

# Quark and Lepton Scattering at the Highest Energies

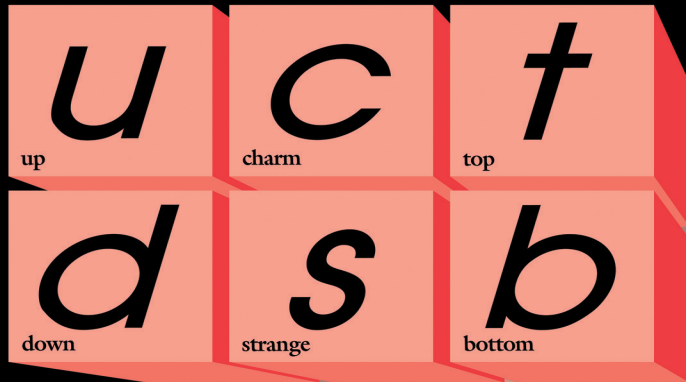
Jon Butterworth

*Sid Drell Symposium*

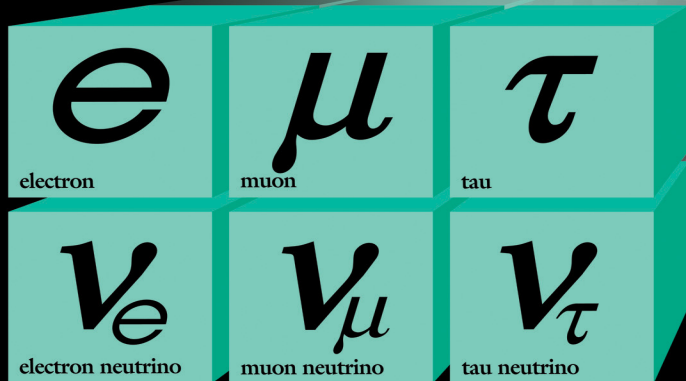
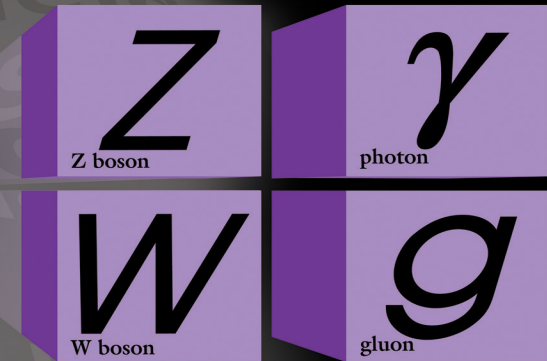
SLAC

January 2018

# Quarks

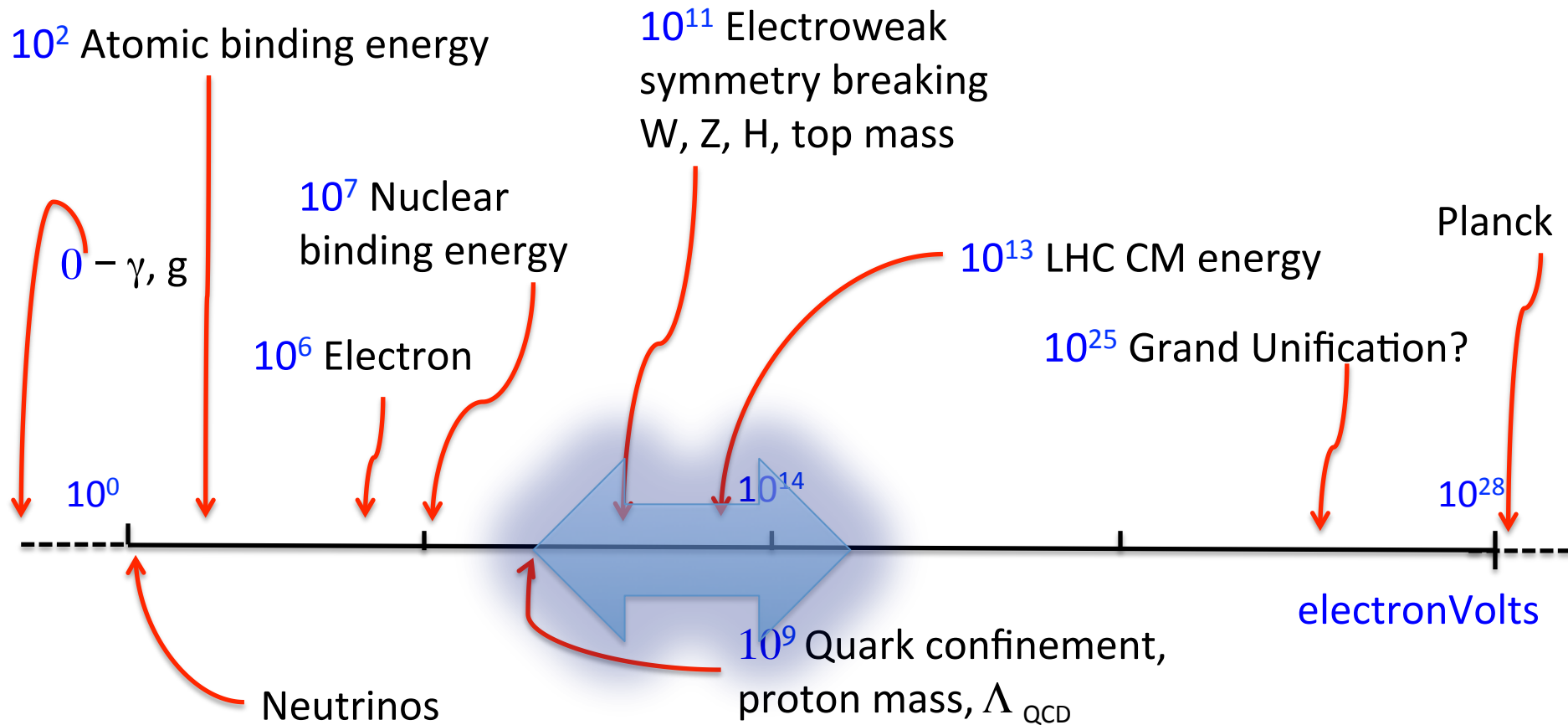


# Forces

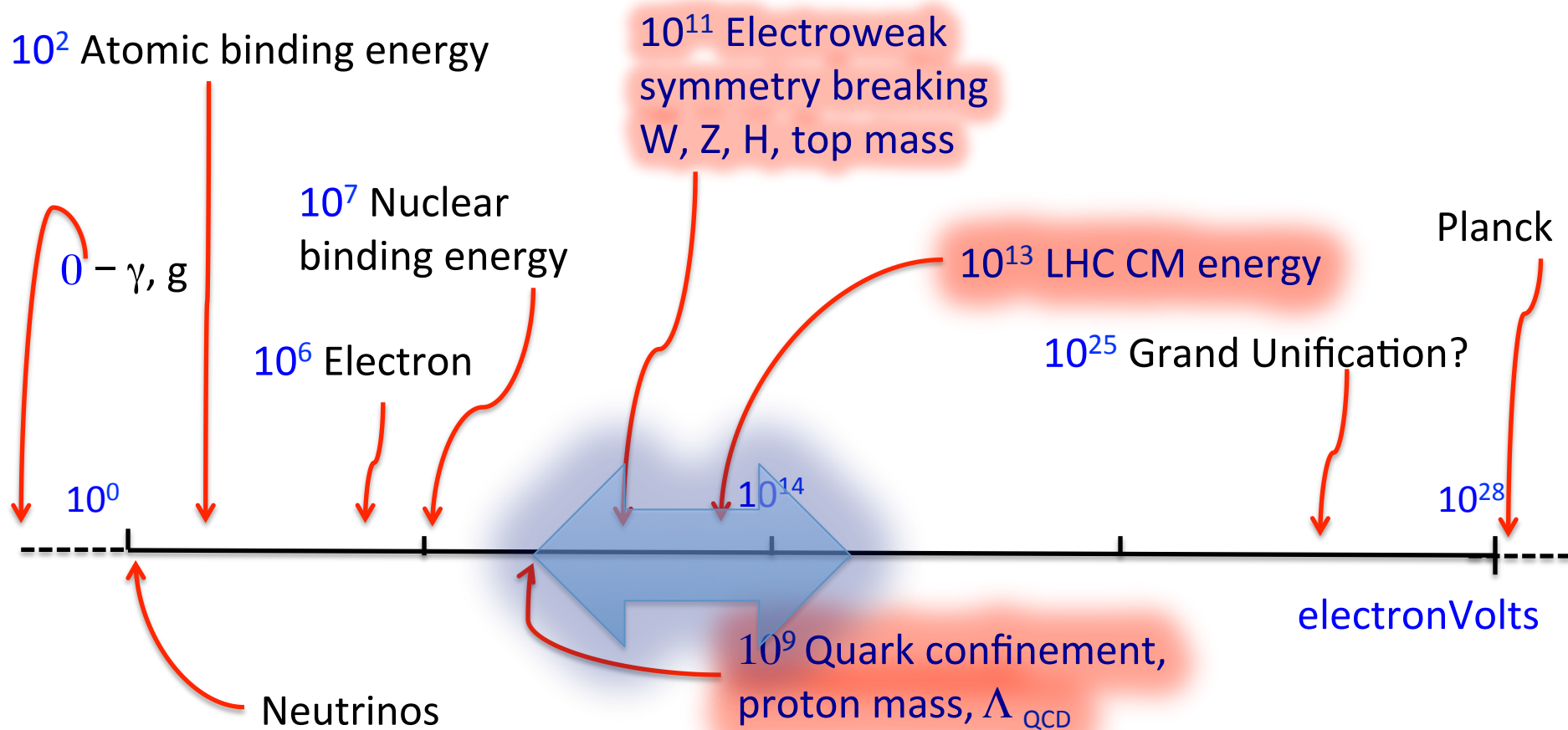


# Leptons

# Where are these degrees of freedom relevant?

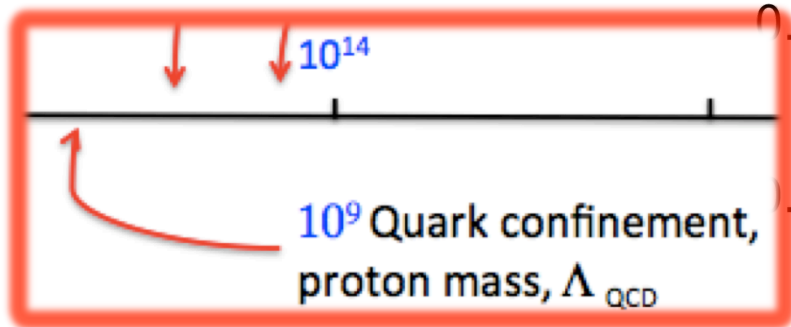
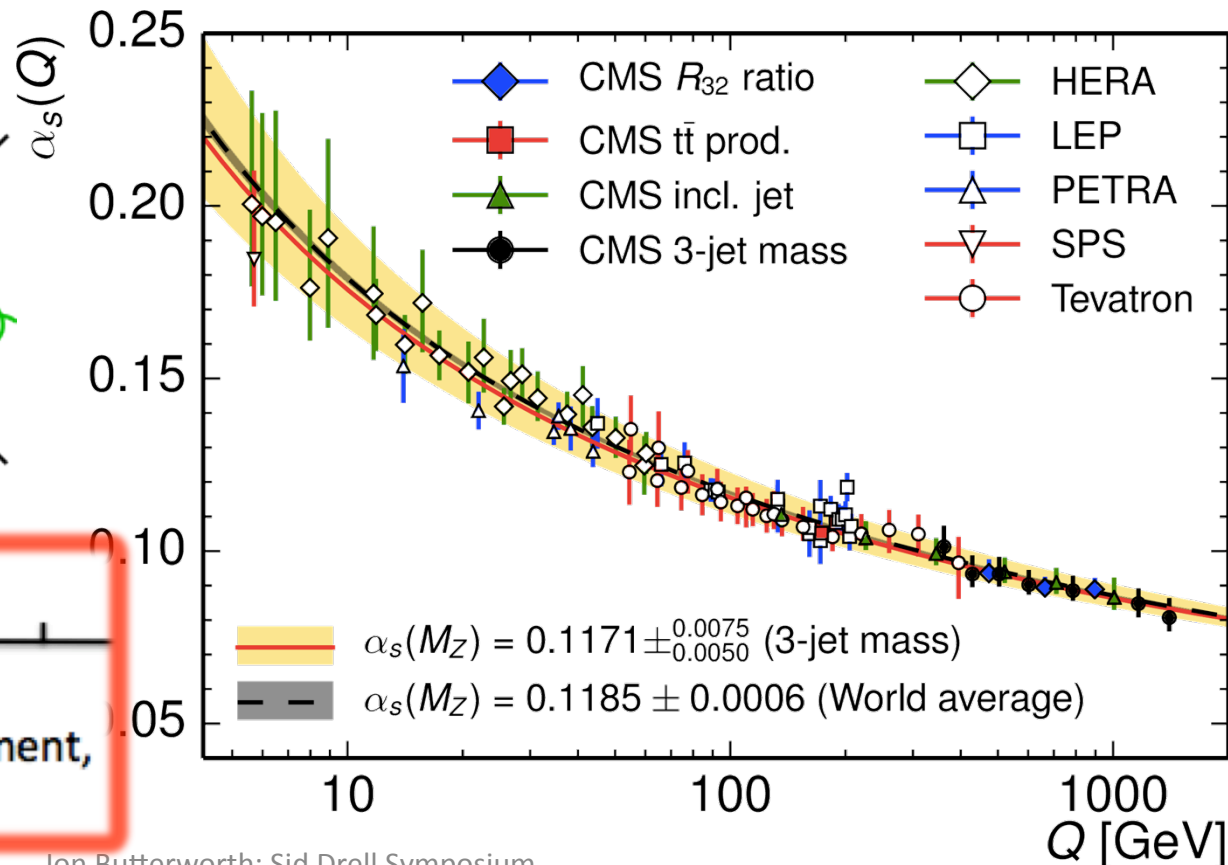
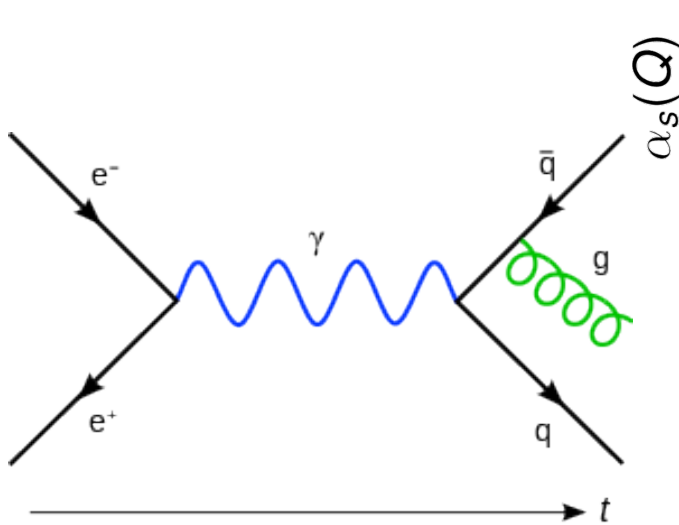


