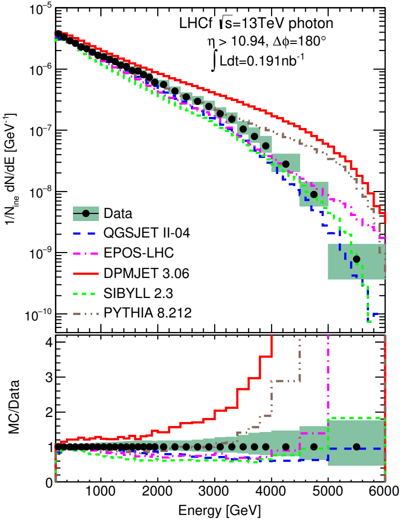
Forward Physics in PYTHIA 8

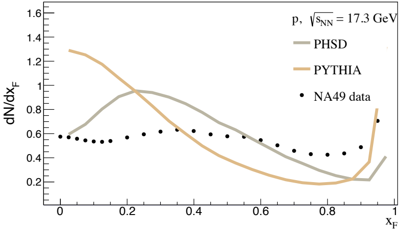
Torbjörn Sjöstrand

Department of Astronomy and Theoretical Physics
Lund University
Sölvegatan 14A, SE-223 62 Lund, Sweden

Forward Physics Facility Kickoff Meeting, 9-10 November 2020

Forward data - 1





V. Kireyeu et al., arXiv:2006.14739

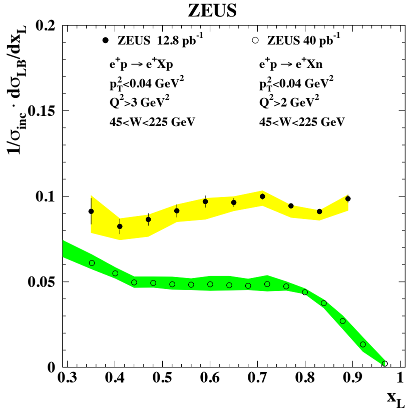
LHCf, PLB 78, 233

Need mechanism for protons to take more energy (from pions)? Diffractive-related or not?

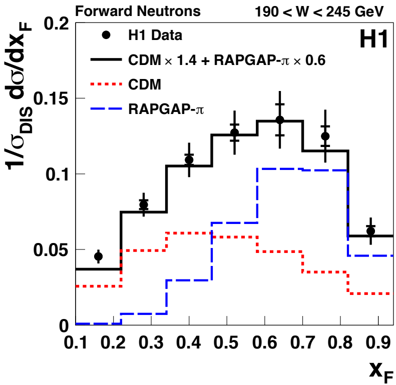
Forward region also important for cosmic-ray physics.

Forward data - 2

Cleanest environment may be DIS:



ZEUS, JHEP 06 (2009) 074



H1, EPJC 74 (2014) 2915

Data exists, but need RIVET analyses to facilitate comparisons.

Simple remnants

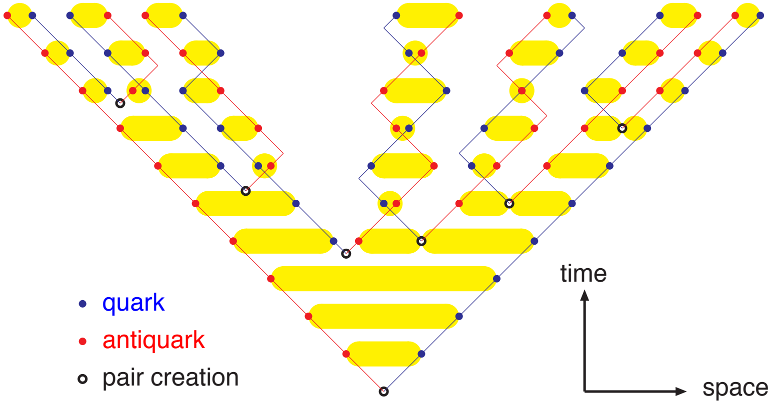
Assume **one** parton kicked out of proton, in pp (or DIS):

1. Kick out valence quark: colour triplet diquark left,
   $\Rightarrow$ single string stretched out from beam remnant.
2. Kick out gluon: colour octet $q_1 q_2 q_3$ remnant left
   $\Rightarrow$ split momentum between two strings,
   one to $q_1 q_2$ antitriplet and one to q_3 triplet.
3. Kick out sea antiquark $\overline{q}_4$: colour triplet $q_1 q_2 q_3 q_4$ remains,
   $\Rightarrow$ split momentum between $B = q_1 q_2 q_4$ singlet
   and string to q_3 triplet.
4. Kick out sea quark q_4: colour antitriplet $q_1 q_2 q_3 \overline{q}_4$ remains,
   $\Rightarrow$ split momentum between $M = q_1 \overline{q}_4$ singlet
   and string to $q_2 q_3$ antitriplet.

