100 TEV ⟷ EFFECTIVE FIELD THEORY

Workshop on Physics at a 100 TeV Collider

April 24, 2014

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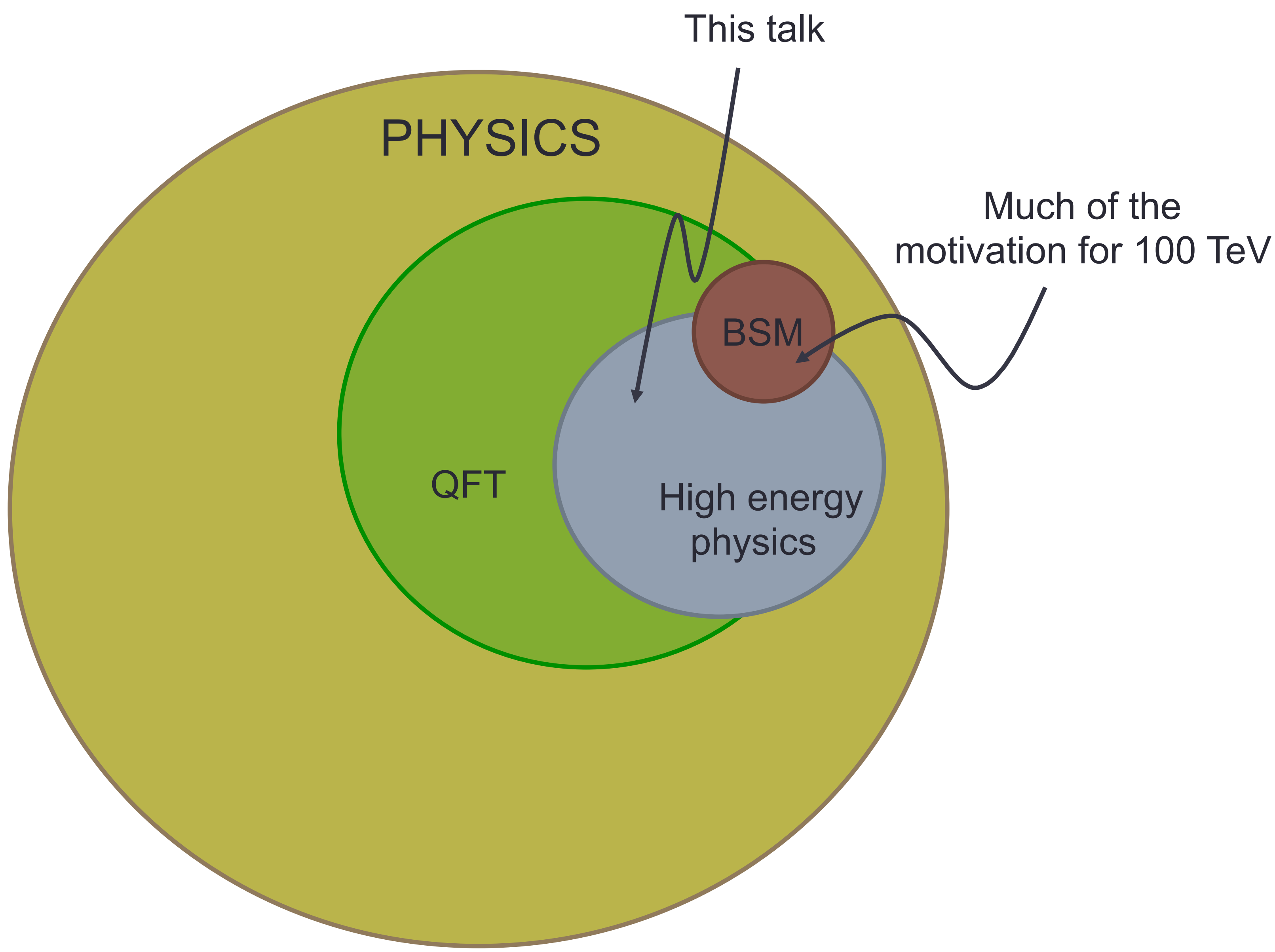
Harvard University


This talk
PHYSICS
Much of the
motivation for 100 TeV
BSM
QFT
High energy
physics

PART 1:
WHY 100 TEV NEEDS EFT

Why will EFTs be useful at 100 TeV?

1. Resummation of large logarithms
   - Critical for precision jet substructure (e.g. jet mass)
2. They clarify scale setting issues
   - Inclusive cross sections (e.g. Z boson p_T distribution)
   - Phase space cuts (e.g. p_T vetos)
3. Factorization
   - Parameterization of non-perturbative effects
   - Lets us exploit universality (e.g. PDFs)
4. They reveal hidden symmetries

