Multi-parton and multi-nucleon correlations: theory

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Multiparton Interactions, from pp to pA

- General purpose event generators are built on MPI models.
- MPI description of pp events are long established...
- ...transfer to pA and AA is desirable if feasible.
- Cannot go to measurables without FS effects!
- Here: Microscopic QCD inspired models, could also consider hydro.
- This talk:
  1. The Pythia and DIPSY models.
  2. Final state effects: Ropes and junctions.
  3. Beyond pp, fluctuations in Glauber model(s).
  4. Particle production in pA.
  5. Outlook.

MPIs in Pythia 8: proton collisions

Sjöstrand and Skands: arXiv:hep-ph/0402078

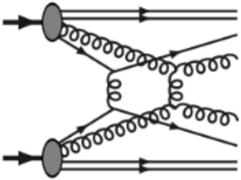


Figure T. Sjöstrand

- Several partons taken from the PDF.
- Hard subcollisions with $2 \to 2$ ME:

$$\frac{d\sigma_{2\to 2}}{dp_\perp^2} \propto \frac{\alpha_s^2(p_\perp^2)}{p_\perp^4} \to \frac{\alpha_s^2(p_\perp^2 + p_{\perp 0}^2)}{(p_\perp^2 + p_{\perp 0}^2)^2}.$$

- Momentum conservation and PDF scaling.
- Ordered emissions: $p_{\perp 1} > p_{\perp 2} > p_{\perp 4} > \ldots$ from:

$$\mathcal{P}(p_\perp = p_{\perp i}) = \frac{1}{\sigma_{nd}} \frac{d\sigma_{2\to 2}}{dp_\perp} \exp\left[-\int_{p_\perp}^{p_{\perp i-1}} \frac{1}{\sigma_{nd}} \frac{d\sigma}{dp'_\perp} dp'_\perp\right]$$

- Number distribution narrower than Poissonian (momentum and flavour rescaling).

Color reconnection

- Many partonic subcollisions $\Rightarrow$ Many hadronizing strings.
- But! $N_c = 3$, not $N_c = \infty$ gives interactions.
- Easy to merge low-$p_\perp$ systems, hard to merge two hard-$p_\perp$.

$$\mathcal{P}_{merge} = \frac{(\gamma p_{\perp 0})^2}{(\gamma p_{\perp 0})^2 + p_\perp^2}$$

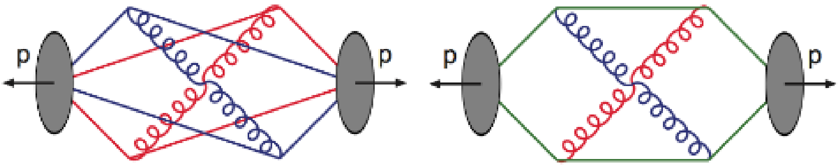


Figure T. Sjöstrand

- Actual merging is decided by minimization of "potential energy":

$$\lambda = \sum_{dipoles} \log(1 + \sqrt{2}E/m_0)$$

Junction CR Christiansen and Skands arXiv:1505.01681 [hep-ph]

- New CR allows for more configurations.
- Selection relies on λ-measure

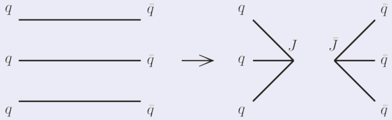
Ordinary string reconnection

($q\bar{q}$: 1/9, gg: 1/8, model: 1/9)

Double junction reconnection

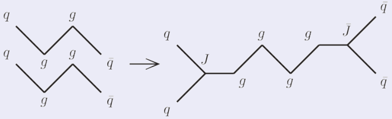
(qq: 1/3, gg: 10/64, model: 2/9)

Triple junction reconnection



($q\bar{q}$: 1/27, gg: 5/256, model: 2/81)

Zipping reconnection



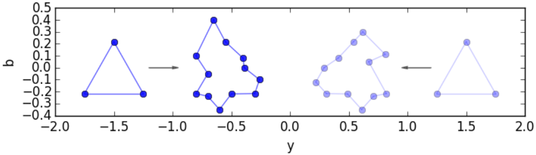
(Depends on number of gluons)

The DIPSY model Flensburg et al. arXiv:1103.4321 [hep-ph]

- A very different view on MPIs, built on Mueller dipole model (Mueller and Patel arXiv:hep-ph/9403256).
- Proton structure built up dynamically from dipole splittings:

Model implemented as a MC event generator
Dipole evolution in **I**mpact **P**arameter **S**pace and rapidit**Y**.

