

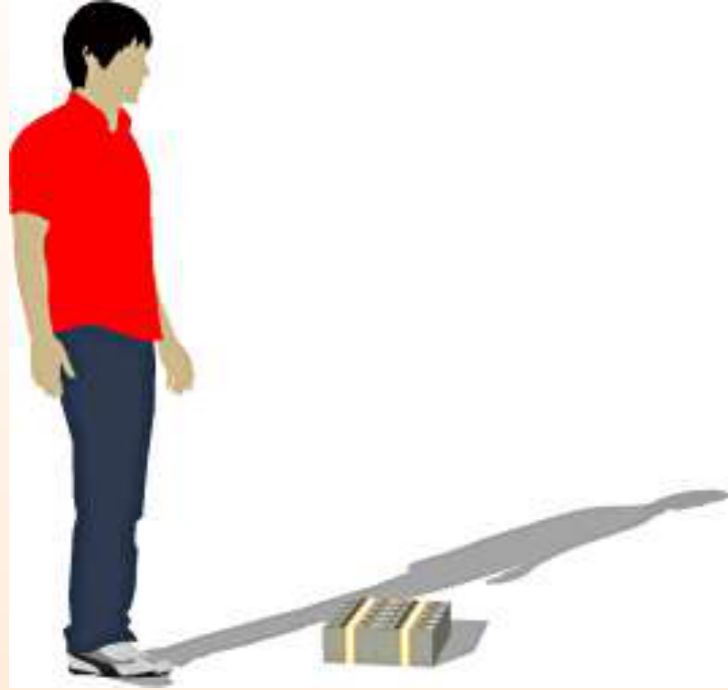
A 9 Billion Dollar Venture
to
Shake up the Laws of Nature

Iain Stewart
MIT

Physics IAP Lecture Series

2012

1 million



1 million



100 million



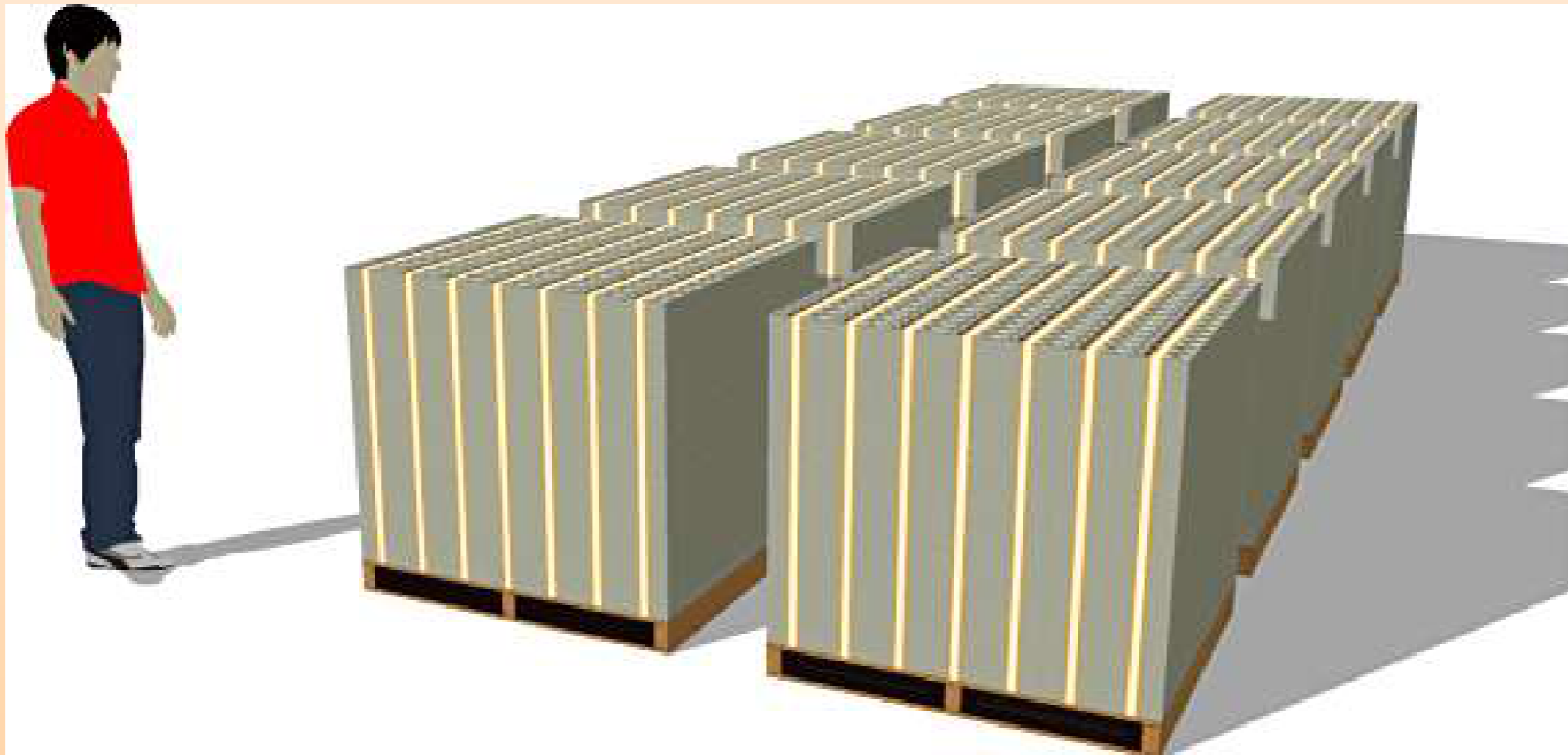
1 million



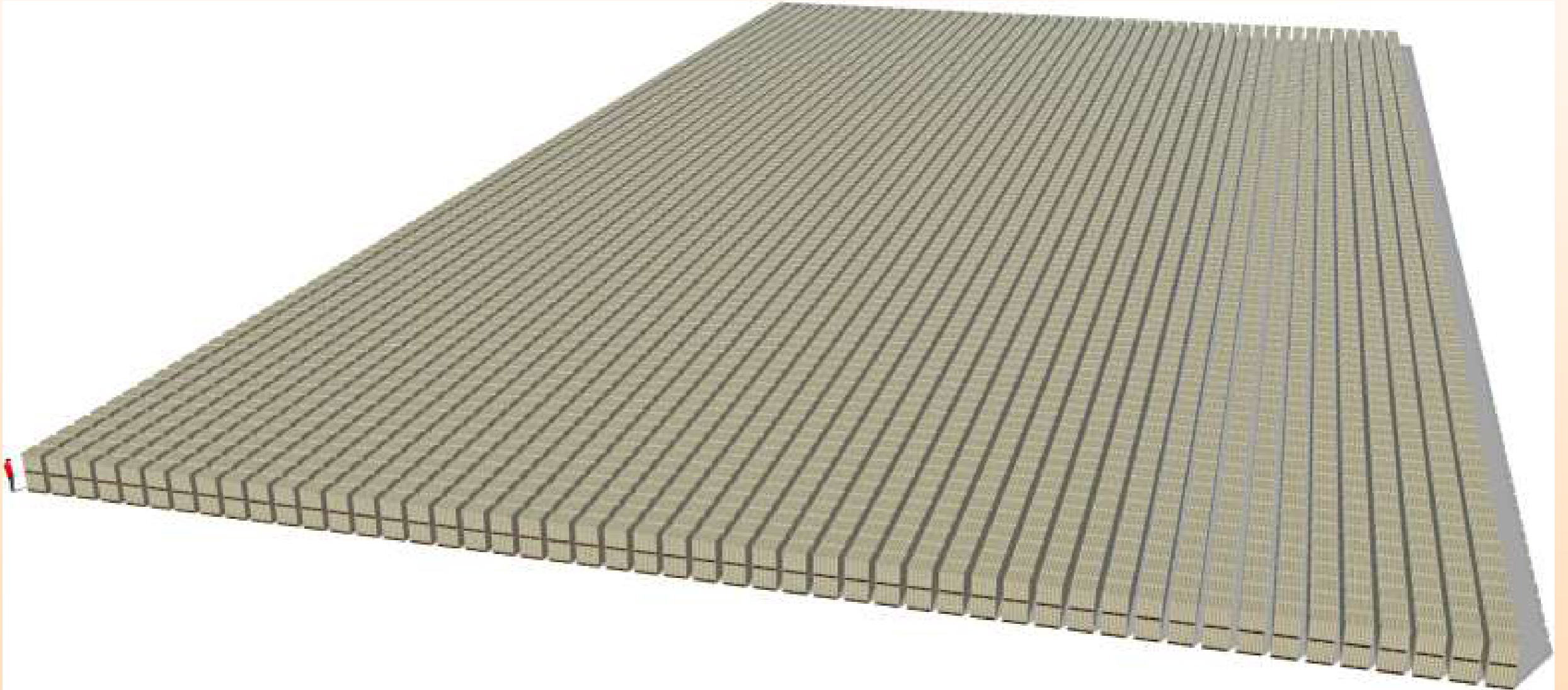
100 million



1 billion



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

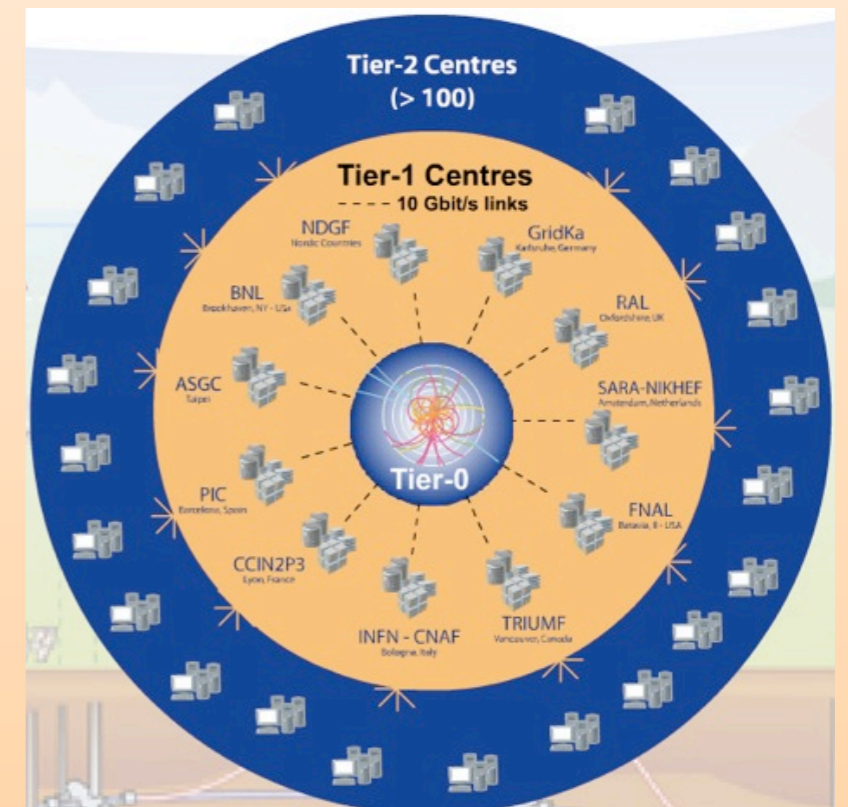
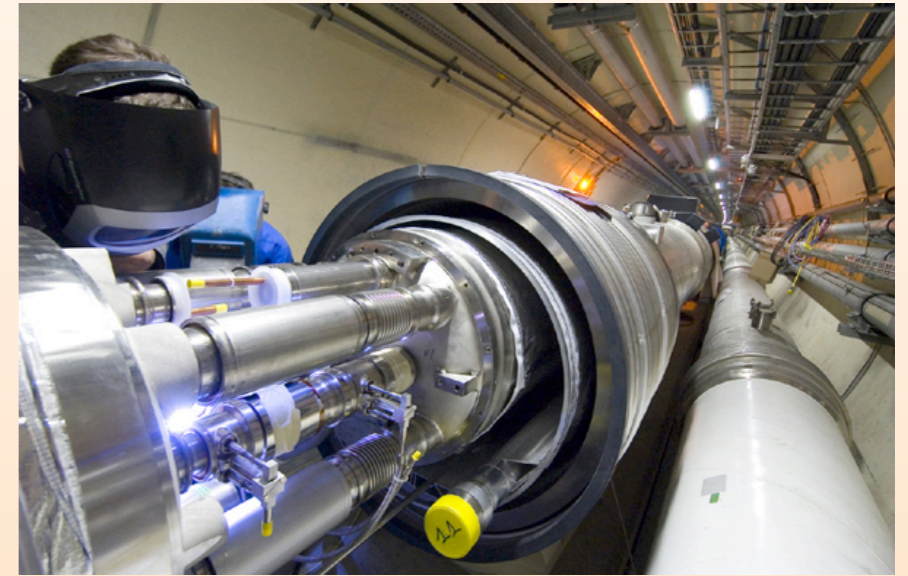


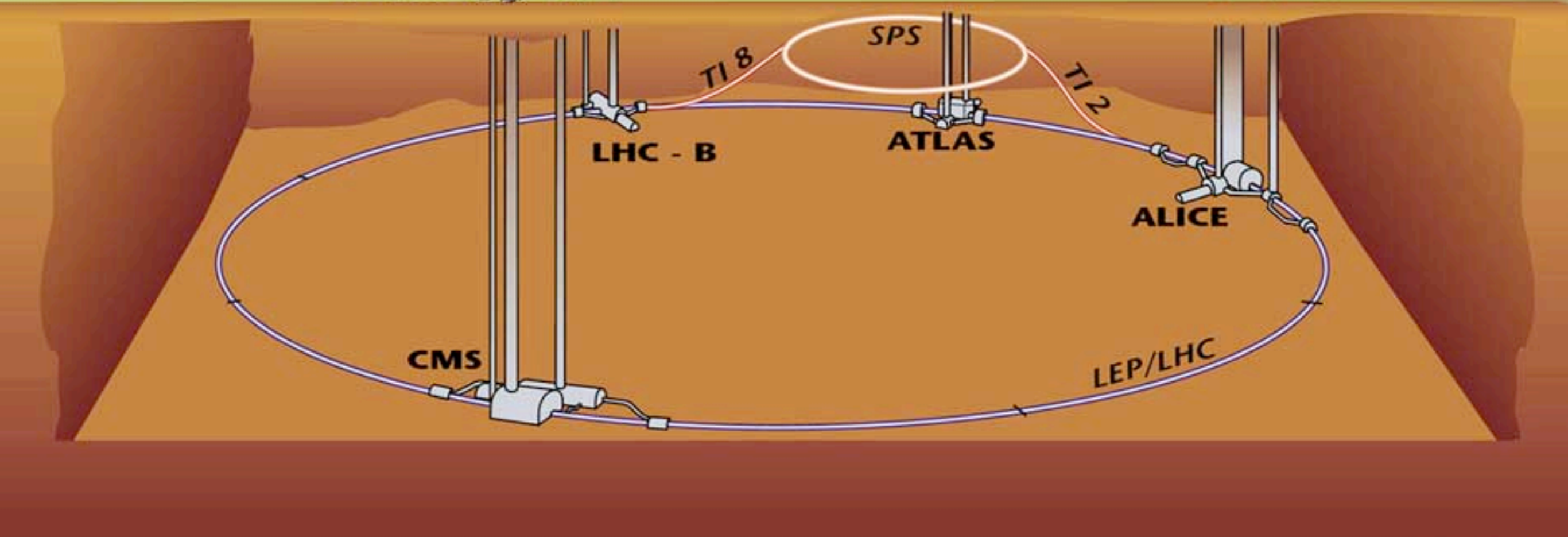
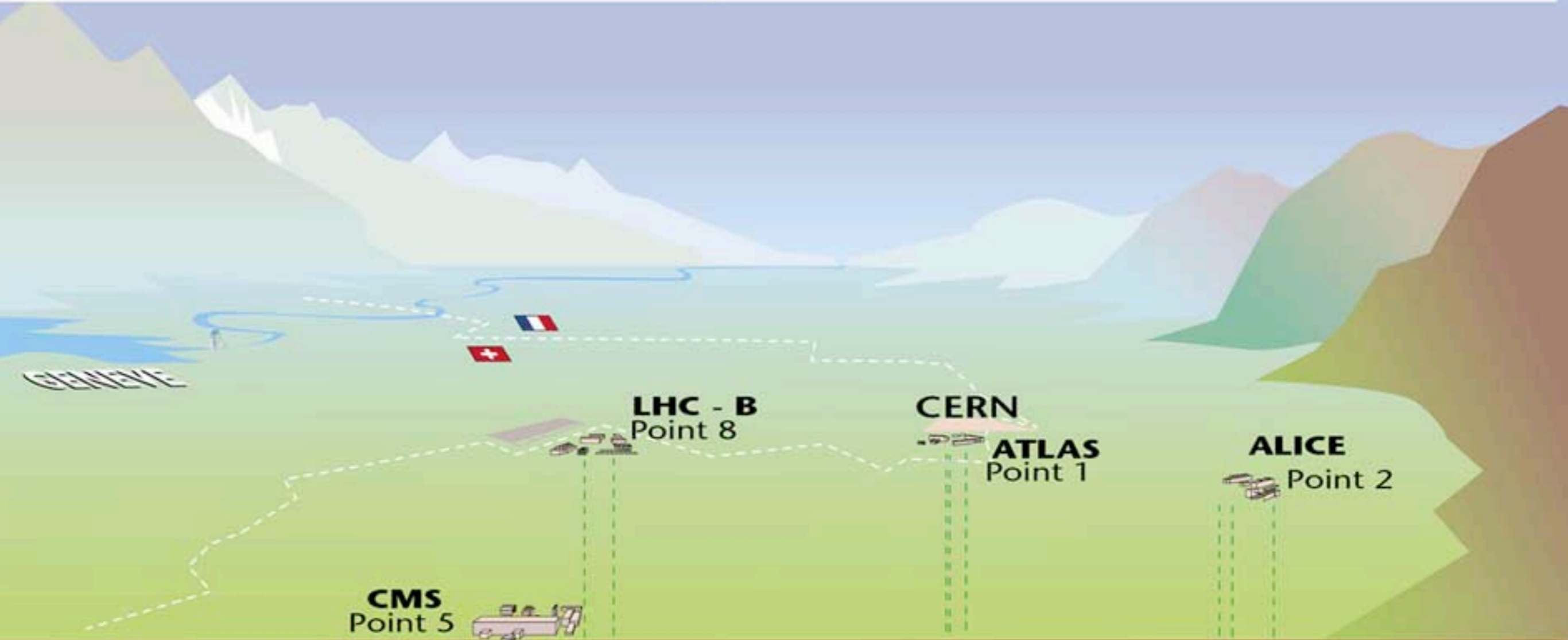
What does one get for 9 billion dollars?

(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

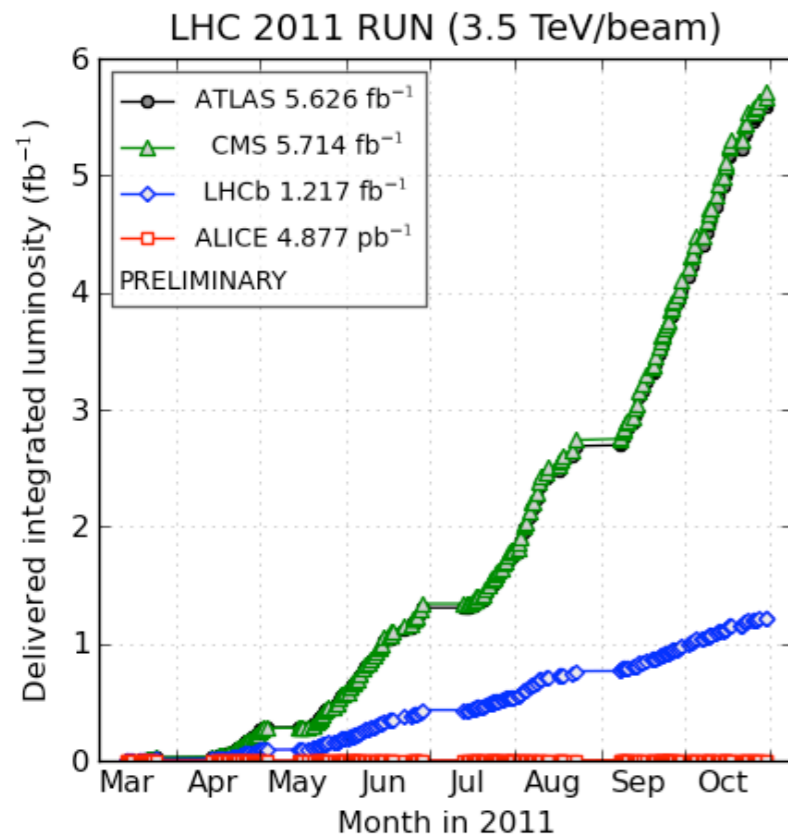
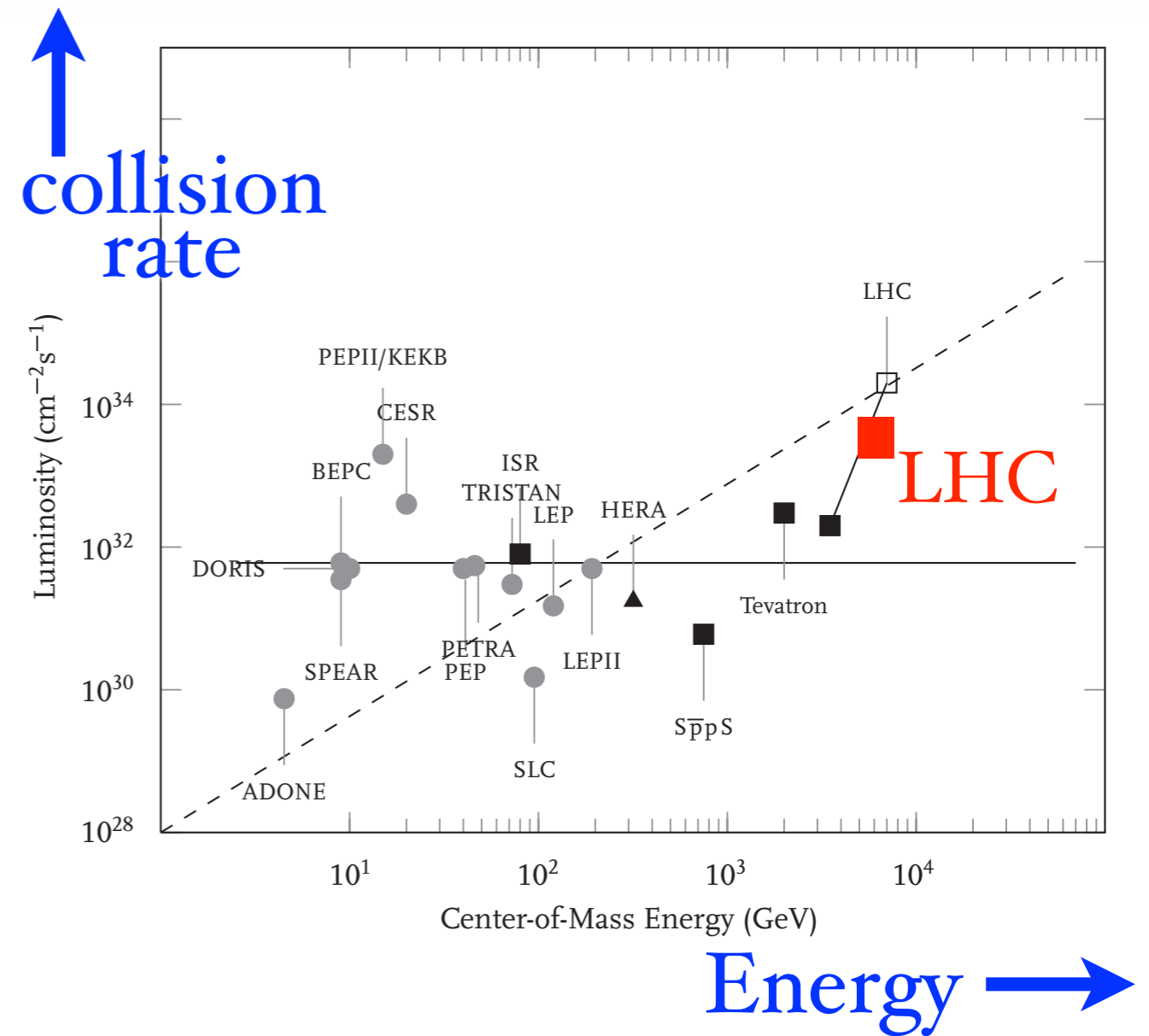




Want to maximize
collision rate & energy

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

Higgs: $1 : 10^{10}$



(generated 2011-12-01 19:35 including fill 2267)

- More energy means we can produce new heavy particles

$$m = E/c^2$$

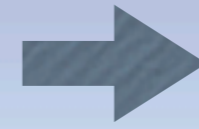
LHC(2011): $E = 7 \text{ TeV}$

non-relativistic

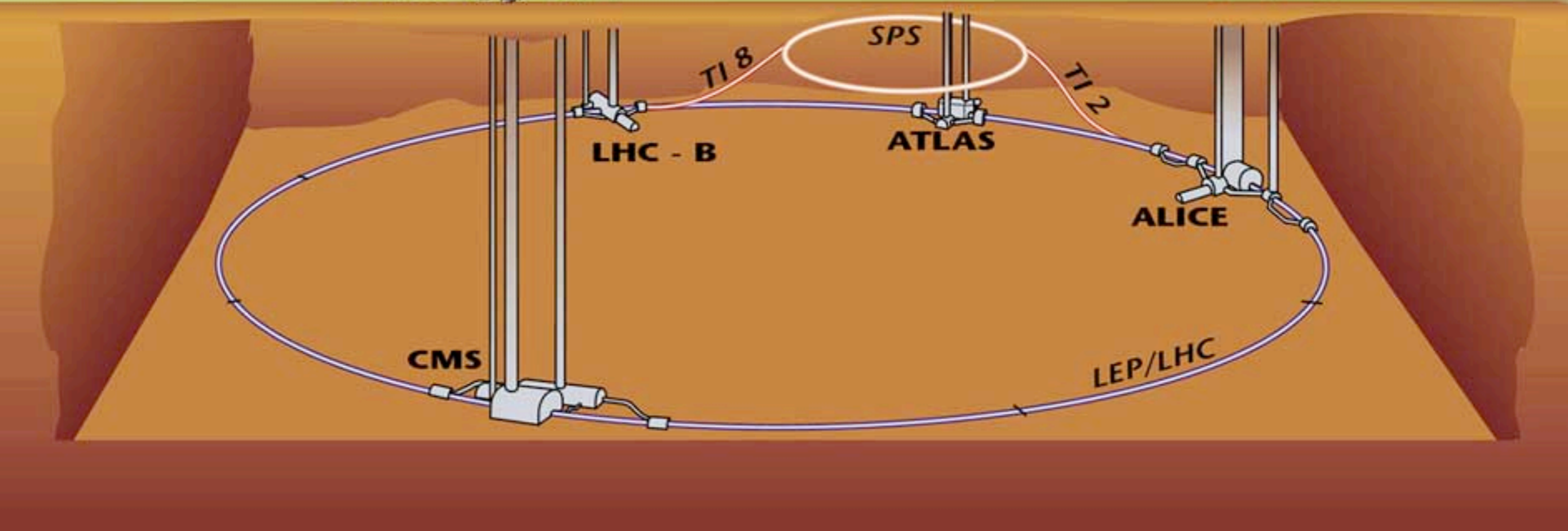
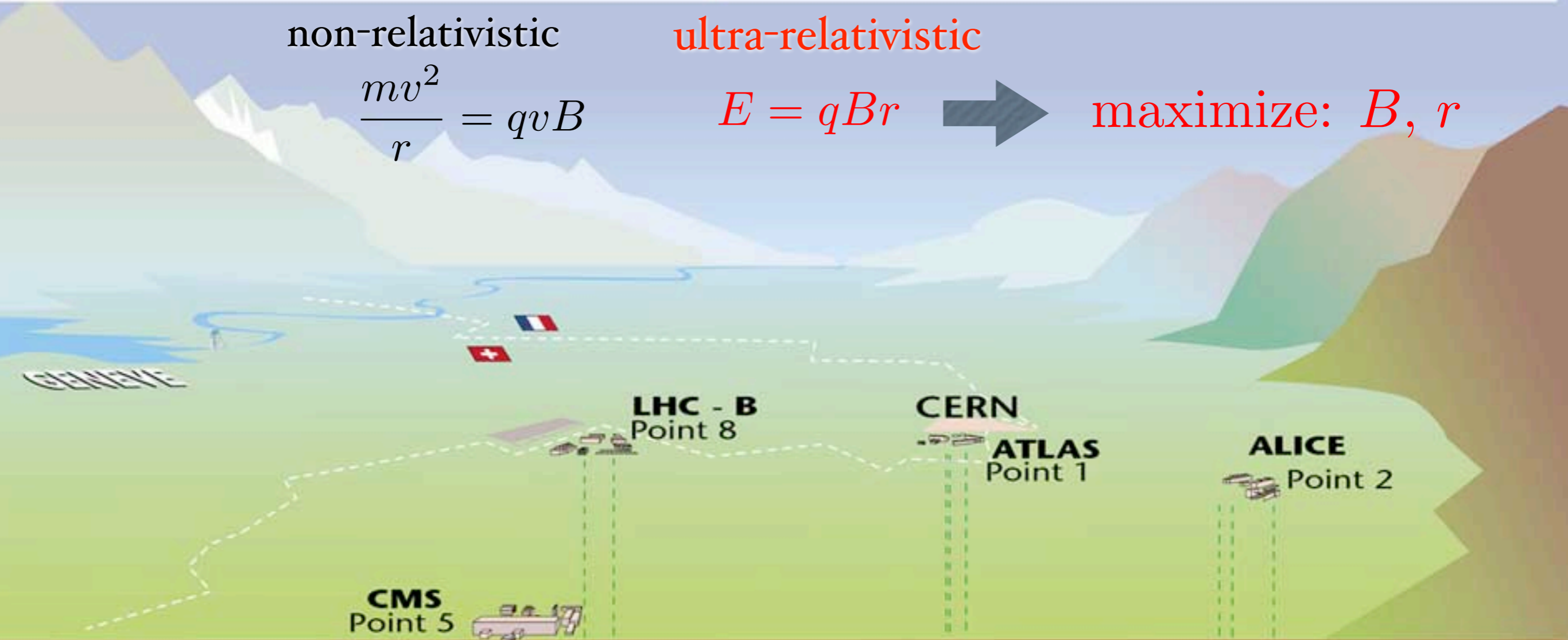
$$\frac{mv^2}{r} = qvB$$

ultra-relativistic

$$E = qBr$$



maximize: B, r



Particles and Forces

Basic Constituents of Matter?

