Emergent Phenomena in High-Energy Particle Collisions

Peter Skands (Monash University)

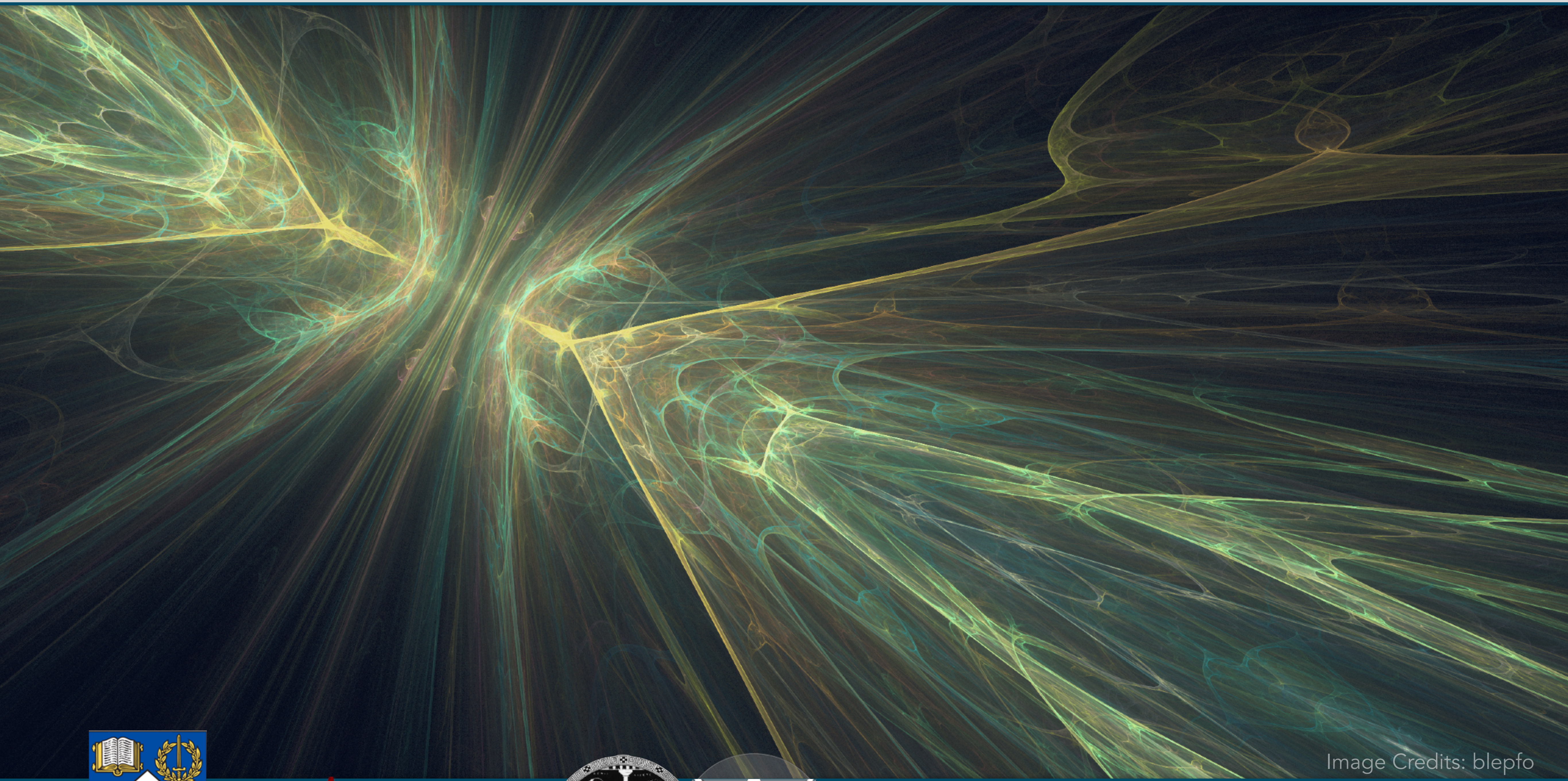


Image Credits: blepfo

January, 2020

Universitetet i Stavanger

Monash University

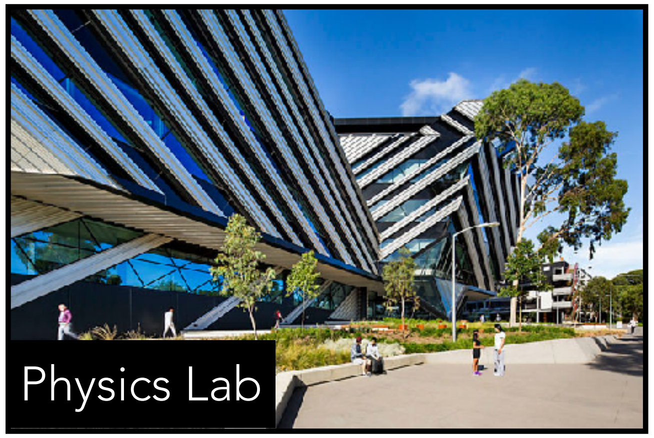
Named for General **Sir John Monash**
(Australian WWI military commander)

Founded in 1958

70,000 students

(Australia's largest uni)

~ 20km SE of Melbourne City Centre



Physics Lab

School of Physics & Astronomy;
4 HEP theorists
2 HEP experimentalists **(LHCb, CMS, COMET)**
+ post docs & students
(Also: LIGO, SKA, …)

Melbourne

Emergence

G. H. Lewes (1875): "*the emergent is unlike its components insofar as …it cannot be reduced to their sum or their difference*."

In Quantum Field Theory:

Components = Elementary interactions encoded in the Lagrangian

Perturbative expansions ~ elementary interactions to n^{th} power

What else is there? Structure beyond (fixed-order) perturbative expansions (in Quantum Chromodynamics)**:**

- *<u>Fractal scaling</u>, of jets within jets within jets …* (can actually be guessed)
- *<u>Confinement</u>, of coloured partons within hadrons* ($1M for proof)

Quantum Chromodynamics (QCD)

The theory of quarks and gluons; the strong nuclear force

Elementary interactions encoded in the Lagrangian

$$\mathcal{L} = \bar{\psi}_q^i (i\gamma^\mu)(D_\mu)_{ij}\psi_q^j - m_q \bar{\psi}_q^i \psi_{qi} - \frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu}$$

$$D_{\mu ij} \;=\; \delta_{ij}\partial_\mu - i g_s T^a_{ij} A^a_\mu$$

Gauge Covariant Derivative: makes *L* invariant under $SU(3)_C$ rotations of ψ_q

m_q: Quark Mass Terms (Higgs + QCD condensates)

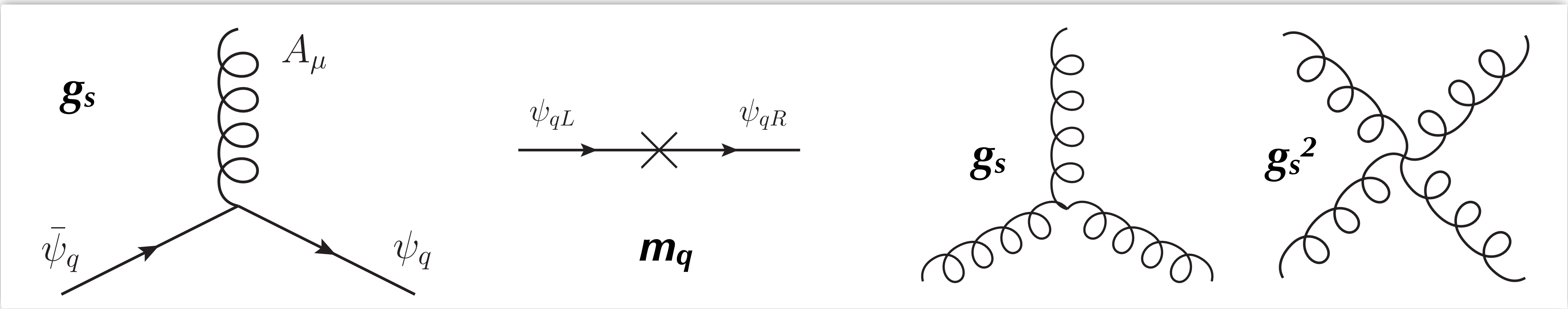
Gluon-Field Kinetic Terms and Self-Interactions

$$F^a_{\mu\nu} \;=\; \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g_s f^{abc} A^b_\mu A^c_\nu$$

Perturbative expansions ➜ Feynman diagrams

($g_s^2 = 4\pi\alpha_s$)

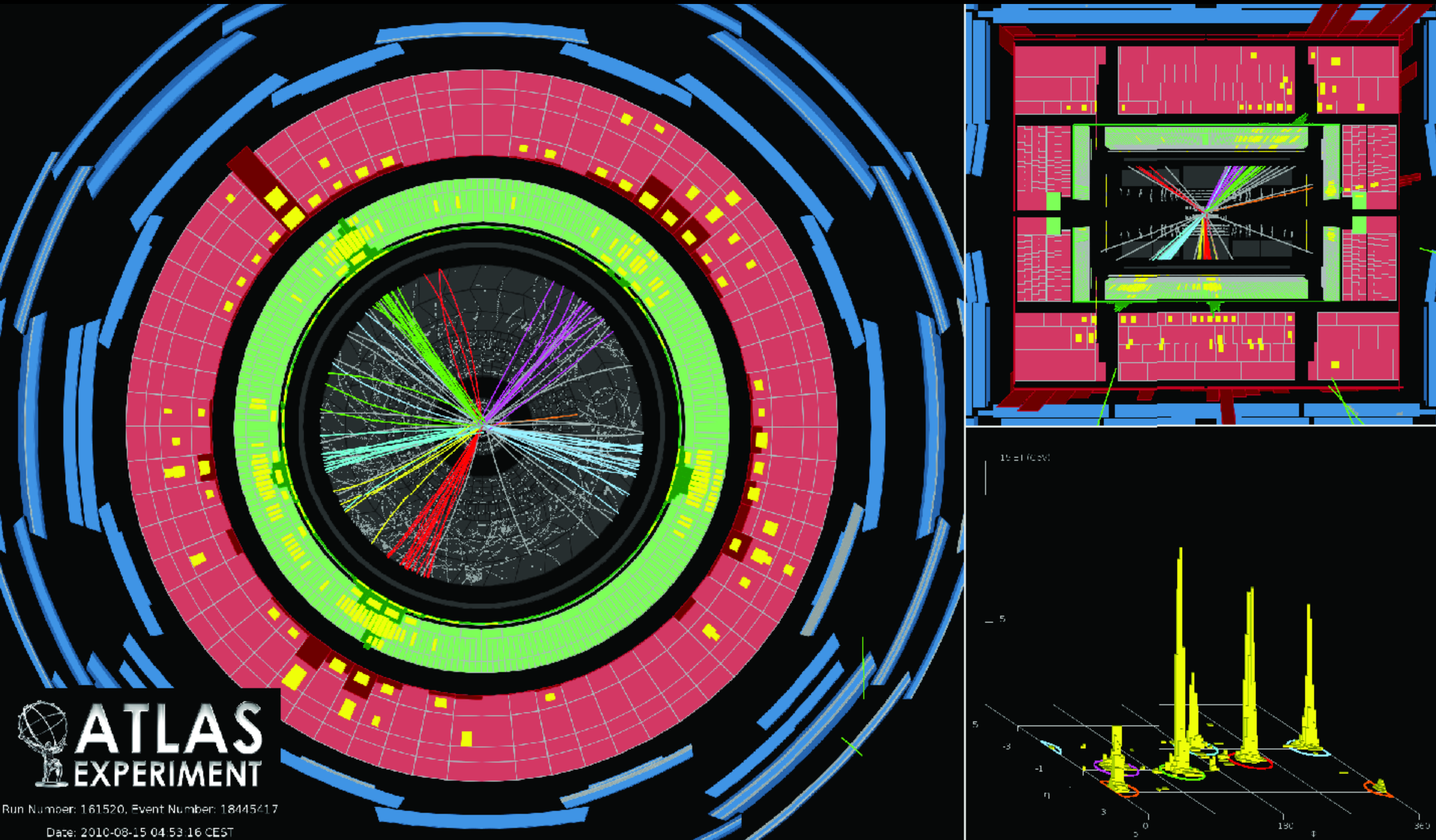
$$\psi_q^j = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \end{pmatrix}$$



Would anything interesting happen if we put lots of these together?