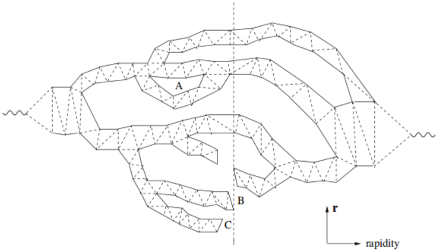
$$\frac{dP}{dY} = \frac{3\alpha_s}{2\pi^2} d^2\vec{z} \frac{(\vec{x}-\vec{y})^2}{(\vec{x}-\vec{z})^2(\vec{z}-\vec{y})^2}, \; f_{ij} = \frac{\alpha_s^2}{8}\left[\log\left(\frac{(\vec{x}_i-\vec{y}_j)^2(\vec{y}_i-\vec{x}_j)^2}{(\vec{x}_i-\vec{x}_j)^2(\vec{y}_i-\vec{y}_j)^2}\right)\right]^2$$

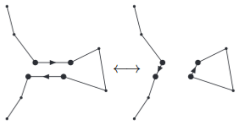


- MPIs are included by construction.
- Formalism generalizes to HI (very time consuming).
- No PDFs (also: no quarks, no ME ⇒ few hard jets).

Saturation and swings

- In DIPSY MPIs are fluctuations going on shell in interactions.
- Similar to saturation in another frame: Initial state swing.
- Multiple scatterings of a single dipole $\Leftrightarrow$ Several swings (Avsar, E.: arXiv:0709.1371 [hep-ph])
- Re-absorption of non-interacting branches.





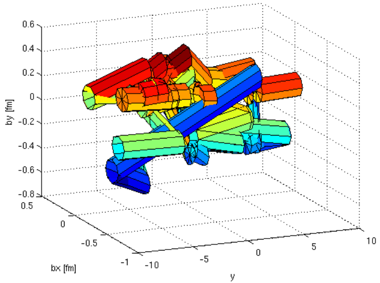
- Initial state swing competes with emission.
- All gluons get index from 1 to N_c^2, reconnect if compatible with:

$$\frac{\mathcal{P}_{(12)(34)}}{\mathcal{P}_{(14)(32)}} = \frac{(\vec{x}_1 - \vec{x}_4)^2(\vec{x}_3 - \vec{x}_2)^2}{(\vec{x}_1 - \vec{x}_2)^2(\vec{x}_3 - \vec{x}_4)^2}.$$

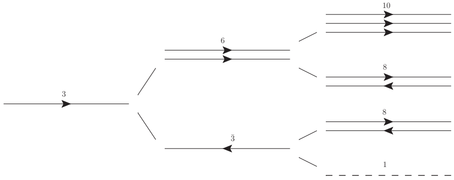
Ropes, swings and junctions CB et al. arXiv:1412.6259 [hep-ph]

- Final state interactions: Many overlapping strings (like CR)

  Old in HI: Biro et al: Nucl.Phys. B245 (1984) 449-468.
- SU(3) multiplet structure decided by random walk.
- Effects implemented from perturbative (parton shower) to non-perturbative (hadronization) scales.