13 TeV pp nondiffractive collisions:
$\sim$85% gluons, $\sim$5% each for others;
(but no gluons for DIS to LO)

The Lund Model

Combine yo-yo-style string motion with string breakings!

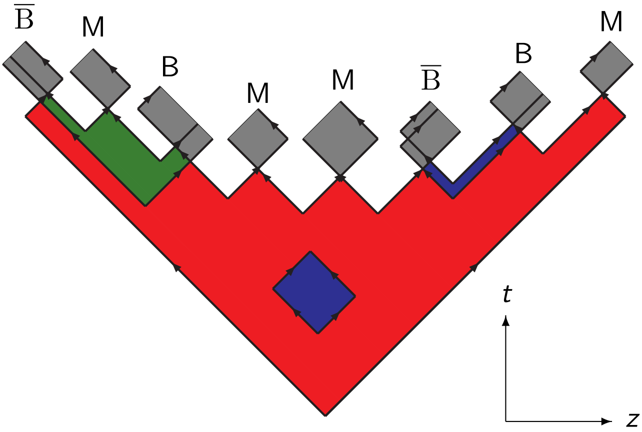


A q from one string break combines with a $\overline{\mathrm{q}}$ from an adjacent one.

String tension $\kappa \approx 1$ GeV/fm relates $(t, \mathbf{x})$ and $(E, \mathbf{p})$.

Gives simple but powerful picture of hadron production.

The popcorn model for baryon production



- SU(6) (flavour×spin) Clebsch-Gordans needed.
- Expected strong suppression of multistrange and spin 3/2 baryons damped by effective parameters.

Fragmentation and beam remnants

Recursive fragmentation from one end:

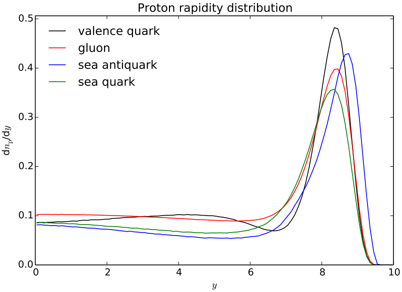
$$f(z) \propto \frac{1}{z} (1-z)^a \exp\left(-\frac{b m_\perp^2}{z}\right) , \quad z = \frac{(E+p_z)_{\mathrm{hadron}}}{(E+p_z)_{\mathrm{left\ in\ string}}}$$

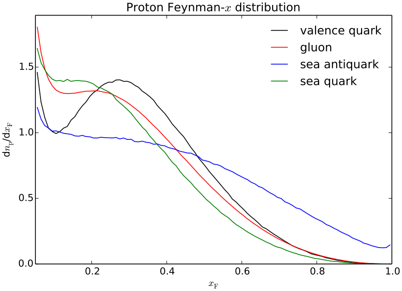
By default $a = 0.68$ and $b = 0.98$ GeV^{-2} from LEP tune.
To be continued ...

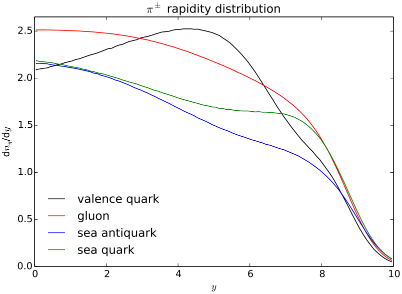
Split momentum between remnant parts:

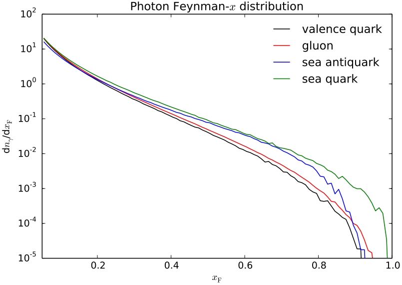
1. for each valence quark pick x_i according to $(1-x_i)^p/\sqrt{x_i}$, with $p = 3.5$ for u and $p = 2.0$ for d
2. for diquark form $x_{ij} = 2(x_i + x_j)$ from above
3. for sea (anti)quark use kicked-out sister x (in hard process) as if pair comes a from $\mathrm{g} \to \mathrm{q}_4\overline{\mathrm{q}}_4$ perturbative splitting
4. rescale sum to remaining beam momentum

