathrm{D}} \\ p_{\perp\mathrm{L}} &= \frac{\max(E_1, E_2)}{E_1 + E_2} p_{\perp\mathrm{D}} \end{aligned}$$

ARIADNE dipole:



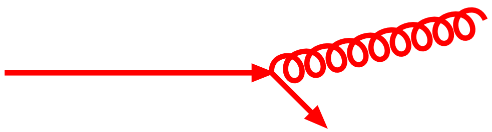
$$p_\perp^2 = E_3^2 = \frac{(2E_1E_3)(2E_2E_3)}{4E_1E_2} = \frac{m_{13}^2 m_{23}^2}{m_{12}^2} \approx \frac{m_{13}^2 m_{23}^2}{m_{123}^2} = p_{\perp\mathrm{A}}^2$$

$$m_{13}^2 \to 0 \implies p_{\perp\mathrm{A}}^2 \to m^2 \frac{m_{23}^2}{m_{123}^2} = m^2 (1 - x_1) = (1 - z)\, m^2$$



$z \to 1 \;\Leftrightarrow\;$ soft-gluon limit:

$$p_{\perp\mathrm{A}}^2 \approx (1 - z) m^2 \approx p_{\perp\mathrm{L}}^2$$



$z \to 0 \;\Leftrightarrow\;$ hard-gluon tail:

$$p_{\perp\mathrm{A}}^2 \approx m^2 \gg z\, m^2 \approx p_{\perp\mathrm{L}}^2$$

The ISR algorithm

1) Start with two incoming partons at hard interaction.

2) Evolve both radiators downwards from common $p_{\perp \mathrm{max}}$.
Pick the one that branches at the largest actual $\mathrm{p}_{\perp \mathrm{evol}}$.

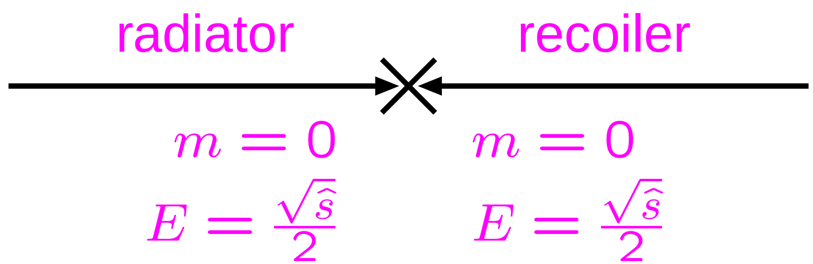
a) Massive quarks: not yet considered.

b) $z_{\mathrm{min}}(\mathrm{p}^2_{\perp \mathrm{evol}}, \hat{s}, x) < z < z_{\mathrm{max}}(\mathrm{p}^2_{\perp \mathrm{evol}}, \hat{s})$
with $\hat{s} = m_{12}^2 = (p_1 + p_2)^2 = x_1 x_2 s$.

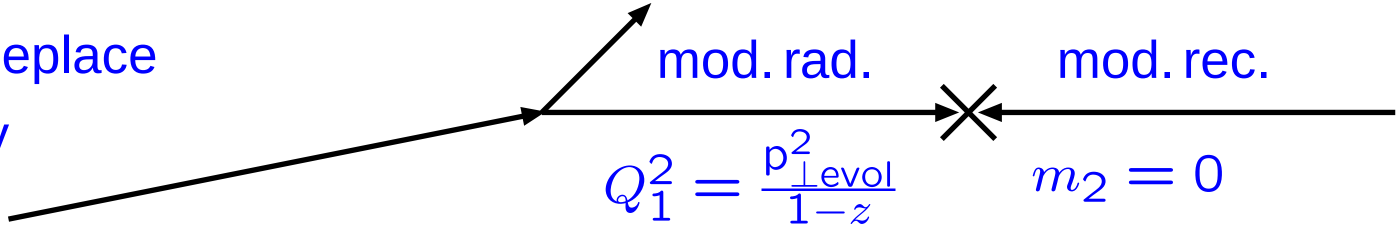
c) Matrix-element merging by veto for Z/W/H production.

3) Construct kinematics of branching:

a) Boost radiator+recoiler
to their rest frame;
radiator along $\pm z$ axis



b) Replace by

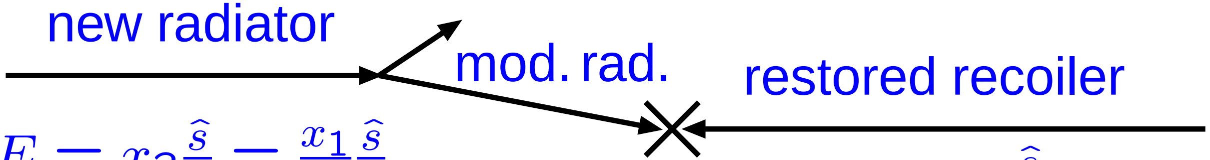


$Q_1^2 = \frac{p_{\perp\mathrm{evol}}^2}{1-z}$ $\quad m_2 = 0$

$m_{32}^2 = \frac{\hat{s}}{z} = x_3 x_2 s$ $\quad E_1 = \frac{\hat{s}-Q_1^2}{2\sqrt{\hat{s}}}$ $\quad E_2 = \frac{\hat{s}+Q_1^2}{2\sqrt{\hat{s}}}$

c) φ angle currently isotropic

d) Rotate and boost back



$E = x_3\frac{\hat{s}}{2} = \frac{x_1}{z}\frac{\hat{s}}{2}$ $\quad E = x_2\frac{\hat{s}}{2}$

Actual $p_\perp^2 = (1-z)Q_1^2 - z\frac{Q_1^4}{\hat{s}} < p_{\perp\mathrm{evol}}^2$

since now z invariant-mass^2 fraction, not lightcone

(so that simpler merging with matrix elements, e.g. resonance mass).

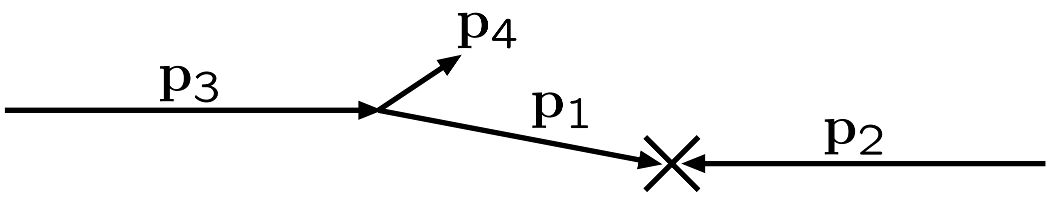
4) Continue evolution on both sides from recently picked $p_{\perp\mathrm{evol}}$.

