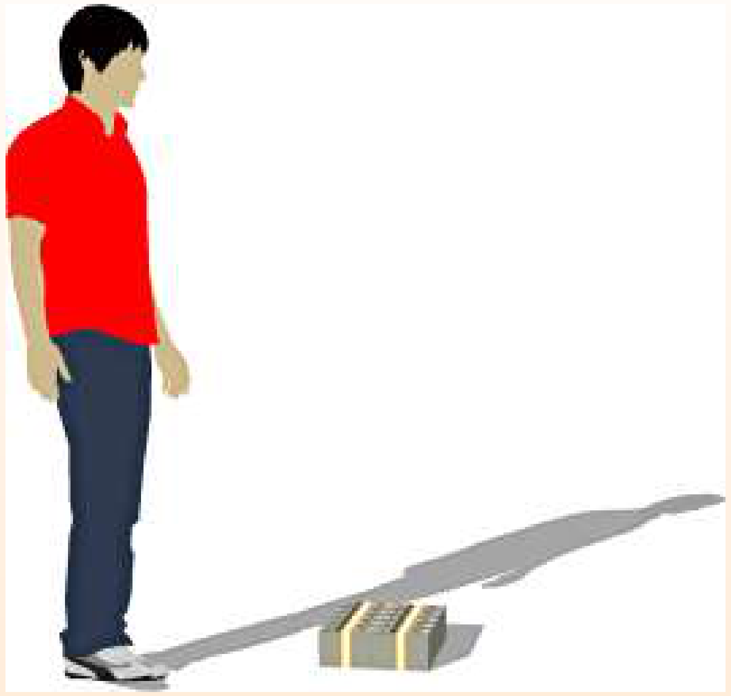
A 9 Billion Dollar Venture
to
Shake up the Laws of Nature

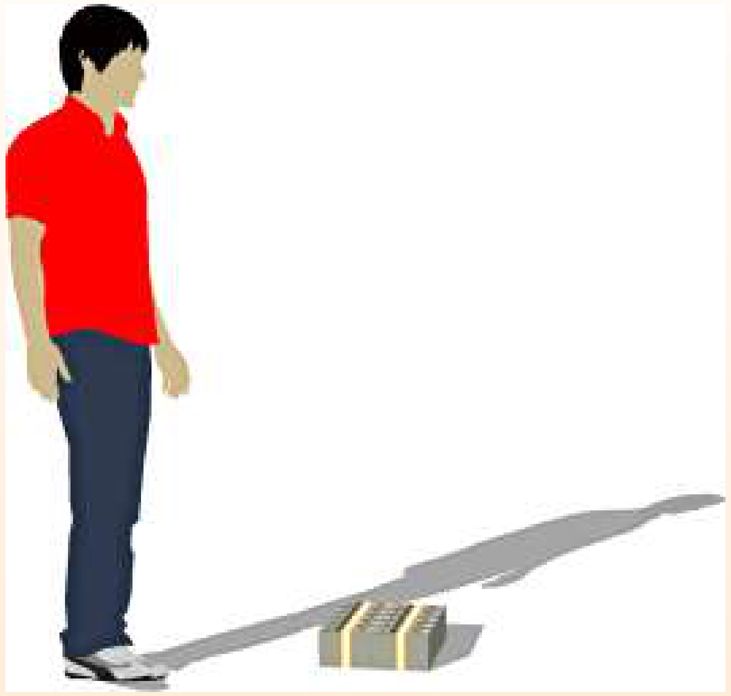
Iain Stewart
MIT

Physics IAP Lecture Series
2012

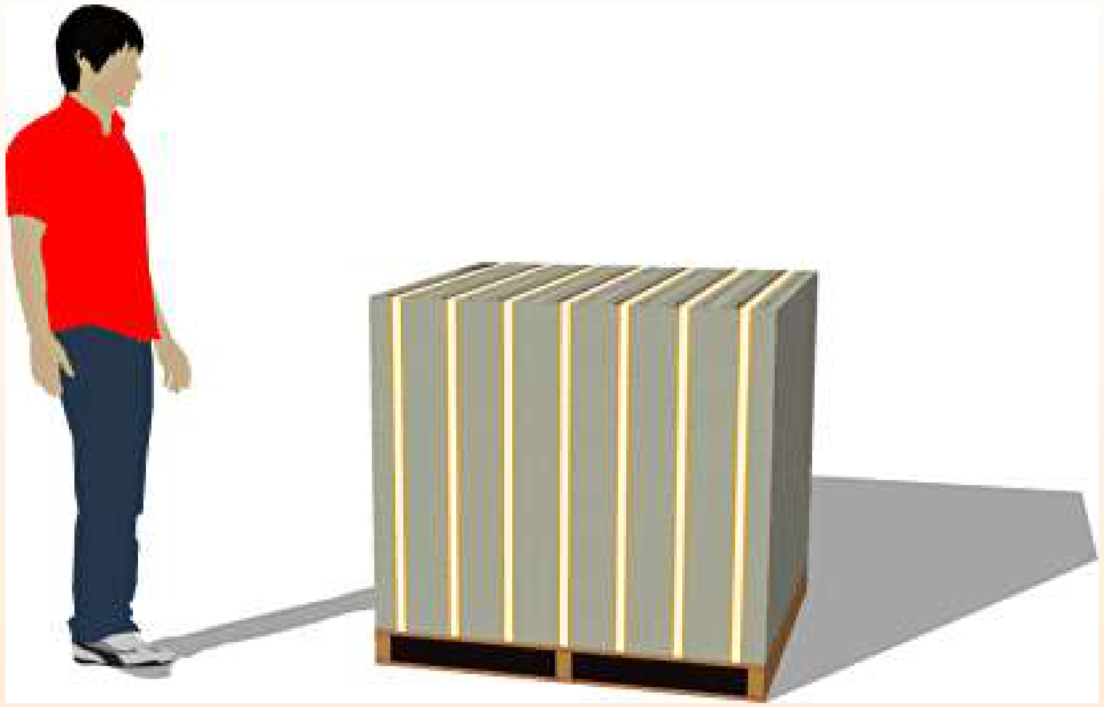
1 million



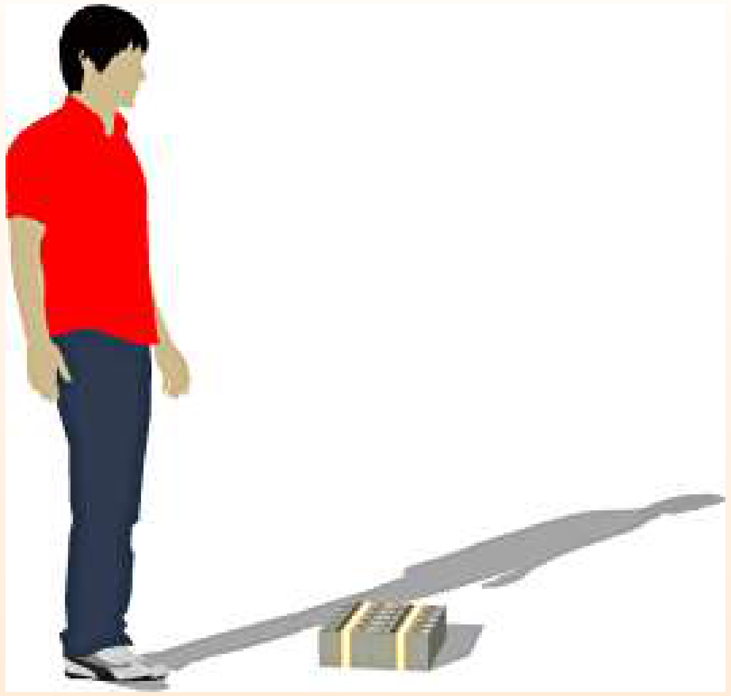
1 million



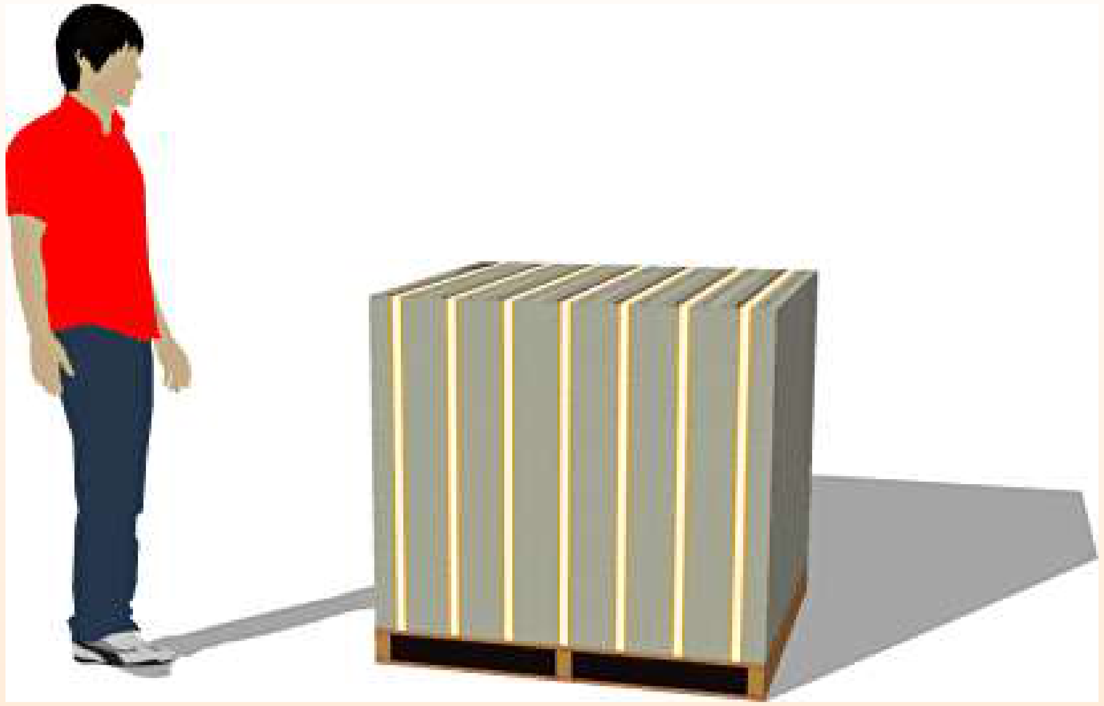
100 million



1 million

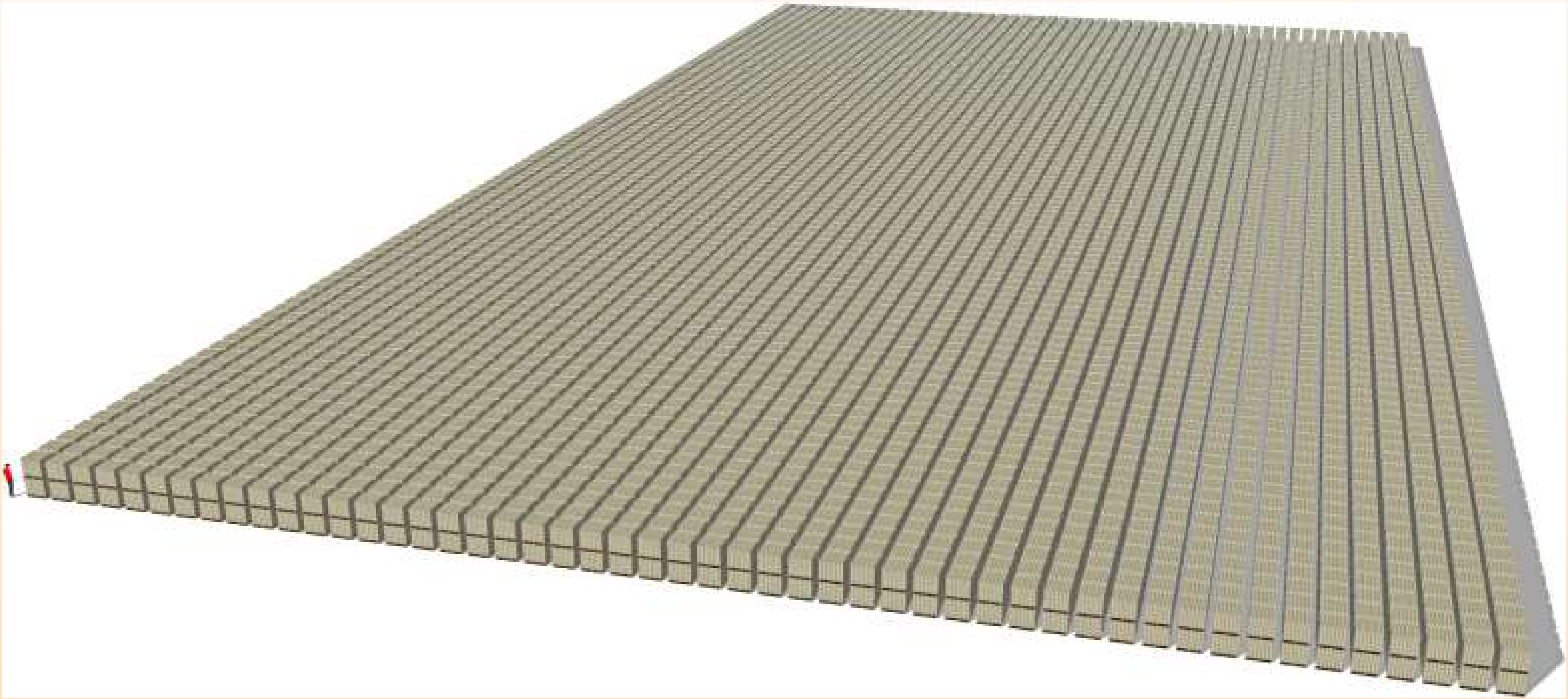


100 million



1 billion

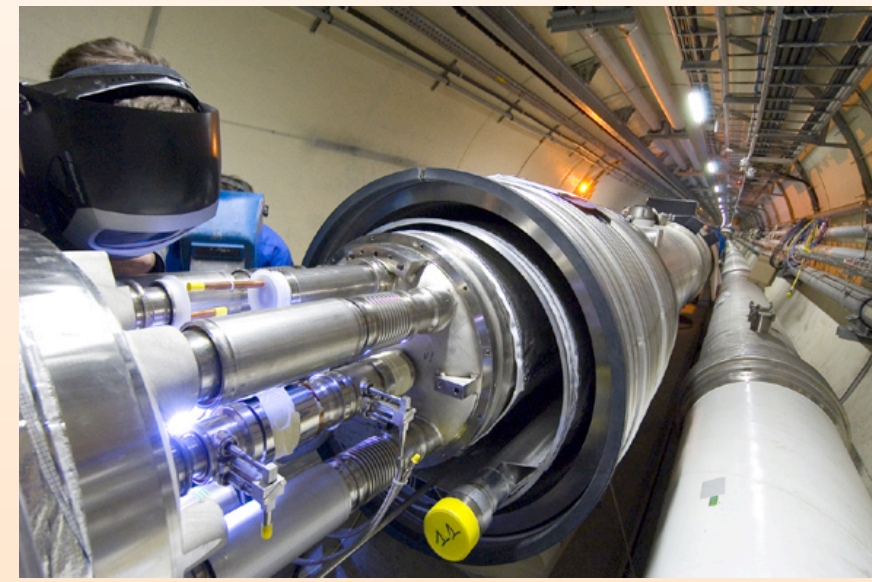
(not the same units as those of the US national debt)



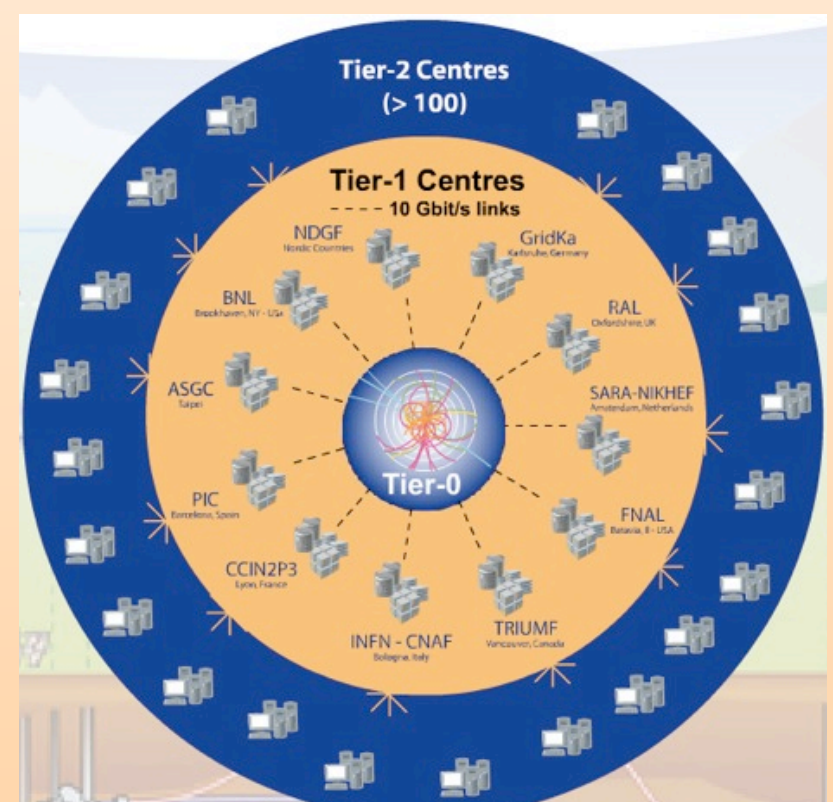
What does one get for 9 billion dollars?

(cost as of mid 2010, soon after collisions began) (US share 0.5 billion, majority from Europe)

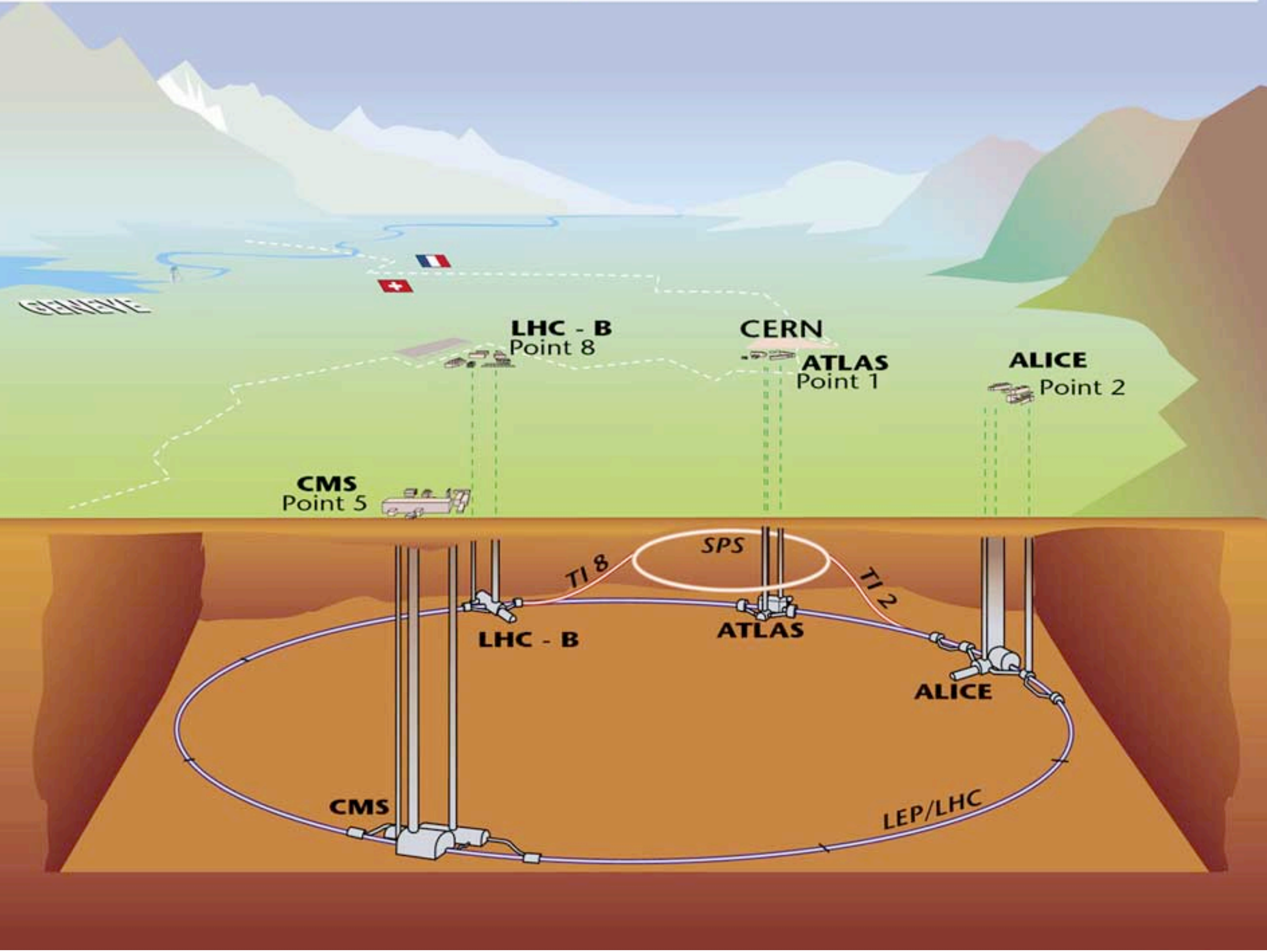
- work from 10000 scientists and engineers from ~60 countries
- a particle accelerator with 4 detectors all placed in a 27 km circular tunnel, 175m deep



- 30000 tons of 8.4 Tesla magnets, and 90 tons of liquid helium to keep them at 1.9 Kelvin
- colliding beams of protons with 7 TeV of (center of mass) energy
- detectors that can handle collision rates of 10^9 Hz (25 collisions every 25 ns)



- computer resources to handle read out of 100 million channels, writing interesting events to tape ~300 times/s, plus analysis of 15 Petabytes (15×10^{15} bytes) each year

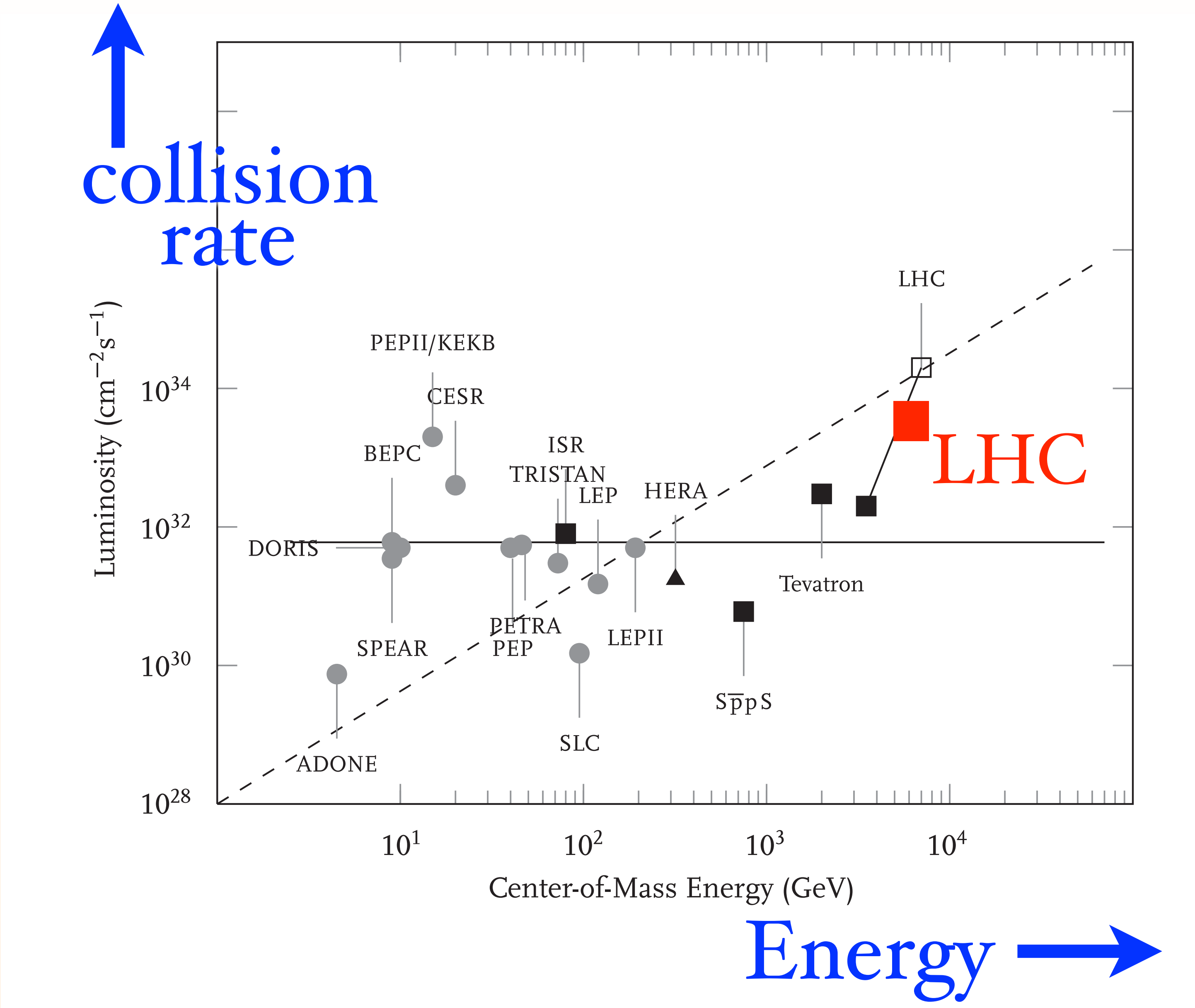


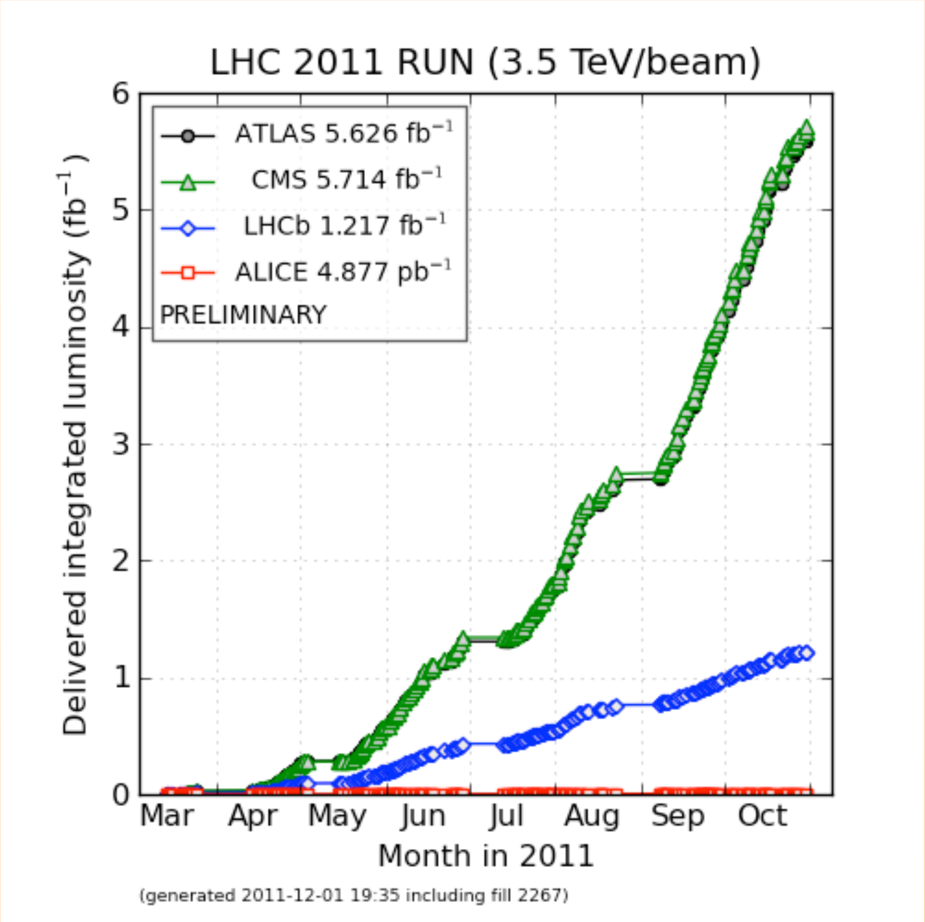
GENEVE
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC

Want to maximize collision rate & energy

- More collisions means more chance of seeing new particles or interactions

Higgs: $1 : 10^{10}$





- More energy means we can produce new heavy particles

$$m = E/c^2$$

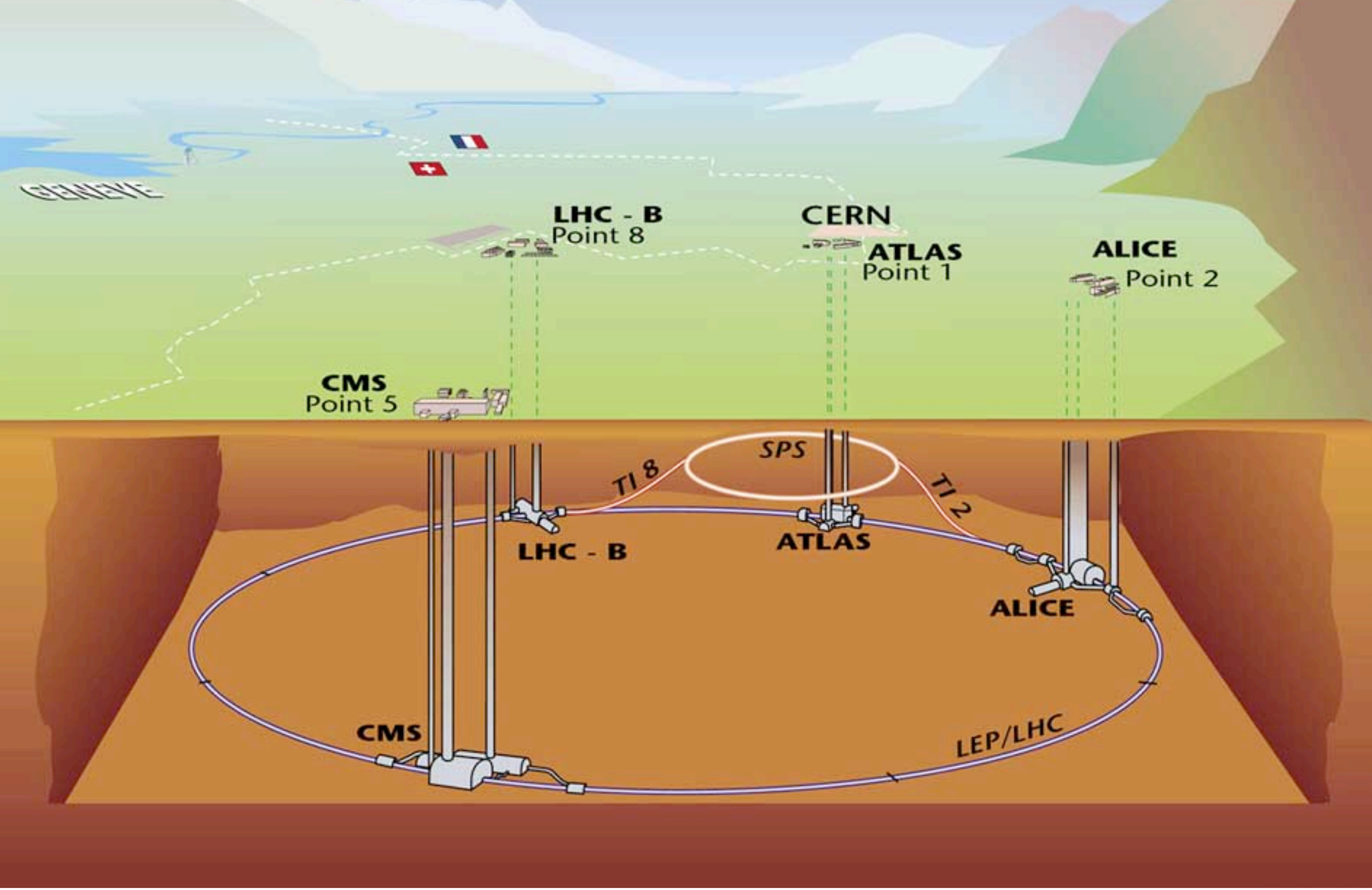
LHC(2011): $E = 7\,\text{TeV}$

non-relativistic

$$\frac{mv^2}{r} = qvB$$

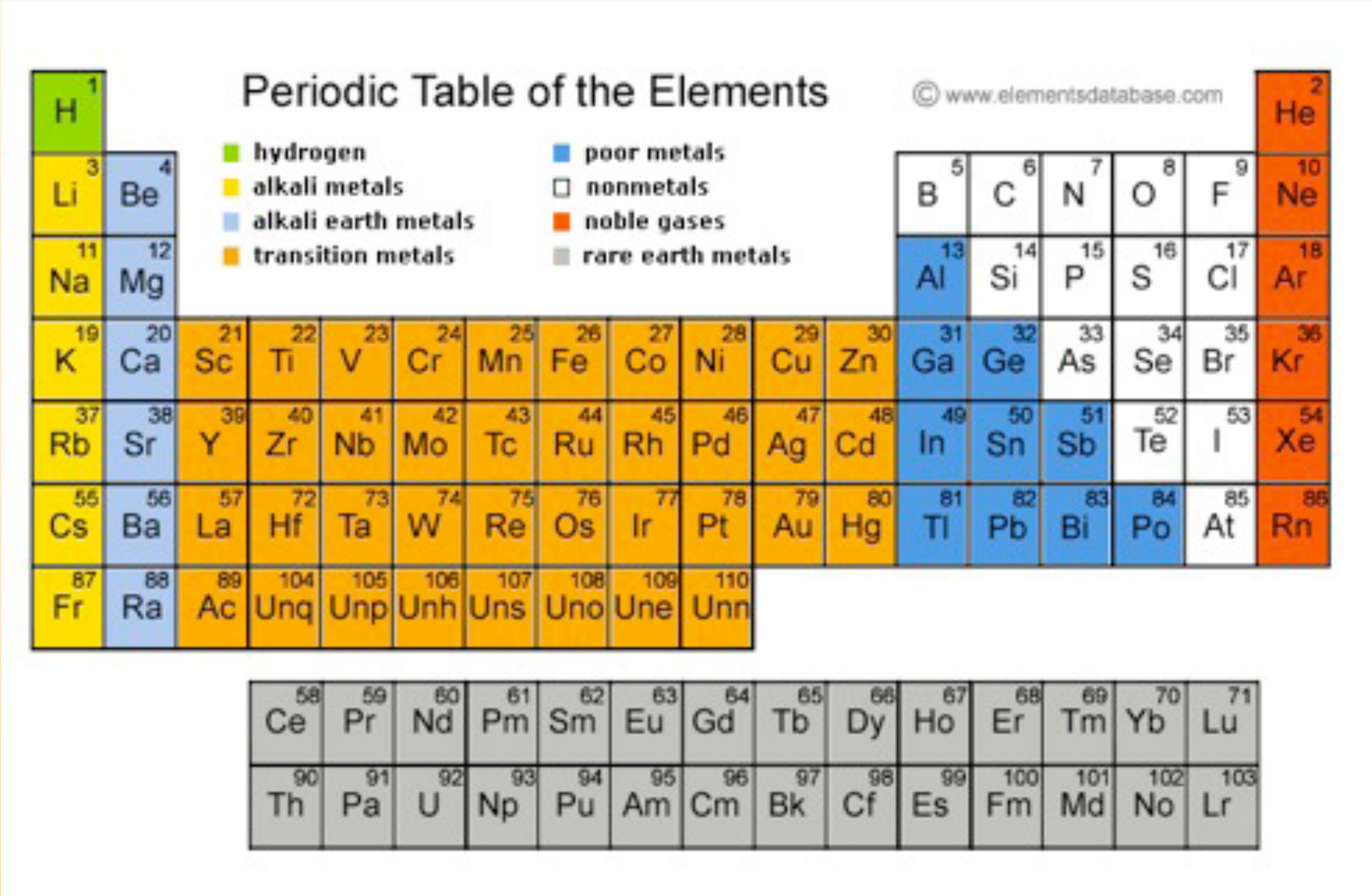
ultra-relativistic

$$E = qBr \quad \Rightarrow \quad \text{maximize: } B,\, r$$



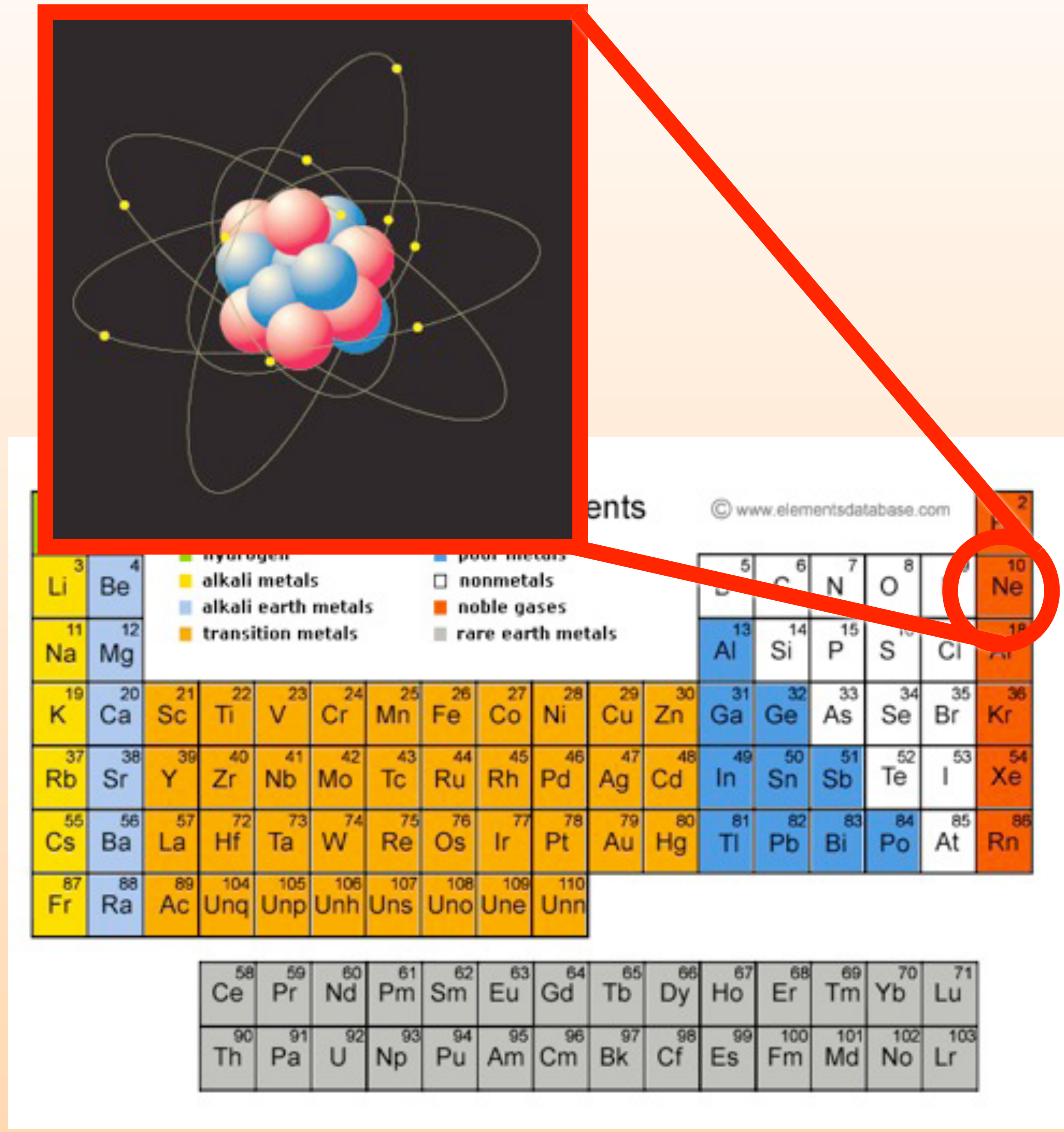
Particles and Forces

Basic Constituents of Matter?



Basic Constituents of Matter?

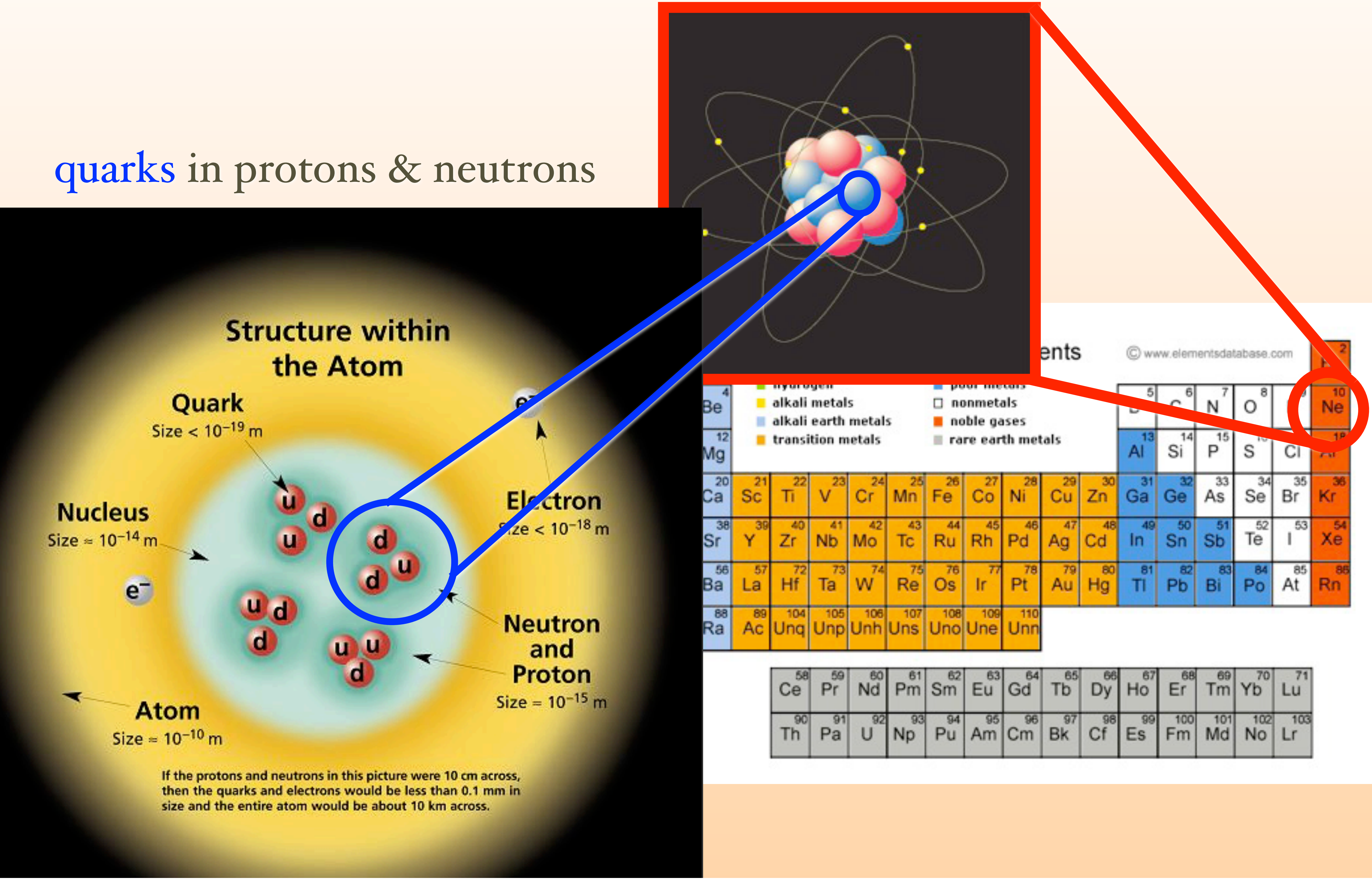
protons & neutrons in a nucleus



Basic Constituents of Matter?

protons & neutrons in a nucleus

quarks in protons & neutrons



Standard Model's Elementary Particles

Force Mediators

Leptons	e	μ	τ
	ν_e	ν_μ	ν_τ
Quarks	u	c	t
	d	s	b

Higgs H

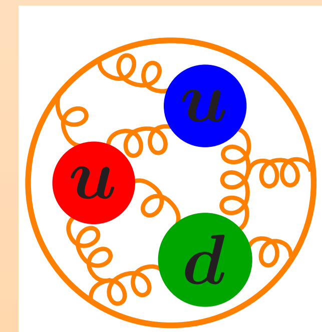
γ Electromagnetism
Quantum Electrodynamics (QED)

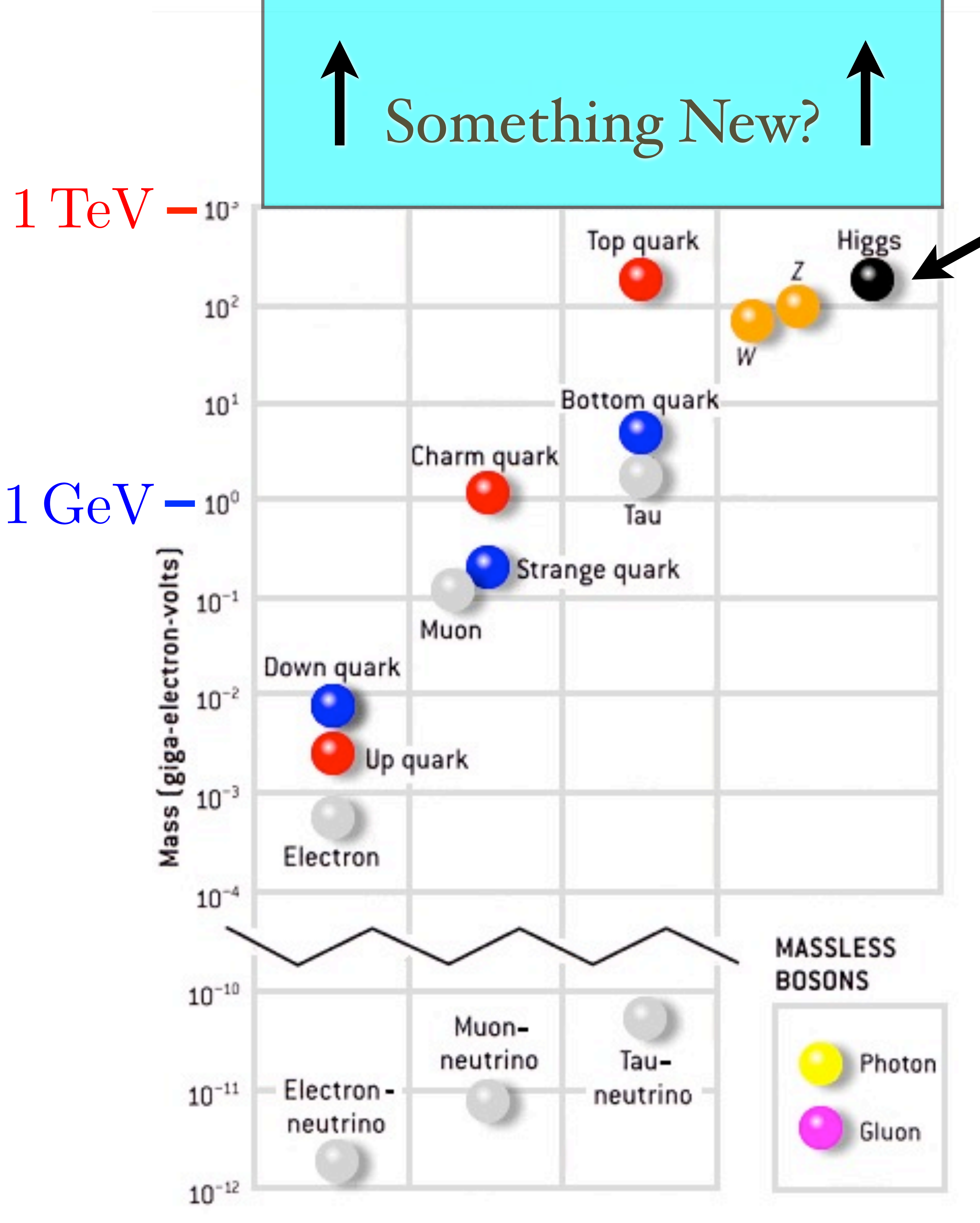
Z, W Weak Force

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

g Strong Force
Quantum Chromodynamics (QCD)

& Gravity
(gravitons)

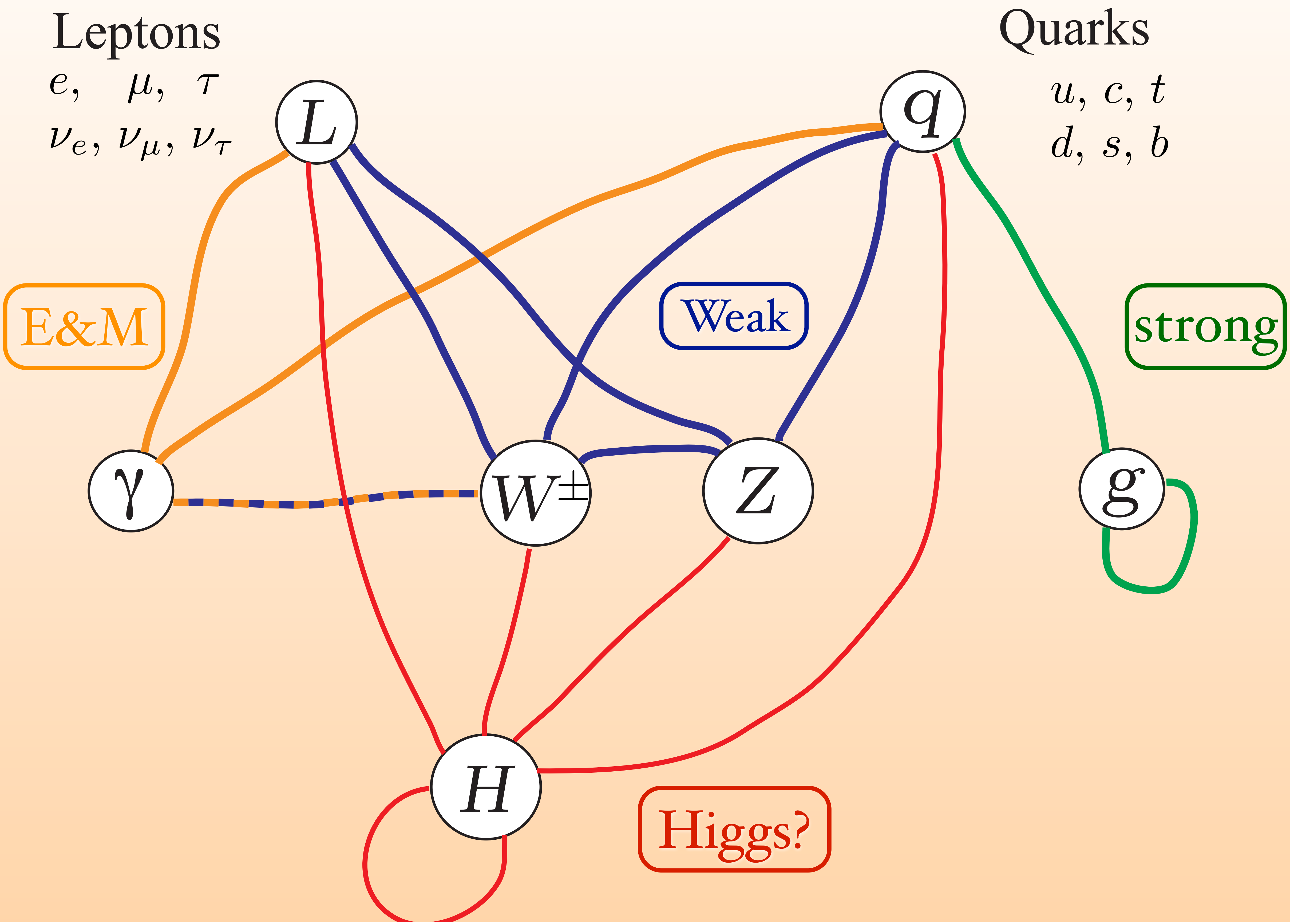




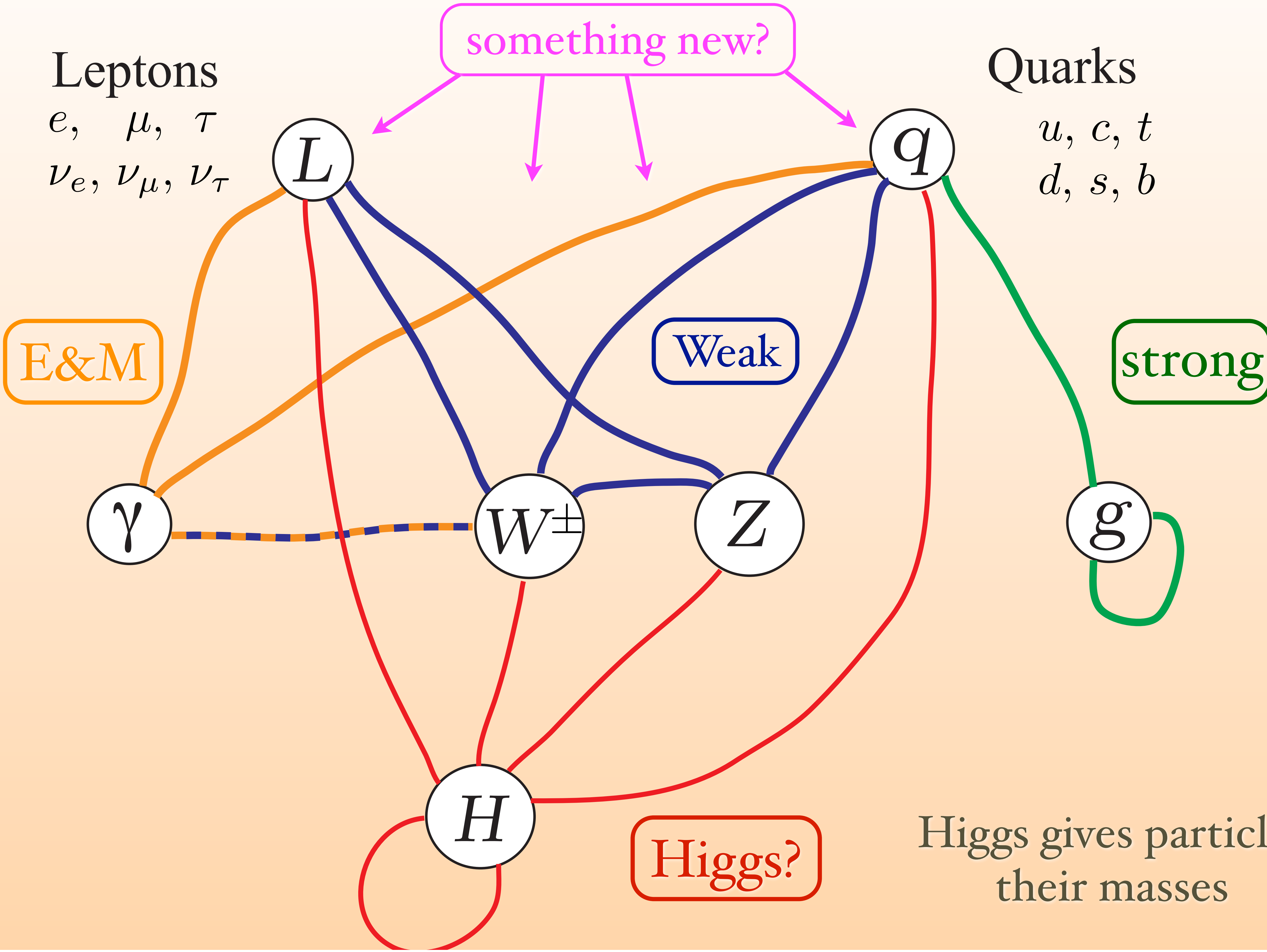
hints for Higgs at LHC, but not yet definitively observed

Particle Masses

Particle Forces/Interactions



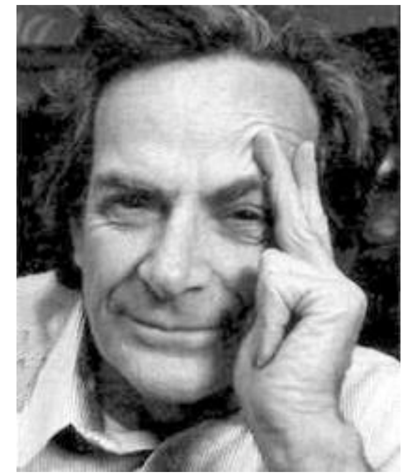
Particle Forces/Interactions



Higgs gives particles their masses

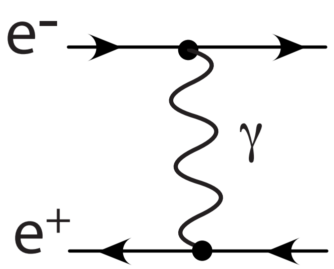
Particle Forces/Interactions

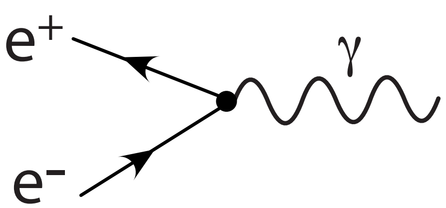
Feynman Diagrams

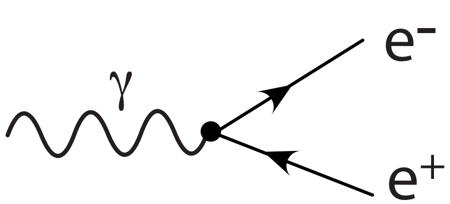


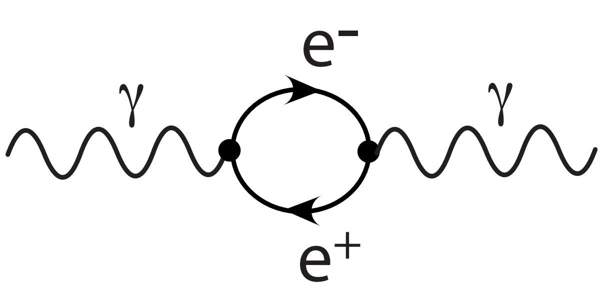
E&M

coupling α

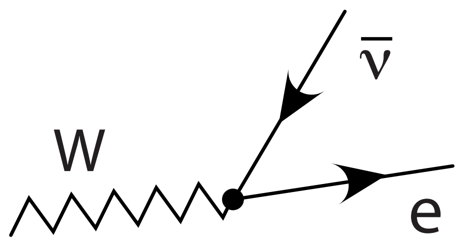




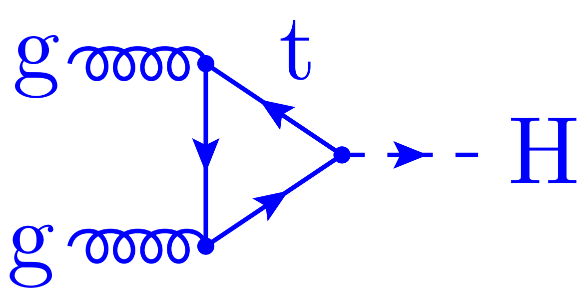


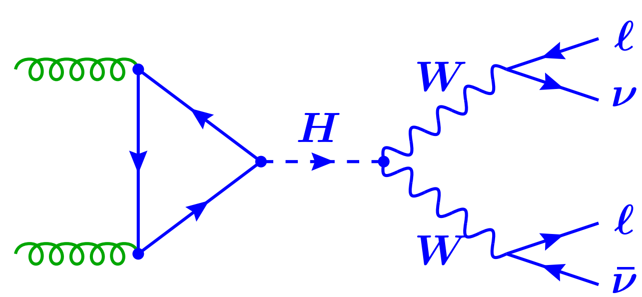


Weak



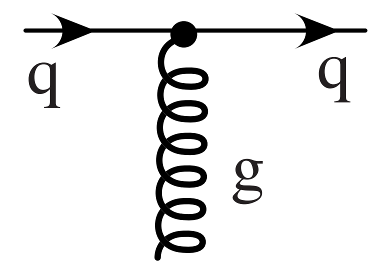
Higgs?