Simple results



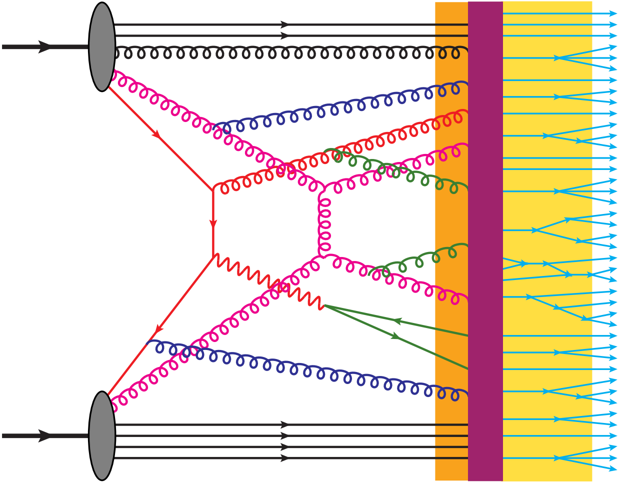






The structure of an event

An event consists of many different physics steps to be modelled:



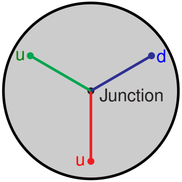
PDF
ME
ISR
FSR
M&M
MPI
BBR
CR
Fragmentation
Decays
Rescattering
BE
$\sigma_{\mathrm{tot}} = \cdots$
Unknown?

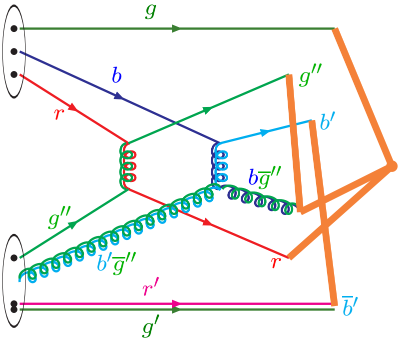
Fragmentation can include clusters, strings, ropes, QGP, shove, . . .

Junctions and the baryon number

A proton can be visualized as a Y-shaped topology, with a valence quark at the end of each leg and a junction in the middle.

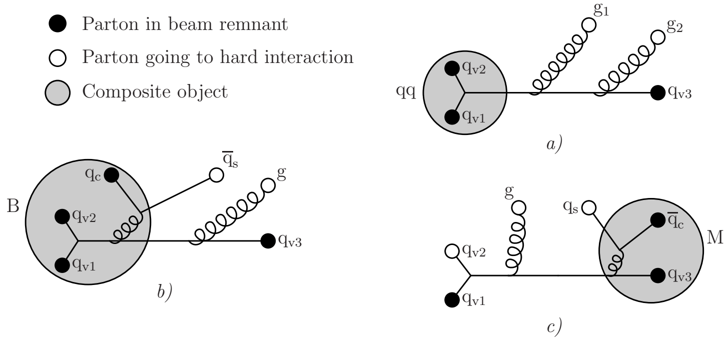
Two valence quarks can be kicked out if two or more MPIs.





The junction then can be shifted in towards center of event, carrying the baryon number and baryon production with it.

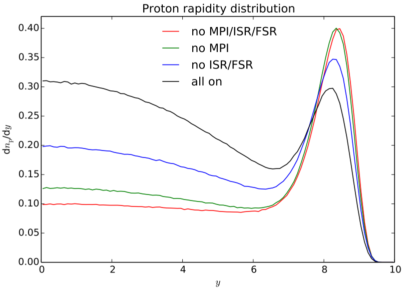
Beam remnants – the general case

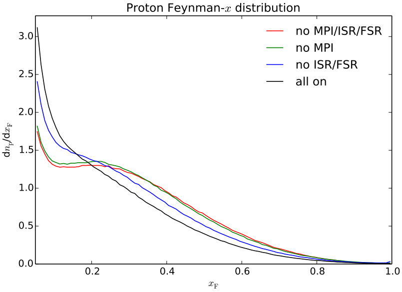


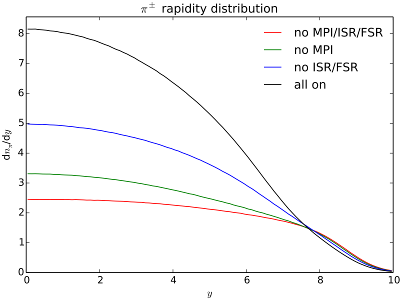
Need to model:

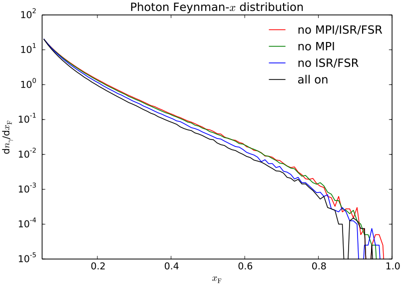
- Flavour content of remnant; also valence vs. sea/companion
- Colour structure of partons; including junctions and CR
- Longitudinal sharing of momenta
- Transverse sharing of momenta — primordial $k_\perp$ (nontrivially relates to low-$p_\perp$ ISR handling)

Results for full model



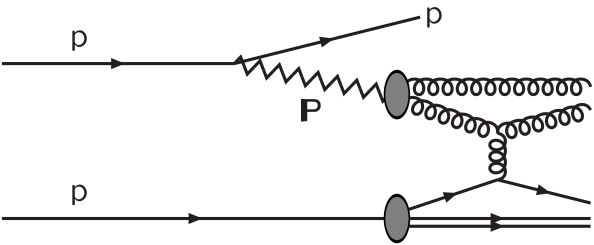






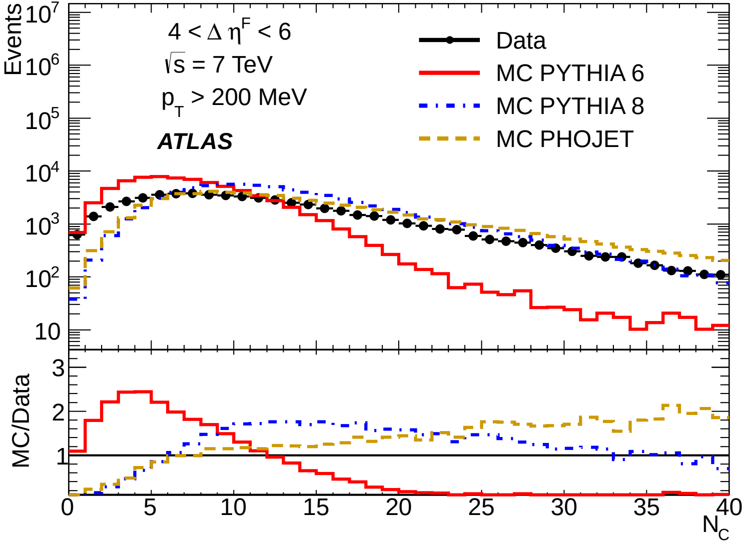
Diffraction

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



- Differential cross sections set by Reggeon theory, $\sim \mathrm{d}M_X^2/M_X^2$.
- Smooth transition from low-mass simple model
  to high-mass $\mathbb{P}$p with full pp machinery: MPIs, showers, etc.
- High-mass diffractive system ≈ like nondiffractive proton end,
  but recoling proton in single diffraction $\sim \mathrm{d}x_{\mathrm{F}}/(1 - x_{\mathrm{F}})$.

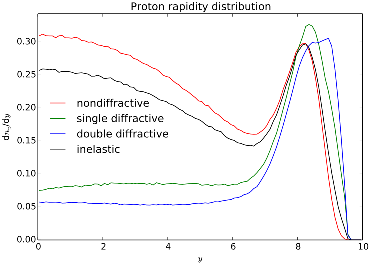
Multiplicity in diffractive events

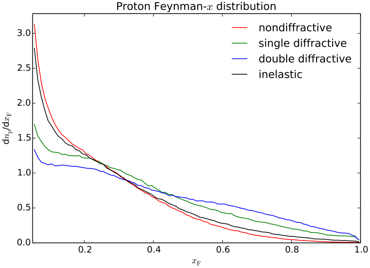


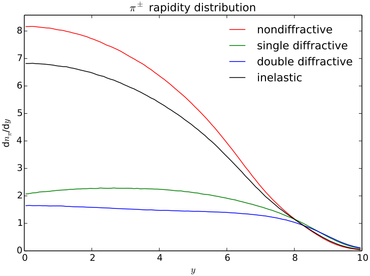
PYTHIA 6 lacks MPI, ISR, FSR in diffraction, so undershoots.

