Modeling Hadronic Interactions in PYTHIA

Peter Skands (CERN Theory Dept)
(From October: Monash University, Melbourne)

Particle Physics Seminar
Warwick University, July 3rd, 2014

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**

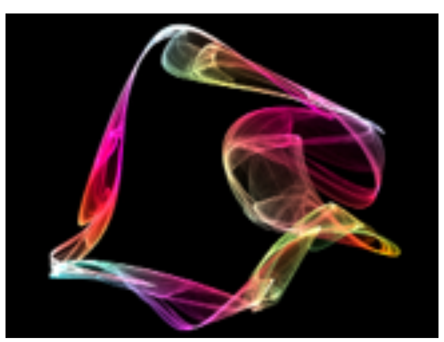
Event Structure at Colliders

Dominated by QCD

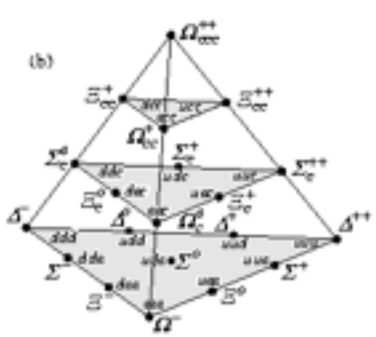
More than just a perturbative expansion in α_s

Emergent phenomena:

Jets (the QCD fractal) ⟷ amplitude structures ⟷ fundamental quantum field theory. Precision jet (structure) studies, jet vetoes.



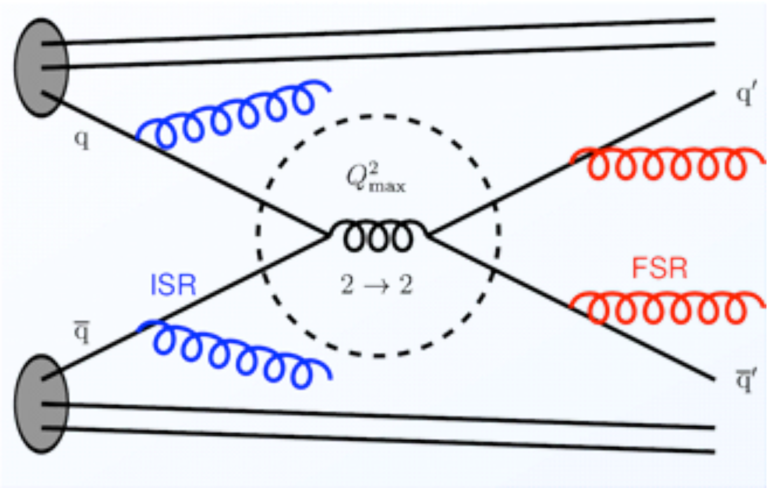
Strings (strong gluon fields) ⟷ quantum-classical correspondence. String physics. Dynamics of hadronization phase transition. Colour correlations.



Hadrons ⟷ Spectroscopy (incl excited and exotic states), lattice QCD, (rare) decays, mixing. Identified particles: rates, spectra (FFs), correlations. Hadron beams → PDFs, MPI, diffraction, …

See eg TASI lectures, e-Print: arXiv:1207.2389

General-Purpose Event Generators



Calculate Everything ≈ solve QCD → requires compromise!

Improve lowest-order perturbation theory,
by including the 'most significant' corrections
→ complete events (can evaluate any observable you want)

The Workhorses

PYTHIA : Successor to JETSET (begun in 1978). Originated in hadronization studies: Lund String.
HERWIG : Successor to EARWIG (begun in 1984). Originated in coherence studies: angular ordering.
SHERPA : Begun in 2000. Originated in "matching" of matrix elements to showers: CKKW-L.
+ MORE SPECIALIZED: ALPGEN, MADGRAPH, HELAC, ARIADNE, VINCIA, WHIZARD, (a)MC@NLO, POWHEG, HEJ, PHOJET, EPOS, QGSJET, SIBYLL, DPMJET, LDCMC, DIPSY, HIJING, CASCADE, BLACKHAT, GOSAM, NJETS, …

PYTHIA

PYTHIA anno 1978

(then called JETSET)

LU TP 78-18
November, 1978

A Monte Carlo Program for Quark Jet Generation

T. Sjöstrand, B. Söderberg

A Monte Carlo computer program is presented, that simulates the fragmentation of a fast parton into a jet of mesons. It uses an iterative scaling scheme and is compatible with the jet model of Field and Feynman.

Note:
Field-Feynman was an early fragmentation model
Now superseded by the String (in PYTHIA) and Cluster (in HERWIG & SHERPA) models.