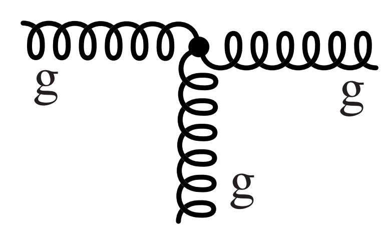


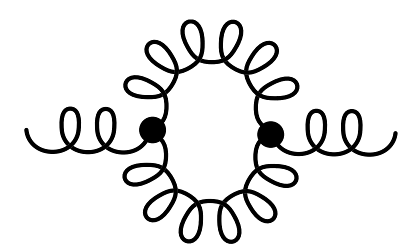


strong

coupling α_s





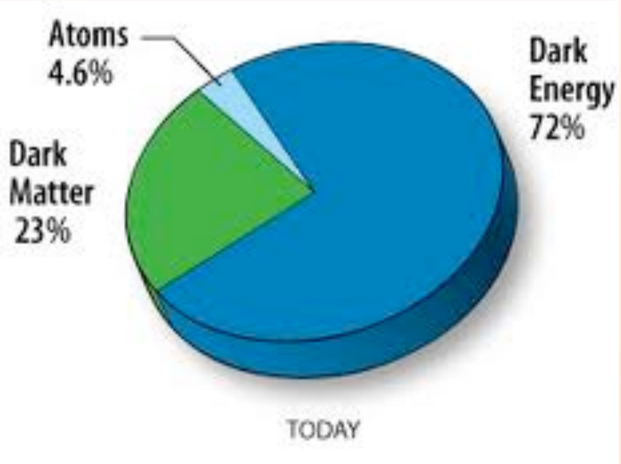


LHC Physics

New Physics @ LHC

Might Answer:

- What is Dark Matter? Can we make it with a collider?



- Do the forces we know unify into one force at high energies?
- Are there new principles of nature? new symmetries? new particles?
- What happened to antimatter in the early universe?
- Are there extra (small compact) spatial dimensions?
- Why are there 3 families of leptons & quarks?
- Is a standard model Higgs boson natural?

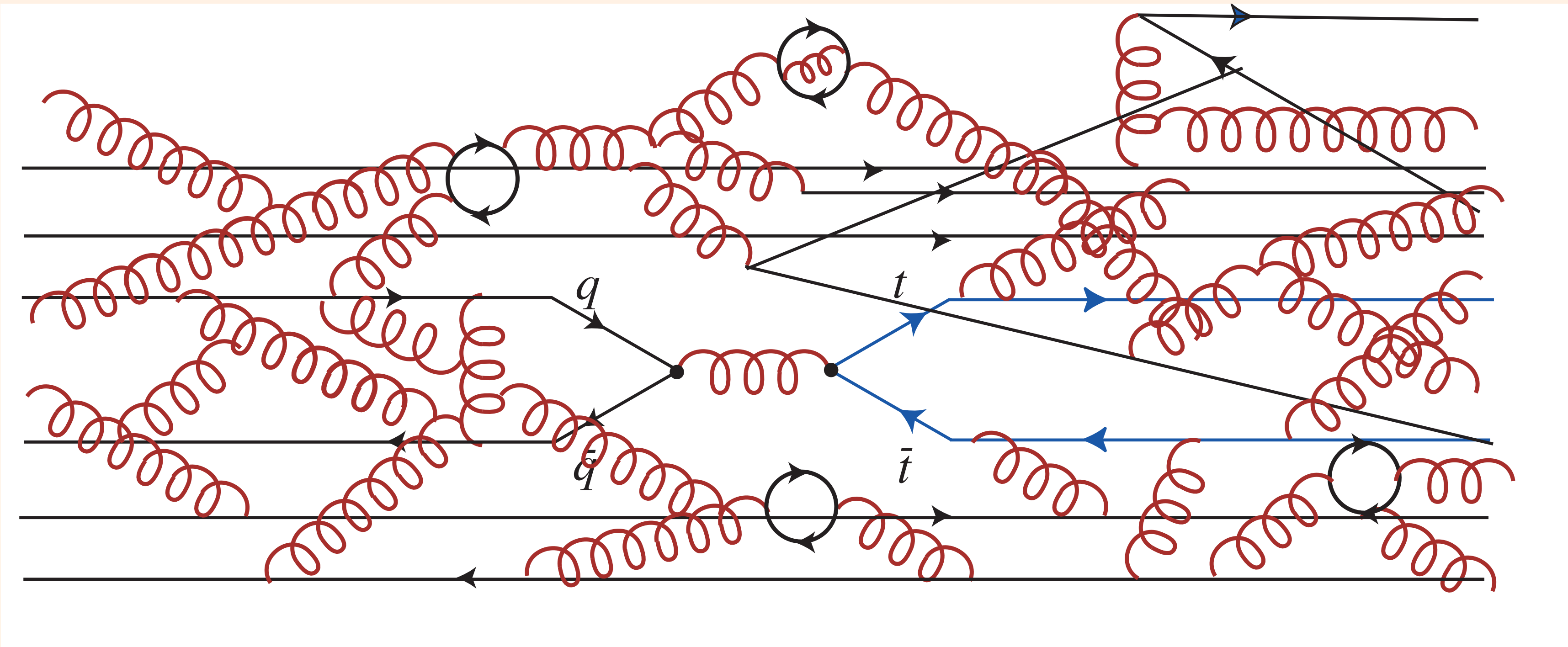
Will Answer: Does a Standard Model-like Higgs boson exist?

The Hunt for New Physics
often requires
Accurate Predictions
for collisions from the known
Standard Model

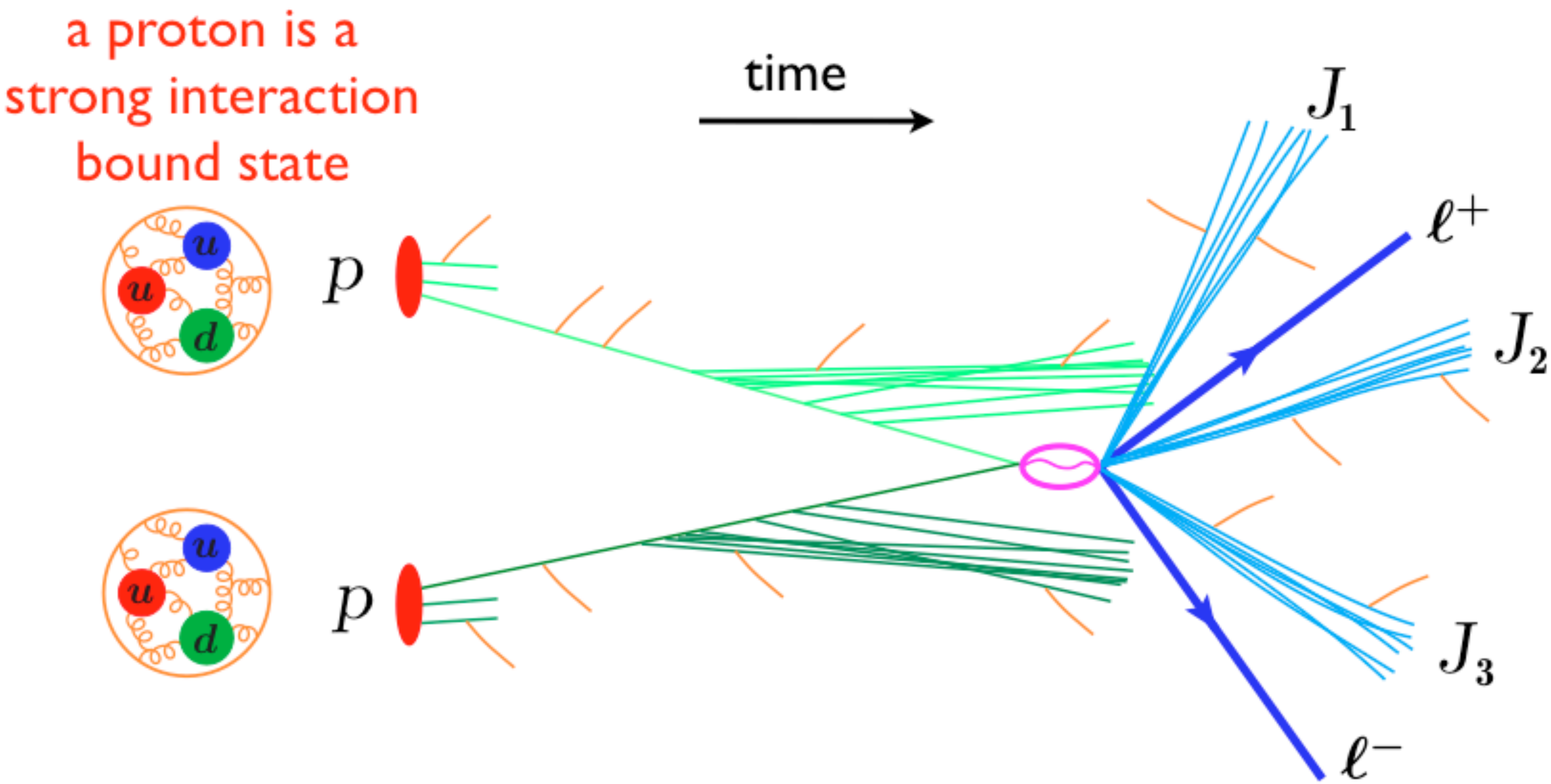
How well can we do?

The Issue:

The LHC is like Feynman on QCD Steroids

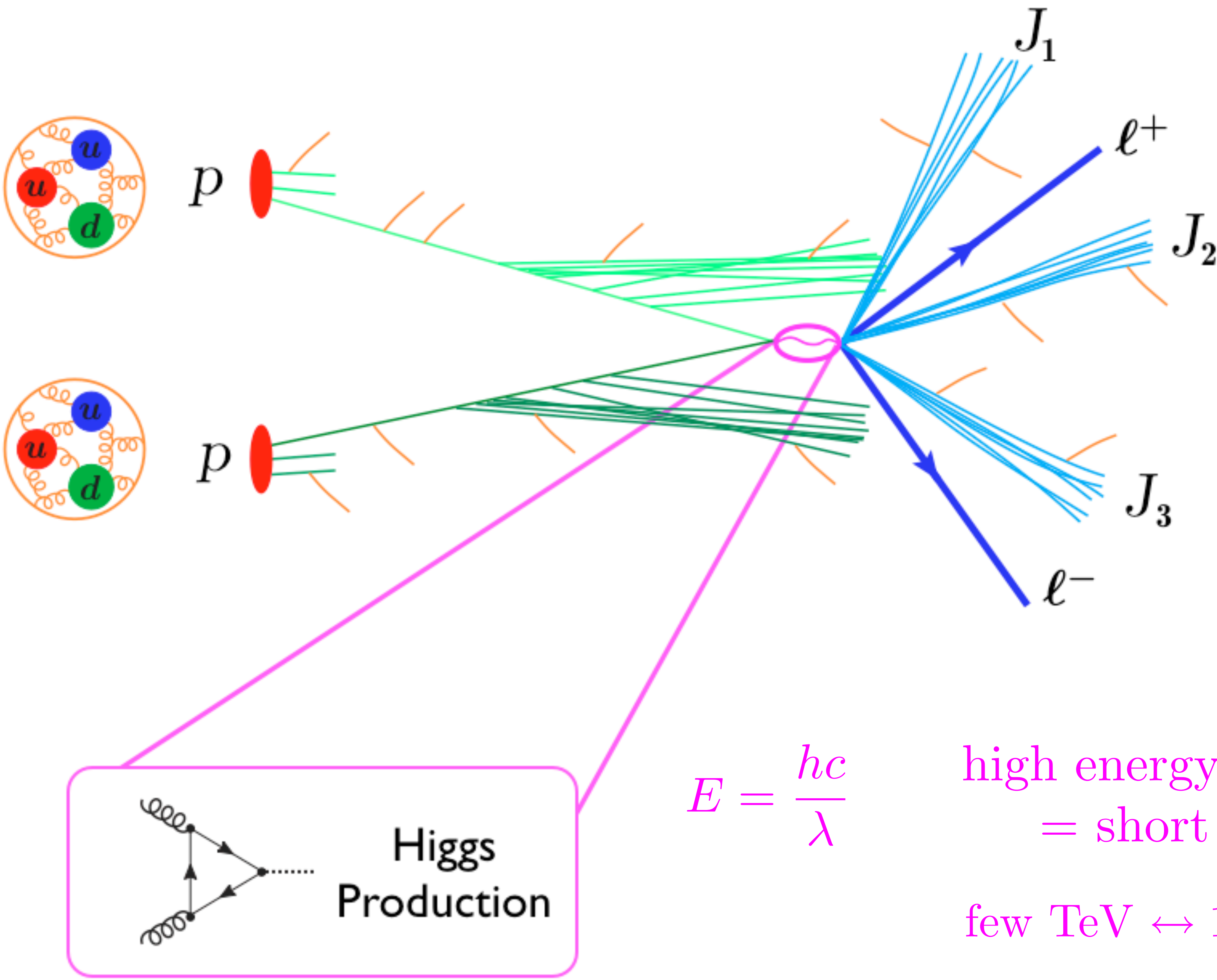


Anatomy of a High Energy Collision of Two Protons



Anatomy of a High Energy Collision of Two Protons

Search for New Heavy Particles at short distances



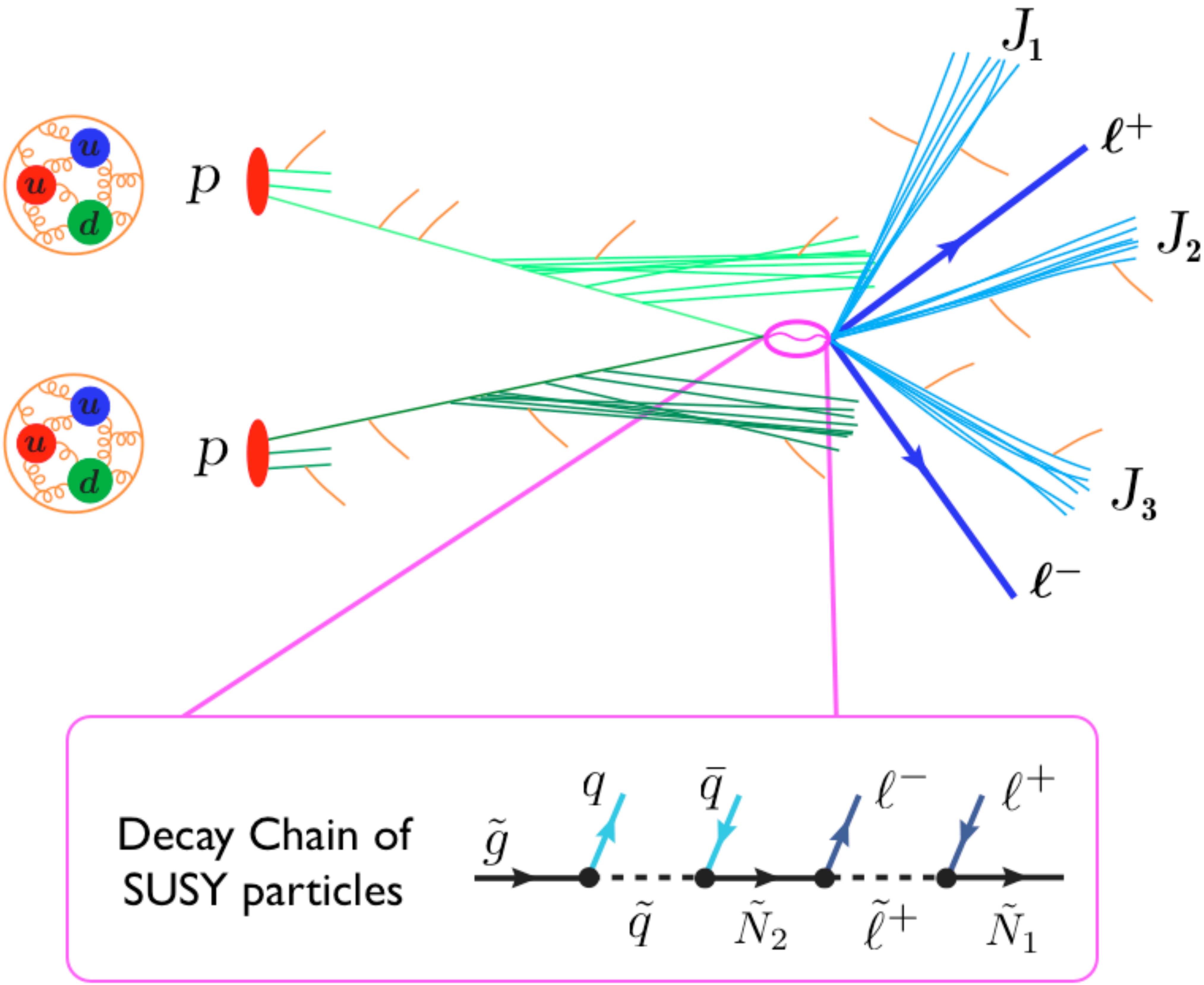
$$E = \frac{hc}{\lambda}$$

high energy E
$= \text{short distance } \lambda$

few TeV $\leftrightarrow 10^{-19} m$

Anatomy of a High Energy Collision of Two Protons

Search for New Heavy Particles at short distances



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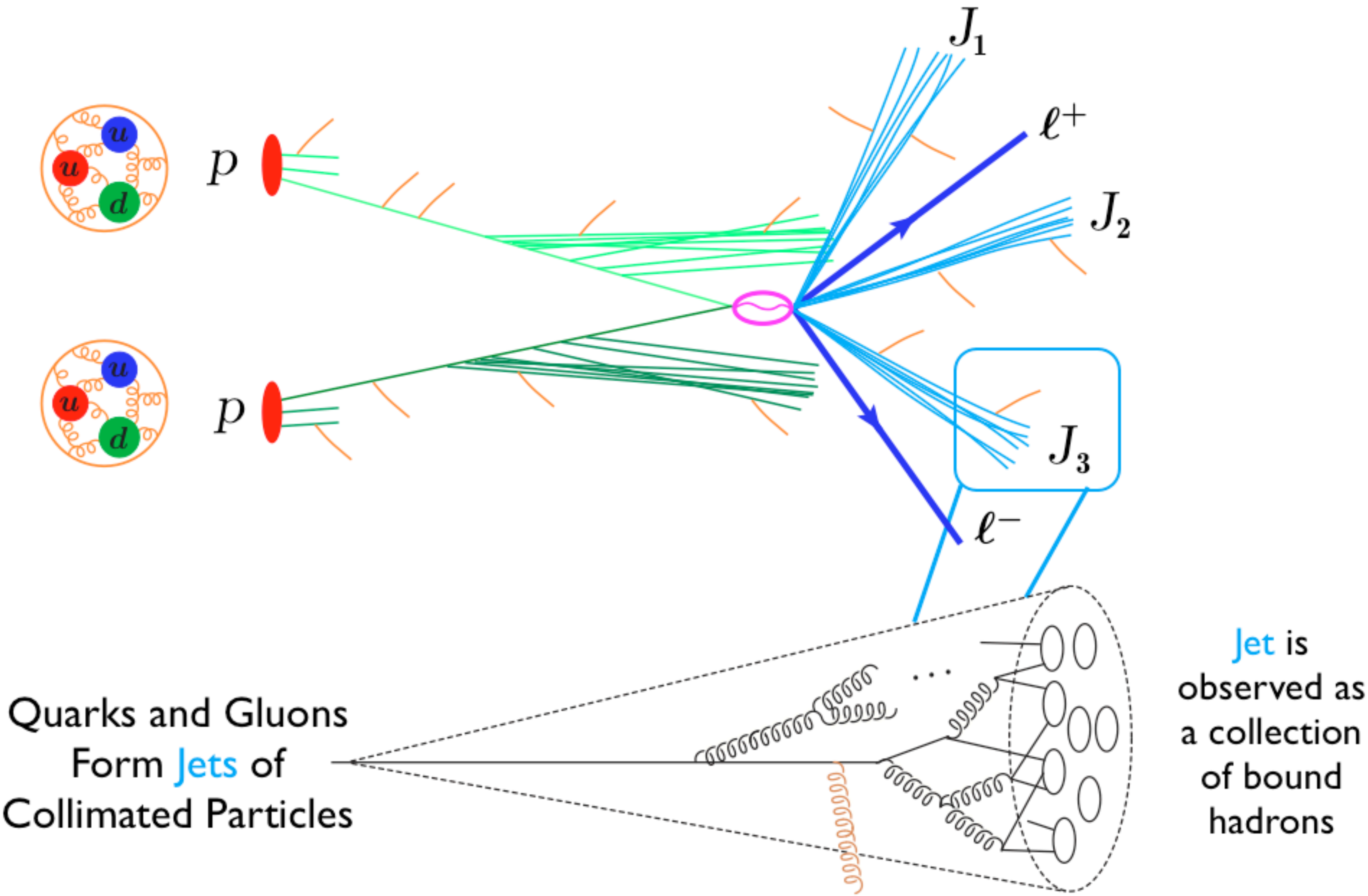

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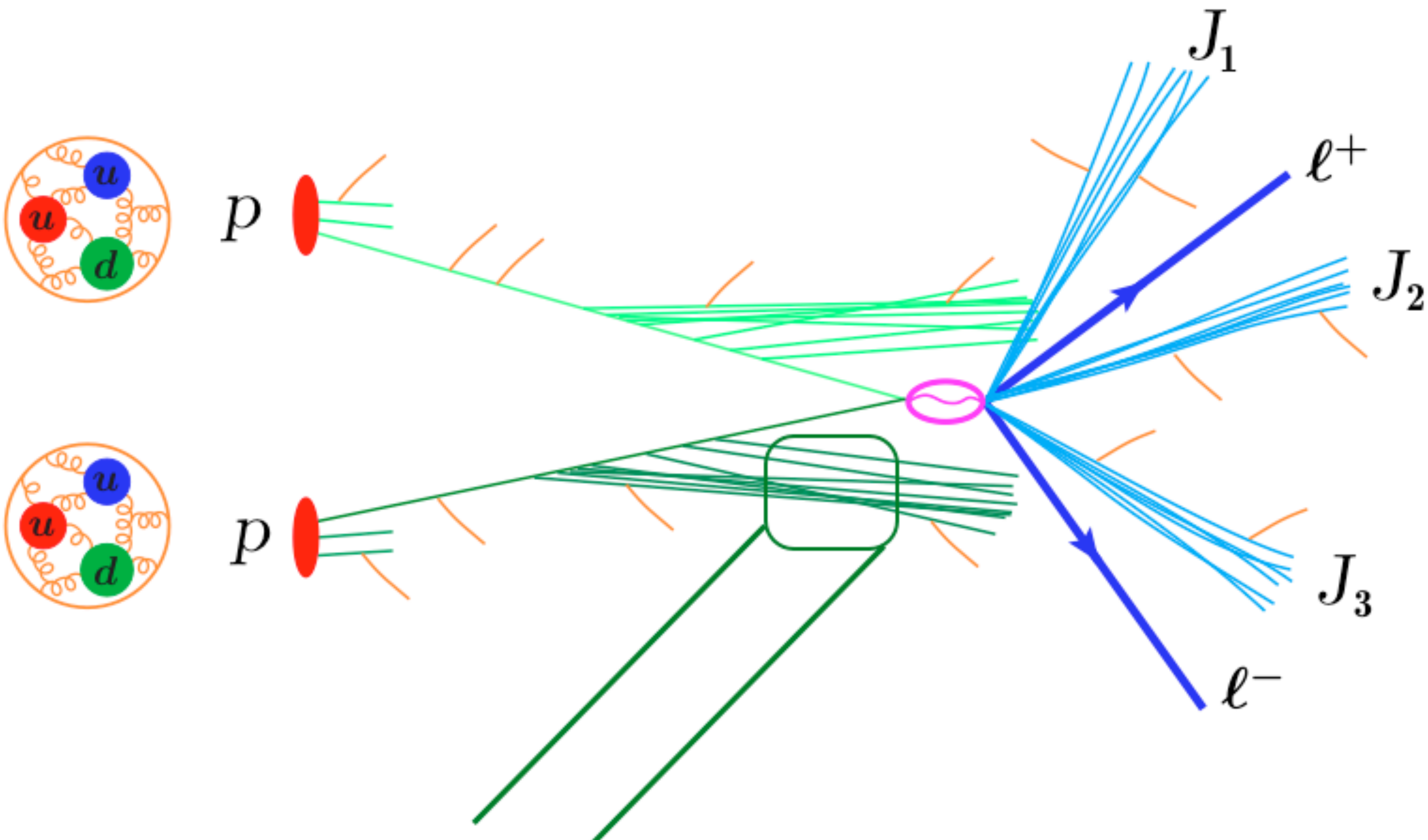
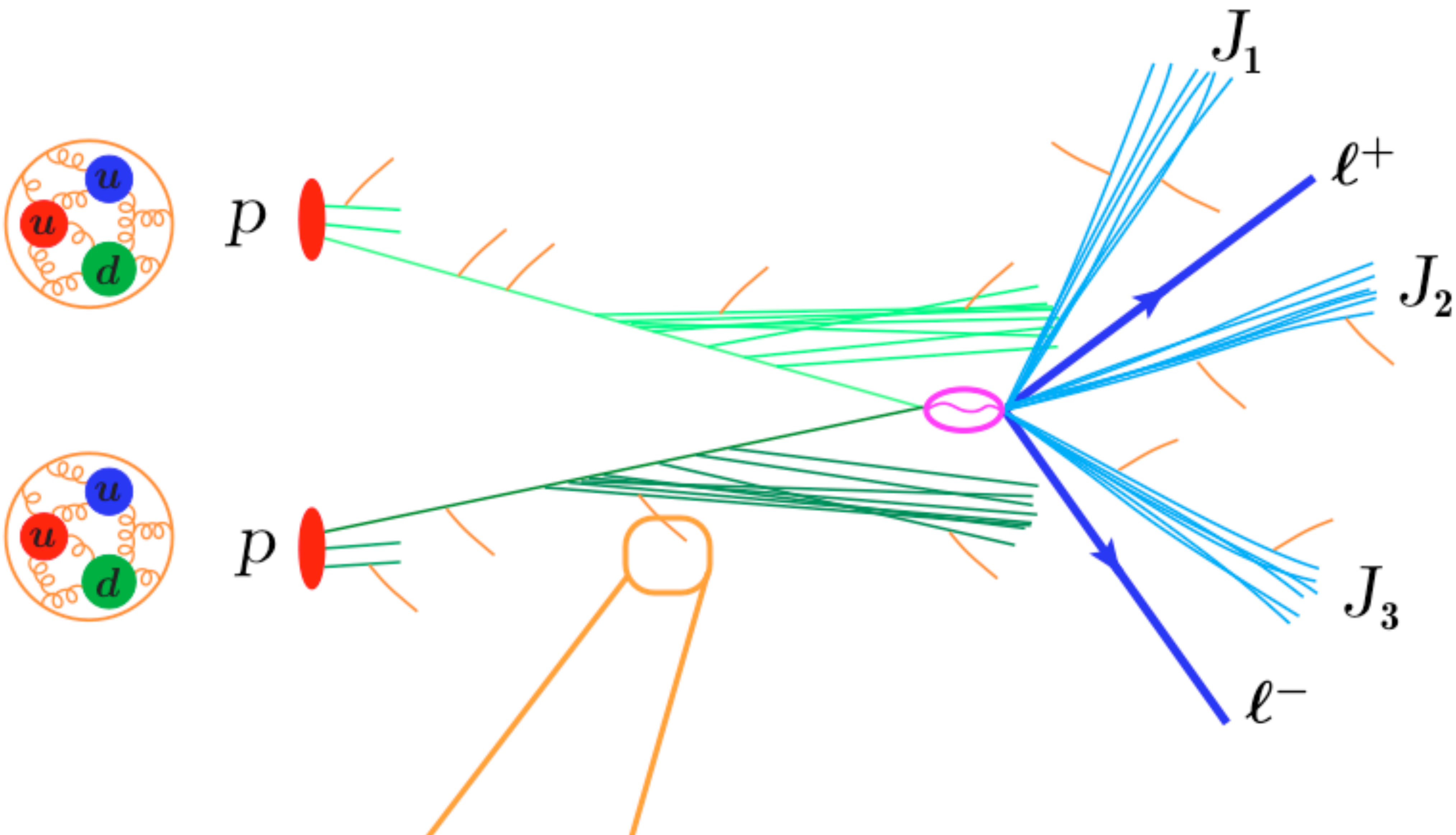