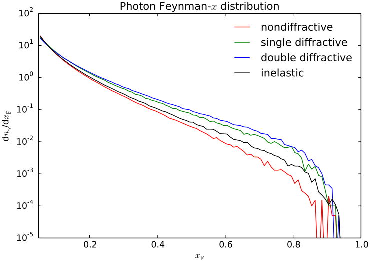
Results with diffraction

Excluding "elastically scattered" proton of single diffraction





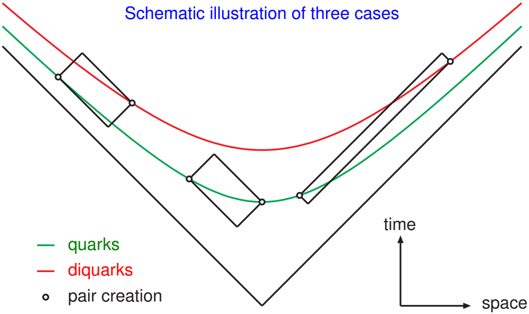




More on fragmentation functions

$$f(z) \propto \frac{1}{z} (1-z)^a \exp\left(-\frac{bm_\perp^2}{z}\right) \quad \Leftrightarrow \quad \mathcal{P}(\Gamma) \propto \Gamma^a \exp(-b\Gamma)$$

where $\Gamma = (\kappa\tau)^2$,
$\kappa \approx 1$ GeV/fm.

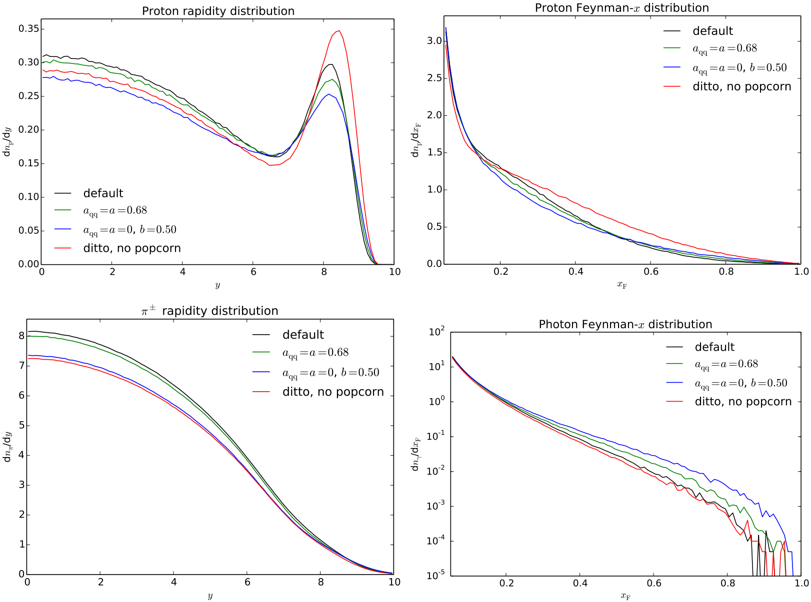


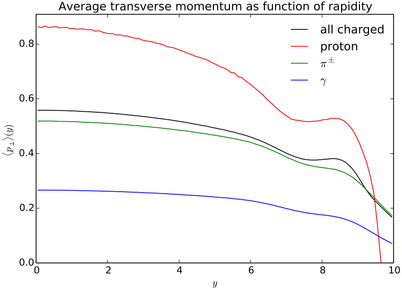
What if diquark takes longer to produce?
Favoured by LEP data:
$a_\mathrm{q} = 0.68$, $a_\mathrm{qq} = 1.65$.

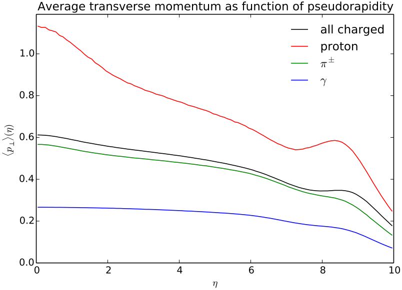
$$i \to j: \qquad f(z) \propto \frac{1}{z} z^{a_i} \left(\frac{1-z}{z}\right)^{a_j} \exp\left(-\frac{bm_\perp^2}{z}\right)$$

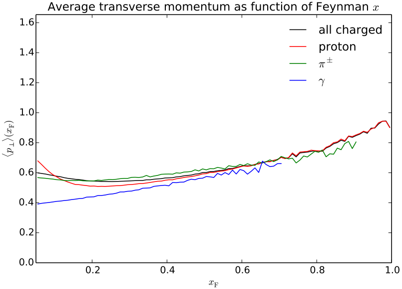
You do not escape from $(1-z)^a$ suppression for $z \to 1$!