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```
      SUBROUTINE JETGEN(N)
      COMMON /JET/ K(100,2), P(100,5)
      COMMON /PAR/ PUD, PS1, SIGMA, CX2, EBEG, WFIN, IFLBEG
      COMMON /DATA1/ MESO(9,2), CMIX(6,2), PMAS(19)
      IFLSGN=(10-IFLBEG)/5
      W=2.*EBEG
      I=0
      IPD=0
C 1 FLAVOUR AND PT FOR FIRST QUARK
      IFL1=IABS(IFLBEG)
      PT1=SIGMA*SQRT(-ALOG(RANF(0)))
      PHI1=6.2832*RANF(0)
      PX1=PT1*COS(PHI1)
      PY1=PT1*SIN(PHI1)
  100 I=I+1
C 2 FLAVOUR AND PT FOR NEXT ANTIQUARK
      IFL2=1+INT(RANF(0)/PUD)
      PT2=SIGMA*SQRT(-ALOG(RANF(0)))
      PHI2=6.2832*RANF(0)
      PX2=PT2*COS(PHI2)
      PY2=PT2*SIN(PHI2)
C 3 MESON FORMED, SPIN ADDED AND FLAVOUR MIXED
      K(I,1)=MESO(3*(IFL1-1)+IFL2,IFLSGN)
      ISPIN=INT(PS1+RANF(0))
      K(I,2)=1+9*ISPIN+K(I,1)
      IF(K(I,1).LE.6) GOTO 110
      TMIX=RANF(0)
      KM=K(I,1)-6+3*ISPIN
      K(I,2)=8+9*ISPIN+INT(TMIX+CMIX(KM,1))+INT(TMIX+CMIX(KM,2))
C 4 MESON MASS FROM TABLE, PT FROM CONSTITUENTS
  110 P(I,5)=PMAS(K(I,2))
      P(I,1)=PX1+PX2
      P(I,2)=PY1+PY2
      PMTS=P(I,1)**2+P(I,2)**2+P(I,5)**2
C 5 RANDOM CHOICE OF X=(E+PZ)MESON/(E+PZ)AVAILABLE GIVES E AND PZ
      X=RANF(0)
      IF(RANF(0).LT.CX2) X=1.-X**(1./3.)
      P(I,3)=(X*W-PMTS/(X*W))/2.
      P(I,4)=(X*W+PMTS/(X*W))/2.
C 6 IF UNSTABLE, DECAY CHAIN INTO STABLE PARTICLES
  120 IPD=IPD+1
      IF(K(IPD,2).GE.8) CALL DECAY(IPD,I)
      IF(IPD.LT.I.AND.I.LE.96) GOTO 120
C 7 FLAVOUR AND PT OF QUARK FORMED IN PAIR WITH ANTIQUARK ABOVE
      IFL1=IFL2
      PX1=-PX2
      PY1=-PY2
C 8 IF ENOUGH E+PZ LEFT, GO TO 2
      W=(1.-X)*W
      IF(W.GT.WFIN.AND.I.LE.95) GOTO 100
      N=I
      RETURN
      END
```

Note:
Field-Feynman was an early fragmentation model
Now superseded by the String (in PYTHIA) and Cluster (in HERWIG & SHERPA) models.

PYTHIA

PYTHIA anno 2014

(now called PYTHIA 8)

~ 100,000 lines of C++

What a modern MC generator has inside:

LU TP 07-28 (CPC 178 (2008) 852)
October, 2007

A Brief Introduction to PYTHIA 8.1

T. Sjöstrand, S. Mrenna, P. Skands

The Pythia program is a standard tool for the generation of high-energy collisions, comprising a coherent set of physics models for the evolution from a few-body hard process to a complex multihadronic final state. It contains a library of hard processes and models for initial- and final-state parton showers, multiple parton-parton interactions, beam remnants, string fragmentation and particle decays. It also has a set of utilities and interfaces to external programs. […]

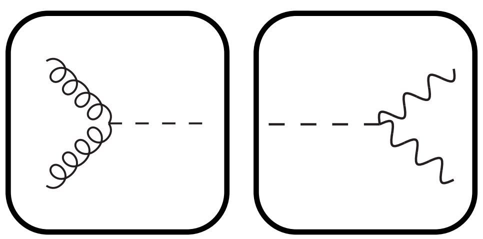
- Hard Processes (internal, interfaced, or via Les Houches events)
- BSM (internal or via interfaces)
- PDFs (internal or via interfaces)
- Showers (internal or inherited)
- Multiple parton interactions
- Beam Remnants
- String Fragmentation
- Decays (internal or via interfaces)
- Examples and Tutorial
- Online HTML / PHP Manual
- Utilities and interfaces to external programs

