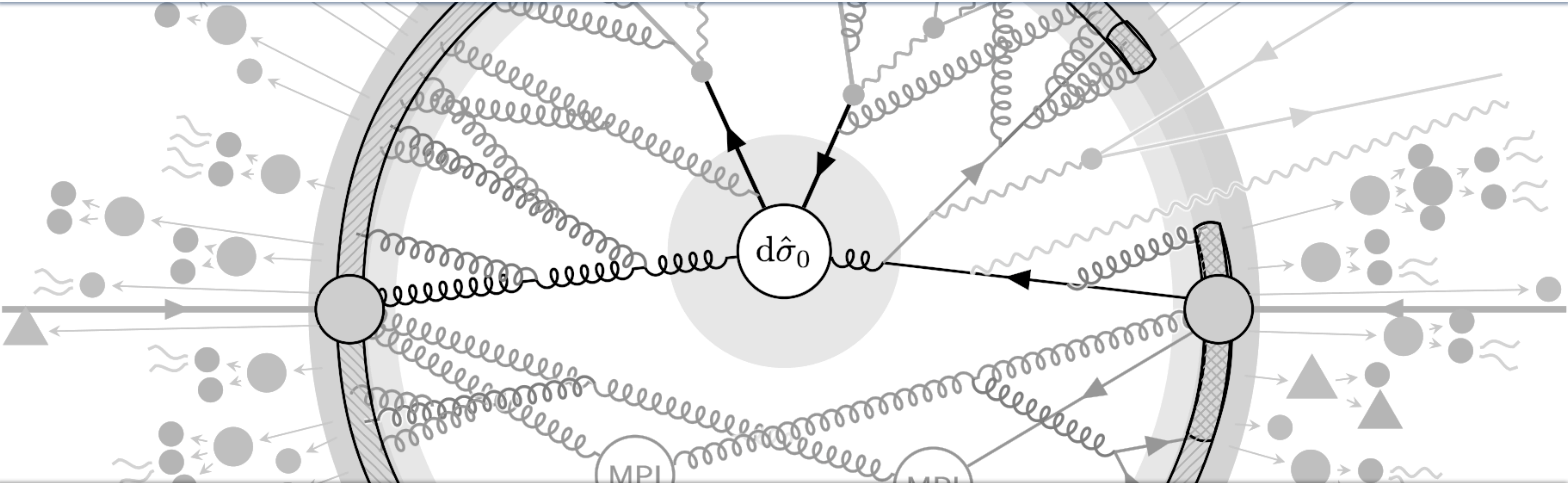
# Anatomy of an LHC Collision
# — and Challenges for the Future




**Peter Skands**

RS Wolfson Visiting Fellow, U of Oxford / Merton College, and Monash U.

# LHC Collisions – Theory vs Real Life

**Theory Goal:** Use LHC measurements to test hypotheses about Nature.


But have no **exact** solutions to QFT for the SM or Beyond

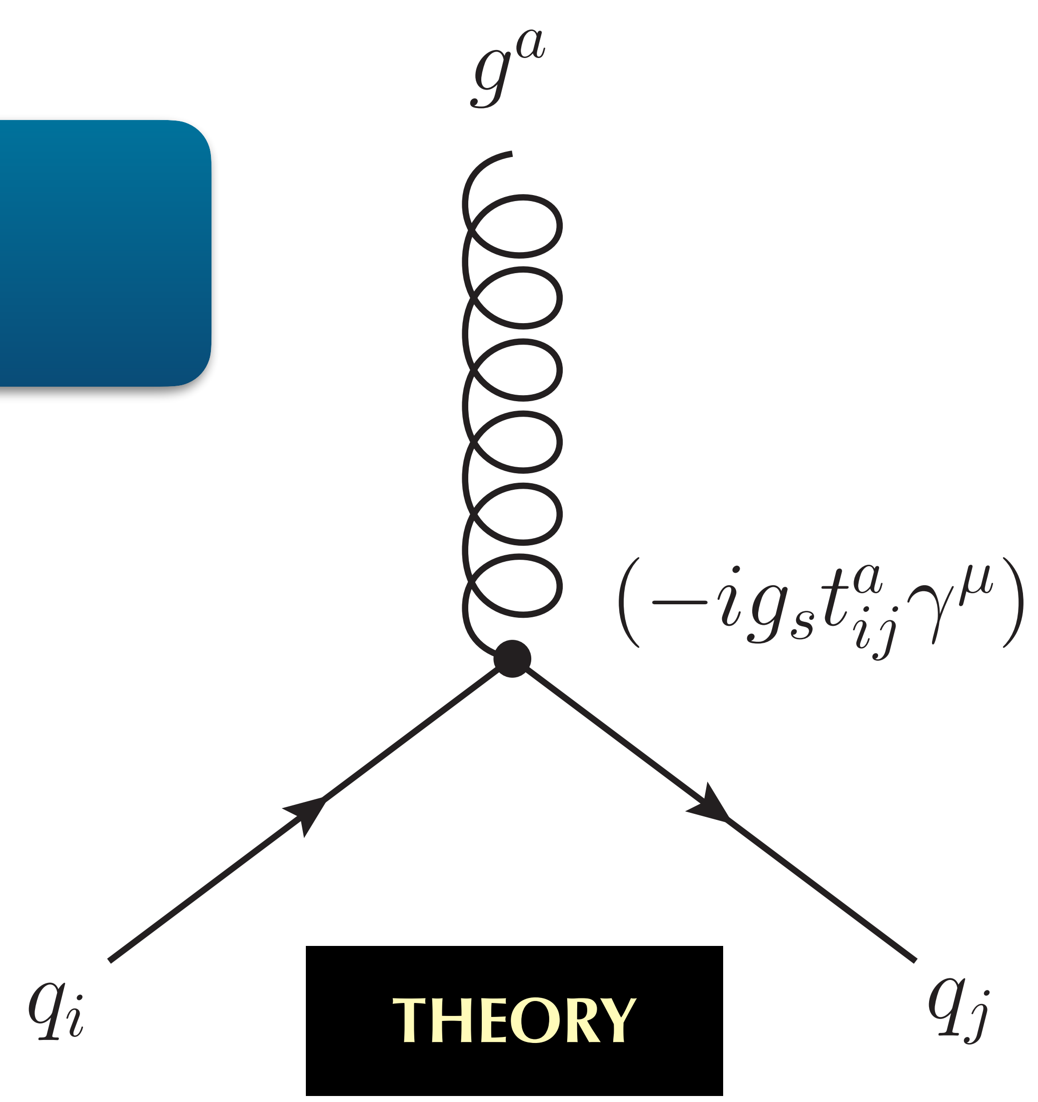
How to make predictions to form **(reliable)** conclusions?

## Problem #1: we are colliding — and observing — hadrons

Strongly bound states of quarks and gluons (non-perturbative QCD)

### How do we connect this…

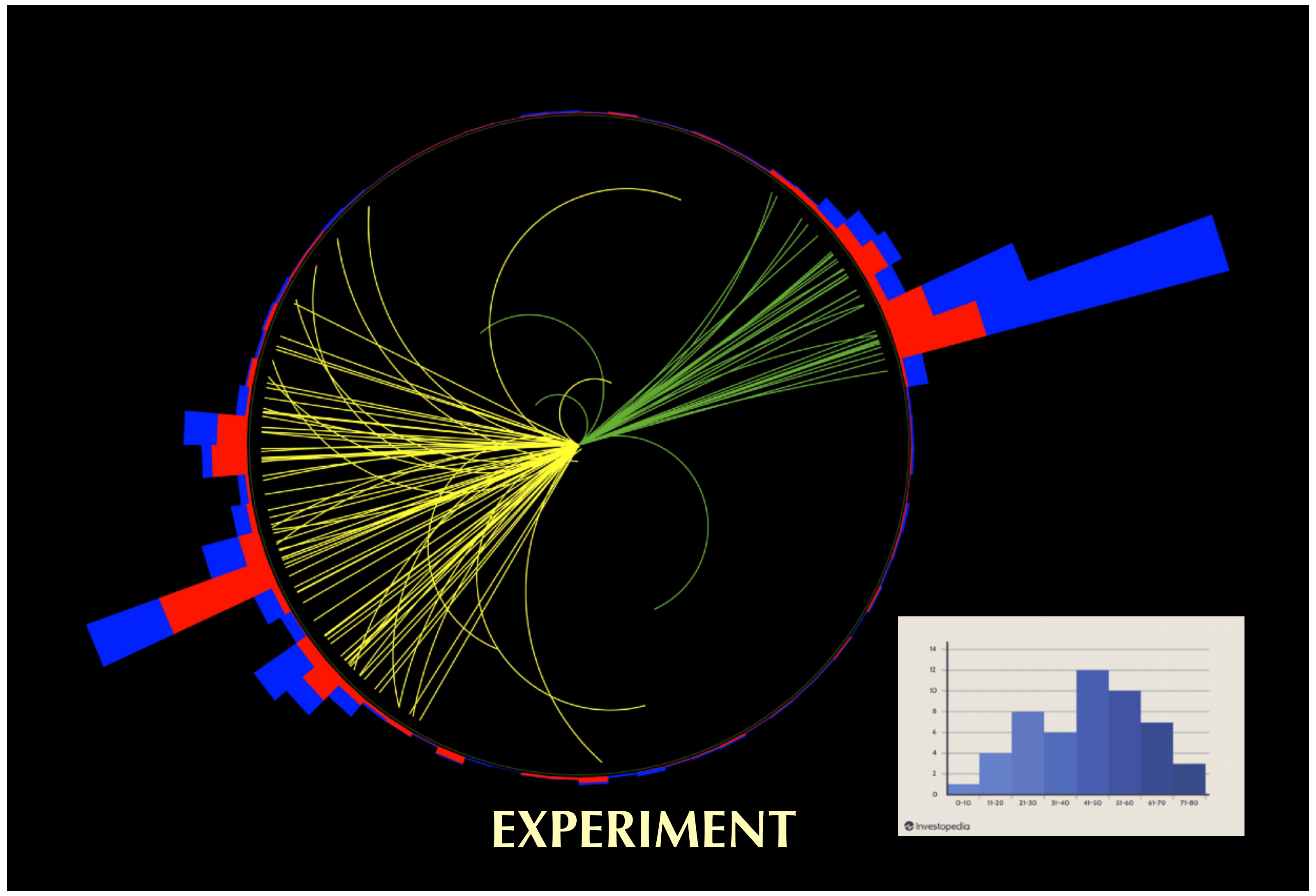
$\mathscr{L} = \dots$




Elementary Fields & Symmetries
"Fundamental" parameters.
Asymptotic freedom, perturbative QFT

**CONFINEMENT**

### … with this?




"Emergent" degrees of freedom
Jets of hadrons

# What do I mean by "Emergent" degrees of freedom?

**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:**

*Fractal scaling, of jets within jets within jets …* JETS (& RGEs)

