# Modeling of hadronization

6th FCC PHYSICS WORKSHOP

KRAKÓW

Jan 23 – 27, 2023

https://indico.cern.ch/event/1176398

FUTURE CIRCULAR COLLIDER

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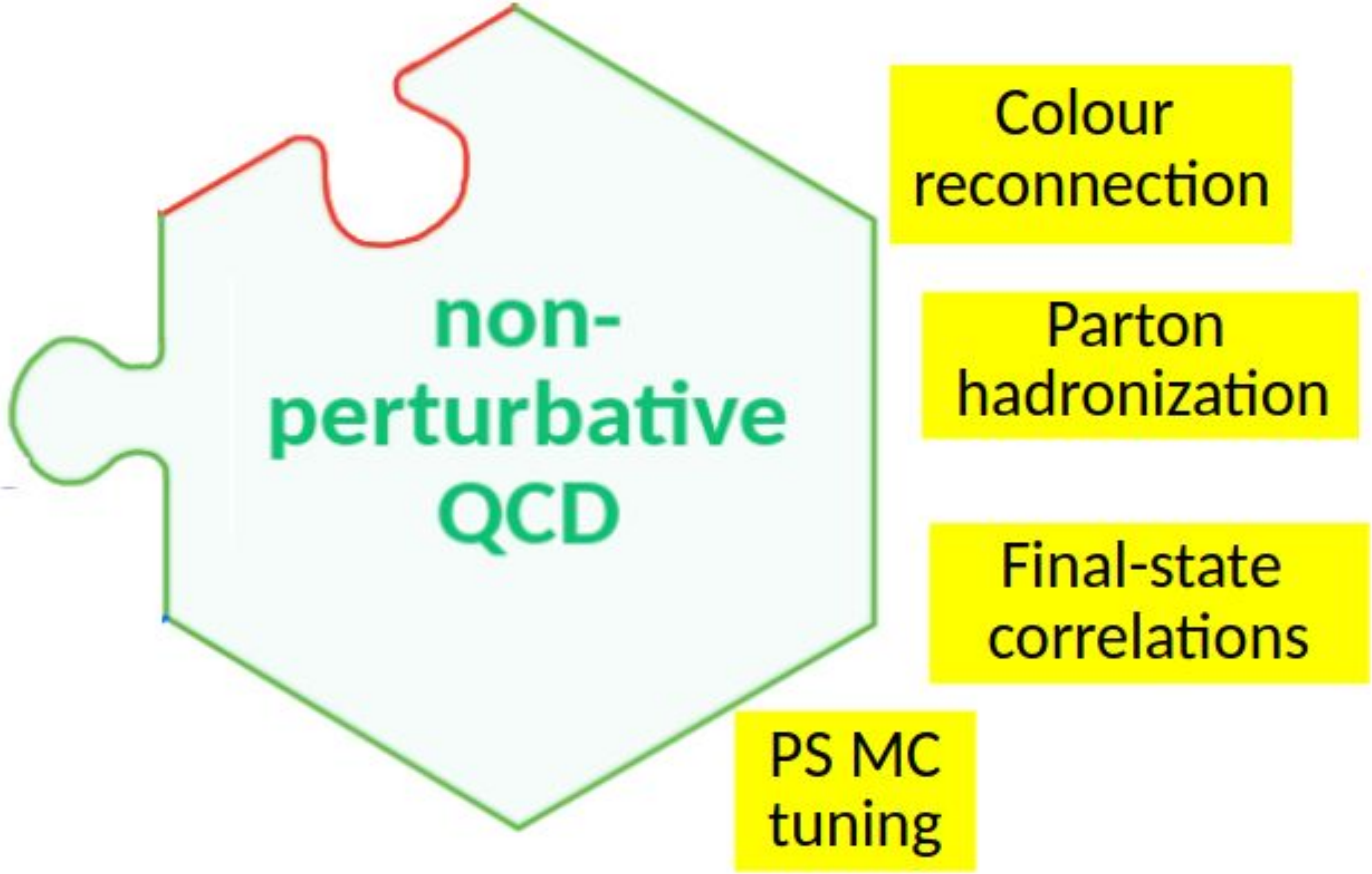
NCN: 2019/34/E/ST2/00457

MCnet

# Outline



non-perturbative QCD

Colour reconnection

Parton hadronization

Final-state correlations

PS MC tuning

Thanks to David d'Enterria

# Motivation - Monte Carlo Event Generators (MCEG)

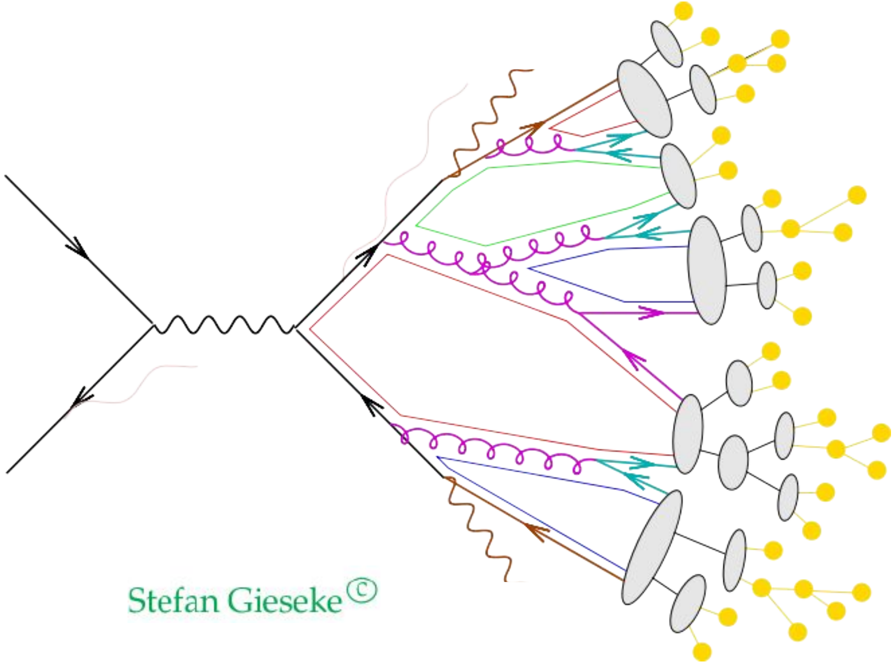
QCD correctly describes strong interactions in each energy range but its complex mathematical structure makes it very difficult to obtain precise predictions (Millennium Prize Problem $1,000,000)

**High energy**

- **perturbative QCD**
- **in theory we know what to do**
- **in practice very difficult**

**Low energy**

- **non-perturbative QCD**
- **we don't know what to do**
- **phenomenological models (with many free parameters)**



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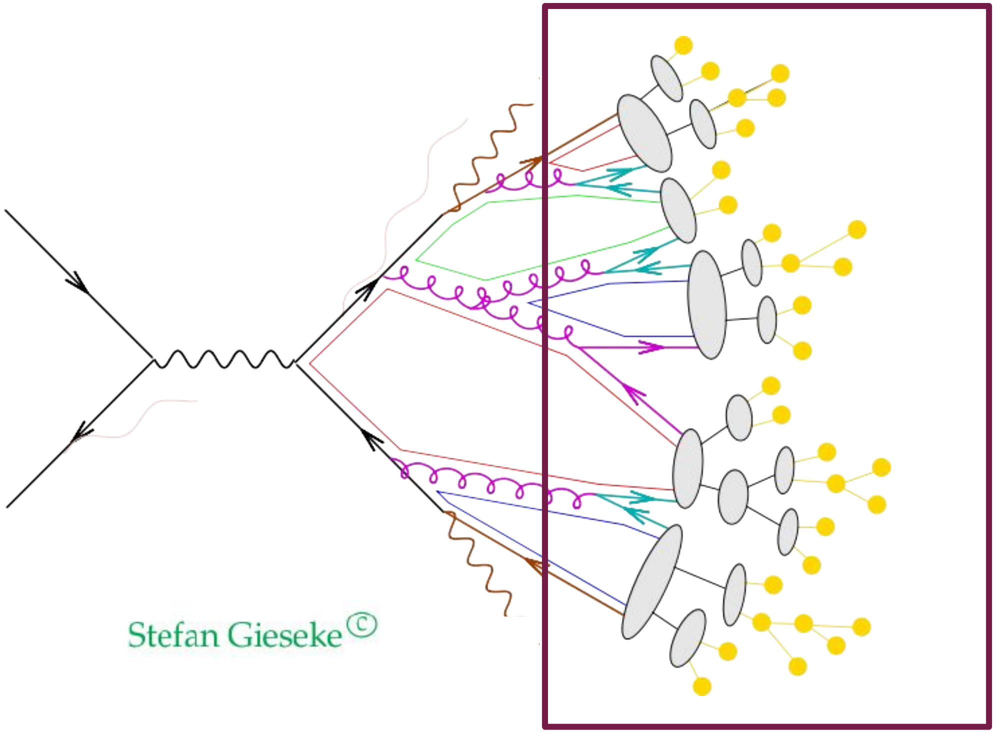


Hadronization:
one of the least understood elements of MCEG

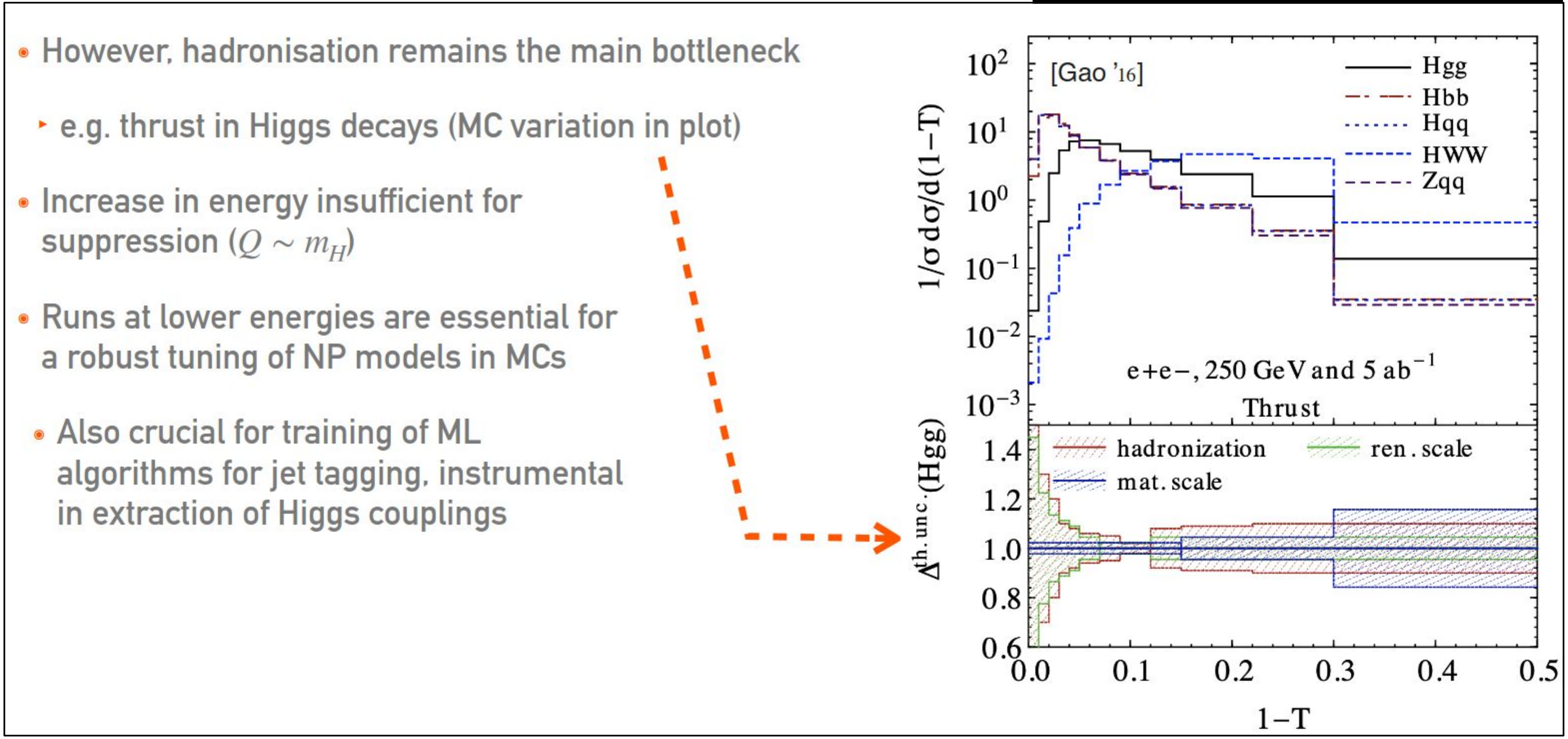
# Motivation - Hadronization

## Hadronization:

➔ Increased control of perturbative corrections ⇒ more often LHC measurements are limited by non-perturbative components, such as hadronization.

  - W mass measurement using a new method [Freytsis at al. JHEP 1902 (2019) 003]
  - Extraction of the strong coupling in [M. Johnson, D. Maître, Phys.Rev. D97 (2018) no.5]
  - Top mass [S. Argyropoulos, T. Sjöstrand, JHEP 1411 (2014) 043]
  - ...

**Pier Moni's talk**



- However, hadronisation remains the main bottleneck
  - e.g. thrust in Higgs decays (MC variation in plot)
- Increase in energy insufficient for suppression ($Q \sim m_H$)
- Runs at lower energies are essential for a robust tuning of NP models in MCs
  - Also crucial for training of ML algorithms for jet tagging, instrumental in extraction of Higgs couplings

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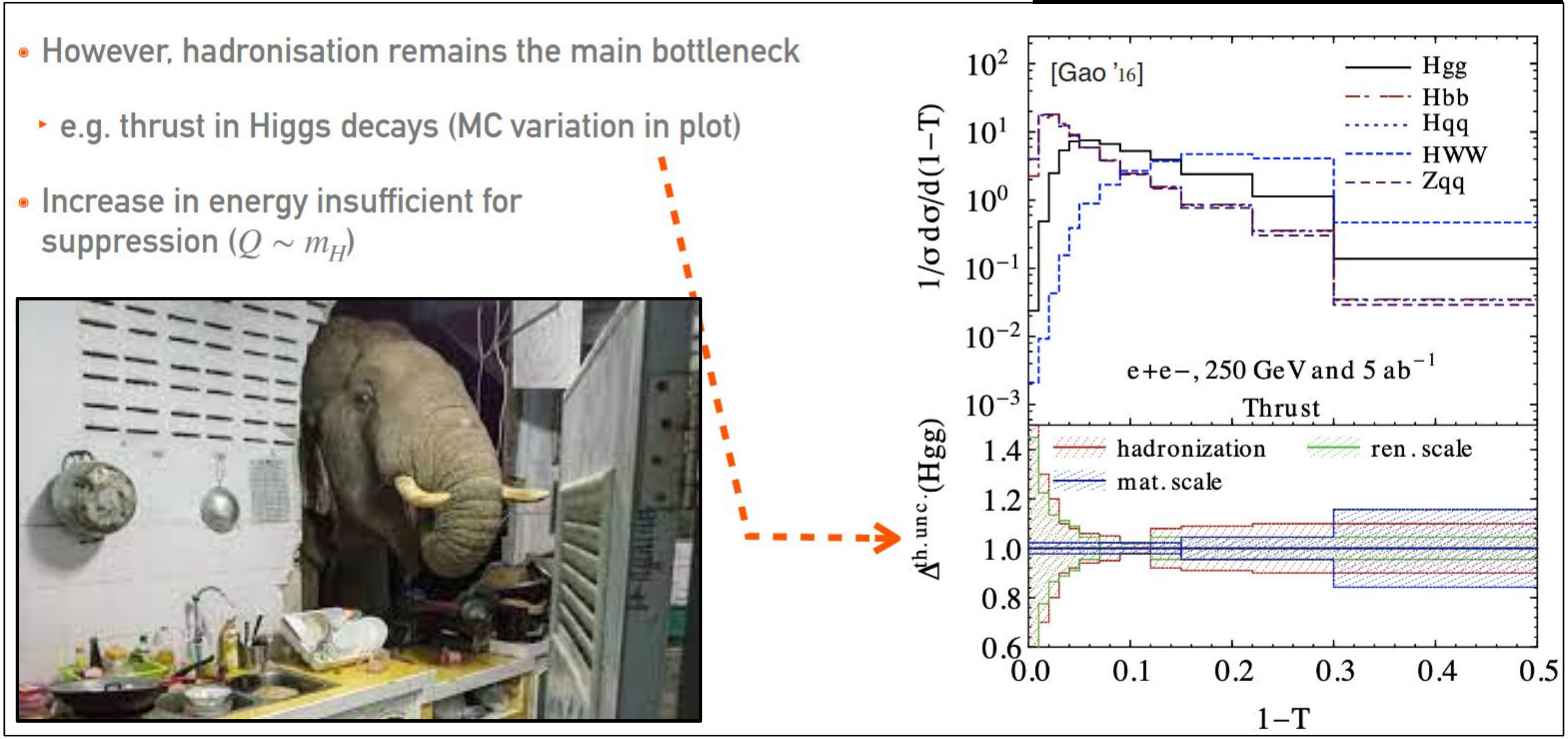

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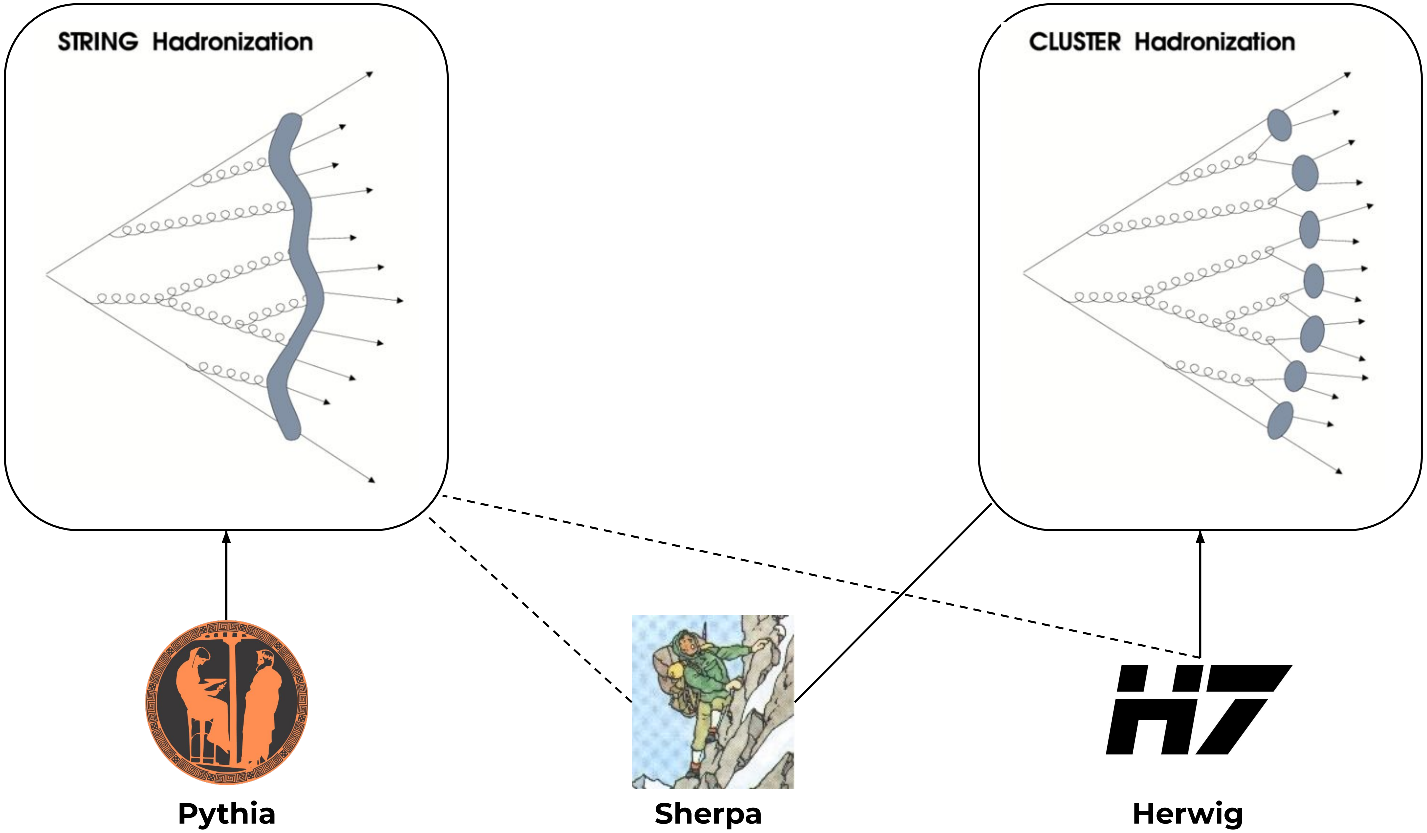
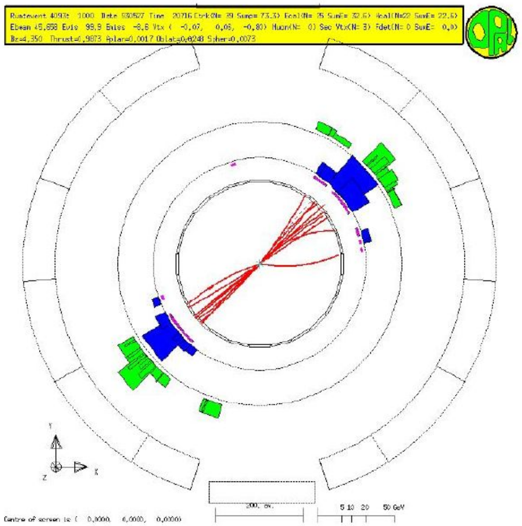