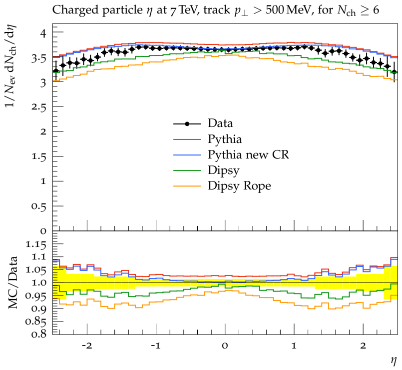


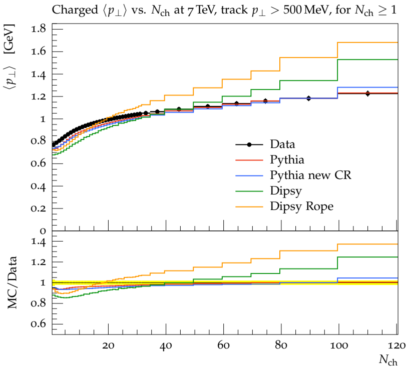
- Three options
  1. Highest multiplet (higher string tension).
  2. Lower multiplet (junction+higher st.).
  3. Singlet Final State swing (similar to CR).



Data comparisons Data from ATLAS: arXiv:1012.5104 [hep-ex]

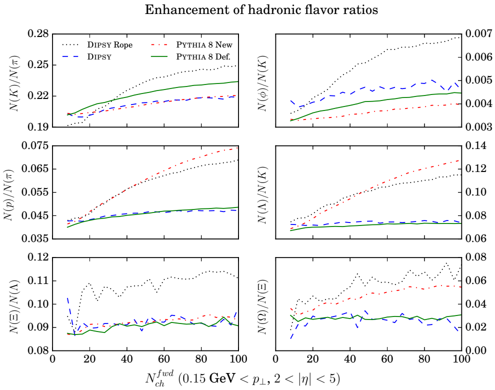
- Total multiplicity and $\langle p_\perp \rangle (N_{ch})$ from MPI and CR.
- Notice how DIPSY no CR gets N_{ch} dependence.
- DIPSY has to many high-$p_\perp$ events in general.

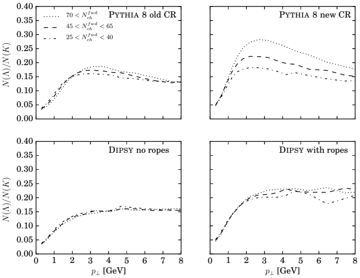




Ropes, junctions and flavours CB and Christiansen: arXiv:1507.02091 [hep-ph]

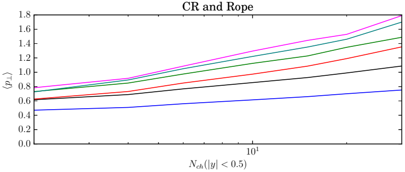
- Strange enhancement: confirmed, baryons are not.
- Possible solution: Stepwise production mechanism for baryons.
- Flowlike behaviour from junction model.

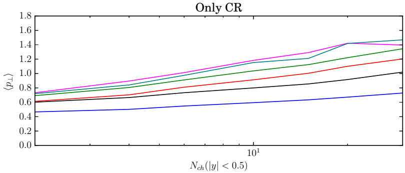


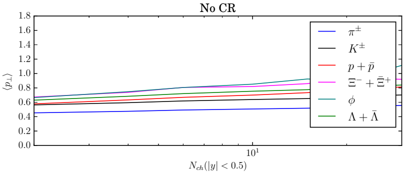


Ropes, CR and mass splitting

- Influenced heavily by FS effects.
- Tuning and quantitative comparison.
- Remember: Tuning $\neq$ fitting.







