QCD Phenomenology and Event Generators

DIS 2017, Birmingham
April 03, 2017
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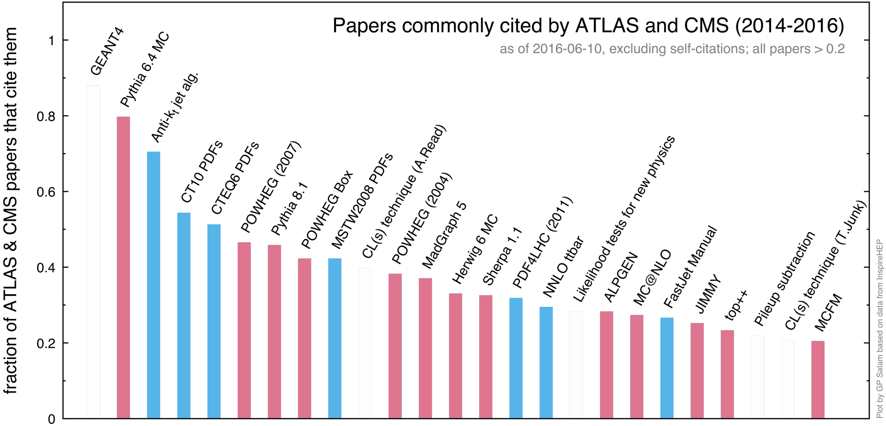
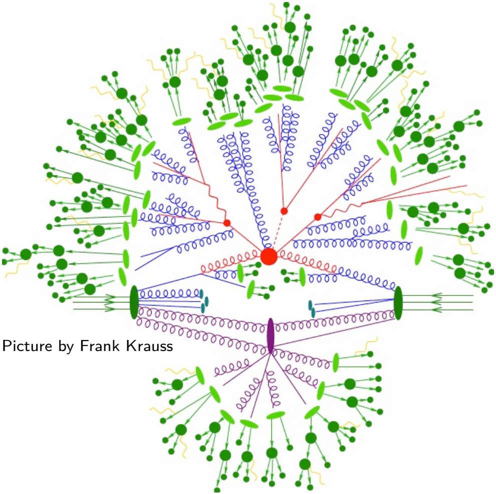
Chart adapted from Gavin Salam





Picture by Frank Krauss

Experiments to learn from:
High & low-energy DIS, $\ell\ell + hh$ *collider measurements, cosmic rays, heavy-ion collisions...*

(QCD) theory toolbox:
Factorization, fixed-order QCD, resummation, double parton scattering, diffraction, (3D) nucleon structure

Hard interaction → Radiative cascade
→ Secondary interactions → Hadron formation
→ Hadron decay, rescattering, Bose-Einstein effects...

General Purpose Monte Carlo Event Generators (MCEGs)
– *Combine all aspects of scattering events.*
– *Are repositories for our knowledge of scattering processes.*

Common high-energy MCEGs are **HERWIG**, **PYTHIA** and **SHERPA**.

They include knowledge of $\mathcal{O}$(40 research years) – per person, in some cases ...and still, there are many things yet to learn!

Generator cheat-sheet and news

	Handles	*"Best" PQCD*	*pp Multiple Int^{ns}*	*Fragmentation*
HERWIG	ee, ep, pp	NLO+PS matched	Eikonal	Cluster
PYTHIA	ee, ep, pp	NLO+PS merged	Interleaved	String
SHERPA	ee, ep, pp	NNLO+PS matched	Traditional	Cluster

HERWIG7 news	PYTHIA8 news	SHERPA news
on-the-fly PQCD uncertainties, two (three) new NLO matching schemes, NLO merging, improved online documentation	on-the-fly PQCD uncertainties, two new showers, improved diffraction, thermodynamic string hadronization	on-the-fly PQCD uncertainties, one new shower, NLO electroweak effects, news on V+b processes.

