PYTHIA 8 STATUS

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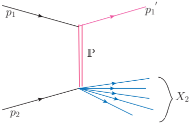
PYTHIA 8

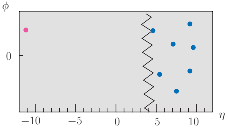
- PYTHIA 8 is the C++ rewrite of PYTHIA 6
- Some features removed, some not yet implemented
  - Independent fragmentation and mass-ordered showers removed
  - No ep, $\gamma\mathrm{p}$ and $\gamma\gamma$ beam configurations

- Focus of new development; many new features not found in PYTHIA 6.4
  - Fully interleaved $p_{\perp}$-ordered MPI/ISR/FSR evolution
  - Richer mix of underlying-event processes (γ, J/ψ, DY, ...)
  - Can select two hard interactions in the same event
  - Hard diffractive component (S. Navin)
  - τ lepton polarisation in production and decay (P. Ilten)
  - Updated decay data and LO PDF sets (T. Kasemets)

Diffraction

- Move from INEL/NSD $\rightarrow$ INEL$>$0 datasets
  - Reproducible definitions!
  - Diffractive description more important
- Soft description same as in PYTHIA 6
  - Pomeron kicks out valence quark or gluon from the proton
- New high-mass diffractive framework using Ingelman-Schlein picture
  - "Diffraction in Pythia," S. Navin, arXiv:1005.3894 [hep-ph]
- Single diffraction
  - Proton emits Pomeron according to Pomerom PDF, $f_{\mathbb{P}/\mathrm{p}}(x_{\mathbb{P}}, t)$
  - Pomeron–proton collision using the full machinery of proton–proton collisions

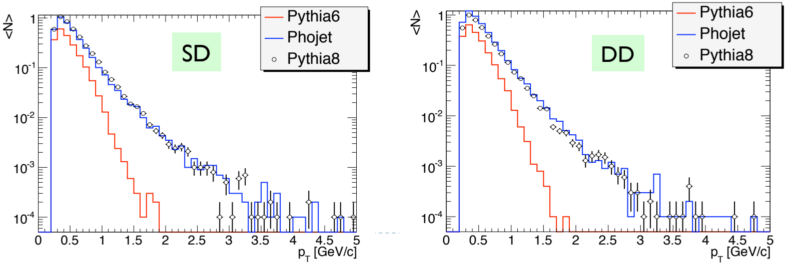




- Double diffraction: modelled as two Pomeron–proton collisions

Diffraction

- PYTHIA 8 and PHOJET agree quite well



Beate Heinemann, MB/UE Working Group

- Choice between 5 Pomeron PDFs
- Free parameter $\sigma_{\mathbb{P}}$ needed to fix $\langle n_{\mathrm{int}} \rangle = \sigma_{\mathrm{jet}} / \sigma_{\mathbb{P}}$
- Framework still needs more testing and tuning!

Interleaved evolution

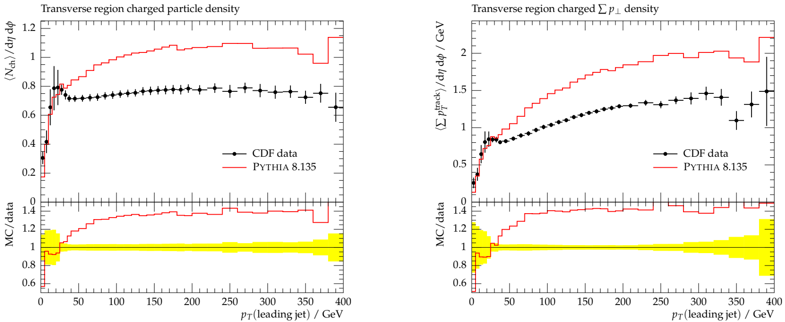
- Interleaved evolution for ISR, FSR and MPI, all $p_\perp$ ordered

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

- ISR and MPI compete for beam momentum
- Hybrid approach to shower recoils:
  - FSR is dipole: nearest colour-connected neighbour
  - ISR is traditional: whole hard-scattering system affected (as ISR dipole gives wrong answer e.g. for $p_{\perp \mathrm{Z}}$)

Interleaved FSR

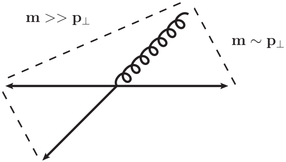
- Problems in describing the underlying event (PYTHIA 8.135)



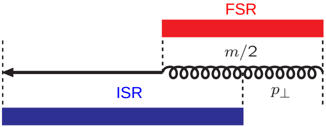
- No longer a universal minimum bias and underlying event tune
- ISR and MPI already interleaved in PYTHIA 6.4; issue with FSR?