Proton-Proton Collision at E_{CM} = 7 TeV

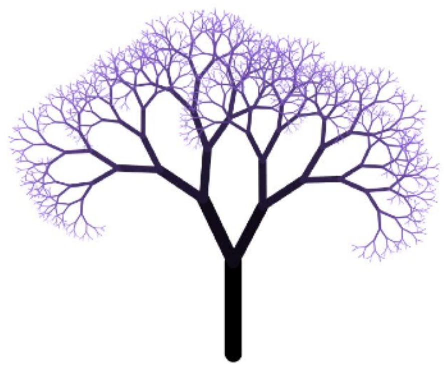
ATL-2011-030



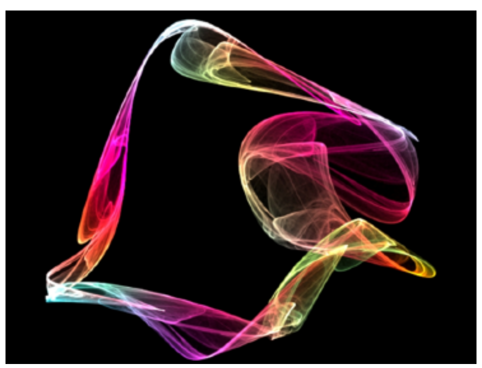
More than just a (fixed-order perturbative) expansion

Multi-parton structures beyond fixed-order perturbation theory

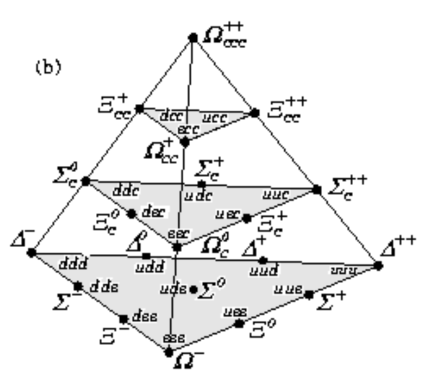
most of my research



Jets (the fractal of perturbative QCD) ⟷ Infinite-order perturbative structures of indefinite particle number ⟷ universal amplitude structures in QFT



Strings (strong gluon fields) ⟷ Dynamics of confinement ⟷ Hadronization phase transition ⟷ quantum-classical correspondence. Non-perturbative dynamics. String physics. String breaks.



Hadrons ⟷ Spectroscopy (incl excited and exotic states), lattice QCD, (rare) decays, mixing, light nuclei. Hadron beams → multiparton interactions, diffraction, …

(Ulterior Motives for Studying QCD)

The Standard Model

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$
$$+ i \bar{\psi} \not{D} \psi + h.c.$$
$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$
$$+ |D_\mu \phi|^2 - V(\phi)$$

There are more things in heaven and earth, Horatio, than are dreamt of in your philosophy *Hamlet*

+ ... ... ?

LHC Run 1+2: no "low-hanging" new physics

90% of data still to come ➜ higher sensitivity to smaller signals.

High-statistics data ↔ high-accuracy theory

1) Perturbative QCD

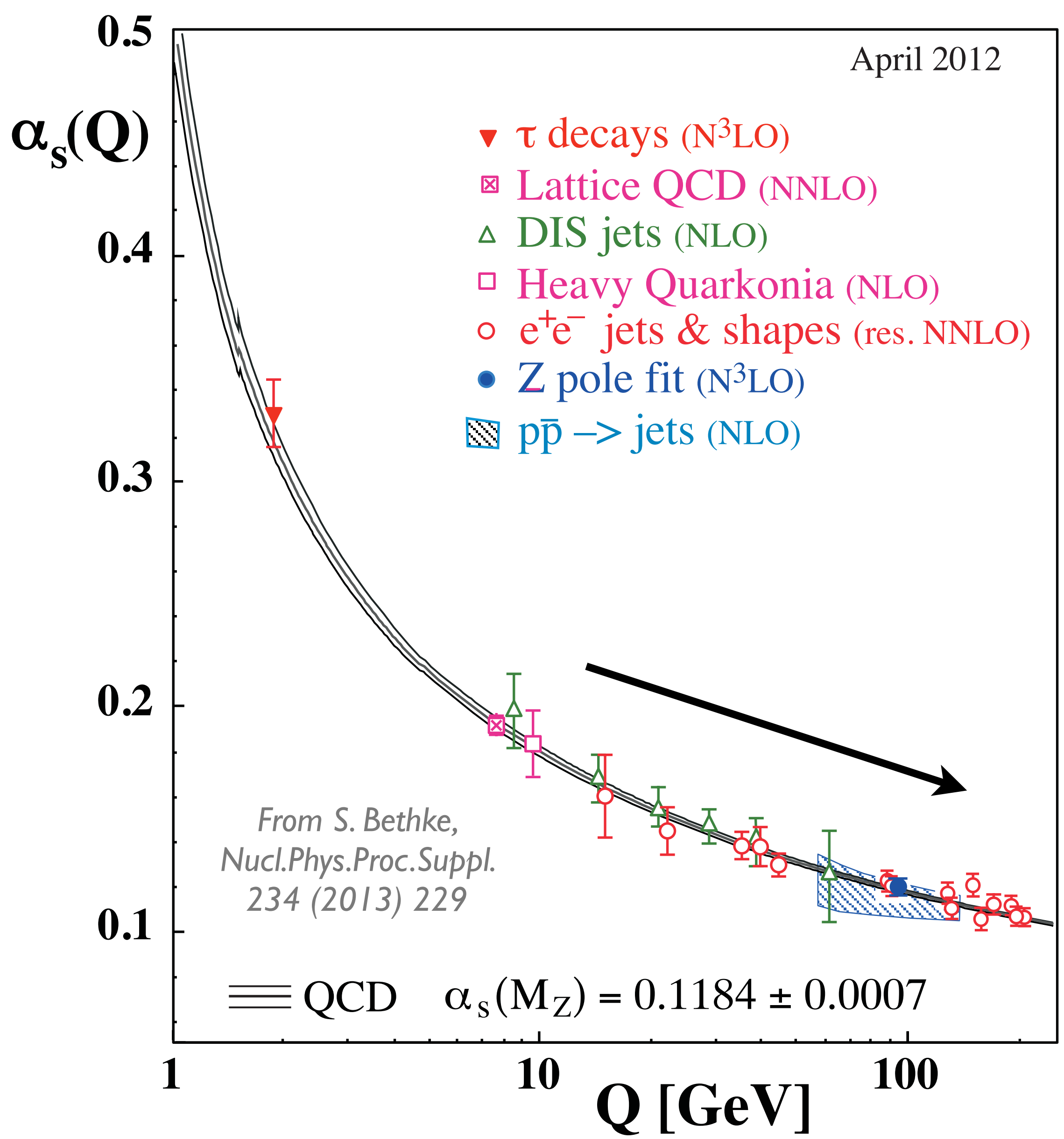
The "running" of α_s: $$Q^2 \frac{\partial \alpha_s}{\partial Q^2} = -\alpha_s^2 (b_0 + b_1 \alpha_s + b_2 \alpha_s^2 + \ldots) \ ,$$

$$b_0 = \frac{11 C_A - 2 n_f}{12\pi}$$ C_A=3 for SU(3)

$$b_1 = \frac{17 C_A^2 - 5 C_A n_f - 3 C_F n_f}{24\pi^2} \underset{C}{=} \frac{153 - 19 n_f}{24\pi^2}$$

$$b_2 = \frac{2857 - 5033 n_f + 325 n_f^2}{128\pi^3}$$

$$b_3 = \text{known}$$



Full symbols are results based on N3LO QCD, open circles are based on NNLO, open triangles and squares on NLO QCD. The cross-filled square is based on lattice QCD.

At high scales Q >> 1 GeV

Coupling $\alpha_s(Q)$ << 1

Perturbation theory in α_s should be **reliable**: LO, NLO, NNLO, …

E.g., in the event shown a few slides ago, each of the six "jets" had $Q \sim E_T$ = 84 - 203 GeV

The Infrared Strikes Back

Naively, QCD radiation suppressed by $\alpha_s \approx 0.1$

Truncate at fixed order = LO, NLO, …

E.g., $\sigma(X+\text{jet})/\sigma(X) \propto \alpha_s$

Example: Pair production of SUSY particles at LHC$_{14}$, with $M_{SUSY} \approx 600$ GeV

LHC - sps1a - m~600 GeV

Plehn, Rainwater, PS PLB645(2007)217

FIXED ORDER pQCD	σ_{tot}[pb]	$\tilde{g}\tilde{g}$	$\tilde{u}_L\tilde{g}$	$\tilde{u}_L\tilde{u}_L^*$	$\tilde{u}_L\tilde{u}_L$	TT
$p_{T,j} > 100$ GeV	σ_{0j}	4.83	5.65	0.286	0.502	1.30
inclusive **X + 1 "jet"**	σ_{1j}	2.89	2.74	0.136	0.145	0.73
inclusive **X + 2 "jets"**	σ_{2j}	1.09	0.85	0.049	0.039	0.26
$p_{T,j} > 50$ GeV	σ_{0j}	4.83	5.65	0.286	0.502	1.30
	σ_{1j}	5.90	5.37	0.283	0.285	1.50
	σ_{2j}	4.17	3.18	0.179	0.117	1.21

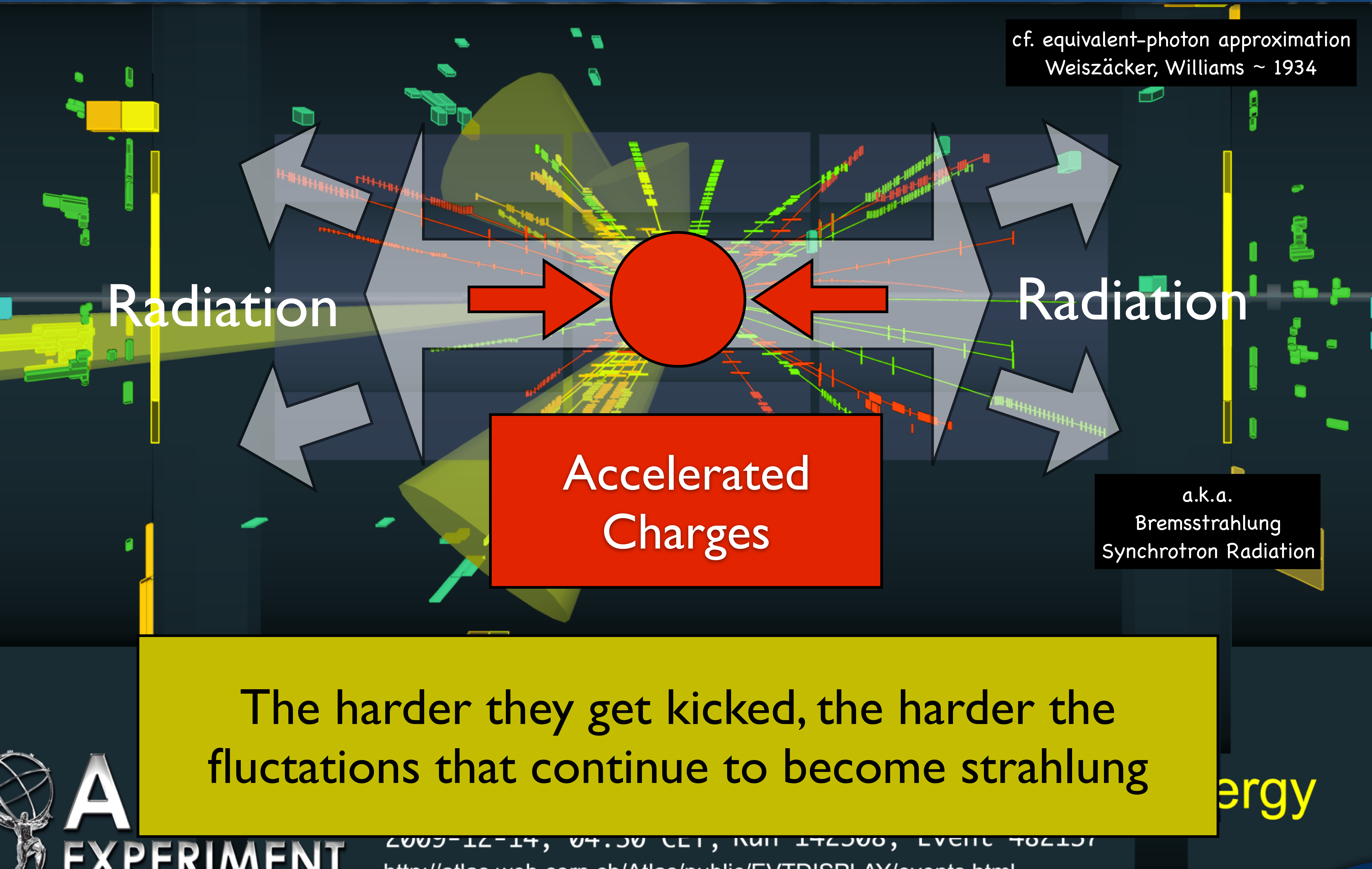
(Computed with SUSY-MadGraph)

