Vision for QCD in the 2030s and Beyond

DIS XXVIII: April 12-16, 2021
George Sterman
Stony Brook University

1. **Looking to the Future of QCD Studies**
2. **QCD in the Grand Scheme of Things**
3. **How We Learned to Look Closely and from Afar**
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1. Looking to the Future of QCD Studies

- This talk isn't meant to be an exercise in prediction, and 2030 is still a long way off. The study of quantum chromodynamics, however, is largely driven by evolving experimental capabilities, so we have some sense of what may happen in the meantime.

- Ten years ago, the last of the great Standard Model discovery machines, the Tevatron, closed up shop, following LEP and HERA, while RHIC entered its second fruitful decade. The decade just past saw the historic LHC Runs I and II, as CEBAF transitioned from 6 to 12 GeV at Jefferson Lab.

- Starting with RHIC, many accelerator capabilities have been designed with QCD in mind, at JLab of course, and in the decade unfolding, the EIC. The LHC wasn't built for QCD, but the insightful designs of its detectors make it (of necessity) a powerful QCD machine.

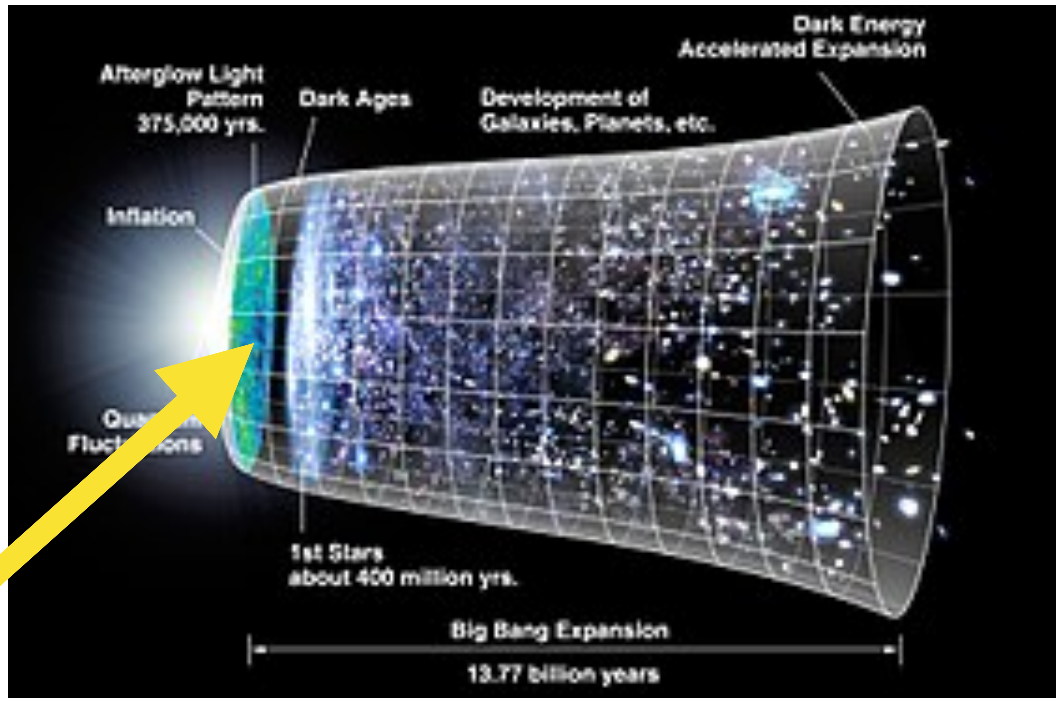
- Over the past twenty years, QCD has brought nuclear and particle physics (back) together. Roads from Newport News and Upton lead to Geneva (and back).

- The specifically QCD experimental capabilities that will link the 2020s and the 2030s, including fixed target experiments at Fermilab, JLab, CERN and Brookhaven, have already paved the way for the Electron Ion Collider project, based on the demonstrated need for high statistics to reveal the structure of the nucleon, and high energy to unlock the dense gluonic matter from which the mass of the visible universe is generated.

- That same energy is needed to provide a window into the emergence of hadronic from partonic matter.

- The story that follows is one sketch of some lessons we have learned about QCD's role in nature, and some we may hope to learn in the coming years.

2. QCD In the Grand Scheme of Things



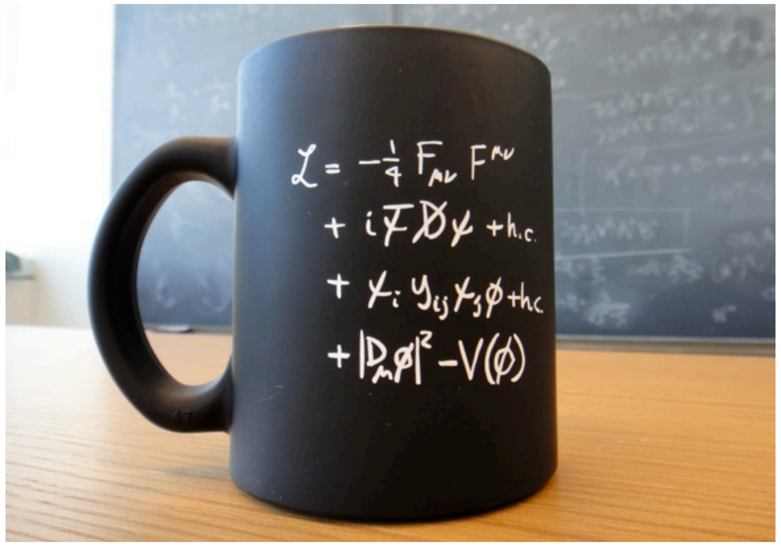
Very early on, quarks and gluons secluded themselves to a nearly vanishingly small, and ever-decreasing, proportion of space, occupying something like

one 10^{-45} th

of the volume of the observable universe.

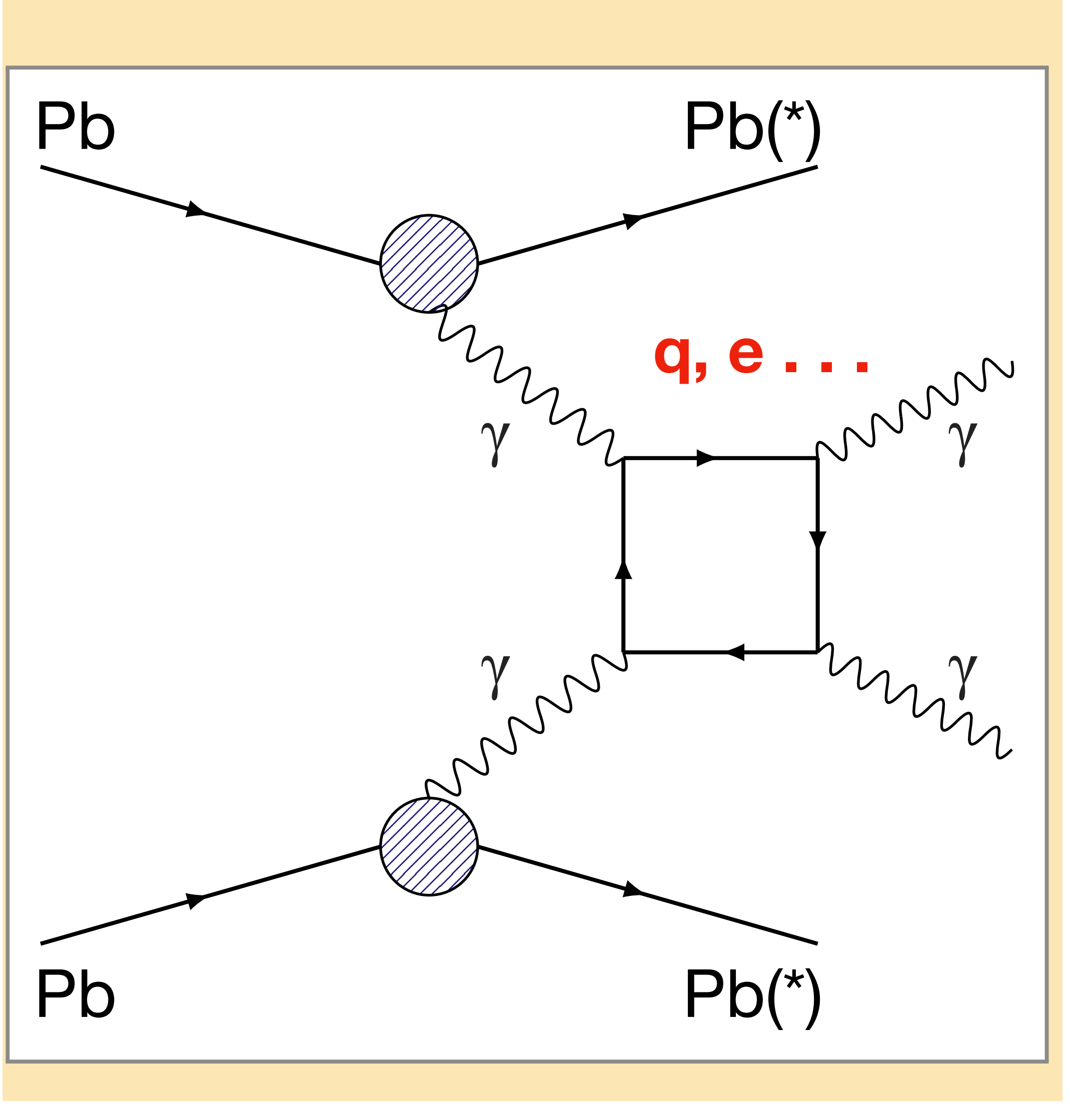
The reason, so far as we understand it, lies in the nonabelian phase invariance of the quarks: three utterly indistinguishable colors, connected by gluonic excitations. This, of course, is QCD.