Divide and Conquer

Factorization → Split the problem into many (nested) pieces

+ **Quantum mechanics** → Probabilities → Random Numbers (MC)

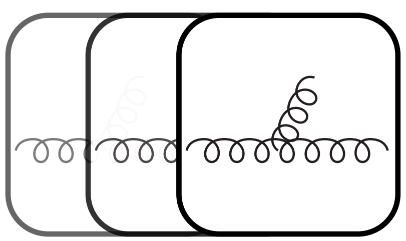
$$\mathcal{P}_{\mathrm{event}} = \mathcal{P}_{\mathrm{hard}} \otimes \mathcal{P}_{\mathrm{dec}} \otimes \mathcal{P}_{\mathrm{ISR}} \otimes \mathcal{P}_{\mathrm{FSR}} \otimes \mathcal{P}_{\mathrm{MPI}} \otimes \mathcal{P}_{\mathrm{Had}} \otimes \ldots$$



Hard Process & Decays:

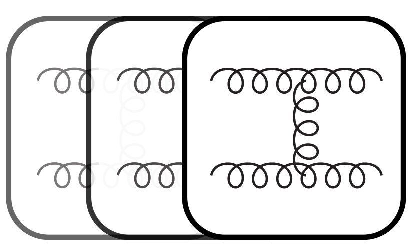
Use (N)LO matrix elements

→ Sets "hard" resolution scale for process: Q_{MAX}



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

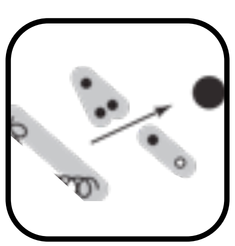
Altarelli-Parisi equations → differential evolution, dP/dQ^2, as function of resolution scale; run from Q_{MAX} to ~ 1 GeV



MPI (Multi-Parton Interactions)

Additional (soft) parton-parton interactions: LO matrix elements

→ Additional (soft) "Underlying-Event" activity



Hadronization

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

Bremsstrahlung

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

cf. equivalent-photon approximation
Weiszäcker, Williams
~ 1934


Bremsstrahlung
a.k.a. Initial- and Final-state radiation
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cf. equivalent-photon approximation Weiszäcker, Williams ~ 1934
Accelerated Charges
ATLAS EXPERIMENT
Jet Event at 2.36 TeV Collision Energy
2009-12-14, 04:30 CET, Run 142308, Event 482137
http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

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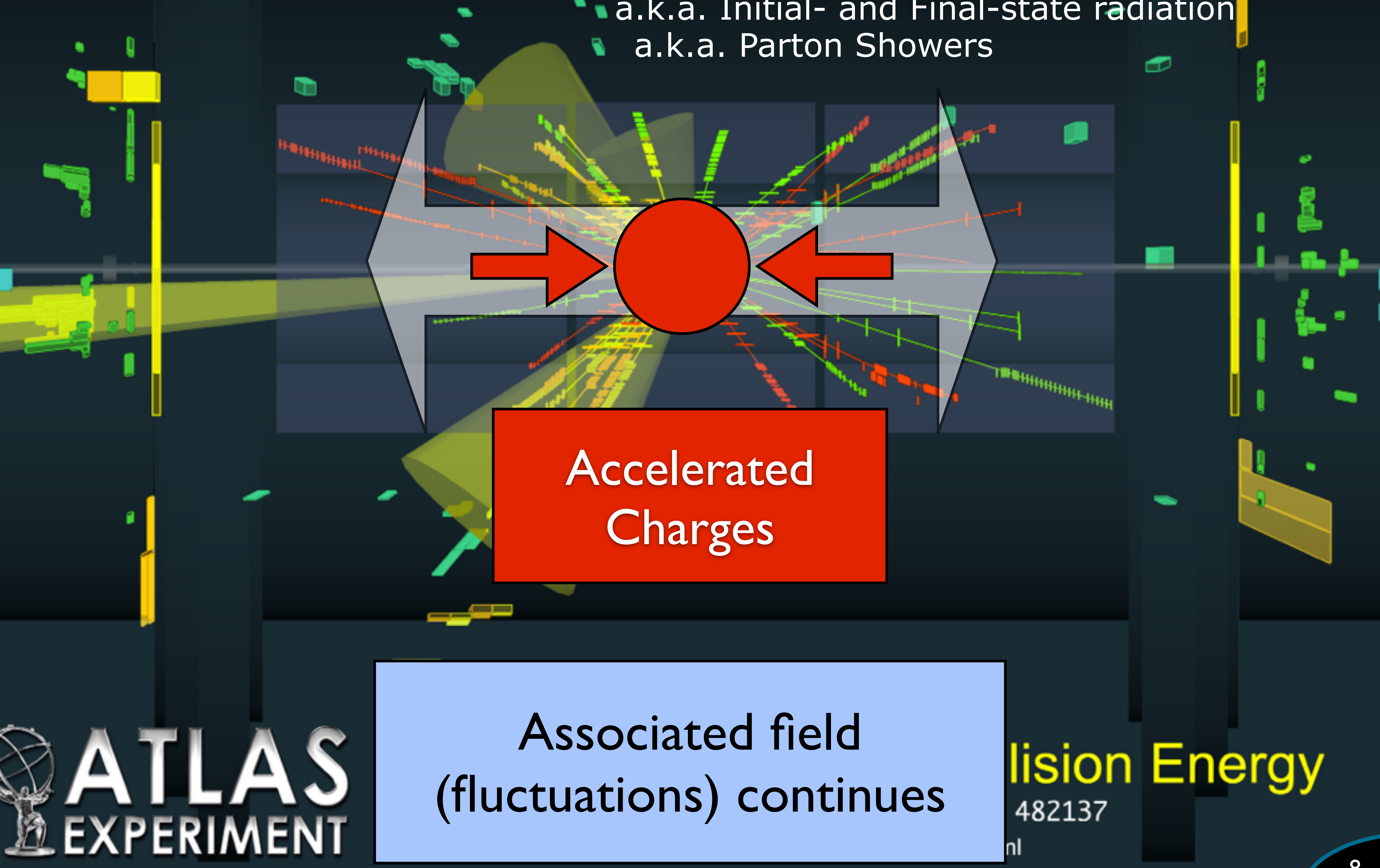

Associated field (fluctuations) continues

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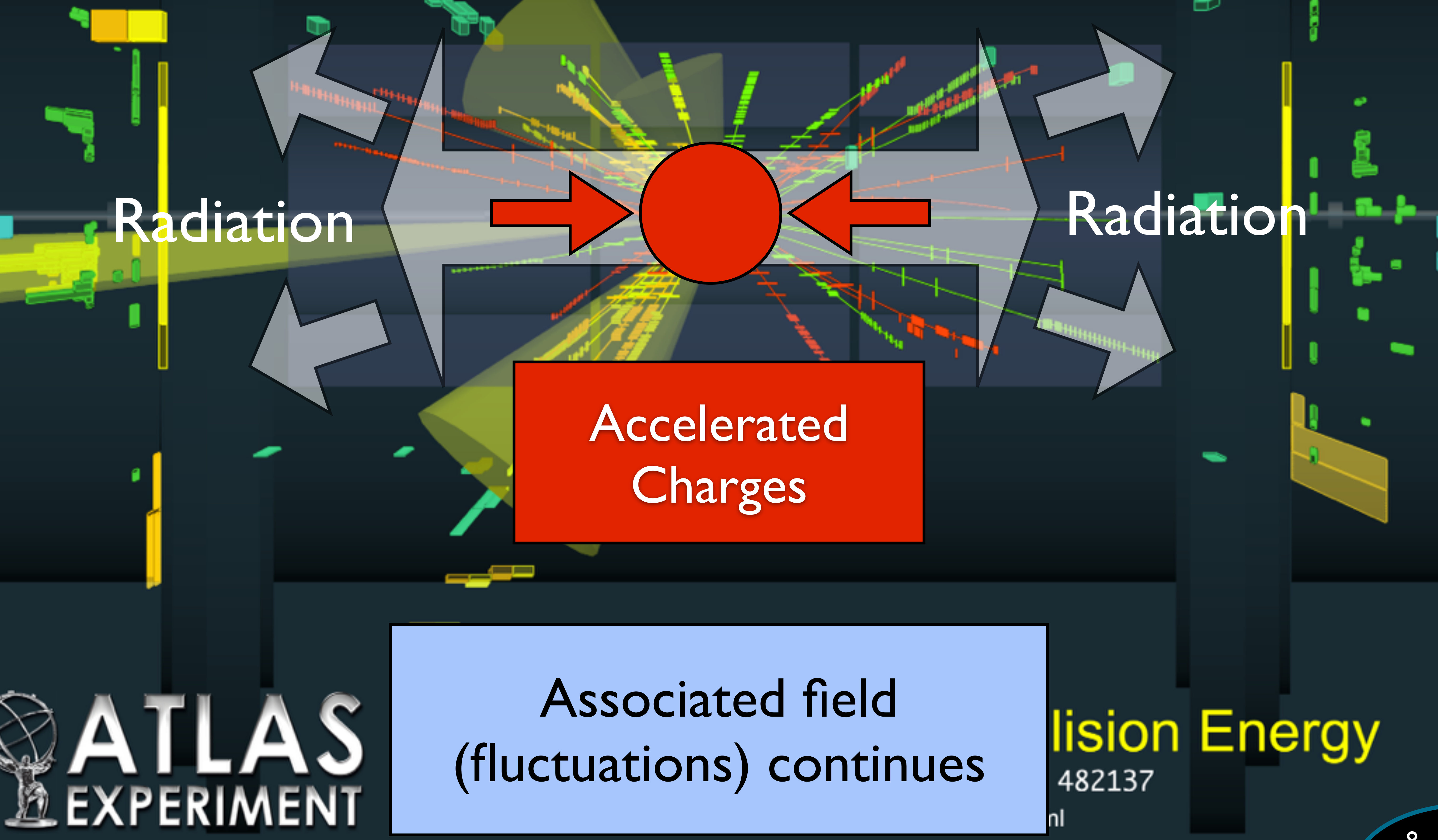

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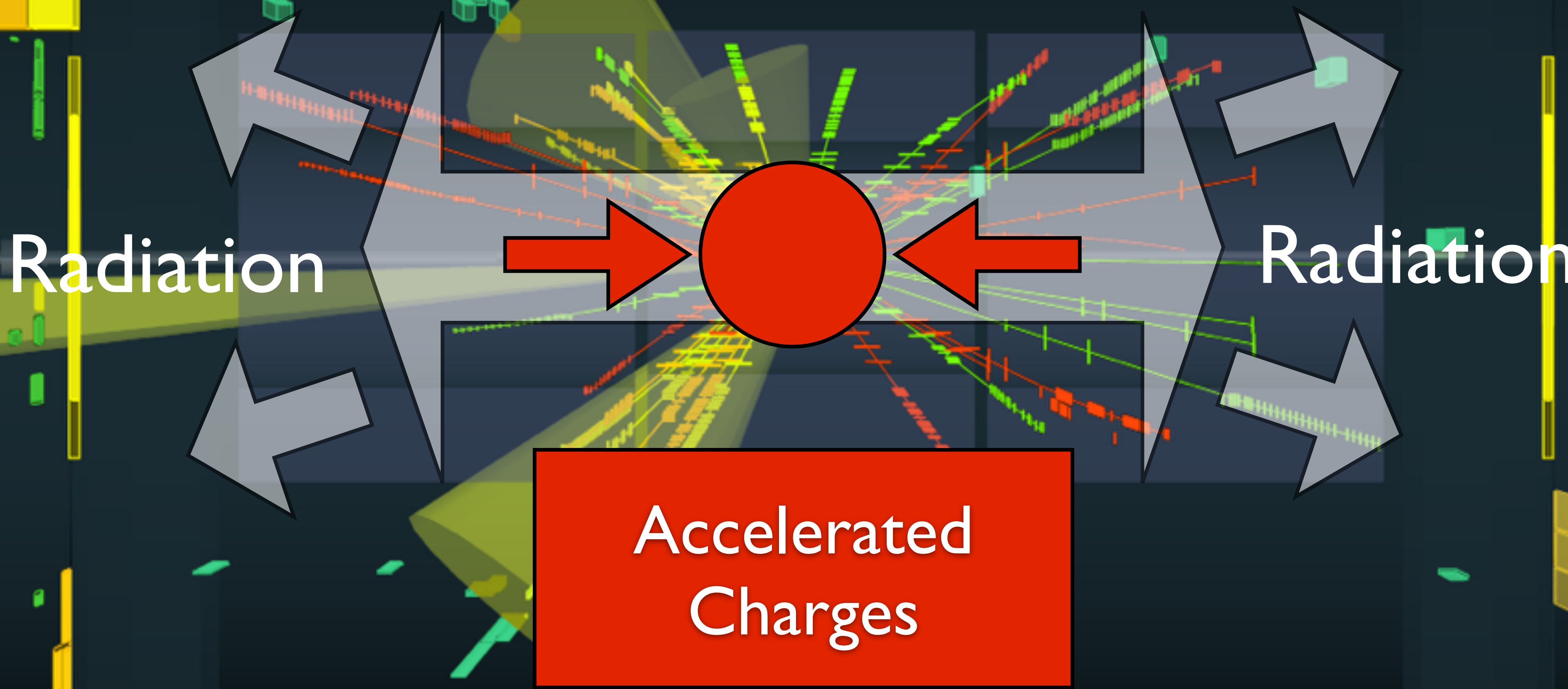
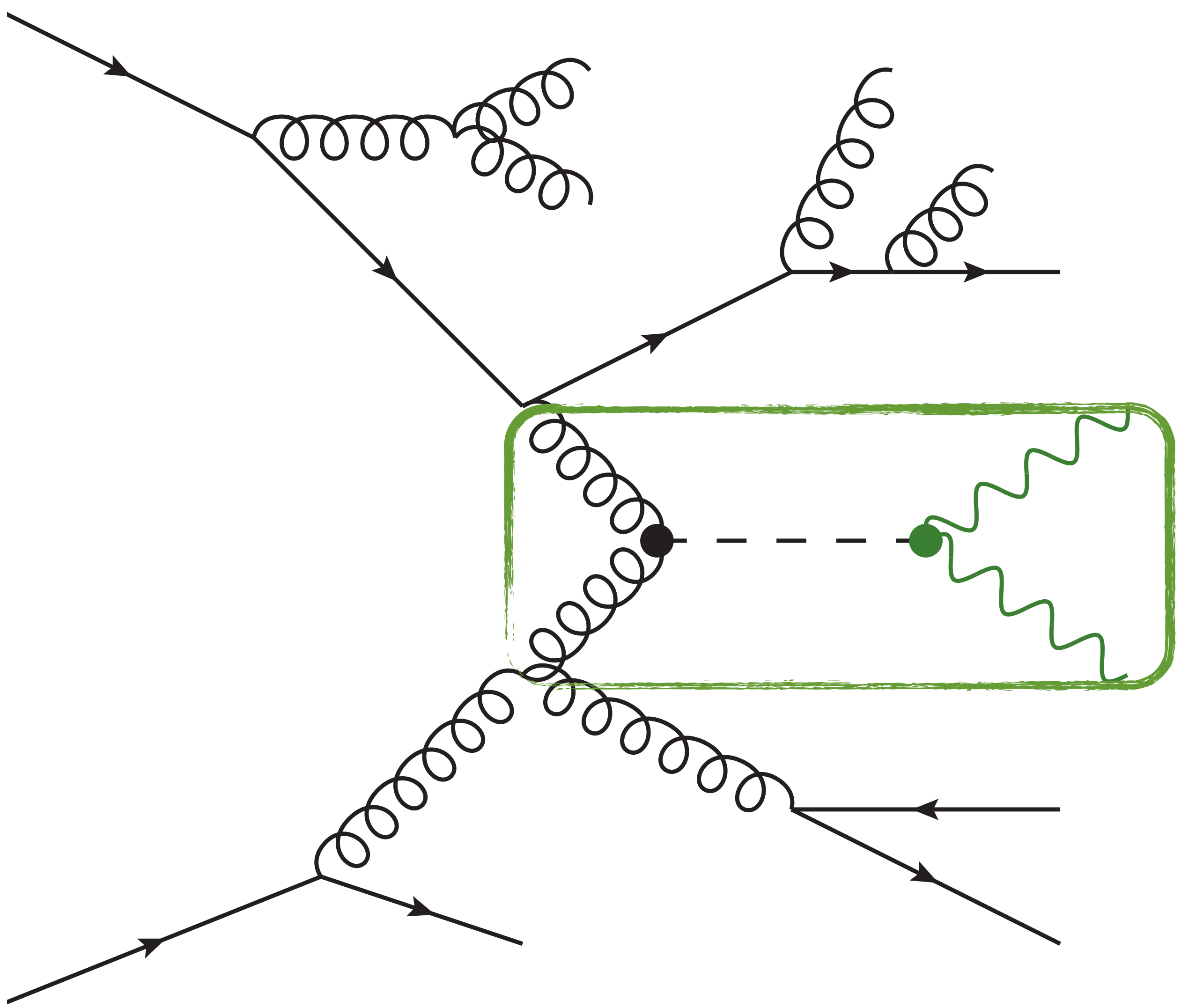


The harder they get kicked, the harder the fluctations that continue to become strahlung

Jets ≈ Fractals

Most bremsstrahlung is driven by divergent propagators → simple structure

Amplitudes factorize in singular limits (→ universal "conformal" or "fractal" structure)



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

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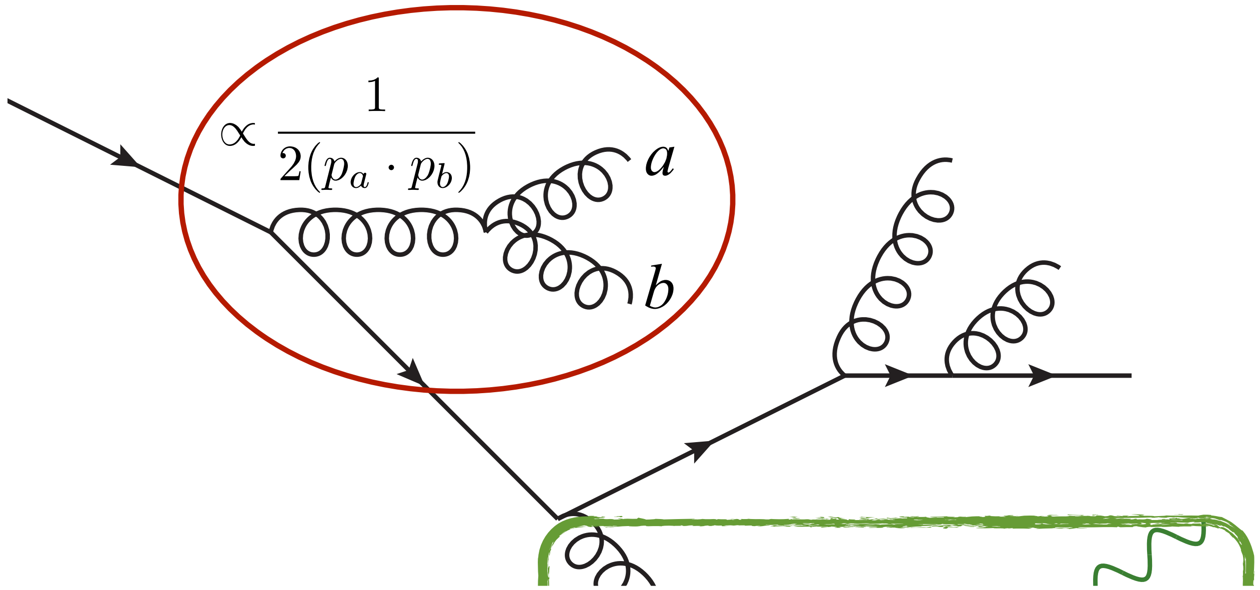

Partons ab → "collinear":

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

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

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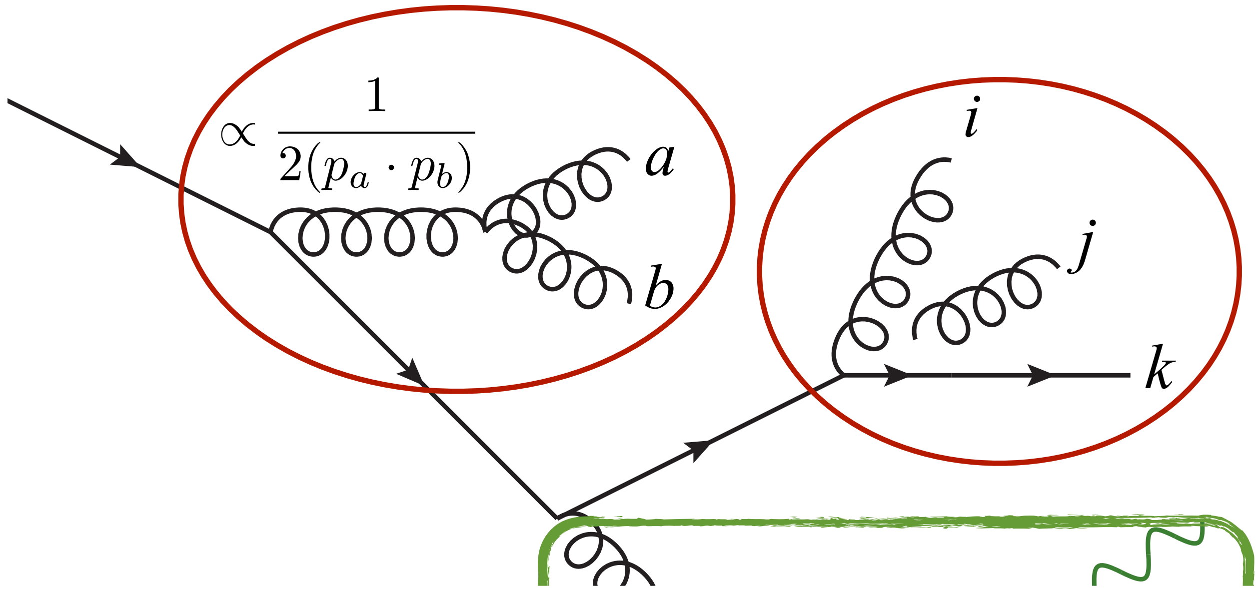

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Gluon j → "soft":

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

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

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

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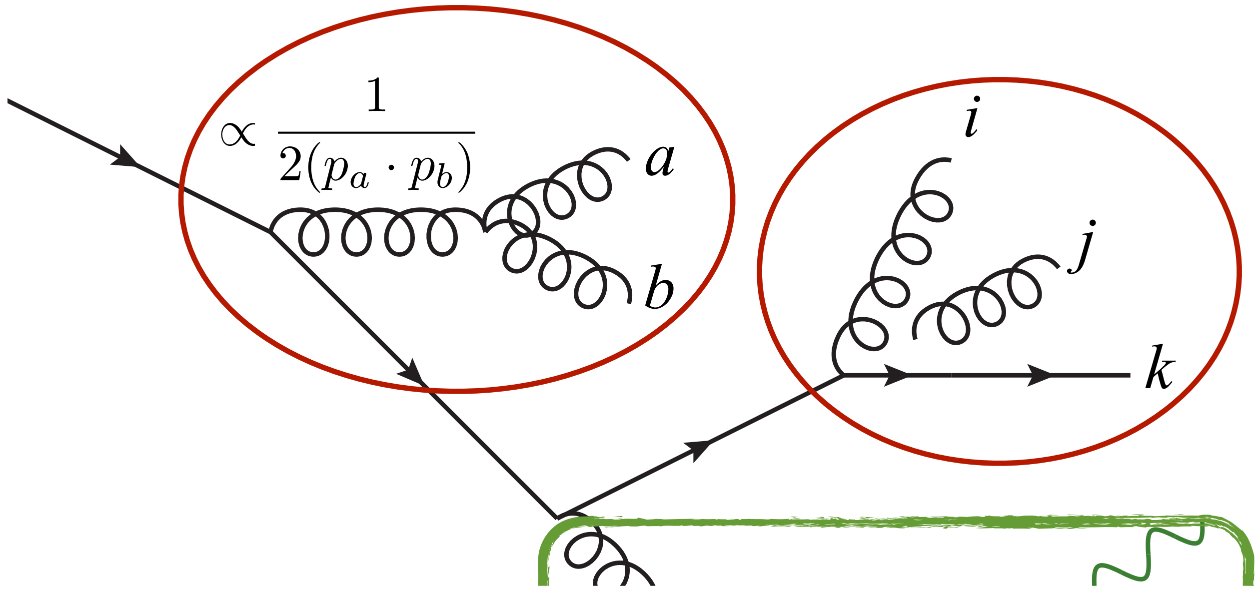

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Can apply this many times