*Confinement (in QCD), of coloured partons within hadrons* STRINGS

Image Credits: mrwallpaper.com

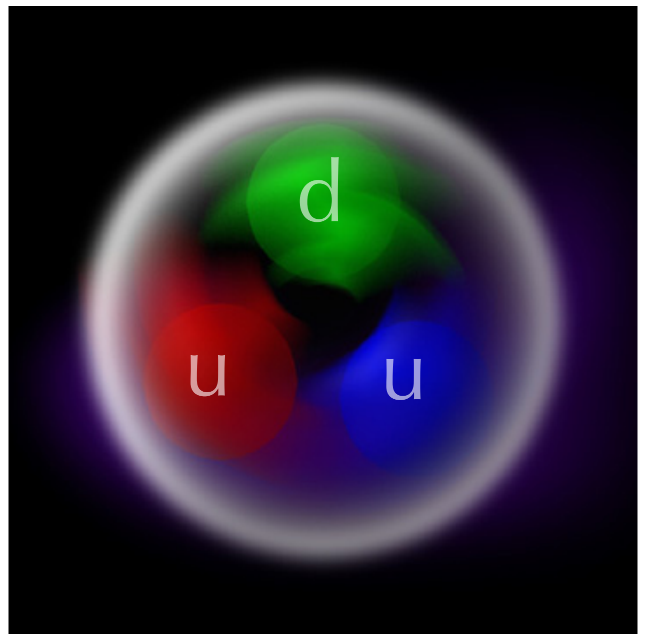
Image Credits: Yeimaya

# Consider a hadron; why is it complicated?

**Textbook "quark-model" proton:**

Three quarks

➤ Quark-model flavour ⊗ spin wave functions




**Real-life hadrons**

Are composite & strongly bound, with time-dependent structure

**For wavelengths ~ confinement scale:**

quark & gluon plane waves are not going to be good approximations

⟹ **forget about the interaction picture and perturbation theory**

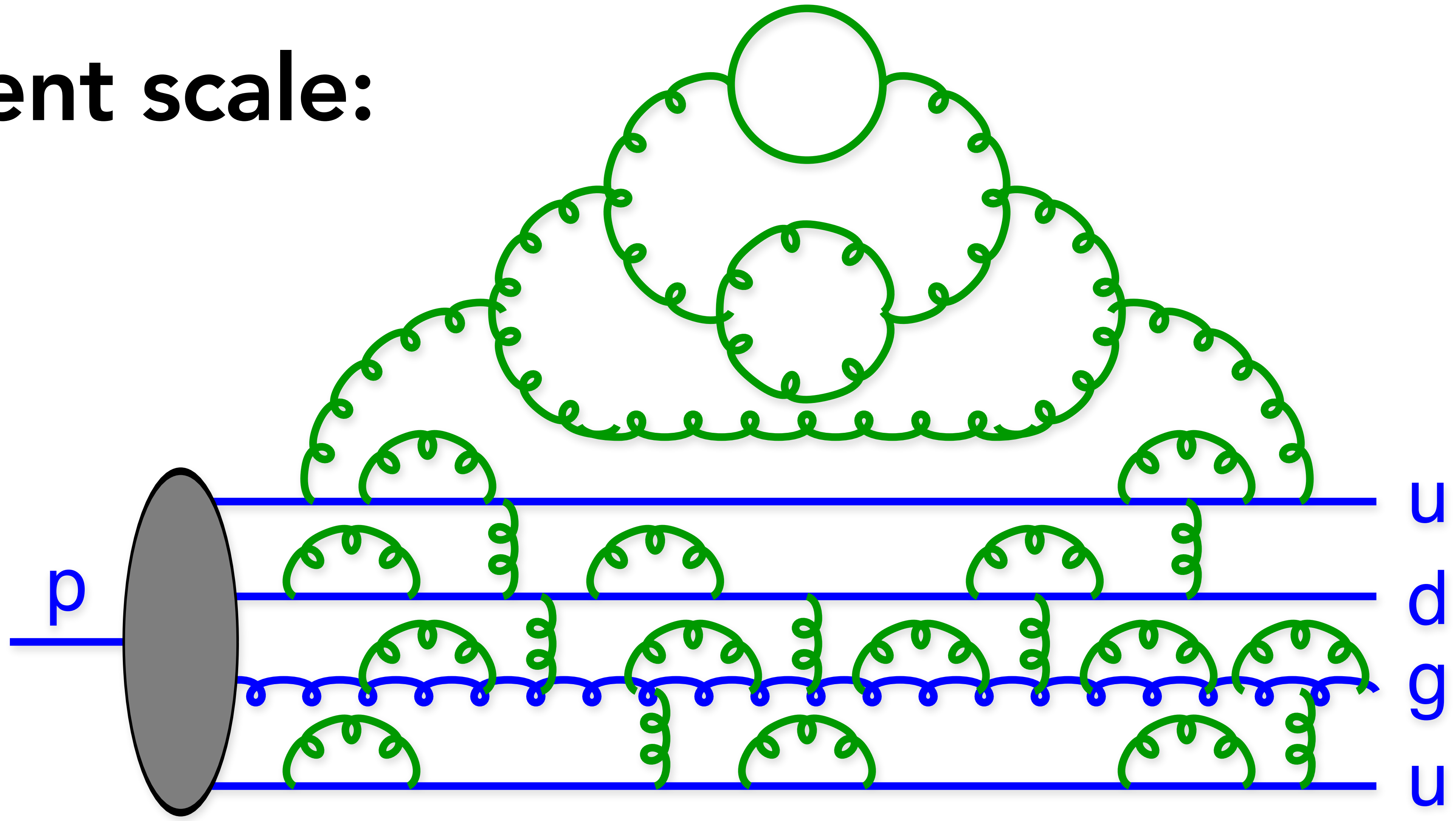
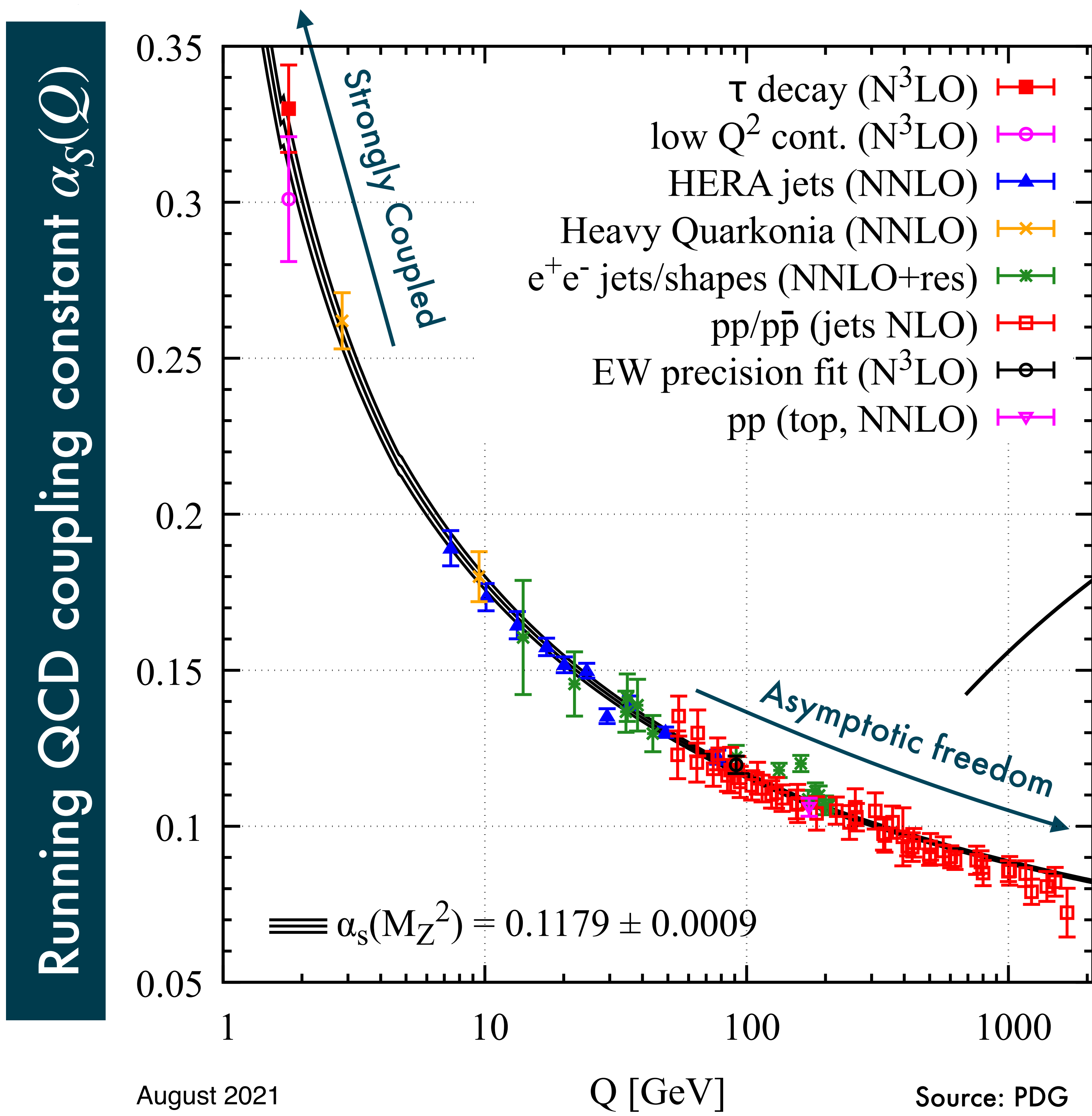



Figure by T. Sjöstrand

## Asymptotic Freedom in QCD (Gross, Politzer, Wilczek — Nobel 2004)

Over **short** distances, quarks and gluons **do** behave like *almost* free particles

**Then** it's OK to start from free-field solutions (plane waves) and treat interactions as perturbations ⟹ The interaction picture and perturbation theory are saved!




Parametrise "mess" in terms of (measurable) probability densities for each type of plane wave: **Parton Distribution Functions (PDFs)**

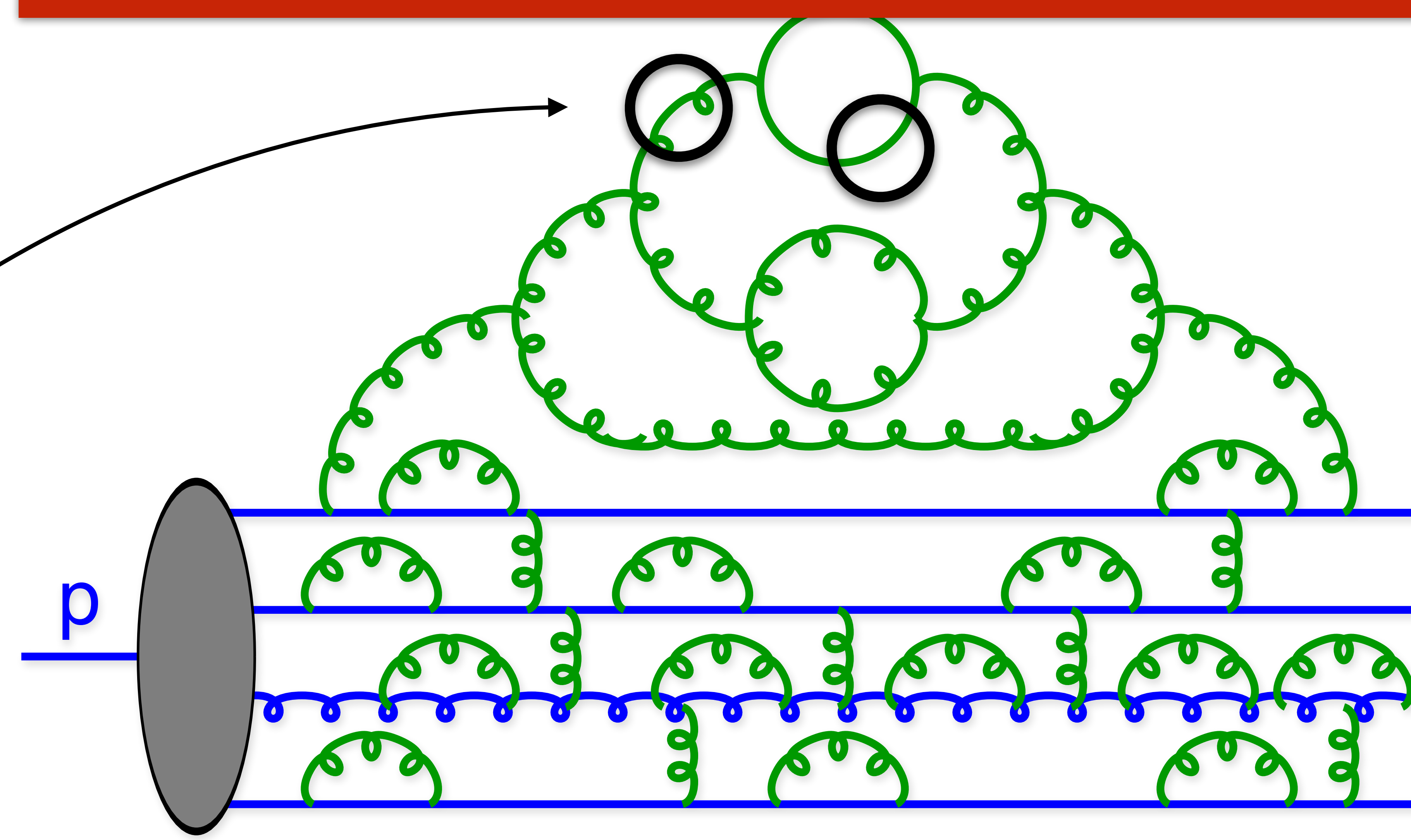



Figure by T. Sjöstrand

# Mathematically, the cross section **factorises**

(Collins, Soper, '87)

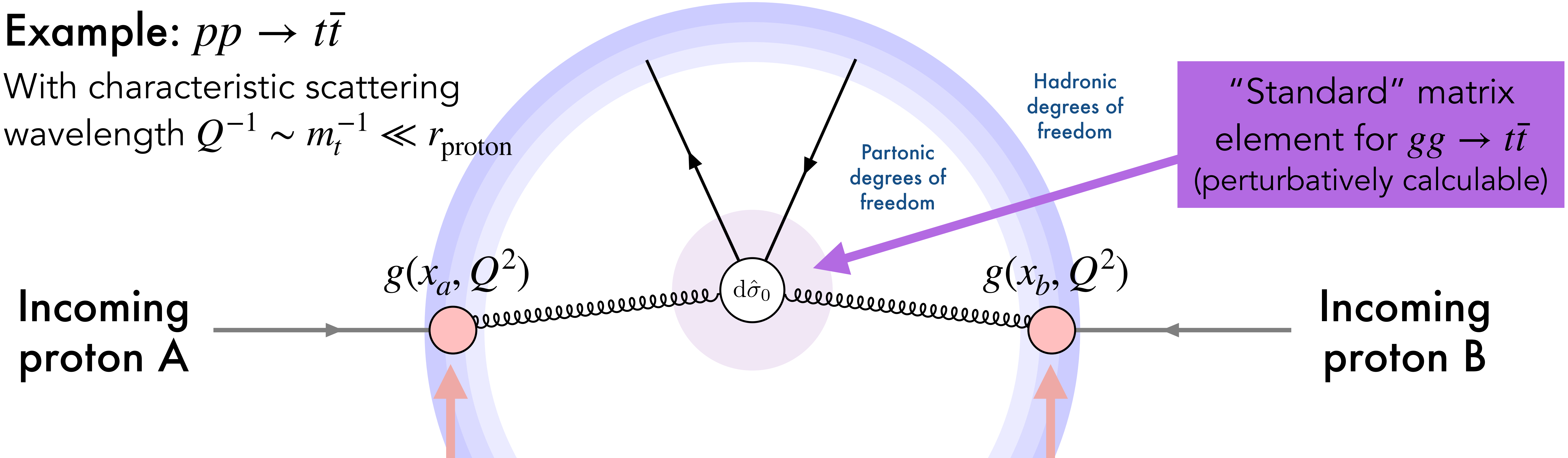
**Hadron-level cross sections can be computed as (sums over):**

**Perturbative Parton-level cross sections $\otimes$ Parton Distribution Functions**

Thus, we can compute, e.g., the total top-quark-pair cross section we expect at LHC:

**Example:** $pp \to t\bar{t}$

With characteristic scattering wavelength $Q^{-1} \sim m_t^{-1} \ll r_{\text{proton}}$



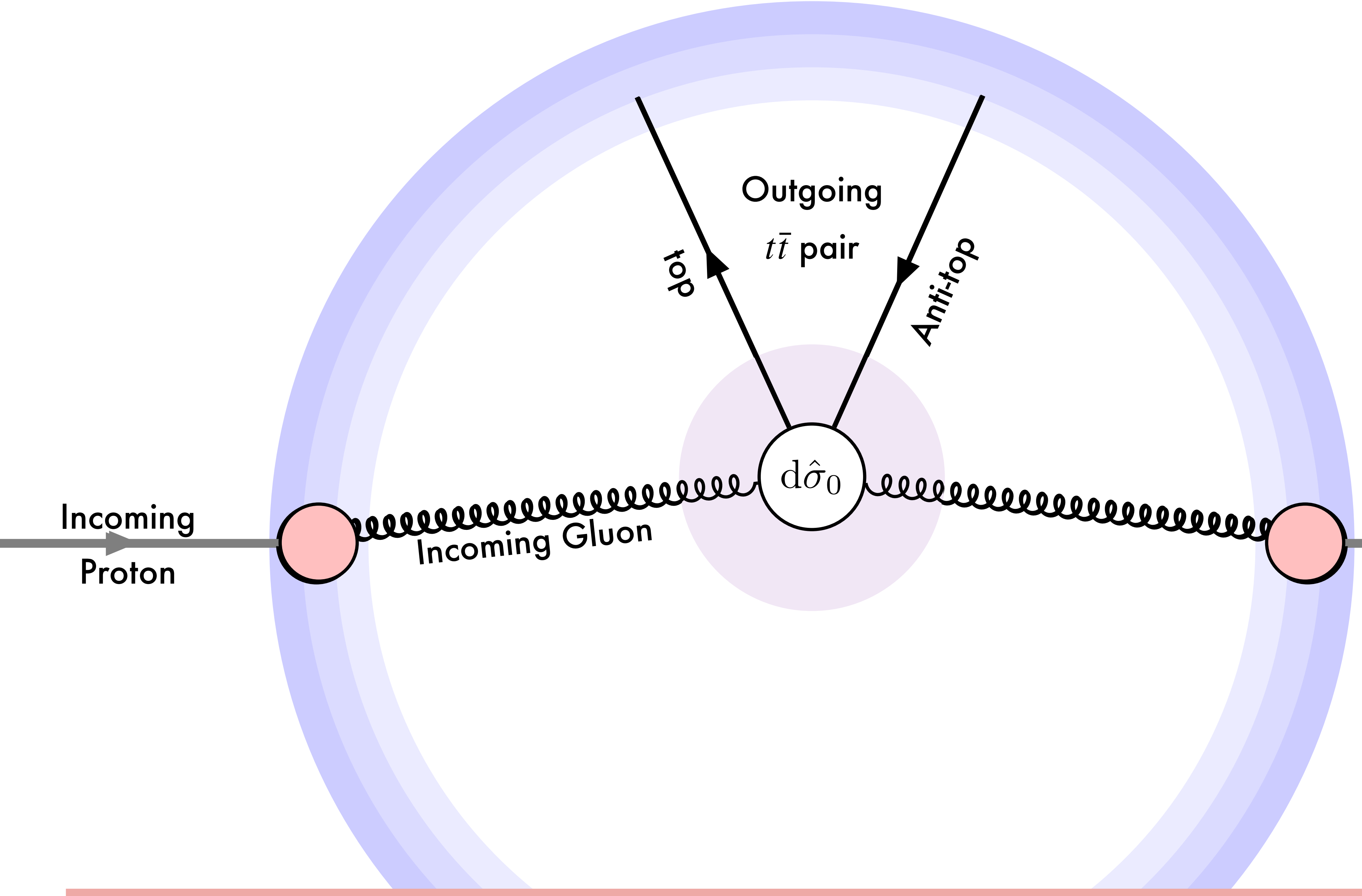

**Probability densities for finding gluons inside protons A and B**
(carrying fractions $x_a$ and $x_b$ of the respective proton energies)

These (& equivalent quark ones) were measured at previous colliders (esp. HERA); increasingly now also at LHC itself.