From inside nuclei, the quarks speak to the outside world through the rest of the Standard Model. Nucleons and nuclei give electrons a reason to stick around and form the world we can see.



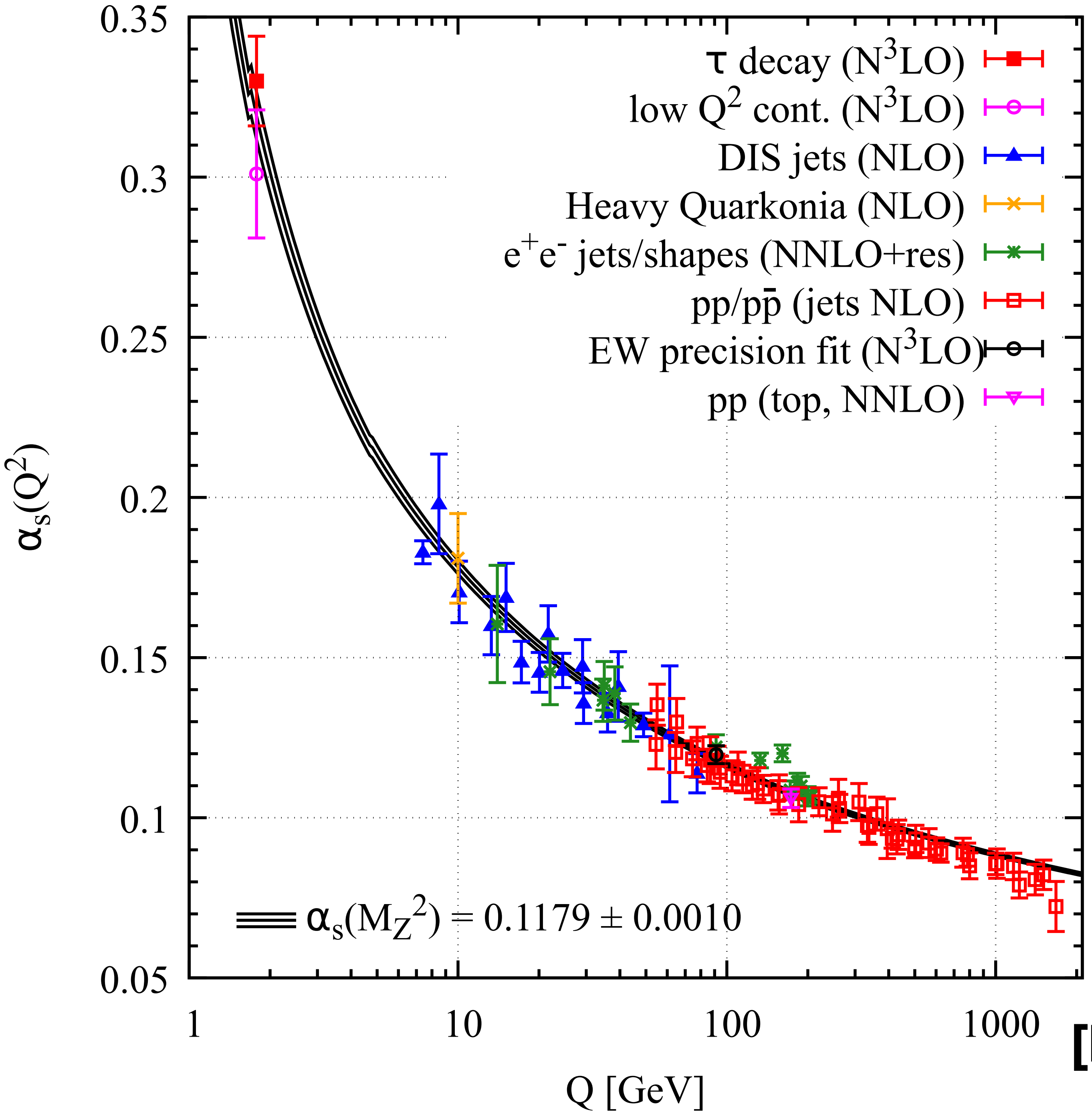
[Dawson]

But the QCD degrees of freedom are always available, lurking in the vacuum, ready to lend a hand and work alongside the rest of the Standard Model, whenever enough energy arrives in the neighborhood.



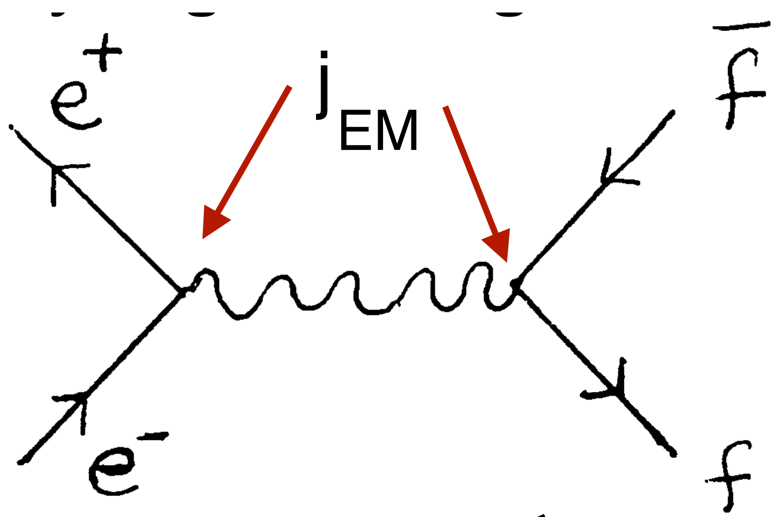
[Lappi]

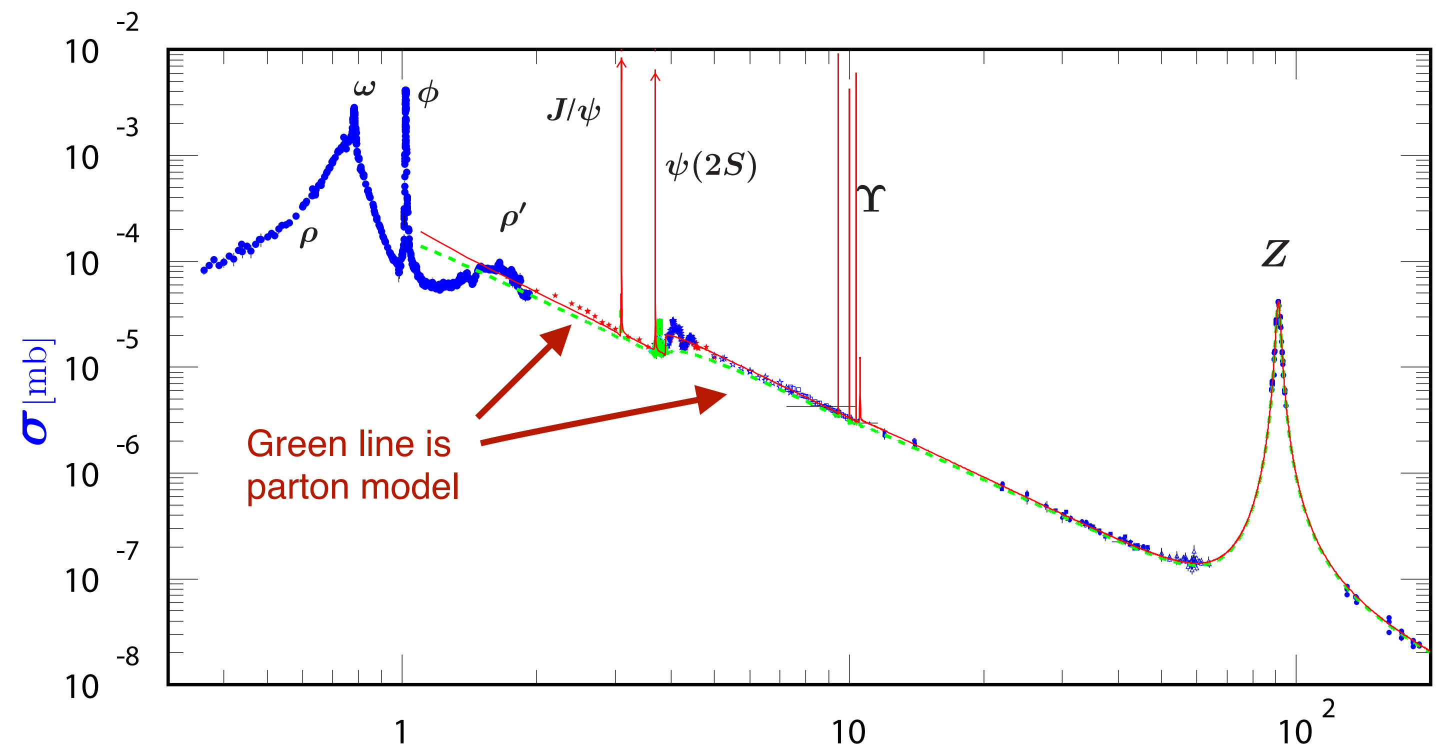
The very same theory possesses asymptotic freedom, which has opened windows to its fundamental degrees of freedom.



