# Mastering Jets:
## New Windows into the Strong Interaction and Beyond

Iain Stewart
MIT & Harvard

The University of Arizona
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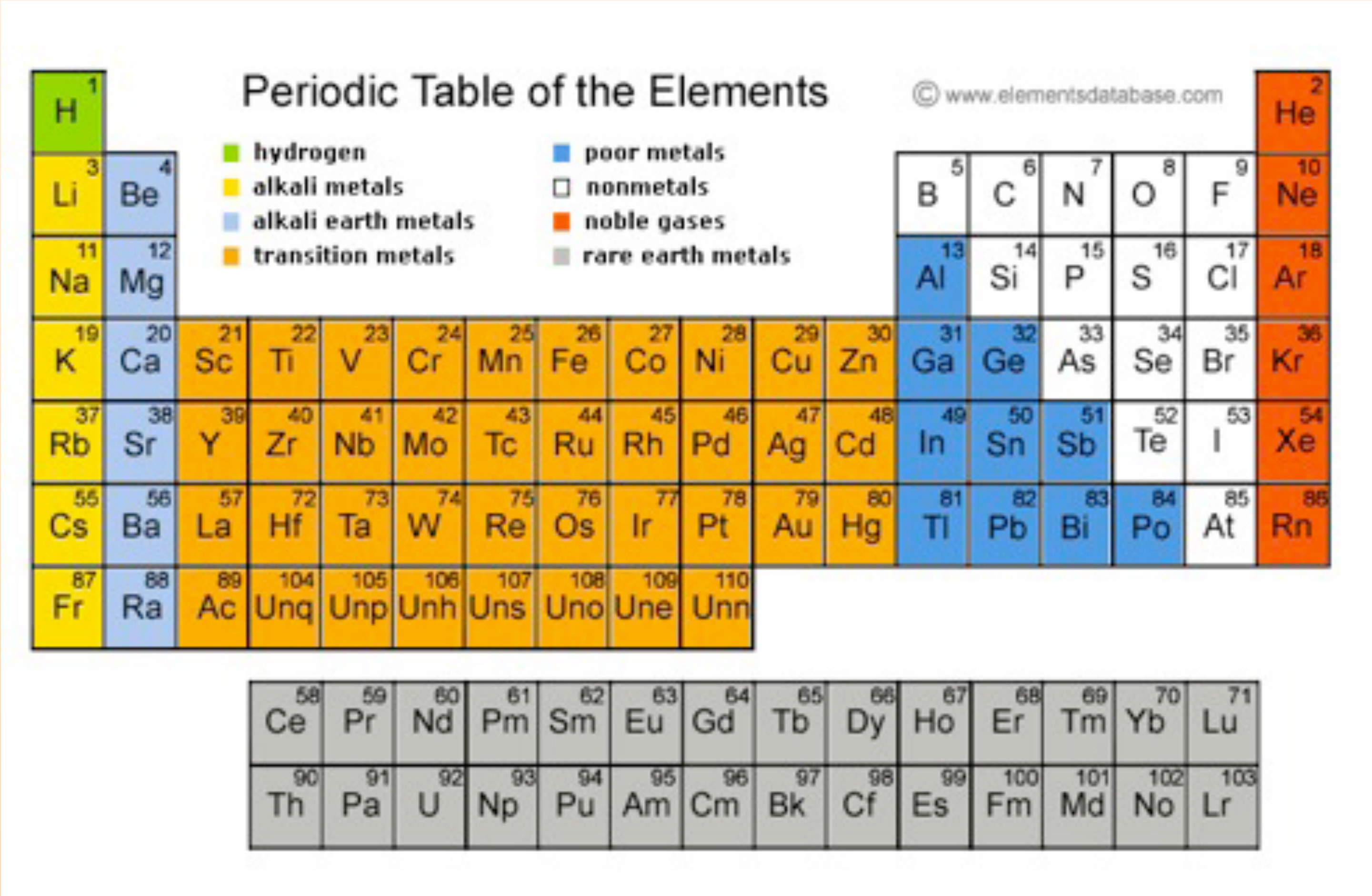
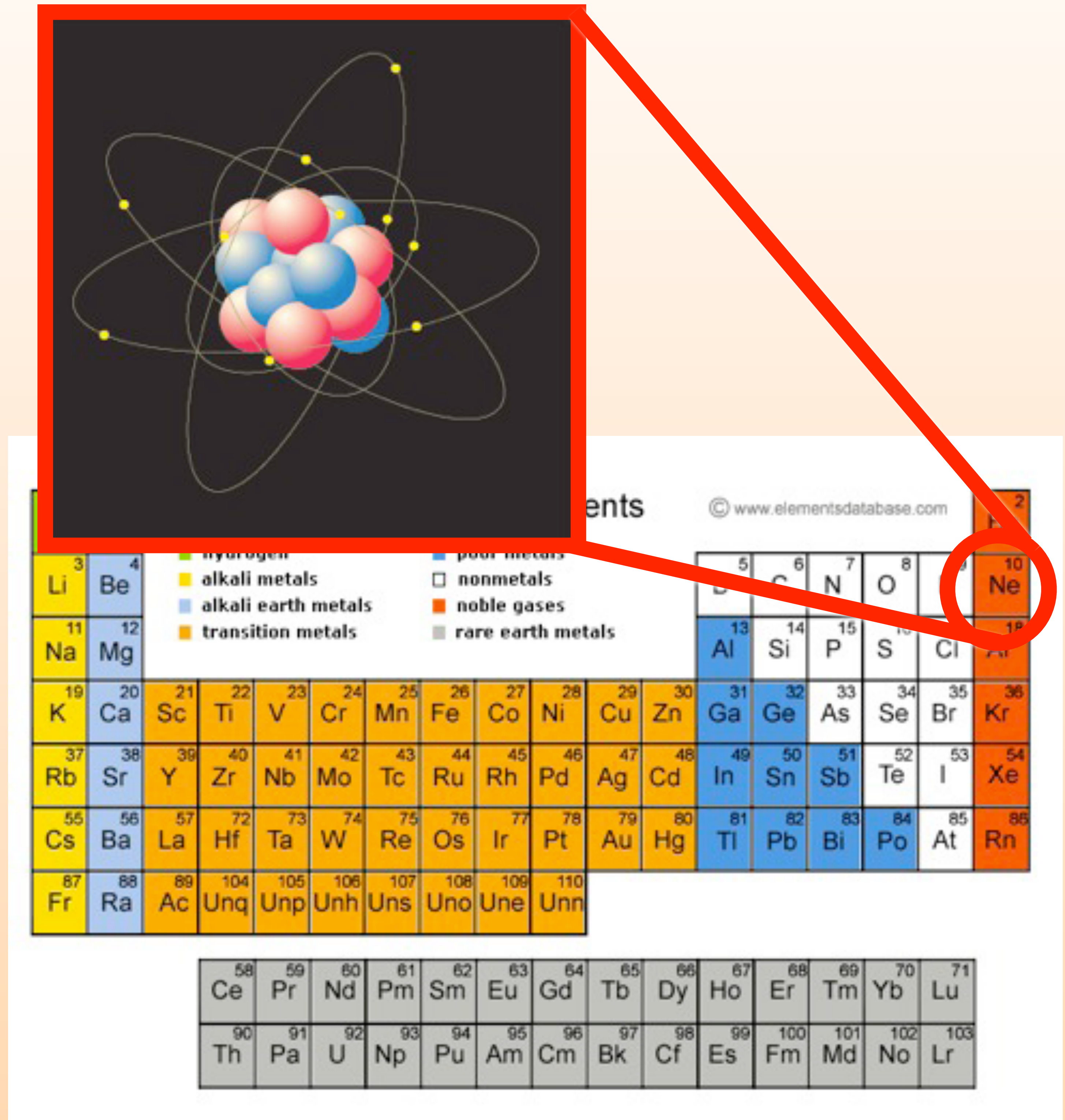
# Particles and Forces

# Constituents of Matter



# Constituents of Matter

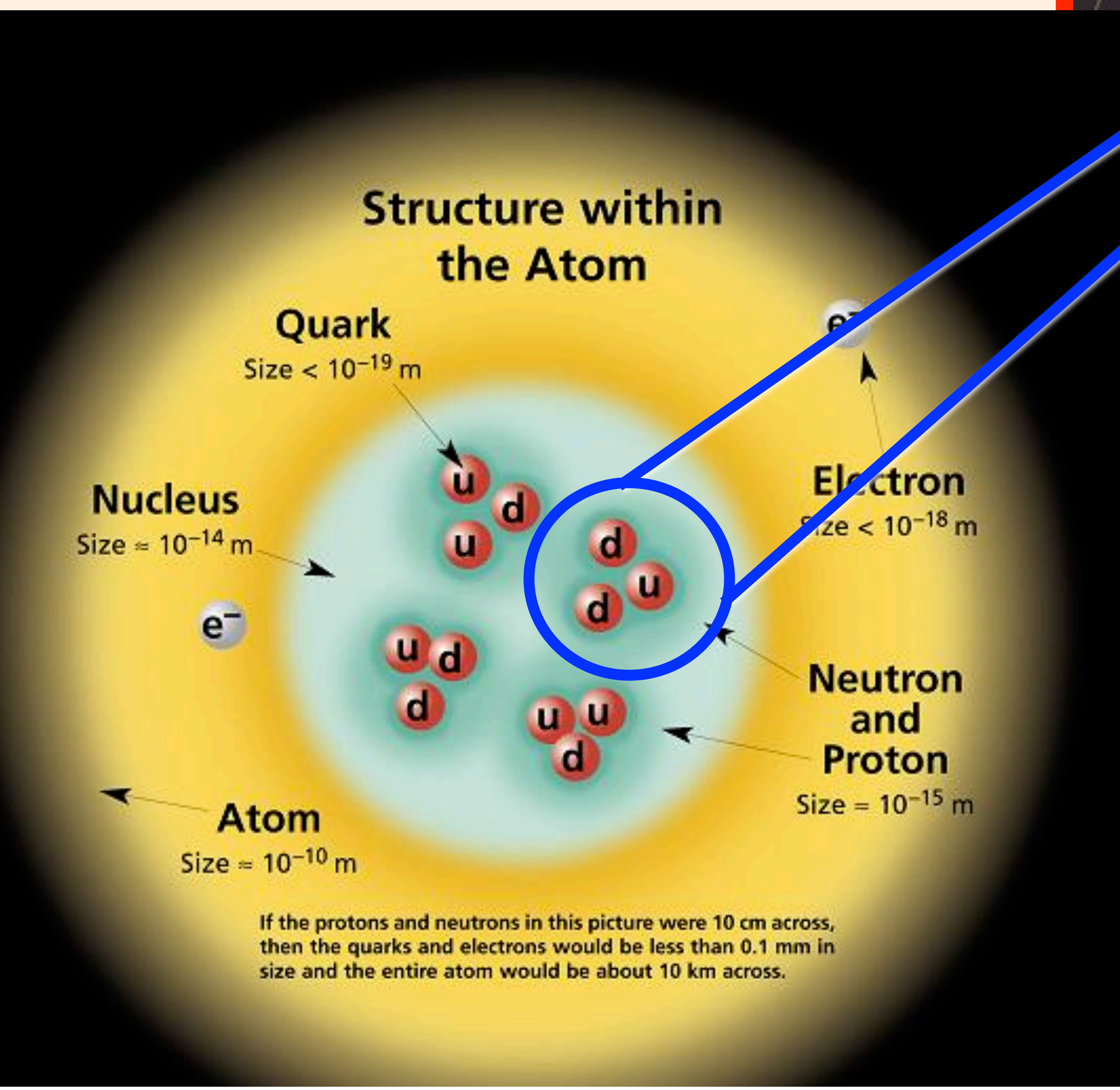
protons & neutrons in a nucleus

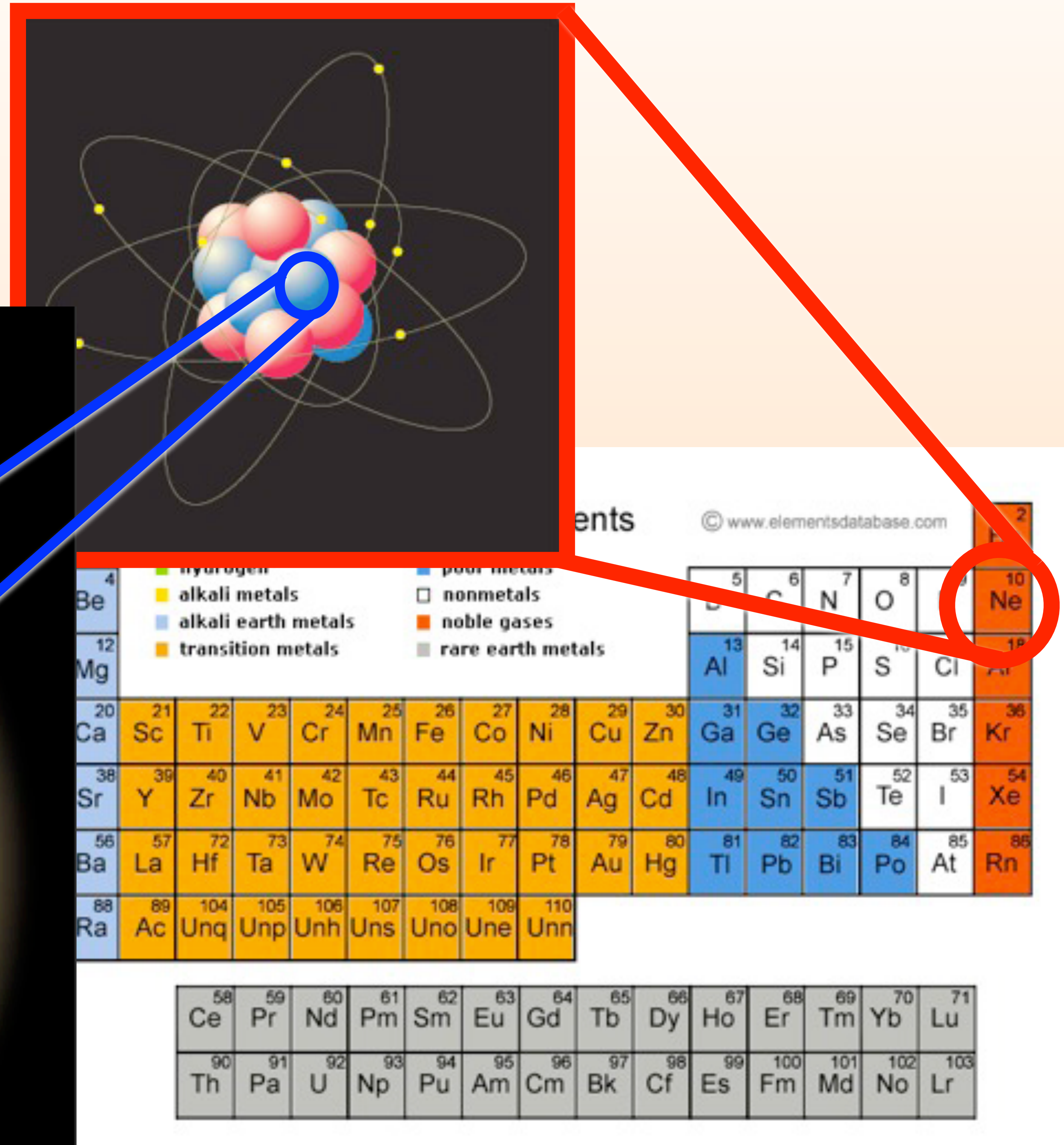


# Constituents of Matter

protons & neutrons in a nucleus

quarks in protons & neutrons



# Standard Model

## Force Mediators

Leptons

| | | |
|---|---|---|
| $e$ | $\mu$ | $\tau$ |
| $\nu_e$ | $\nu_\mu$ | $\nu_\tau$ |

Quarks

| | | |
|---|---|---|
| $u$ | $c$ | $t$ |
| $d$ | $s$ | $b$ |

Higgs $H$

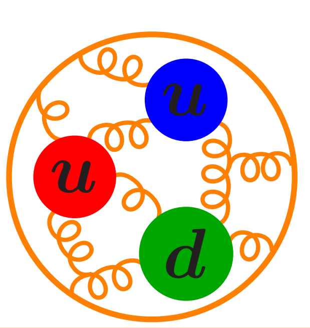
$\gamma$ Electromagnetism
Quantum Electrodynamics
(QED)

$Z$ $W$ Weak Force

$$d \to u\, e^- \, \bar{\nu}_e$$

$$(\, n \to p\, e^- \, \bar{\nu}_e \,)$$

$g$ Strong Force
Quantum Chromodynamics
(QCD)



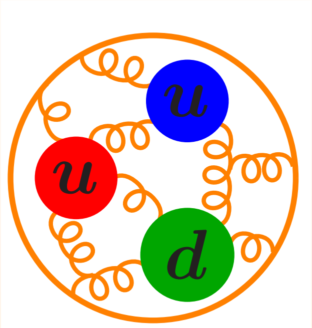

**& Gravity**
(gravitons)

# Strong Force, QCD

Quarks

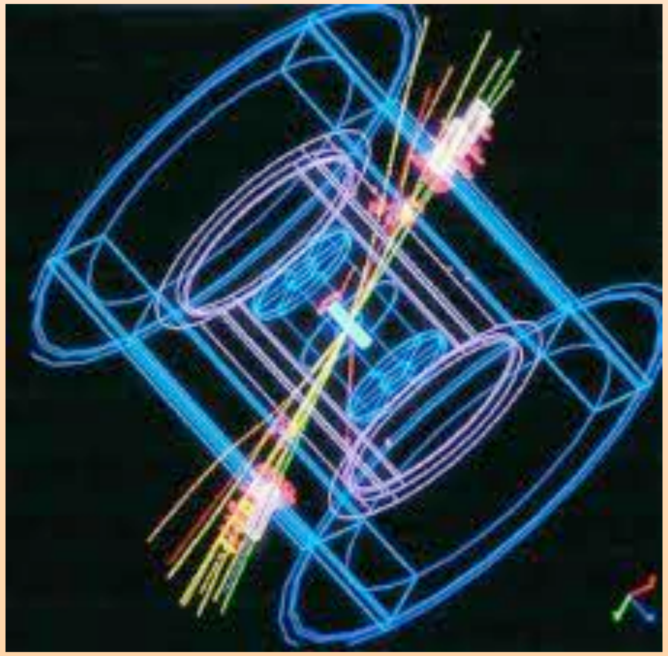
| | | |
|---|---|---|
| $u$ | $c$ | $t$ |
| $d$ | $s$ | $b$ |

$g$ gluon




- Calculations are difficult
- Rich Phenomenology (hadrons, jets, quark-gluon plasma, ...)
- Crucial for Collider Physics, where we smash together protons and/or electrons at high energies:

$e^+e^-$ (LEP expt.)

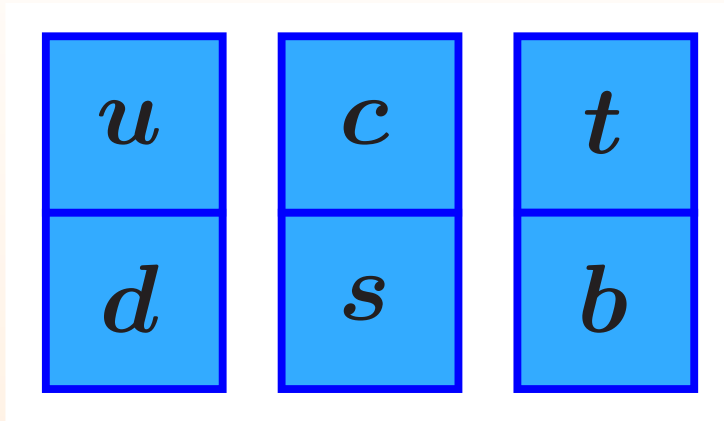


$e^-p$ (Jefferson lab)

$pp$ (Large Hadron Collider)

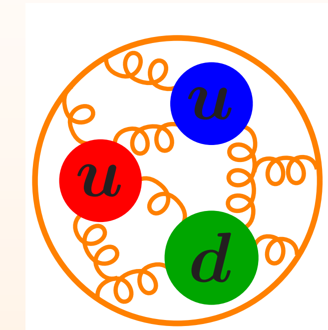
# Strong Force, QCD

Quarks





gluon




- Test & study our understanding of QCD

## Related Goals:

- Measure fundamental parameters of the Standard Model of Particle and Nuclear physics

- Search for missing particles (Higgs, Dark Matter), and for signals of new physics (particles / forces)

# Outline

- Intro to QED, $\alpha = \frac{1}{137.035...}$
  QCD, $\alpha_s$

- The Physics of Jets

- Energetic Particles & Soft-Collinear Effective Theory

Applications:

i) Measuring $\alpha_s$ with Jets

ii) Top Quark Mass from Jets

iii) Higgs and Jets

# QED

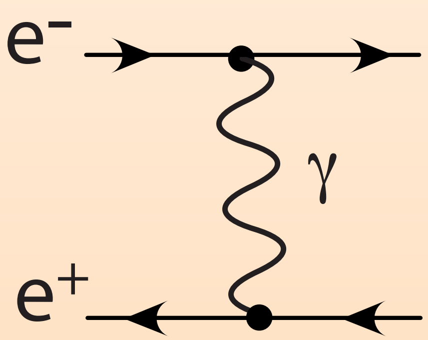
(quantum electromagnetism)

QED $\begin{cases} \text{Special Relativity:} & \text{spacetime,} \quad v \leq c \\ \text{Quantum Mechanics:} & \text{quantization,} \quad \Delta x \Delta p \geq \frac{\hbar}{2} \end{cases}$

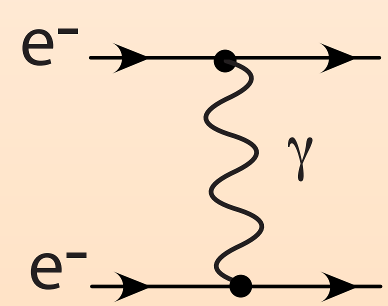
⇒ antiparticles, spin, gauge-theory

⇒ parameters: charge & masses

## Interactions



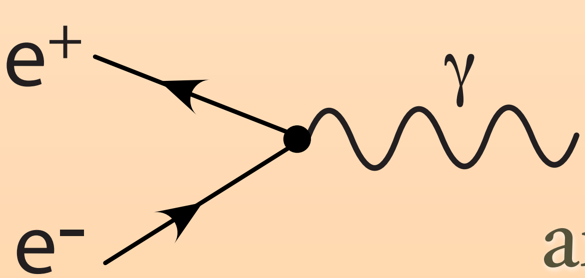

$$V = -\frac{e^2}{r}$$



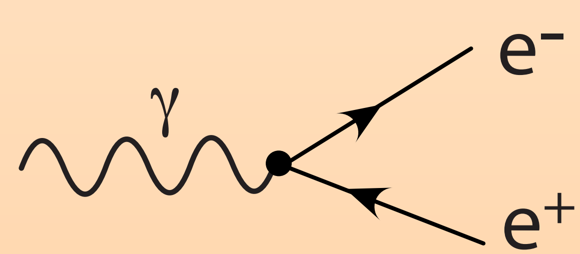

$$V = +\frac{e^2}{r}$$

two factors of the coupling

$$\alpha = \frac{e^2}{4\pi}$$

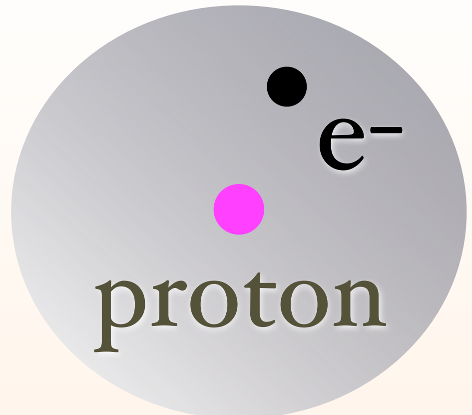



pair annihilation




pair creation

# For Hydrogen

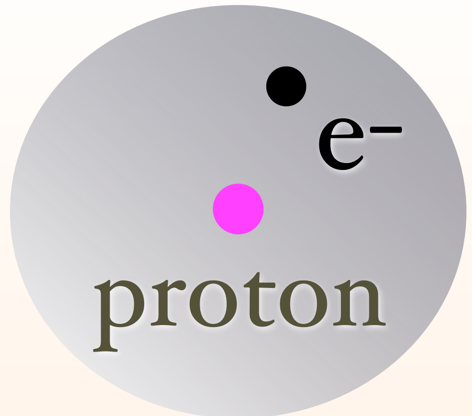



- the system is non-relativistic: $p_e \ll m_e$
- the coupling is small: $\alpha \ll 1$

$$\text{QED} \quad = \quad \underbrace{\begin{array}{c}\text{Quantum} \\ \text{Mechanics} \\ \text{(non-relativistic)}\end{array} \; + \; \mathcal{O}\left(\frac{p_e}{m_e}\right) \; + \; \mathcal{O}\left(\frac{p_e^2}{m_e^2}\right) \; + \dots}_{\text{NRQED}}$$

(a theory that makes calculations simpler)

# Hydrogen




$$\alpha = \frac{1}{137.035\ldots} \ll 1$$

$$E \simeq -\frac{m_e \alpha^2}{2n^2}$$

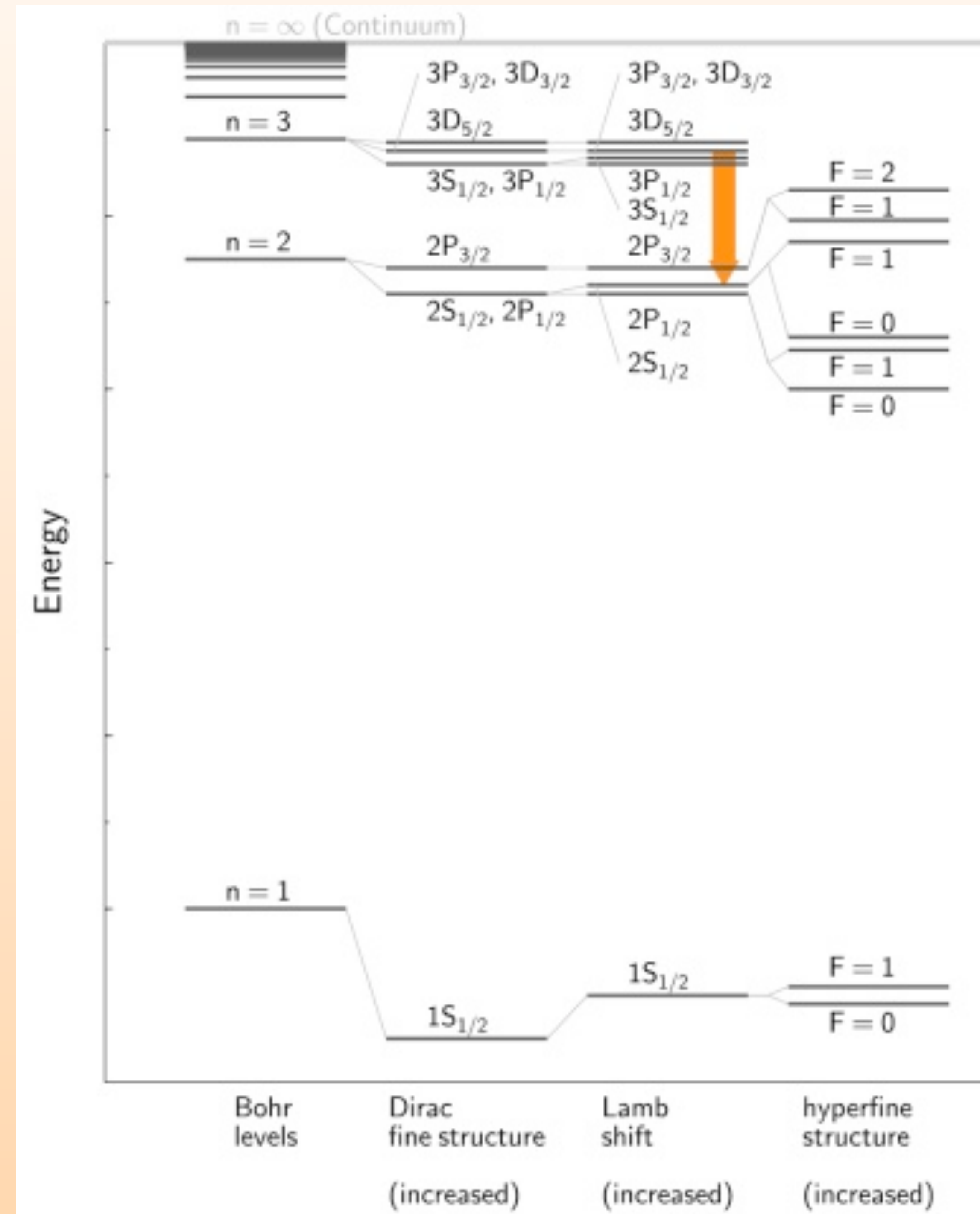
$$+ \quad m_e \alpha^4 + \frac{m_e^2}{m_p} \mu_e \mu_p \alpha^4$$

$$+ \quad m_e \alpha^5 \ln(\alpha) + m_e \alpha^5$$

$$+ \quad m_e \alpha^6 \ln(\alpha) + m_e \alpha^6$$

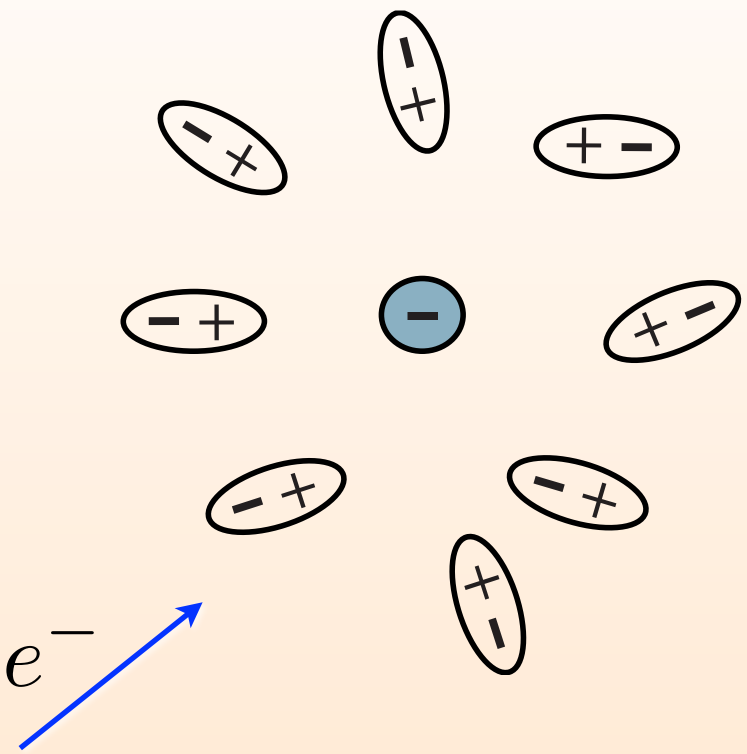
$$+ \quad m_e \alpha^7 \ln^2(\alpha) + m_e \alpha^7 \ln(\alpha) + \ldots$$