Jets also can form prior to the hard collision

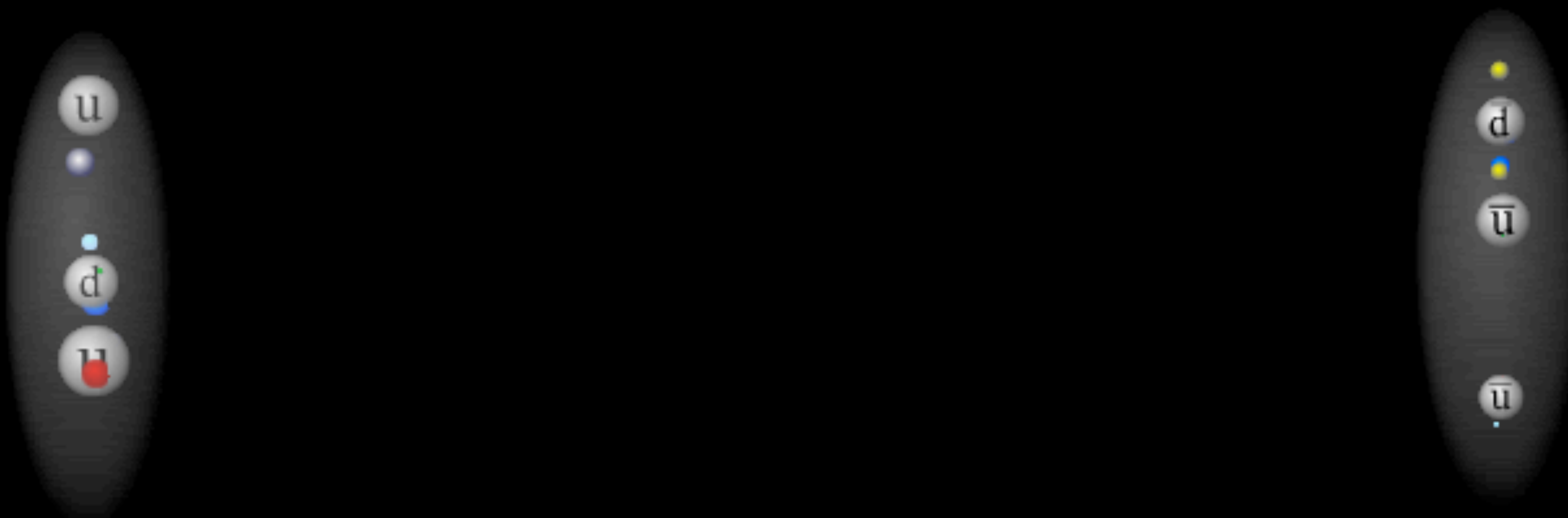
Anatomy of a High Energy Collision of Two Protons



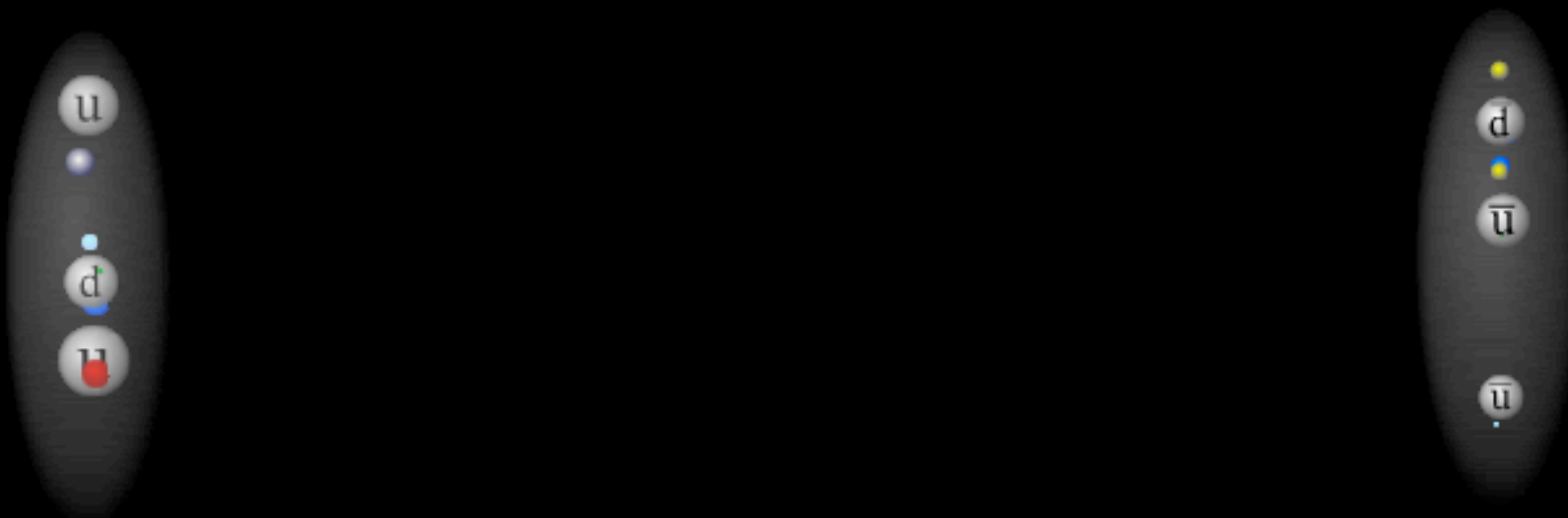
All colored particles can also
emit lower energy
soft gluon radiation

from Madgraph

from Madgraph

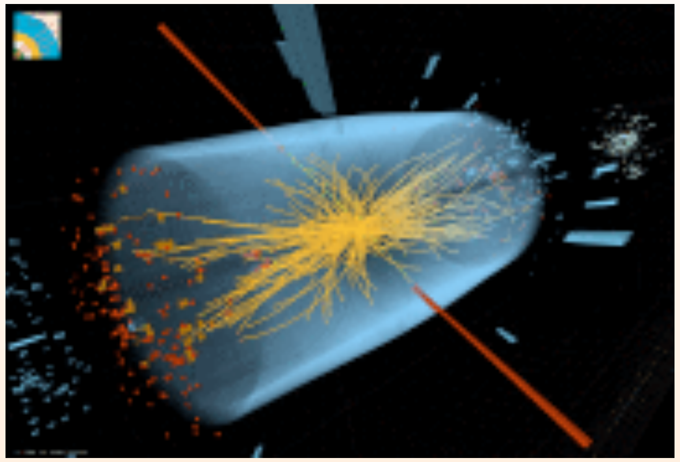


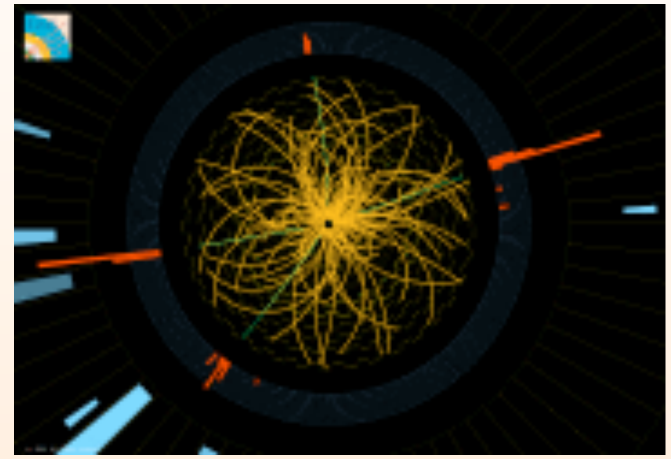
from Madgraph



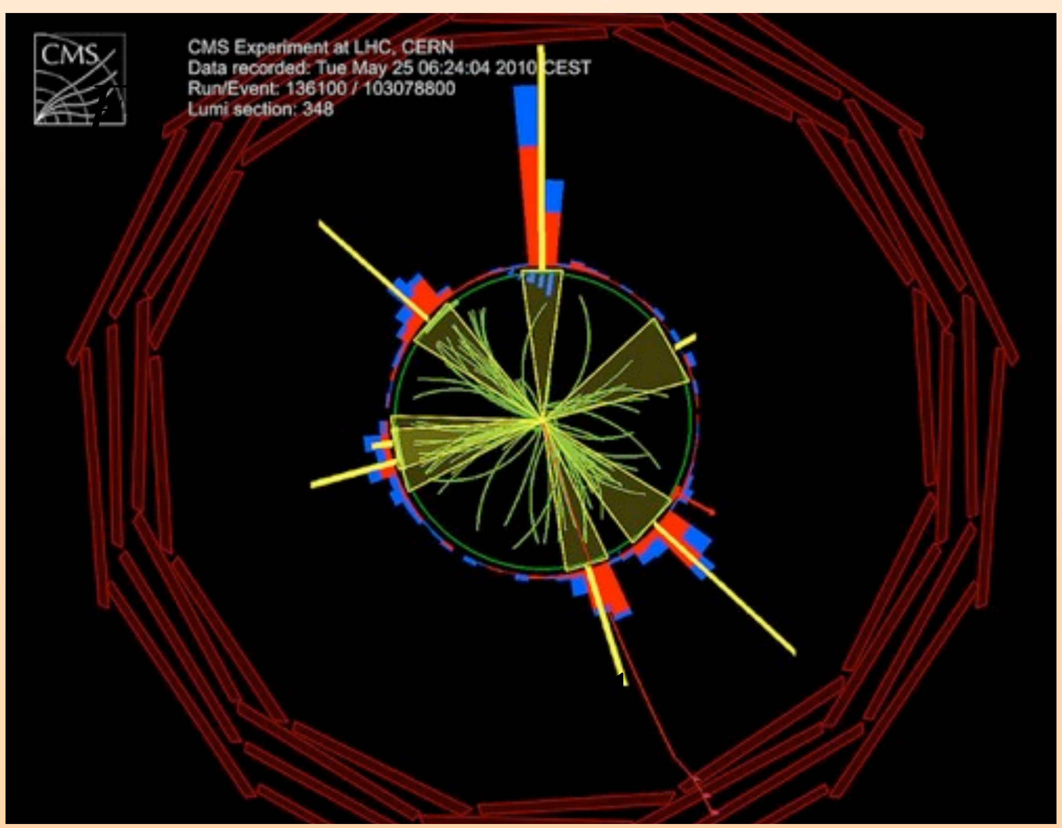
Here we collide hadrons and produce hadrons

CMS 2 photon event

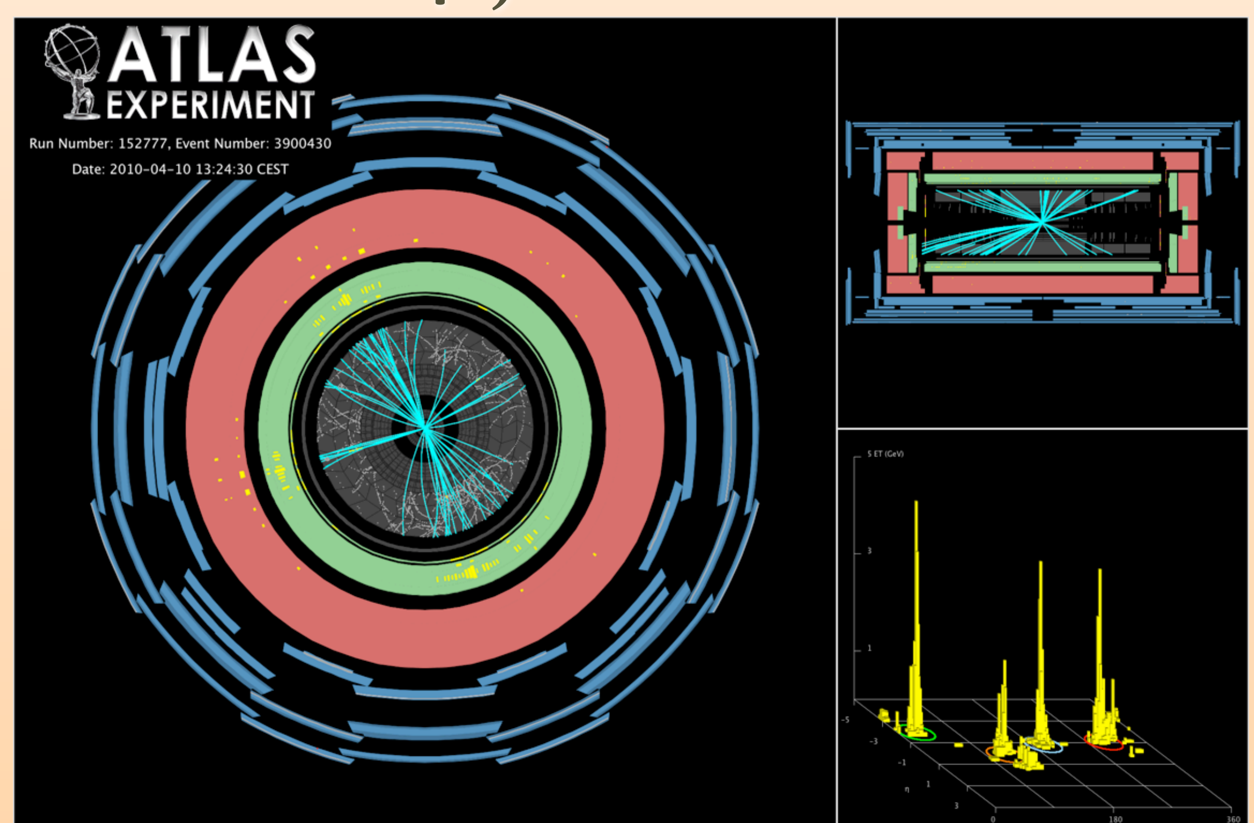




CMS multi-jet event

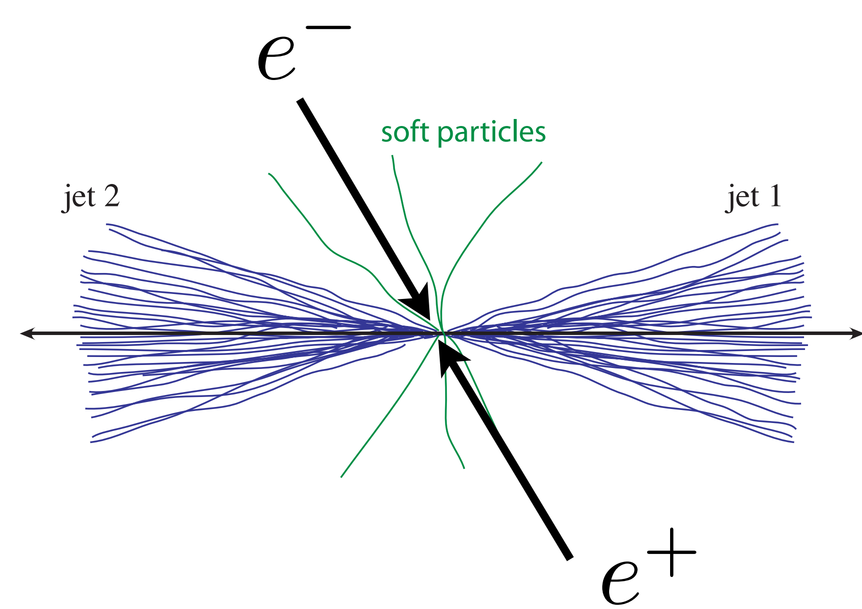


ATLAS 4-jet event

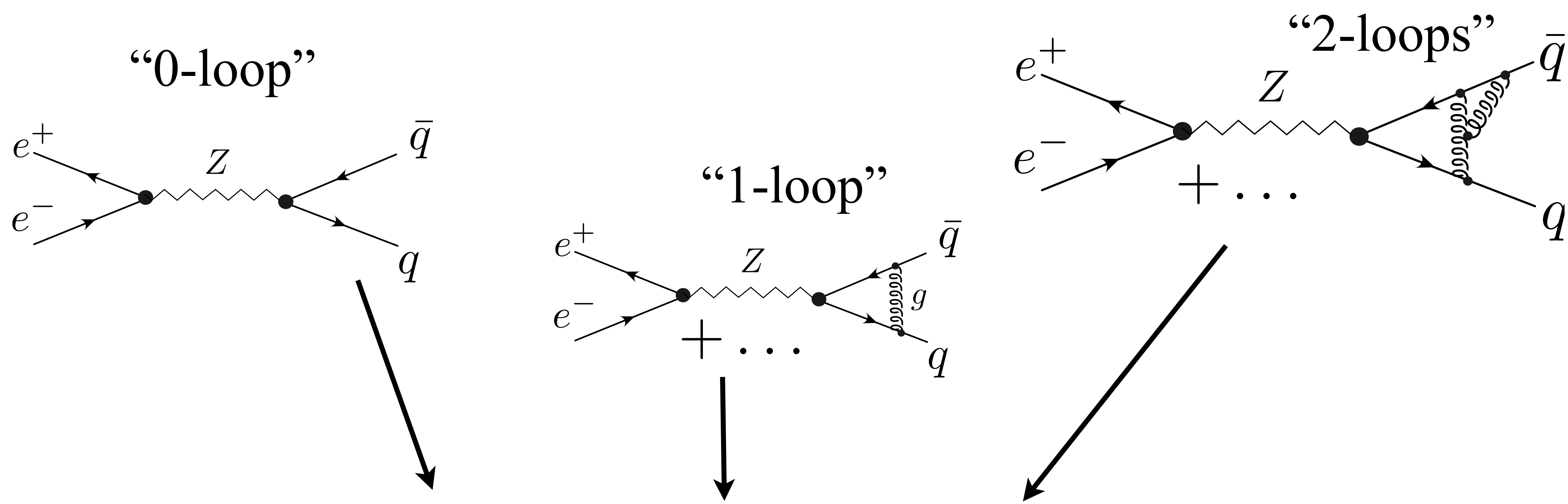


A key tool for Theorists: Taylor Series

Example 1 $e^+e^- \to Z \to 2\,\text{jets}$



- Feynman diagrams give rules for finding: A = quantum amplitude
- Probability $\propto |\text{A}|^2$

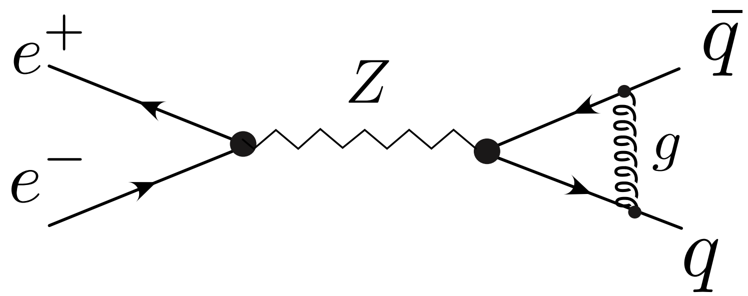


$$A = A_0 + \alpha_s A_1 + \alpha_s^2 A_2 + \dots$$

Series in α_s

Feynman Loop graphs are integrals

$\alpha_s A_1 =$



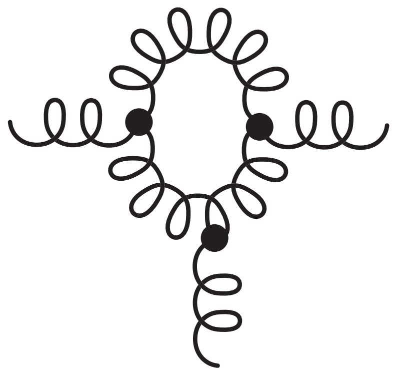
$$= \int d^4q \frac{Numerator}{(q^2)(q+p)^2(q-\bar{p})^2}$$

- $q^2 = (q_0)^2 - (\vec{q}\,)^2$ Lorentz Symmetry constrains integrands
- more loops → more integrals, calculations get tough
- the more legs poking out, the harder the integrals

  state of the art for multi-legs is 6 legs at 1-loop

  state of the art for multi-loop is 2 legs at 4-loops
- to handle results with 100's of legs (with 0-loops) we use approximations

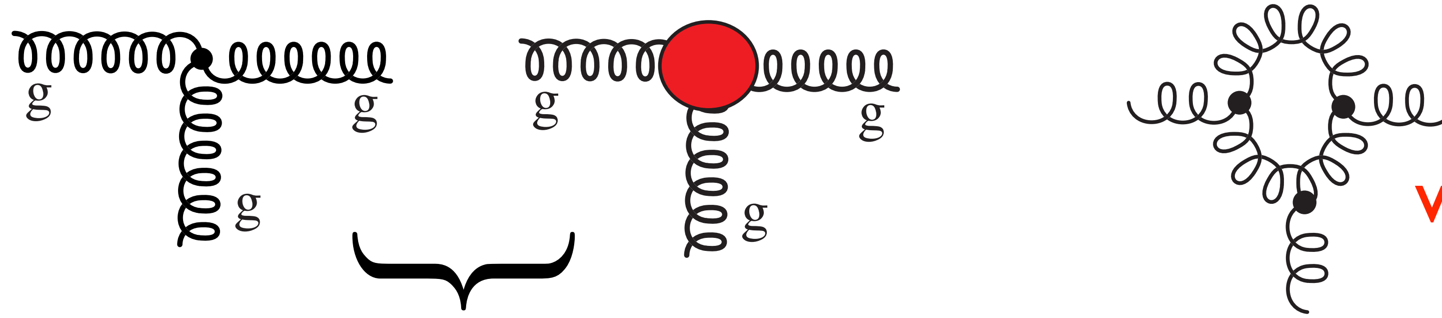
Integrals can DIVERGE as $q \longrightarrow \infty$



$$= \int d^4q \frac{q^2 + \dots}{(q^2)(q+p)^2(q-\bar{p})^2} \sim \int \frac{d^4q}{q^4} + \dots$$

- forces us to be careful how we define α_s
- introduce a cutoff parameter μ to remove large momentum parts and make the integrals well defined.
- absorb large momentum parts into the coupling

$-q^2 > \mu^2$ $\qquad$ $-q^2 < \mu^2$

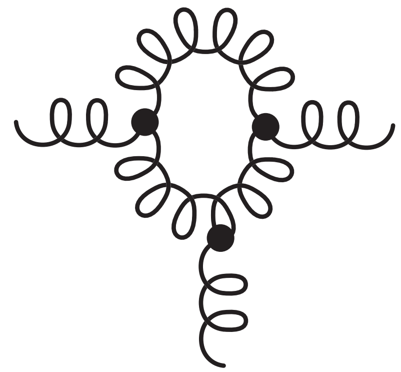


$\alpha_s(\mu)$

well defined

(You may have guessed that I'm oversimplifying, but this is morally correct)

Integrals can DIVERGE as $q \longrightarrow \infty$



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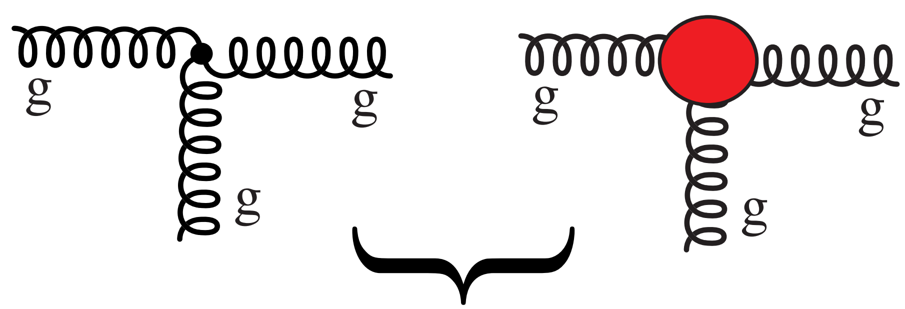
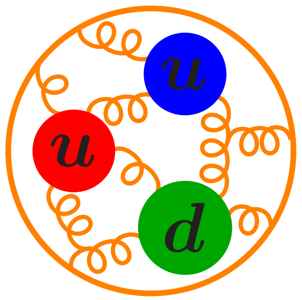


$\alpha_s(\mu)$

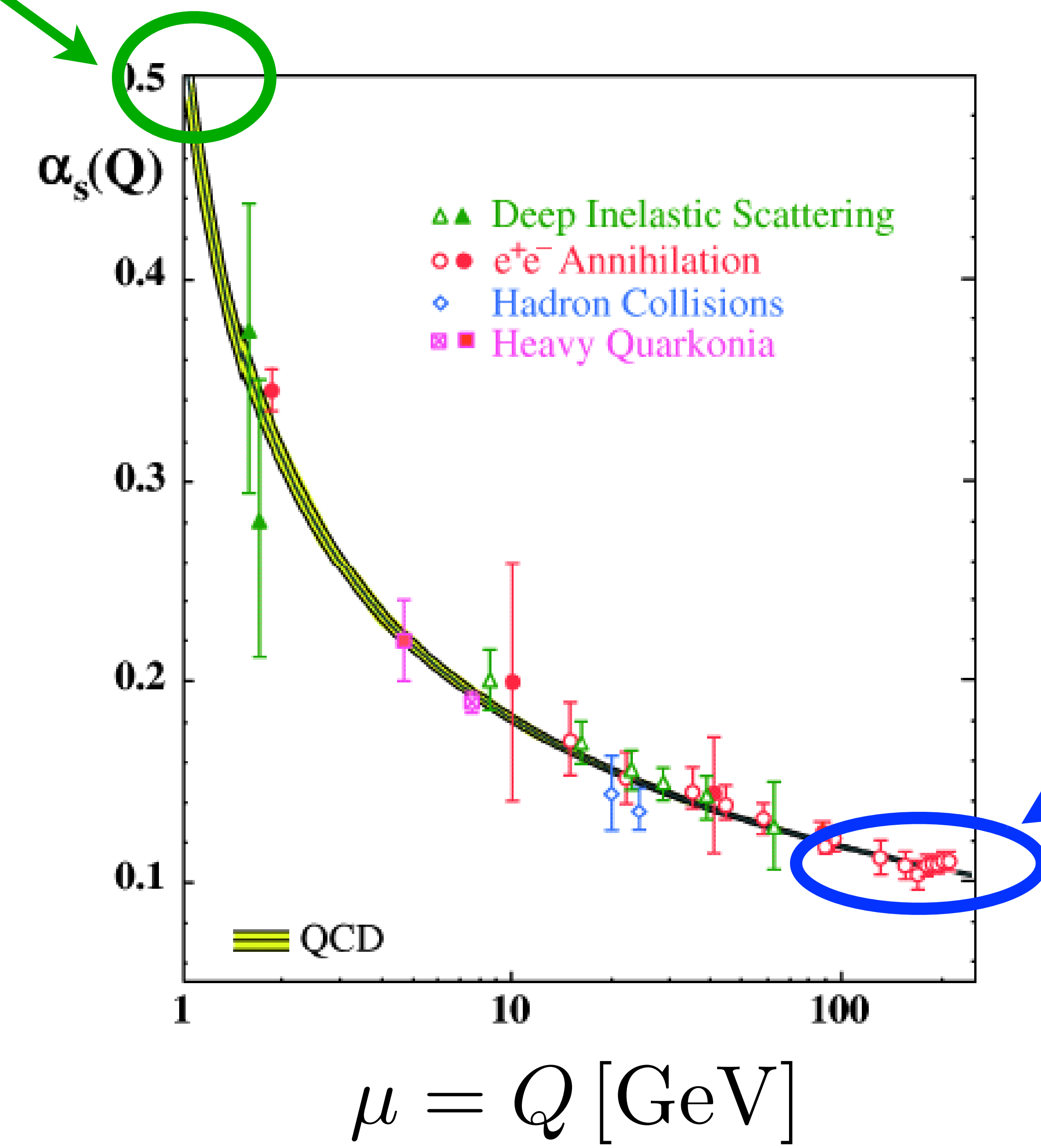
- coupling now depends on a parameter: $\alpha_s(\mu)$
- ALL large momentum divergences in Standard Model can be treated in this way !

Coupling Changes with resolution μ



proton

large α_s
bound quarks



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

small α_s,
free quarks

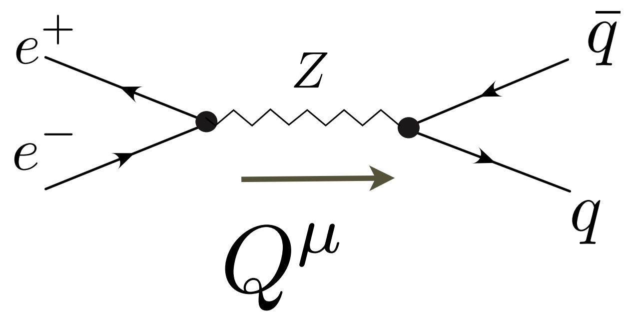
- How do we know what μ to pick for our Taylor Series?

$$A = A_0 + \alpha_s(\mu) A_1 + \alpha_s^2(\mu) A_2 + \ldots$$

The Series gives us a hint. $\text{eg. } e^+e^- \to \text{anything}$

$$A = A_0 + \alpha_s(\mu) A_1 + \alpha_s^2(\mu)\left[A_2^L \ln\left(\frac{\mu}{Q}\right) + A_2^0\right] + \alpha_s^3(\mu)\left[A_3^L \ln^2\left(\frac{\mu}{Q}\right) + \ldots\right] + \ldots$$

$Q =$ physical momentum associated to process we're considering



$$Q = \sqrt{Q^2}$$

- Need: $\mu \sim Q$
- If instead: $\mu \ll Q \text{ or } \mu \gg Q$ then $\alpha_s(\mu)\ln\left(\frac{\mu}{Q}\right) \sim 1$

and we need an infinite number of terms

In fact, we can sum up an infinite series: $\sum_k A_k^L \left[\alpha_s(\mu)\ln\left(\frac{\mu}{Q}\right)\right]^k$

and prove that a choice $\mu \sim Q$ is correct

The Series gives us a hint. eg. $e^+e^- \rightarrow \text{anything}$

$$A = A_0 + \alpha_s(\mu)A_1 + \alpha_s^2(\mu)\left[A_2^L \ln\left(\frac{\mu}{Q}\right) + A_2^0\right] + \alpha_s^3(\mu)\left[A_3^L \ln^2\left(\frac{\mu}{Q}\right) + \ldots\right] + \ldots$$

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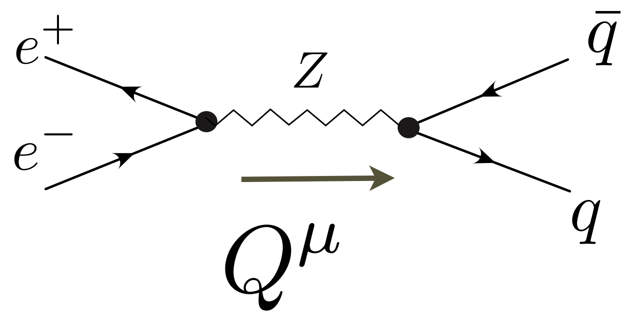


$$Q = \sqrt{Q^2}$$

- Need: $\mu \sim Q$

- The precise choice $\mu = Q$ is not required, we can equally well pick $\mu = Q/2$ or $\mu = 2Q$

Use this freedom to estimate higher order terms in the series.

