Modeling an LHC Collision

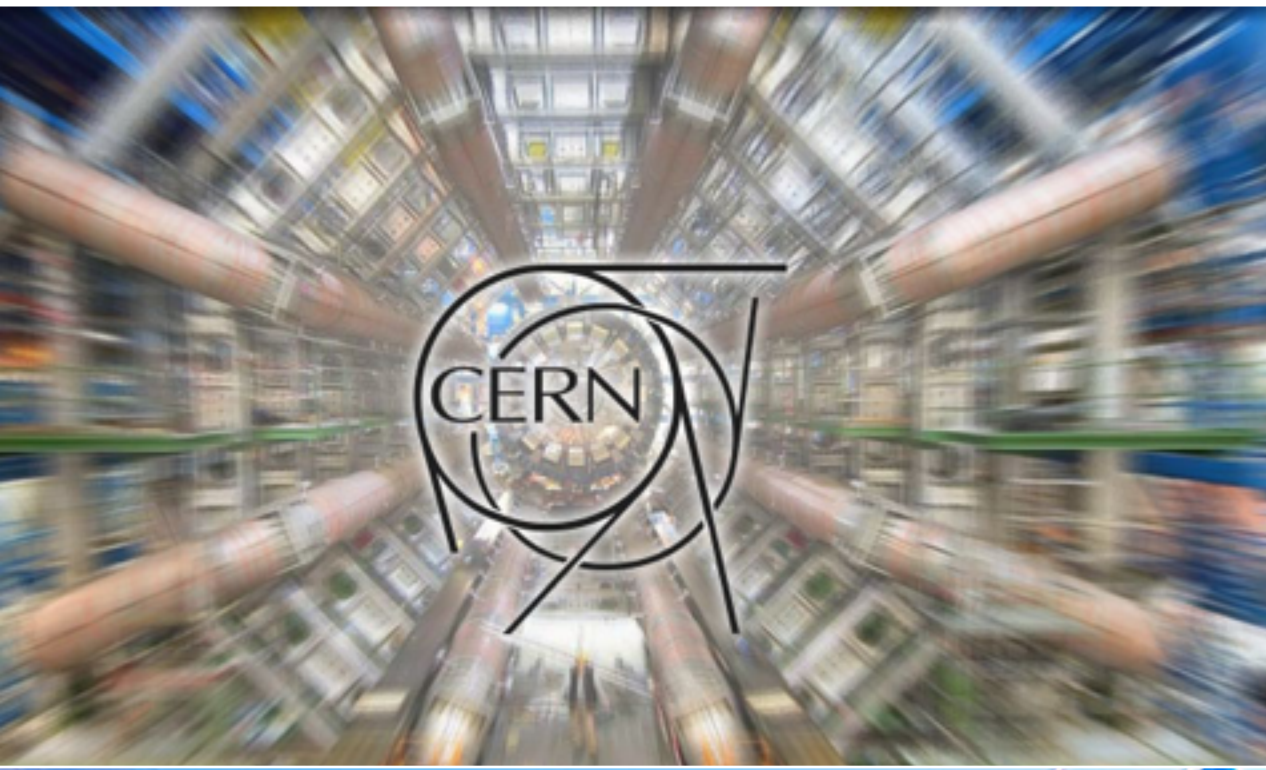
Peter Skands (CERN Theoretical Physics Dept)

Physics Colloquium
Monash University, Melbourne, 21 November, 2013

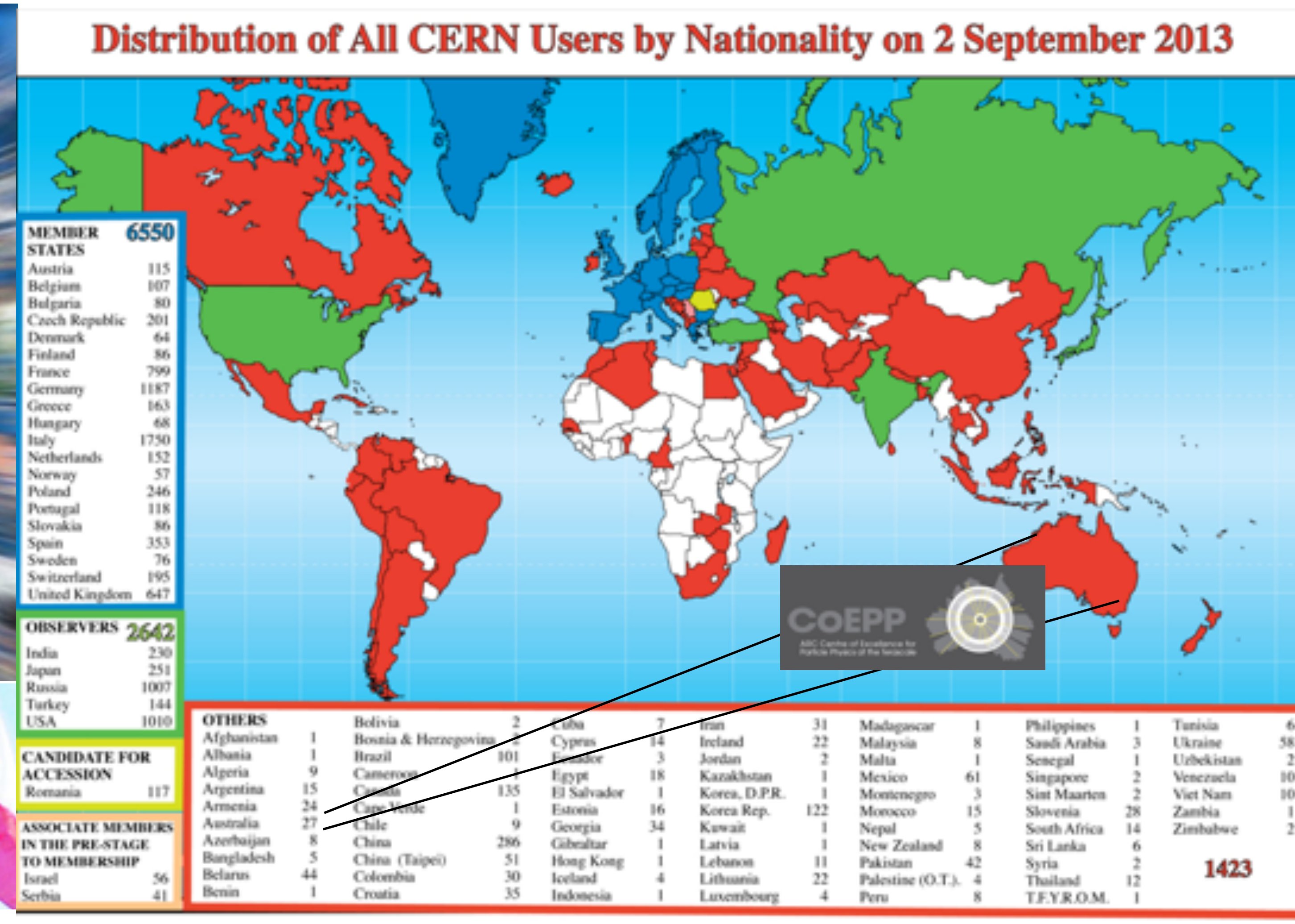
CERN: European Organization for Nuclear Research

20 European Member States and around 60 other countries

~ 10 000 scientists work at CERN



Flags of CERN's Member States



theory group: ~ 20 staff, 40 fellows, 700 visitors/yr

What goes on at CERN - what this talk is about
The Large Hadron Collider (LHC)

The ATLAS Experiment at the LHC

ATLAS collision event at 7 TeV from March 2010

http://atlas.ch

ATLAS EXPERIMENT

LHC Collision at 7 TeV
ATLAS, March 2010

What’s the aim?