$\alpha^2$ $\quad \alpha^4$ $\quad \alpha^5$ $\quad \frac{m_e}{m_p}\alpha^4$



# Is the fine structure constant really constant?

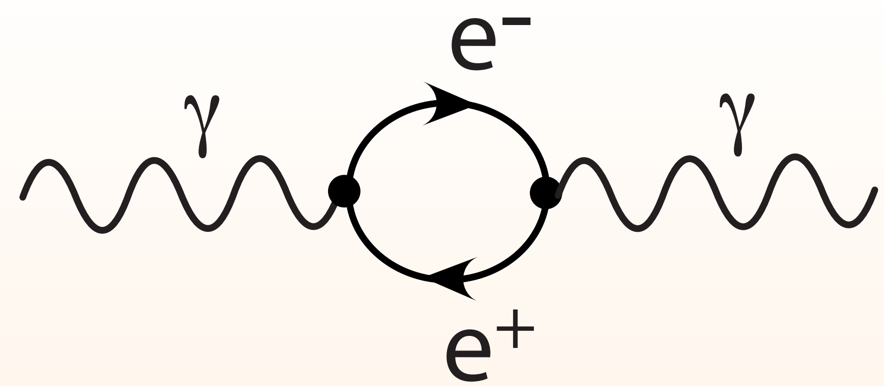
# Vacuum Polarization




like a dielectric,
gives screening

at larger energy E, we
probe shorter distances
and see a larger charge

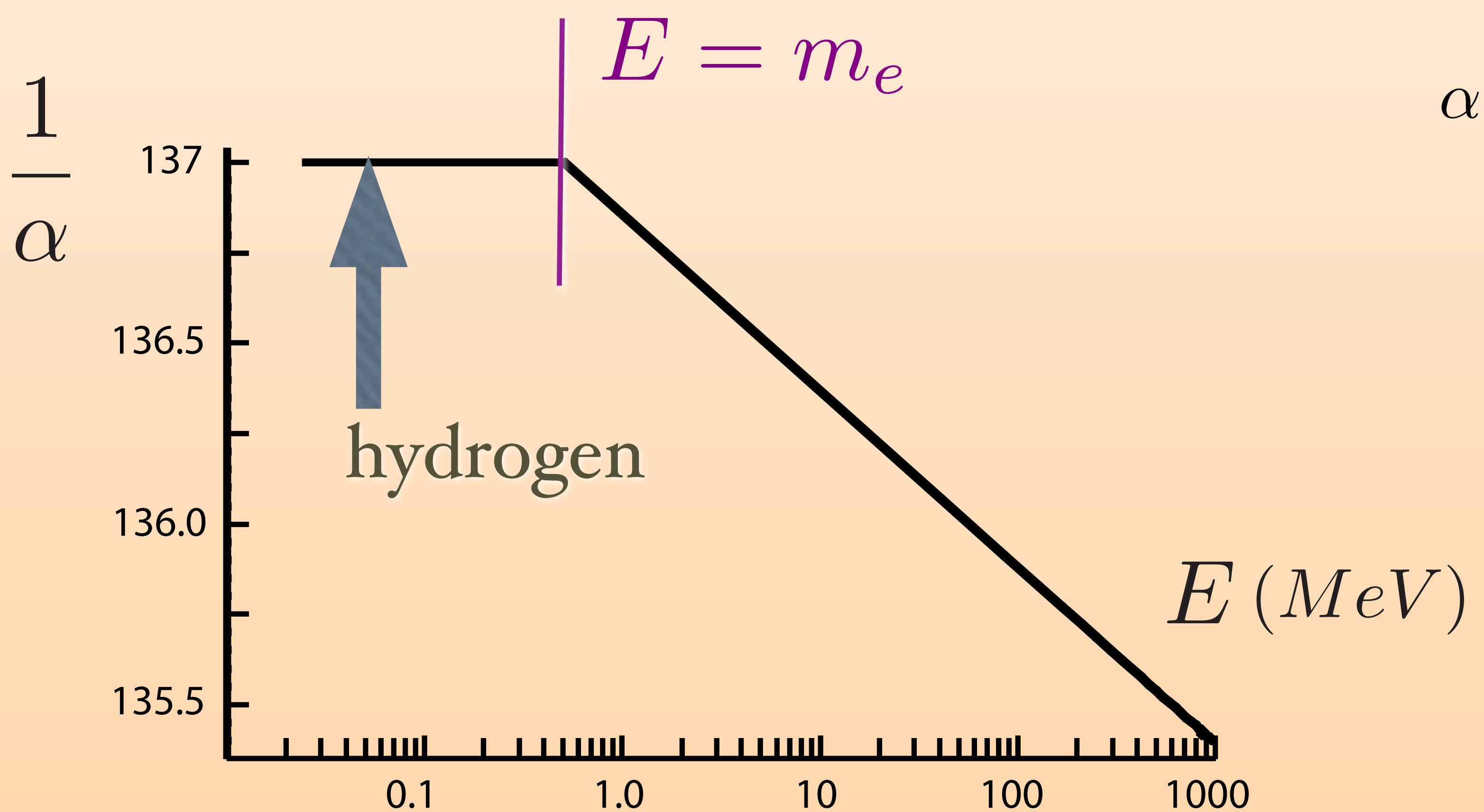
resolution $\mu = E$




$$\mu \frac{d}{d\mu} \alpha(\mu) = \frac{2}{3\pi} \alpha^2(\mu)$$

$$\alpha(E) = \frac{\alpha(0)}{1 - \frac{\alpha(0)}{3\pi} \ln\left(\frac{E^2}{m_e^2}\right)}$$

$$\alpha(0) + \frac{\alpha^2(0)}{3\pi} \ln\left(\frac{E^2}{m_e^2}\right) + \ldots = \alpha(E)$$



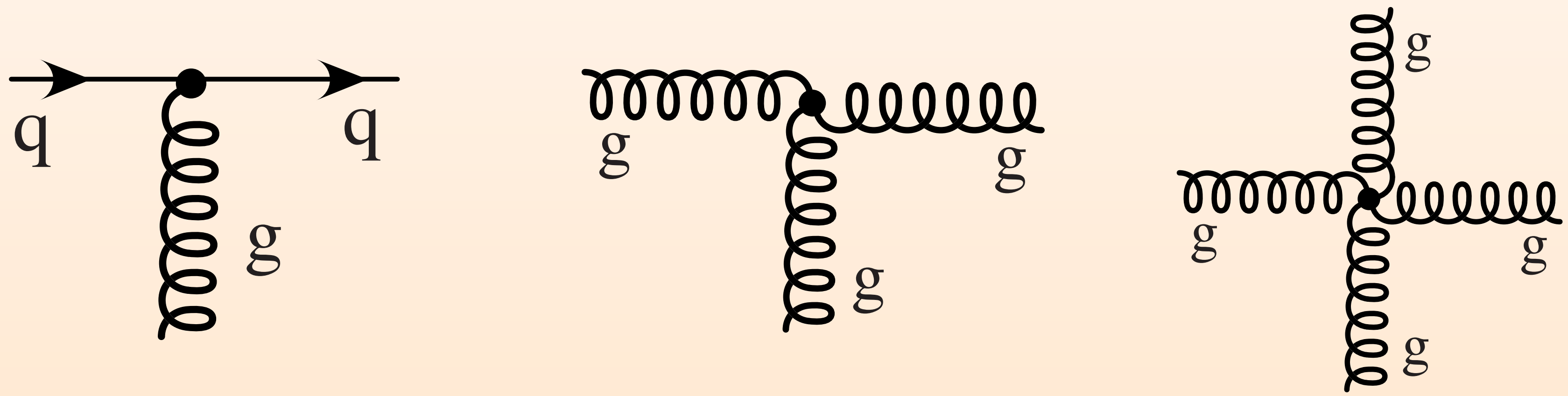

A small effect.

# QCD

for quarks (q) & gluons (g)

strong coupling: $g(\mu)$ $\qquad$ $\alpha_s(\mu) = \frac{g(\mu)^2}{4\pi}$

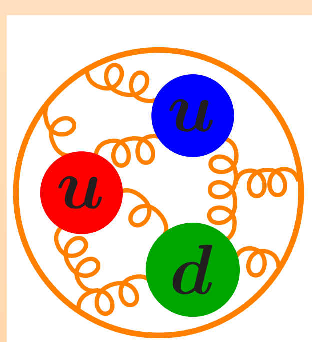
## Interactions




these interactions involve
the same coupling
(gauge symmetry)

- almost all systems of interest are highly relativistic
- the coupling is much larger

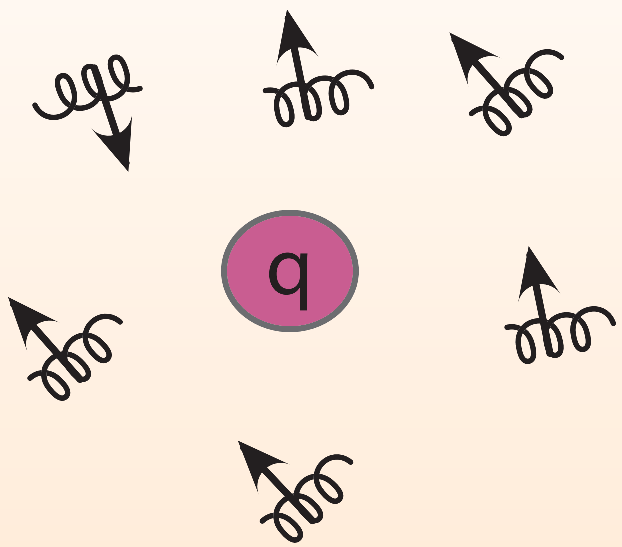
proton

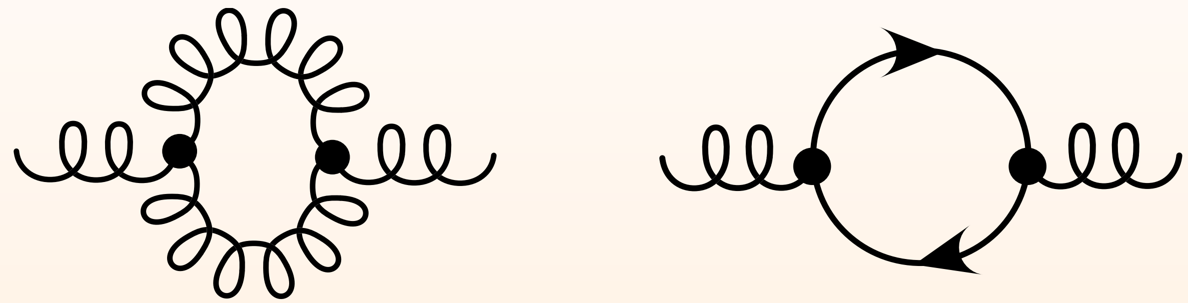



$$E = \alpha_s + \alpha_s^2 + \alpha_s^3 + \ldots$$

here all terms are equally important

## Vacuum response?



gluons have spin, carry color charge

behave like a paramagnet

anti-screen the charge

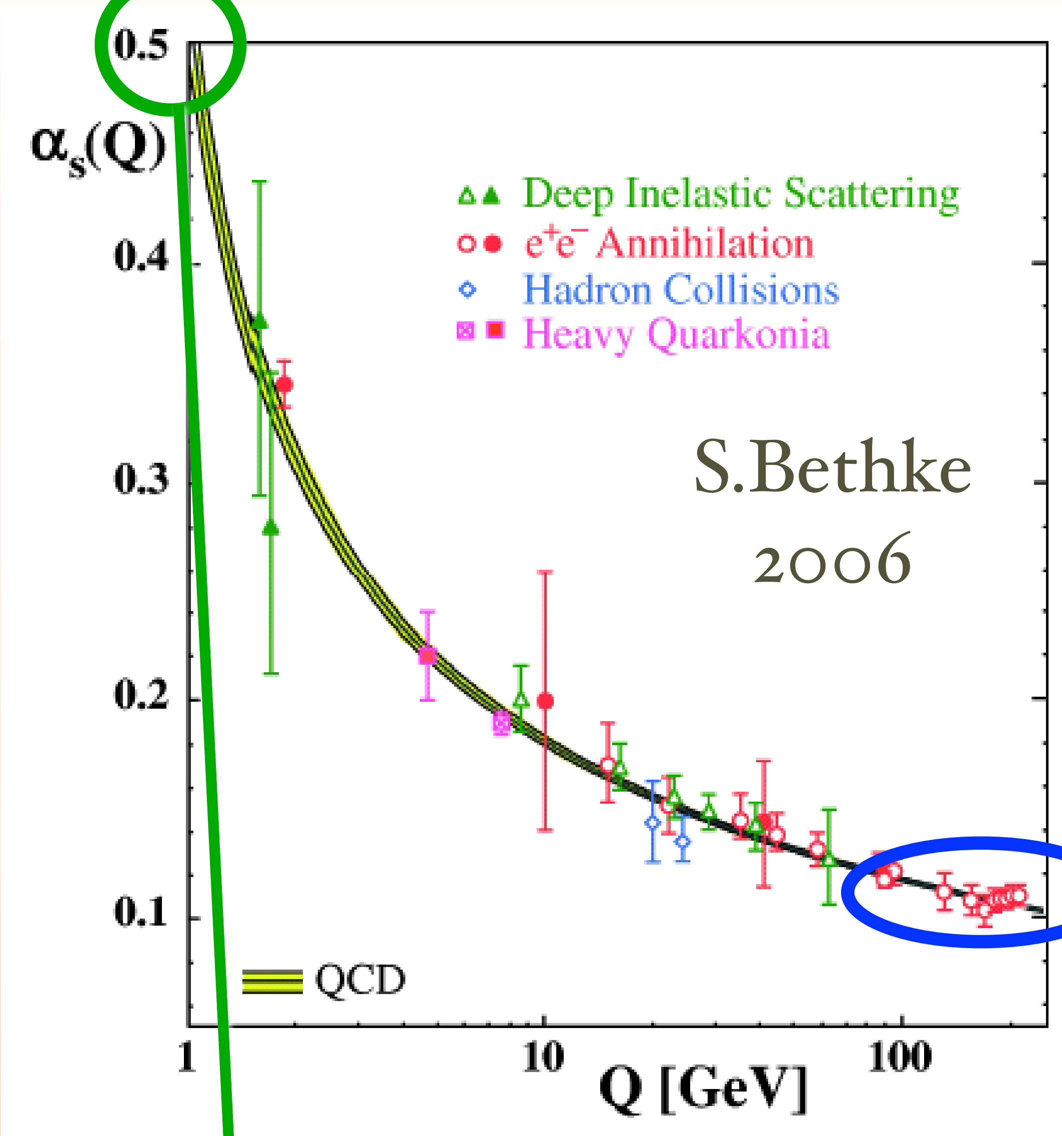
$$\beta(\alpha_s) = \mu \frac{d}{d\mu}\alpha_s(\mu) = -\frac{\alpha_s(\mu)^2}{2\pi}\left(11 - \frac{2}{3}n_f\right) \quad < 0$$

In QCD, the coupling , $\alpha_s(\mu)$, behaves in the opposite way to QED, it gets weaker at short distance/high energy

And here vacuum polarization is very important

# Asymptotic freedom

$$\alpha_s(\mu) = \frac{g(\mu)^2}{4\pi} \qquad \beta(\alpha_s) = \mu \frac{d}{d\mu}\alpha_s(\mu) < 0$$

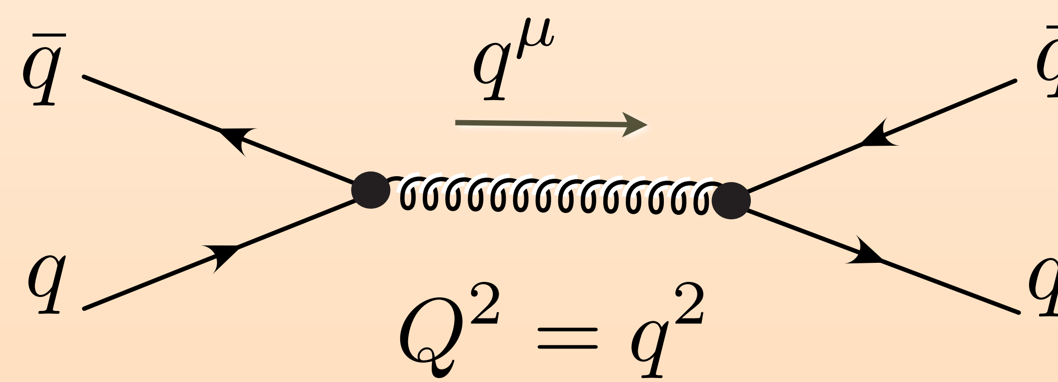


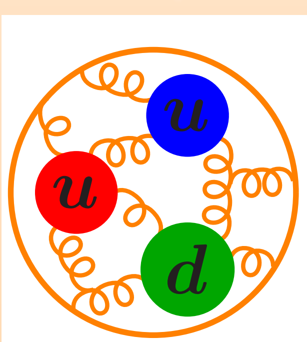

large change in the value

large $\mu = Q$, small $\alpha_s$, free quarks

so use perturbation theory for high energy collisions!

$$q\bar{q} \longrightarrow q\bar{q}$$



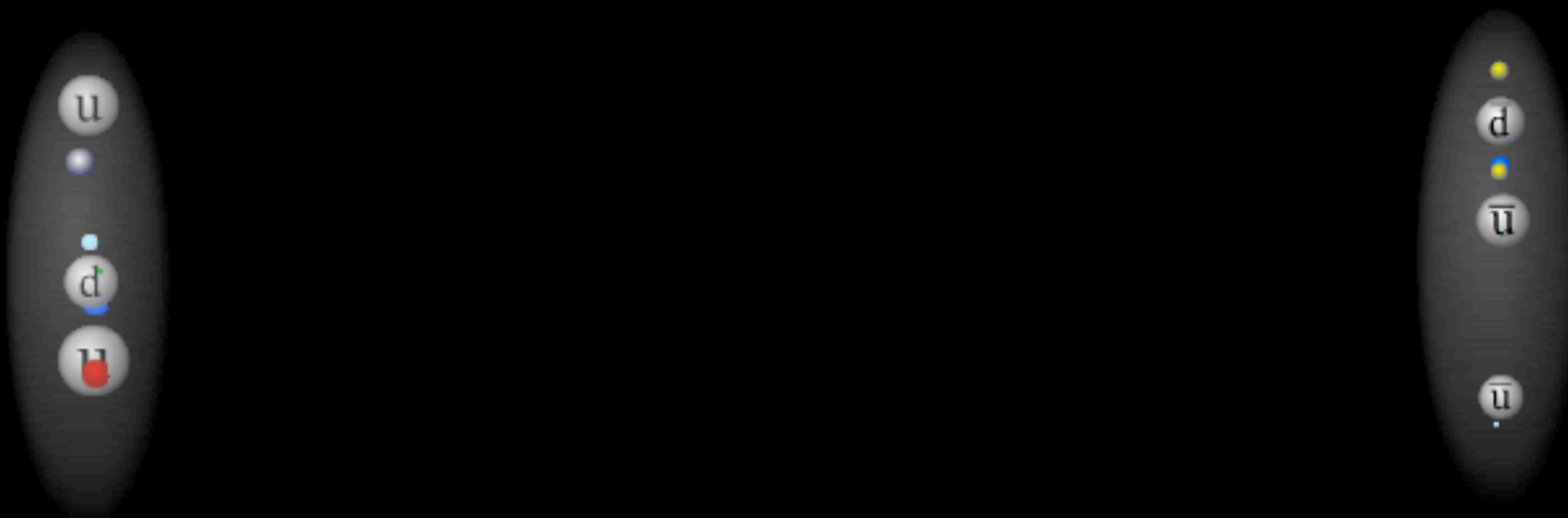

bound quarks

$$r = \Lambda_{\rm QCD}^{-1} \simeq 1\,\text{fm} \simeq (200\,\text{MeV})^{-1}$$

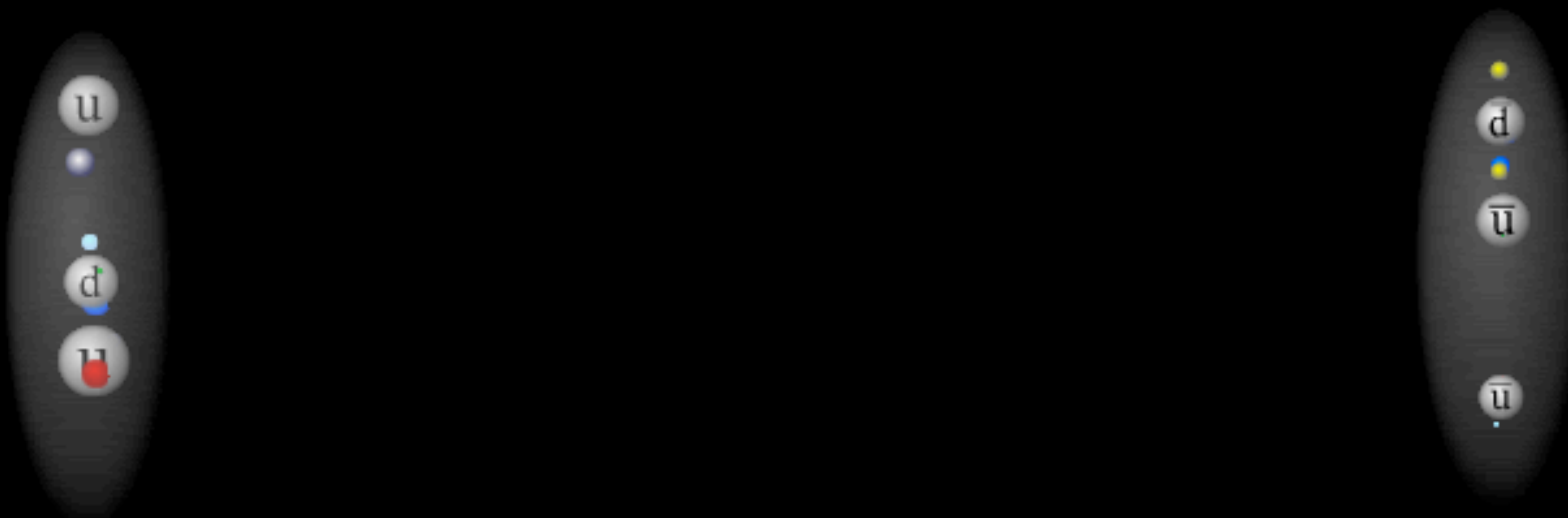
So what does a scattering experiment look like?

from Madgraph

## from Madgraph



from Madgraph

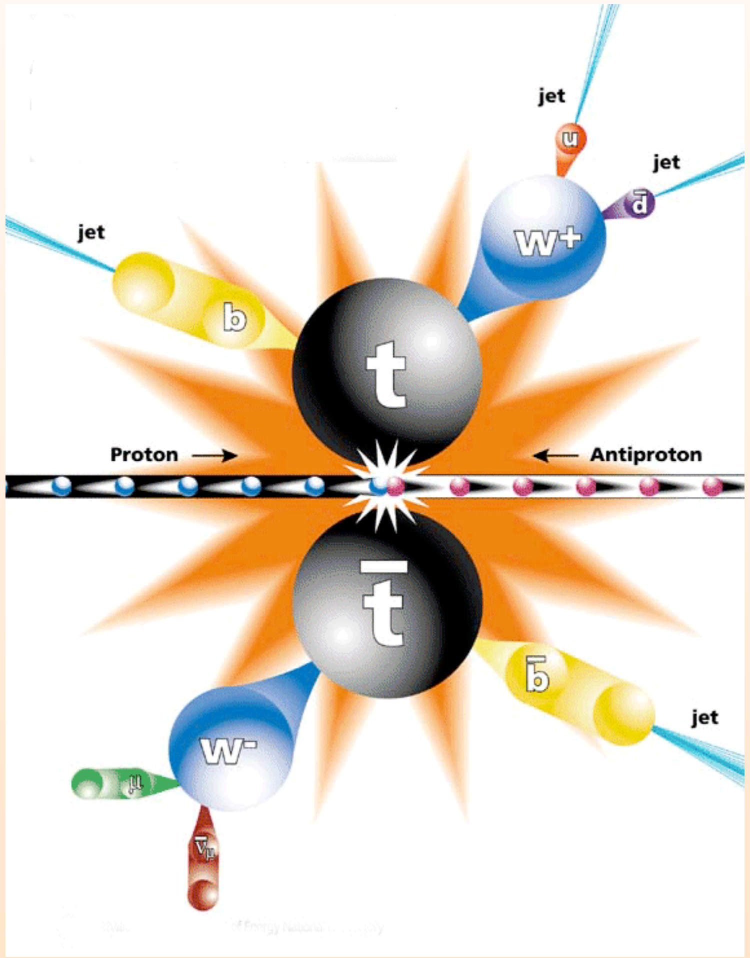



Here we collide hadrons and produce hadrons

The KEY simplification is that the problem factorizes into pieces.

The probability can be computed by:

$$\mathrm{Prob}(A|B) = \sum_C \mathrm{Prob}(A|C)\,\mathrm{Prob}(C|B)$$




Probability for p$\bar{\mathrm{p}}$ collision to produce these hadrons

$$= \begin{array}{l} \mathrm{Prob}\Big(q(\vec{p})\ \mathrm{in\ p}\Big) \\ \quad \times\ \mathrm{Prob}\Big(\bar{q}(\vec{p}\,')\ \mathrm{in}\ \bar{p}\Big) \end{array} \times\ \mathrm{Prob}(q\bar{q} \to t\bar{t}) \times\ \mathrm{Prob}\begin{pmatrix} t\bar{t}\ \text{to produce} \\ \text{hadrons} \end{pmatrix}$$

we can determine which parts are perturbative

Probability for p$\bar{\text{p}}$ collision
to produce these hadrons

$$= \begin{array}{l}\text{Prob}\Big(q(\vec{p}\,)\text{ in p}\Big) \\ \quad \times\ \text{Prob}\Big(\bar{q}(\vec{p}\,'\,)\text{ in }\bar{p}\Big)\end{array} \times \text{Prob}(q\bar{q} \to t\bar{t}) \times \text{Prob}\begin{pmatrix} t\bar{t} \text{ to produce} \\ \text{hadrons} \end{pmatrix}$$

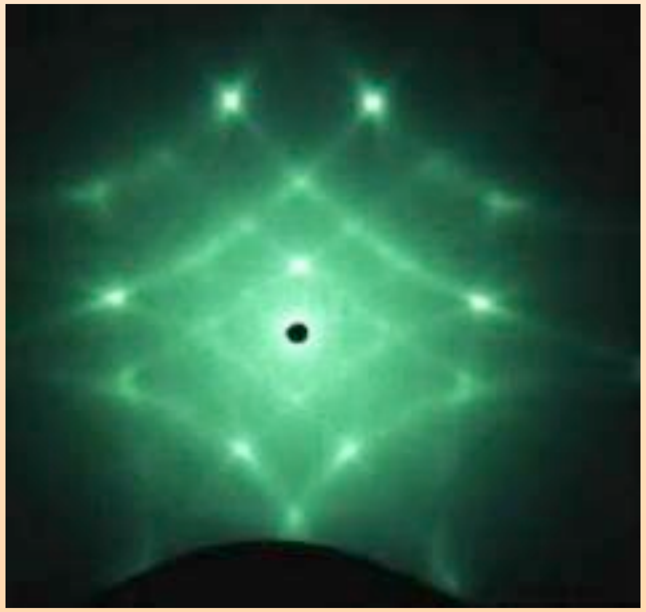
Unfortunately this is not as simple as just multiplying numbers. Typically we have probability densities that must be integrated against each other.

eg.

$$\sigma_{hadrons} = \int dx \int dy\ f_{q/p}(x)\ f_{\bar{q}/\bar{p}}(y)\ \sigma_{q\bar{q}\to t\bar{t}}(x, y) \cdots$$

probability of finding a quark of
momentum "x" in the proton

analogy: Bragg scattering of X-rays on a crystal, for this time scale the atoms are at rest



Probability for $p\bar{p}$ collision
to produce these hadrons

$$= \begin{array}{l} \text{Prob}\Big(q(\vec{p}) \text{ in p}\Big) \\ \quad \times \text{Prob}\Big(\bar{q}(\vec{p}\,') \text{ in } \bar{p}\Big) \end{array} \times \text{Prob}(q\bar{q} \to t\bar{t}) \times \underbrace{\text{Prob}\left(\begin{array}{c} t\bar{t} \text{ to produce} \\ \text{hadrons} \end{array}\right)}_{=1}$$

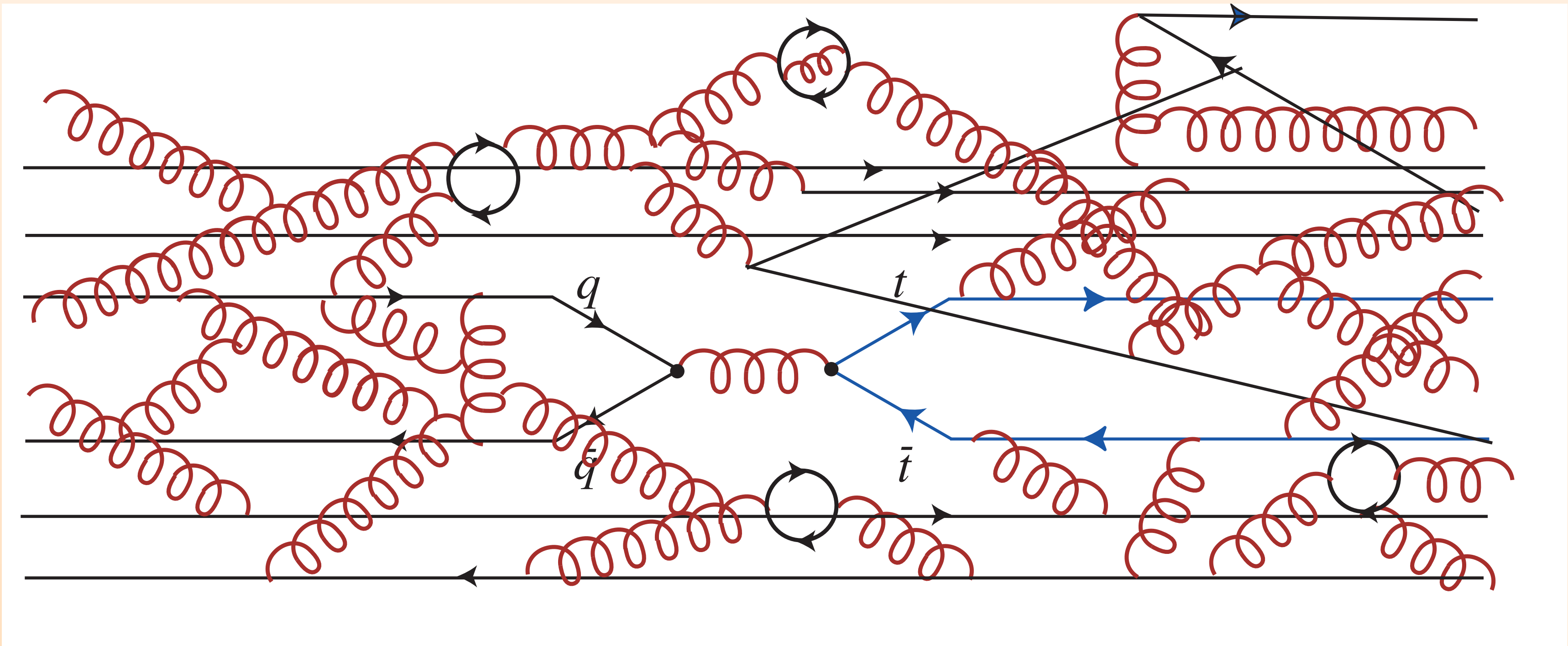
Possible simplification:

if we sum over all
possible things that
$t\bar{t}$ can produce

This simplification is usually not realistic since we are interested in specific final states, or must impose experimental cuts.

Probability for $\mathrm{p\overline{p}}$ collision
to produce these hadrons

$$= \begin{array}{l} \mathrm{Prob}\Big(q(\vec{p})\ \text{in p}\Big) \\ \quad \times\ \mathrm{Prob}\Big(\bar{q}(\vec{p}\,')\ \text{in}\ \bar{p}\Big) \end{array} \times \mathrm{Prob}(q\bar{q} \to t\bar{t}) \times \mathrm{Prob}\left(\begin{array}{c} t\bar{t}\ \text{to produce} \\ \text{hadrons} \end{array}\right)$$




Because these probability formulas have a lot of structure and deriving them is involved, they get to be called "Factorization Theorems"

# Jets

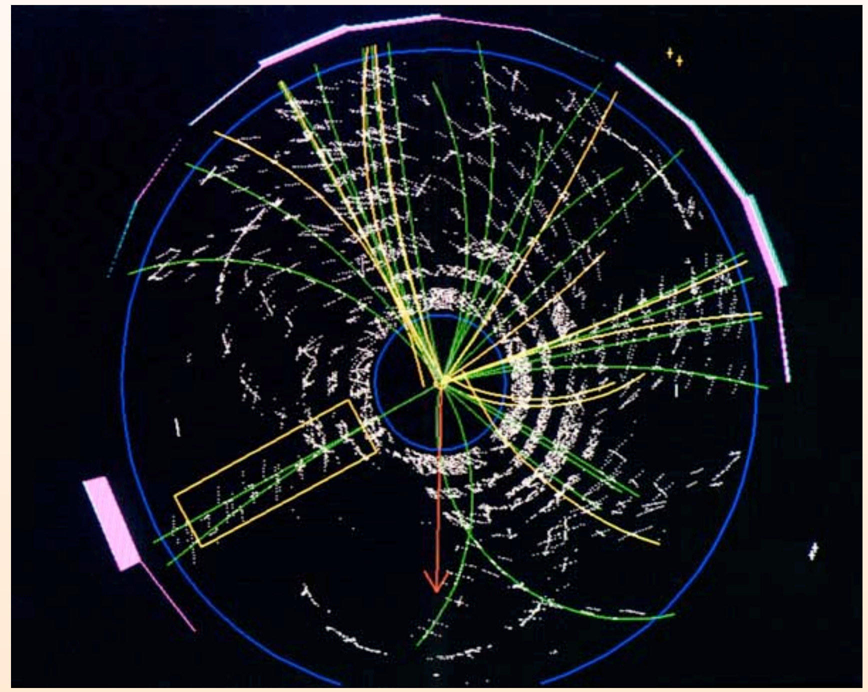
| | |
|---|---|
| Wing span | 21 m |
| MTOW | 15200 kg |
| Engines | 2xPratt & Whitney 306B (6050 lb static std) |
| Cabin | 32 pax |
| Certified altitude | FL350 |
| Vmo/Mmo | 300 KCAS/M0.66 |
| 32 pax range | 900 NM |


not this kind of jet ...