Iterate until no branching above $p_{\perp\mathrm{min}}$.

$\Rightarrow$ One combined sequence $p_{\perp\mathrm{max}} > p_{\perp 1} > p_{\perp 2} > \ldots > p_{\perp\mathrm{min}}$.

Transverse momentum definition(s)

Study kinematics of $3 \to 1 + 4$ in rest frame of $3 + 2$:

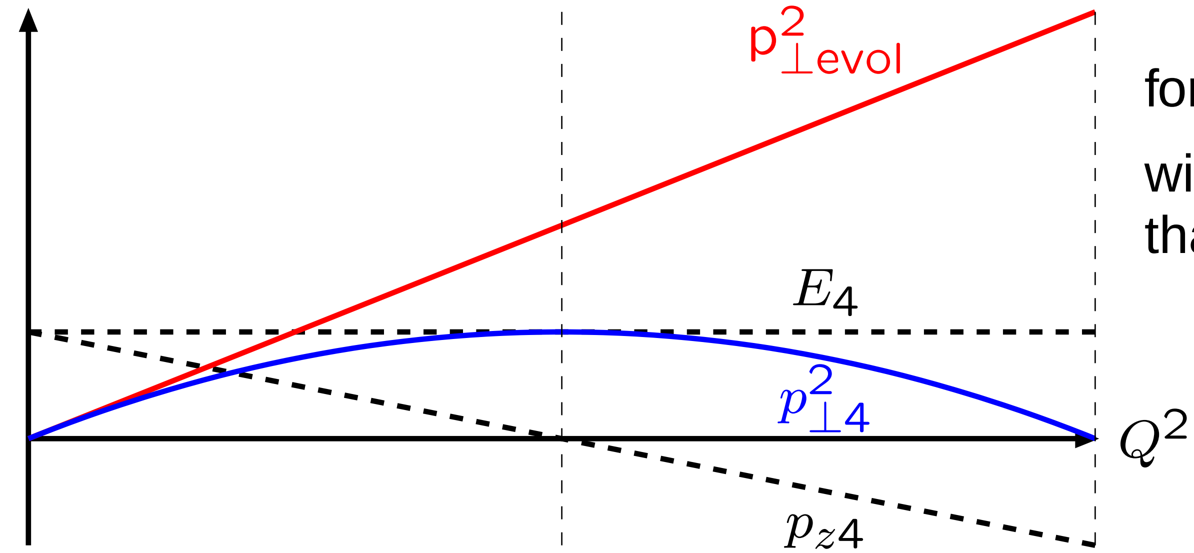


$$(p_1 + p_2)^2 = \widehat{s}$$

$$(p_3 + p_2)^2 = \frac{\widehat{s}}{z} = \widehat{s}'$$

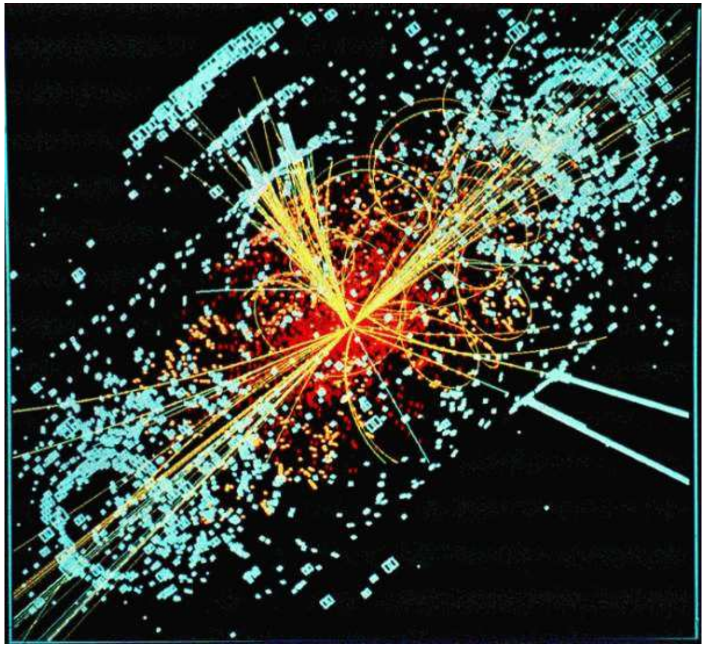
$$p_{3,2} = \frac{\sqrt{\widehat{s}'}}{2}(1; 0, 0, \pm 1)$$

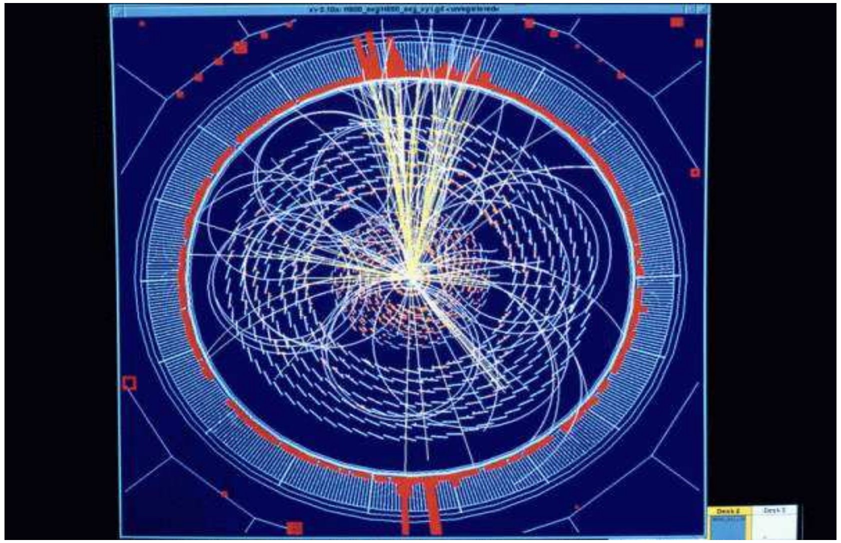
$$p_4 = \left(\frac{\sqrt{\widehat{s}'}}{2}(1-z); \sqrt{(1-z)Q^2 - \frac{Q^4}{\widehat{s}'}}, 0, \frac{\sqrt{\widehat{s}'}}{2}\left(1 - z - \frac{2Q^2}{\widehat{s}'}\right) \right)$$