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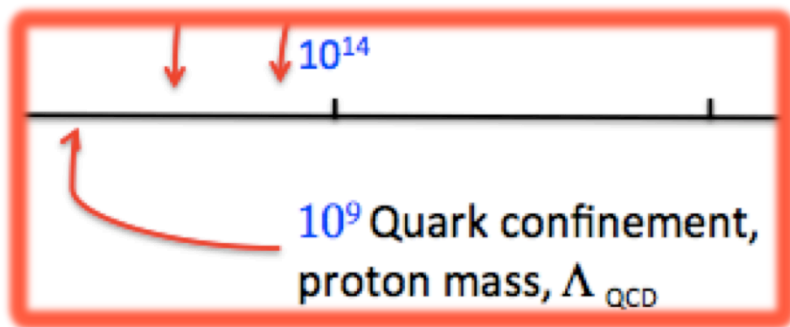
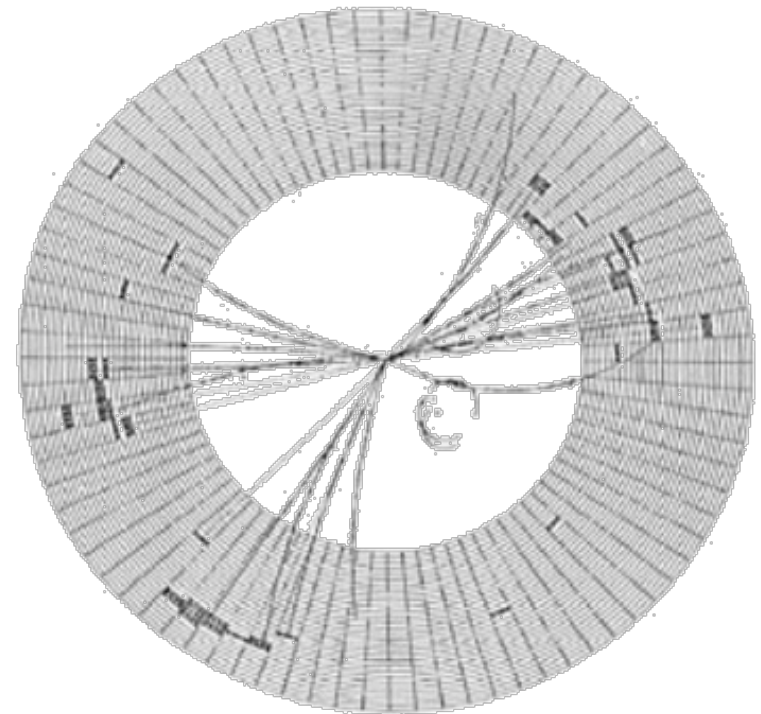
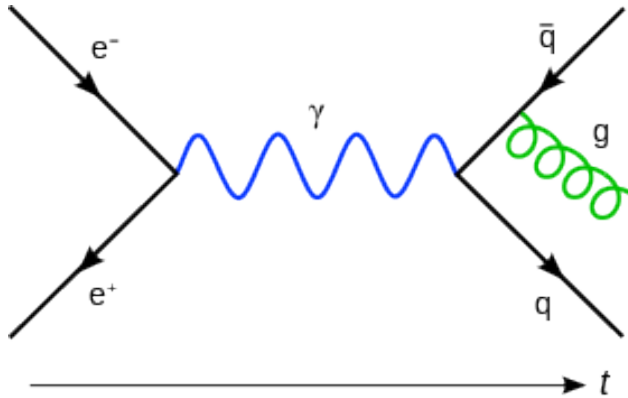
# 'Hard' QCD

- Asymptotic freedom at short distances/high energies... strong becomes weak(er)



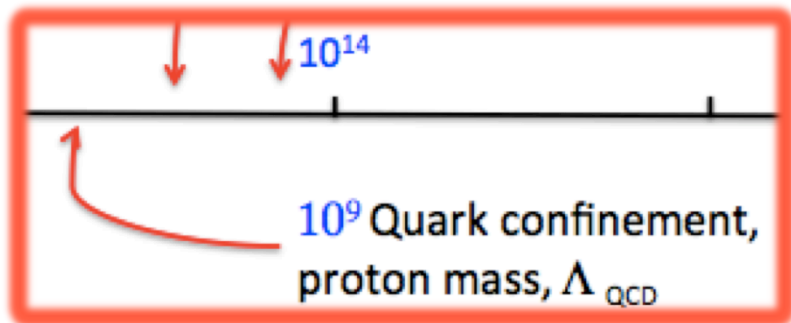
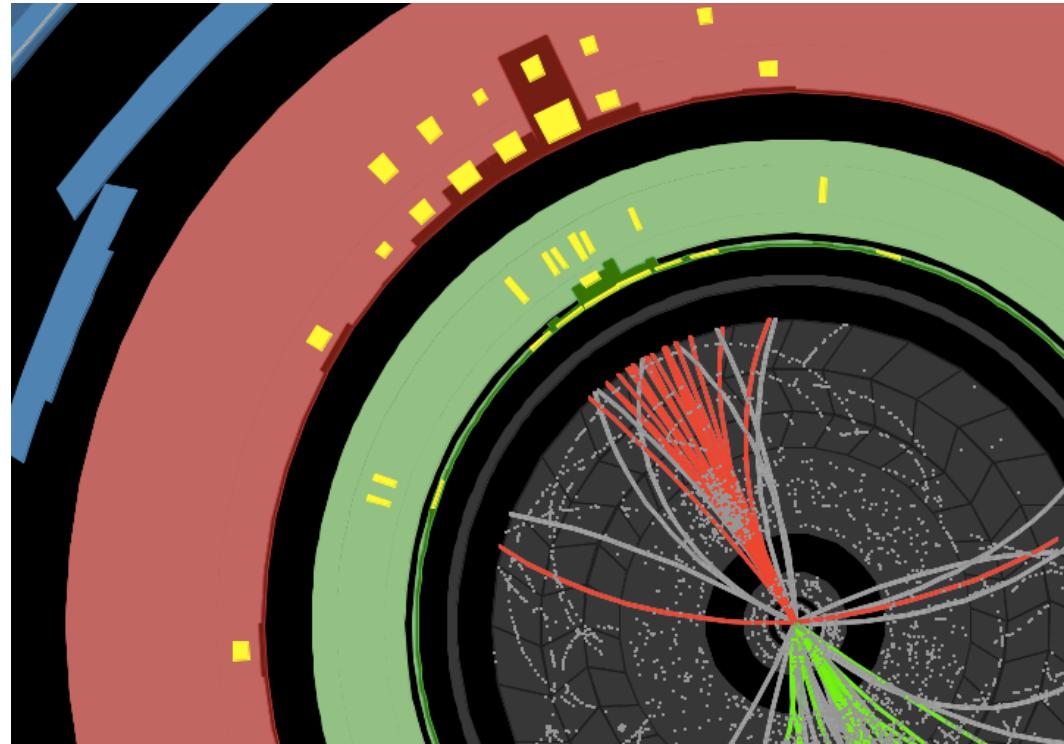
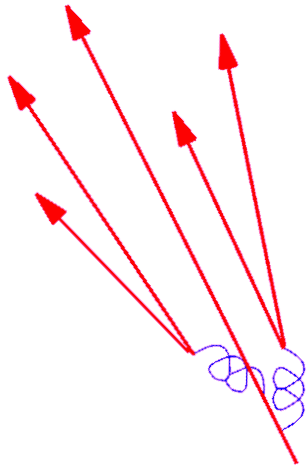
# 'Hard' QCD

- When quarks and gluons make a break for it...  
Jets!



# 'Hard' QCD

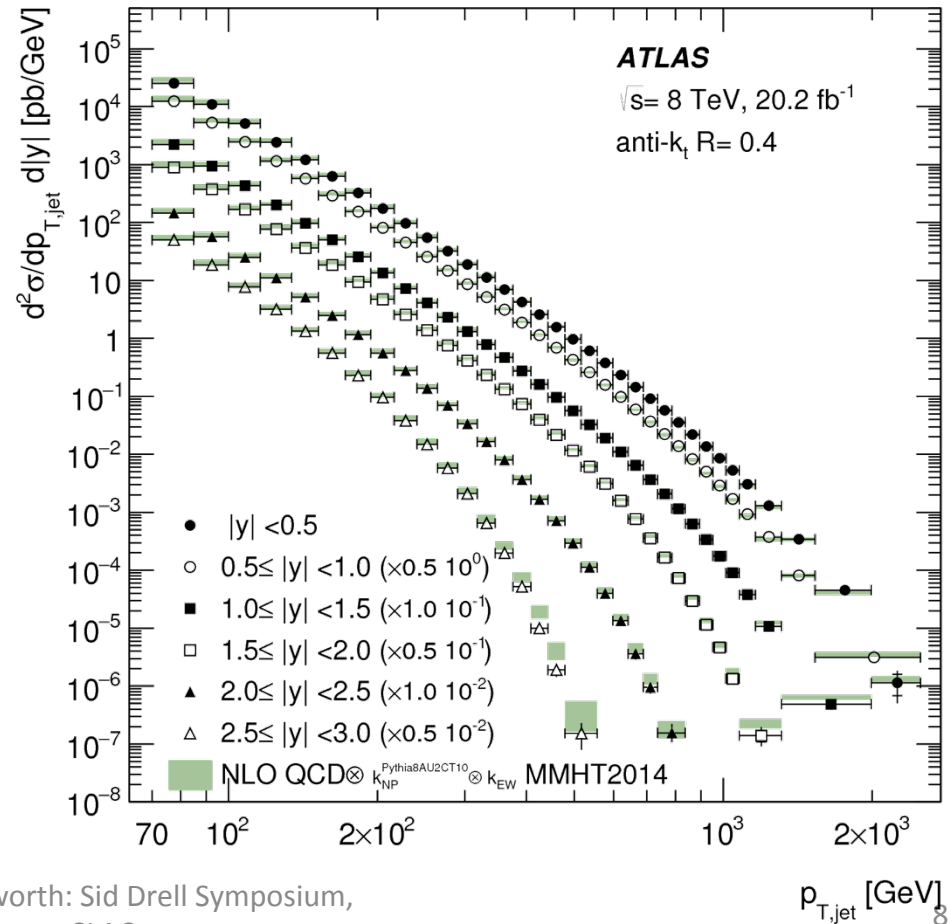
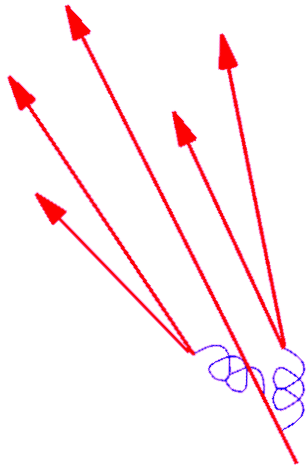
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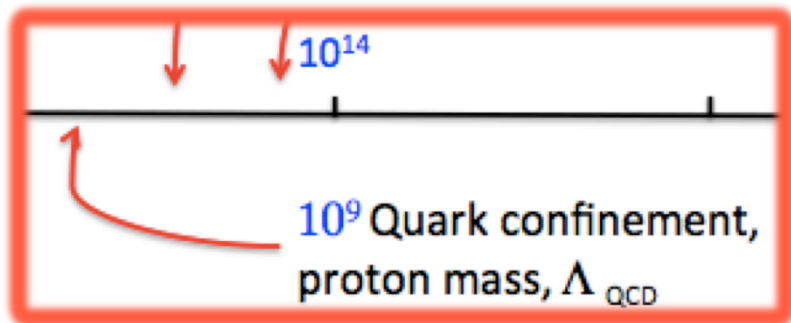
# 'Hard' QCD

- When quarks and gluons make a break for it...

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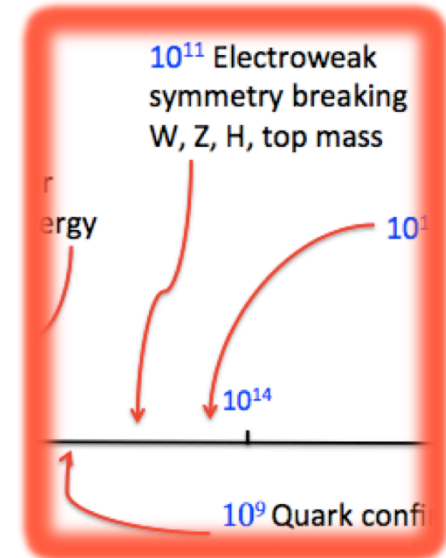
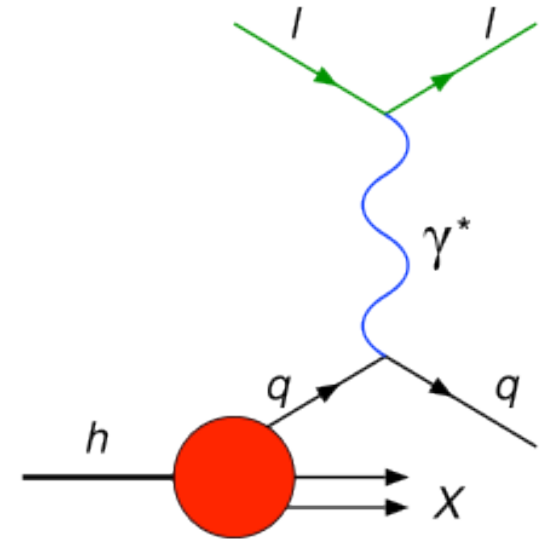
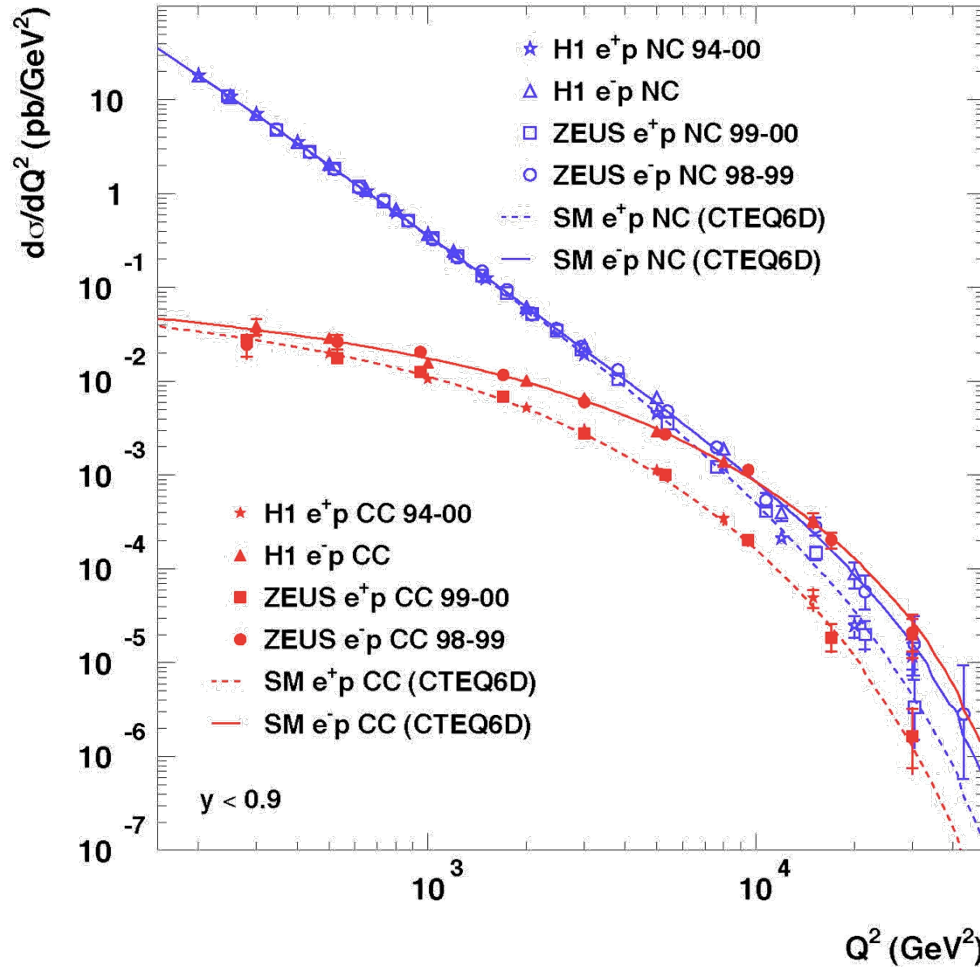
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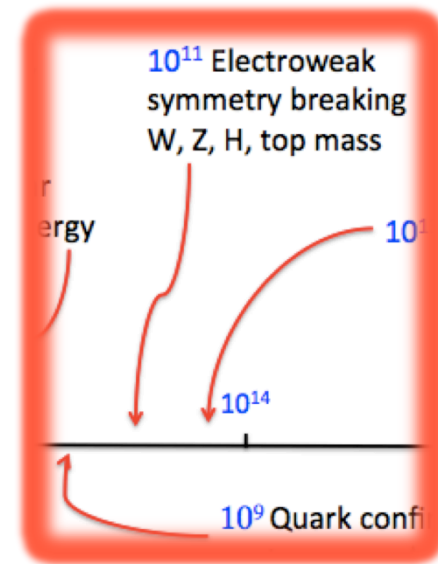
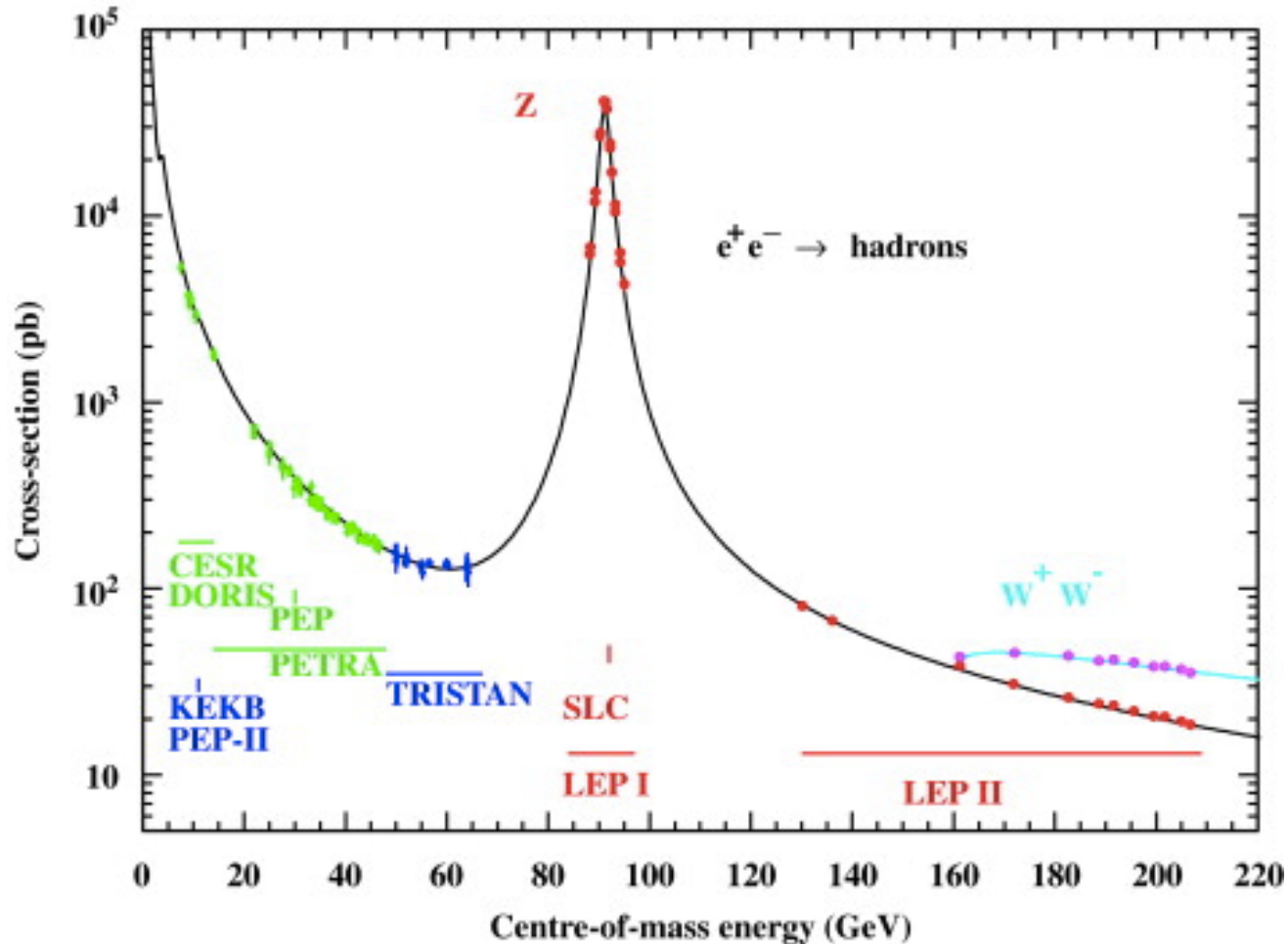