From pp to pA

- Wounded quarks ≈ MPIs Białas: arXiv:1202.4599 [hep-ph]
- Particle production time $1/m_\perp \Rightarrow$ absorptive pp scaling at large $p_\perp$.

$$L_{probe} = v\tau \approx \frac{\sinh y_{lab}}{\sqrt{m^2 + p_\perp^2}} < L_{structure}$$

- Standard Glauber approach: interaction through absorptive channels.
- Right for high $p_\perp$, multiplicity will be wrong.
- Wounded nucleons updated to include fluctuations.
- Optical theorem in impact parameter space:

$$T \equiv -iA_{el} \Rightarrow \frac{d\sigma_{el}}{d^2b} = \langle T(b) \rangle^2$$

$$\frac{d\sigma_{tot}}{d^2b} = 2\langle T(b) \rangle, \frac{d\sigma_{abs}}{d^2b} = 2\langle T(b) \rangle - \langle T(b) \rangle^2$$

The wounded cross section

- Fluctuations related to diffractive excitations: Good-Walker.

$$\frac{d\sigma_{tot}}{d^2b} = 2\left\langle T \right\rangle_{t,p}, \ \frac{d\sigma_{el}}{d^2b} = \left\langle T \right\rangle_{t,p}^2, \ \frac{d\sigma_{SD,(p|t)}}{d^2b} = \left\langle \left\langle T \right\rangle_{(t|p)}^2 \right\rangle_{(p|t)} - \left\langle T \right\rangle_{p,t}^2$$

$$\frac{d\sigma_{DD}}{d^2b} = \left\langle T^2 \right\rangle_{p,t} - \left\langle \left\langle T \right\rangle_t^2 \right\rangle_p - \left\langle \left\langle T \right\rangle_p^2 \right\rangle_t + \left\langle T \right\rangle_{p,t}^2$$

- In DIPSY: $T = 1 - \exp(-\sum_{ij} f_{ij})$, and we can calculate:

$$\frac{d\sigma_w}{d^2b} = \frac{d\sigma_{abs}}{d^2b} + \frac{d\sigma_{SD,t}}{d^2b} + \frac{d\sigma_{DD}}{d^2b} = 2\left\langle T \right\rangle_{p,t} - \left\langle \left\langle T \right\rangle_t^2 \right\rangle_p.$$

- Contributions to "centrality" observable: absorptively wounded, diffractively wounded, NOT elastically scattered.

Glauber-Gribov fluctuations (GG or GGCF)

- Fluctuations included in Glauber-Gribov formalism Alvioli and Strikman: arXiv:1301.0728 [hep-ph]:
- Parameterization of total cross section:

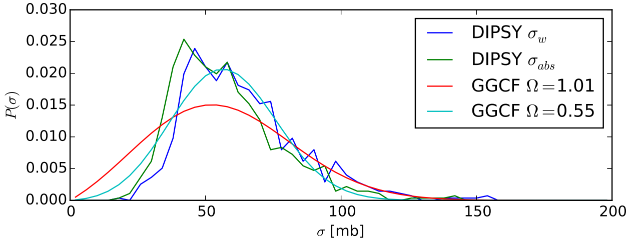
$$\sigma_{tot} = \int d\sigma \sigma P_{tot}(\sigma) = \int d\sigma \rho \frac{\sigma^2}{\sigma + \sigma_0} \exp\left[-\frac{(\sigma/\sigma_0 - 1)^2}{\Omega^2}\right]$$

- Usage: With black disk, scale to total inelastic $\sigma_{in} = \lambda \sigma_{tot}$.
- From arguments above, should be σ_w
- BUT! Setting $\sigma_{Glauber} = \sigma_w$ in GG/GGCF is not enough, no fluctuations in projectile.
- Must also *distinguish* between diffractively excited wounded and absorptive wounded.

- Scale GGCF to σ_{abs} and compare to DIPSY, where now:

$$\sigma_{w,DIPSY} \propto \sum_p \sum_b \left[\sum_t 2T(b) - \left(\sum_t T(b) \right)^2 \right]$$

$$\sigma_{abs,DIPSY} \propto \sum_p \sum_b \sum_t \left[2T(b) - T^2(b) \right]$$

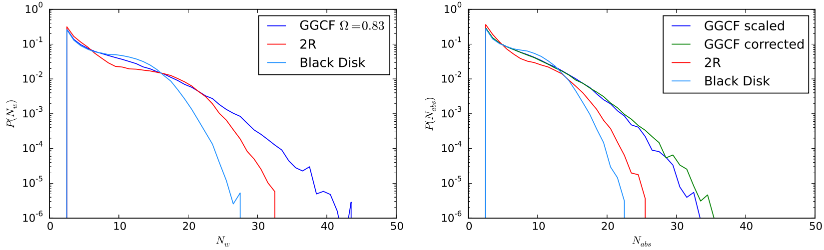


Wounded nucleons

- Distinguish: Simple two-radius model, reproduce $\sigma_{abs}, \sigma_{el}, \sigma_{DX}$ and σ_{DD} with four parameters:

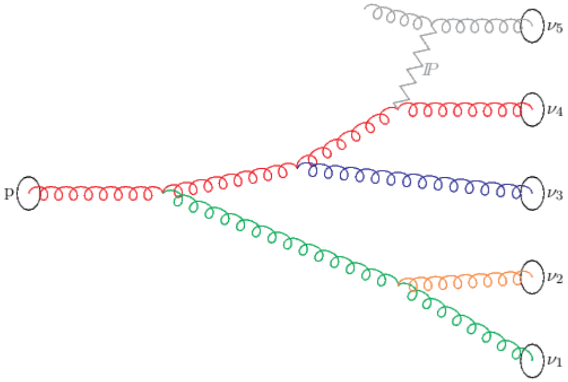
$$T(b) = \alpha\Theta(r_p + r_t - b)$$

- Crude fluctuations does the job.

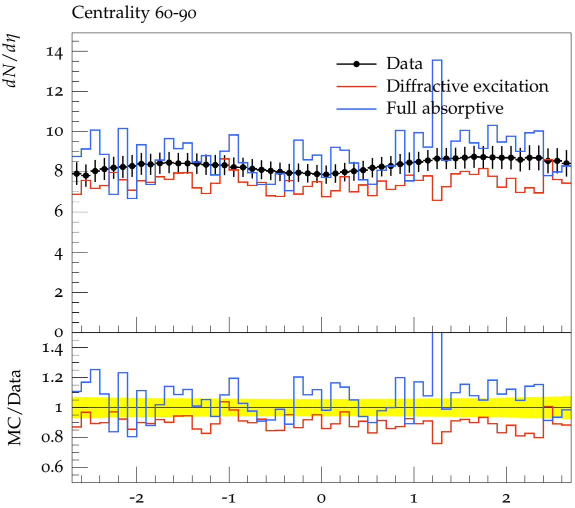


Full final states: String-like interaction model

- One absorptive collision contributes to full rapidity span.
- The rest contributes similarly to diffrative excitation (plus a colour exchange).
- Full collision as a sum of Pythia 8 events.



Data comparison



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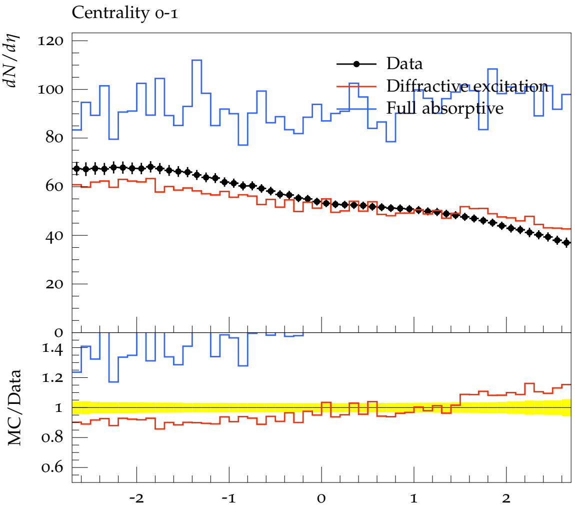
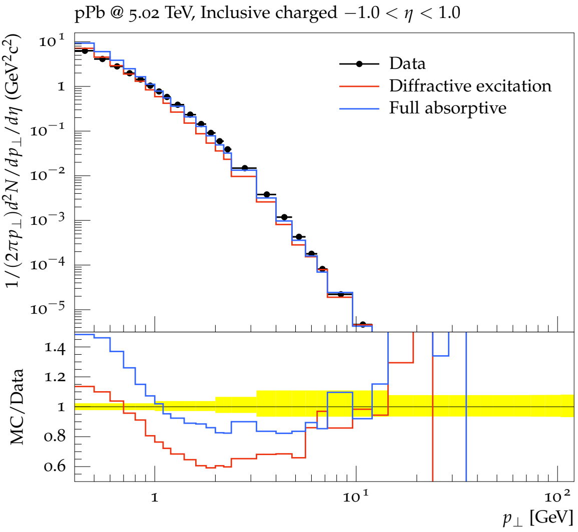