Results for varied fragmentation function





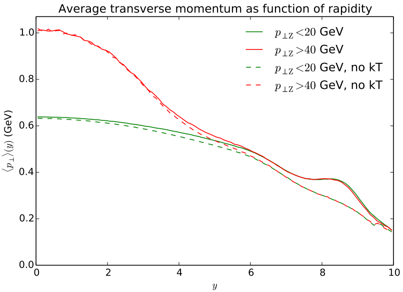


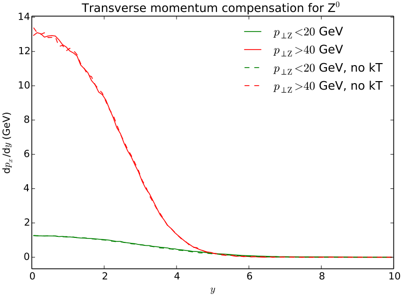


Is $\langle p_\perp \rangle$ increasing or decreasing in forward region?
Depends on what it is plotted as a function of!

Transverse momentum for hard process

Consider e.g. inclusive Z^0 production, with known $p_\perp$.
How is this compensated by the other particles in the event?





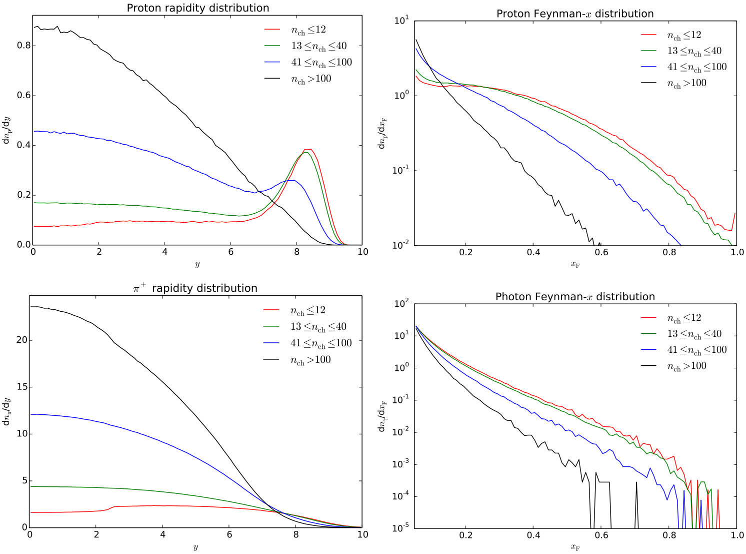
(Z^0 along $-x$ axis in transverse plane; π^0 set stable)

Conclusion 1: Primordial $k_\perp$ kicks are imposed on beam remnants, and does give higher $\langle p_\perp \rangle$ for $|y| > 5$.

Conclusion 2: hard $p_\perp$ kick does not influence $|y| > 5$ region.

Impact of central activity on forward one

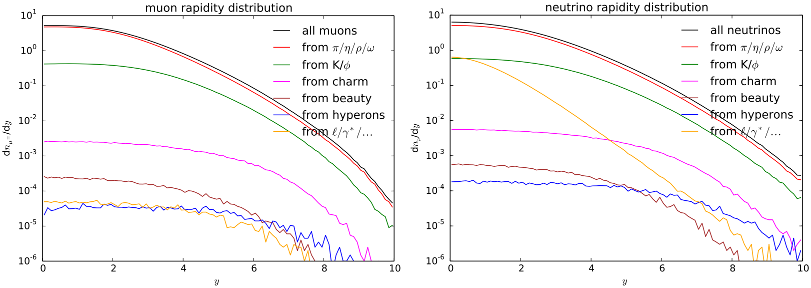
Classify nondiffractive events by charged multiplicity in $|\eta| < 2.5$:



Forward muons and neutrinos

Capability to trace full history of particle production and decay, including space–time evolution from fm to km scales.

Example: flux of muons and neutrinos 100 m from interaction, for total cross section (elastic/diffractive/nondiffractive):



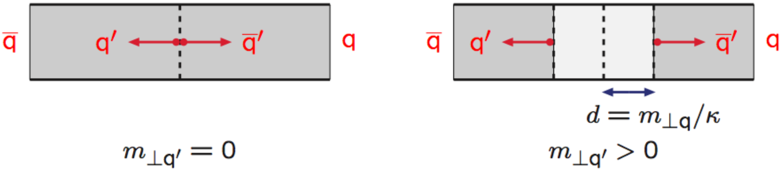
(note: secondary decays $\mathrm{D} \to \pi \to \mu$ count as π, not charm)

Summary

Forward physics is extensively modelled in PYTHIA . . .
. . . but little tested, and rather constrained,
e.g. central MPI activity $\Rightarrow$ possible remnant structures.
Action list:

- Gather existing data, implement in RIVET analyses
- Compare DIS and pp forward spectra
- Find way that gives more forward protons?
  (P. Edén, G. Gustafson, Z.Phys.C75 (1997) 41, "curtain quarks"?)
- Compare rate of different forward baryons (p, n, Λ, . . .)
  and mesons (π^+, π^-, $\mathrm{K}^0_{\mathrm{S}}$, . . .)
- Correlate flavour, y/x_{F} and $p_{\perp}$ for leading vs. second-leading particle. Consistent with single or multiple strings?
- Correlate central and forward activity
- Develop and implement new physics mechanisms?