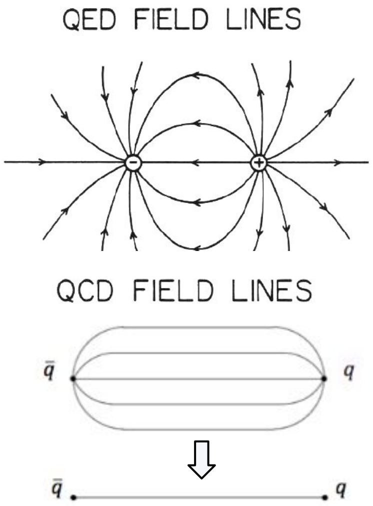
# String Model in nutshell [Andersson, Gustafson, Ingelman, Sjostrand, Phys.Rept.97(1983)31]

Originally invented without perturbative physics of parton showers in mind.

We start with 2-jet events in
e+ e− → hadrons.



Self coupling of gluons
“attractive field line”

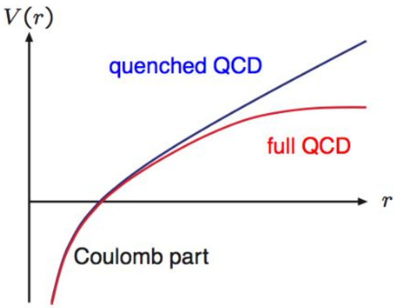


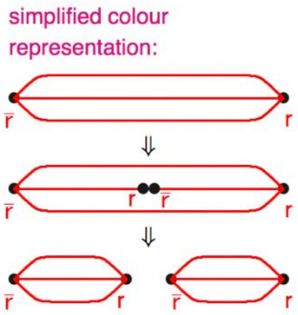
1+1 - dim. object: **string**

Linear static potential:

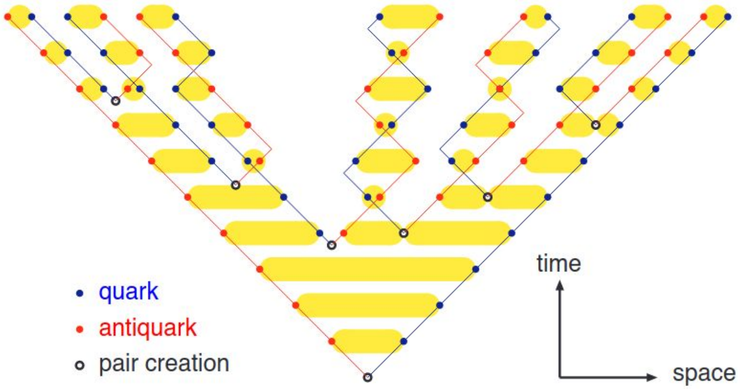
$$F(r) \approx \text{const} = \kappa \approx 1\ \text{GeV/fm} \iff V(r) \approx \kappa r$$

Picture supported by lattice QCD





**Lund string model: like rubber band that is pulled apart and breaks into pieces**



Plots from T. Sjostrand

# String Model in nutshell

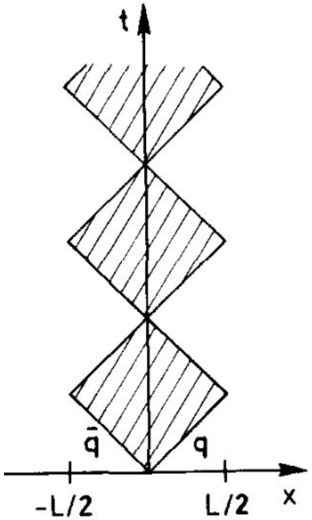
[Andersson, Gustafson, Ingelman, Sjostrand, Phys.Rept.97(1983)31]

## String motion

From linear static potential $V(r) \approx \kappa r$ and linearity between space–time and energy–momentum:

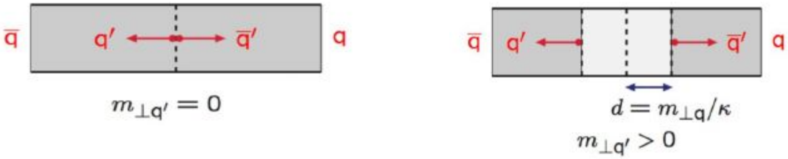
$$\left|\frac{\mathrm{d}E}{\mathrm{d}z}\right| = \left|\frac{\mathrm{d}p_z}{\mathrm{d}z}\right| = \left|\frac{\mathrm{d}E}{\mathrm{d}t}\right| = \left|\frac{\mathrm{d}p_z}{\mathrm{d}t}\right| = \kappa$$

We get a “YoYo“ state which we interpret as a meson.



## String breakdowns

The quarks obtain a mass and a transverse momentum in the breakup through a tunneling mechanism



with a probability:

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

- Suppression of heavy quarks:
  uu : dd : ss : cc ≈ 1 : 1 : 0.3 : $10^{-11}$
- Common Gaussian pT spectrum, <pT>~ 0.4 GeV
- Diquark (qq - q̄q̄ breakups) ~ antiquark
  ⇒ simple model for baryon production.

Iterative process (left-right symmetry) leads to distribution of momentum fraction taken by each hadron as:

$$f(z) \propto \frac{(1-z)^a}{z} \exp\left(-\frac{bm^2}{z}\right)$$

**Summary:**

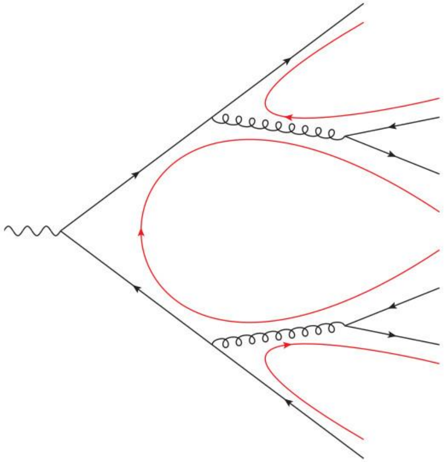
String model has very good energy-momentum picture however it is unpredictive in understanding of hadron mass effects ⇒ many parameters, 10-30 depending on how you count.

# Cluster model in nutshell

[Webber NPB238(1984)492]

What if we have PS (more perturbative input before hadronization).

**The philosophy of the model:** use information from perturbative QCD as an input for hadronization. QCD **pre-confinement** discovered by Amati & Veneziano [*Phys.Lett.B* 83 (1979) 87-92]:



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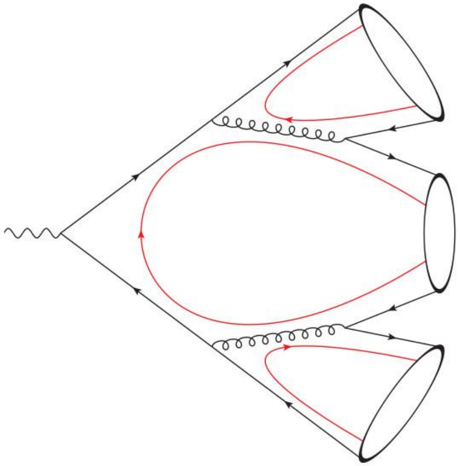

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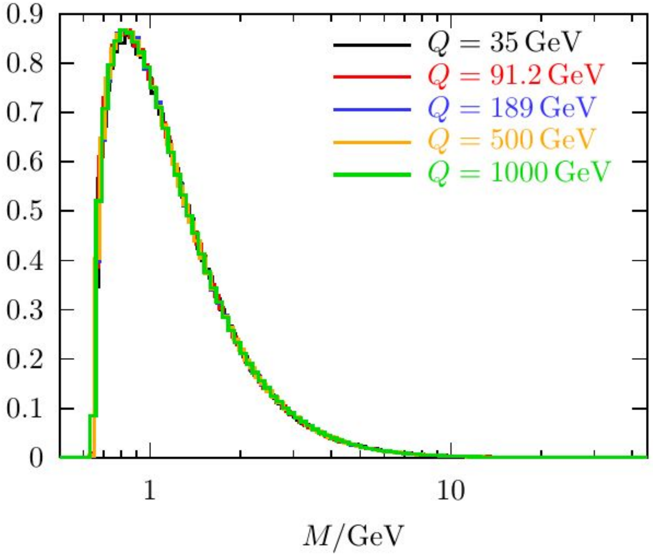
[S. Gieseke, A. Ribon, MH Seymour, P Stephens, B Webber JHEP 0402 (2004) 005]



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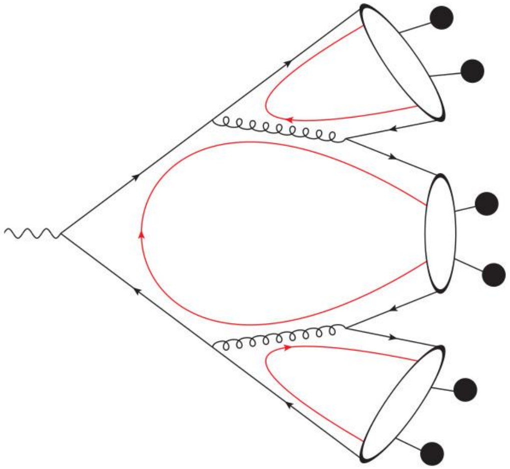

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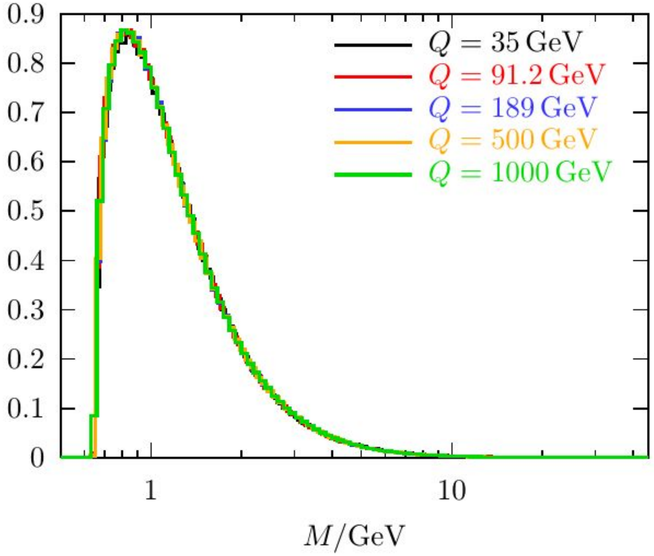

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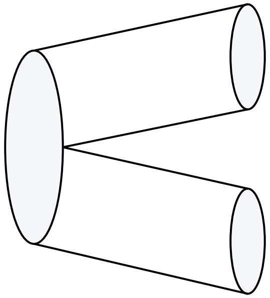
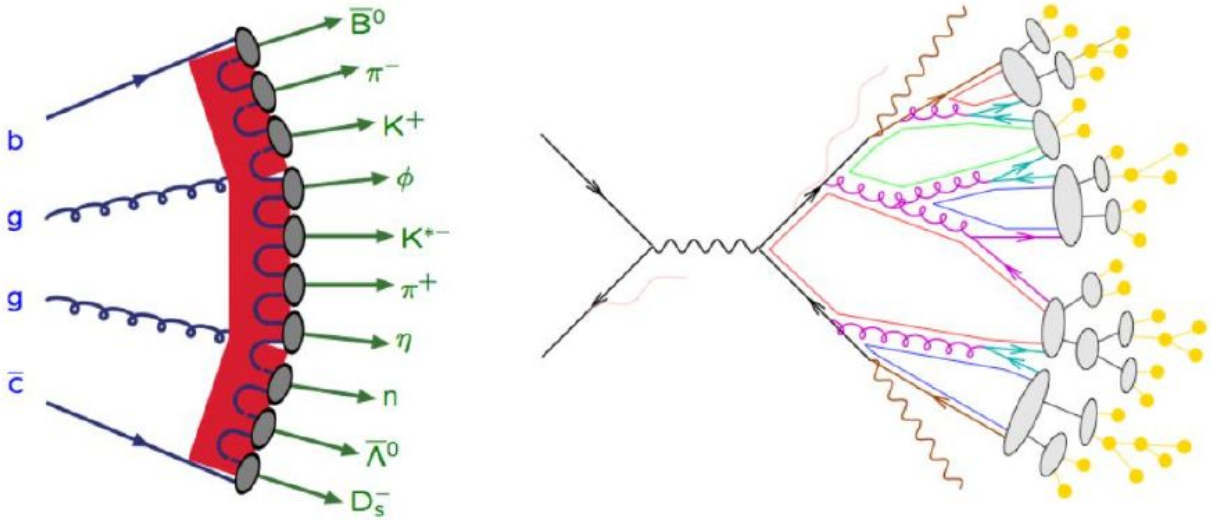
- Small fraction of clusters too heavy for isotropic two-body decay, heavy cluster decay first into lighter cluster C → CC, or radiate a hadron C → HC, it is rather string-like.
- ~ 15% of primary clusters get split but ~ 50% of hadrons come from them! *(see Simon Pleatzer's talk for some progress)*



# String vs Cluster model



| program | PYTHIA | Herwig |
|---|---|---|
| model | string | cluster |
| energy–momentum picture | powerful | simple |
| | predictive | unpredictive |
| parameters | few | many |
| flavour composition | messy | simple |
| | unpredictive | in-between |
| parameters | many | few |

Taken from T. Sjostrand

# Colour reconnection in Pythia

Introduced by T. Sjostrand and M. van Zijl
[Phys.Rev. D36 (1987) 2019]
to describe SppS data:

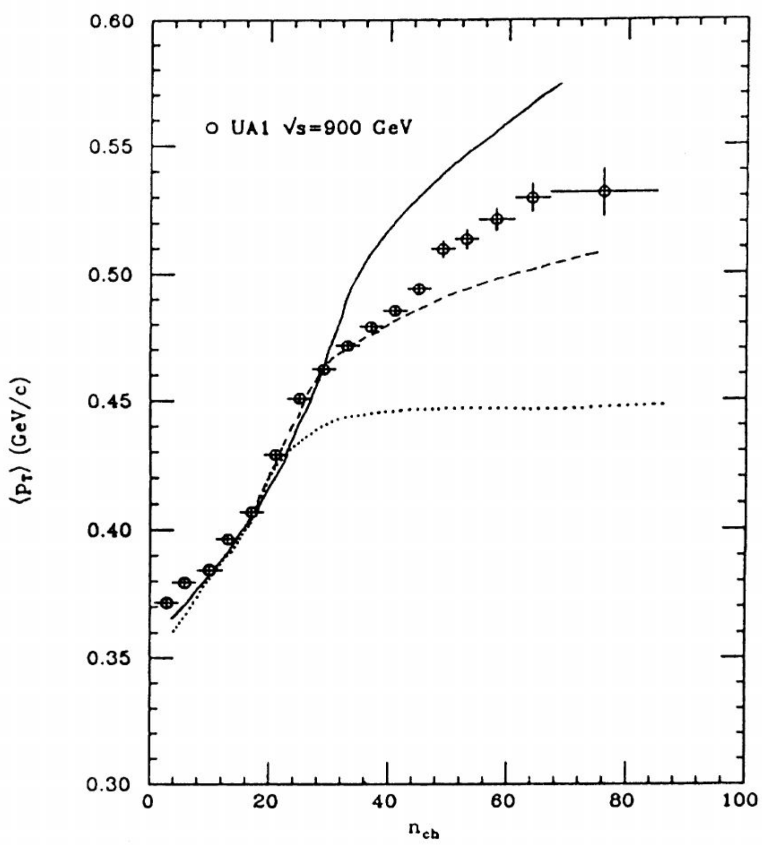
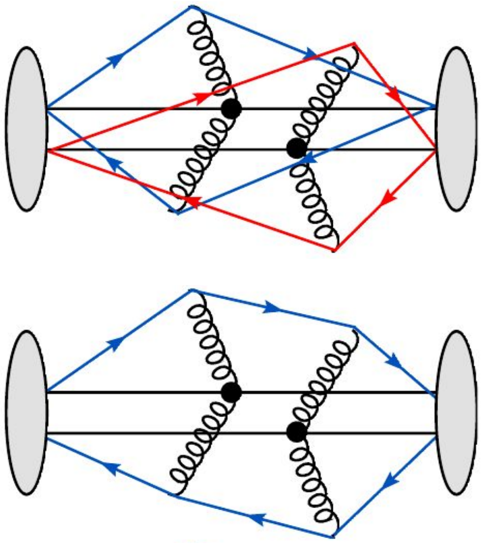


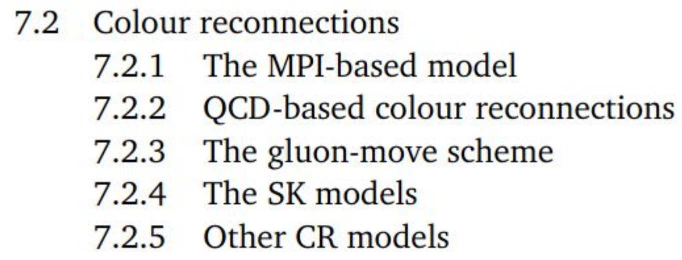
FIG. 27. Average transverse momentum of charged particles in $|\eta| < 2.5$ as a function of the multiplicity. UA1 data points (Ref. 49) at 900 GeV compared with the model for different assumptions about the nature of the subsequent (nonhardest) interactions. Dashed line, assuming $q\bar{q}$ scatterings only; dotted line, $gg$ scatterings with "maximal" string length; solid line $gg$ scatterings with "minimal" string length.