# Great! Now can we compare to measurements?

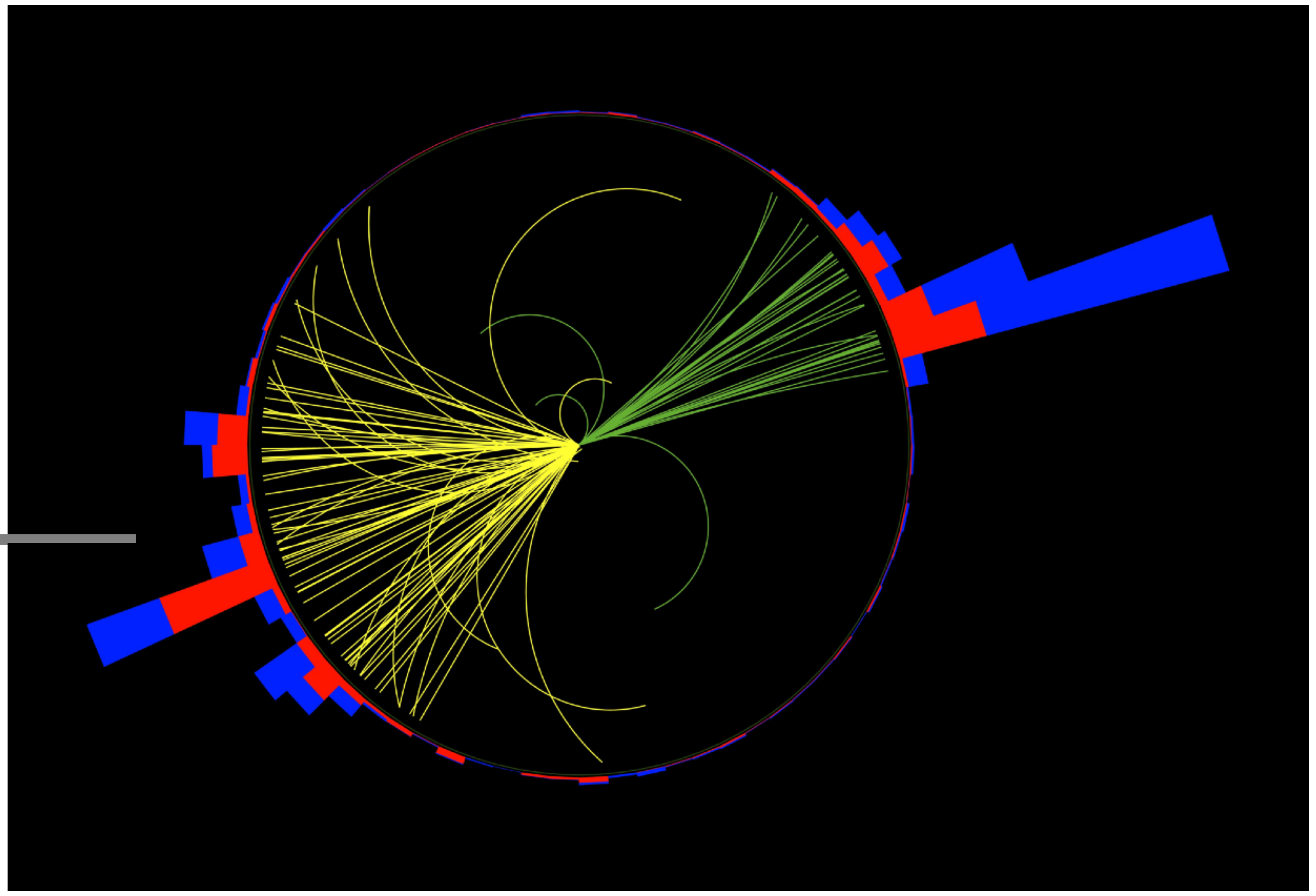
**Theorist:**

***This is a $t\bar{t}$ event***




**Experimentalist:**

***Is this a $t\bar{t}$ event?***



With factorisation, we recover the use of perturbation theory (for high-scale processes*)

But we also lose a lot of detail (and still cannot address low scales)

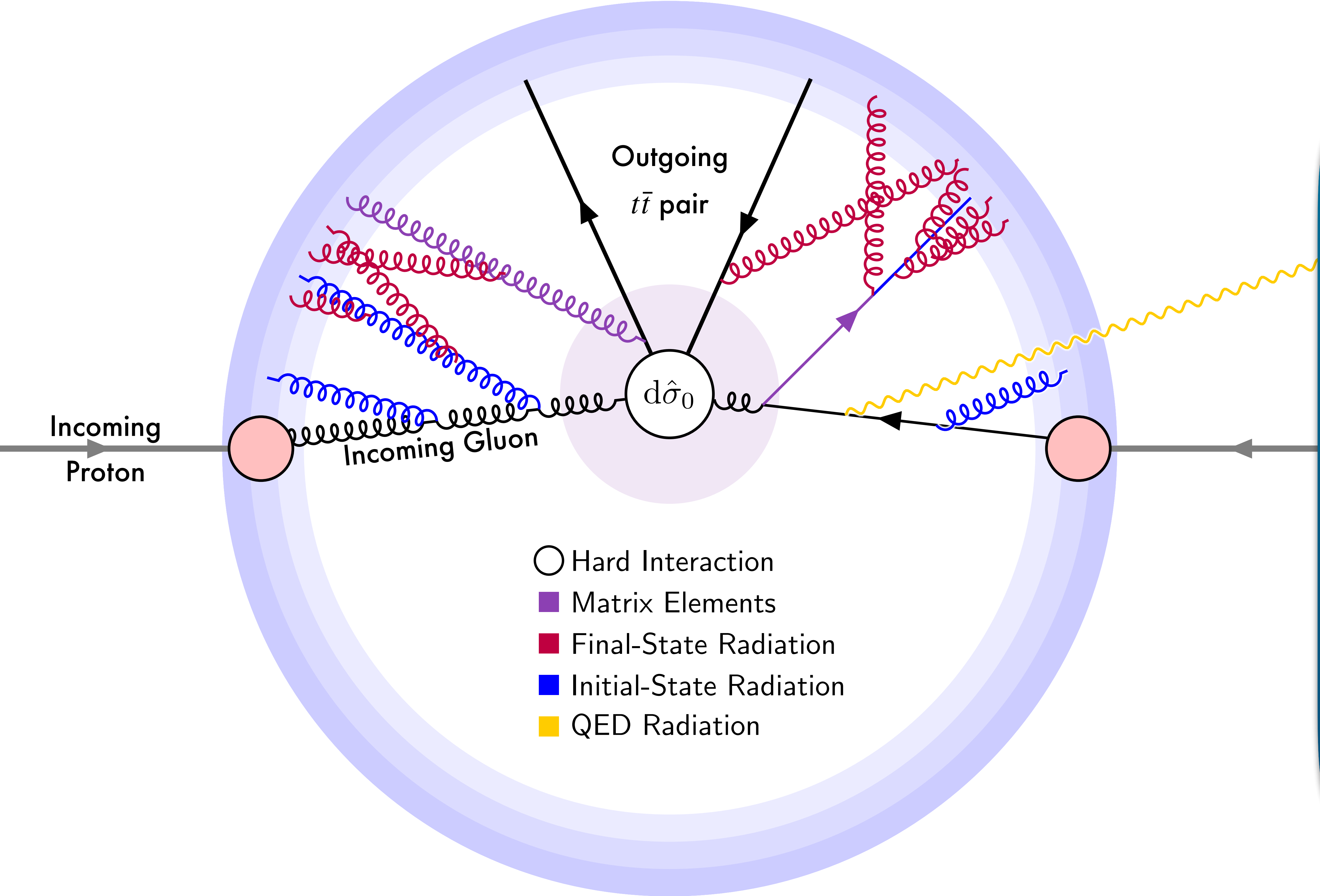
*for so-called Infrared and Collinear Safe Observables

# Accuracy & Detail 1: Radiative Corrections

**The scattered partons carry QCD and/or electric charges**

Will give off bremsstrahlung radiation, at wavelengths > 1/Q.

Probabilities can be computed order by order in perturbation theory




**Beware: scale hierarchies**

In a $t\bar{t}$ + jets event like this one, there are a lot of different scales

The top mass and pT values
Jet pT scales
Substructure scales?
Top (and W) decay scales
...

# The problem with fixed-order perturbation theory

**The relative accuracy of fixed-order pQCD is reduced for processes/ observables that involve scale hierarchies**

**Schematic example**

NNLO calculation of the rate of events passing a jet veto

$$\overbrace{F_0}^{\text{LO}} \;+\; \overbrace{\alpha_s(L^2 + L + F_1)}^{\text{NLO}} \;+\; \overbrace{\alpha_s^2(L^4 + L^3 + L^2 + L + F_2)}^{\text{NNLO}}$$

$L \propto \ln(p_{\perp\text{veto}^2} / Q^2_{\text{hard}})$

Total loss of predictivity if the veto scale $p_{\perp\text{veto}}$ is so small that $\alpha_s L^2 \sim 1$.

Reduced precision even for higher veto scales. Logs counteract naive suppression.

**Fixed-Order calculations most accurate for single-single scale problems**

Effective accuracy reduced for processes/observables with scale hierarchies

# Practical Example

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

→ Truncate at fixed order = LO, NLO, …

But beware the jet-within-a-jet-within-a-jet …

$\Longrightarrow$ 100 GeV can be "soft" at the LHC

## Example: SUSY pair production at LHC$_{14}$, with $M_{SUSY} \approx 600$ GeV

LHC - sps1a - m~600 GeV

Plehn, Rainwater, PS PLB645(2007)217

| FIXED ORDER pQCD | $\sigma_{tot}$[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 | $\sigma_{0j}$ | 4.83 | 5.65 | 0.286 | 0.502 | 1.30 |
| inclusive X + 1 "jet" → | $\sigma_{1j}$ | 2.89 | 2.74 | 0.136 | 0.145 | 0.73 |
| inclusive X + 2 "jets" → | $\sigma_{2j}$ | 1.09 | 0.85 | 0.049 | 0.039 | 0.26 |
| $p_{T,j} > 50$ GeV | $\sigma_{0j}$ | 4.83 | 5.65 | 0.286 | 0.502 | 1.30 |
| | $\sigma_{1j}$ | 5.90 | 5.37 | 0.283 | 0.285 | 1.50 |
| | $\sigma_{2j}$ | 4.17 | 3.18 | 0.179 | 0.117 | 1.21 |

(Computed with SUSY-MadGraph)

σ for X + jets much larger than naive factor-$\alpha_s$ estimate

σ for 50 GeV jets ≈ larger than total cross section
→ what is going on?

All the scales are high, $Q \gg 1$ GeV, so perturbation theory **should** be OK

# Perturbation theory for Multiscale Problems

**Fixed Order:**

$$\overbrace{F_0}^{\text{LO}} + \overbrace{\alpha_s(L^2 + L + F_1)}^{\text{NLO}} + \overbrace{\alpha_s^2(L^4 + L^3 + L^2 + L + F_2)}^{\text{NNLO}}$$

**Extend perturbation theory by resumming logs to all orders**

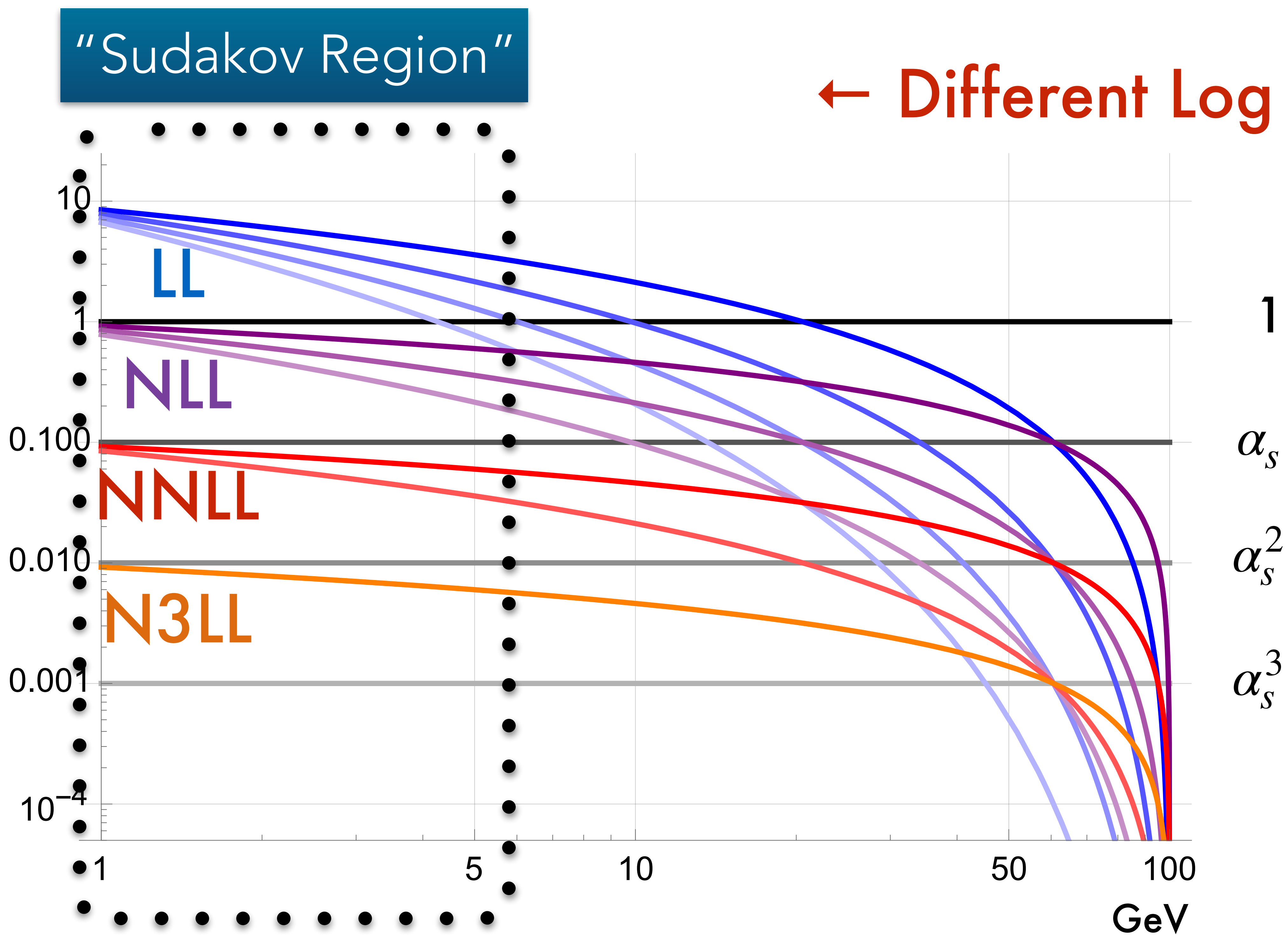
$$\left(\overbrace{F_0}^{\text{LO}} + \overbrace{\alpha_s F_1}^{\text{NLO}} + \overbrace{\alpha_s^2 F_2}^{\text{NNLO}}\right) \times \exp\left(\overbrace{-\alpha_s L^2}^{\text{DL}} \; \overbrace{-\alpha_s L - \alpha_s^2 L^3}^{\text{NDL}} \; \overbrace{-\alpha_s^2 L^2 - \alpha_s^3 L^4}^{\text{NNDL}} \right.$$
$$\left. \underbrace{-\alpha_s^2 L - \alpha_s^3 L^3 - \alpha_s^4 L^5}_{\text{N3DL}} \; \underbrace{-\alpha_s^3 L^2 - \alpha_s^4 L^4 - \alpha_s^5 L^6}_{\text{N4DL}}\right)$$

(Here using a slightly unconventional exponentiated "double-log" counting based on $\alpha_s L^2 \sim 1$ instead of $\alpha_s L \sim 1$

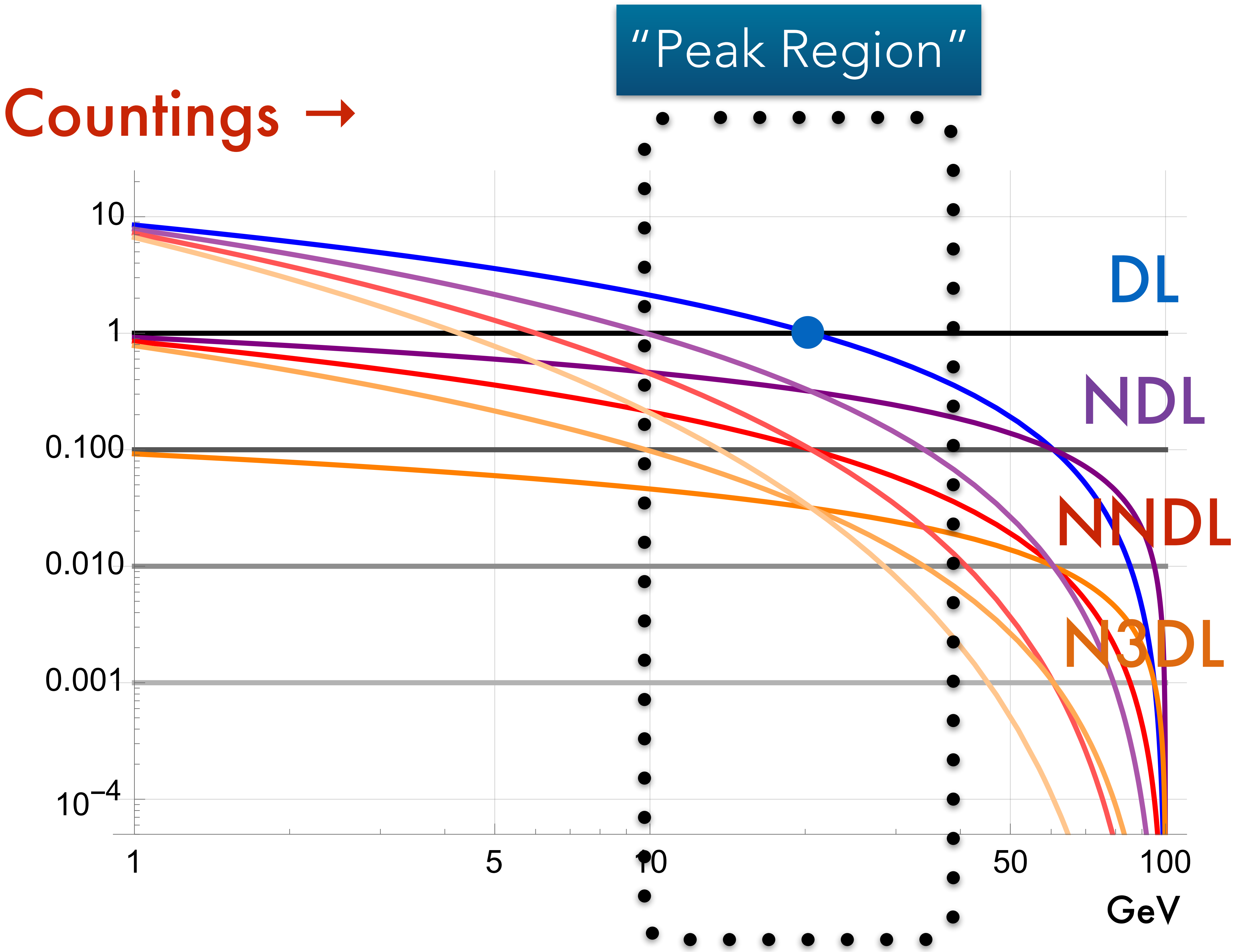
# What does this look like?