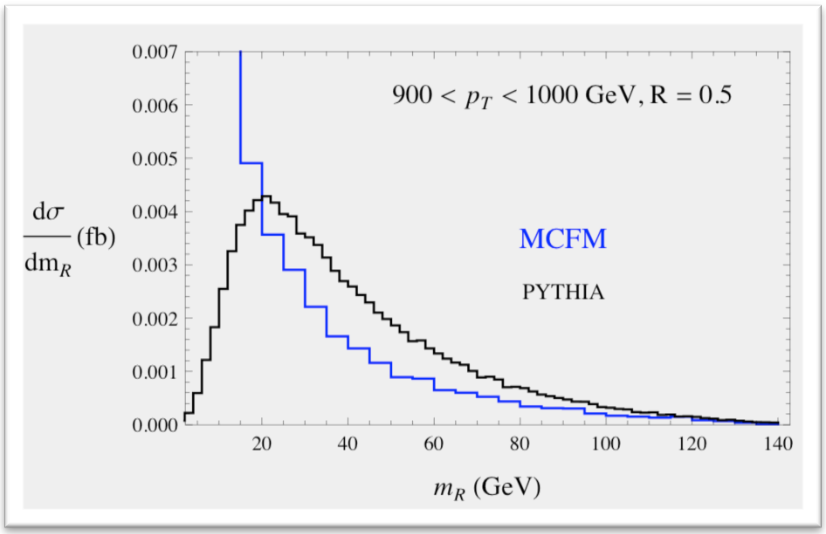
(Items 1–4: Reasons EFTs have been useful at other energies)

5. ….
6. EFTs always useful, in ways that are hard to predict ahead of time

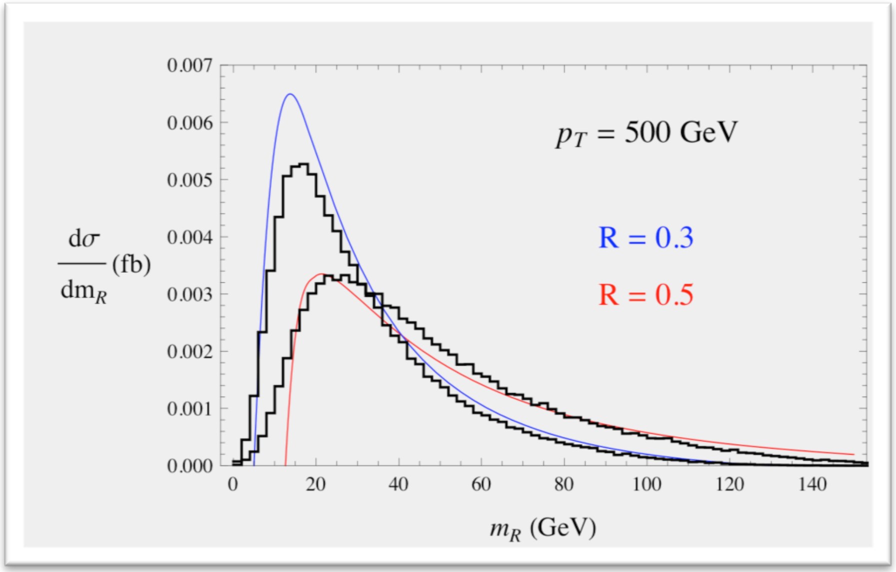
1. RESUMMATION

Jet mass at the LHC

- Fixed order calculations **cannot** even qualitatively **describe** most jet shapes



- Resummed distributions using EFT look great



Chien, Kelley, MDS, Zhu arXiv:1208.0010

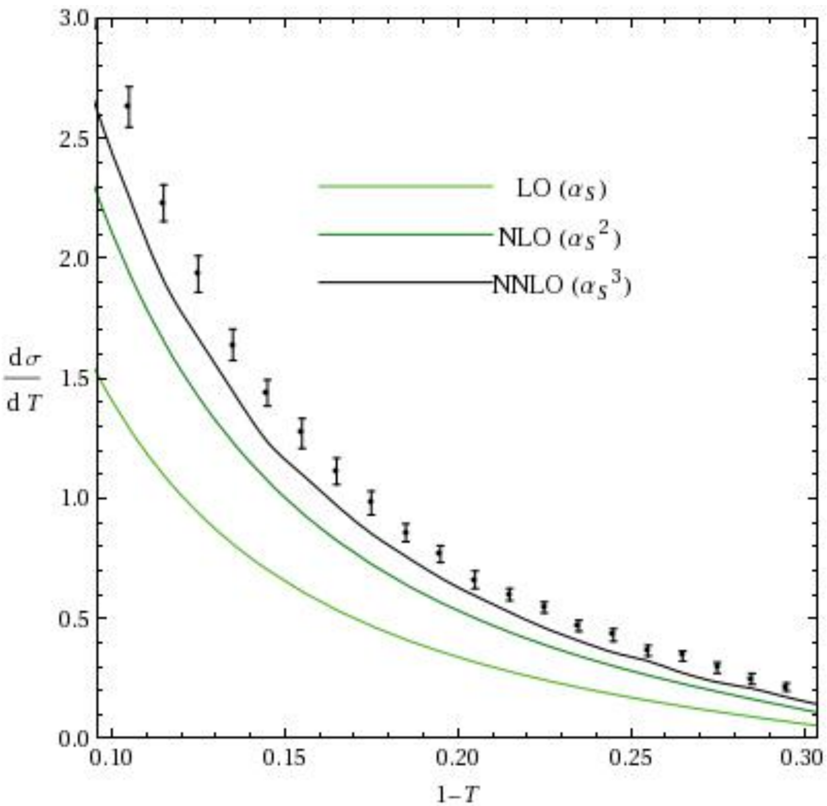
- See also
  Dasgupta et. al (arXiv:1207.1640)
  Jottenus et al (arXiv: 1302.0846)

- Resummation using EFT methods is systematically improvable.
- Much progress
  - More complicated jet shapes
  - Jet algorithm dependence
  - Non-global structure
  - Automation
  - …