Data comparison



The end

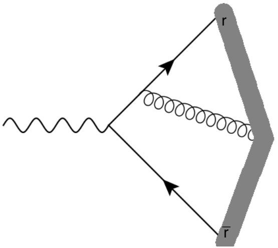
- MPI frameworks diverse and developed in pp.
- Correlation effects by additional IS and FS effects not fully understood.
- New data continues to drive development - important: means of comparison.
- Extending MPI picture to pA and AA desirable but still immature.
- Several complementary approaches to different parts of collision.
- Lesson from pp: Common interfaces are neccesary!

Bonus slides

String Hadronization hep-ph/0603175

- Non-perturbative phase of final state.
- *Breaking*/tunneling with $\mathcal{P} \propto \exp\left(-\frac{\pi m_\perp^2}{\kappa}\right)$ gives hadrons.
- Left-right symmetry in the breaking gives

$$f(z) \propto z^{-1}(1-z)^a \exp\left(\frac{-bm_\perp}{z}\right).$$



- a and b related to total multiplicity.
- Flavours determined by relative probabilities:

$$\rho = \frac{\mathcal{P}_{\text{strange}}}{\mathcal{P}_{\text{u or d}}}, \xi = \frac{\mathcal{P}_{\text{diquark}}}{\mathcal{P}_{\text{quark}}}$$

- Probabilities are related to κ via tunneling equation.

Change of string tension

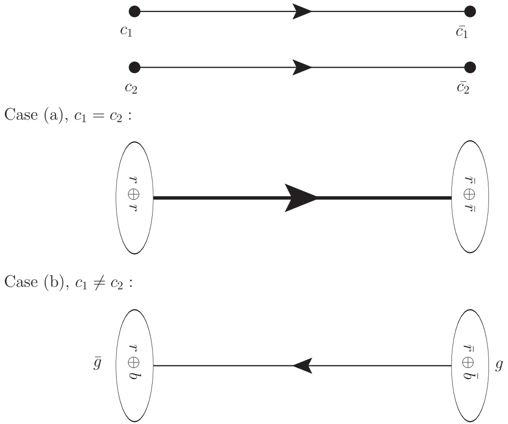
- Field changes when strings overlap - Simple Regge: $2\pi E/l = \kappa$.
- Effective string tension: $\kappa \mapsto \tilde{\kappa} = h\kappa$ from number of overlapping strings.
- Electrodynamics: Principle of superposition, simple.
- QCD: Not so simple. Secondary Casimir operator of multiplet.

$$\kappa \propto C_2 \Rightarrow h = \tilde{\kappa}/\kappa = \frac{C_2(\text{multiplet})}{1\ \text{GeV/fm}}$$

- Confirmed on the lattice, static case.