$\langle p_\perp \rangle (n_{\mathrm{ch}})$ sensitive to colour structure



**Many new models**

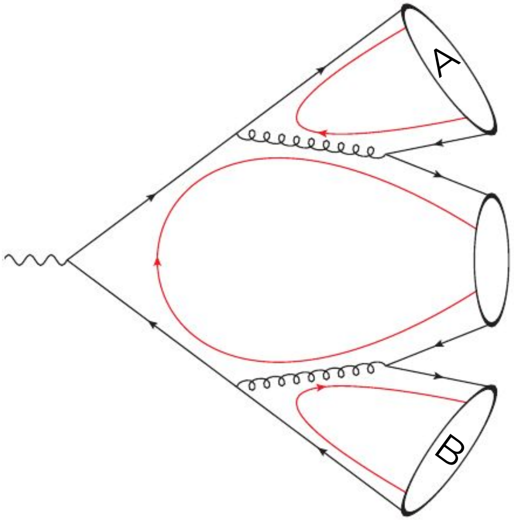
["PYTHIA 8.3 guide" arXiv:2203.11601]



J. Christiansen, P. Skands, JHEP 1508 (2015) 003
S. Argyropoulos, T Sjostrand, JHEP 1411 (2014) 043
…

# Example: Plain Colour reconnection in Herwig

[Gieseke, Röhr, **AS**, EPJC 72 (2012)]



Extending Herwig's hadronization model:

- QCD parton showers provide *pre-confinement* ⇒ colour-anticolour pairs form highly excited hadronic states, the *clusters*

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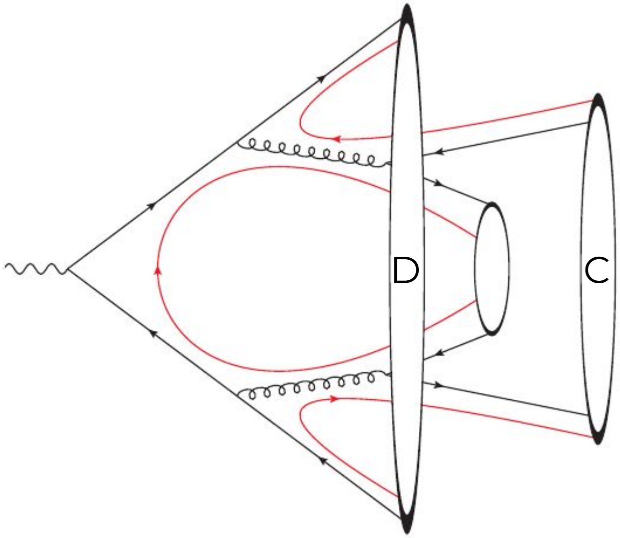
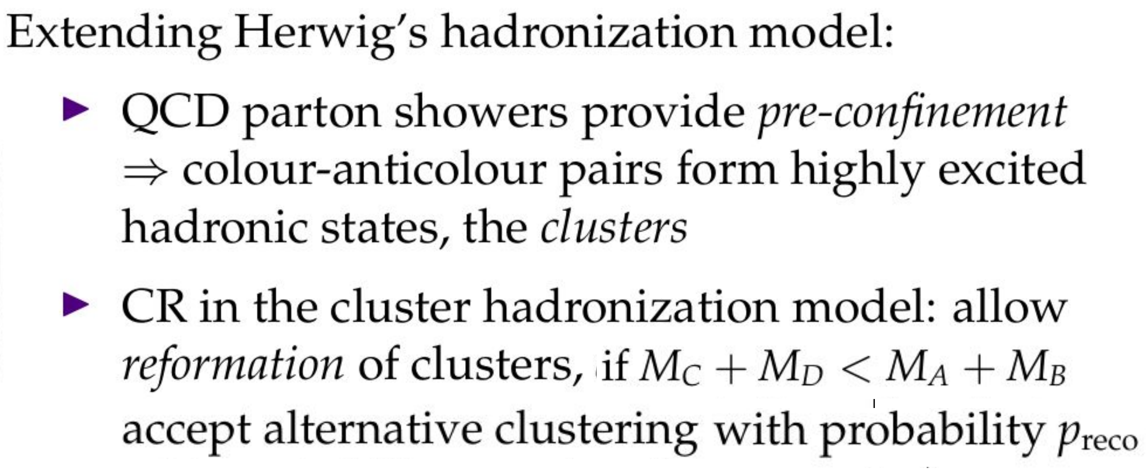


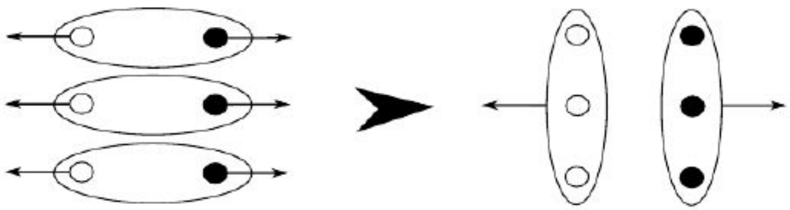


Extending Herwig’s hadronization model:

- ▶ QCD parton showers provide *pre-confinement* ⇒ colour-anticolour pairs form highly excited hadronic states, the *clusters*
- ▶ CR in the cluster hadronization model: allow *reformation* of clusters, if $M_C + M_D < M_A + M_B$ accept alternative clustering with probability $p_{\text{reco}}$

Different approaches in Herwig

- “Space-time CR” [J. Bellm, C. Duncan, S. Gieseke, M. Myska, **AS** EPJC 79 (2019) no.12, 1003]
- “Baryonic colour reconnection” [S. Gieseke, P. Kirchgaeßer, S. Plätzer Eur.Phys.J. C78 (2018)]



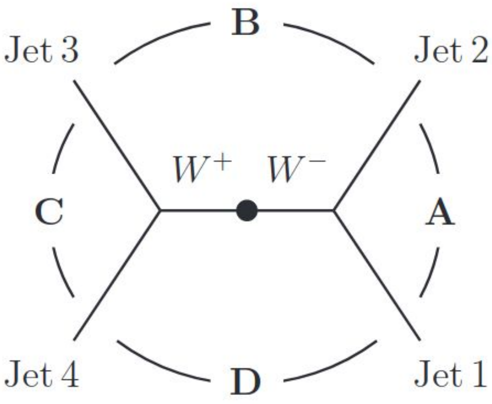
- Colour Reconnection from Soft Gluon Evolution [Gieseke, Kirchgaesser, Plätzer, **AS** JHEP 11 (2018) 149]

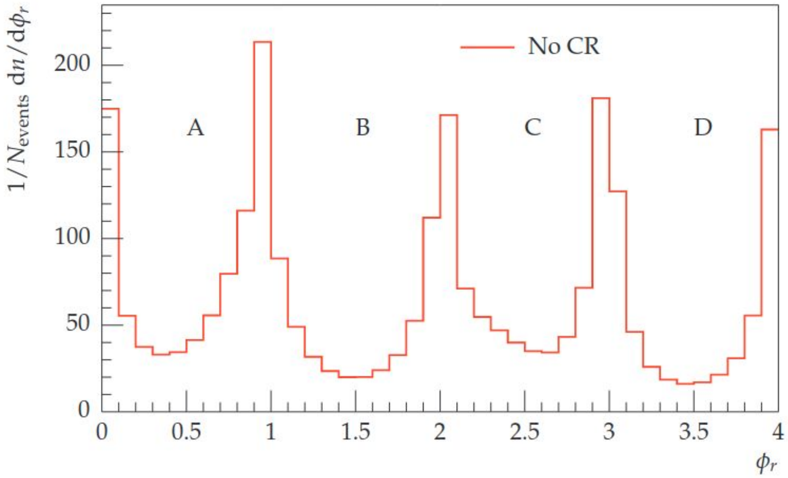
(see Simon’s Pleatzer talk)

# Is Colour reconnection important for lepton colliders?

- Effect is less severe than in hadron machines
- However, we are aiming in very precise measurement so we will need to control/constrain it

[hep-ex/0612034]





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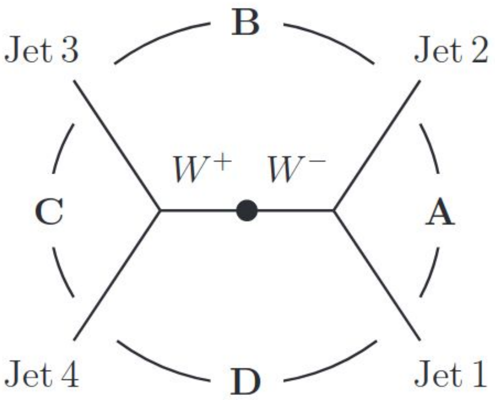
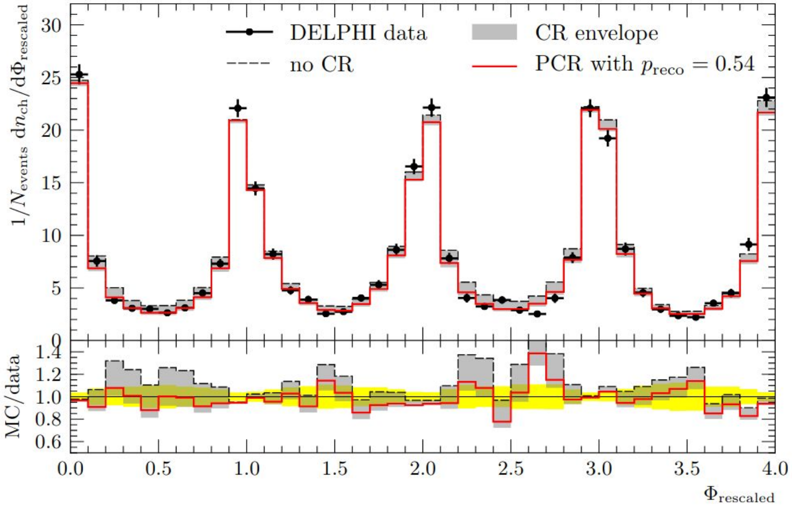


Herwig Plain CR passed the check, some models ruled out by LEP



[Gieseke, Röhr, **AS**, EPJC 72 (2012)]

- CR at future e + e − colliders [J. Christiansen & T. Sjostrand, EPJ C75 (2015) 9, 441]
  - FCC-ee promises $M_W < 1$ MeV ⇒ test CR models by $M_W$ shift in hadronic decays
  - Hadronic Higgs parity measurement

$$H^0 \rightarrow W^+W^- \rightarrow q_1\bar{q}_2q_3\bar{q}_4$$

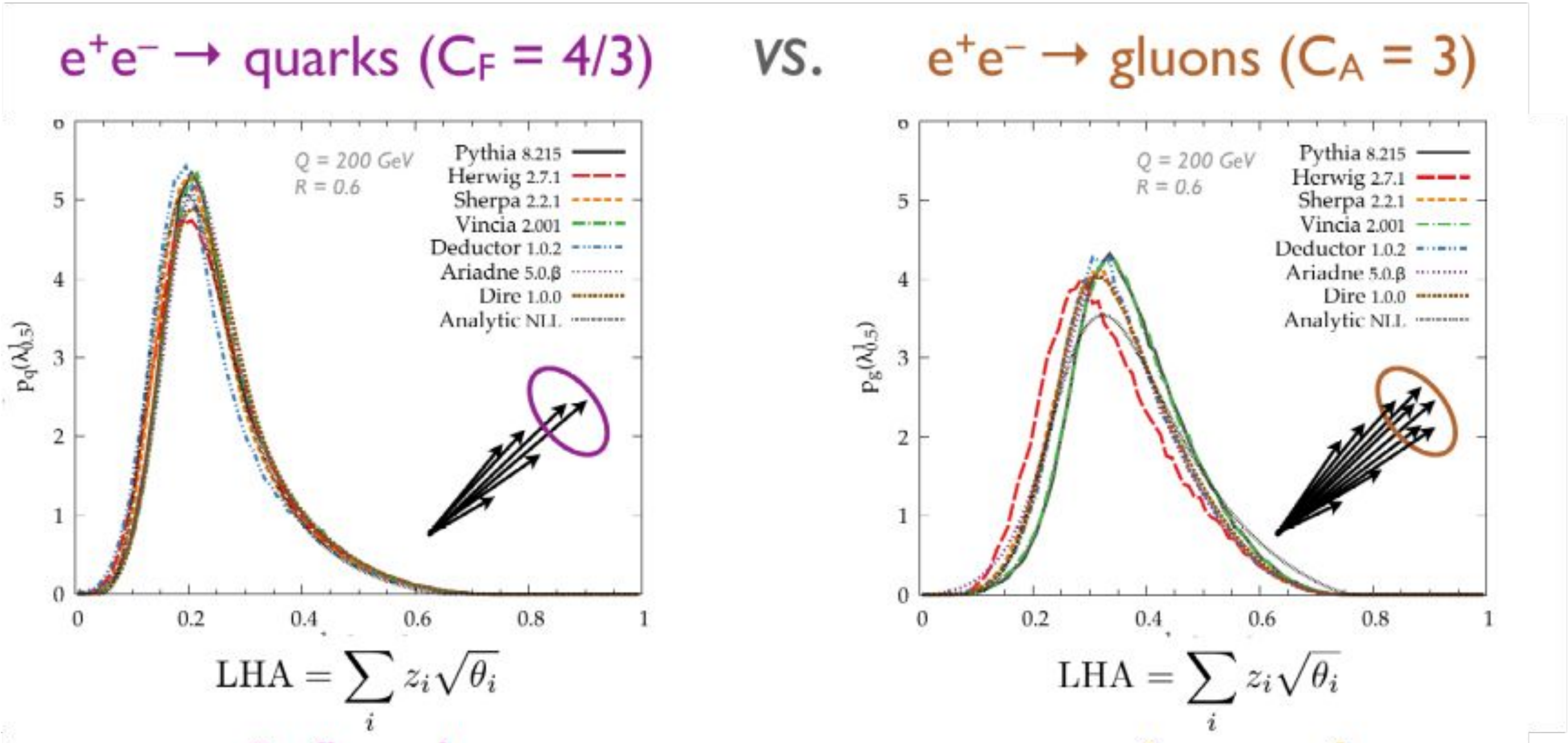
CR important for precision below 5 %

  - Di-photons? (suggested by Stefan Kluth)

| Model | $\langle \delta \overline{m}_{\mathrm{W}} \rangle$ (MeV) | | |
|---|---|---|---|
| | 170 GeV | 240 GeV | 350 GeV |
| SK-I | +18 | +95 | +72 |
| SK-II | -14 | +29 | +18 |
| SK-II’ | -6 | +25 | +16 |
| GM-I | -41 | -74 | -50 |
| GM-II | +49 | +400 | +369 |
| GM-III | +2 | +104 | +60 |
| CS | +7 | +9 | +4 |

# Quark/Gluon jets at e+e-

[Gras, Hoeche, Kar, Larkoski, Lönnblad, Plätzer, AS, Skands, Soyez, Thaler, JHEP 1707 (2017) 091]



$e^+e^- \to$ quarks ($C_F = 4/3$) vs. $e^+e^- \to$ gluons ($C_A = 3$)

$$\mathrm{LHA} = \sum_i z_i \sqrt{\theta_i}$$

**Small spread**

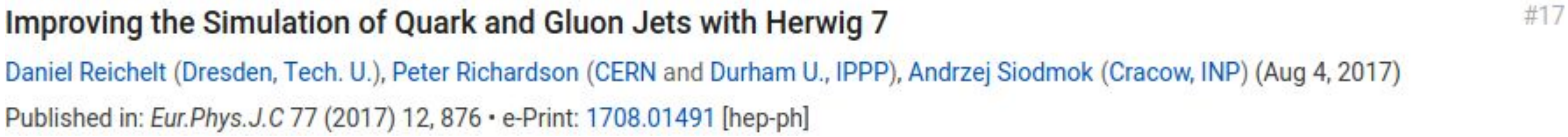
Constrained by LEP

**Large spread**

Up to now no e+e- data has been used to constrain it.

Colour reconnection turned out to be most important here!

# Is Colour reconnection important for lepton colliders?



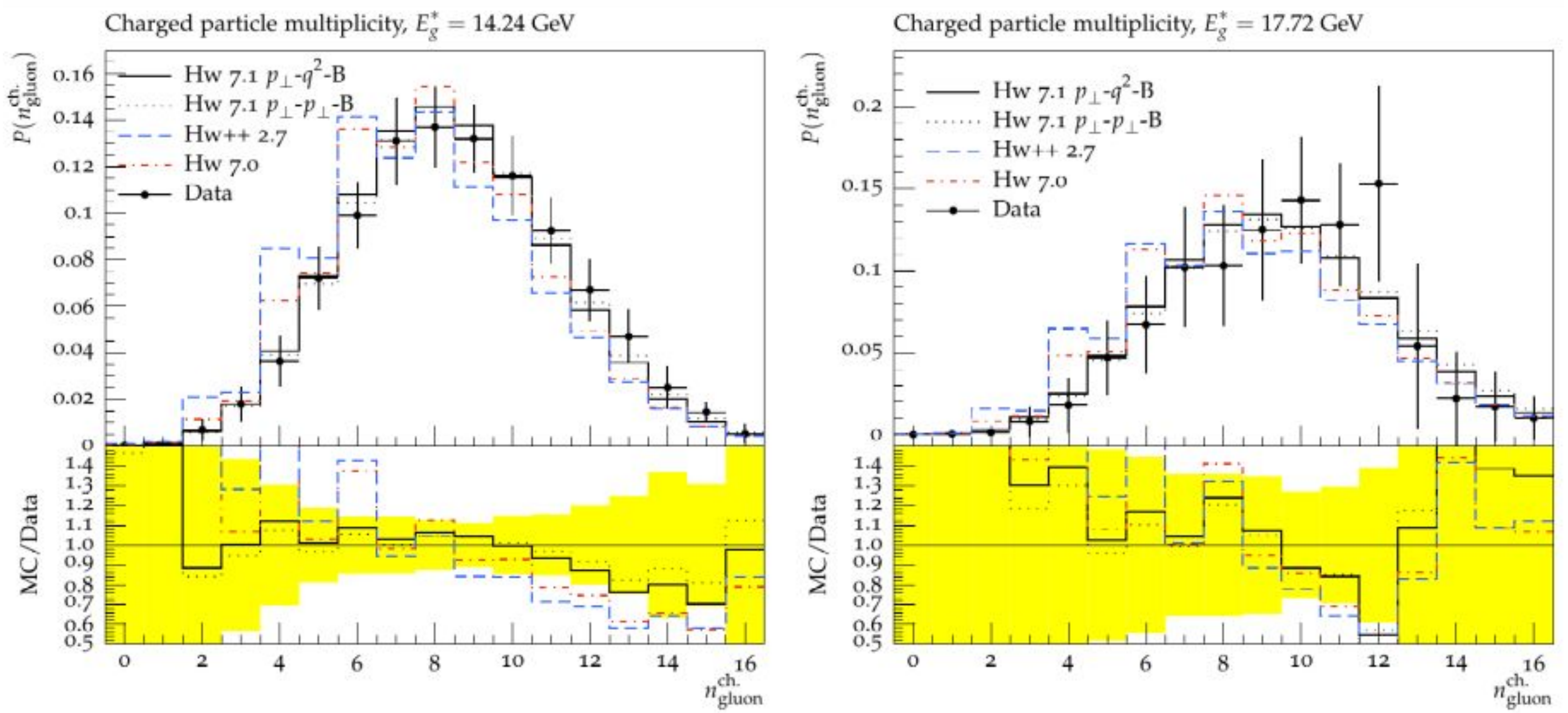
#17

**Improving the Simulation of Quark and Gluon Jets with Herwig 7**

Daniel Reichelt (Dresden, Tech. U.), Peter Richardson (CERN and Durham U., IPPP), Andrzej Siodmok (Cracow, INP) (Aug 4, 2017)

Published in: *Eur.Phys.J.C* 77 (2017) 12, 876 • e-Print: 1708.01491 [hep-ph]

Multiplicity distribution of charged particles in gluons jets for two different gluon energies.