## Schematic Example: starting scale = 100 GeV

← Different Log Countings →



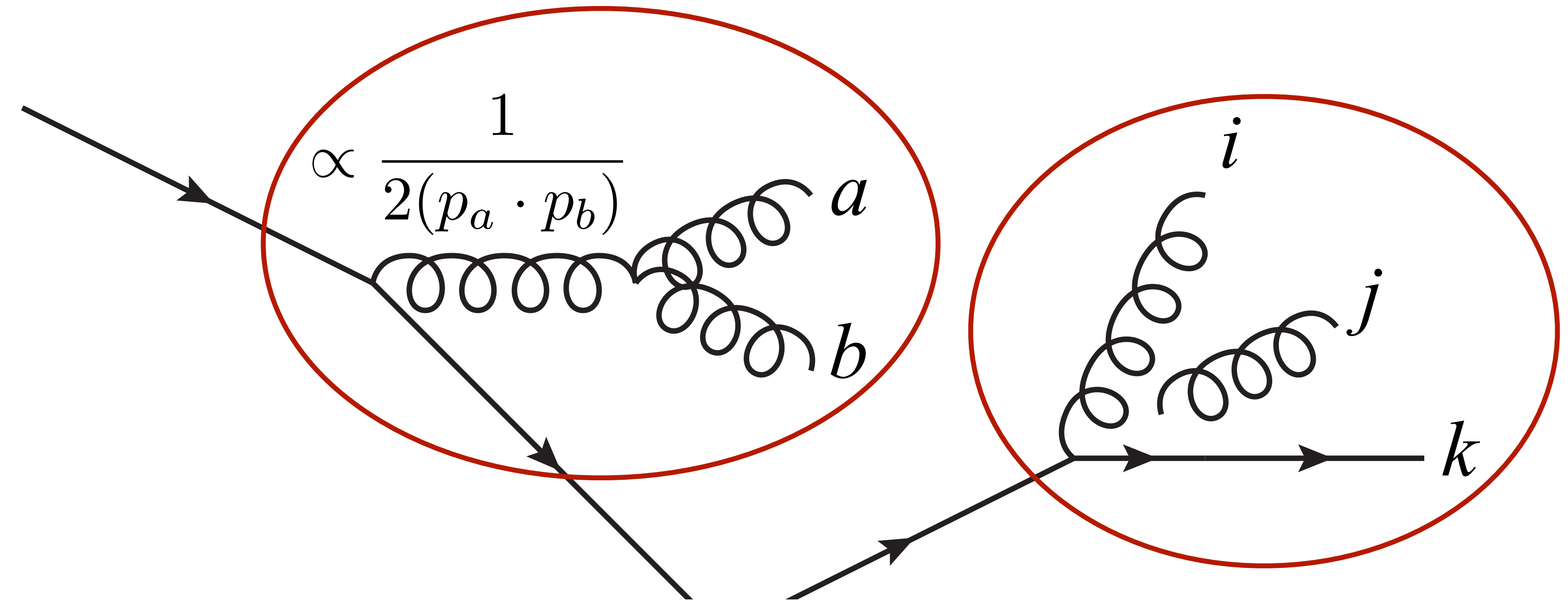

Conventional
("Caesar-style") log counting
Based on $\alpha_s L \sim 1$




Exponentiated
"double-log" counting
Based on $\alpha_s L^2 \sim 1$

# Universality of Bremsstrahlung Logs

Most bremsstrahlung is driven by **divergent propagators** → simple universal structure, independent of process details




**Amplitudes *factorise* in singular limits**

In **collinear** limits, we get so-called DGLAP splitting kernels:

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

In **soft** limits ($E_g/Q \to 0$), we get dipole factors (same as classical):

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

**These limits are not independent; they overlap in phase space.**

How to treat the two consistently has given rise to **many** individual approaches:

Angular ordering, angular vetos, dipoles, global antennae, sector antennae, …

# After 40 years of development, how far have we got?

**In fixed-order perturbative QCD (pQCD):**

LO → NLO → NNLO → N$^3$LO ⟵ State of the art for simple processes

(NLO, NNLO) State of the art for complex processes

Translates to accuracies of order a few per cent or better

**For all-orders showers, it makes no sense to count "orders"**

Instead, we count "logarithms" (arising from $1/Q^2$ propagators on previous slide integrated over phase spaces ∝ $\mathrm{d}Q^2$)

**Until very recently:** (NB: several ways to count logs, here using conventional $\alpha_s L \sim 1$ counting)

**Angular ordering** (80s): (N)LL

Modern **dipole/antenna** showers: (N)LL

**Colour flow** also still "leading colour"

(with small refinements)

**Last remaining "leading" frontiers in pQCD**

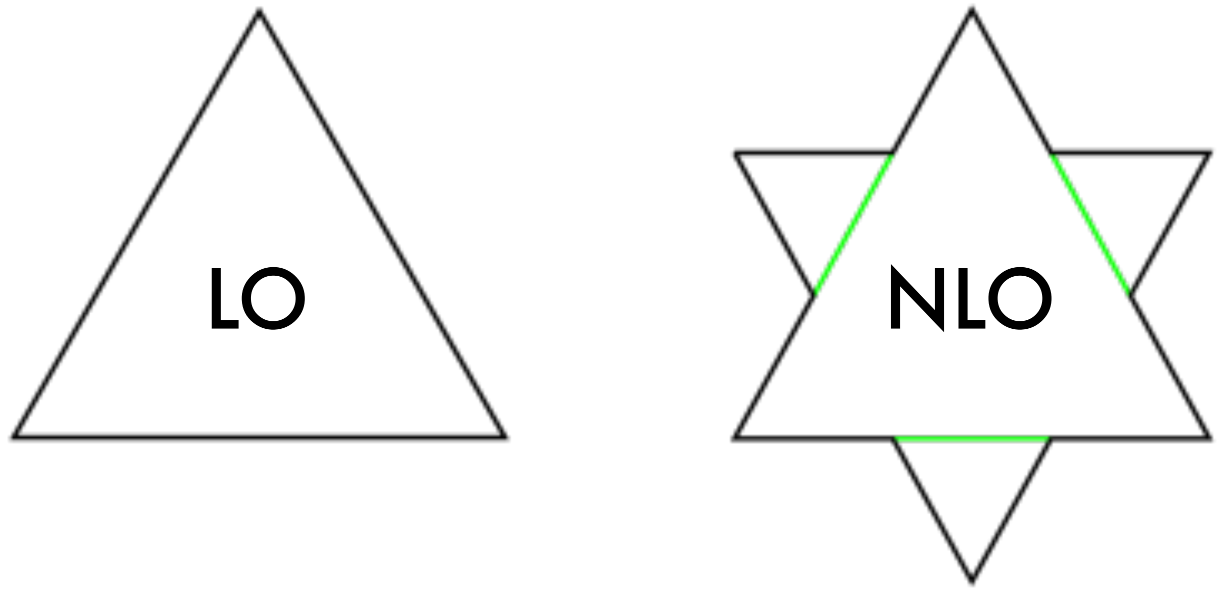
**Many new efforts over the past decade!**

(Notably, PanScales, here in Oxford)

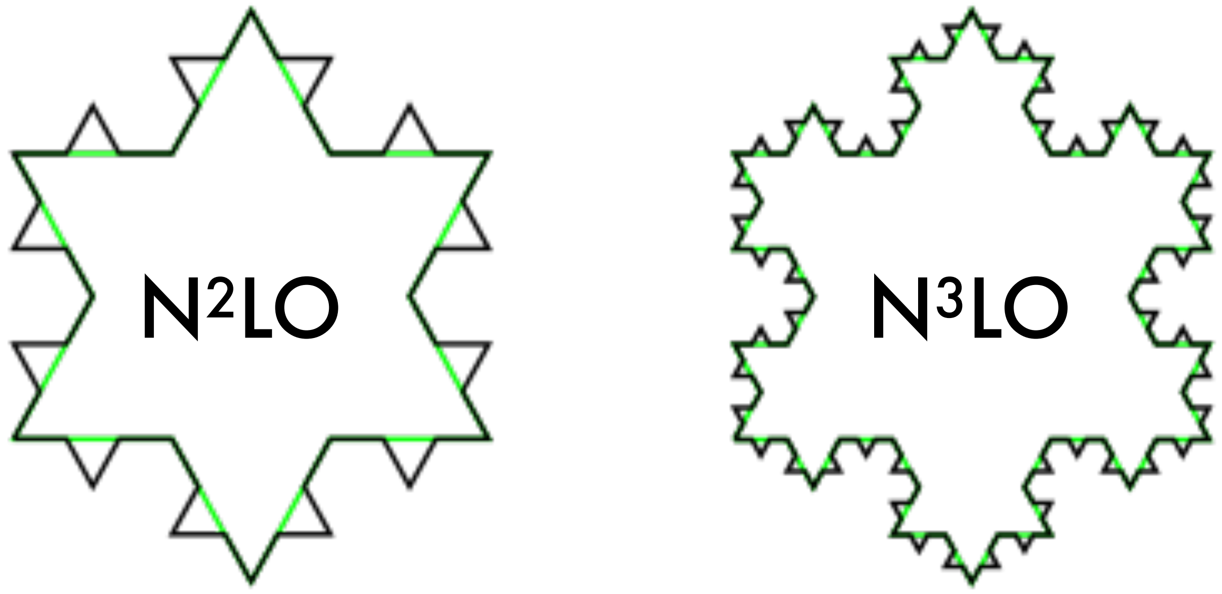
# Why is that hard?

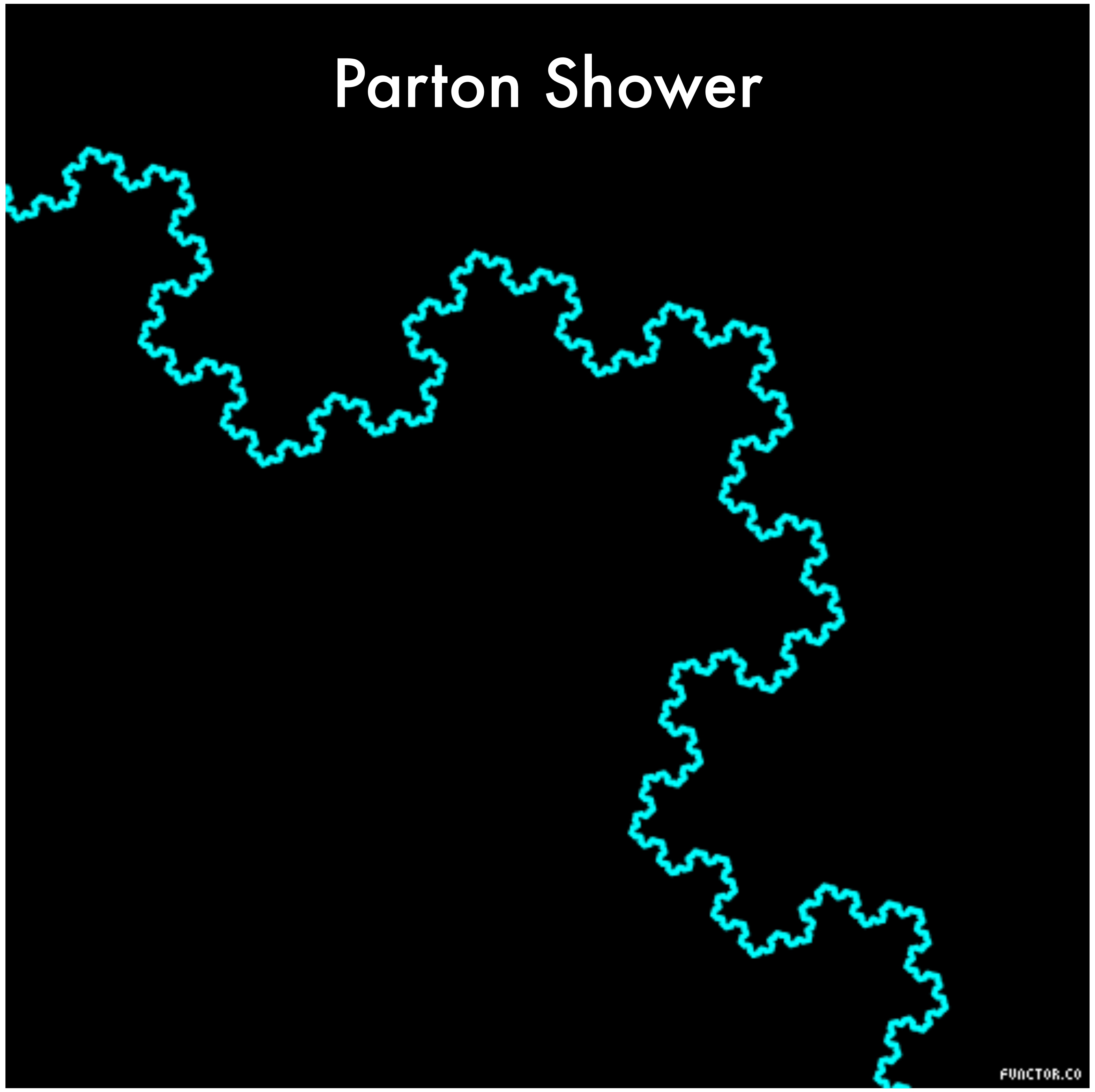
Simplified analogy:

Fixed Order




Using a "Koch snowflake" as a stand-in for perturbation theory



# Some Complications

**Showers are quantum stochastic processes,** not deterministic rules

**Several branching types:**

$q \to qg, g \to gg, \ldots$

On multiparton phase spaces

(+ overlaps/double-counting/dead zones)