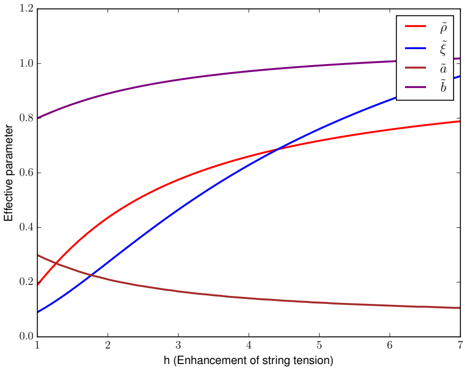
Example arXiv:1412.6259 [hep-ph]

- The simplest example: Two $q\bar{q}$ pairs act coherently.
- Two distinct possibilities:



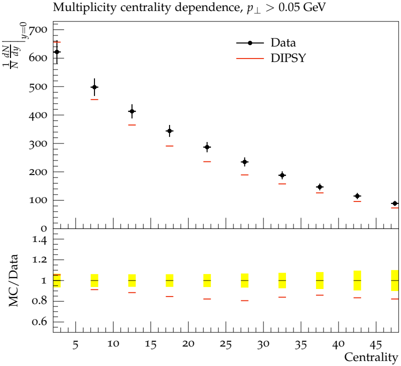
Effect on hadronization parameters

- All parameters related through string tension.
- ρ (strange) and ξ (baryon) are very sensitive.

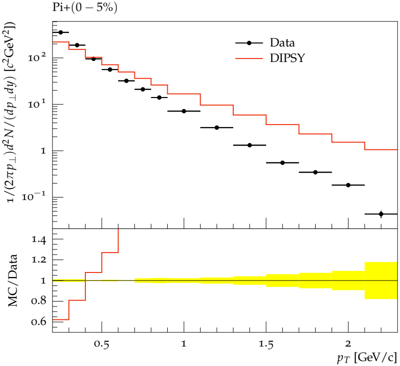


- Large effect on hadronic flavours.
- Smaller effect on hadron $p_{\perp}$ and multiplicity (tunable).

DIPSY and HI



Multiplicity centrality dependence, $p_\perp > 0.05$ GeV
$\frac{1}{N}\frac{dN}{dy}|_{y=0}$
Data
DIPSY
MC/Data
Centrality



Pi+(0 − 5%)
$1/(2\pi p_\perp) d^2N/(dp_\perp dy)$ [c^2GeV^2])
Data
DIPSY
MC/Data
p_T [GeV/c]

Highest multiplet

- All higher multiplets represents a coherent interaction.
- Fundamental quantum numbers p and q from recursion relations.
- Number of random (anti)-triplets added decided by overlaps.

$$\{p, q\} \otimes \vec{3} = \{p+1, q\} \oplus \{p, q+1\} \oplus \{p, q-1\}$$

$$\underbrace{\boxminus \otimes \boxminus \otimes \ldots \otimes \boxminus}_{\text{All anti-triplets}} \otimes \underbrace{\square \otimes \square \otimes \ldots \otimes \square}_{\text{All triplets}}$$

- Transform to $\tilde{\kappa} = \frac{2p+q+2}{4}\kappa$ and $2N = (p+1)(q+1)(p+q+2)$.
- N (multiplicity of the multiplet) serves as a state's weight.
- String hadronized with $\tilde{\kappa}$.

Junction handling

- Extra junctions handled through simplistic, popcorn-based approach.

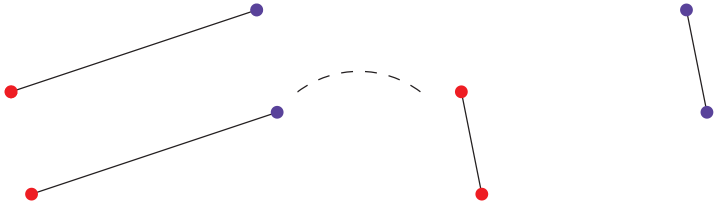
- Extra parameter for colour fluctuations (no data handle).
- Better: Dynamical handling in a "swing".

- Related: recent Pythia 8 model arXiv:1505.01681 [hep-ph]

The singlet swing

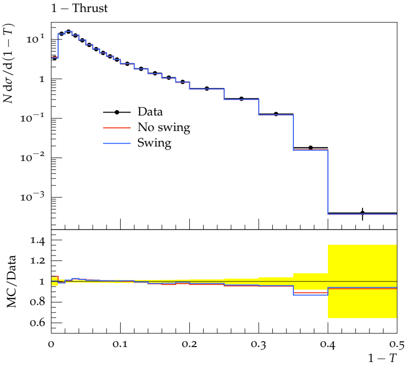
- Singlets are handled already in the FS shower (Ariadne).
- Matching colours *swing* with each other, competing w. emission.