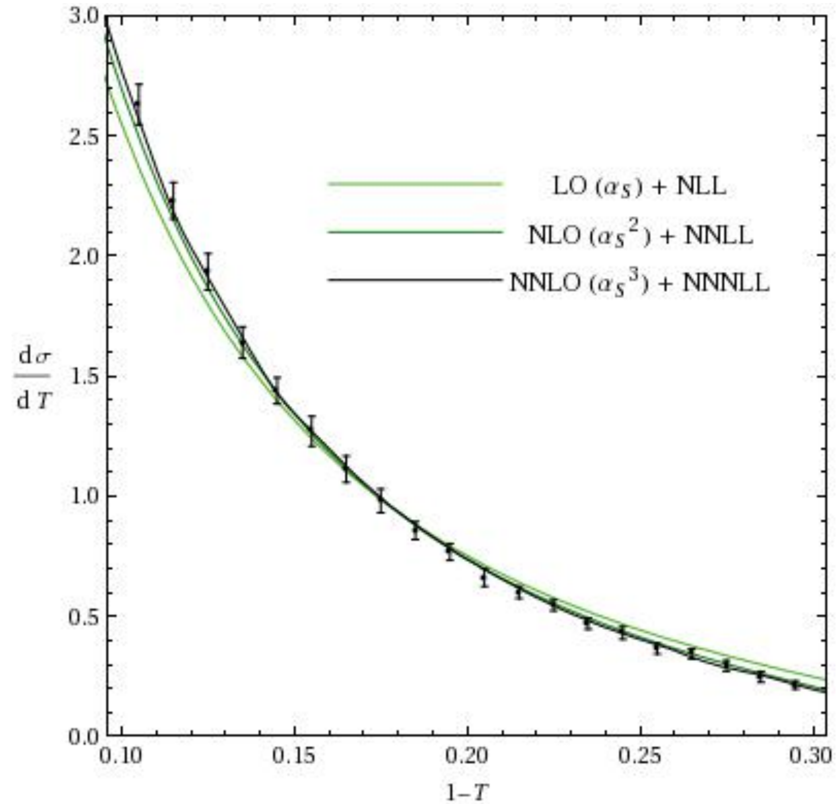
Resummation improves convergence

Thrust distribution in $e^+e^- \rightarrow$ jets

Fixed Order



Effective Field Theory

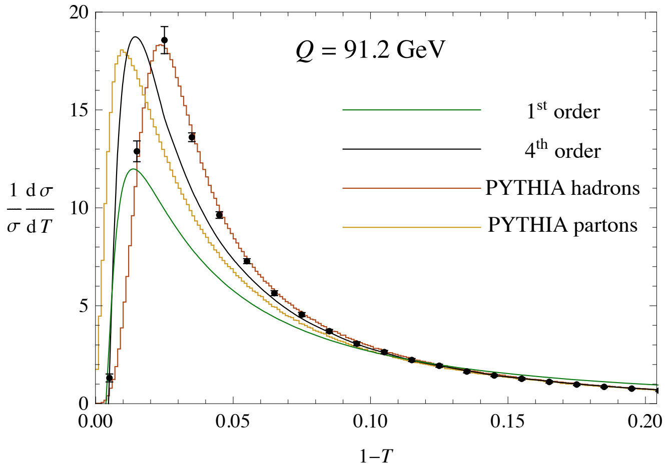


Resummation useful even if logarithms are not that large

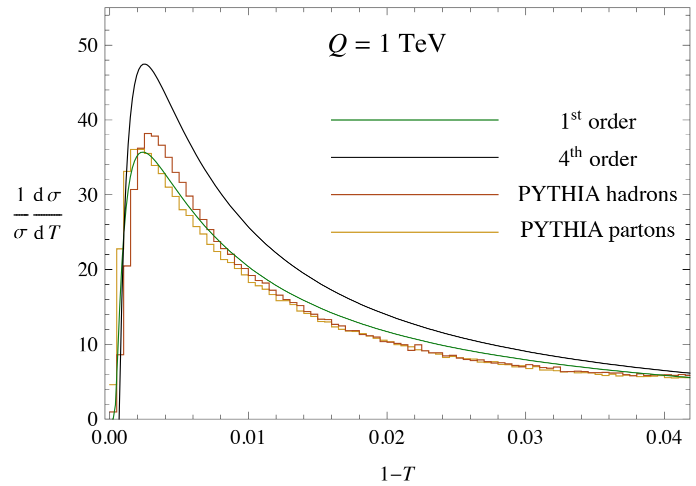
Resummation beyond NLL may be critical at 100 TeV