Periodic Table of the Elements © www.elementsdatabase.com

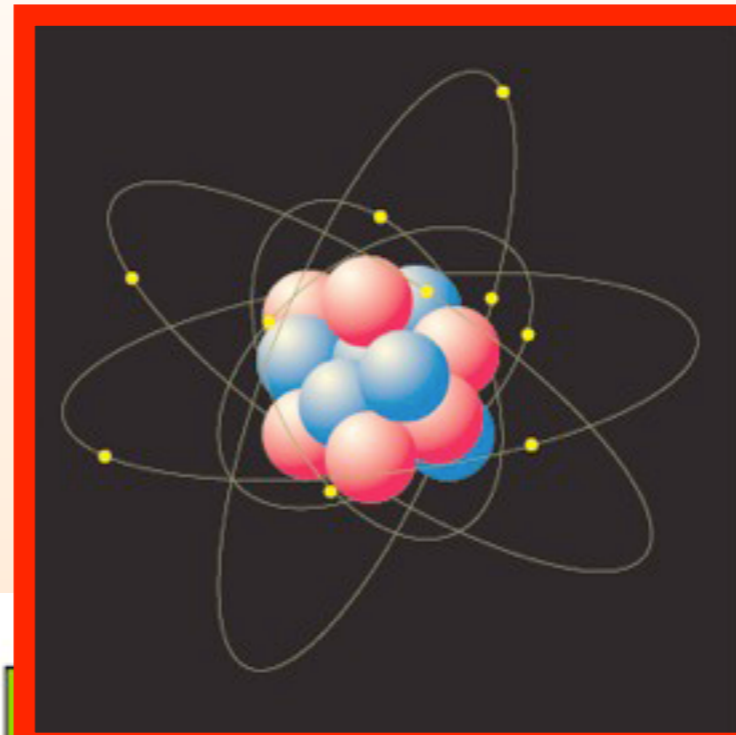
- hydrogen
- alkali metals
- alkali earth metals
- transition metals

- poor metals
- nonmetals
- noble gases
- rare earth metals

1 H																	2 He																												
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne																												
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar																												
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr																												
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe																												
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn																												
87 Fr	88 Ra	89 Ac	104 Unq	105 Unp	106 Unh	107 Uns	108 Uno	109 Une	110 Unn																																				
<table border="1" style="width: 100%; border-collapse: collapse; text-align: center; margin-top: 10px;"> <tbody> <tr> <td>58 Ce</td><td>59 Pr</td><td>60 Nd</td><td>61 Pm</td><td>62 Sm</td><td>63 Eu</td><td>64 Gd</td><td>65 Tb</td><td>66 Dy</td><td>67 Ho</td><td>68 Er</td><td>69 Tm</td><td>70 Yb</td><td>71 Lu</td> </tr> <tr> <td>90 Th</td><td>91 Pa</td><td>92 U</td><td>93 Np</td><td>94 Pu</td><td>95 Am</td><td>96 Cm</td><td>97 Bk</td><td>98 Cf</td><td>99 Es</td><td>100 Fm</td><td>101 Md</td><td>102 No</td><td>103 Lr</td> </tr> </tbody> </table>																		58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr
58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu																																
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr																																

Basic Constituents of Matter?

protons & neutrons in a nucleus



Periodic Table of Elements

© www.elementsdatabase.com

Legend:

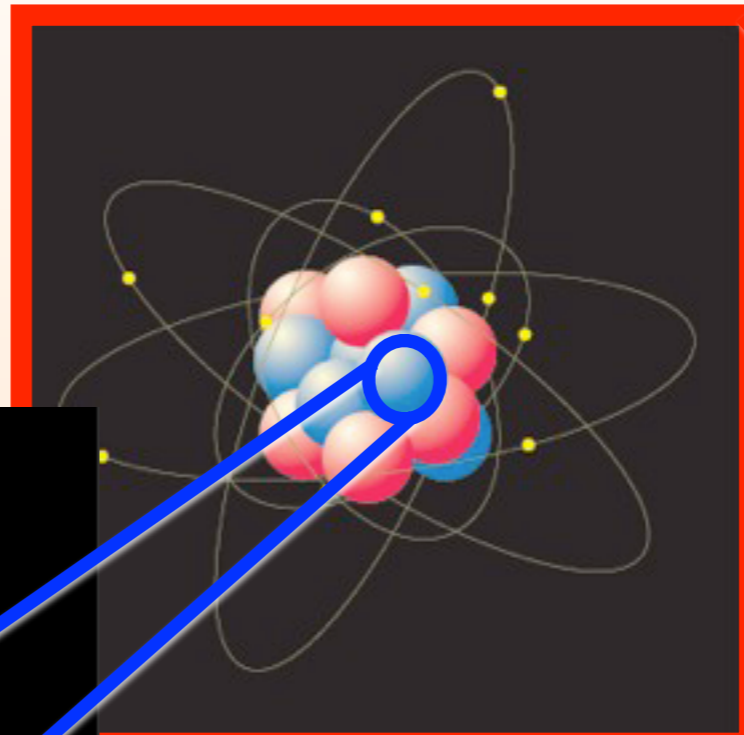
- hydrogen
- alkali metals
- alkali earth metals
- transition metals
- poor metals
- nonmetals
- noble gases
- rare earth metals

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118																																																																										
H	He	Li	Be	B	C	N	O	F	Ne	Na	Mg	Al	Si	P	S	Cl	Ar	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe	Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn	Fr	Ra	Ac	Unq	Unp	Unh	Uns	Uno	Une	Uun	119	120	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144	145	146	147	148	149	150	151	152	153	154	155	156	157	158	159	160	161	162	163	164	165	166	167	168	169	170	171	172	173	174	175	176	177	178	179	180	181	182	183	184	185	186	187	188	189	190	191	192	193	194	195	196	197	198	199	200
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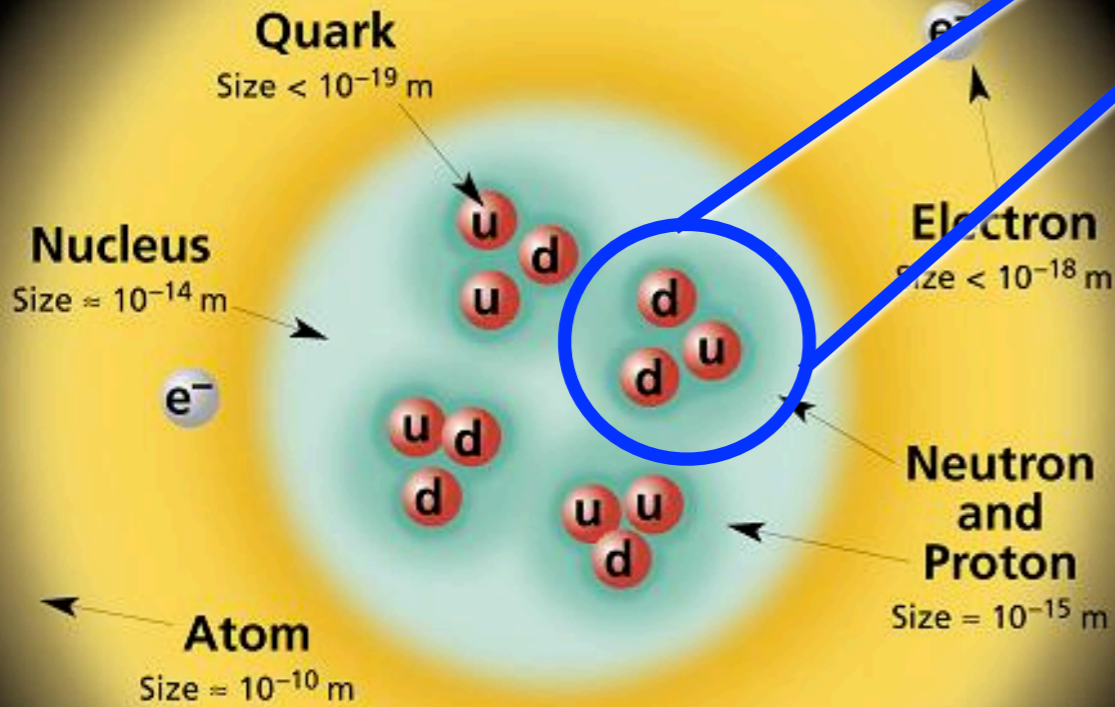
Basic Constituents of Matter?

protons & neutrons in a nucleus

quarks in protons & neutrons



Structure within the Atom



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

Periodic Table of Elements

© www.elementsdatabase.com

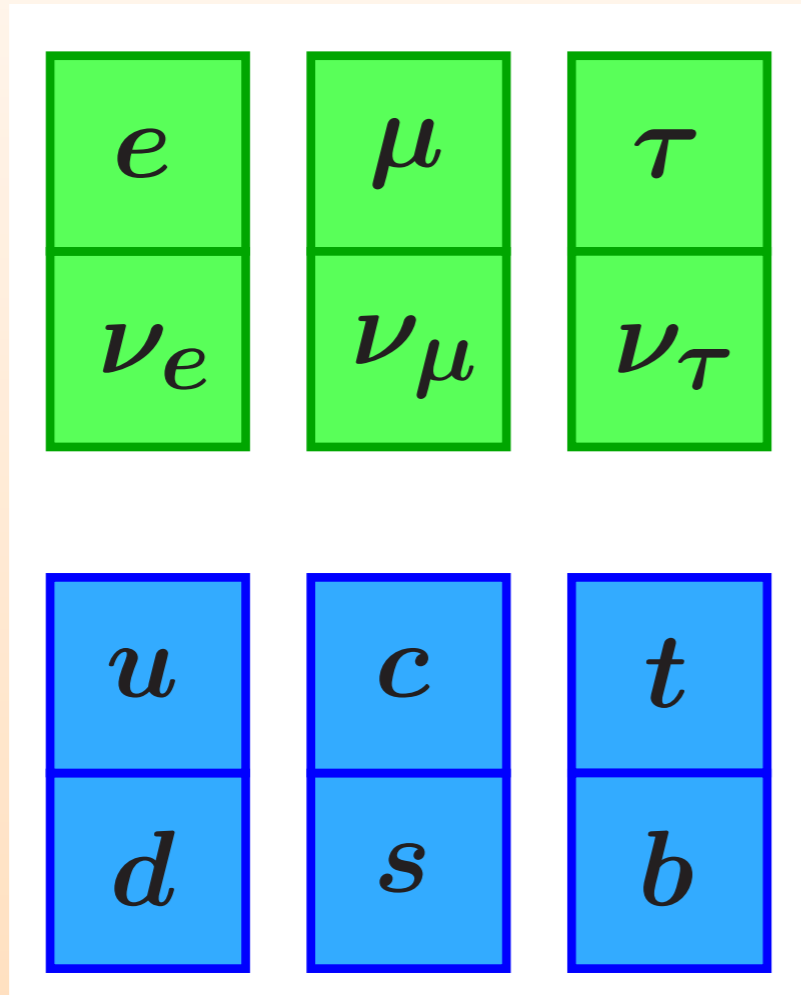
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Be	B	C	N	O	F	Ne	Na	Mg	Al	Si	P	S	Cl	Ar		
20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
56	57	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86
Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
88	89	104	105	106	107	108	109	110								
Ra	Ac	Unq	Unp	Unh	Uns	Uno	Une	Unn								

58	59	60	61	62	63	64	65	66	67	68	69	70	71
Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
90	91	92	93	94	95	96	97	98	99	100	101	102	103
Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

Standard Model's Elementary Particles

Force Mediators

Leptons



Quarks



Electromagnetism

Quantum Electrodynamics
(QED)



Weak Force

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



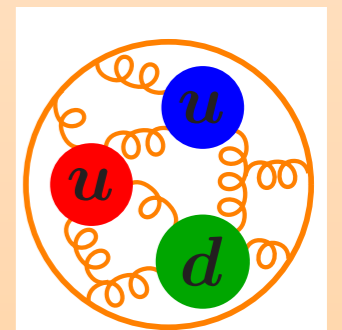
Strong Force

Quantum Chromodynamics
(QCD)

Higgs



& Gravity
(gravitons)



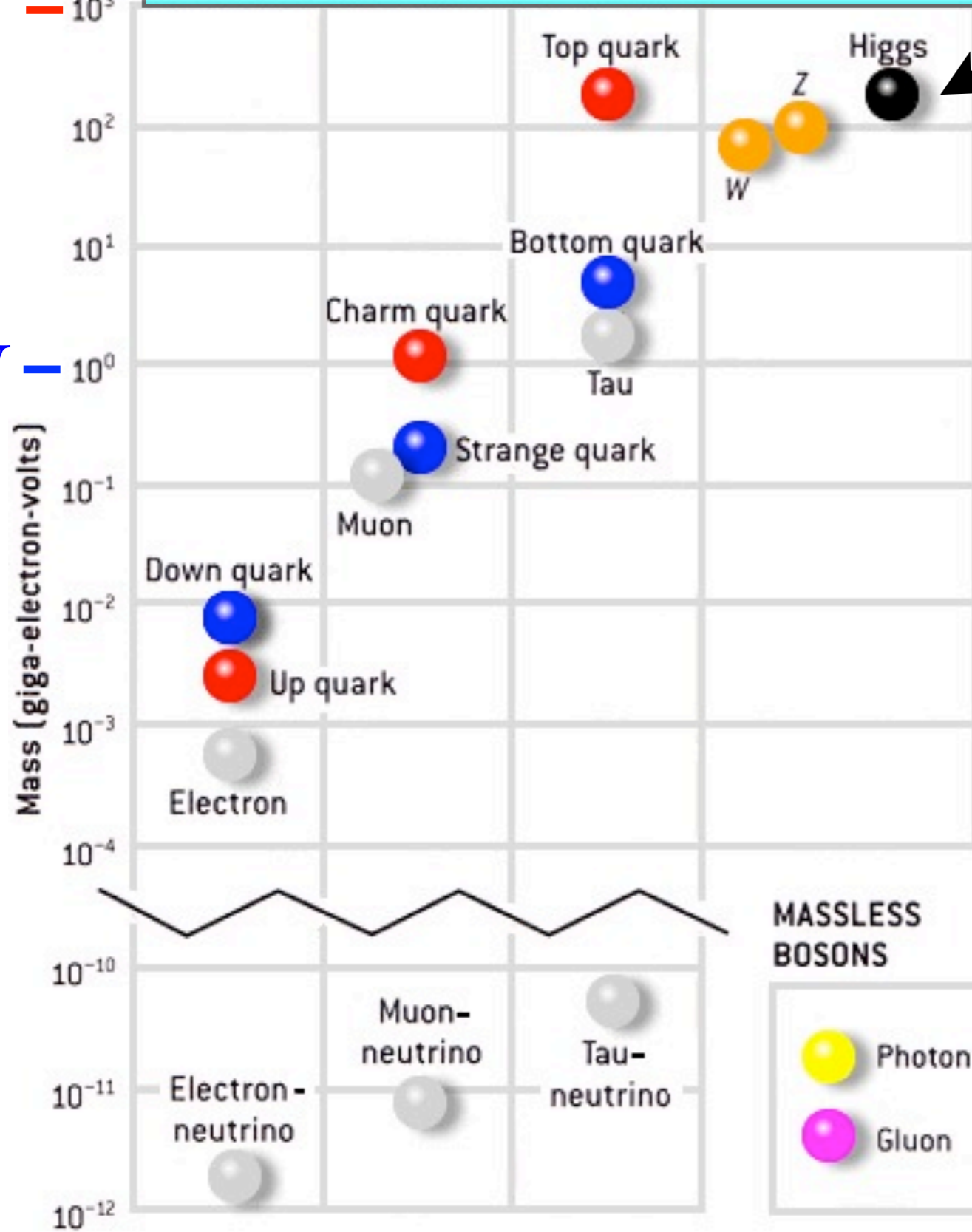
↑ Something New? ↑

hints for Higgs at LHC,
but not yet definitively
observed

1 TeV — 10^3

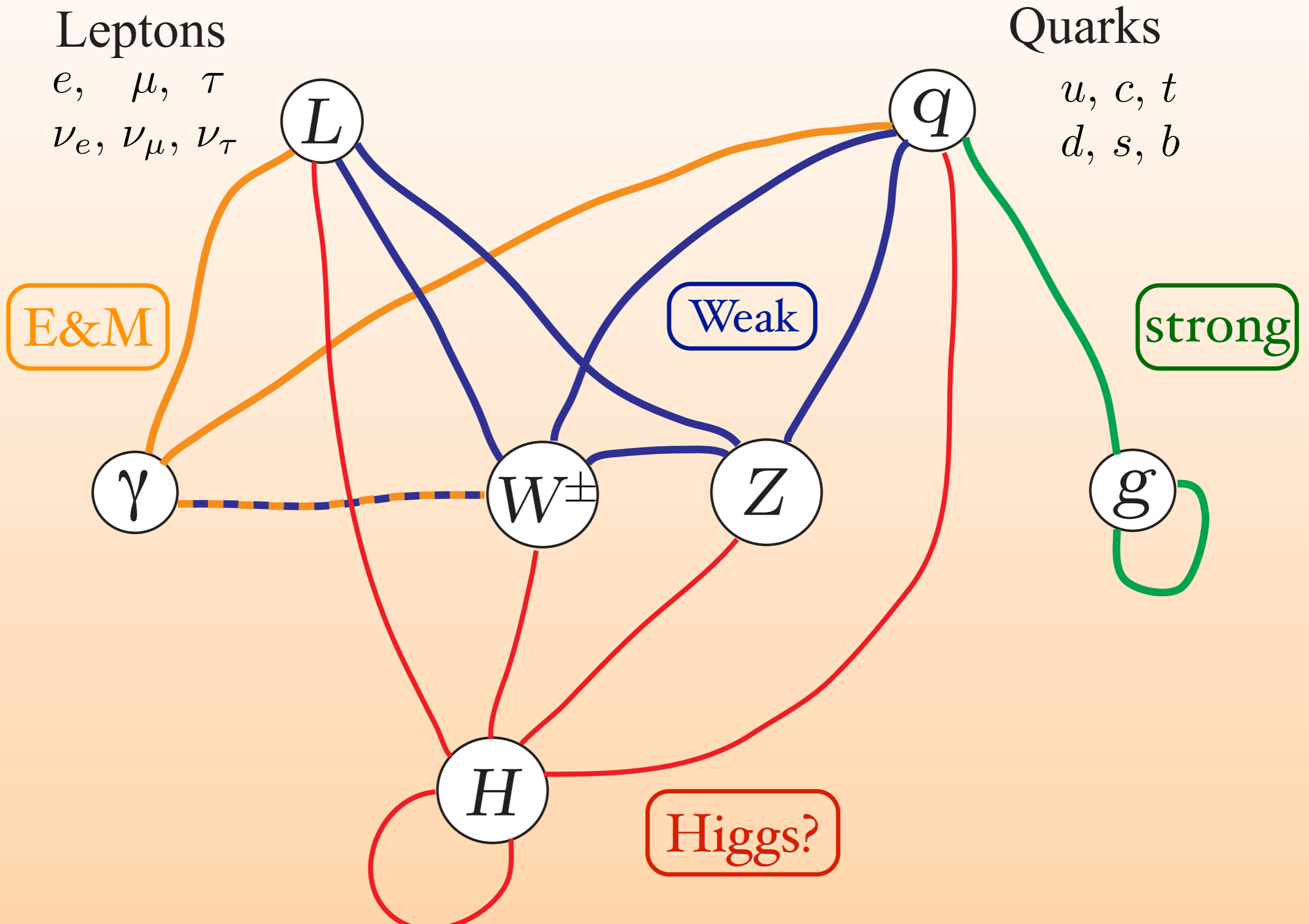
1 GeV — 10^0

Mass [giga-electron-volts]

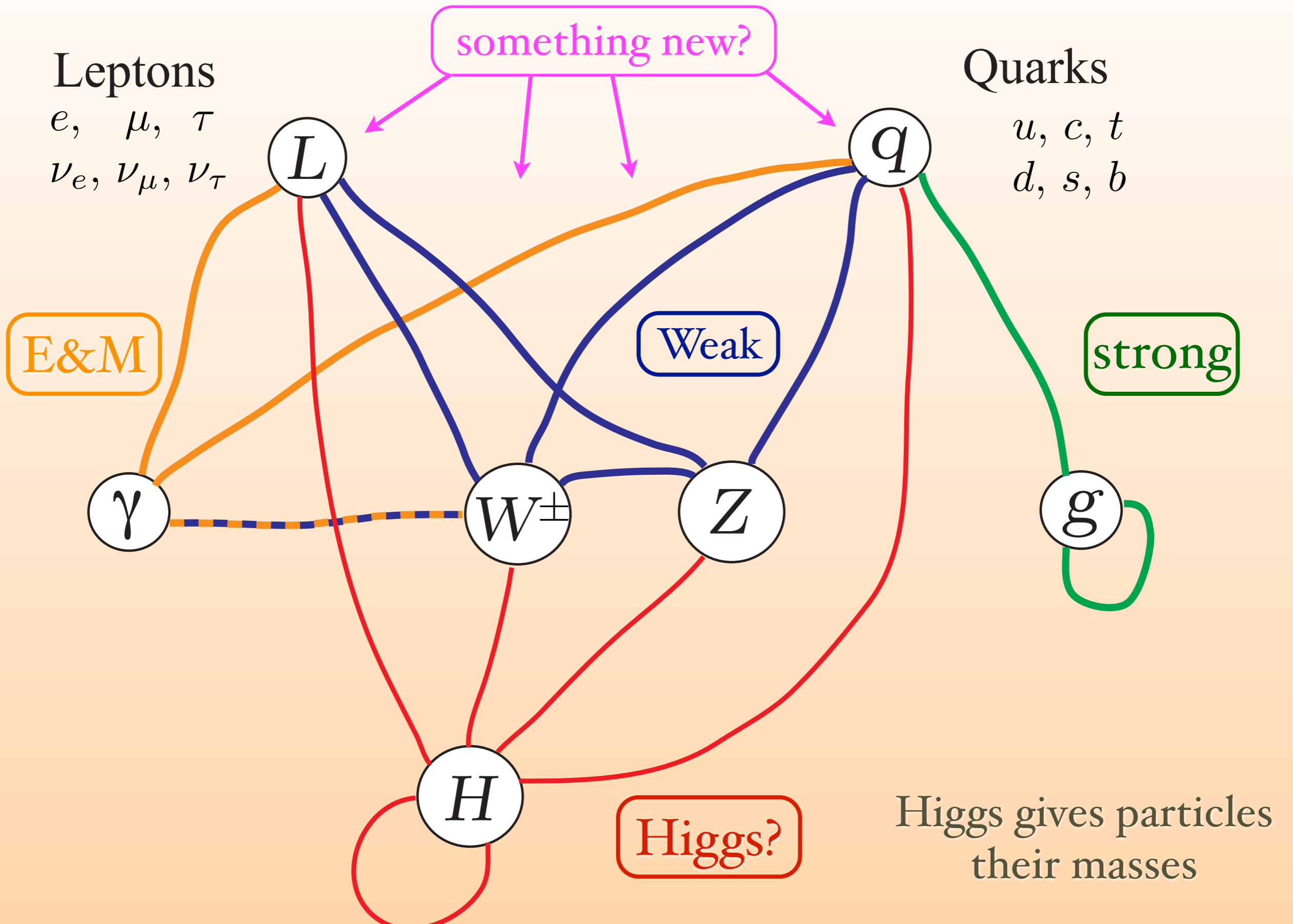


Particle Masses

Particle Forces/Interactions

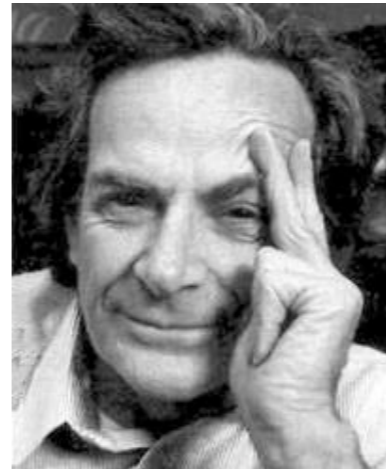


Particle Forces/Interactions



Particle Forces/Interactions

Feynman Diagrams



E&M

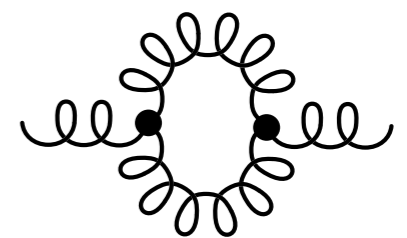
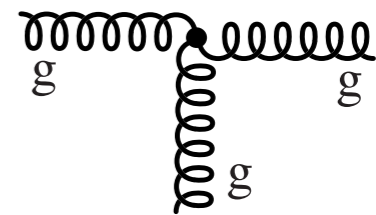
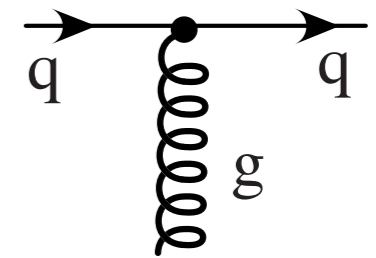
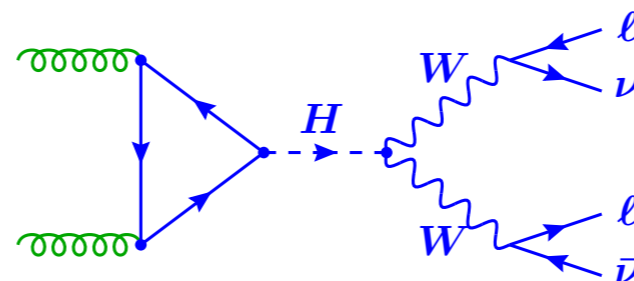
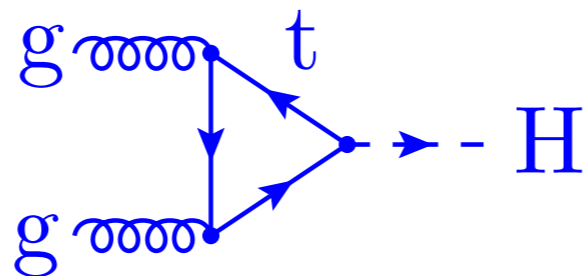
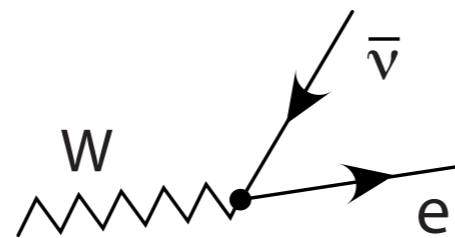
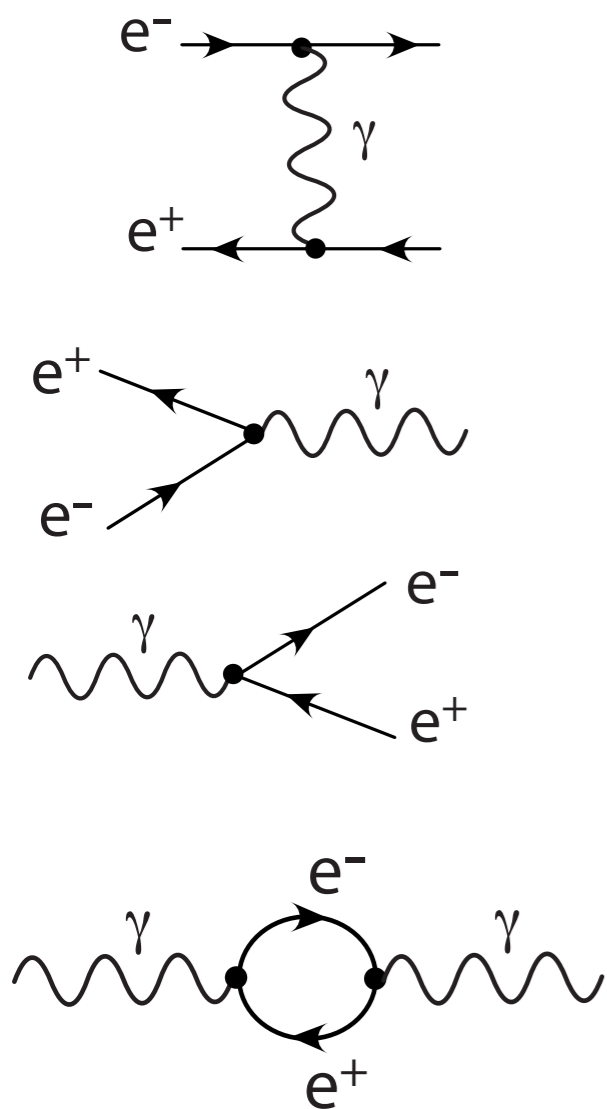
coupling α

Weak

strong

coupling α_s

Higgs?