Long-distance effects factorize from short-distance physics

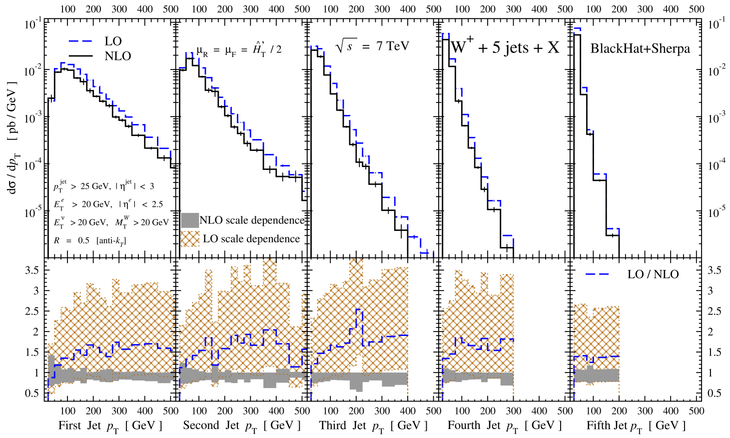
$$\sigma = \int d\sigma_{(ab\to X+N\ \text{partons})}(\text{high energy})$$
$$\otimes f_{a\in \mathrm{A}}(\{x\}_a, \text{high energy}) \otimes f_{b\in \mathrm{B}}(\{x\}_b, \text{high energy})$$
$$\otimes \mathcal{D}(p_A, p_B, p_1, \ldots, p_N) + \textit{power corrections}$$

f & $\mathcal{D}$ are non-perturbative functions

- ⋄ Extract/fit f and $\mathcal{D}$ where corrections are small (low energy).
- ⋄ Use perturbation theory to calculate $d\sigma$ at high energy.

Reliable perturbative predictions

PRD 88 (2013) 1, 014025



Use perturbative (NLO, NNLO) QCD for largest possible part of the dynamics before using non-perturbative physics.
⇒ Well-defined uncertainty, non-perturbative model can still be universal.

arXiv:1602.05612, arXiv:1606.03991

17 calc^{ns} in [2000, 2014]
20+ calc^{ns} in [2014, present]

due to breakthrough in reg^{n} schemes:

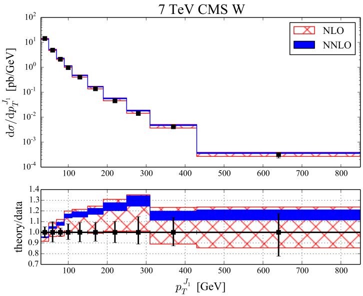
“Slicing†”

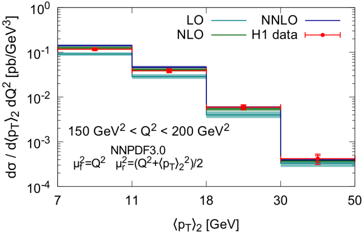
$$\sigma = [c + \ln(cut)]\, f(0) + \int_{cut} dz \frac{f(z)}{z}$$

“Subtraction‡”

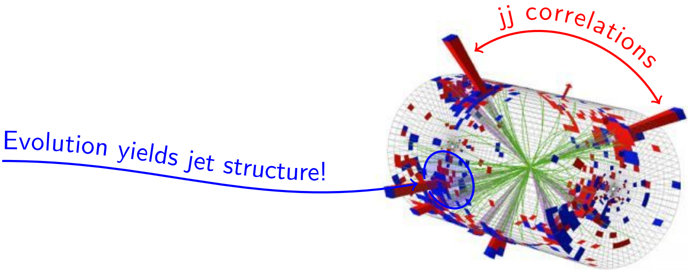
$$\sigma = [c + ct]\, f(0) + \int dz \frac{f(z) - f(0)}{z}$$

Bottleneck: 2-loop master integrals





† qT subt^{n} (e.g. MATRIX), N-jettiness subt^{n} (e.g. MCFM)
‡ sector dec^{n}, antenna subt^{n} (e.g. NNLOJET), sector-improved residue subt^{n}, Colorful subt^{n}, Projection-to-Born



Fixed-order corrections are calculated at a high energy.
Distribution functions extracted at low energy.