Interleaved FSR

- Final-state parton may have colour partner in the initial state
- How to subdivide FSR and ISR in this kind of dipole?
- Large mass $\rightarrow$ large rapidity range for emission



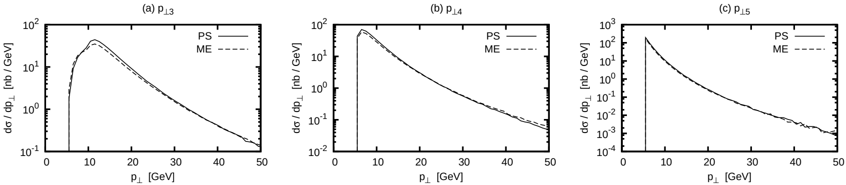
- In dipole rest frame



- Suppress final-state radiation in double-counted region

Matrix element comparisons

- Study how well the parton shower fills the phase space
  - Eventual goal: full matching to 2 $\rightarrow$ 3 real-emission matrix elements
  - Start with a comparison of the first shower emission
  - Would changing the shower starting scale give better agreement?



$p_{\perp 3}^{\min} = 5.0\,\text{GeV},\ p_{\perp 5}^{\min} = 5.0\,\text{GeV},\ R_{\text{sep}} = 0.10$

- Good qualitative agreement
  - Best in soft and collinear regions
  - Accuracy degrades when jets are hard and widely separated
  - Large region of phase space well described
  - No indication for a change in starting scale

MPI overview

- MPI framework one of the most important sources of tunable parameters
- Regularise cross section with $p_{\perp 0}$ as free parameter

$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}p_\perp^2} \propto \frac{\alpha_s^2(p_\perp^2)}{p_\perp^4} \to \frac{\alpha_s^2(p_{\perp 0}^2 + p_\perp^2)}{(p_{\perp 0}^2 + p_\perp^2)^2}$$

- $p_{\perp 0}$ has energy dependence

$$p_{\perp 0}(E_{\mathrm{CM}}) = p_{\perp 0}^{\mathrm{ref}} \times \left(\frac{E_{\mathrm{CM}}}{E_{\mathrm{CM}}^{\mathrm{ref}}}\right)^{E_{\mathrm{CM}}^{\mathrm{pow}}}$$

- Impact parameter, b, with matter profile
  - Single Gaussian; no free parameters
  - Overlap function

$$\exp\left(-b^{E_{\exp}^{\mathrm{pow}}}\right)$$

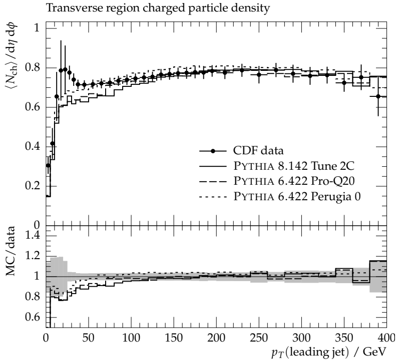
  - Double Gaussian

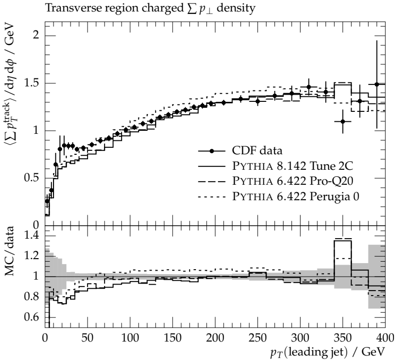
$$\rho(r) \propto \frac{1-\beta}{a_1^3}\exp\left(-\frac{r^2}{a_1^2}\right) + \frac{\beta}{a_2^3}\exp\left(-\frac{r^2}{a_2^2}\right)$$