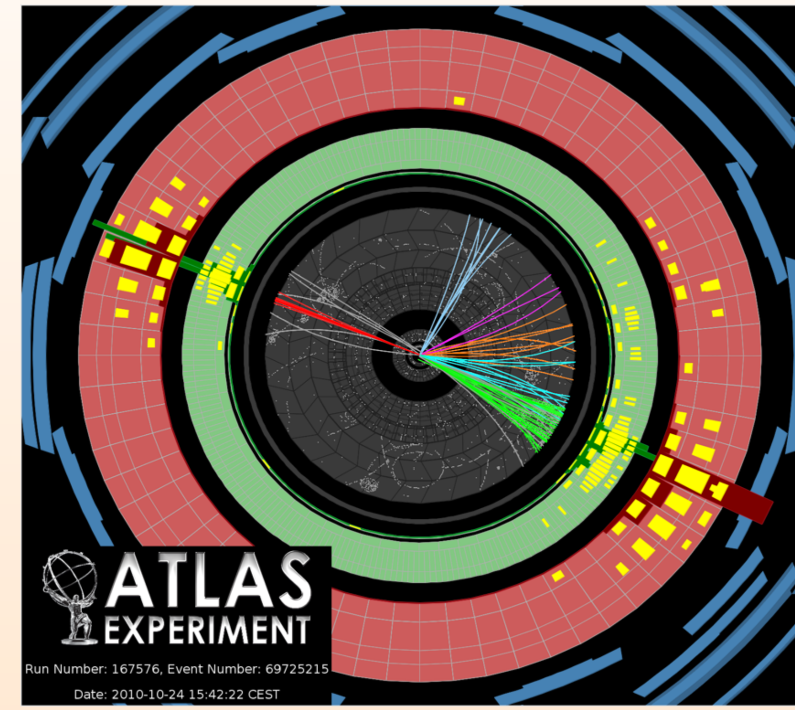
# QCD collisions like to produce Jets:

## a cluster of hadrons moving in the same direction

LEP 2 jet event

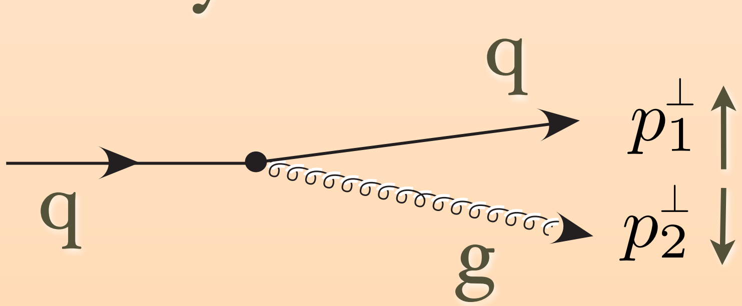


CDF 4 jet top event




2 jet event at LHC

Why?



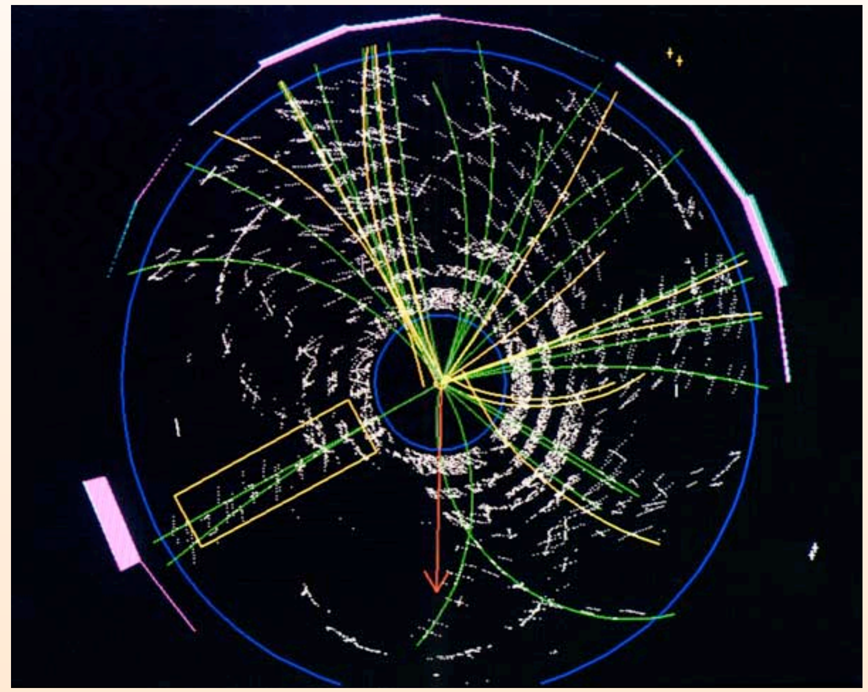

repeat to get a "shower":

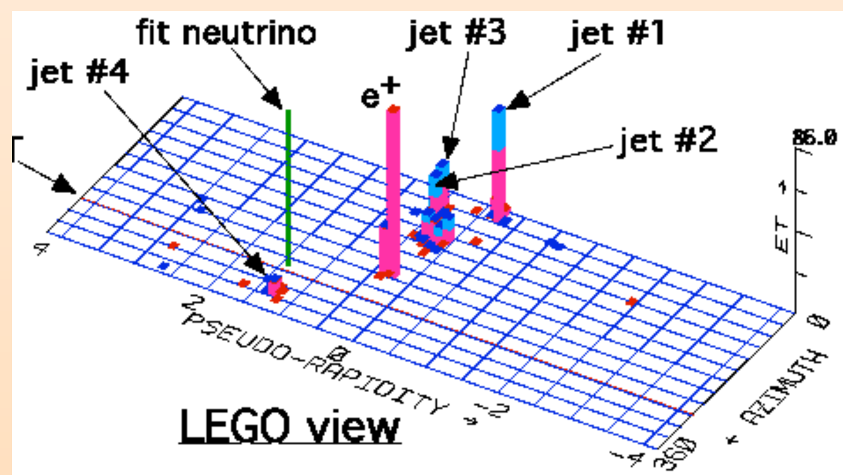
collinear enhancement

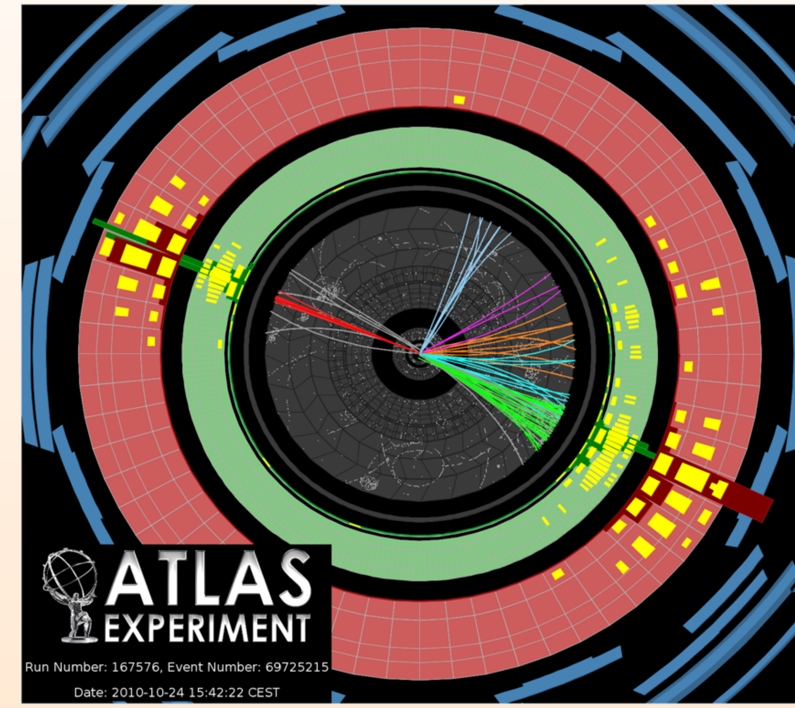
larger $\alpha_s$

# QCD collisions like to produce Jets:
## a cluster of hadrons moving in the same direction

LEP 2 jet event



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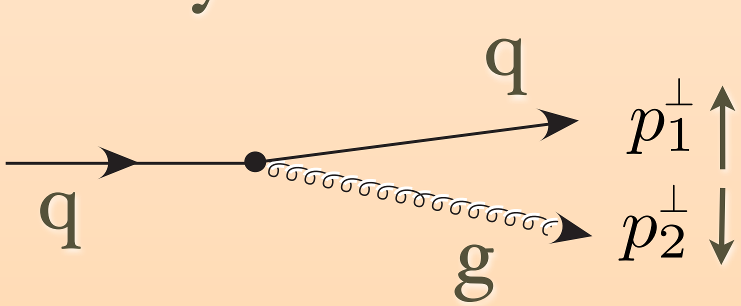
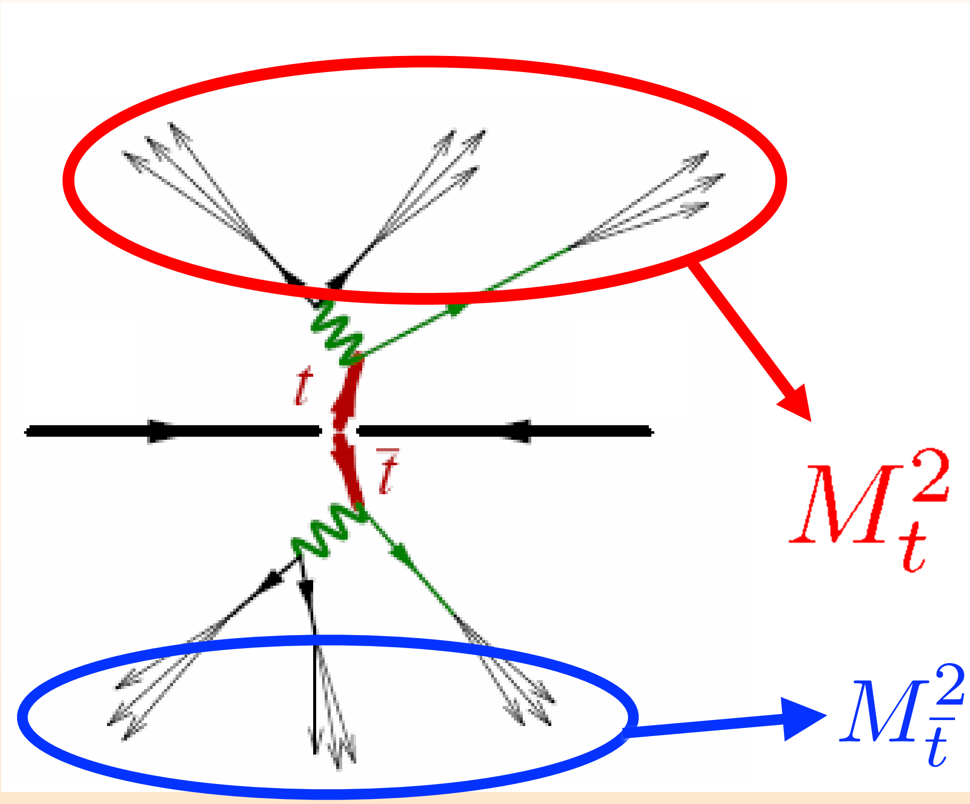



collinear enhancement

larger $\alpha_s$

repeat to get a "shower":

Instead of measuring properties of hadrons we can measure properties of jets




eg. invariant mass

$$M_t^2 = \left(\sum_i p_i^\mu\right)^2 \simeq p_t^2 = m_t^2$$

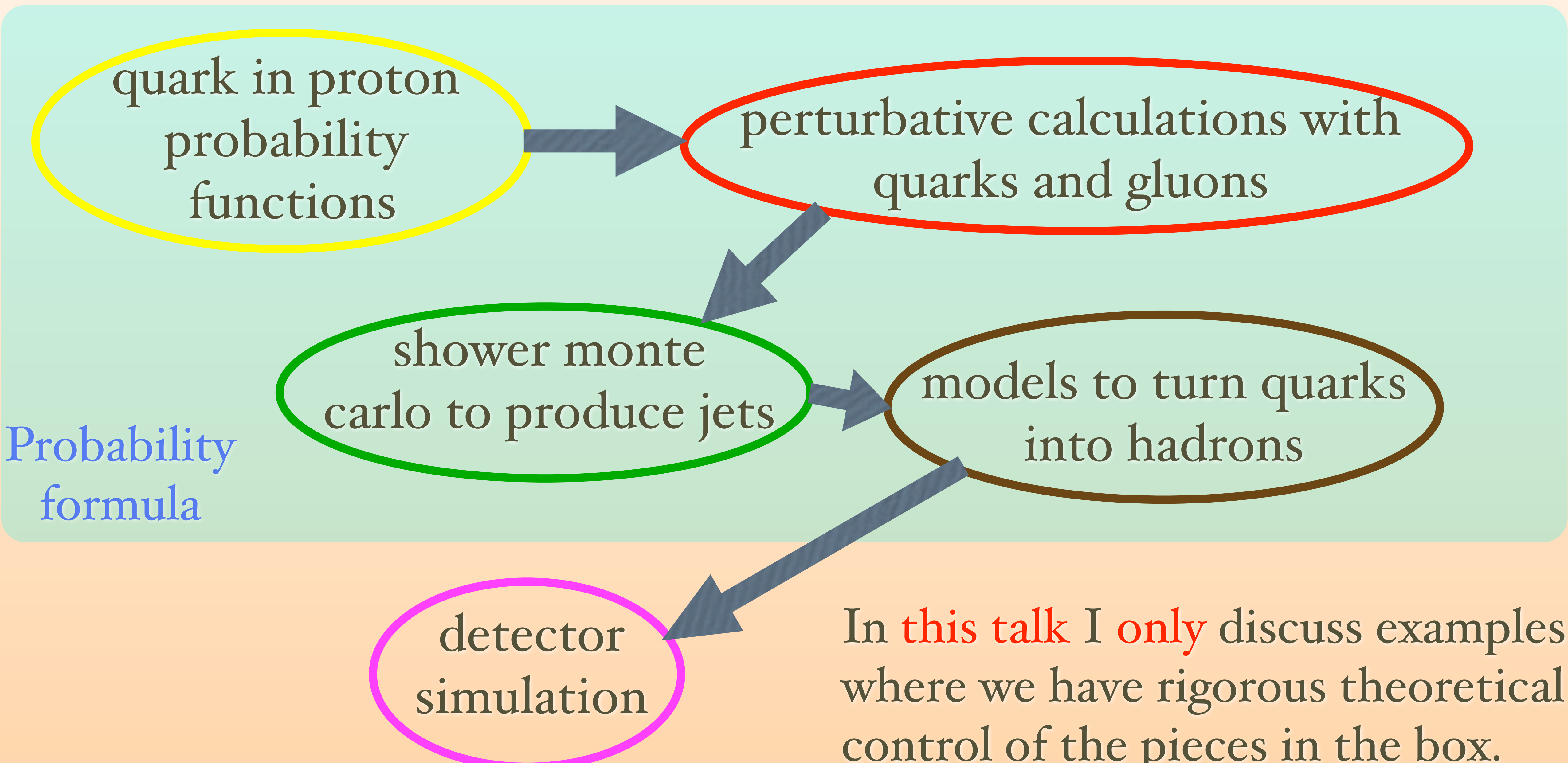
Effectively we treat the jets much like we would treat single particles.

eg. Probability is given by a differential cross section

$$\frac{d^2\sigma}{dM_t^2 dM_{\bar{t}}^2}$$

Only for simpler cases do explicit derivations of these probability formulas for jets exist. There is not a general user friendly formula.

Many Collider calculations are therefore done just by following the factorization paradigm. This may not be 100% correct in all the details, but should capture the bulk of what is going on:




In this talk I only discuss examples where we have rigorous theoretical control of the pieces in the box.

# Soft - Collinear Effective Theory

"SCET"

Bauer, Pirjol, I.S., Fleming

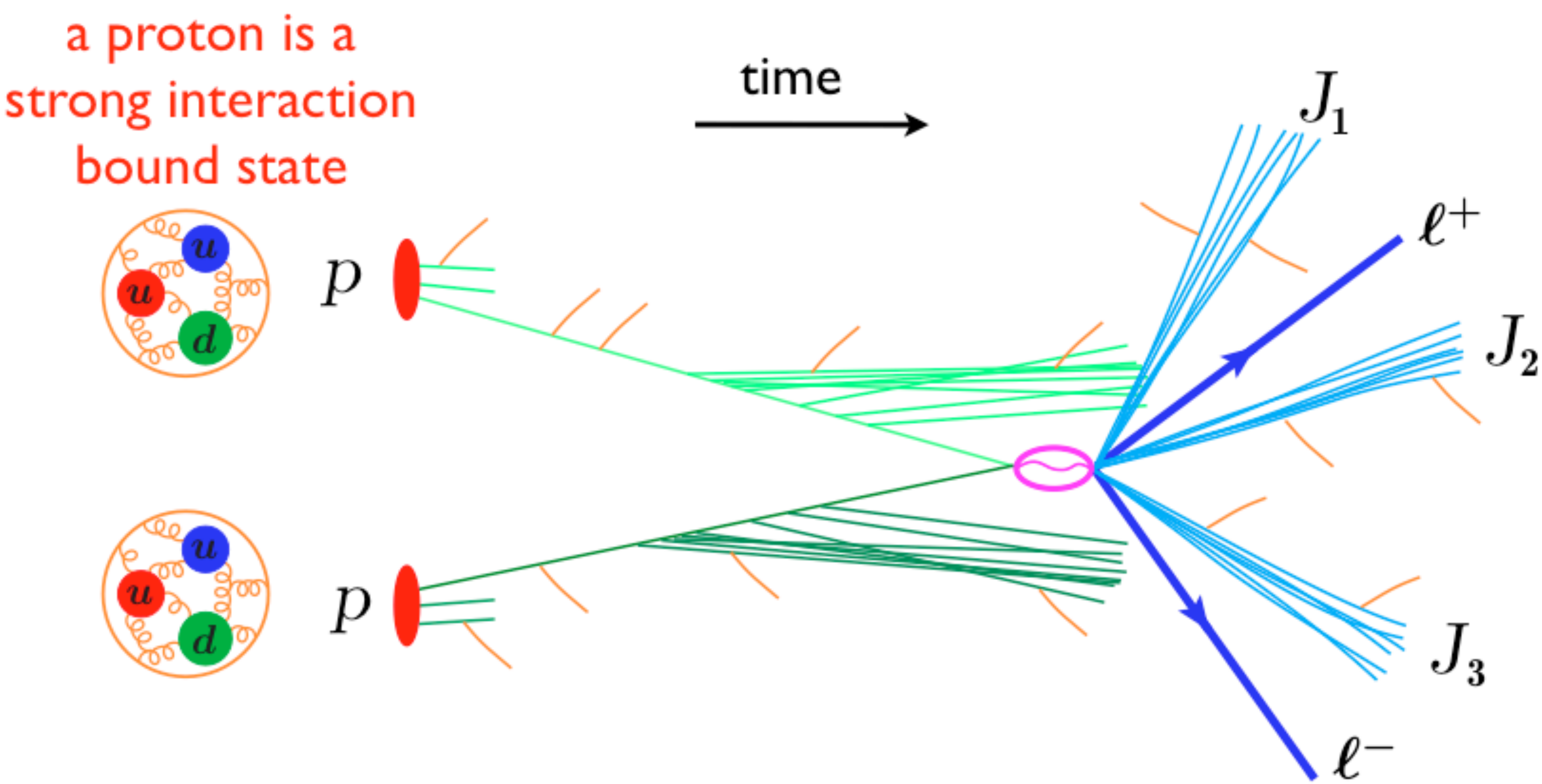
A framework derived from QCD that makes it easier to find the probability formulas for high energy scattering. In addition it makes the approximations required to do so explicit, and allows corrections to be computed systematically.

(Much like NRQED provides a simplified version of QED for certain processes.)

Soft: low energy, particles without a preferred direction

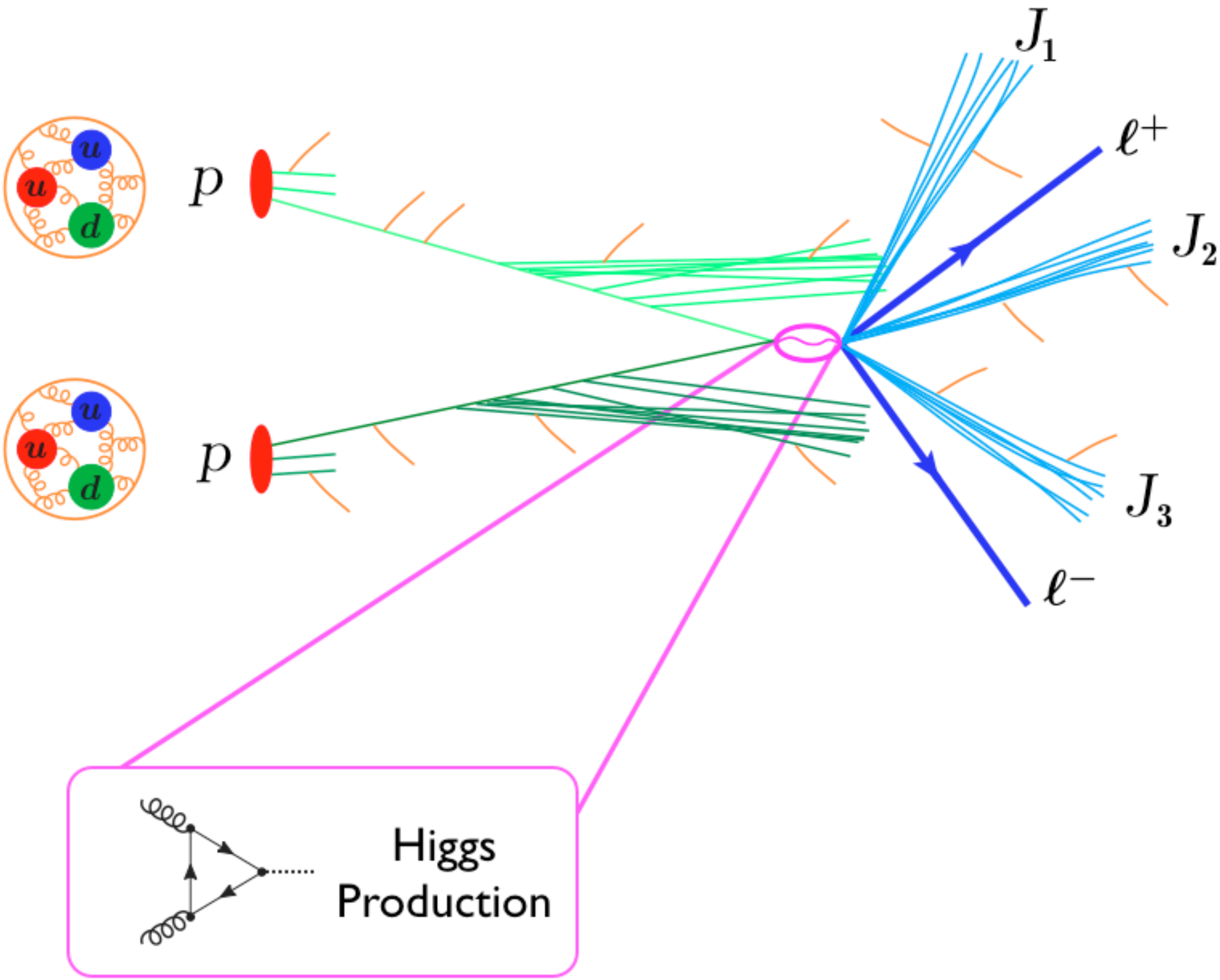
Collinear: energetic hadrons & jets, $E \gg \Lambda_{\mathrm{QCD}}$ , collimated

# Anatomy of a High Energy Collision of Two Protons



# Anatomy of a High Energy Collision of Two Protons

Search for New Heavy Particles at short distances



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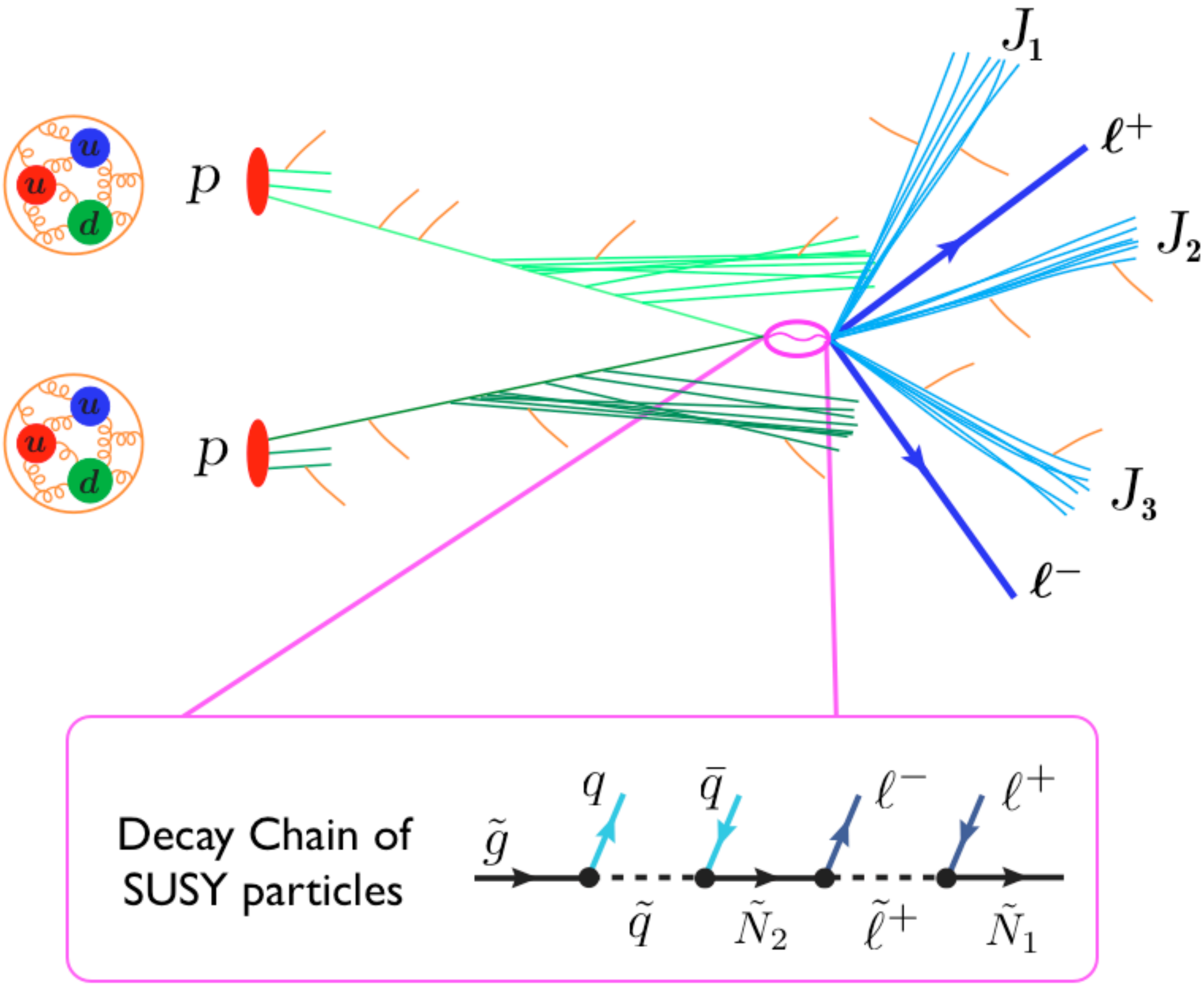

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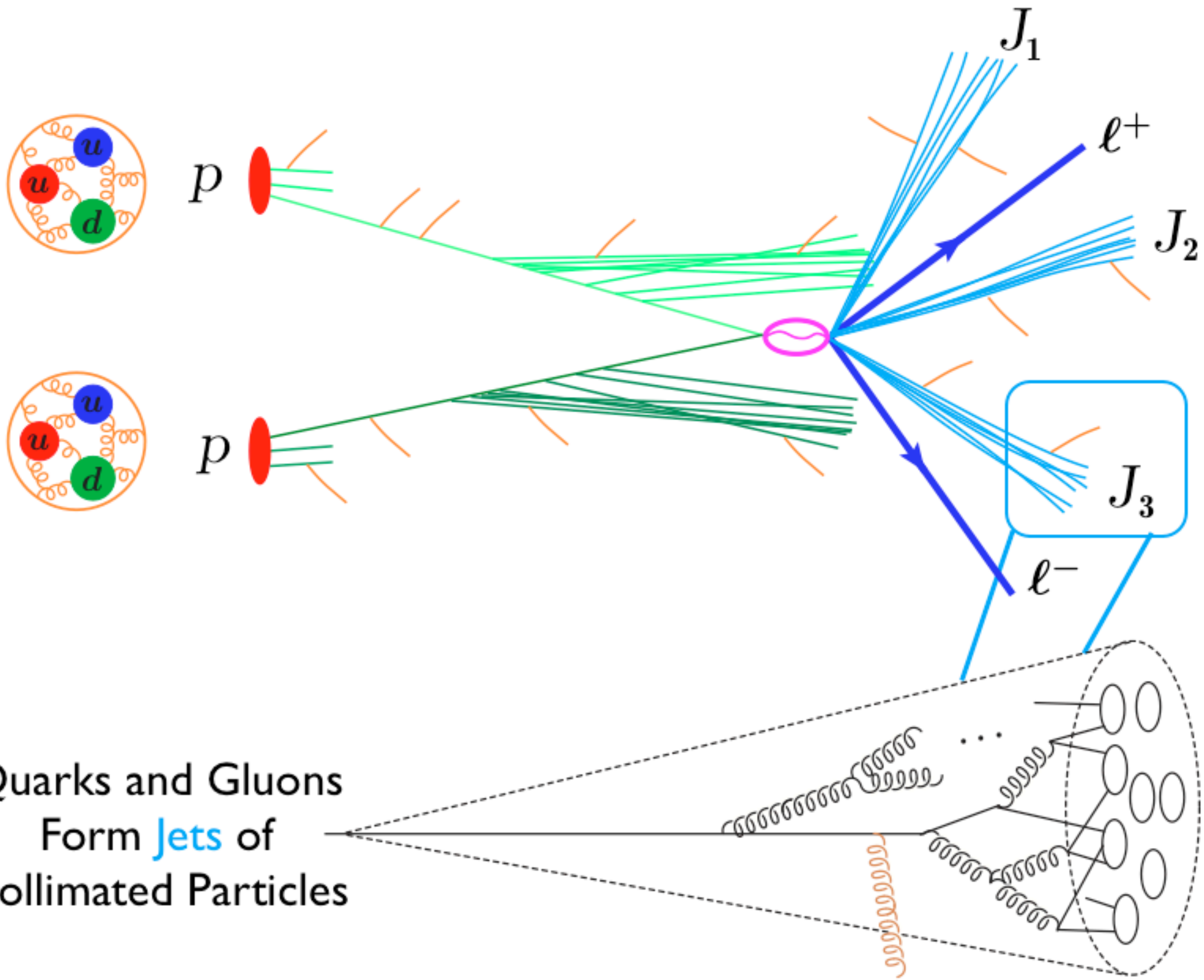
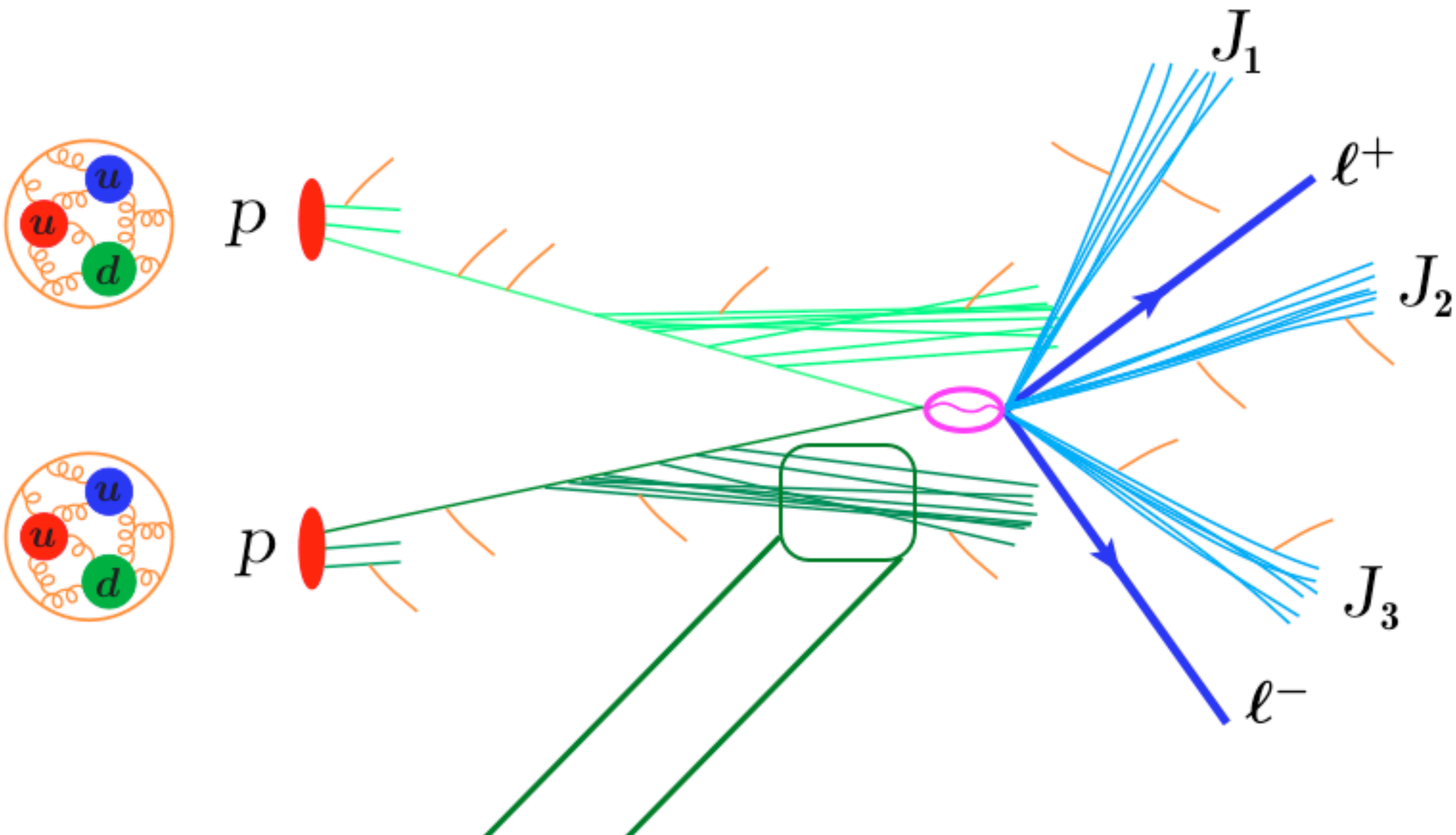