Parton shower (PS) evolves high energy fixed-order cross section to low energy, summing large perturbative corrections.
⇒ All perturbatively calculable differential information generated.

Reliable predictions need
◇ accurate fixed-order
◇ accurate parton shower
◇ reliable combination scheme
◇ smooth match to NP physics.

Matching & Merging
◇ NLO (NNLO) hard scattering (can combine many calc^{ns})
◇ PS higher-order corrections

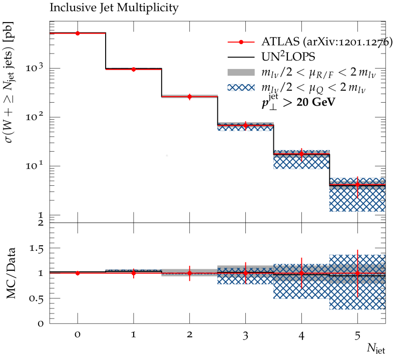
Well-developed for "simple" processes.

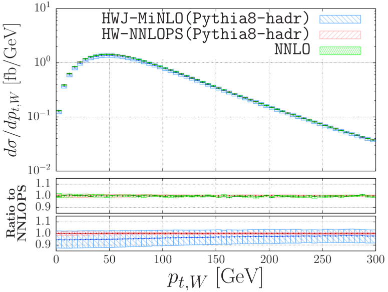
Landmark: NNLO+PS matching

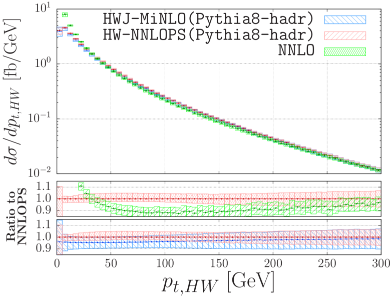
JHEP 1310 (2013) 222, arXiv:1405.3607, arXiv:1603.01620

- ✓NNLO for incl. cross-section
- ✓NLO+PS for 1-parton observables
- ✓LO+PS for 2-parton observables

Two schemes: NNLOPS/MINLO and UN^{2}LOPS

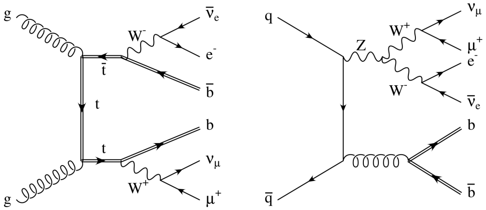






JHEP1512(2015)065, JHEP1606(2016)027, arXiv:1607.04538

Remember the skeletons...



Assigning correct "higher-order correction" very important

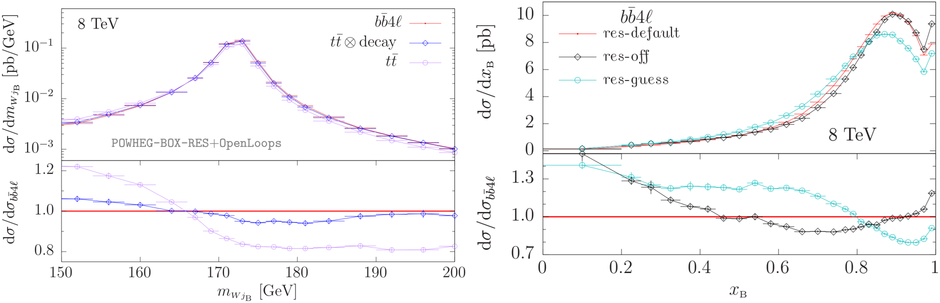
... for precision measurements

... when many different final-state objects are combined

Both apply to **calculations for top mass extraction**.