**Data** was one of the **key for the improvement** and it is still needed for the progress.
FCCee will be crucial to constrain the CR and hadronization models.

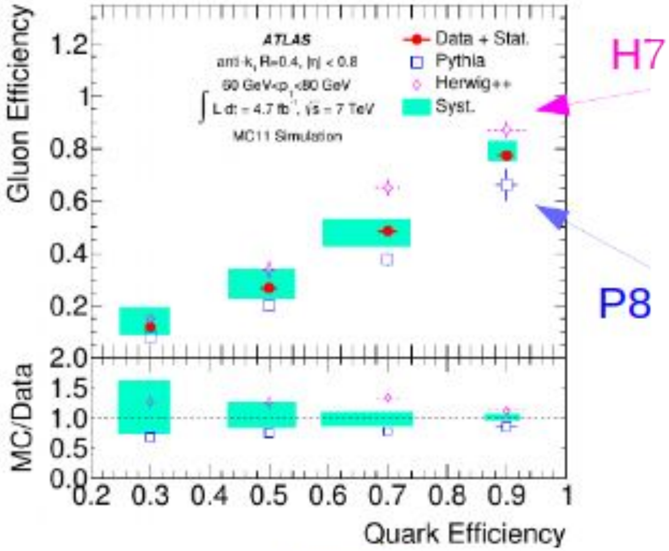
Similarly like LEP ⇒ LHC we will benefit enormously from FCCee ⇒ FCChh

# Example of non-perturbative “loop” correction

Idea use q/g jets for BSM search

Quark: $C_F = 4/3$ vs. Gluon: $C_A = 3$

Validate the idea against the data



[Gras, Höche, Kar, Larkoski, Lönnblad, Plätzer, Siódmok, Skands, Soyez, Thaler JHEP, 1707 , 091 (2017)]

Improve description of q/g jets in MCEG

[Reichelt, Richardson, Siodmok EPJC C77 (2017)]

Construct new observables sensitive q/g jets [Baron, Seymour, Siodmok]

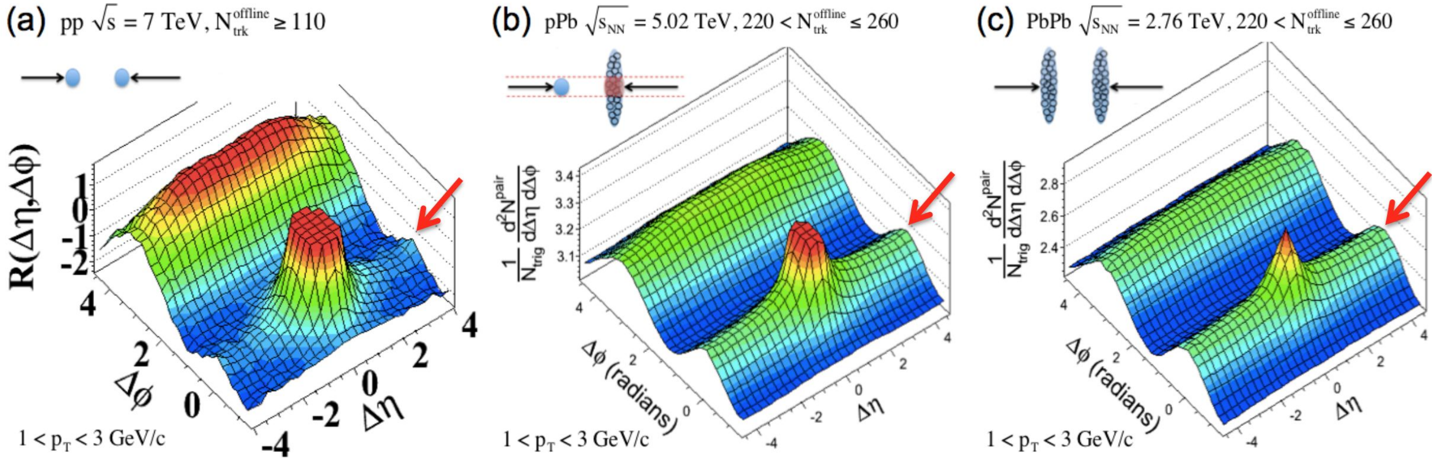
# Lund string model - updates

[“PYTHIA 8.3 guide” arXiv:2203.11601]

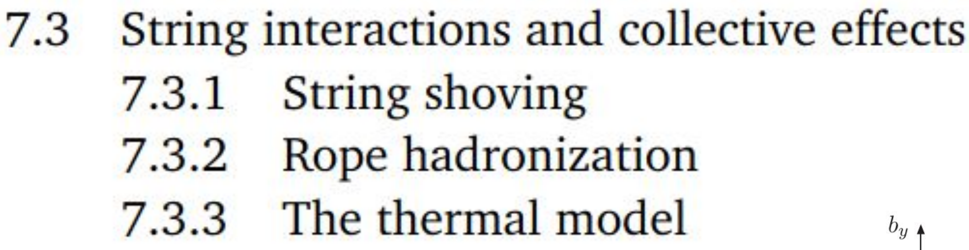
“A comprehensive guide to the physics and usage of PYTHIA 8.3” [arXiv:2203.11601]

> *“... hadronization are identical to previous versions of PYTHIA, the past years have seen significant activity in the area of fragmentation dynamics, guided by the discovery of heavy-ion-like effects in hadronic collisions.”*

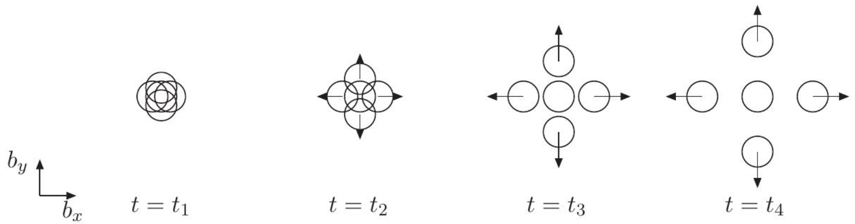
Hadronization of very dense systems shows unexpected correlations



LEP 2 data re-analysis shows no correlations in e+e-, worth to measure in FCC-ee!

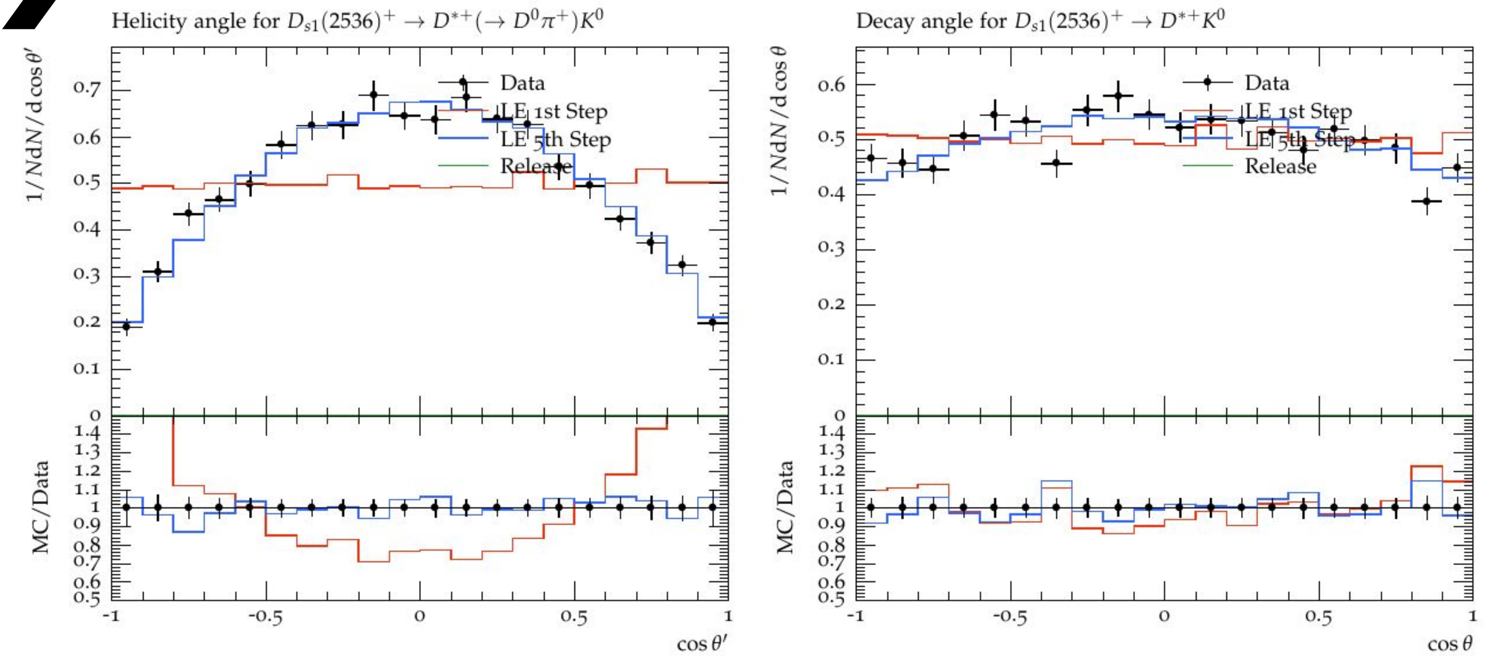


7.3 String interactions and collective effects
  7.3.1 String shoving
  7.3.2 Rope hadronization
  7.3.3 The thermal model



7.3.1 [Ch. Bierlich, S. Chakraborty, G. Gustafson, L. Lönnblad *JHEP* 03 (2021) 270]
7.3.2 [Ch. Bierlich, S. Chakraborty, G. Gustafson, L. Lönnblad *SciPost Phys.* 13 (2022)]
7.3.3 [N. Fischer, T. Sjöstrand *JHEP* 01 (2017) 140]

# Cluster model recent development


Helicity angle for $D_{s1}(2536)^+ \to D^{*+}(\to D^0\pi^+)K^0$

Decay angle for $D_{s1}(2536)^+ \to D^{*+}K^0$

LEP measurement of decay angles in the decay $D_{s1}(2536)^+ \to D^{\star +}K^0$ at $\sqrt{s} = 10.6$ GeV.

- “Polarization of Heavy Hadrons“ Aidin Masouminia & Peter Richardson [to be published]
- Dark Cluster Hadronization (see Simon Pleatzer’s talk)

Further develop and tune cluster hadronization, and a model for colour reconnection Sherpa (2203.11385).

# Tuning

- Fixing parameters of hadronization (tuning) using mainly e+e- LEP data (example next slide)
- A tune encapsulates the knowledge from previous experiments!
- Pythia has plenty tunes, Herwig and Sherpa have much less

**Pythia**

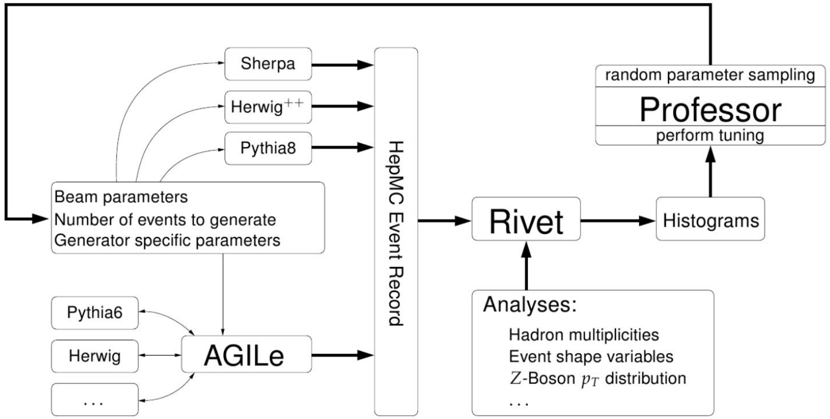
H7

**Herwig**

**Sherpa**

- Tuning still more like an art than science (many choices to do), however automatized tools: like Professor help a lot!

## Rivet and Professor



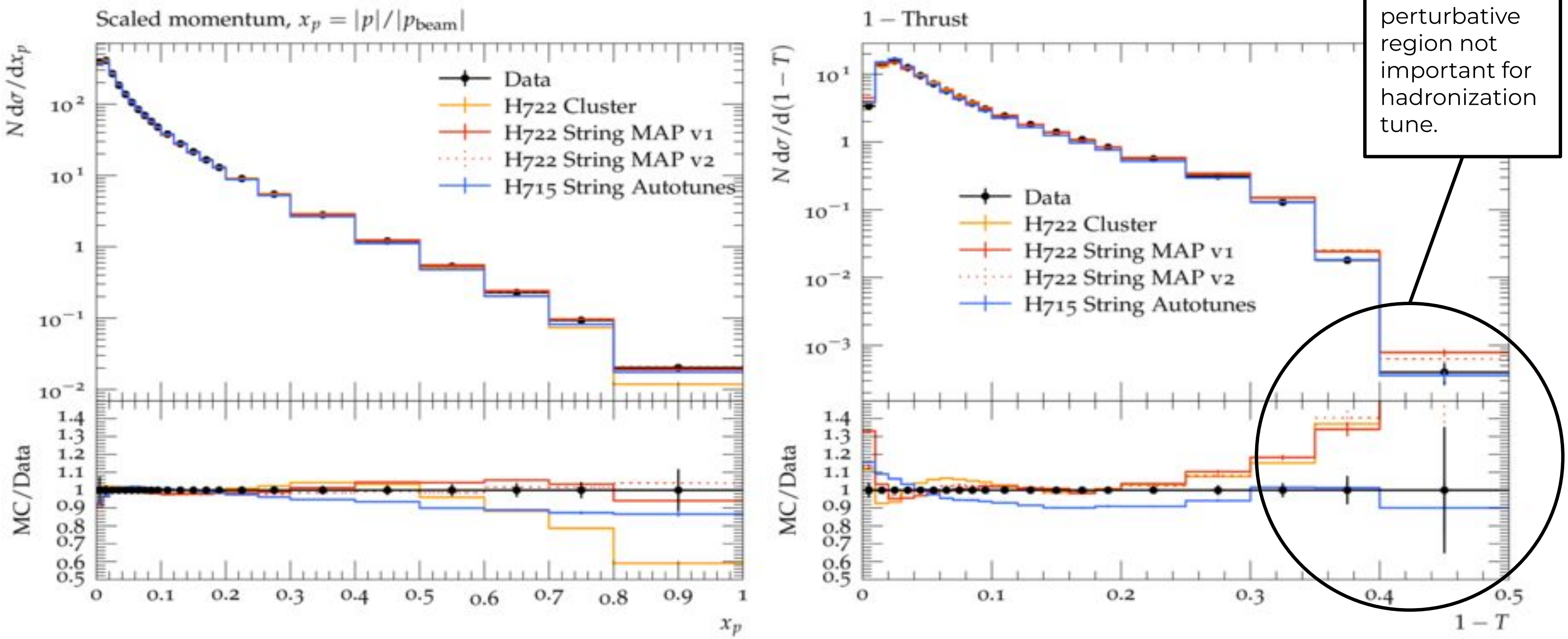
Sherpa
Herwig$^{++}$
Pythia8
Beam parameters
Number of events to generate
Generator specific parameters
Pythia6
Herwig
. . .
AGILe
HepMC Event Record
Rivet
Analyses:
Hadron multiplicities
Event shape variables
$Z$-Boson $p_T$ distribution
. . .
Histograms
random parameter sampling
Professor
perform tuning

- Warnings:
  - One must be very careful not to overdo tuning (force hadronization to describe perturbative physics - see and S. Pleatzer's talk)
  - Do not ignore past data (some ATLAS tune ignored LEP data, some changes helped to get better description of LHC data but ruined description of LEP)

# Tuning Angular Ordered PS + String [M.Myska, P. Sarmah, AS to be published]

To **evaluate uncertainties** stemming from the hadronization, Sherpa provides an interface to the Lund string fragmentation in Pythia 6, Herwig has an interface using P8I [Lönnblad] to the Lund string fragmentation in Pythia 8

- Plots from the analysis DELPHI_1996_S3430090

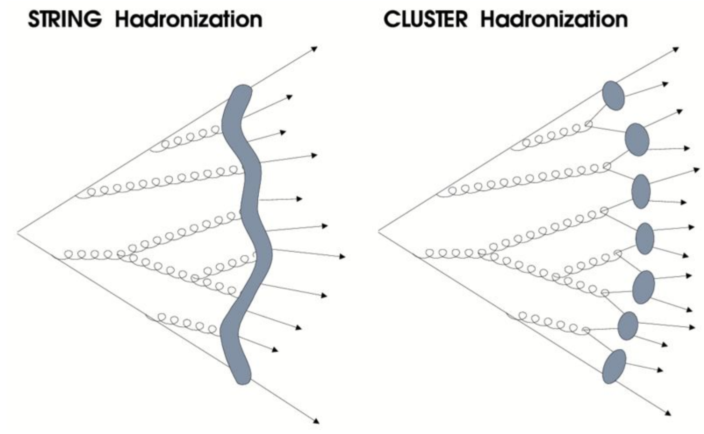


This is perturbative region not important for hadronization tune.

# ML Hadronization

## Hadronization:

Early 1980's
(since then not a lot development)



# ML Hadronization

**Hadronization:**

Early 1980's
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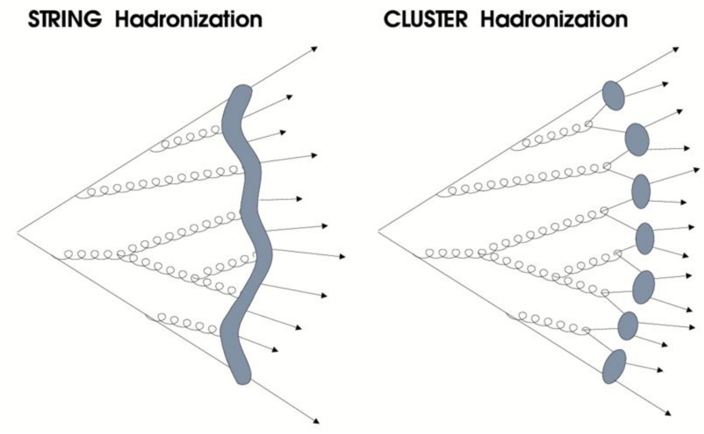
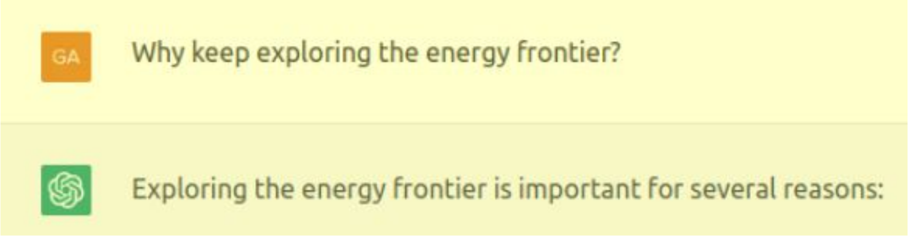


Early 2020's
(lot of progress in ML)



Why keep exploring the energy frontier?