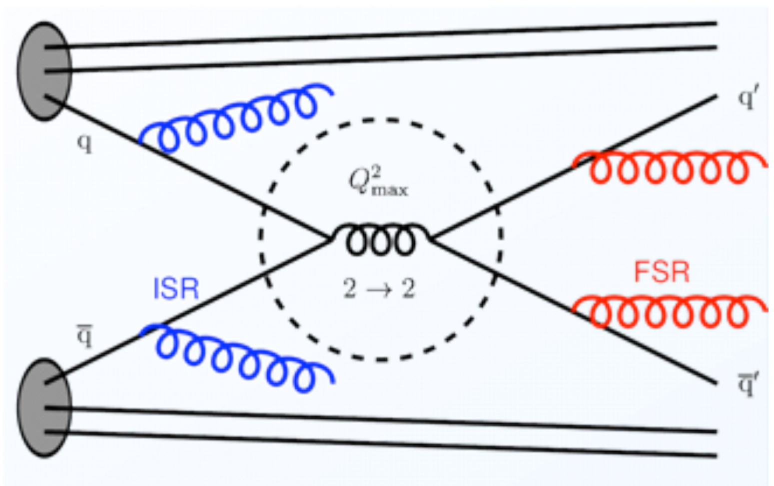
Theory

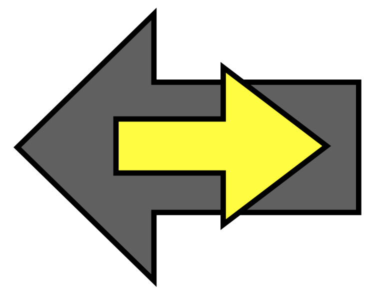
Experiment

Adjust this to agree with this

- Many interesting **dynamical phenomena** under active investigation (e.g., higher-order quantum corrections, hadronization, electroweak physics, diffraction, hadron structure, …)
- Strong indications from both theory and experiment, that the mathematical structure of the **Standard Model is incomplete**
- **New physics, where art thou?** (So far, physics at LHC looks ~ SM)
- We are now going into an era of **high statistics and high precision**

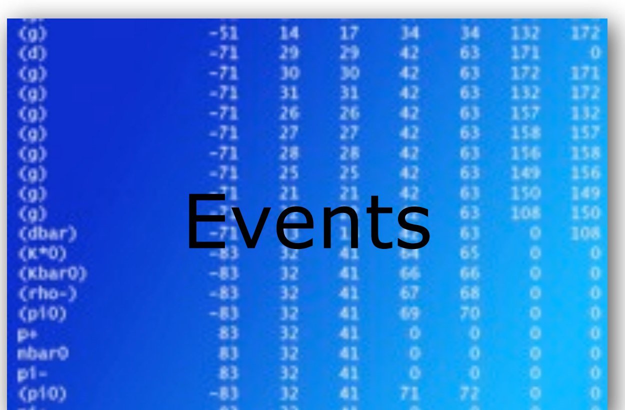
Collider Calculations



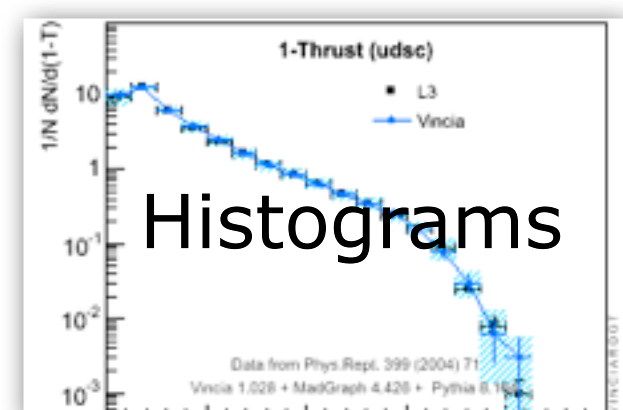


Calculate Everything ≈ solve QFT* → requires compromise!

Start from lowest-order perturbation theory,
Include the 'most significant' corrections
→ complete events



connect with the observable world
↔
of hadrons, photons, and leptons



+ *Quantum Mechanics: only physical observables are meaningful!*

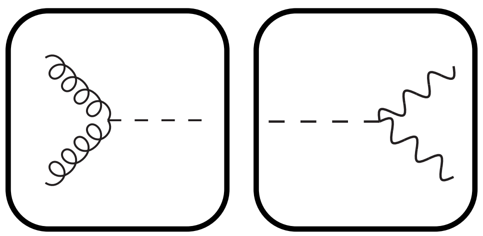
*QFT = Quantum Field Theory

Organizing the Calculation

Divide and Conquer → Split the problem into many (nested) pieces

+ Quantum mechanics → Probabilities → Random Numbers

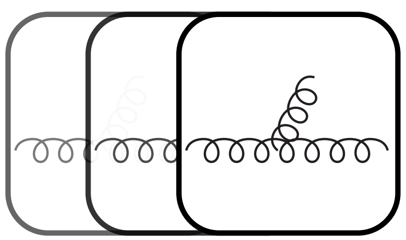
$$\mathcal{P}_{\mathrm{event}} = \mathcal{P}_{\mathrm{hard}} \otimes \mathcal{P}_{\mathrm{dec}} \otimes \mathcal{P}_{\mathrm{ISR}} \otimes \mathcal{P}_{\mathrm{FSR}} \otimes \mathcal{P}_{\mathrm{MPI}} \otimes \mathcal{P}_{\mathrm{Had}} \otimes \ldots$$



Hard Process & Decays:

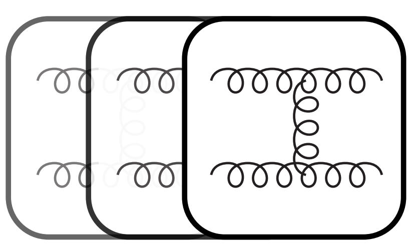
The basic hard process. E.g., $gg \to H^0 \to \gamma\gamma$

→ Sets highest resolvable scale: Q_{MAX}



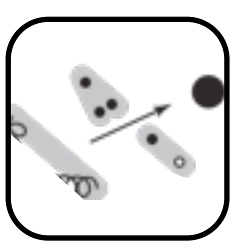
Initial- & Final-State Radiation (ISR & FSR):

Bremsstrahlung, driven by differential evolution equations, dP/dQ^2, as function of resolution scale; run from Q_{MAX} to ~ 1 GeV



MPI (Multi-Parton Interactions)

Protons contain lots of partons → can have additional (soft) parton-parton interactions → Additional (soft) "Underlying-Event" activity

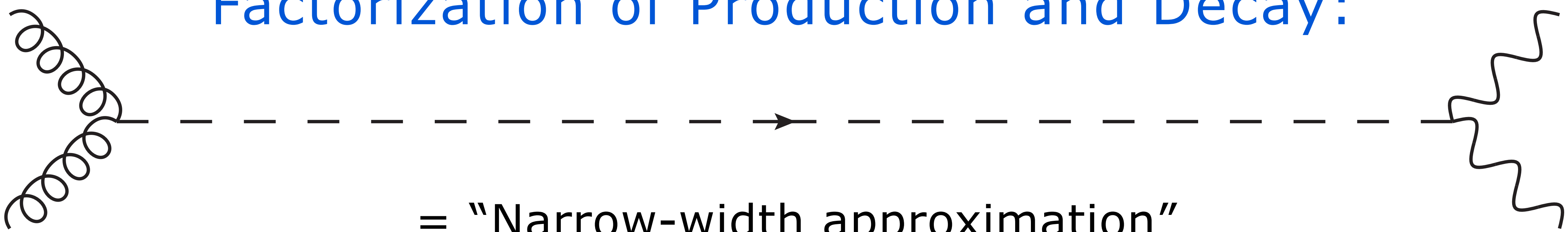


Hadronization

Non-perturbative modeling of parton → hadron transition

Factorization

Factorization of Production and Decay:

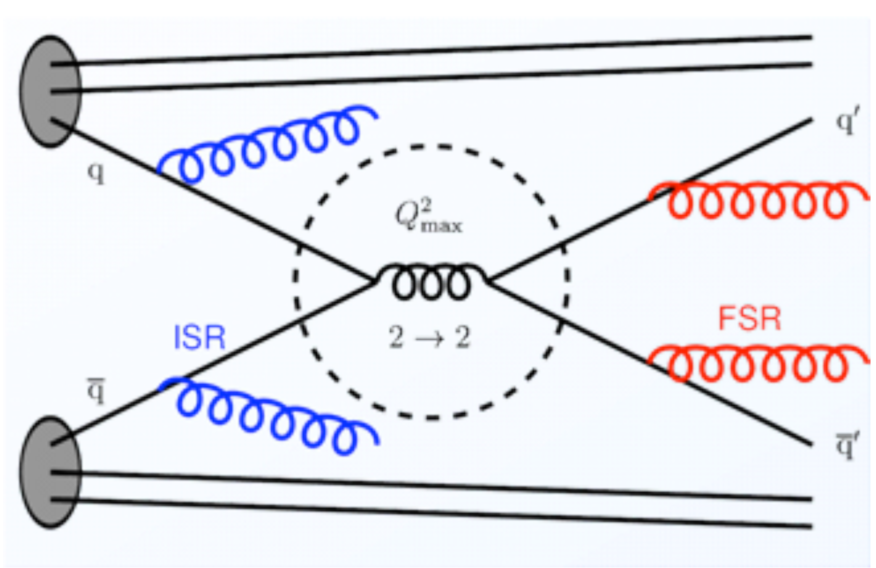


= "Narrow-width approximation"