Matching $WbWb$ with POWHEG-BOX-RES

arXiv:1607.04538



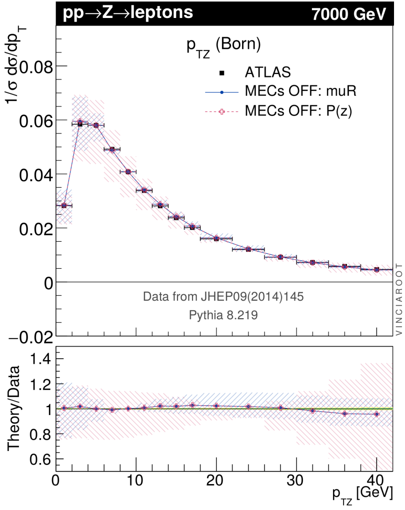
$\ell\ell\nu\nu b\bar{b}$ @ NLO with massive b-quarks $\Longrightarrow$ Most realistic calc^n of $m_{t,rec}$

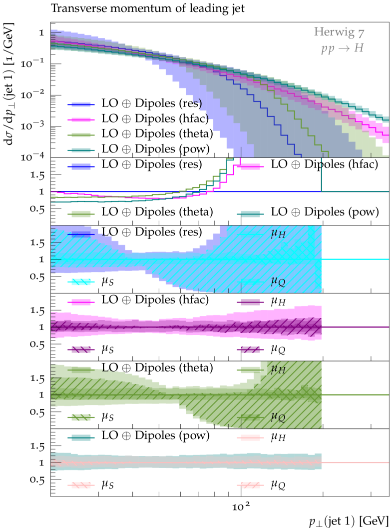
Much more sophisticated/subtle matching compared to e.g. Drell-Yan

b fragmentation *very sensitive* to details of matching/shower.

How large are shower uncertainties?

arXiv:1605.01338, arXiv:1605.08352, arXiv:1606.08753

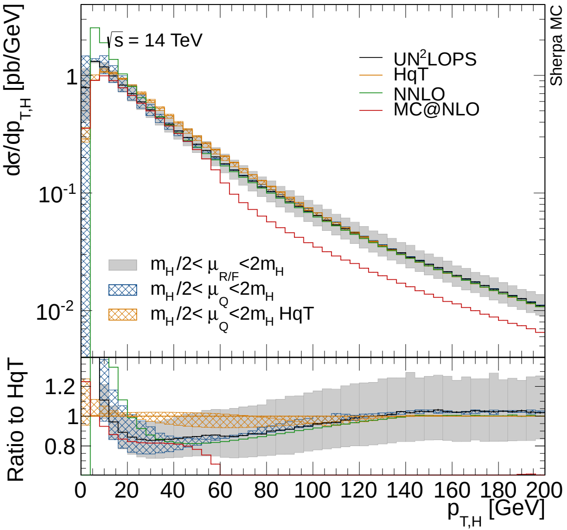




MCEGs offer efficient automatic PQCD scale variations.
Large uncertainties at *low* $p_\perp$. Reduced if sub-leading logs were fixed?

Motivations for new parton showers

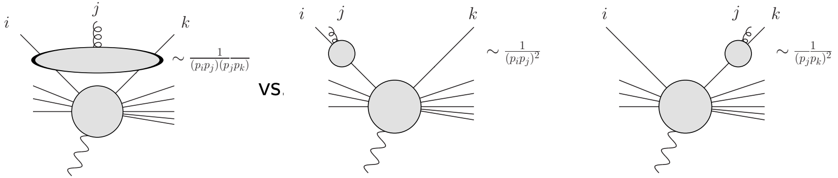
PRD90(2014)5,054011



PQCD evol^n dominant uncertainty in resummation/TMD region

Goal of Deductor/Dire/Vincia projects: More accurate & precise showers.