for fixed $\widehat{s}$ and $z = 1/2$,

with units such that $E_4 = 1$





The structure of an event

Multiple interactions

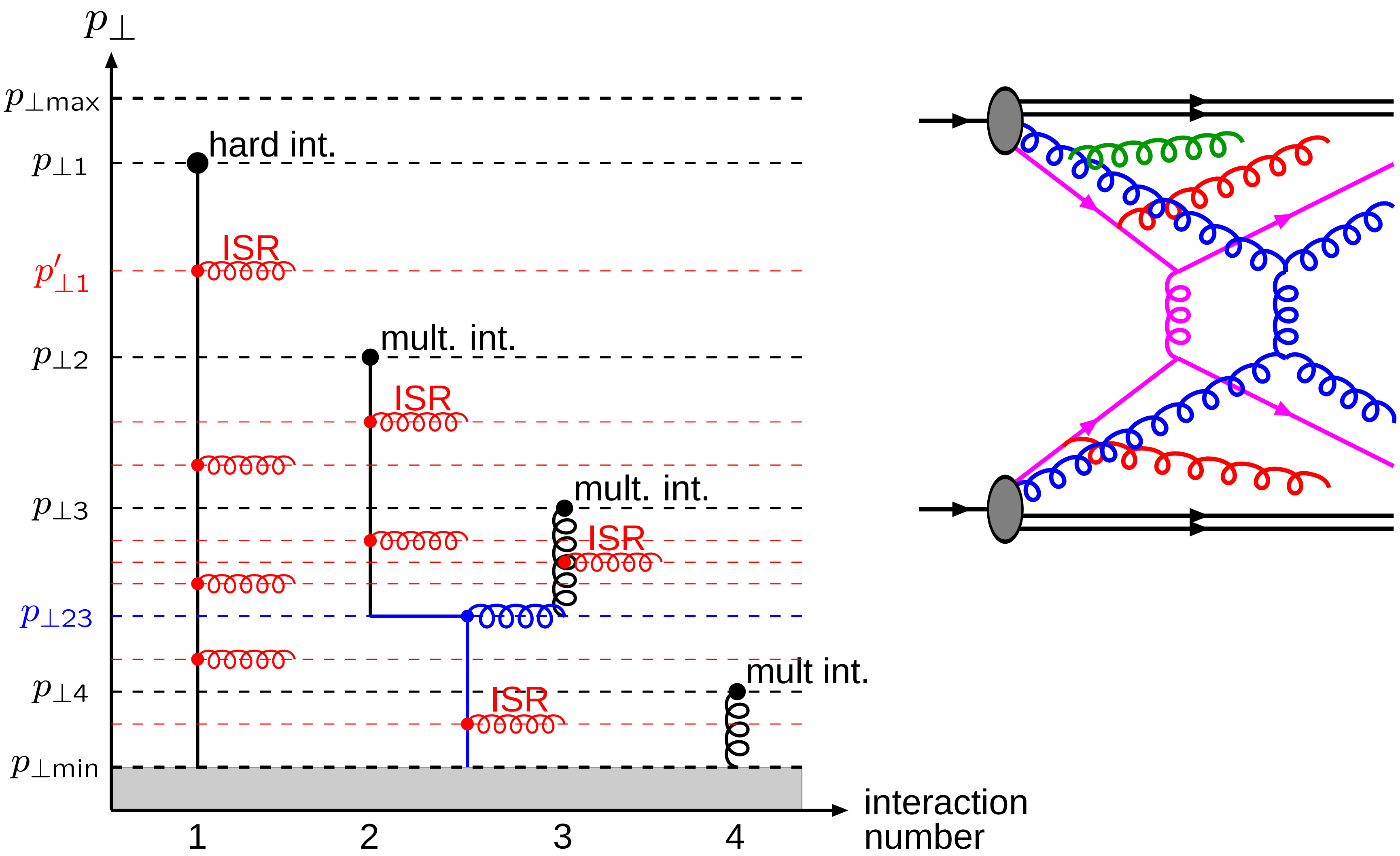
The $p_\perp$-based philosophy

$p_\perp$-ordered showers

Interleaved interactions

Outlook

Interleaved Multiple Interactions



Competition

"Evolution" equation, only Multiple Interactions:

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

Evolution equation, only Initial State Radiation:

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

Evolution equation, MI + ISR, with competition for PDF and phase space:

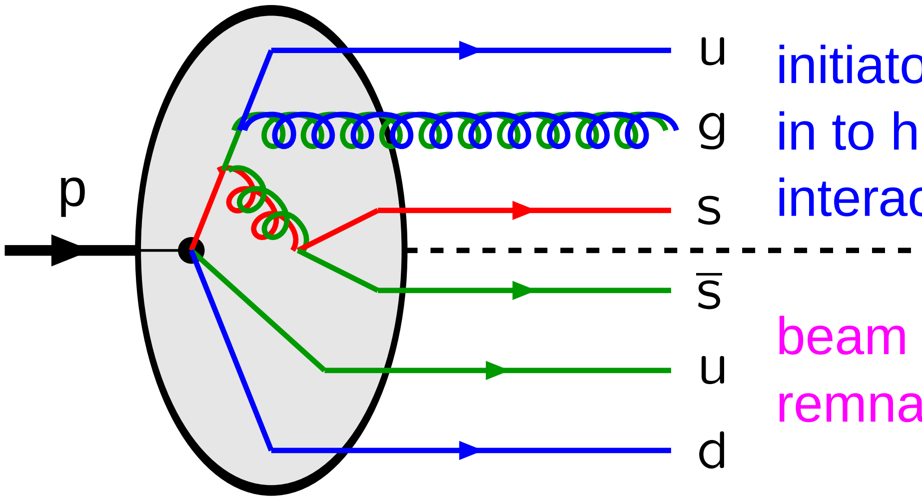
$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}p_\perp} = \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MI}}}{\mathrm{d}p_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p_\perp}\right) \exp\left(-\int_{p_\perp}^{p_{\perp i-1}} \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MI}}}{\mathrm{d}p'_\perp}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

with ISR sum running over all previous MI

$\Rightarrow$ one interleaved sequence of MI and ISR

FSR: no competition so not required (but nice for ME merging)

Initiators and Remnants



Need to assign:

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

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

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

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

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

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

Various issues

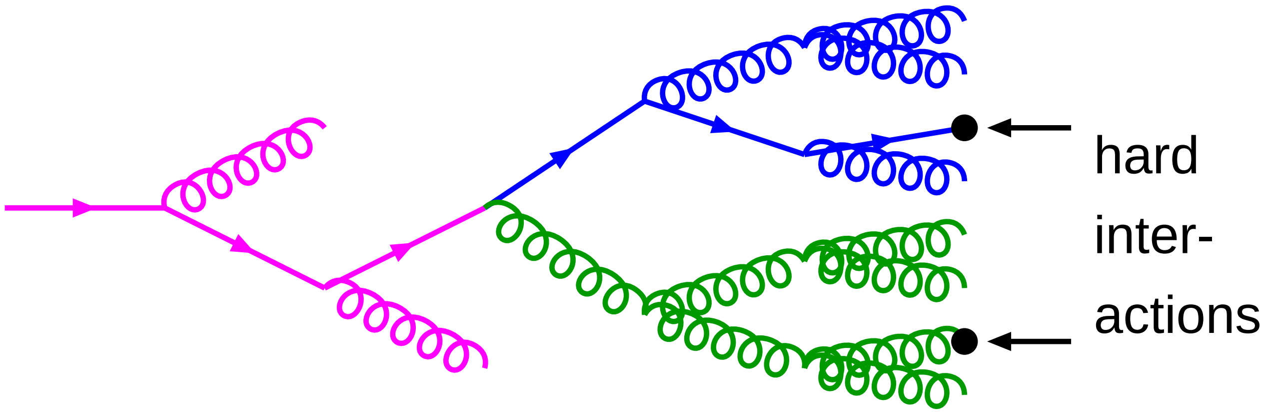
- **Regularization procedure:**

$$\alpha_s(p_\perp^2)\frac{dp_\perp^2}{p_\perp^2} \to \alpha_s(p_{\perp 0}^2 + p_\perp^2)\frac{dp_\perp^2}{p_{\perp 0}^2 + p_\perp^2}$$

common for MI (quadratically) and ISR by colour neutralization

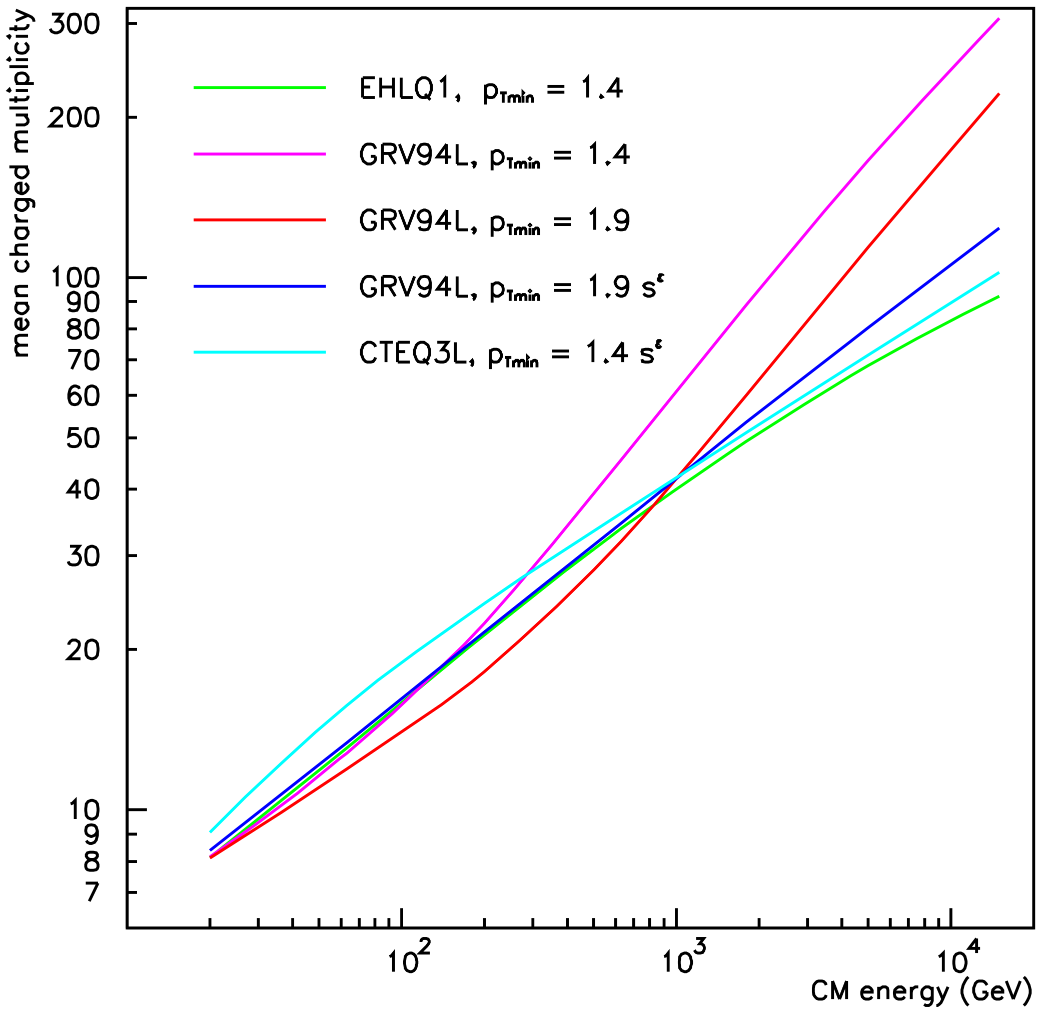
$p_{\perp 0} \approx$ 2–3 GeV energy-dependent

- **Intertwined interactions:**



Not (yet) explicitly included, but estimated; shown not to be critical

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



Larger collision energy

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

$\Rightarrow$ smaller colour screening length d

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

Post-HERA PDF fits steeper at small x

$\Rightarrow$ stronger energy dependence

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

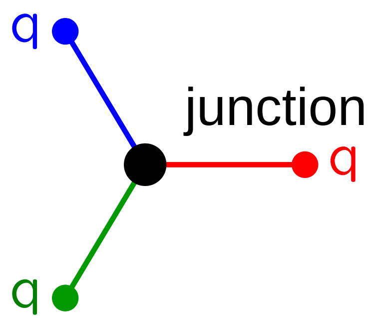
$$p_{\perp\mathrm{min}}(s) = 2.0 \text{ GeV} \left(\frac{s}{(1.8 \text{ TeV})^2} \right)^{0.08}$$