# Deep Inelastic Scattering

HERA

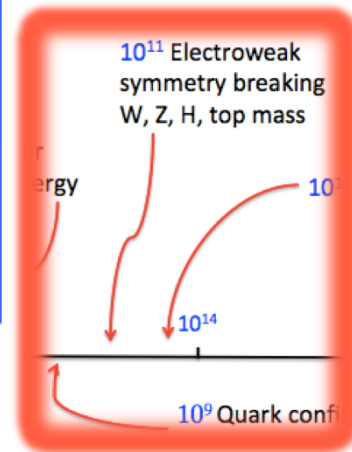
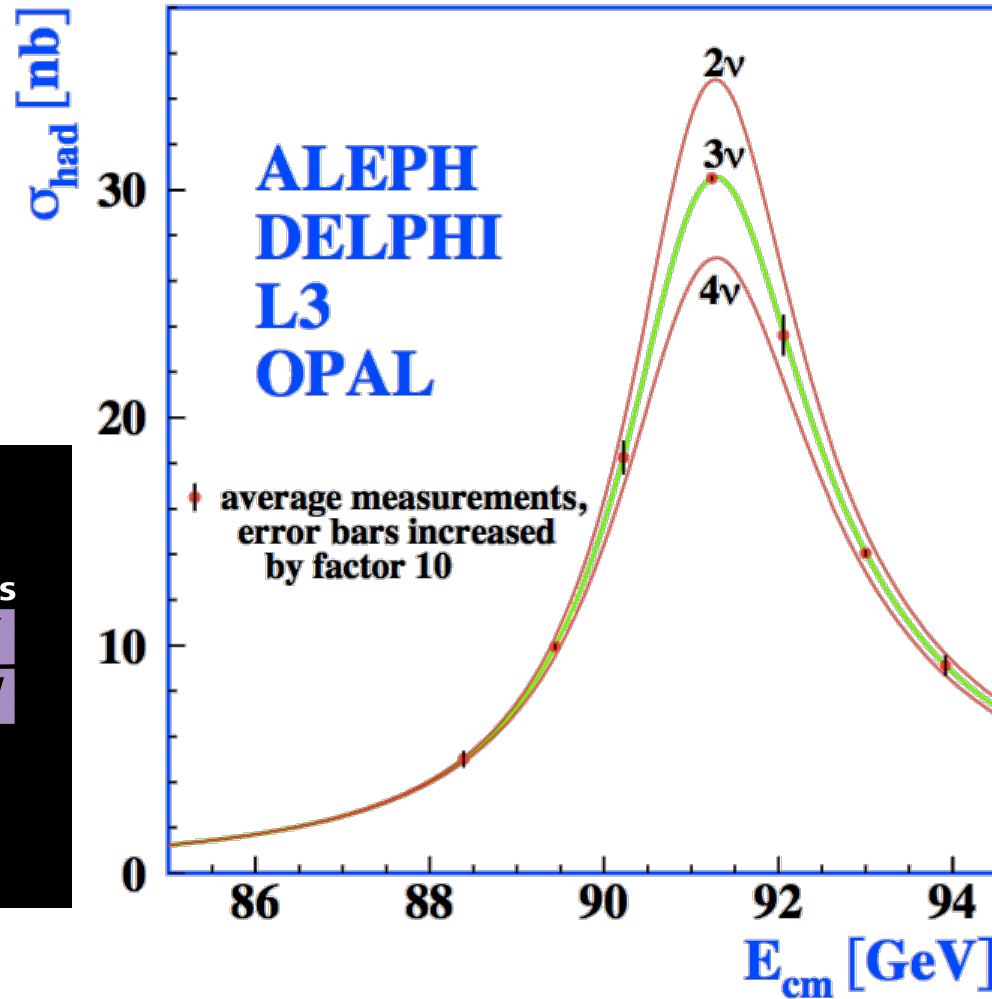
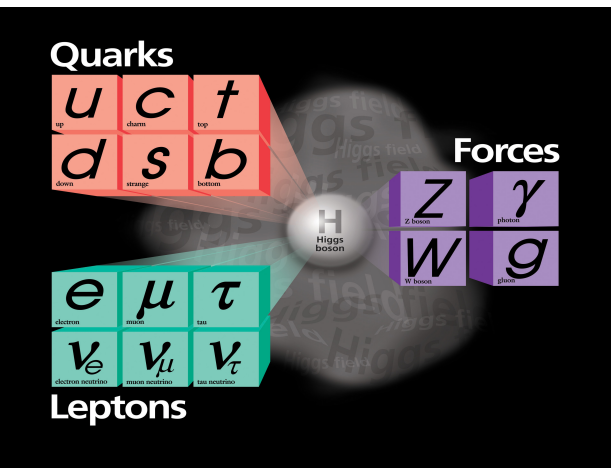


# $e^+e^-$ annihilation

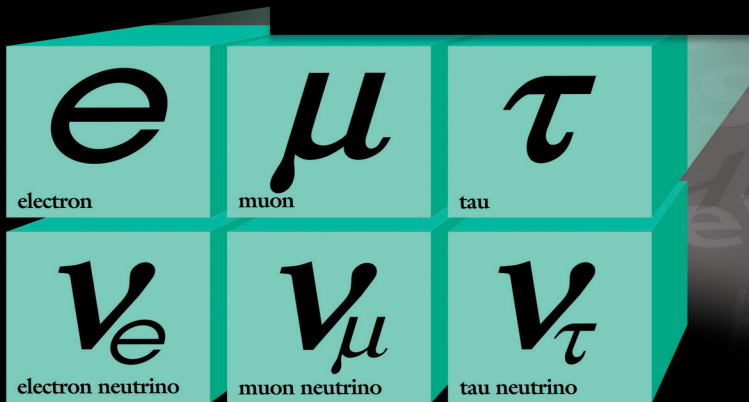
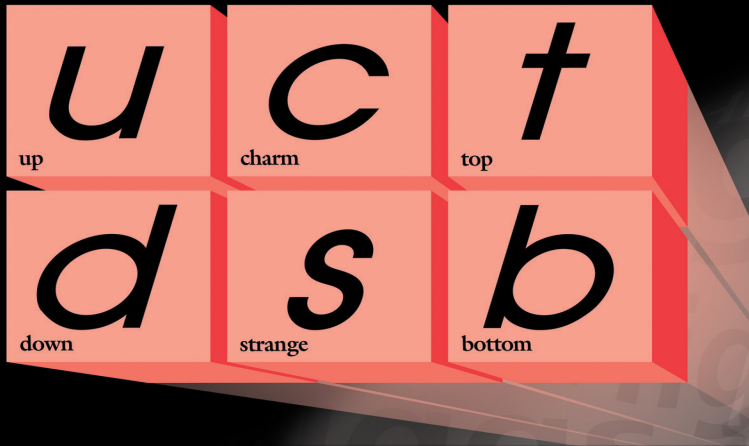


# LEP and the neutrinos

There are 3 generations of matter... (and other precision results!)



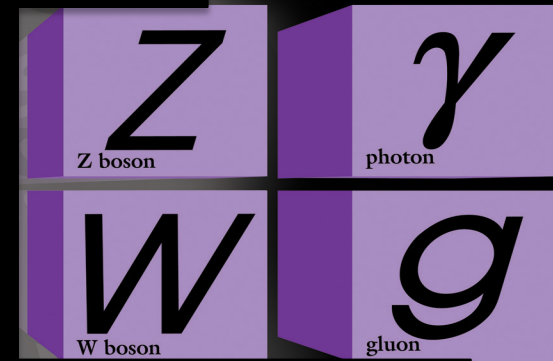
# Quarks



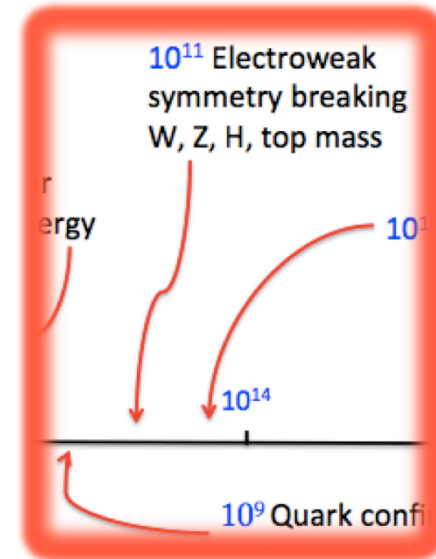
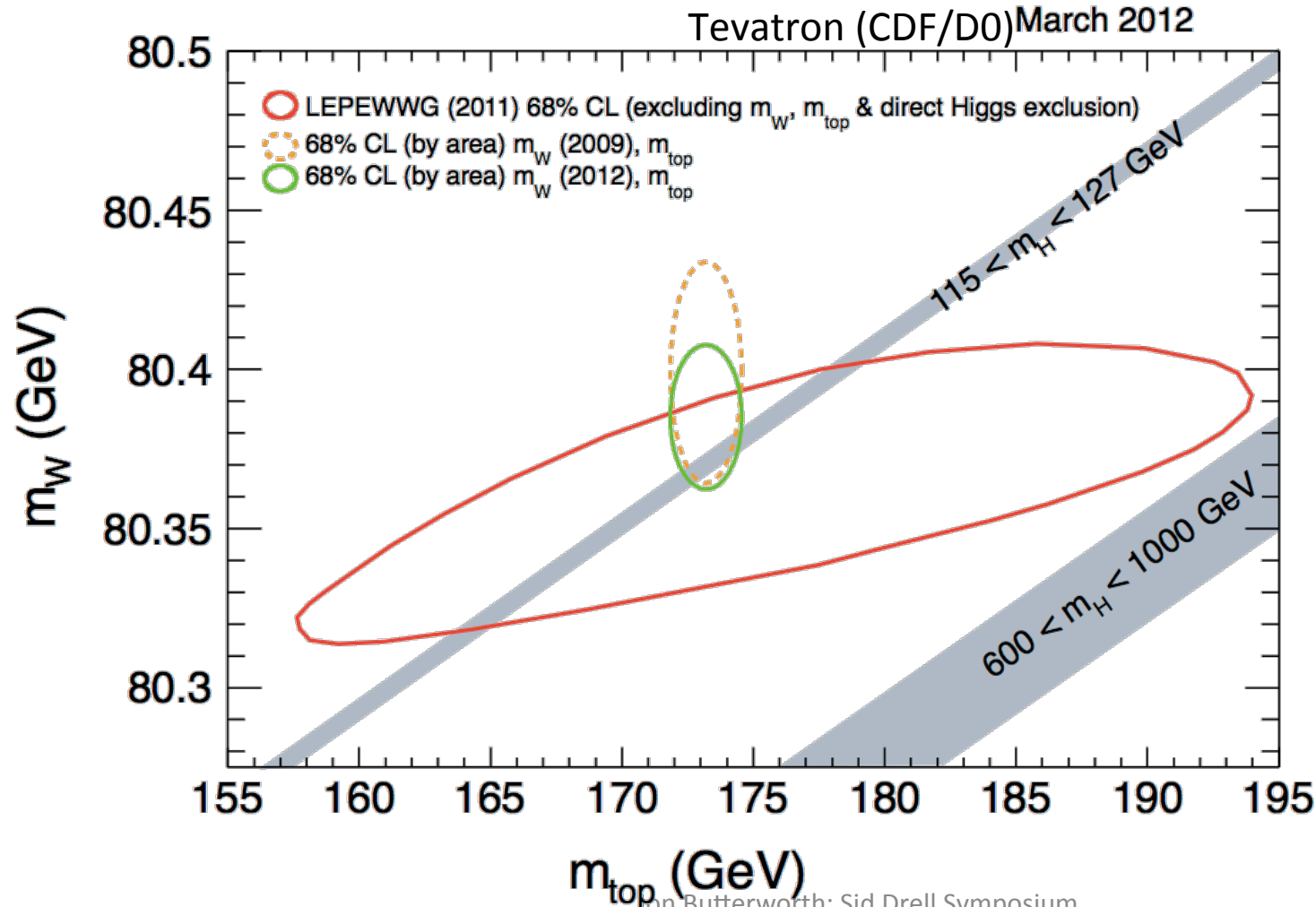
# Leptons