Valid up to corrections Γ/m → breaks down for large Γ

More subtle when colour/charge flows *through* the diagram

Factorization of Long and Short Distances



Scale of fluctuations inside a hadron

~ Λ_{QCD} ~ 200 MeV

Scale of hard process ≫ Λ_{QCD}

→ proton looks "frozen"

Instantaneous snapshot of long-wavelength structure, independent of nature of hard process

Quantum Corrections

Standard Paradigm: consider a single physical system; a single physical process

- Explicit solutions (to given perturbative order)
  - Standard-Model: typically NLO or NNLO
  - Beyond-SM: typically LO or NLO
- Limited generality

LO: Leading Order (Born)
NLO = Next-to-LO, …

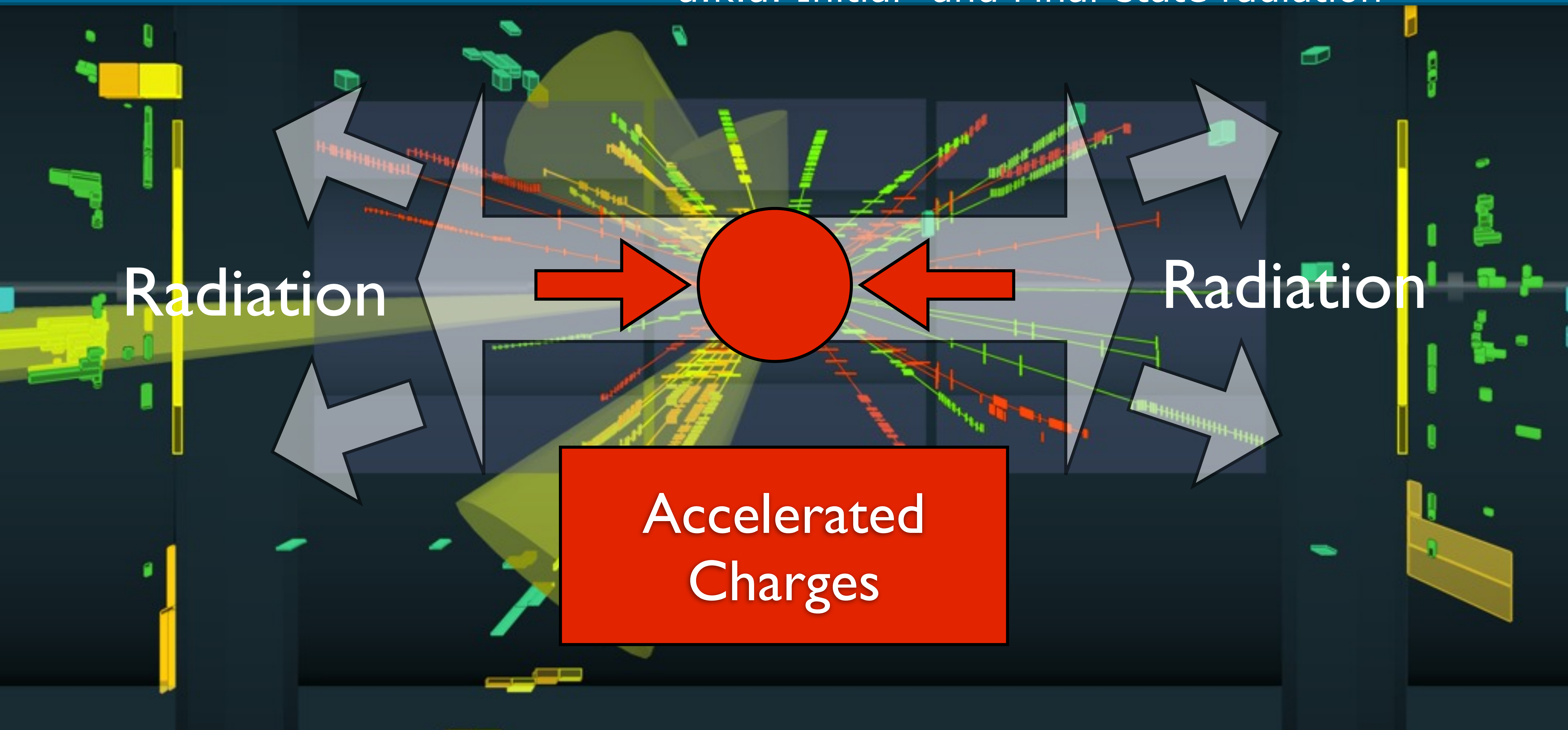
Event generators: consider *all possible physical processes* (within perturbative QFT)

- Approximate solutions
  - Process-dependence = subleading correction (will return to this)
- Maximum generality
  - Emphasis is on universalities; physics
  - Common property of all processes is, for instance, limits in which they factorize!

Bremsstrahlung

cf. equivalent-photon approximation
Weiszäcker, Williams
~ 1934

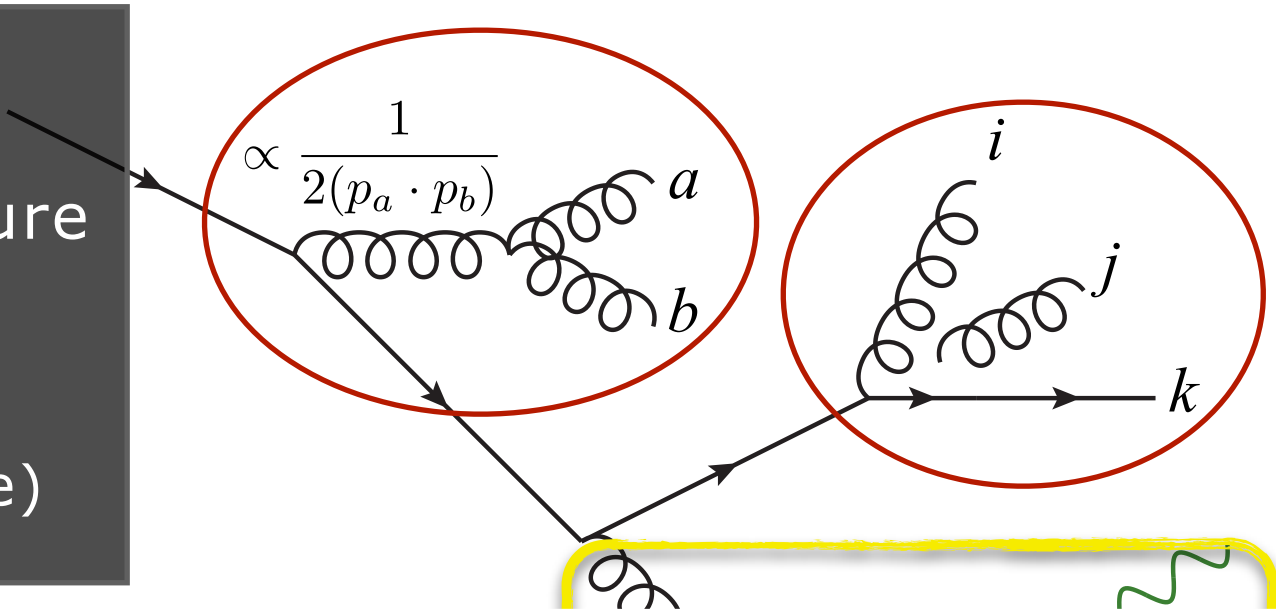
a.k.a. Initial- and Final-state radiation



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

Jets ≈ Fractals

- **Most bremsstrahlung** is driven by divergent propagators → simple structure
- **Amplitudes factorize in singular limits** (→ universal "conformal" or "fractal" structure)



Partons ab → "collinear":

P(z) = DGLAP splitting kernels, with z = energy fraction = $E_a/(E_a+E_b)$

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

Gluon j → "soft":

Coherence → Parton j really emitted by (i,k) "colour antenna"