"theory uncertainty"

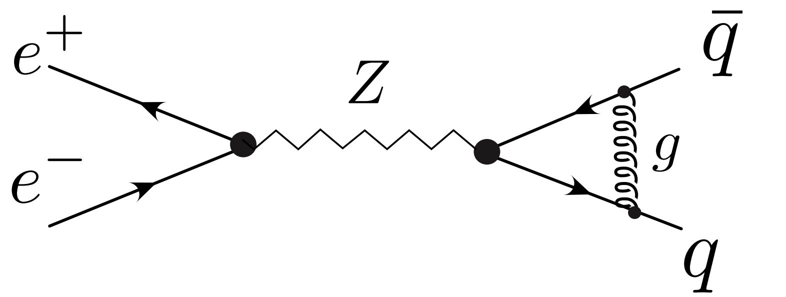
$$A = A_0 + \alpha_s(\mu) A_1 + \alpha_s^2(\mu)\left[A_2^L \ \ln\left(\frac{\mu}{Q}\right) + A_2^0\right] + \alpha_s^3(\mu)\left[A_3^L \ \ln^2\left(\frac{\mu}{Q}\right) + \ldots\right] + \ldots$$

What if there were two scales in the series? or more?

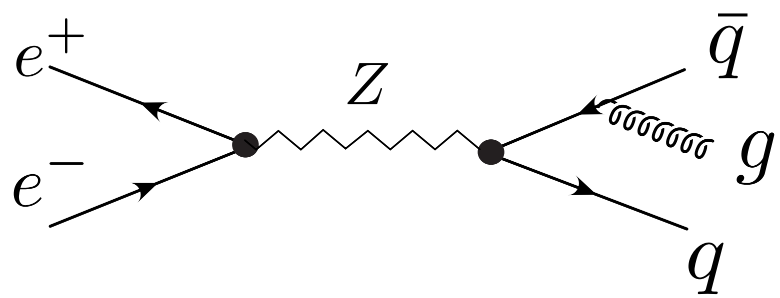
$$Q_1, \, Q_2$$

More about this later.

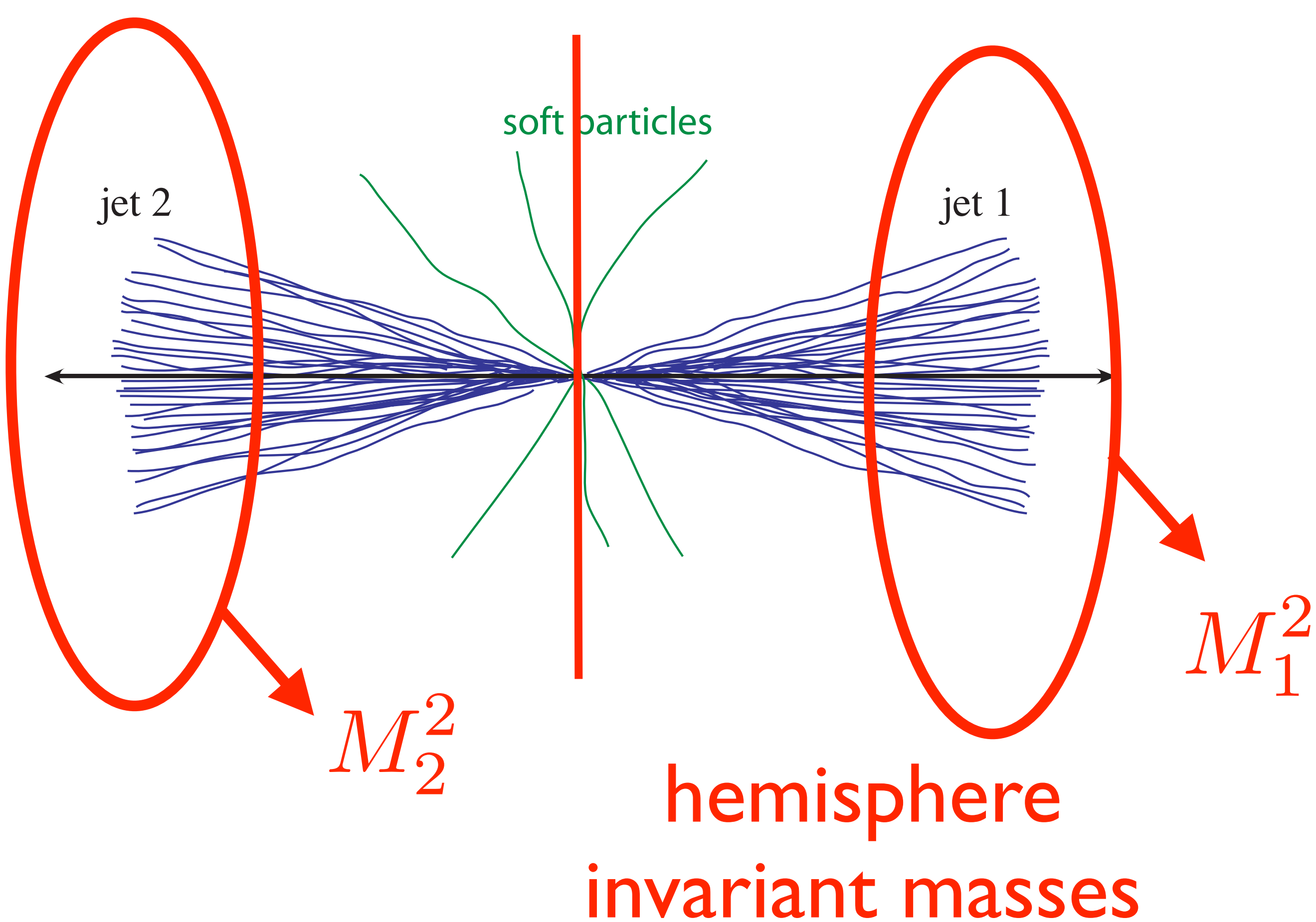
Integrals can DIVERGE as $q \longrightarrow 0$



$$= \int d^4q \frac{Numerator}{(q^2)(q+p)^2(q-\bar{p})^2} \sim \int \frac{d^4q}{q^4} + \ldots$$



Must be careful about defining observables



$$M_1^2 = \left(\sum_{i \in \text{hemi1}} p_i^\mu \right)^2$$

define $\bar{M}^2 = M_1^2 + M_2^2$

$\bar{M}^2 \ll Q^2$ ensures there are only 2 jets

Taylor Series for 2 Jets

Probability for 2 Jets $\propto \quad \sigma(\Delta) = \int_0^{\Delta^2} d\bar{M}^2 \, \frac{d\sigma}{d\bar{M}^2}$

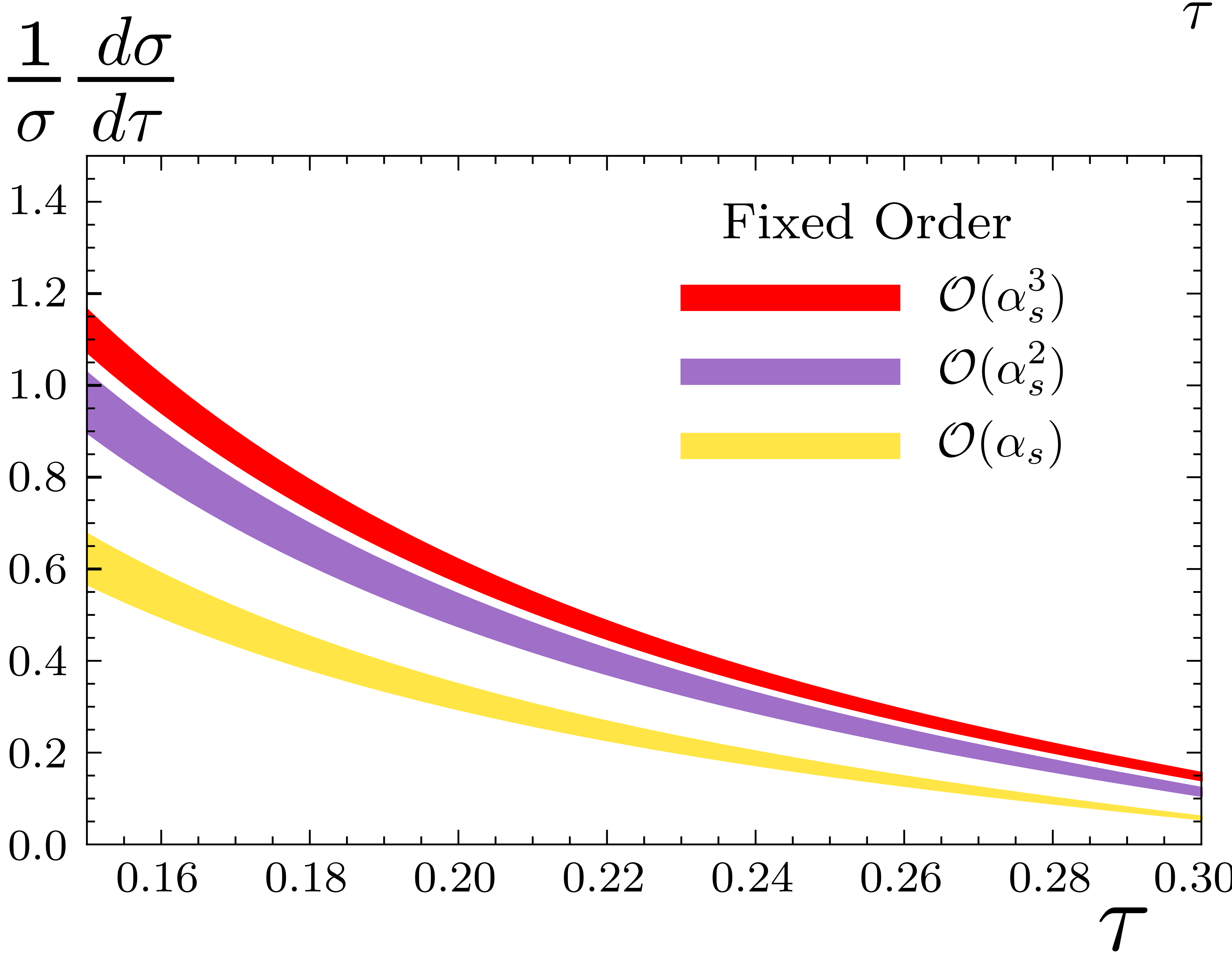
$$\begin{array}{lllll}
 & \mathcal{O}(\alpha_s) & \mathcal{O}(\alpha_s^2) & \mathcal{O}(\alpha_s^3) & \\
\sigma(\Delta) = 1 & + \alpha_s L^2 & + \alpha_s^2 L^4 & + \alpha_s^3 L^6 & + \ldots \\
 & + \alpha_s L & + \alpha_s^2 L^3 & + \alpha_s^3 L^5 & + \ldots \\
 & + \alpha_s & + \alpha_s^2 L^2 & + \alpha_s^3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

$$L = \ln\left(\frac{\Delta^2}{Q^2}\right)$$

"double logs"

Fixed Order Theory Uncertainty

$$\tau \simeq \frac{\bar{M}^2}{Q^2}$$



Gehrmann, Gehrmann-De Ridder, Glover, Heinrich; Weinzierl

Large Logs $\alpha_s \ll 1$ but $\alpha_s L^2 \sim 1$

solved by log summation

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

$$L = \ln\left(\frac{\Delta^2}{Q^2}\right)$$

Large Logs $\alpha_s \ll 1$ but $\alpha_s L^2 \sim 1$

solved by log summation

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

$$L = \ln\left(\frac{\Delta^2}{Q^2}\right)$$

Large Logs $\alpha_s \ll 1$ but $\alpha_s L^2 \sim 1$

solved by log summation

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

$$L = \ln\left(\frac{\Delta^2}{Q^2}\right)$$

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

solved by log summation

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

LL

NLL

NLL$'$

NNLL

$$L = \ln\left(\frac{\Delta^2}{Q^2}\right)$$

Large Logs $\alpha_s \ll 1$ but $\alpha_s L^2 \sim 1$

solved by log summation

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

$$L = \ln\left(\frac{\Delta^2}{Q^2}\right)$$

Large Logs $\alpha_s \ll 1$ but $\alpha_s L^2 \sim 1$

solved by log summation

$$
\begin{array}{llllll}
\sigma(\Delta) = 1 & + \alpha_s L^2 & + \alpha_s^2 L^4 & + \alpha_s^3 L^6 & + \ldots & \text{LL} \\
& + \alpha_s L & + \alpha_s^2 L^3 & + \alpha_s^3 L^5 & + \ldots & \text{NLL} \\
& + \alpha_s & + \alpha_s^2 L^2 & + \alpha_s^3 L^4 & + \ldots & \text{NLL}' \\
& & + \alpha_s^2 L & + \alpha_s^3 L^3 & + \ldots & \text{NNLL} \\
& & + \alpha_s^2 & + \alpha_s^3 L^2 & + \ldots & \text{NNLL}' \\
& & & + \alpha_s^3 L & + \ldots & \text{N}^3\text{LL} \\
& & & + \alpha_s^3 & + \ldots & \\
& & & & \ddots &
\end{array}
$$

$$L = \ln\left(\frac{\Delta^2}{Q^2}\right)$$

Large Logs $\alpha_s \ll 1$ but $\alpha_s L^2 \sim 1$

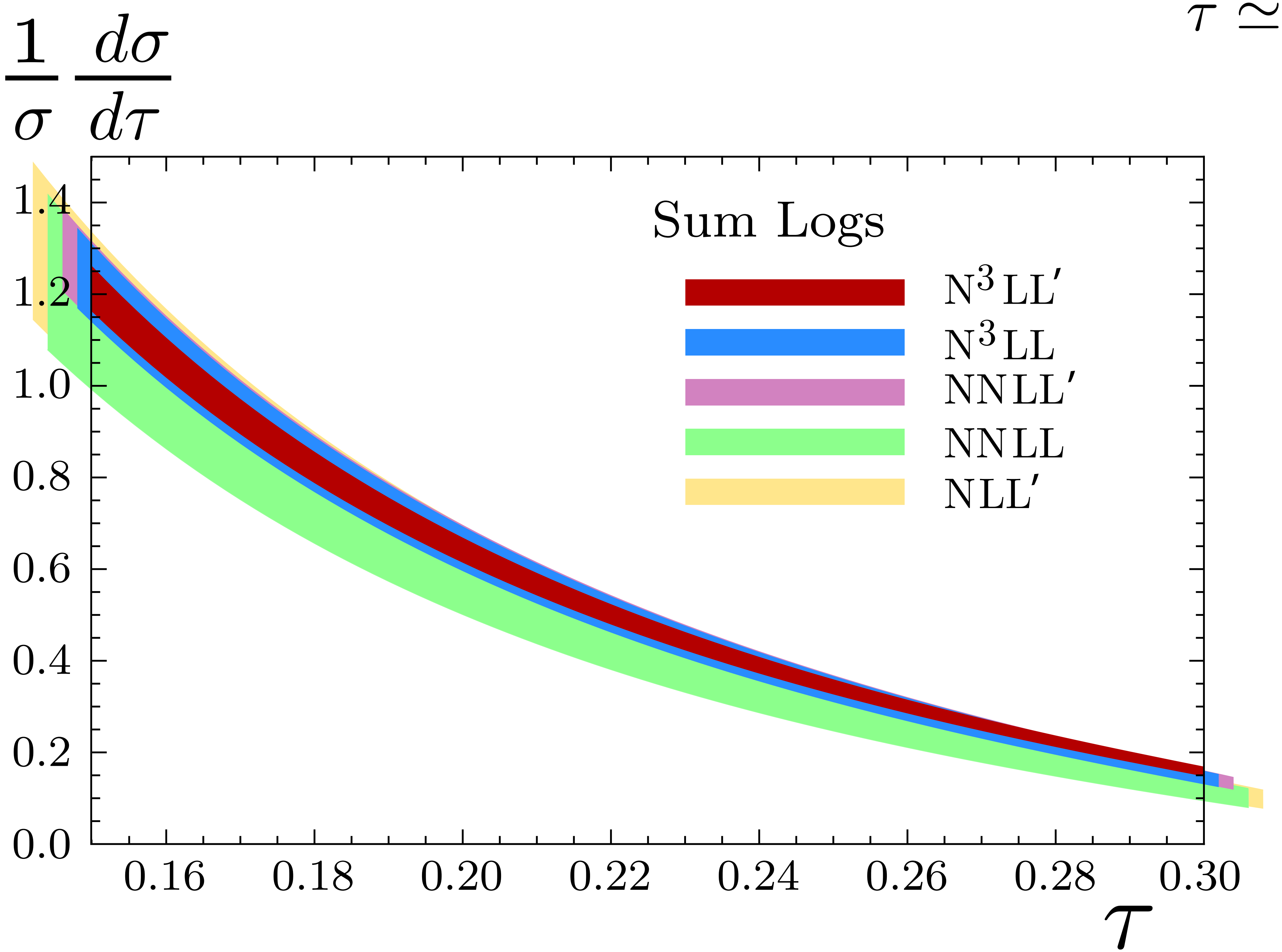
solved by log summation

$$
\begin{array}{lllllll}
\sigma(\Delta) = & 1 & + \alpha_s L^2 & + \alpha_s^2 L^4 & + \alpha_s^3 L^6 & + \ldots & \text{LL} \\
 & & + \alpha_s L & + \alpha_s^2 L^3 & + \alpha_s^3 L^5 & + \ldots & \text{NLL} \\
 & & + \alpha_s & + \alpha_s^2 L^2 & + \alpha_s^3 L^4 & + \ldots & \text{NLL}' \\
 & & & + \alpha_s^2 L & + \alpha_s^3 L^3 & + \ldots & \text{NNLL} \\
 & & & + \alpha_s^2 & + \alpha_s^3 L^2 & + \ldots & \text{NNLL}' \\
 & & & & + \alpha_s^3 L & + \ldots & \text{N}^3\text{LL} \\
 & & & & + \alpha_s^3 & + \ldots & \text{N}^3\text{LL}' \\
 & & & & & \ddots &
\end{array}
$$

$$L = \ln\left(\frac{\Delta^2}{Q^2}\right)$$

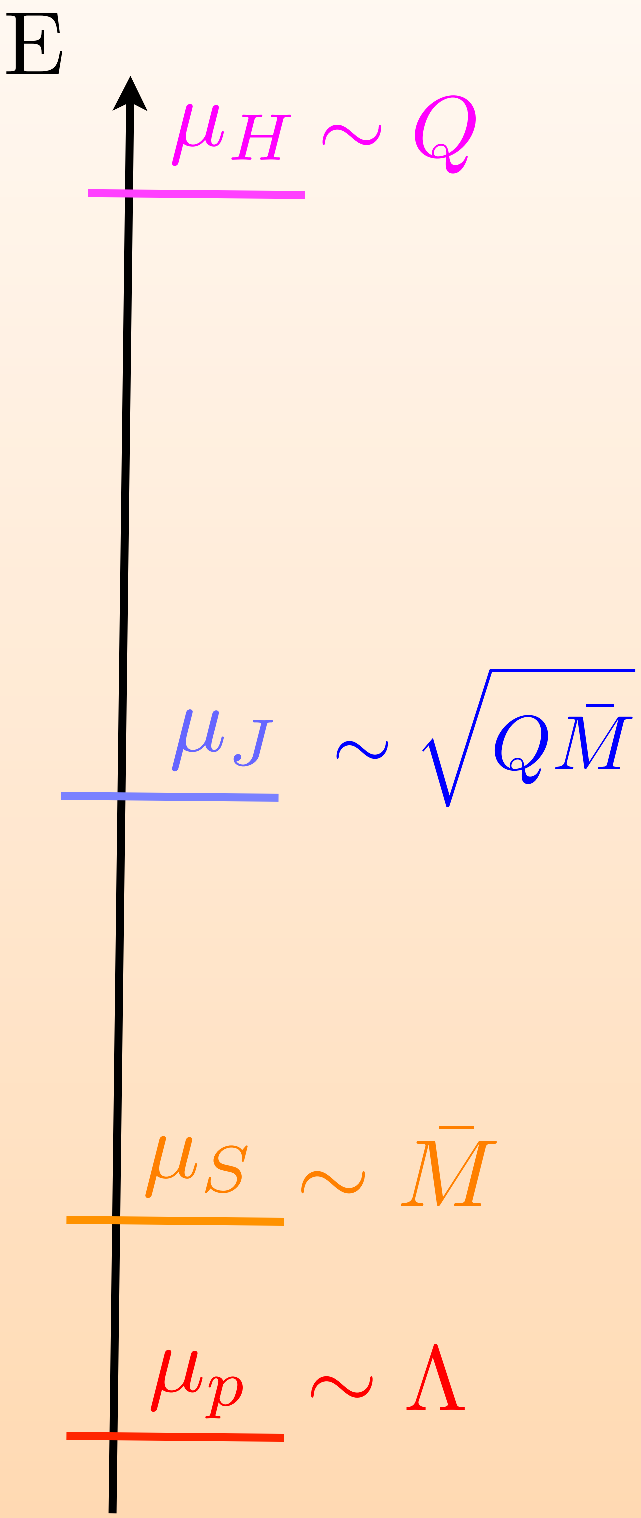
Theory Uncertainty with Log Summation

$$\tau \simeq \frac{\bar{M}^2}{Q^2}$$



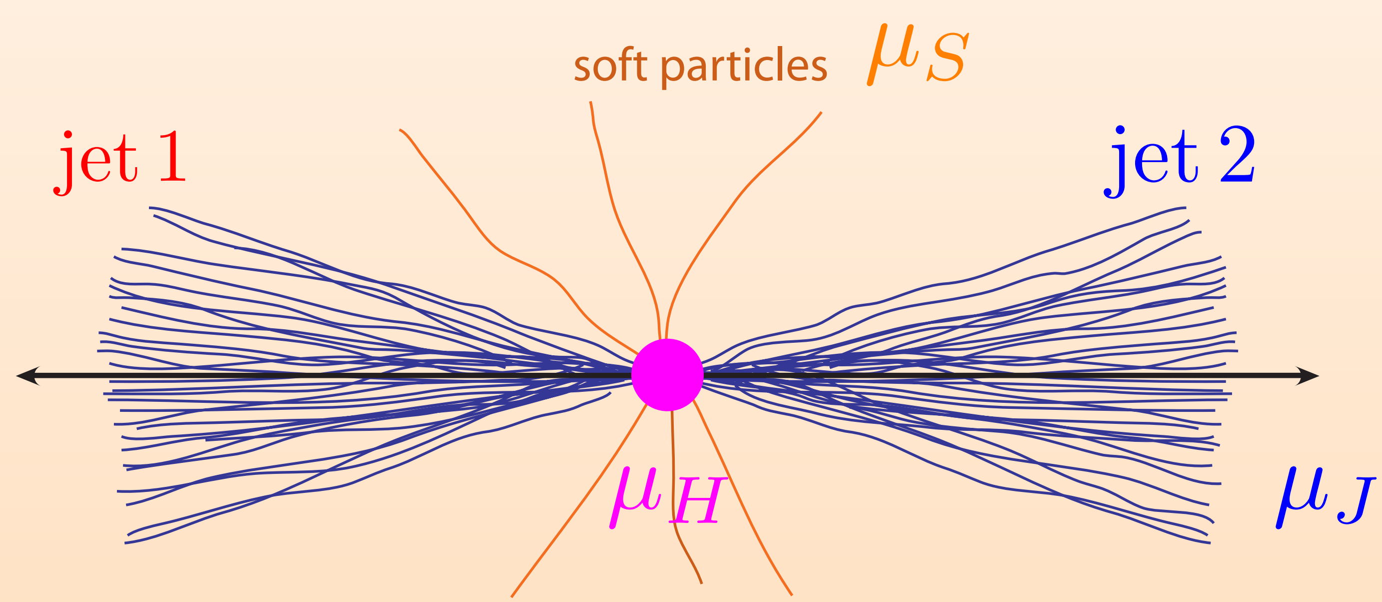
Becher, Schwartz; Abbate, Fickinger, Hoang, Mateu, I.S.

How?



$$\ln^2\left(\frac{\bar{M}}{Q}\right) = 2\ln^2\left(\frac{\mu}{Q}\right) - \ln^2\left(\frac{\mu^2}{Q\bar{M}}\right) + 2\ln^2\left(\frac{\mu}{\bar{M}}\right)$$

$$\left[1 + \alpha_s \ln^2(\bar{M}/Q) + \ldots\right] = \left[1 + 2\alpha_s \ln^2(\mu/Q) + \ldots\right] \times \left[1 - \alpha_s \ln^2(\mu^2/Q\bar{M}) + \ldots\right] \times \left[1 + 2\alpha_s \ln^2(\mu/\bar{M}) + \ldots\right]$$

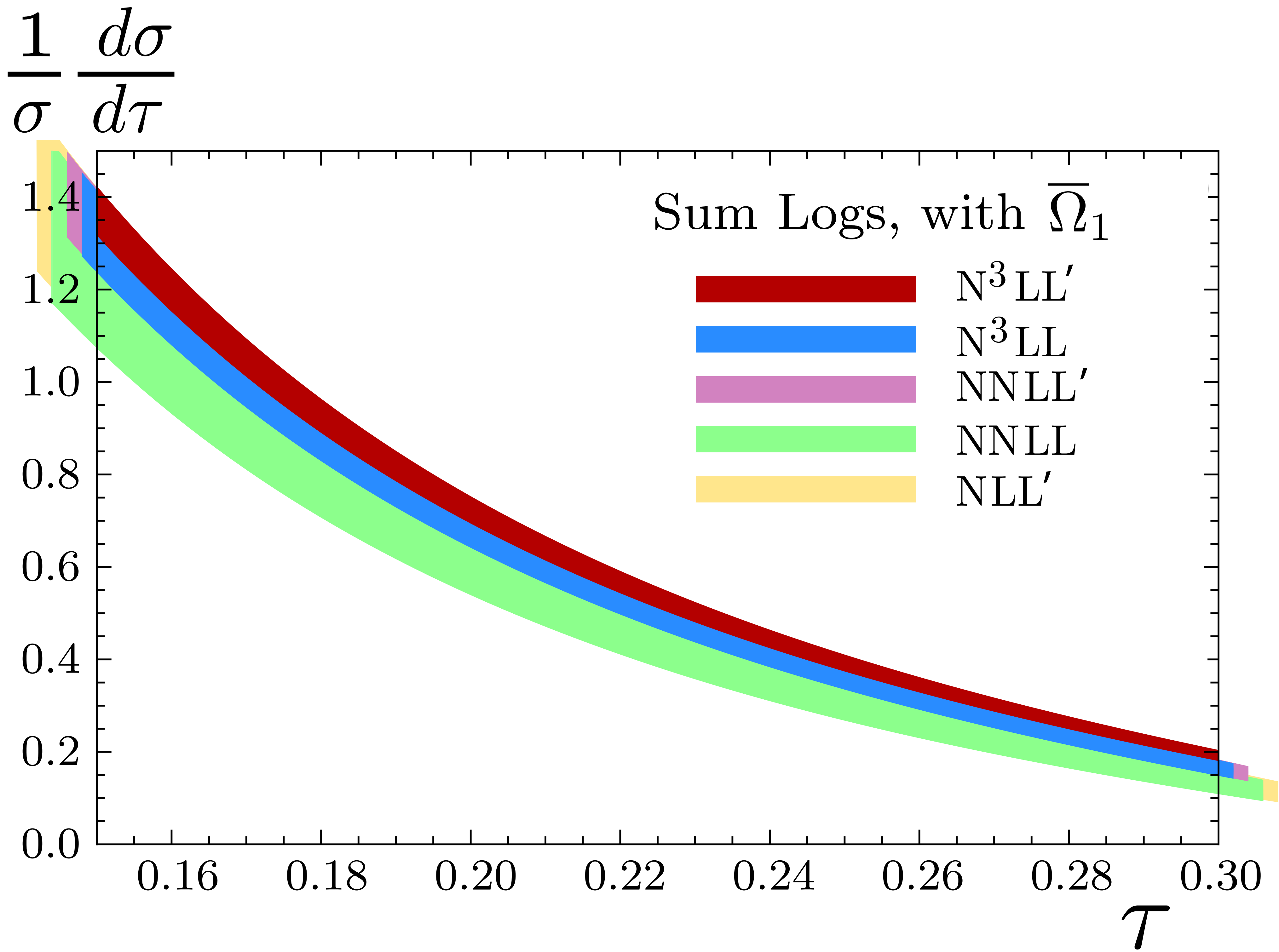


all orders: $\sigma = HJ \otimes S \otimes F$ **"Factorization"**

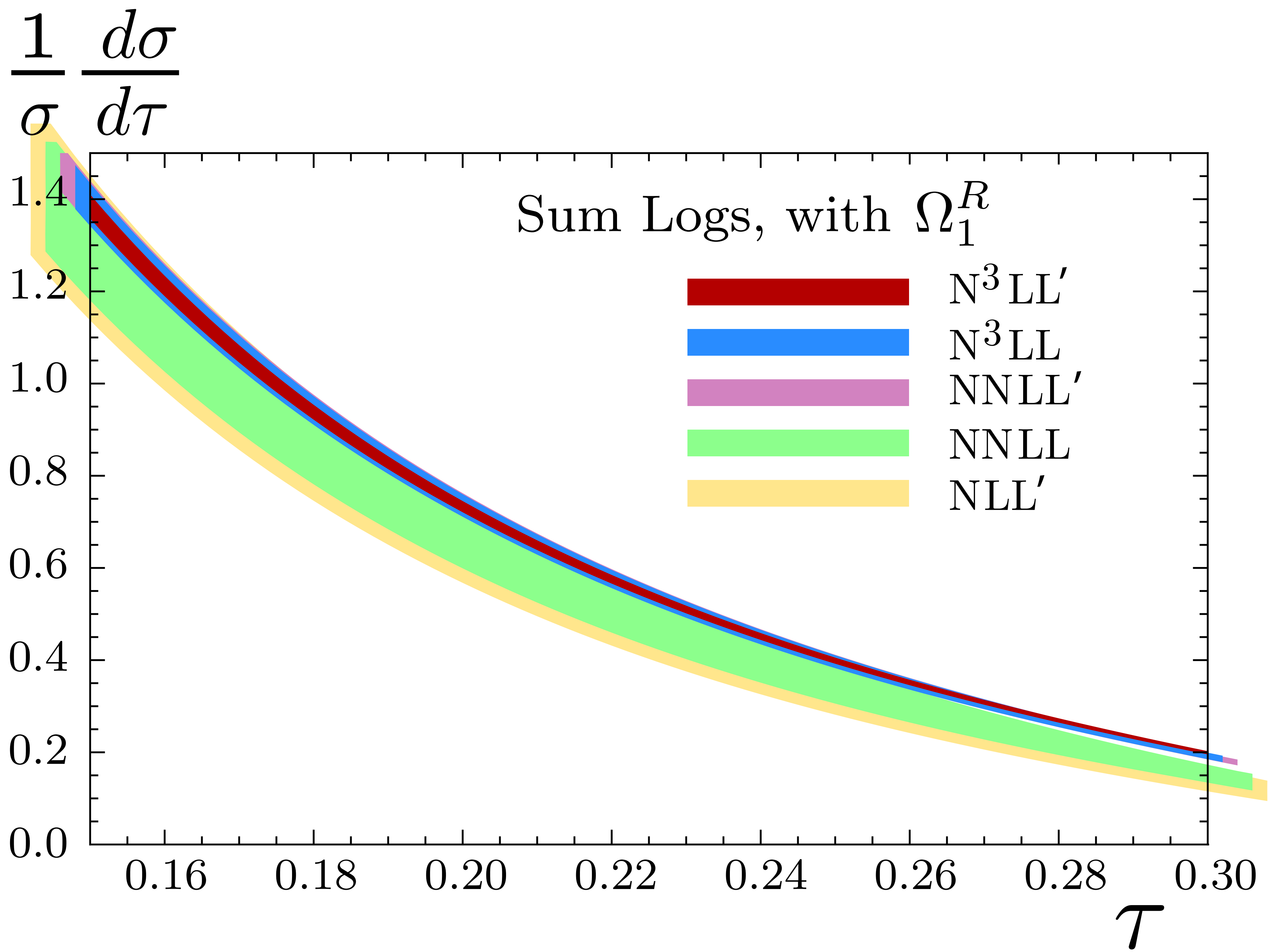
F induces series : $\tau - \frac{\Lambda}{Q}\left[\alpha_s \ln(\mu/\Lambda) + \alpha_s^2 \ln^2(\mu/\Lambda) \ldots\right]$