[PDG]

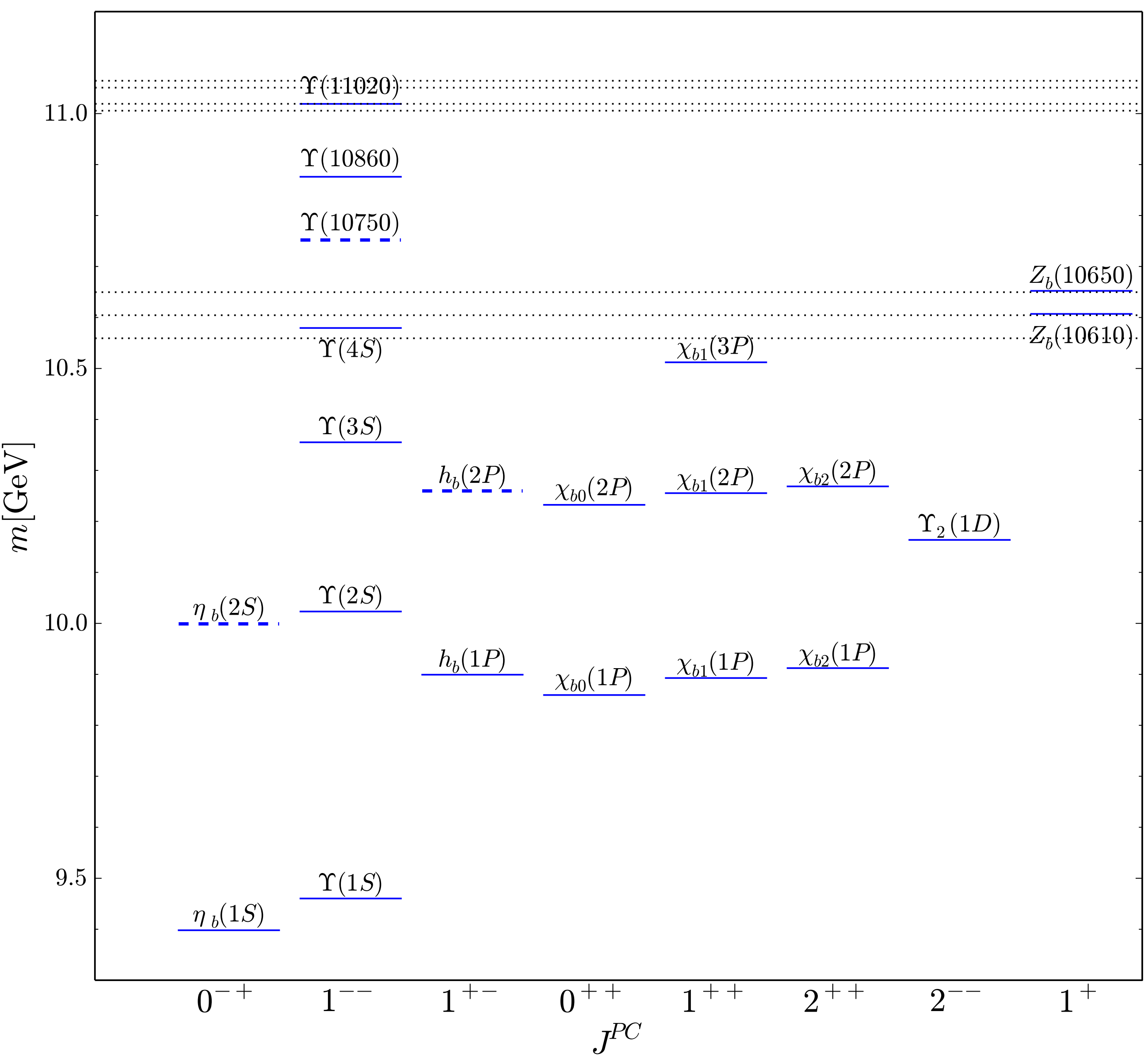
Just knowing that QCD is asymptotically free is enough to get a good estimate of an important physical process as if the theory were free:





While at long distances forming only bound states, the meson, baryons and exotics

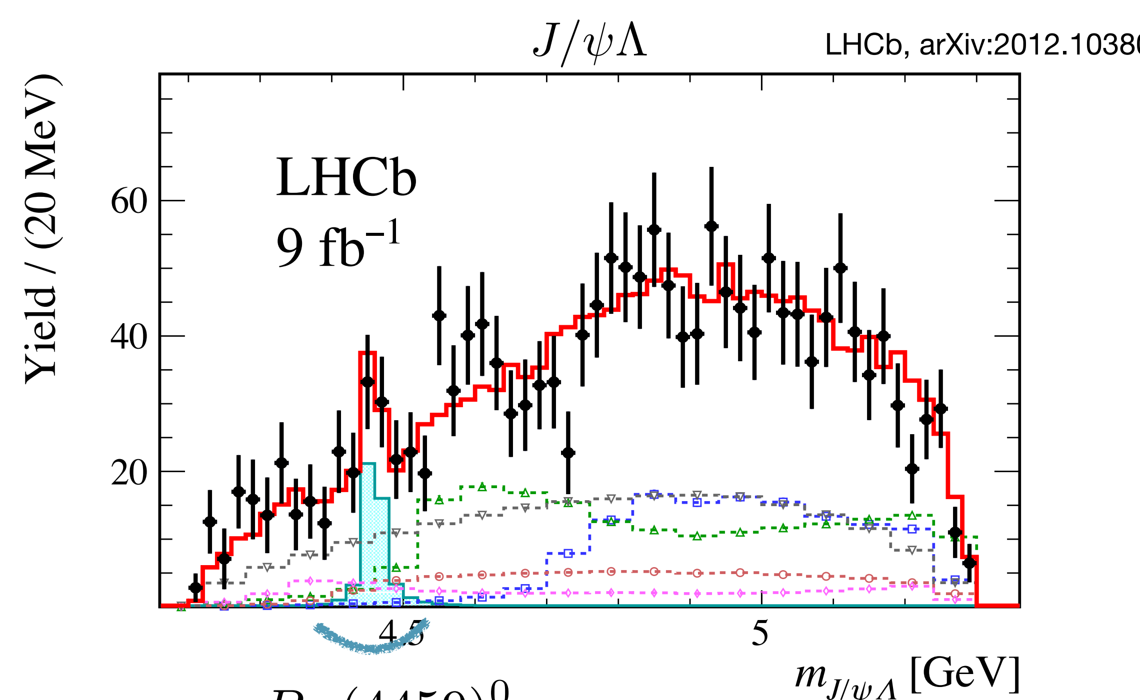
bottomonium spectrum



N. Brambilla et al., Phys. Rep. 873 (2020) 1–154

Search for pentaquark with strangeness: $\Xi_b^- \to J/\psi \Lambda K^-$

$udsc\bar{c}$



$P_{cs}(4459)^0$

significance: 3.1 σ

[van Hulse]

3. Looking Closely and from Afar

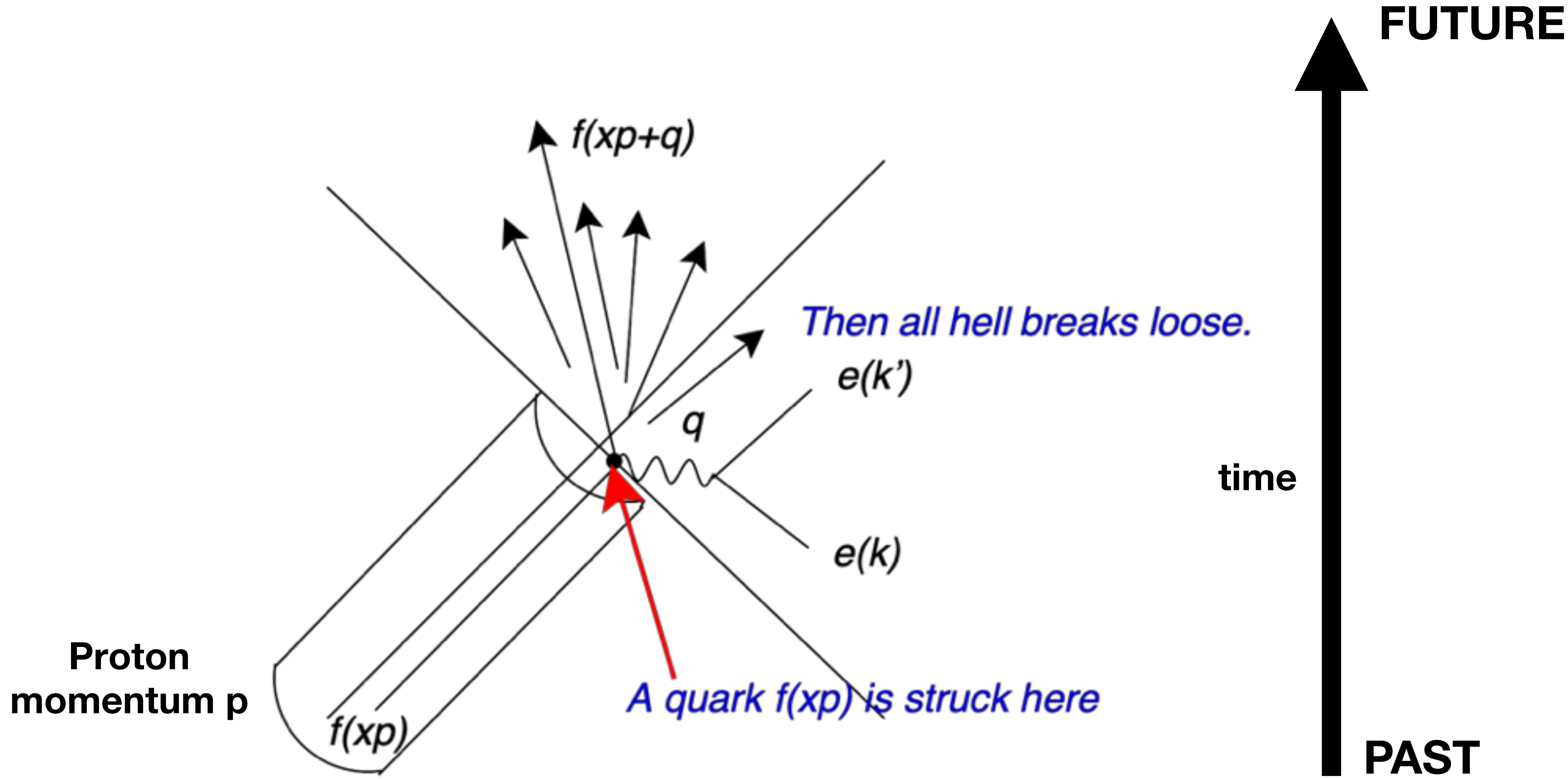
partonic process
(perturbative)