EPJC 75 (2015) 9, 461



Disentangle soft limit and collinear limits

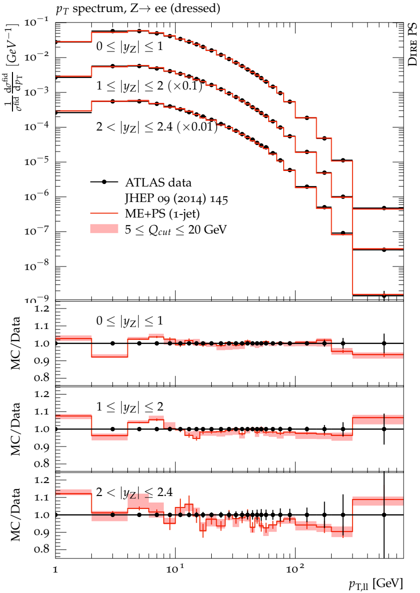
Reproduce dominant two-particle correlation in soft limit

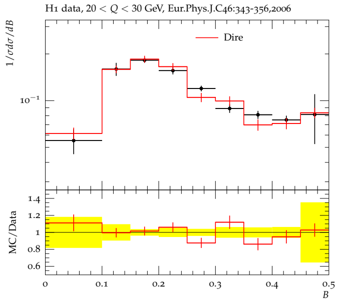
Use simple phase space boundaries

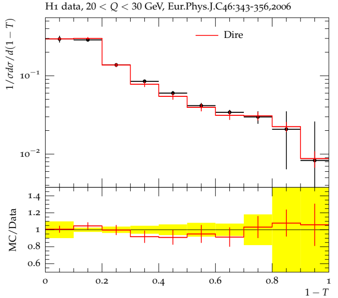
⇒ Manageable analytic structure allows systematic improvements

- ◇ Combines "traditional" *parton* showers and *dipole* showers.
- ◇ Two independent implementations, carefully cross-validated
- ◇ PQCD model of one MCEG fully reproducible in another.

DIRE predictions

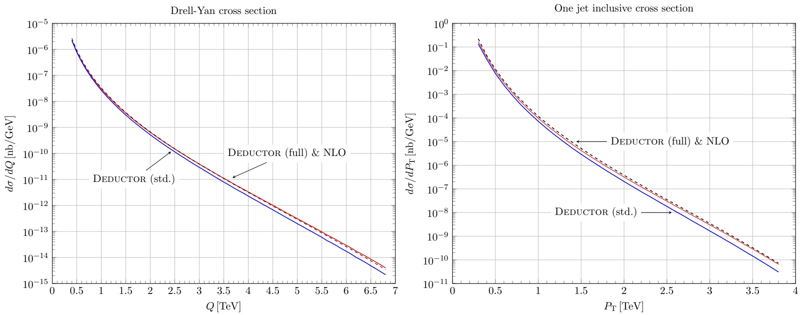






DEDUCTOR: Summing threshold logs in a shower

arXiv:1605.05845



DEDUCTOR framework:

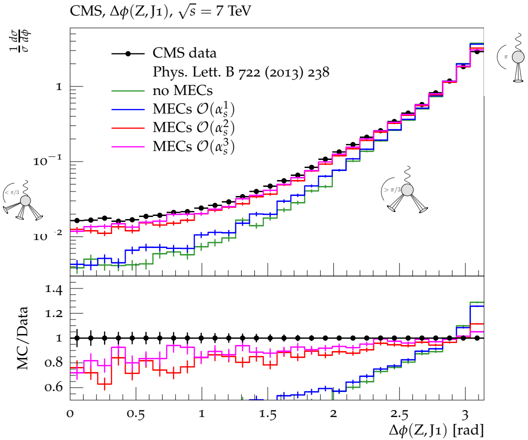
◇ PS based on Nagy-Soper dipoles, set up for amplitude-level evolution