→ nested factorizations

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

Factorization

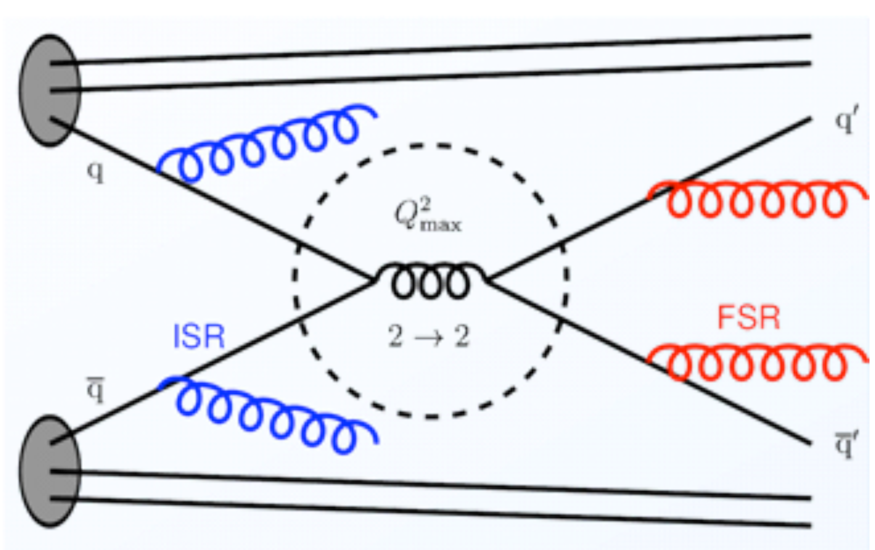
Factorization of Production and Decay:

= "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

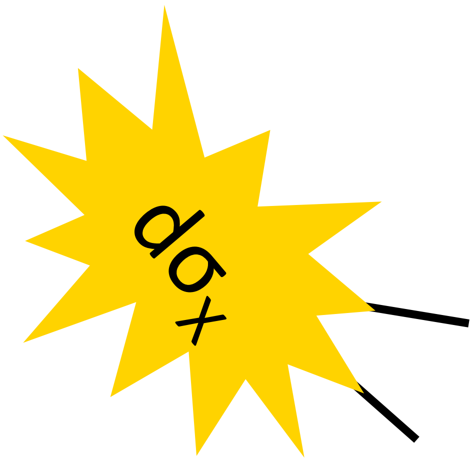
$\sim \Lambda_{QCD} \sim 200$ MeV

Scale of hard process $\gg \Lambda_{QCD}$

→ proton looks "frozen"

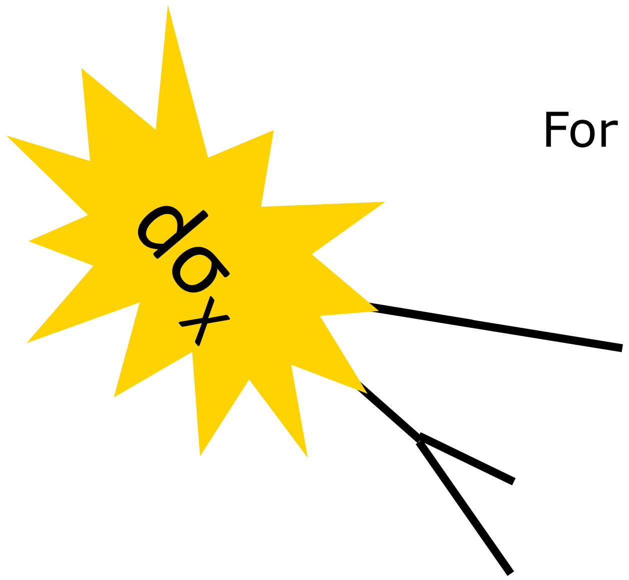
Instantaneous snapshot of long-wavelength structure, independent of nature of hard process

Practical Examples



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

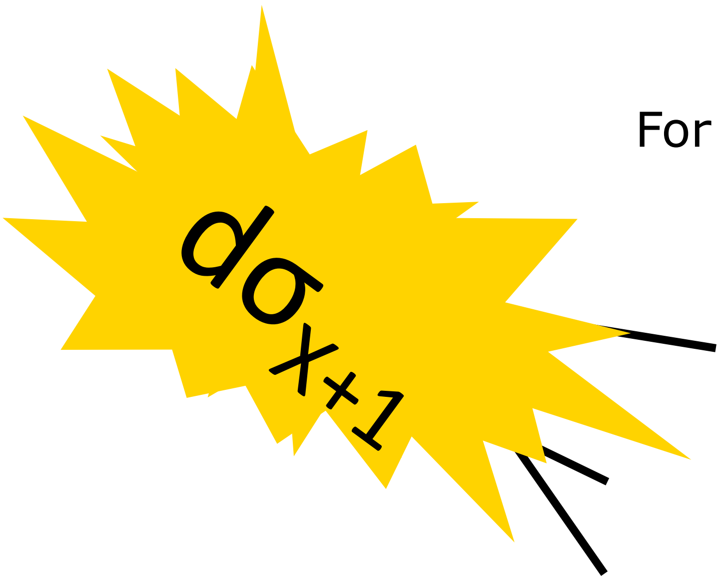
Practical Examples



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

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

Practical Examples



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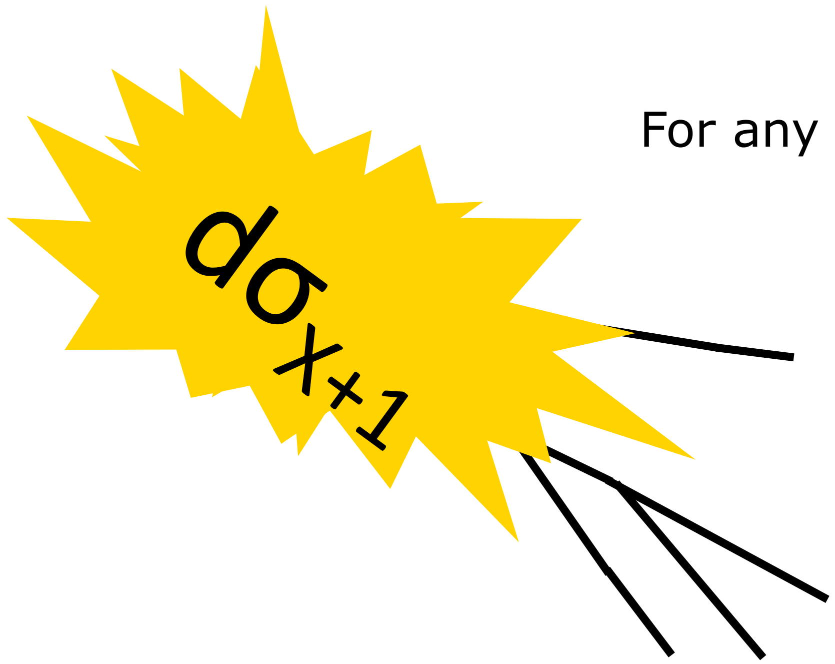

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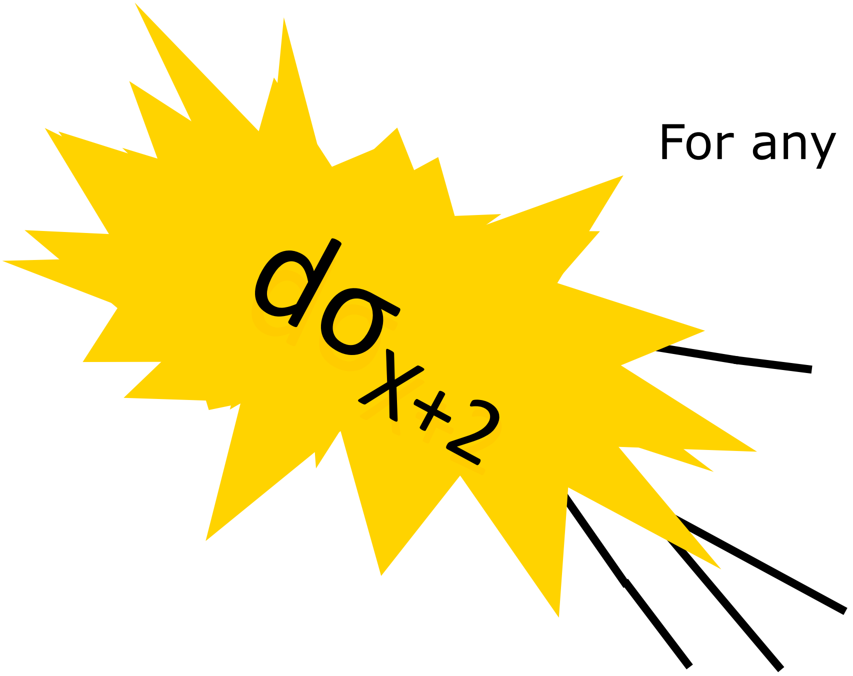
Practical Examples



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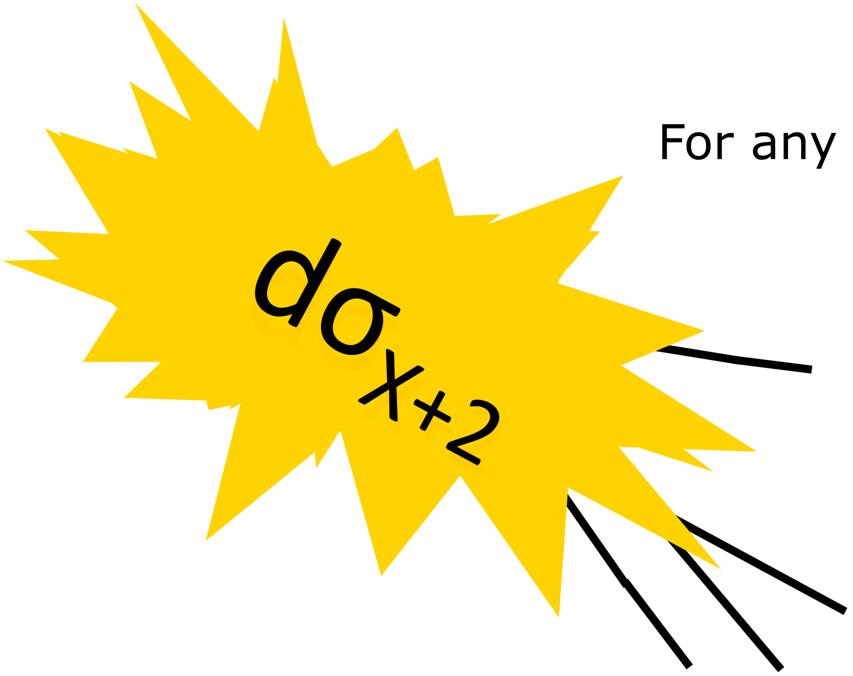

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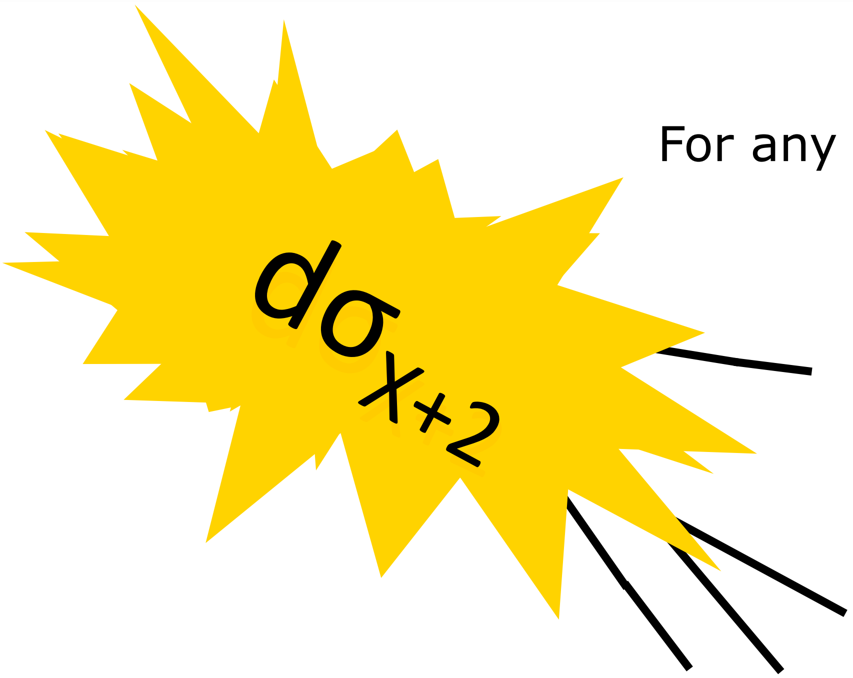
$$d\sigma_{X+3} \sim N_C 2 g_s^2 \frac{ds_{i3}}{s_{i3}} \frac{ds_{3j}}{s_{3j}} d\sigma_{X+2} \quad \ldots$$

Practical Examples



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

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

SOFT COLLINEAR

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

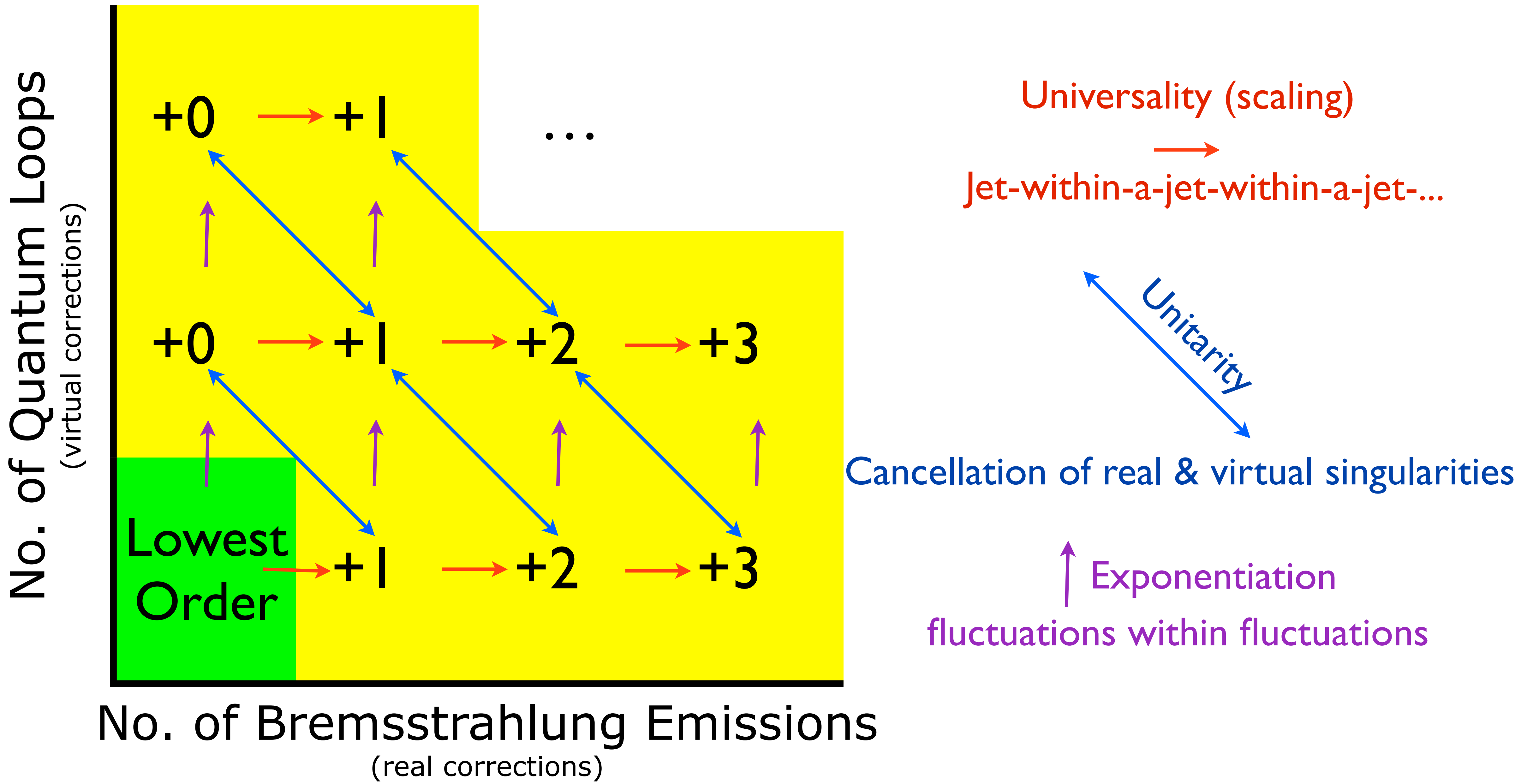
$$\frac{|\mathcal{M}(H^0 \to q_i g_j \bar{q}_k)|^2}{|\mathcal{M}(H^0 \to q_I \bar{q}_K)|^2} = g_s^2\, 2C_F \left[\frac{2 s_{ik}}{s_{ij} s_{jk}} + \frac{1}{s_{IK}} \left(\frac{s_{ij}}{s_{jk}} + \frac{s_{jk}}{s_{ij}} + 2 \right) \right]$$

SOFT COLLINEAR+F

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)



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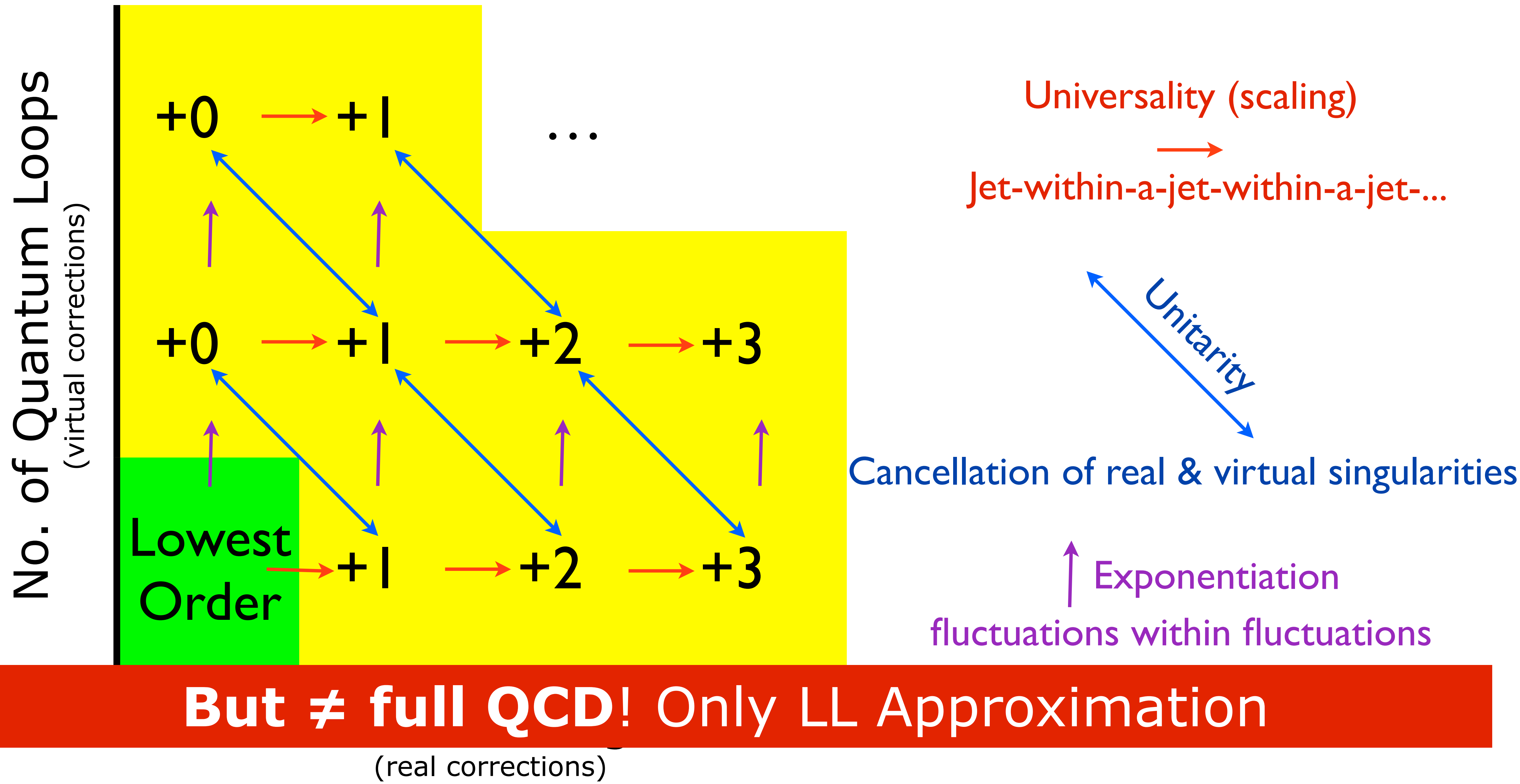


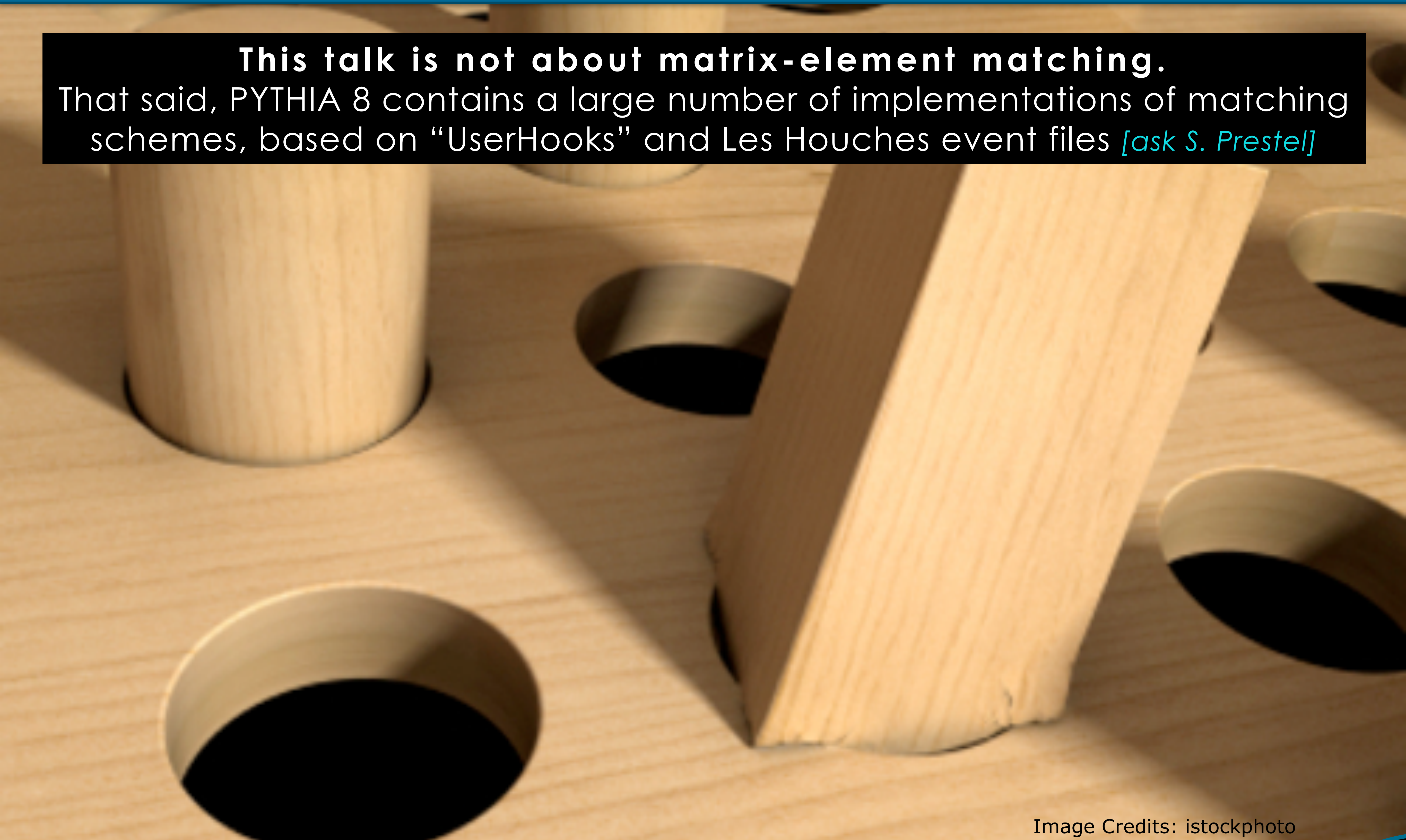
But ≠ full QCD! Only LL Approximation

Process-Dependence
(Matrix-Element Corrections)

Image Credits: istockphoto

Process-Dependence
(Matrix-Element Corrections)

This talk is not about matrix-element matching.
That said, PYTHIA 8 contains a large number of implementations of matching schemes, based on “UserHooks” and Les Houches event files *[ask S. Prestel]*



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(Matrix-Element Corrections)

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TREE LEVEL

CKKW-L

MLM
(jet matching, a la AlpGen or MadGraph)

UMEPS
(~unitarized CKKW-L)

- Les Houches Accord
- SUSY Les Houches Accord
- HepMC Interface
- Semi-Internal Processes
- Semi-Internal Resonances
- MadGraph 5 Processes
- Alpgen Event Interface
- Matching and Merging
  - POWHEG Merging
  - CKKW-L Merging
  - Jet Matching
  - UMEPS Merging
  - NLO Merging
- User Hooks
- Hadron-Level Standalone
- External Decays