Backup: How does the string break?



String breaking modelled by tunneling:

$$\mathcal{P} \propto \exp\left(-\frac{\pi m_{\perp q}^2}{\kappa}\right) = \exp\left(-\frac{\pi p_{\perp q}^2}{\kappa}\right) \exp\left(-\frac{\pi m_{q}^2}{\kappa}\right)$$

- Common Gaussian $p_\perp$ spectrum, $\langle p_\perp \rangle \approx 0.4$ GeV.
- Suppression of heavy quarks,
  $\mathrm{u\overline{u}} : \mathrm{d\overline{d}} : \mathrm{s\overline{s}} : \mathrm{c\overline{c}} \approx 1 : 1 : 0.3 : 10^{-11}$.
- Diquark $\sim$ antiquark $\Rightarrow$ simple model for baryon production.
  Extended by popcorn model: consecutive $\mathrm{q\overline{q}}$ pair production

Backup: MPIs in PYTHIA

- MPIs are gererated in a falling sequence of $p_\perp$ values; recall Sudakov factor approach to parton showers.
- Core process QCD $2 \to 2$, but also onia, γ's, $\mathrm{Z}^0, \mathrm{W}^\pm$.
- Energy, momentum and flavour conserved step by step: subtracted from proton by all "previous" collisions.
- Protons modelled as extended objects, allowing both central and peripheral collisions, with more or less activity.
- Colour screening increases with energy, i.e. $p_{\perp 0} = p_{\perp 0}(E_{\mathrm{cm}})$, as more and more partons can interact.
- Colour connections: each interaction hooks up with colours from beam remnants, but also correlations inside remnants.
- Colour *re*connections: many interaction "on top of" each other $\Rightarrow$ tightly packed partons $\Rightarrow$ colour memory loss?

Backup: Interleaved evolution in PYTHIA

- Transverse-momentum-ordered parton showers for ISR and FSR
- MPI also ordered in $p_\perp$

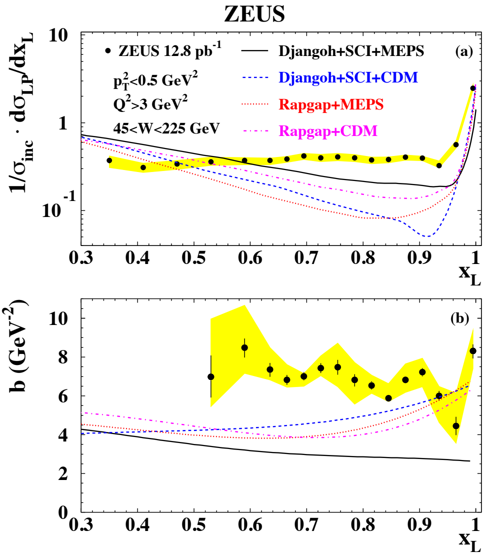
$\Rightarrow$ Allows interleaved evolution for ISR, FSR and MPI:

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

Ordered in decreasing $p_\perp$ using “Sudakov” trick.
Corresponds to increasing “resolution”:
smaller $p_\perp$ fill in details of basic picture set at larger $p_\perp$.

- Start from fixed hard interaction $\Rightarrow$ underlying event
- No separate hard interaction $\Rightarrow$ minbias events
- Possible to choose two hard interactions, e.g. $\mathrm{W}^-\mathrm{W}^-$