- Many partons produced close in space–time $\to$ colour rearrangement

Tevatron tunes

- FSR and hadronisation tuned to LEP data (H. Hoeth)
- Identify key parameters and start with by-hand tune
- Rivet for comparisons against data
- Tunes 2C (CTEQ6L1) and 2M (MRST LO**)

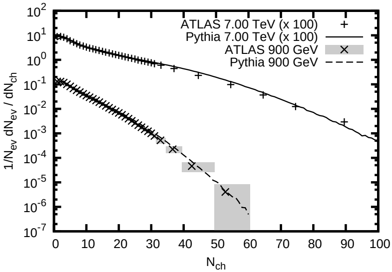


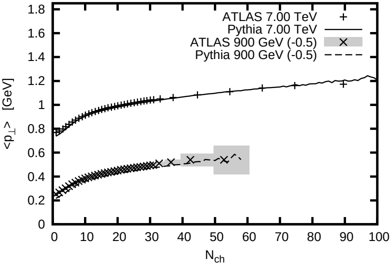


- Unified MB/UE tune!

LHC tunes

- Comparisons against early LHC UE/MB data
- Tevatron tunes give too little activity when compared against LHC data
- Start with Tune 2C and vary only MPI parameters → Tune 4C





- Gives reasonable agreement with LHC data
- More details: RC, T. Sjöstrand, JHEP 1103 (2011) 032.
- `http://mcplots.cern.ch/` for more plots and generator comparisons

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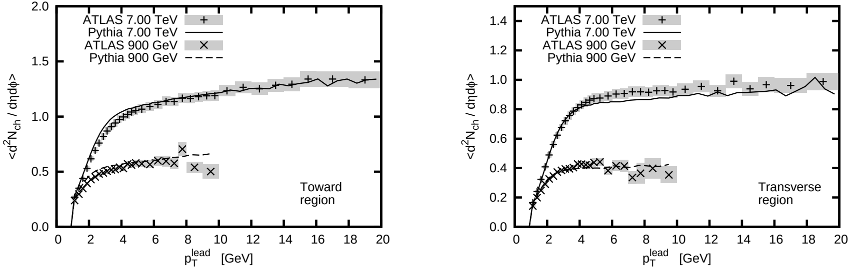

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An x-dependent proton size

- Normally assume PDFs factorise in longitudinal and transverse space

$$f(x, r) = f(x)\rho(r)$$

- Contradicts theoretical expectations?
  - BFKL, Balitsky-JIMWLK, Colour Glass Condensate ...
  - Mueller's dipole cascade (e.g. Lund DIPSY, study by Avsar)
  - Froissart-Martin $\sigma_{\mathrm{tot}} \propto \ln^2 s \to$ Gribov theory $r_{\mathrm{p}} \propto \ln(1/x)$

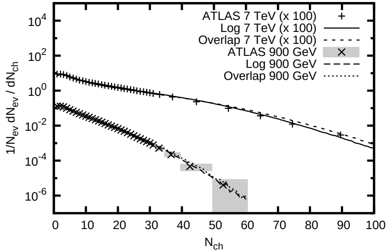
- Address this in inelastic non-diffractive events
  RC, T. Sjöstrand, JHEP 1105 (2011) 009.

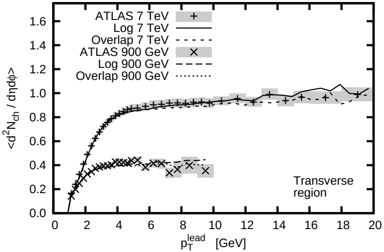
$$\rho(r, x) \propto \frac{1}{a^3(x)} \exp\left(-\frac{r^2}{a^2(x)}\right) \quad \text{with} \quad a(x) = a_0 \left(1 + a_1 \ln\frac{1}{x}\right)$$

- $a_1 \approx 0.15$ tuned to **rise** of σ_{ND}
  (Donnachie & Landshoff + Schuler & Sjöstrand)
- a_0 tuned to **value** of σ_{ND} (dependent on PDFs, $p_{\perp 0}$, etc..)