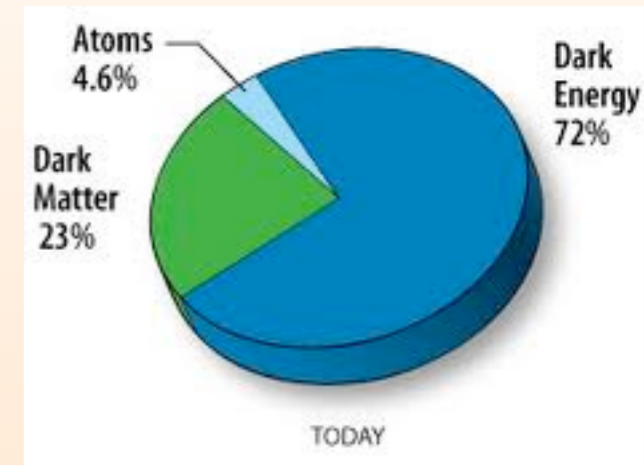


LHC Physics

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?



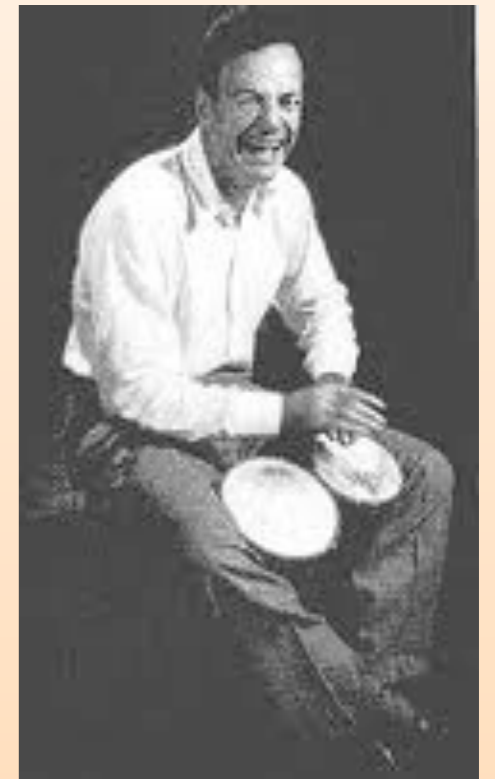
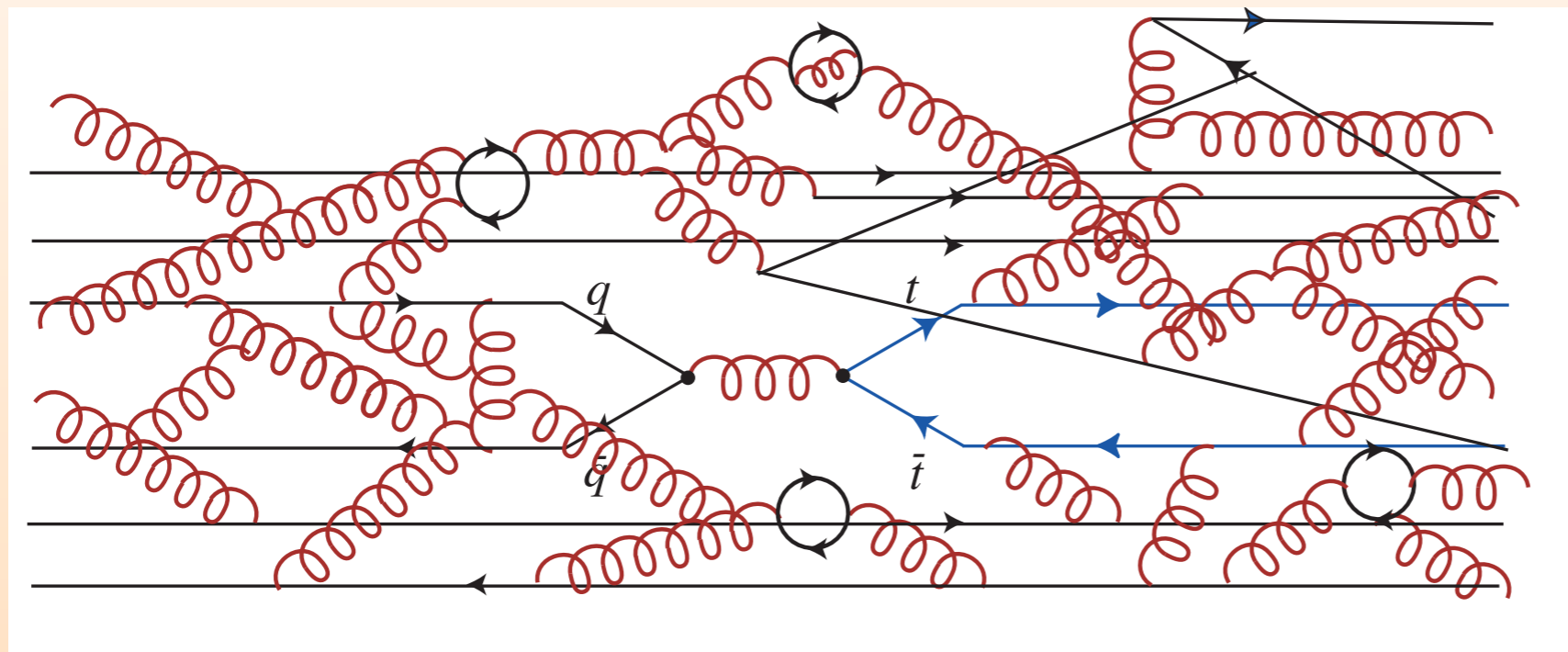
Will Answer: Does a Standard Model-like Higgs boson exist?

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

How well can we do?

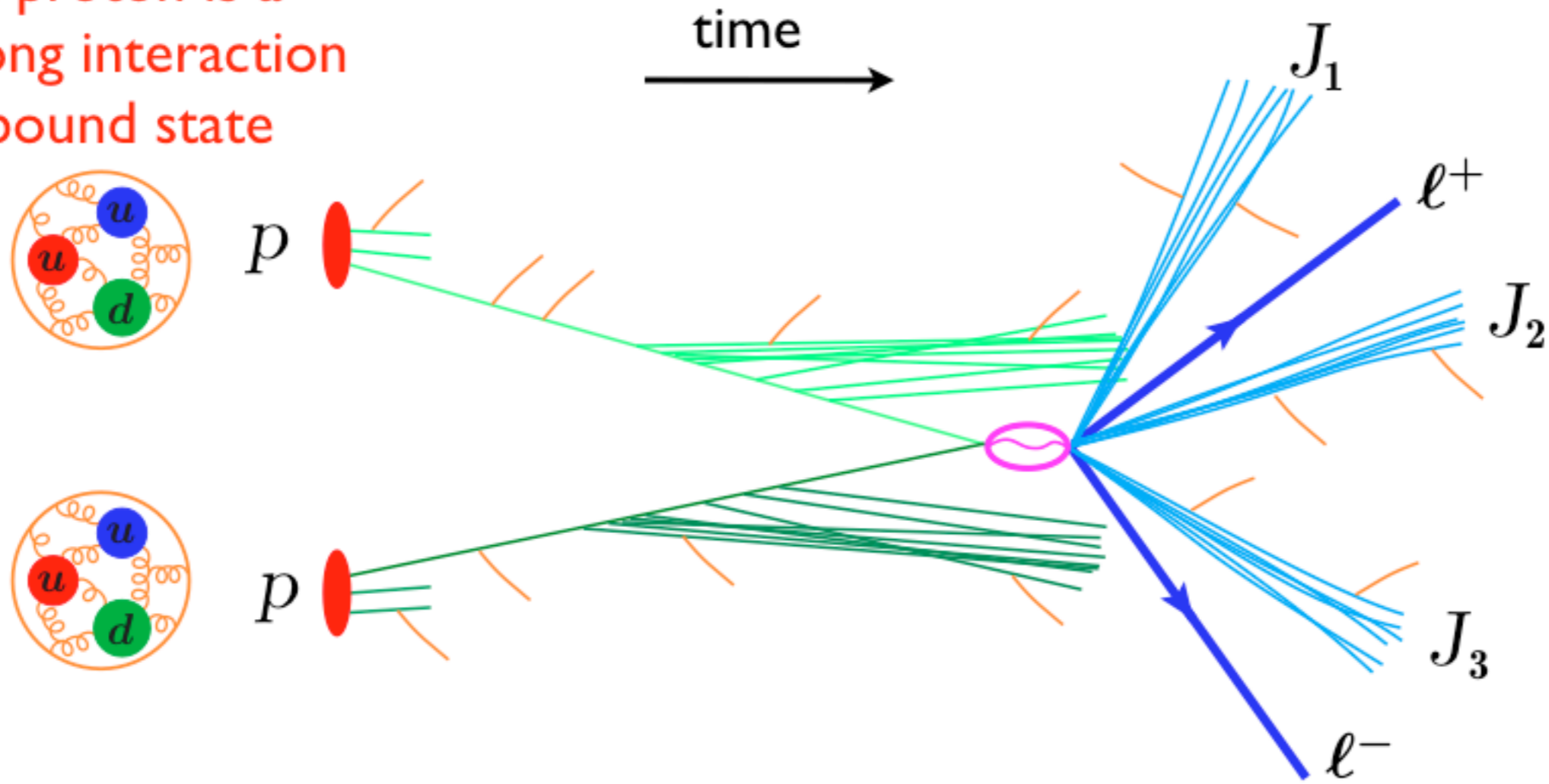
The Issue:

The LHC is like Feynman on QCD Steroids



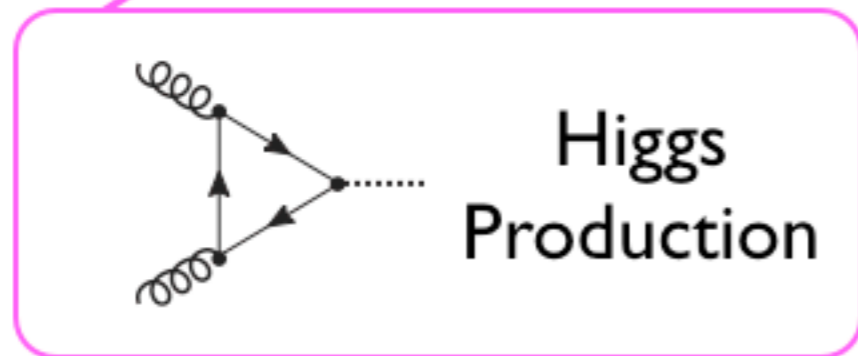
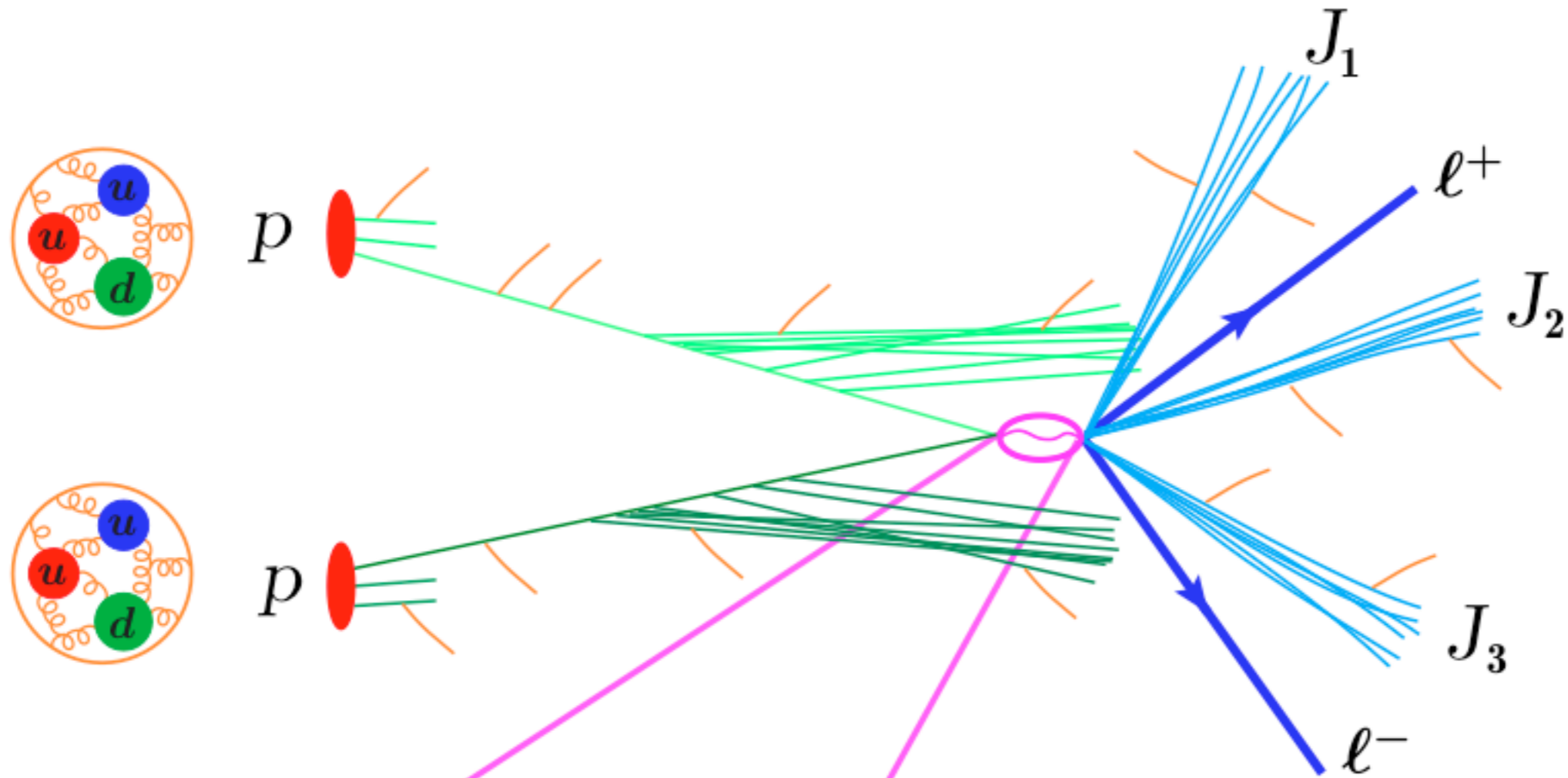
Anatomy of a High Energy Collision of Two Protons

a proton is a
strong interaction
bound state



Anatomy of a High Energy Collision of Two Protons

Search for New Heavy Particles at short distances



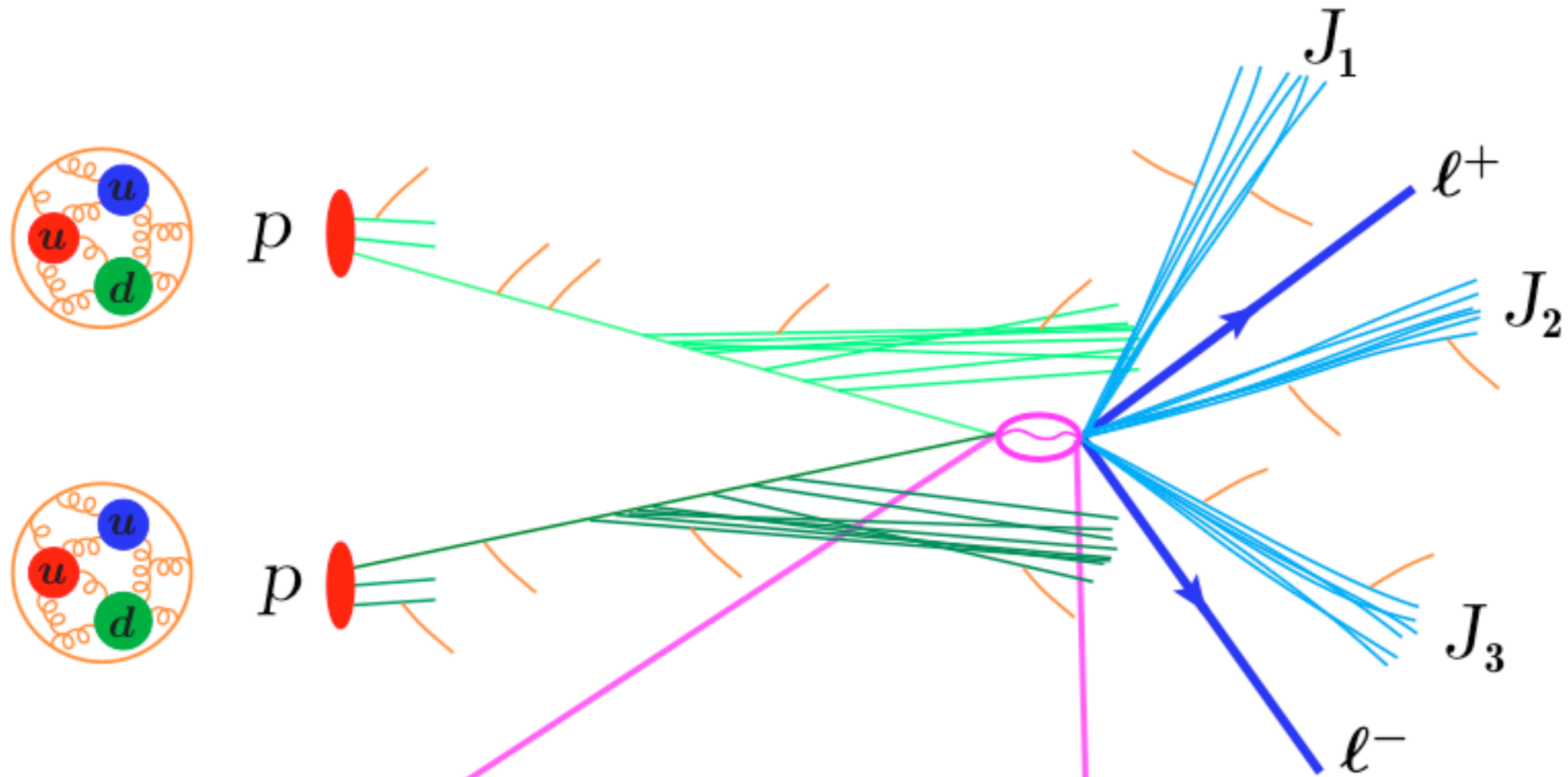
$$E = \frac{hc}{\lambda}$$

high energy E
= short distance λ

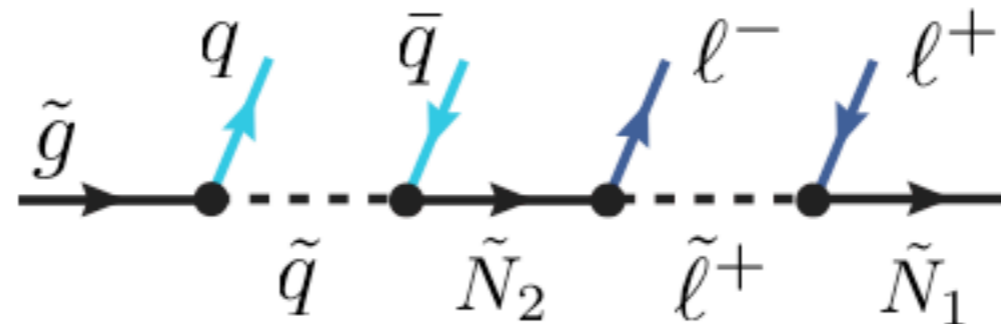
few TeV $\leftrightarrow 10^{-19}m$

Anatomy of a High Energy Collision of Two Protons

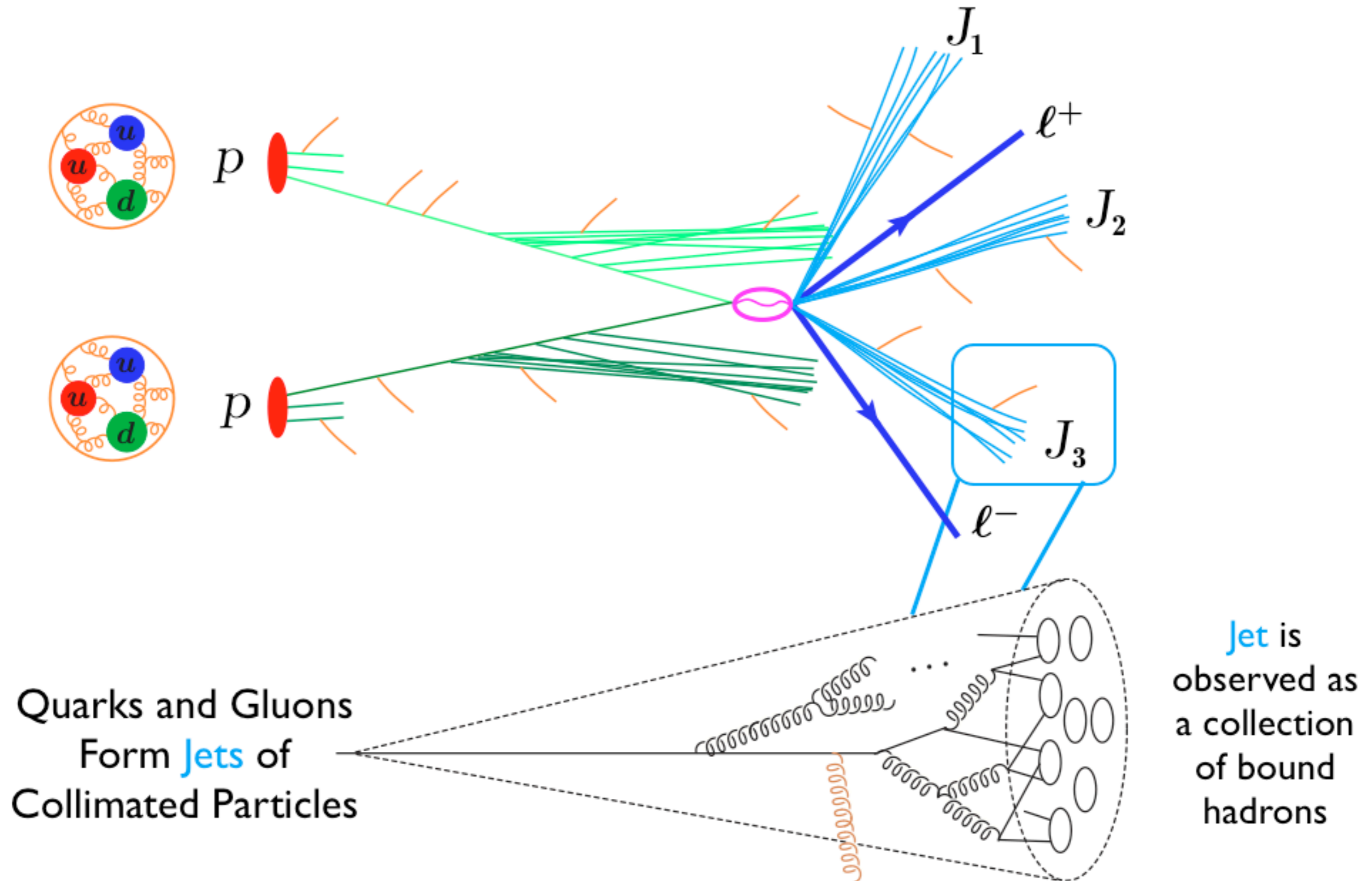
Search for New Heavy Particles at short distances