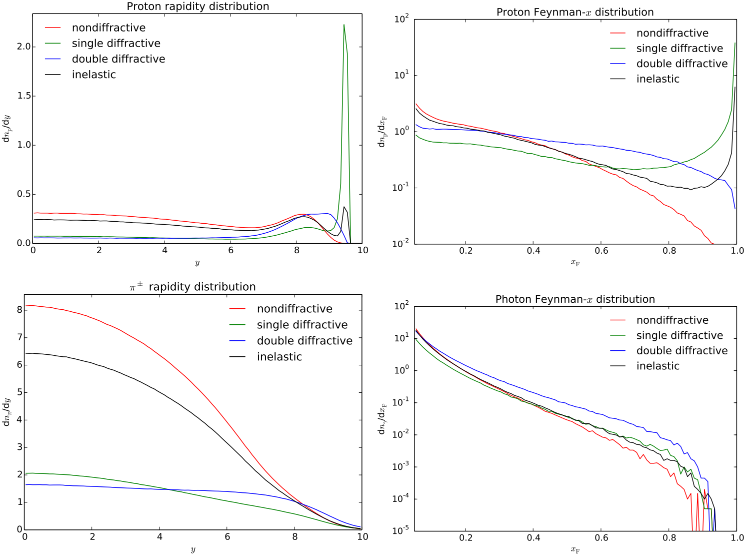
Backup: ZEUS comparison



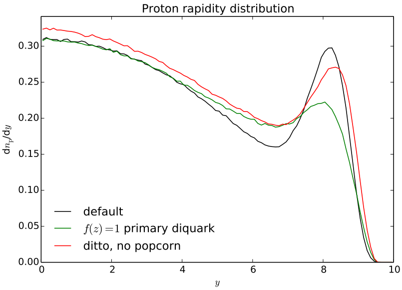
ZEUS,
JHEP 06 (2009) 074

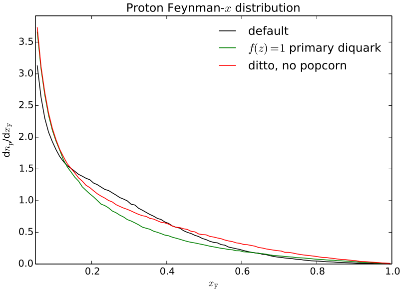
Backup: Results with diffraction

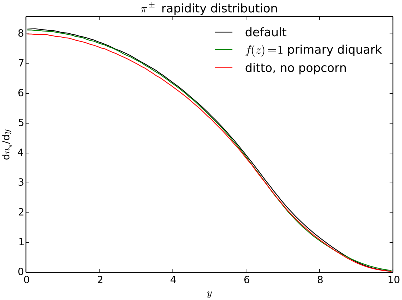
Including "elastically scattered" proton of single diffraction

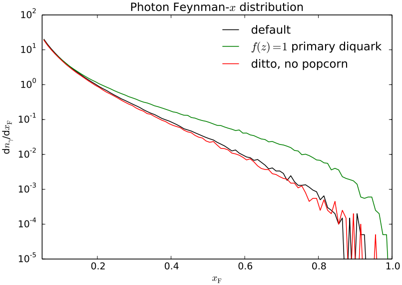


Backup: Results for flat $f(z)$ for primary diquark

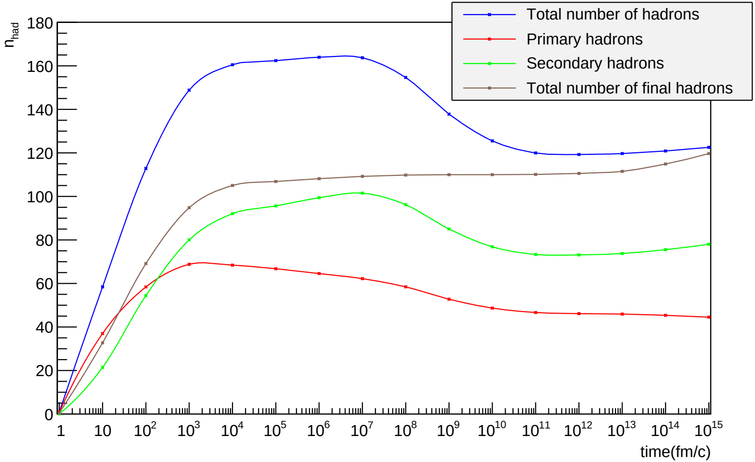








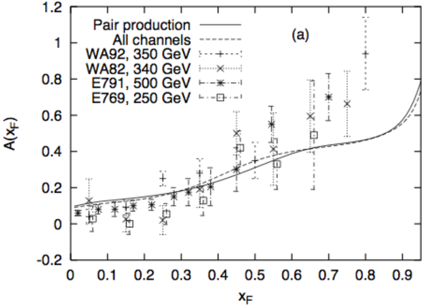
PYTHIA can calculate production vertex of each particle,
e.g. number of hadrons as a function of time for pp at 13 TeV:



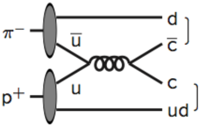
S. Ferreres-Solé, TS, EPJC 78, 983

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

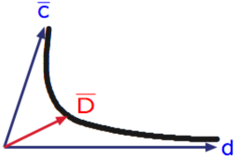
$$A(x_F) = \frac{\#D^- - \#D^+}{\#D^- + \#D^+}$$



(also B asymmetries at LHC, but small)



If low-mass string e.g.:
$\bar{c}d$: 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