An x-dependent proton size

- Tune 4C + x-dependent proton size + lower $p_{\perp 0}$ $\rightarrow$ Tune 4Cx

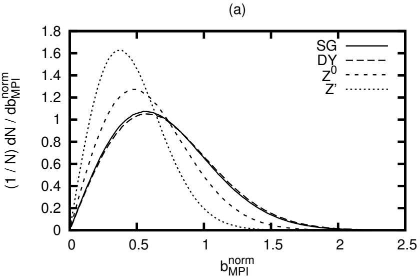




- Consistent with minimum-bias and underlying-event data
- Parameter a_1 more constrained than other options?

An x-dependent proton size

- Differences in the underlying event accompanying hard processes
- With e.g. single Gaussian matter profile, Sudakov already saturated at scales above $\sim$ 10 GeV
  - Same impact-parameter profile if hard process has scale 100 GeV or 1 TeV
- With x-dependence, collisions at large x likely to be at small b
  - Further large-to-medium-x MPIs are enhanced



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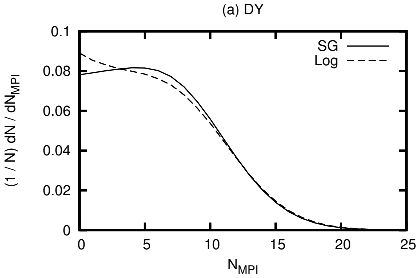
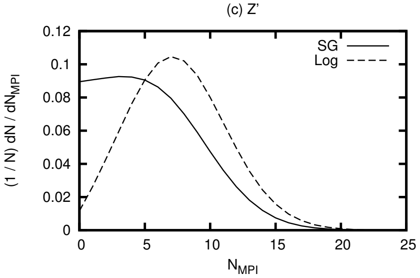
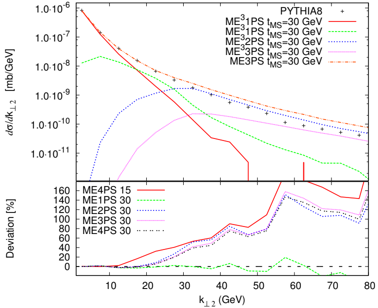
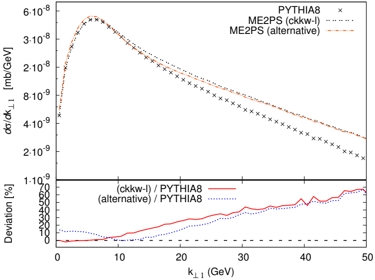




CKKW-L merging

- Consistently combine higher-order tree-level matrix elements and parton shower description
- Leif Lönnblad and Stefan Prestel working to include CKKW-L merging
  - Reconstruct a shower history for the ME state
  - Trial showers to get Sudakov factor
  - Consistent inclusion of interleaved MPI





- Article + code coming soon!

BSM physics

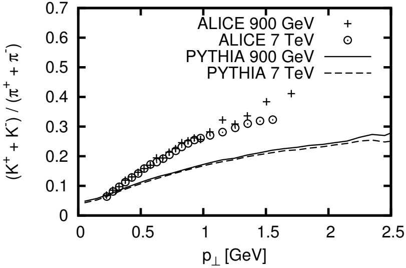
- SLHA interface updated; QNUMBERS now supported
- Calculation of SUSY decay widths (N. Desai)

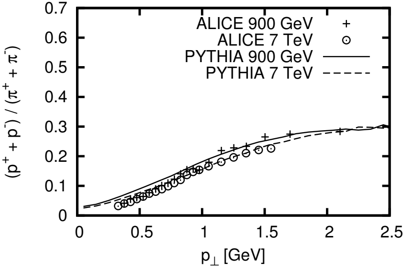
- *R*-hadronisation now integrated into PYTHIA 8
  - Long-lived coloured particles e.g. $\tilde{g}$ or $\tilde{t}_1 \rightarrow$ *R*-hadrons
  - *R*-mesons ($\tilde{g}q\bar{q}$, $\tilde{t}_1\bar{q}$), *R*-baryons ($\tilde{g}qqq$, $\tilde{t}_1qq$) or glueballs ($\tilde{g}g$)
  - A.C. Kraan, Eur. Phys. J. C37 (2004) 91
    M. Fairbairn et al., Phys. Rep. 438 (2007) 1
    CMS, arXiv:1101.1645