- **Where does the baryon number go?**

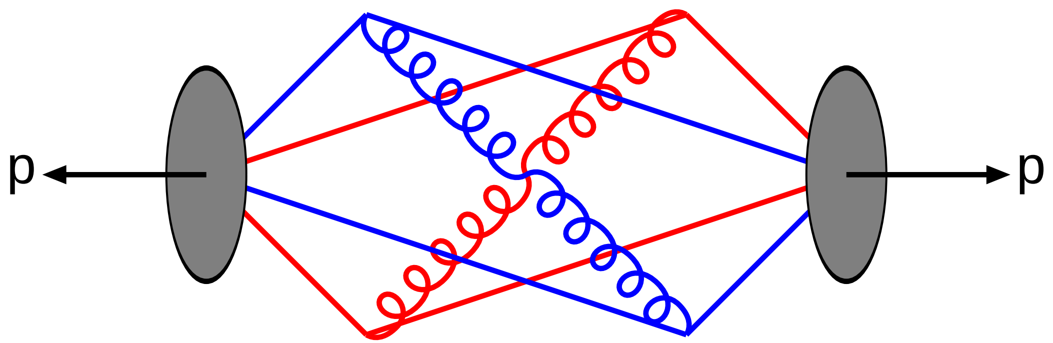
Junction "carries" baryon number!

Motion determined by colour flow attached to it.

Messy hadronization (but handled with model)



- **Colour correlations**



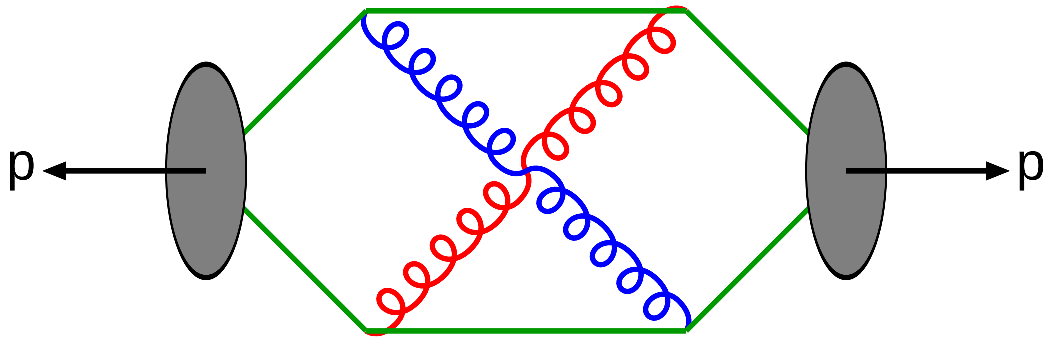
long strings to remnants

$\Rightarrow$ much n_{ch}/interaction

$\Rightarrow$ few interactions

$\Rightarrow$ little $p_{\perp\text{pert}}$

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



short strings (more central)