σ for X + jets much larger than naive estimate

$\sigma_{50} \sim \sigma_{tot}$ tells us that there will "always" be a ~ 50-GeV jet "inside" a 600-GeV process

All the scales are high, Q >> 1 GeV, so perturbation theory **should** be OK …

This is just the physics of Bremsstrahlung

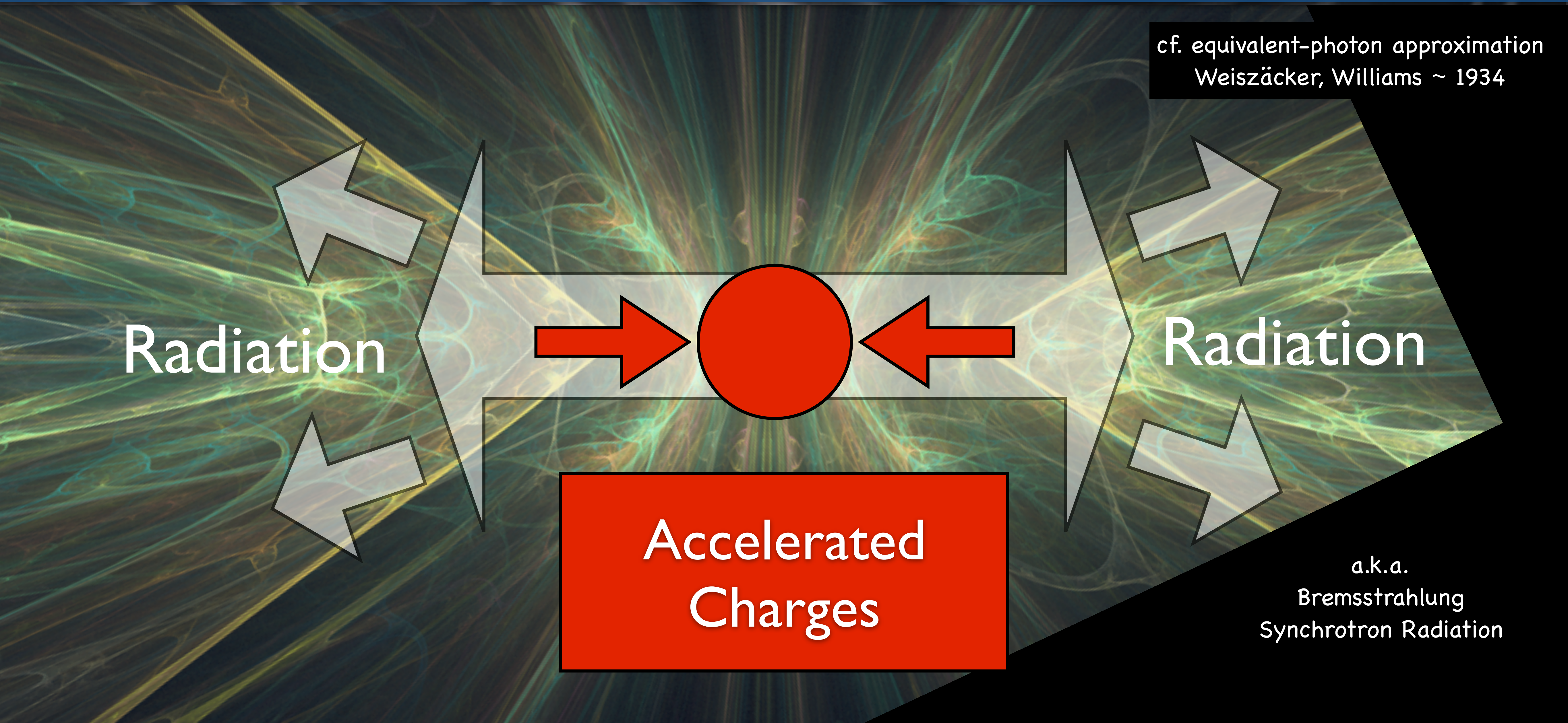


cf. equivalent-photon approximation
Weiszäcker, Williams ~ 1934

a.k.a.
Bremsstrahlung
Synchrotron Radiation

The harder they get kicked, the harder the fluctations that continue to become strahlung

Can we build a simple theoretical model of this?



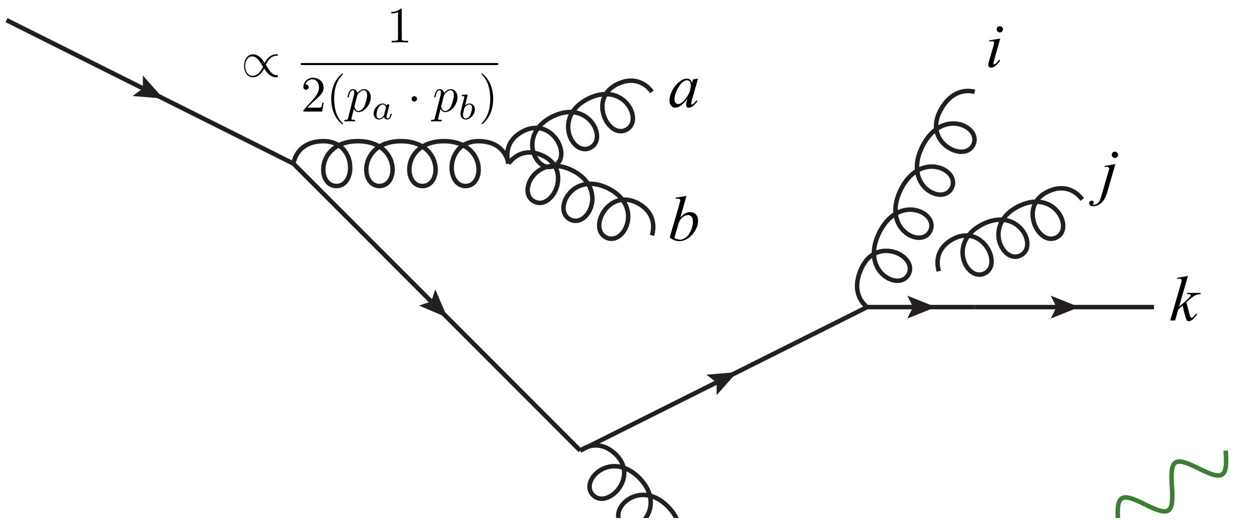
The Lagrangian of QCD is **scale invariant** (neglecting small quark masses)

Characteristic of point-like constituents ➤ Observables depend on **dimensionless quantities**, like **angles** and energy **ratios**

The rules of bremsstrahlung

see e.g PS, *Introduction to QCD*, TASI 2012, arXiv:1207.2389

Most bremsstrahlung is driven by divergent propagators → simple structure



Gauge amplitudes factorize in singular limits (→ universal *"conformal"* or *"fractal"* structure)

Partons ab → collinear:
$$|\mathcal{M}_{F+1}(\ldots,a,b,\ldots)|^2 \stackrel{a||b}{\rightarrow} g_s^2 \mathcal{C} \frac{P(z)}{2(p_a \cdot p_b)} |\mathcal{M}_F(\ldots,a+b,\ldots)|^2$$

P(z) = "Dokshitzer-Gribov-Lipatov-Altarelli-Parisi **splitting kernels**", with $z = E_a/(E_a+E_b)$

Gluon j → soft:
$$|\mathcal{M}_{F+1}(\ldots,i,j,k\ldots)|^2 \stackrel{j_g\rightarrow 0}{\rightarrow} g_s^2 \mathcal{C} \frac{(p_i \cdot p_k)}{(p_i \cdot p_j)(p_j \cdot p_k)} |\mathcal{M}_F(\ldots,i,k,\ldots)|^2$$

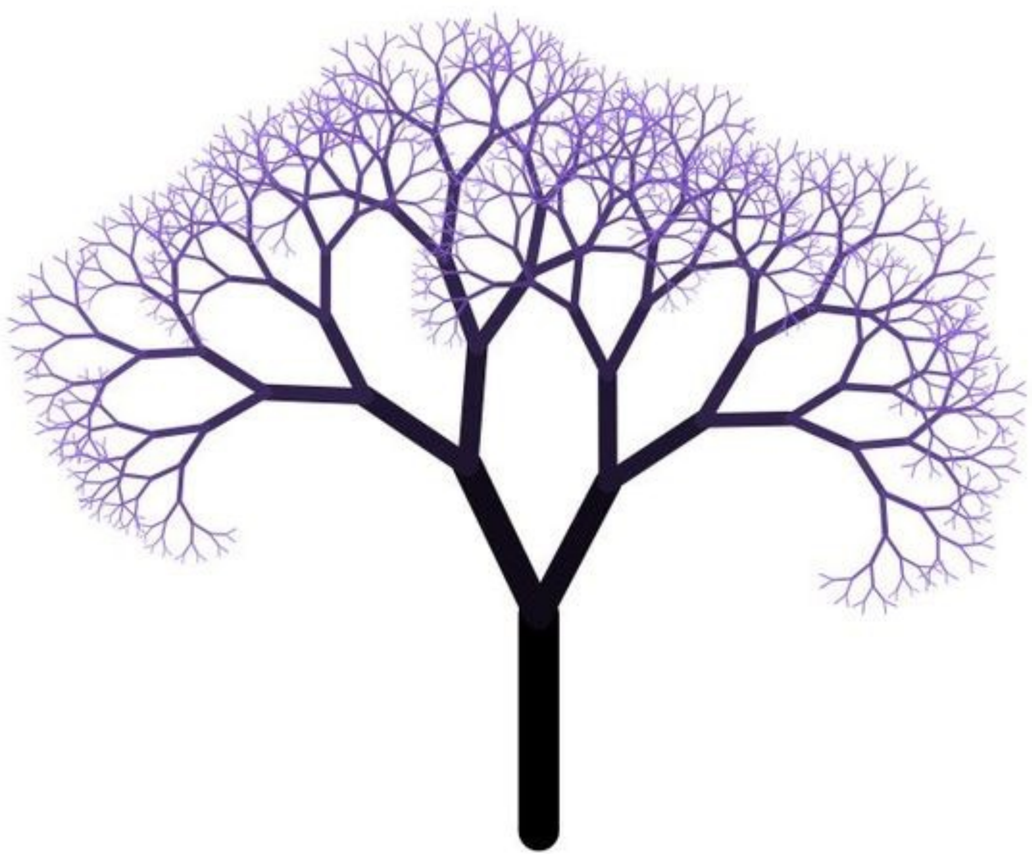
Coherence → Parton j really emitted by (i,k) "dipole" or **"antenna"**