- Hidden valley/secluded sector framework
  - New gauge groups at low energy scales, hidden by potential barrier or weak couplings (Strassler & Zurek)
  - Can pick Abelian $U(1)$ or non-Abelian $SU(N)$ gauge group
  - Different production mechanisms (e.g. massize Z', kinetic mixing, ...)
  - Interleaved shower in QCD, QED and HV sectors
  - Hadronisation in hidden $SU(N)$ sector
  - L. Carloni & T. Sjöstrand, JHEP 09 (2010) 105
    L. Carloni, J. Rathsman & T. Sjöstrand, JHEP 04 (2011) 091

Hadron spectra

- Know that certain hadron flavours need more $p_\perp$
- Latest $\pi/\mathrm{K}/\mathrm{p}$ $p_\perp$ spectra from LHC
  - ALICE 900 GeV - inelastic events, $|y| < 0.5$, arXiv:1101.4110v3
  - ALICE 7 TeV - read from public talks (assume same acceptance as 900 GeV)
- Compare against PYTHIA 8





Final-state hadron scattering

- Final-state hadron scattering
  - No need to significantly change particle composition, only (partial) collective flow?
  - Low-energy scatterings in CM frame and boost back
  - Higher masses take bigger kick, c.f. collective flow in heavy ion
  - Ideally assign production vertices to outgoing hadrons and follow path
- Simple model based on distance in $y - \phi$ space
  - High-$p_\perp$ hadrons in jets formed at later times and less likely to scatter
  - Scattering probability

$$P_{ij} = (1 - \mathrm{e}^{-k\sigma_{ij}^{\mathrm{el}}(s)}) \max\left(0,\, 1 - \frac{\Delta R_{ij}^2}{R_{\mathrm{max}}^2}\right)$$

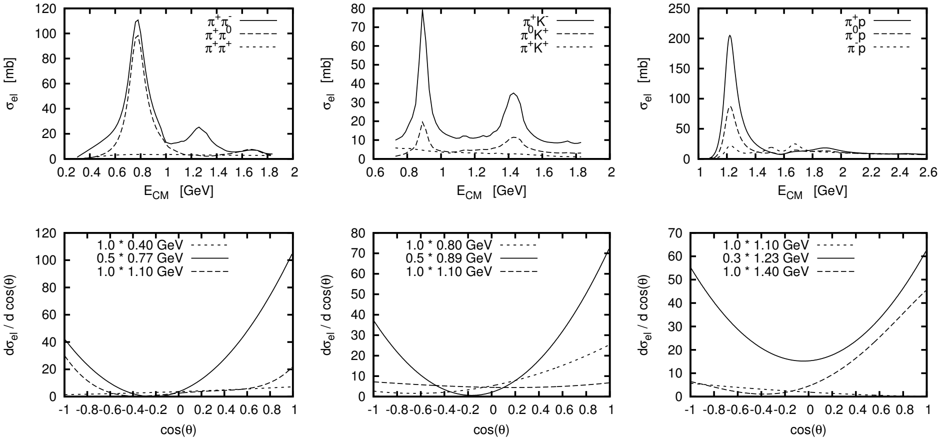
  - Order scatterings based on "relative transverse velocity"

$$v_{\perp ij} = \left| \frac{p_{\perp i}}{m_{\perp i}} - \frac{p_{\perp j}}{m_{\perp j}} \right|$$

  - Dominated by pions, so focus on $\pi\pi$, $\pi\mathrm{K}$ and $\pi\mathrm{p}$
  - Most scatterings close to threshold

Final-state hadron scattering

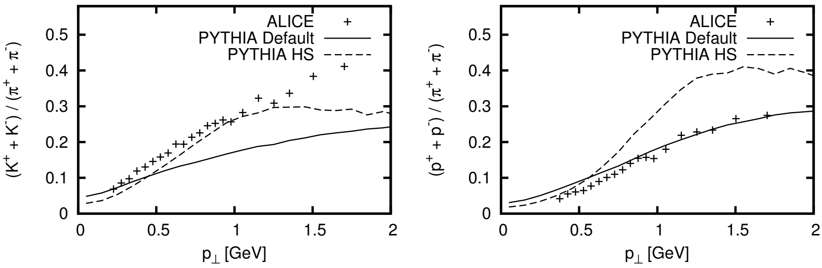
- Isospin partial-wave parameterisations (no Columb corrections)