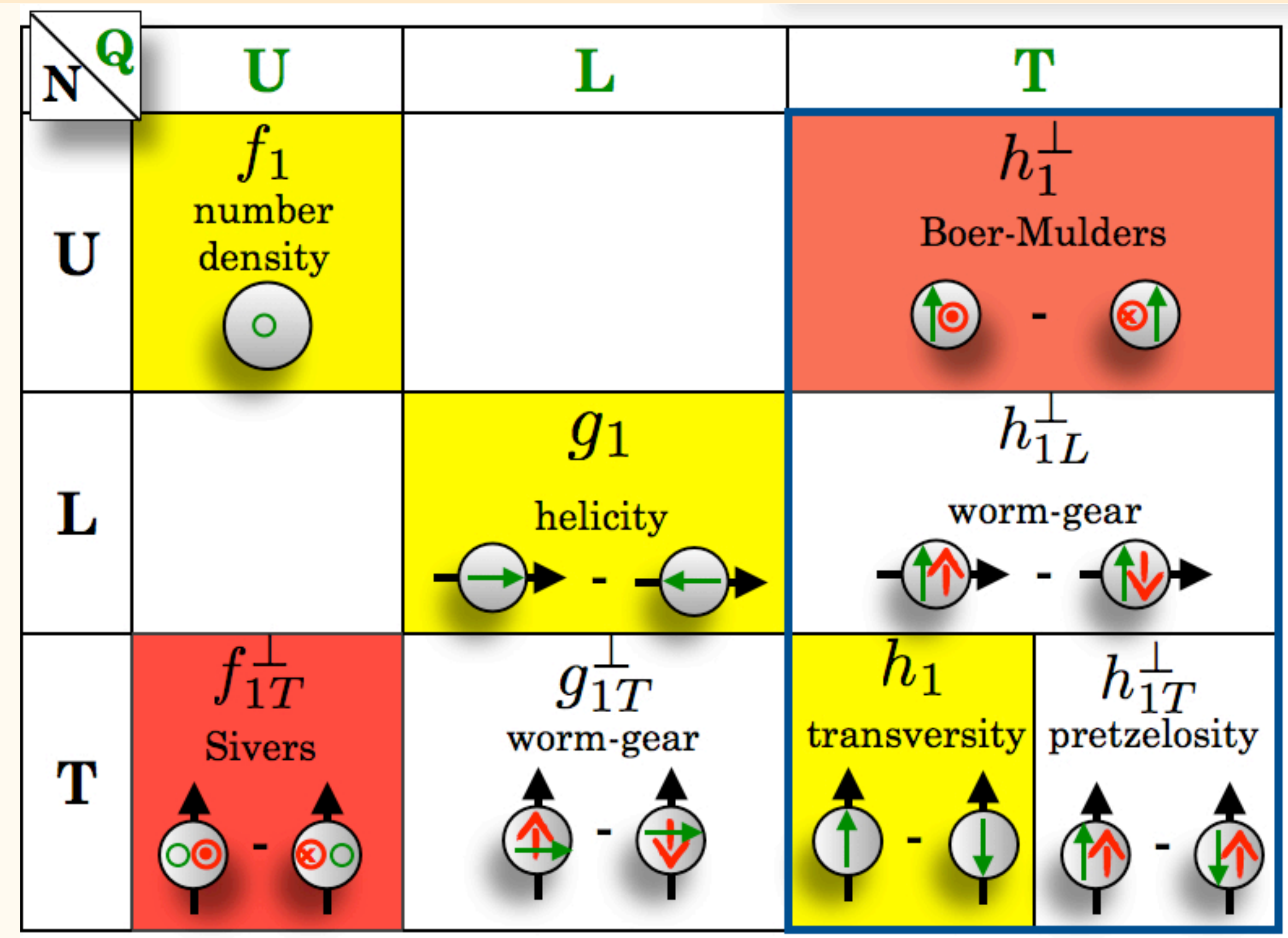
S = C x F

hadronic
matrix element
(nonperturbative)

The "universal" form of hard-scattering observables
"Factorization" for cross sections and amplitudes.

Picturing a typical "deep inelastic" ep event, in the usual variables

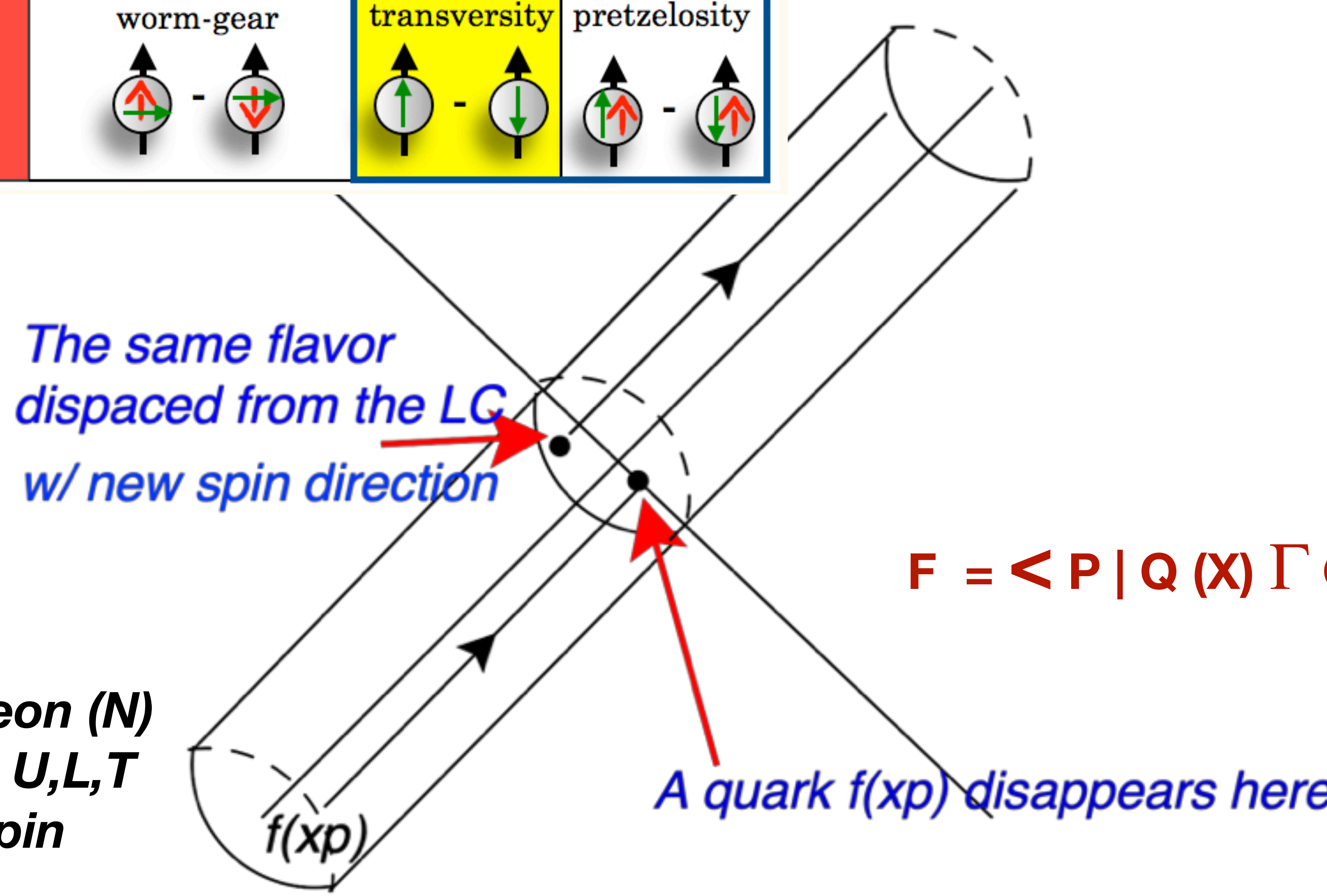




Yet appropriate sums over final states provide measurements of nucleon (spin) structure

The same proton in the future.

[Riedl]



A proton in the past.