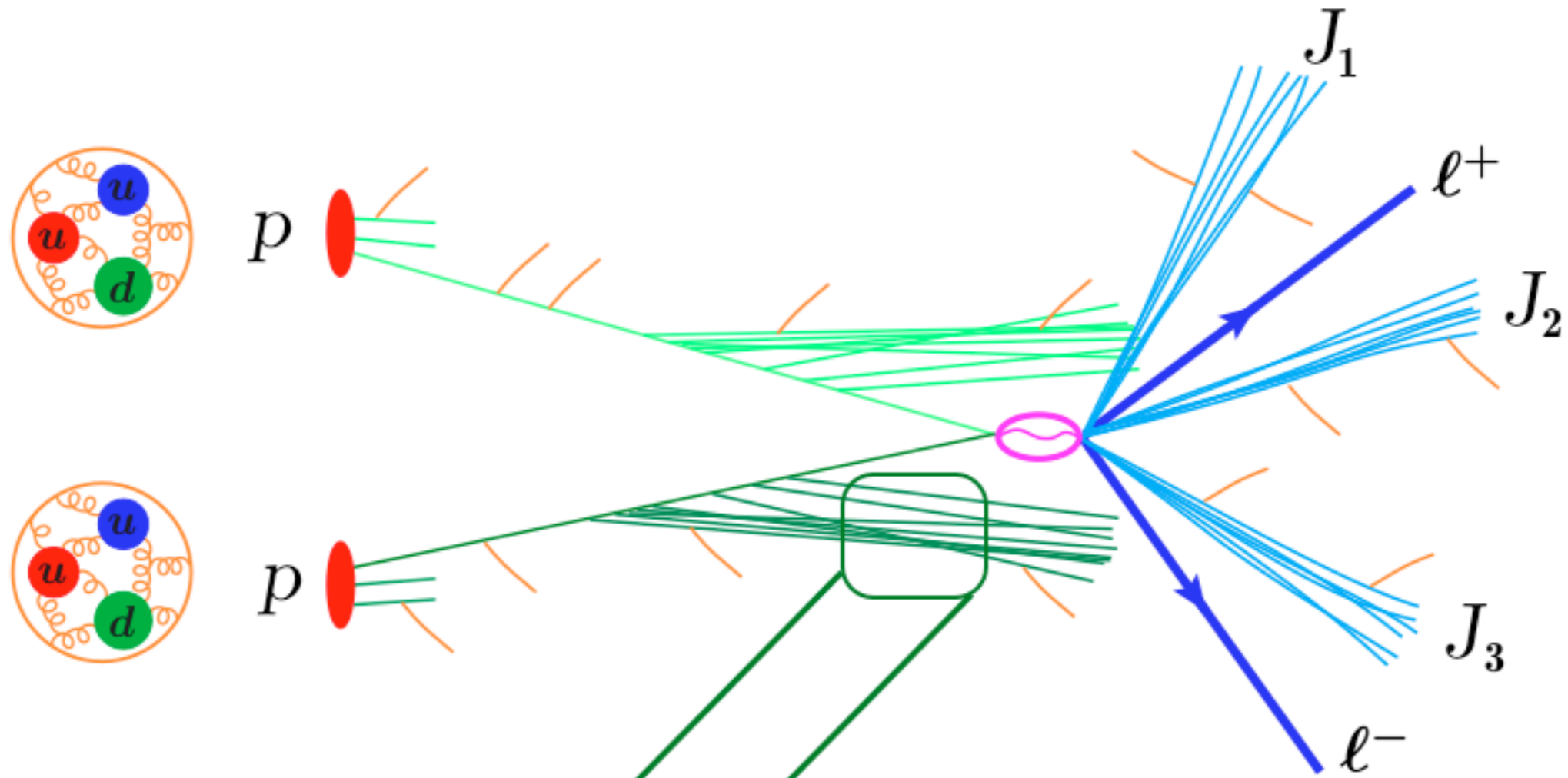
Decay Chain of SUSY particles



Anatomy of a High Energy Collision of Two Protons

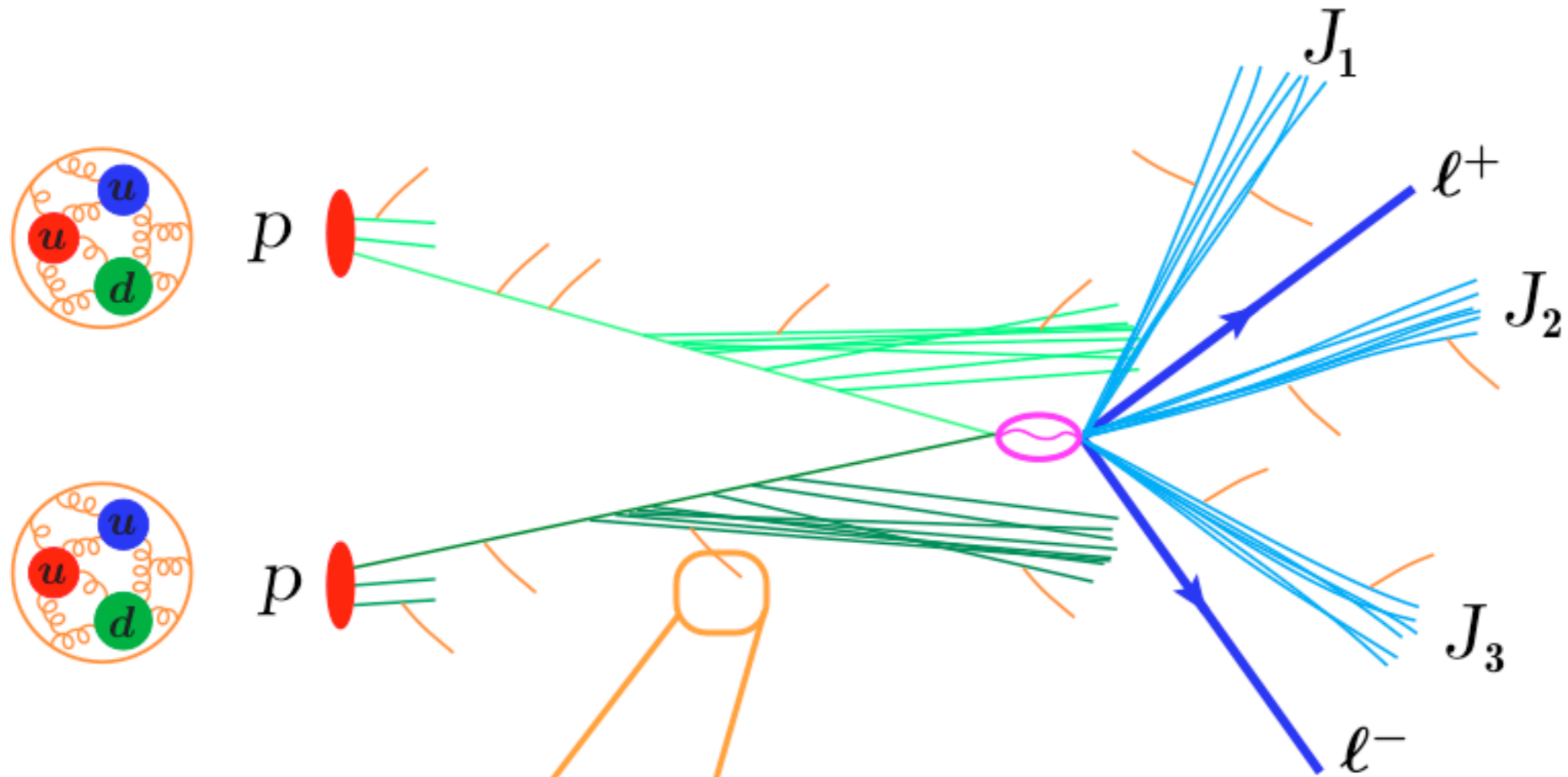


Anatomy of a High Energy Collision of Two Protons



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

from Madgraph

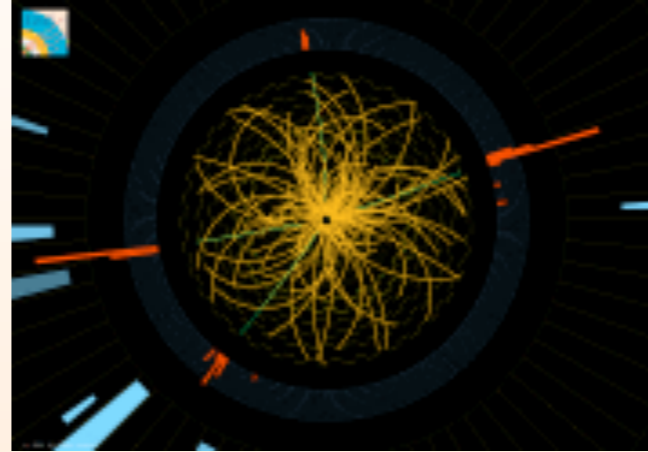
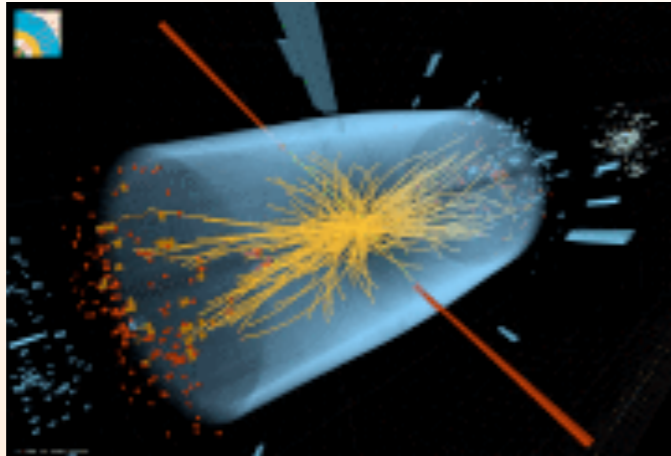
from Madgraph



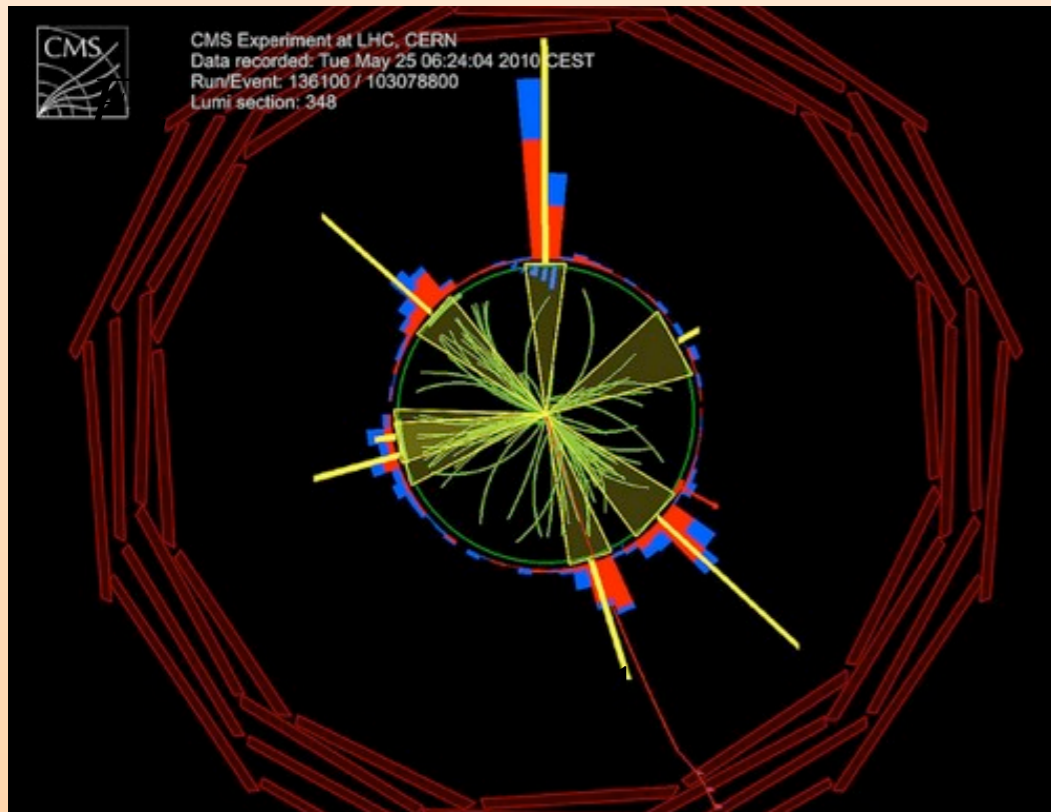


Here we collide hadrons and produce hadrons

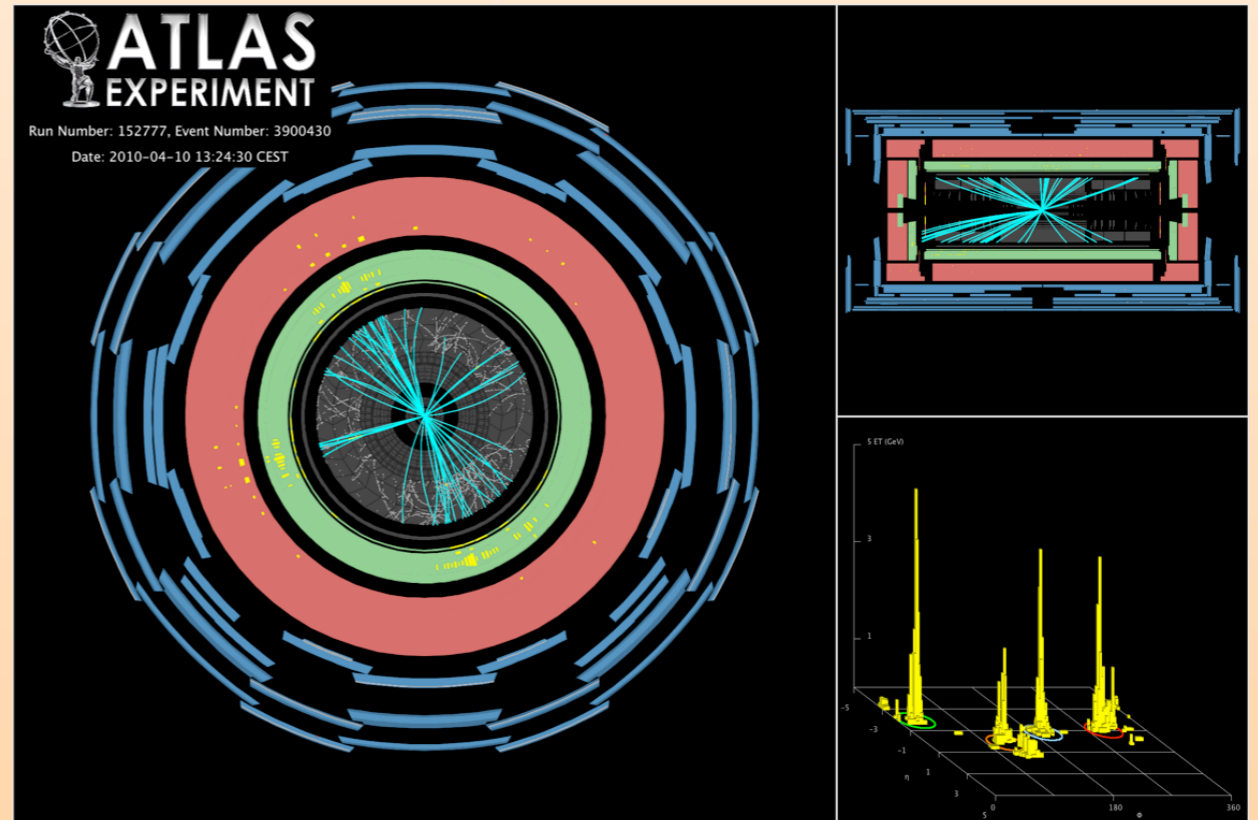
CMS 2 photon event



CMS multi-jet event



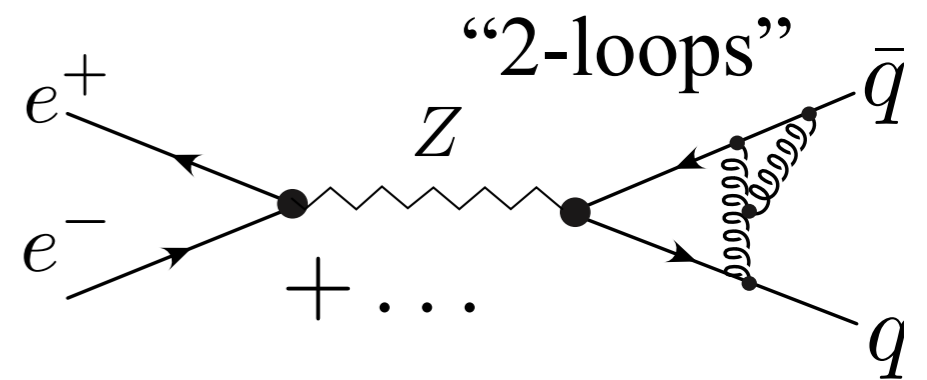
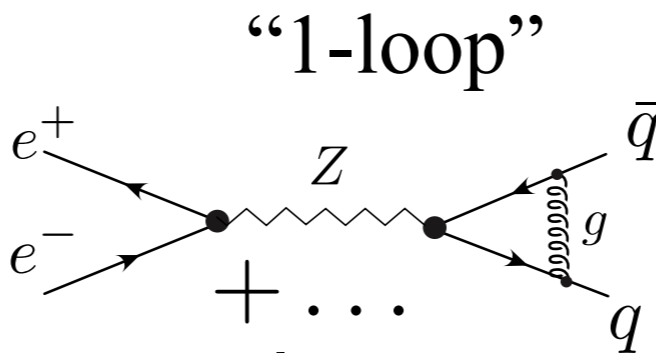
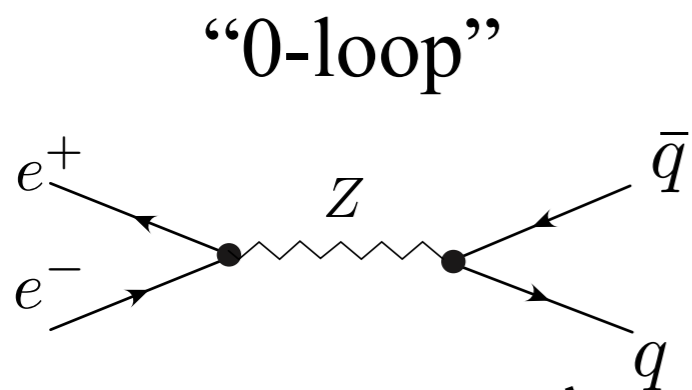
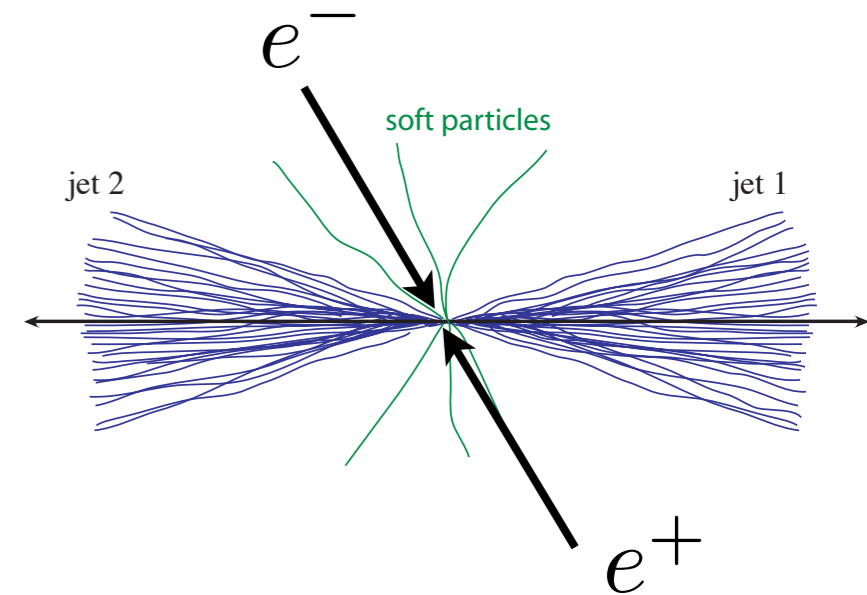
ATLAS 4-jet event



A key tool for Theorists:
Taylor Series

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

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



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

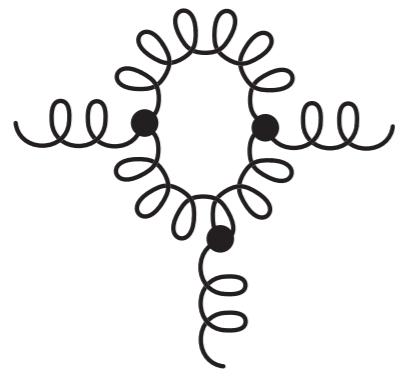
Series in α_s

Feynman Loop graphs are integrals

$$\alpha_s A_1 = \text{Diagram} = \int d^4 q \frac{\text{Numerator}}{(q^2)(q+p)^2(q-\bar{p})^2}$$

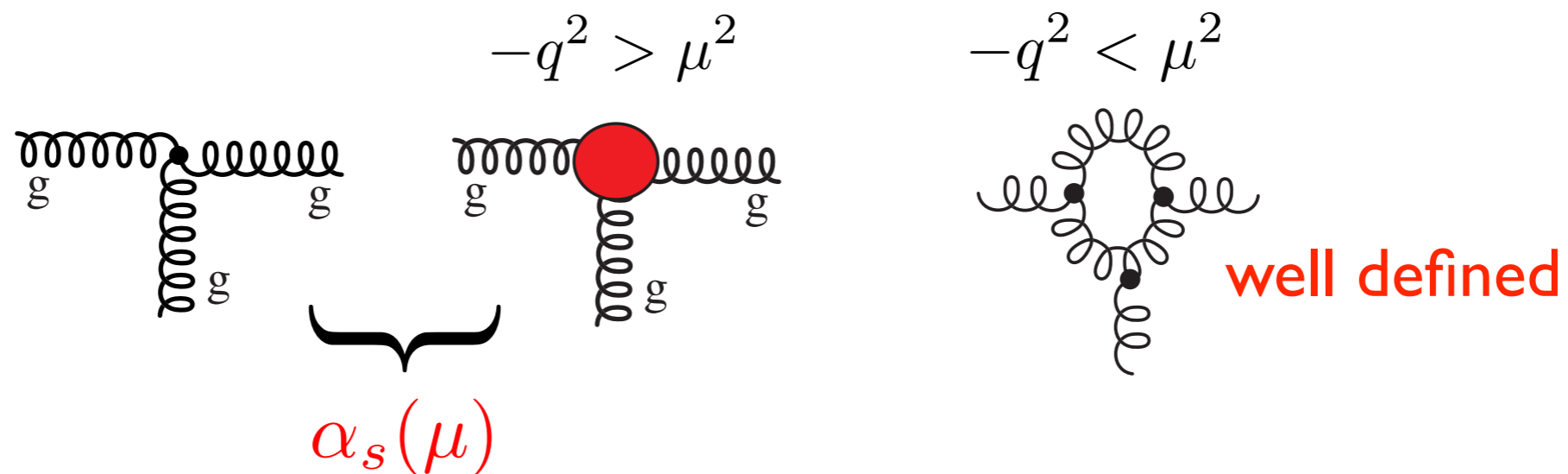
- $q^2 = (q_0)^2 - (\vec{q})^2$ Lorentz Symmetry constrains integrands
- **more loops** \rightarrow more integrals, calculations get **tough**
- the **more legs** poking out, the **harder** the integrals
state of the art for multi-legs is 6 legs at 1-loop
state of the art for multi-loop is 2 legs at 4-loops
- to handle results with 100's of legs (with 0-loops) we use approximations

Integrals can DIVERGE as $q \rightarrow \infty$



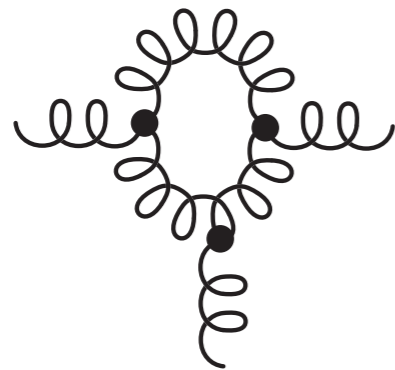
$$= \int d^4q \frac{q^2 + \dots}{(q^2)(q+p)^2(q-\bar{p})^2} \sim \int \frac{d^4q}{q^4} + \dots$$

- 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



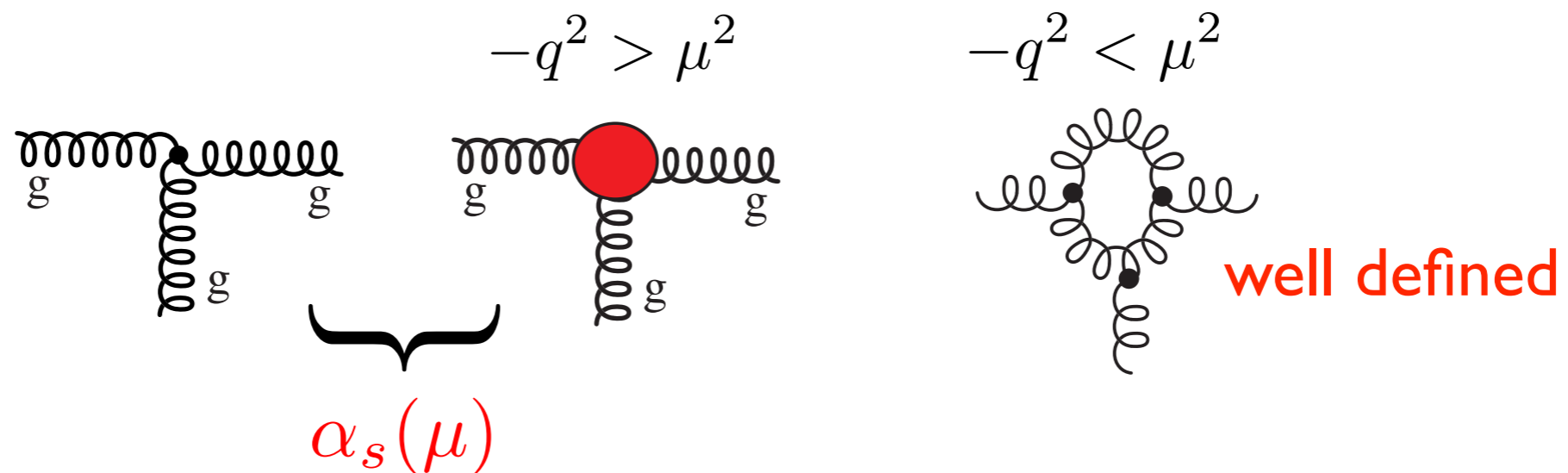
(You may have guessed that I'm oversimplifying, but this is morally correct)

Integrals can DIVERGE as $q \rightarrow \infty$

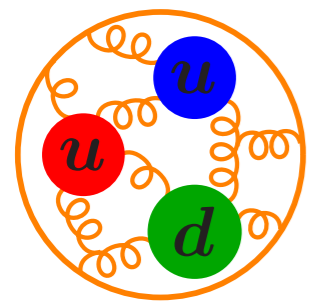


$$= \int d^4q \frac{q^2 + \dots}{(q^2)(q+p)^2(q-\bar{p})^2} \sim \int \frac{d^4q}{q^4} + \dots$$

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- introduce a cutoff parameter μ to remove large momentum parts and make the integrals well defined.
- absorb large momentum parts into the coupling



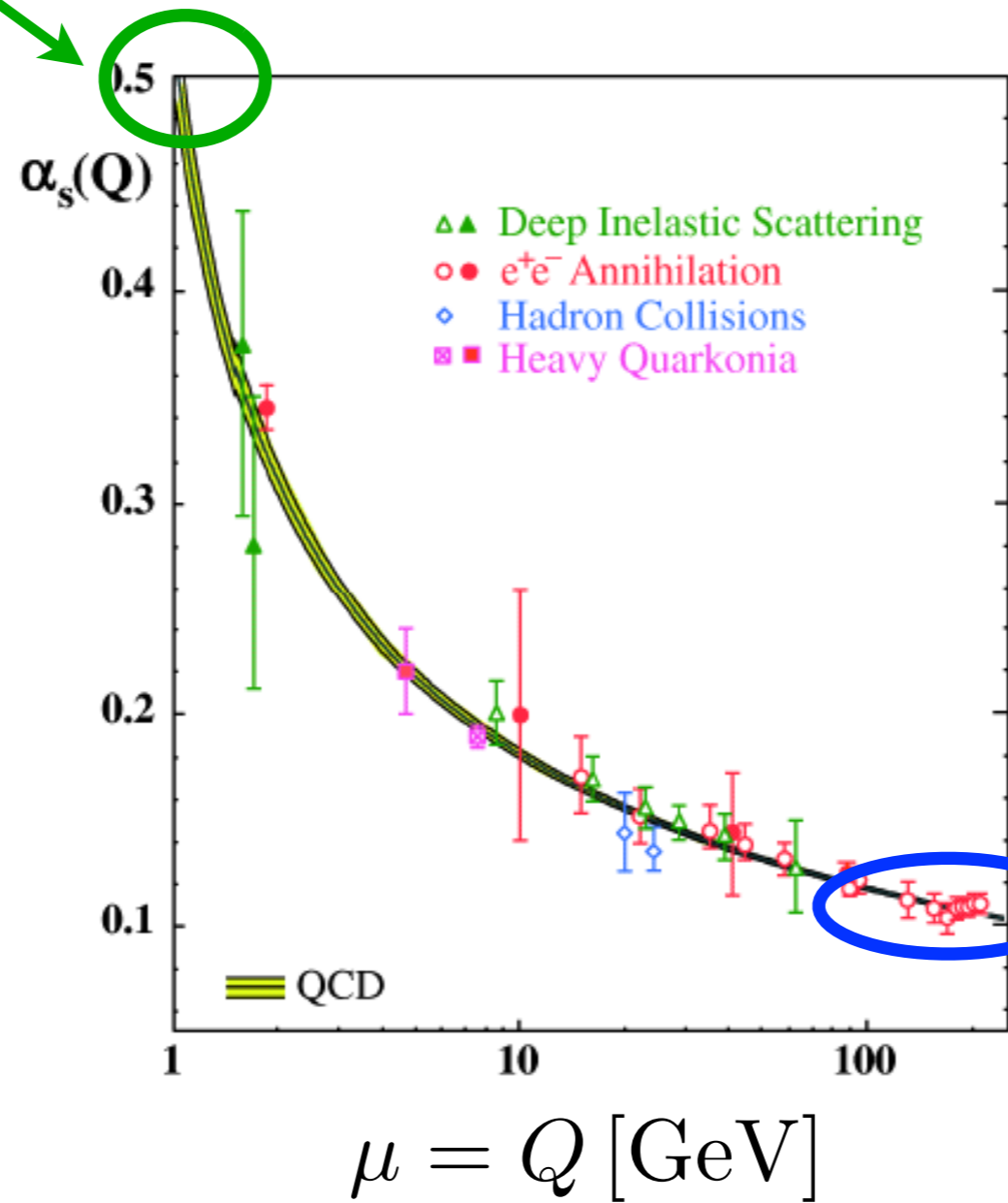
- coupling now depends on a parameter: $\alpha_s(\mu)$
- ALL large momentum divergences in Standard Model can be treated in this way !



proton

large α_s
bound quarks

Coupling Changes with resolution μ



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

small α_s ,
free quarks

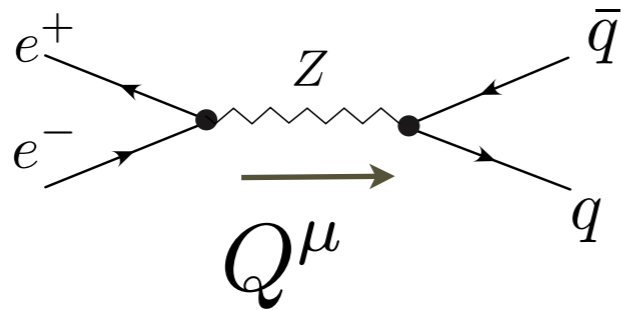
- How do we know what μ to pick for our Taylor Series?