Pre 2012

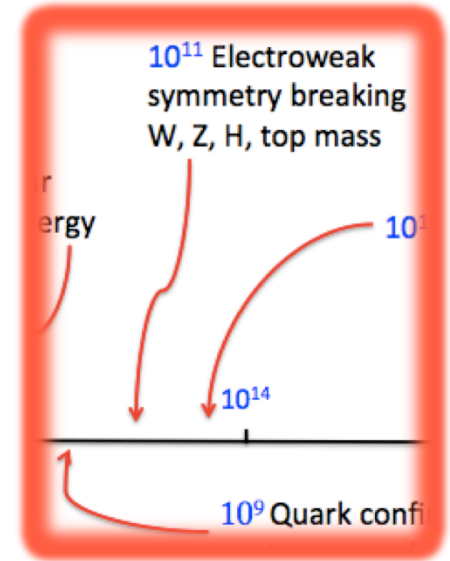
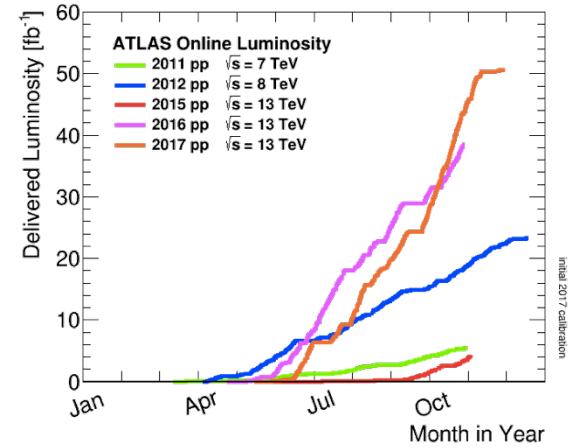
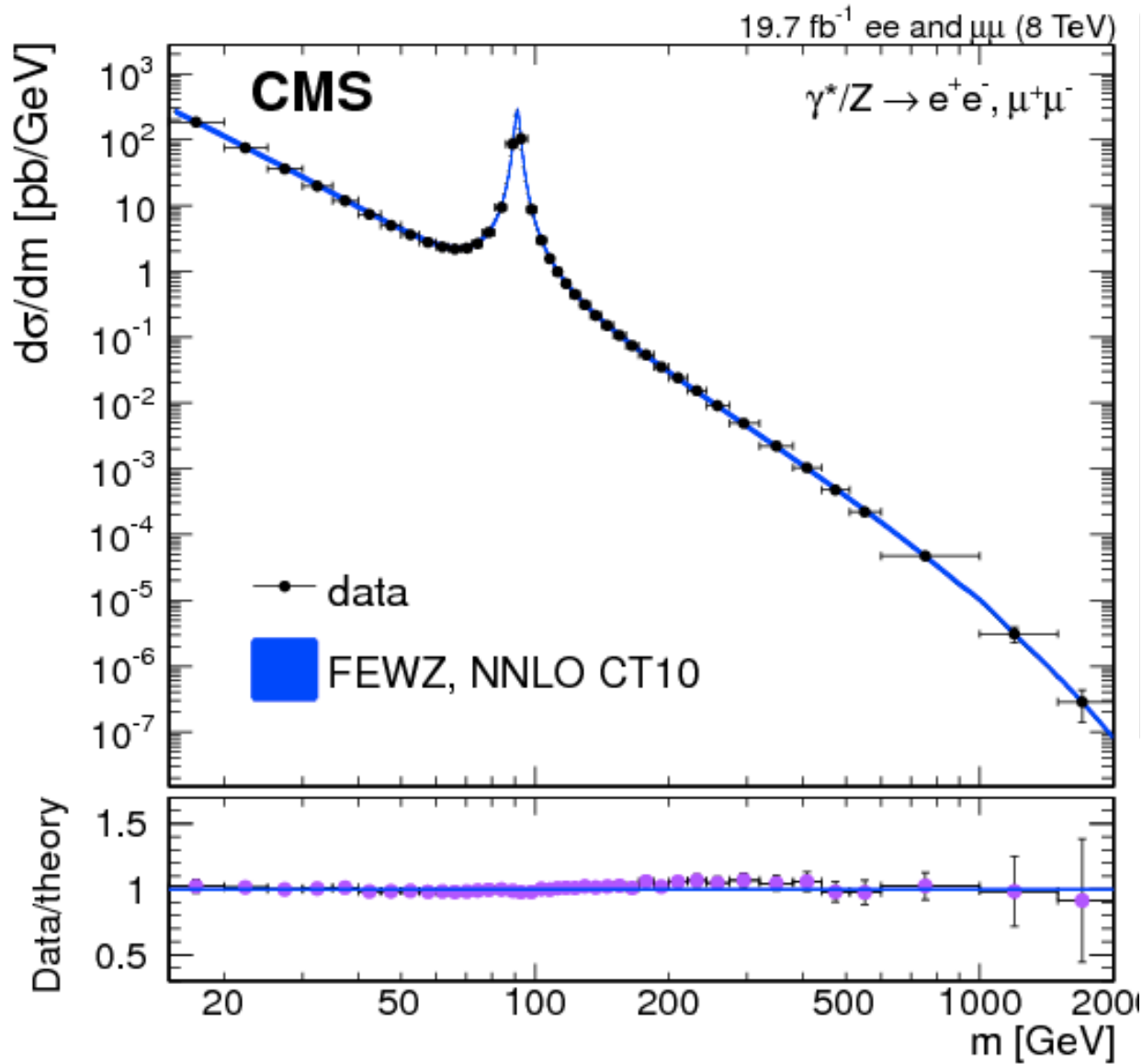
# Forces

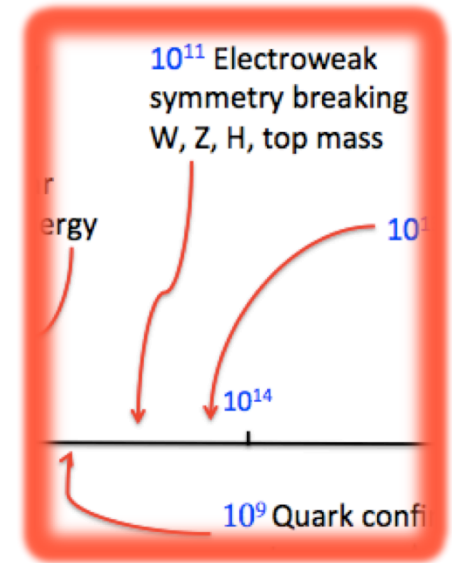
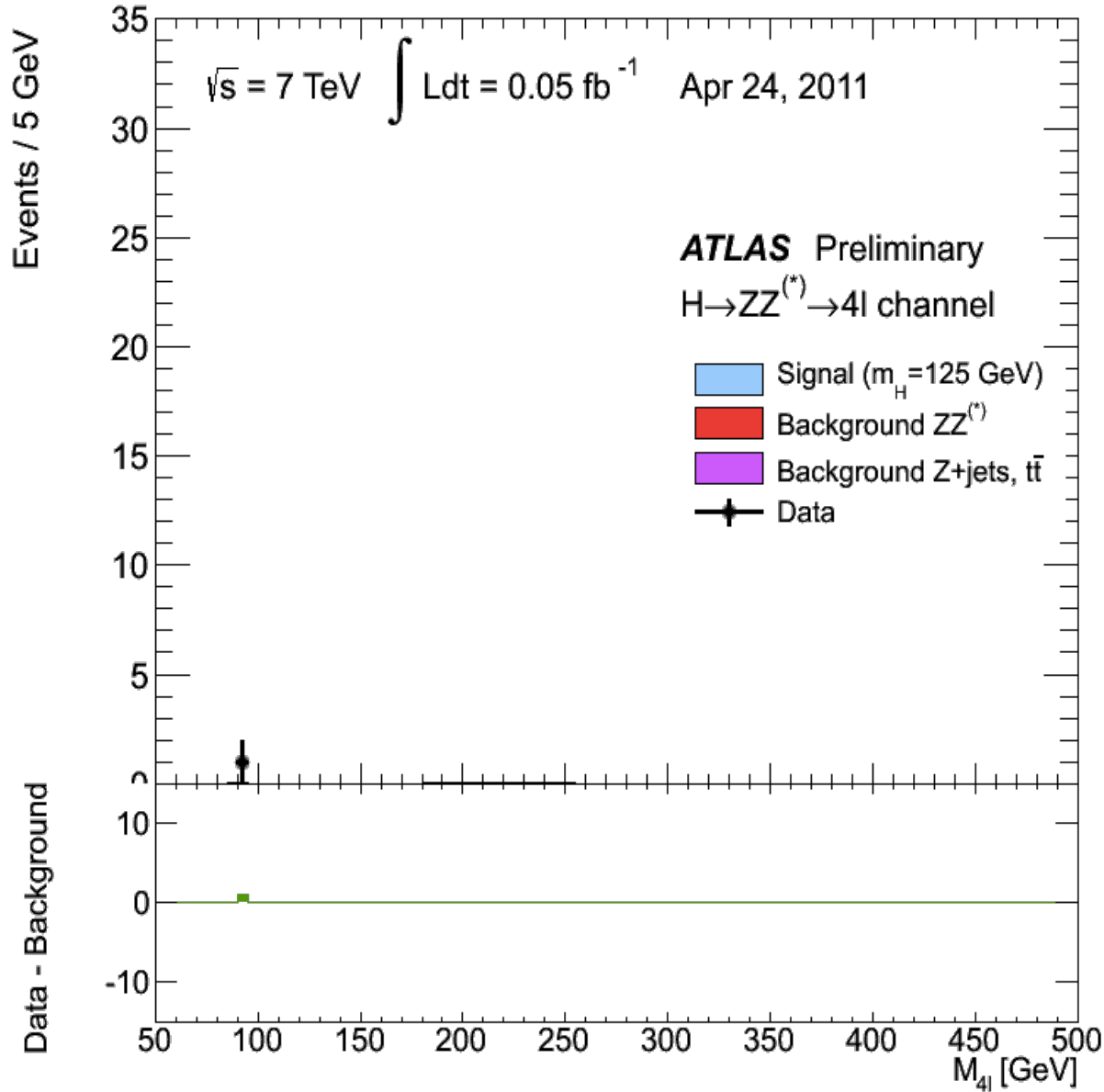


# Electroweak symmetry breaking



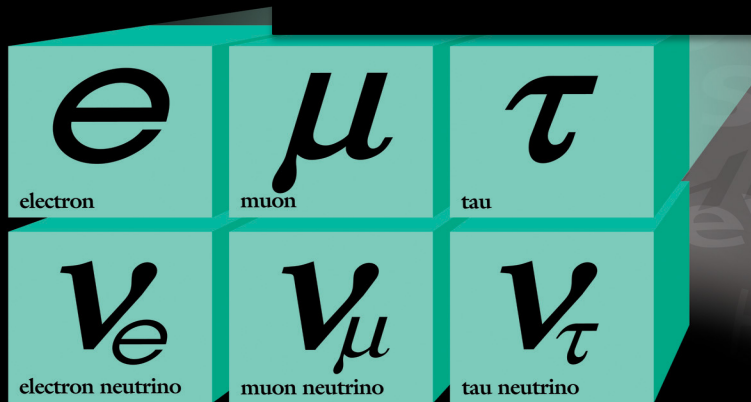
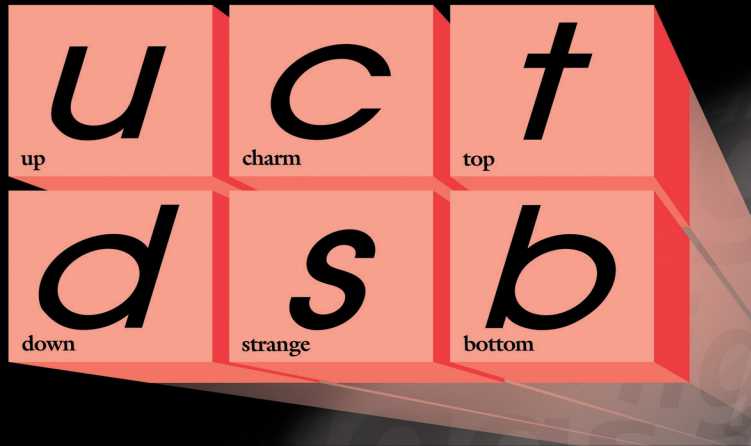








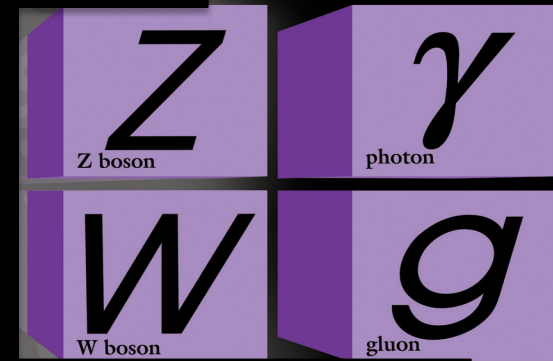
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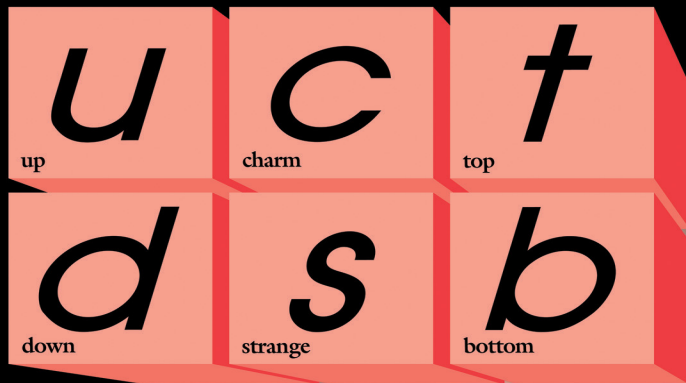
# Leptons

Pre 2012

# Forces

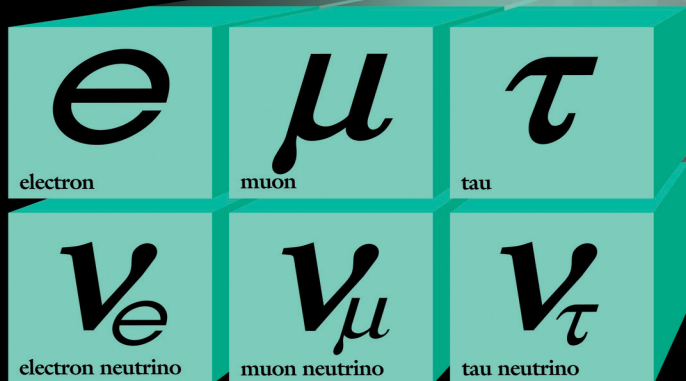
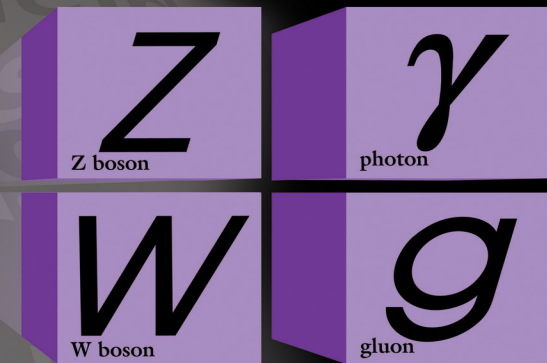