**Colour and spin structure**

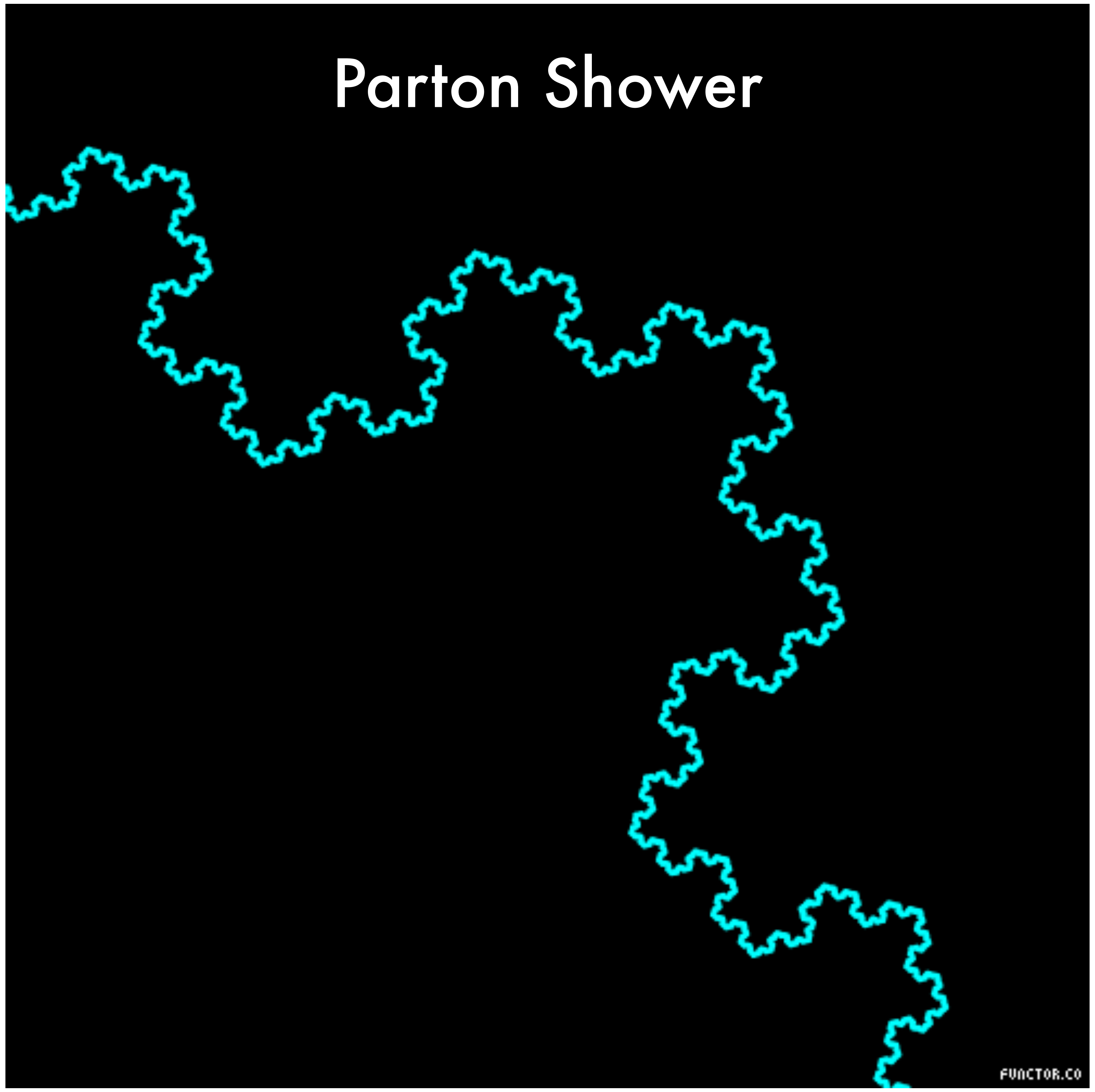
+ Interference effects

**Universality**

Start from *any* hard process ~ starting shape

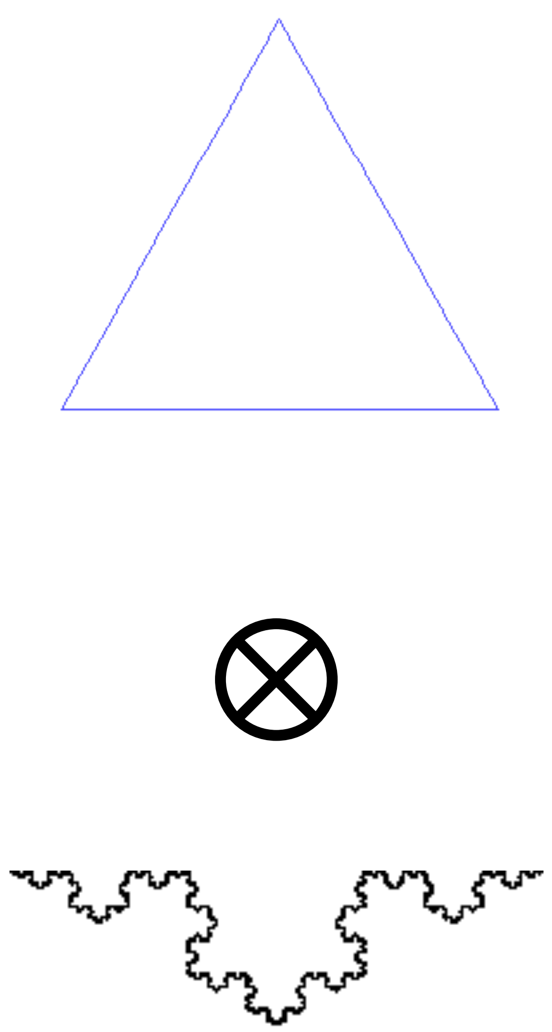
**Scaling violation** (QCD is not conformal)

**Exact Conservation Laws**




**Unitarity:** need *perfect* cancellations between (singular) real and virtual corrections.

# Well Established for **First Few Orders**



**Matching, Merging, and Matrix-Element Corrections**

Essentially: use exact rule for first few orders; then let shower approximation take over

- LO matrix-element corrections (➤ Sjöstrand et al., 80s)
- LO merged calculations (➤ CKKW, Lönnblad, '00s + more recent)
- NLO matched calculations (➤ MC@NLO, POWHEG '00s)

**State of the art (for LHC phenomenology right now):**

**Merging several NLO + PS matched calculations** (➤ UNLOPS, FxFx, …)

**Intense activity;** here just using "my" projects as representative examples:

- NNLO + PS matching (Proof of concept ➤ Campbell, Hoeche, Li, Preuss, PS, '21)
- Iterated LO matrix-element corrections (➤ soon…)
- Iterated NLO matrix-element corrections (➤ in a while 🐊)
- Limiting factors are **complexity growth** & **shower accuracy**

# **Complexity Growth:** a bottleneck for matching and merging

**In conventional** ("global") **showers, each phase-space point receives contributions from many possible branching "histories"** (="clusterings")

~ sum over (singular) diagrams $\Longrightarrow$ full singularity structure ✅

Number of Histories for $n$ Branchings (Starting from a single $q\bar{q}$ pair)

| | $n=1$ | $n=2$ | $n=3$ | $n=4$ | $n=5$ | $n=6$ | $n=7$ |
|---|---|---|---|---|---|---|---|
| CS Dipole | 2 | 8 | 48 | 384 | 3840 | 46080 | 645120 |
| Global Antenna | 1 | 2 | 6 | 24 | 120 | 720 | 5040 |

Fewer partial-fractionings, but still factorial growth

**For CKKW-L style merging:** (incl UMEPS, NL3, UNLOPS, ...)

Need to take all contributing shower histories into account.

Bottleneck at high multiplicities (+ high code complexity)

# Sector Showers

## New in PYTHIA (8.3): Sectorized Antenna Showers in Vincia

PartonShowers:Model = 2 Brooks, Preuss & PS 2003.00702 (+ Lopez-Villarejo & PS 1109.3608)

## Sector antennae: no partial-fractioning of any singularities.

Divide the *n*-gluon phase space up into *n* non-overlapping sectors, inside each of which **only the most singular** (~ "classical") kernel is allowed to contribute.

**Kosower**, hep-ph/9710213
hep-ph/0311272 (+ Larkoski & Peskin 0908.2450, 1106.2182)

## Lorentz-invariant def of "most classical" gluon based on "ARIADNE $p_T$":

Gustafson & Pettersson, NPB 306 (1988) 746

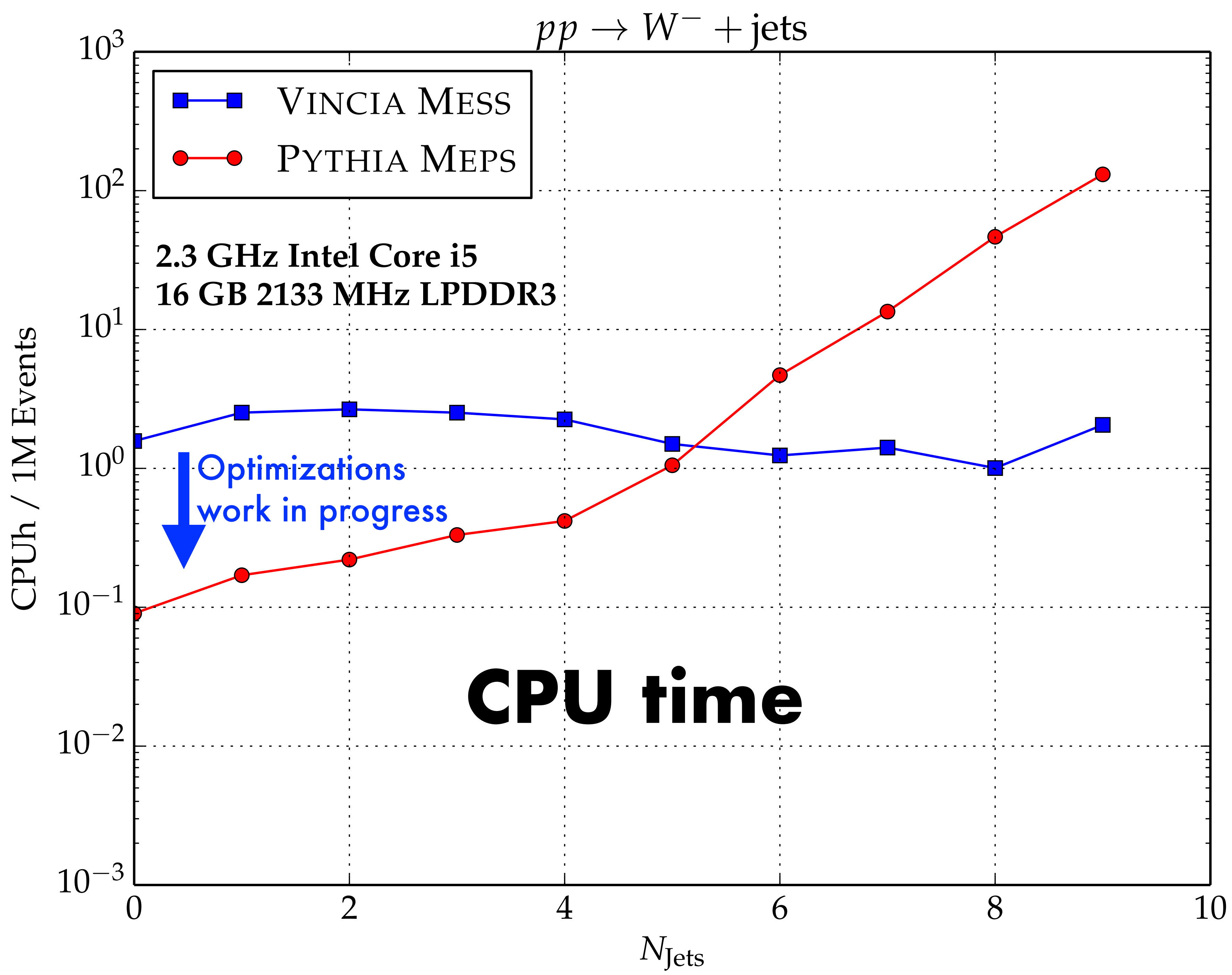
$$p_{\perp j}^2 = \frac{s_{ij}s_{jk}}{s_{ijk}}$$ with $s_{ij} \equiv 2(p_i \cdot p_j)$ (+ generalisations for heavy-quark emitters)

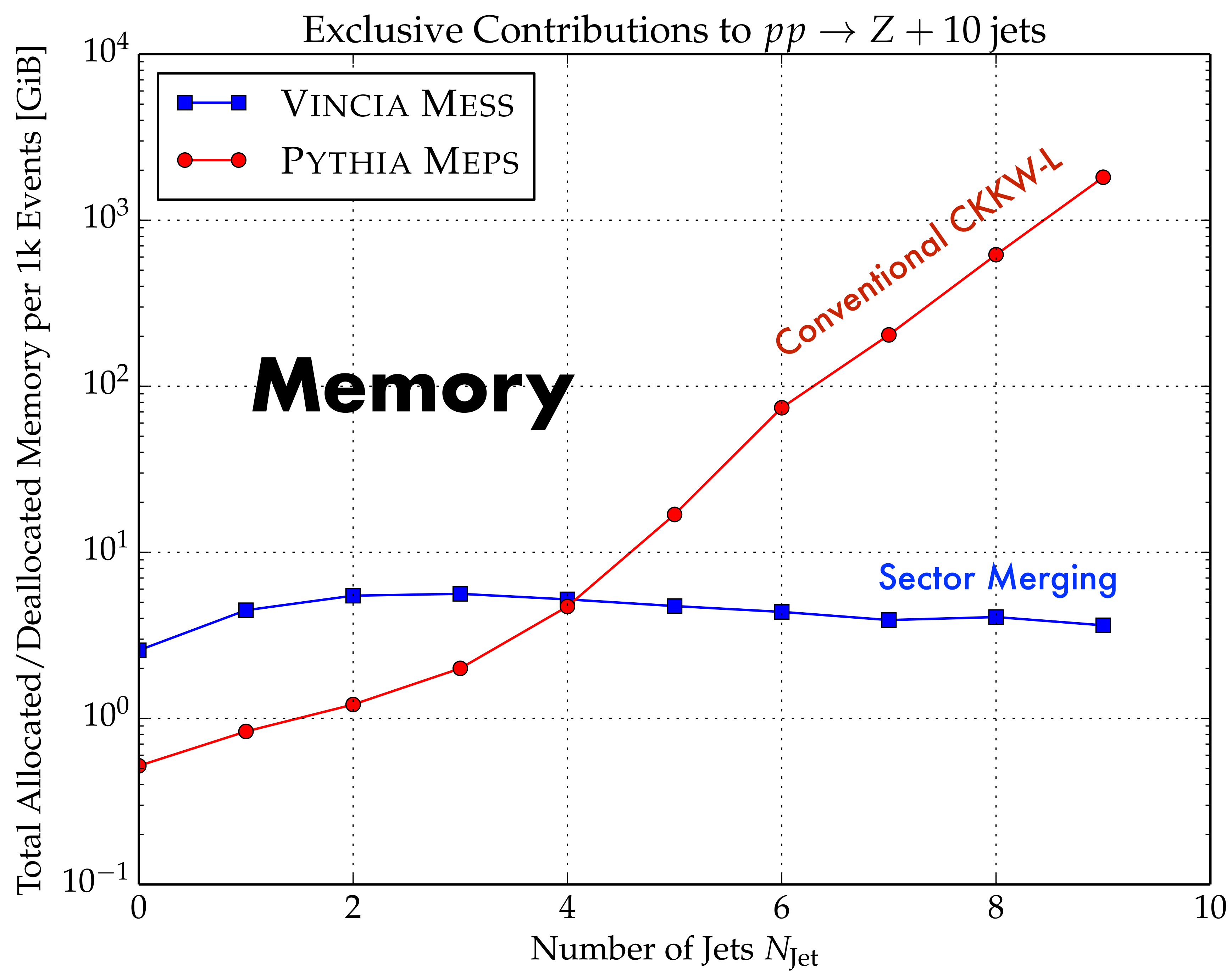
## Achieves (N)LL with a single history.

Factorial → **constant scaling** in number of gluons.

Generalisation to $g \to q\bar{q} \Longrightarrow$ factorial in # of same-flavour quark pairs.

# **New:** Sectorized CKKW-L Merging in Pythia 8.306




*Brooks & Preuss, "Efficient multi-jet merging with the VINCIA sector shower", 2008.09468*

## Ready for serious applications

Work ongoing to optimise baseline algorithm.