$\Rightarrow$ less n_{ch}/interaction

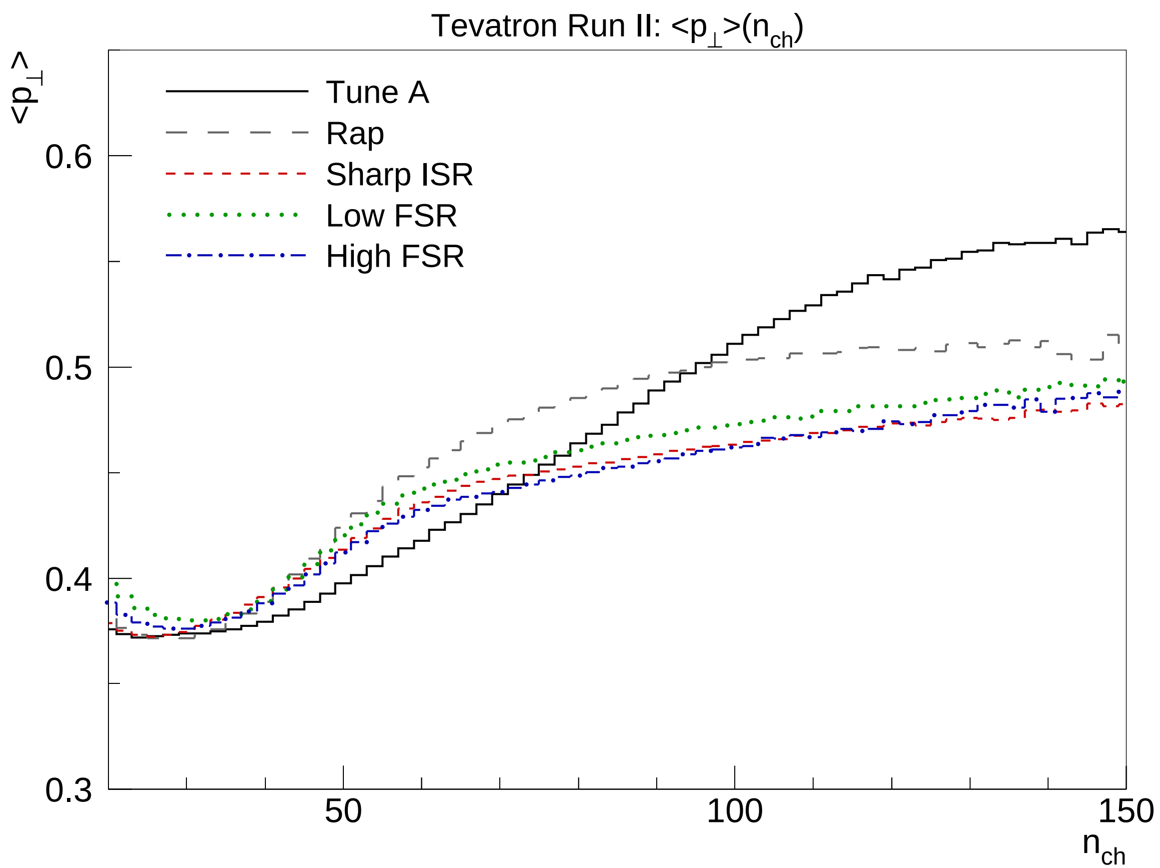
$\Rightarrow$ more interactions

$\Rightarrow$ more $p_{\perp\text{pert}}$

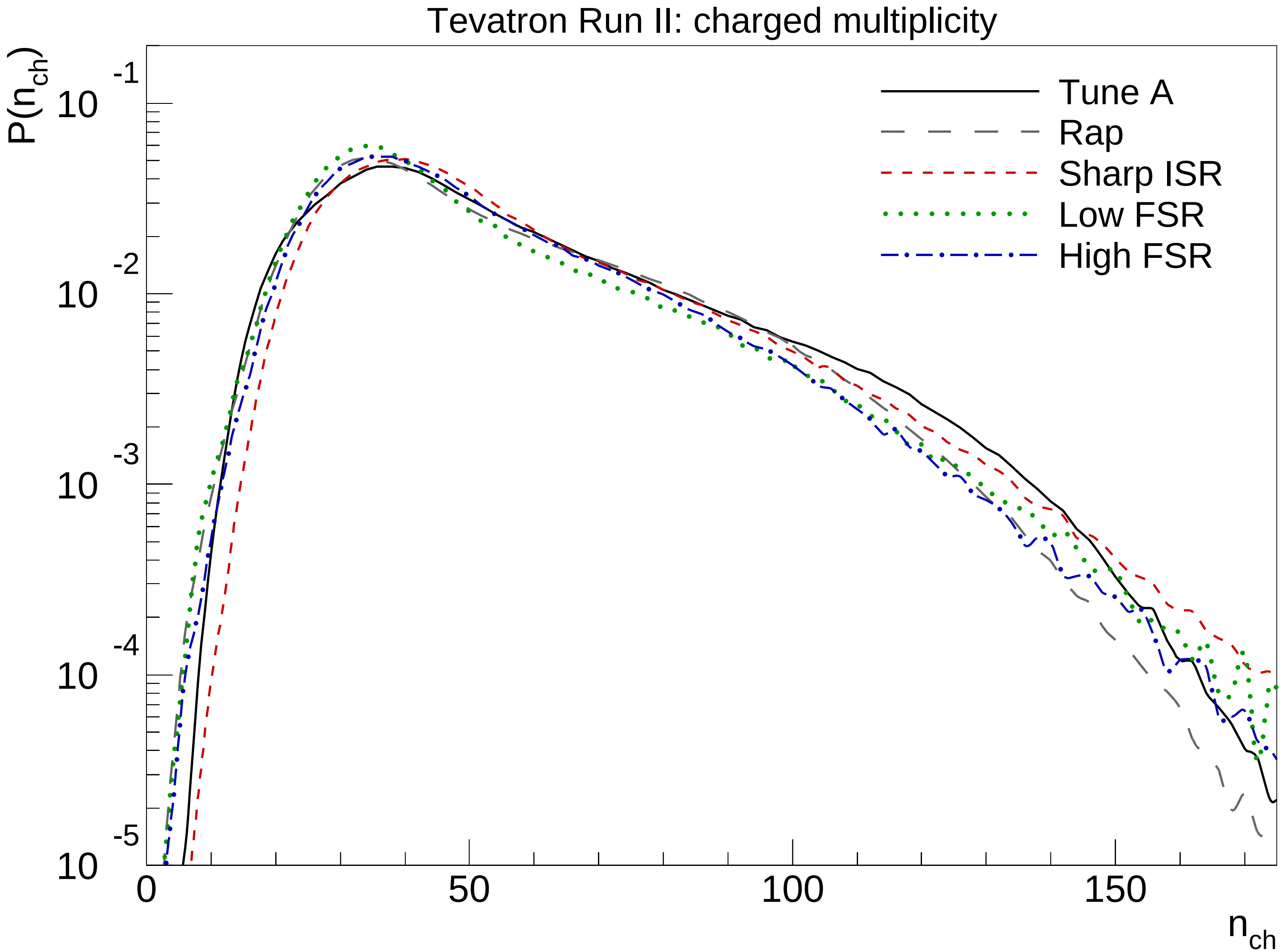
$\Rightarrow$ $\langle p_\perp \rangle (n_{\text{ch}})$ rising