Exploring the energy frontier is important for several reasons:

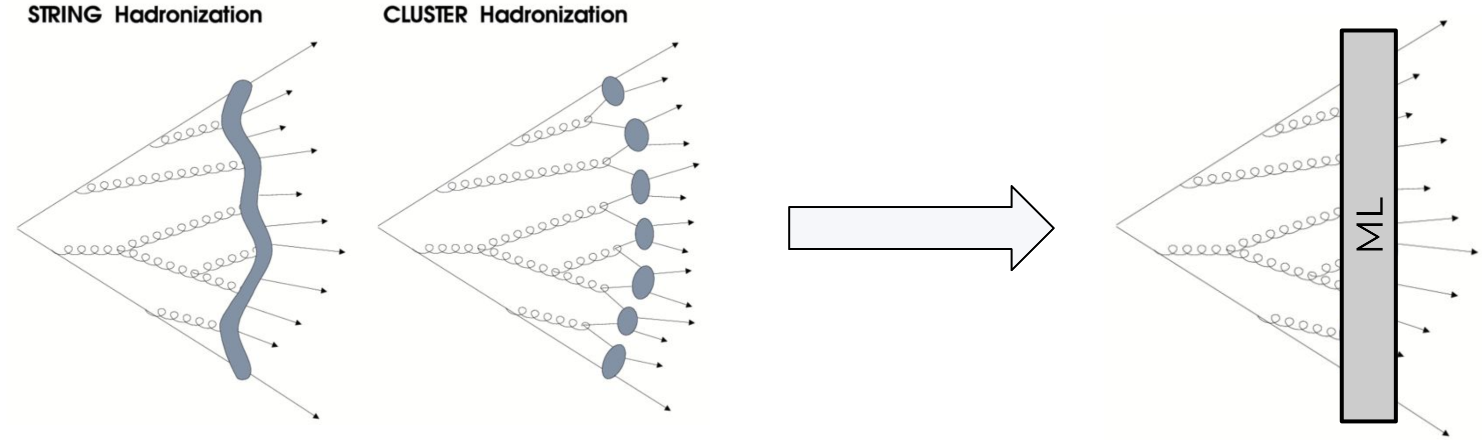
(Gauthier Durieux's talk)

# ML Hadronization

## Hadronization:

Early 1980's
(since then not a lot development)

Early 2020's
(lot of progress in ML)



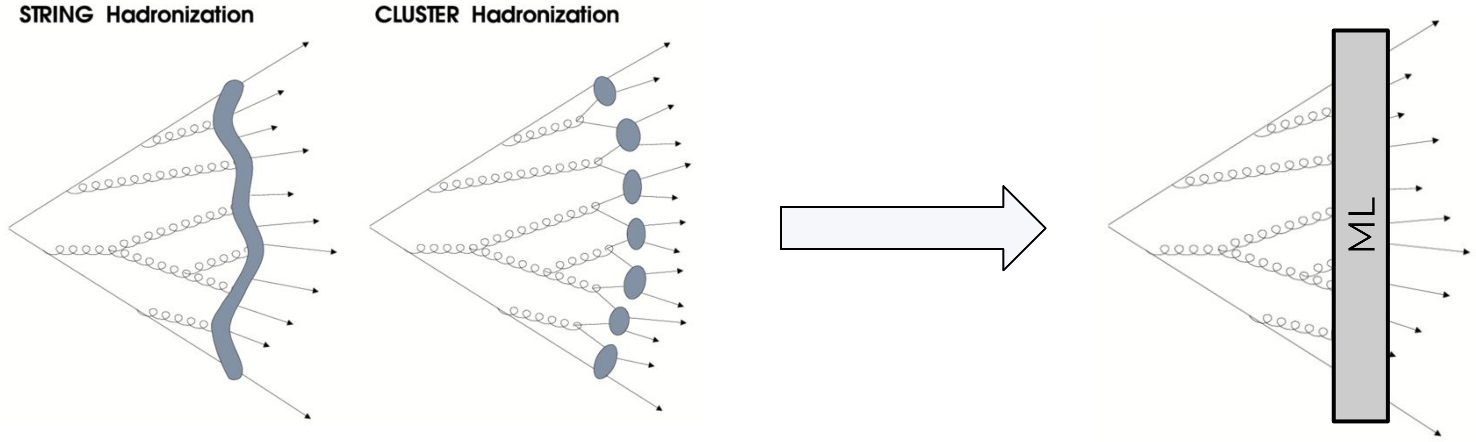
- ➔ Increased control of perturbative corrections ⇒ more often the precision of LHC measurements is limited by MCEG's non-perturbative components, such as hadronization.
- ➔ Hadronization (phenomenological models with many free parameters ~ 30 parameters)
- ➔ Hadronization is a fitting problem ML is proved to be well suited for such a problems.

# ML Hadronization

## Hadronization:

Early 1980's
(since then not a lot development)

Early 2020's
(lot of progress in ML)



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- ➔ Hadronization (phenomenological models with many free parameters ~ 30 parameters)
- ➔ Hadronization is a fitting problem ML is proved to be well suited for such a problems.

NNPDF

NNPDF used successfully ML to nonperturbative Parton Density Functions (PDF)
Early on, lated to fragmentation functions (closely related to hadronization) were considered the counterpart of PDFs.

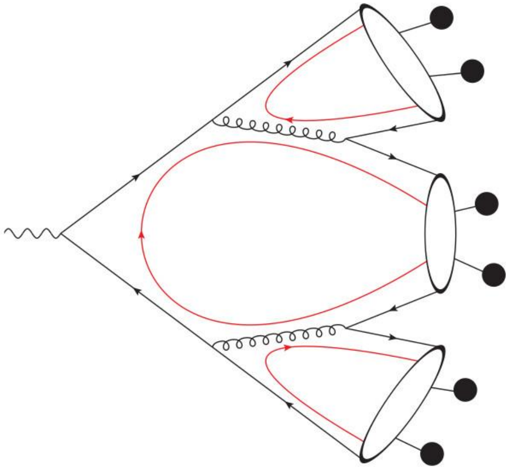
First steps for ML hadronization:

- HADML - Generative Adversarial Networks [A. Ghosh, Xi. Ju, B. Nachman **AS**, *Phys.Rev.D* 106 (2022) 9]
- MLhad - Variational Autoencoder [P. Ilten, T. Menzo, A. Youssef and J. Zupan, arXiv:2203.04983]

# Cluster hadronization model

**The philosophy of the model:** use information from perturbative QCD as an input for hadronization.

QCD **pre-confinement** discovered by Amati & Veneziano:



- QCD provide pre-confinement of colour
- Colour-singlet pair end up close in phase space and form highly excited hadronic states, the clusters
- Pre-confinement states that the spectra of clusters are independent of the hard process and energy of the collision
- Peaked at low mass (1-10 GeV) typically decay into 2 hadrons

# ML Cluster hadronization

[A. Ghosh, Xi. Ju, B. Nachman AS, Phys.Rev.D 106 (2022) 9]

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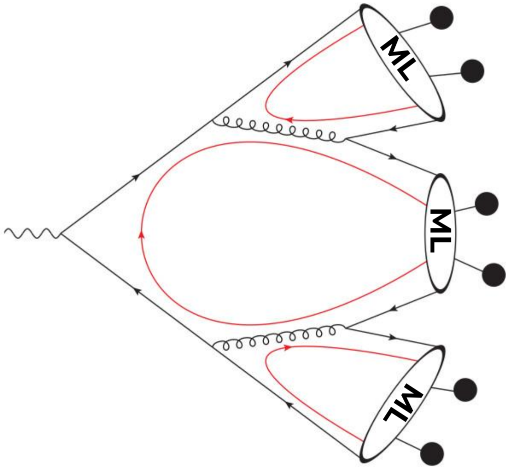

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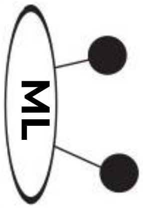
- Peaked at low mass (1-10 GeV) typically decay into 2 hadrons
- **ML hadronization**
  1st step: generate kinematics of a cluster decay:



- **How?**
  Use Generative Adversarial Networks (**GAN**)

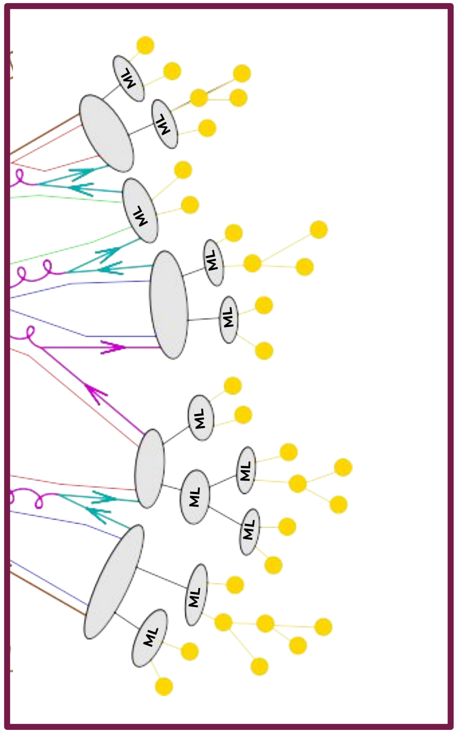
# HADML Results

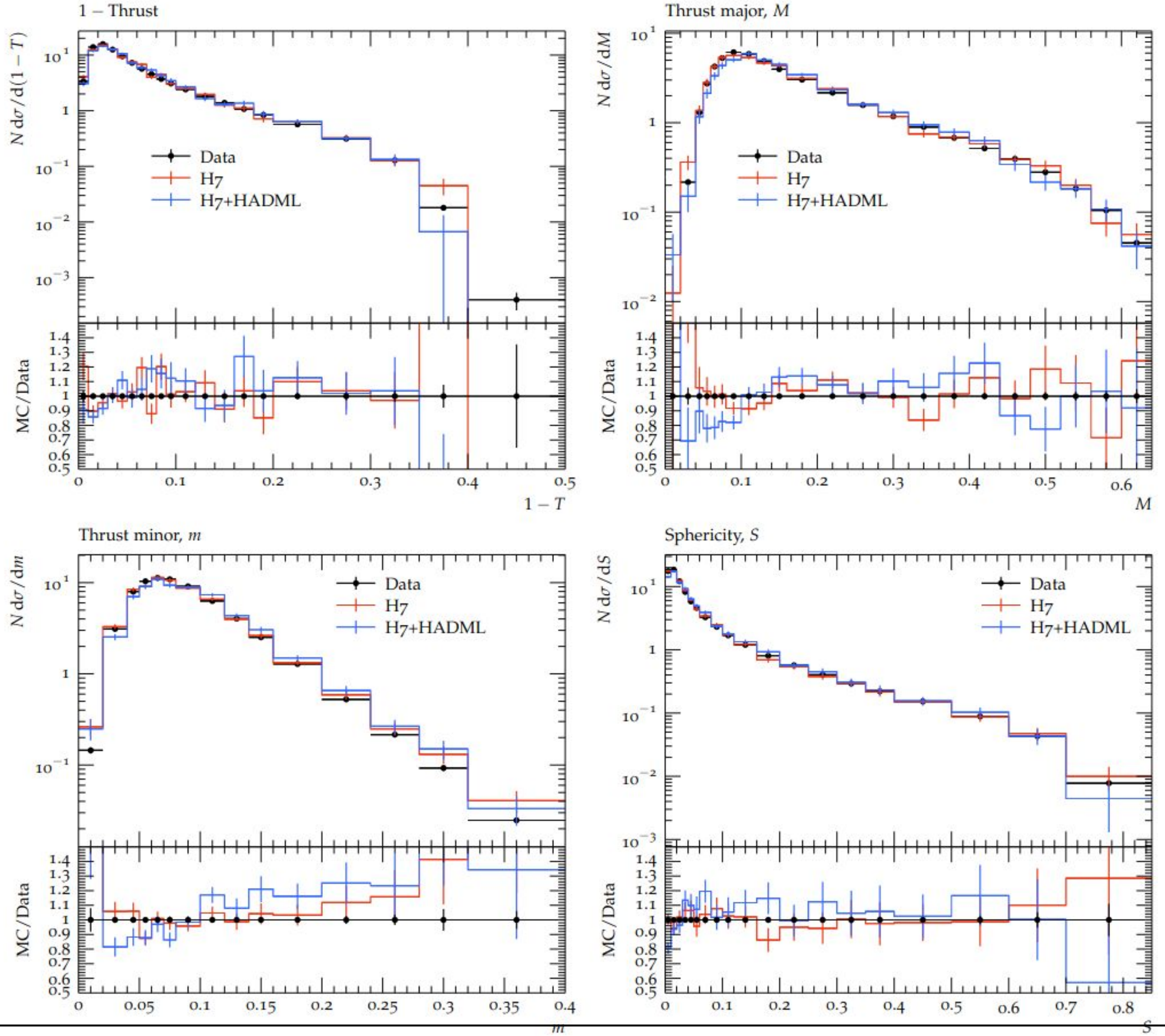
[A. Ghosh, Xi. Ju, B. Nachman AS, Phys.Rev.D 106 (2022) 9]

## Full-event Validation

(Full events using HADML integrated into Herwig 7)

**LEP** DELPHI **Data**





The ultimate goal of is to train the ML model directly on data to improve hadronization models.

# Summary and Outlook

- Progress in perturbative QCD ⇒
  more often measurements are limited by hadronization.

- Two different models of hadronization: string and clasters (early 80's)

  + some new elements (collective effects, polarization, … )
- Both have weak and strong sides - useful for systematics.
- A tune encapsulates the knowledge from previous experiments!
- Colour reconnection - it is important to constrain it.
- Better Hadronization
  - Steady improvements of string and cluster models.
  - New measurements.
  - Better control of the interface of PS and hadronization.
  - Lattice QCD?
  - Machine Learning?

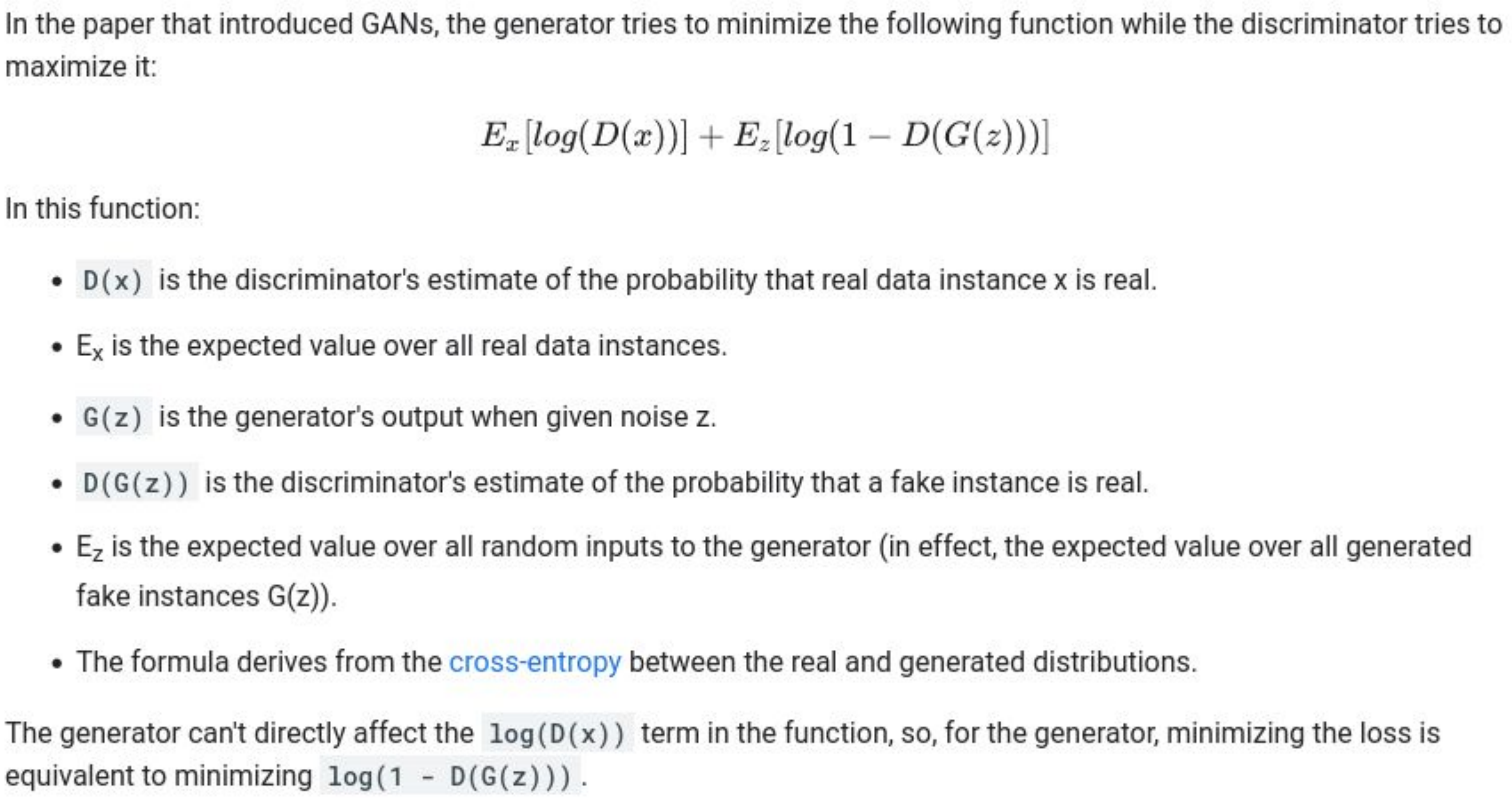
# Advertisement

## postdoc in ML/HEP positions openings

JAGIELLONIAN UNIVERSITY
IN KRAKÓW

If you are interested please contact me:
andrzej@cern.ch

# Minimax Loss



In the paper that introduced GANs, the generator tries to minimize the following function while the discriminator tries to maximize it:

$$E_x[log(D(x))] + E_z[log(1 - D(G(z)))]$$

In this function:

- `D(x)` is the discriminator's estimate of the probability that real data instance x is real.
- $E_x$ is the expected value over all real data instances.
- `G(z)` is the generator's output when given noise z.
- `D(G(z))` is the discriminator's estimate of the probability that a fake instance is real.
- $E_z$ is the expected value over all random inputs to the generator (in effect, the expected value over all generated fake instances G(z)).
- The formula derives from the cross-entropy between the real and generated distributions.

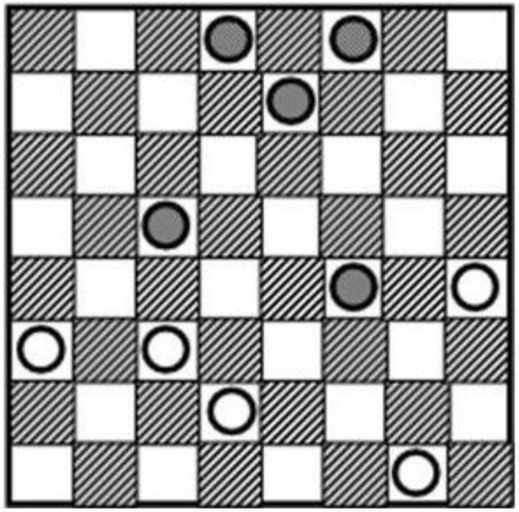
The generator can't directly affect the `log(D(x))` term in the function, so, for the generator, minimizing the loss is equivalent to minimizing `log(1 - D(G(z)))`.