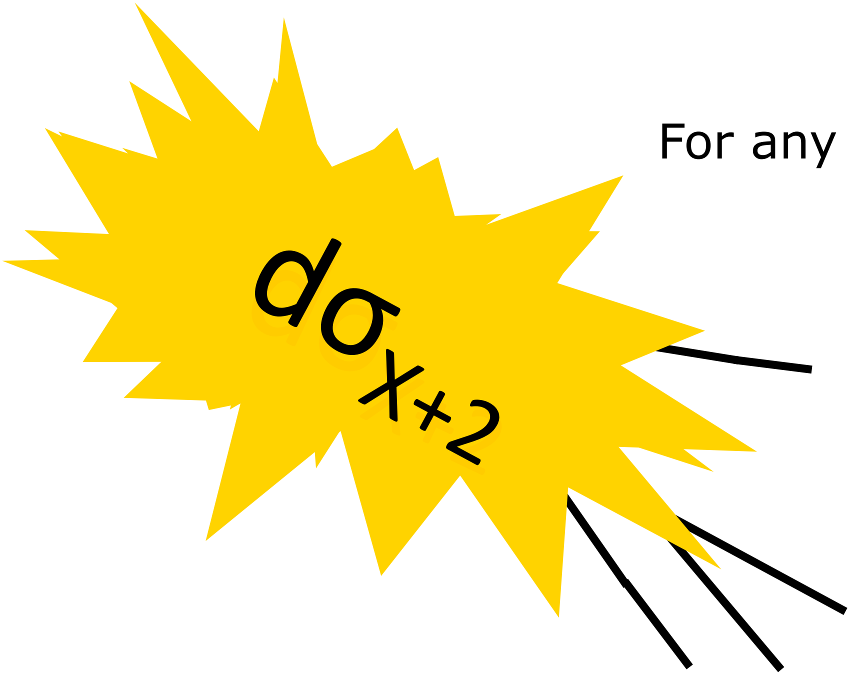
$$|\mathcal{M}_{F+1}(\ldots,i,j,k\ldots)|^2 \overset{j_g\to 0}{\to} g_s^2 \mathcal{C} \frac{(p_i \cdot p_k)}{(p_i \cdot p_j)(p_j \cdot p_k)} |\mathcal{M}_F(\ldots,i,k,\ldots)|^2$$

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

Can apply this many times → nested factorizations

See: PS, *Introduction to QCD*, TASI 2012, arXiv:1207.2389

Practical Examples



For any basic process $d\sigma_X$ = ✓ (calculated process by process)

$$d\sigma_{X+1} \sim N_C 2 g_s^2 \frac{ds_{i1}}{s_{i1}} \frac{ds_{1j}}{s_{1j}} d\sigma_X \quad ✓$$

$$d\sigma_{X+2} \sim N_C 2 g_s^2 \frac{ds_{i2}}{s_{i2}} \frac{ds_{2j}}{s_{2j}} d\sigma_{X+1} \quad ✓$$

$$d\sigma_{X+3} \sim N_C 2 g_s^2 \frac{ds_{i3}}{s_{i3}} \frac{ds_{3j}}{s_{3j}} d\sigma_{X+2} \quad \ldots$$

Singularities: mandated by gauge theory
Non-singular terms: process-dependent

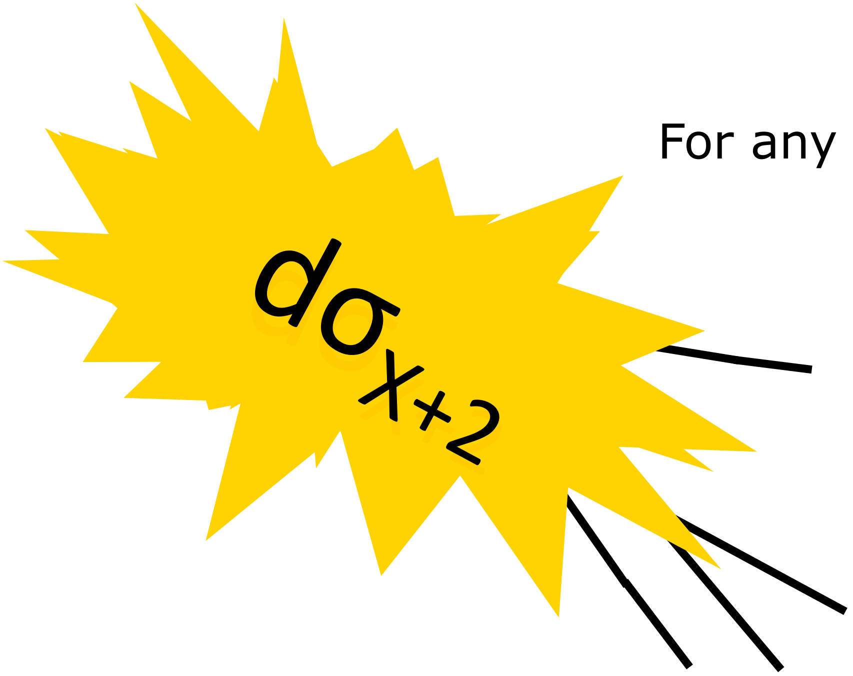
SOFT COLLINEAR

$$\frac{|\mathcal{M}(Z^0 \to q_i g_j \bar{q}_k)|^2}{|\mathcal{M}(Z^0 \to q_I \bar{q}_K)|^2} = g_s^2 \, 2C_F \left[\frac{2 s_{ik}}{s_{ij} s_{jk}} + \frac{1}{s_{IK}} \left(\frac{s_{ij}}{s_{jk}} + \frac{s_{jk}}{s_{ij}} \right) \right]$$

$$\frac{|\mathcal{M}(H^0 \to q_i g_j \bar{q}_k)|^2}{|\mathcal{M}(H^0 \to q_I \bar{q}_K)|^2} = g_s^2 \, 2C_F \left[\frac{2 s_{ik}}{s_{ij} s_{jk}} + \frac{1}{s_{IK}} \left(\frac{s_{ij}}{s_{jk}} + \frac{s_{jk}}{s_{ij}} + 2 \right) \right]$$

SOFT COLLINEAR+F

Infinite Orders



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Iterated factorization

Gives us a universal approximation to ∞-order tree-level cross sections.

Exact in singular (strongly ordered) limit.

Finite terms (non-universal) → Uncertainties for non-singular (hard) radiation

But something is not right … Total σ would be infinite …

Unitarity = Evolution

Infinite amplitude to emit a parton

But also an infinite amplitude to reabsorb it

In fixed-order QCD, this looks like canceling positive and negative infinities.

Wrong expansion

Unitarity

Kinoshita-Lee-Nauenberg:
(sum over degenerate quantum states = finite)

$$\text{Loop} = -\,\text{Int(Tree)} + \text{F}$$

Parton Showers neglect F

→ *Leading-Logarithmic (LL) Approximation*

Imposed by Event *evolution*:

When (X) branches to (X+1):
Gain one (X+1). Loose one (X).

→ *evolution equation with kernel* $\frac{d\sigma_{X+1}}{d\sigma_X}$

Evolve in some measure of *resolution*
~ hardness, 1/time … ~ fractal scale

→ includes both real (tree) and virtual (loop) corrections

Evolution Equations

What we need is a differential equation

Boundary condition: a few partons defined at a high scale (Q_F)

Then evolves (or "runs") that parton system down to a low scale (the hadronization cutoff ~ 1 GeV) → It's an evolution equation in Q_F

Close analogue: nuclear decay

Evolve an unstable nucleus.

Check if it decays + follow chains of decays.

Decay constant

$$\frac{\mathrm{d}P(t)}{\mathrm{d}t} = c_N$$

Probability to remain undecayed in the time interval [t_1,t_2]

$$\Delta(t_1,t_2) = \exp\left(-\int_{t_1}^{t_2} c_N \, \mathrm{d}t\right) = \exp\left(-c_N \, \Delta t\right)$$