TIME

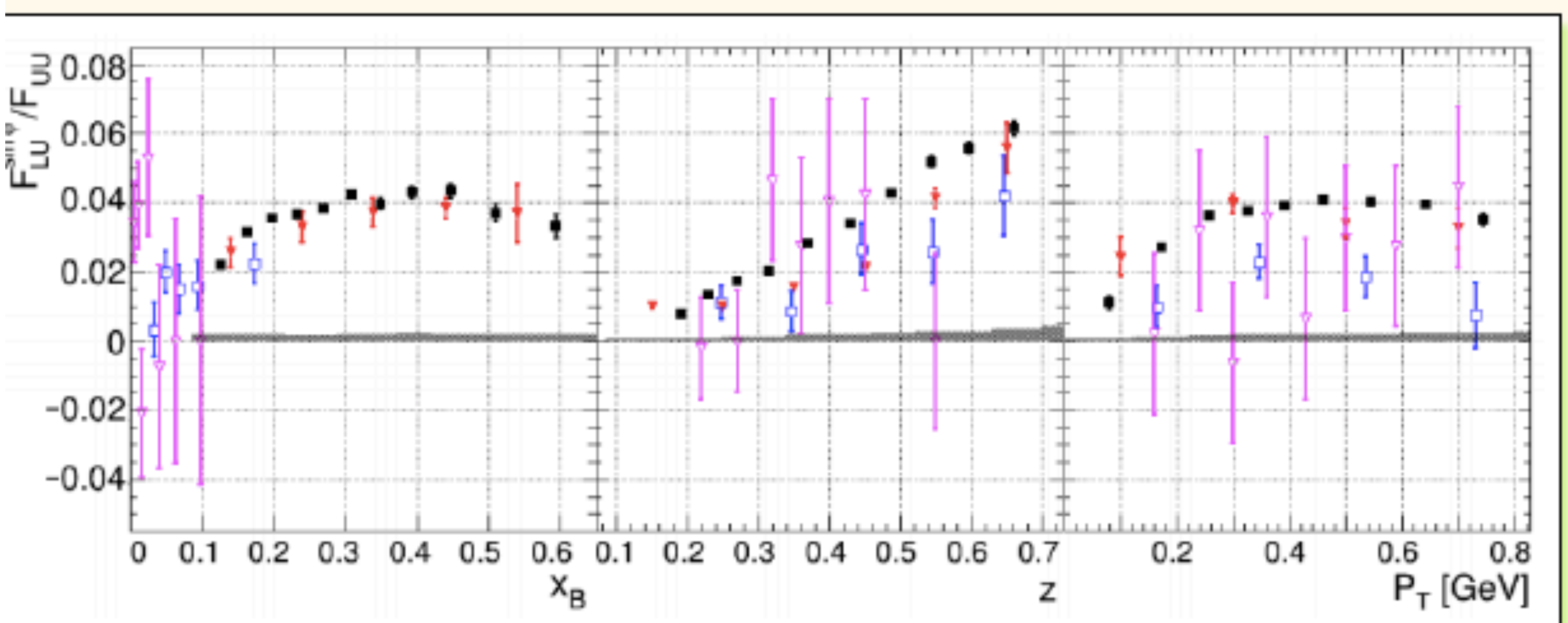
F = < P | Q (X) Γ Q(0) | P >

But S = C x F is only the first term in a series expansion in momentum transfer. “Higher twist”

terms involve more fields, like: $(1/Q)\ \langle P\,|\,Q(X)\ \Gamma\ G(y)\ Q(0)\,|\,P\rangle$

For some observables, its the leading effect . . .

- Sizeable recent asymmetries from unpolarized target and longitudinally polarized lepton beam. Expected to be suppressed by $\mathcal{O}(M/Q)$
- Provides access to so-far poorly known subleading twist-3 TMD PDFs & fragmentation functions containing information about **quark-gluon correlations in the proton and in the hadronization process**

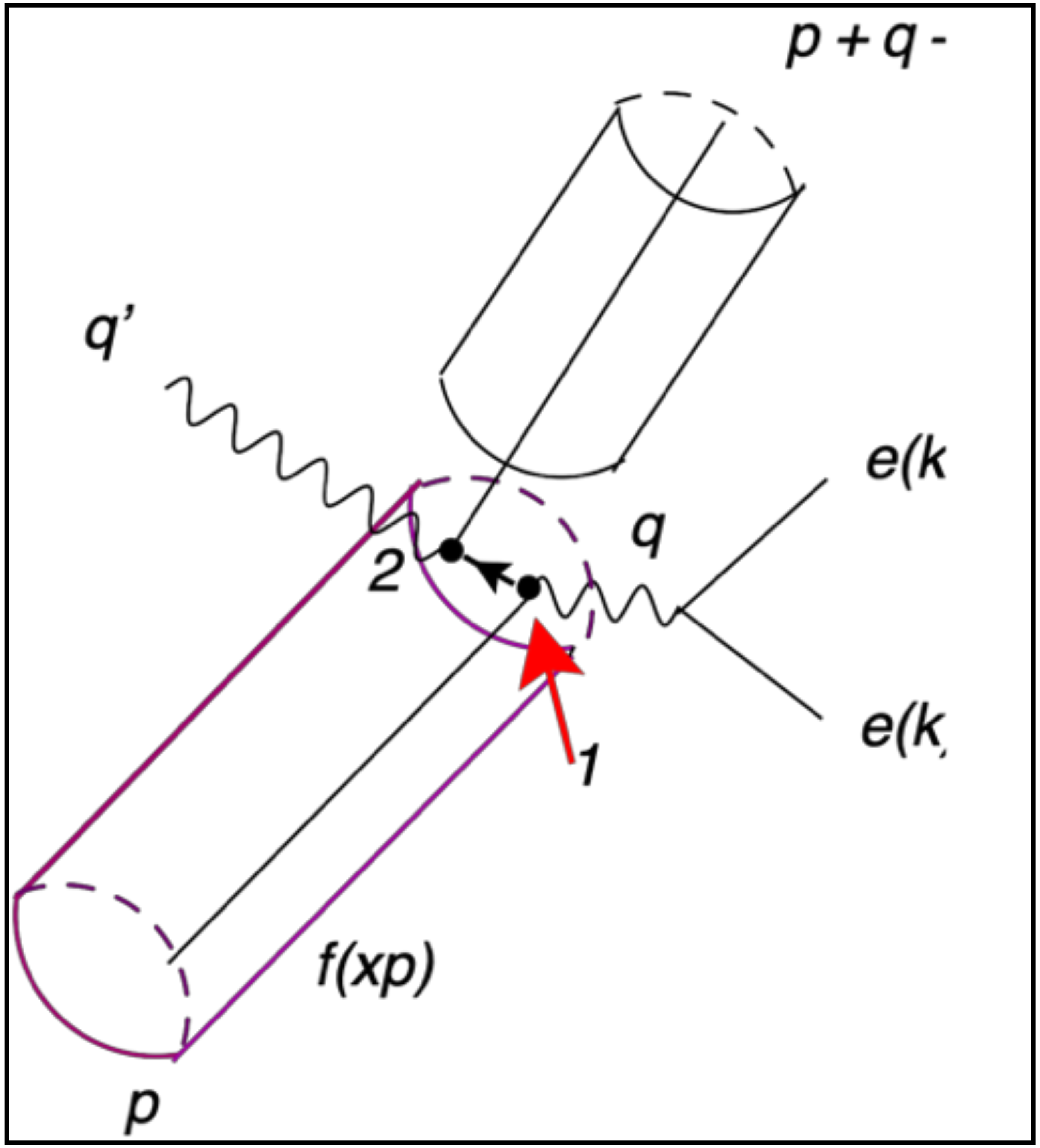


[Riedl]

Exclusive final states provide even more direct measurements.

If the quark is almost free between points 1 and 2 we measure

F = < P+ q | Q (x) Γ Q(0) | P >



$$J^{q,g} = \frac{1}{2}\int_{-1}^{1} dx\, x\, \left(H^{q,g}(x,\xi,0) + E^{q,g}(x,\xi,0)\right) \qquad L^q = J^q - \frac{1}{2}\Delta\Sigma$$

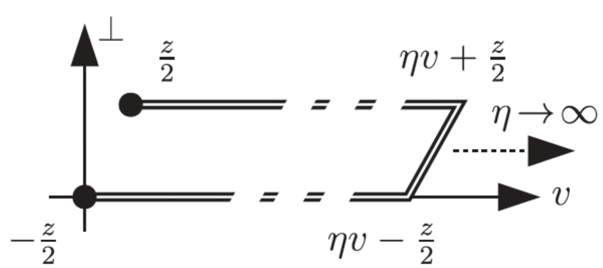
[Pasquini]

Experiments bring us to:

$$< P+q \,|\, Q(X)\, \Gamma\, Q(0) \,|\, P > \qquad < P \,|\, Q(z/2)\, \Gamma\, Q(-z/2) \,|\, P >$$

These quantities are increasingly accessible to lattice calculations. Example, the implementation of "links" Γ related to definitions of orbital angular momentum . . .