Quarks and Gluons
Form Jets of
Collimated Particles

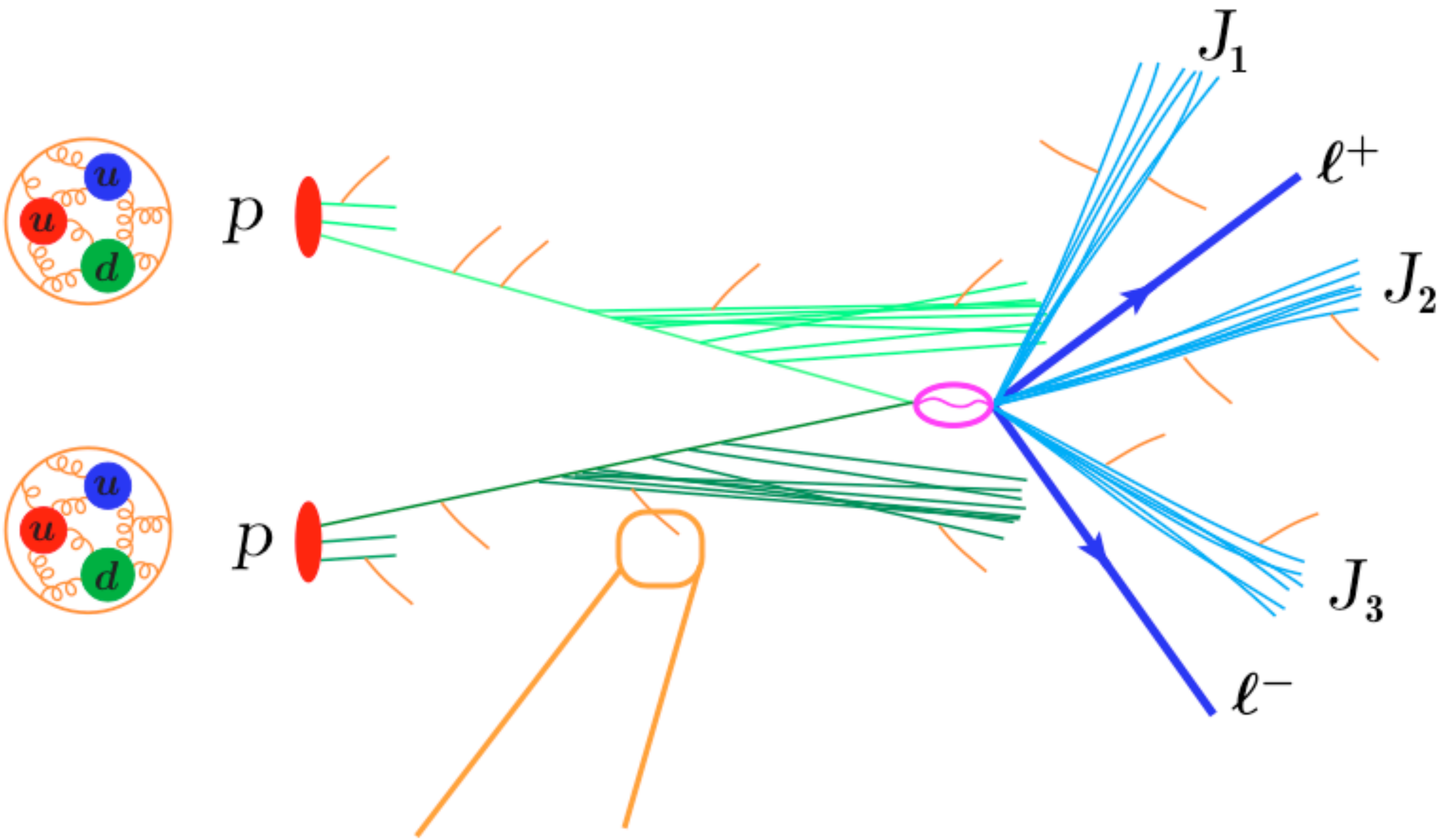
Jet is
observed as
a collection
of bound
hadrons

# Anatomy of a High Energy Collision of Two Protons



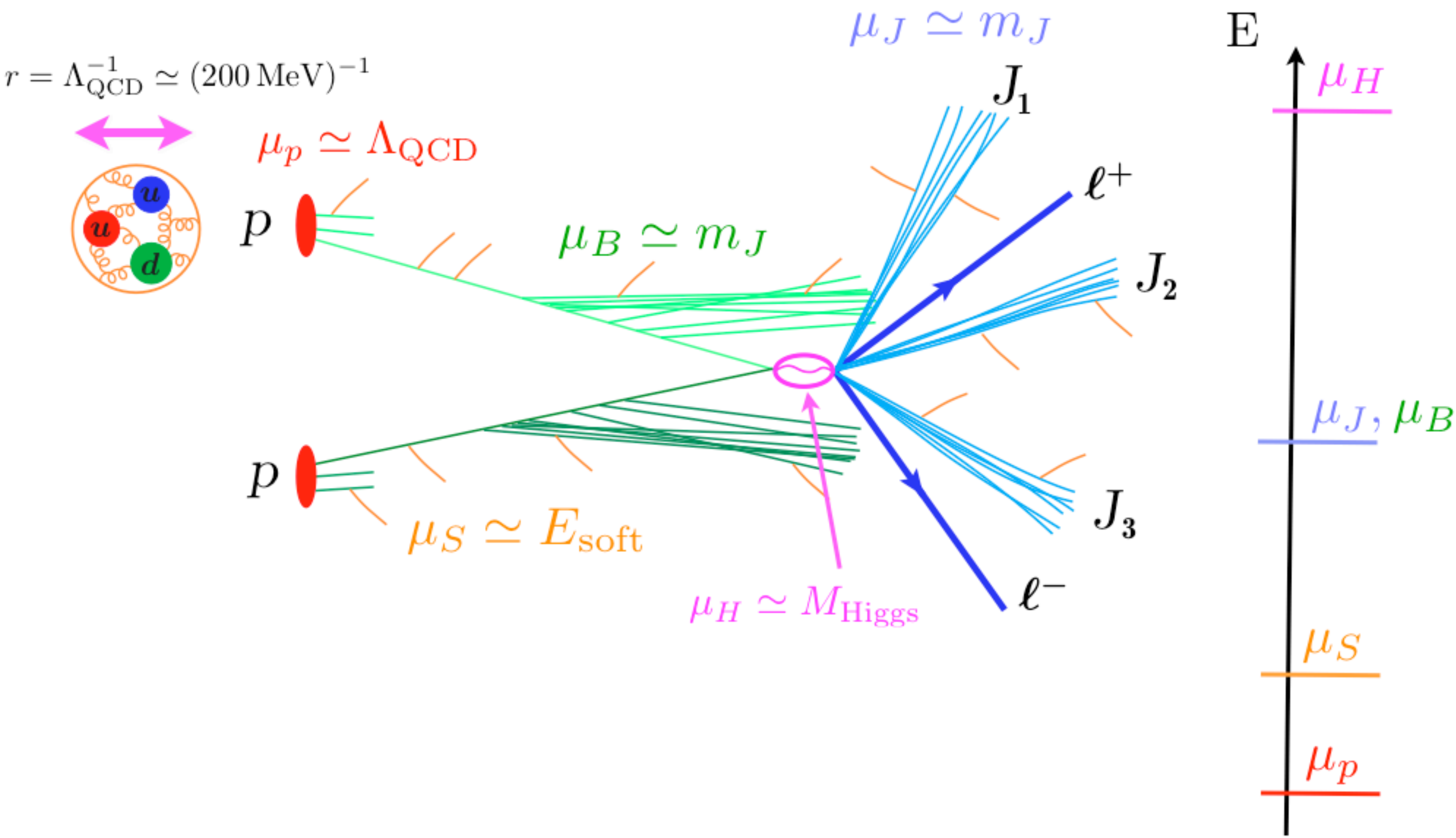

Jets also can form
prior to the
hard collision

# Anatomy of a High Energy Collision of Two Protons

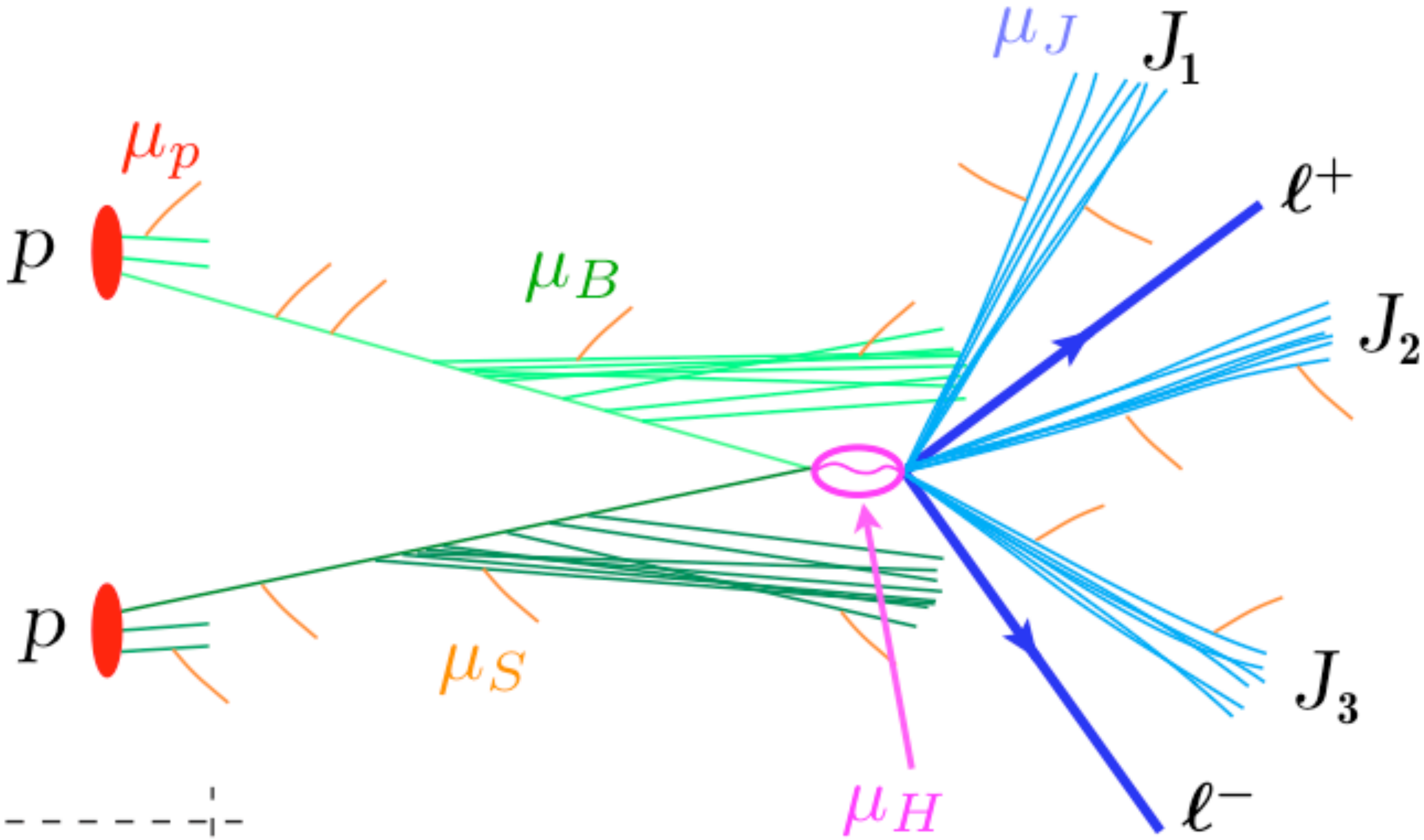


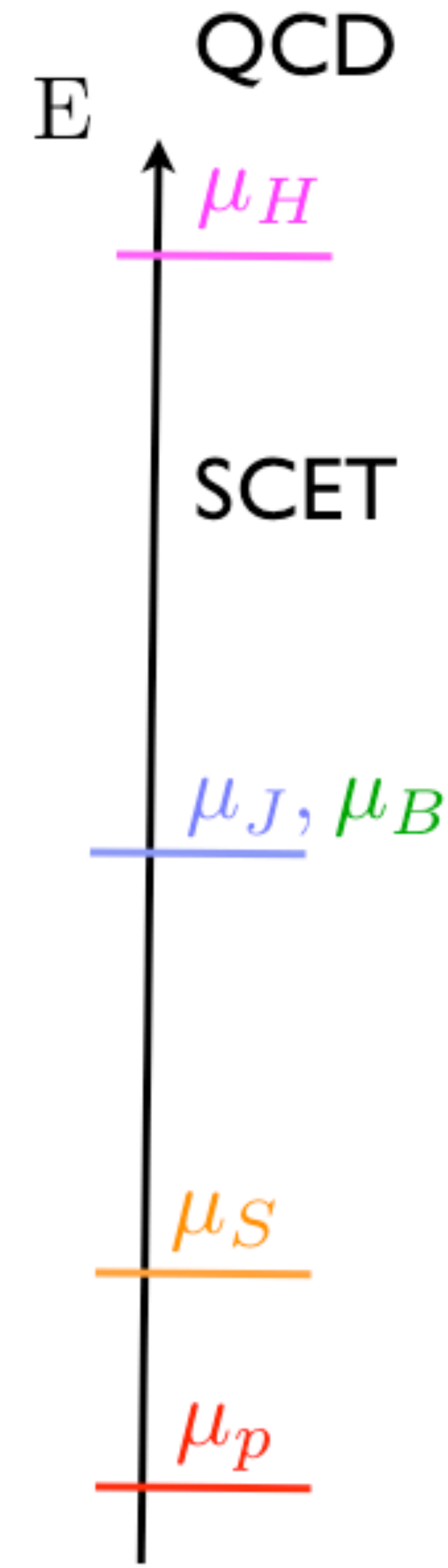

All colored particles can also
emit lower energy
soft gluon radiation

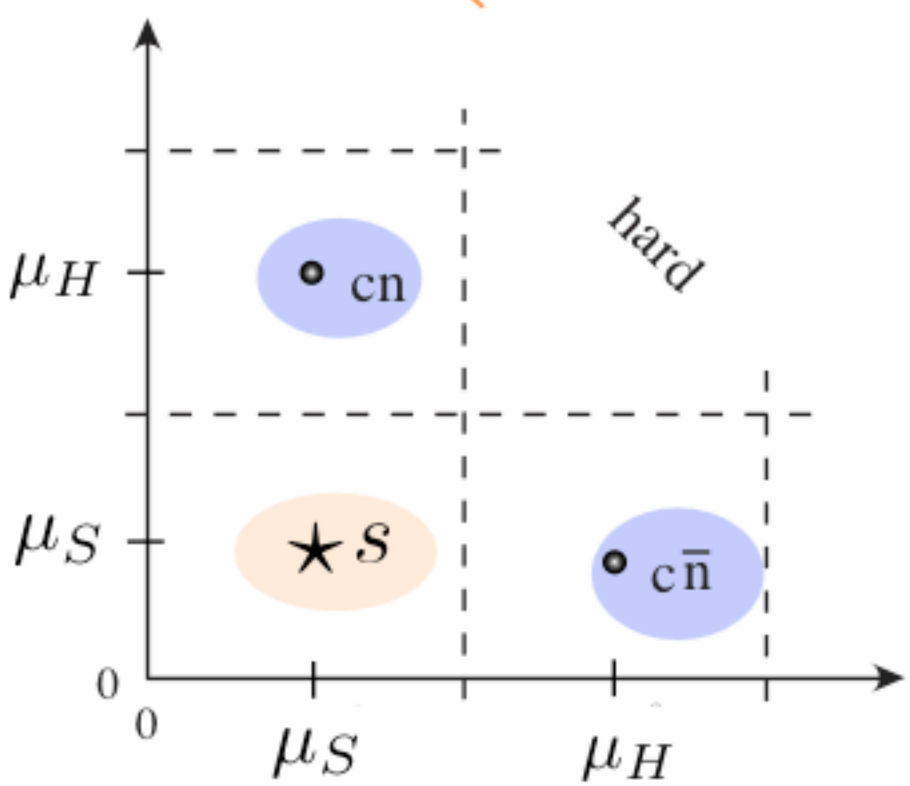
Key Simplifying Principle is to Exploit the Hierarchy of Energy Scales $\mu_i$



We essentially treat one scale at a time, constructing simpler effective field theories for the lower energy dynamics



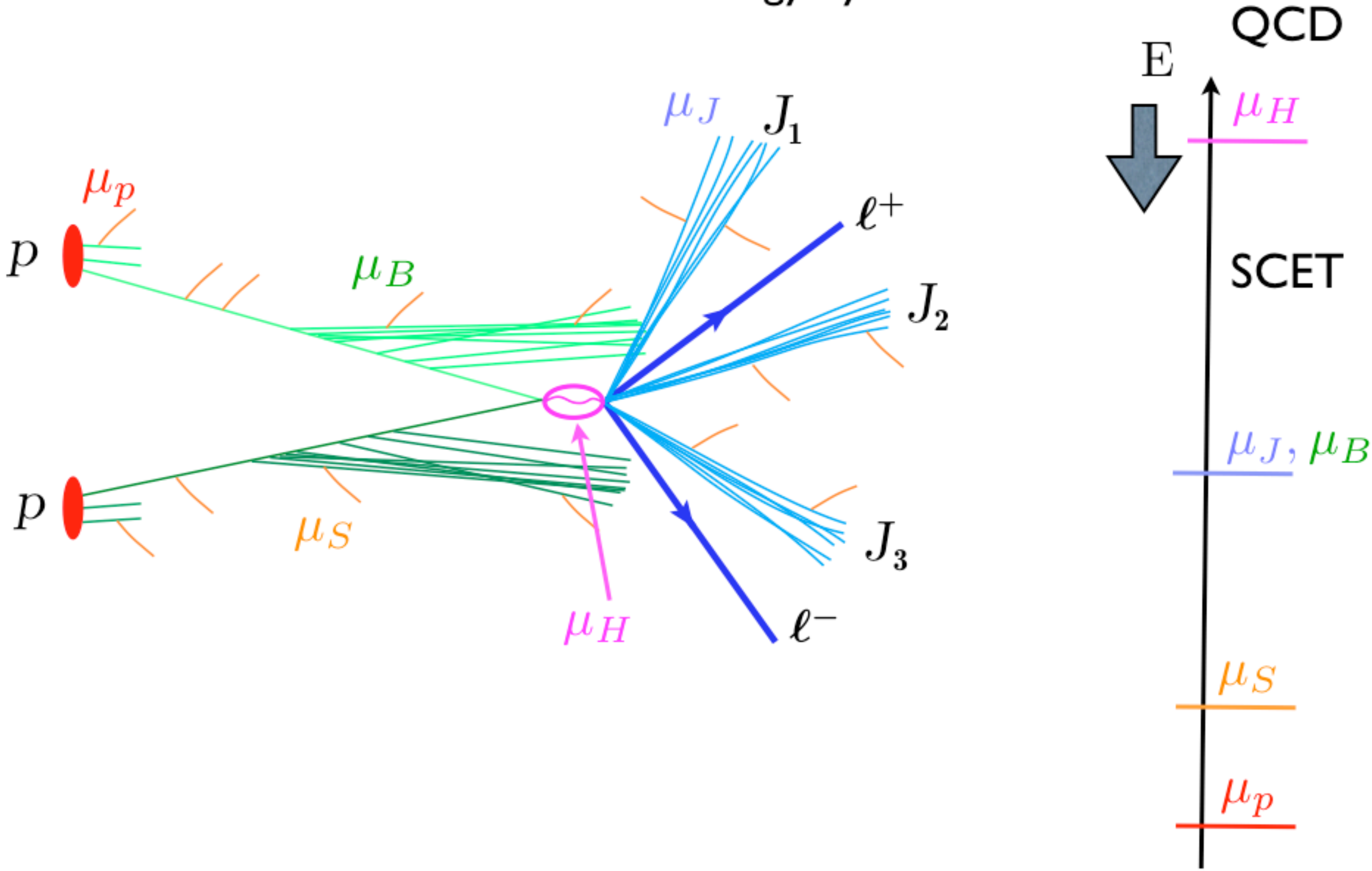




Expand: $\dfrac{\mu_{J,B}}{\mu_H} \ll 1\;,\quad \dfrac{\mu_{S,p}}{\mu_J} \ll 1$

SCET = Soft-Collinear Effective Theory

We essentially treat one scale at a time, constructing simpler effective field theories for the lower energy dynamics

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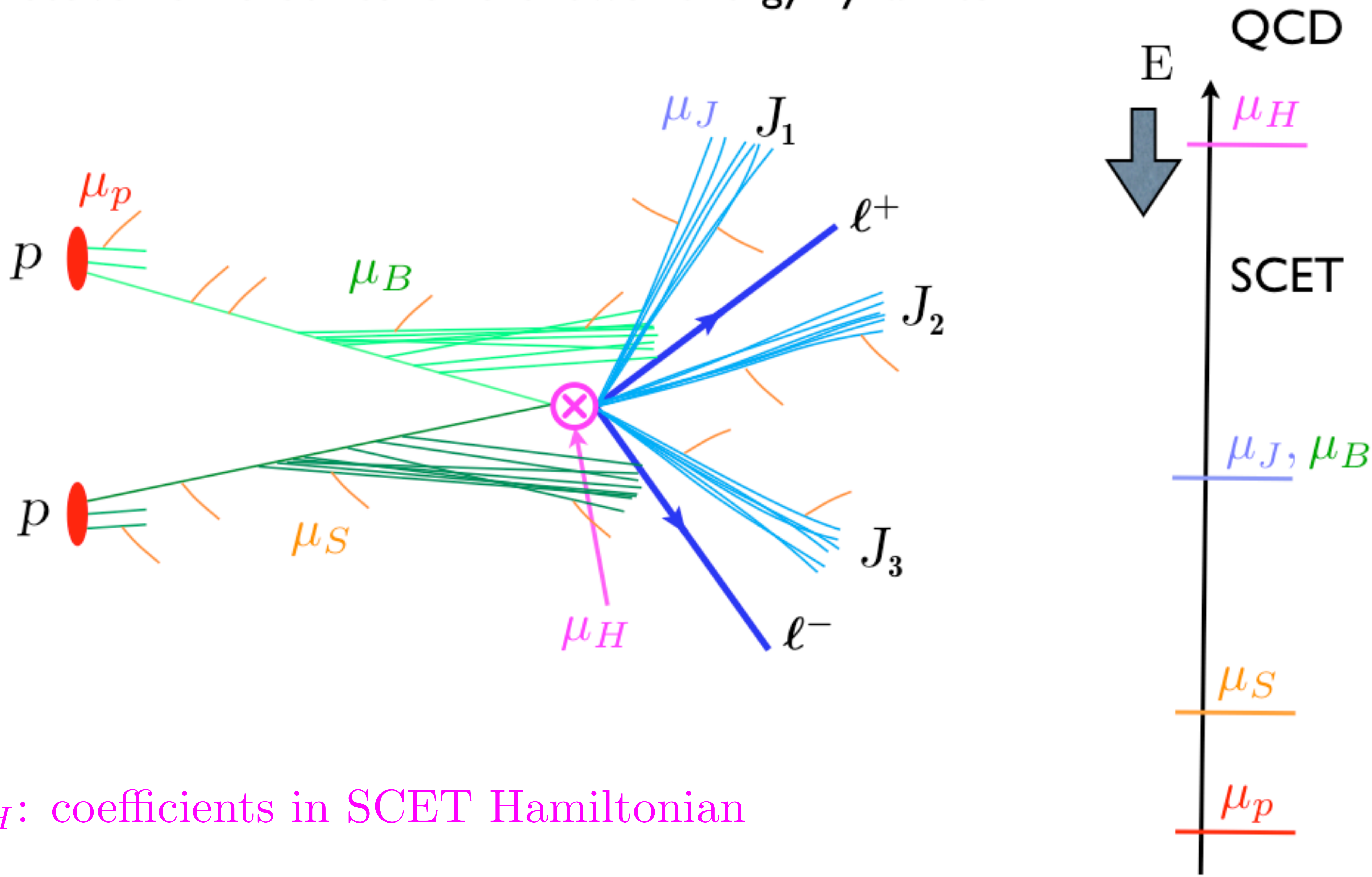


$\mu_H$: coefficients in SCET Hamiltonian

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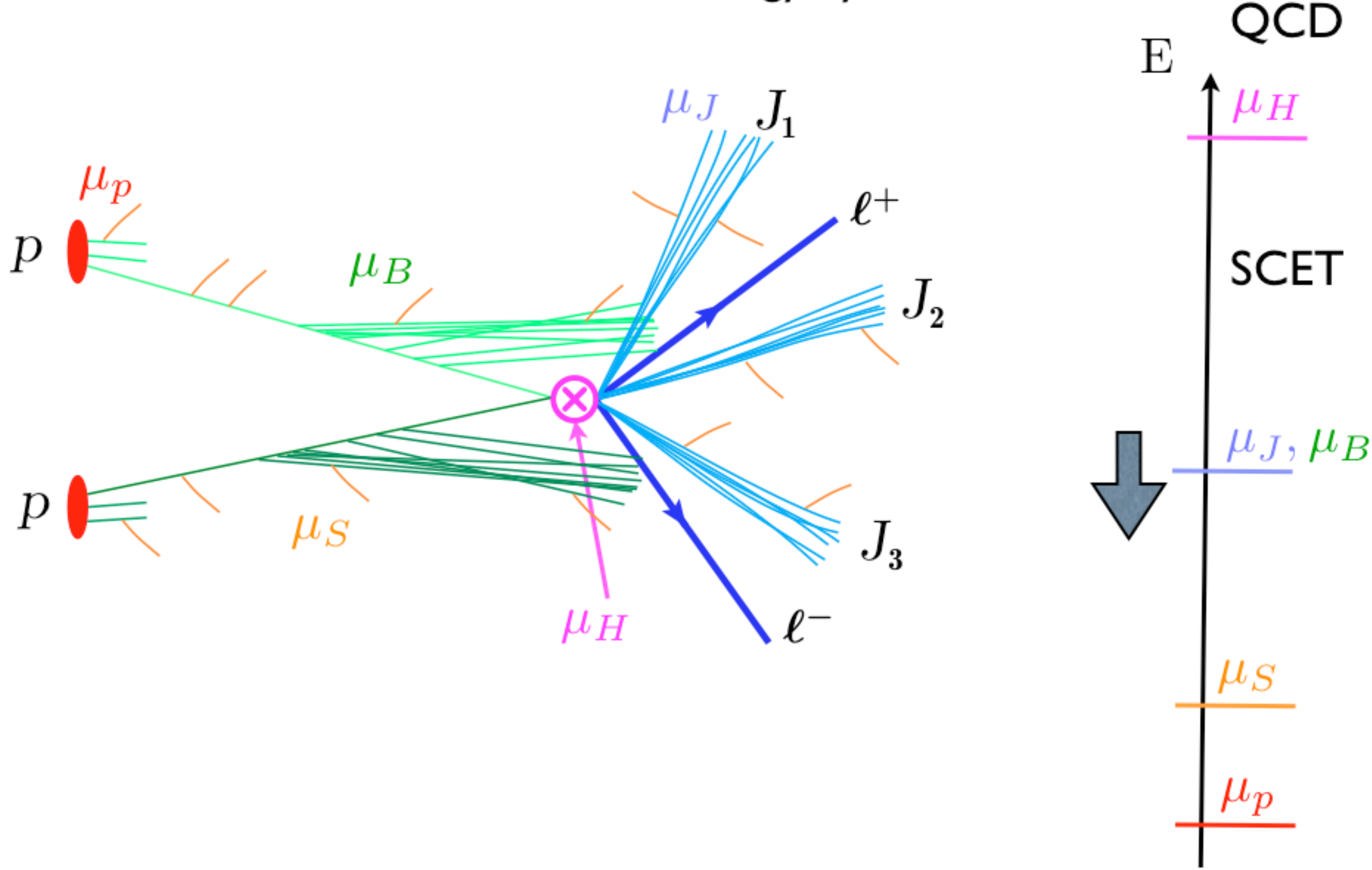