+ scaling violation: $g_s^2 \rightarrow 4\pi\alpha_s(Q^2)$

Iterating the structure

Repeated application of bremsstrahlung rules → **nested factorizations**

More and more partons resolved at increasingly smaller scales



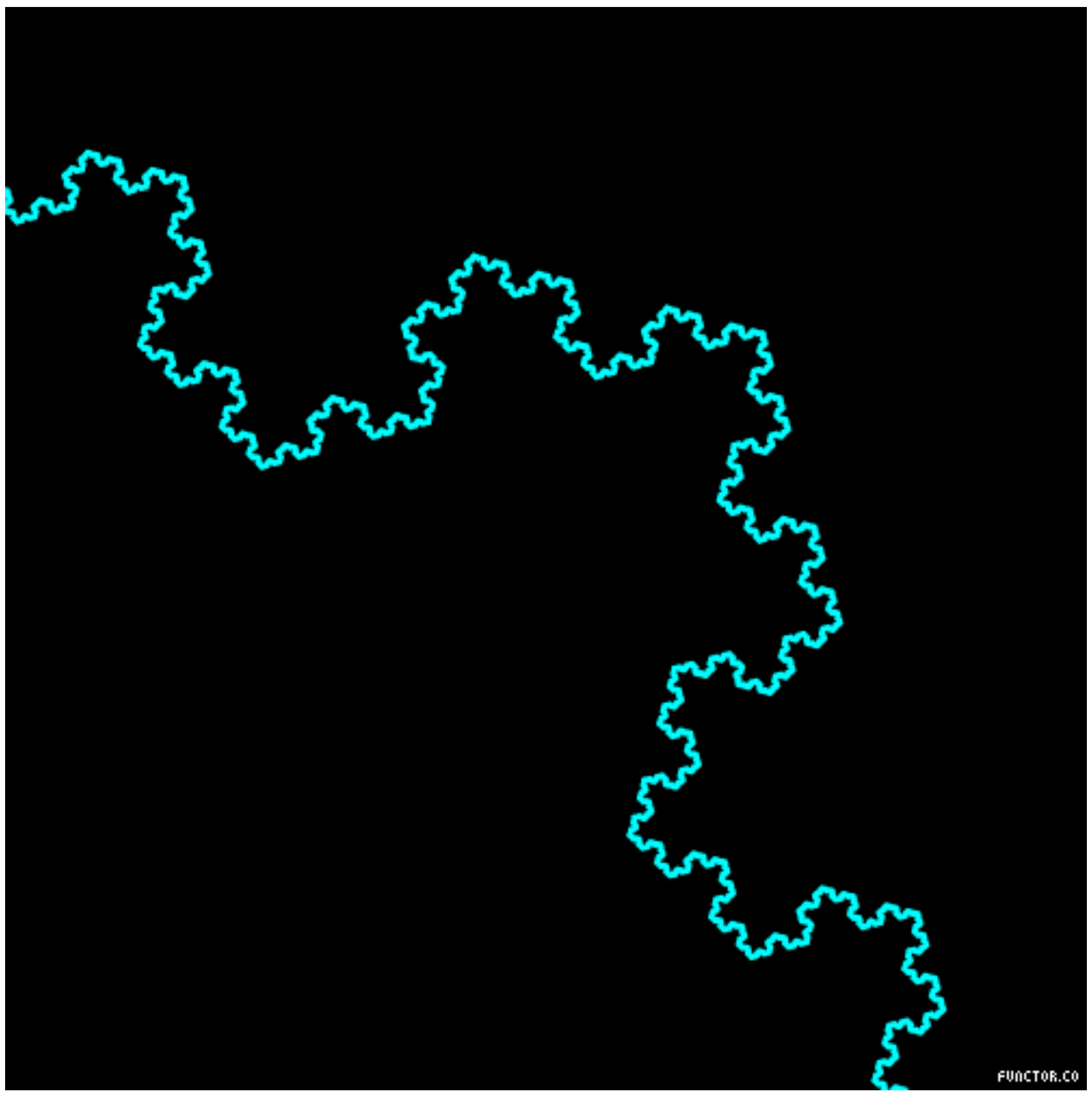
Can be cast as a **differential evolution**:

$d\mathcal{P}/dQ^2$: differential probability to resolve more structure as function of a "resolution scale", $Q^2 \sim$ **virtuality**

Iterating the structure

Repeated application of bremsstrahlung rules → **nested factorizations**

More and more partons resolved at increasingly smaller scales



Can be cast as a **differential evolution**:

$d\mathcal{P}/dQ^2$: differential probability to resolve more structure as function of a "resolution scale", Q^2 ~ **virtuality**

It's a ***quantum fractal***: $\mathcal{P}$ is **probability** to resolve another parton as we decrease Q^2: gluon → two gluons, quark → quark + gluon, gluon → quark-antiquark pair.

As we continue to "zoom", the integrated probability for resolving another "jet" can naively exceed 100%

That's what the X+jet cross sections were trying to tell us earlier: σ(X+jet) > σ(X)

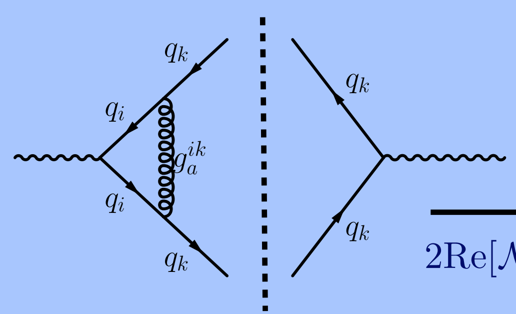
(From Legs to Loops)

see e.g PS, *Introduction to QCD*, TASI 2012, arXiv:1207.2389

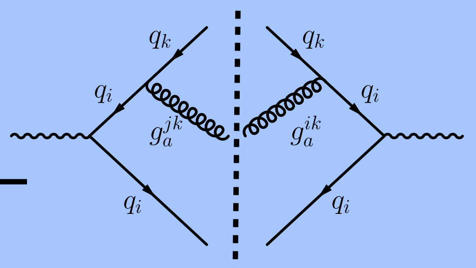
Unitarity: sum(probability) = 1

Kinoshita-Lee-Nauenberg:

(sum over degenerate quantum states = finite: infinities must cancel!)



$$\xrightarrow[2\mathrm{Re}[\mathcal{M}^{(1)}\mathcal{M}^{(0)*}]]{} \text{Loop} = -\int \text{Tree} + F \xleftarrow[\left|\mathcal{M}^{(0)}_{+1}\right|^2]{}$$



Neglect non-singular piece, F → "Leading-Logarithmic" (LL) Approximation

→ **Can also include loops-within-loops-within-loops …**

→ Bootstrap for All-Orders Quantum Corrections!

Parton Showers: reformulation of pQCD corrections as gain-loss diff eq.

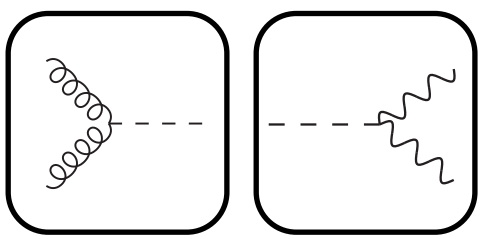
- Iterative (Markov-Chain) evolution algorithm, based on universality and unitarity
- With evolution kernel ~ $\frac{|\mathcal{M}_{n+1}|^2}{|\mathcal{M}_n|^2}$ (or soft/collinear approx thereof)
- Generate explicit fractal structure across all scales (via Monte Carlo Simulation)
- Evolve in some measure of *resolution* ~ hardness, virtuality, 1/time … ~ fractal scale
- + account for scaling violation via quark masses and $g_s^2 \to 4\pi\alpha_s(Q^2)$

Divide and Conquer

Iterated/Nested Factorizations → Split the problem into many ~ simple pieces

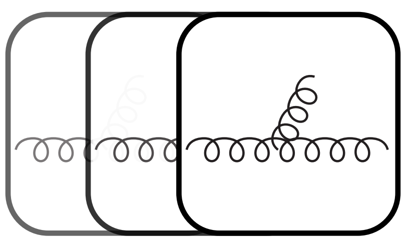
$$\mathcal{P}_{\mathrm{event}} = \underbrace{\mathcal{P}_{\mathrm{hard}} \otimes \mathcal{P}_{\mathrm{dec}} \otimes \mathcal{P}_{\mathrm{ISR}} \otimes \mathcal{P}_{\mathrm{FSR}} \otimes \mathcal{P}_{\mathrm{MPI}} \otimes \mathcal{P}_{\mathrm{Had}} \otimes \ldots}$$

Quantum mechanics → Probabilities → Make Random Choices (as in nature)
➜ Method of Choice: **Markov-Chain Monte Carlo** ➜ *"Event Generators"*



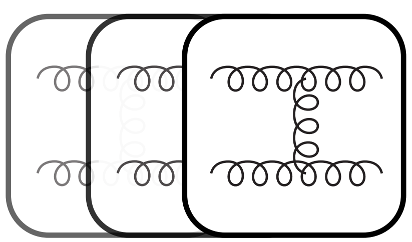
Hard Process & Decays:

Use process-specific (N)LO matrix elements
→ Sets "hard" resolution scale for process: Q_{MAX}



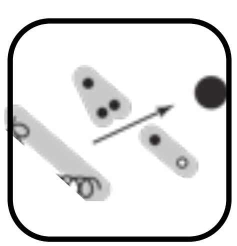
ISR & FSR (Initial & Final-State Radiation):

Universal DGLAP equations → differential evolution, dP/dQ^2, as function of resolution scale; run from Q_{MAX} to $Q_{Confinement}$ ~ 1 GeV



MPI (Multi-Parton Interactions)

Additional (soft) parton-parton interactions: LO matrix elements
→ Additional (soft) "Underlying-Event" activity (Not the topic for today)

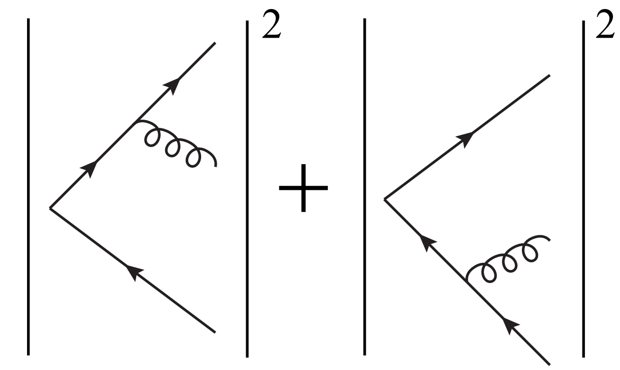


Hadronization

Non-perturbative model of color-singlet parton systems → hadrons

Our Research

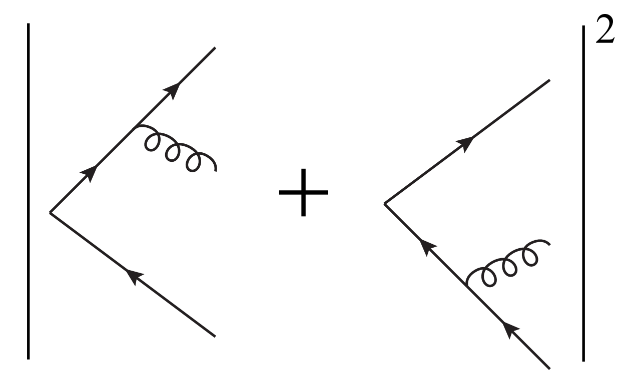
Parton Showers are based on 1→2 splittings



Each **parton** undergoes a sequence of splittings

- Some interference effects included via "angular ordering" or via "dipole functions" (~dipole pattern partitioned into 2 terms)
- (E,p) conservation achieved via (ambiguous) recoil effects

At Monash, we develop an **Antenna Shower**, in which splittings are fundamentally 2→3 (+ working on 2→4…)



Includes dipole interference

Evolution in terms of colour **dipoles/antennae**

- + Intrinsically coherent (to leading power of $1/N_C^2 \sim 10\%$)
- + Manifestly Lorentz invariant kinematics with local (E,p) cons.

What's new in our approach?