Final-state hadron scattering

- Results from simple model; try to boost K/π ratio
- Perform scattering after first round of hadron decays ($\eta \to \pi$)

900 GeV



- Exact shape depends on how “soft” hadrons are picked
- Protons get too much of a kick

Final-state hadron scattering

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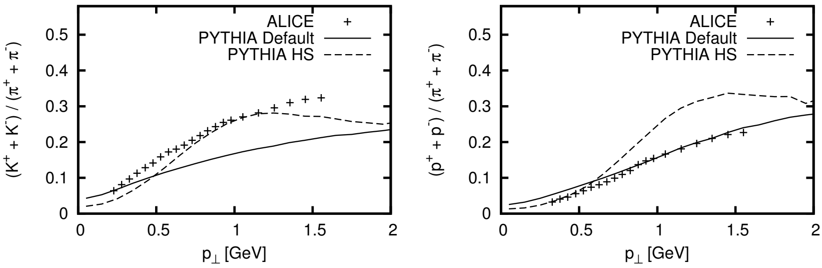
7 TeV



- Exact shape depends on how “soft” hadrons are picked
- Protons get too much of a kick

Conclusions

- PYTHIA 6 is still supported, but no longer actively developed
- PYTHIA 8 is the natural successor
  - Number of new features available only in PYTHIA 8 continuing to grow
  - Starting to have competitive tunes
  - Welcome other tuning efforts (and reports on the outcome!)
  - Provide feedback; both negative and positive!
- Announcement list:
  http://www.hepforge.org/lists/listinfo/pythia8-announce

Backup slides

An x-dependent proton size

- Time integrated overlap

$$\tilde{\mathcal{O}}(b; x_1, x_2) = \frac{1}{\pi} \frac{1}{a^2(x_1) + a^2(x_2)} \exp\left(- \frac{b^2}{a^2(x_1) + a^2(x_2)} \right)$$

- Define $\overline{n}(b)$ as average number of interactions at b

$$\overline{n}(b) = \sum_{i,j} \iiint \mathrm{d}x_1 \, \mathrm{d}x_2 \, \mathrm{d}p_\perp^2 \; f_i(x_1, p_\perp^2) \, f_j(x_2, p_\perp^2) \; \left. \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_\perp^2} \right|_{\mathrm{reg}} \; \tilde{\mathcal{O}}(b; x_1, x_2)$$

- Such that

$$\begin{aligned} \sigma_{\mathrm{hard}} &= \int \overline{n}(b) \, \mathrm{d}^2 b \\ \sigma_{\mathrm{ND}} &= \int P_{\mathrm{int}} \, \mathrm{d}^2 b = \int \left(1 - e^{-\overline{n}(b)} \right) \mathrm{d}^2 b \end{aligned}$$

Final-state hadron scattering

- Probability that a hadron is soft enough to scatter:

$$P_{\text{soft}} = \frac{N \exp\left(-\frac{p_\perp^2}{4\sigma_{\text{frag}}^2}\right)}{(1-k)\exp\left(-\frac{p_\perp^2}{4\sigma_{\text{frag}}^2}\right) + k\frac{p_{\perp 0}^p}{\left(p_{\perp 0}^2 + p_\perp^2\right)^{p/2}}}$$

- $N \sim 1$, $k \sim 0.5$ and $p \sim 6$ for results

- Isospin partial-wave parameterisations:
  - $\pi\pi$ - Froggatt and Petersen, Nucl. Phys. B129 (1977) 89-110
  - $\pi\mathrm{K}$ - Estabrooks et. al., Nucl. Phys. B133 (1978) 490-524
  - $\pi\mathrm{N}$ - GWU SAID WI08 solution
    SP06 - Phys. Rev. C74 045205 (2006)
    WI08 - http://gwdac.phys.gwu.edu/analysis/pin_analysis.html