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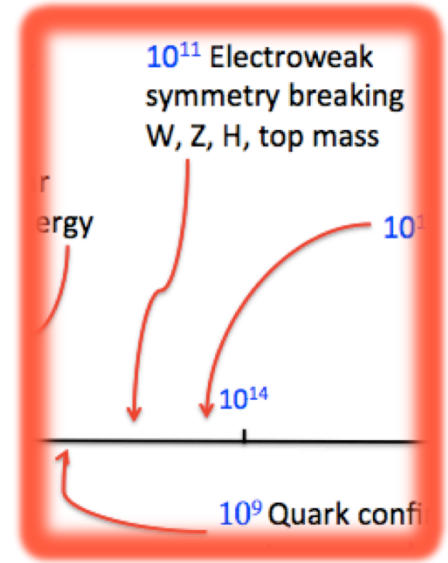
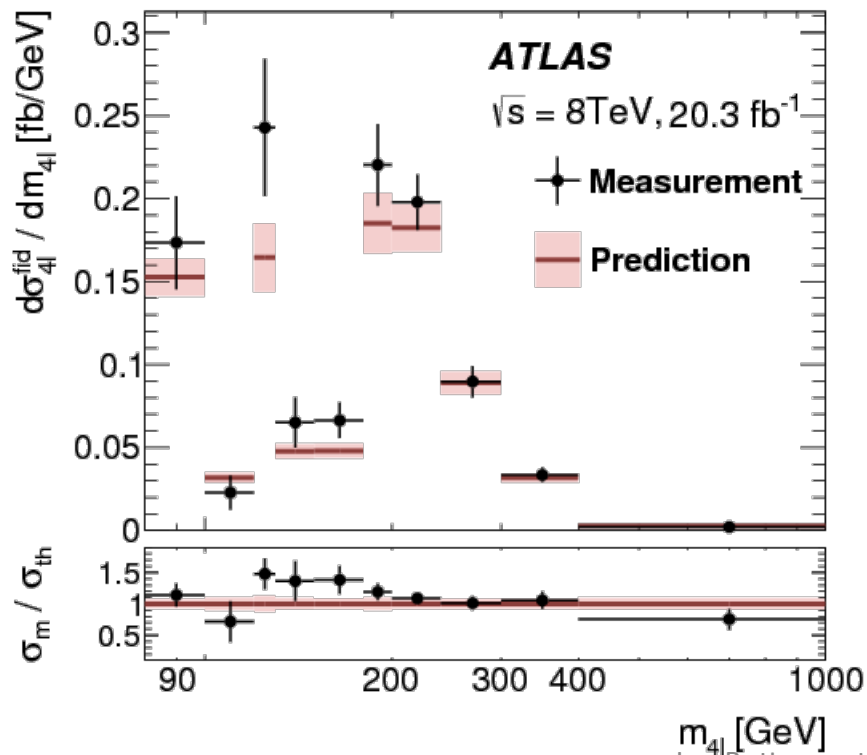
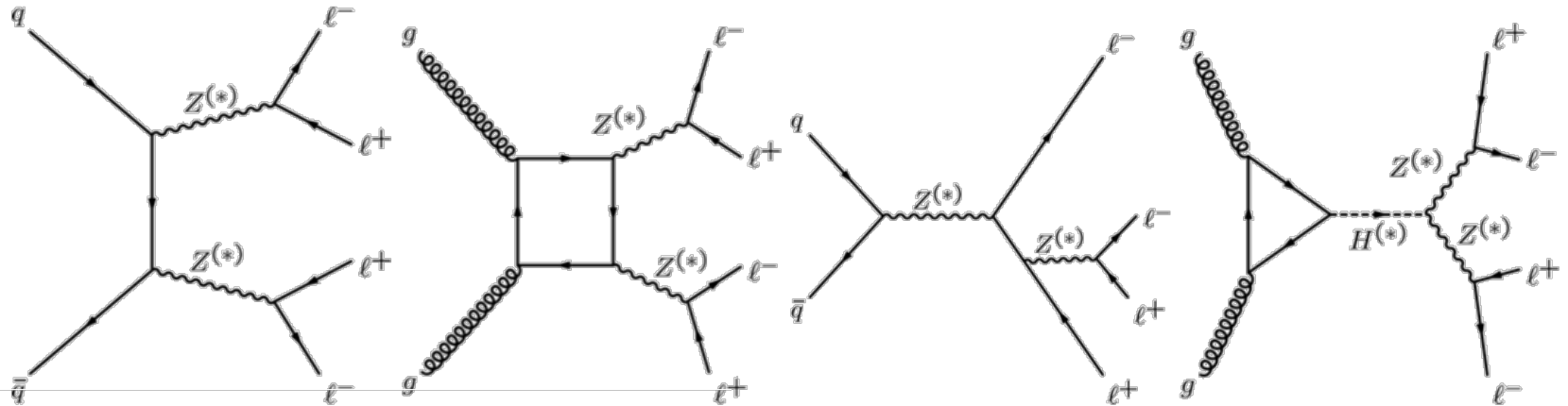


Post 2012

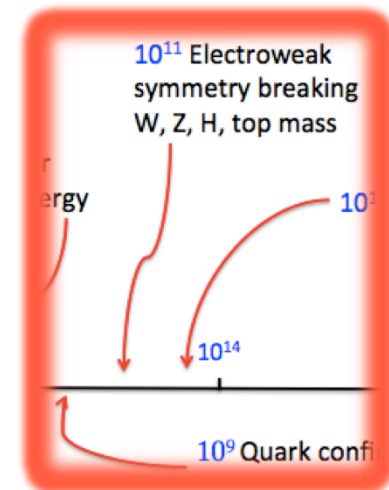
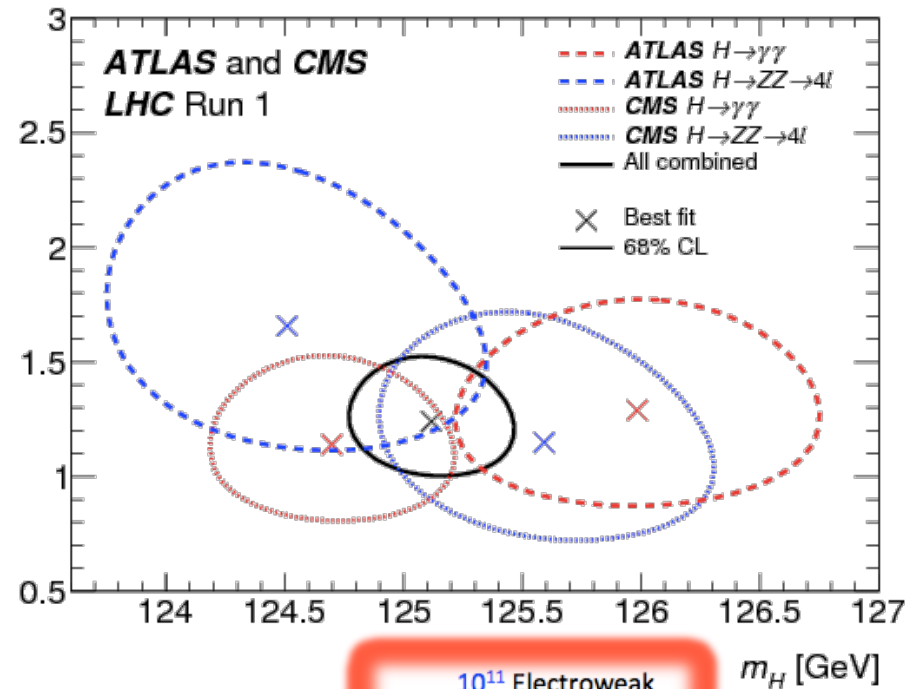
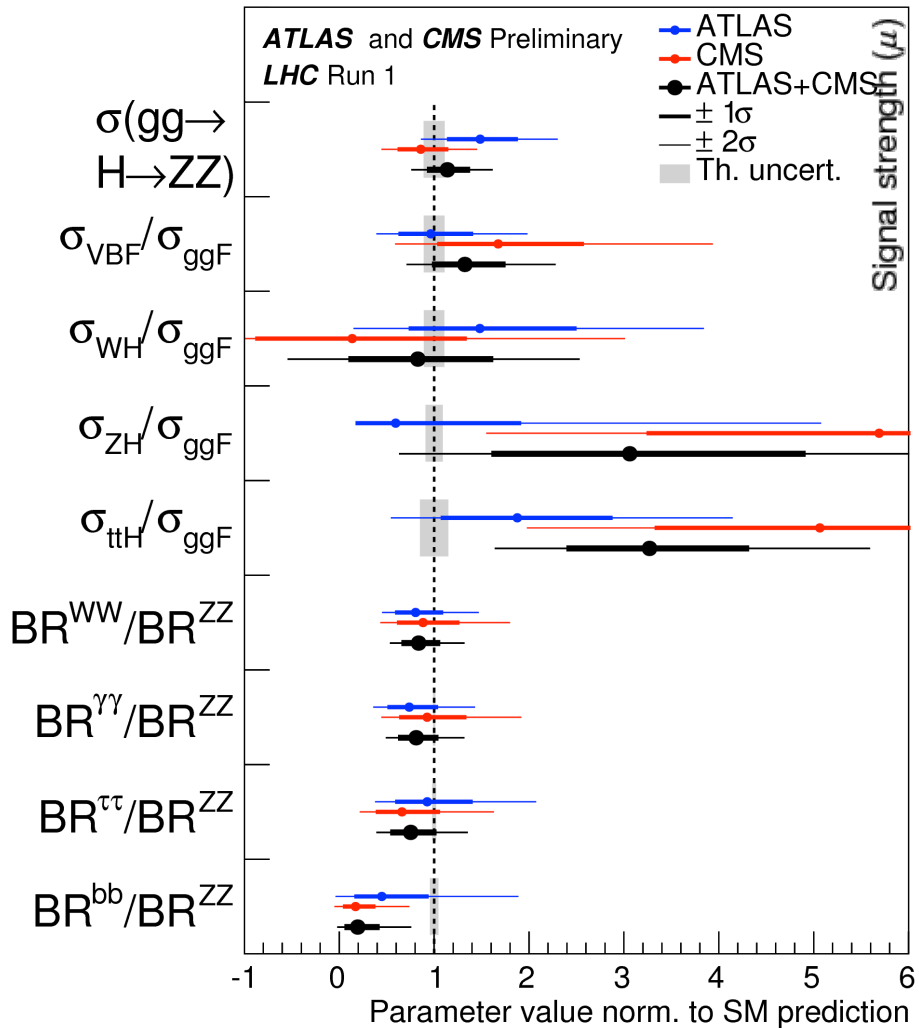
# Forces



# Leptons

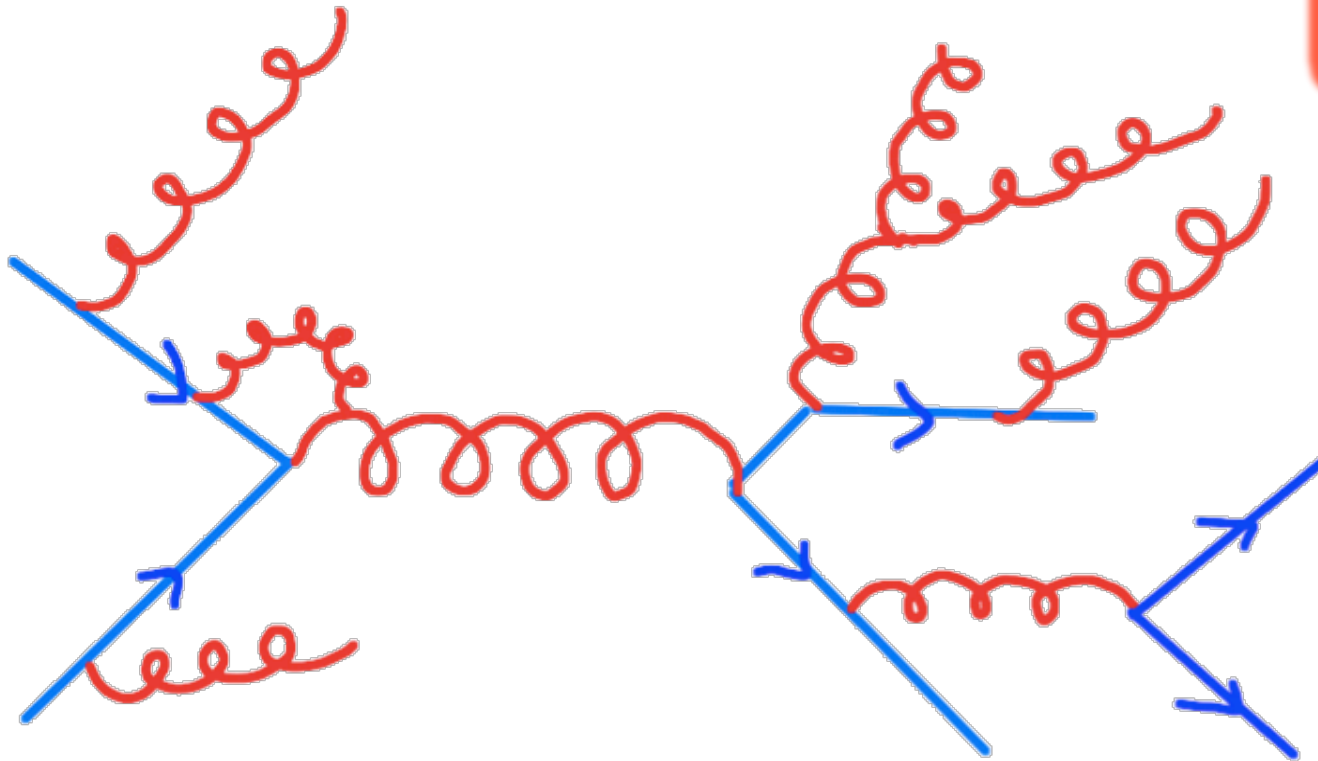
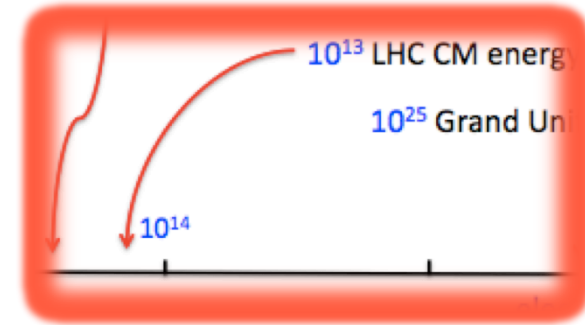


# Precision Higgs



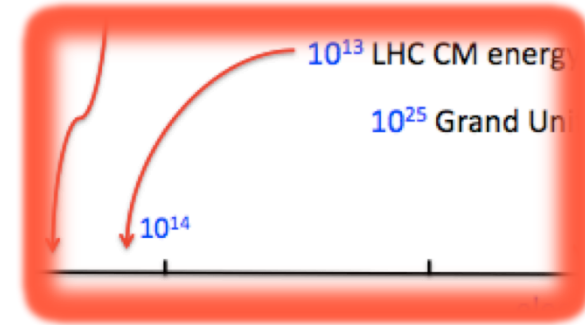
# To the TeV scale and beyond...