LOOP LEVEL

POWHEG

NL3
(~ CKKW-L @ NLO)

UNLOPS
(~ multileg POWHEG)

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Process-Dependence
(Matrix-Element Corrections)

This talk is not about matrix-element matching.
That said, PYTHIA 8 contains a large number of implementations of matching schemes, based on "UserHooks" and Les Houches event files *[ask S. Prestel]*

TREE LEVEL

CKKW-L

MLM
(jet matching, a la AlpGen or MadGraph)

UMEPS
(~unitarized CKKW-L)

- Les Houches Accord
- SUSY Les Houches Accord
- HepMC Interface
- Semi-Internal Processes
- Semi-Internal Resonances
- MadGraph 5 Processes
- Alpgen Event Interface
- Matching and Merging
  - POWHEG Merging
  - CKKW-L Merging
  - Jet Matching
  - UMEPS Merging
  - NLO Merging
- User Hooks
- Hadron-Level Standalone
- External Decays

LOOP LEVEL

POWHEG

NL3
(~ CKKW-L @ NLO)

UNLOPS
(~ multileg POWHEG)

UserHooks gives further possibilities to control event generation / implement new schemes
Can also implement own processes, decays, or shower model(s) (e.g.,VINCIA plug-in)

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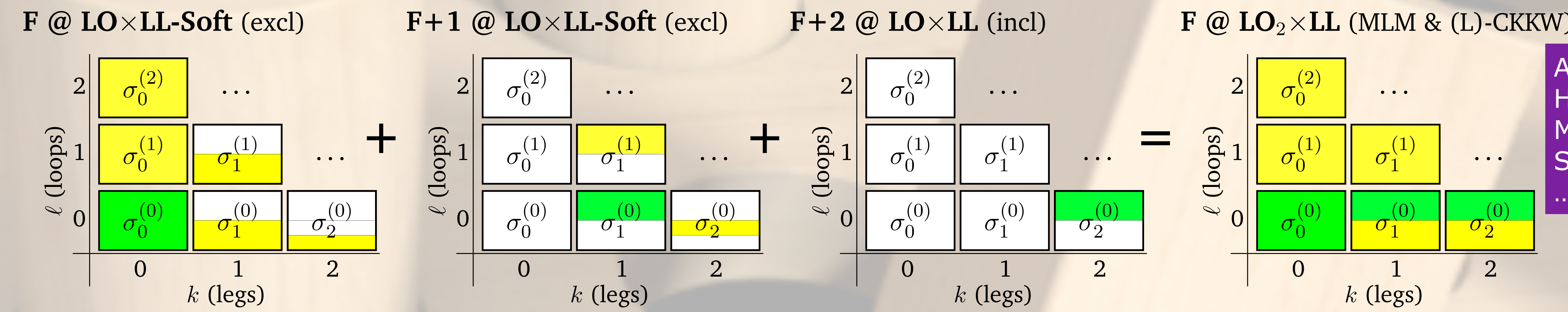
Examples

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



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ALPGEN
HERWIG
MADGRAPH
SHERPA
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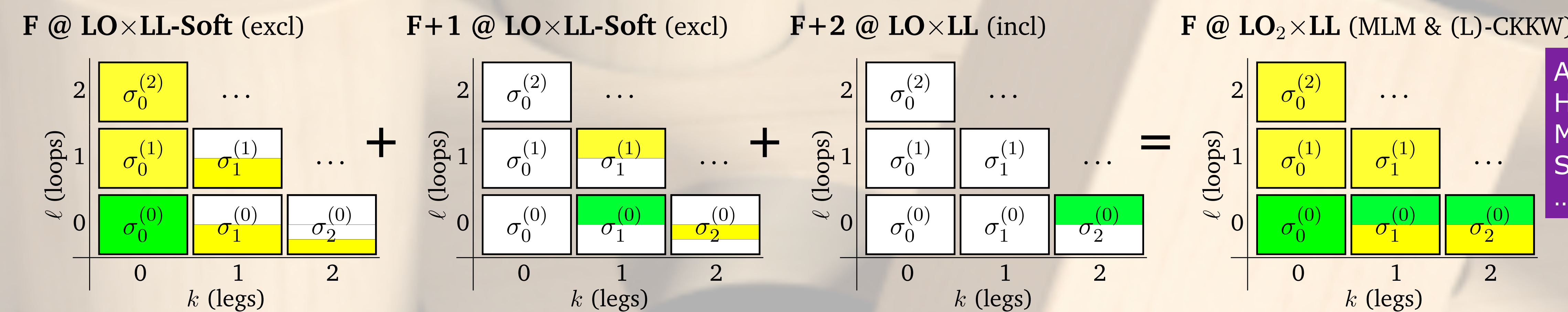

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Corrected Showers:

the "GKS" prescription

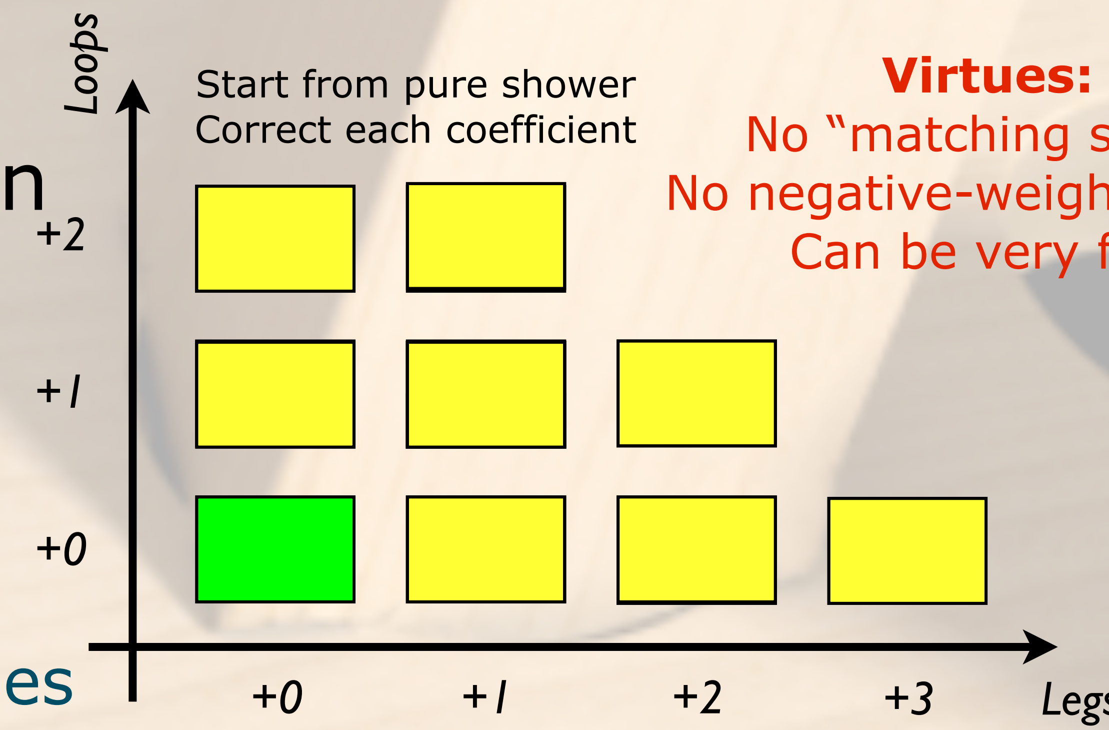
NEW

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

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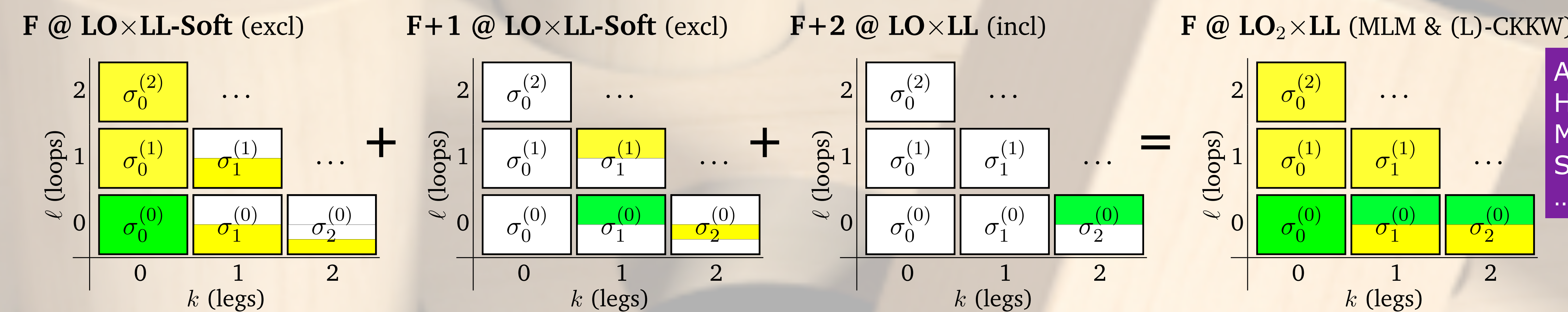

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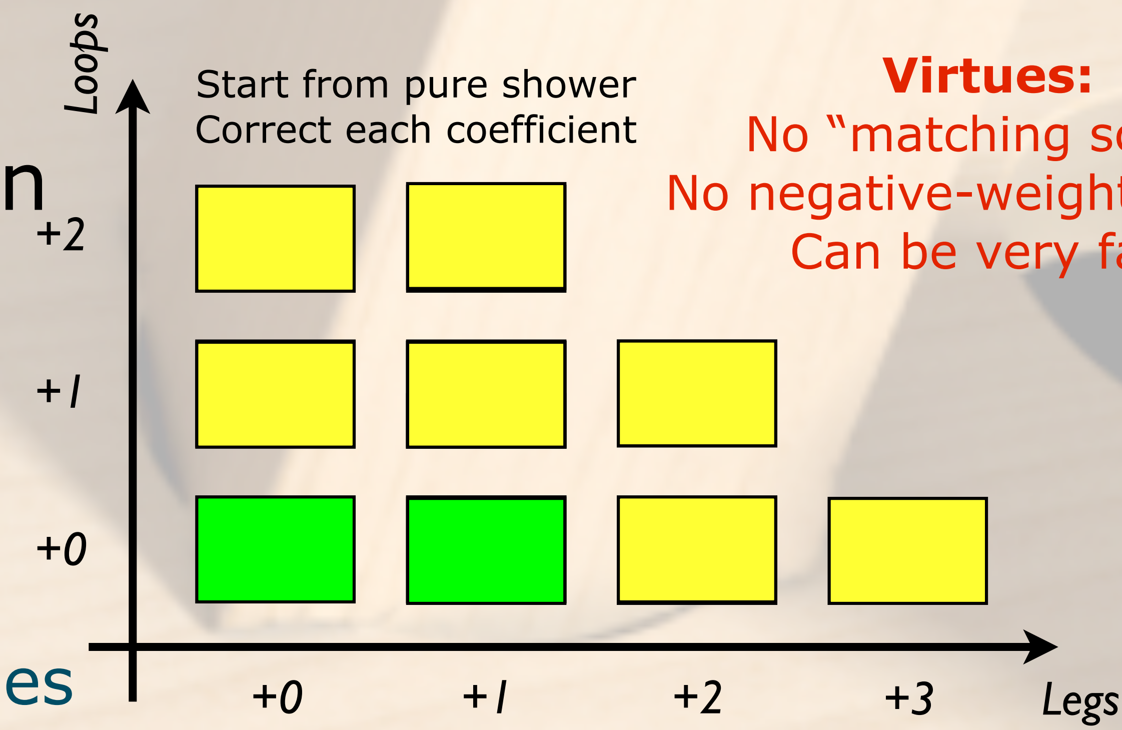

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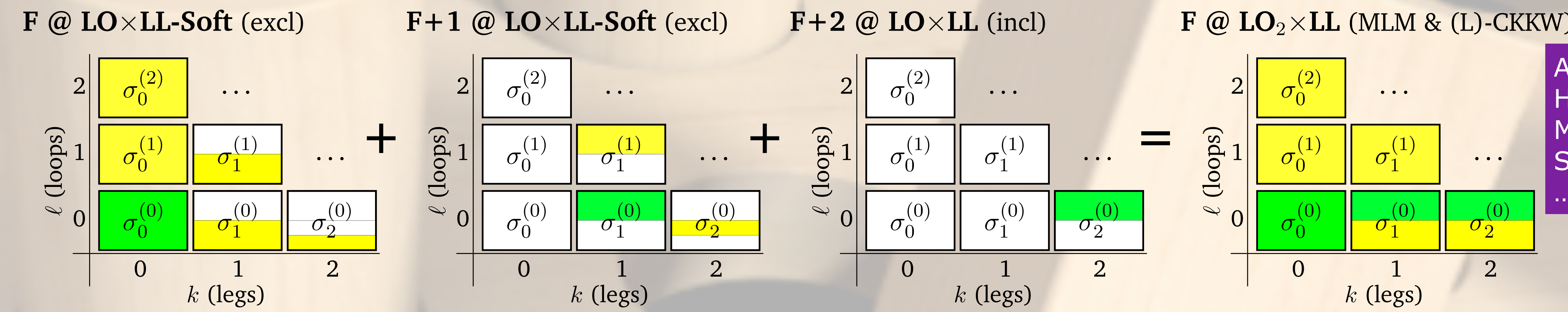

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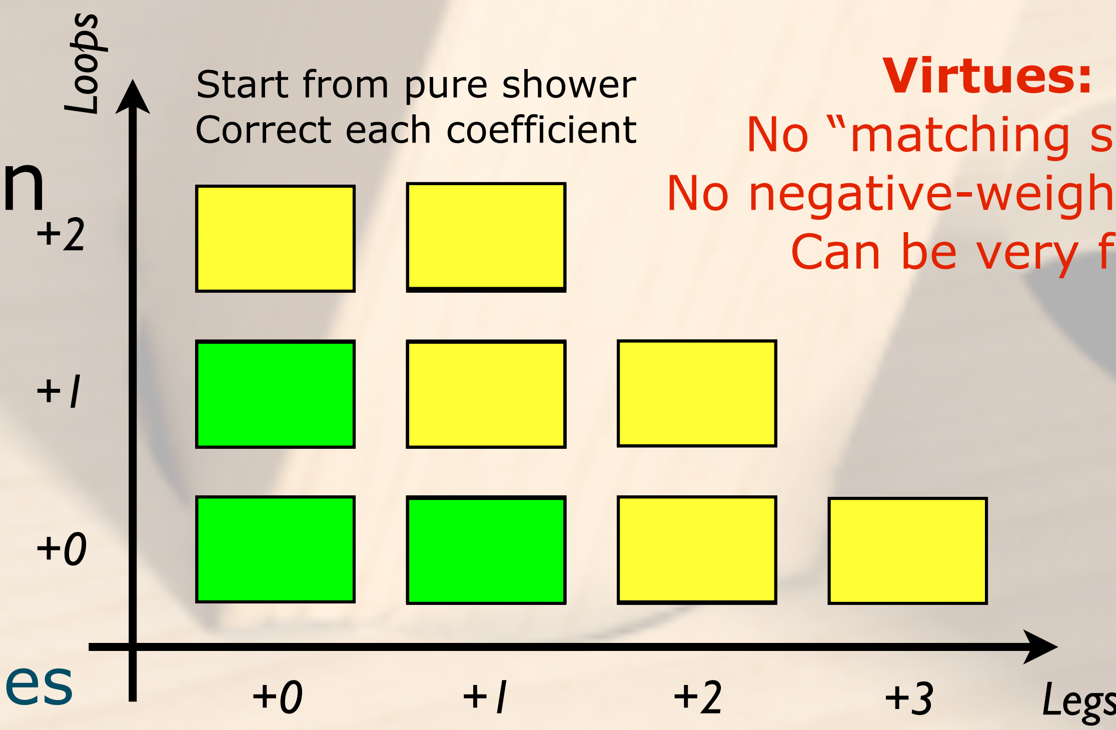

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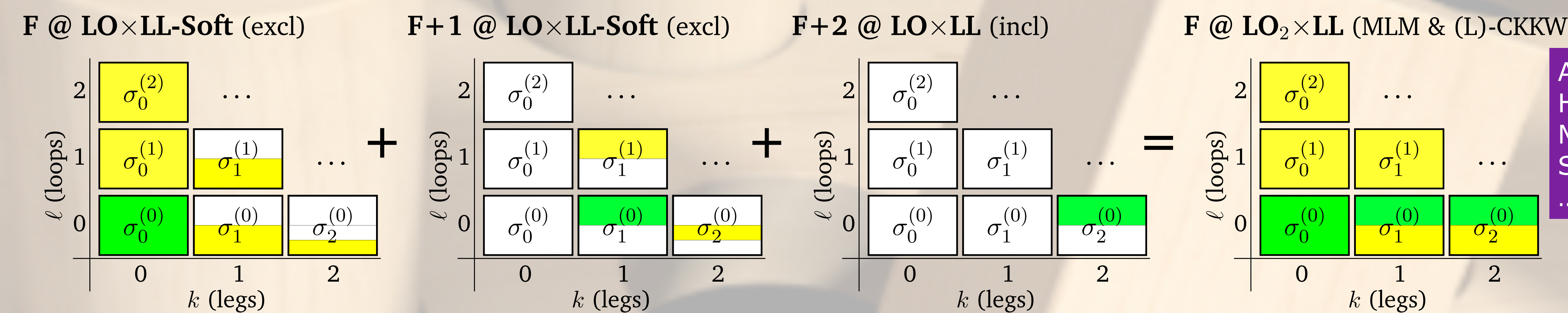

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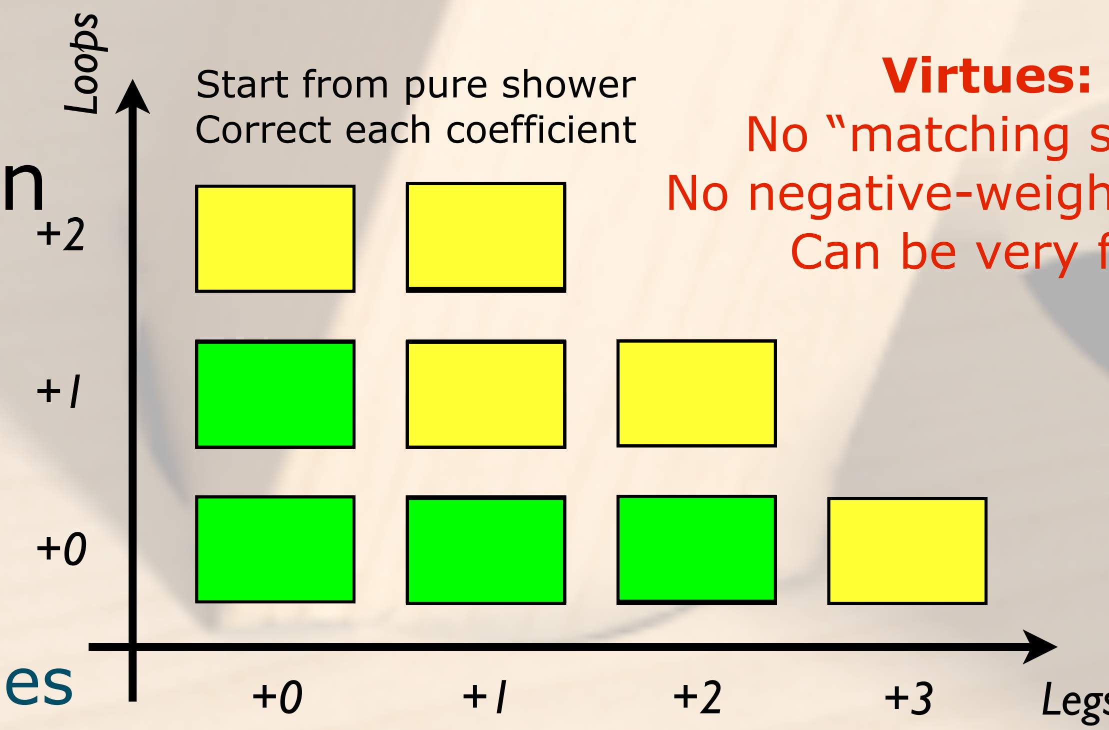

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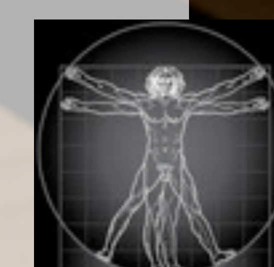

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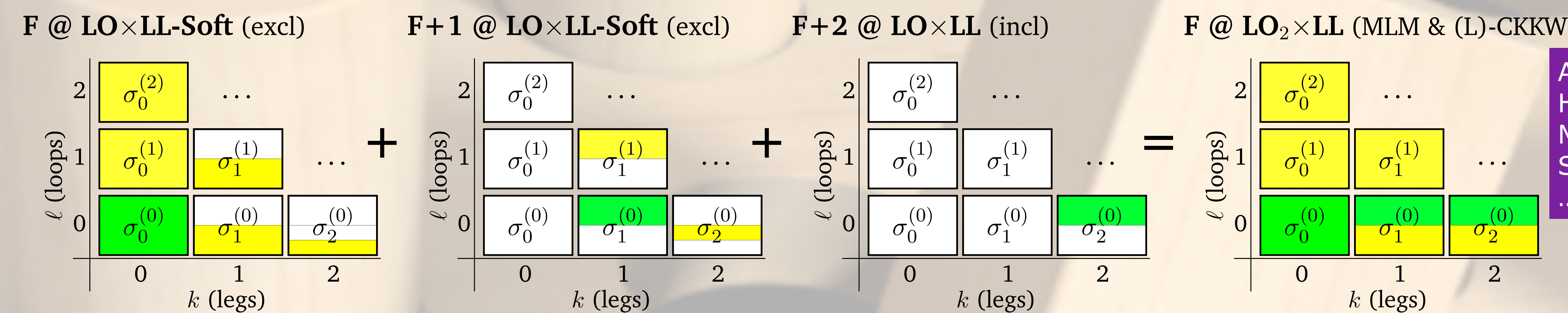

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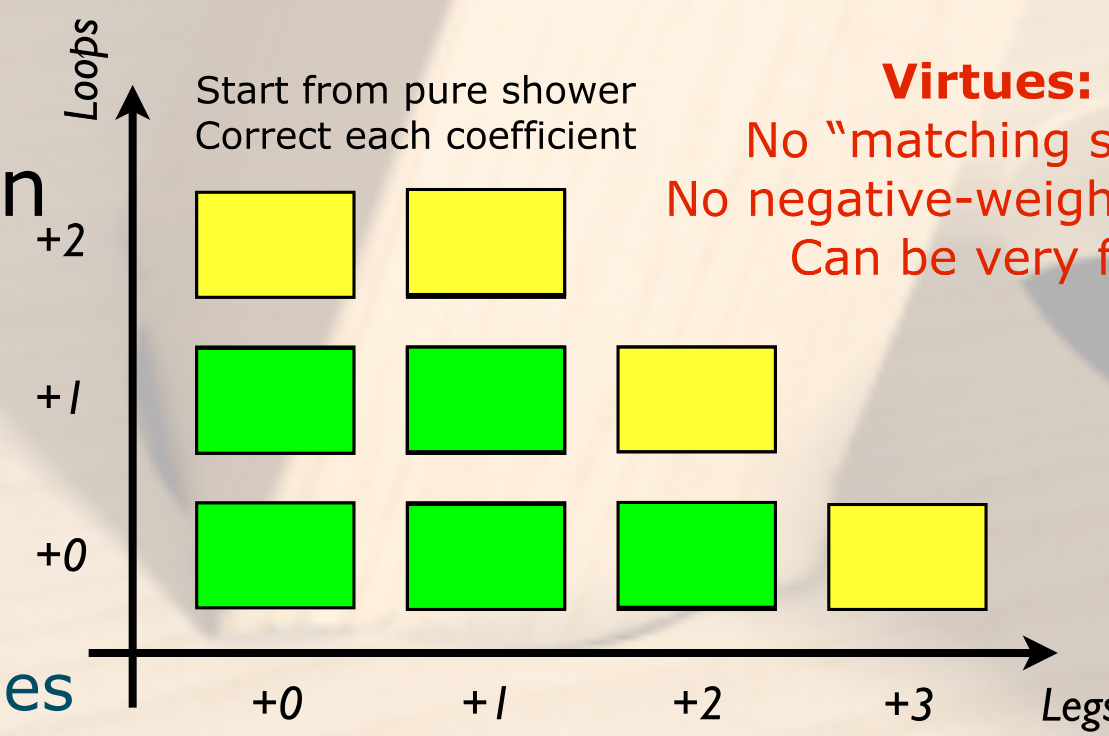

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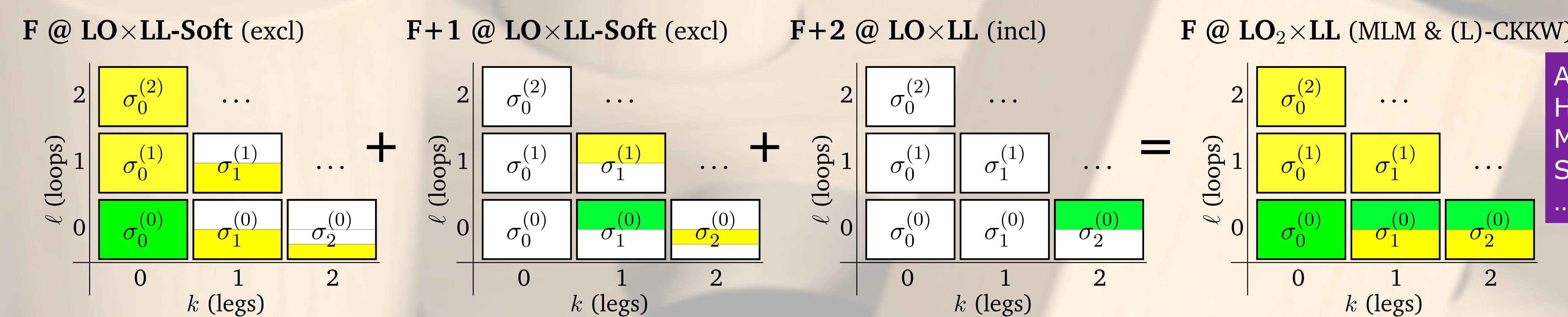

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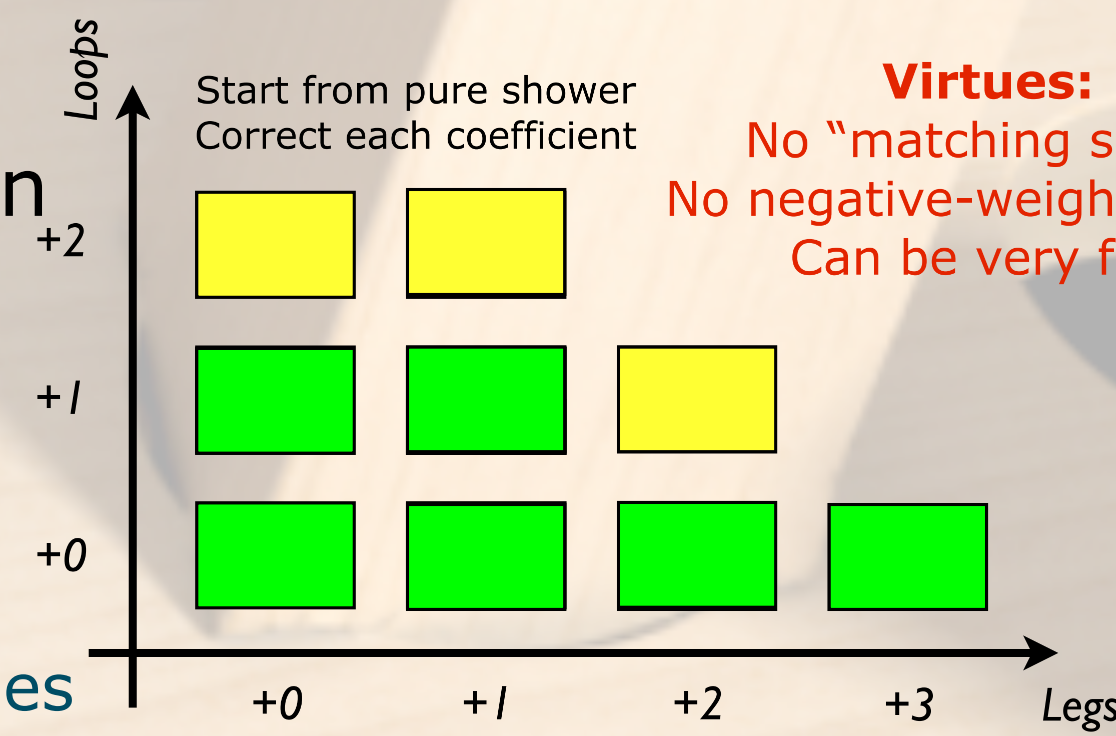

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Comparison : A Tale of Two Paradigms

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, …

Shower Paradigm: consider all possible physical processes (within perturbative QFT)

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

Hadronization

Hadronization