- Antenna evolution also for **initial state** and **coloured resonances**
- Higher-order **perturbative corrections** can be introduced via calculable corrections in an elegant and very efficient way

VINCIA

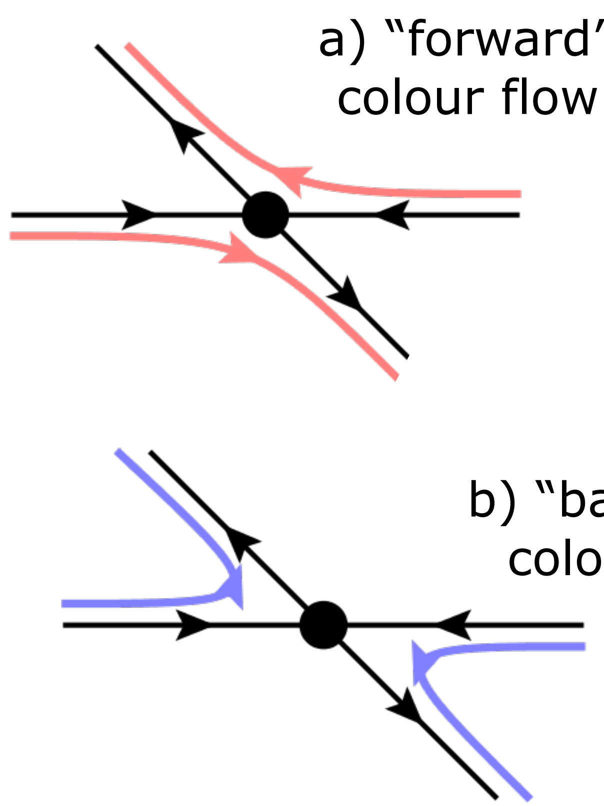
Example: Coherence in Quark-Quark Scattering

Ritzmann, Kosower, PS, PLB718 (2013) 1345

Quark-quark scattering in hadron collisions (eg at LHC)

Consider one specific phase-space point (eg scattering at 45^o)

2 possible colour flows: a and b



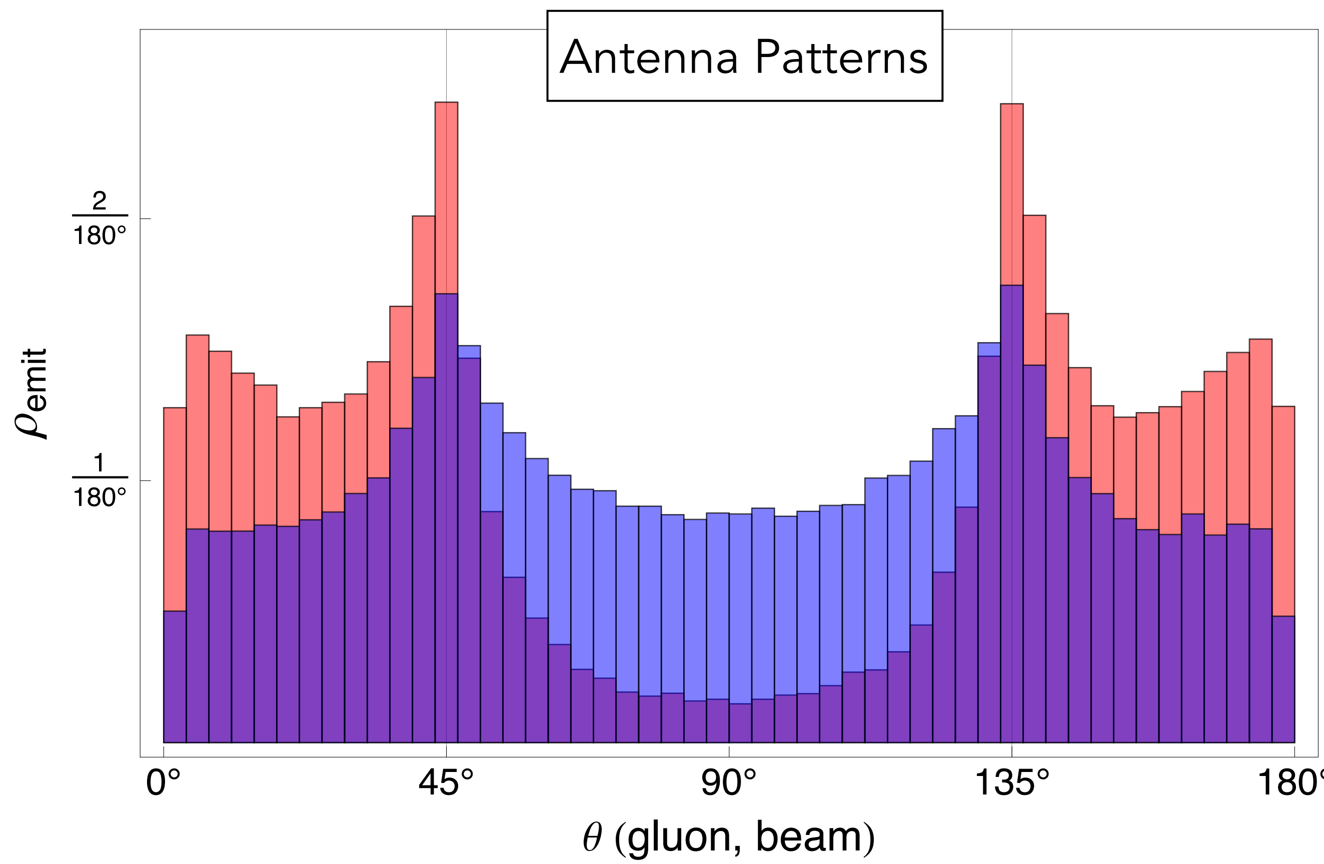


Figure 4: Angular distribution of the first gluon emission in $qq \to qq$ scattering at 45°, for the two different color flows. The light (red) histogram shows the emission density for the forward flow, and the dark (blue) histogram shows the emission density for the backward flow.

April 2016
First public release
of Vincia 2.0 (LHC)
(restricted to massless QCD)

Fractal Schmactal

We have an explicit representation of the fractal structure - great

Required approximations: "Leading Logarithm", "Leading Colour", …

- **Only good to about 10%**

I thought LHC physics was supposed to be high-precision stuff?

What good is Peta-Bytes of data if we can only calculate to 10% ?

Go back to fixed order? Sum inclusively over the fractal structure

In fixed order, I can predict ~ the **number** of jets (at some fixed scale)

Good enough if I don't ask questions about their internal structure, or the number of jets at disparate scales

State of the art is NNLO (few-% accuracy), some calculations even N^{3}LO

But somewhat unsatisfactory … even at N^{3}LO the events look far from real

Why not combine the two types of calculations?

Problem: double counting of terms present in both expansions

VINCIA: Markovian pQCD*

*⁾pQCD : perturbative QCD

Start at Born level

$$|M_F|^2$$

Generate "shower" emission

$$|M_{F+1}|^2 \overset{LL}{\sim} \sum_{i\in \mathrm{ant}} a_i \; |M_F|^2$$

Correct to Matrix Element

$$a_i \to \frac{|M_{F+1}|^2}{\sum a_i |M_F|^2} a_i$$

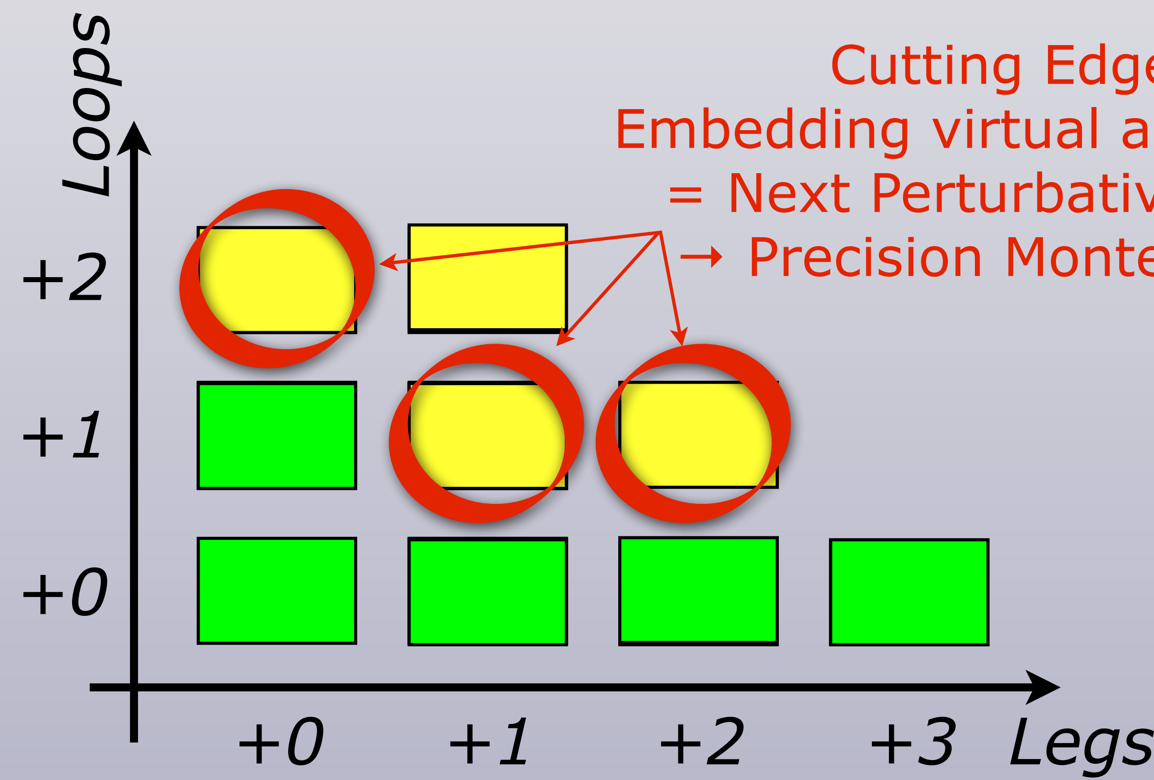
Unitarity of Shower

$$\mathrm{Virtual} = -\int \mathrm{Real}$$

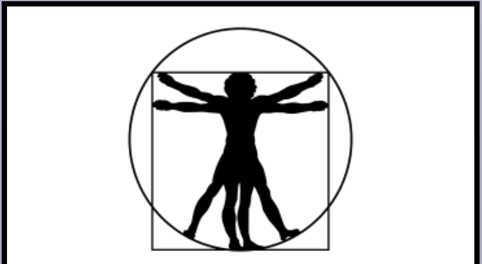
Correct to Matrix Element

$$|M_F|^2 \to |M_F|^2 + 2\mathrm{Re}[M_F^1 M_F^0] + \int \mathrm{Real}$$

Repeat



Cutting Edge:
Embedding virtual amplitudes
= Next Perturbative Order
→ Precision Monte Carlos



The VINCIA Code

+

PYTHIA 8

"Higher-Order Corrections To Timelike Jets"
GeeKS: Giele, Kosower, Skands, PRD 84 (2011) 054003

"An Introduction to PYTHIA 8.2"
Sjöstrand et al., Comput.Phys.Commun. 191 (2015) 159

+ Applications (why other people care)

Example: The Top Quark

Heaviest known elementary particle:
$m_t \sim 187\ u\ (\sim m_{Au})$
Lifetime: 10^{-24} s
Complicated decay chains:

$$t \to bW^+ \qquad \bar{t} \to \bar{b}W^-$$

$$W \to \{q\bar{q}', \ell\nu\}$$

quarks → jets
b-quarks → b-jets

$$m_t^2 \approx (p_b + p_{W^+})^2$$
$$\approx (p_{b-\mathrm{jet}} + p_{q-\mathrm{jet}} + p_{\bar{q}-\mathrm{jet}})^2$$