Pythia (NLL), EFT (NNNLL+NNLO) & data
all consistent for 91 GeV e+e-

Thrust
e+e-

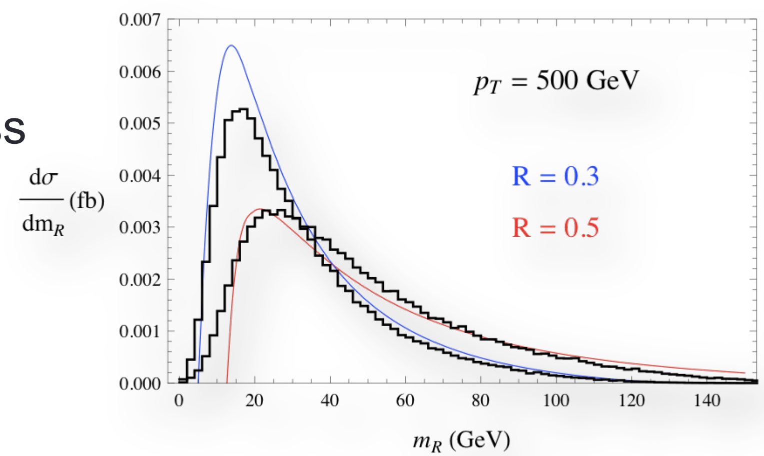


Pythia (NLL) and EFT (NNNLL+NNLO)
Inconsistent at 1 TeV e+ e-



Pythia (NLL), EFT (NNLL+NLO) & data
all consistent for 500 GeV jets (LHC 7)

Jet mass
pp



p_T = 10 TeV
???

Pythia (NLL) vs EFT (NNNLL+NNLO) vs data
at 100 TeV??

2. SCALE SETTING

Scale setting

- Fixed order calculations have one scale μ to choose
- Choice only clear for **completely inclusive** cross sections
- p_T vetos, jet energy cuts, triggers, etc. introduce **new scales**

Example: Inclusive W production, differential in p_T of the W

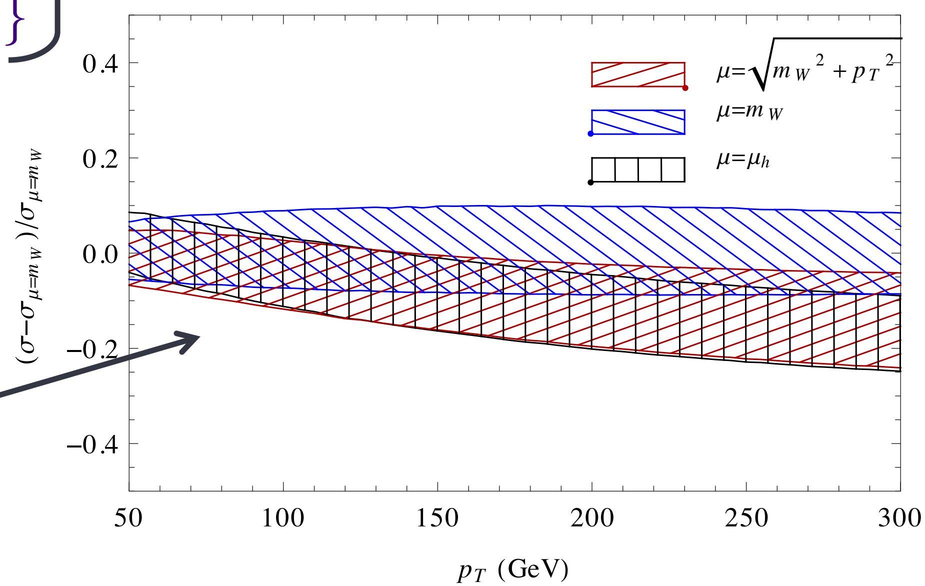
Many reasonable scale choices:

$$\mu = H_T$$

$$\mu = \sqrt{p_T^2 + m_W^2}$$

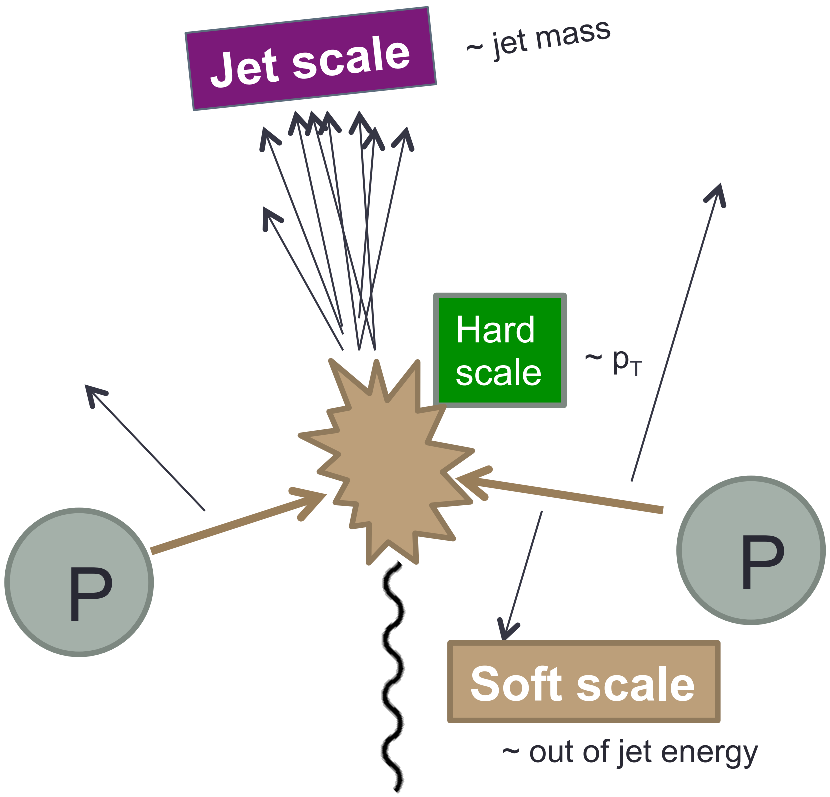
$$\mu = \max\{m_W, E_{\text{jet}}\}$$

Pick one and vary by a factor of 2 or 4 or 100



Differences between parameterizations are larger than the individual variations

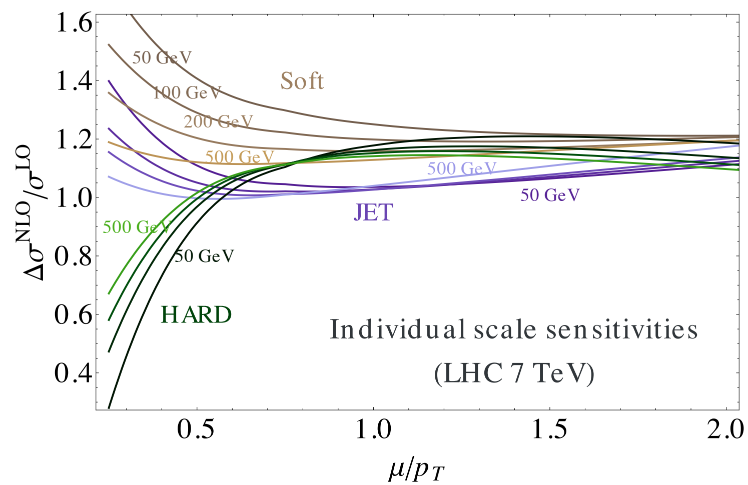
EFTs reveal the relevant scales:



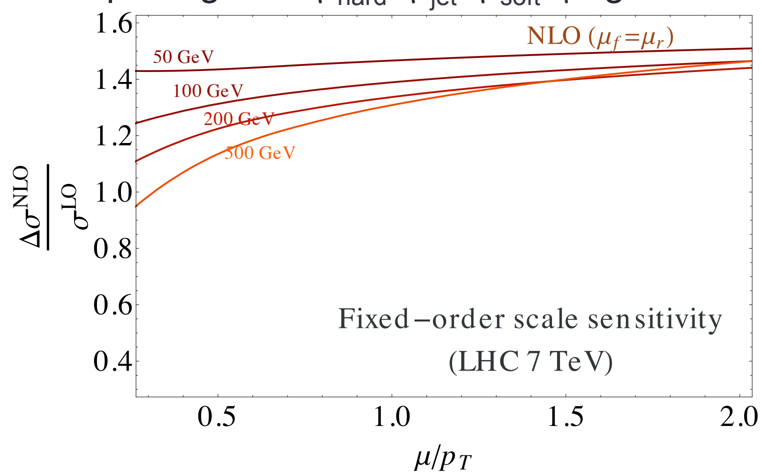
High p_T
W boson

Becher, Lorentzen and **MDS**, Phys.Rev. D 86 (2012)

Individual variation show extrema
(natural μ_{hard}, μ_{jet}, μ_{soft} scales, like Q)