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

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

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

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



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

- Need: $\mu \sim Q$

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

and we need an infinite number of terms

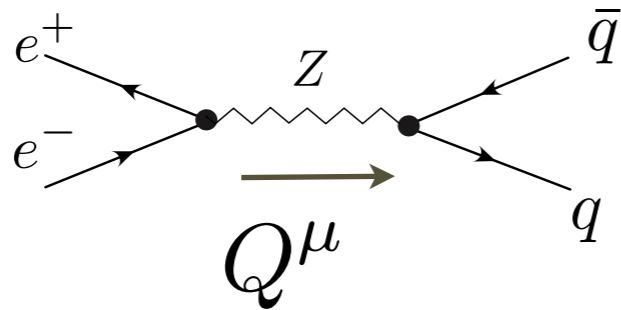
In fact, we can sum up an infinite series: $\sum_k A_k^L \left[\alpha_s(\mu) \ln\left(\frac{\mu}{Q}\right) \right]^k$

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

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

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

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



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

- 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”

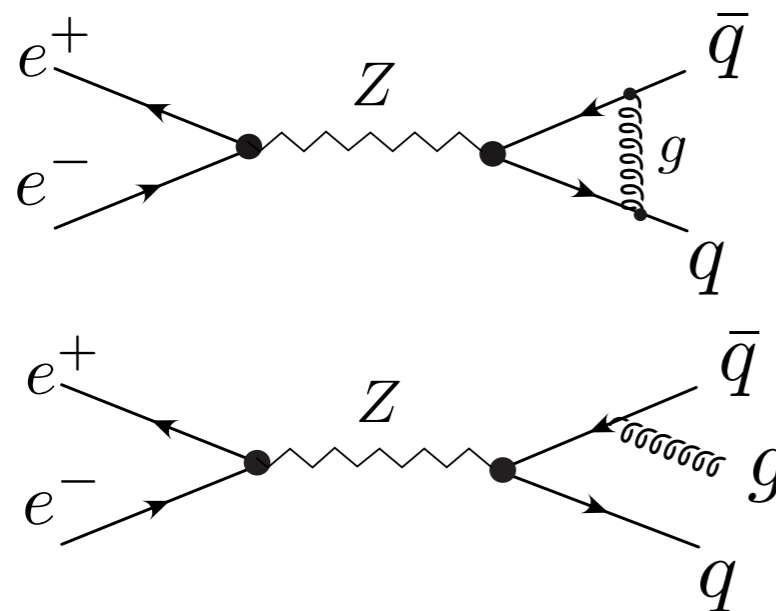
$$A = A_0 + \alpha_s(\mu) A_1 + \alpha_s^2(\mu) \left[A_2^L \ln \left(\frac{\mu}{Q} \right) + A_2^0 \right] + \alpha_s^3(\mu) \left[A_3^L \ln^2 \left(\frac{\mu}{Q} \right) + \dots \right] + \dots$$

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

Q_1, Q_2

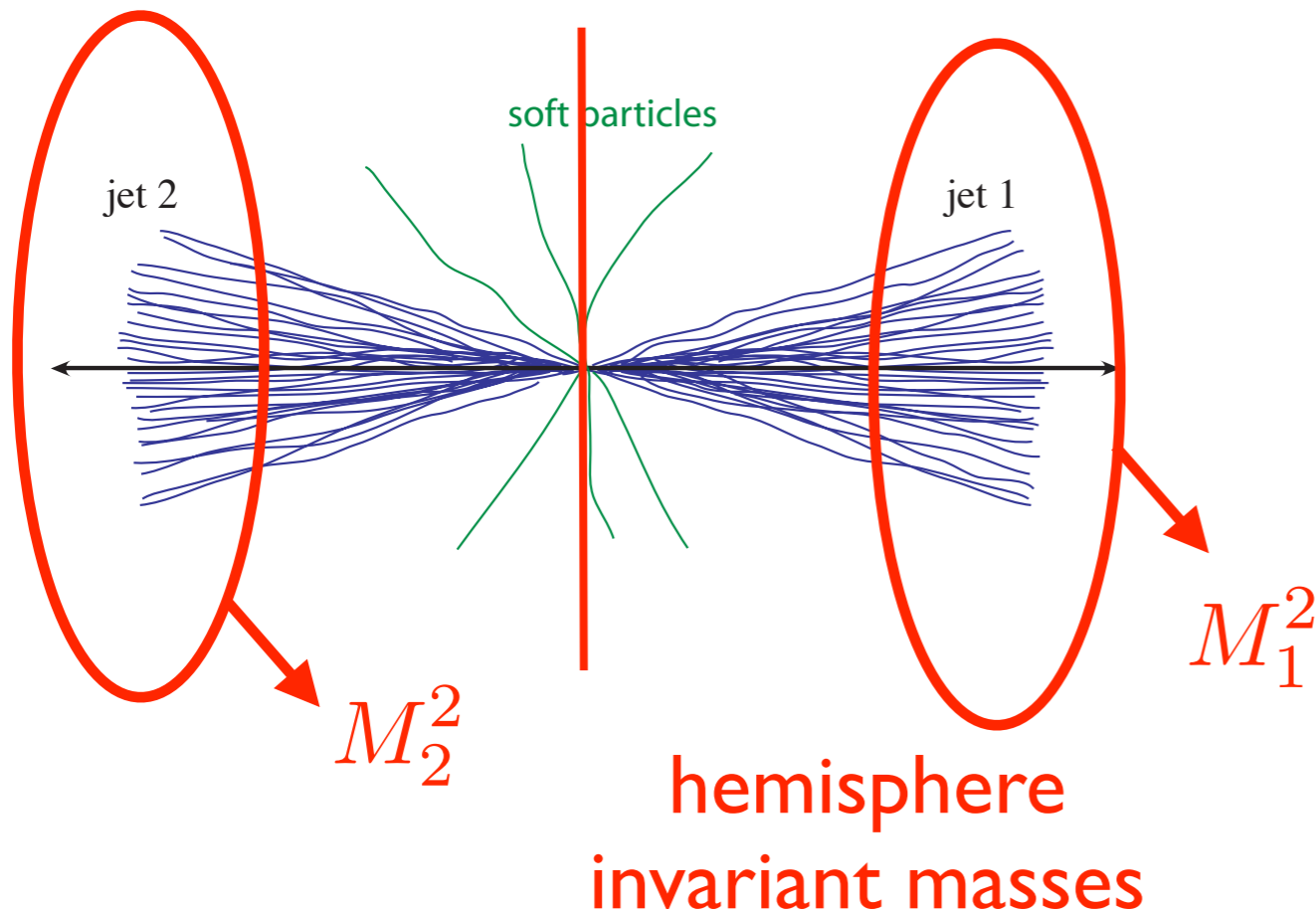
More about this later.

Integrals can DIVERGE as $q \rightarrow 0$



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

Must be careful about defining observables



$$M_1^2 = \left(\sum_{i \in \text{hem1}} p_i^\mu \right)^2$$

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 $\propto \sigma(\Delta) = \int_0^{\Delta^2} d\bar{M}^2 \frac{d\sigma}{d\bar{M}^2}$

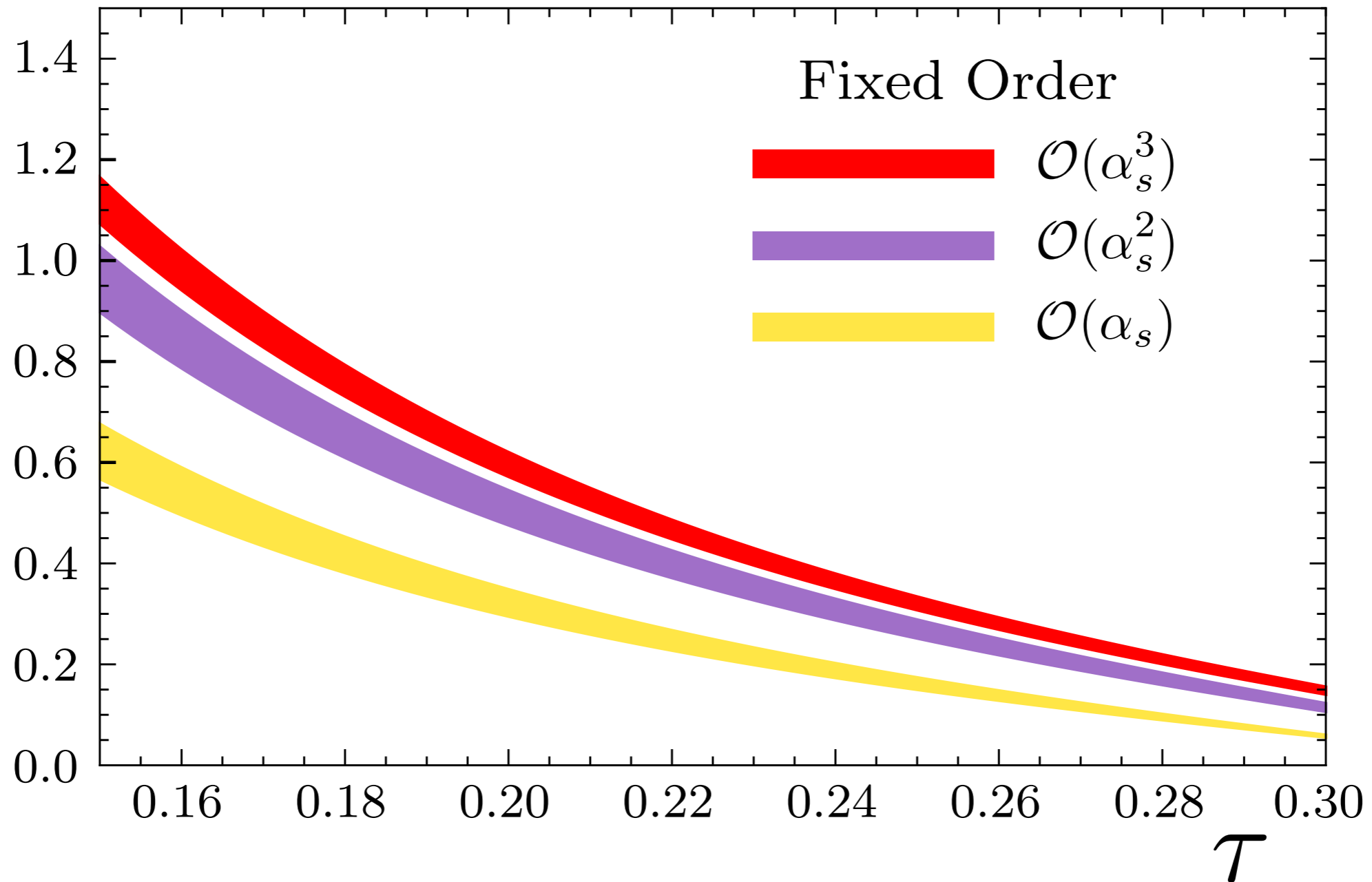
$$\begin{array}{rcccc}
 & \mathcal{O}(\alpha_s) & \mathcal{O}(\alpha_s^2) & \mathcal{O}(\alpha_s^3) & \\
 \sigma(\Delta) = & 1 & + \alpha_s L^2 & + \alpha_s^2 L^4 & + \alpha_s^3 L^6 & + \dots \\
 & + \alpha_s L & + \alpha_s^2 L^3 & + \alpha_s^3 L^5 & + \dots & \\
 & + \alpha_s & + \alpha_s^2 L^2 & + \alpha_s^3 L^4 & + \dots & \\
 & & + \alpha_s^2 L & + \alpha_s^3 L^3 & + \dots & \\
 & & + \alpha_s^2 & + \alpha_s^3 L^2 & + \dots & \\
 & & & + \alpha_s^3 L & + \dots & \\
 & & & + \alpha_s^3 & + \dots & \\
 & & & & \dots & \\
 L = \ln \left(\frac{\Delta^2}{Q^2} \right) & & & & &
 \end{array}$$

“double logs”

Fixed Order Theory Uncertainty

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

$$\frac{1}{\sigma} \frac{d\sigma}{d\tau}$$



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

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

solved by log
summation

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

LL

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

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

solved by log
summation

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

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

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

solved by log
summation

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

LL
NLL
NLL'

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

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

solved by log
summation

$$\sigma(\Delta) = 1 + \alpha_s L^2 + \alpha_s^2 L^4 + \alpha_s^3 L^6 + \dots$$

$$+ \alpha_s L + \alpha_s^2 L^3 + \alpha_s^3 L^5 + \dots$$

$$+ \alpha_s + \alpha_s^2 L^2 + \alpha_s^3 L^4 + \dots$$

$$+ \alpha_s^2 L + \alpha_s^3 L^3 + \dots$$

$$+ \alpha_s^2 + \alpha_s^3 L^2 + \dots$$

$$+ \alpha_s^3 L + \dots$$

$$+ \alpha_s^3 + \dots$$

$$\dots$$

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

$$\sigma(\Delta) = 1 + \alpha_s L^2 + \alpha_s^2 L^4 + \alpha_s^3 L^6 + \dots$$

$$+ \alpha_s L + \alpha_s^2 L^3 + \alpha_s^3 L^5 + \dots$$

$$+ \alpha_s + \alpha_s^2 L^2 + \alpha_s^3 L^4 + \dots$$

$$+ \alpha_s^2 L + \alpha_s^3 L^3 + \dots$$

$$+ \alpha_s^2 + \alpha_s^3 L^2 + \dots$$

$$+ \alpha_s^3 L + \dots$$

$$+ \alpha_s^3 + \dots$$

$$\dots$$

LL
NLL
NLL'
NNLL
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

$$\sigma(\Delta) = 1 + \alpha_s L^2 + \alpha_s^2 L^4 + \alpha_s^3 L^6 + \dots$$
$$+ \alpha_s L + \alpha_s^2 L^3 + \alpha_s^3 L^5 + \dots$$
$$+ \alpha_s + \alpha_s^2 L^2 + \alpha_s^3 L^4 + \dots$$
$$+ \alpha_s^2 L + \alpha_s^3 L^3 + \dots$$
$$+ \alpha_s^2 + \alpha_s^3 L^2 + \dots$$
$$+ \alpha_s^3 L + \dots$$
$$+ \alpha_s^3 + \dots$$

...

LL

NLL

NLL'

NNLL

NNLL'

N³LL

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

Large Logs

$\alpha_s \ll 1$

but

$\alpha_s L^2 \sim 1$

solved by log
summation

$$\sigma(\Delta) = 1 + \alpha_s L^2 + \alpha_s^2 L^4 + \alpha_s^3 L^6 + \dots$$
$$+ \alpha_s L + \alpha_s^2 L^3 + \alpha_s^3 L^5 + \dots$$
$$+ \alpha_s + \alpha_s^2 L^2 + \alpha_s^3 L^4 + \dots$$
$$+ \alpha_s^2 L + \alpha_s^3 L^3 + \dots$$
$$+ \alpha_s^2 + \alpha_s^3 L^2 + \dots$$
$$+ \alpha_s^3 L + \dots$$
$$+ \alpha_s^3 + \dots$$
$$L = \ln \left(\frac{\Delta^2}{Q^2} \right)$$

LL

NLL

NLL'

NNLL

NNLL'

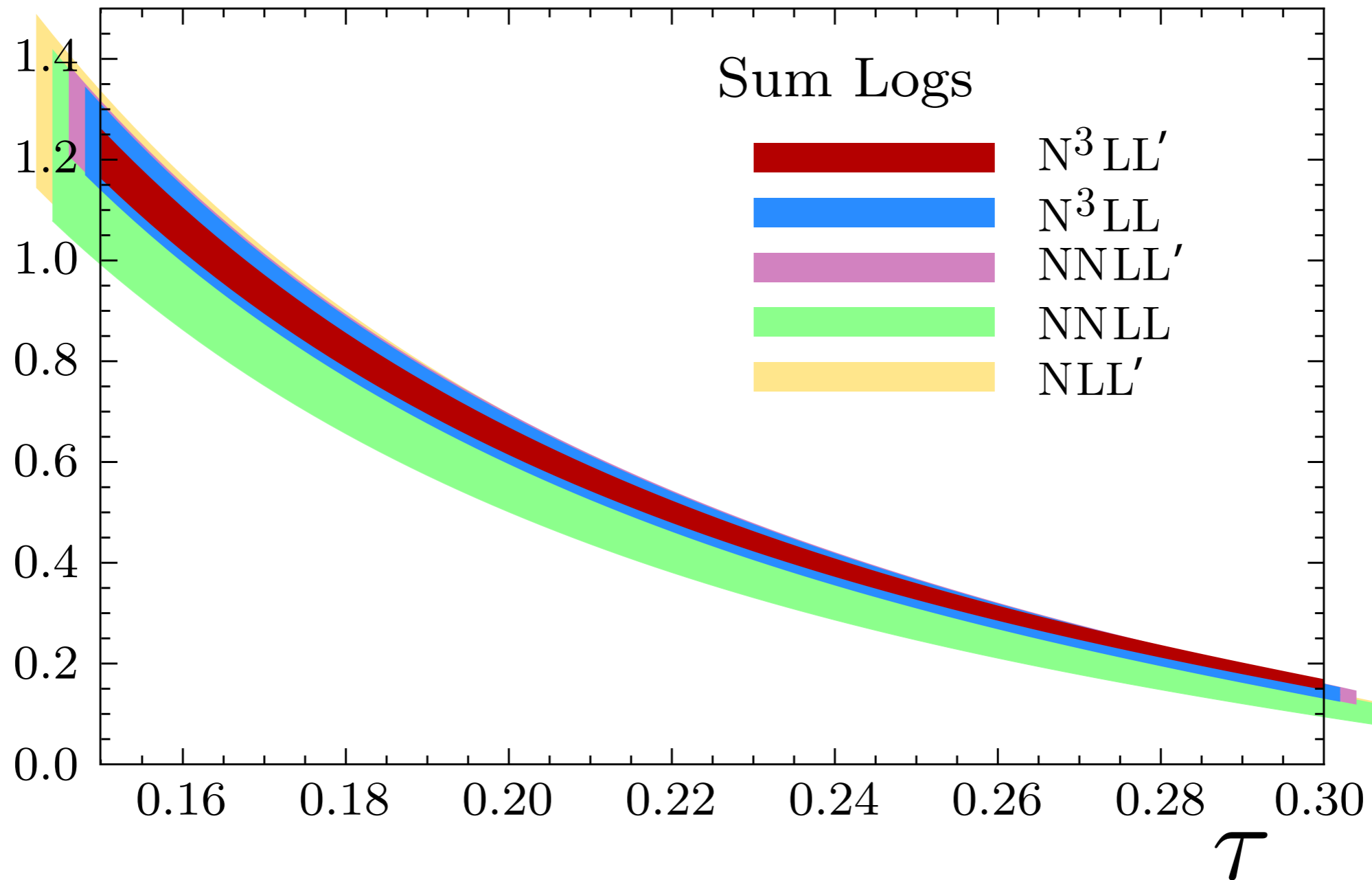
N³LL

N³LL'

Theory Uncertainty with Log Summation

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

$$\frac{1}{\sigma} \frac{d\sigma}{d\tau}$$

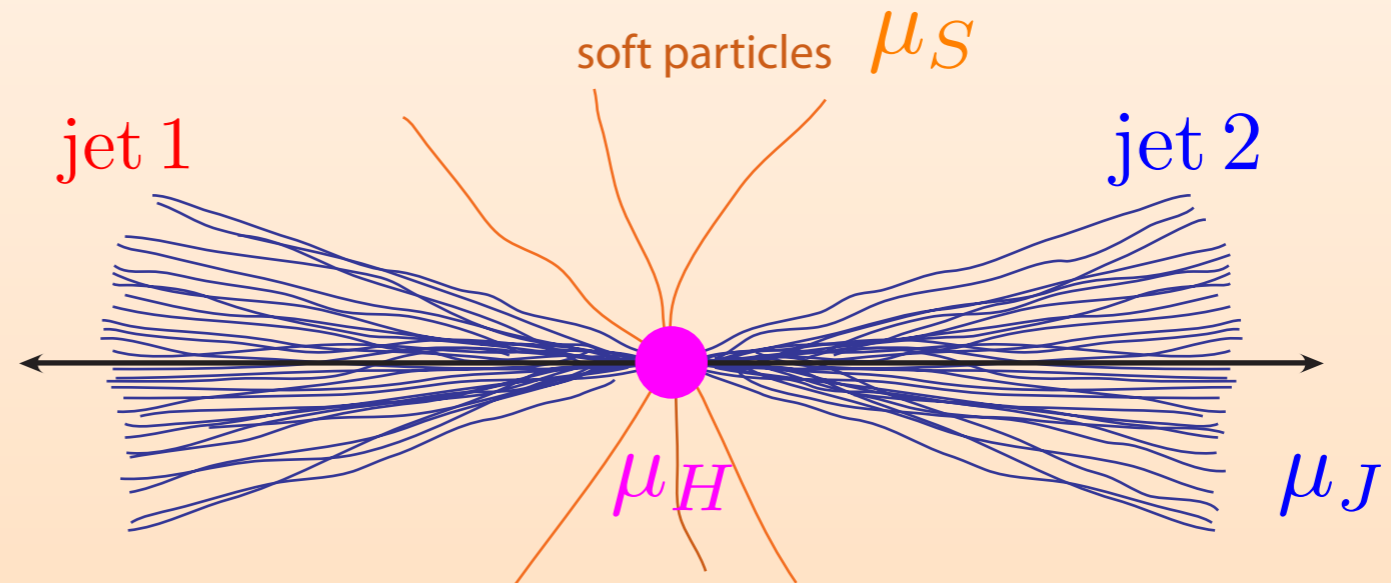
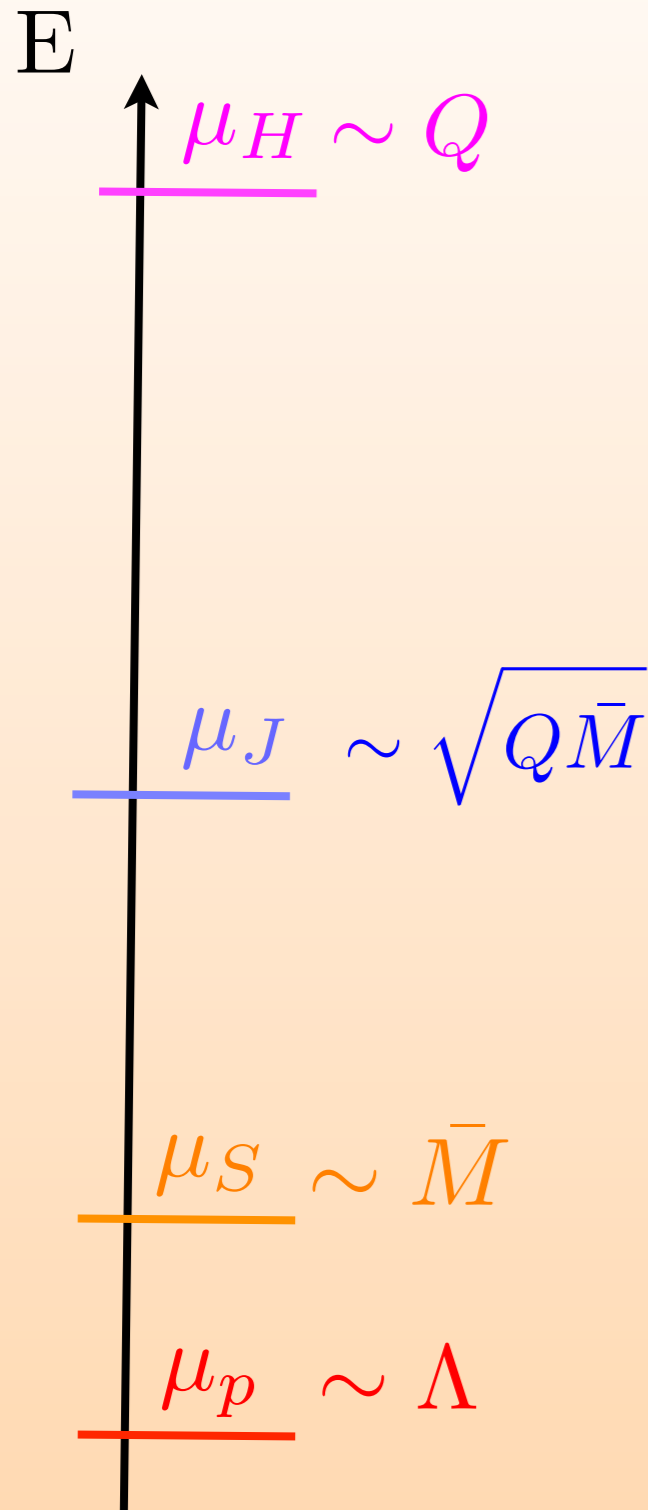


Becher, Schwartz; Abbate, Fickinger, Hoang, Mateu, I.S.

How?

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

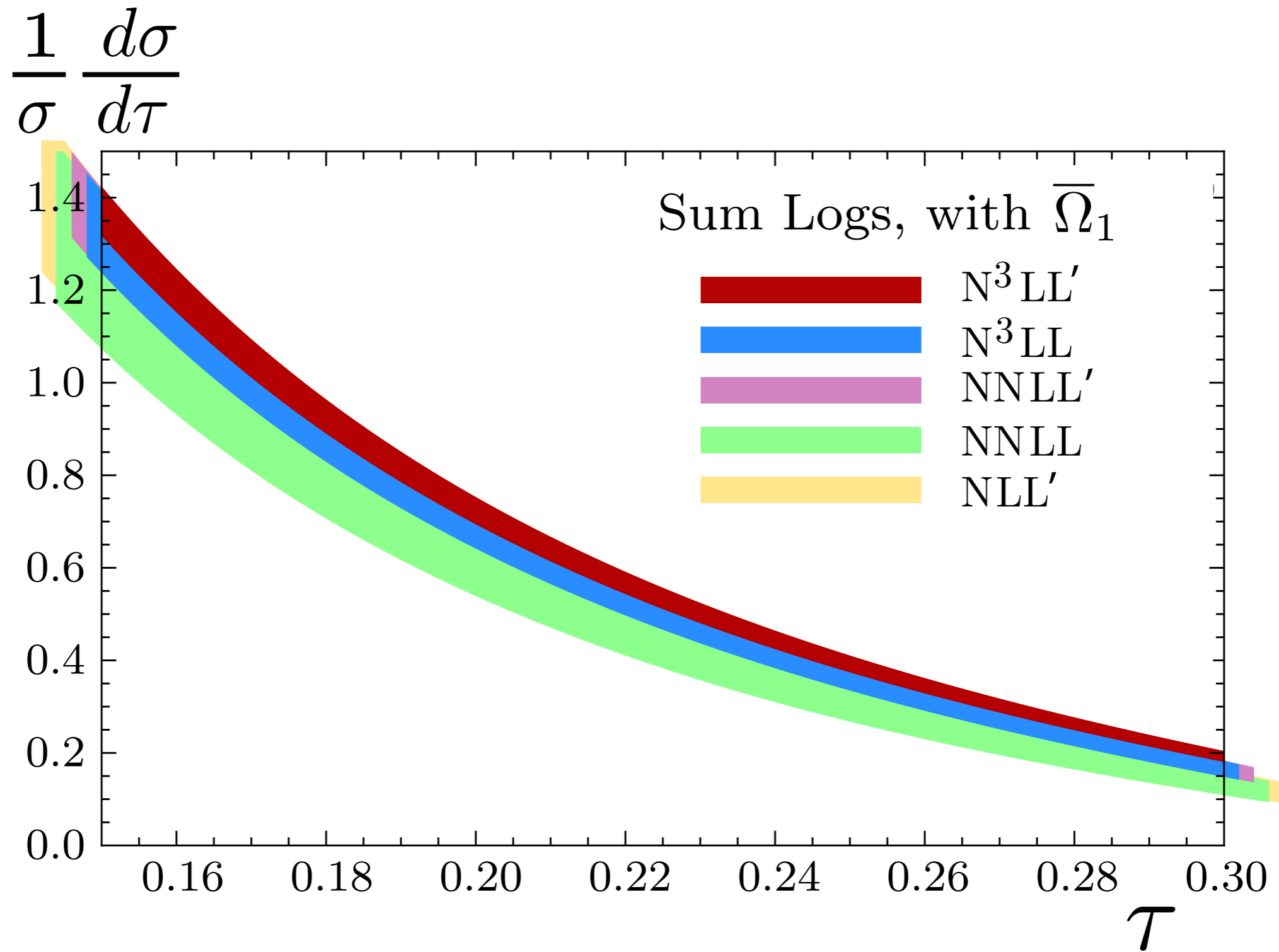
$$\begin{aligned} \left[1 + \alpha_s \ln^2(\bar{M}/Q) + \dots\right] &= \left[1 + 2\alpha_s \ln^2(\mu/Q) + \dots\right] \\ &\times \left[1 - \alpha_s \ln^2(\mu^2/Q\bar{M}) + \dots\right] \\ &\times \left[1 + 2\alpha_s \ln^2(\mu/\bar{M}) + \dots\right] \end{aligned}$$