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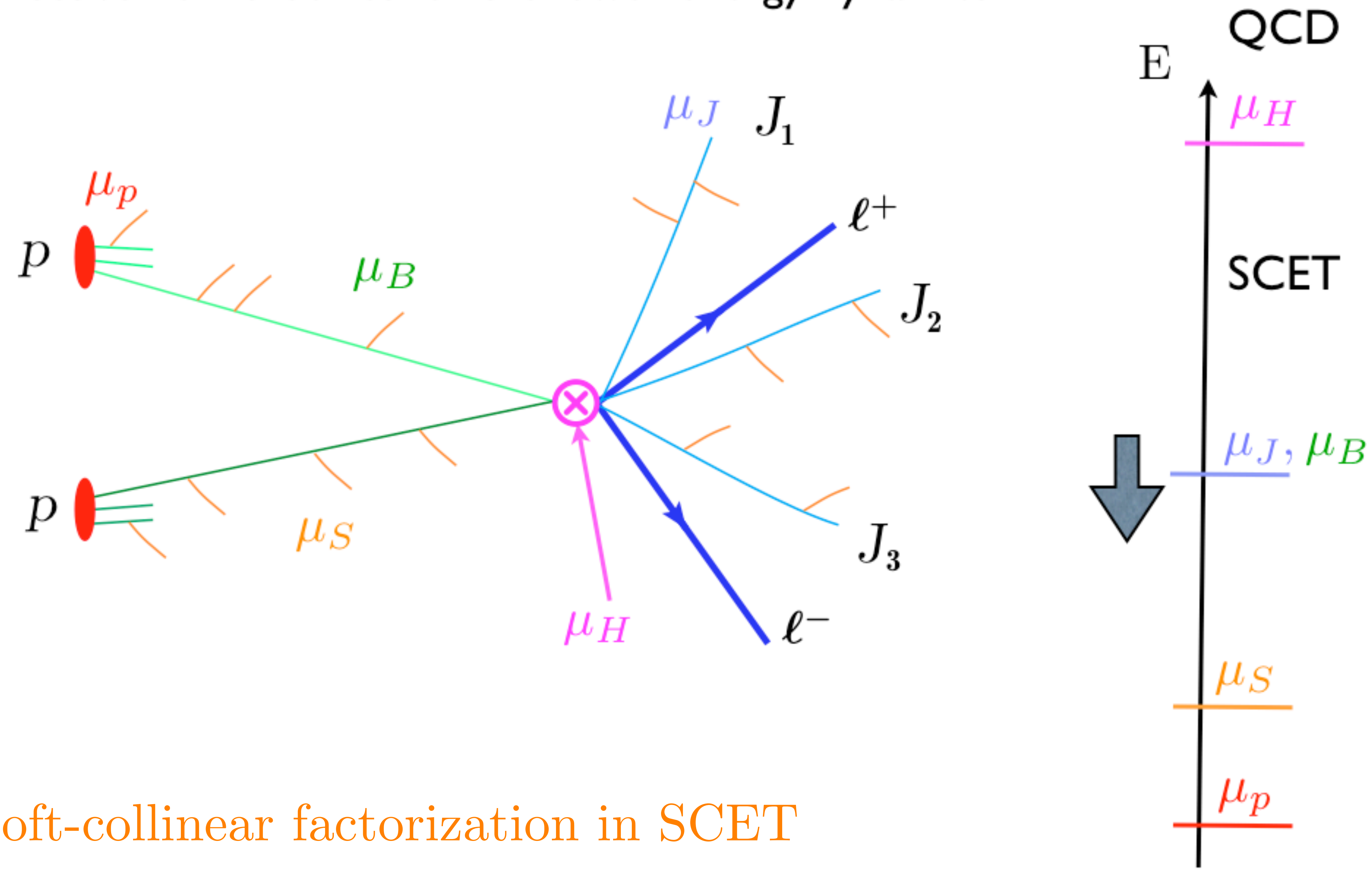
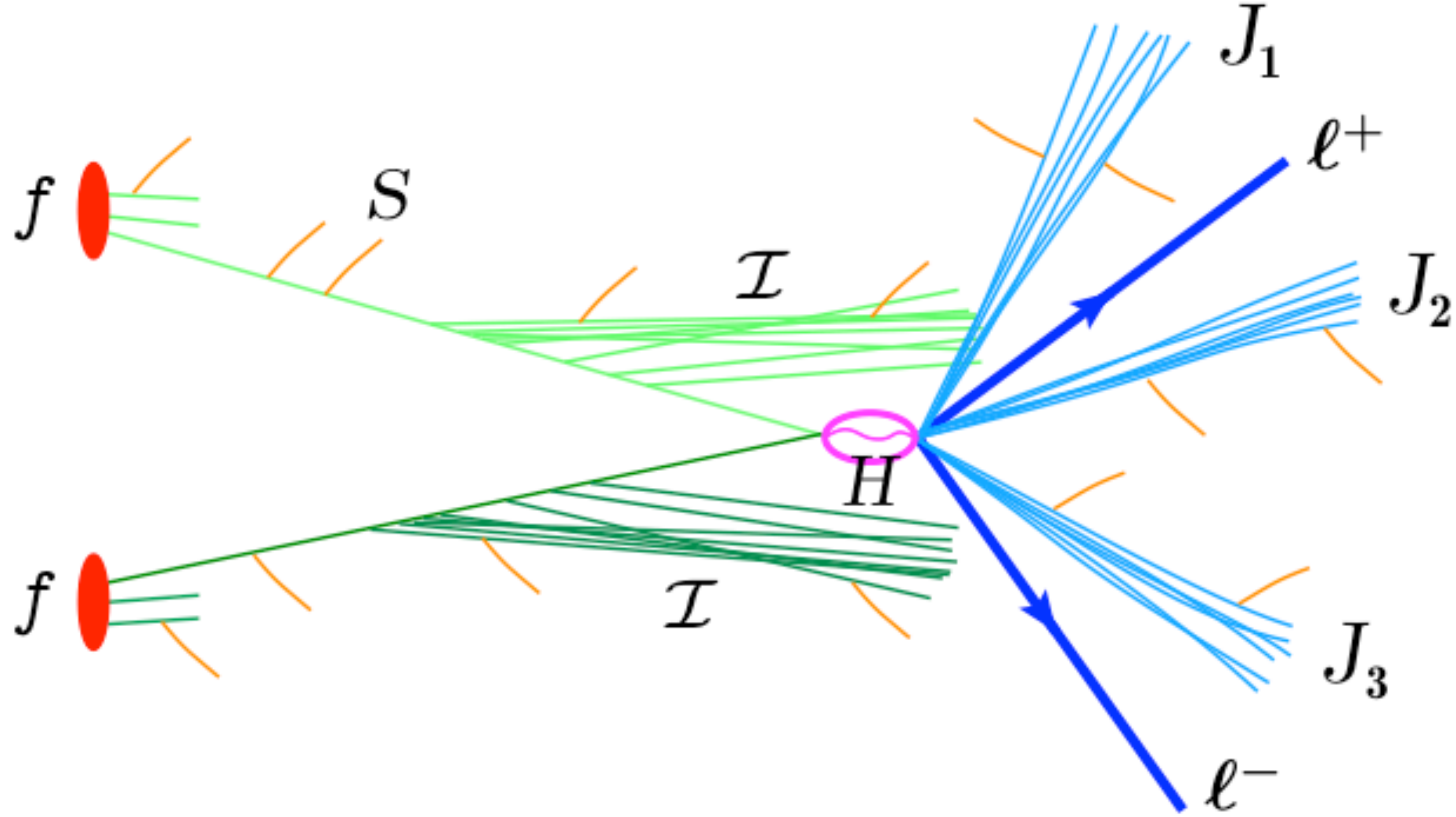
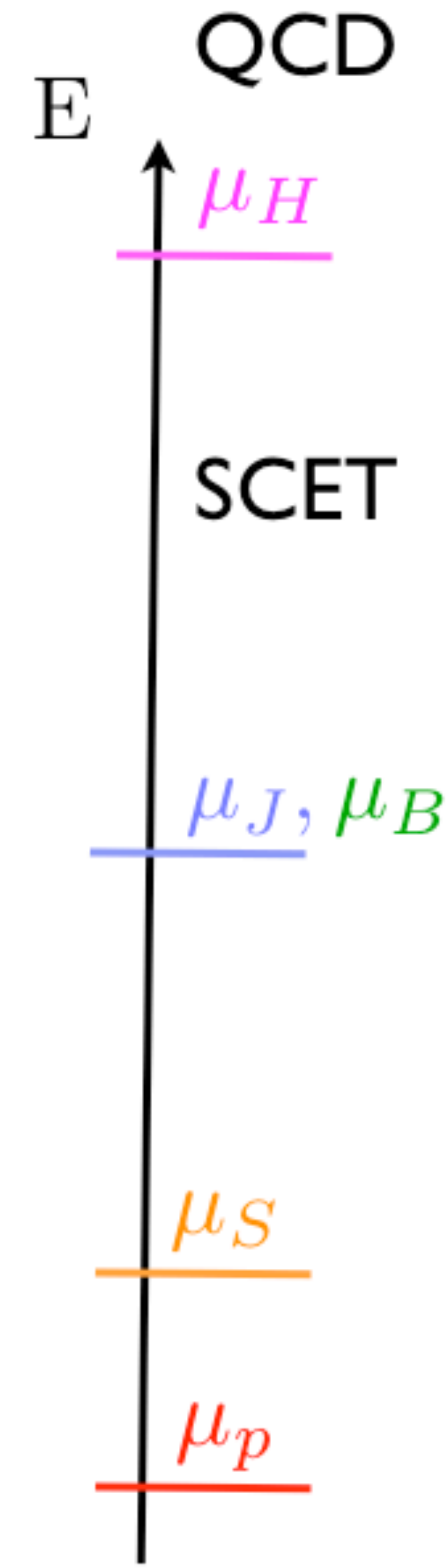



soft-collinear factorization in SCET



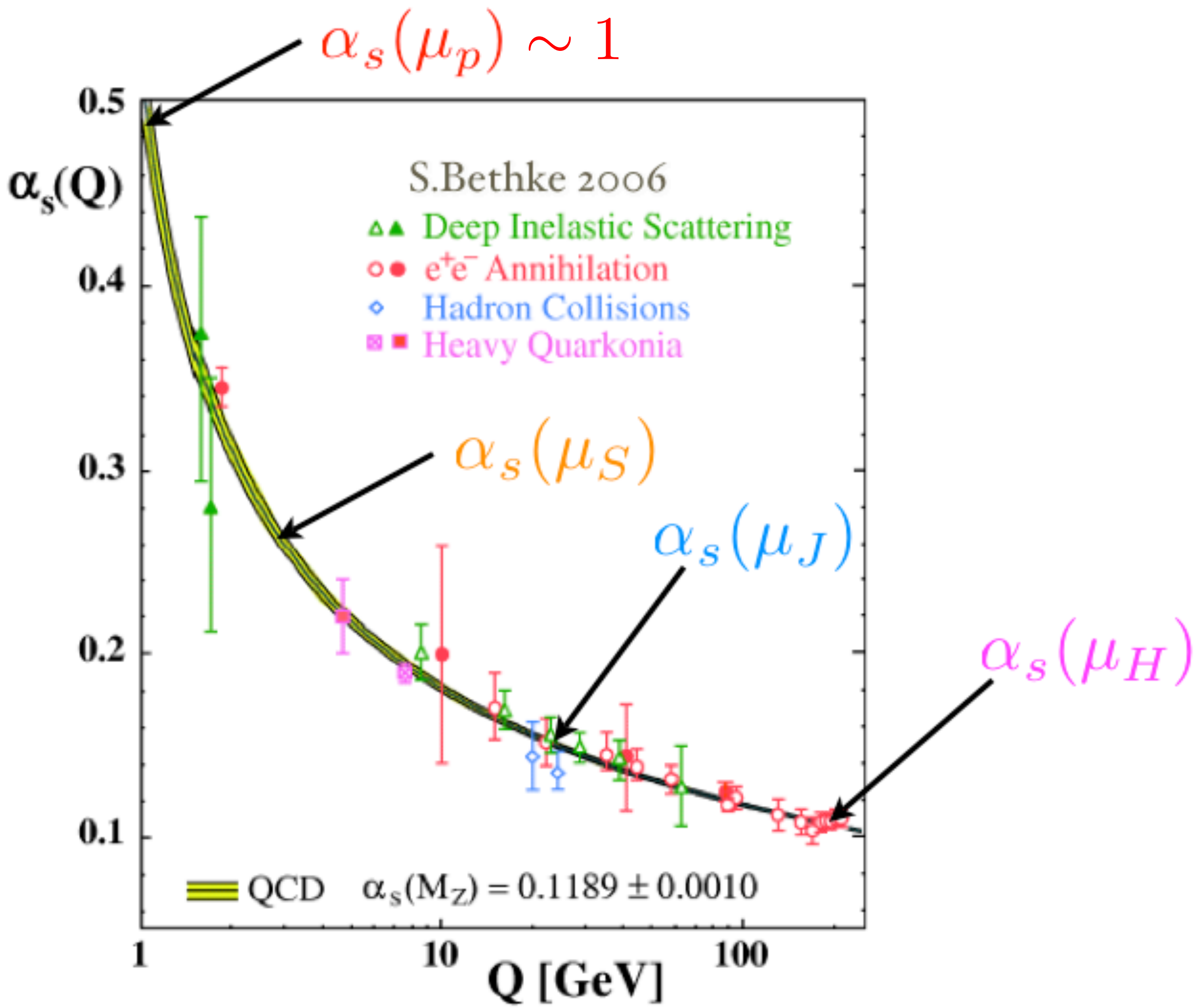




Final Results are

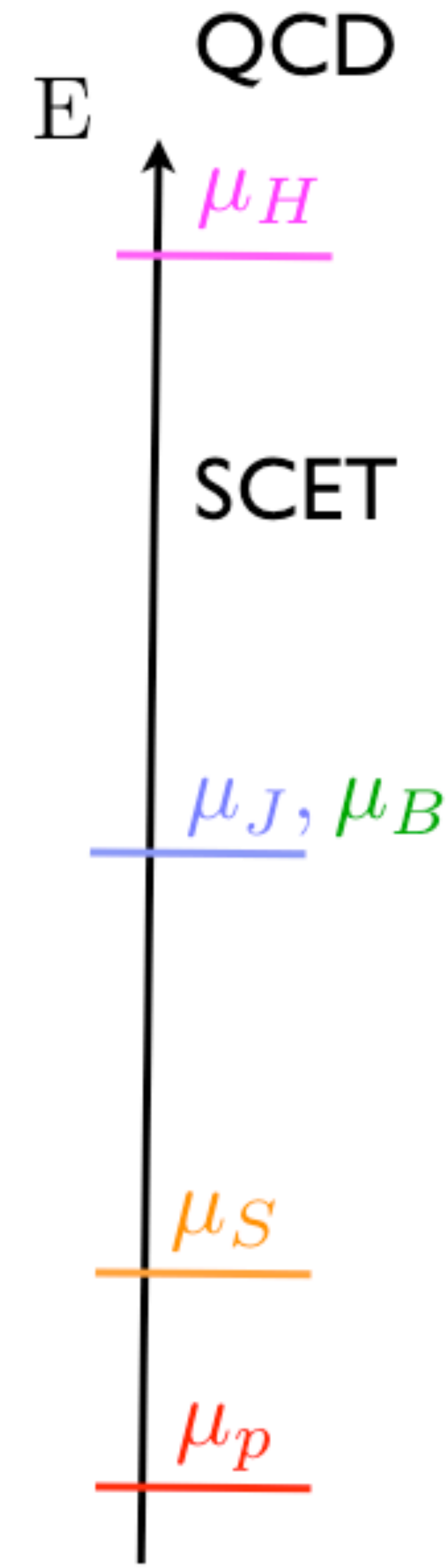
Factorization formulas for individual cross sections:

$$\mathbf{d}\boldsymbol{\sigma} = \boldsymbol{f_{a,b}} \otimes \boldsymbol{\mathcal{I}_{a,b}} \otimes H \otimes \prod_i \boldsymbol{J_i} \otimes \boldsymbol{S}$$

$$\boldsymbol{\Lambda_{\mathrm{QCD}}} \qquad \boldsymbol{\mu_B} \qquad \mu_H \qquad \boldsymbol{\mu_J} \qquad \boldsymbol{\mu_S}$$




Our treatment ensures we can use appropriate values for the strong coupling.



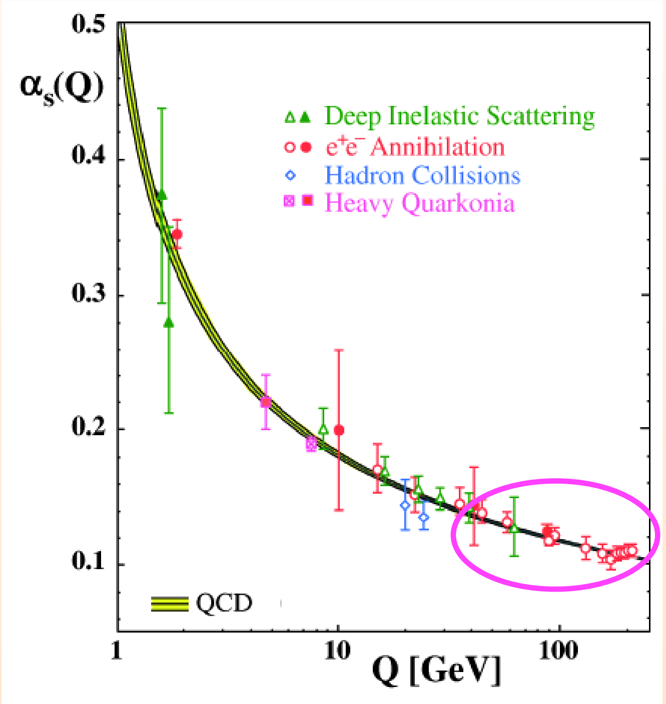
# Applications

i) Measuring $\alpha_s$ with Jets

ii) Top Quark Mass from Jets

iii) Higgs and Jets

# Measuring the Strong Coupling with Jets




$$\boxed{e^+e^- \xrightarrow{Q} \text{jets}}$$

Aim at 1% precision

(factor of $\sim 5$ improvement)

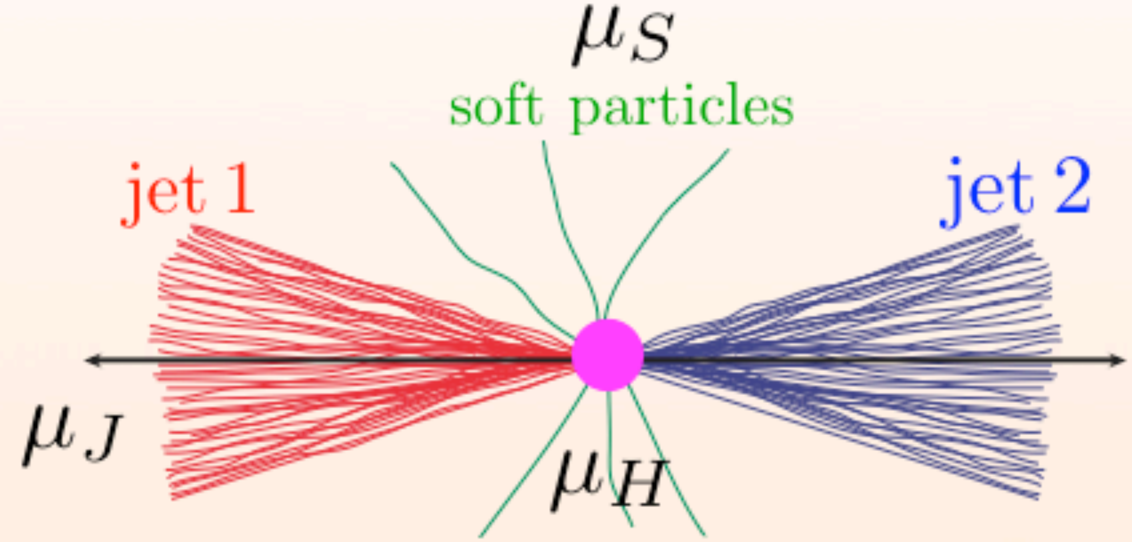
Abbate, Fickinger, Hoang, Mateu, I.S.
arXiv:1006.3080

use work by: Gehrmann et al. & Weinzierl $\mathcal{O}(\alpha_s^3)$

Becher, Schwartz $\mathrm{N^3LL}$

eg. $e^+e^- \to Z \to 2\,\text{jets} + X_{\text{soft}}$

$$m_Z^2 \gg M_{\text{jet}}^2 \gg E_{\text{soft}}^2$$

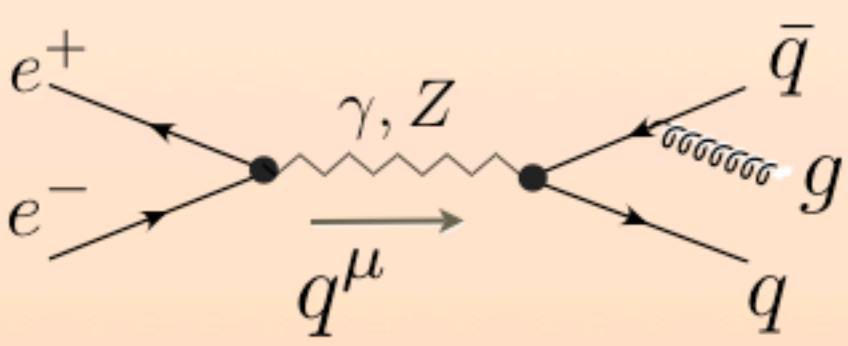



$$\mu_H \simeq m_Z = 91.2\,\text{GeV}$$

$$\mu_J \simeq M_{\text{jet}} \simeq 20\,\text{GeV}$$

$$\mu_S \simeq E_{\text{soft}} \simeq 5\,\text{GeV}$$

Three jet events are proportional to $\alpha_s$, good sensitivity




$$Q^2 = q^2$$

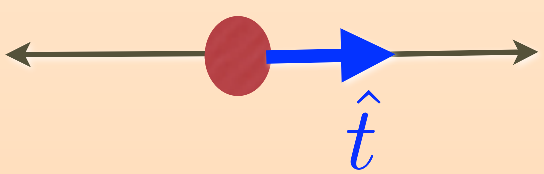
# Measure a classic "event-shapes" called Thrust

$$\tau = 1 - \max_{\hat{t}} \frac{\sum_i |\hat{\mathbf{t}} \cdot \vec{p}_i|}{Q}$$

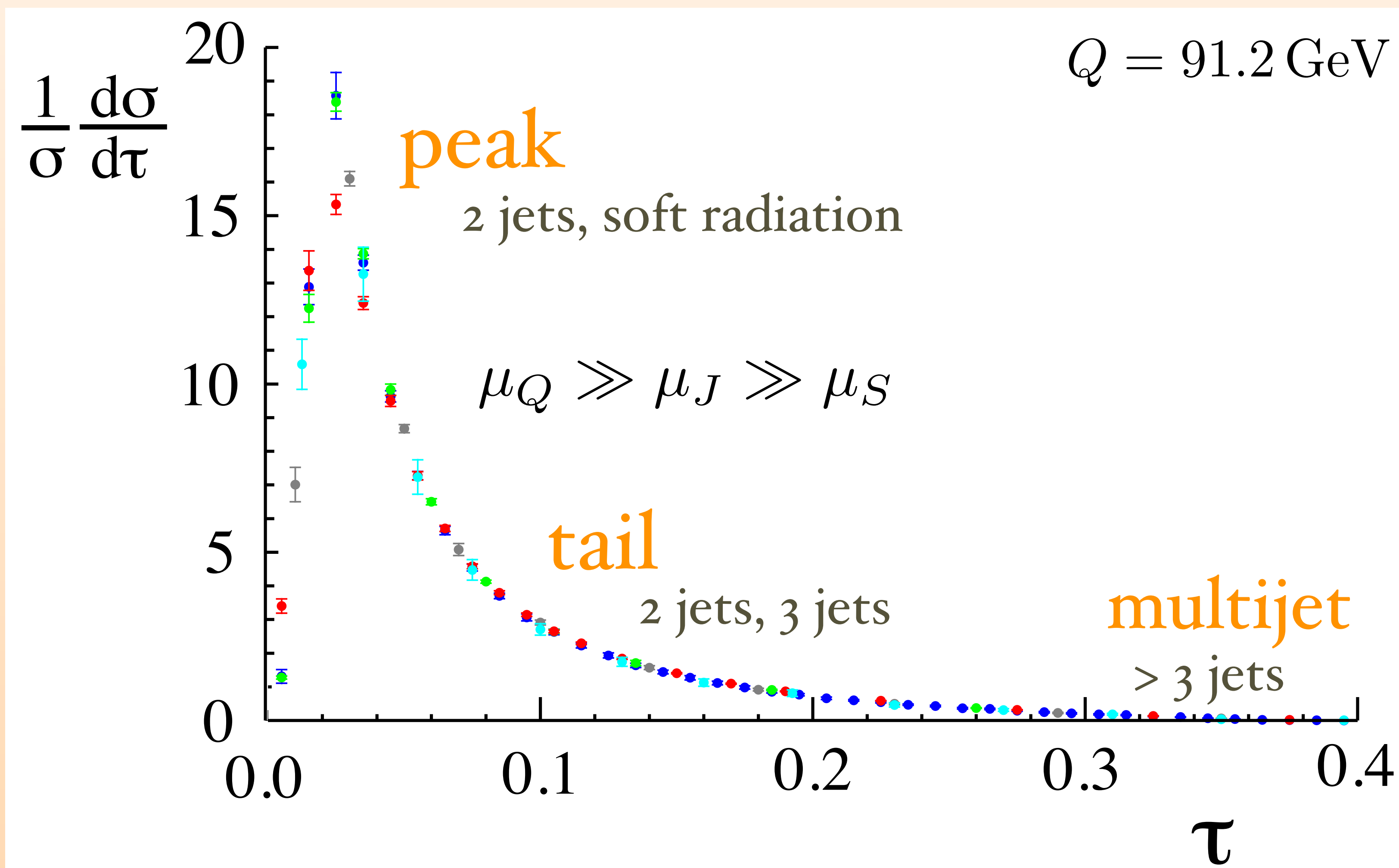
experiments: ALEPH, DELPHI, L3, OPAL, SLD

(also TASSO, JADE, Amy)

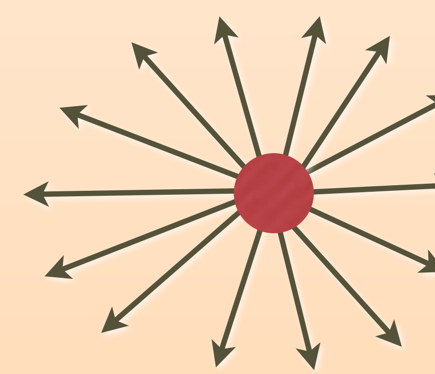
2 jets




$\tau = 0$




spherical event



$\tau = 1/2$

## Large Logs

$$L = \ln(\mu_Q/\mu_J) = \ln(\mu_J/\mu_S) = \ln(1/\tau)$$

$\alpha_s \ll 1$ **but** $\alpha_s L^2 \sim 1$

$$\begin{array}{lllll}
 & \mathcal{O}(\alpha_s) & \mathcal{O}(\alpha_s^2) & \mathcal{O}(\alpha_s^3) & \\
\sigma(\Delta) = 1 & + \alpha_s L^2 & + \alpha_s^2 L^4 & + \alpha_s^3 L^6 & + \dots \\
 & + \alpha_s L & + \alpha_s^2 L^3 & + \alpha_s^3 L^5 & + \dots \\
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 & & & + \alpha_s^3 L & + \dots \\
 & & & + \alpha_s^3 & + \dots \\
 & & & & \ddots
\end{array}$$

**no good**

small print:

here $\sigma(\Delta) = \int_0^\Delta d\tau \frac{d\sigma}{d\tau}$

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solved by log summation

$$\begin{aligned}\sigma(\Delta) = \boxed{1 + \alpha_s L^2 + \alpha_s^2 L^4 + \alpha_s^3 L^6 + \ldots} \quad & \text{LL} \\ + \alpha_s L + \alpha_s^2 L^3 + \alpha_s^3 L^5 + \ldots & \\ + \alpha_s + \alpha_s^2 L^2 + \alpha_s^3 L^4 + \ldots & \\ + \alpha_s^2 L + \alpha_s^3 L^3 + \ldots & \\ + \alpha_s^2 + \alpha_s^3 L^2 + \ldots & \\ + \alpha_s^3 L + \ldots & \\ + \alpha_s^3 + \ldots & \\ \ddots & \end{aligned}$$

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here $\sigma(\Delta) = \int_0^\Delta d\tau \frac{d\sigma}{d\tau}$ ; sum's are actually in exponent

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& && && && + \alpha_s^3 && + \ldots \\
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LL

NLL

NLL$'$

NNLL

NNLL$'$

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N$^3$LL

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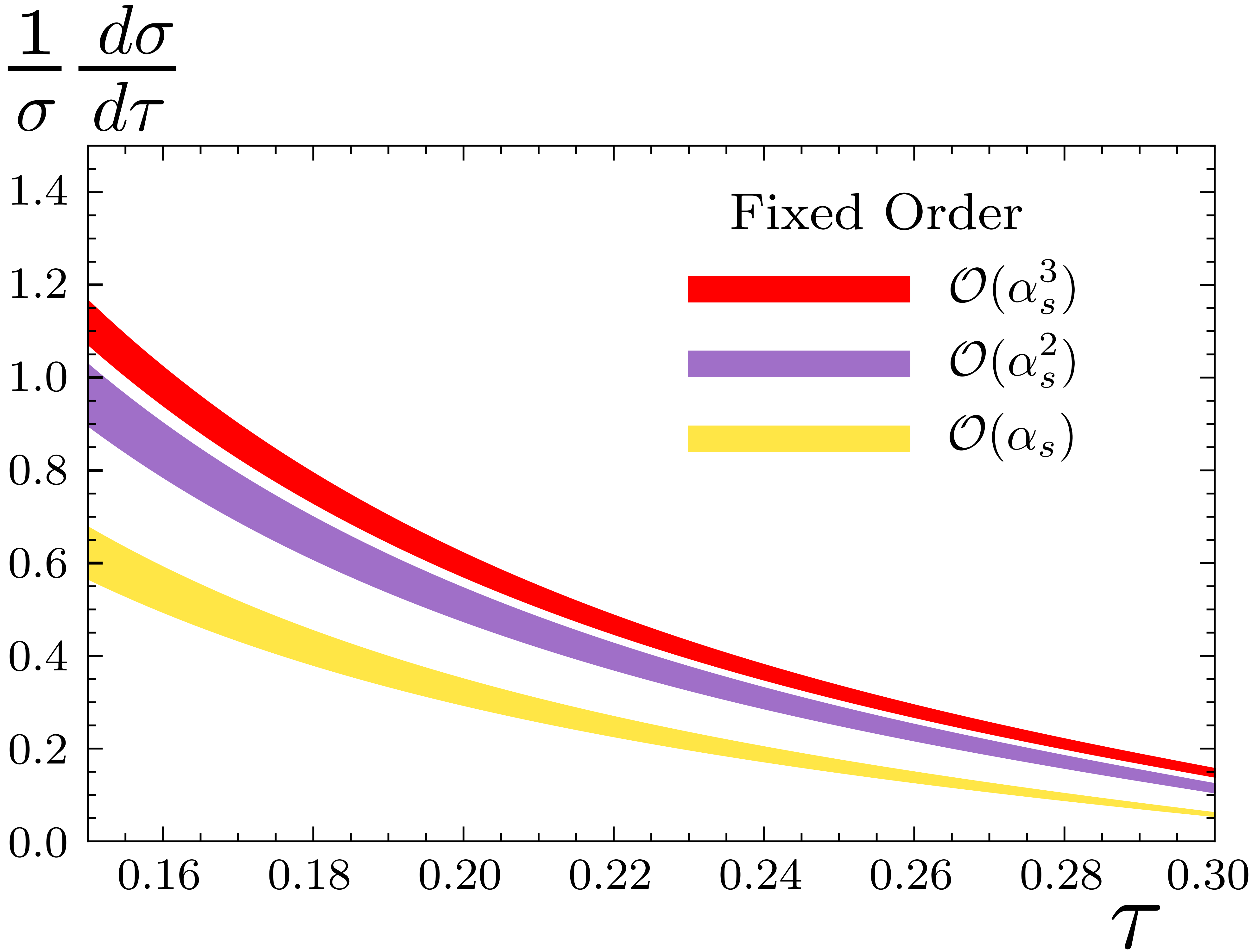
# Theory Errors on Tail Cross Sections



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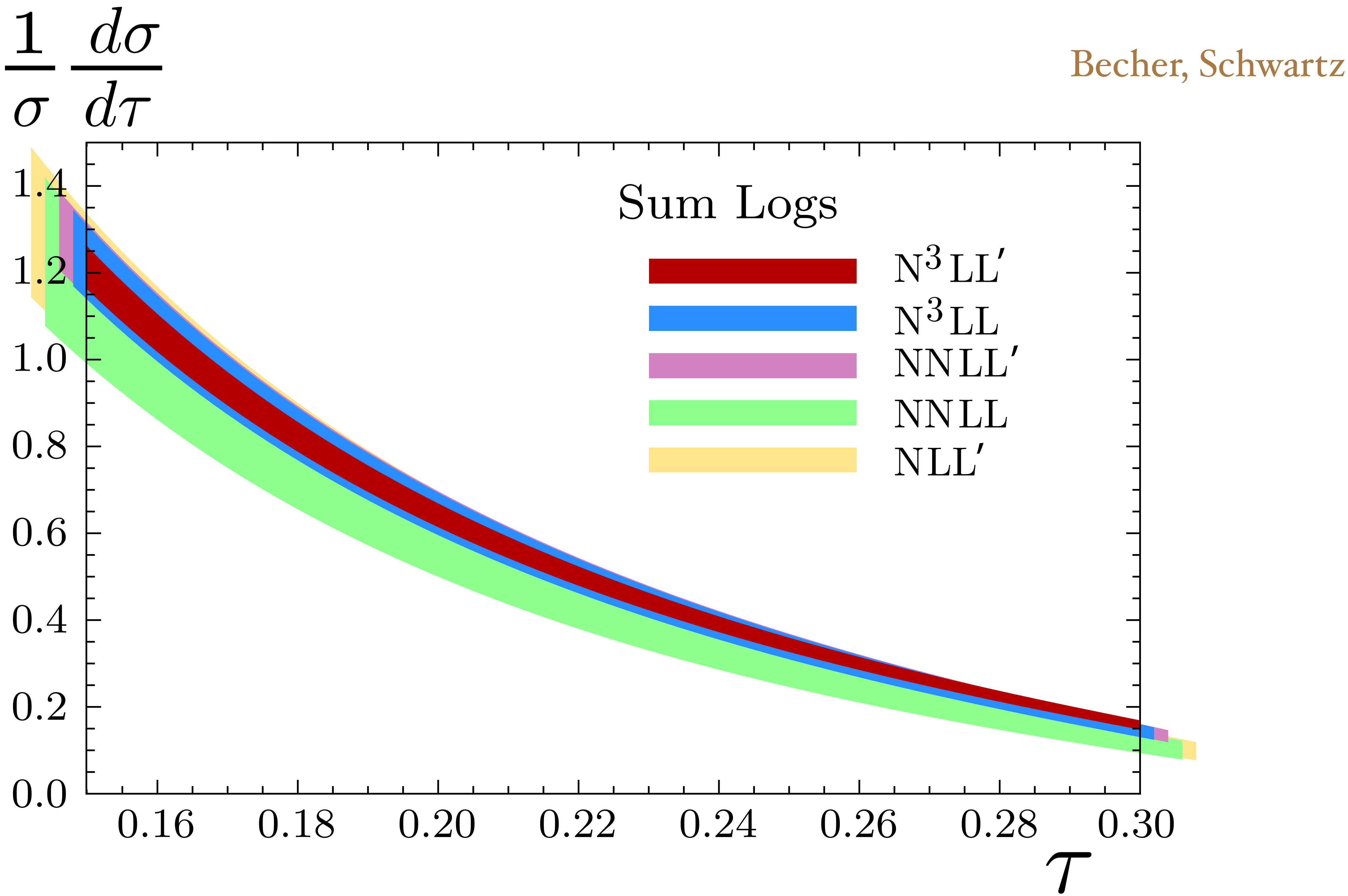

# Nonperturbative Effects $\alpha_s(\mu) \sim 1$

At the end of the LEP era (2000) the common method used was tuning hadronization models.