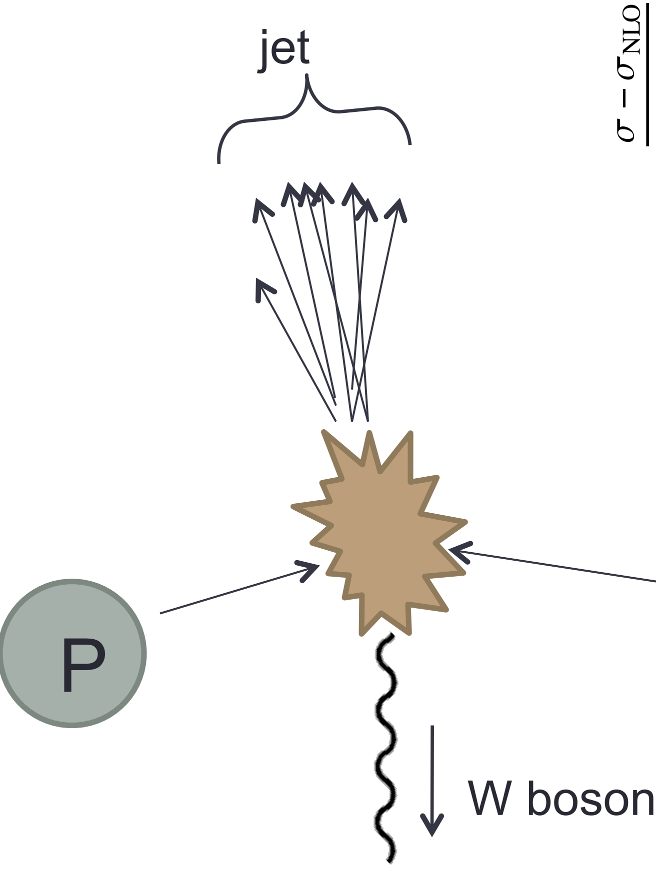


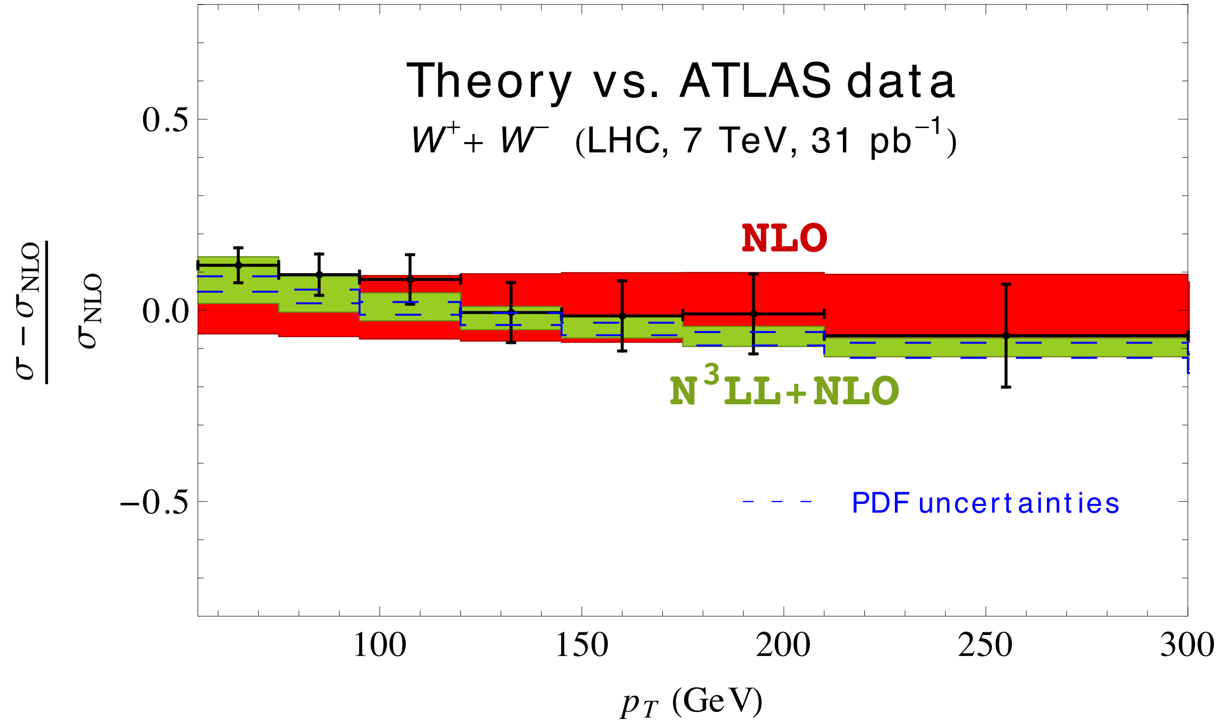
When put together $\mu_{hard}=\mu_{jet}=\mu_{soft}=\mu$ gives NLO



No natural μ at NLO (or N^nLO). **Cannot set all scales equal**.

W + JET at the LHC





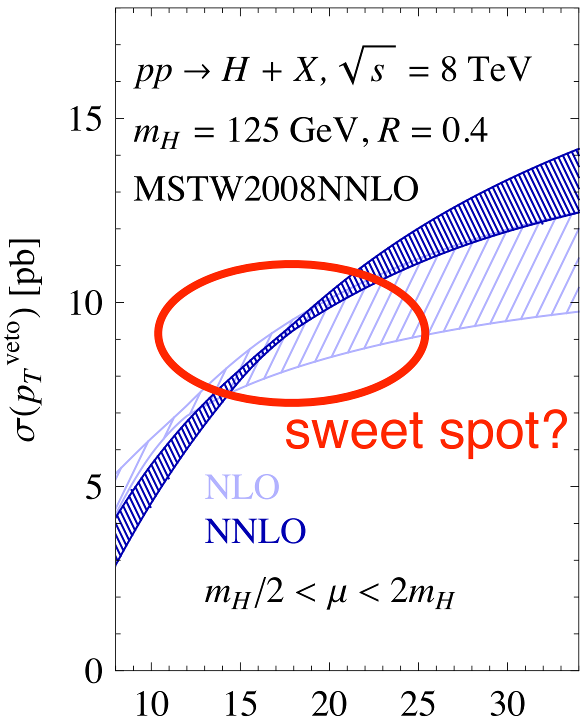
Becher, Lorentzen, and MDS, (2010, 2011, 2012, 2013 …)

PeTeR: public code for high-p_T W/Z/γ

http://peter.hepforge.org/

Higgs cross section with p_T veto

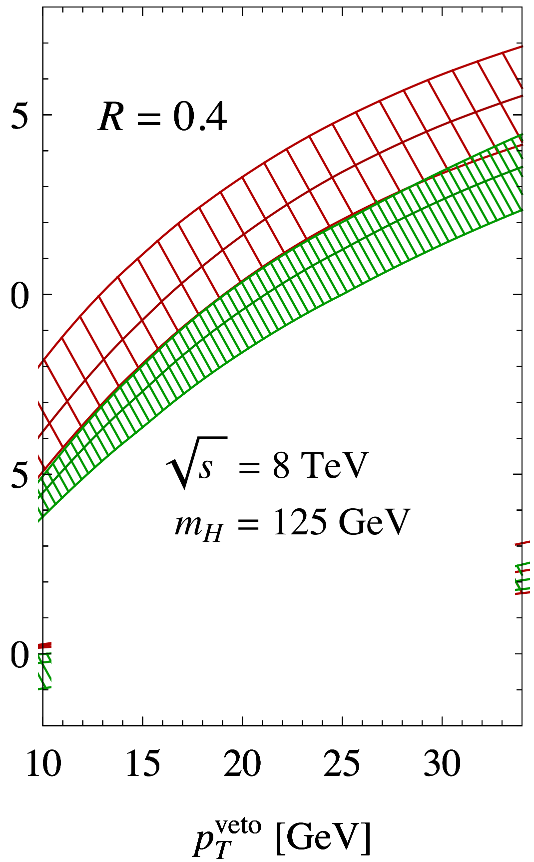
Fixed order (NNLO)