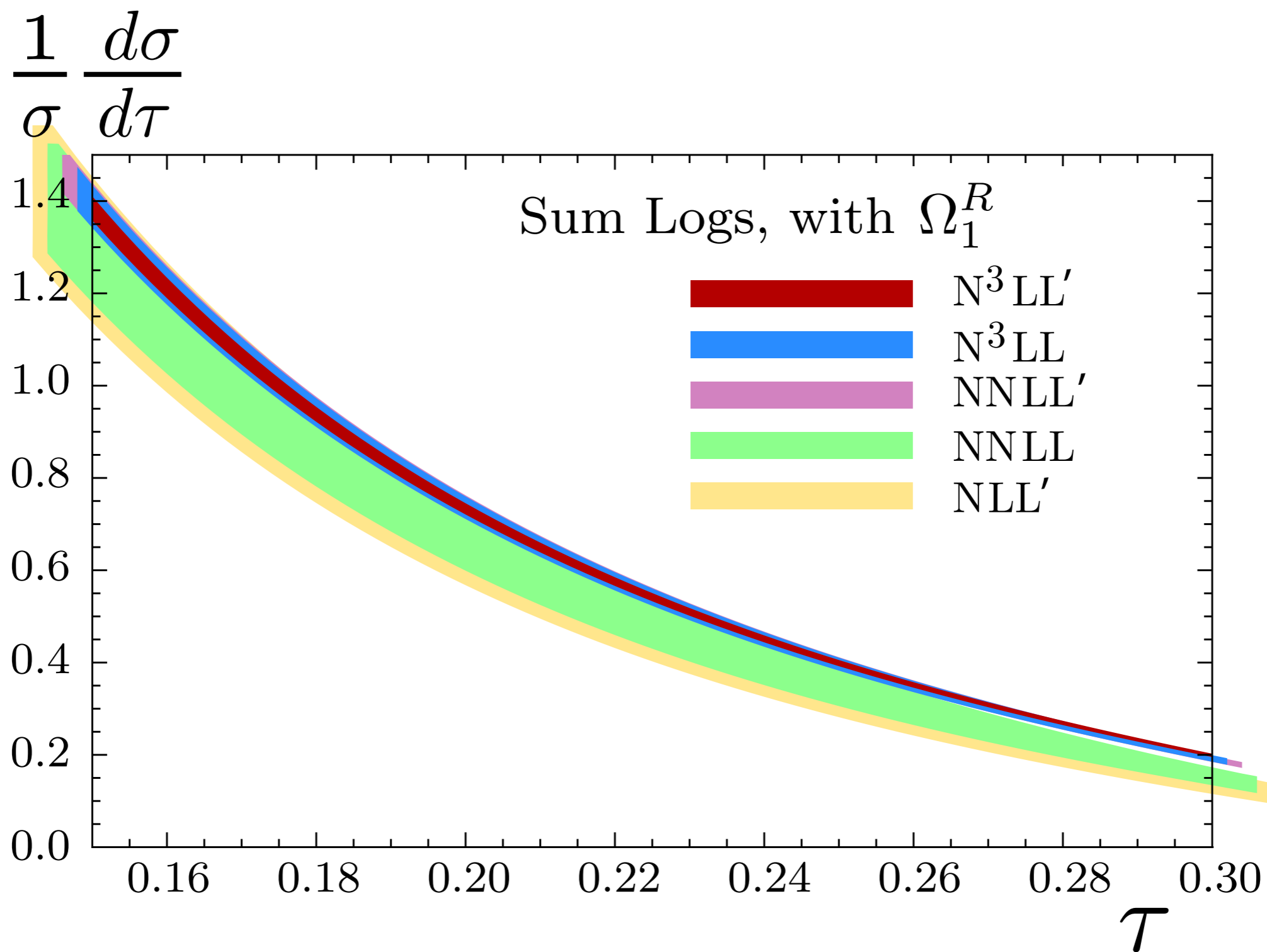
all orders: $\sigma = H J \otimes S \otimes F$ **“Factorization”**

$$\begin{aligned} F \text{ induces series : } \tau &= \frac{\Lambda}{Q} \left[\alpha_s \ln(\mu/\Lambda) + \alpha_s^2 \ln^2(\mu/\Lambda) \dots \right] \\ &= \tau - \frac{2\Omega_1}{Q} \qquad \alpha_s(\Lambda) \sim 1 \end{aligned}$$

Theory Uncertainty & Hadronic effects



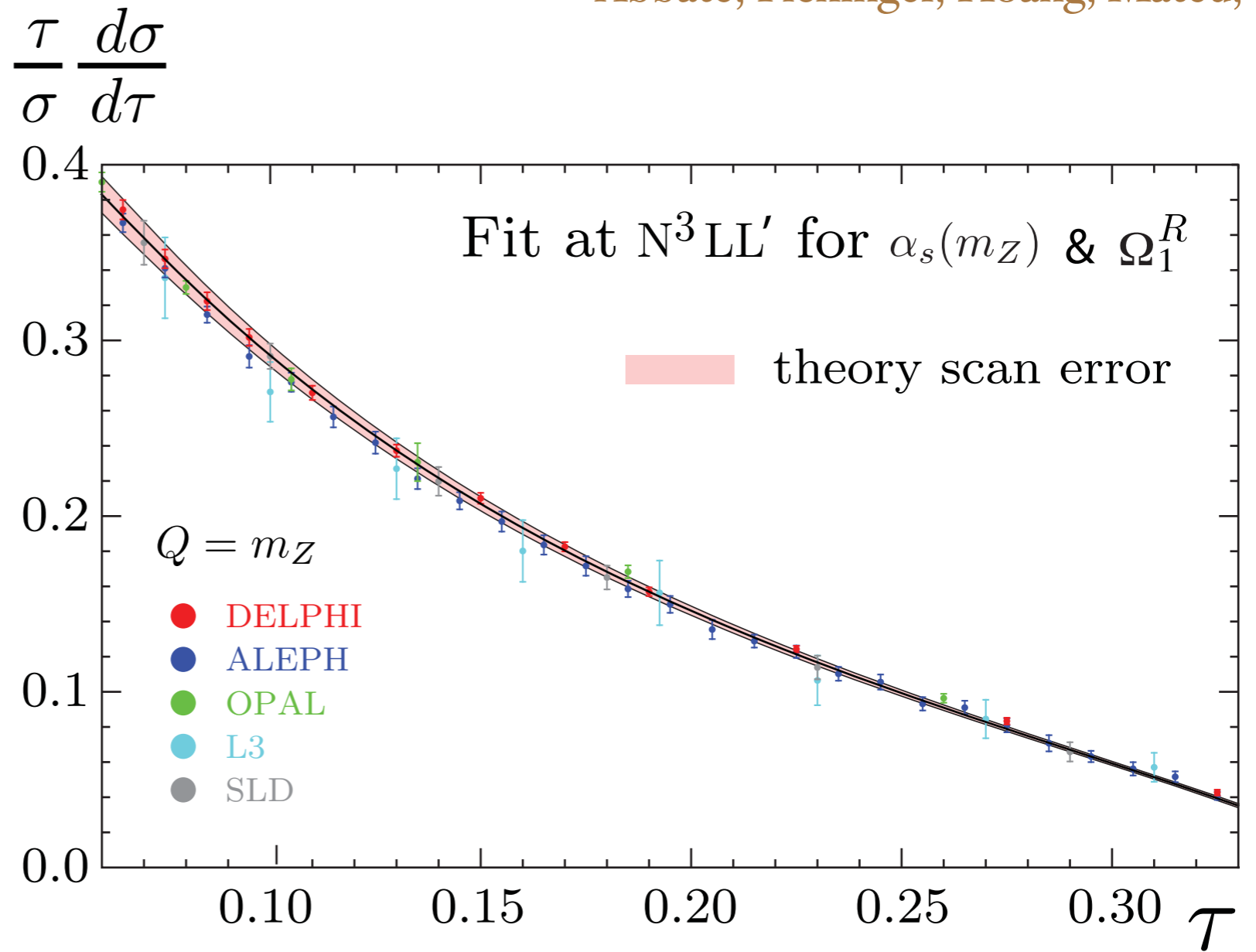
Theory Uncertainty & Hadronic effects



A Tail Fit

two parameter fit:

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



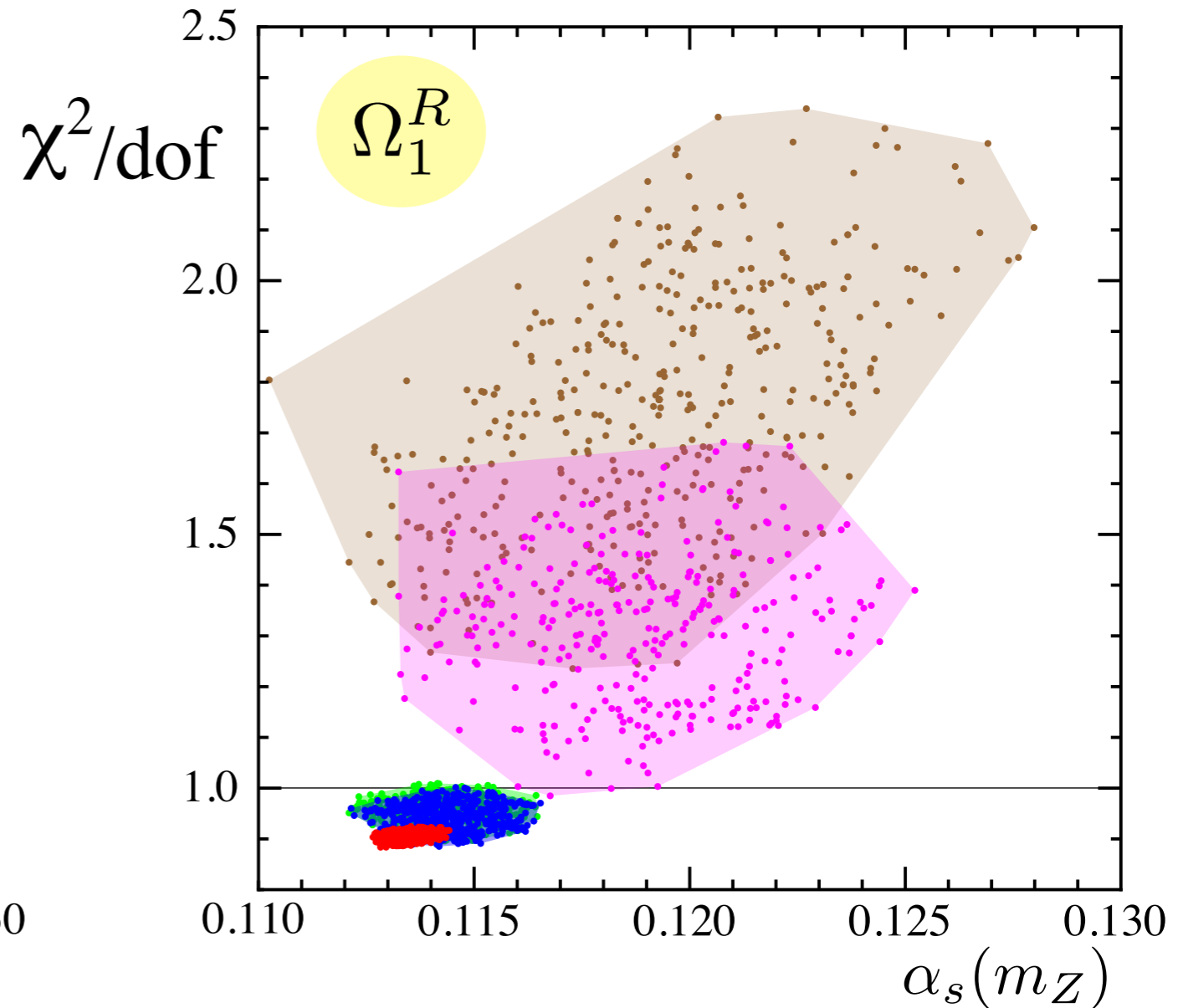
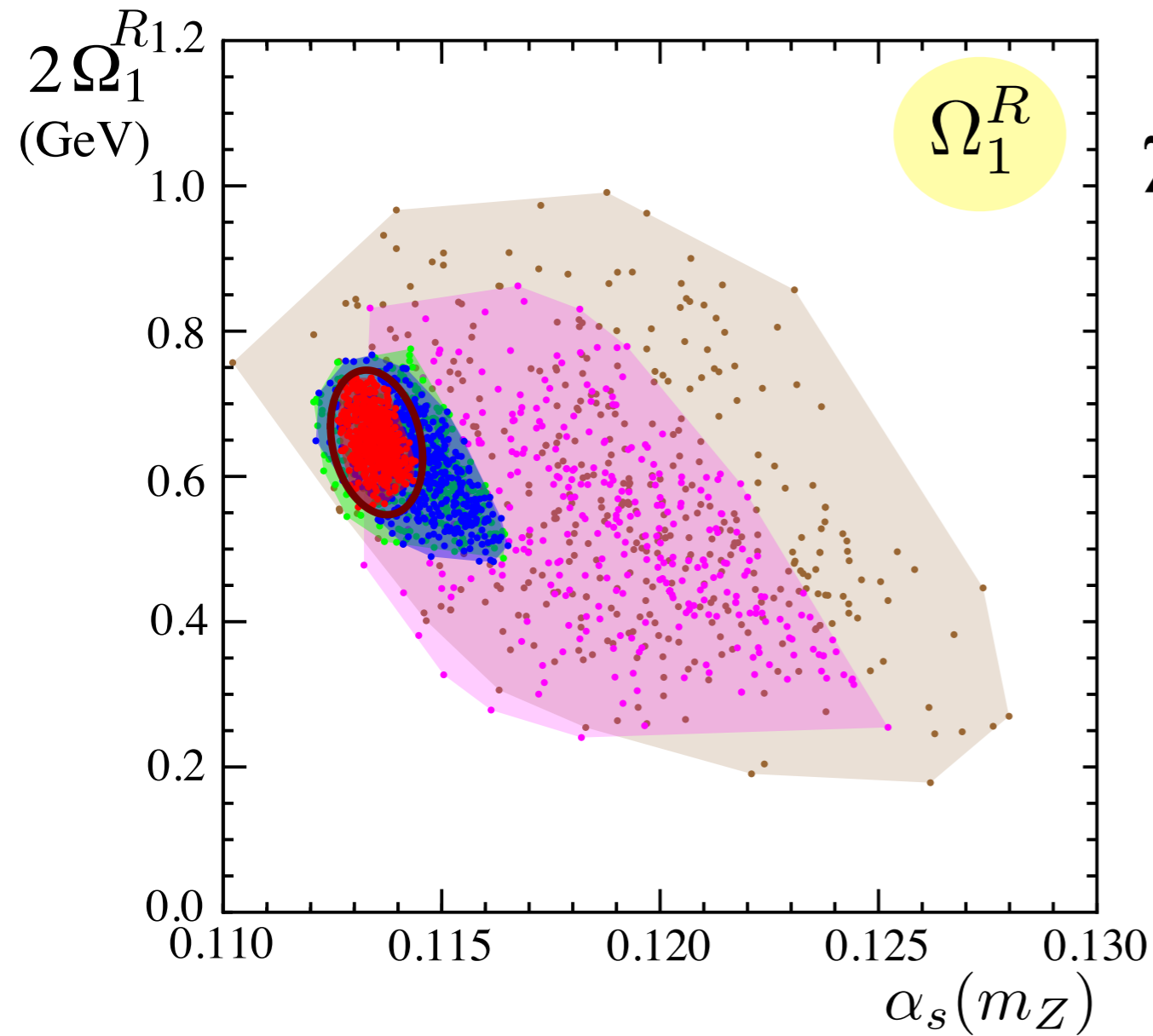
Fit Uncertainties: statistical errors + systematic errors + hadronization
($2\Omega_1^R$)

Higher Order Theory

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

Theory Scan Results

NLL', NNLL, NNLL', N³LL, N³LL'



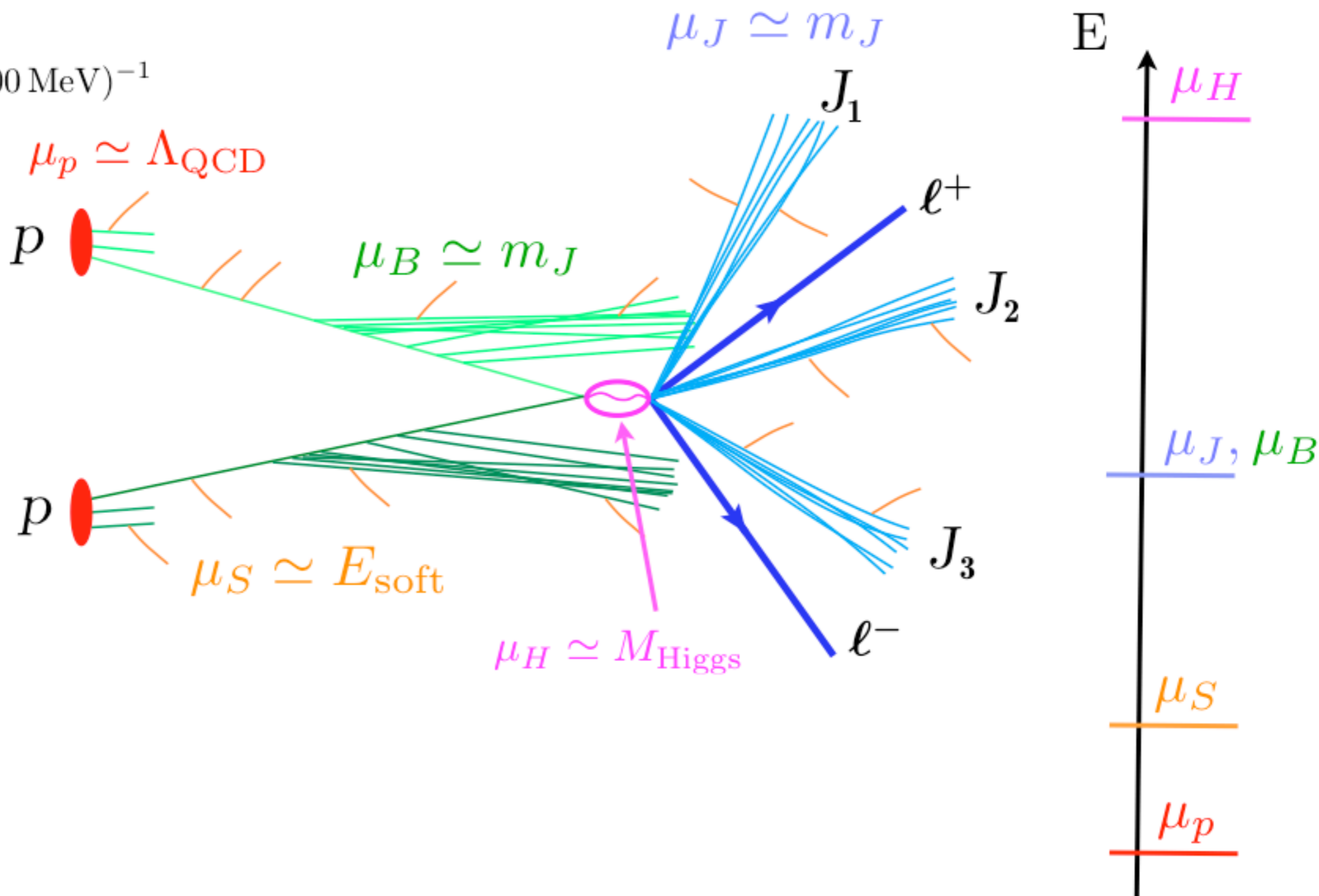
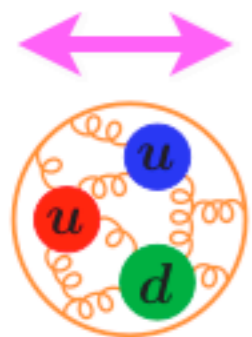
$$\alpha_s(m_Z) = 0.1135 \pm (0.00002)_{\text{expt}} \pm (0.00005)_{\text{hadr}} \pm (0.00009)_{\text{pert}}$$

$$\Omega_1 = 0.324 \pm (0.0009)_{\text{expt}} \pm (0.013)_{\Omega_2} \pm (0.030)_{\alpha_s(m_Z)} \pm (0.045)_{\text{pert}} \text{ GeV}$$

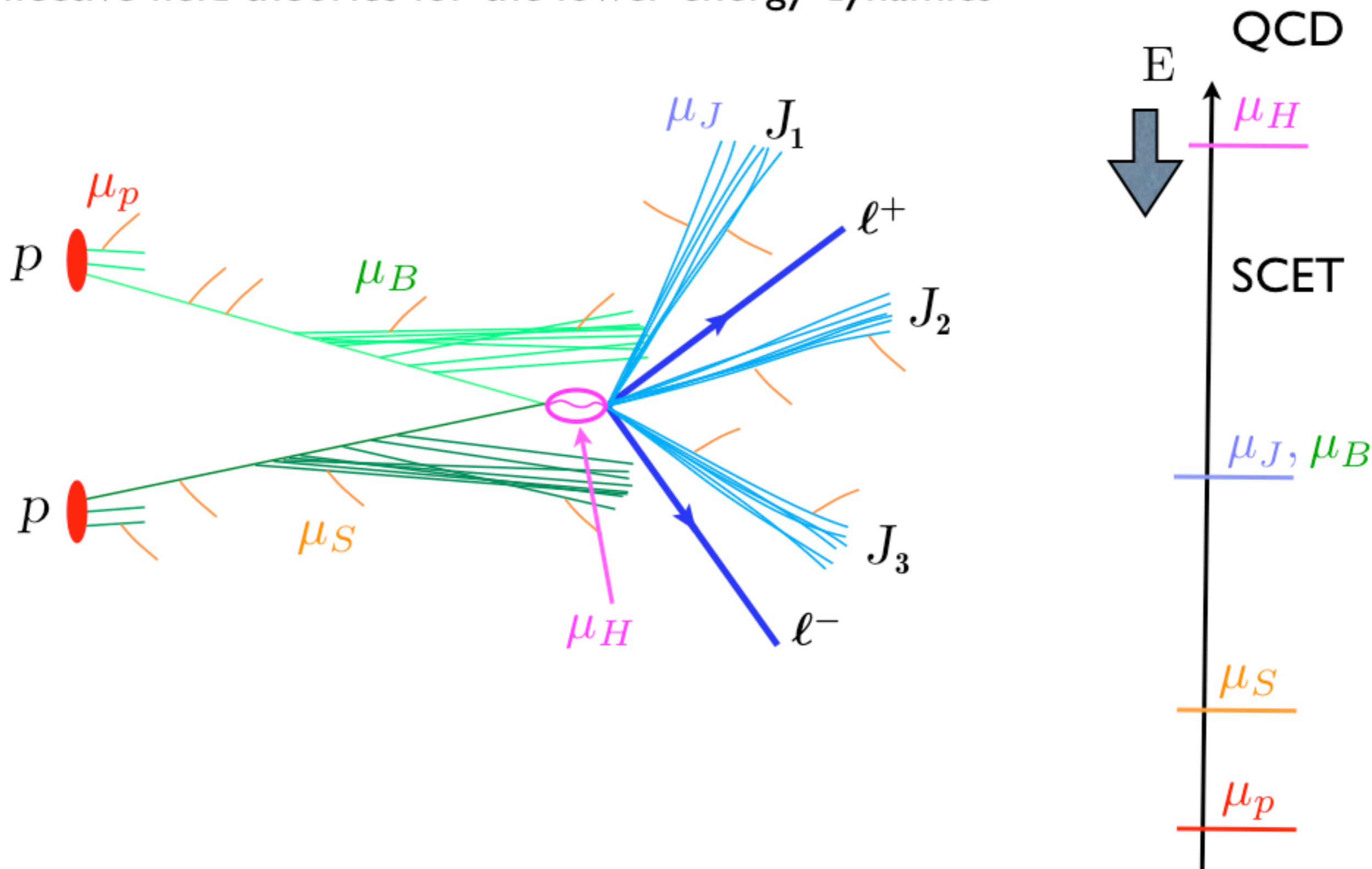
Back to the LHC

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

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

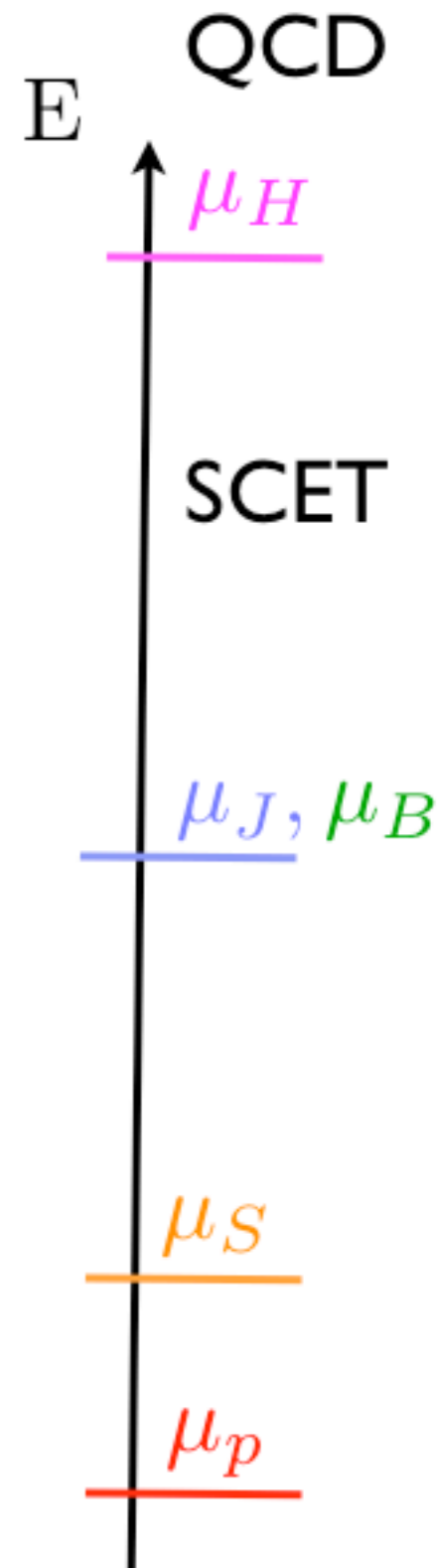
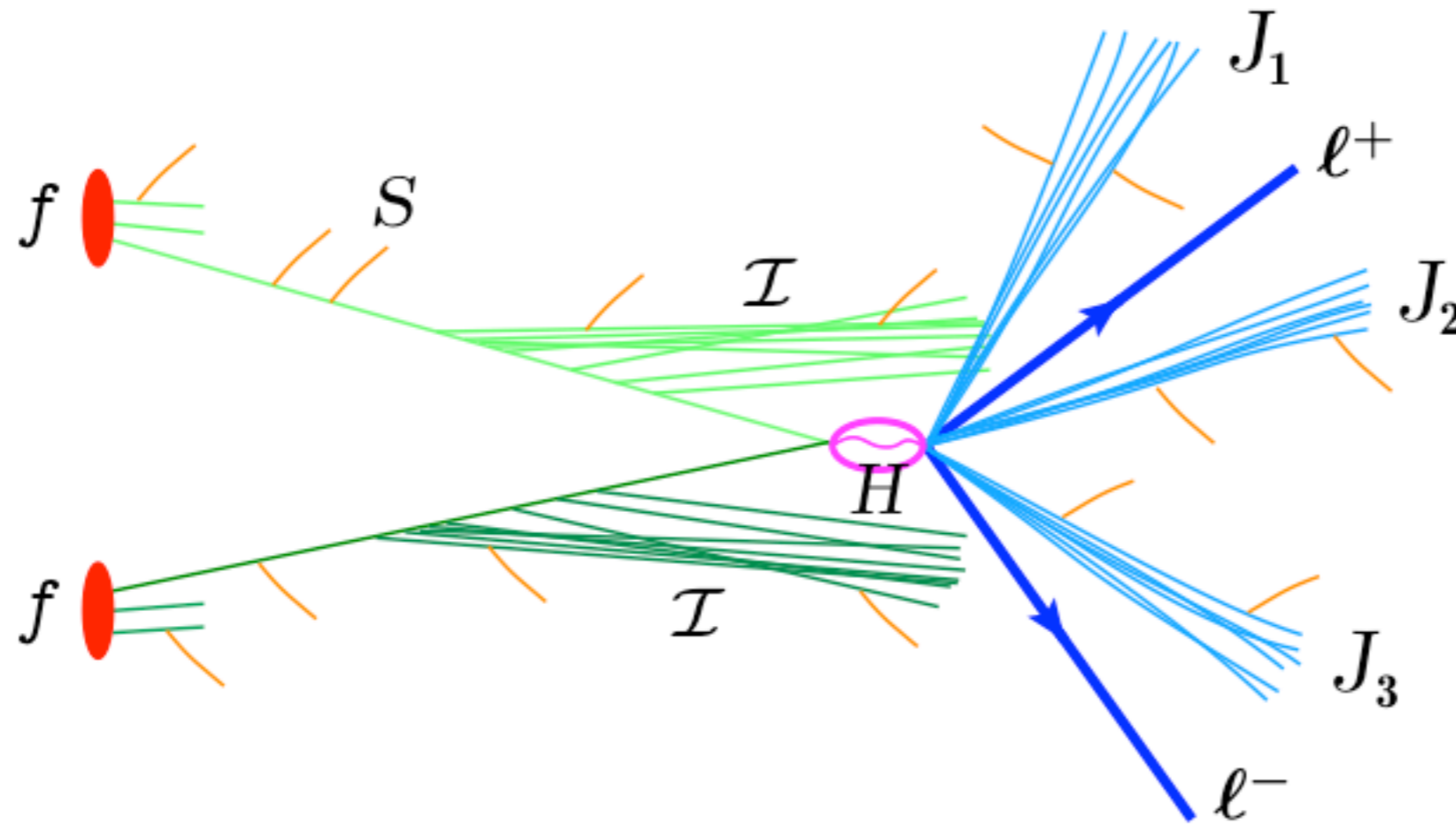


We essentially treat one scale at a time, constructing simpler effective field theories for the lower energy dynamics



SCET = Soft-Collinear Effective Theory

“Factorization”