"With four parameters I can fit an elephant, and with five I can make him wiggle his trunk"

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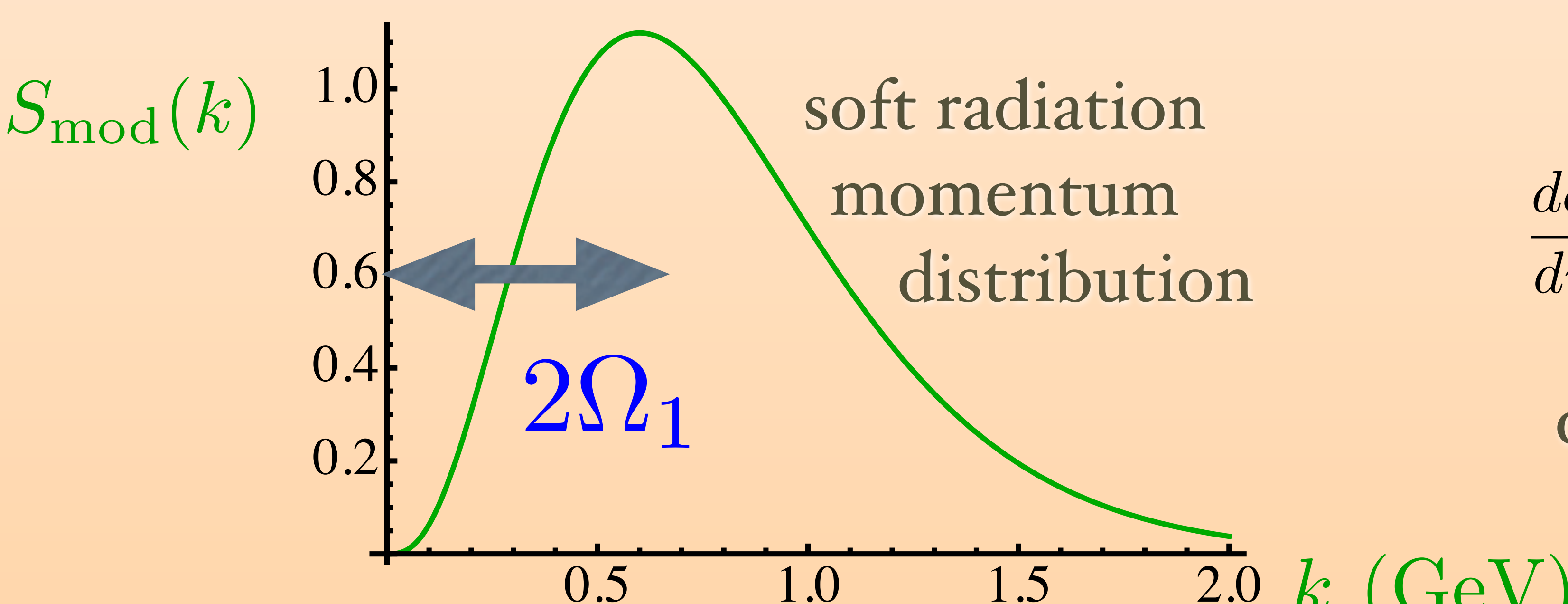
Real issues:

- Effect on cross section is highly correlated with $\alpha_s(m_Z)$ — do multiple Q global-fit
- Parametrically effect is large: $\frac{\delta\alpha_s}{\alpha_s} \simeq \frac{-14\Lambda_{\rm QCD}}{m_Z} \simeq -10\%$ — rigorous theory & fit $\Omega_1$




$$\frac{d\sigma}{d\tau} = \int dk \, \frac{d\sigma^{\rm pert}}{d\tau}\Big(\tau - \frac{k}{Q}\Big) S_{\rm mod}(k)$$

define $\Omega_1$ in field theory

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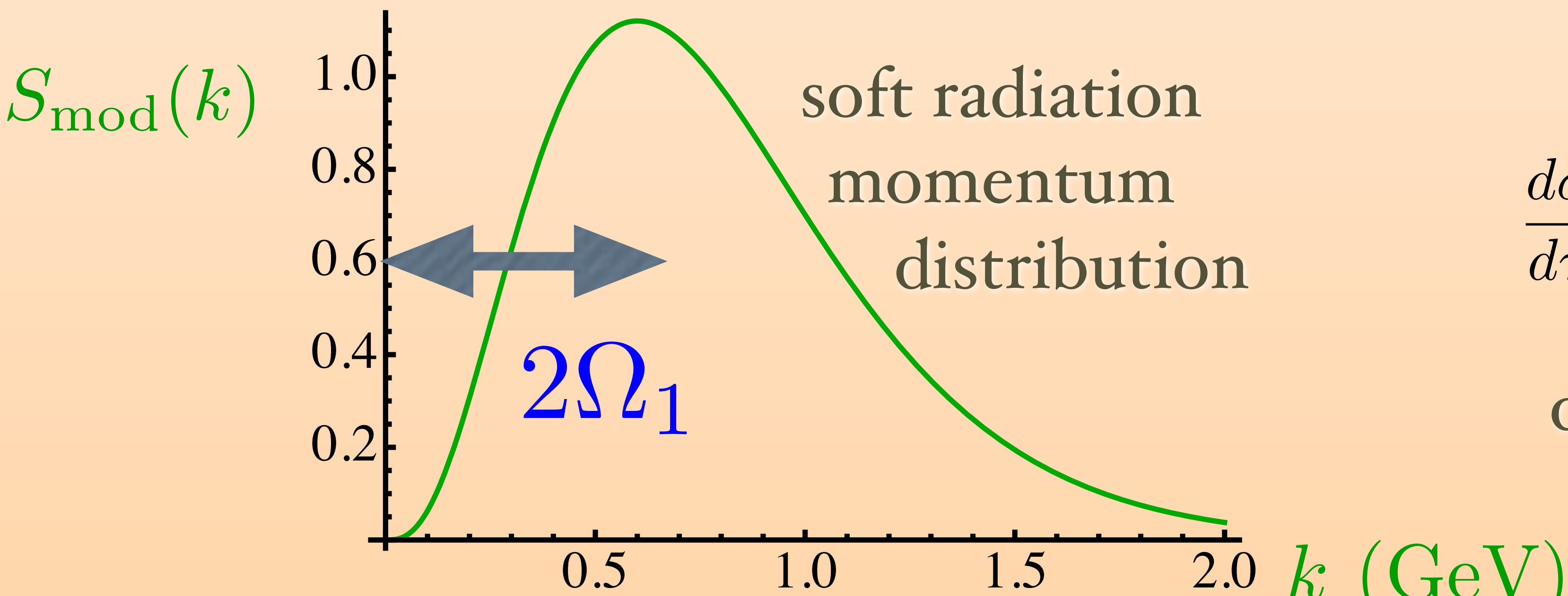


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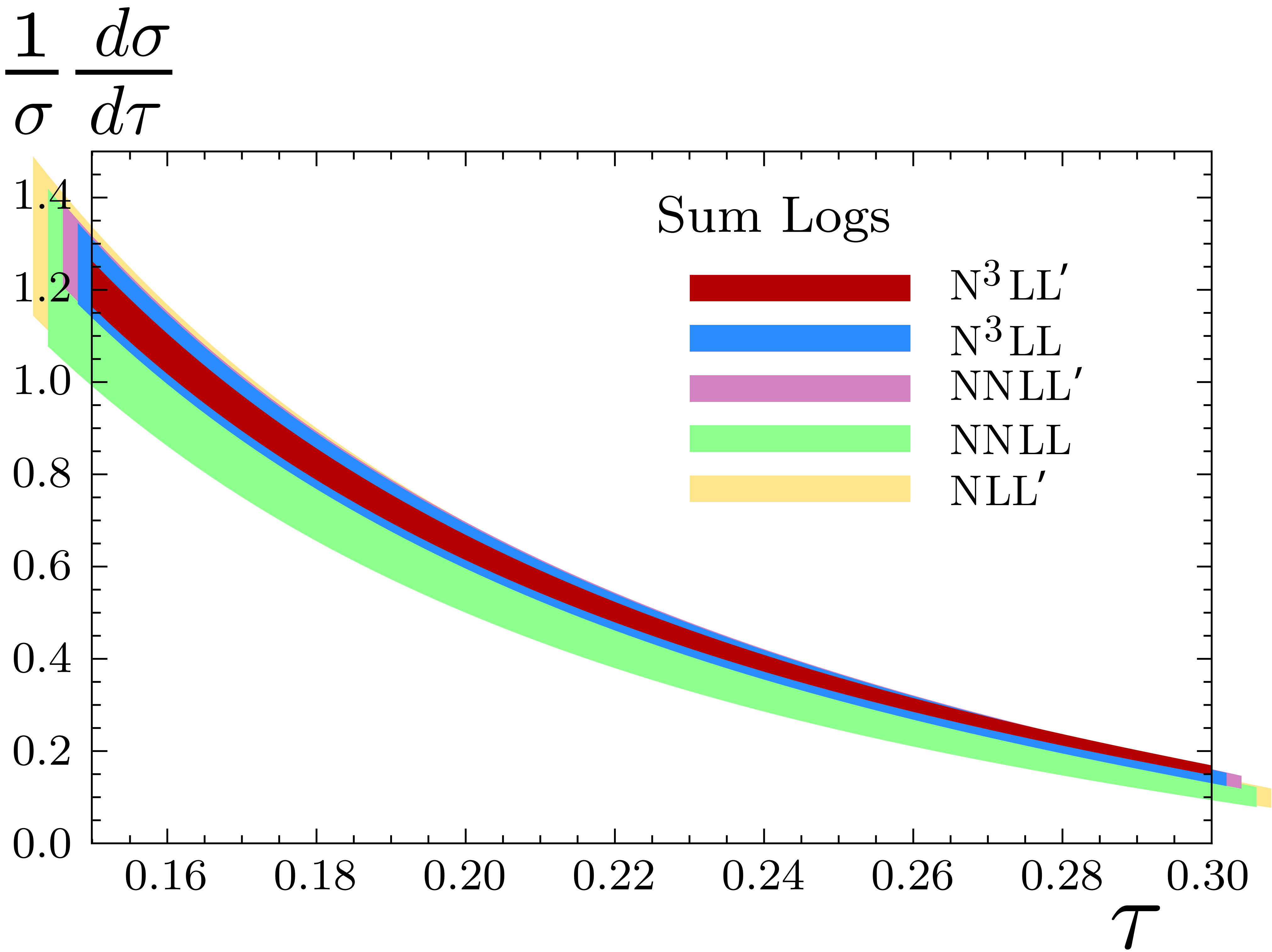

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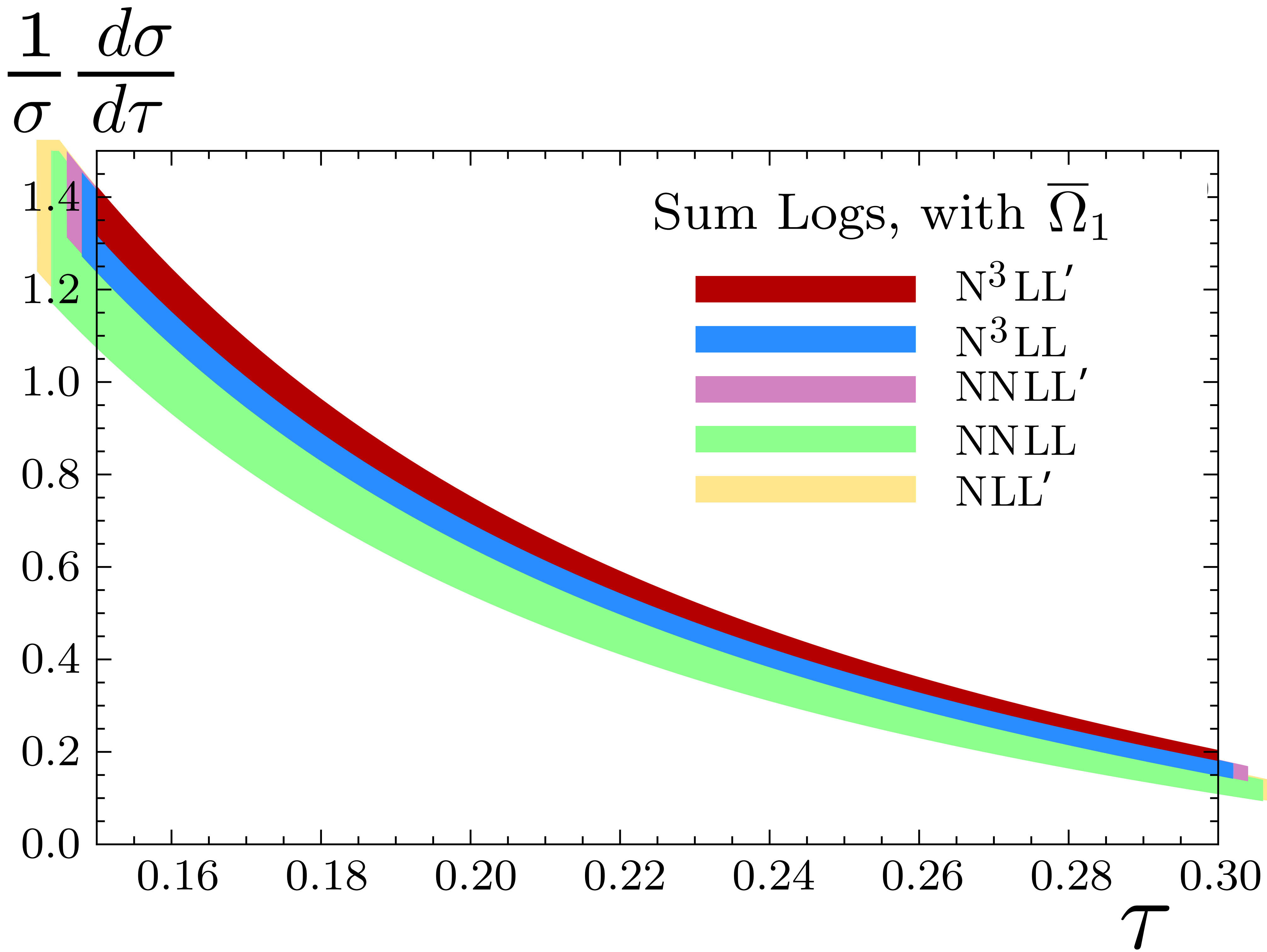

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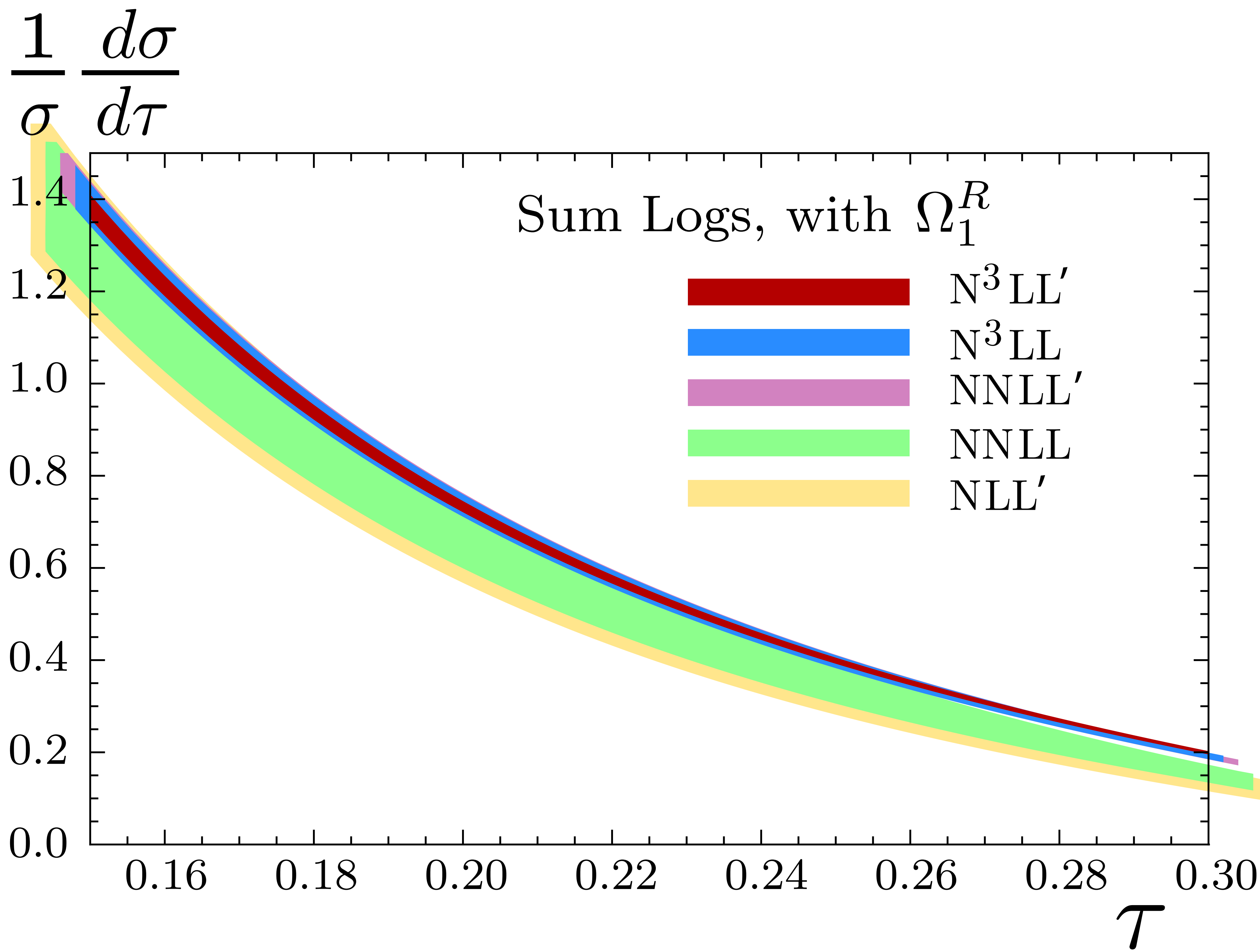
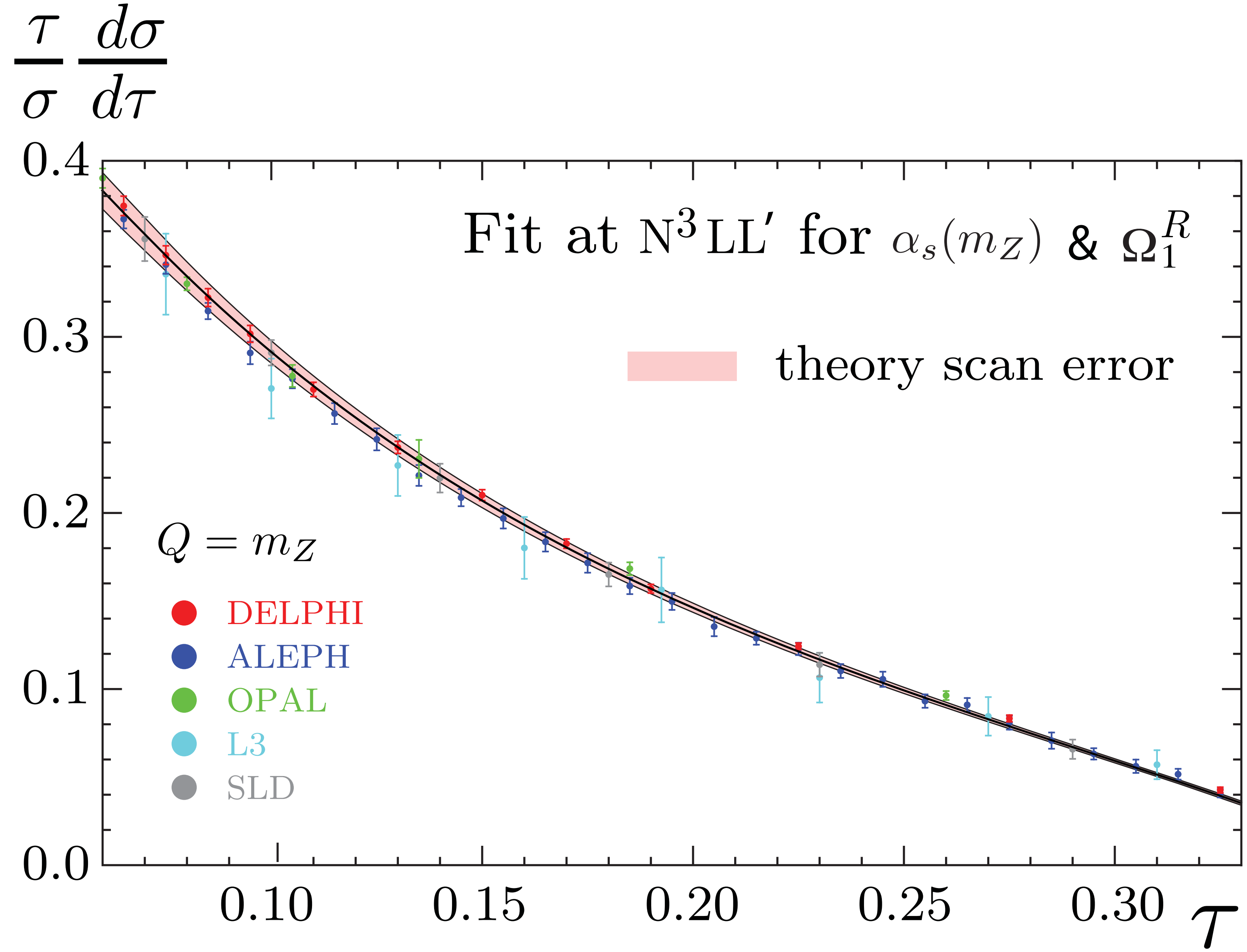


# A Tail Fit

two parameter fit:

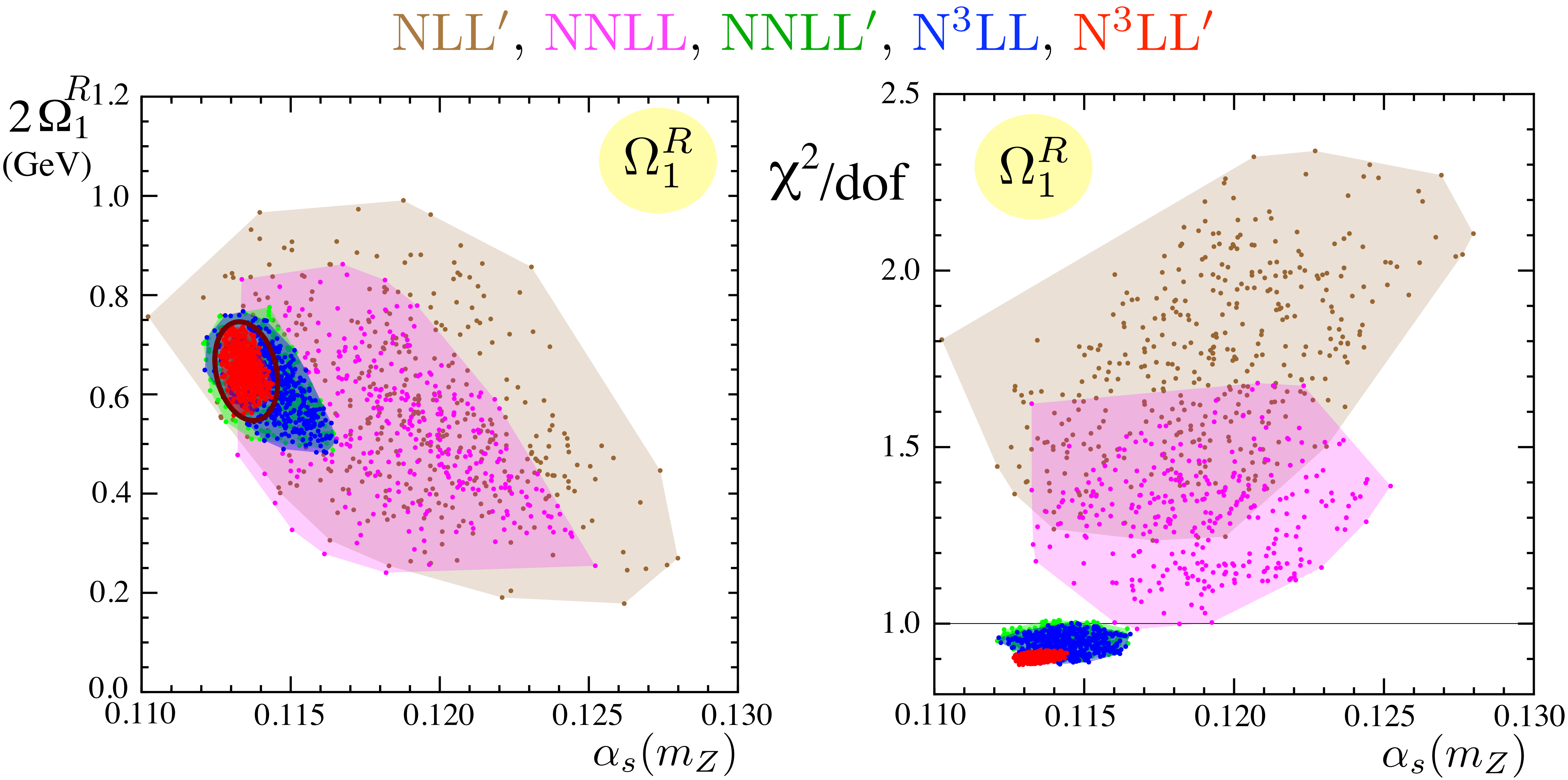
$$\{\alpha_s(m_Z), \Omega_1^R\}$$




**Fit Uncertainties:** statistical errors + systematic errors + hadronization ( $2\Omega_1^R$ )

**Higher Order Theory Uncertainties:** scan over theory parameters (vary $\mu$'s )

# Theory Scan Results




$$\alpha_s(m_Z) = 0.1135 \pm (0.0002)_{\mathrm{expt}} \pm (0.0005)_{\mathrm{hadr}} \pm (0.0009)_{\mathrm{pert}}$$

$$\Omega_1 = 0.324 \pm (0.009)_{\mathrm{expt}} \pm (0.013)_{\Omega_2} \pm (0.030)_{\alpha_s(m_Z)} \pm (0.045)_{\mathrm{pert}}\ \mathrm{GeV}$$

# Top Quark Mass from Jets

$\boxed{t}$

# Motivation

- The new particles we hope to discover at the Large Hadron Collider (LHC) at CERN are massive. Many of them are highly unstable and decay to jets.

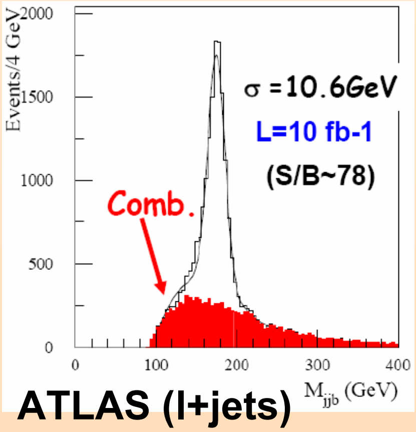
Of the particles we know of, the top quark is the closest to these, so it behooves us to understand the physics of top jets precisely.

- The LHC @14 TeV is a top quark factory, producing

8 million $t\bar{t}$ / year

Measuring the top quark mass is a major goal, but doing significantly better than the world average will be tough work.

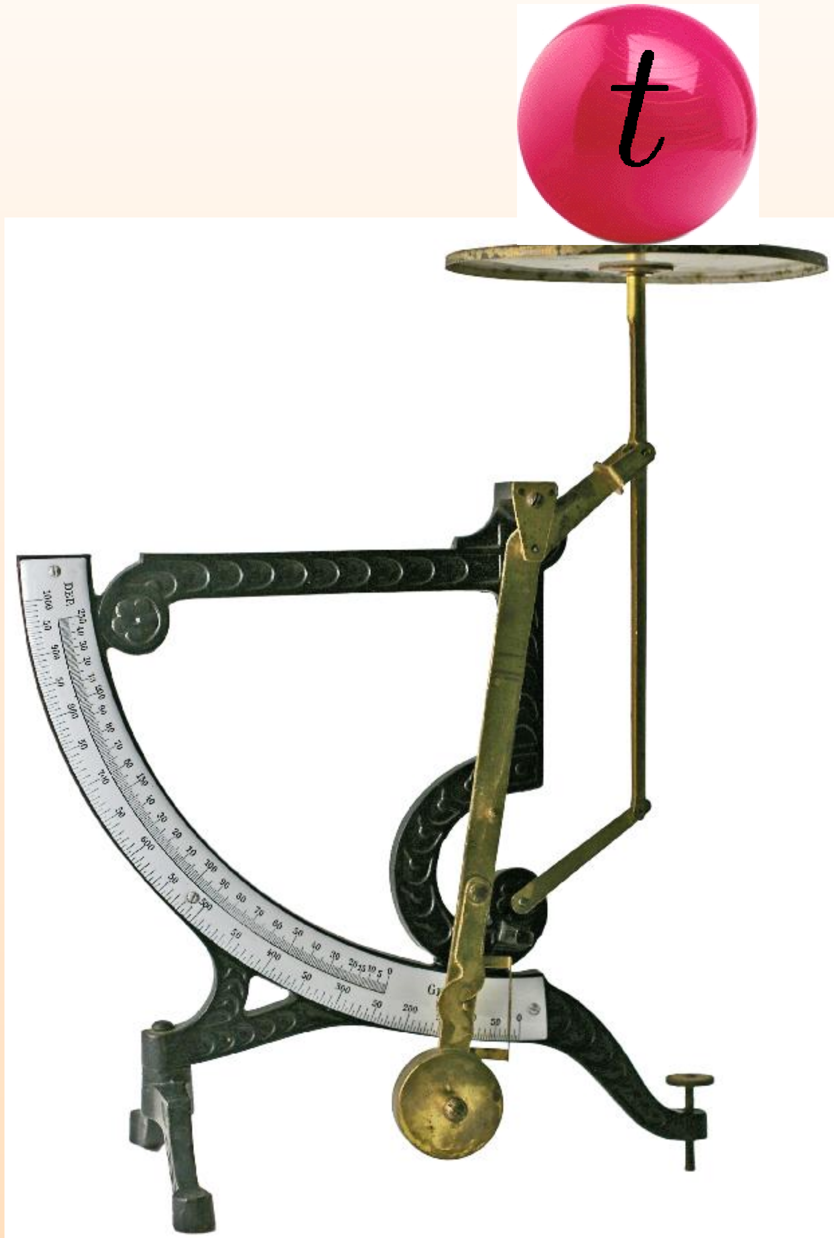
$\delta m_t \sim 1\,\mathrm{GeV}$ systematics dominated




- Current world average (CDF & DO experiments):

$m_t = 173.3 \pm 0.6(\mathrm{stat}) \pm 0.9(\mathrm{syst})\ \mathrm{GeV}$

An elementary particle which is as heavy as 180 protons!




mass definition?