$$= 1 - c_N \Delta t + \mathcal{O}(c_N^2)$$

Decay probability per unit time

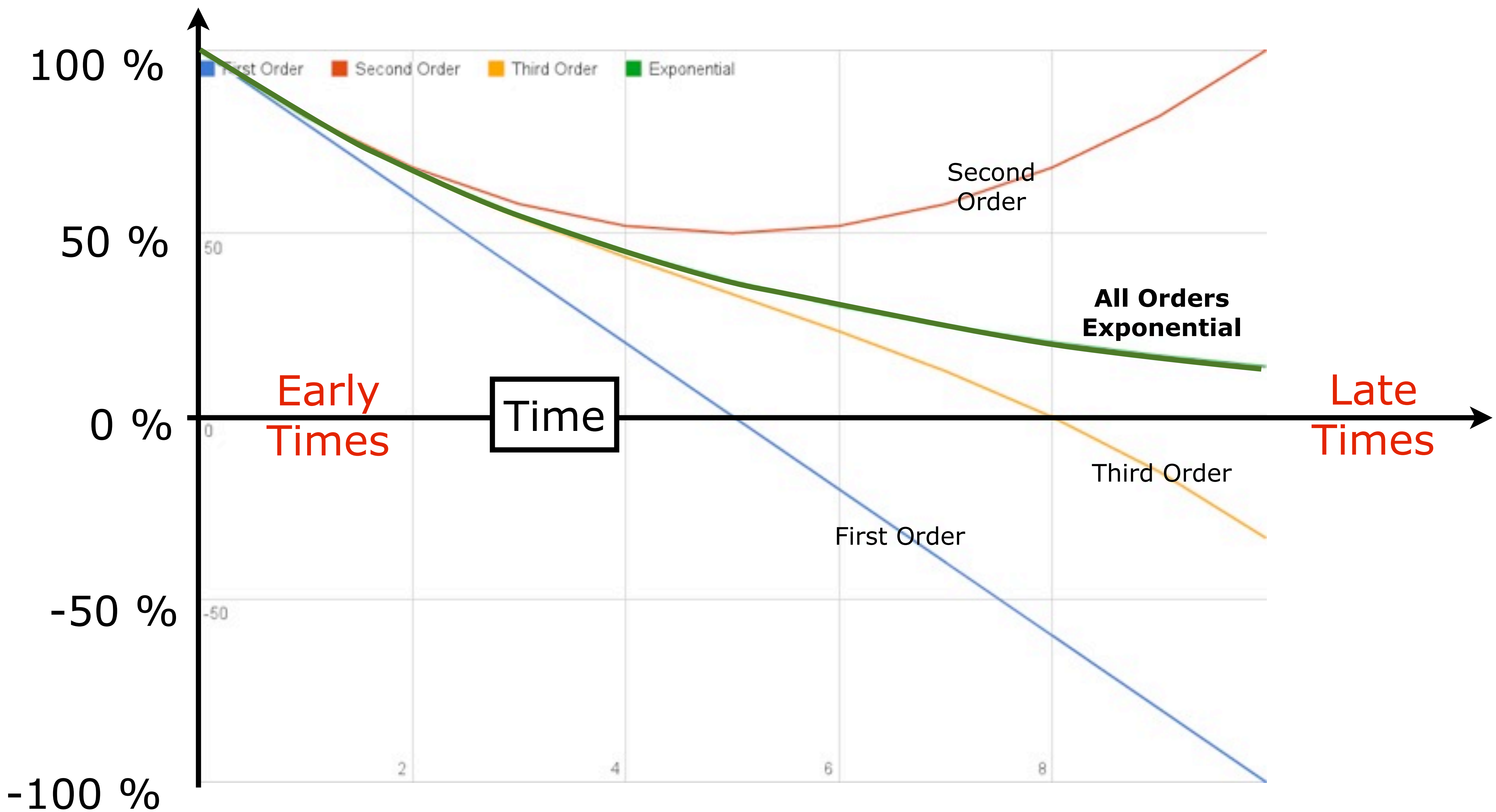
$$\frac{\mathrm{d}P_{\mathrm{res}}(t)}{\mathrm{d}t} = \frac{-\mathrm{d}\Delta}{\mathrm{d}t} = c_N \, \Delta(t_1,t)$$

(requires that the nucleus did not already decay)

$\Delta(t_1,t_2)$: "Sudakov Factor"

Nuclear Decay

Nuclei remaining undecayed after time t $= \Delta(t_1, t_2) = \exp\left(-\int_{t_1}^{t_2} \mathrm{d}t \, \frac{\mathrm{d}\mathcal{P}}{\mathrm{d}t}\right)$



The Sudakov Factor

In nuclear decay, the "Sudakov factor" counts:

How many nuclei remain undecayed after a time t

Probability to remain undecayed in the time interval $[t_1, t_2]$

$$\Delta(t_1, t_2) = \exp\left(-\int_{t_1}^{t_2} c_N \, \mathrm{d}t\right) = \exp\left(-c_N \, \Delta t\right)$$

The Sudakov factor for a parton system counts:

The probability that the parton system doesn't evolve (branch) when we run the factorization scale (~1/time) from a high to a low scale

Evolution probability per unit "time"

$$\frac{\mathrm{d}P_{\mathrm{res}}(t)}{\mathrm{d}t} = \frac{-\mathrm{d}\Delta}{\mathrm{d}t} = c_N \, \Delta(t_1, t)$$

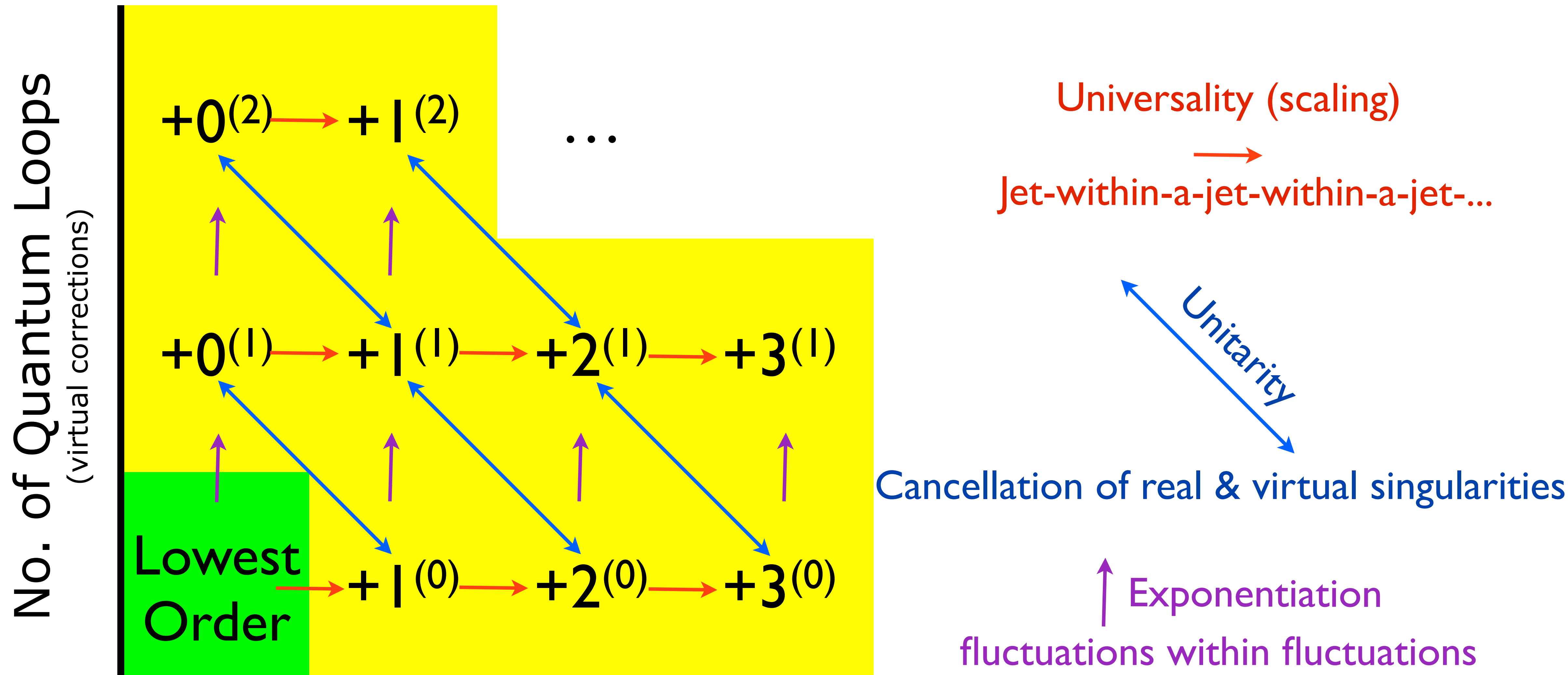
(replace *t* by shower evolution scale)

(replace c_N by proper shower evolution kernels)

Bootstrapped Perturbation Theory

Start from an **arbitrary lowest-order** process (green = QFT amplitude squared)

Parton showers generate the bremsstrahlung terms of the rest of the perturbative series (approximate infinite-order resummation)