- Precision theory, exclusive calculations, fixed orders & resummed & matched

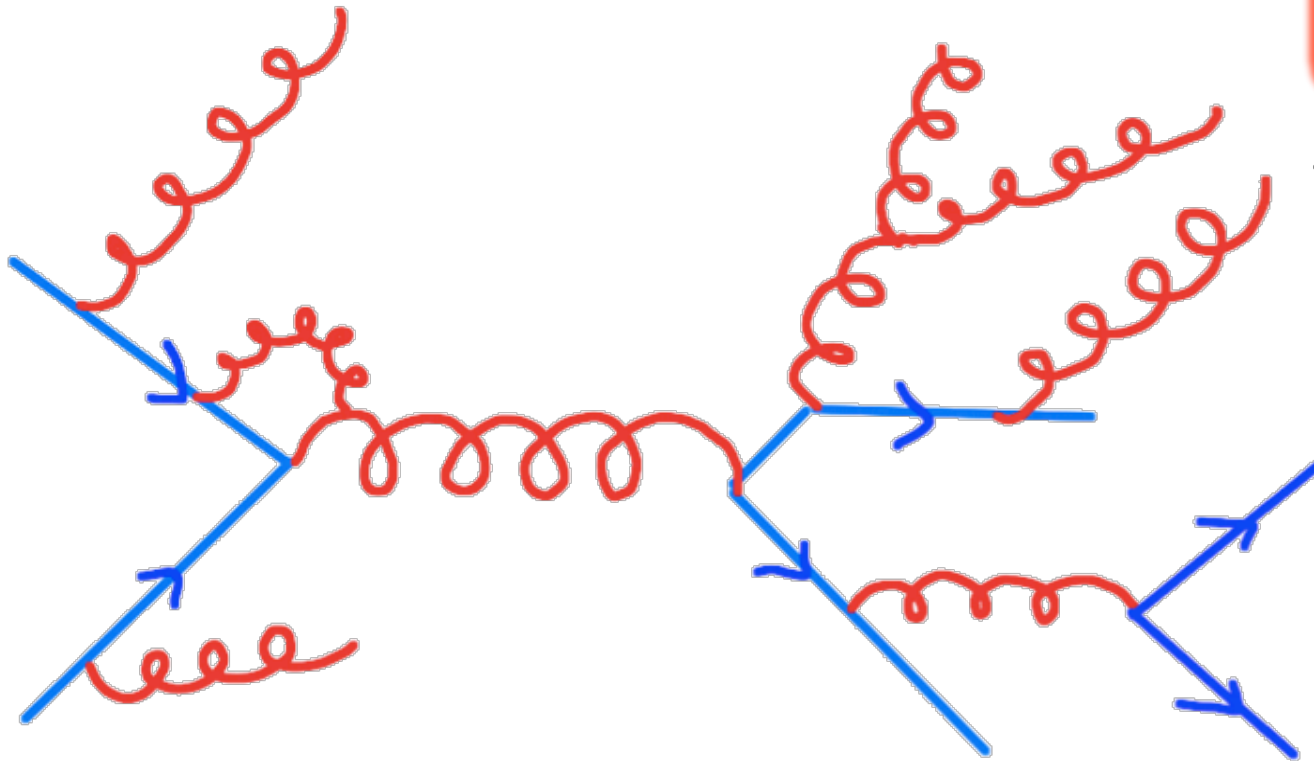


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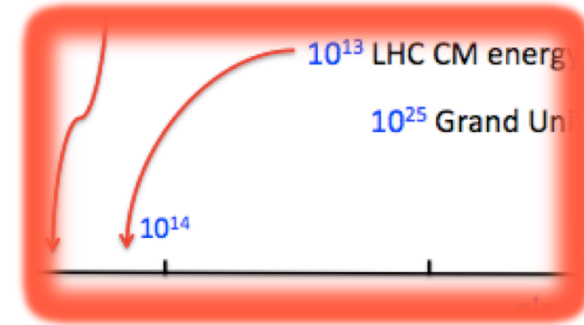


- Vertices  $\rightarrow \alpha_s, \mathcal{O}(0.1)$

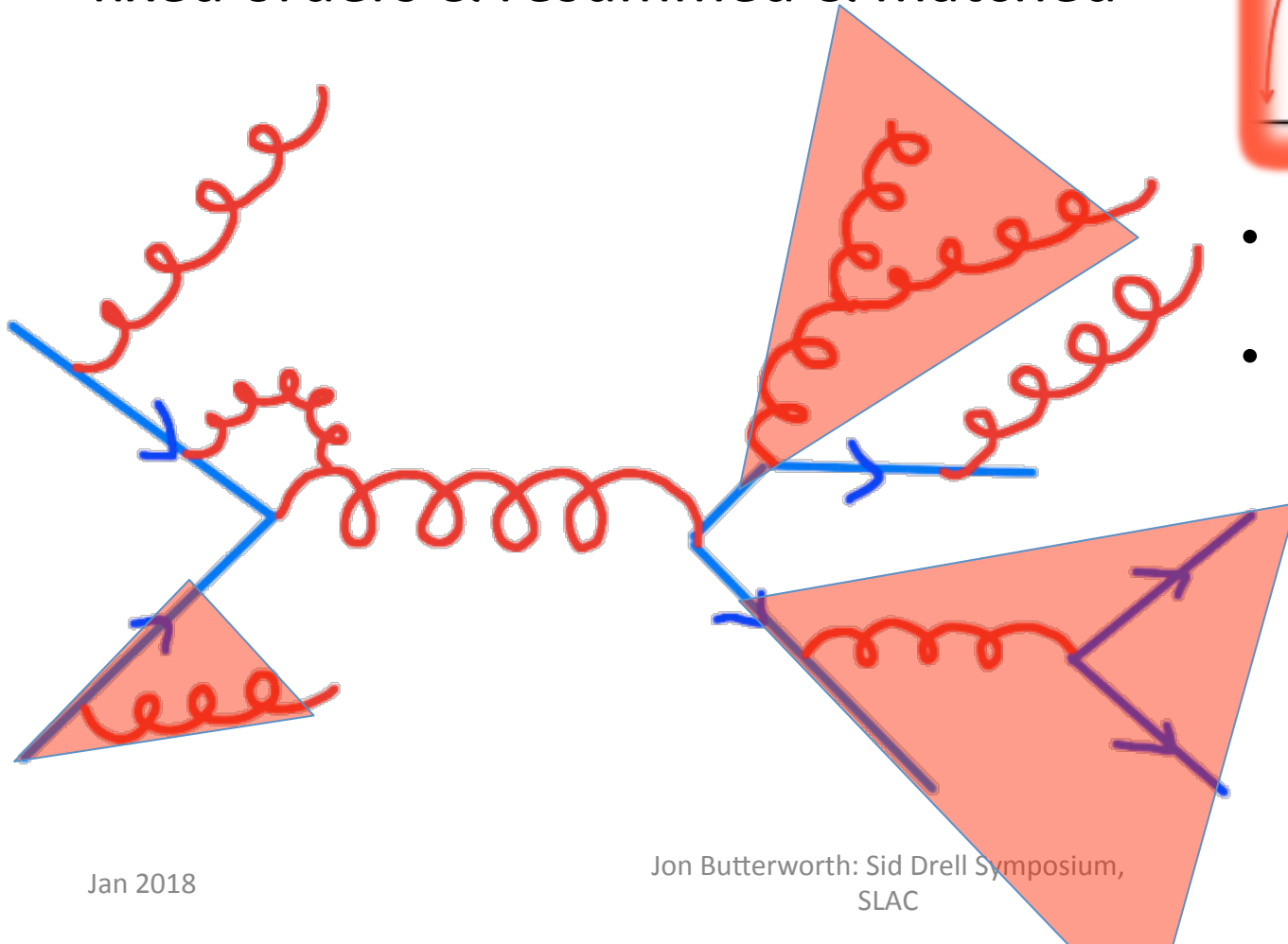


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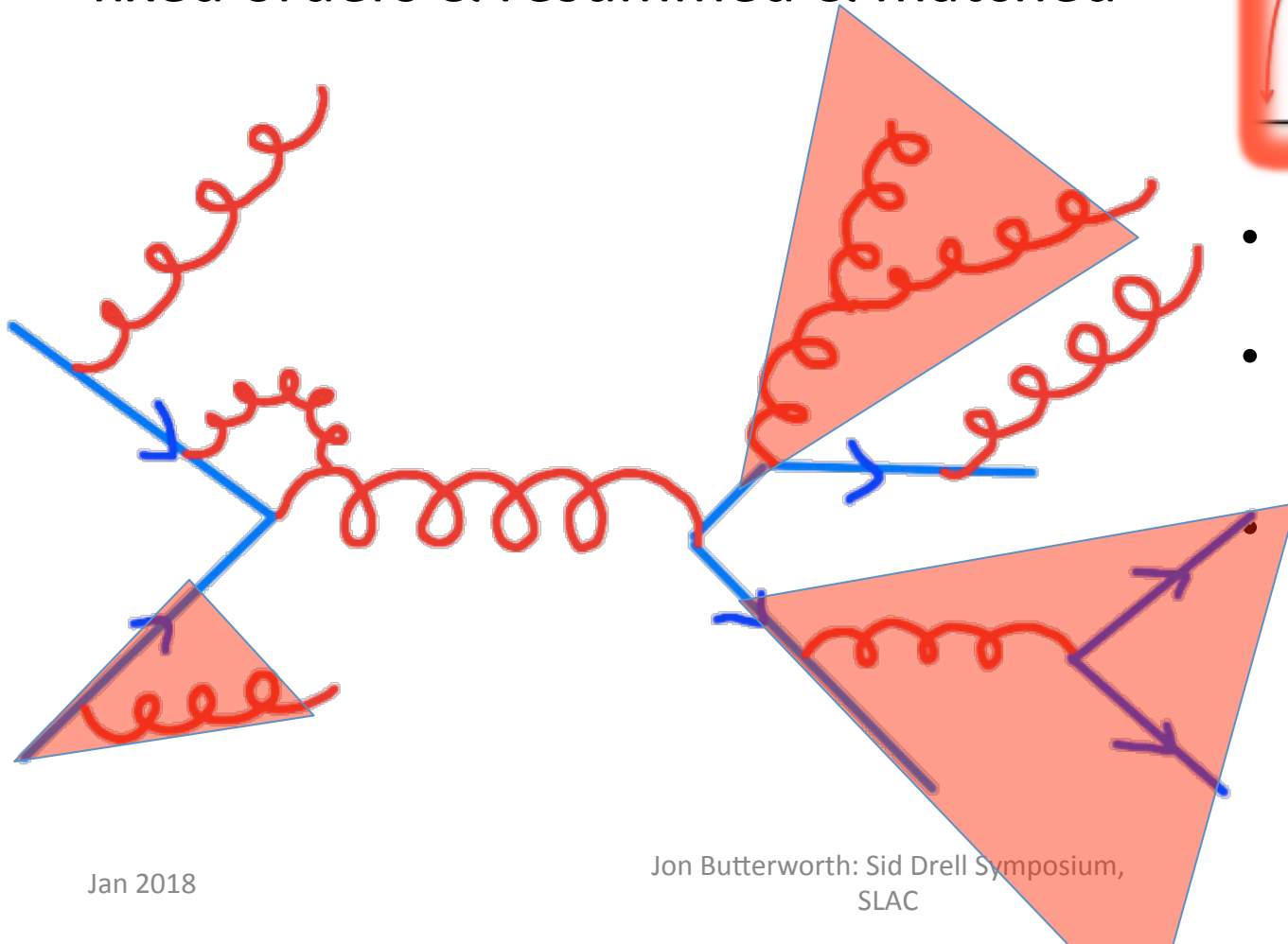
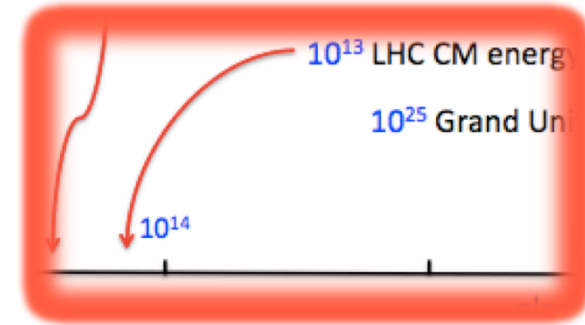


- Vertices  $\rightarrow \alpha_s, \mathcal{O}(0.1)$
- Soft or collinear kinematics  $\rightarrow \log(\text{scales}) \mathcal{O}(10)$



# To the TeV scale and beyond...

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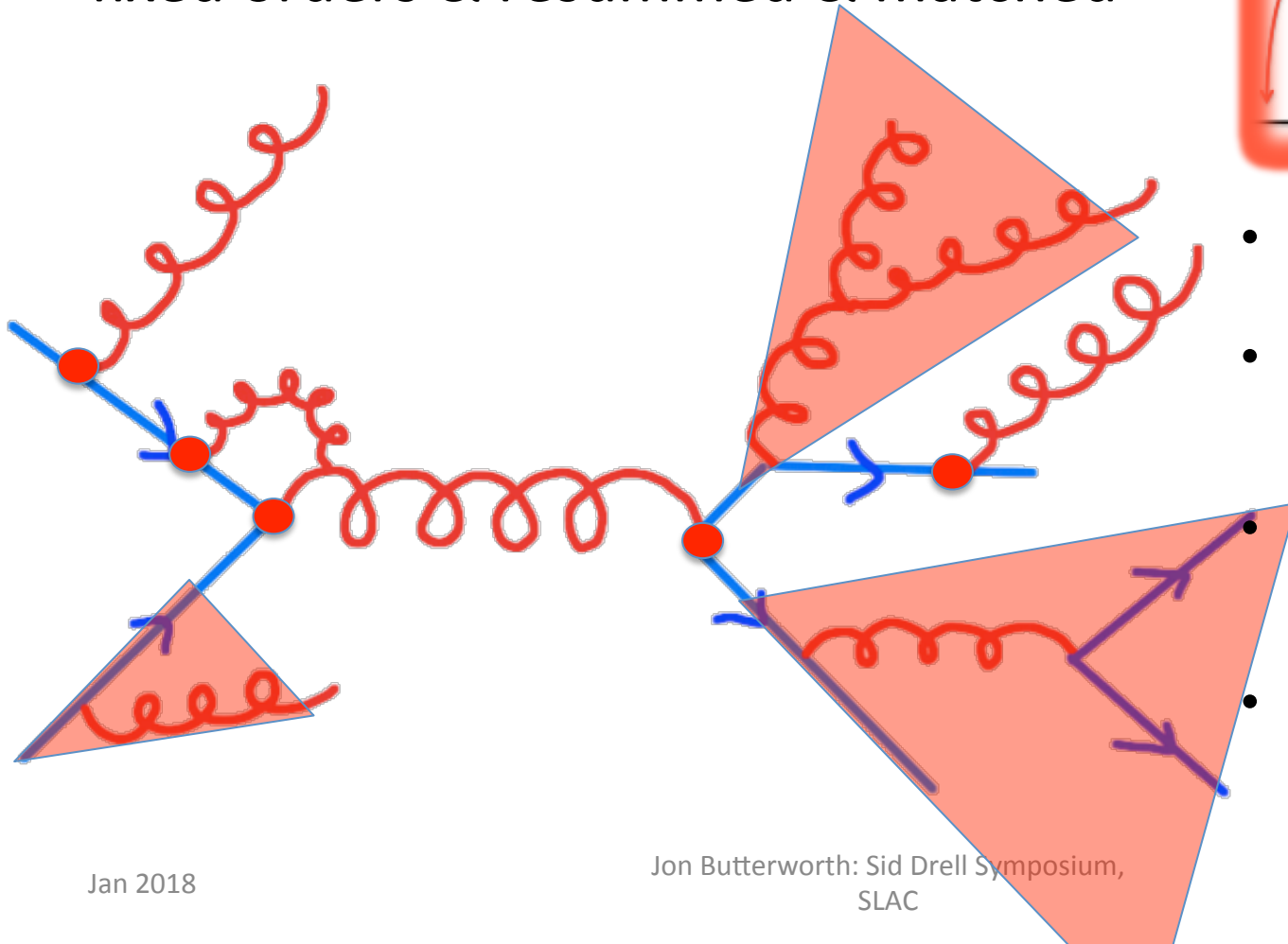
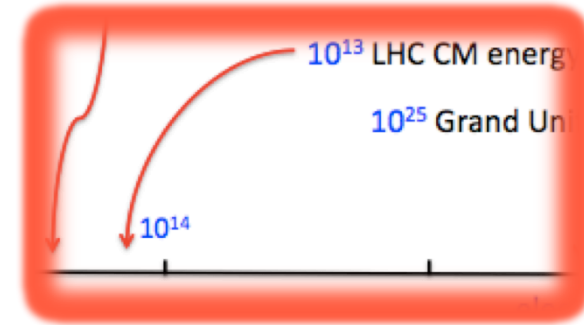