Accurate jet energy calibrations → m_t

Analogously for any process / measurement involving coloured partons

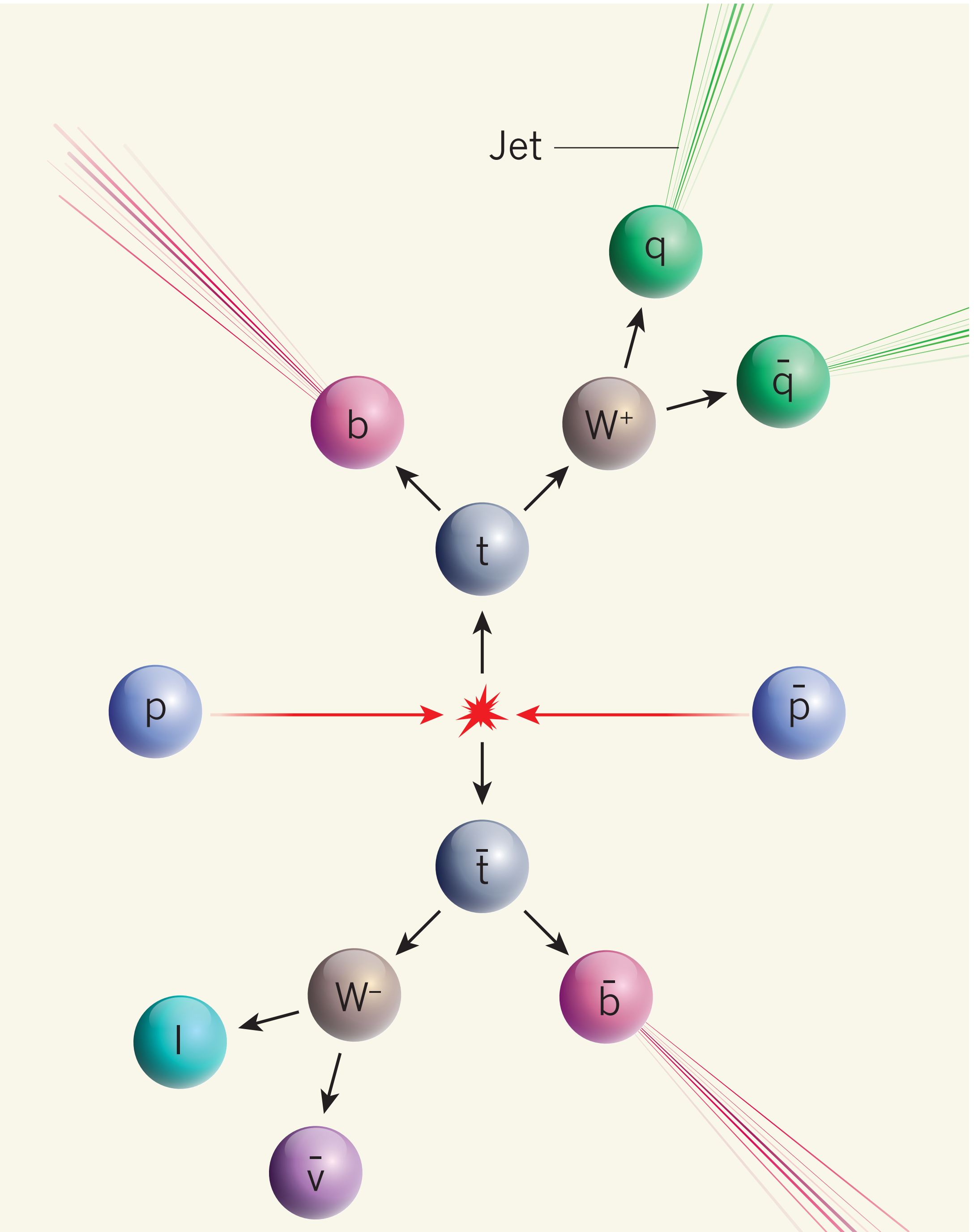


Illustration from: *P Skands, Nature* **514** (2014) 174

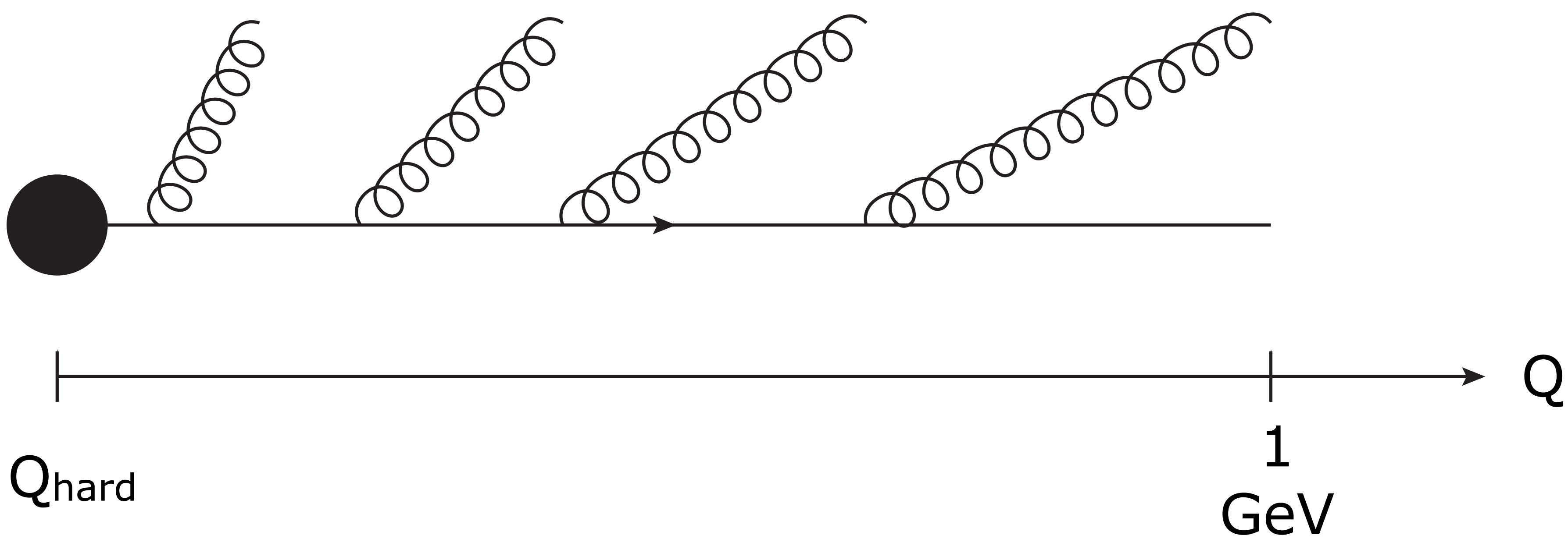
Brooks, Skands, "Coherent Showers in Decays of Coloured Particles", **PRD100 (2019)076006**

Here’s a fast parton

Fast: It starts at a high factorization scale $Q = Q_F = Q_{hard}$

It showers (bremsstrahlung)

It ends up at a low effective factorization scale $Q \sim m_\rho \sim 1$ GeV



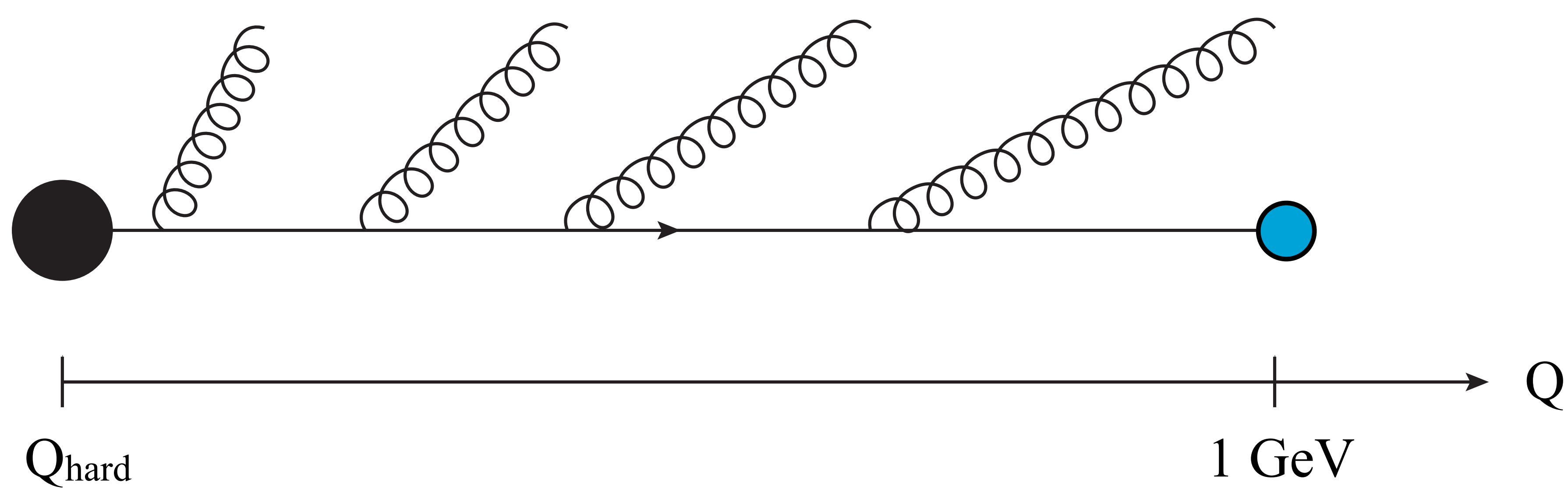
2) Non-Perturbative QCD

Here's a fast parton

Fast: It starts at a high factorization scale $Q = Q_F = Q_{hard}$

It showers (bremsstrahlung)

It ends up at a low effective factorization scale $Q \sim m_\rho \sim 1$ GeV



How about I just call it a hadron?

→ "Local Parton-Hadron Duality"

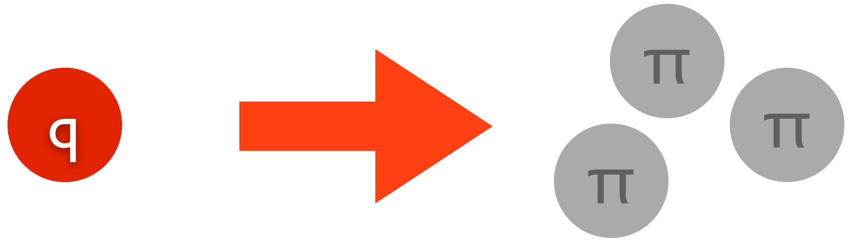
From Partons to Pions

Early models: "Independent Fragmentation"

Local Parton Hadron Duality (LPHD) can give useful results for inclusive quantities in collinear fragmentation

Motivates a simple model:

"Independent Fragmentation"



But …

The point of confinement is that partons are coloured

Hadronisation = the process of **colour neutralisation**

→ Unphysical to think about independent fragmentation of a single parton into hadrons

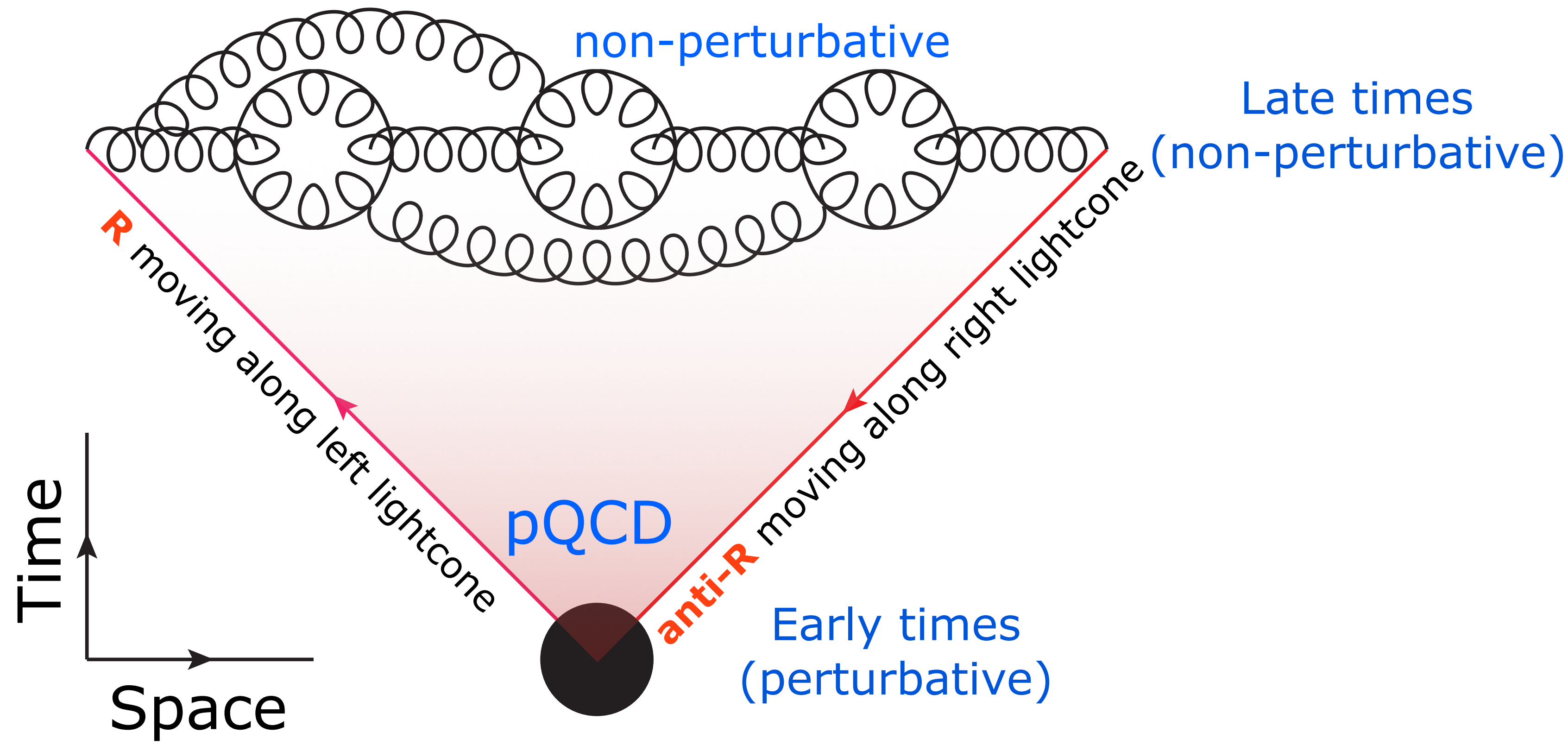
→ Too naive to see LPHD (inclusive) as a justification for Independent Fragmentation (exclusive)