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

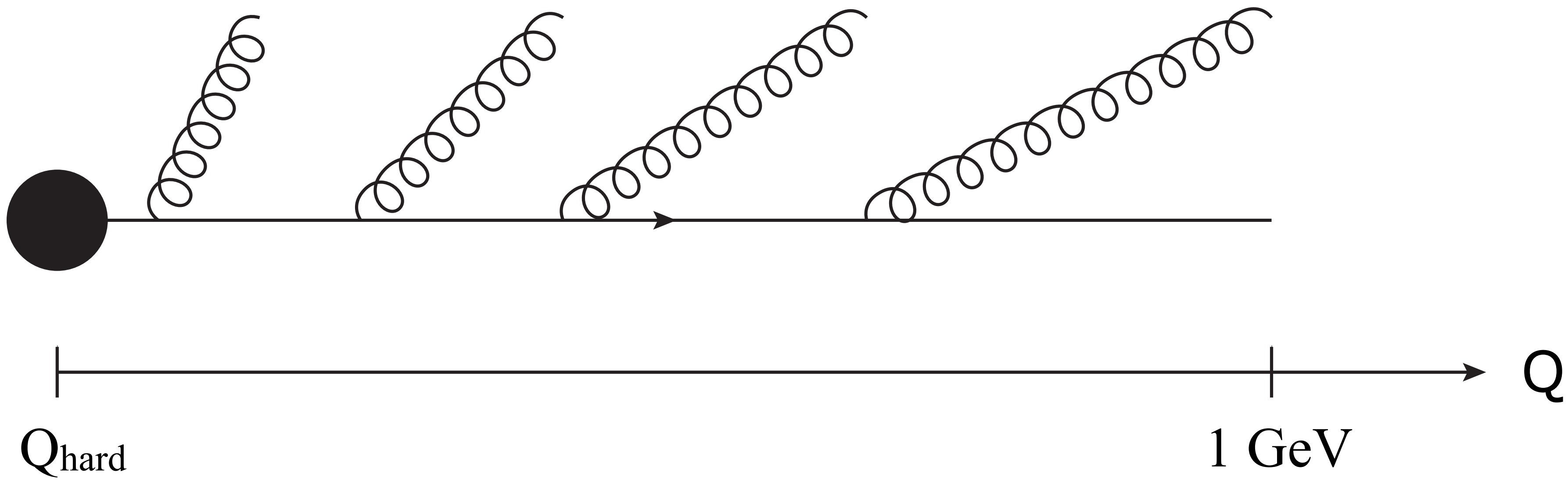
From Partons to Pions

… the fragmentation of a fast parton into a jet …

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

It showers (perturbative bremsstrahlung)

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



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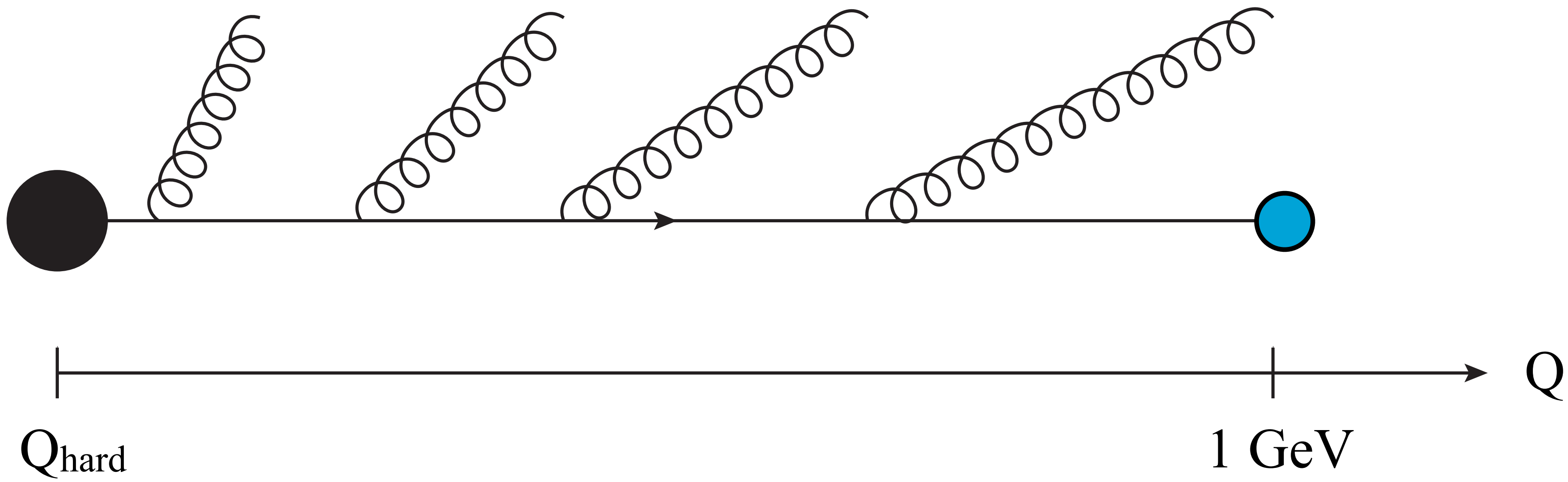

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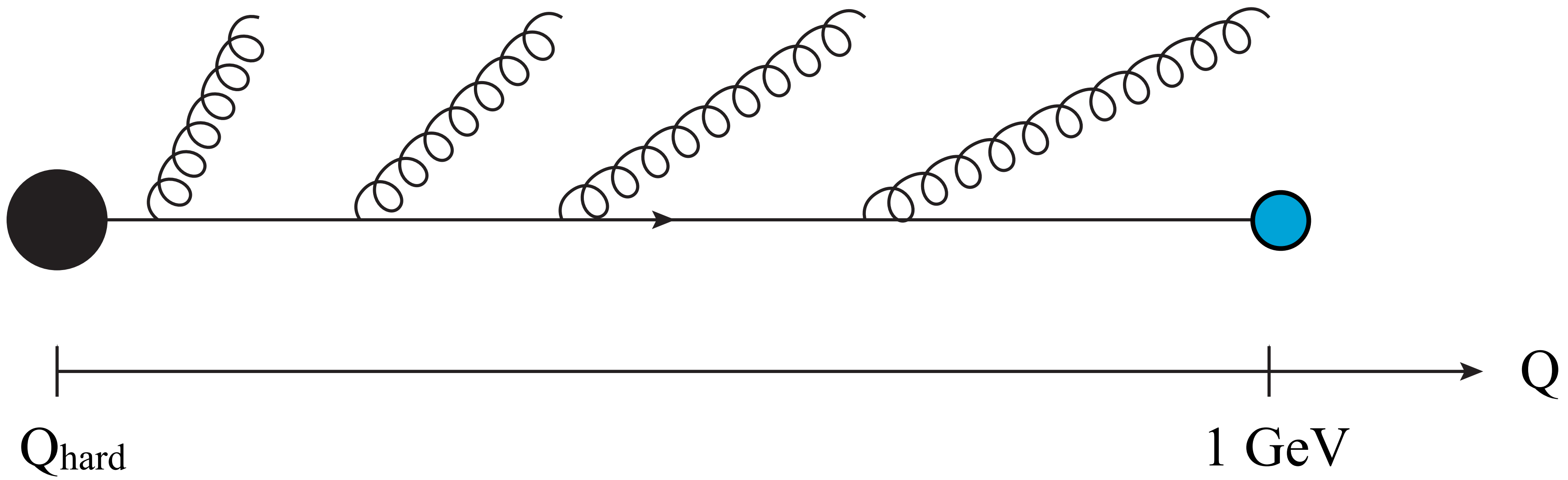


How about I just call it a hadron?

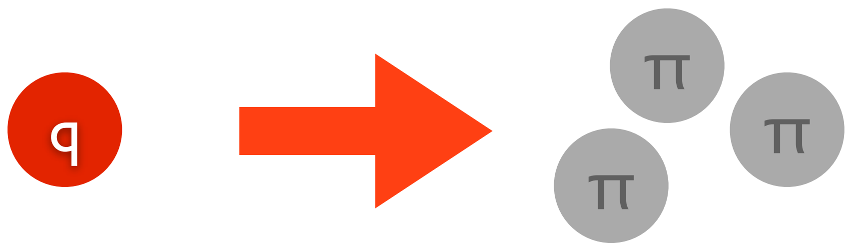
→ "Local Parton-Hadron Duality"

Parton → Hadrons?

Early models: "Independent Fragmentation"

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

Motivates a simple model:



But …

The point of confinement is that partons are coloured

Hadronization = the process of colour neutralization

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

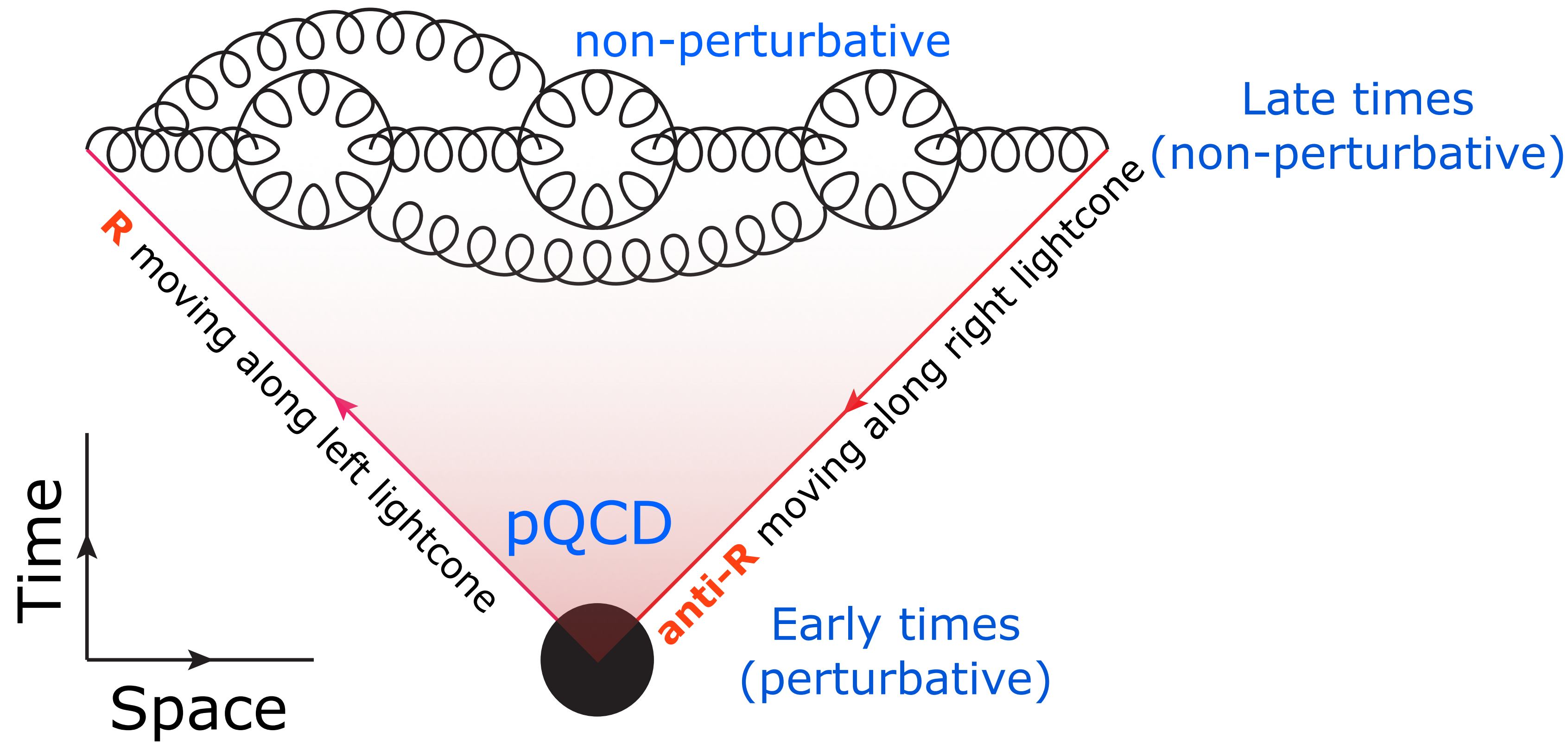
→ Too naive to see LPHD (inclusive) as a justification for Independent Fragmentation (exclusive)

→ More physics needed

Colour Neutralization

A physical hadronization model

Should involve at least **2** partons, with opposite color charges (e.g., **R** and **anti-R**)

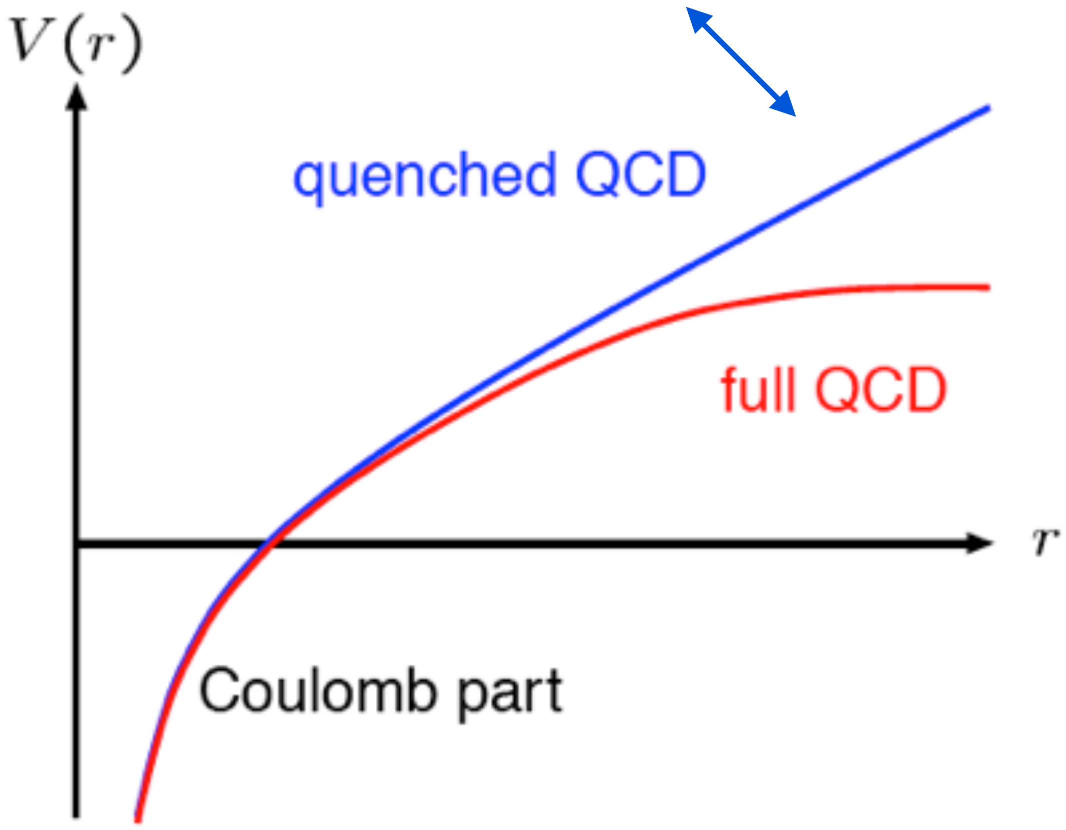


Strong “confining” field emerges between the two charges when their separation > ~ 1fm

Linear Confinement → Strings

Lattice QCD

Linear potential (without string breaks)



Illustrations by
T. Sjöstrand

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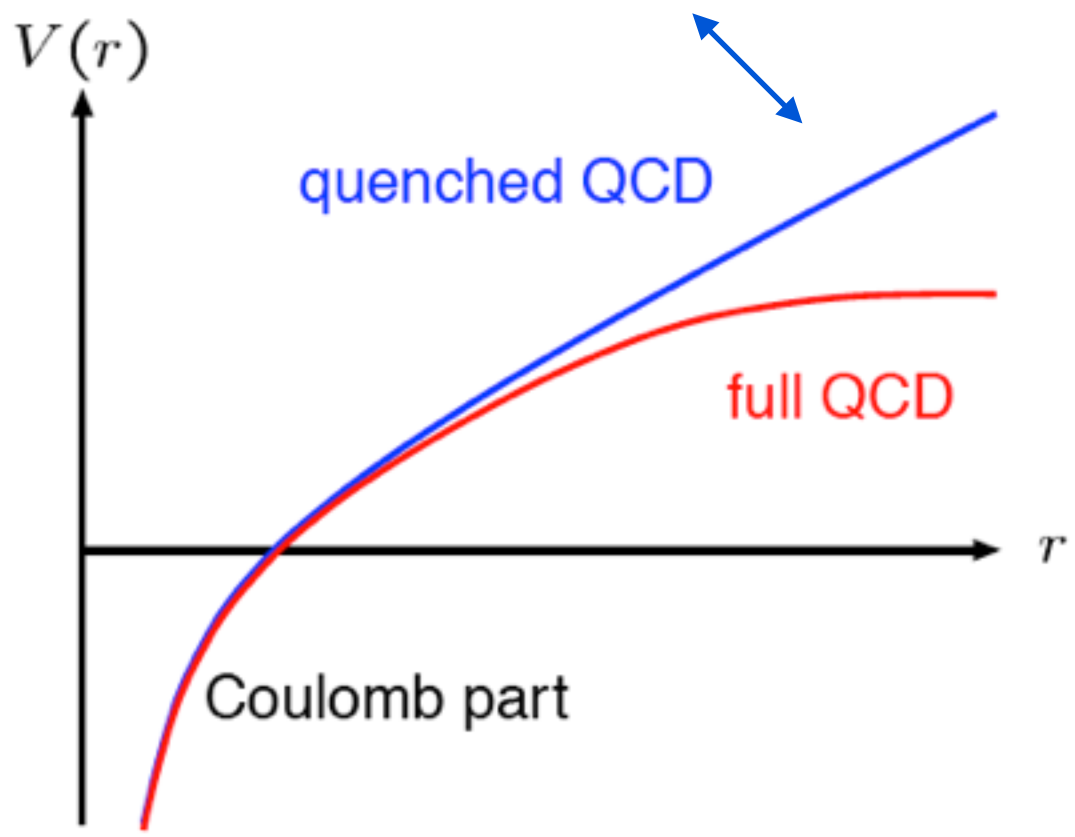

$F(r) \approx \mathrm{const} = \kappa \approx 1\ \mathrm{GeV/fm} \iff V(r) \approx \kappa r$

~ Force required to lift a 16-ton truck

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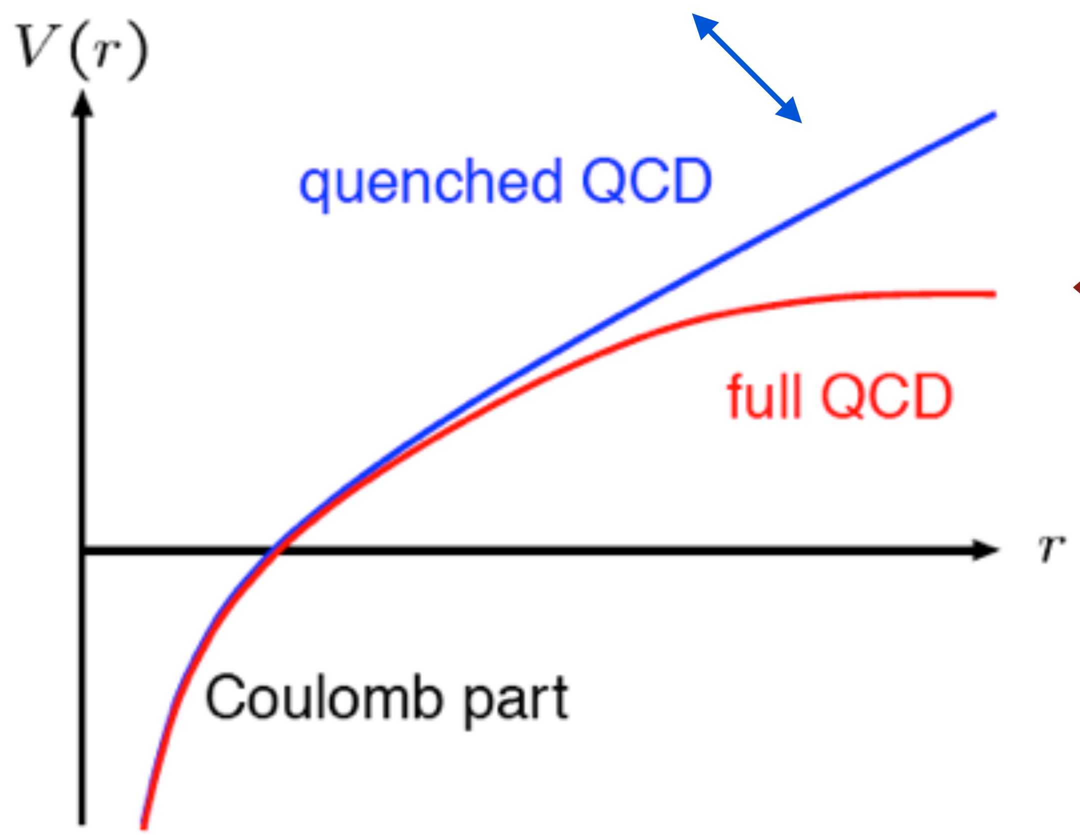

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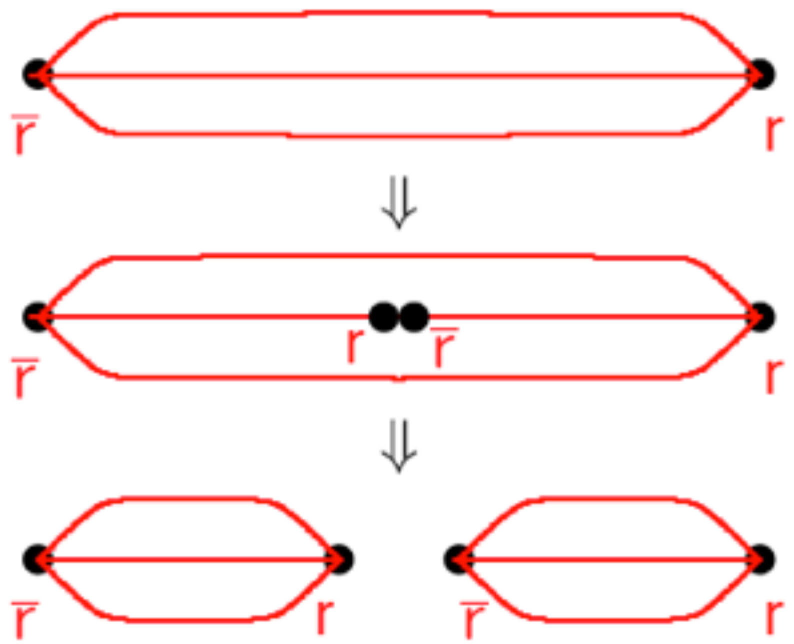
Lund Model

+ string breaks via Quantum Tunneling



(simplified colour representation)

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

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

Illustrations by T. Sjöstrand

Iterative String Breaks

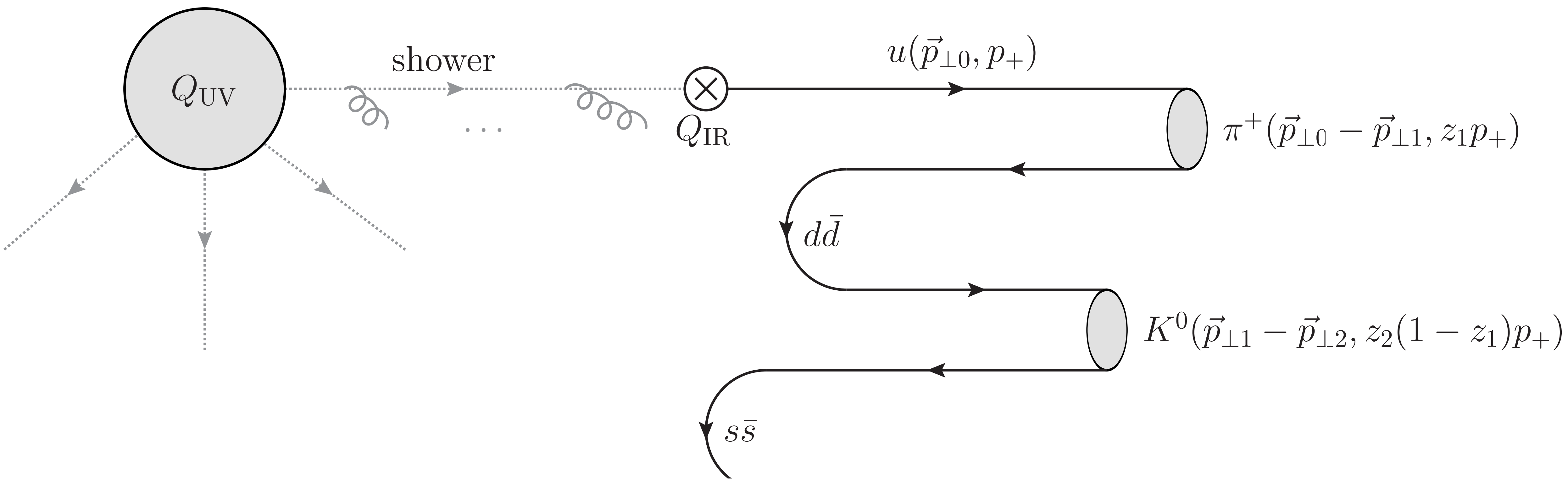
> … the fragmentation of a fast parton into a jet …

Iterate String → Hadron + String'

Causality + Left-Right Symmetry:

$$f(z) \propto \frac{1}{z}(1-z)^a \exp\left(-\frac{b\,(m_h^2 + p_{\perp h}^2)}{z}\right)$$

Lund Symmetric String Fragmentation Function



The Lund

Tuning

means different things to different people

Tuning

means different things to different people

10% agreement is great for (N)LO + LL

MB/UE/Soft: larger uncertainties since driven by non-factorizable and non-perturbative physics

Complicated dynamics: “If a model is simple, it is wrong” *(T. Sjöstrand)*

Recent PYTHIA Models/Tunes

Note: I focus on default / author tunes here
(Important complementary efforts undertaken by LHC experiments)