◇ Recovers CSS equation @ NLL Drell-Yan $q_\perp$ spectrum

First fully exclusive resummation of threshold logarithms

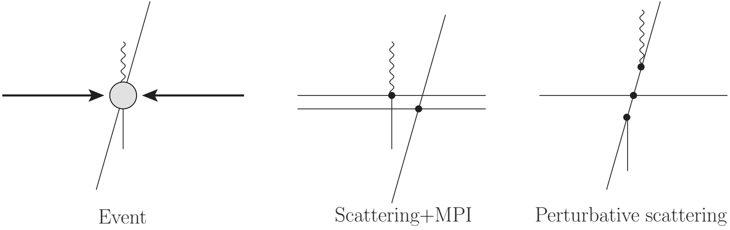
Achieved by relaxing PS unitarity condition in controlled fashion arXiv:1605.06142

Simultaneously integrates + resums fixed-order multi-jet MEs.



Take-home message: PS resummation should systematically move beyond LL. Old and new improvement ideas are becoming feasible.

Multiparticle states have many sources!



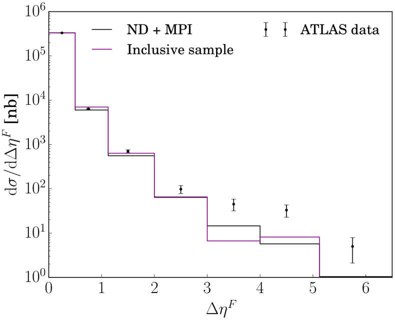
Inclusion of all (soft) particle production mechanisms important.

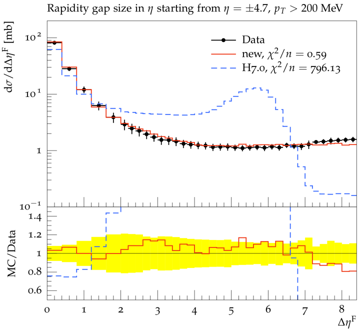
Crucial for forward physics, e.g.

cosmic ray measurements $\Longleftrightarrow$ *fixed-target on steroids*

News on diffractive physics

arXiv:1512.05525, arXiv:1612.04701





New PYTHIA8 diffraction, including dynamical gap survival probability.

Physical mechanism separating diffractive & non-diffractive proc^s.

Double diffraction currently missing.

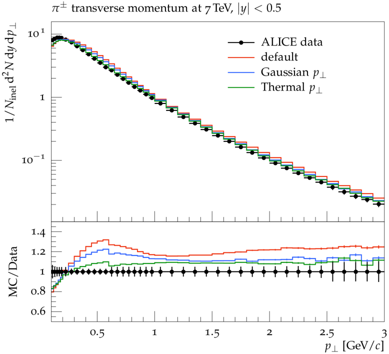
New single/double/non-diffractive processes & soft MPI in HERWIG7.

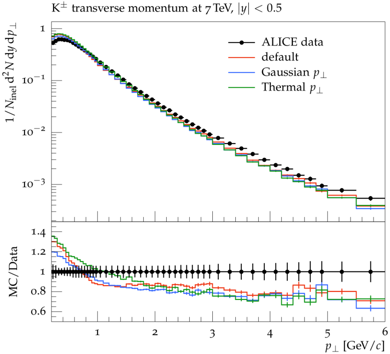
No additional parameters w.r.t. old model.

Describes MinBias very well.

Hadronization news: How does a string break?

arXiv:1610.09818



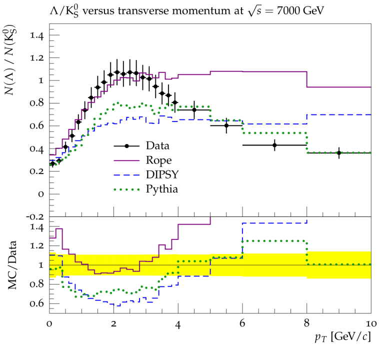


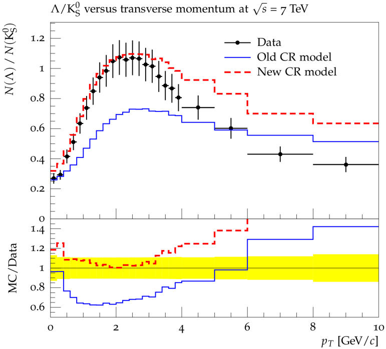
String model very predictive for dynamics, but not for flavour: Motivated by tunneling, $p_{\perp h}$ inherited from $m_{\perp q} \Longrightarrow \mathcal{O}(20)$ parameters.