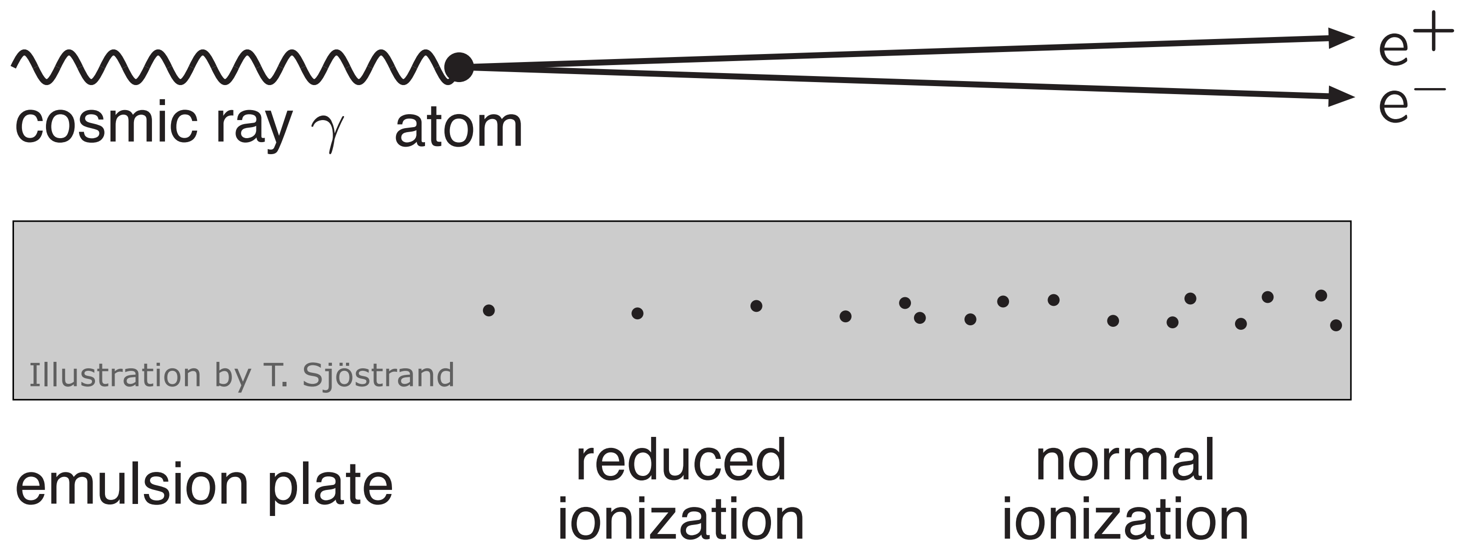


But ≠ full QCD! Only LL Approximation

(real corrections)

Coherence

QED: Chudakov effect (mid-fifties)



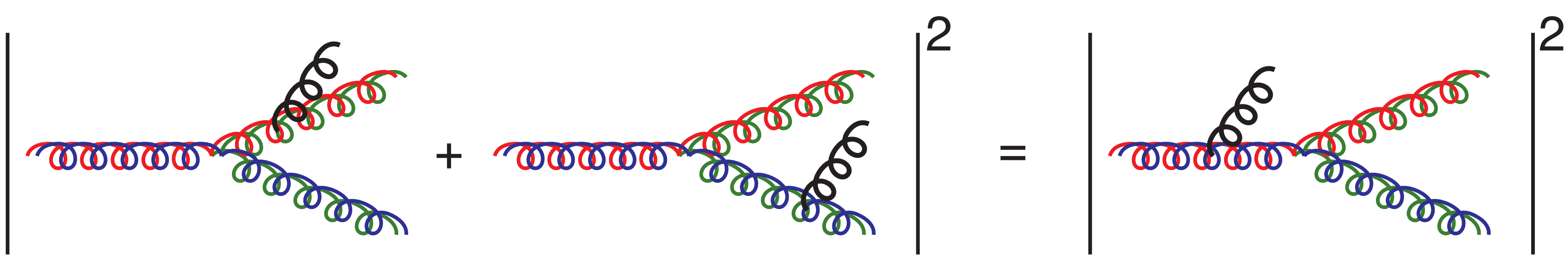
Approximations to Coherence:

Angular Ordering (HERWIG)

Angular Vetos (PYTHIA)

Coherent Dipoles/Antennae (ARIADNE, Catani-Seymour, VINCIA)

QCD: colour coherence for **soft** gluon emission



→ an example of an interference effect that can be treated probabilistically

More interference effects can be included by matching to full matrix elements

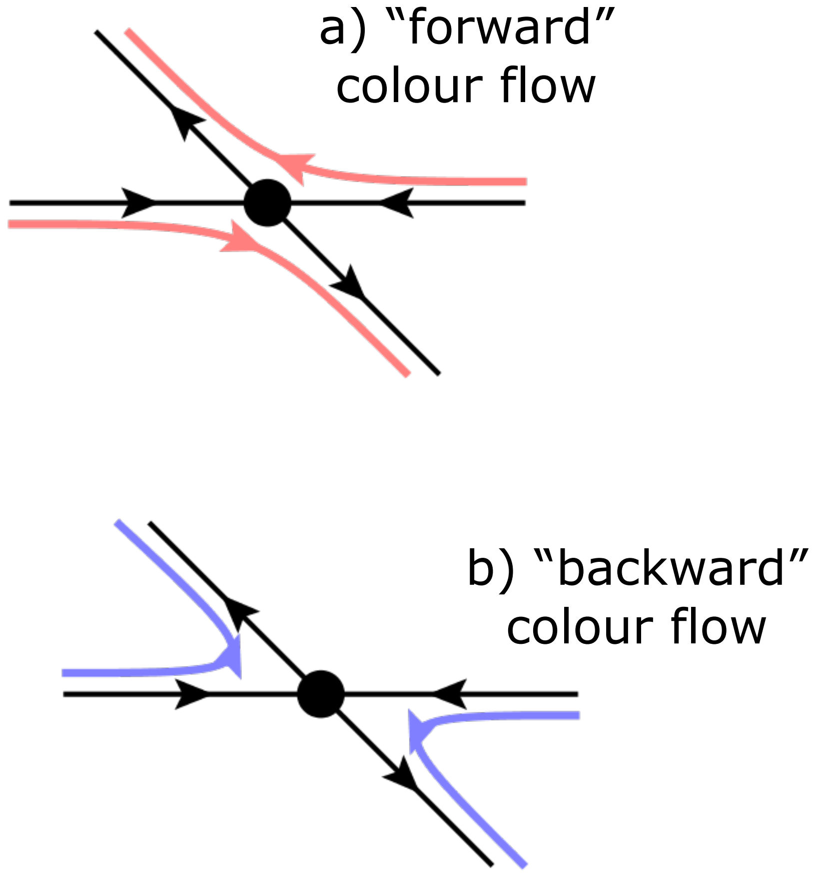
Coherence at Work

Example taken from: Ritzmann, Kosower, PS, PLB718 (2013) 1345

Example: quark-quark scattering in hadron collisions

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

2 possible colour flows: a and b



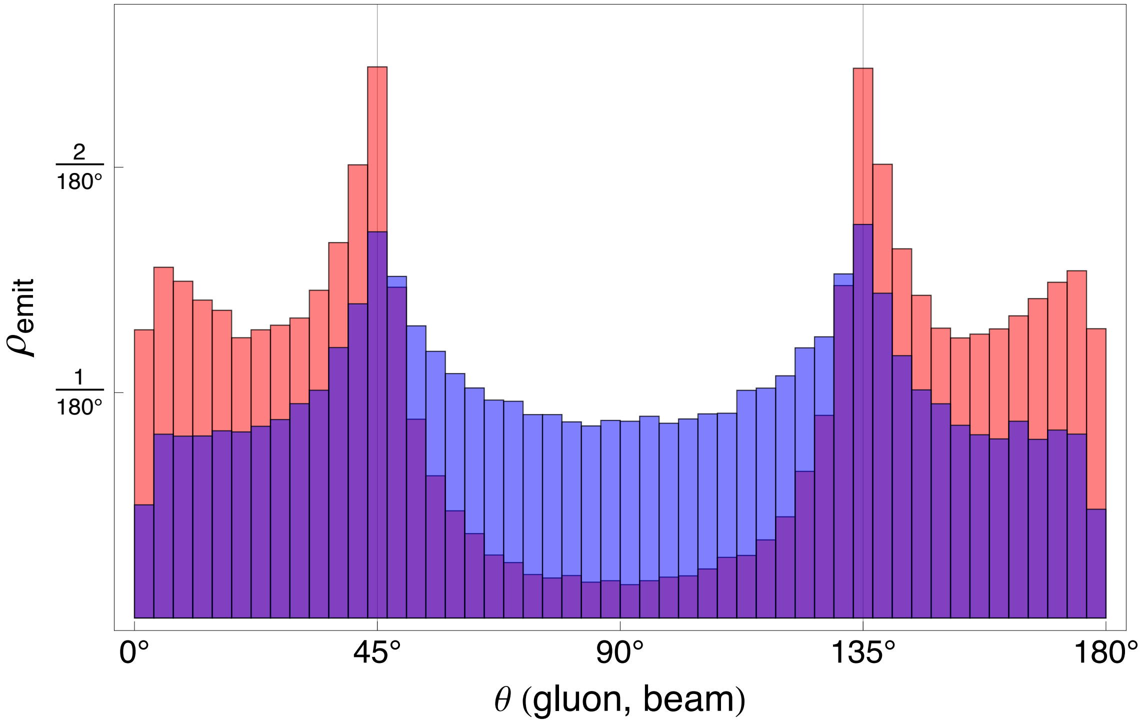


Figure 4: Angular distribution of the first gluon emission in $qq \to qq$ scattering at 45°, for the two different color flows. The light (red) histogram shows the emission density for the forward flow, and the dark (blue) histogram shows the emission density for the backward flow.