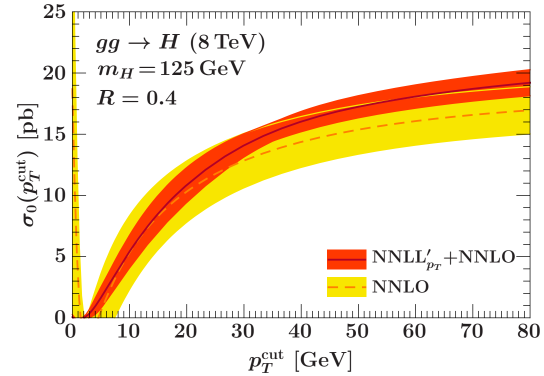
From M. Nebuert

Resummed (3 different groups)

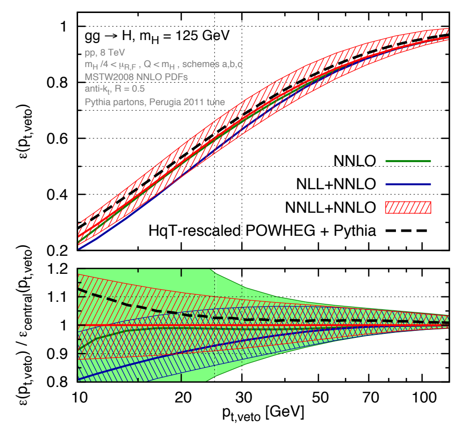
Becher, Neubert, Rothen



Stewart, Tackmann, Walsh, Zuberi



Banfi, Salam, Monni, Zanderighi



- **NNLO** has cancellation which **underestimates uncertainty** (Anastasiou, Dissertori, Stockli)
- Resumming logs of mH/pTveto changes cross section by 10-20% vs NNLO.
- Resummed prediction has more reliable uncertainties

3. FACTORIZATION

What do we know about factorization?

Not proven

PDFs are universal

Soft and collinear factorization

Not always

Hadronization is suppresed by Λ_{QCD}/Q

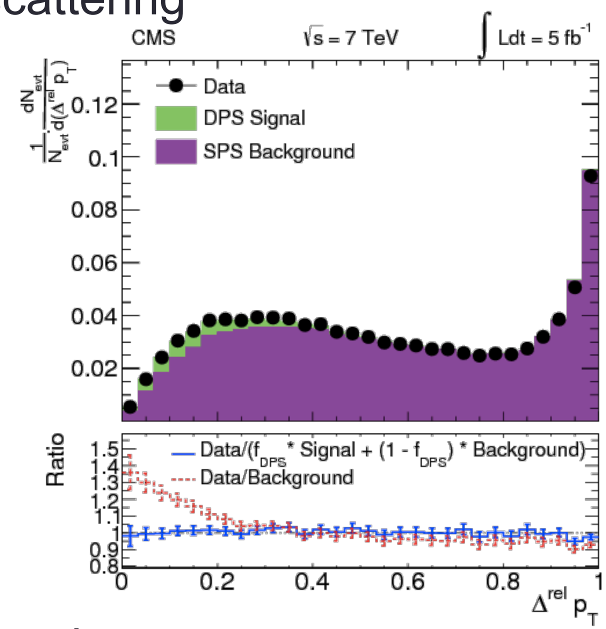
Maybe not

- Factorization makes sense physically
- pp collisions are complicated; little has been proven

e.g. double parton scattering

$$\sigma_{X,b\bar{b}} \simeq \frac{\sigma_X \sigma_{b\bar{b}}}{\sigma_{\text{DPS}}}$$

Made up formula

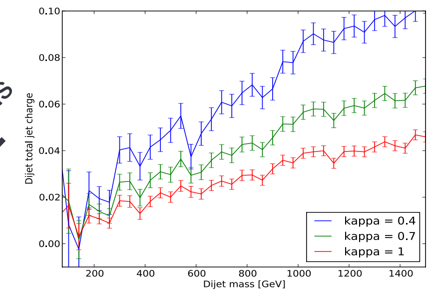


Factorization violation may be critical at 100 TeV

- There is still a lot we do not know about factorization and the IR structure of gauge theories