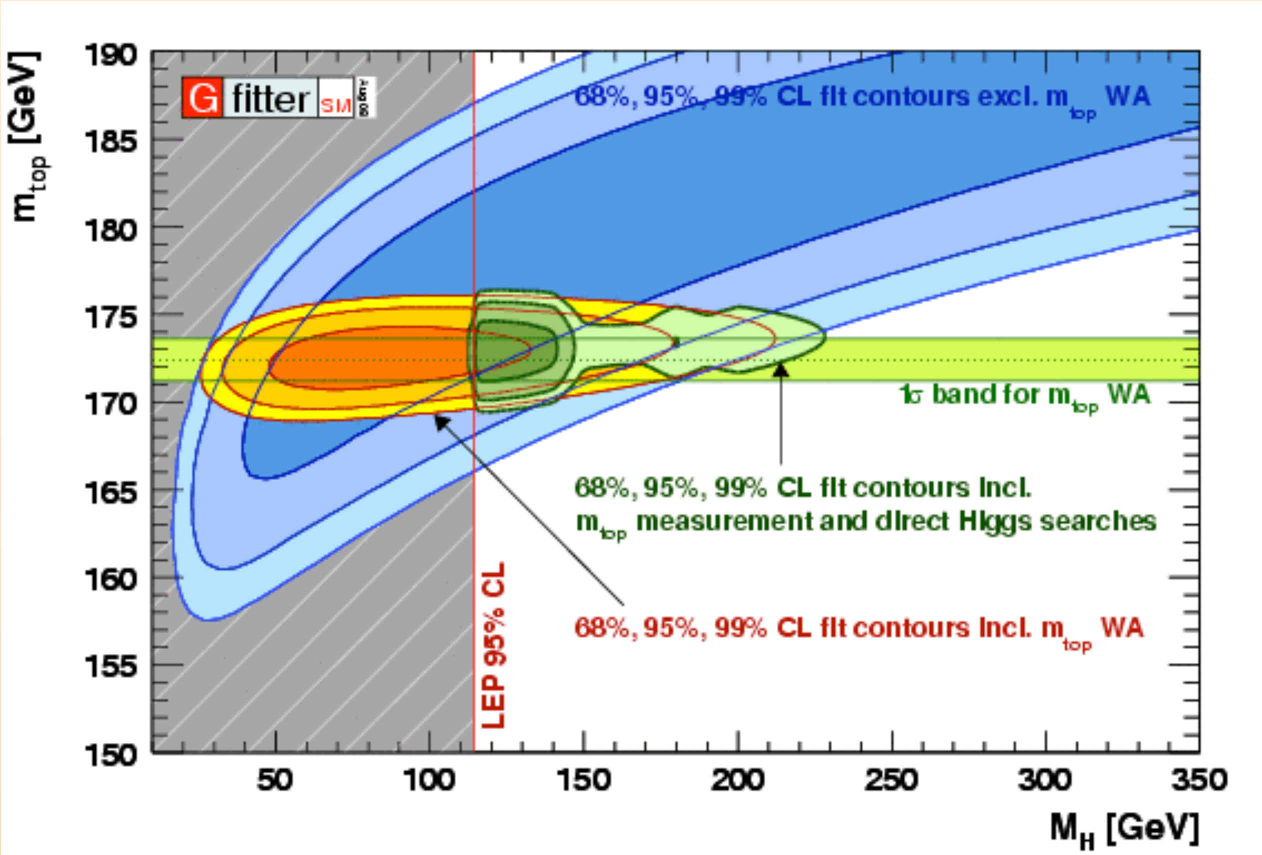
Many other scattering processes are sensitive to $m_t$ , so we would like to know it as precisely as possible.

eg. Take the Higgs particle, the only unobserved particle in the standard model.

Precision data constrains its mass $m_H$ .

Gfitter, 2010

The top mass measurement favors a light Higgs.



For the LHC we need to understand $pp \to t\bar{t}X \to \text{jets} + \text{leptons}$

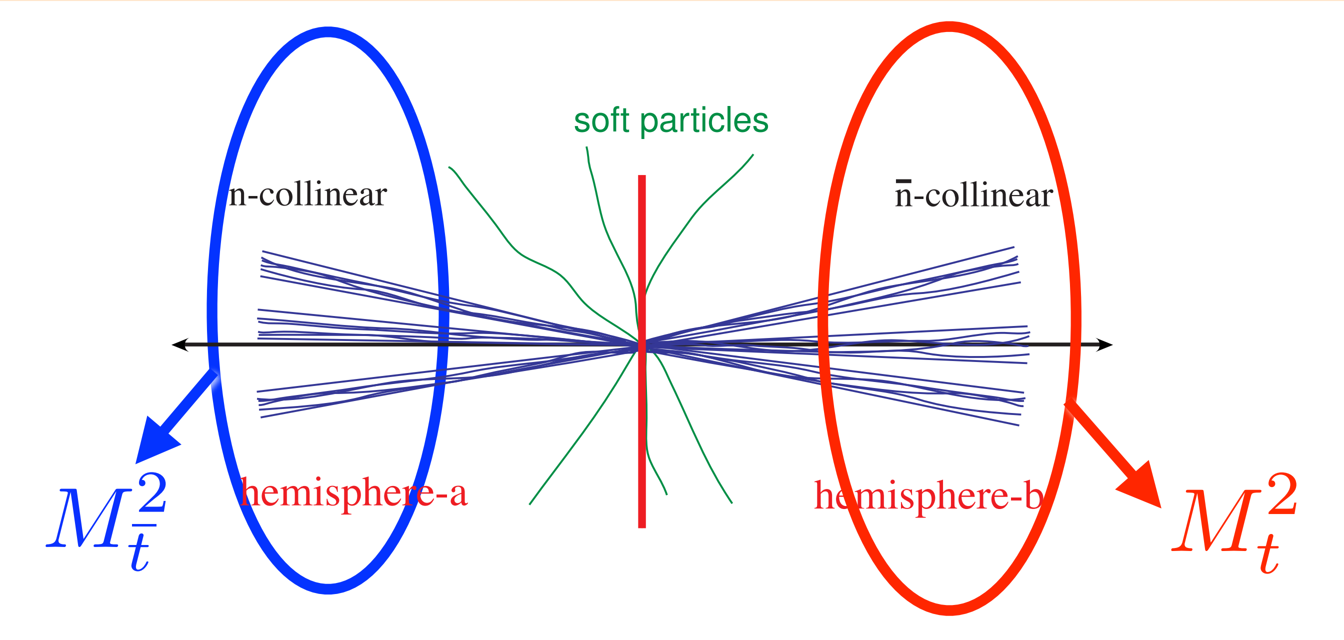
Using SCET, one can derive a factorization theorem for the case of high energy tops produced in $e^+e^- \underset{Q}{\to} t\bar{t}X \to \text{jets} + \text{leptons}$

Mantry, Fleming, Hoang, I.S.

$$\boxed{\frac{d^2\sigma}{dM_t^2\, dM_{\bar{t}}^2} = \sigma_0 H(Q,m,\mu) \int dx\, dy\, B_t\Big(s_t - \frac{Qx}{m}, \mu\Big) B_{\bar{t}}\Big(s_{\bar{t}} - \frac{Qy}{m}, \mu\Big) S(x,y,\mu)}$$

jet function for heavy particles
(calculate perturbatively in $\alpha_s$)

probability for soft radiation
(not perturbative)

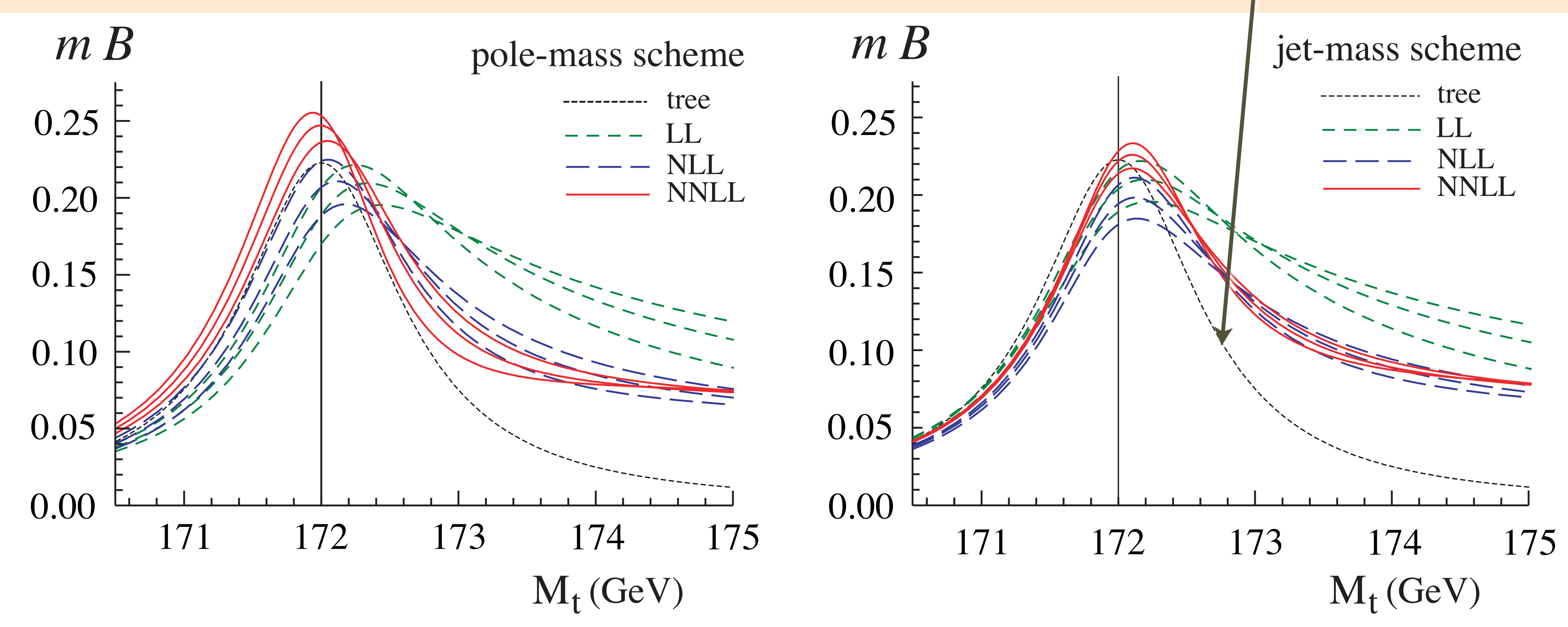


For the LHC we need to understand $pp \to t\bar{t}X \to \text{jets} + \text{leptons}$

Using SCET, our group derived a new factorization theorem for the case of high energy tops produced in $e^+e^- \underset{Q}{\to} t\bar{t}X \to \text{jets} + \text{leptons}$

$$\boxed{\frac{d^2\sigma}{dM_t^2\, dM_{\bar{t}}^2} = \sigma_0 H(Q,m,\mu) \int dx\, dy\, \underbrace{B_t\Big(s_t - \frac{Qx}{m}, \mu\Big)}_{\text{Breit-Wigner}+\text{logs}+\alpha_s+\alpha_s^2} B_{\bar{t}}\Big(s_{\bar{t}} - \frac{Qy}{m}, \mu\Big) S(x,y,\mu)}$$

Jain, Scimemi, I.S.



$$\frac{d^2\sigma}{dM_t^2 dM_{\bar{t}}^2} = \sigma_0 H(Q,m,\mu) \int dx\, dy\, B_t\Big(s_t - \frac{Qx}{m},\mu\Big) B_{\bar{t}}\Big(s_{\bar{t}} - \frac{Qy}{m},\mu\Big) S(x,y,\mu)$$

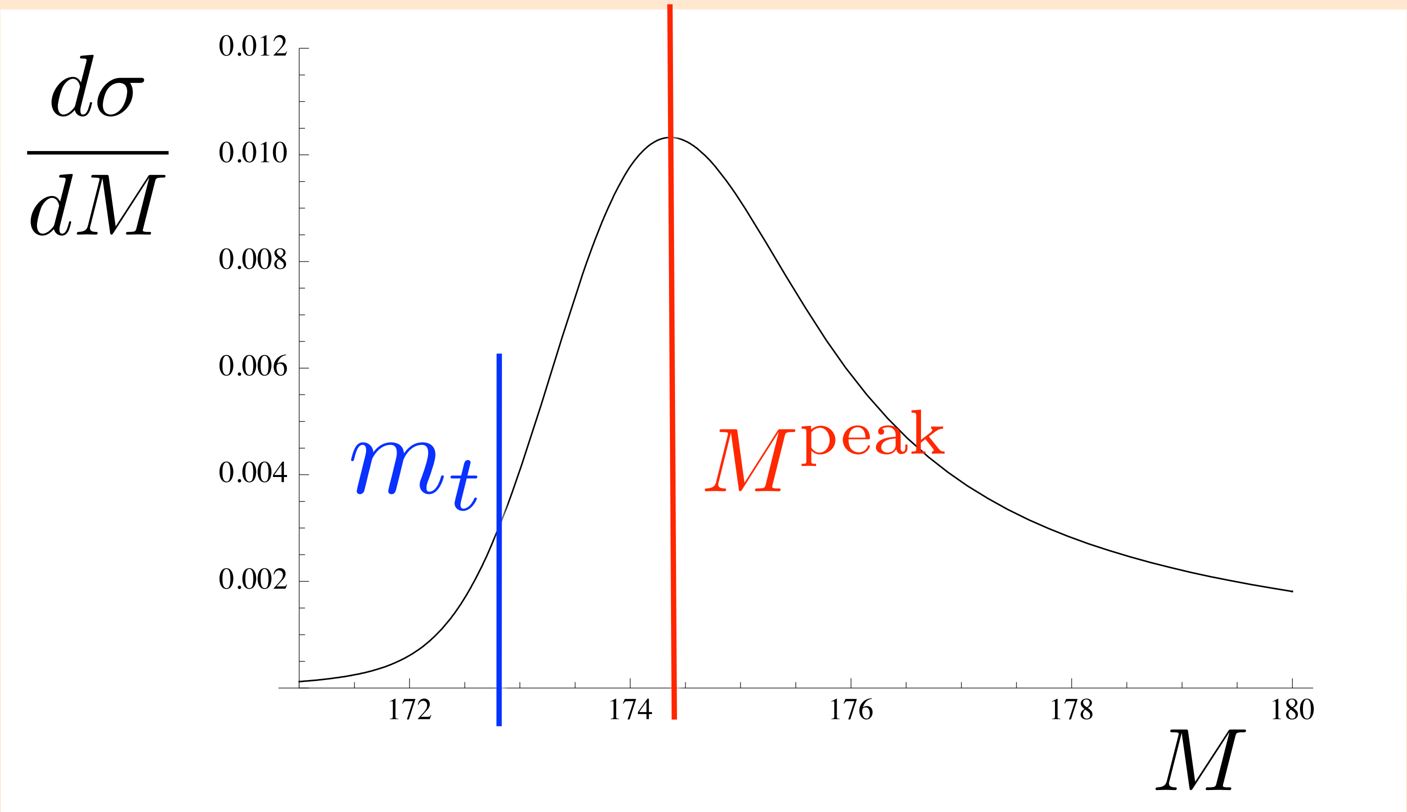
$$M^{\rm peak} = m_t + \Gamma_t(\alpha_s + \alpha_s^2 + \ldots) + \frac{Q\,\Omega_1}{m_t} + \mathcal{O}\Big(\frac{m_t \Lambda_{\rm QCD}}{Q}\Big)$$

measure this

extract this

$\Omega_1 \sim \Lambda_{\rm QCD}$

was determined above




So everything is known explicitly!

$$\frac{d^2\sigma}{dM_t^2\, dM_{\bar t}^2} = \sigma_0 H(Q,m,\mu) \int dx\, dy\, B_t\Big(s_t - \frac{Qx}{m}, \mu\Big) B_{\bar t}\Big(s_{\bar t} - \frac{Qy}{m}, \mu\Big) S(x,y,\mu)$$

$$M^{\rm peak} = m_t + \Gamma_t(\alpha_s + \alpha_s^2 + \ldots) + \frac{Q\,\Omega_1}{m_t} + \mathcal{O}\Big(\frac{m_t \Lambda_{\rm QCD}}{Q}\Big)$$

measure this

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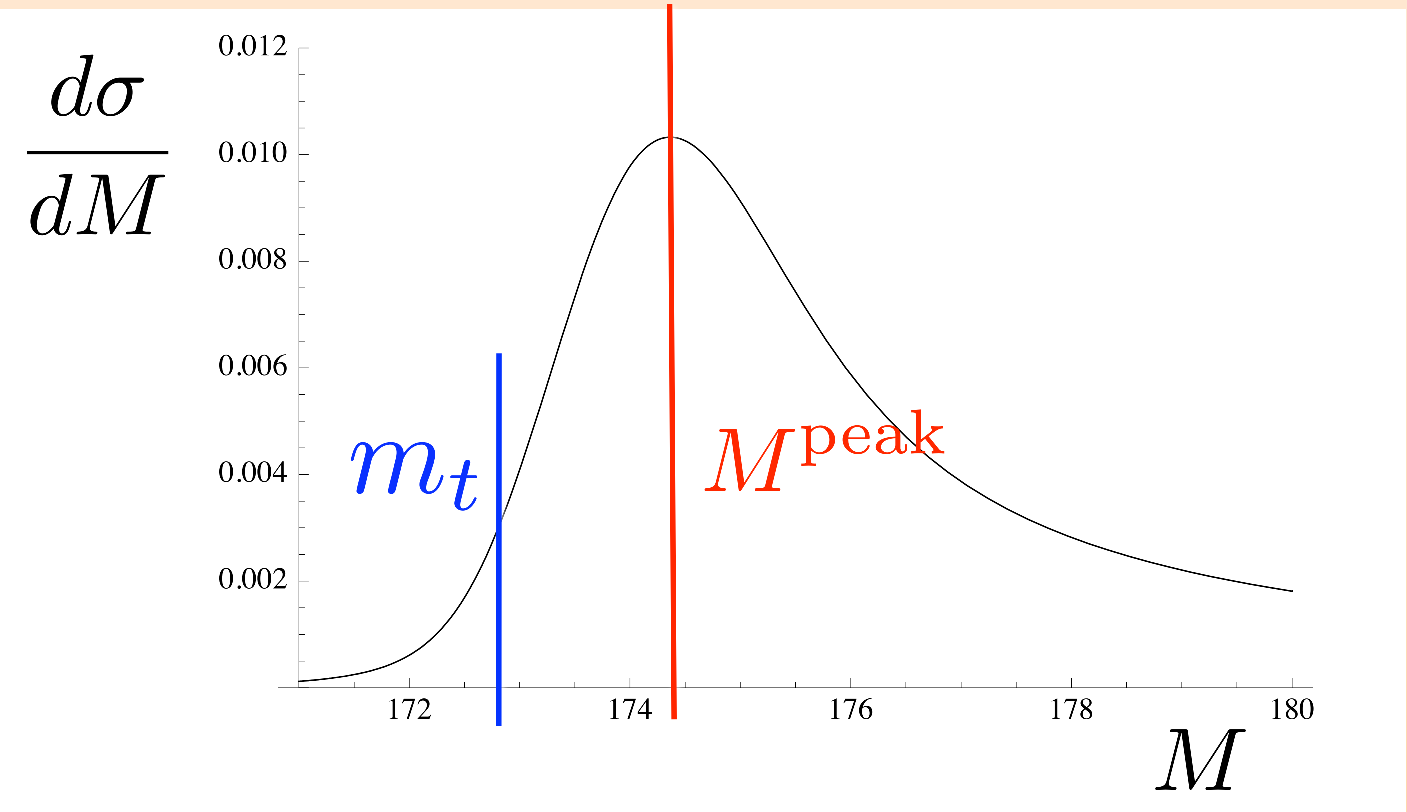


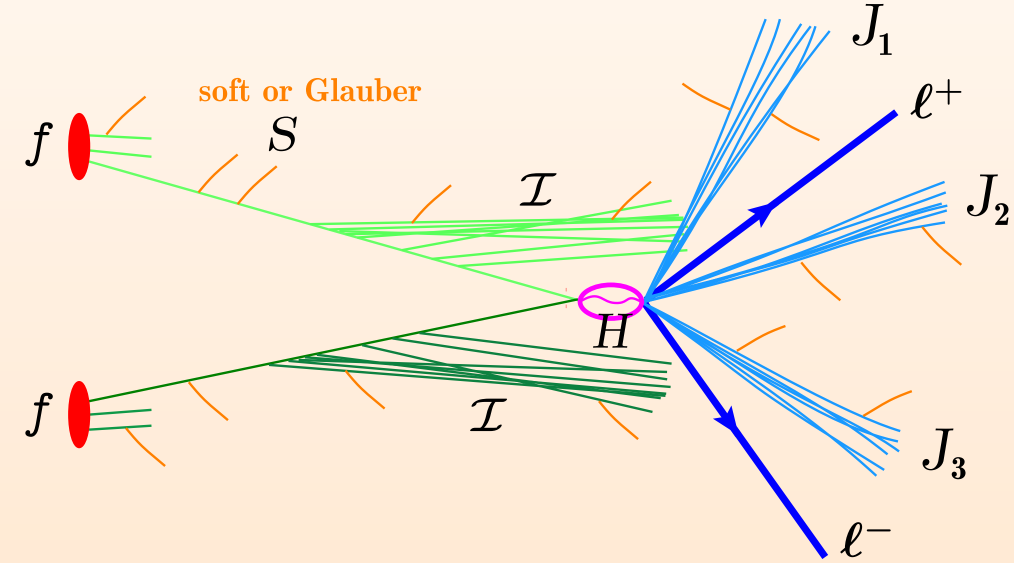

So everything is known explicitly!

This can be extended to high pT top jets at the LHC

# New Physics Searches with Jets

Searches for new physics often require strong cuts (restrictions on final states) to reduce background

introduces new resolution scales $\mu_i$




eg. Higgs without Jets

Higgs + 0 jets

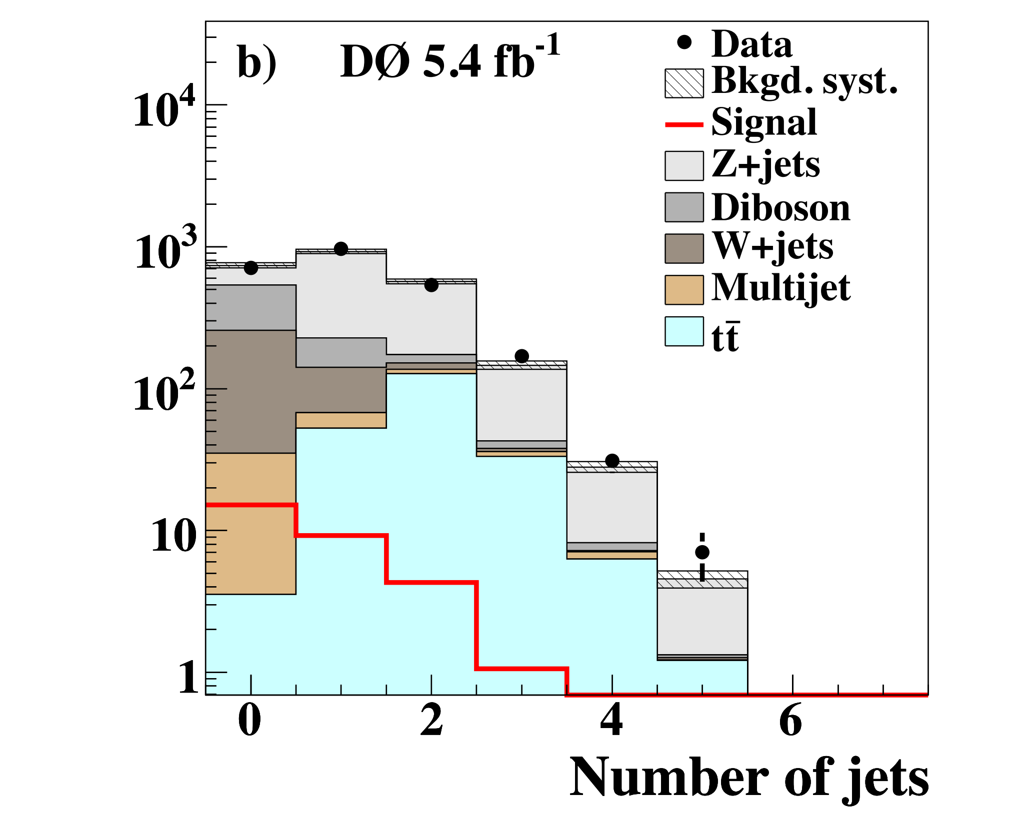
$gg \to H \to WW \to \ell\bar{\nu}\bar{\ell}\nu$

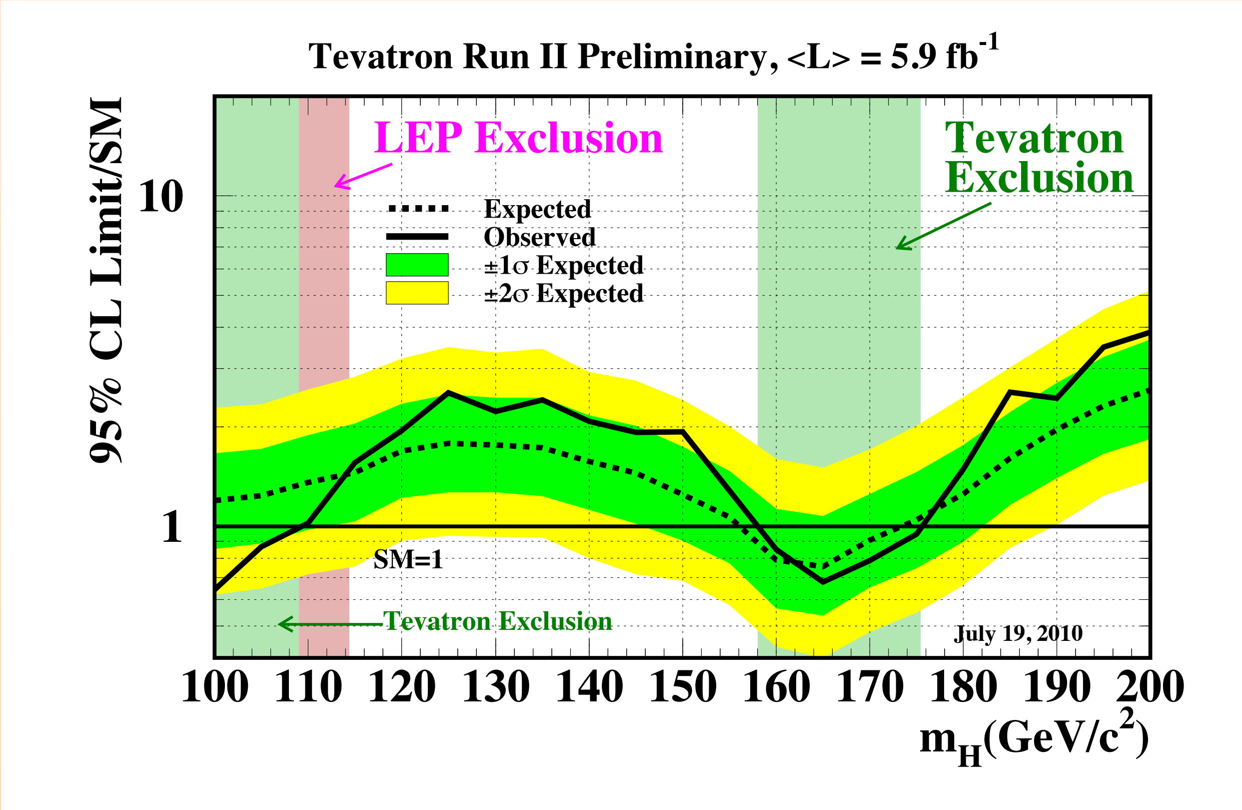
- Strong discovery potential at the LHC for $m_H \gtrsim 130\,\mathrm{GeV}$

$$pp \to H \to WW \to \mu^+\nu_\mu e^-\bar{\nu}_e$$

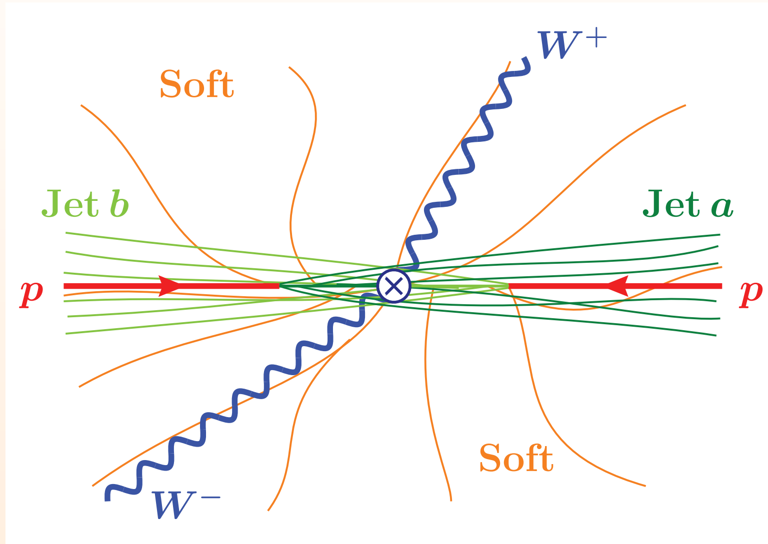
- dominant channel in Tevatron search

$$p\bar{p} \to H \to WW \to \mu^+\nu_\mu e^-\bar{\nu}_e$$

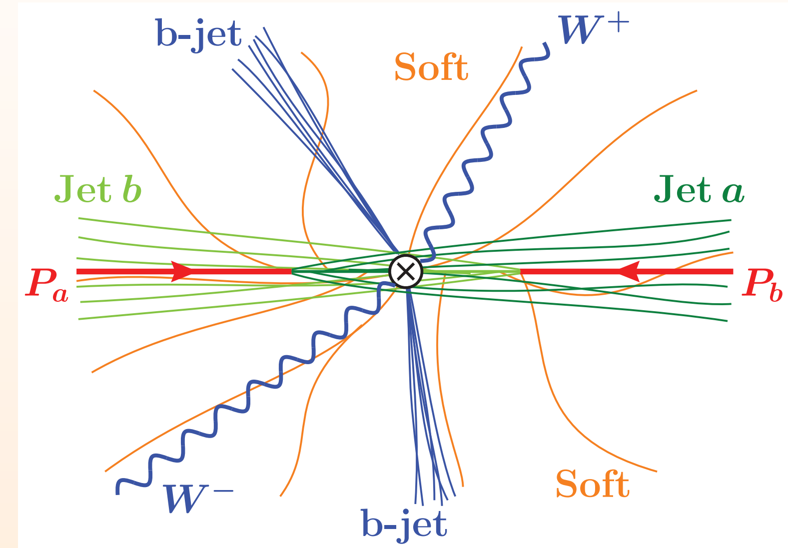


Want $p\bar{p} \to \text{Higgs} + 0 \text{ jets}$ to remove $p\bar{p} \to t\bar{t} \to WWb\bar{b}$




zero central jets
(only two forward jets)




At LHC the top background is >40 times the Higgs signal, prior to vetoing central jets.