$\Gamma =$



Continuous interpolation between the Ji limit $\eta = 0$ and the Jaffe-Manohar limit $\eta \to \infty$

Staple direction off the light-cone

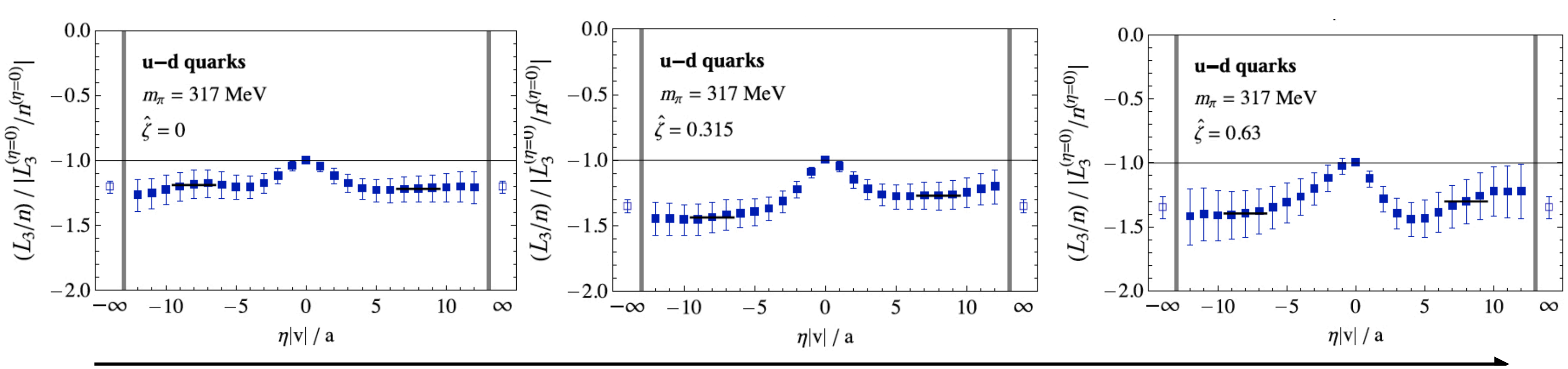
light-cone limit for $\hat{\zeta} = \frac{v \cdot P}{\sqrt{|v^2|}\sqrt{|P^2|}} \to \infty$

M. Engelhardt, Phys. Rev. D95, 094505 (2017)

M. Engelhardt et al., PRD102, 074505 (2020)

[Pasquini]

Jaffe-Manohar OAM ← Ji OAM ↓ → Jaffe-Manohar OAM

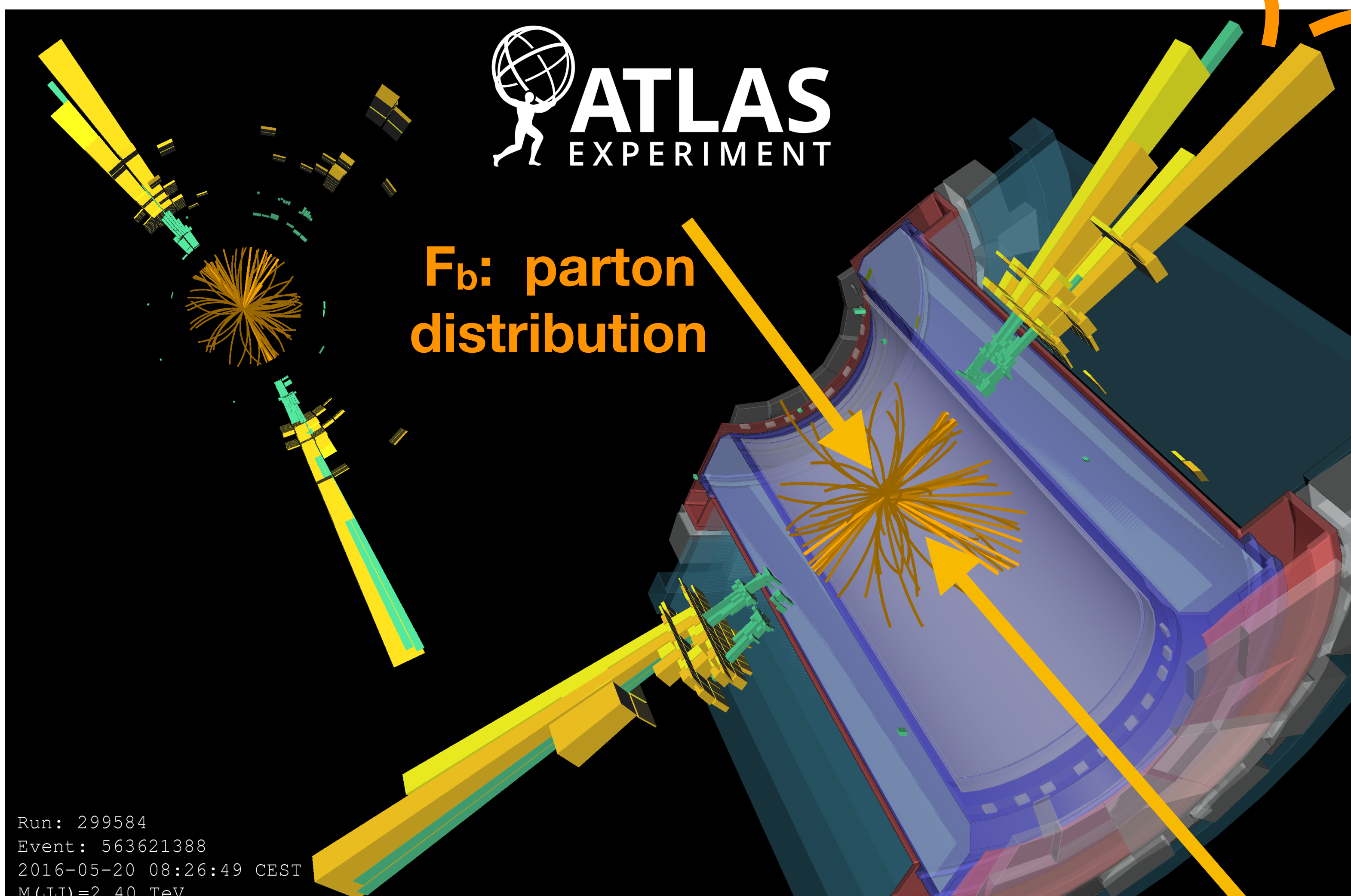


Jets: Energy and Momentum at Large Times

$$\sum_j \langle 0 \,|\, T_{0i}(\,\Omega\,) \,|\, p_j \rangle$$

ω_1

ω_2



F_b: parton distribution

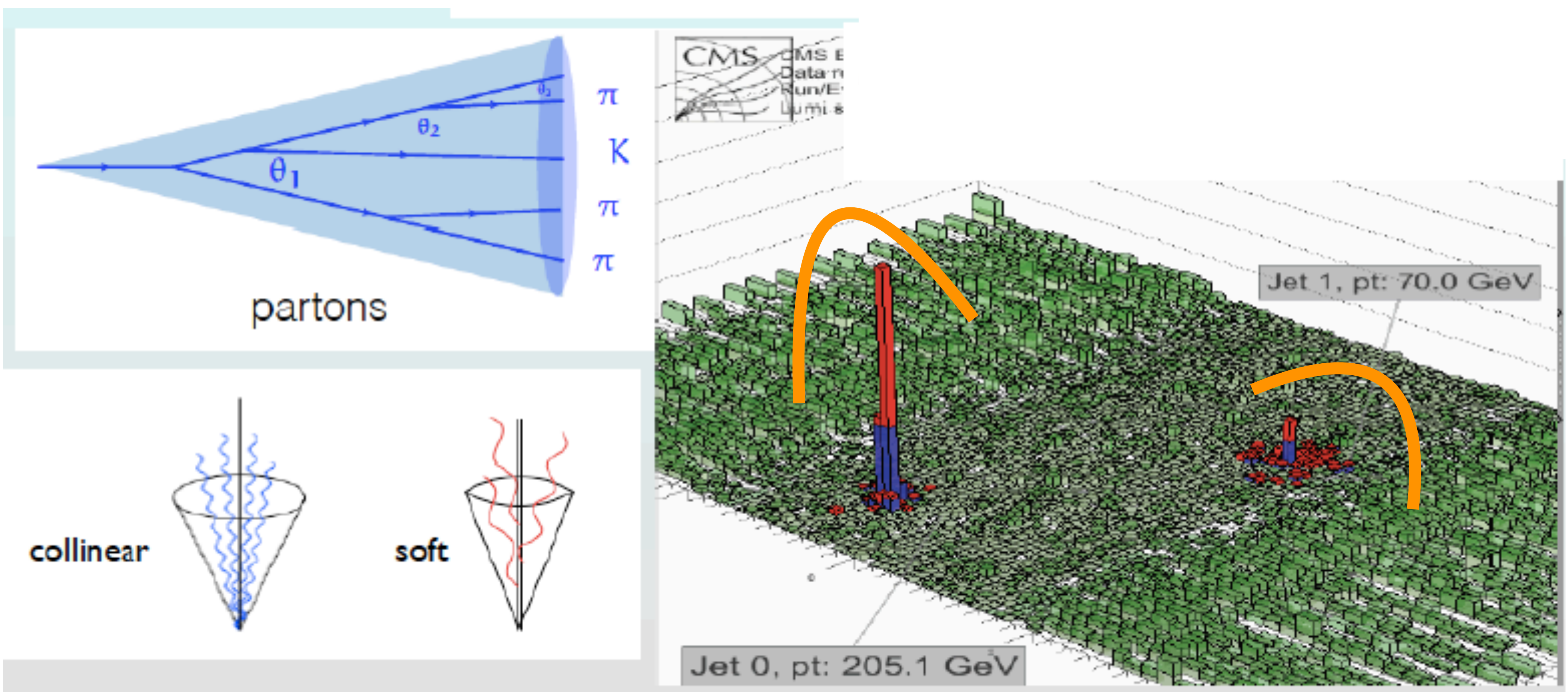
Ω is a region on the detector. The smaller the region the longer the time that's probed.