$= \tau - \frac{2\Omega_1}{Q}$ $\alpha_s(\Lambda) \sim 1$

Theory Uncertainty & Hadronic effects



Theory Uncertainty & Hadronic effects

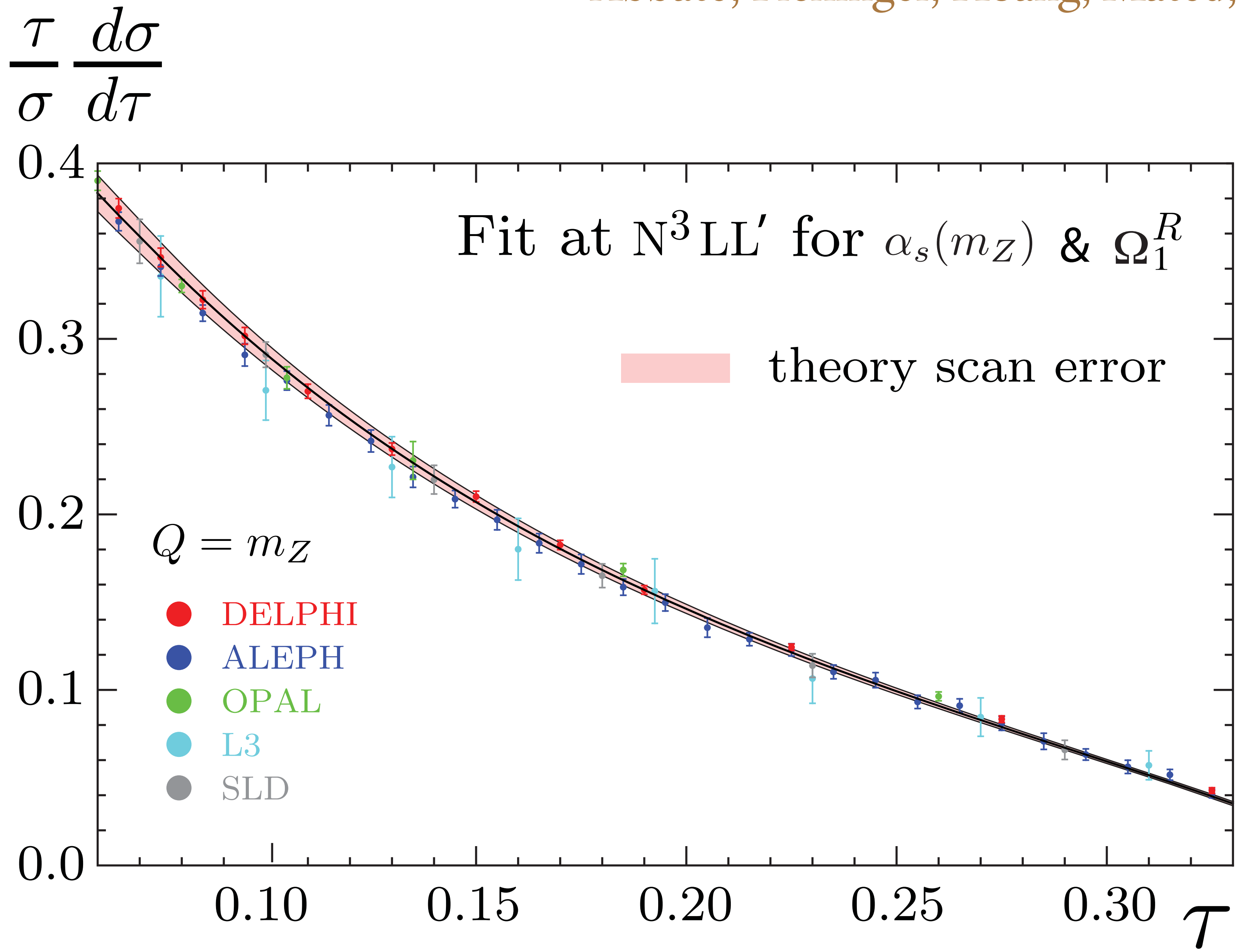


Abbate, Fickinger, Hoang, Mateu, I.S.

A Tail Fit

two parameter fit:

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

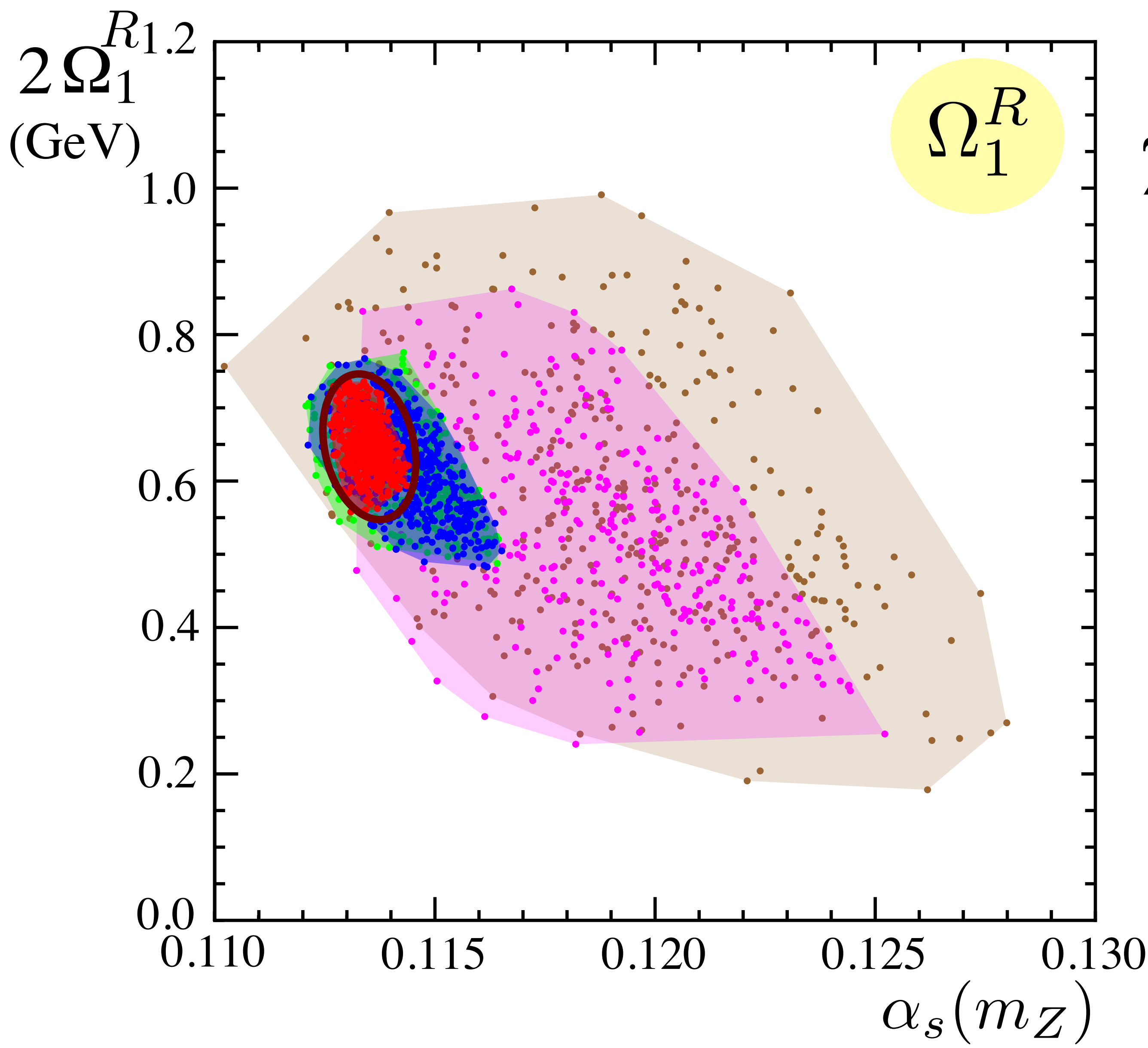


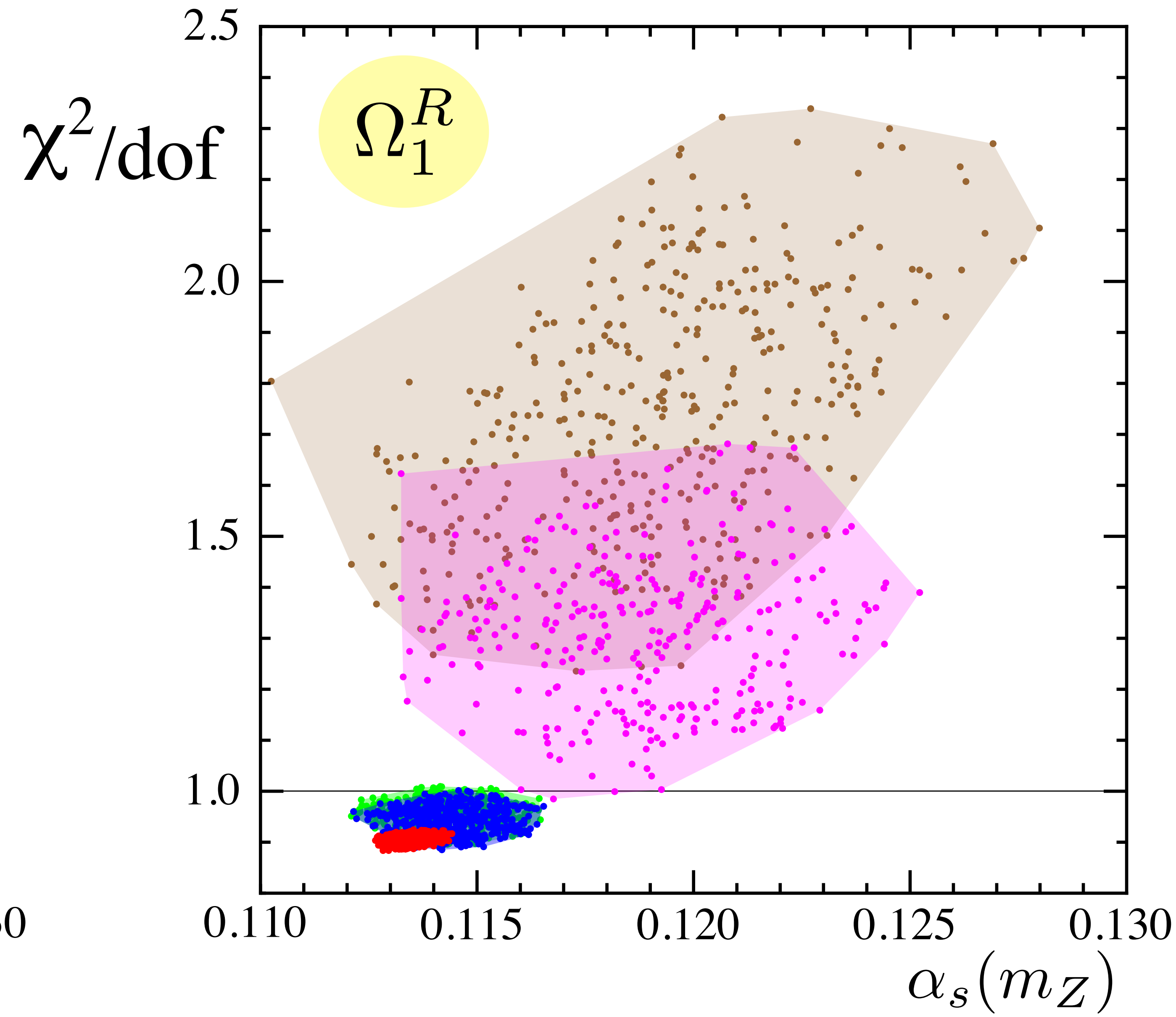
Fit Uncertainties: statistical errors + systematic errors + hadronization ($2\Omega_1^R$)

Higher Order Theory Uncertainties: scan over theory parameters (vary μ's)

Theory Scan Results

NLL′, NNLL, NNLL′, N^3LL, N^3LL'



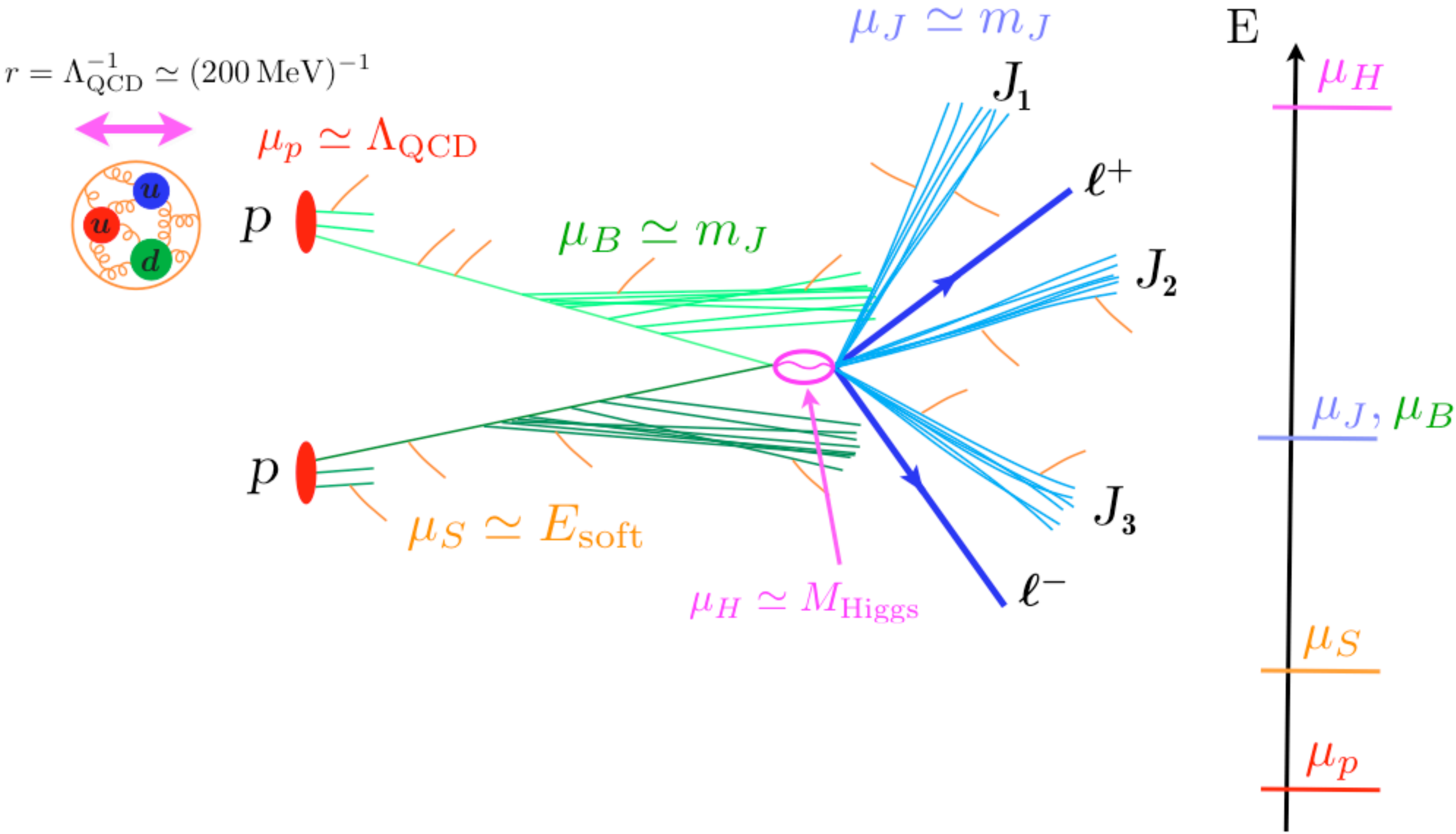


$$\alpha_s(m_Z) = 0.1135 \pm (0.0002)_{\rm expt} \pm (0.0005)_{\rm hadr} \pm (0.0009)_{\rm pert}$$

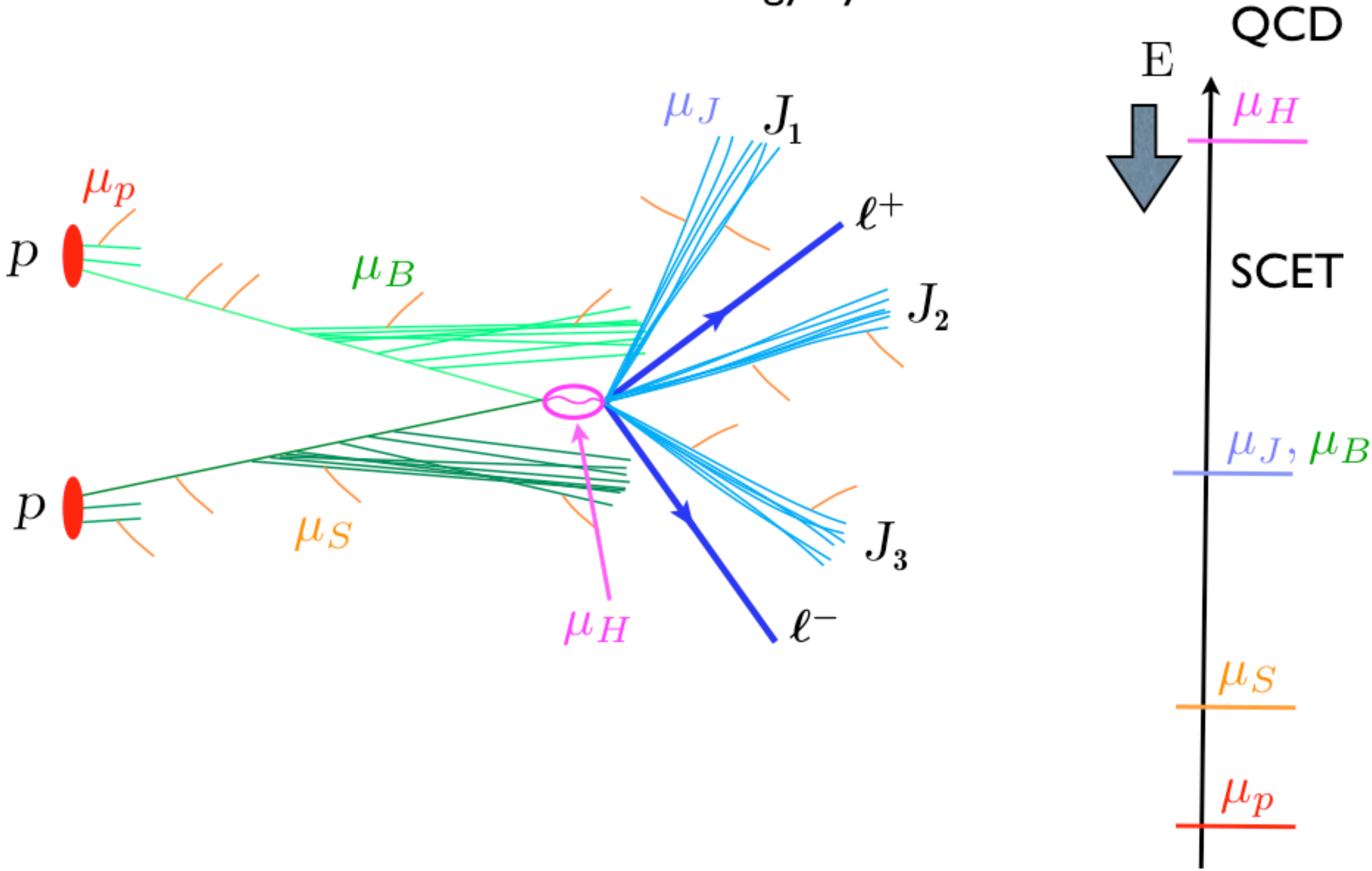
$$\Omega_1 = 0.324 \pm (0.009)_{\rm expt} \pm (0.013)_{\Omega_2} \pm (0.030)_{\alpha_s(m_Z)} \pm (0.045)_{\rm pert}\ {\rm GeV}$$

Back to the LHC

Key Simplifying Principle is to Exploit the Hierarchy of Energy Scales μ_i

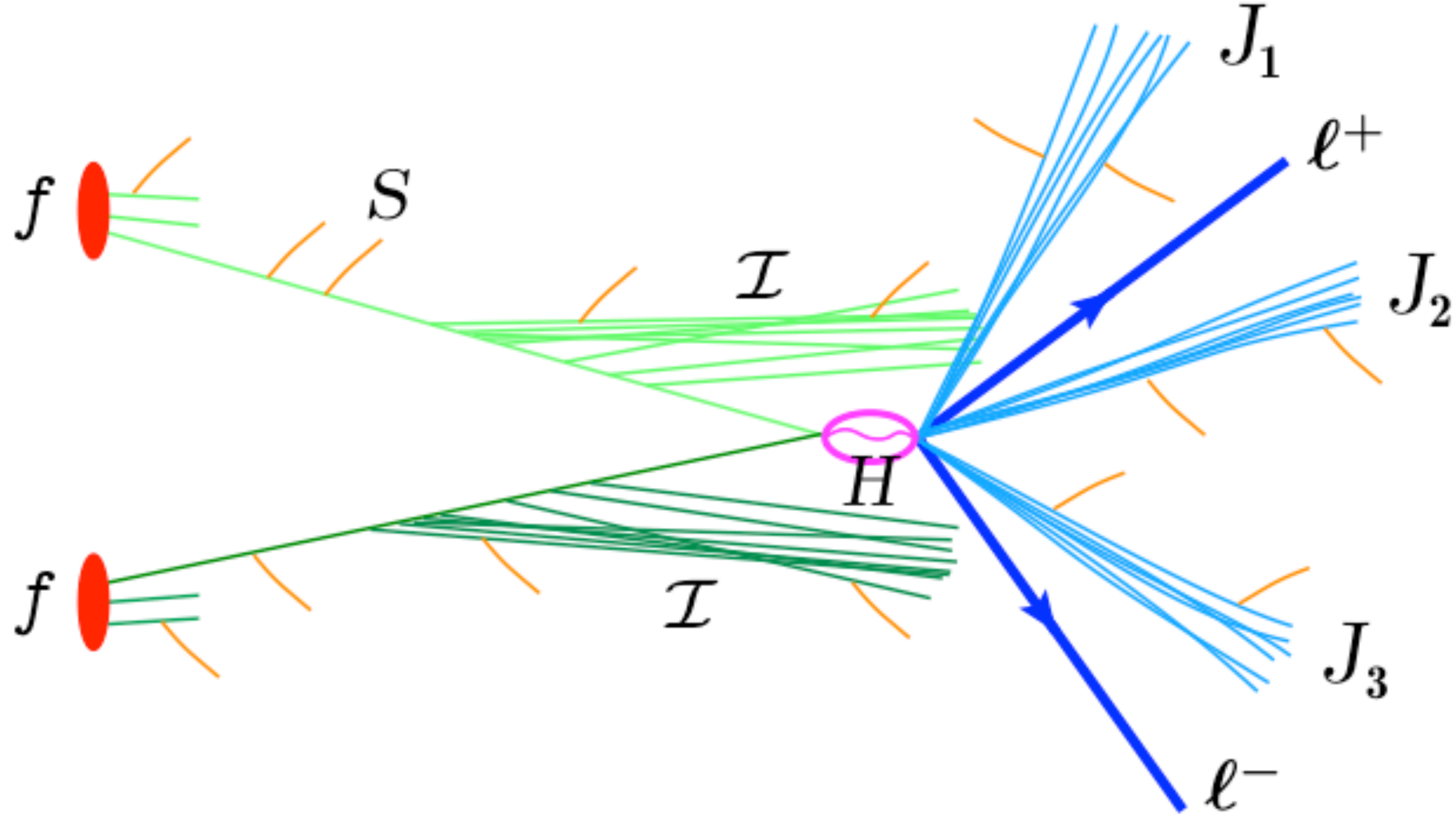


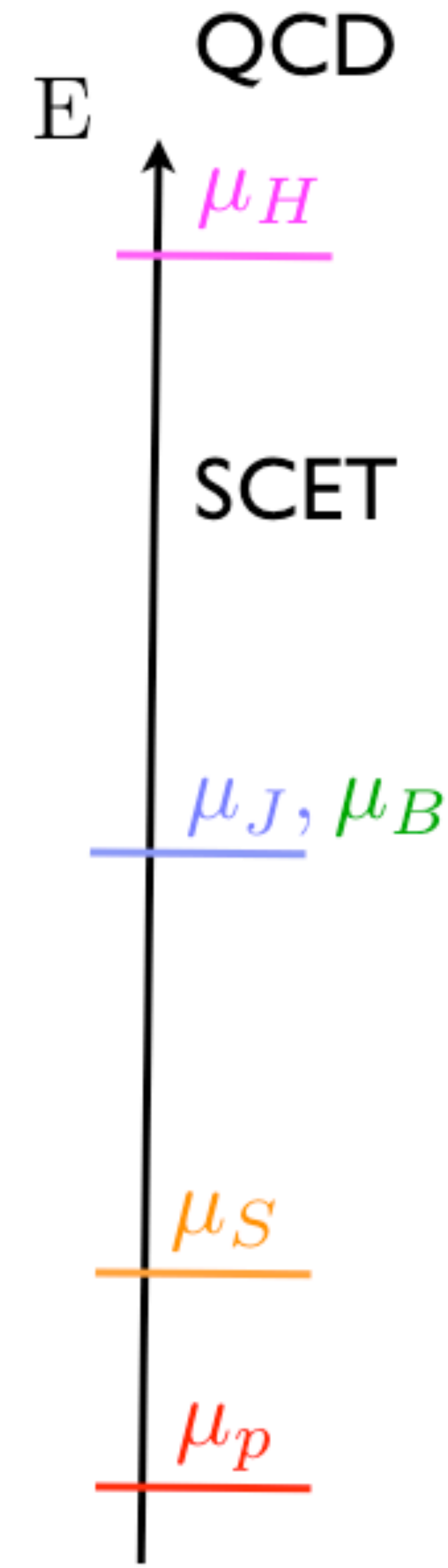
We essentially treat one scale at a time, constructing simpler effective field theories for the lower energy dynamics



SCET = Soft-Collinear Effective Theory

"Factorization"