New: Motivated by Hagedorn phase transition (QGP $\to$ hadrons), use mechanism directly based on $m_{\perp h} \Longrightarrow \mathcal{O}(5)$ parameters.

Ideas about dense color fields

JHEP 1503 (2015) 148, JHEP 1508 (2015) 003





Color ropes in DIPSY:

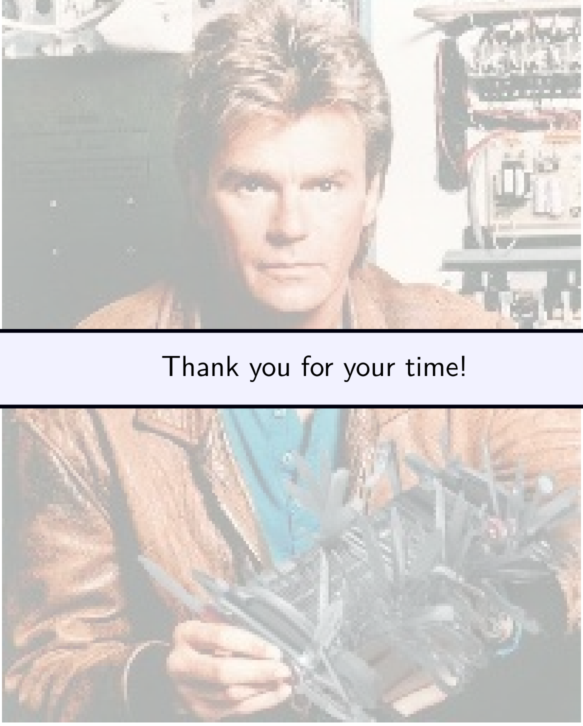
High string density converts strings to “ropes”. Ropes have higher tension → changed hadron spectrum.

New color-recon^n in PYTHIA:

Non-perturbative color swaps (determined from weight in SU(3) multiplets) before strings form.

- QCD phenomena are omnipresent in measurements.
- Availability of NNLO QCD calculations rapidly increasing.
- Event generators crucial for many experiments. Development continues on many topics:
  - Matching & merging community very active.
  - Renewed interest in improved parton showers.
  - More physical/microscopic diffractive models being developed.
  - Hadrochemistry at LHC tackled from many angles.

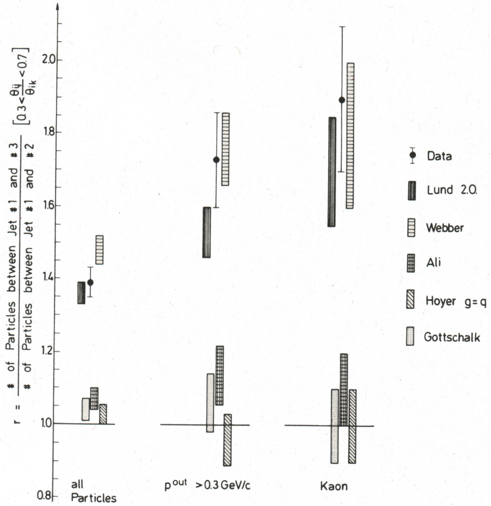
$\Longrightarrow$ Still a lot to do, and a lot to learn!



Thank you for your time!

Back-up

Remember: Jets are only an approximation!



Data shows that jets at LEP "talk to each other". The phenomenon is called string effect. It's perturbative incarnation is called *color coherence*.