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 $\alpha_s \log$  terms  $\mathcal{O}(1)$ , must be resummed (exponentiated)



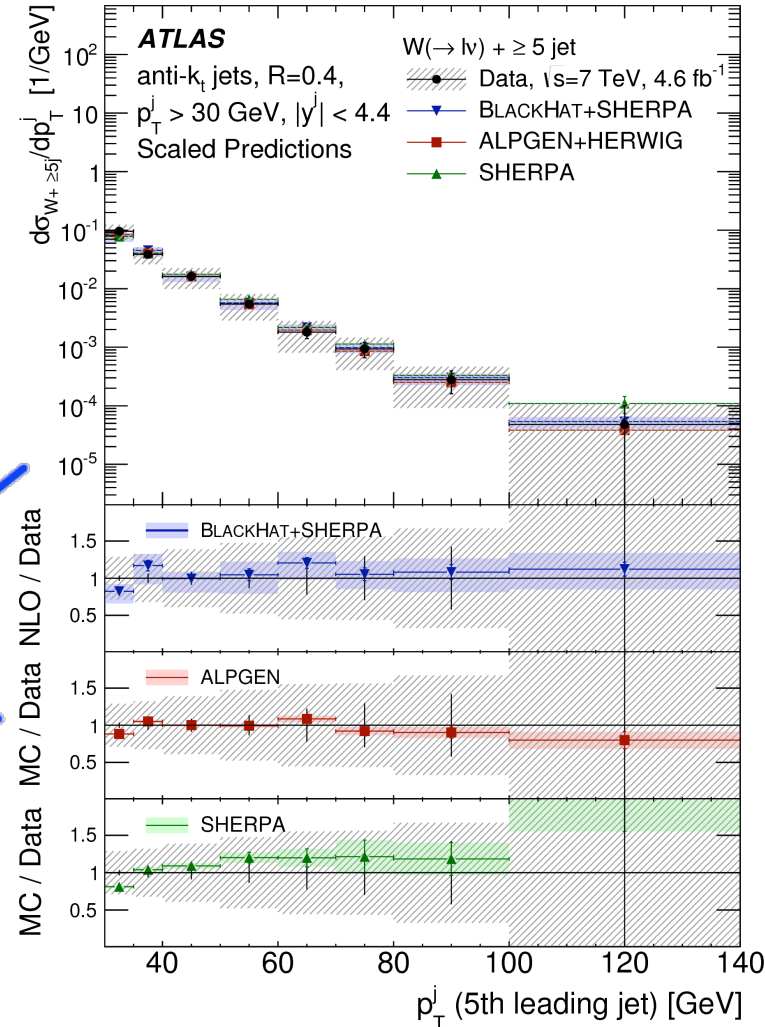
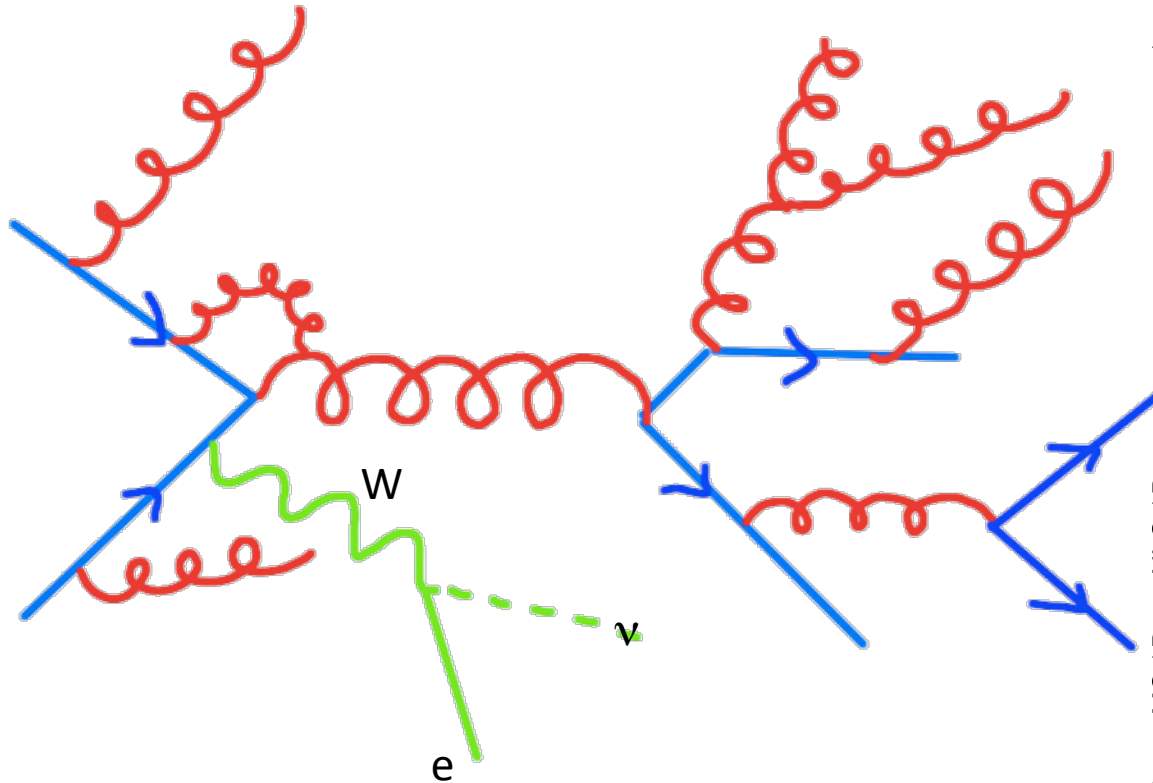
# To the TeV scale and beyond...

- Precision theory, exclusive calculations, fixed orders & resummed & matched

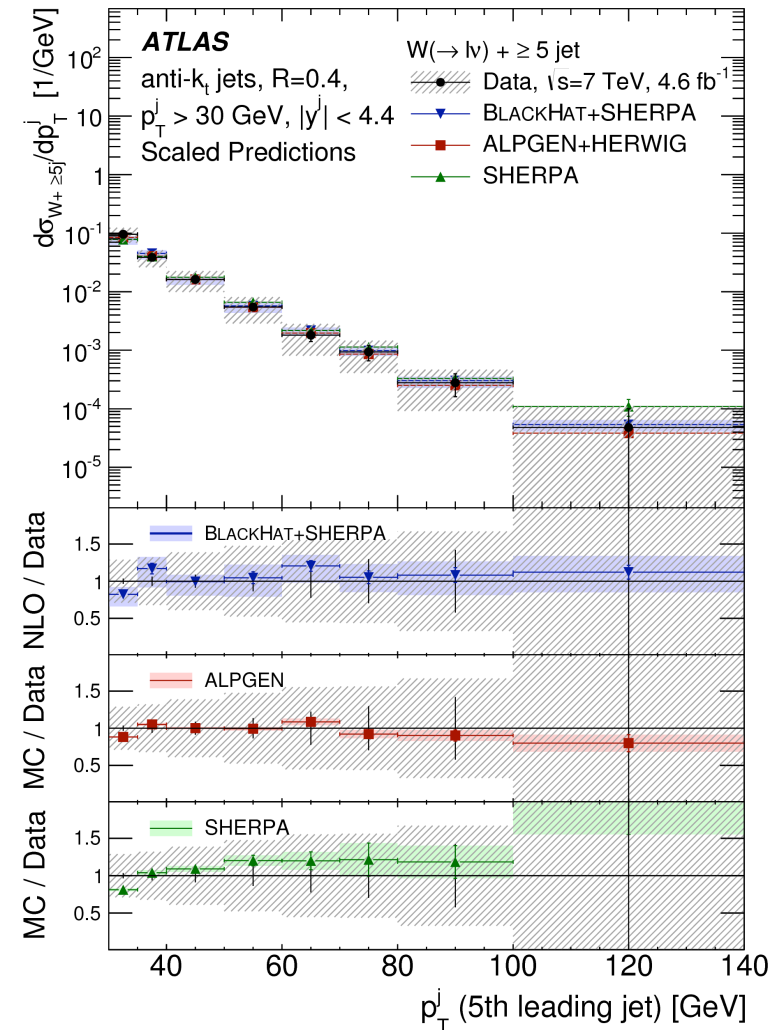
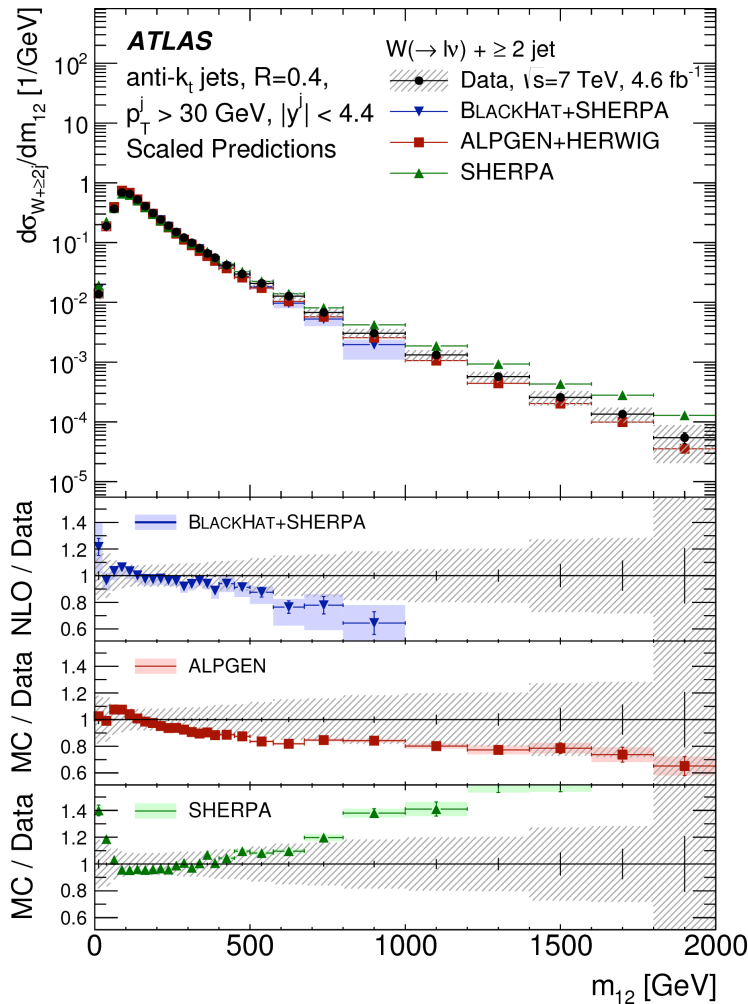


- Vertices  $\rightarrow \alpha_s$ ,  $\mathcal{O}(0.1)$
- Soft or collinear kinematics  $\rightarrow \log(\text{scales}) \mathcal{O}(10)$   
 $\alpha_s \log$  terms  $\mathcal{O}(1)$ , must be resummed (exponentiated)
- Still need fixed-order  $\alpha_s$  outside these enhanced regions

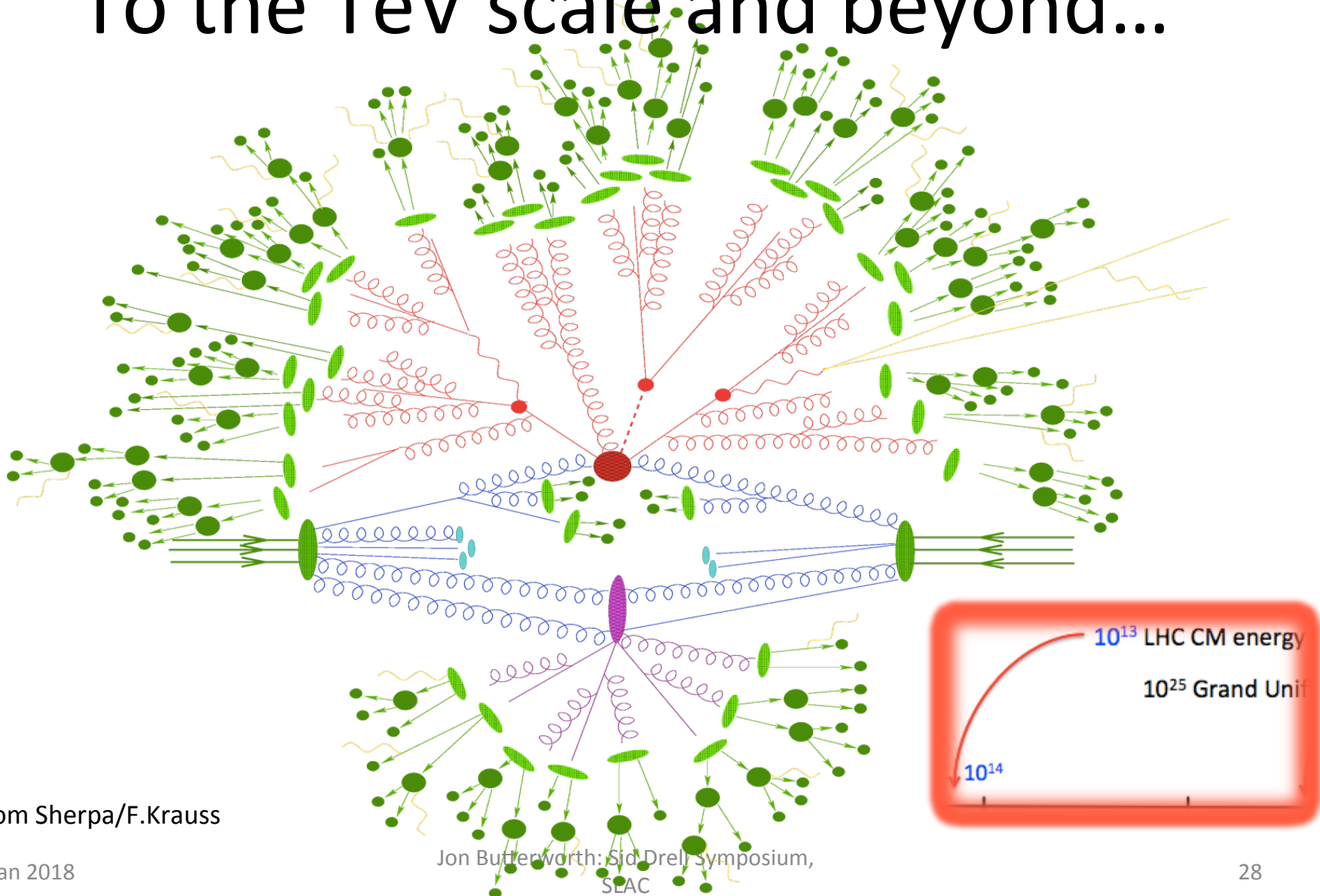
# To the TeV scale and beyond...