→ More physics needed

Colour Neutralisation

A physical hadronization model

Should involve at least TWO partons, with opposite color charges (e.g., **R** and **anti-R**)



Strong “confining” field emerges between the two charges when their separation > ~ 1fm

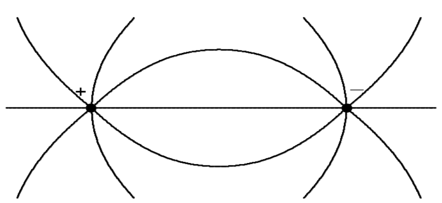
The Ultimate Limit: Wavelengths > 10-15 m

Quark-Antiquark Potential

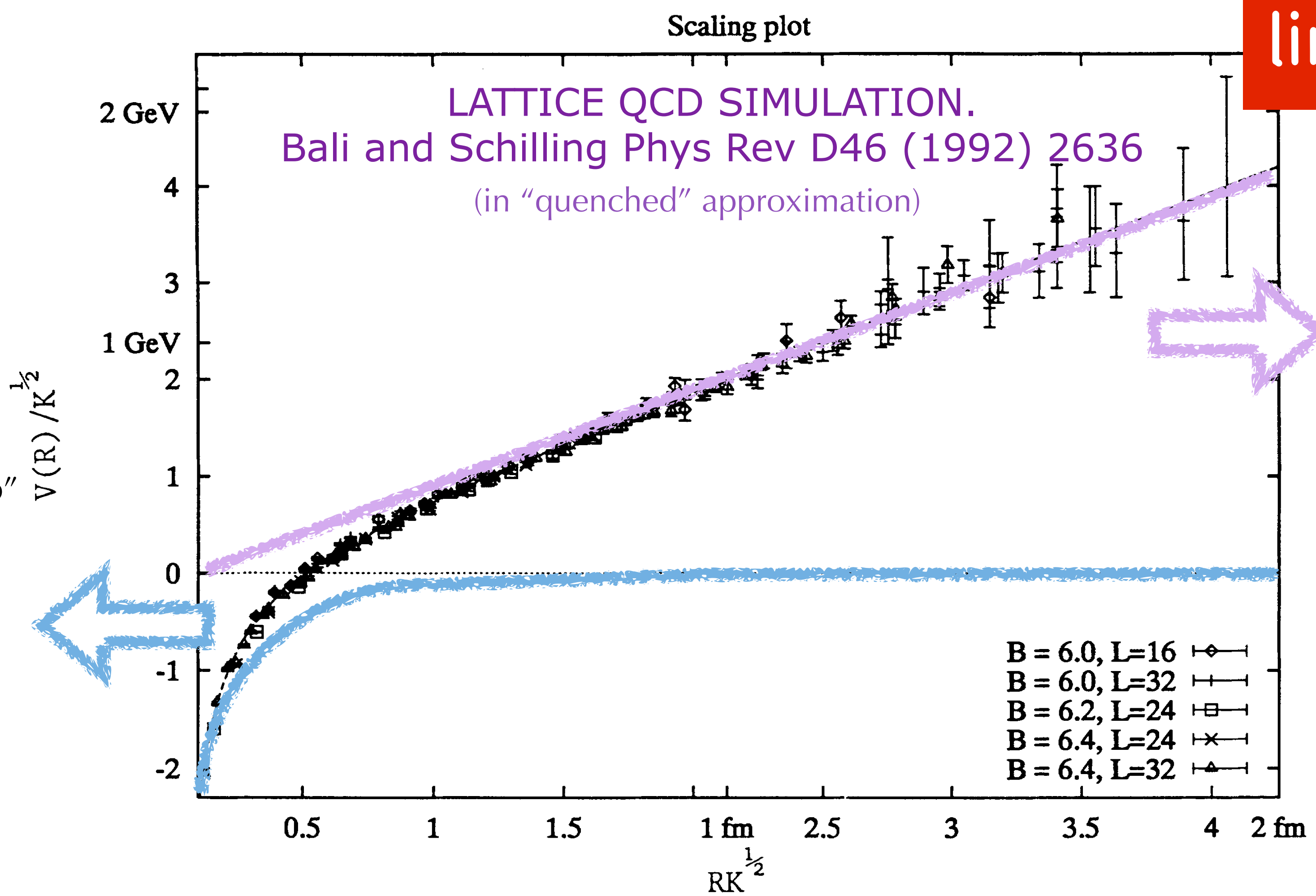
As function of separation distance

What physical system has a linear potential?

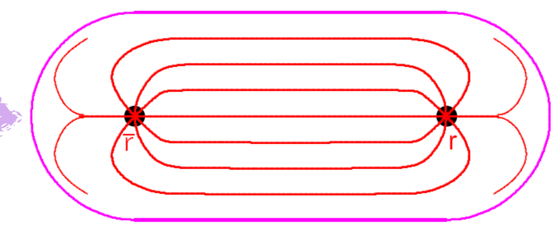
Short Distances ~ "Coulomb"



"Free" Partons



Long Distances ~ Linear Potential



"Confined" Partons
(a.k.a. Hadrons)

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

~ Force required to lift a 16-ton truck

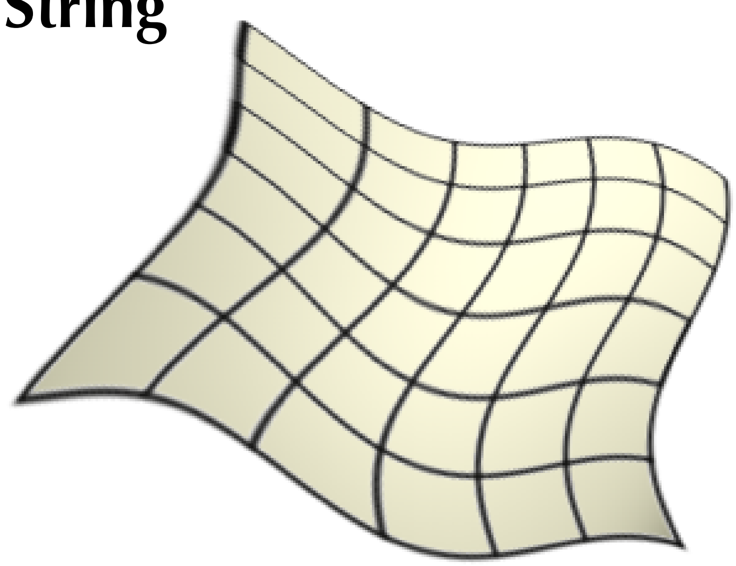
Motivates a model:

Let colour field collapse into a (infinitely) narrow flux tube of uniform energy density

κ ~ 1 GeV / fm

→ Relativistic 1+1 dimensional worldsheet

String

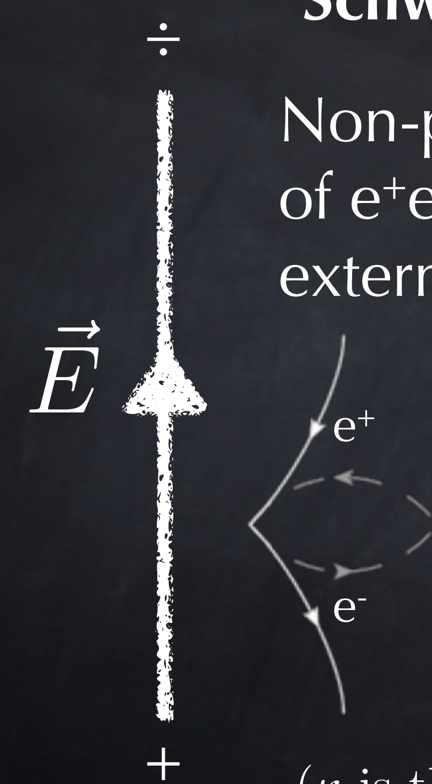


Pedagogical Review: B. Andersson, *The Lund model.* Camb. Monogr. Part. Phys. Nucl. Phys. Cosmol., 1997.

In "unquenched" QCD

g→qq → The strings will break

Schwinger Effect



Non-perturbative creation of e^+e^- pairs in a strong external Electric field

Probability from Tunneling Factor

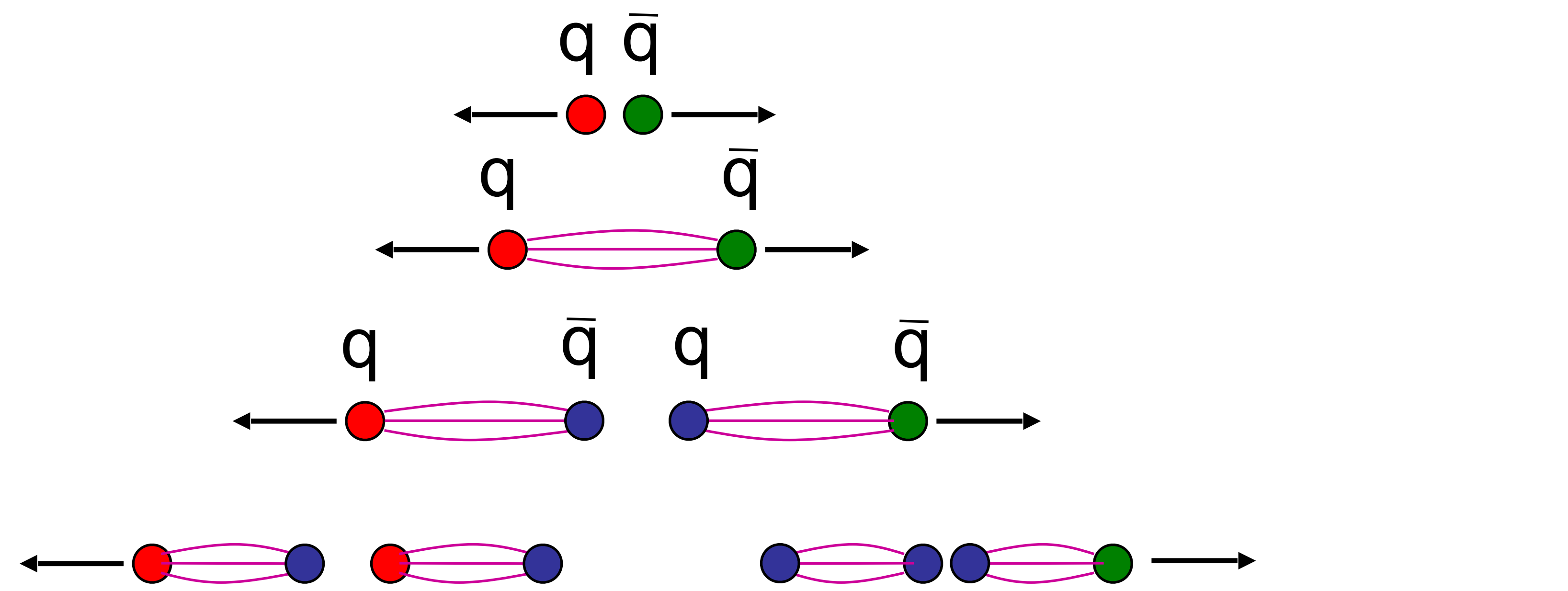
$$\mathcal{P} \propto \exp\left(\frac{-m^2 - p_\perp^2}{\kappa/\pi}\right)$$

(κ is the string tension equivalent)

→ Gaussian p_T spectrum
Heavier quarks suppressed. Prob(q=d,u,s,c) ≈ 1 : 1 : 0.2 : 10^{-11}