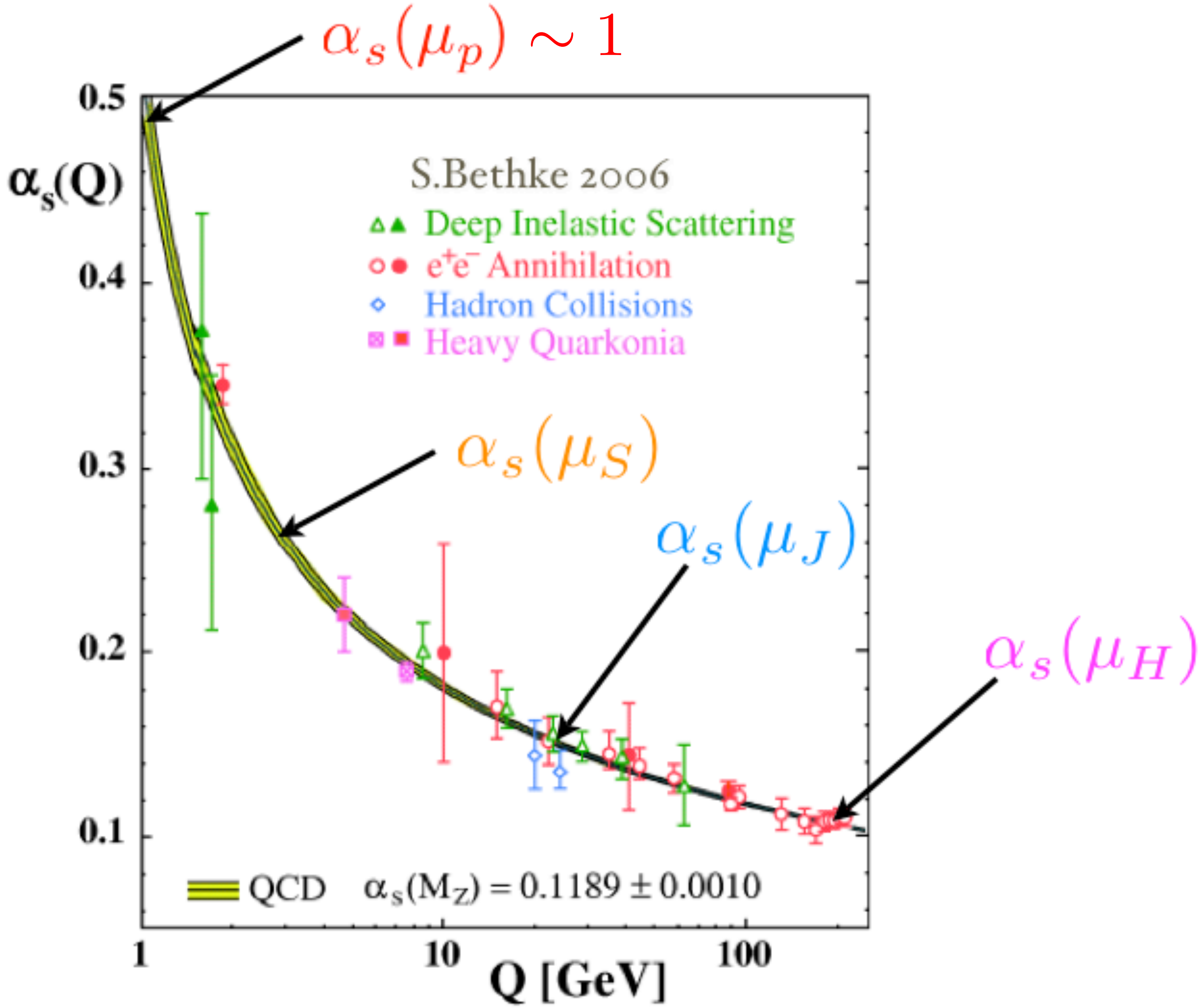


Final Results are

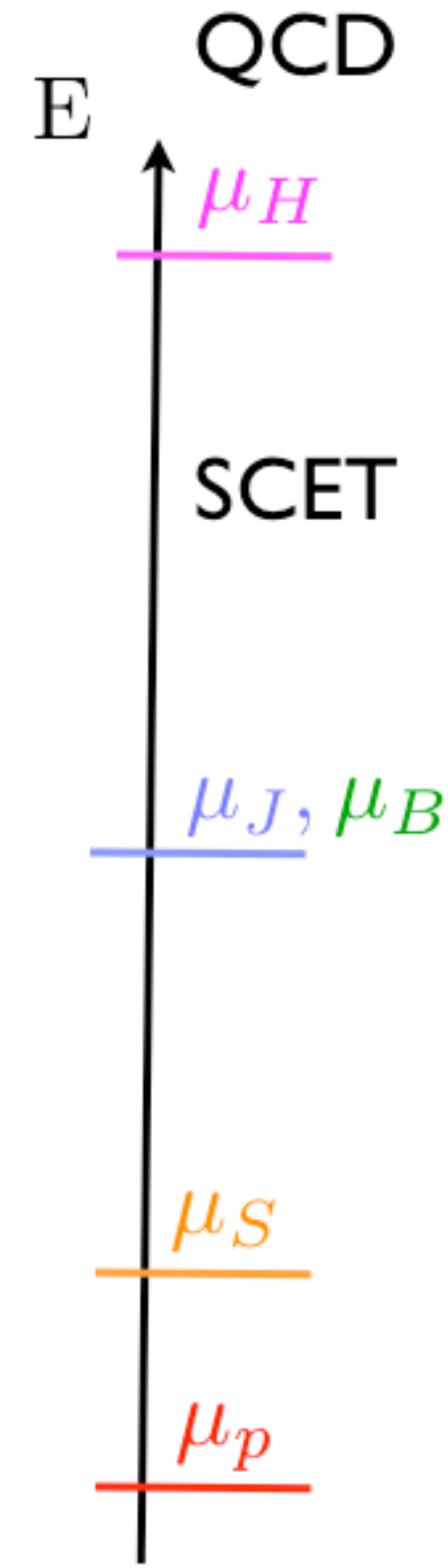
Factorization formulas for individual cross sections:

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

$$\Lambda_{QCD} \quad \mu_B \quad \mu_H \quad \mu_J \quad \mu_S$$

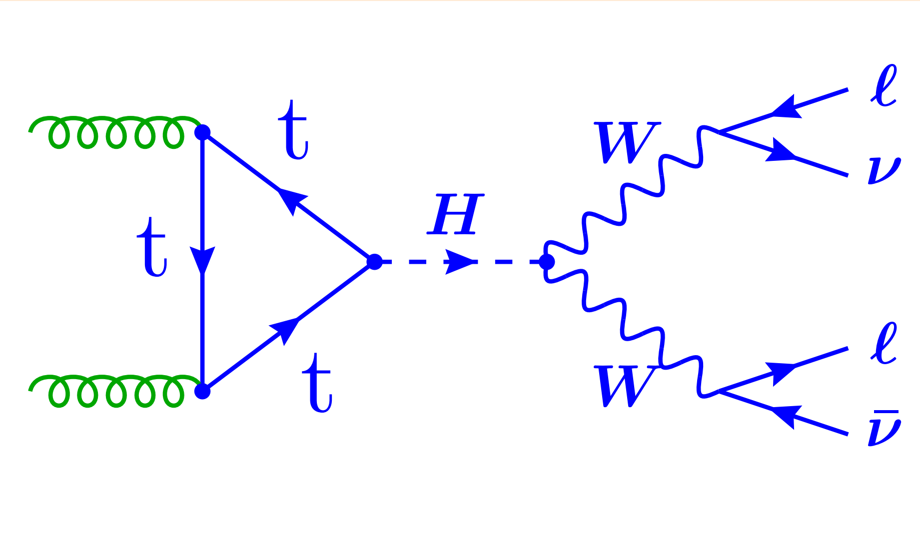


Our treatment ensures we can use appropriate values for the strong coupling.



Application: Higgs Production

$$pp \rightarrow H \rightarrow WW \rightarrow \ell\nu\ell\bar{\nu}$$



Taylor Series

$$pp \to (H \to WW) + \text{(all possible jets)}$$

$$\sigma_{\text{total}} \simeq \sigma_B \left[1 + \alpha_s + \alpha_s^2 + \mathcal{O}(\alpha_s^3)\right]$$

$$= (3.32\,\text{pb})\left[1 + 9.5\,\alpha_s + 35\,\alpha_s^2 + \mathcal{O}(\alpha_s^3)\right]$$

$$\mu = m_H/2$$

$$m_H = 165\,\text{GeV}$$

$$\alpha_s(\mu) \simeq 0.1$$

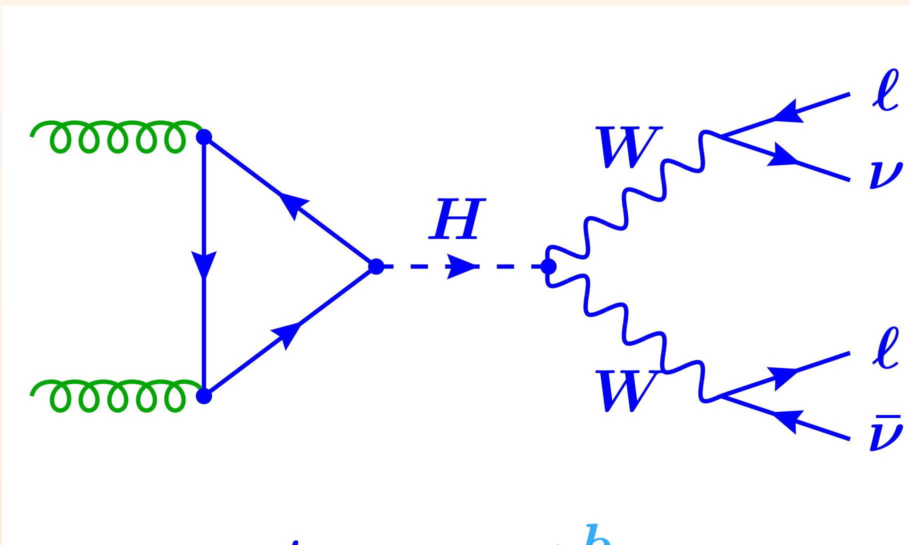
large coefficients

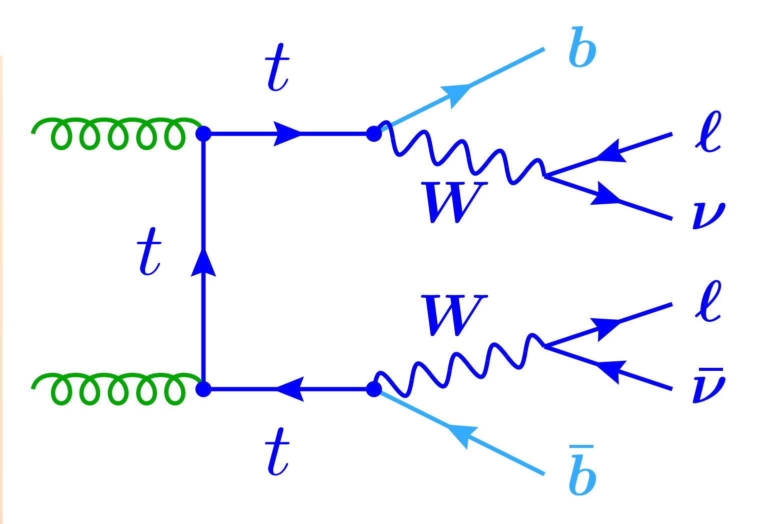
[Harlander, Kilgore; Anastasiou, Melnikov; Ravindran, Smith, van Neerven]
[Pak, Rogal, Steinhauser; Harlander, Mantler, Marzani, Ozeren]

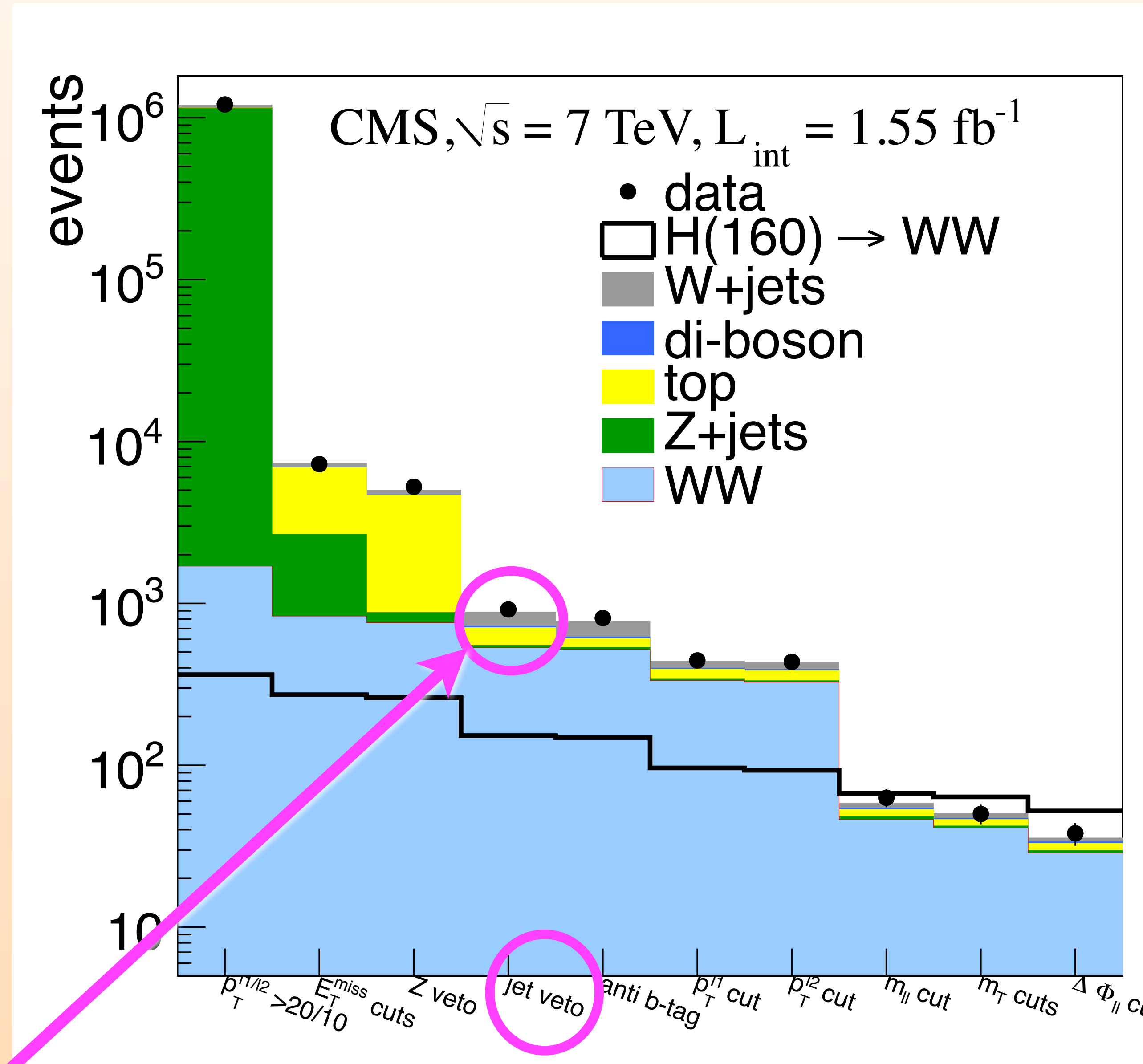
Taylor Series

$pp \to (H \to WW) + \text{(0 jets)}$ Why?

large top background





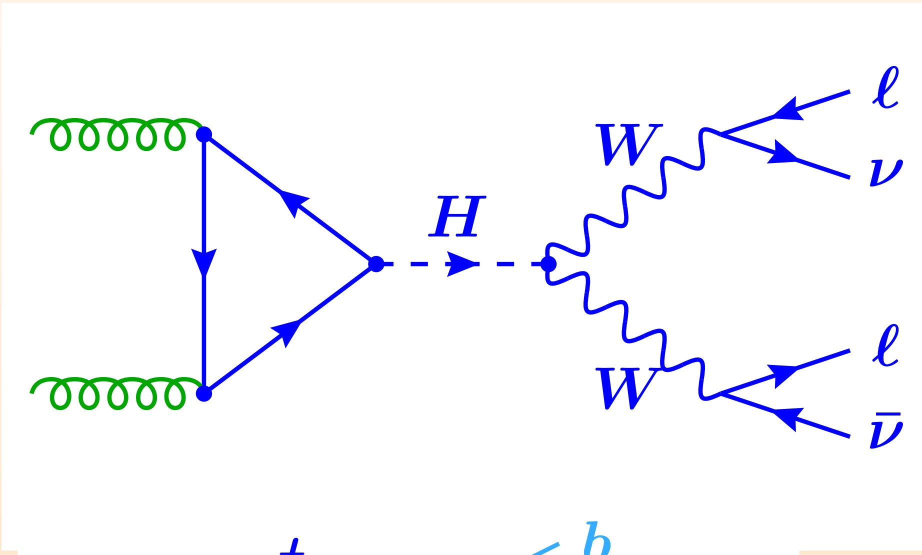


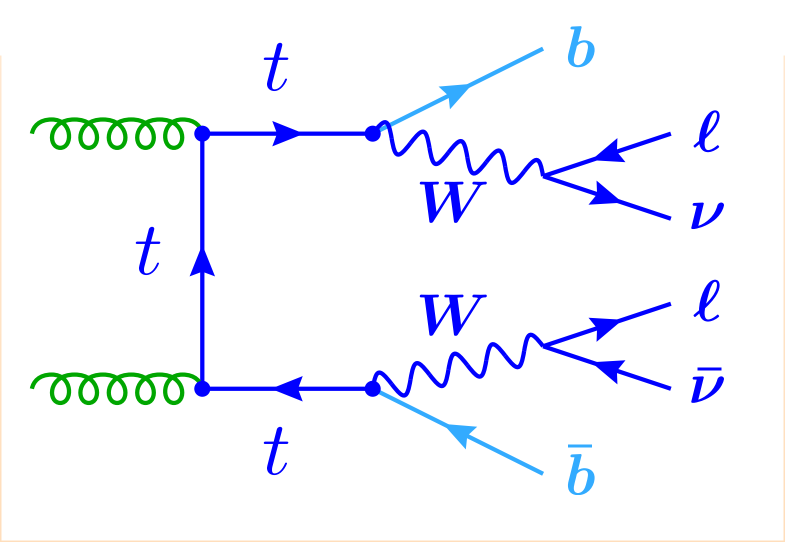
0-jet bin
vetoes
tops

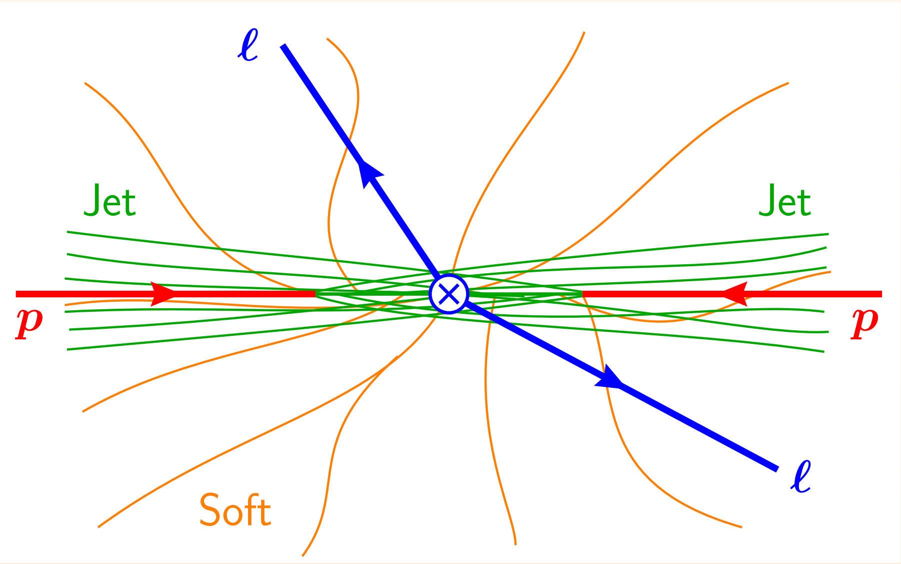
Taylor Series

$pp \to (H \to WW) + (0 \text{ jets})$ Why?

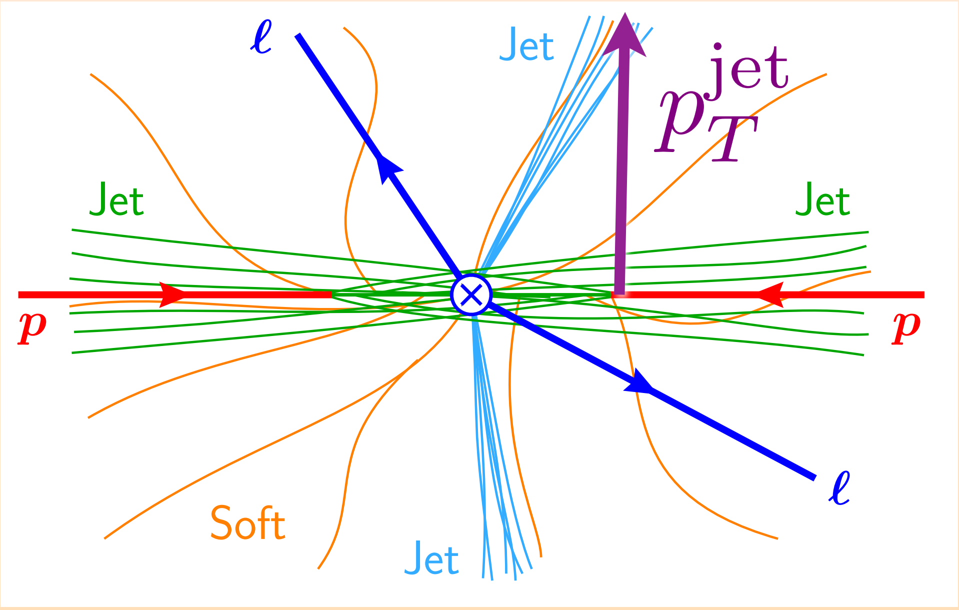
large top background







0-jets

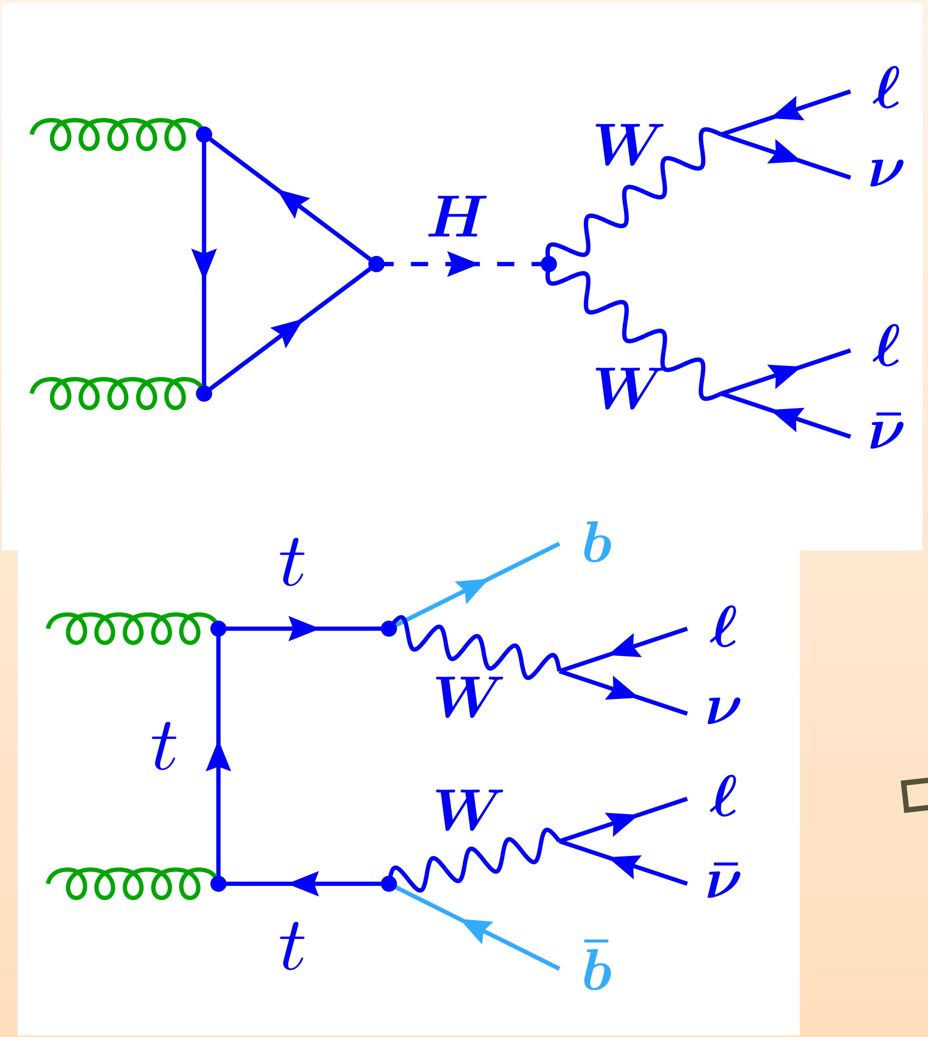


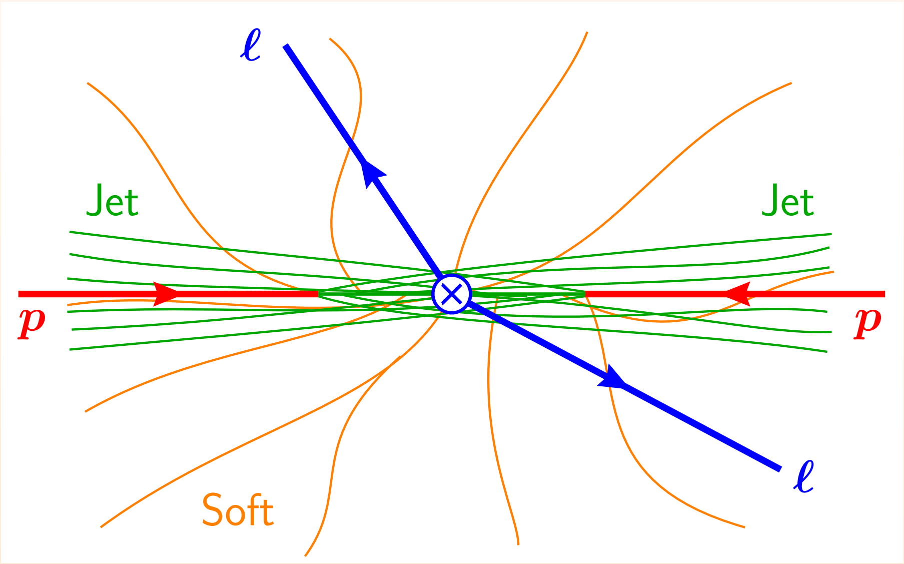
2-jets

Taylor Series

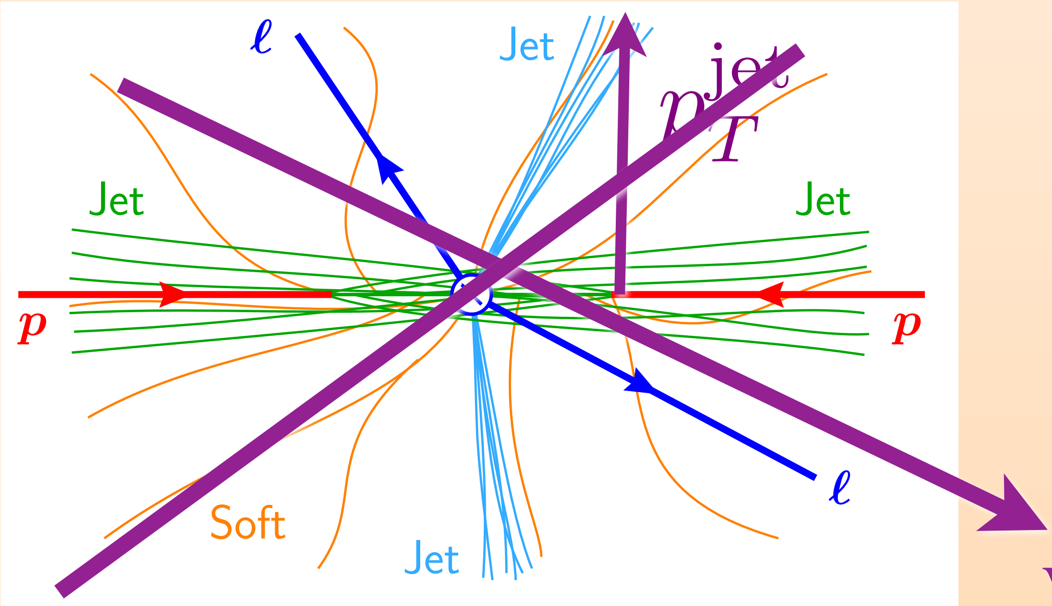
$pp \to (H \to WW) + (0 \text{ jets})$ Why?

large top background





0-jets



veto

$p_T^{\text{jet}} < p_T^{\text{cut}}$

Taylor Series

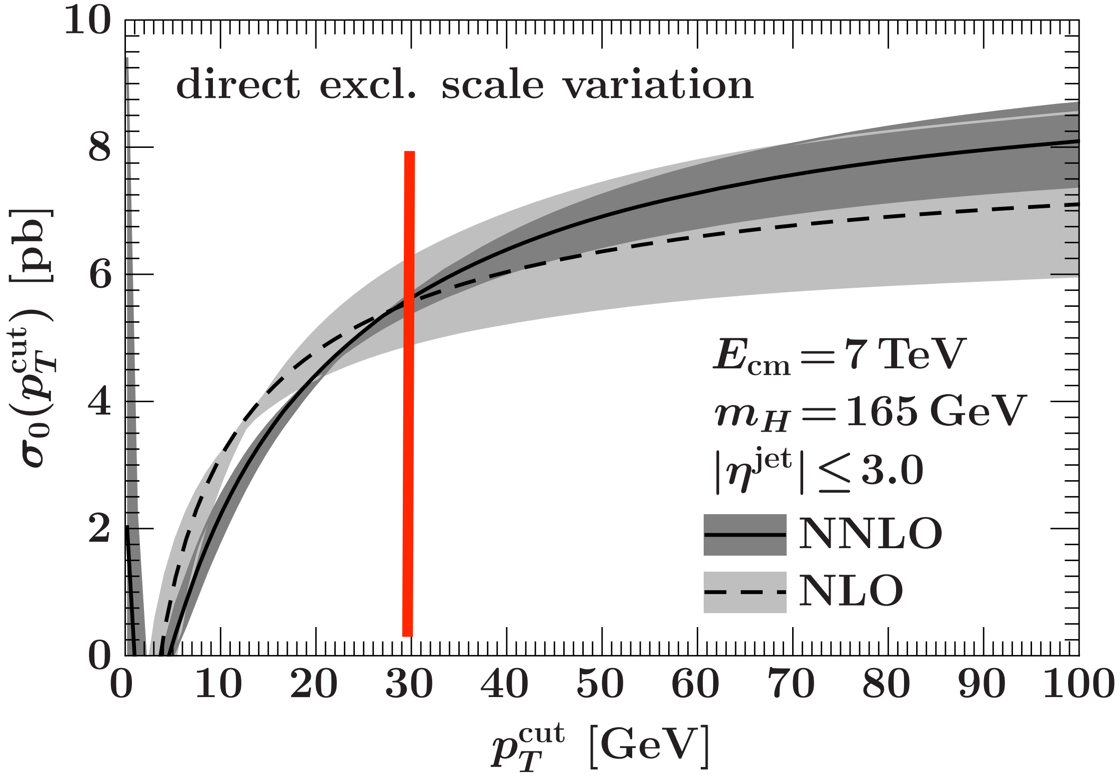
$$L = \ln\left(\frac{p_T^{\rm cut}}{m_H}\right)$$