Discovery Project (22): **NNLO** matching, $2 \to 4$ sector antennae, **NLO** interfaces, …

**Vincia tutorial:** http://skands.physics.monash.edu/slides/files/Pythia83-VinciaTute.pdf

# The Final Frontier: **Shower Accuracy**

## 2nd-order radiative corrections

Iterating **only** single emissions, one after the other, will fail to properly describe multi-emission interferences & correlations

Iterating single **and** double emissions ➜ **problematic overlaps, double counting**

## VINCIA sector approach

**➜ Clean separation of phase space** into non-overlapping "iterated" (2→3) and "direct" (2→4) sectors

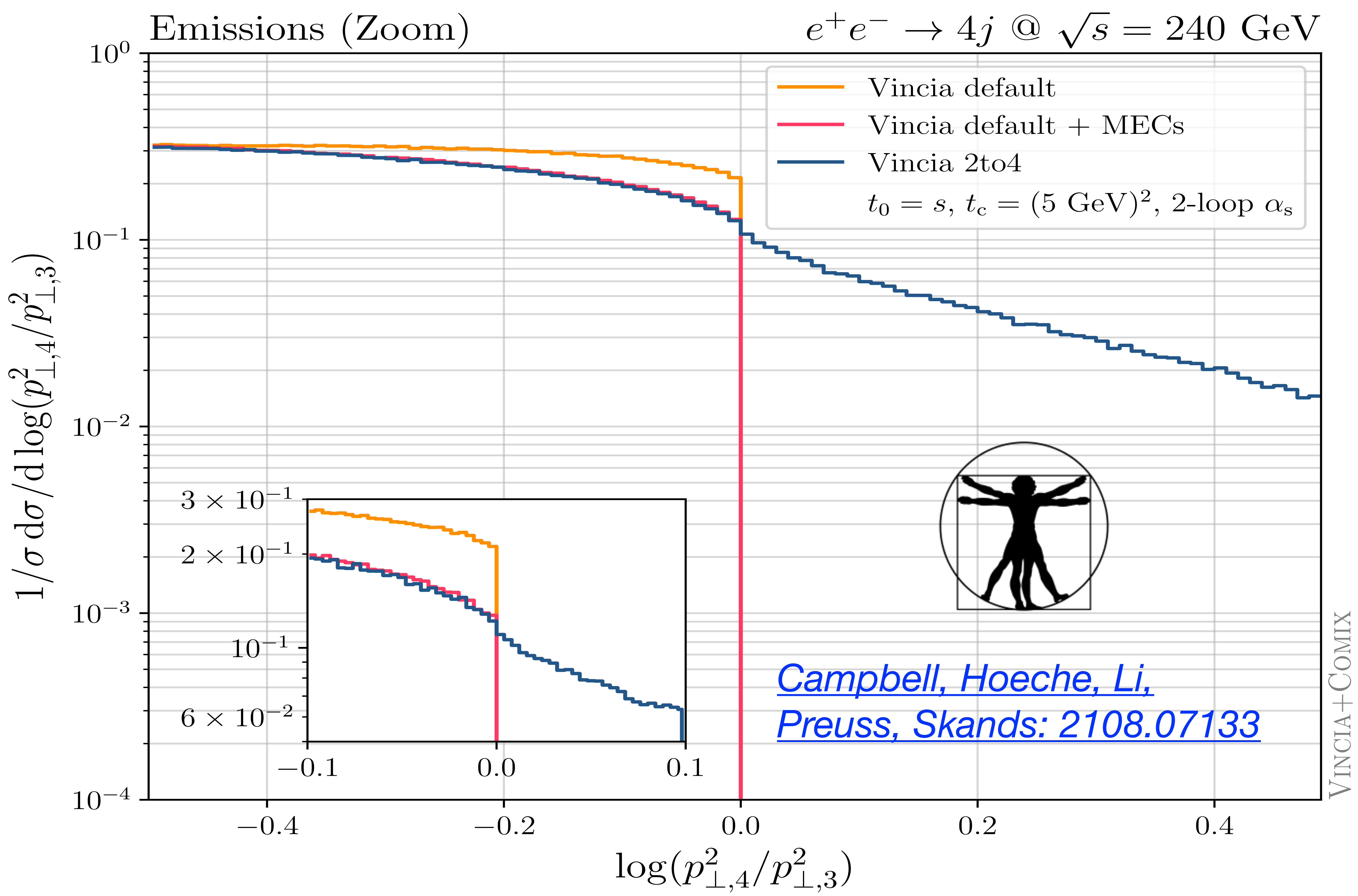
## Proof of concept @ NNLO:

Campbell, Hoche, Li, Preuss, Skands 2108.07133

**Goal:** iterate full structure ➜ shower

## Highly active research field:

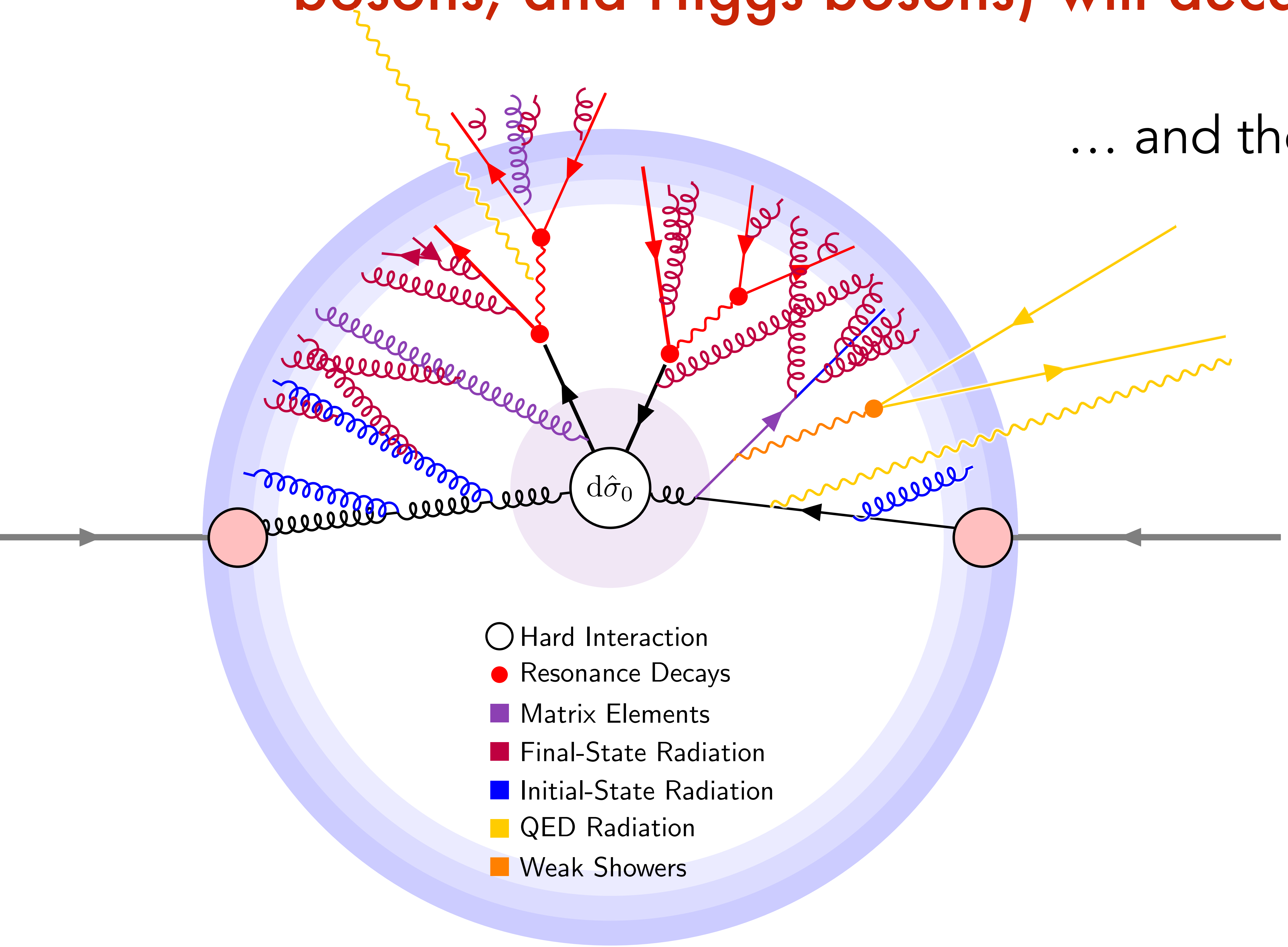
Alternative approaches also hotly pursued: E.g.: **PanScales** (Oxford).



# Next: Resonance Decays

Unstable resonances (top quarks, Z/W bosons, and Higgs bosons) will decay

… and their decay products will shower

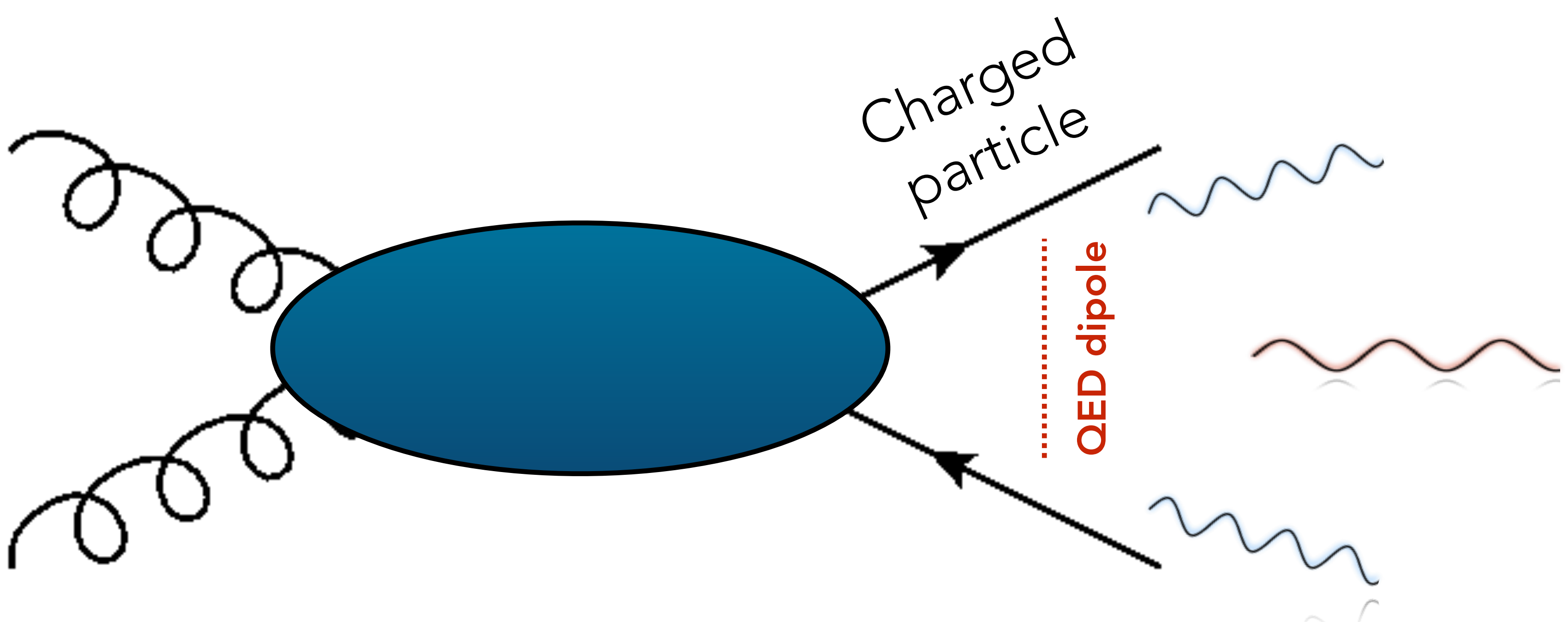


# **2.** How does a process with unstable particles radiate?

First step = factorise production and decay(s)

**Treat production as if all produced particles were stable**

"Radiation in Production"