# AlphaGo

- AlphaGo's victory against Lee Sedol was a major milestone in artificial intelligence research.
- Go had previously been regarded as a hard problem in machine learning that was expected to be out of reach for the technology of the time.
- Most experts thought a Go program as powerful as AlphaGo was at least five years away;some experts thought that it would take at least another decade before computers would beat Go champions. Most observers at the beginning of the 2016 matches expected Lee to beat AlphaGo.
- Netflix document

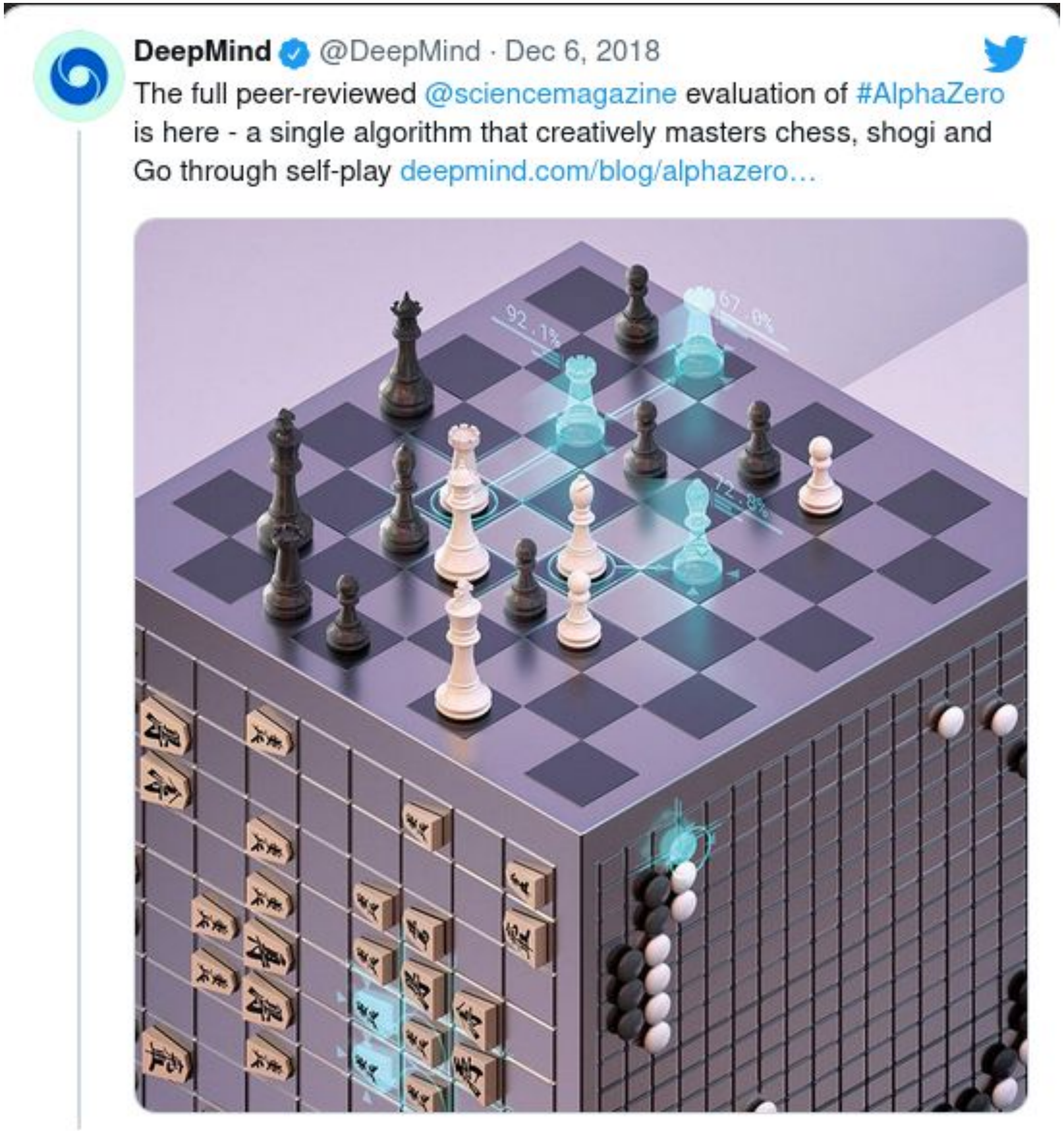
# Adversarial Networks

**Arthur Lee Samuel** (1959) wrote a program that learnt to play checkers well enough to beat him.



- He popularized the term **"machine learning"** in 1959.
- The program chose its move based on a **minimax** strategy, meaning it made the move assuming that the opponent was trying to optimize the value of the same function from its point of view.
- He also had it play thousands of **games against itself** as another way of learning.

# Adversarial Networks



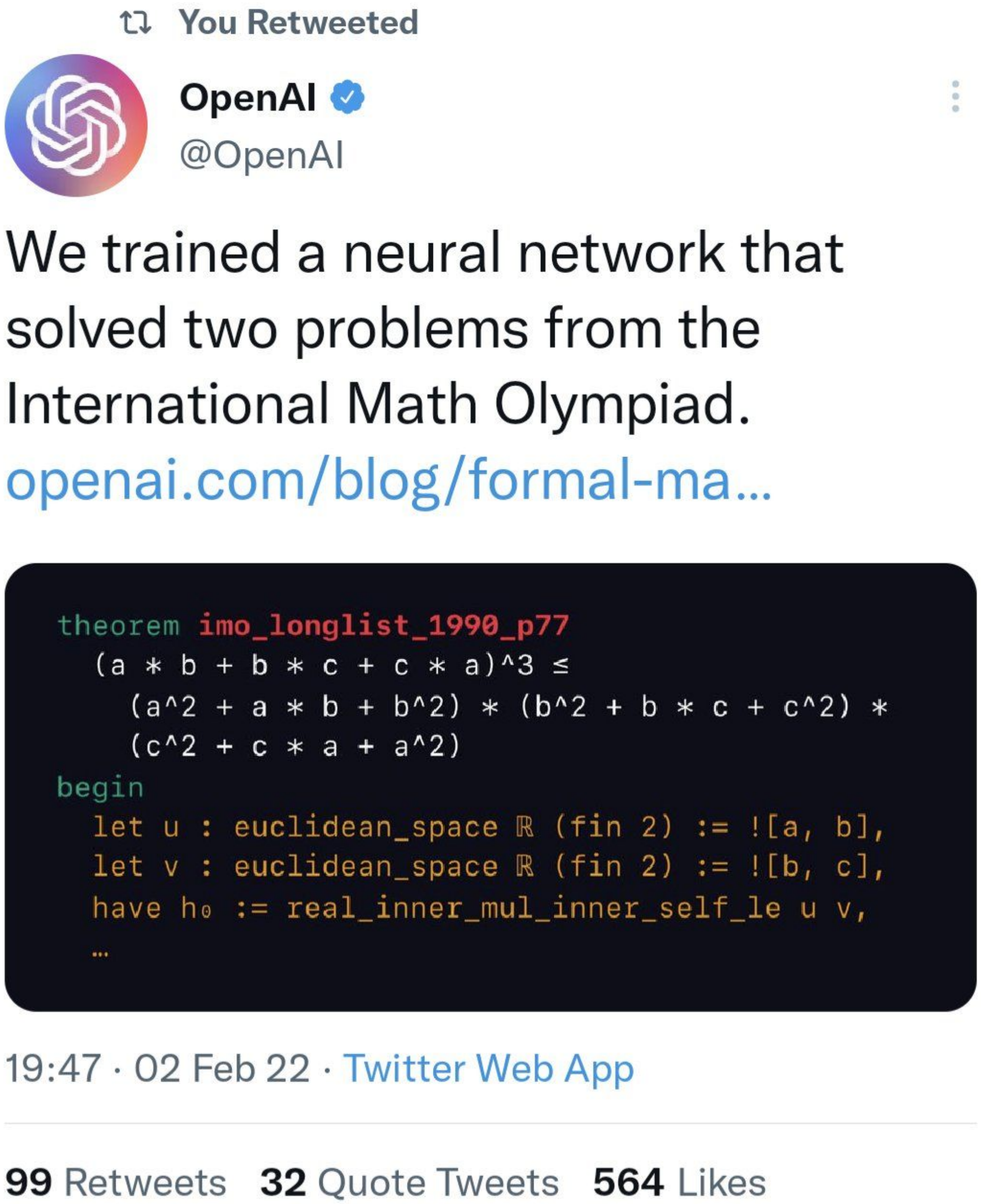
**DeepMind** @DeepMind · Dec 6, 2018

The full peer-reviewed @sciencemagazine evaluation of #AlphaZero is here - a single algorithm that creatively masters chess, shogi and Go through self-play deepmind.com/blog/alphazero…

**Demis Hassabis**
CBE FRS FREng FRSA

By playing **games against itself**, AlphaGo Zero surpassed the strength of AlphaGo Lee in three days by winning 100 games to 0.

# Adversarial Networks



You Retweeted

**OpenAI**
@OpenAI

We trained a neural network that solved two problems from the International Math Olympiad. openai.com/blog/formal-ma...

```
theorem imo_longlist_1990_p77
  (a * b + b * c + c * a)^3 ≤
    (a^2 + a * b + b^2) * (b^2 + b * c + c^2) *
    (c^2 + c * a + a^2)
begin
  let u : euclidean_space ℝ (fin 2) := ![a, b],
  let v : euclidean_space ℝ (fin 2) := ![b, c],
  have h₀ := real_inner_mul_inner_self_le u v,
  …
```

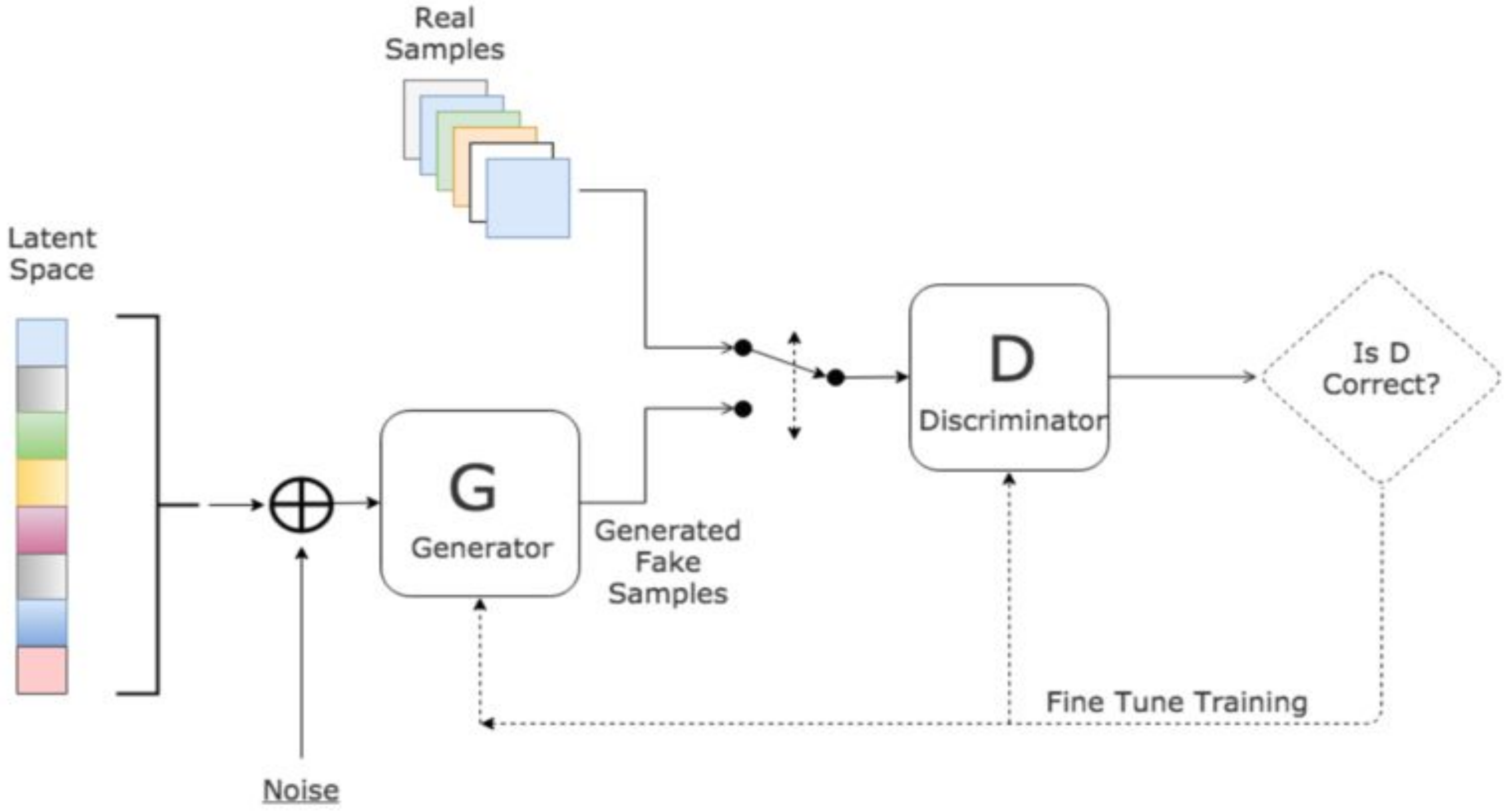
19:47 · 02 Feb 22 · Twitter Web App

**99** Retweets **32** Quote Tweets **564** Likes

**Demis Hassabis**
CBE FRS FREng FRSA

# Generative Adversarial Network (GAN)

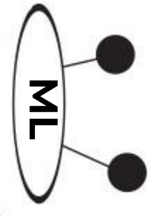
**[Goodfellow et al. “Generative adversarial nets”. arxiv:1406.2661]**



# Towards a Deep Learning Model for Hadronization

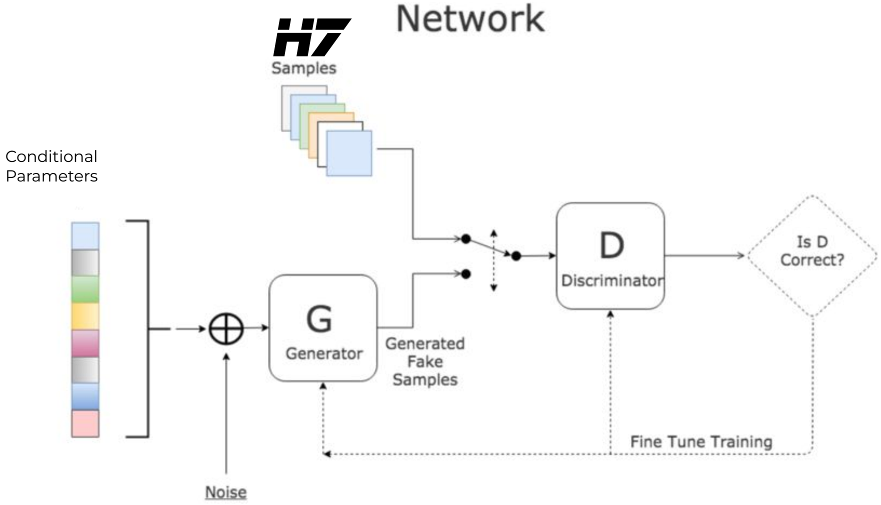
**ML hadronization**

1st step: generate kinematics of a cluster decay to 2 hadrons



**How?**

Generative Adversarial Network

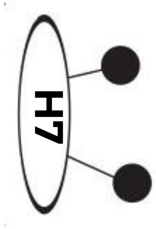


**Training data:**

H7

$e^+e^-$ collisions at $\sqrt{s} = 91.2$ GeV

Cluster $(E,\ p_x,\ p_y,\ p_z)$



$\pi^0(E,\ p_x,\ p_y,\ p_z)$

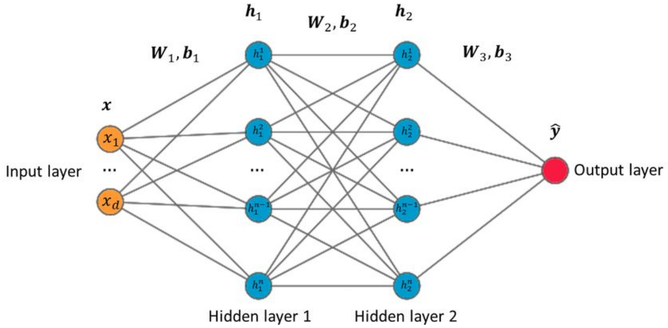
$\pi^0(E,\ p_x,\ p_y,\ p_z)$

Pert = 0/1 memory of quarks direction

# Architecture: conditional GAN

**Generator and the Discriminator are composed of two-layer perceptron**

(each a fully connected, hidden size 256, a batch normalization layer, LeakyReLU activation function)



## Generator

### Input

Cluster $(E,\ p_x,\ p_y,\ p_z)$ and 10 noise features sampled from a Gaussian distribution

### Output (in the cluster frame)

$\phi$ - polar angle

$\theta$ - azimuthal angle

$\Big\}$ we reconstruct the four vectors of the two outgoing hadrons

## Discriminator

### Input

$\phi$ and $\theta$ labeled as signal (generated by Herwig) or background (generated by Generator)

### Output

Score that is higher for events from Herwig and lower for events from the Generator

# Wasserstein distance

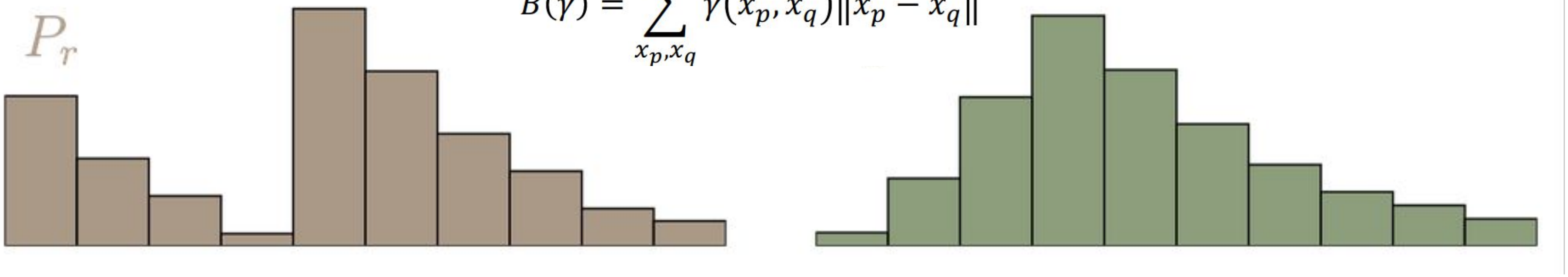
## The Wasserstein distance

- For discrete probability distributions, the Wasserstein distance is called the earth mover's distance (EMD):
- EMD is the minimal total amount of work it takes to transform one heap into the other.