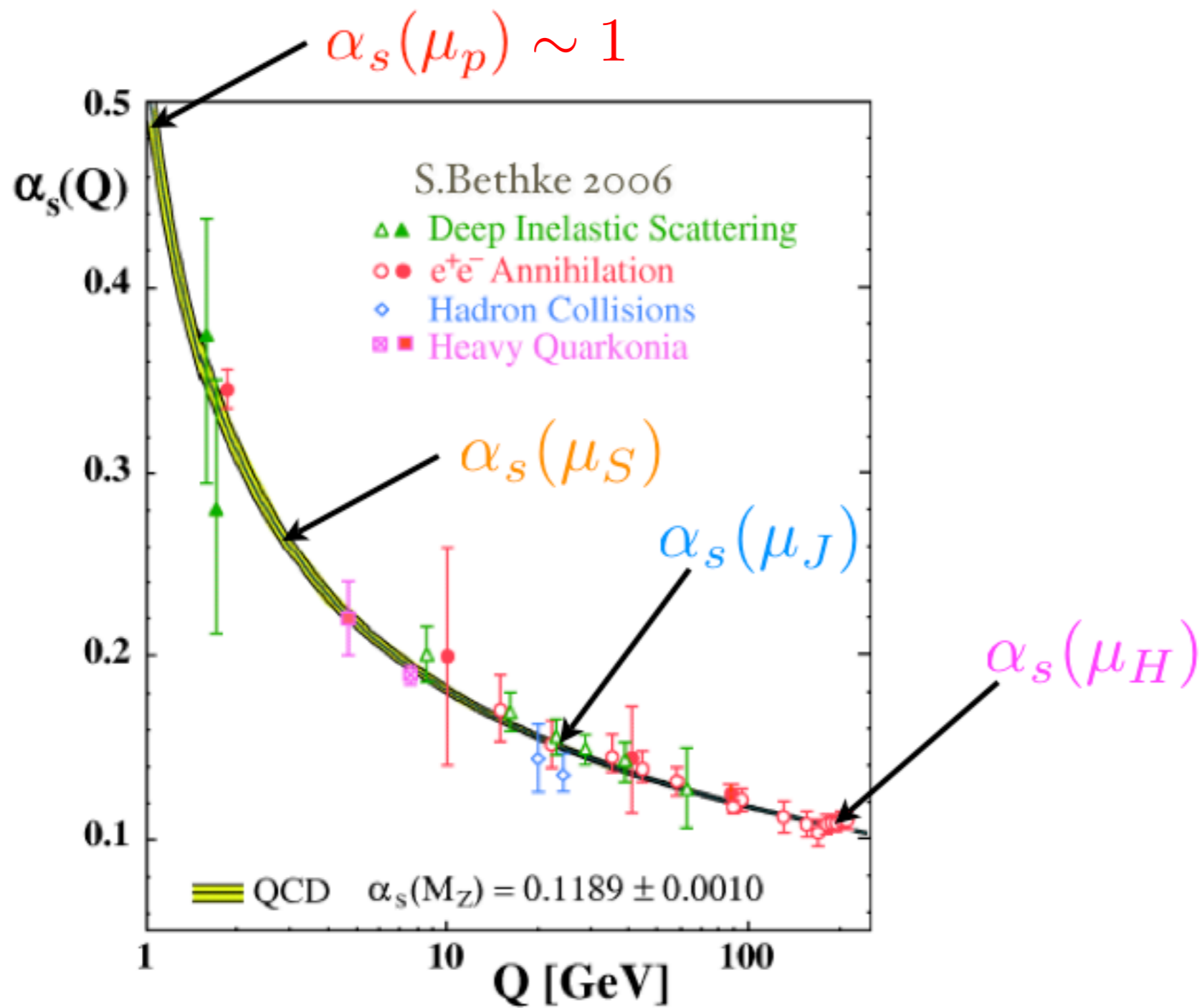


Final Results are

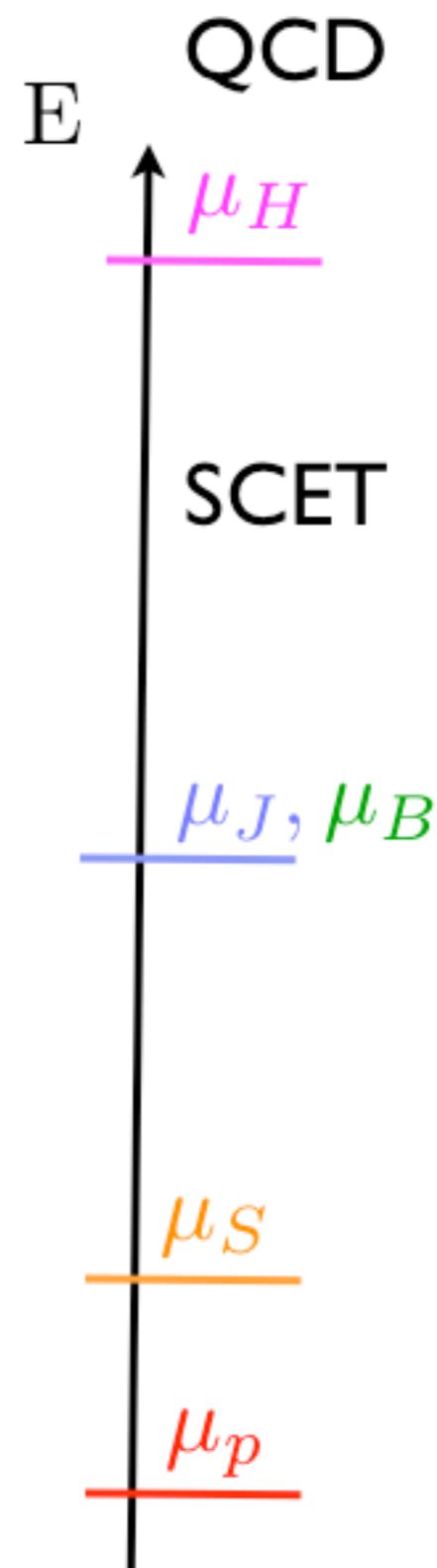
Factorization formulas for individual cross sections:

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

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

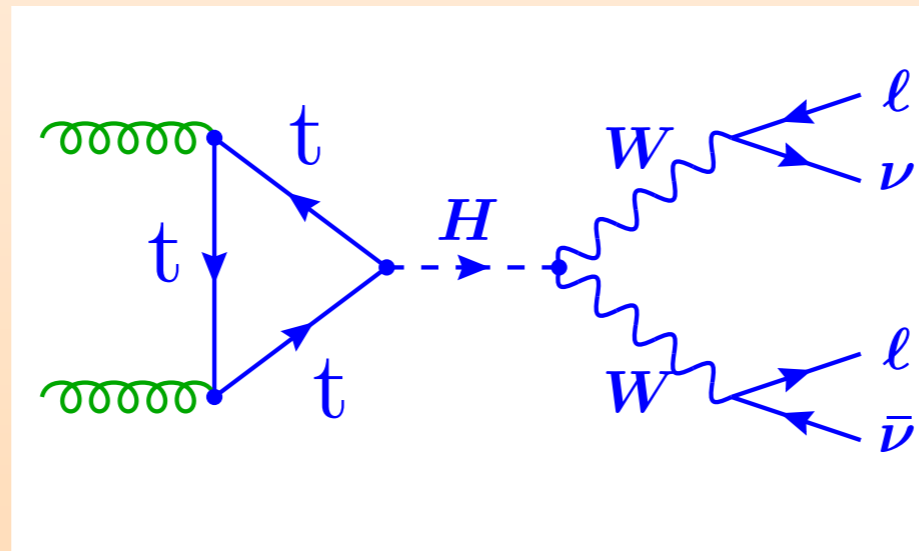


Our treatment ensures we can use appropriate values for the strong coupling.



Application: Higgs Production

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



Taylor Series

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

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

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

$$\mu = m_H/2$$

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

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

large coefficients

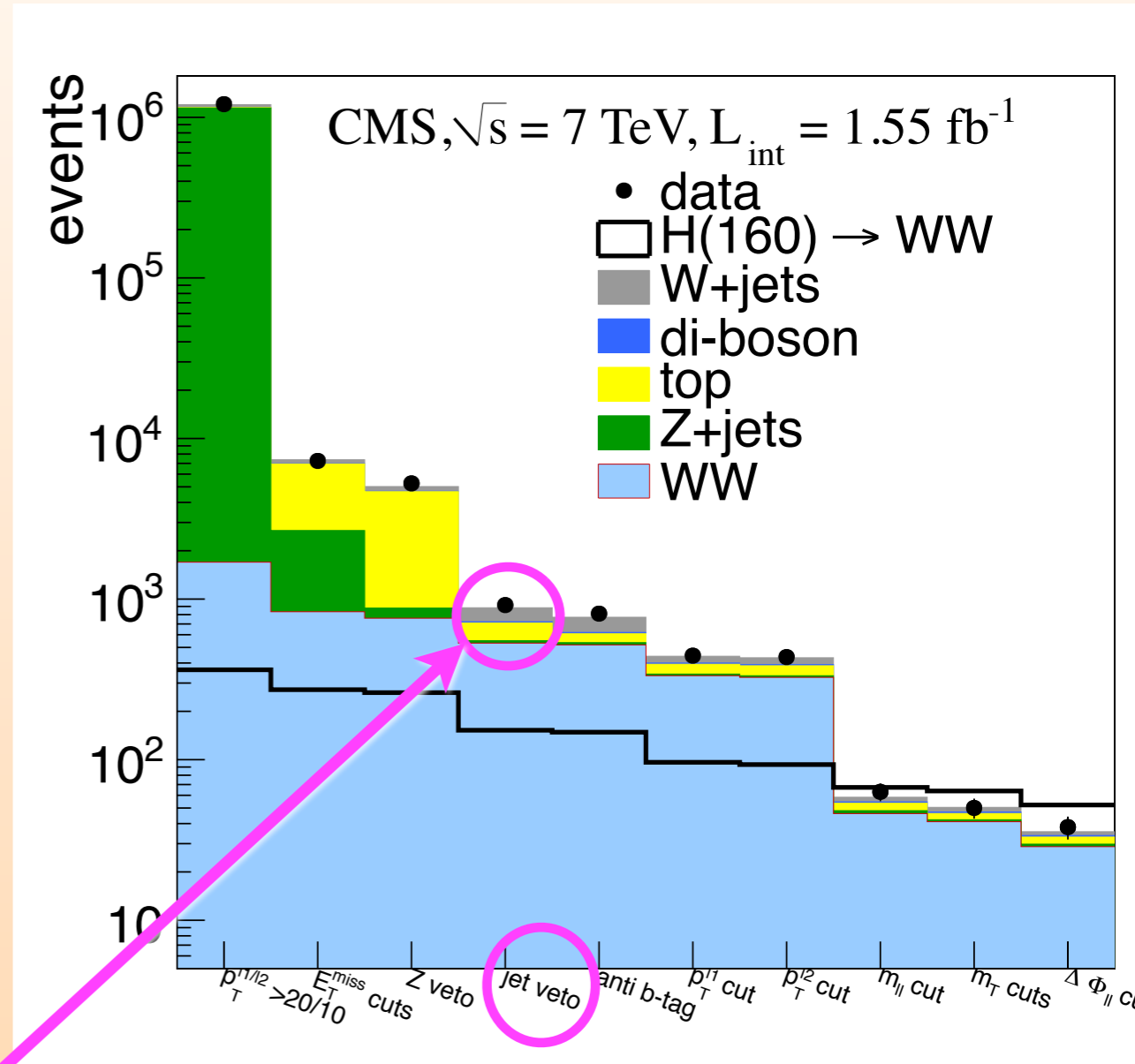
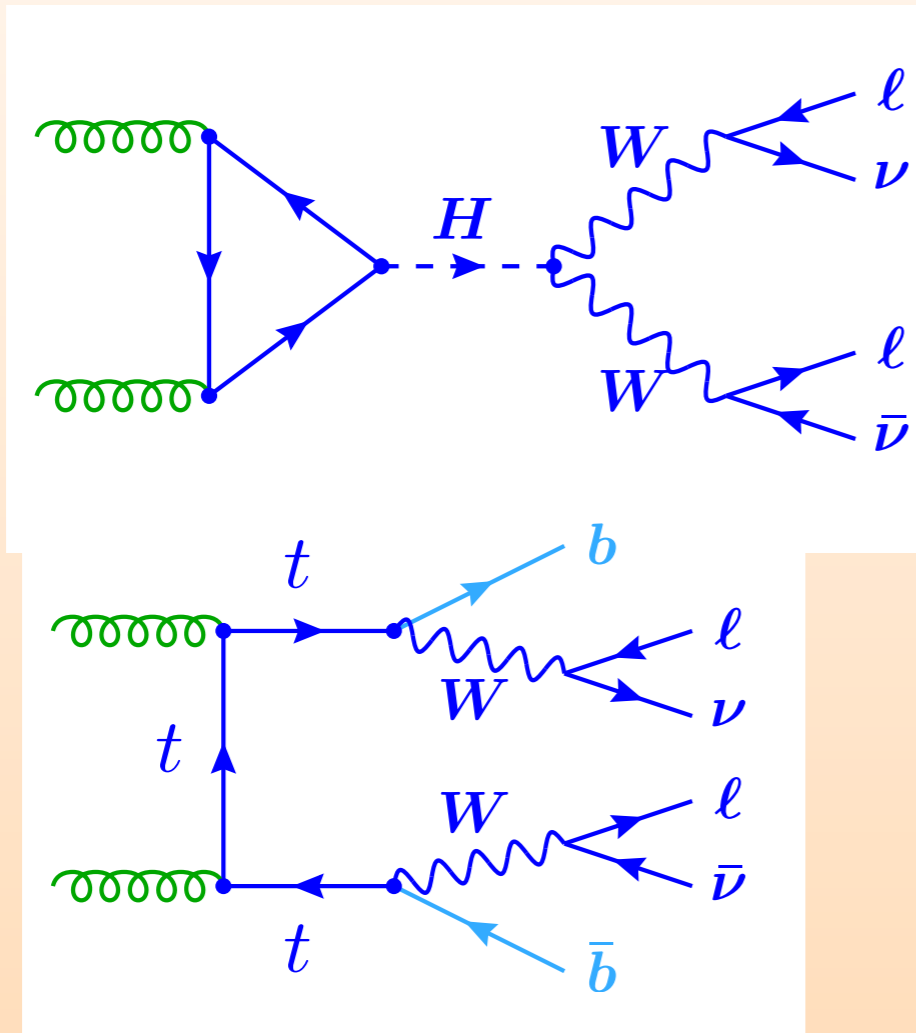
[Harlander, Kilgore; Anastasiou, Melnikov; Ravindran, Smith, van Neerven]
[Pak, Rogal, Steinhauser; Harlander, Mantler, Marzani, Ozeren]

Taylor Series

$$pp \rightarrow (H \rightarrow WW) + (0 \text{ jets})$$

Why?

large top background

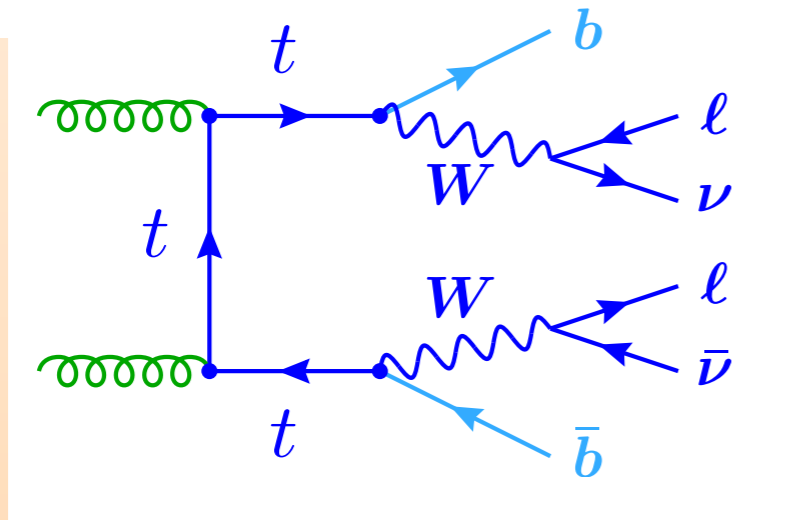
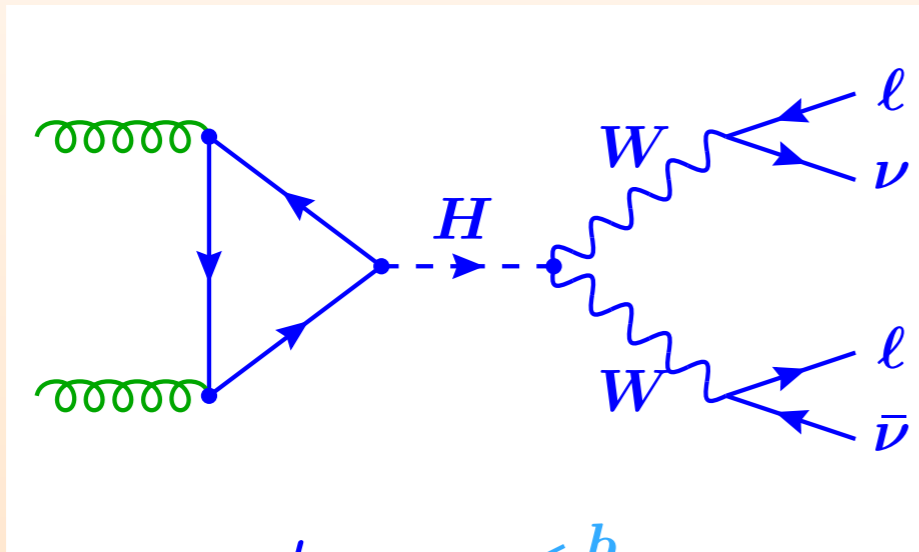


o-jet bin
vetoes
tops

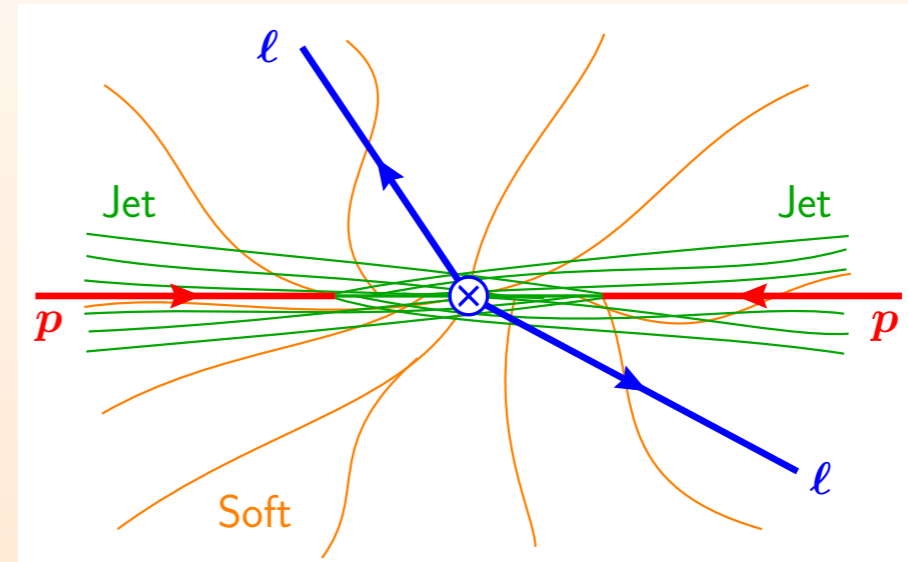
Taylor Series

$$pp \rightarrow (H \rightarrow WW) + (0 \text{ jets})$$

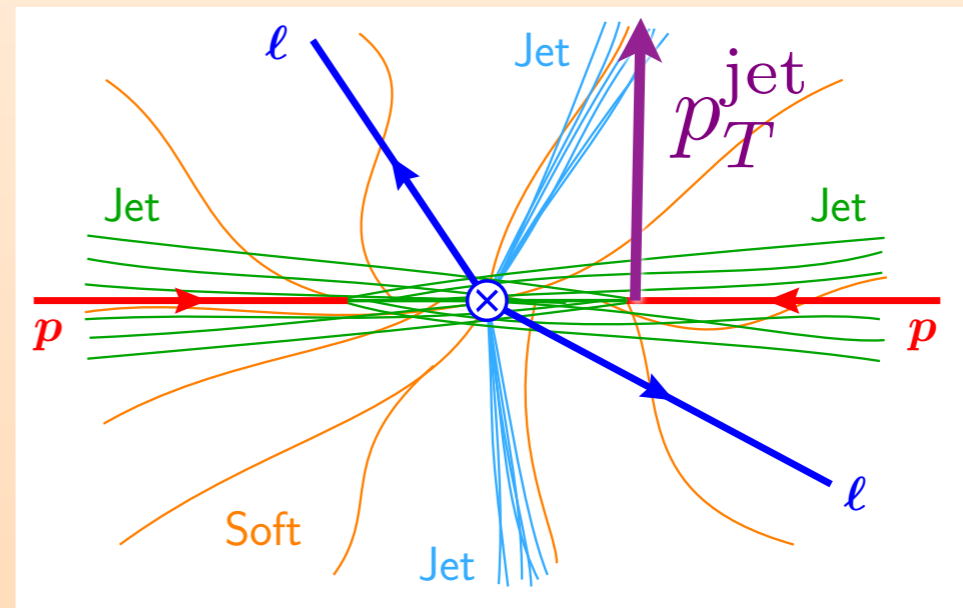
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Why?



0-jets

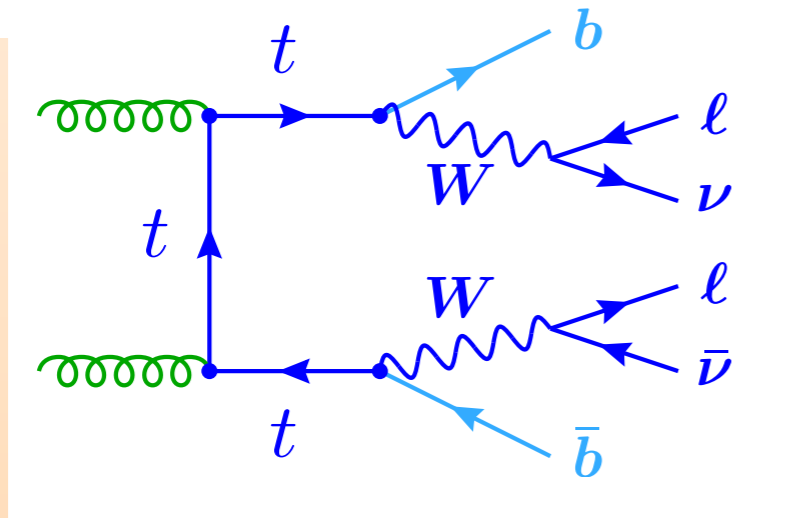
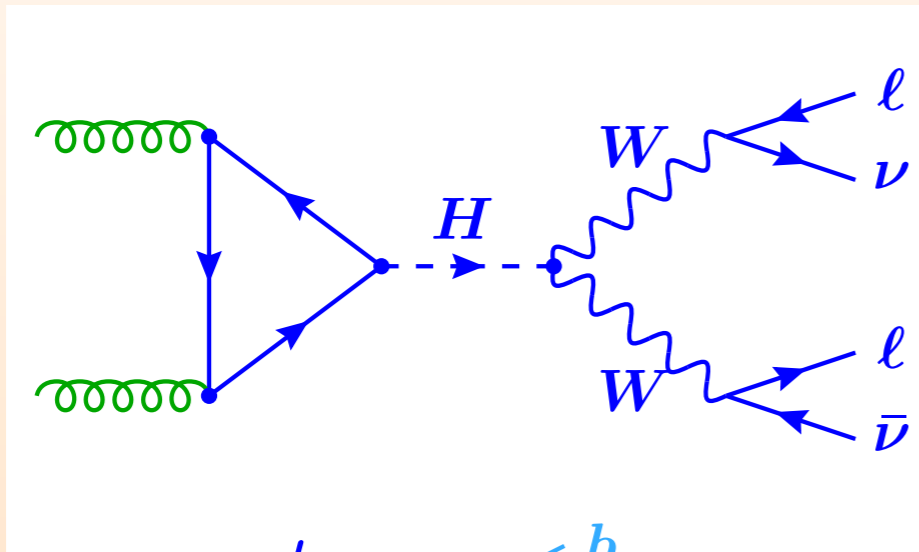


2-jets

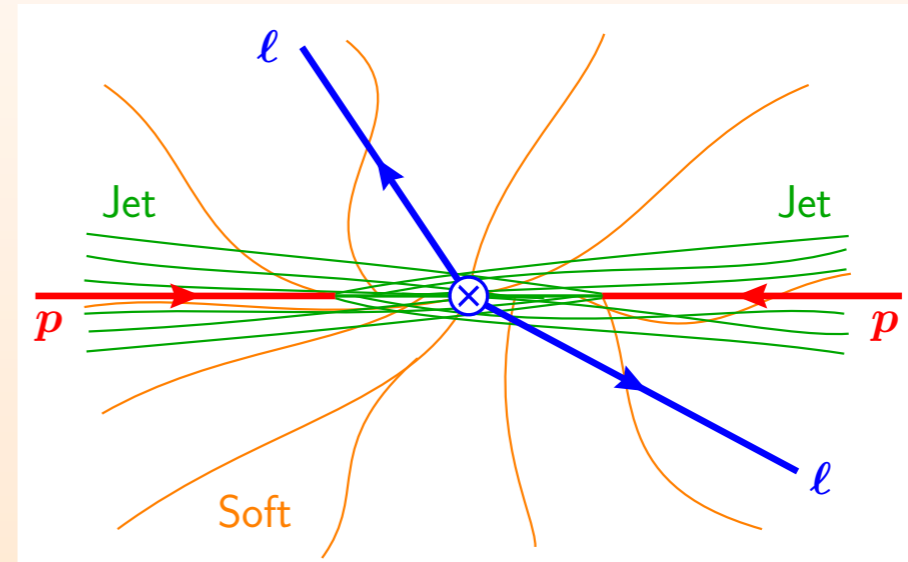
Taylor Series

$$pp \rightarrow (H \rightarrow WW) + (0 \text{ jets})$$

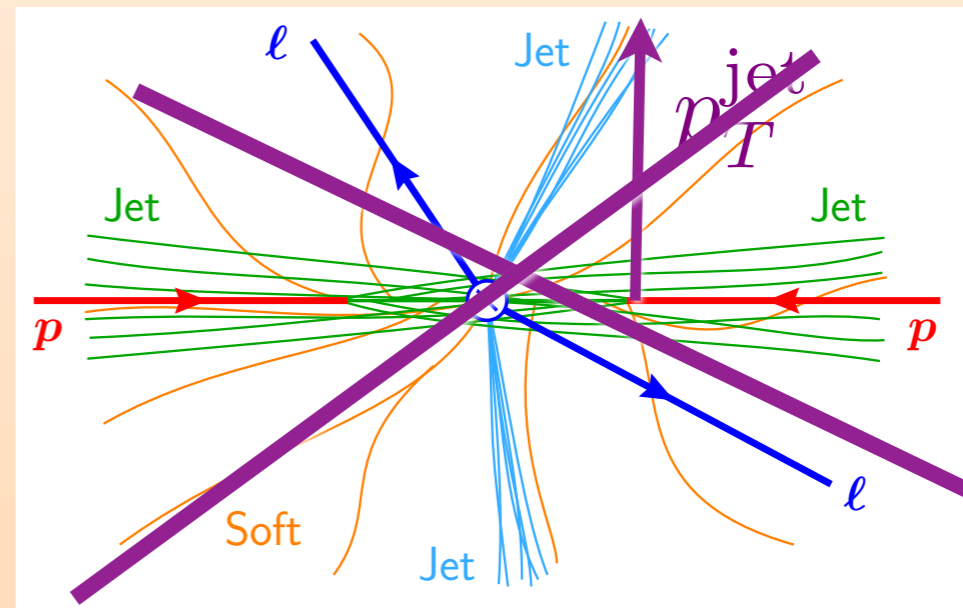
large top background



Why?