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PYTHIA 8.1

Current Default = **4C** (from 2010)

Tunes 2C & 4C: e-Print: arXiv:1011.1759

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Aims for the Monash 2013 Tune

Monash 2013 Tune: e-Print: arXiv:1404.5630

Set M13 Tune: → in PYTHIA 8

Tune:ee = 7
Tune:pp = 14

- Revise (and document) constraints from e^+e^- measurements
  - In particular in light of possible interplays with LHC measurements
- Test drive the new NNPDF 2.3 LO PDF set (with $\alpha_s(m_Z) = 0.13$) for pp & ppbar
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PYTHIA 6.4 (*warning:* no longer actively developed)

Perugia Tunes: e-Print: arXiv:1005.3457
(+ 2011 & 2012 updates added as appendices)

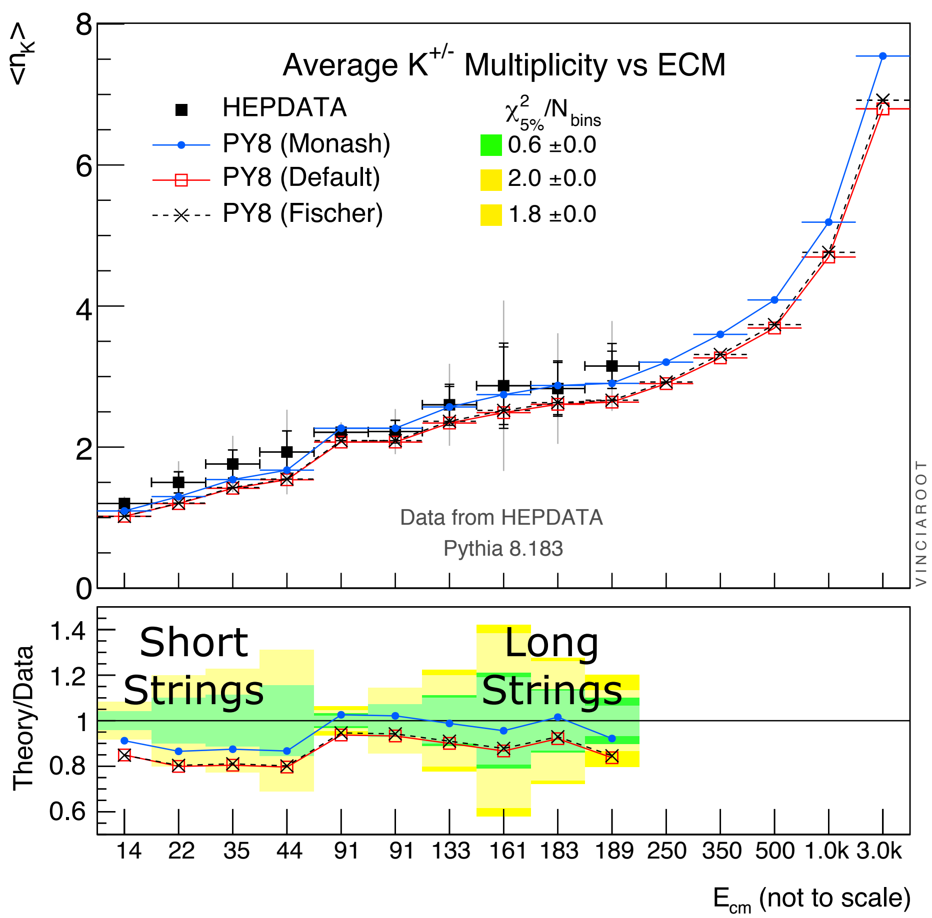
Default: still rather old Q^2-ordered tune ~ Tevatron Tune A

Most recent: Perugia 2012 set of p_T-ordered tunes (370 - 382) + Innsbruck (IBK) Tunes (G. Rudolph)

Monash 2013 Tune Highlights

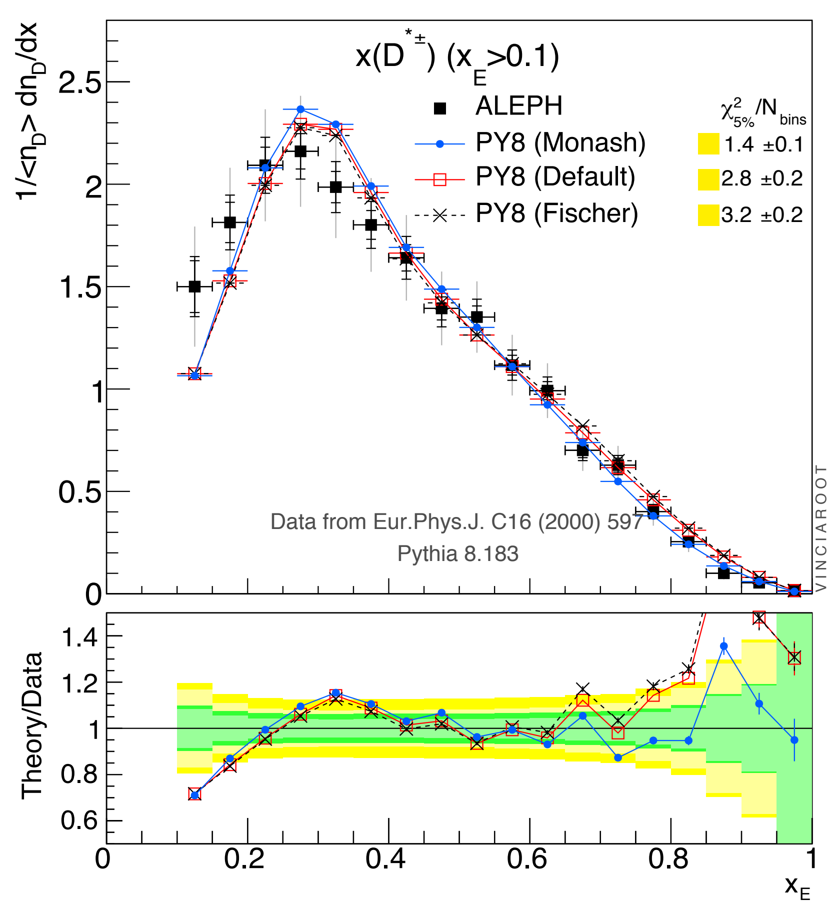
Monash 2013 Tune: e-Print: arXiv:1404.5630

10% more strangeness



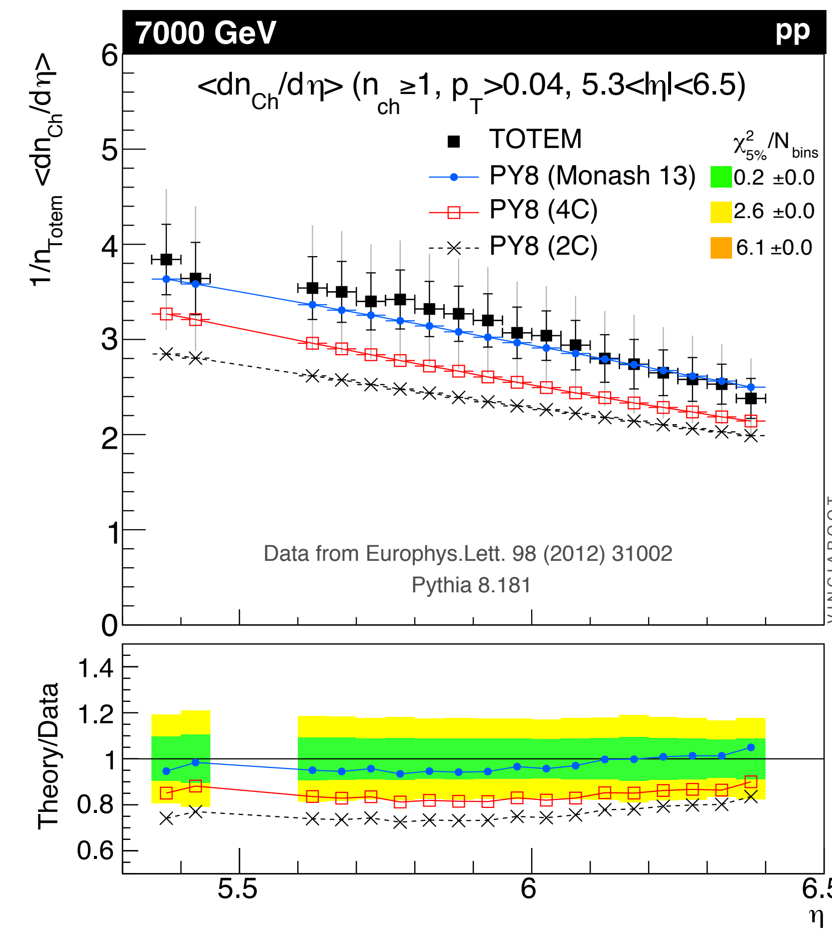
Better agreement with ee identified-strange measurements across all energies, and with Kaons at LHC

Softer D and B spectra near z = 1



Ultra-hard tail of c and b fragmentation agrees better with LEP and SLD, including event shapes in b-tagged events

More forward activity



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Monash 2013 Tune Highlights

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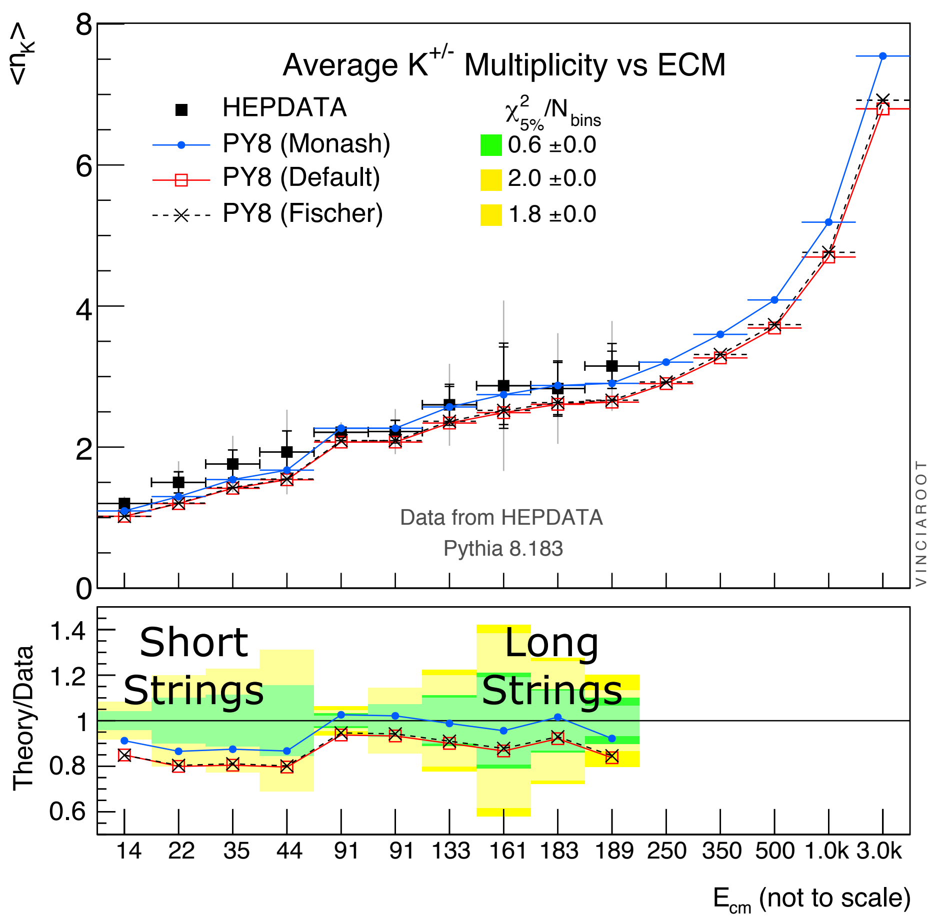

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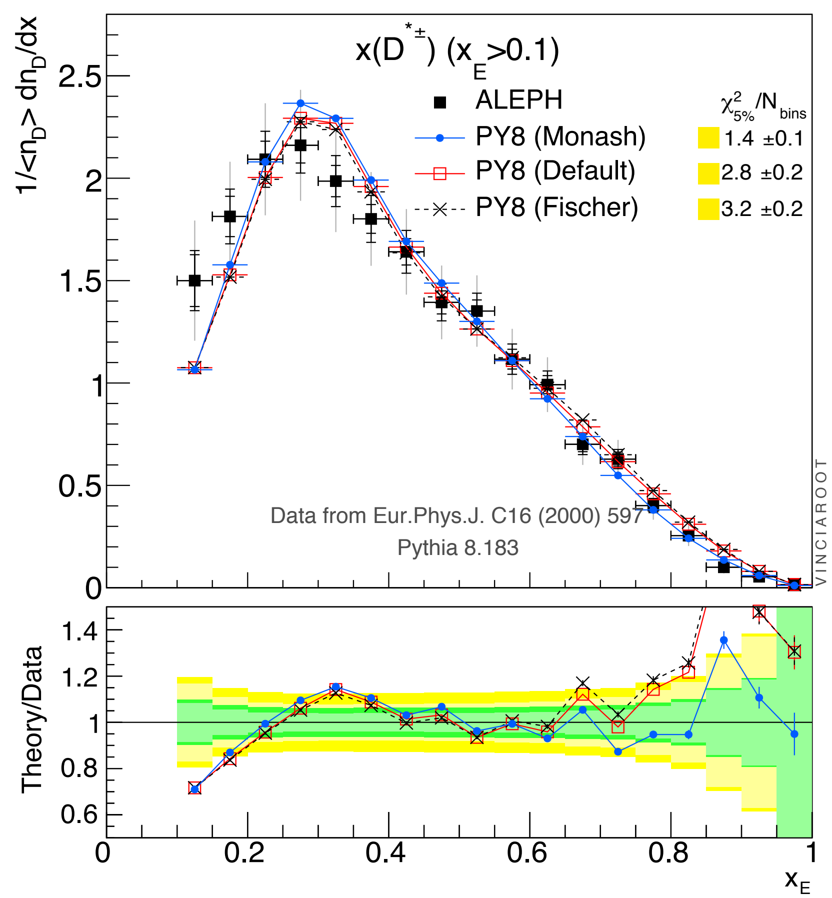

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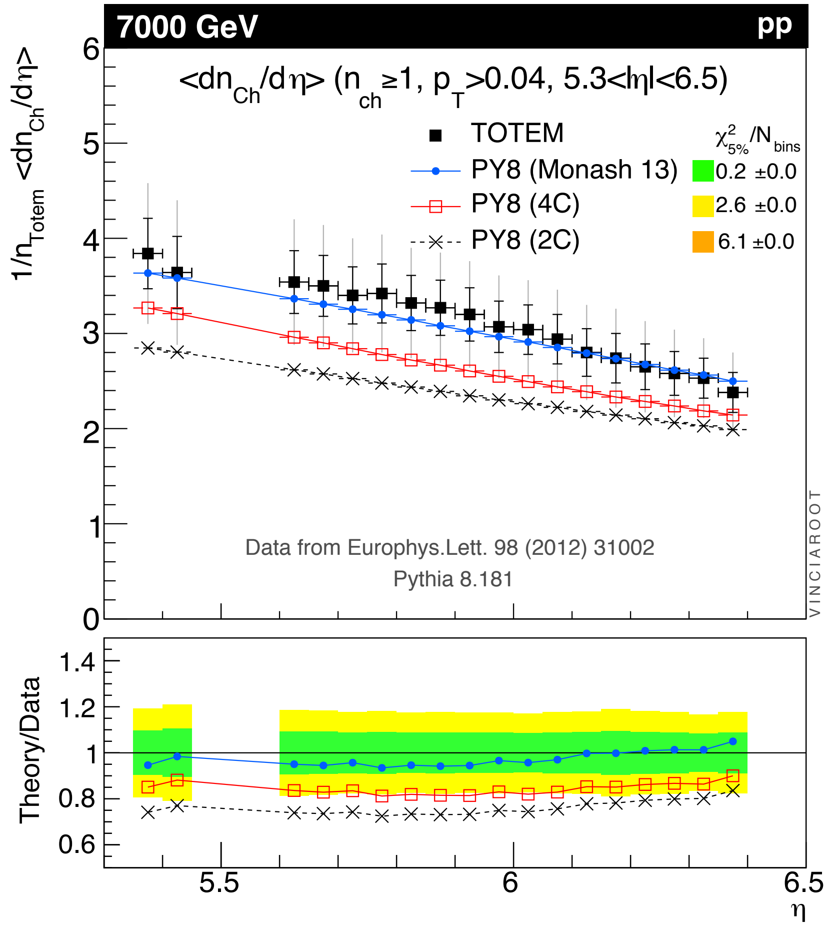

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Puzzles (a selection of)

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Monash
Warwick
Alliance

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The physics and consequences of Colour Reconnections (vs Flow?) ↔ Top Quark Mass

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Gluon/Quark discrimination and G→QQ splittings in gluon jets

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.

Emergent QCD phenomena: **Jets, Strings, Hadrons**

Non-perturbative QCD is still hard

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

Lots of input from LHC to spur model building. **Aims for run 2?**

"Solving the LHC" is both interesting and rewarding

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

Key to high precision → max information about the Terascale

What's the evolution kernel?

DGLAP splitting functions

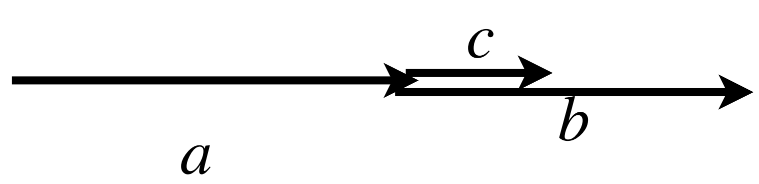
Can be derived from *collinear limit* of MEs $(p_b+p_c)^2 \rightarrow 0$

\+ evolution equation from invariance with respect to Q_F → RGE

DGLAP

(E.g., PYTHIA)

$$\mathrm{d}\mathcal{P}_a = \sum_{b,c} \frac{\alpha_{abc}}{2\pi} P_{a\to bc}(z)\,\mathrm{d}t\,\mathrm{d}z\ .$$