We're just now learning how far we can push this. How small can we make the region and still compute "C".

F_a: parton distribution

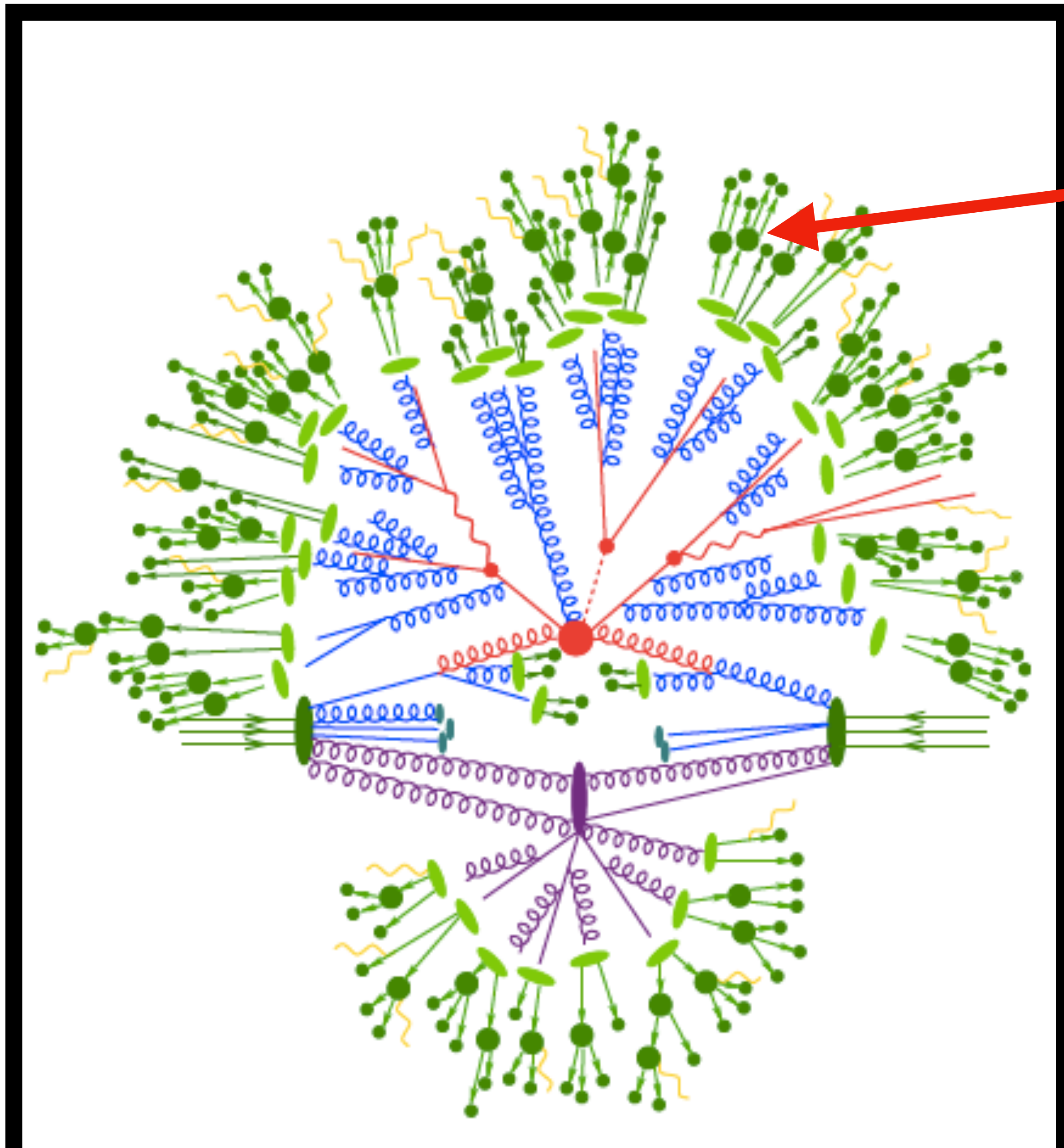
Many jet cross sections for one event: $F_a\, F_a\, C(\, E(\Omega)\,)$, $F_a\, F_a\, C(\, E_1(\omega_1)\,,\, E_2(\omega_2)\,)\,\ldots$

Jets in a dense medium. times long after the partonic collision determine energy flow into specific regions.



[Jacak]

3. Putting the Pieces Together



What's going on right here?

Translation from the language of partons to that of hadrons how "current quarks" generate mass from radiative energy, becoming "constituents".

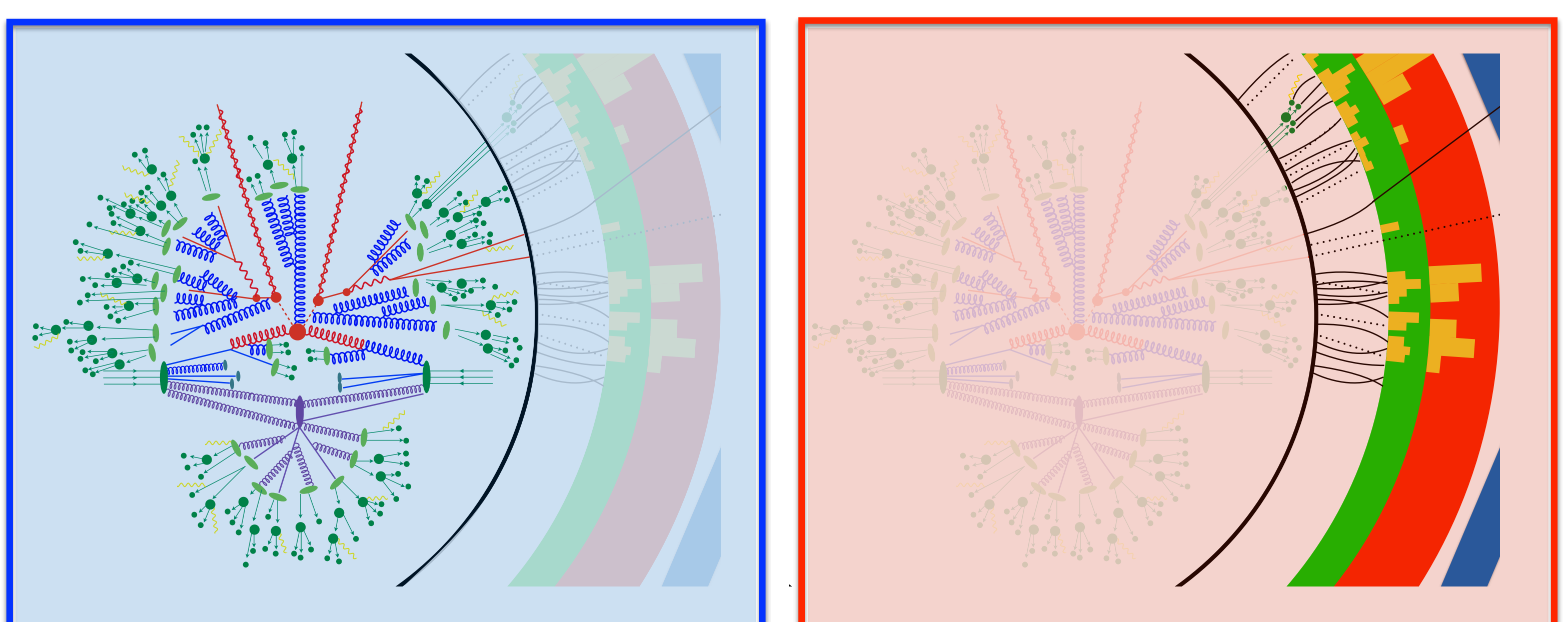
How to quantify this transition?

Are there observables sensitive to this period? Extra photons, for example.