NNLO

	LO	NLO	NNLO	N^{3}LO		
$\sigma_0(p_T^{\rm cut}) =$	1	$+\,\alpha_s L^2$	$+\,\alpha_s^2 L^4$	$+\,\alpha_s^3 L^6$	$+\dots$	LL
		$+\,\alpha_s L$	$+\,\alpha_s^2 L^3$	$+\,\alpha_s^3 L^5$	$+\dots$	NLL
		$+\,\alpha_s$	$+\,\alpha_s^2 L^2$	$+\,\alpha_s^3 L^4$	$+\dots$	
			$+\,\alpha_s^2 L$	$+\,\alpha_s^3 L^3$	$+\dots$	NNLL
			$+\,\alpha_s^2$	$+\,\alpha_s^3 L^2$	$+\dots$	N^{3}LL
				$+\,\alpha_s^3 L$	$+\dots$	
				$+\,\alpha_s^3$	$+\dots$	

[Anastasiou, Melnikov, Petriello; Grazzini]

method A



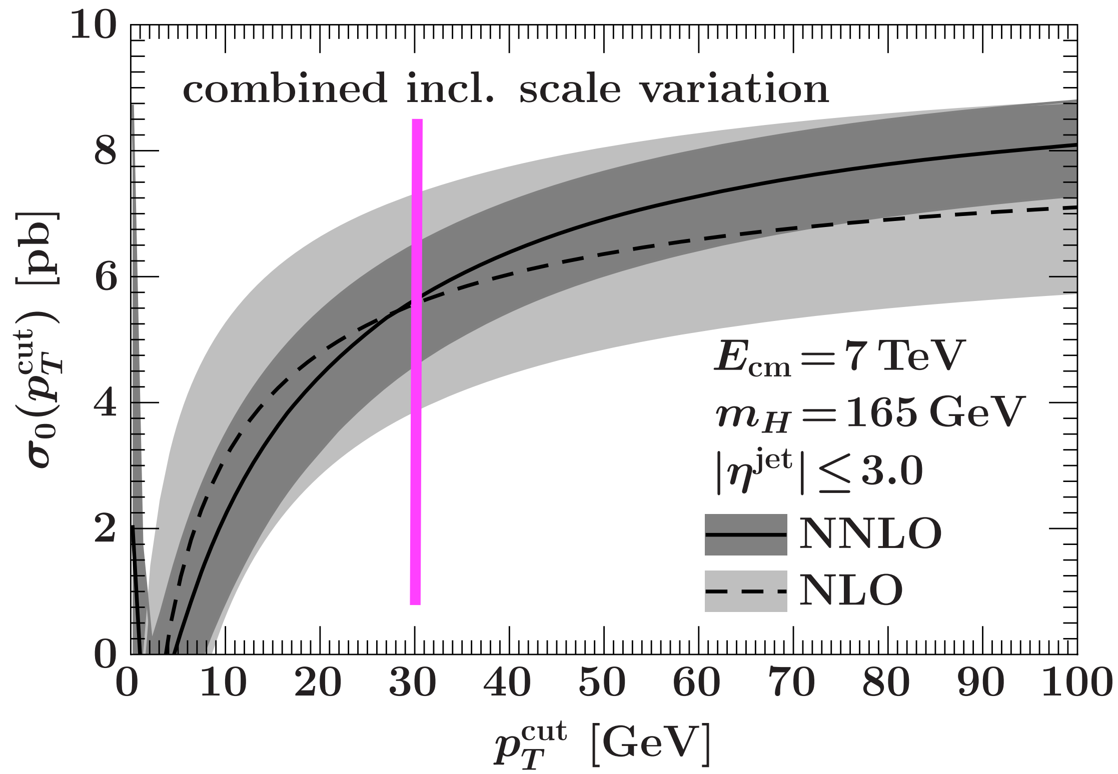
uncertainty from μ variation

gets smaller?

large cancellation at relevant cuts

method B

$$\sigma_0 = \sigma_{\text{total}} - \sigma_{\geq 1}$$



realistic uncertainty
IF
we avoid this cancellation

$$\Delta_0 = (\Delta_{\text{total}}^2 + \Delta_{\geq 1}^2)^{1/2}$$

This Method B is one small ingredient in the LHC Higgs search

[Tackmann, I.S.]

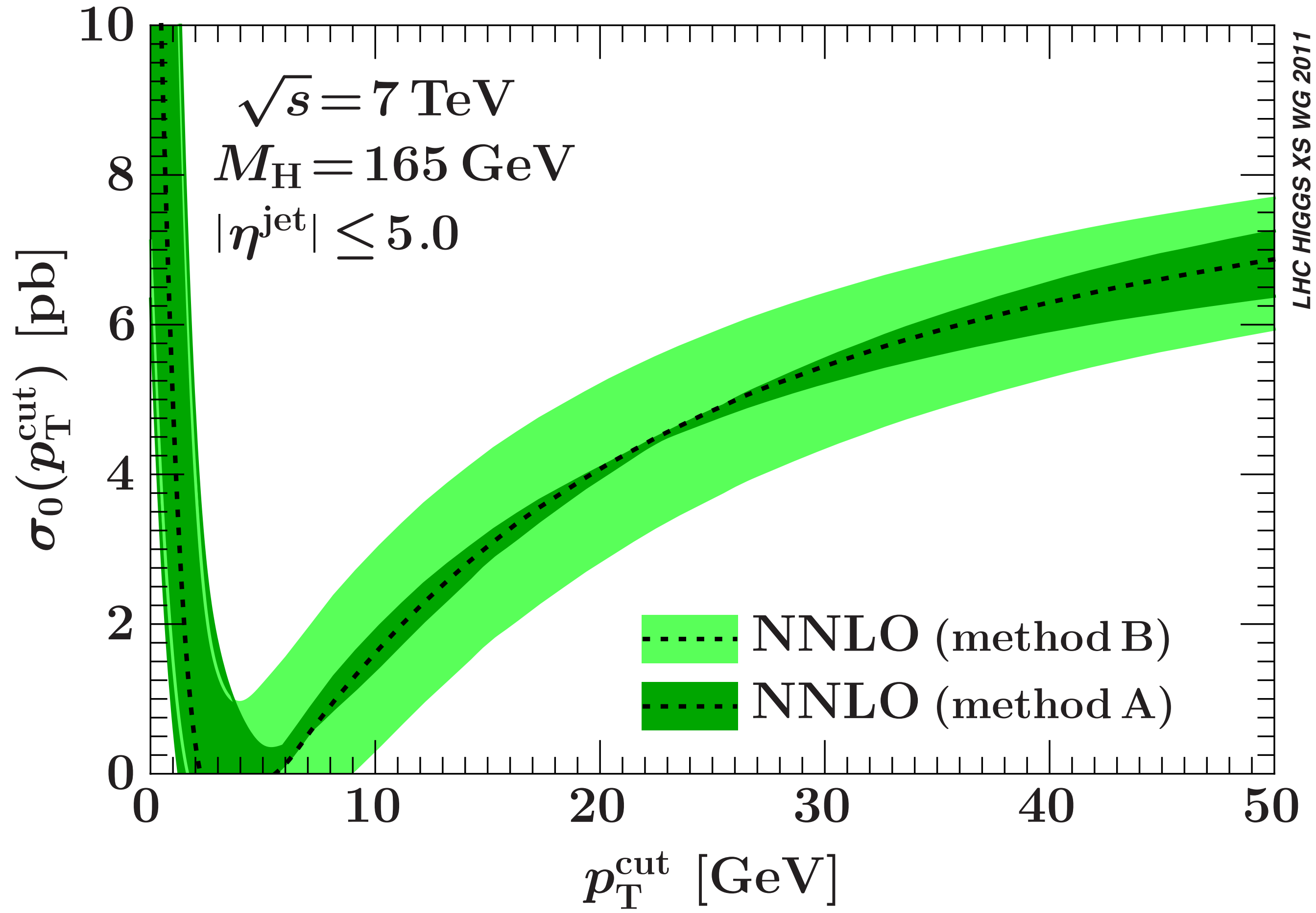
Can we theorists do better?

Sum Large Logs with "Factorization"

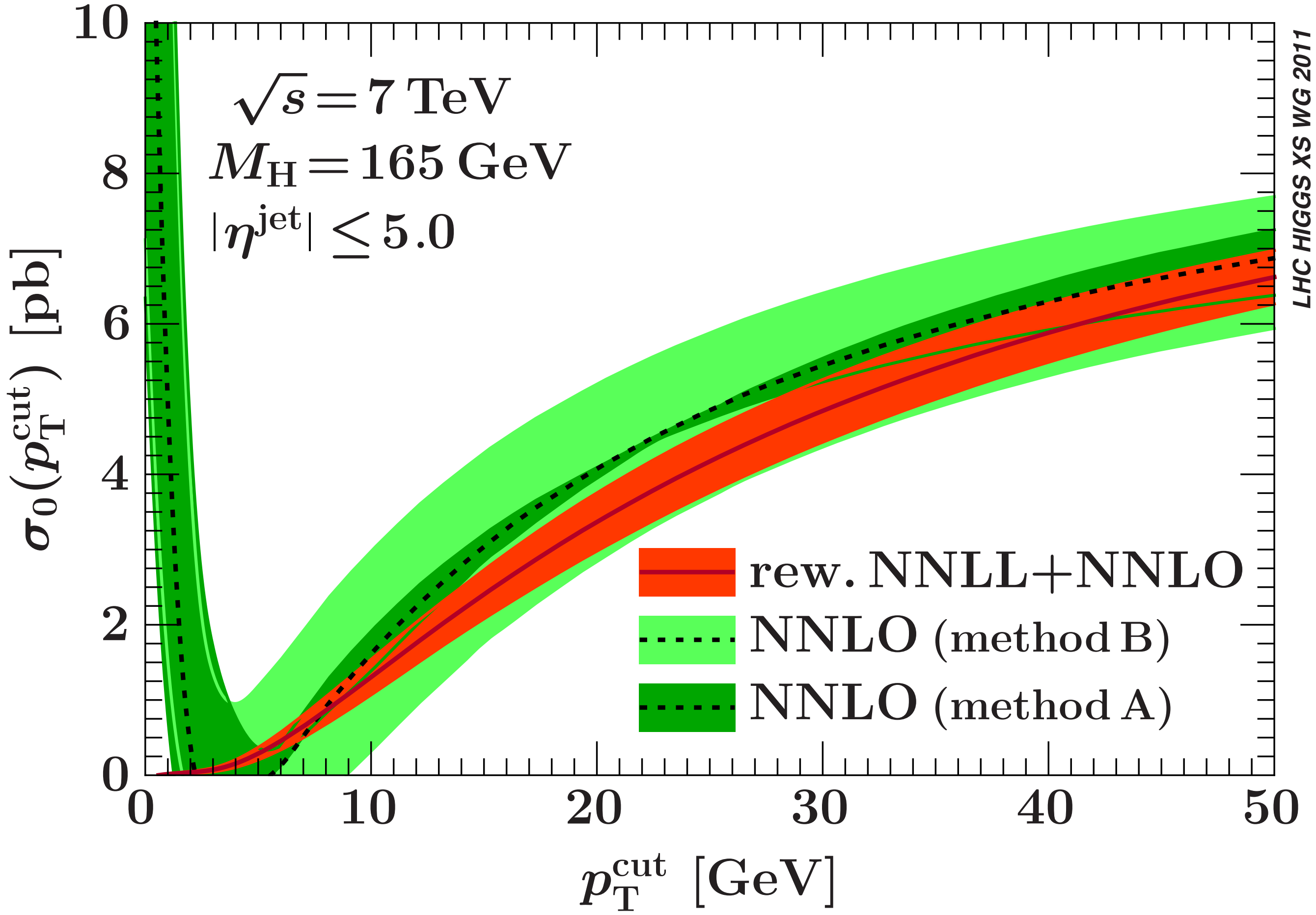
NNLO + NNLL

	LO	NLO	NNLO	N^3LO		
$\sigma_0(p_T^{cut}) =$	1	$+\,\alpha_s L^2$	$+\,\alpha_s^2 L^4$	$+\,\alpha_s^3 L^6$	$+\ldots$	LL
		$+\,\alpha_s L$	$+\,\alpha_s^2 L^3$	$+\,\alpha_s^3 L^5$	$+\ldots$	NLL
		$+\,\alpha_s$	$+\,\alpha_s^2 L^2$	$+\,\alpha_s^3 L^4$	$+\ldots$	
			$+\,\alpha_s^2 L$	$+\,\alpha_s^3 L^3$	$+\ldots$	NNLL
			$+\,\alpha_s^2$	$+\,\alpha_s^3 L^2$	$+\ldots$	
				$+\,\alpha_s^3 L$	$+\ldots$	N^3LL
				$+\,\alpha_s^3$	$+\ldots$	

[C.Berger, C.Marcantonini, I.S., F.Tackmann, W.Waalewjn]



I.S., F.Stockli, F.Tackmann, W.Waalewijn
(Higgs Yellow Report #2)

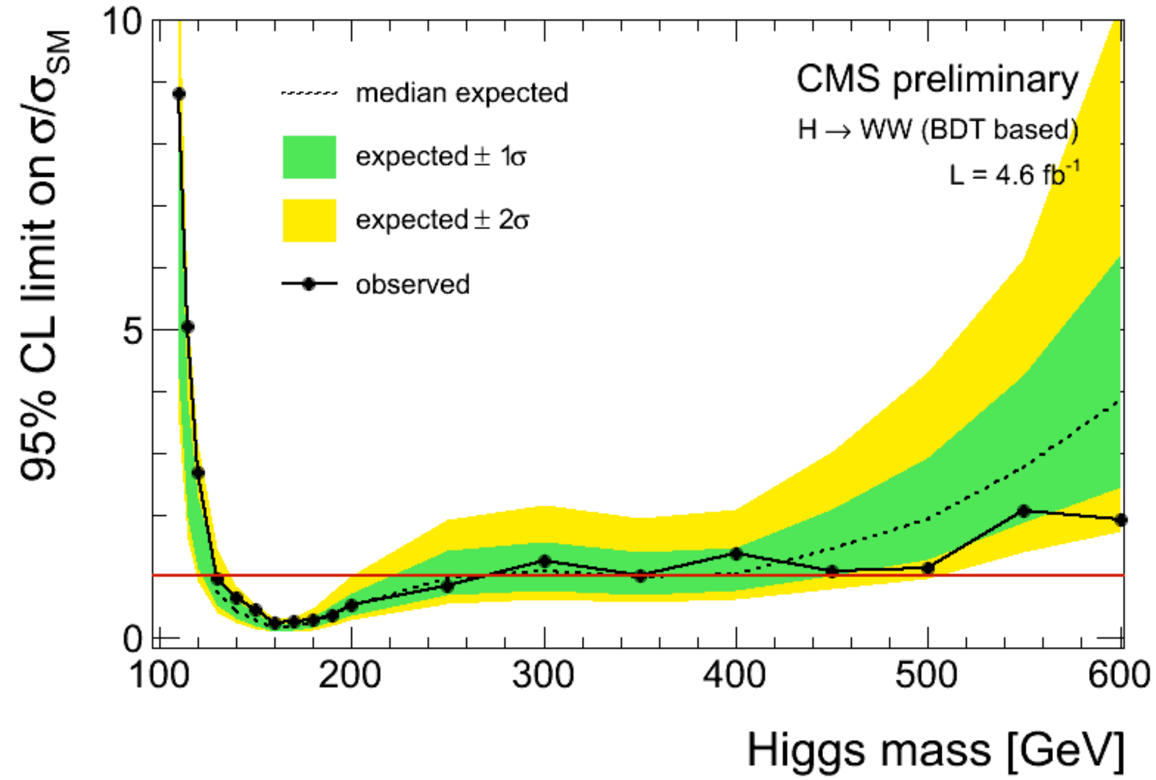


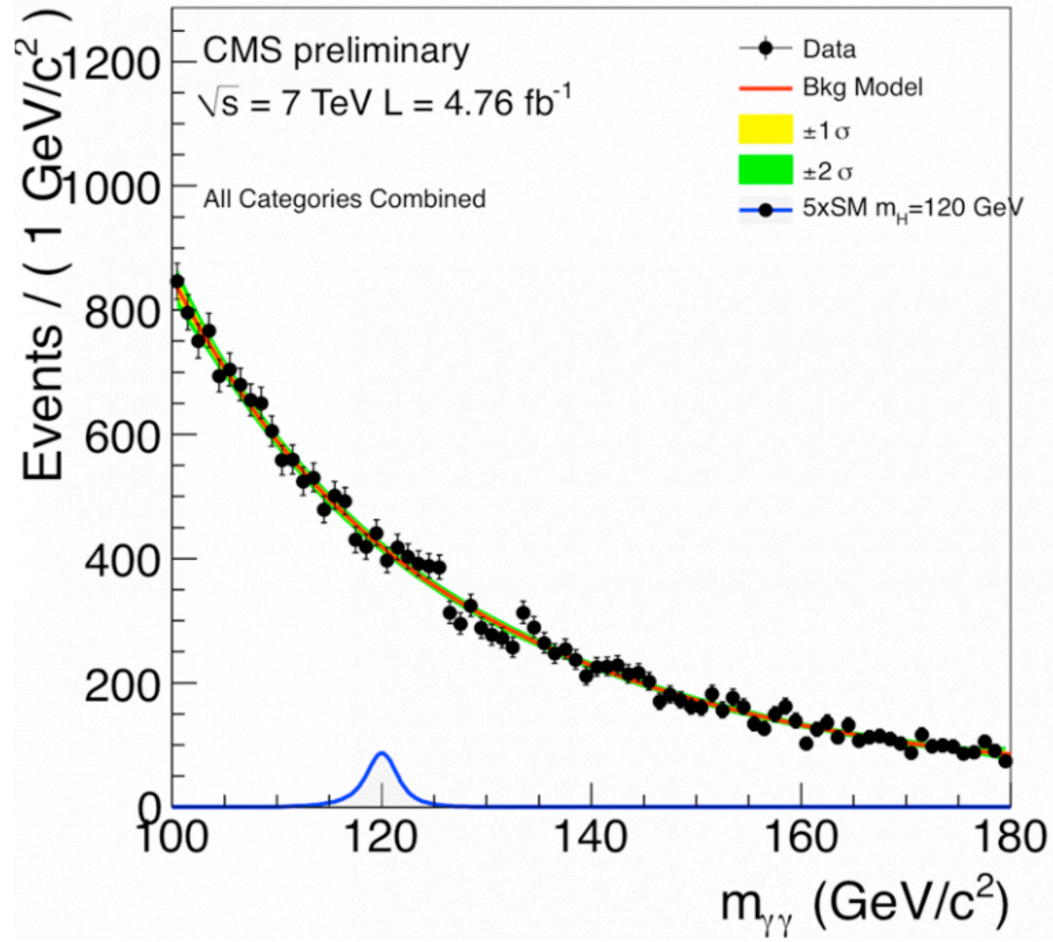
Higher Precision Calculation:

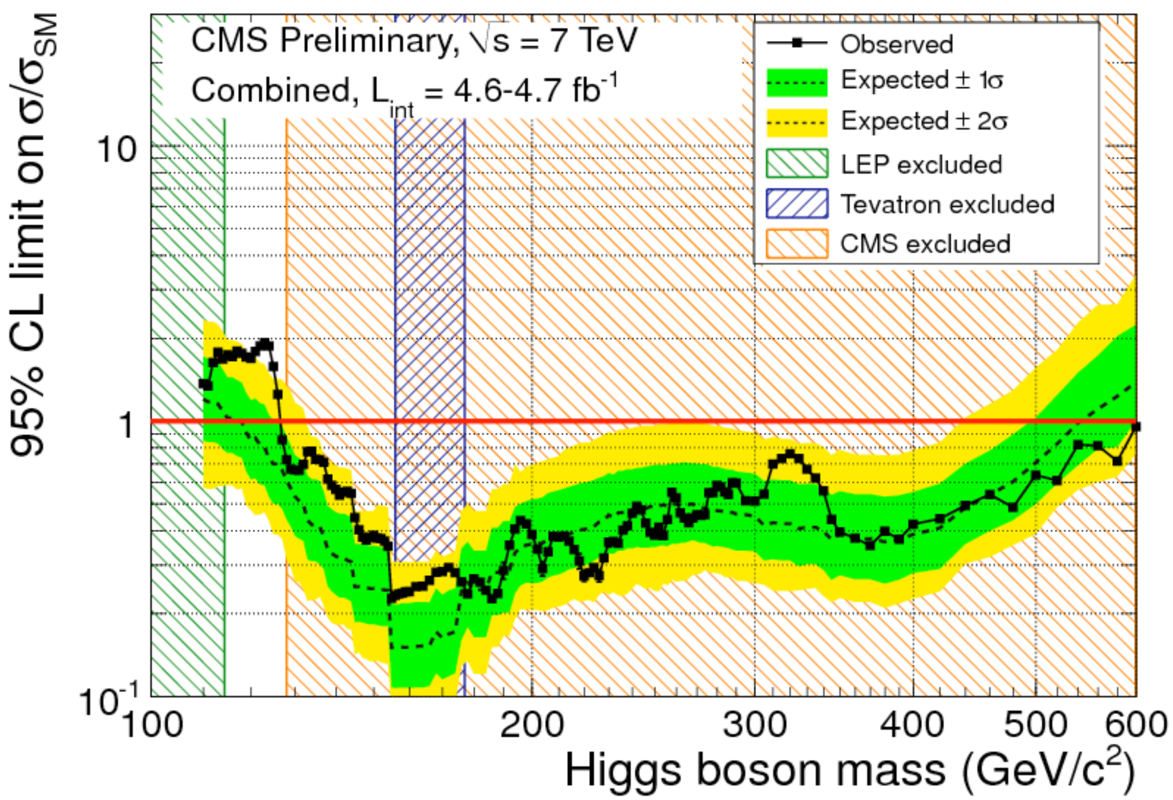
Factor of 2 improvement

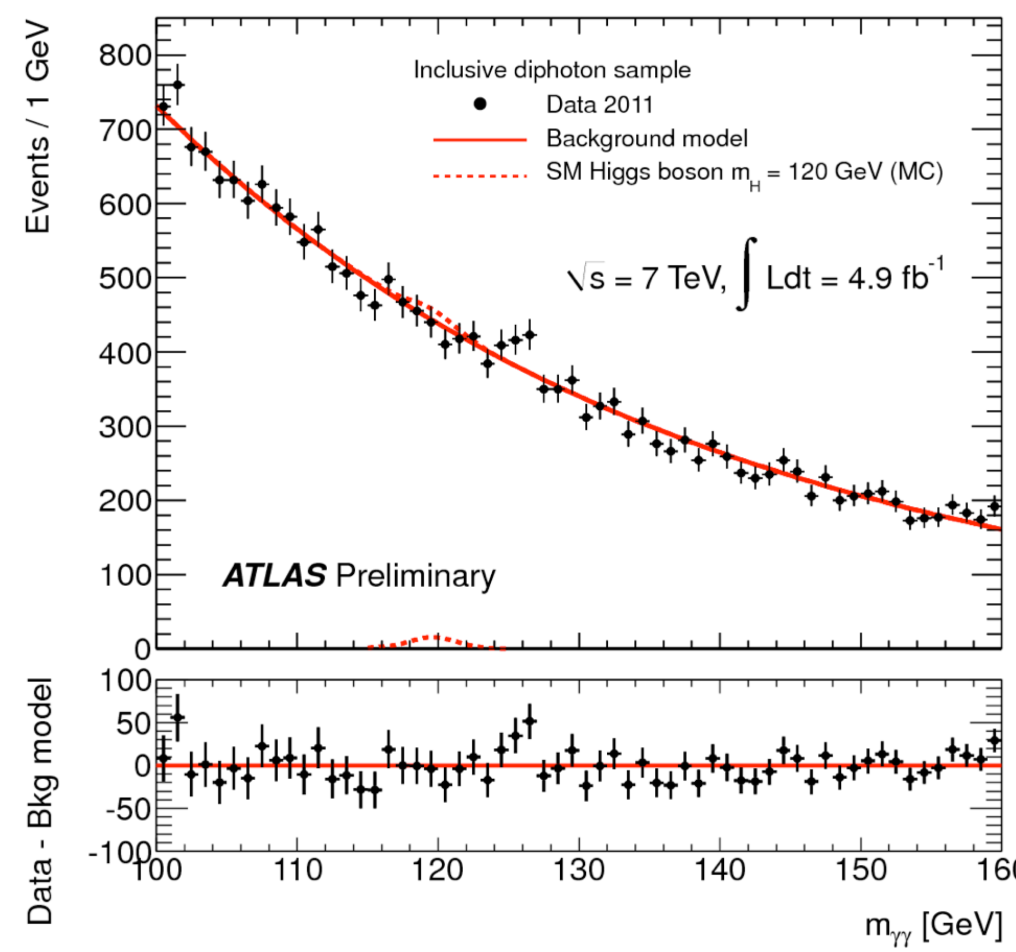
I.S., F.Stockli, F.Tackmann, W.Waalewijn
(Higgs Yellow Report #2)

Higgs Bounds (& Hints?)

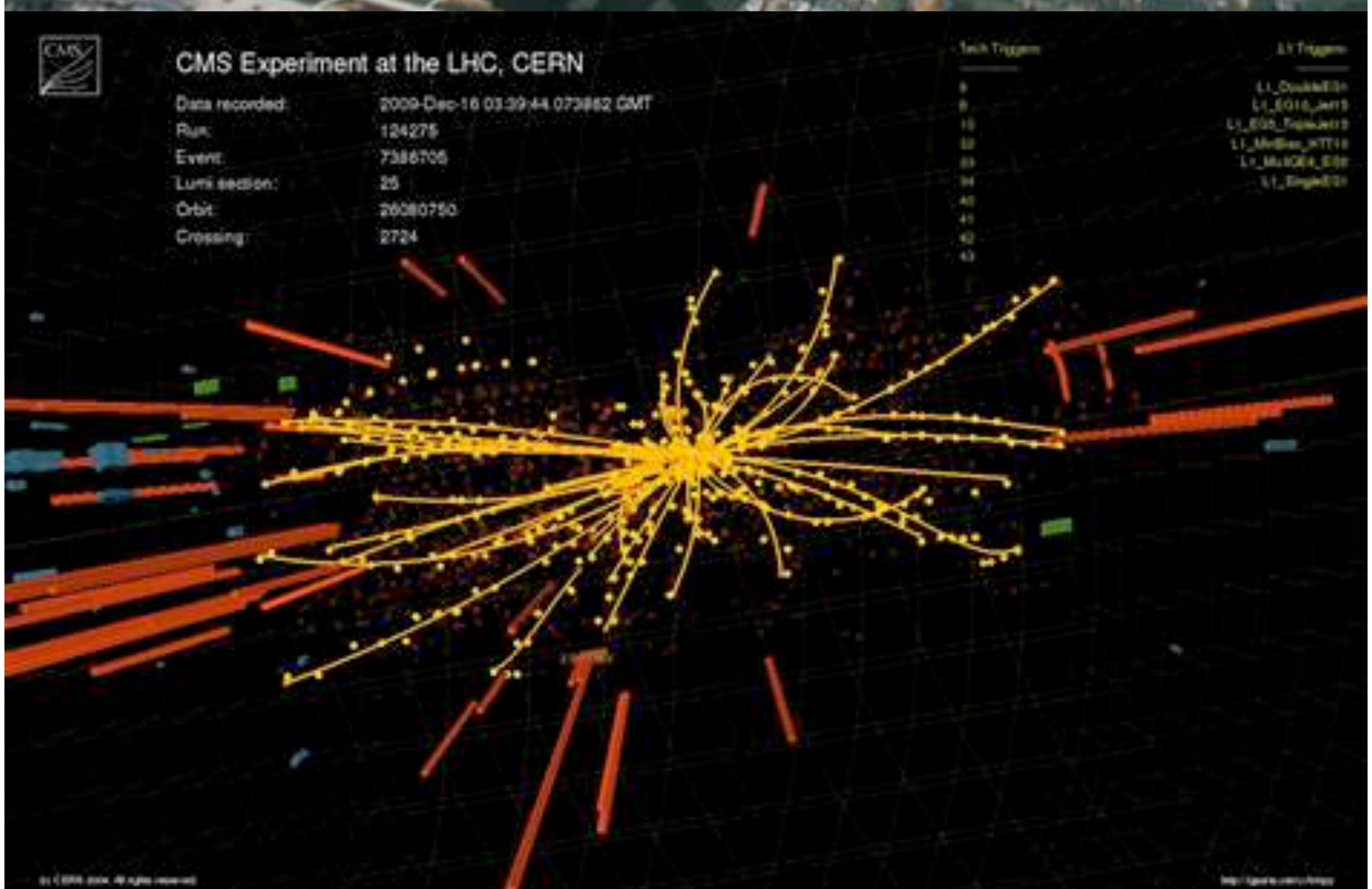








More on this next week in Markus Klute's lecture



LHC !

- closing in on the Higgs, a key missing ingredient in the so far successful Standard Model
- also constraining new physics scenarios, and geared up for discovery