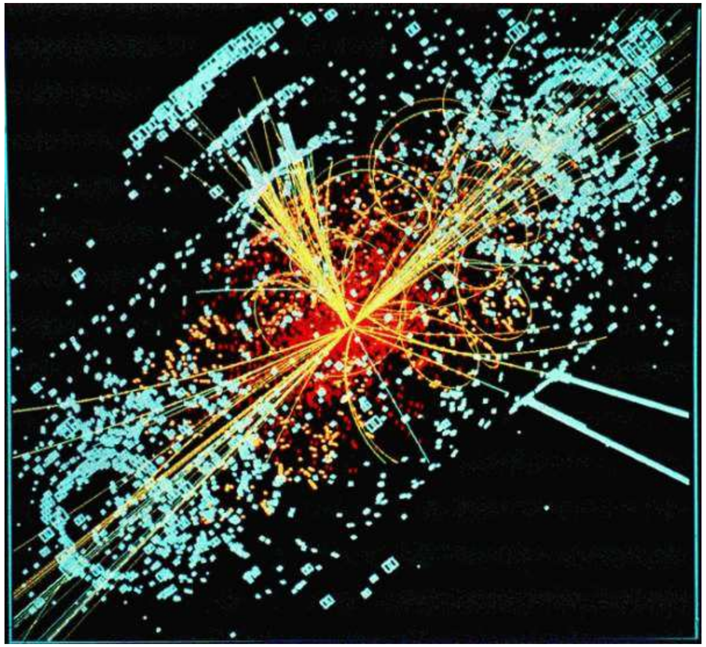
Data comparisons

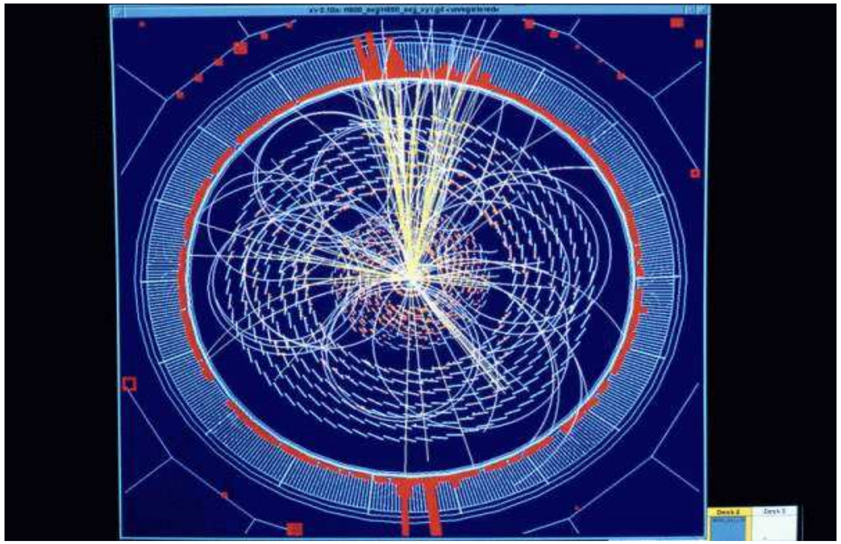
usually comparable with Tune A (for better or worse), but
still in need of good tuning and detailed tests, and . . .
. . . $\langle p_\perp \rangle (n_{ch})$ problematical (need very short string!)



colour correlations not yet understood!


Tevatron Run II: charged multiplicity
$P(n_{ch})$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
50
100
150
n_{ch}
Tune A
Rap
Sharp ISR
Low FSR
High FSR





The structure of an event

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Outlook

How to make progress?

The new MI/ISR/FSR scenario is available in PYTHIA $\geq$6.312,
but is not the end of the road:
Need model building $\Leftrightarrow$ experimental tests

Need reference samples over wide energy range:

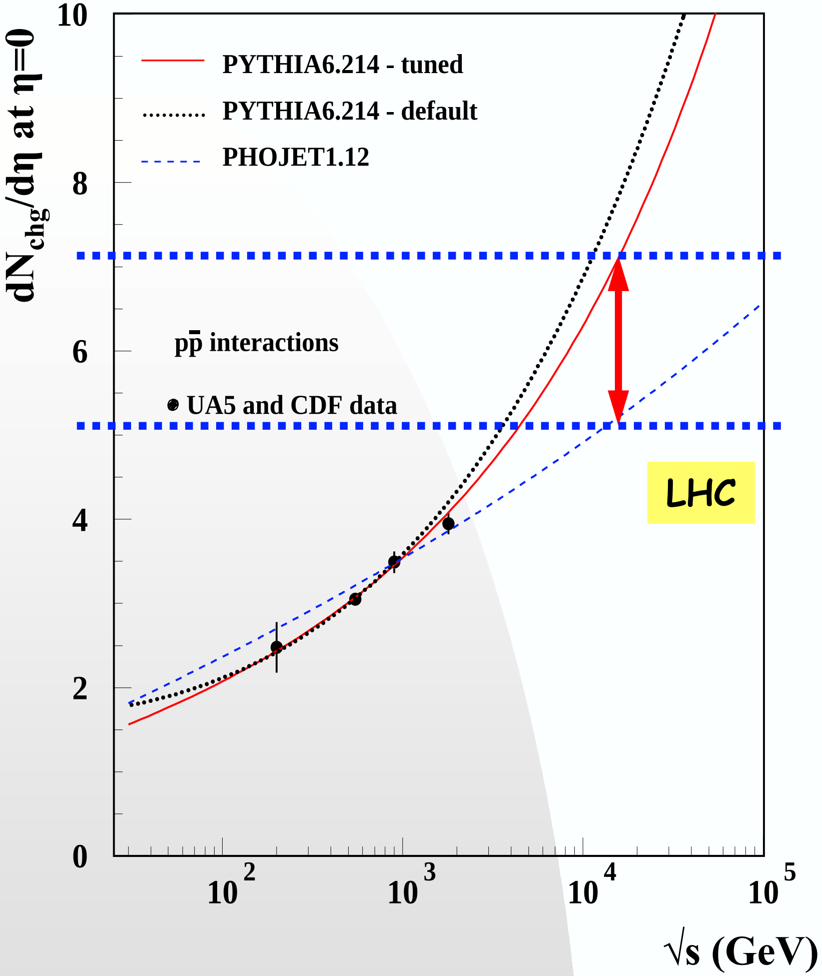
- $\sim$ 20 GeV: fixed target
- $\sim$ 63 GeV: ISR
- $\sim$ 200 GeV: Sp$\overline{\text{p}}$S, RHIC
- $\sim$ 630 GeV: Sp$\overline{\text{p}}$S, Tevatron
- $\sim$ 2 TeV: Tevatron

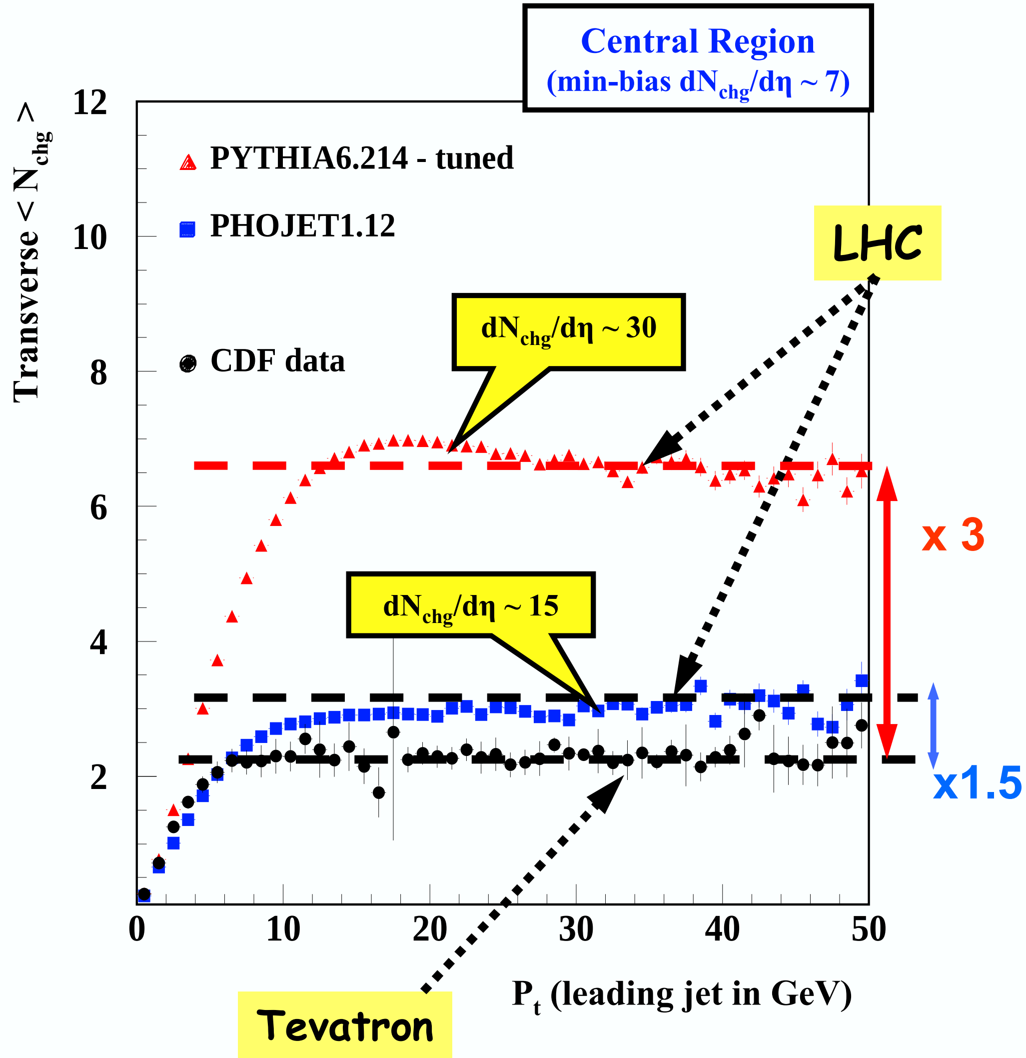
Need corrected and reliable distributions of:

- global quantities: n_{ch}
- single-particle spectra: y and $p_{\perp}$
- correlations: y, $p_{\perp}$, φ, $\langle p_{\perp} \rangle (n_{\text{ch}})$
- jet and minijet properties: $n_{\text{minijet}}(E_{\perp\text{jet}})$, jet profile and pedestal
- rapidity gap size and position
- other interesting properties?

Need it all in a form usable to outsiders $\Longrightarrow$ JetWeb?

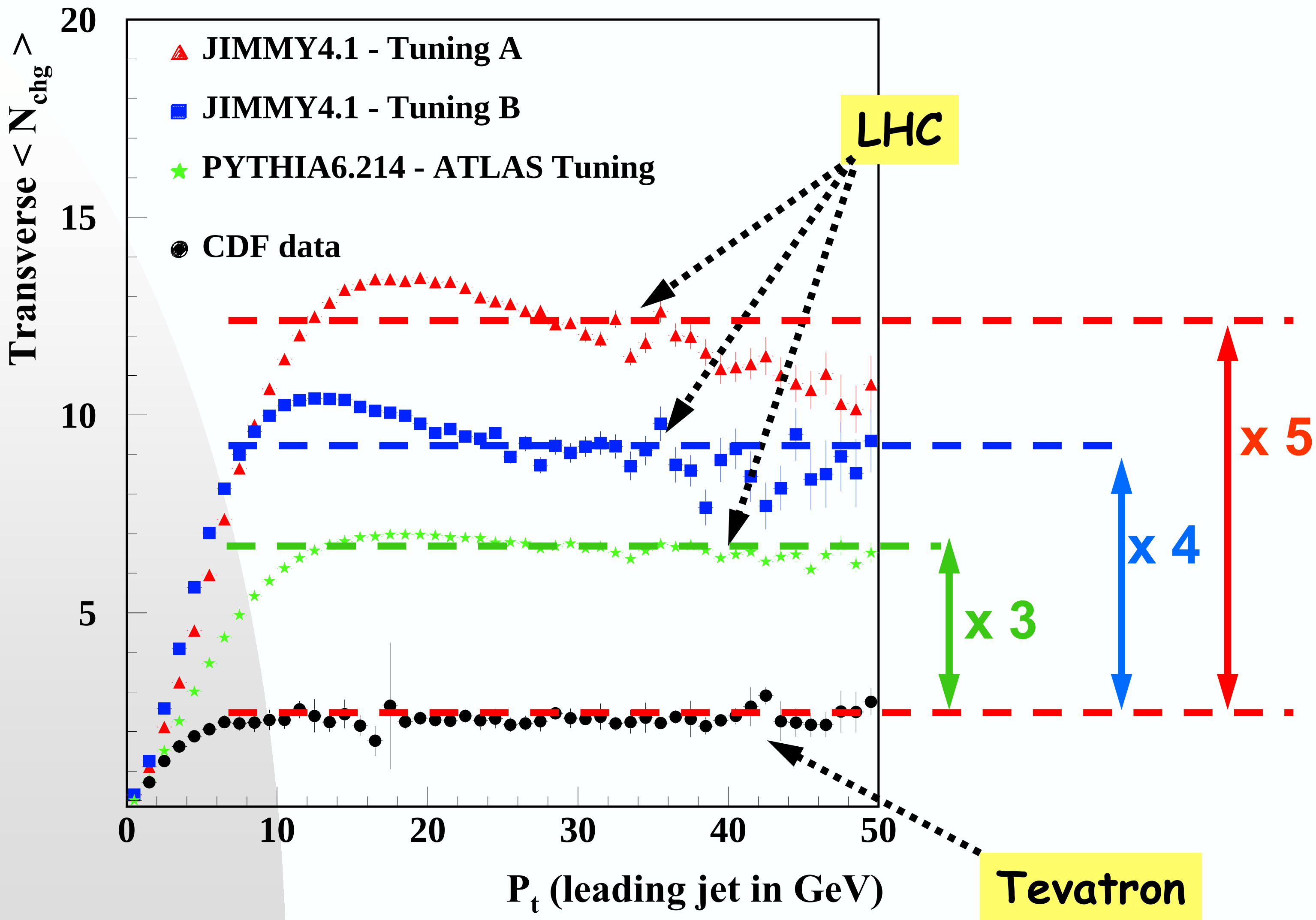
LHC predictions: pp collisions at √s = 14 TeV





- 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)



Outlook

⋆ Multiple interactions concept compelling; it *has to* exist at some level.
By now, **strong** direct evidence, **overwhelming** indirect evidence

⋆ Understanding of multiple interactions crucial for LHC precision physics

⋆ Many details uncertain

- $p_{\perp\mathrm{min}}/p_{\perp 0}$ cut-off
- impact parameter picture
- energy dependence
- multiparton densities in incoming hadron
- colour correlations between scatterings
- interferences between showers
- ...

⋆ 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. . . .