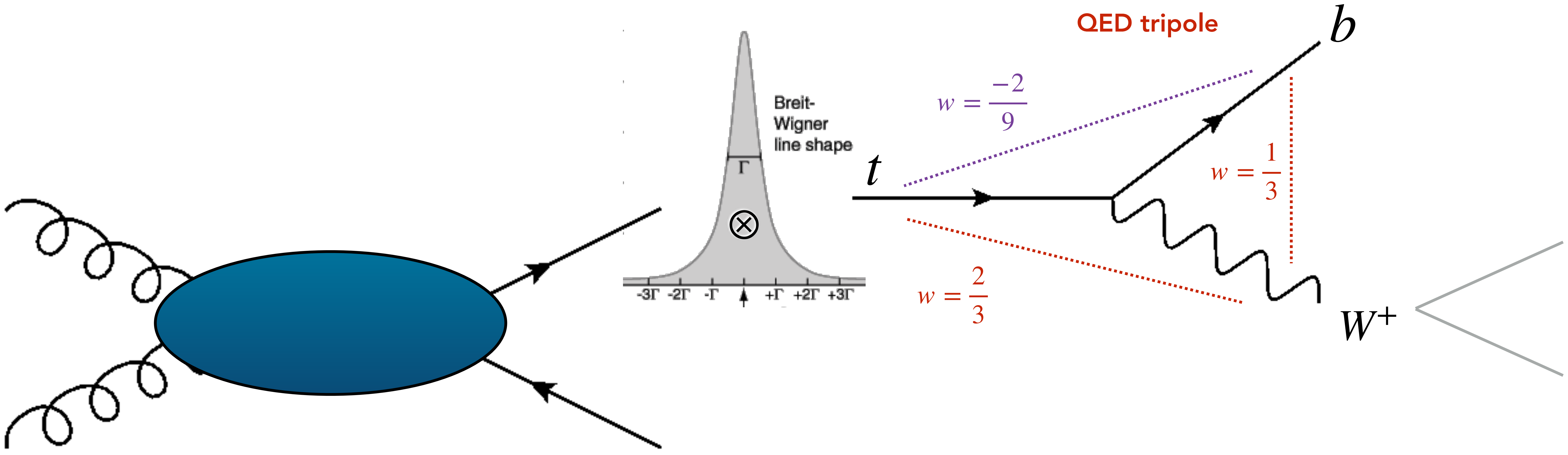

Recoil effects do not change the invariant mass of each particle

**=> Preserves the Breit-Wigner shape**

# Radiation in Decays

## Conventional "sequential" treatment

Treat each decay (sequentially) as if alone in the universe

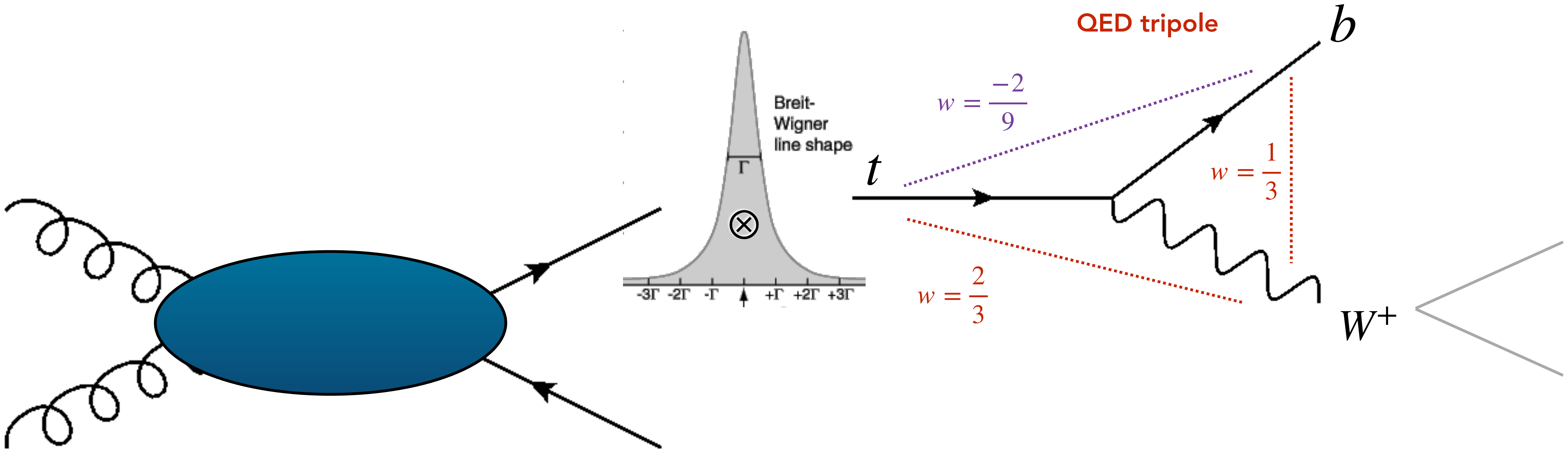



Shower explicitly preserves total invariant mass *inside* each system

**=> Preserves the Breit-Wigner shape**

## Conventional "sequential" treatment

Treat each decay (sequentially) as if alone in the universe

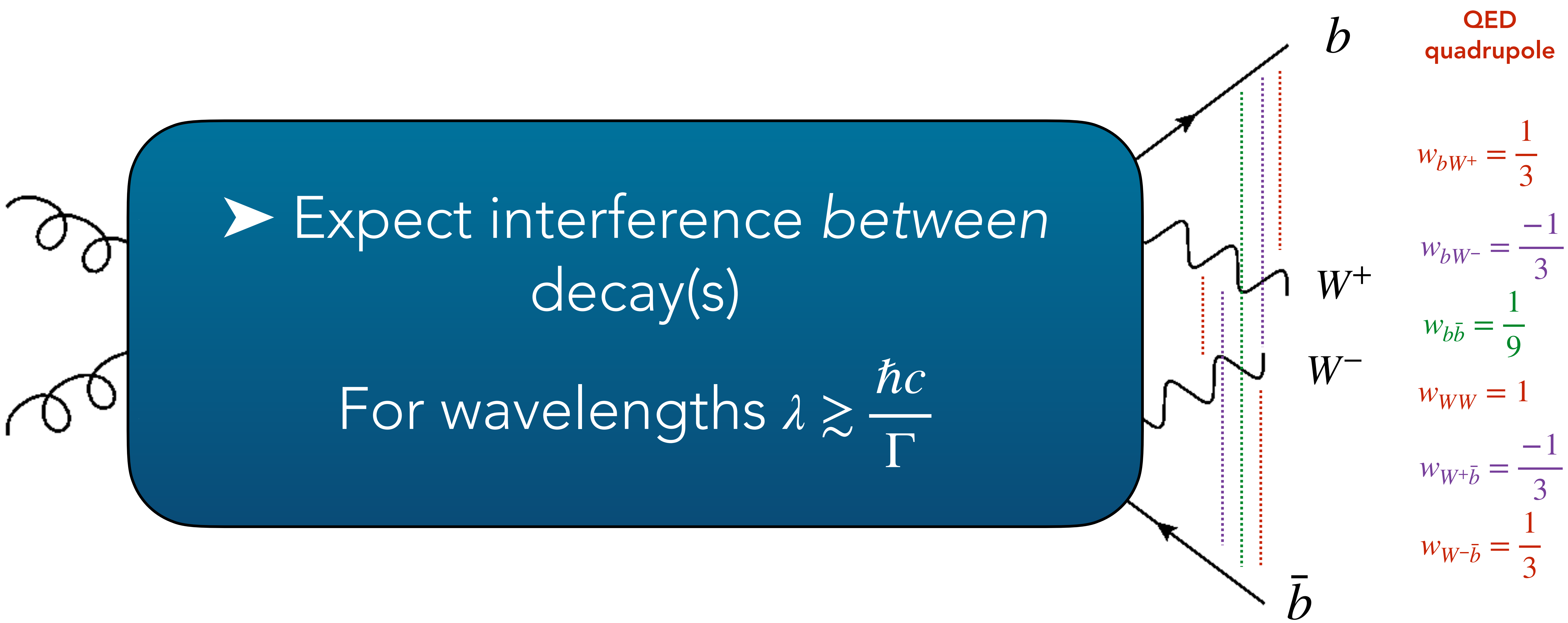



**Question:**

**What about radiation at energies $E_\gamma \lesssim \Gamma_t$ (and $E_\gamma \lesssim \Gamma_W$)?**

## What does a long-wavelength photon see?

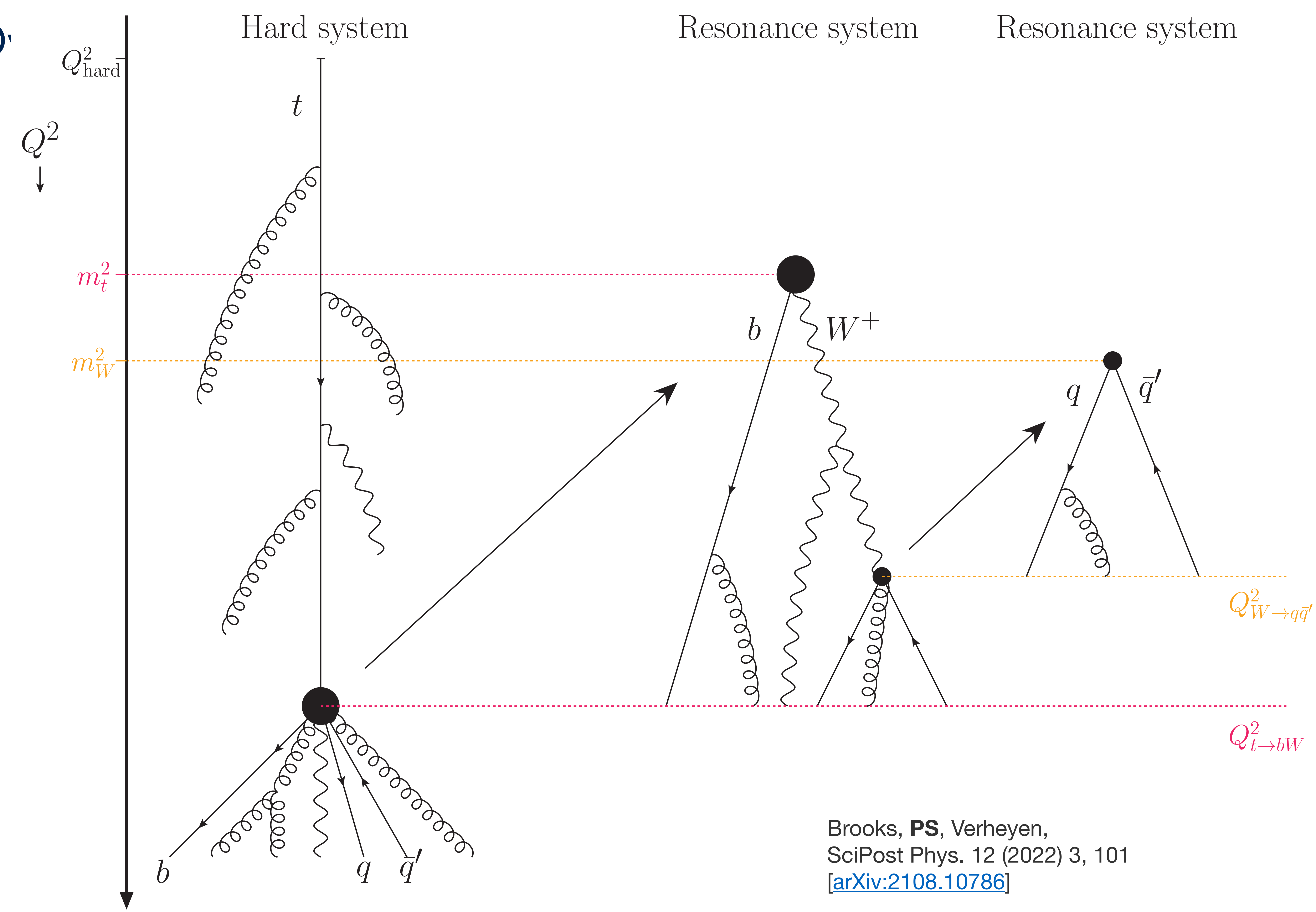
It should not be able to resolve the (short-lived) intermediate state




**Should affect radiation spectrum, for energies $E_\gamma \lesssim \Gamma$**

+ Interferences and recoils *between* systems => ***non-local BW modifications***

# Interleaved Resonance Decays (VINCIA)

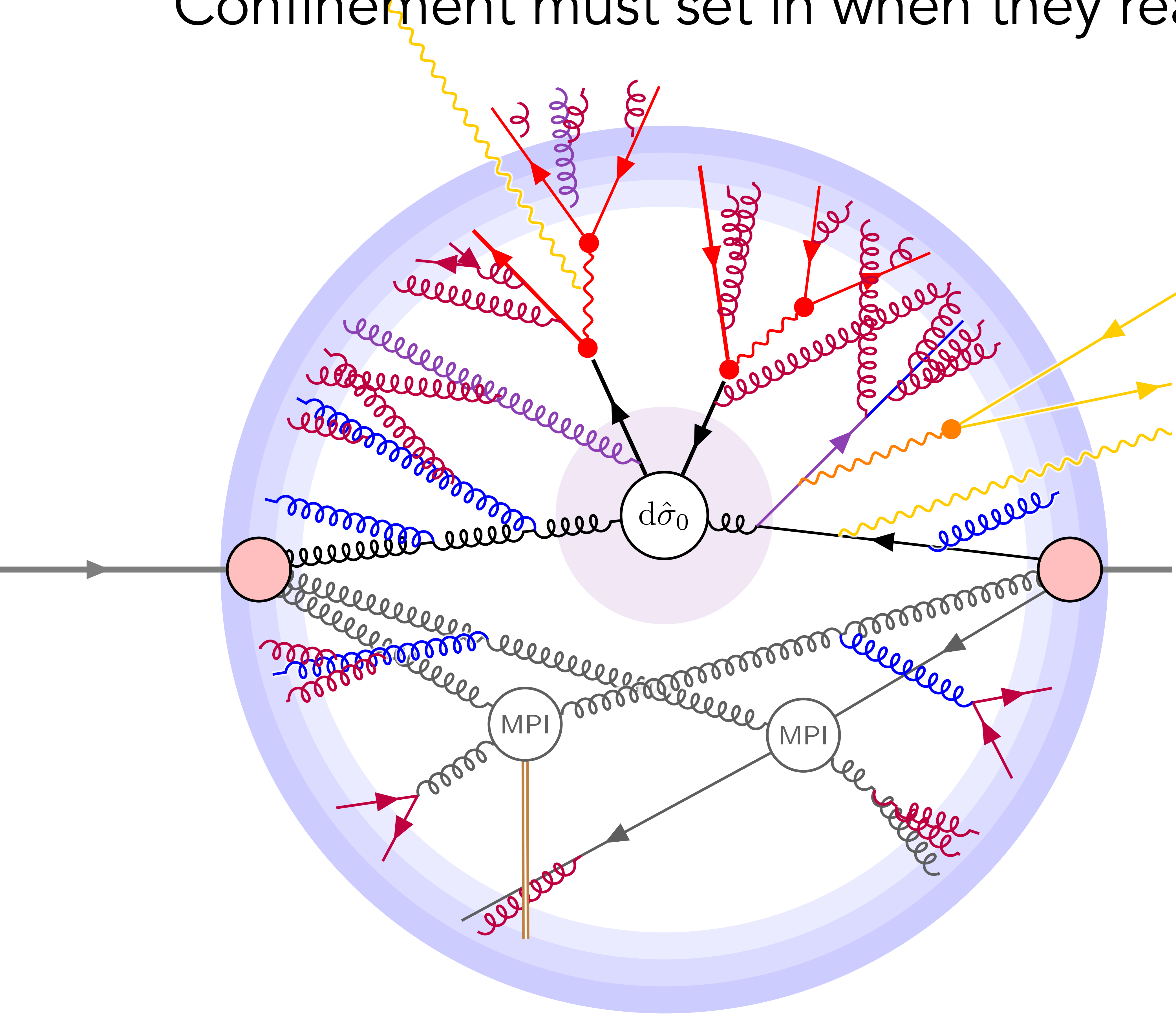



Brooks, **PS**, Verheyen,
SciPost Phys. 12 (2022) 3, 101
[arXiv:2108.10786]

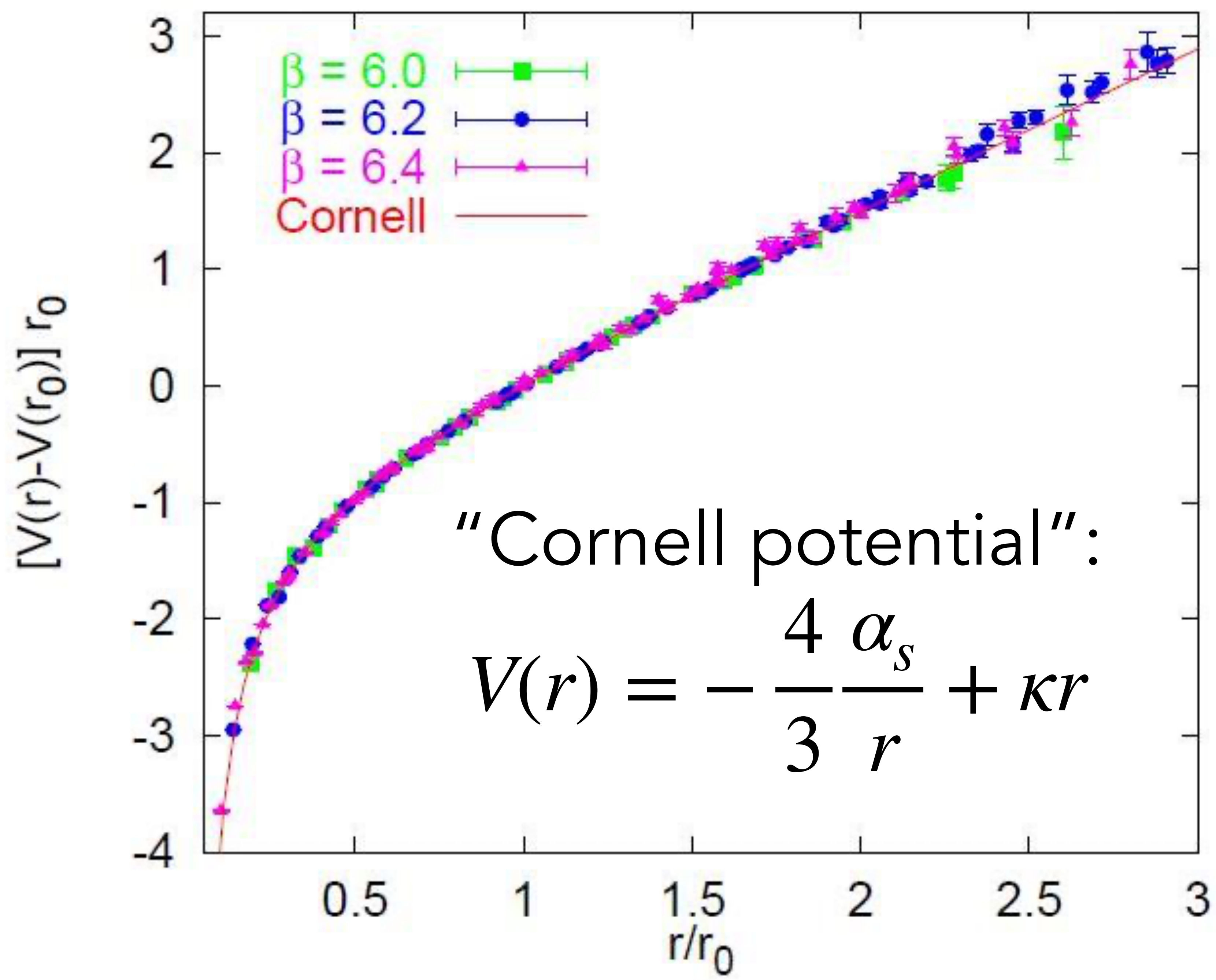
# Confinement

Event structure still in terms of (colour-charged) quarks & gluons

Confinement must set in when they reach O(1fm) relative distances.