Hadronisation and Jets

★ **Consider a quark and anti-quark produced in e^+e^- annihilation**



i) Initially Quarks separate at high velocity

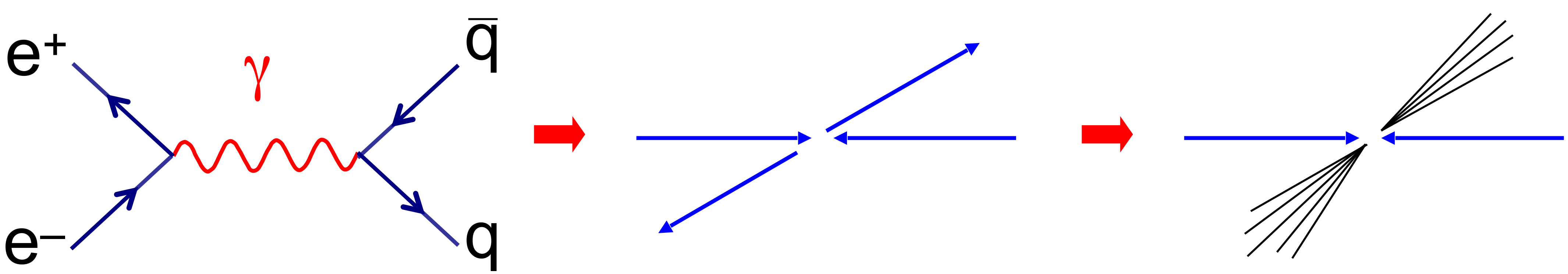
ii) Colour flux tube forms between quarks

iii) Energy stored in the flux tube sufficient to produce $q\bar{q}$ pairs

iv) Process continues until quarks pair up into jets of colourless hadrons

★ **This process is called hadronisation. It is not (yet) calculable from first principles.**

★ **The main consequence is that at collider experiments quarks and gluons observed as multi-particle states: jets of particles**



Models vs Data — A Recent Example

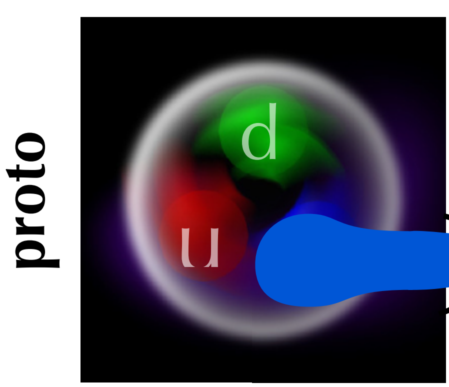
Around 2015, a few teams of theorists proposed a new set of measurements to test a fundamental property of the strong force:

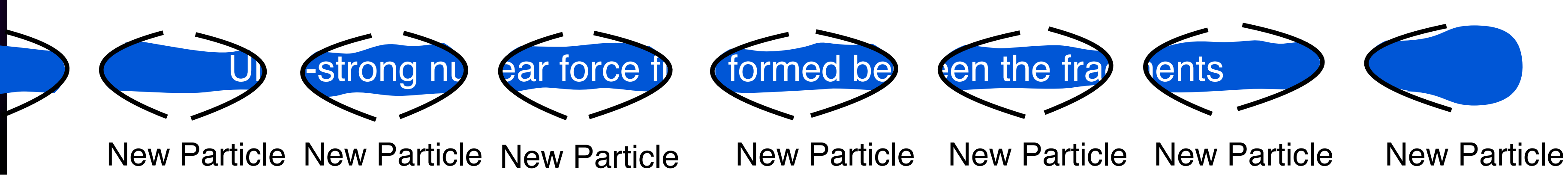
Is the fraction of **“strange”** particles produced in the LHC experiments a constant, or does it depend on how violent the collisions are?

How are 2 colliding protons turned into hundreds of outgoing particles?

Fact: quarks (and gluons) are “confined” inside the proton

What happens if we give one of them a really hard kick?





Fragmentation: Field energy converted to mass of new quark-antiquark pairs

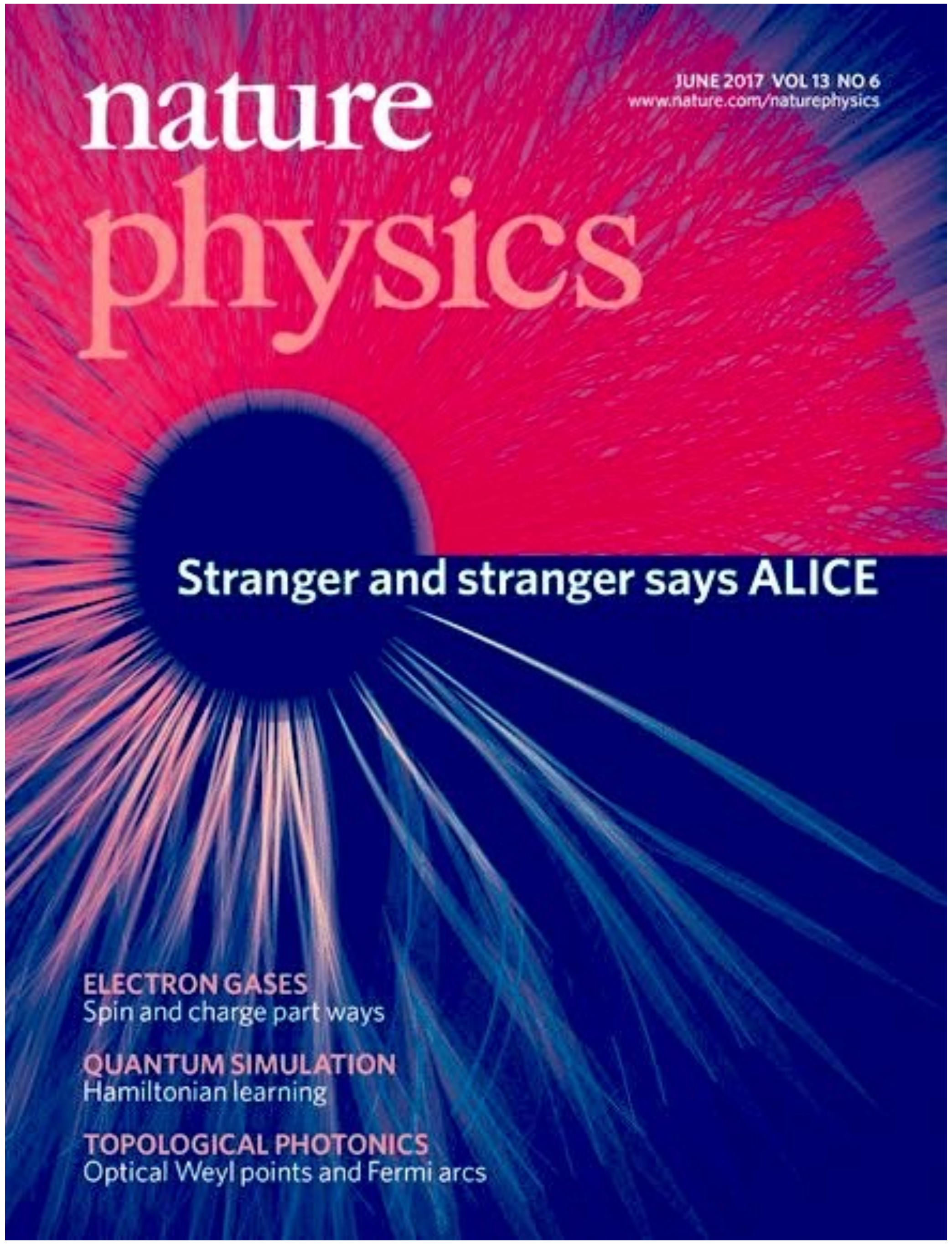
Strange quarks are heavier (need more energy) → produced less often

We wanted to know if "violent" collision events produced higher-strength fields.

Smoking gun would be a higher fraction of strange particles being produced

(higher-strength fields $\Longrightarrow$ more energy per "space-time volume" $\Longrightarrow$ easier to produce higher-mass quark-antiquark pairs)

Jackpot!



June 2017

What a strange world we live in, said Alice [to the queen of hearts]

We wanted to know if "violent" collision events produced higher-strength fields.

Smoking gun would be a higher fraction of strange particles being produced

(higher-strength fields $\Longrightarrow$ more energy per "space-time volume" $\Longrightarrow$ easier to produce higher-mass quark-antiquark pairs)

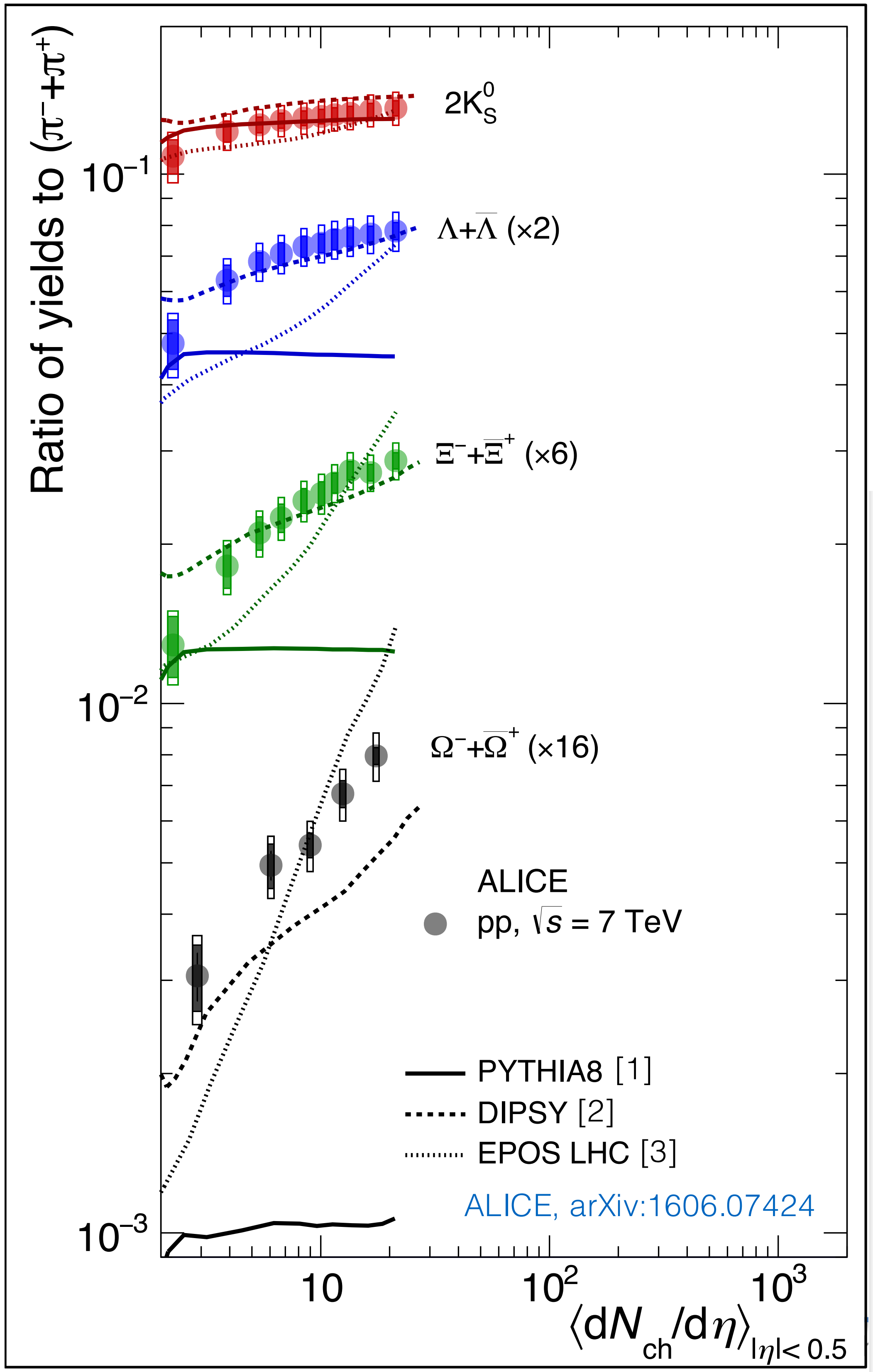
Jackpot!

Now working on models in which nearby fragmenting fields interact with each other.

Interactions between QCD strings!

Higher tensions + repulsion effects ➤ modifications in high-density environments

(Competing idea: the whole thing turns into a near-perfect liquid which gets heated up.)



D.D. Chinellato – 38th International Conference on High Energy Physics

Summary: new research at Monash

- **QCD jets and (sub)structure:** Next order of precision
- **Dynamics of confinement**; hadronisation, QCD strings, interactions
- **Monte Carlo Event Generators**: PYTHIA & VINCIA
- **Precision LHC phenomenology** & future collider studies (FCC, CEPC)