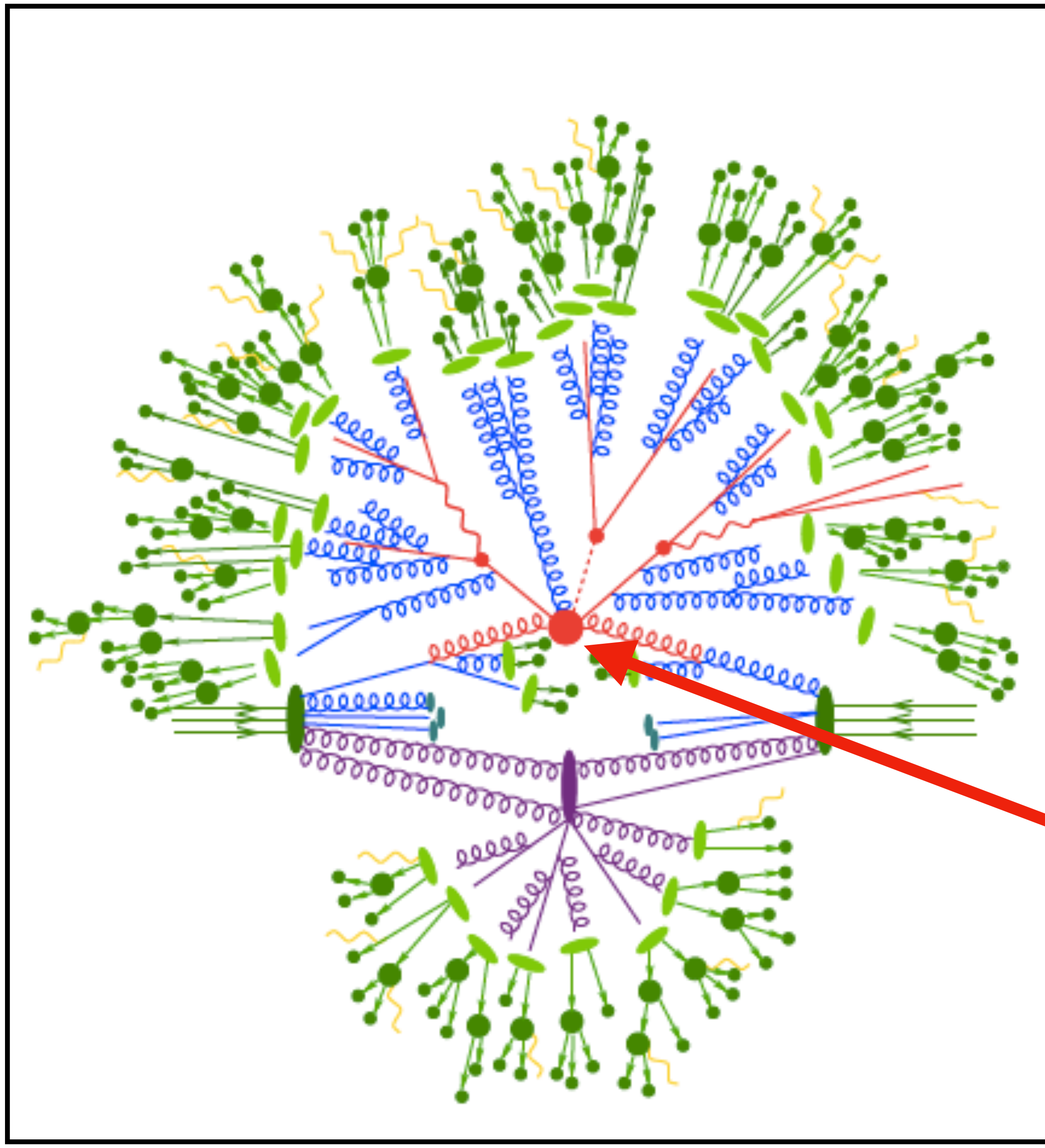
- **Final states provide a countable amount of information, and we should be ready to count it all them to the extent possible. The detailed census within each jet encodes a set of stories. Jet substructure analyses are beginning the process of breaking this code, but it will surely take many new insights, ideas and computing power.**

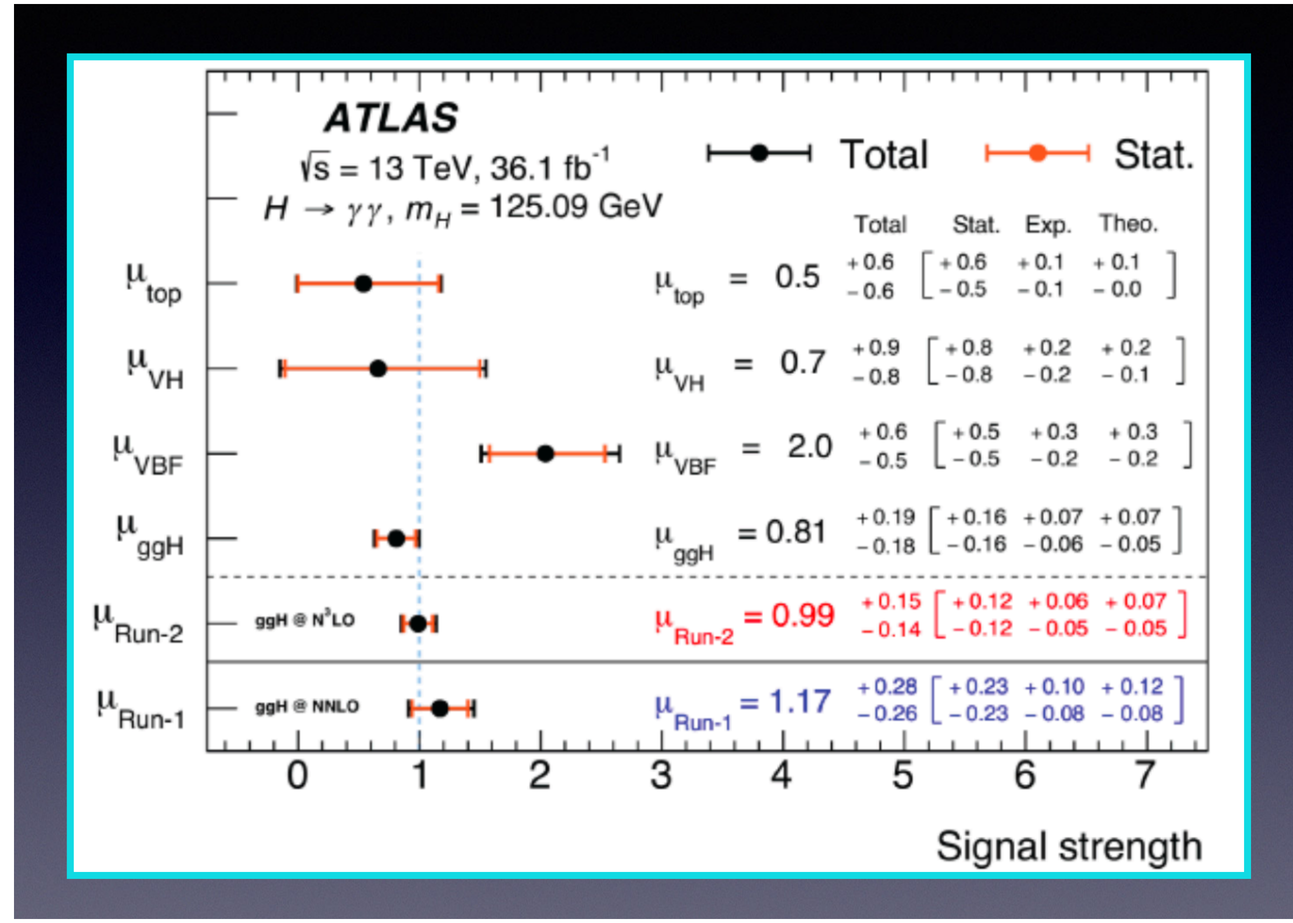
- **A judicious use of machine learning, new ideas of event display and perhaps quantum information will guide the way toward a detailed demystification of the transformations of partons to hadrons.**

What if we can use machine learning to make measurements, unbinned, in variable-dimensions, using low-level information?



[Nachman]





[Boughezal]

For inclusive cross sections, to what orders can we calculate?

- **Analytic fixed-order progress will continue, hand-in-hand with mathematics, while numerically, the “next orders” will become more accessible for cross sections, and experimental cuts easier to implement.**

- We’ll hopefully see “algorithmic” evaluations of complex QCD amplitudes and cross sections.

- Why might this be possible? It’s the magic of unitarity, the same “conservation of probability” that factorizes parton distributions in DIS and makes jet cross sections calculable.

- We can cancel infrared divergences before we integrate over phase space and impose experimental cuts.

- We will learn to calculate in four dimensions and, limit perturbation theory to finite times. This may make room for a new theory of hadronization.

As we continue to learn about QCD . . .
some tentative prognostication if time allows . . .

- QCD will be more and more embedded in the Standard Model, with flavor issues coming in the fore at all scales. (From g-2 all the way to an FCC.)

- Lattice QFT will make even more correlation functions accessible.

- Also with the help of the lattice, we will learn more of the correlations within hadrons and in exotic states of matter in the lab and in the universe.

- “Higher twist” will be subsumed into a theory of quark-hadron duality building on the kind of analysis that led to QCD sum rules, relating hadronic properties to the operator product expansion.

- A solution to “strong CP” may arise in the coming decade, perhaps in connection with an observation of dark matter.

- Perhaps what we learn about QCD will suggest other scenarios for early stages of the universe; matter under extraordinary conditions.

This will bring us back to the beginning.

4. Concluding thoughts

QCD is the “exemplary” quantum field theory:

- Phase structure, now in ions, and perhaps in its collective flow, the in smaller systems too.
- Classical solutions: opened new perspectives in geometry.
- Perturbative amplitudes: modern complex analysis and both classical and quantum general relativity.
- Benchmark concepts for more manageable theories: conformal QFT and “bootstrap” programs.

Even more generally, any answer to the question "what is quantum field theory?" must encompass QCD. Our QFT is a bit like Newton's and Leibnitz calculus, not yet fully defined yet extraordinarily effective . . .

This is why QCD continues to be guided by experiment. (Did we really know that those jets would be there at high energy?)

QCD is approaching its 50th year. For a fundamental theory, it's still young (Newtonian gravity is still going strong at 330.)

It is itself an astounding discovery, with its mysterious unbroken color symmetry.

More than that — QCD makes it possible for us to face the challenge of bridging "fundamental" and the "emergent" in the natural world.

This is a hallmark of 21st Century science, and indeed of human thought.

Congratulations to the organizers of

DIS XXVIII: 2020 / 2021

For making it happen, and to all who took part,

with the hope and expectation that

DIS XXIX will reflect a regained,

and perhaps reimagined, freedom.