0-jets



veto

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

Taylor Series

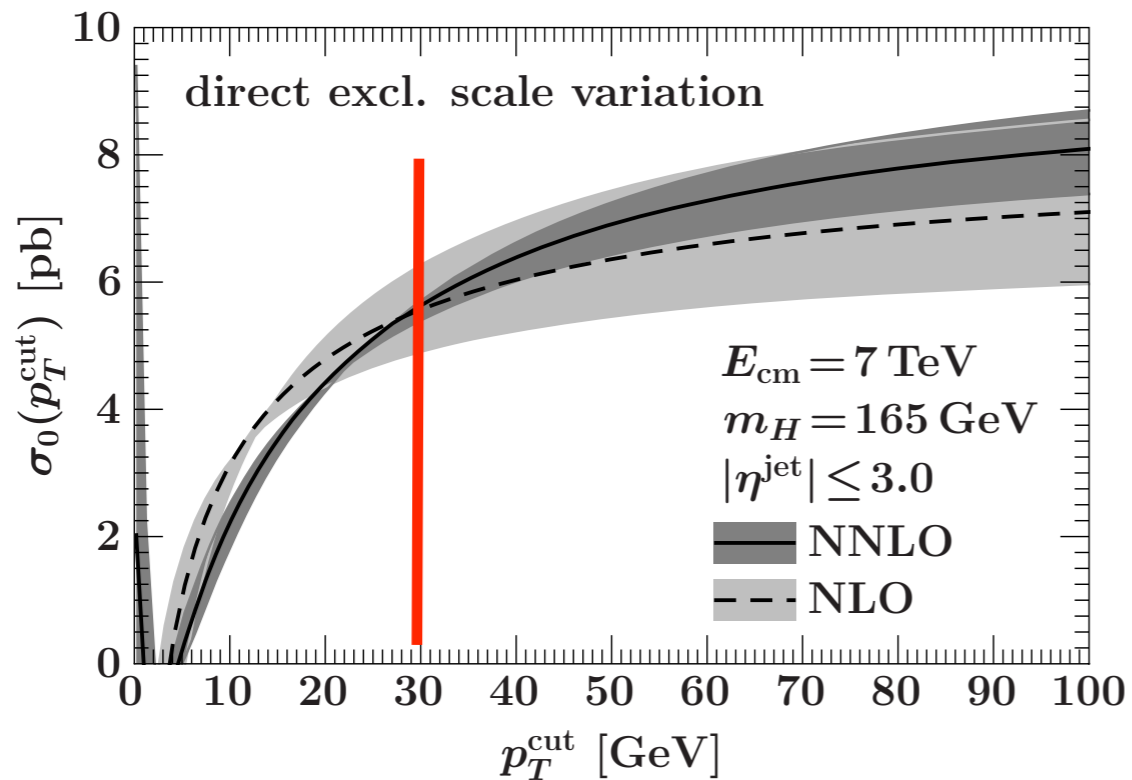
$$L = \ln \left(\frac{p_T^{\text{cut}}}{m_H} \right)$$

NNLO

	LO	NLO	NNLO	N ³ LO		
$\sigma_0(p_T^{\text{cut}}) =$	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
		$+\alpha_s$	$+\alpha_s^2 L^2$	$+\alpha_s^3 L^4$	$+\dots$	NNLL
			$+\alpha_s^2 L$	$+\alpha_s^3 L^3$	$+\dots$	N ³ LL
			$+\alpha_s^2$	$+\alpha_s^3 L^2$	$+\dots$	
				$+\alpha_s^3 L$	$+\dots$	
				$+\alpha_s^3$	$+\dots$	

[Anastasiou, Melnikov, Petriello; Grazzini]

method A

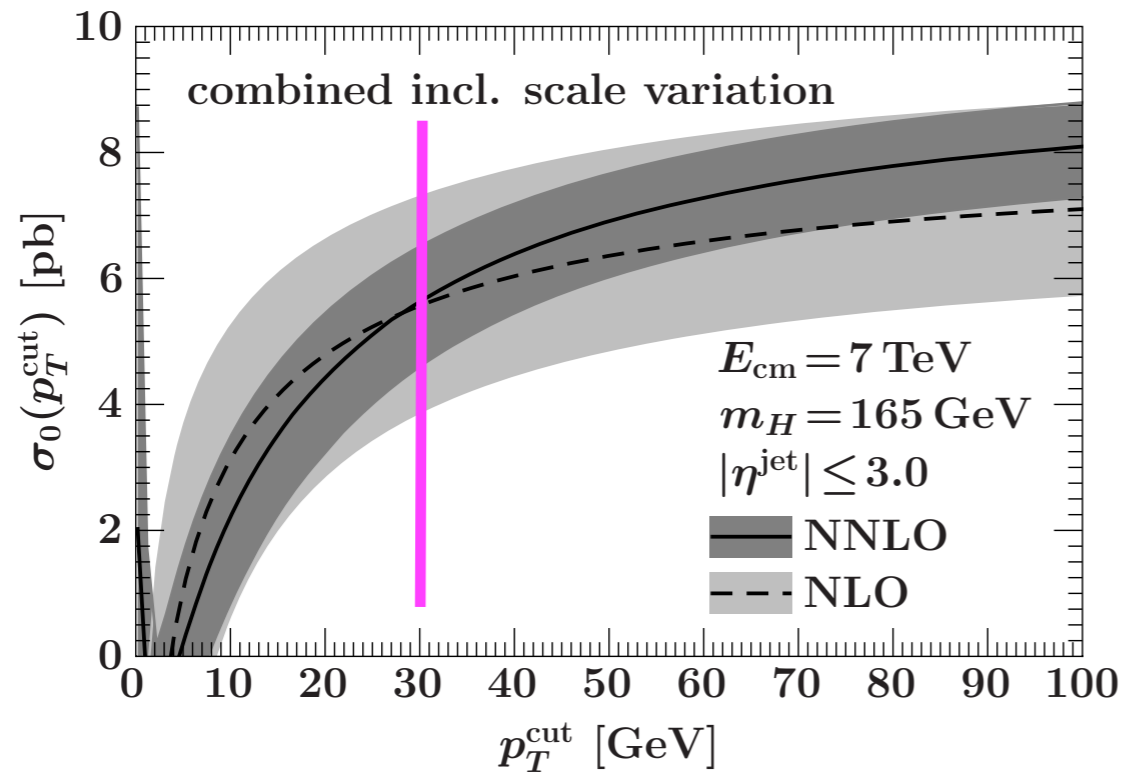


uncertainty from μ variation

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.]

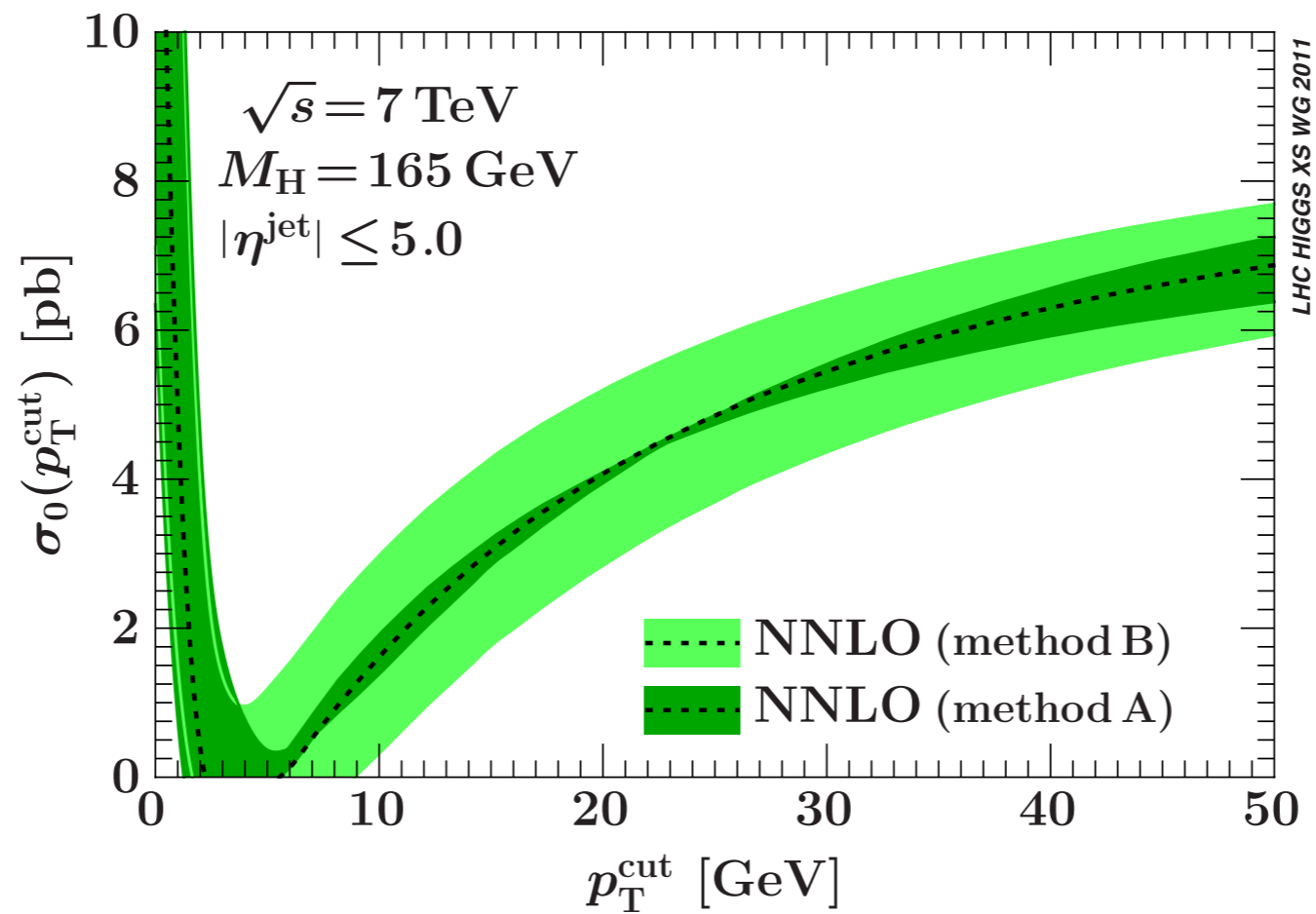
Can we theorists do better?

Sum Large Logs with “Factorization”

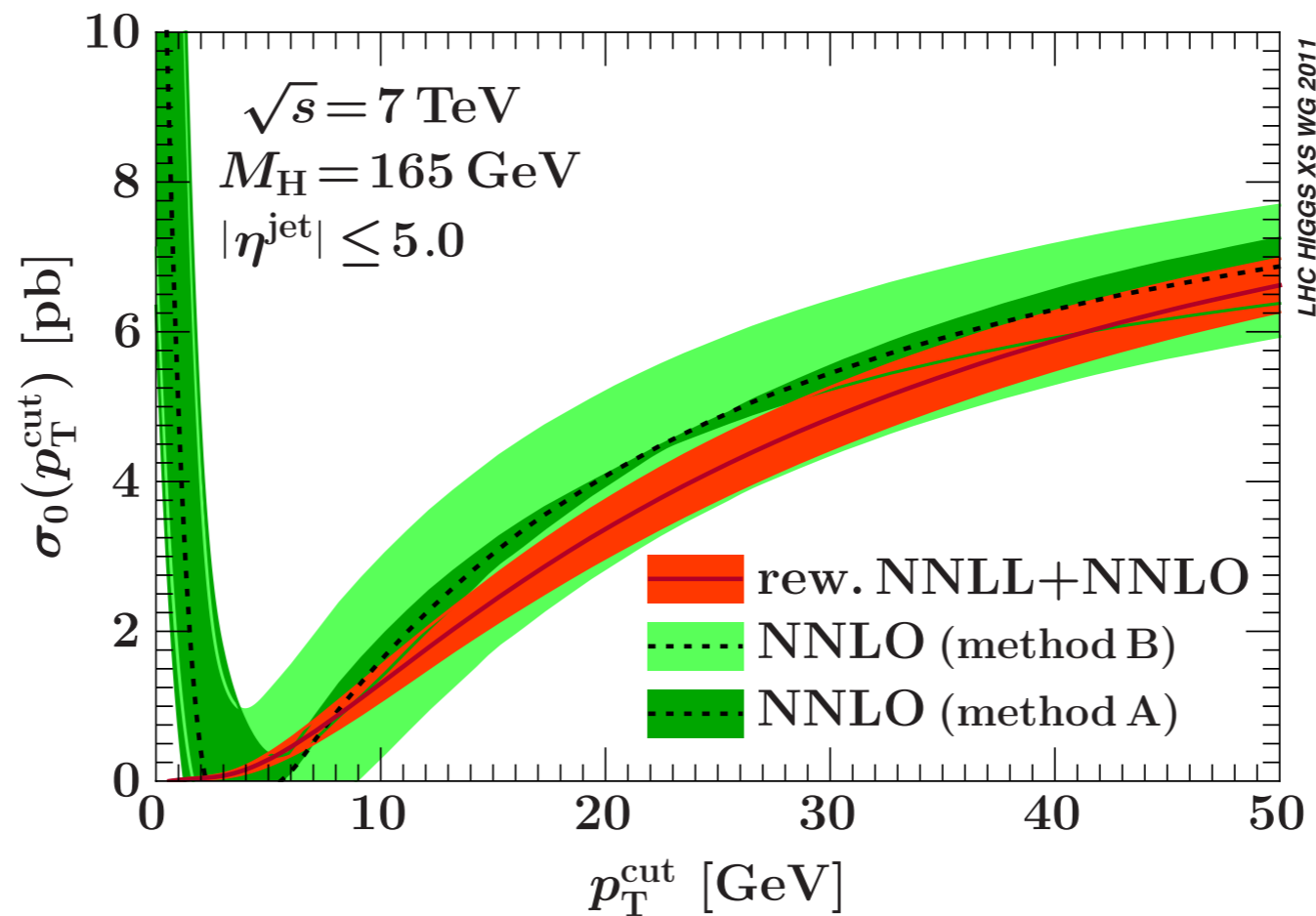
NNLO + NNLL

	LO	NLO	NNLO	N ³ LO		
$\sigma_0(p_T^{\text{cut}}) =$	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
		$+\alpha_s$	$+\alpha_s^2 L^2$	$+\alpha_s^3 L^4$	$+\dots$	NNLL
			$+\alpha_s^2 L$	$+\alpha_s^3 L^3$	$+\dots$	NNLL
			$+\alpha_s^2$	$+\alpha_s^3 L^2$	$+\dots$	N ³ LL
				$+\alpha_s^3 L$	$+\dots$	
				$+\alpha_s^3$	$+\dots$	

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



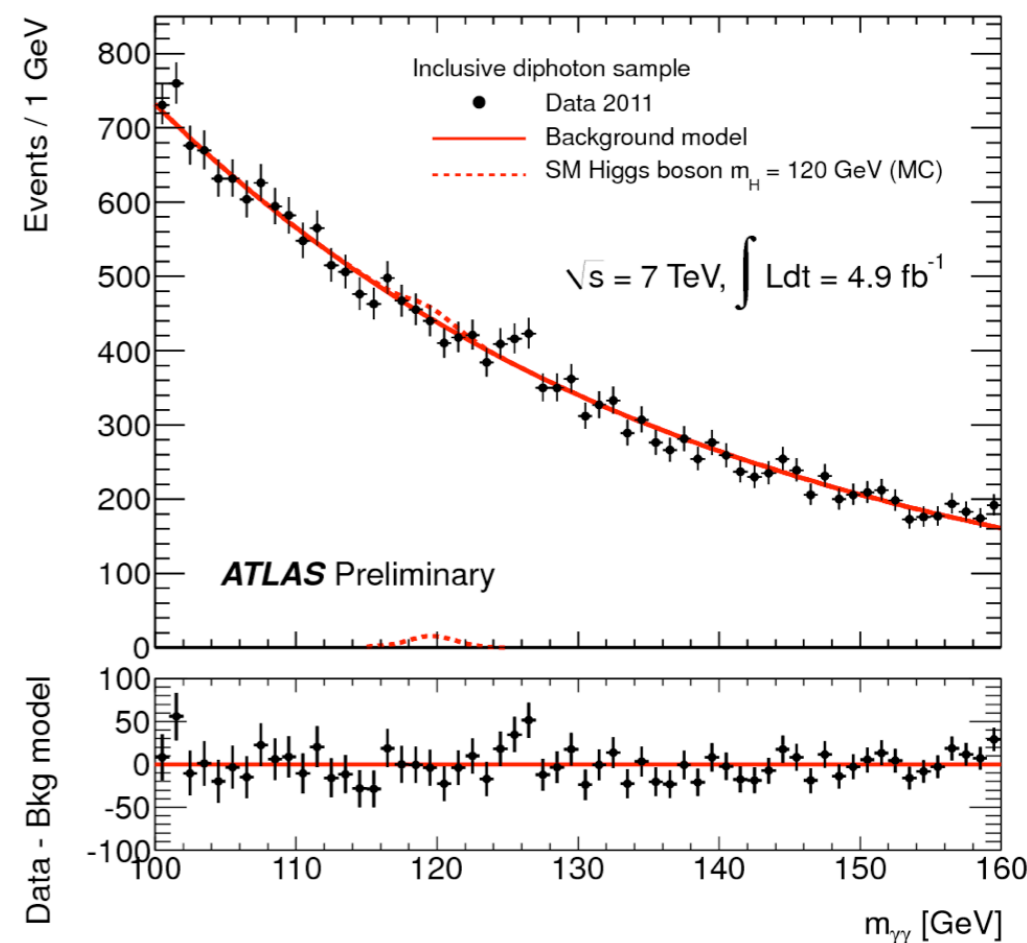
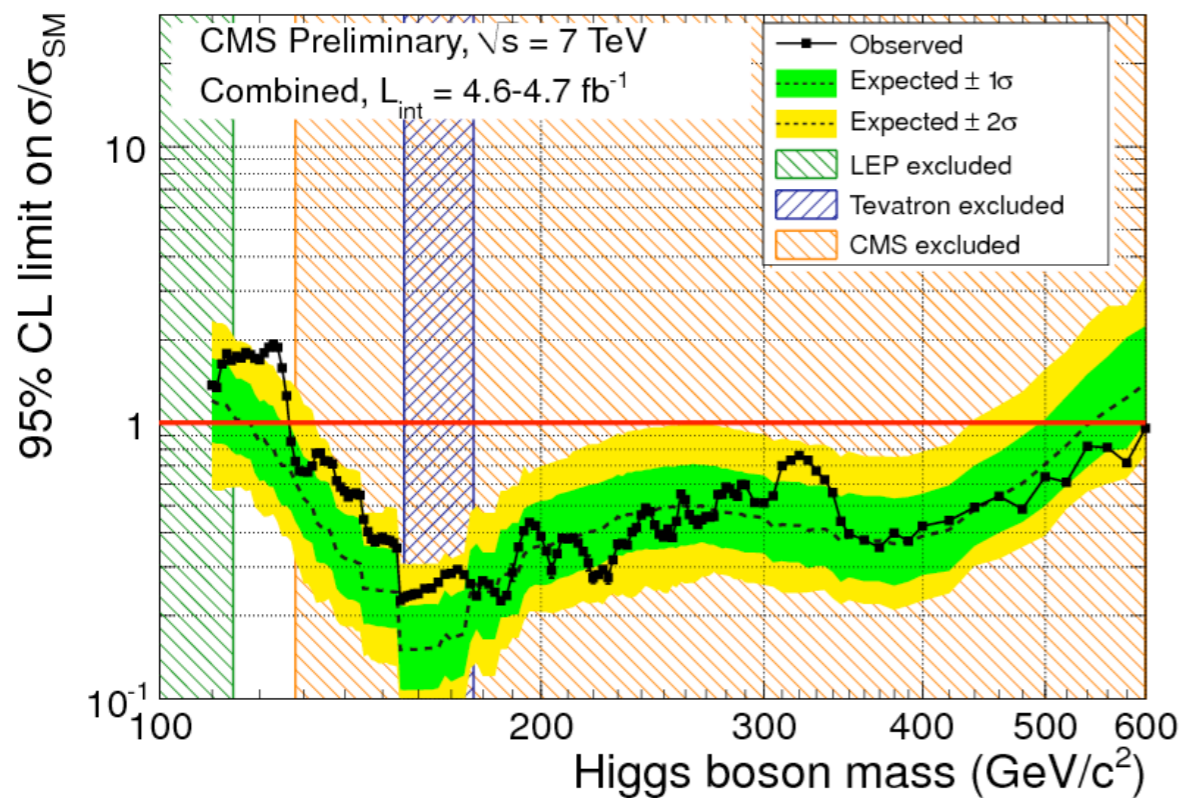
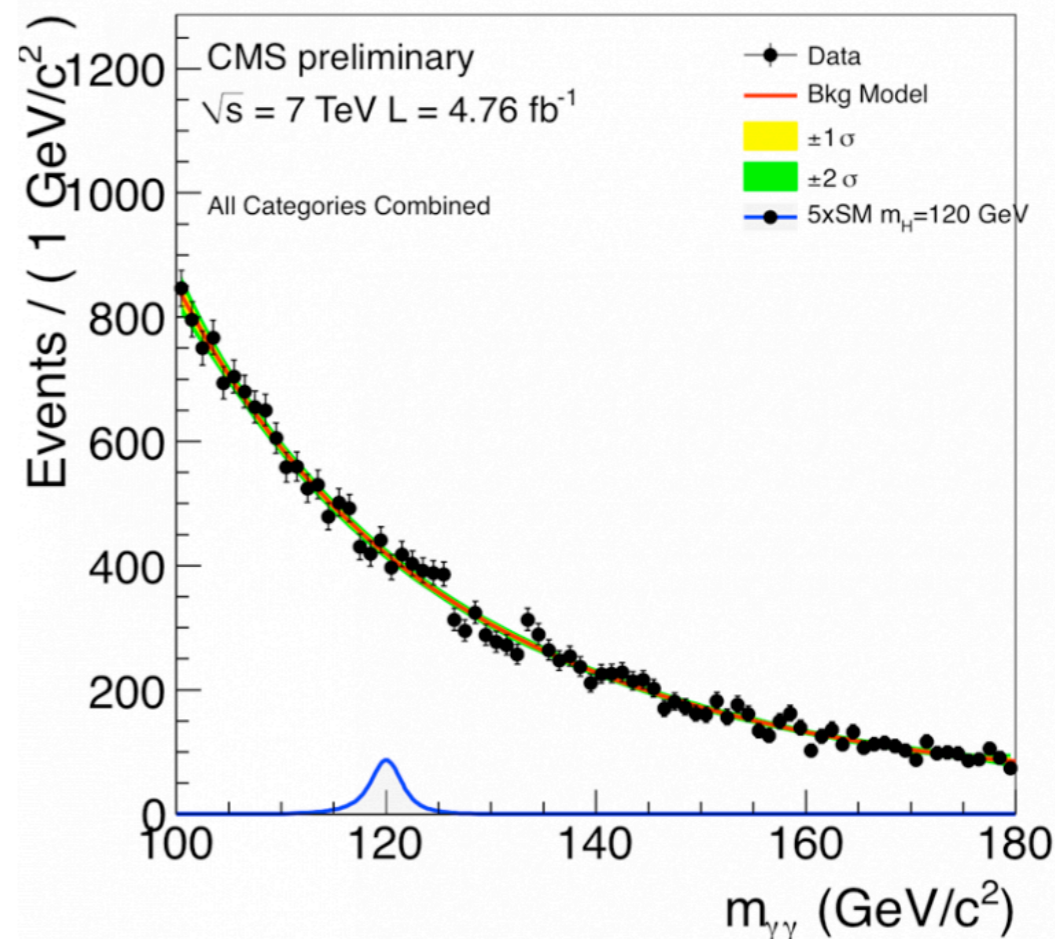
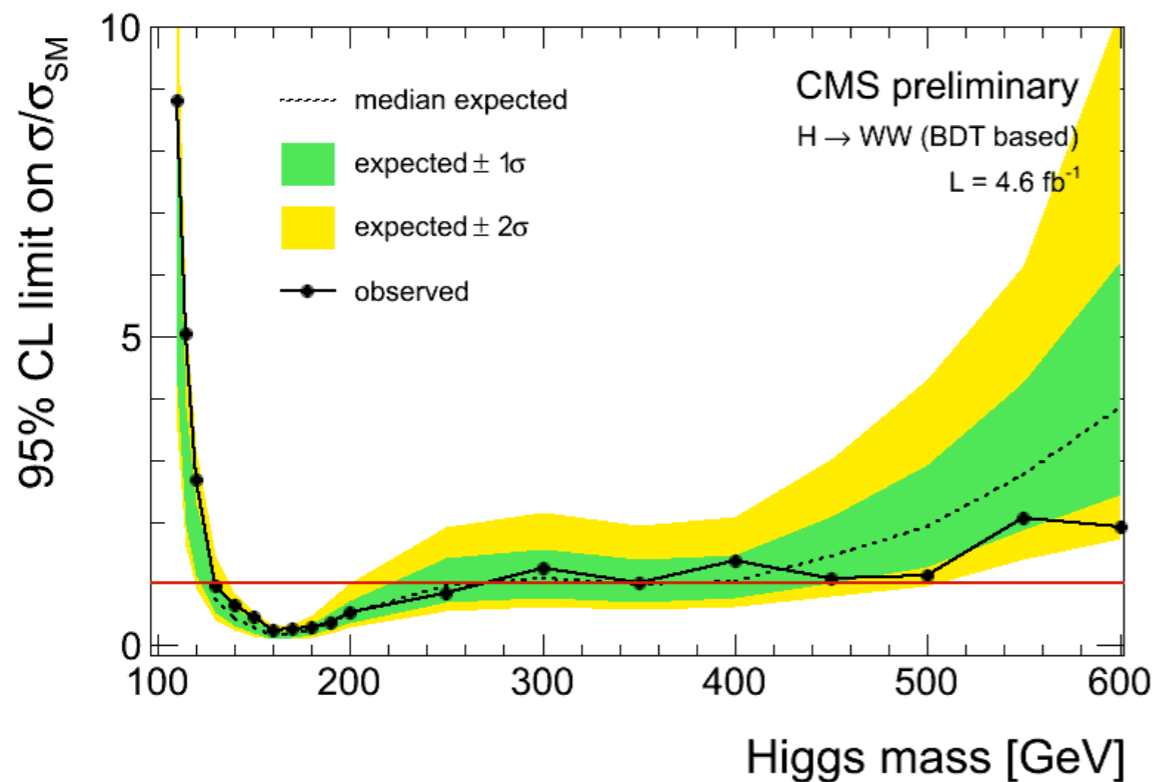
I.S., F.Stockli, F.Tackmann, W.Waalewijn
 (Higgs Yellow Report #2)



Higher Precision Calculation:
Factor of 2 improvement

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

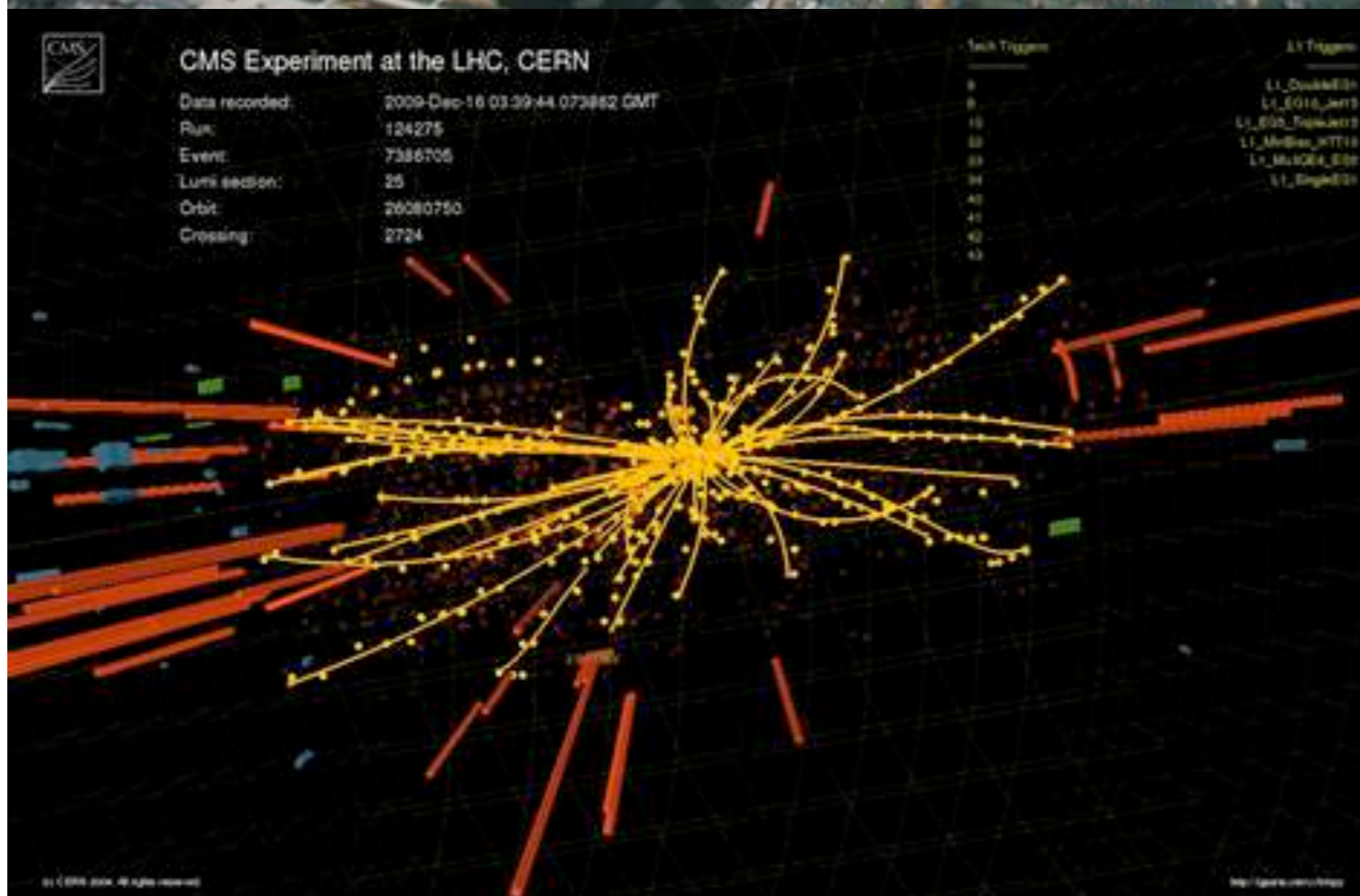
Higgs Bounds (& Hints?)



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