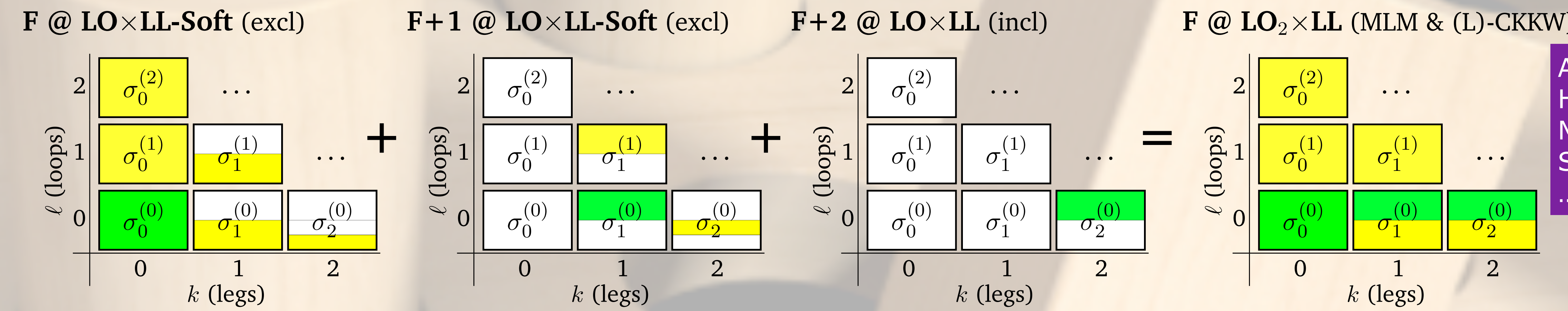
Another good recent example is the SM contribution to the Tevatron top-quark forward-backward asymmetry from coherent showers, see: PS, Webber, Winter, JHEP 1207 (2012) 151

Process-Dependence
(Matrix-Element Corrections)

Image Credits: istockphoto

Process-Dependence
(Matrix-Element Corrections)

Slicing: the "MLM" & "CKKW-L" prescriptions



ALPGEN
HERWIG
MADGRAPH
SHERPA
…

(CKKW & Lönnblad, 2001) (Mangano, 2002) (+many more recent; see Alwall et al., EPJC53(2008)473)

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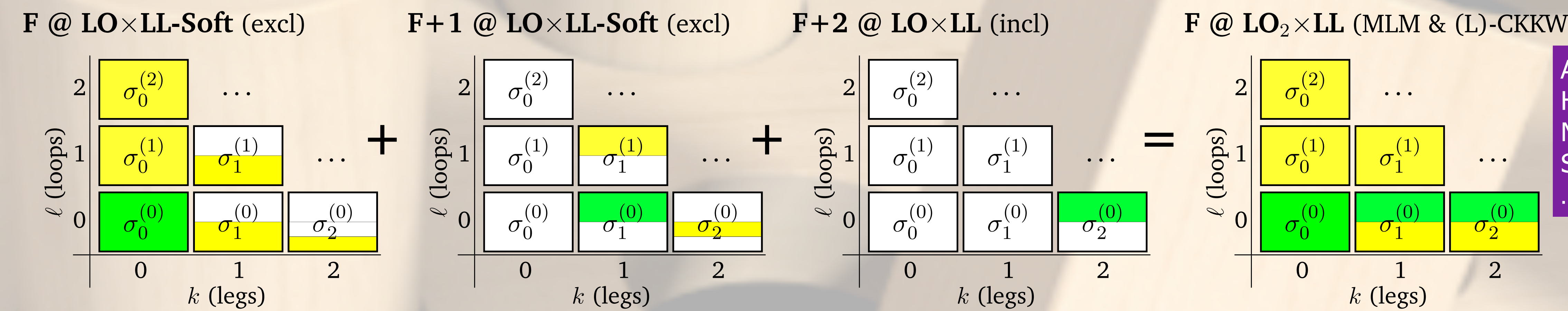

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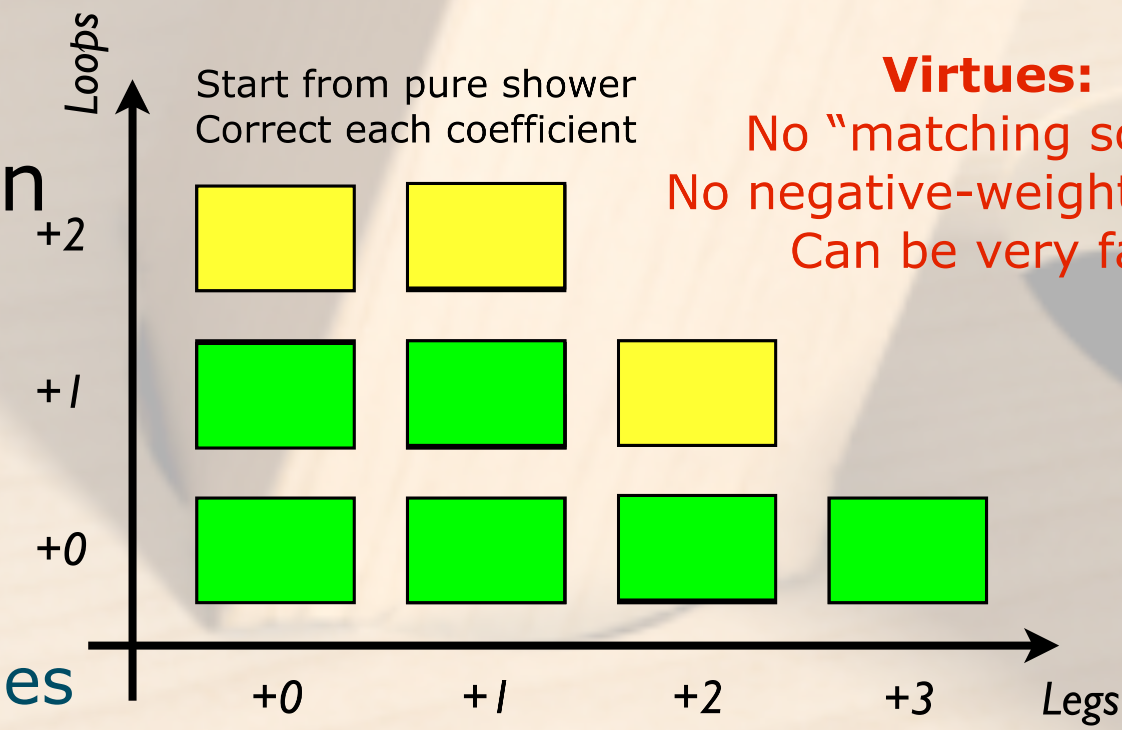
Corrected Showers:

the “GKS” prescription

Reinterpret higher-order matrix elements as radiation functions

Unitarity + Speed

+ systematic uncertainties



Start from pure shower
Correct each coefficient

Virtues:
No “matching scale”
No negative-weight events
Can be very fast

VINCIA

LO: Giele, Kosower, Skands, PRD84(2011)054003

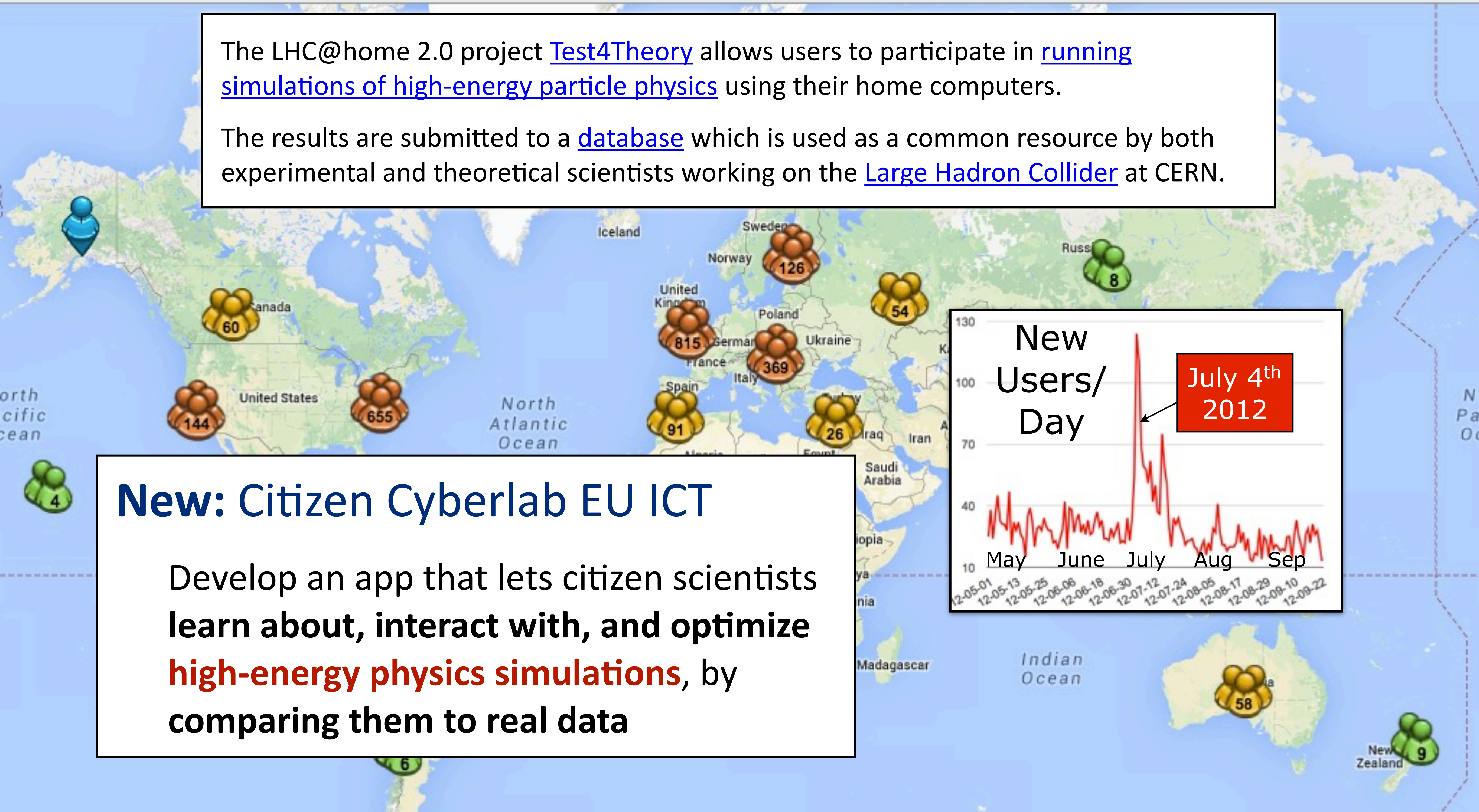
NLO: Hartgring, Laenen, Skands, arXiv:1303.4974

Hadronization

→ how do coloured partons (quarks and gluons)
turn into colourless hadrons …

Test4Theory - LHC@home

LHC@home 2.0 Test4Theory volunteers' machines seen since Sun Nov 17 2013 14:00:00 GMT+1100 (EST) (2804 machines overall)



The LHC@home 2.0 project Test4Theory allows users to participate in running simulations of high-energy particle physics using their home computers.

The results are submitted to a database which is used as a common resource by both experimental and theoretical scientists working on the Large Hadron Collider at CERN.

New: Citizen Cyberlab EU ICT

Develop an app that lets citizen scientists **learn about, interact with, and optimize high-energy physics simulations**, by **comparing them to real data**

Results → mcplots.cern.ch

Menu

- → Front Page
- → LHC@home 2.0
- → Generator Versions
- → Generator Validation
- → Update History

Analysis filter:

- → ALL pp/ppbar
- → ALL ee

Specific analysis:

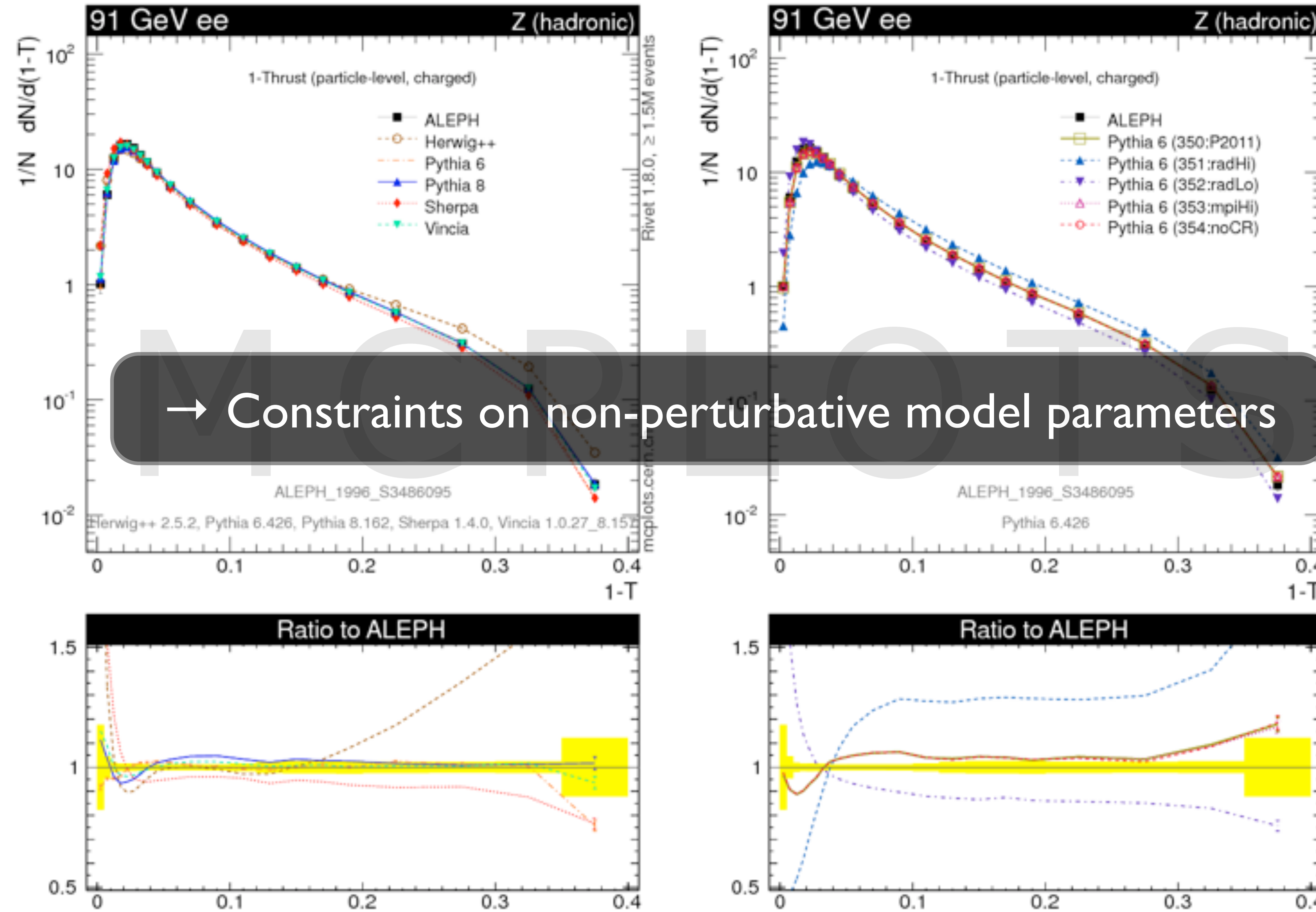
Z (hadronic)

- → Aplanarity
- → B(Total)
- → B(Heavy Hemisph)
- → B(Light Hemisph)
- → C parameter
- → D parameter
- → M(Heavy Hemisph)
- → M(Light Hemisph)
- → ΔM(Heavy-Light)
- → Multiplicity Distributions
- → Planarity
- → pTin (Sph)
- → pTin (Thrust)
- → pTout (Sph)
- → pTout (Thrust)
- → Sphericity
- → Thrust
- → 1-Thrust
- → Thrust Major
- → Thrust Minor

Z (hadronic) : 1-Thrust

(Total number of plots ~ 500,000)

Generator Group: Main Herwig++ Pythia 6 Pythia 8 Sherpa Vincia Custom



→ Constraints on non-perturbative model parameters

Summary

QCD phenomenology is witnessing a rapid evolution:

Driven by demand of **high precision** for LHC environment

Exploring physics: infinite-order structure of quantum field theory. Universalities vs process-dependence.

Non-perturbative QCD is still hard

Lund string model remains best bet, but ~ 30 years old

Lots of input from LHC

"Solving the LHC" is both interesting and rewarding

New ideas needed and welcome on both perturbative and non-perturbative sides → many opportunities for theory-experiment interplay

Key to high precision → max information about the Terascale