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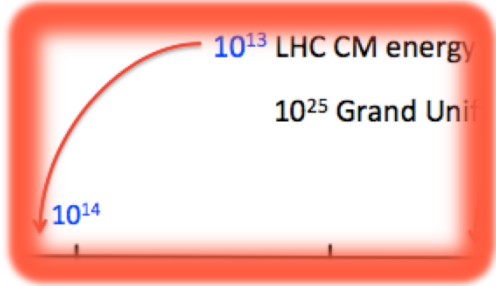


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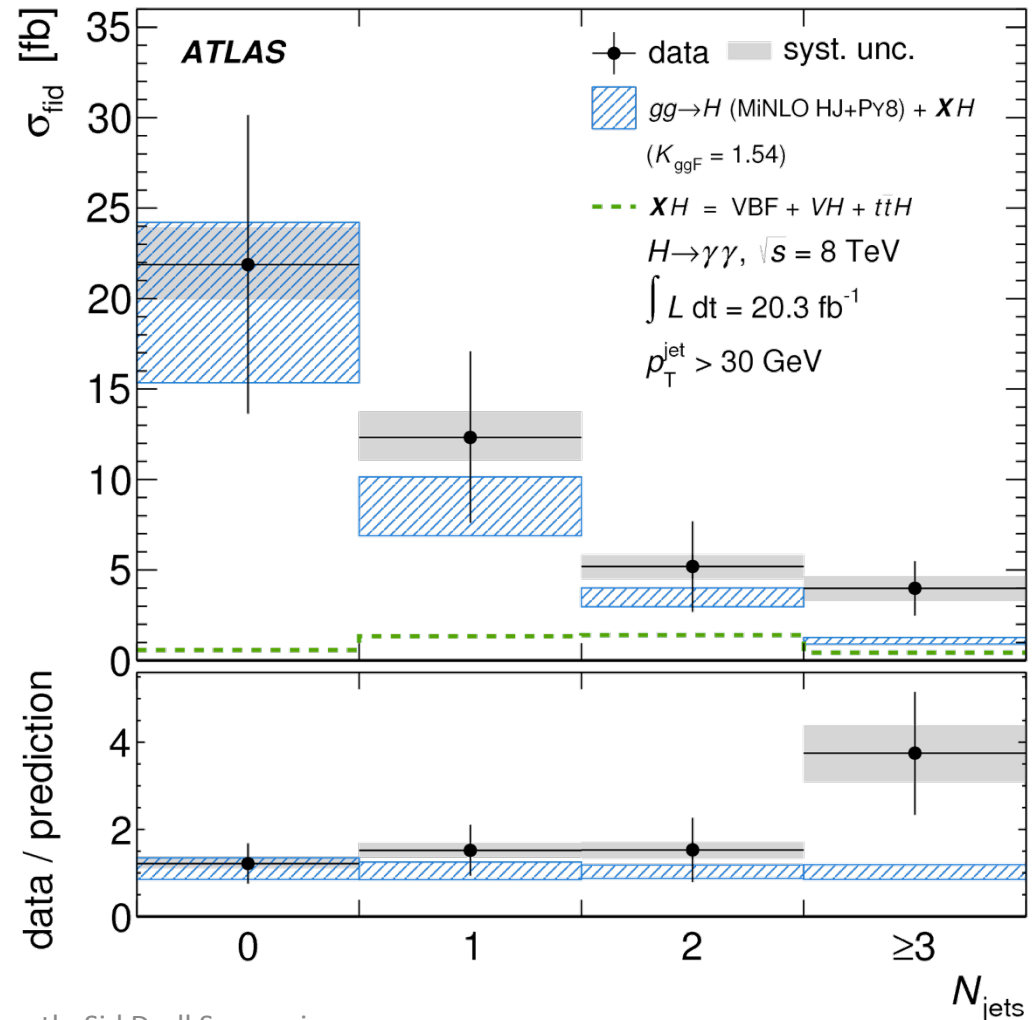


Pic from Sherpa/F.Krauss

# To the TeV scale and beyond...

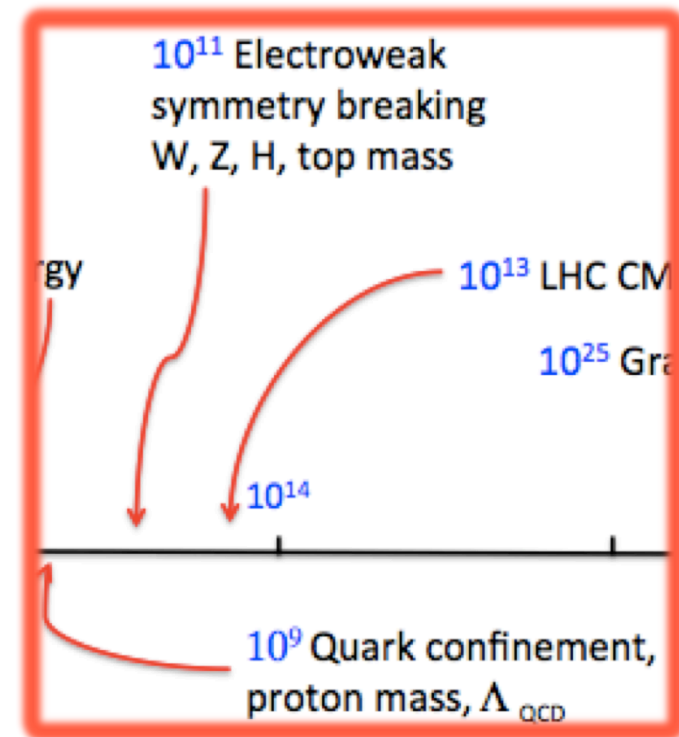
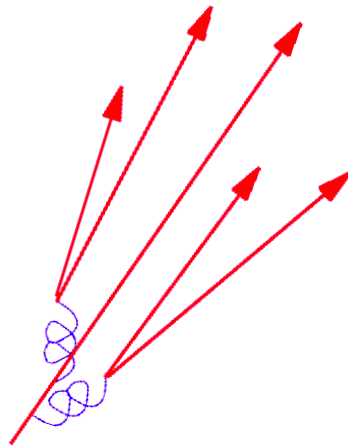


- Into the unknown...
  - Well-defined, precise measurements and calculations.
  - High multiplicities
  - High boosts, even for electroweak-scale objects



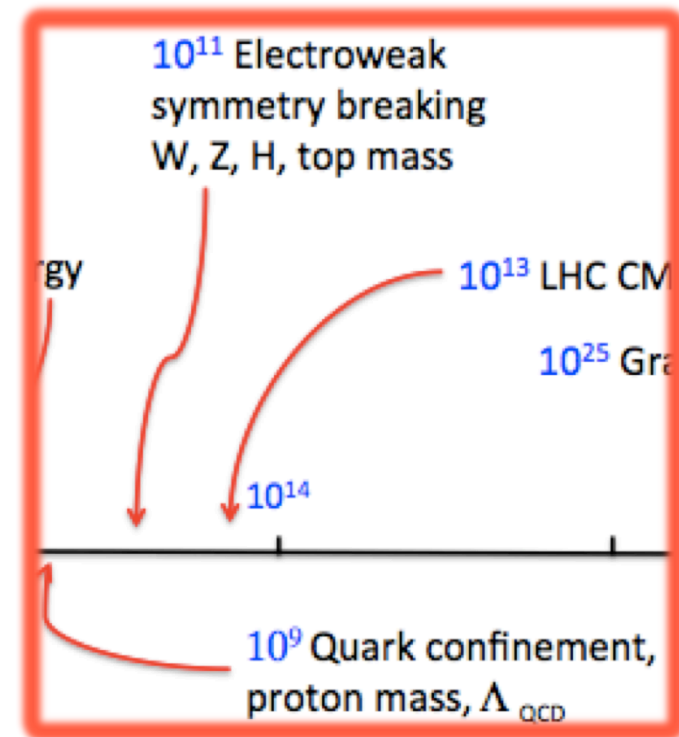
# To the TeV scale and beyond...

- New feature... the boost
- Perturbative QCD between about 1 GeV (hadronisation) and LHC kinematic limit (highest  $p_T$  jet formation)



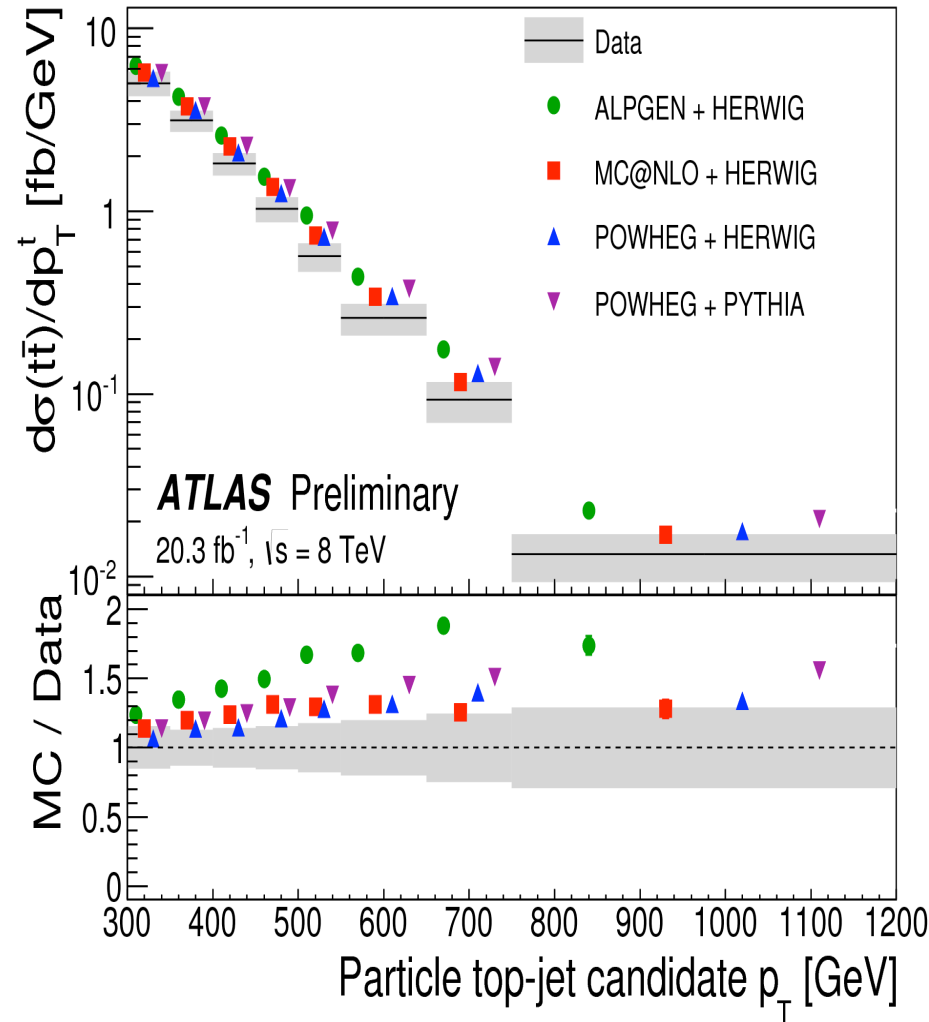
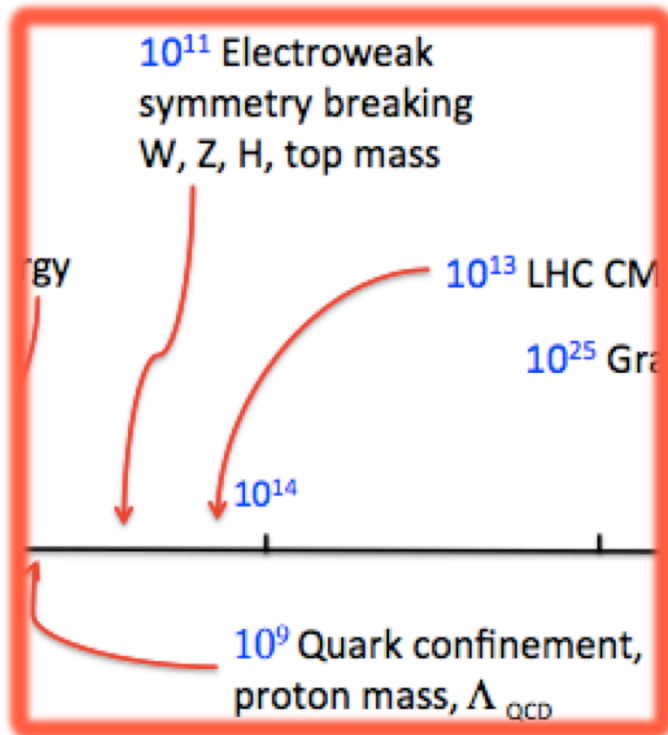
# To the TeV scale and beyond...

- New feature... the boost
- Perturbative QCD between about 1 GeV (hadronisation) and LHC kinematic limit (highest  $p_T$  jet formation)
- Electroweak symmetry breaking scale lies between these scales →
- Electroweak physics “inside” jets (H, W, Z, t – collimated decay products).
- Need to account for this in measurements and searches



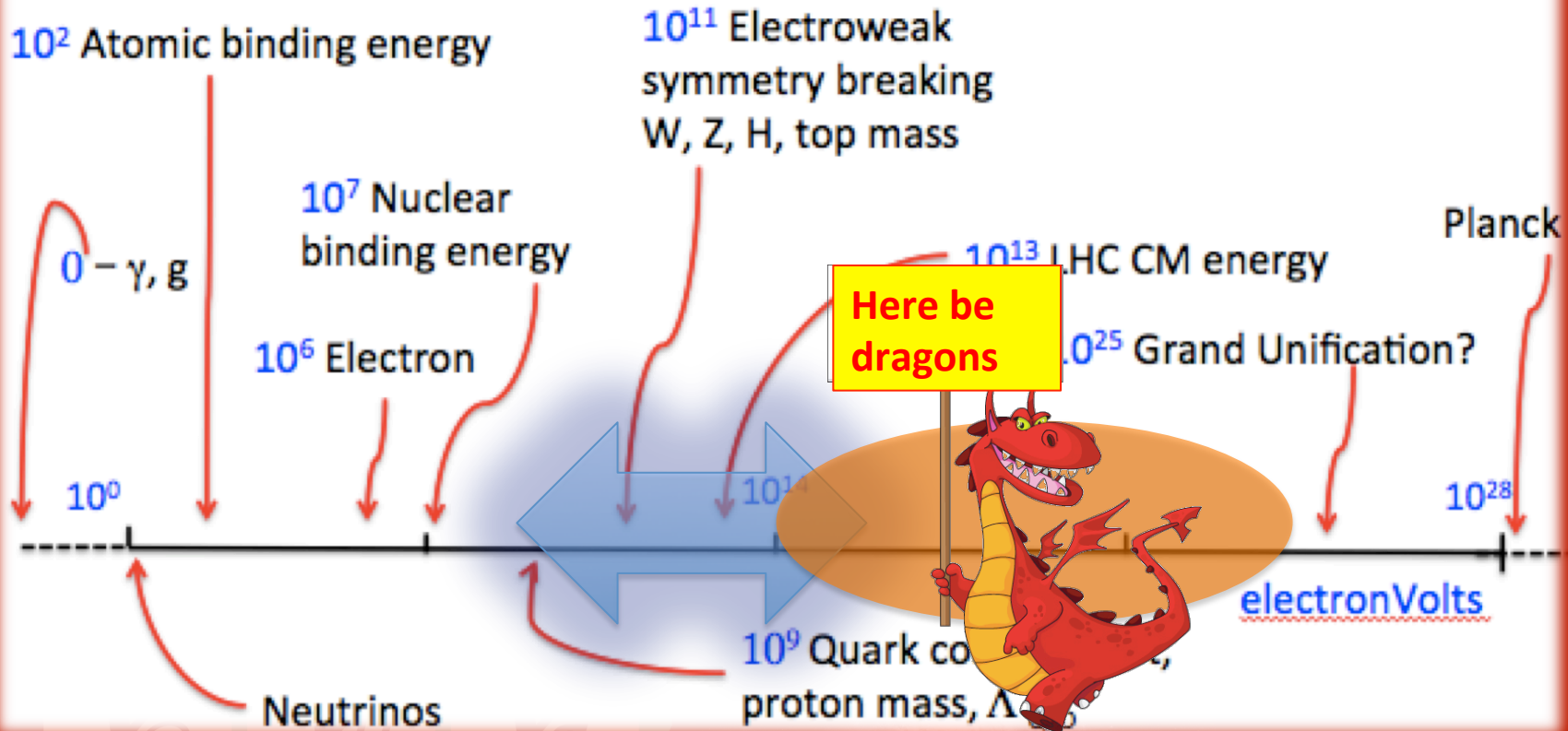
# To the TeV scale and beyond...

- Boosted top differential cross section, built from final-state particles





# Quarks



electron neutrino    muon neutrino    tau neutrino

# Leptons