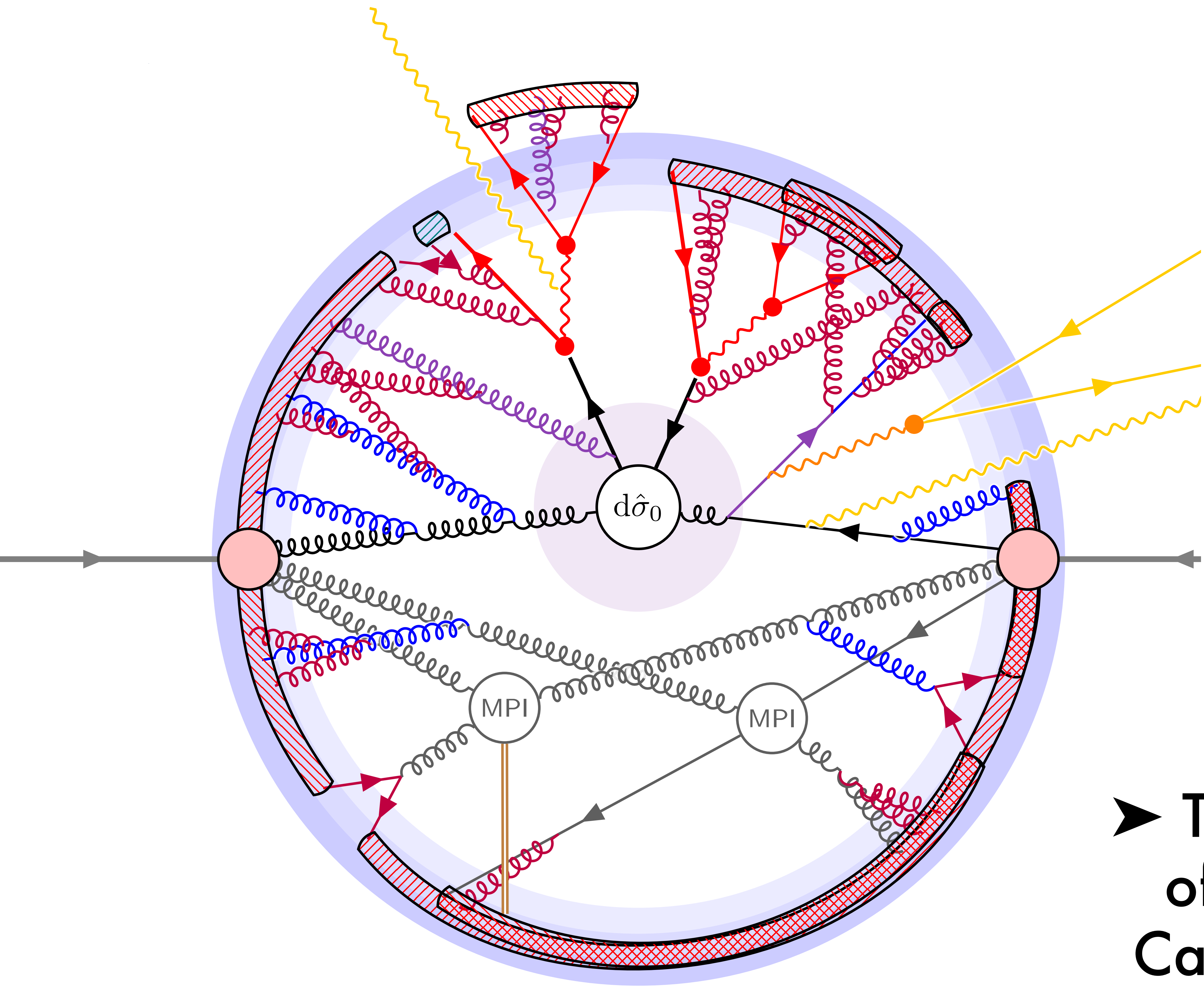



**Between a single quark-antiquark pair, we know the long-distance behaviour is a linear potential**




$r_0 = 0.5\text{fm}$ $\kappa \sim 0.9\,\text{GeV/fm}$

What physical system has a linear potential? A string.



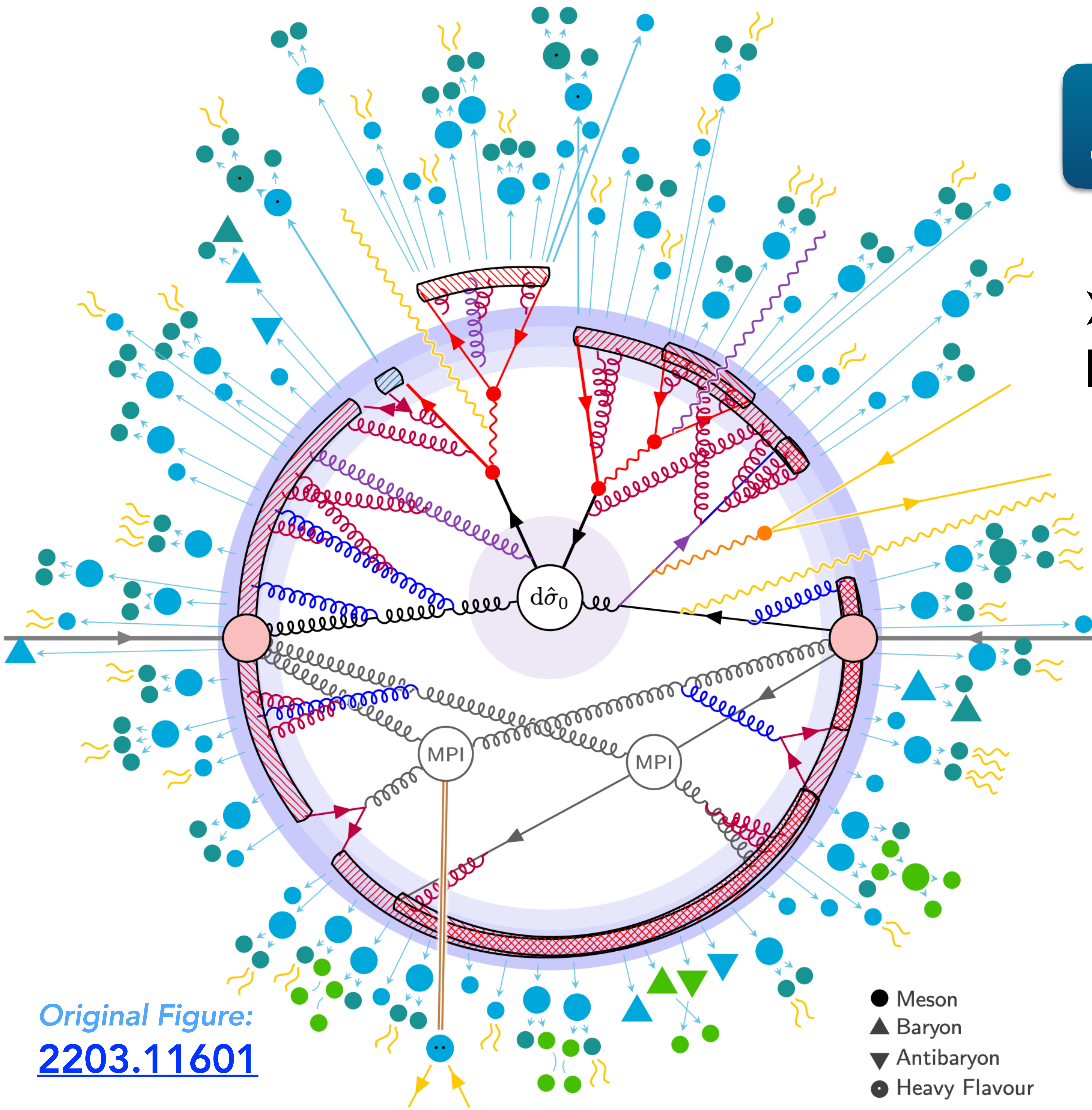

This is the basis for the **Lund String Fragmentation Model**

*Andersson, Gustafson, Pettersson, Sjöstrand, … ('78 - '83)*

A *comparatively* simple 1+1 dimensional model of massless relativistic strings, with tension $\kappa \sim 1$ GeV/fm

➤ **The signature feature of the Pythia Monte Carlo event generator**

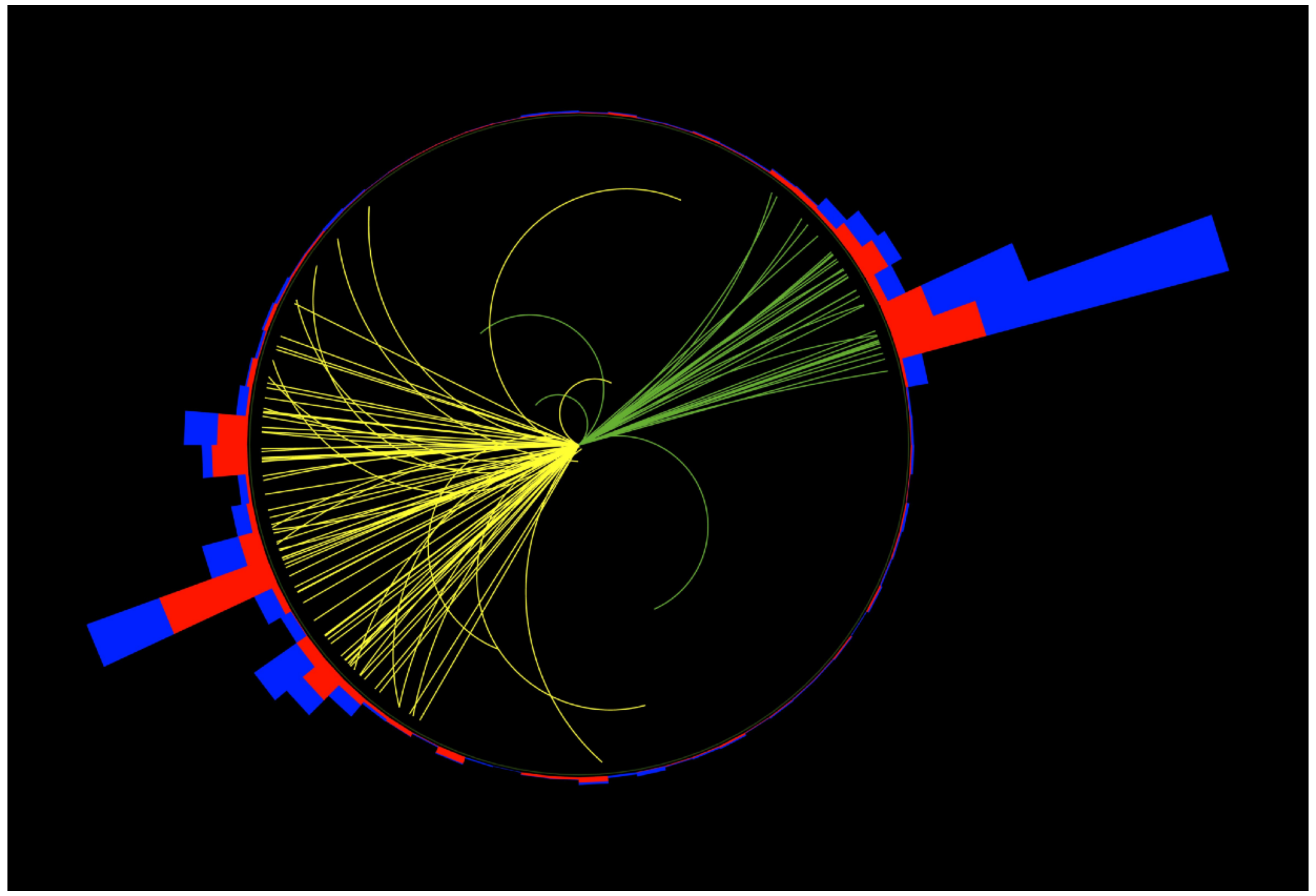
# Hadronisation



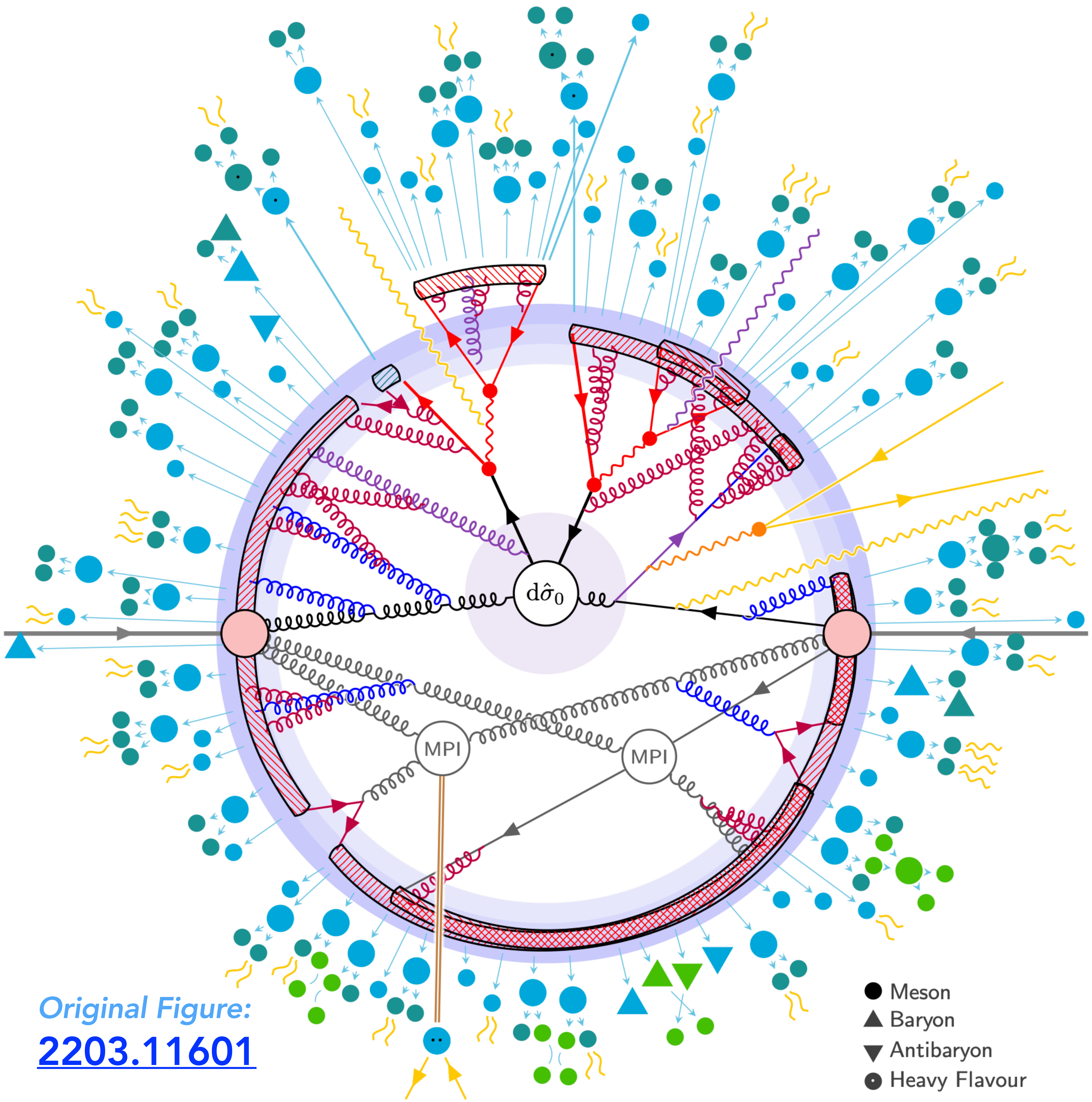

*Original Figure:*
[2203.11601]

More about strings and recent exciting discoveries at LHC in my next seminar Nov 30

➤ **We finally have a model that can be compared to experiments …**



# Anatomy of an LHC Collision




*Original Figure:*
[2203.11601]

- Hard Interaction
- Resonance Decays
- MECs, Matching & Merging
- FSR
- ISR*
- QED
- Weak Showers
- Hard Onium
- Multiparton Interactions
- Beam Remnants*
- Strings
- Ministrings / Clusters
- Colour Reconnections
- String Interactions
- Bose-Einstein & Fermi-Dirac
- Primary Hadrons
- Secondary Hadrons
- Hadronic Reinteractions

*(*: incoming lines are crossed)*