$p_b = z\, p_a$

$p_c = (1\text{-}z)\, p_a$

$$\begin{aligned}
P_{\mathrm{q}\to\mathrm{qg}}(z) &= C_F \frac{1+z^2}{1-z}\ ,\\
P_{\mathrm{g}\to\mathrm{gg}}(z) &= N_C \frac{(1-z(1-z))^2}{z(1-z)}\ ,\\
P_{\mathrm{g}\to\mathrm{q\bar{q}}}(z) &= T_R\,(z^2+(1-z)^2)\ ,\\
P_{\mathrm{q}\to\mathrm{q}\gamma}(z) &= e_{\mathrm{q}}^2 \frac{1+z^2}{1-z}\ ,\\
P_{\ell\to\ell\gamma}(z) &= e_{\ell}^2 \frac{1+z^2}{1-z}\ ,
\end{aligned}$$

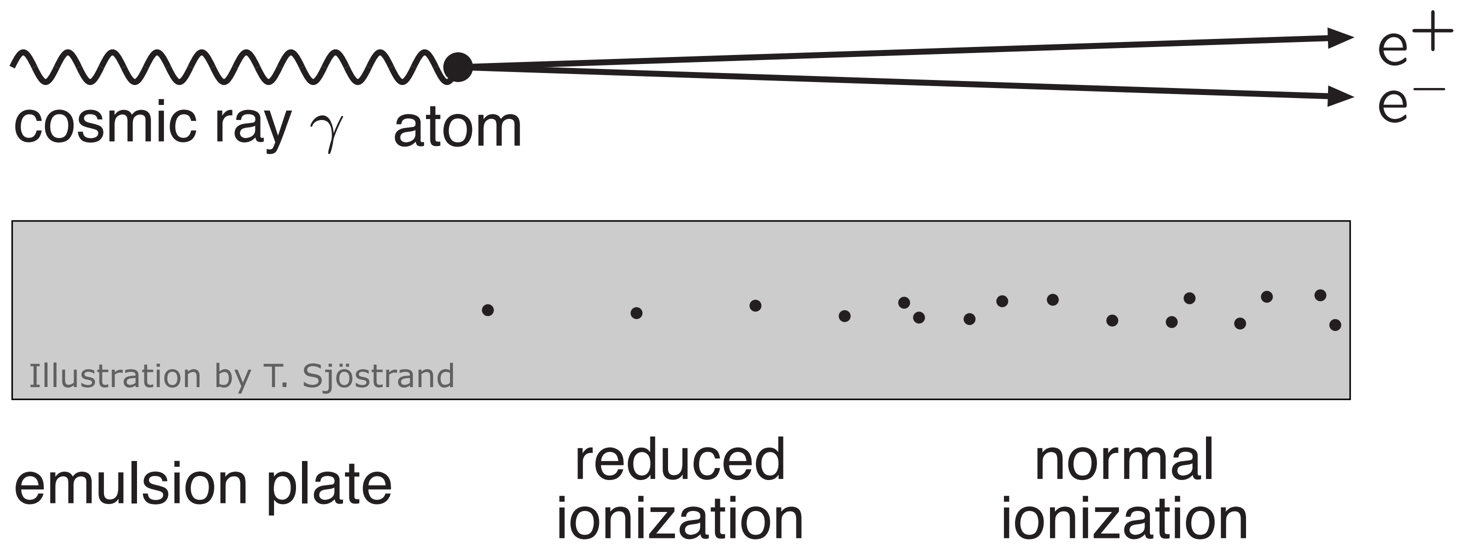
$$\mathrm{d}t = \frac{\mathrm{d}Q^2}{Q^2} = \mathrm{d}\ln Q^2$$

… with Q^2 some measure of "hardness"
= event/jet resolution
measuring parton virtualities / formation time / …

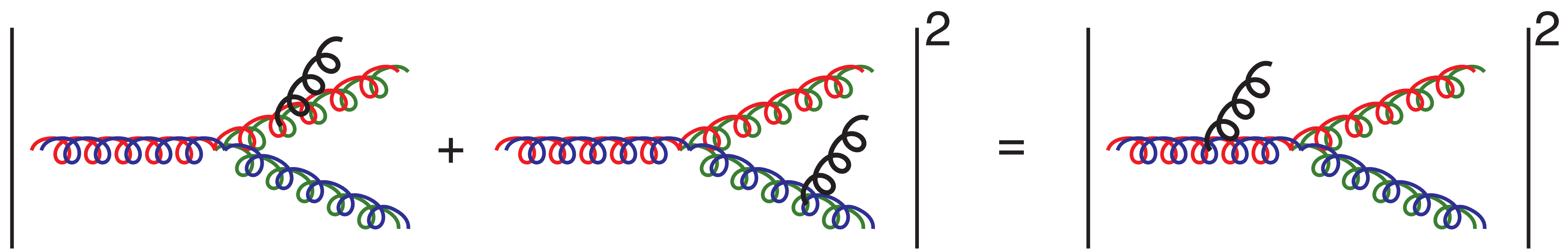
Note: there exist now also alternatives to AP kernels (with same collinear limits!): dipoles, antennae, …

Coherence

QED: Chudakov effect (mid-fifties)



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

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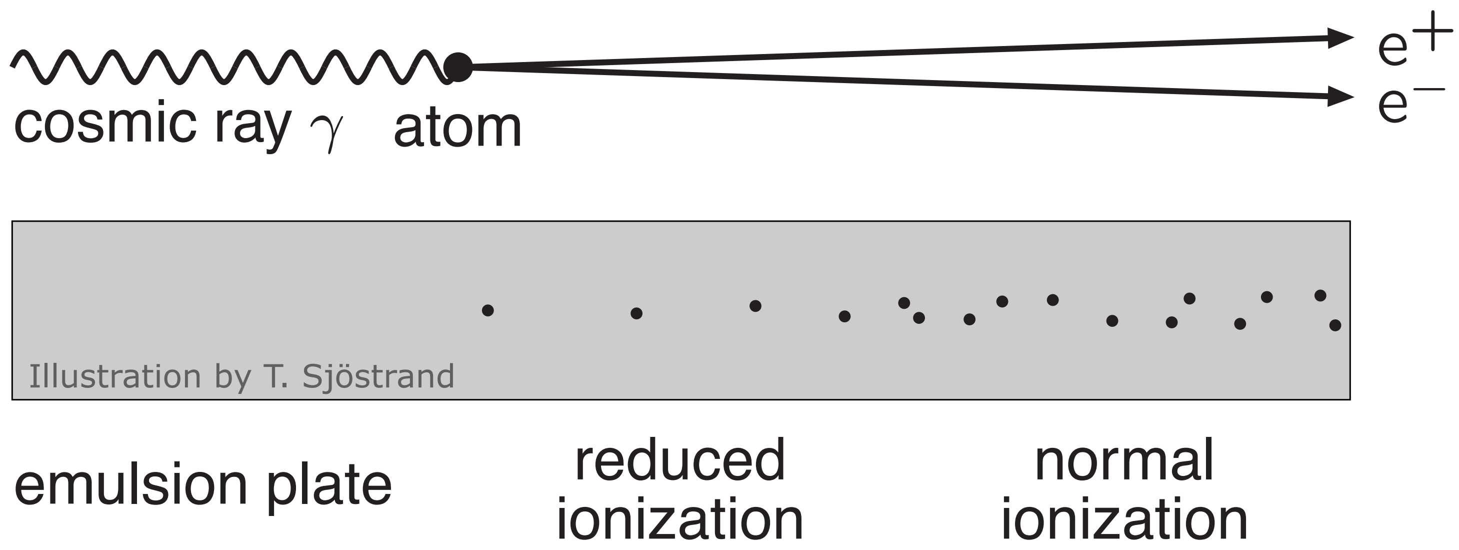


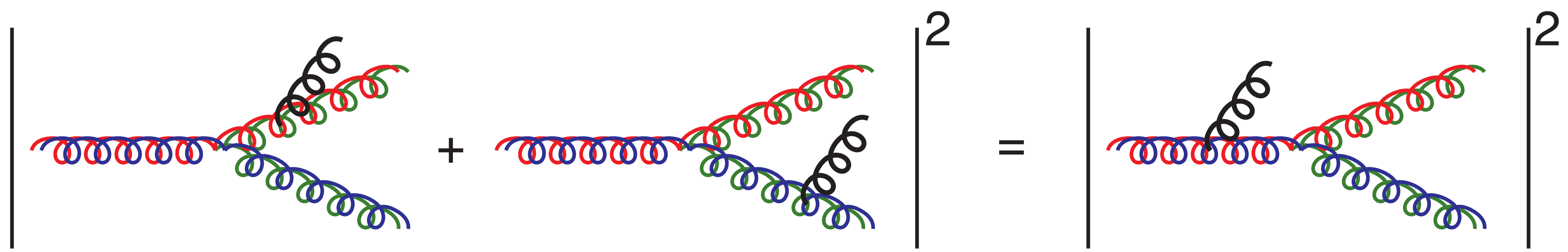
Approximations to Coherence:

Angular Ordering (HERWIG)

Angular Vetos (PYTHIA)

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

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



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

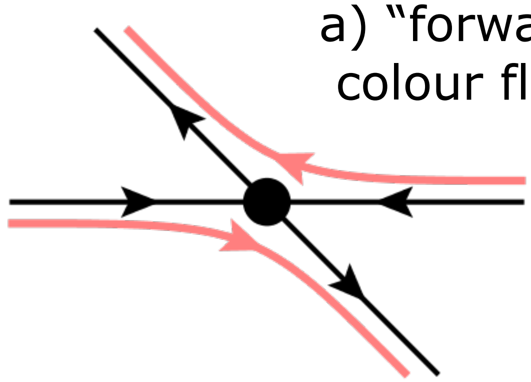
Example taken from: Ritzmann, Kosower, PS, PLB718 (2013) 1345

Example: quark-quark scattering in hadron collisions

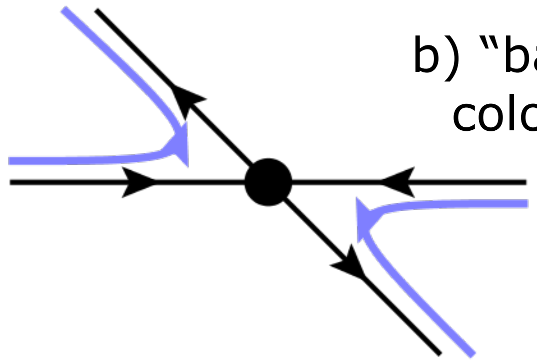
Consider one specific phase-space point (eg scattering at 45^{o})

2 possible colour flows: a and b

a) "forward" colour flow



b) "backward" colour 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

Coherence at Work

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

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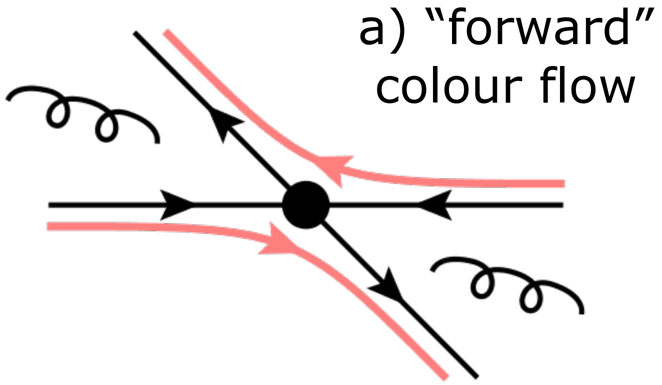

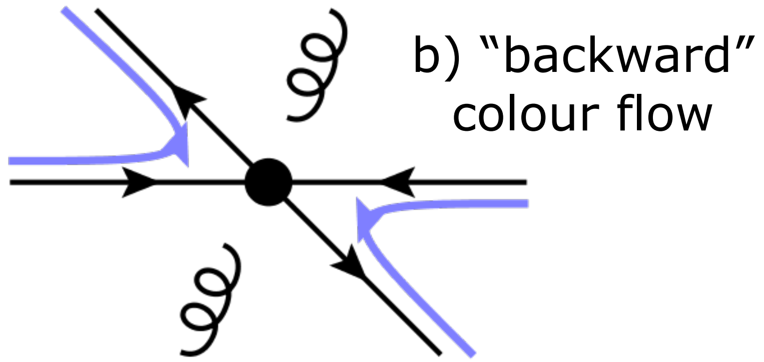

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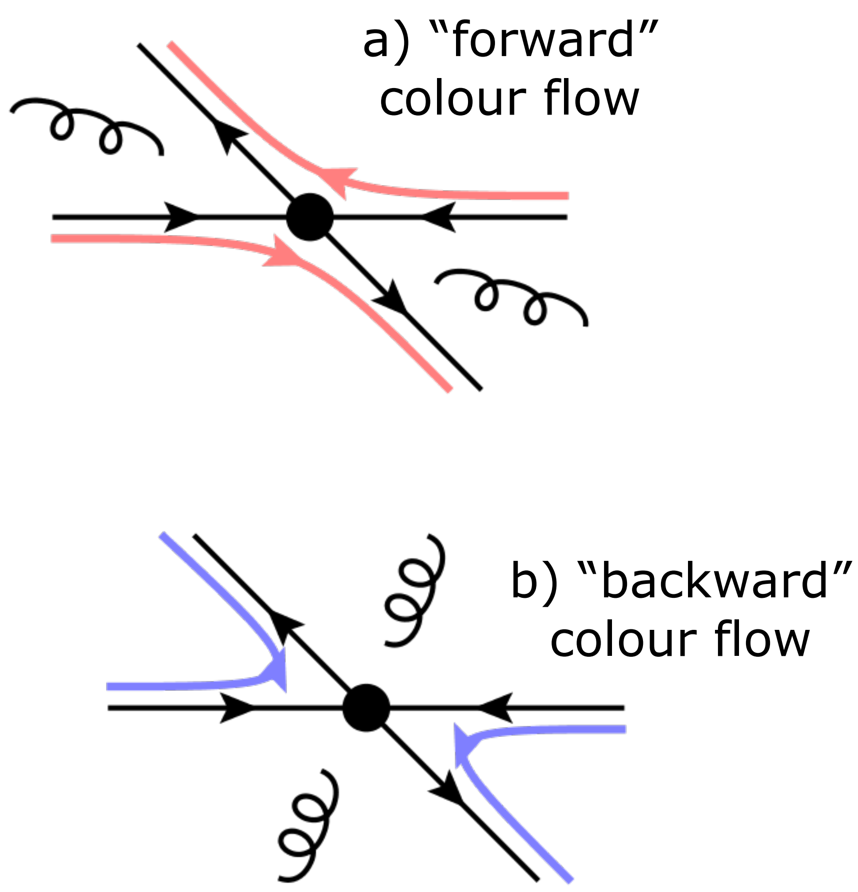


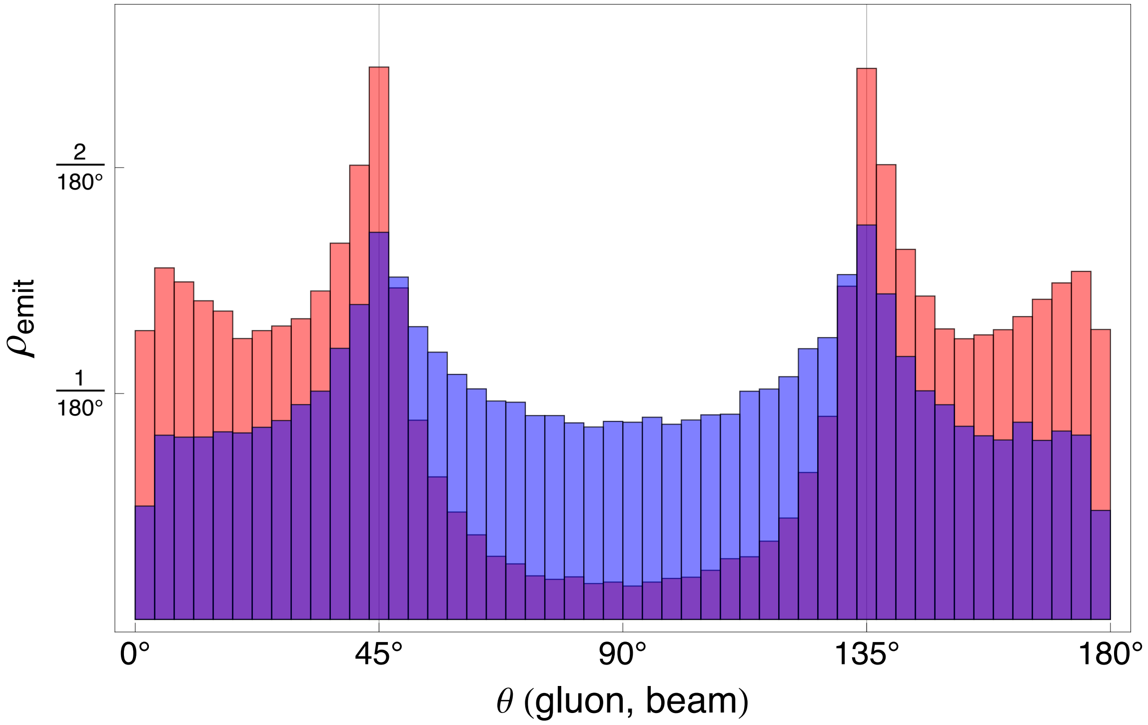
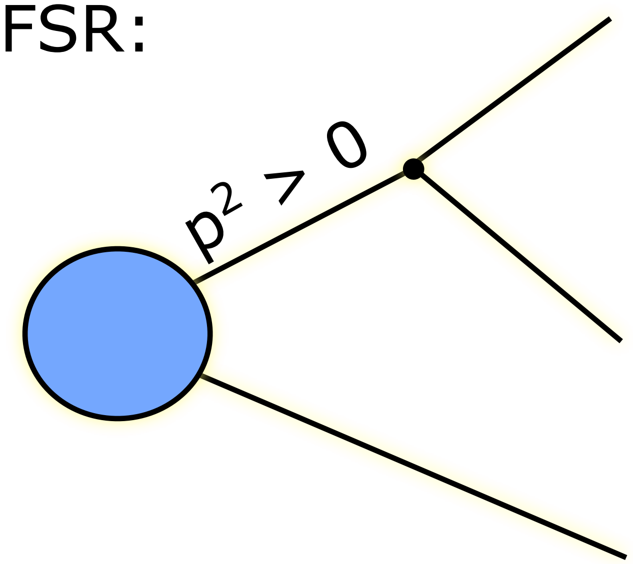


Figure 4: Angular distribution of the first gluon emission in $qq \to qq$ scattering at 45°, for the two different color flows. The light (red) histogram shows the emission density for the forward flow, and the dark (blue) histogram shows the emission density for the backward flow.

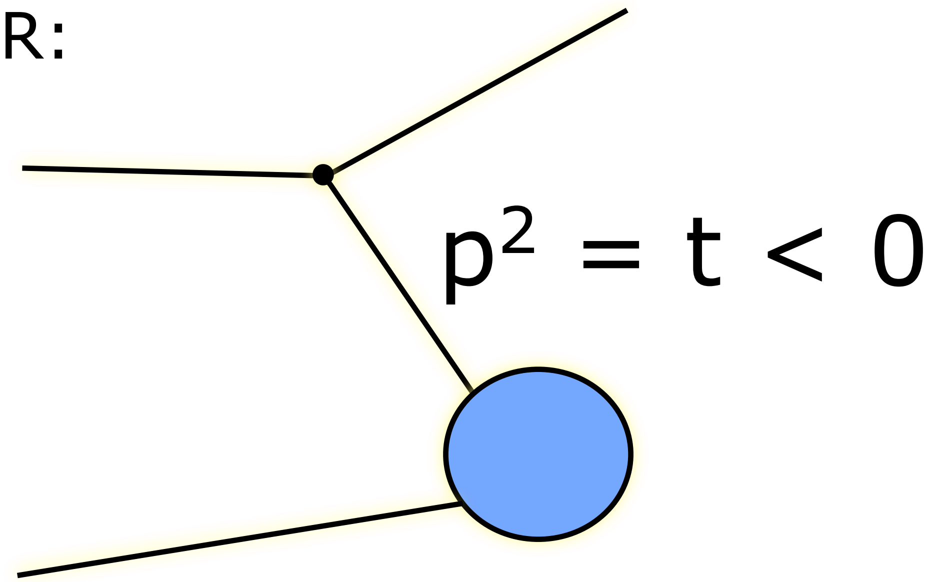
Another good recent example is the SM contribution to the Tevatron top-quark forward-backward asymmetry from coherent showers, see: PS, Webber, Winter, JHEP 1207 (2012) 151

Initial-State vs Final-State Evolution

FSR:



ISR:



Virtualities are Timelike: $p^2>0$

Start at $Q^2 = Q_F^2$
"Forwards evolution"

Virtualities are Spacelike: $p^2<0$

Start at $Q^2 = Q_F^2$
Constrained backwards evolution towards boundary condition = proton

Separation meaningful for collinear radiation, but not for soft …