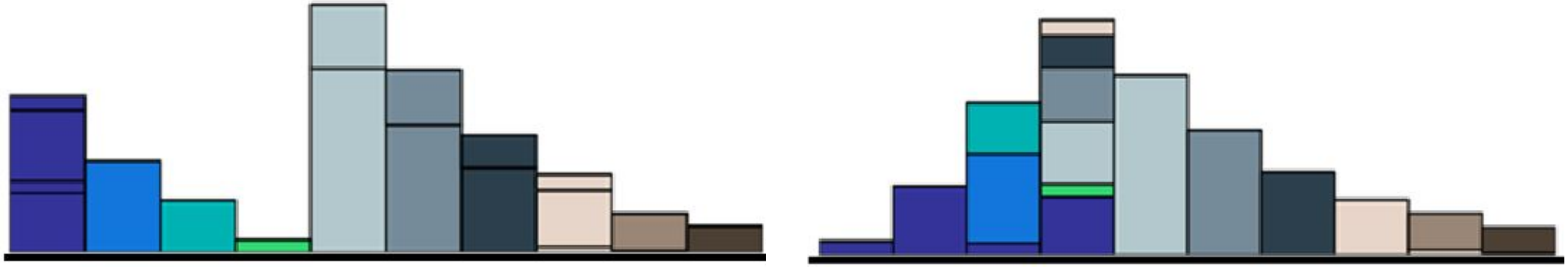
$$W(P,Q) = \min_{\gamma \in \Pi} B(\gamma)$$

- Work is defined as the amount of earth in a chunk times the distance it was moved.

$$B(\gamma) = \sum_{x_p, x_q} \gamma(x_p, x_q) \| x_p - x_q \|$$



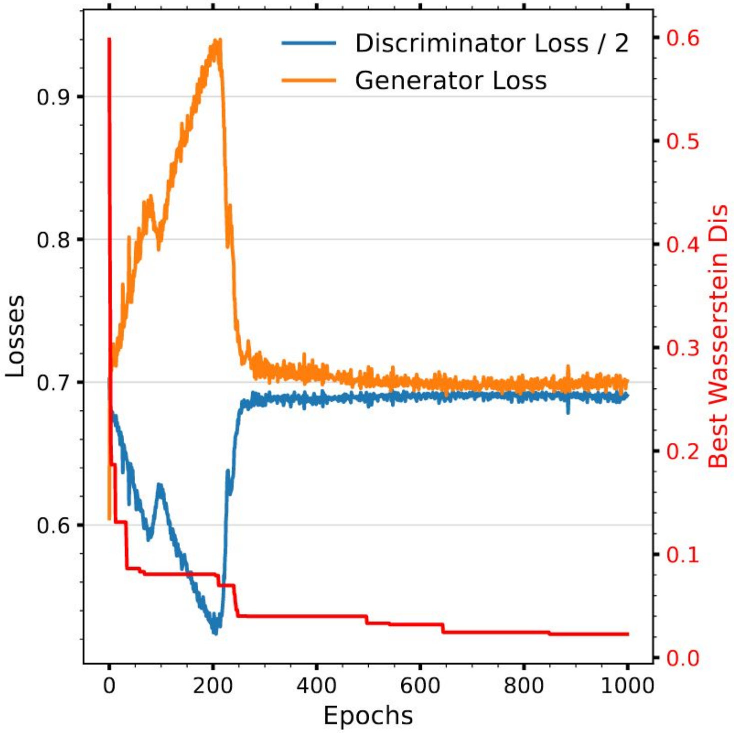
Best "moving plans" of this example



# Training

- **Data normalization:**
  cluster’s four vector and angular variables are scaled to be between -1 and 1 (tanh activation function as the last layer of the Generator)

- **Discriminator** and the **Generator** are trained separately and alternately by two independent Adam optimizers with a learning rate of $10^{-4}$, for 1000 epochs



- **The best model** for events with partons of Pert = 0, is found at the epoch 849 with a total Wasserstein distance of 0.0228.

# Investigation of Colour Reconnection in $WW$ events with the DELPHI detector at LEP-2

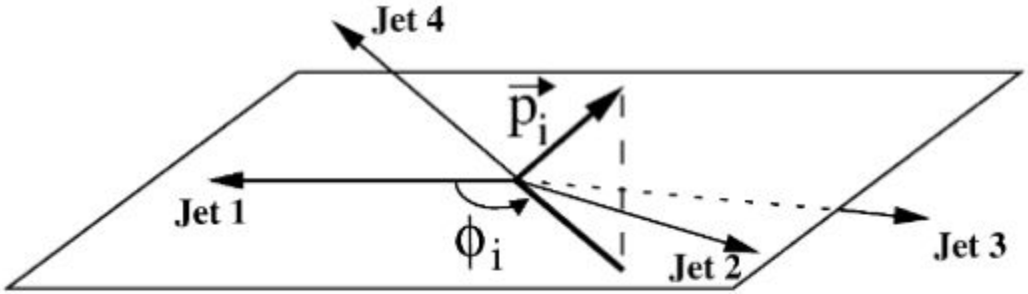


Fig. 1. Determination of the $\phi_i$ angle for the particle $i$.

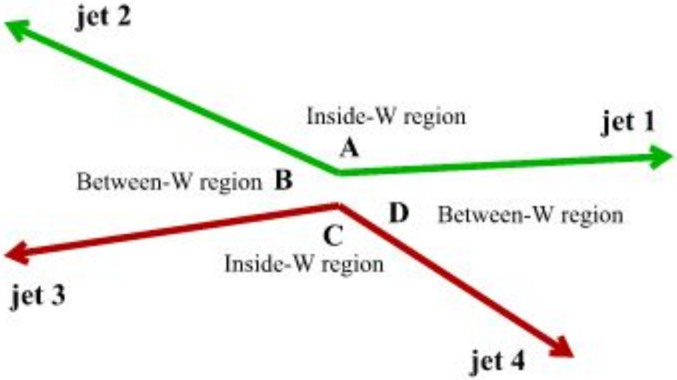
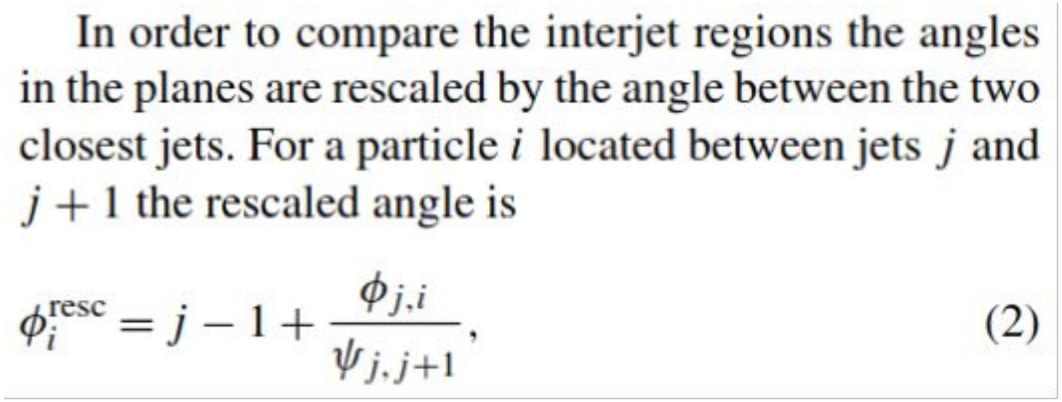


**Fig. 3.** Schematic drawing of the angular selection



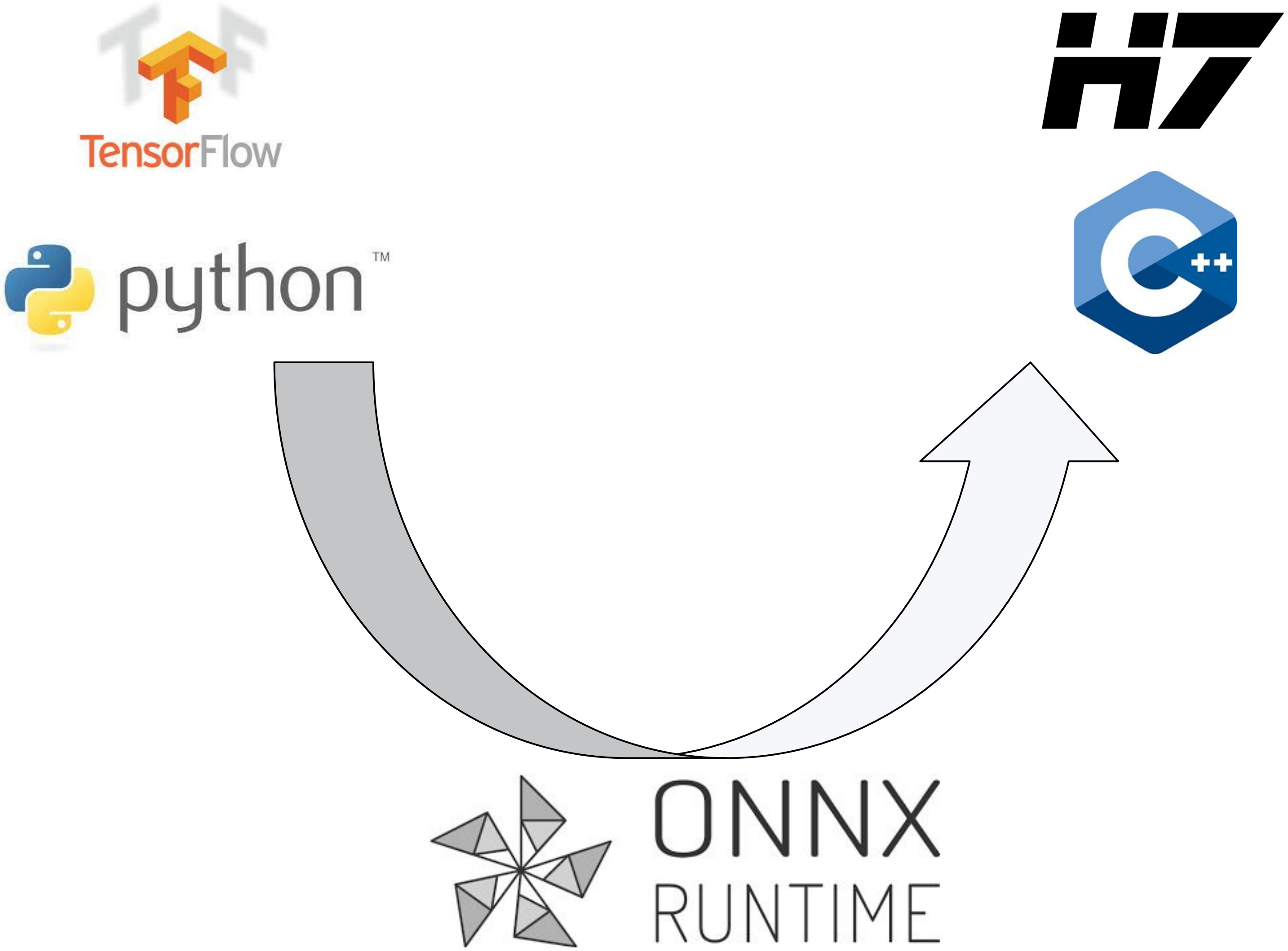
In order to compare the interjet regions the angles in the planes are rescaled by the angle between the two closest jets. For a particle $i$ located between jets $j$ and $j+1$ the rescaled angle is

$$\phi_i^{\text{resc}} = j - 1 + \frac{\phi_{j,i}}{\psi_{j,j+1}}, \tag{2}$$

# Integration into Herwig

**Training**

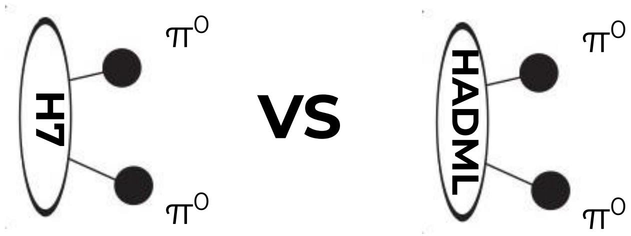
**Event generation**



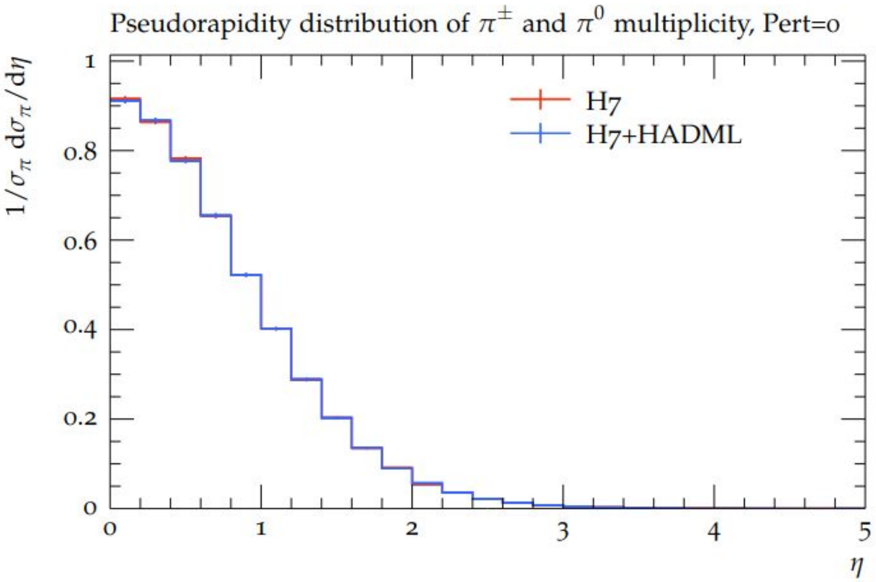
# Results

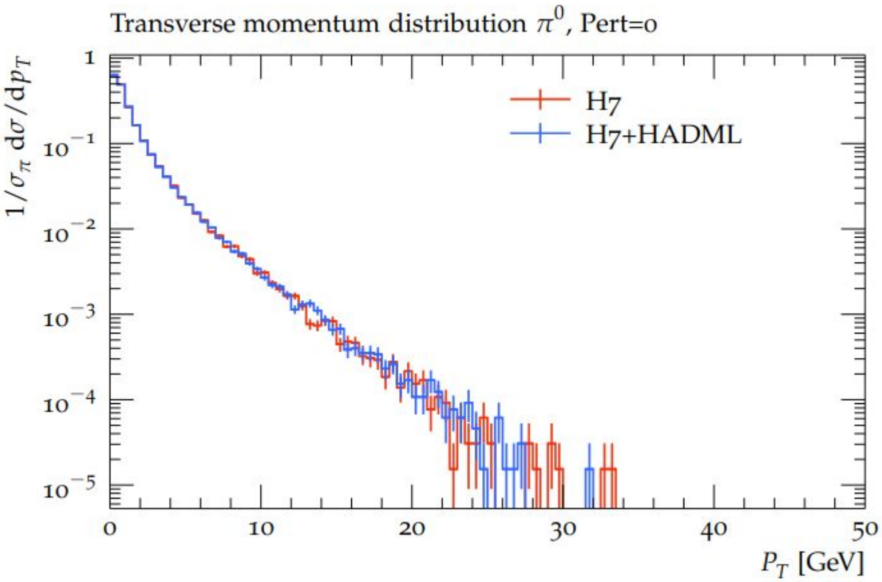
**Low-level Validation**
(similar to training data)

$e^+e^-$ collisions at
$\sqrt{s} = 91.2$ GeV



$\pi^0$ kinematic variables



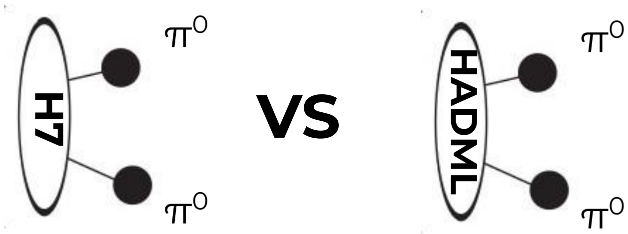


**Pert = 0 (no memory of quark kinematics)**

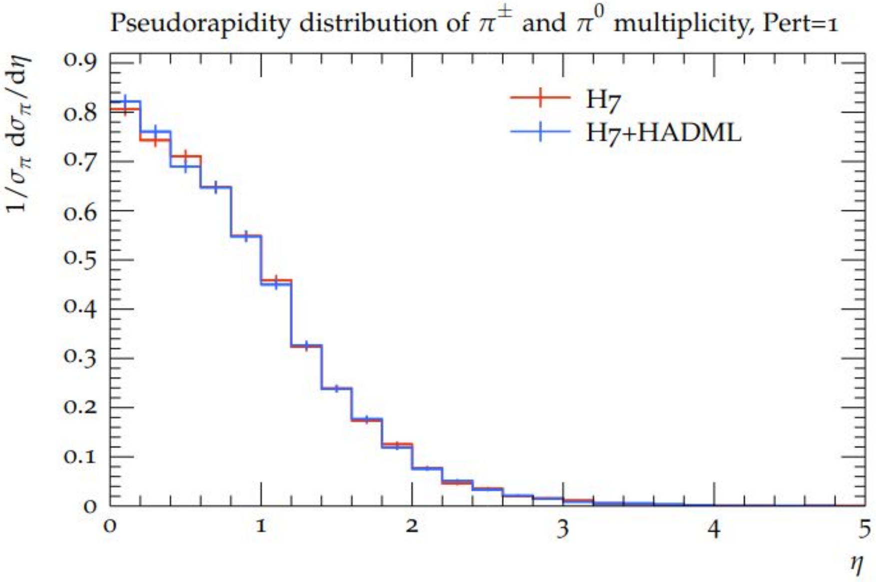
# Results

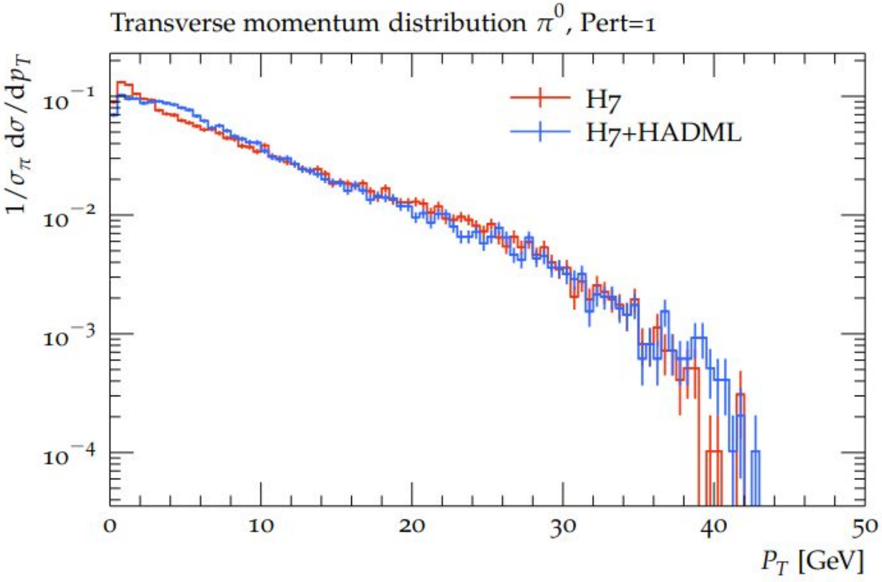
**Low-level Validation**
(similar to training data)