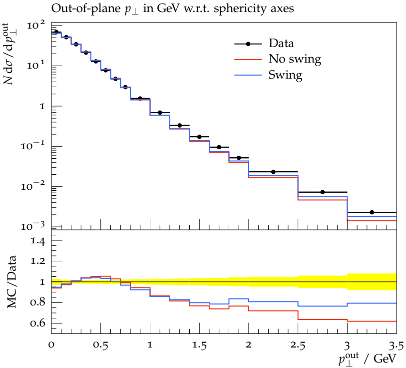
$$\frac{dP_e}{d\ln(p_\perp^2)} \approx dy\frac{C_F\alpha_s}{2\pi} \text{ and } \frac{dP_r}{d\ln(p_\perp^2)} = \lambda\frac{(\vec{p_1}+\vec{p_2})^2(\vec{p_3}+\vec{p_4})^2}{(\vec{p_1}+\vec{p_4})^2(\vec{p_2}+\vec{p_3})^2}$$



Singlet swing and LEP Data: DELPHI

- Comes in already at perturbative level.
- Retuning of shower is neccesary.
- No large difference, $p_\perp^{out}$ somewhat improved.

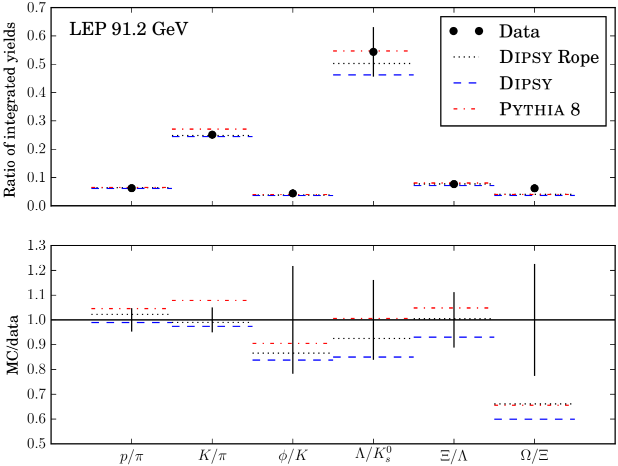




Flavour ratios - LEP

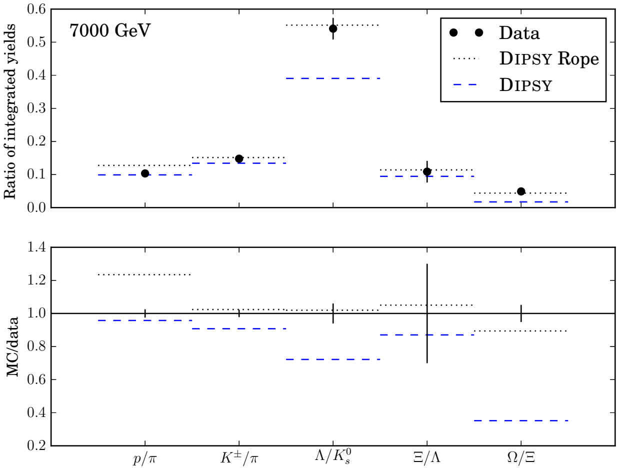
Data: SLD, LEP and PDG Avg.

- String at LEPs. Agreement with data.
- Jet universality: Gain predictive power in *pp* by fixing parameters here.



Flavour ratios - LHC Data: CMS and ALICE

- Ropes at LHC. Overall better agreement, problem with p/π.
- Integrated quantities, need per event quantities as function of activity.



Results from ALICE CERN seminar, 10-11-2015

- Strange enhancement is confirmed, baryonic is not.
- Further work: Baryon enhancement and junctions.