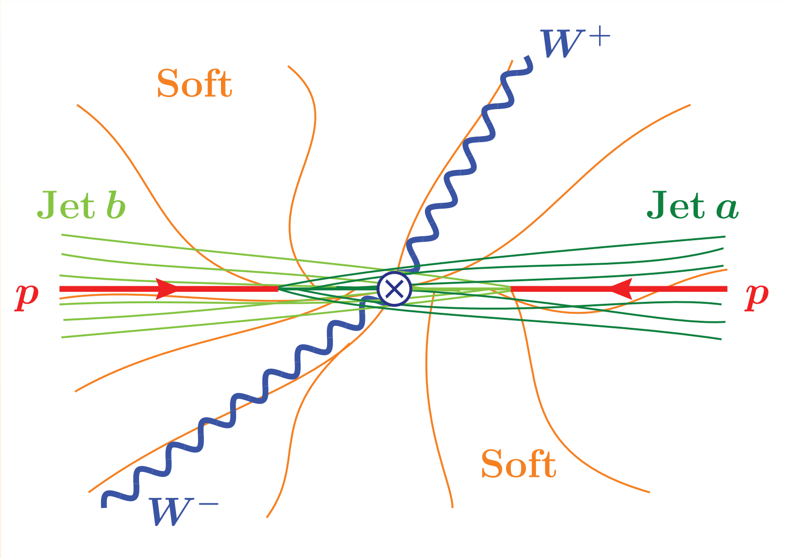
Jet Veto cut gives large logs:

$$\sigma(T^{\text{cut}}) = \begin{array}{lllll} 1 & + \alpha_s L^2 & + \alpha_s^2 L^4 & + \alpha_s^3 L^6 & + \ldots \\ & + \alpha_s L & + \alpha_s^2 L^3 & + \alpha_s^3 L^5 & + \ldots \\ & + \alpha_s & + \alpha_s^2 L^2 & + \alpha_s^3 L^4 & + \ldots \\ & & + \alpha_s^2 L & + \alpha_s^3 L^3 & + \ldots \\ & & + \alpha_s^2 & + \alpha_s^3 L^2 & + \ldots \\ & & & + \alpha_s^3 L & + \ldots \\ & & & + \alpha_s^3 & + \ldots \end{array}$$

SCET allows higher precision calculations.

To carry out more precise calculations we use an event shape variable for the jet veto. Beam Thrust

$$\mathcal{T}_B = \sum_k |\vec{p}_{kT}| e^{-|\eta_k|} = \sum_k (E_k - |p_k^z|) \quad \leq \mathcal{T}^{\text{cut}}$$

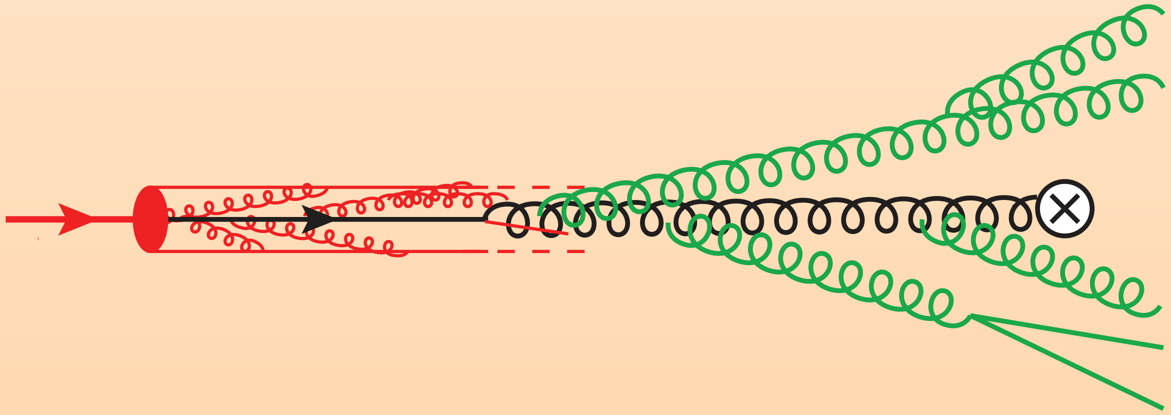



Factorization Theorem involves initial state jets (Beam functions):

$$\sigma(\mathcal{T}^{\text{cut}}) = \sum_{ij} H_{ij} \int B_i(t_a, x_a) B_j(t_b, x_b) \otimes S_B$$

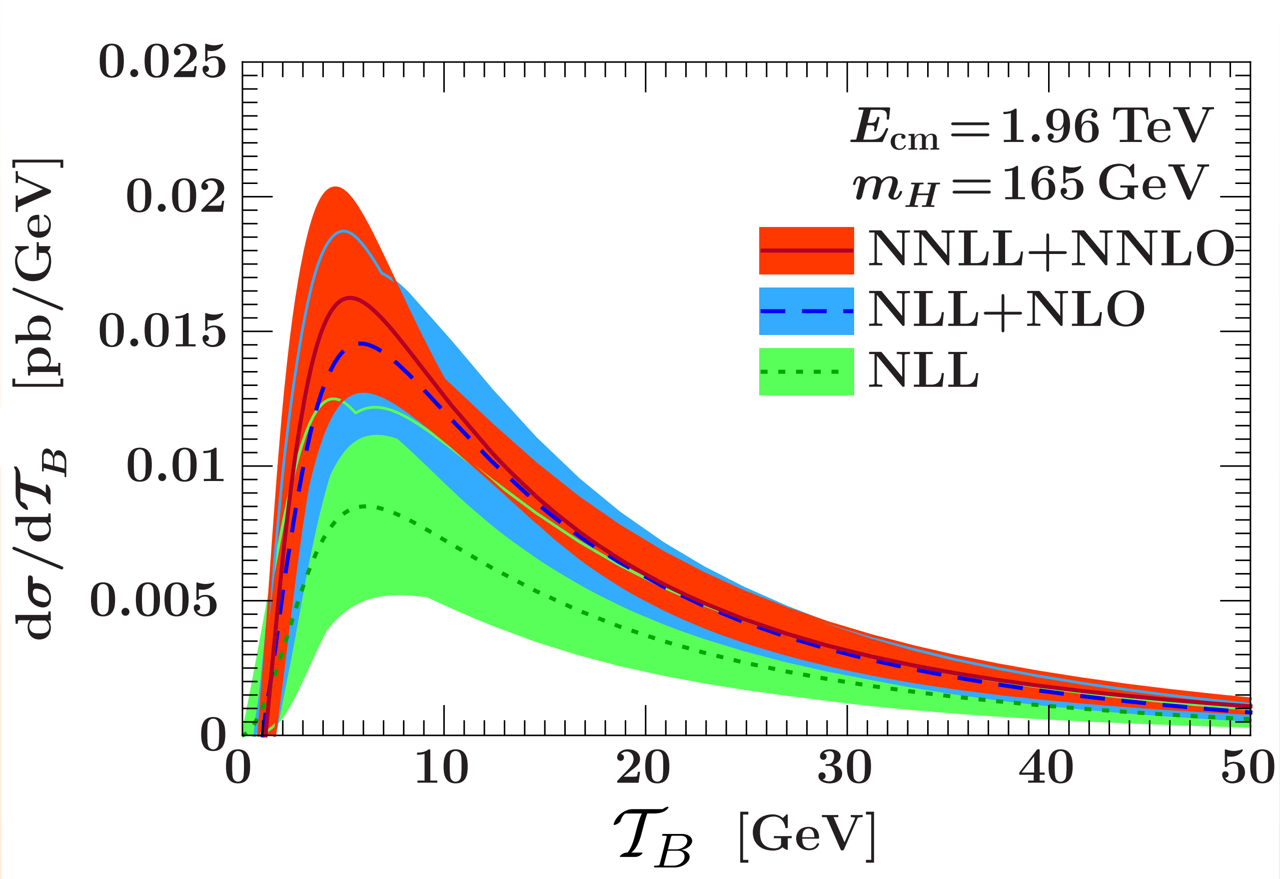
Fleming, Leibovich, Mehen

IS, Tackmann, Waalewijn

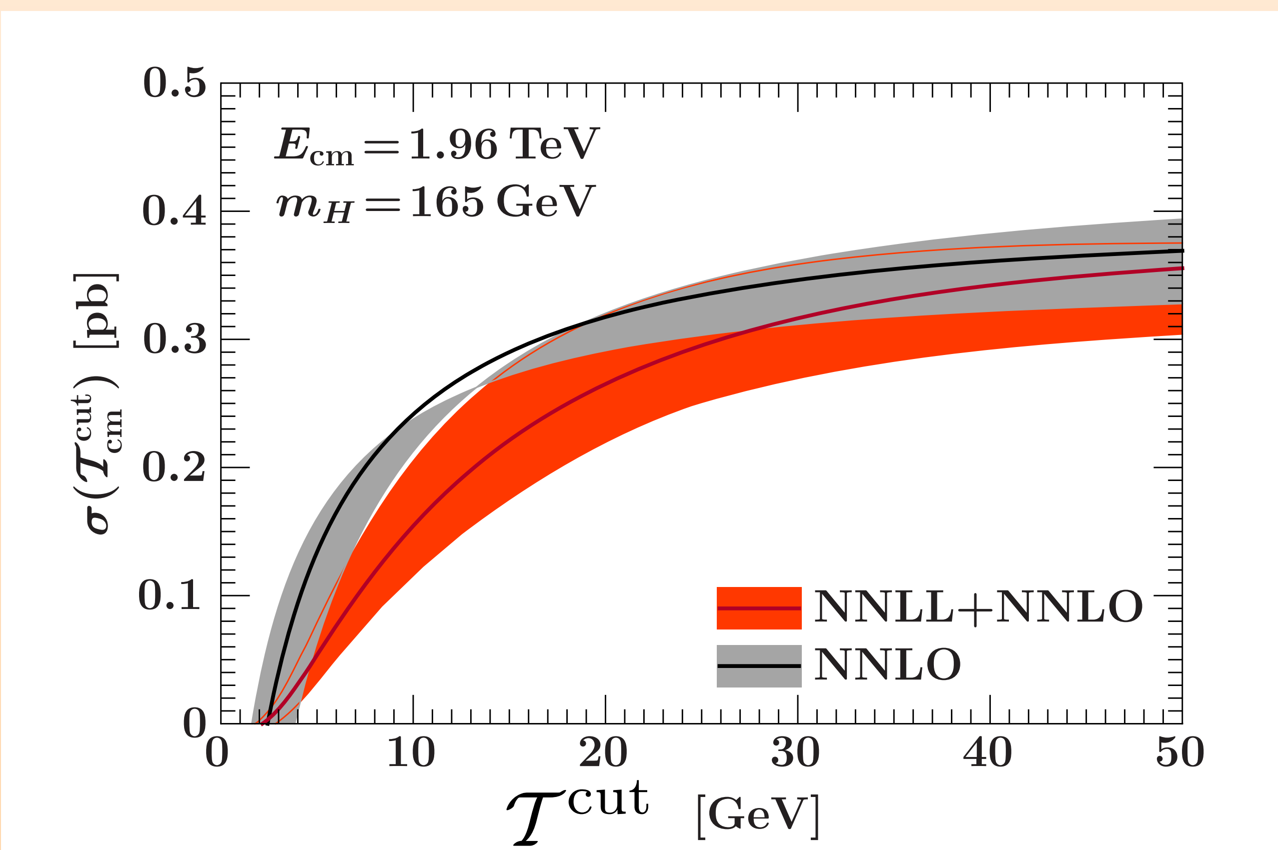


$$B_i(t, x) = \int d\xi \, \mathcal{I}_{ij}(t, x/\xi) \; f_j(\xi)$$

Berger, Marcantonini,
IS, Tackmann, Waalewijn




- two orders of summation beyond LL shower programs
- logs are large
- theory error bands from varying $\mu_i$




- NNLO underestimates size of errors by factor of two
- increased theory errors will impact Higgs bound

# Future Jet Applications at LHC

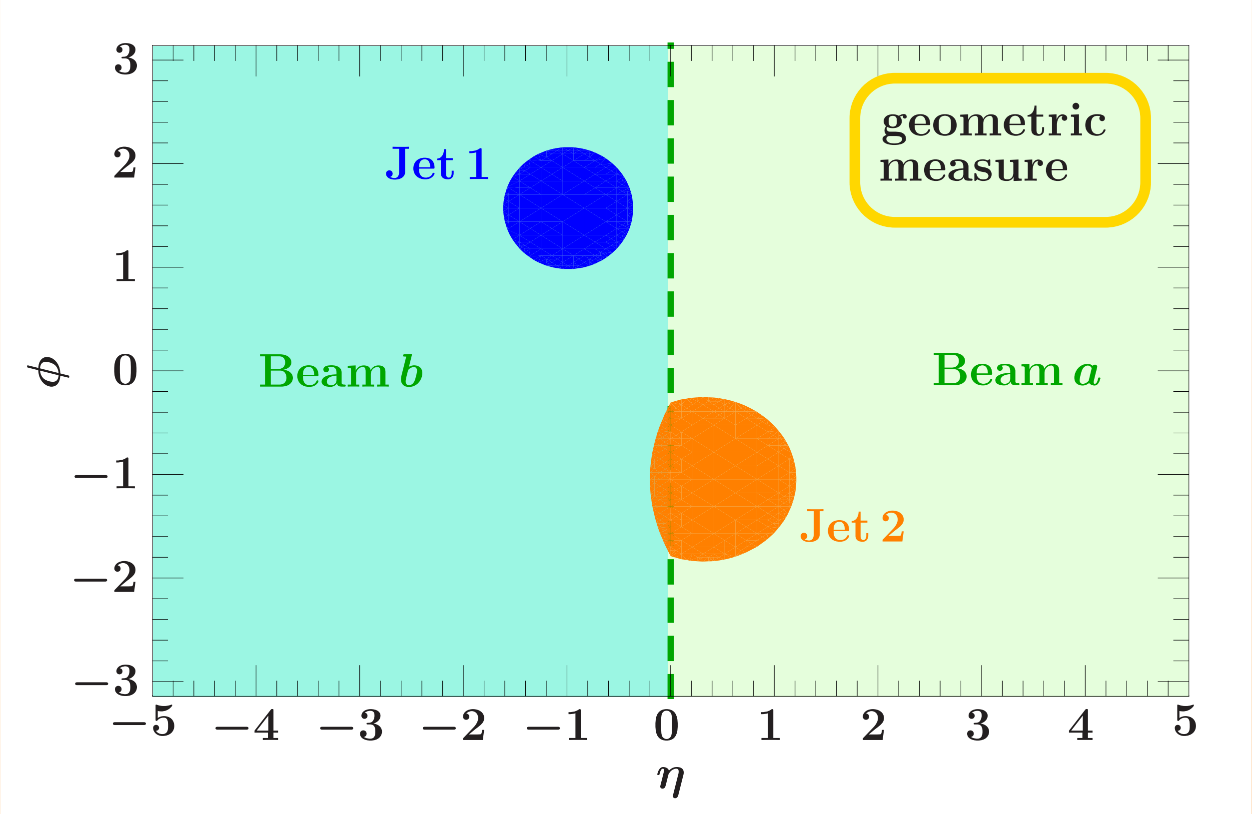
IS, Jouttenus, Tackmann, Waalewijn

Thaler, van Tilburg

1) "N-Jettiness" event shape

$$\mathcal{T}_N = \sum_{i=a,b,1,\ldots,N} \mathcal{T}_N^i$$

like a sum of jet masses




- defines Exclusive N-jet cross sections

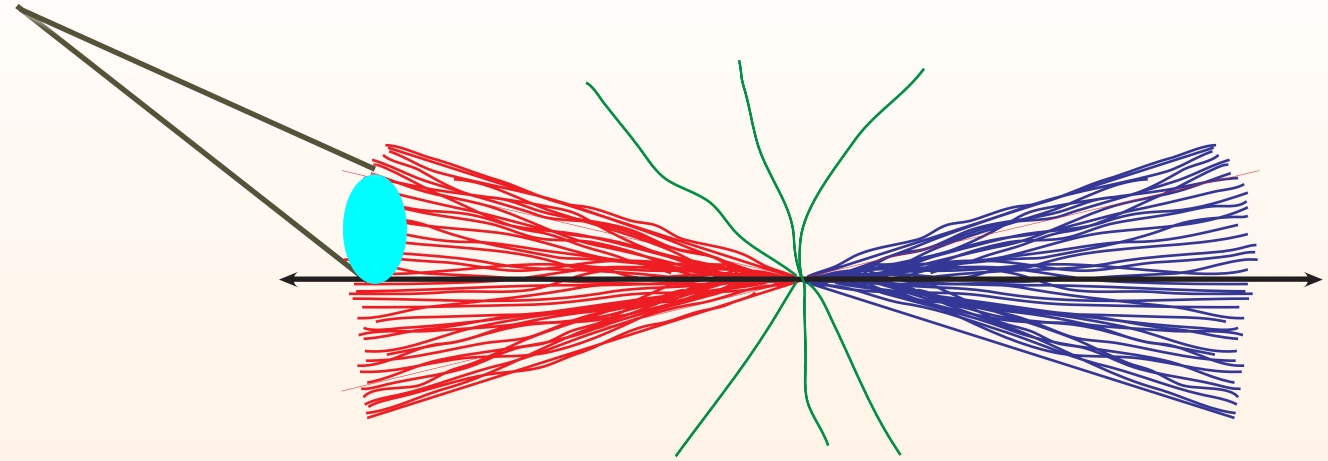
$$\frac{d\sigma}{d\mathcal{T}_N^a \, d\mathcal{T}_N^b \cdots d\mathcal{T}_N^N}$$

- useful for higher precision calculations of:

Prompt Photons
W/Z + jets, H + jets

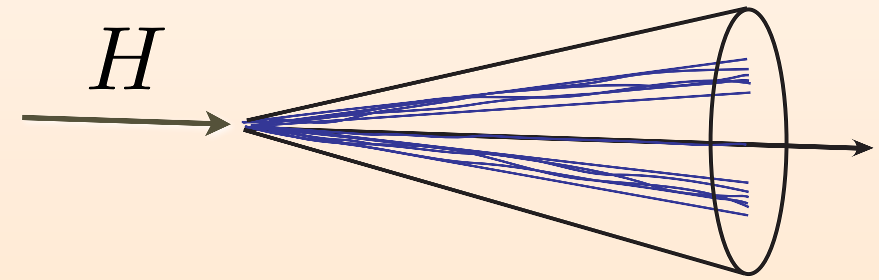
dijet production
top jets

# 2) Probing Jet Substructure



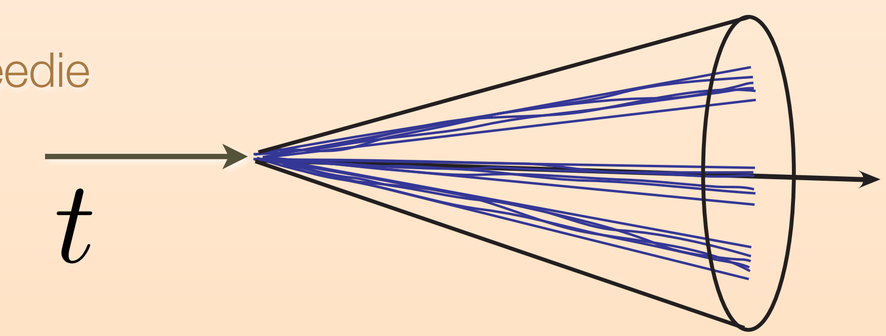
eg. boosted Higgs Butterworth, Davison, Rubin, Salam

$$pp \to ZH, \quad H \to b\bar{b}$$




eg. tagging boosted tops Kaplan, Rehermann, Schwartz, Tweedie

$$t \to Wb \to 3 \text{ jets}$$

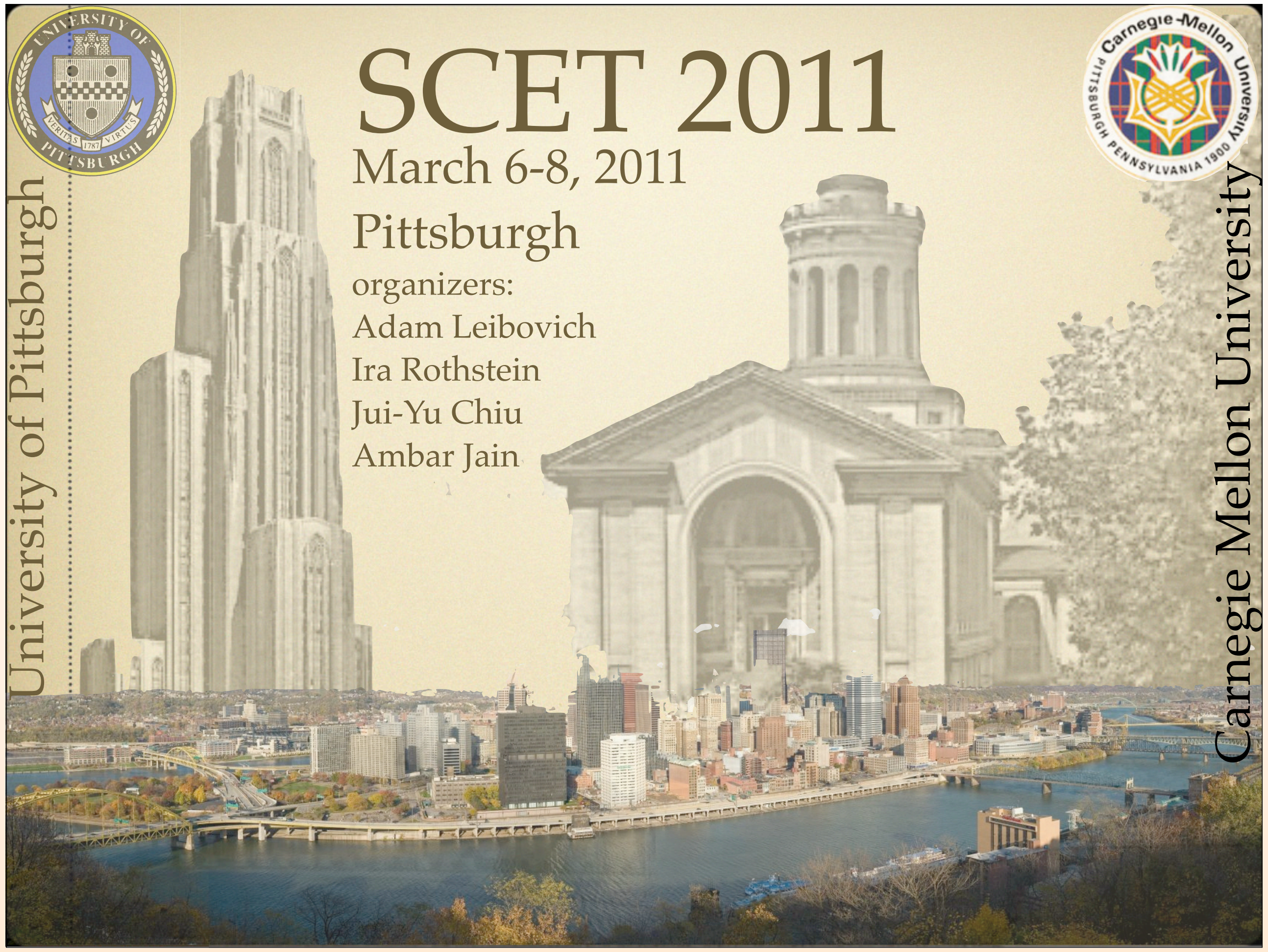



(Important for identifying KK graviton decays in Randall-Sundrum models)

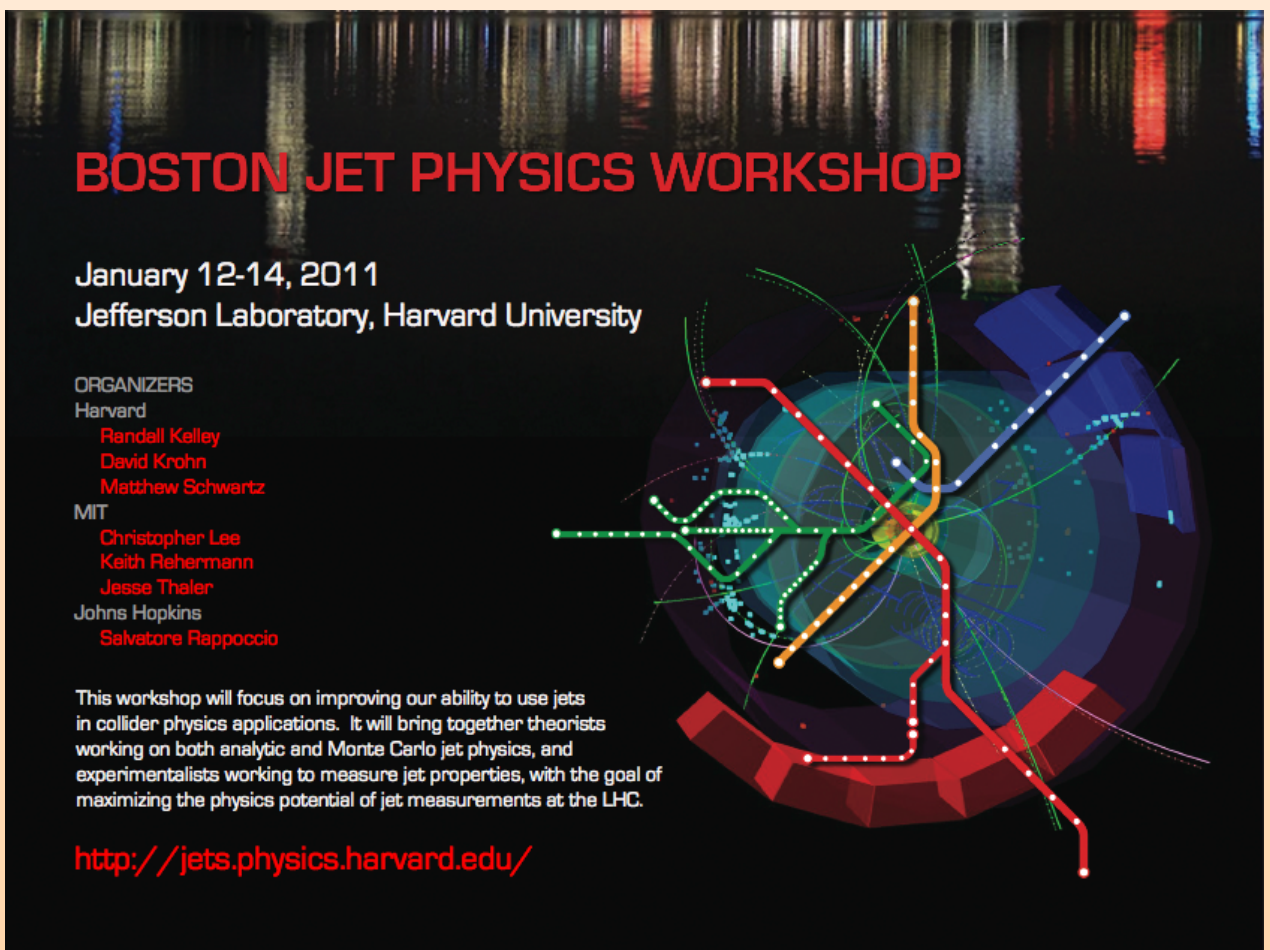
- SCET provides tools for rigorous calculations of jet substructure properties

# More SCET work

- generalization to $p_T$ dependent beam functions — Mantry & Petriello
- other event shapes in $e^+e^-$ — Hornig, Lee, Ovanesyan; Schwartz, Yang-Ting
- applications of SCET to parton showers (LL and beyond) — Bauer, Schwartz; Baumgart, Marcantonini, IS
- Inclusive B Meson Decays & Rare CP violating decays — (many authors)
- $J/\Psi$ and $\Upsilon$ production and decays — Fleming, Leibovich, Mehen
- SCET for jets in medium — Idilbi, Majumder; D'Eramo, Hong, Rajagopal,
- Resummation of Electroweak Sudakov Logs — Chiu, Fuhrer, Kelley, Manohar
- . . .


SCET 2011
March 6-8, 2011
Pittsburgh
organizers:
Adam Leibovich
Ira Rothstein
Jui-Yu Chiu
Ambar Jain
University of Pittsburgh
Carnegie Mellon University


PRINCETON CENTER FOR THEORETICAL SCIENCE
Boost 2011


BOSTON JET PHYSICS WORKSHOP
January 12-14, 2011
Jefferson Laboratory, Harvard University
ORGANIZERS
Harvard
Randall Kelley
David Krohn
Matthew Schwartz
MIT
Christopher Lee
Keith Rehermann
Jesse Thaler
Johns Hopkins
Salvatore Rappoccio
This workshop will focus on improving our ability to use jets in collider physics applications. It will bring together theorists working on both analytic and Monte Carlo jet physics, and experimentalists working to measure jet properties, with the goal of maximizing the physics potential of jet measurements at the LHC.
http://jets.physics.harvard.edu/

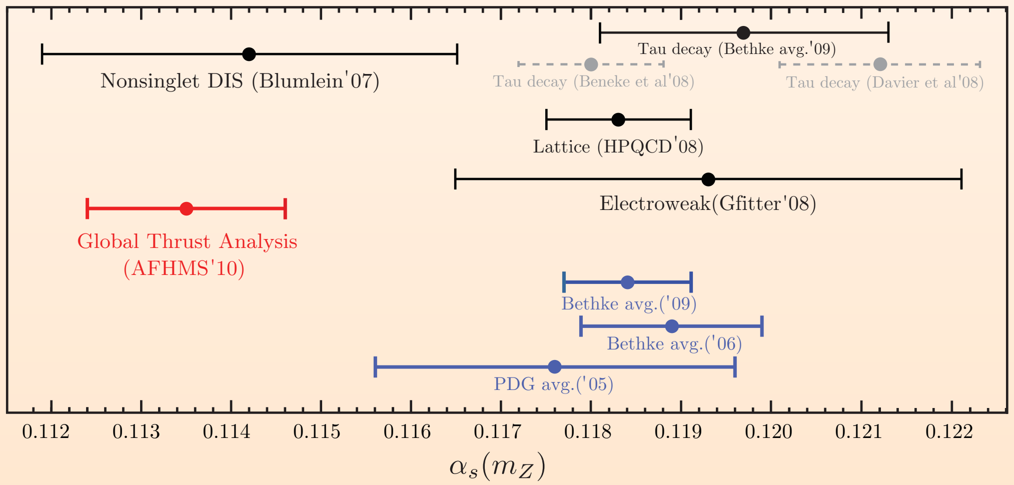

WORKSHOP ON PRECISION MEASUREMENTS OF $\alpha_s$
Max-Planck-Institute for Physics
Munich, Germany
February 9-11, 2011
EVENT SHAPES AND JET PRODUCTION • LATTICE SIMULATIONS • ELECTROWEAK PRECISION OBSERVABLES
TAU DECAYS • DEEP INELASTIC SCATTERING • FUTURE PERSPECTIVES
Confirmed Speakers and Convenors:
S. Aoki
M. Beneke
J. Blümlein
N. Brambilla
S. Brodsky
M. Davier
Y. Dokshitzer
J. Erler
S. Forte
T. Gehrmann
C. Glasman
M. Golterman
A. Höcker
W. Hollik
M. Jamin
A. Kronfeld
J. Kühn
P. Lepage
V. Mateu
S. Menke
K. Mönig
Y. Nomura
F. Petriello
T. Pich
K. Rabbertz
V. Radescu
G. Salam
H. Schulz
E. Shintani
R. Sommer
M. Steinhauser
J. Stirling
B. Webber
C.P. Yuan
G. Zanderighi
Organizers:
S. Bethke
A. Hoang
S. Kluth
J. Schieck
I. Stewart

# Summary & Outlook

- The Soft-Collinear Effective Theory provides a powerful formalism for deriving factorization theorems and analyzing processes with Jets

$\alpha_s(m_Z)$
- SCET has finally provided theorists with a means to catch up to the experimental precision of LEP

Similar computations can be carried out for other event shapes




Top Jets
- For $e^+e^- \to t\bar{t}X$ SCET directly relates the measured jet invariant mass to the top-quark mass parameter. Can be extended to high $p_T$ top jets at the LHC

Higgs
- Experimental cuts on jets can significantly modify expectations. Rigorous predictions are possible.

A new frontier for calculations!


WHAT YOU BROUGHT TO SEMINAR AND WHAT IT SAYS ABOUT YOU:
Stuff to take notes: First year. Foolishly thinks he'll ever need notes again.
Reading material: Third year. Just here for show.
Didn't bring anything: ABD/Postdoc. Has nothing better to do.
Laptop: Young Assistant Professor. Working on three proposals at the same time.
Playing with latest Gadget/Gizmo: Full Professor. Looooves new toys.
tap
tap
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Thanks!