$e^+e^-$ collisions at
$\sqrt{s} = 91.2$ GeV



$\pi^0$ kinematic variables


Pseudorapidity distribution of $\pi^{\pm}$ and $\pi^0$ multiplicity, Pert=1

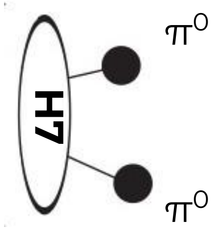

Transverse momentum distribution $\pi^0$, Pert=1

**Pert = 1 (memory of quark kinematics)**

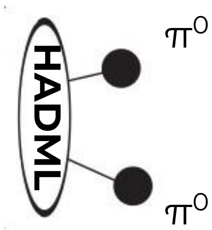
# Results

**Low-level Validation**
(**beyond** training data **different energy**)

$e^+e^-$ collisions at
$\boxed{\sqrt{s} = 192\ \text{GeV}}$

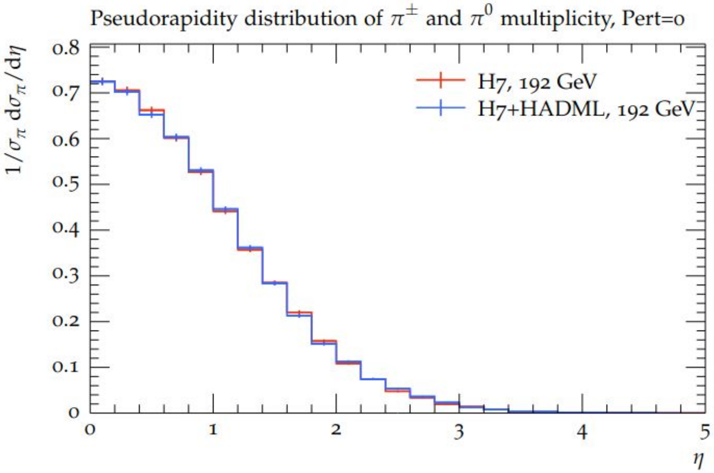


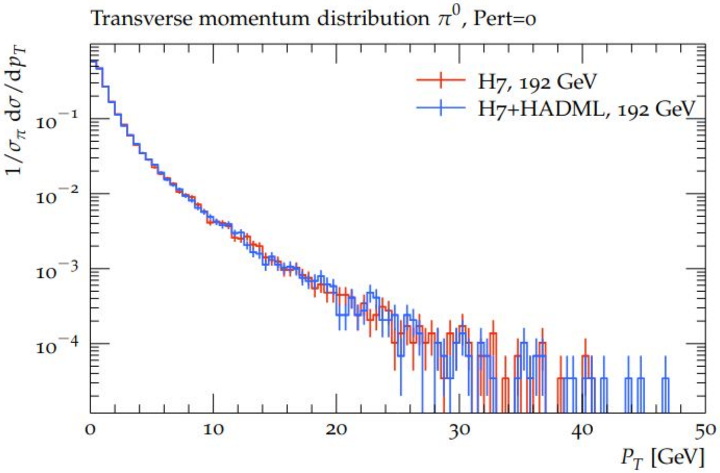
**VS**



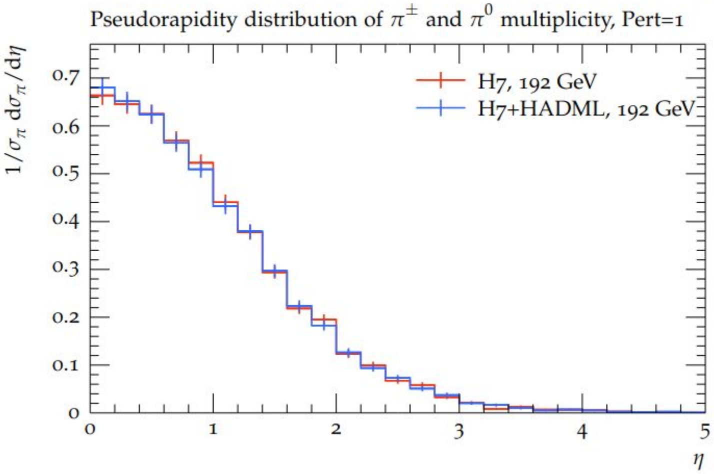
$\pi^0$ kinematic variables

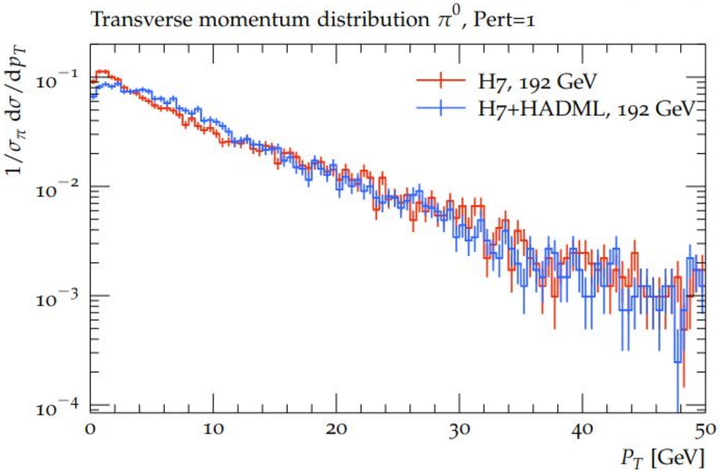
**Pert = 0**


Pseudorapidity distribution of $\pi^\pm$ and $\pi^0$ multiplicity, Pert=0


Transverse momentum distribution $\pi^0$, Pert=0

**Pert = 1**


Pseudorapidity distribution of $\pi^\pm$ and $\pi^0$ multiplicity, Pert=1

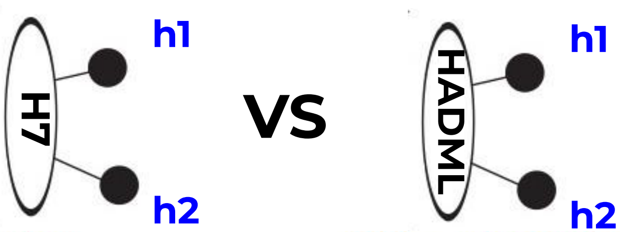

Transverse momentum distribution $\pi^0$, Pert=1

# Results

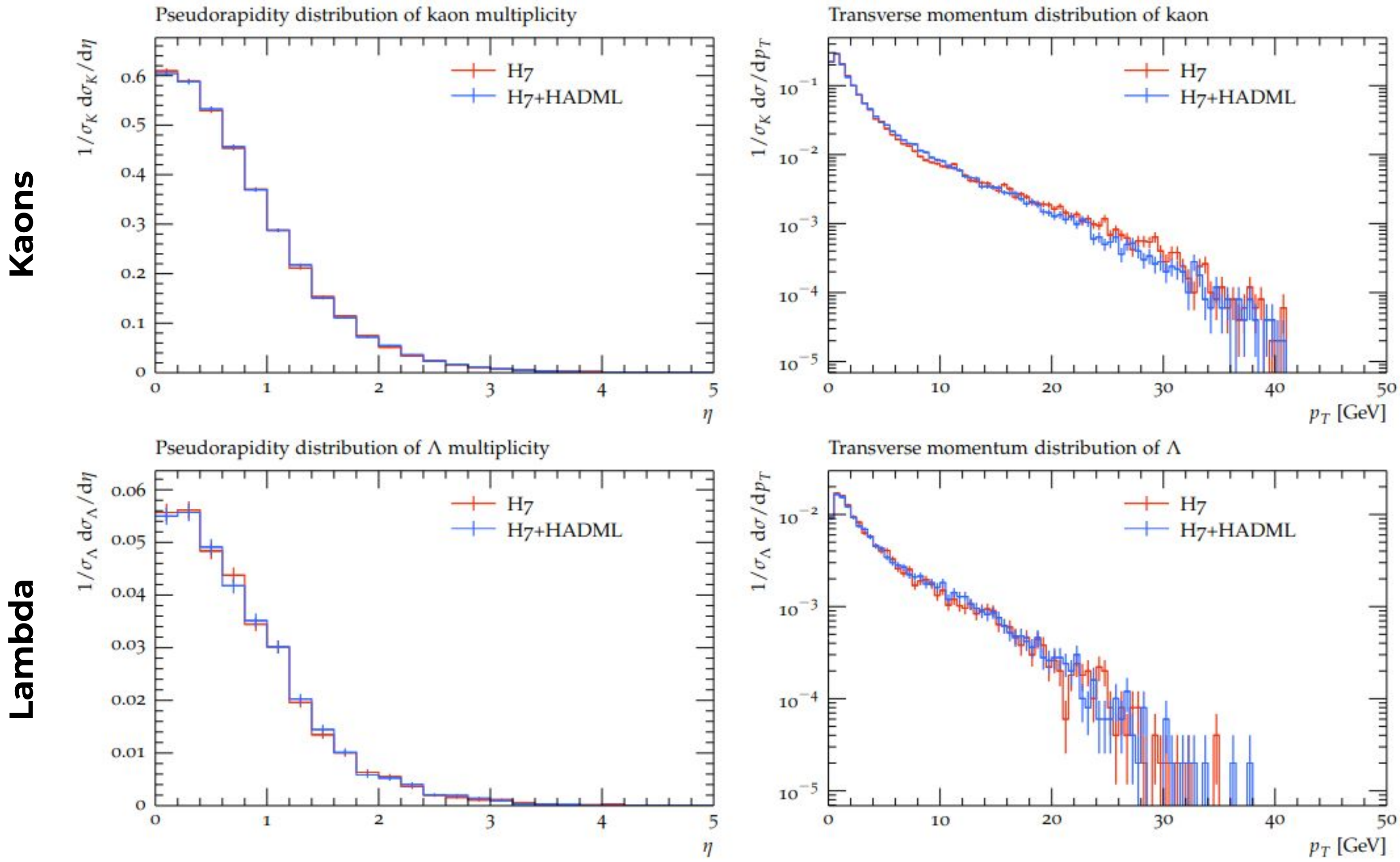
**Low-level Validation**

(**beyond** training data **different hadrons**)

$e^+e^-$ collisions at $\sqrt{s} = 91.2$ GeV



**h** kinematic variables

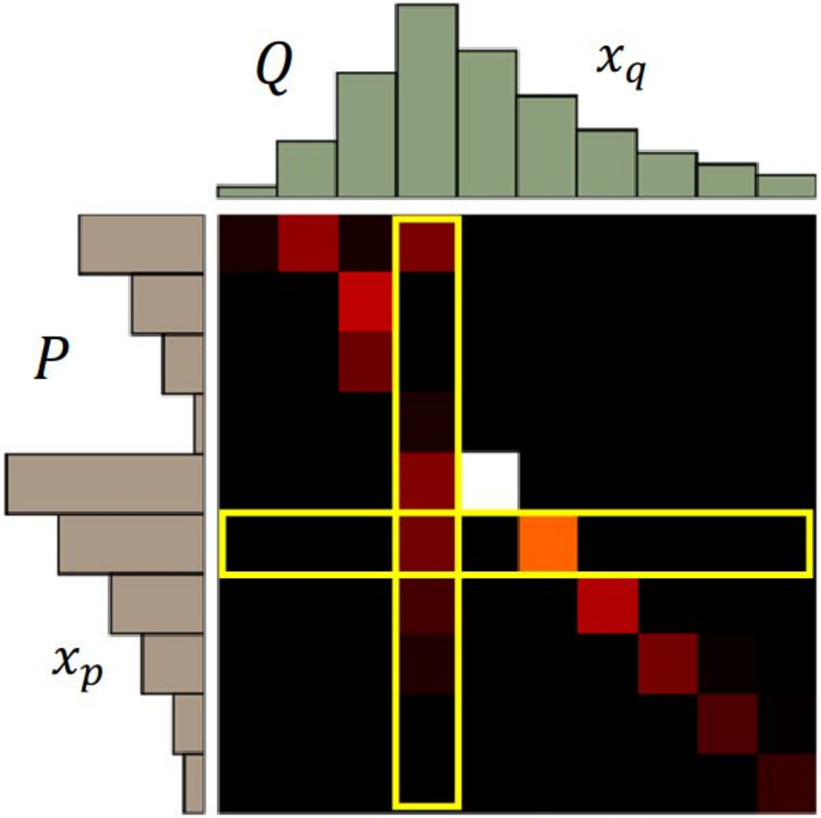

Pseudorapidity distribution of kaon multiplicity

Transverse momentum distribution of kaon

Pseudorapidity distribution of $\Lambda$ multiplicity

Transverse momentum distribution of $\Lambda$

# Wasserstein distance



moving plan $\gamma$

All possible plan $\Pi$

A "moving plan" is a matrix

The value of the element is the amount of earth from one position to another.

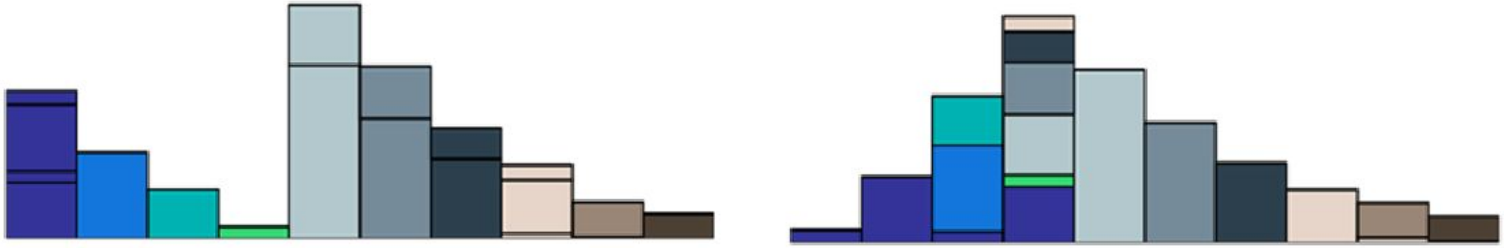
Average distance of a plan $\gamma$:

$$B(\gamma) = \sum_{x_p, x_q} \gamma(x_p, x_q) \|x_p - x_q\|$$

Earth Mover's Distance:

$$W(P, Q) = \min_{\gamma \in \Pi} B(\gamma)$$

The best plan



[Gras, Hoeche, Kar, Larkoski, Lönnblad, Plätzer, AS, Skands, Soyez, Thaler, JHEP 1707 (2017) 091]

Cartoon:

Quark: $C_F = 4/3$ vs. Gluon: $C_A = 3$

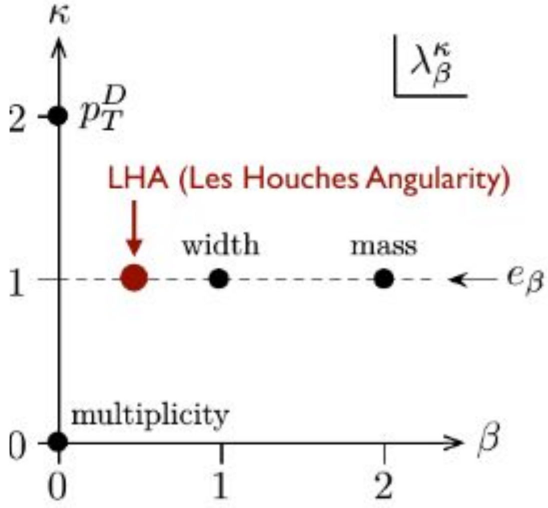
Probe radiation pattern with
e.g. Generalized Angularities

$$\lambda^{\kappa}_{\beta} = \sum_{i \in \text{jet}} z_i^{\kappa} \theta_i^{\beta}$$

momentum fraction

angle to recoil-free axis

$$(\lambda^{\kappa}_{\beta})_{\text{quark}} < (\lambda^{\kappa}_{\beta})_{\text{gluon}}$$

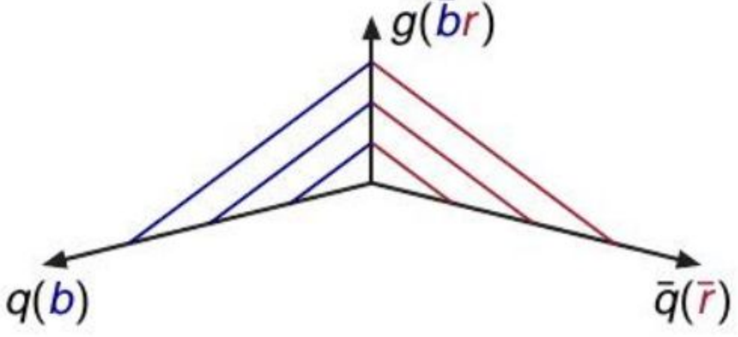


[Larkoski,Salam,Thaler,13]
[Larkoski,Thaler,Waalewijn,14]

# String Model in nutshell

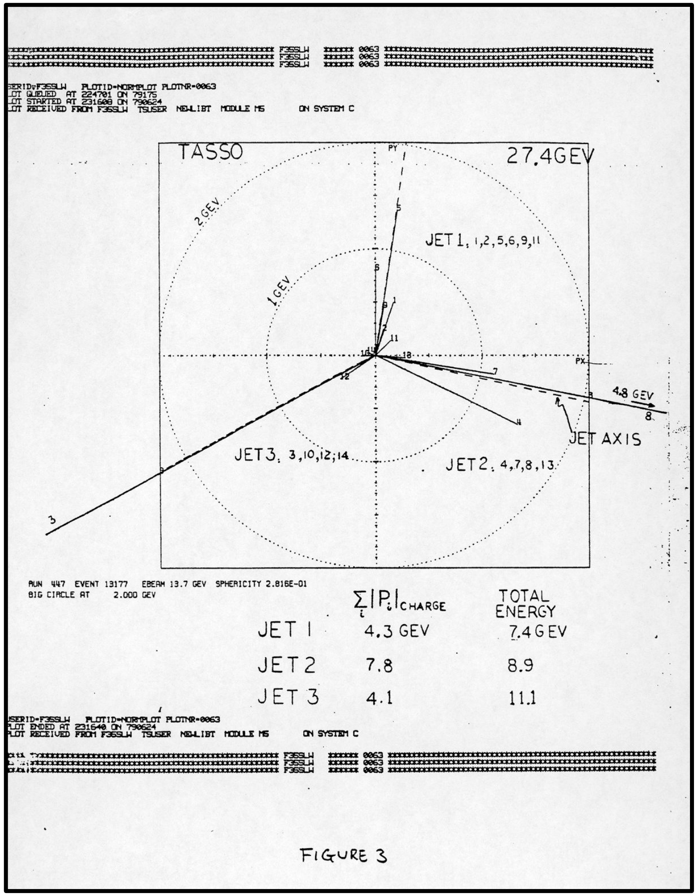
[Andersson, Gustafson, Ingelman, Sjostrand, Phys.Rept.97(1983)31]

## Gluons - a kink in the string



The Lund string model predicted the string effect measured by Jade.

In a three-jet event there are more energy between the gq and gq̄ jets
than between qq̄.



```
F35SLW 0063
F35SLW 0063
F35SLW 0063
SERID=F35SLW   PLOTID=NORMPLOT PLOTNR=0063
LOT QUEUED  AT 224701 ON 79175
LOT STARTED AT 231608 ON 790624
LOT RECEIVED FROM F35SLW  TSUSER  NEWLIBT  MODULE MS       ON SYSTEM C
```

```
RUN 447  EVENT 13177  EBEAM 13.7 GEV  SPHERICITY 2.816E-01
BIG CIRCLE AT     2.000 GEV
```

| | $\sum_i \lvert P_i \rvert_{\mathrm{CHARGE}}$ | TOTAL ENERGY |
|---|---|---|
| JET 1 | 4.3 GEV | 7.4 GEV |
| JET 2 | 7.8 | 8.9 |
| JET 3 | 4.1 | 11.1 |

```
USERID=F35SLW   PLOTID=NORMPLOT PLOTNR=0063
PLOT ENDED AT 231640 ON 790624
PLOT RECEIVED FROM F35SLW  TSUSER  NEWLIBT  MODULE MS       ON SYSTEM C
F35SLW 0063
F35SLW 0063
F35SLW 0063
```

FIGURE 3

**Summary:**

String model has very good energy-momentum picture however it is unpredictive in understanding of hadron mass effects ⇒ many parameters, 10-30 depending on how you count.

# Polarization of Heavy Hadrons

**1st Step**: Passing through the polarization of heavy hadrons at the end of parton shower. [arXiv:hep-ph/9308241]

- For $m_Q \gg \Lambda_{\mathrm{QCD}}$, the light degrees of freedom become insensitive to $m_Q$.
- Heavy quarks act as non-recoiling sources of color at the end of PS.
- A spin-flavor symmetry appears for heavy quarks.
- A net polarization of the initial heavy quark may be detected, either in a polarization of the final ground state or in the decay products of the **excited heavy mesons** and **heavy baryons**.
- **Falk-Peskin "no-win" theorem**: no polarization information would be found in non-excited mesons.

**2nd Step**: Improving the Strong decay modes the excited heavy mesons, i.e charm, and bottom mesons.

- Heavy Quark Effective Field Theory (HQEFT) usually determines which decay modes are possible and also gives the relations between the involving couplings.
- In the absence of experimental data on many of the decays, we need to rely on HQ symmetries to determine the decay modes, widths and branching ratios.
- We consider charm and bottom meson decays with: [arXiv:hep-ph/9209239]
  - $J^P = 0^-, 1^-$ doublets with $l = 0$ ($D$ and $D^*$).
  - $J^P = 1^+, 2^+$ doublets with $l = 1$ and $j = 3/2$ ($D_1$ and $D_2^*$).
  - $J^P = 0^+, 1^+$ doublets with $l = 1$ and $j = 1/2$ ($D_0^*$ and $D_1'$).