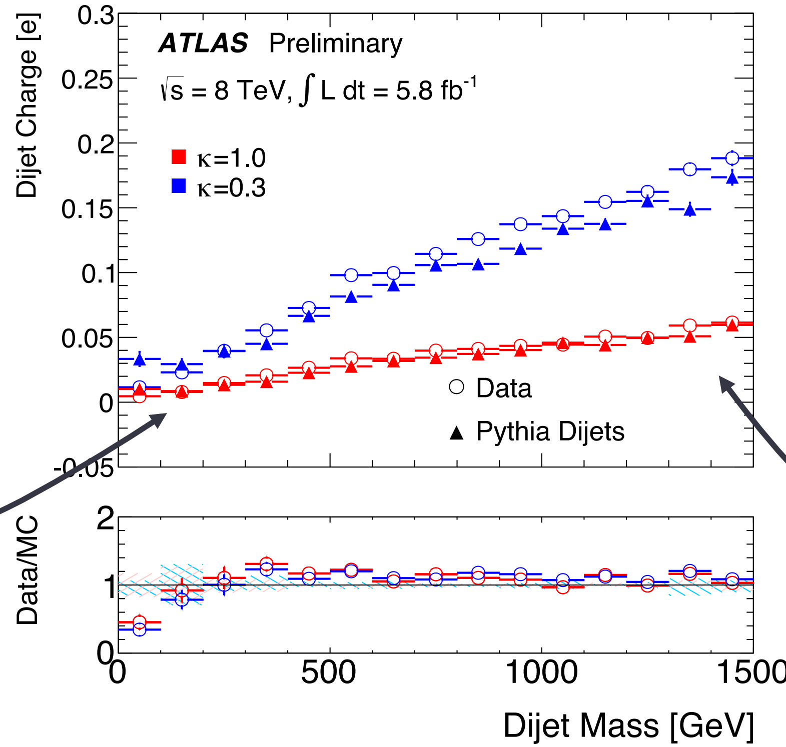
Jet charge in dijet events

Theory paper
[Krohn, Lin, MDS, Waalewijn, 2013]

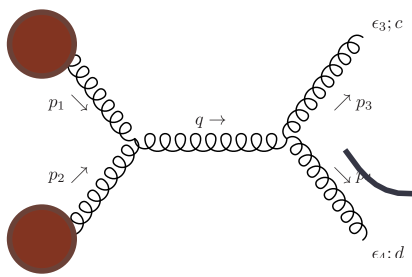


10 months

ATLAS measurement (2013)

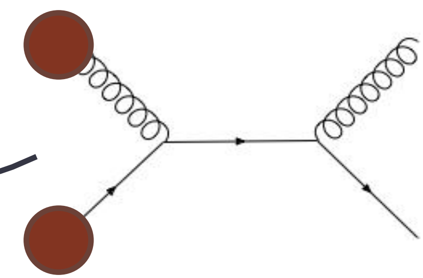


pp ➔ gg



small x
gluons dominate

pp ➔ ug

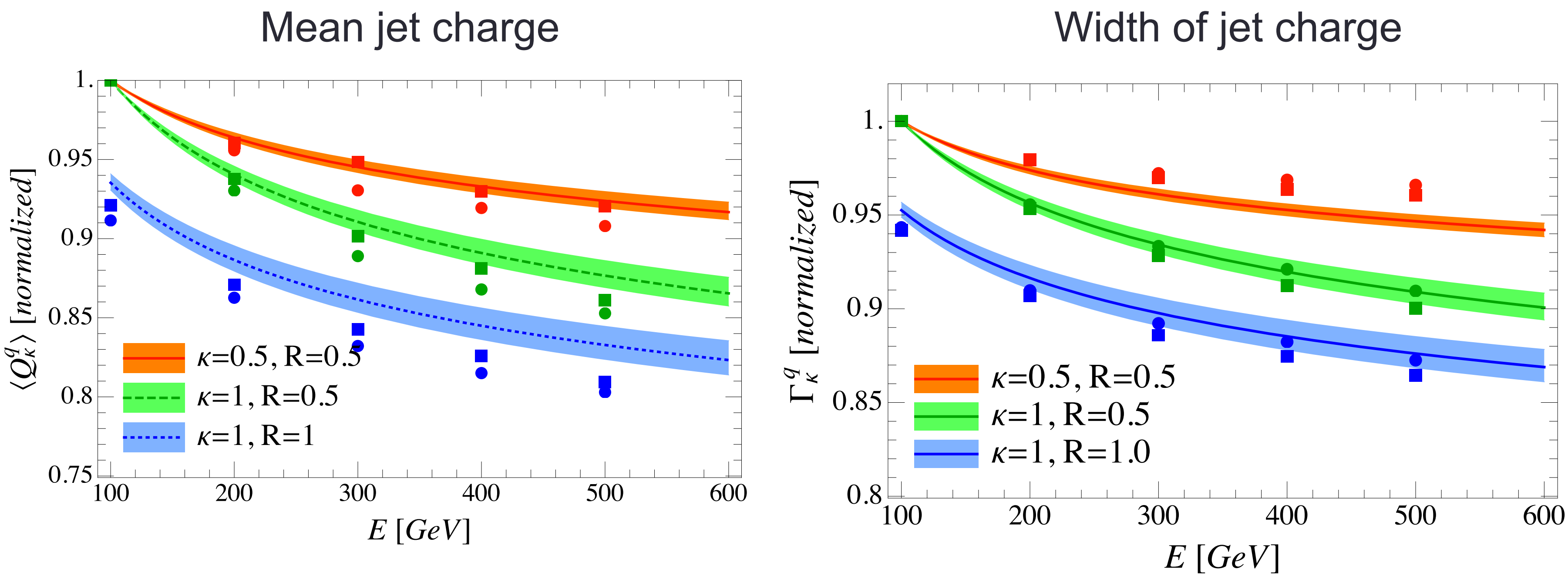


large x
valence quarks dominate

Evidence of valence quarks in PDFs!
Quark charge measured without leptons -- in pure QCD (dijet) events.

Scaling violation

Krohn, Lin, MDS, Waalewijn (2013)
Phys.Rev.Lett. 110 (2013) 212001

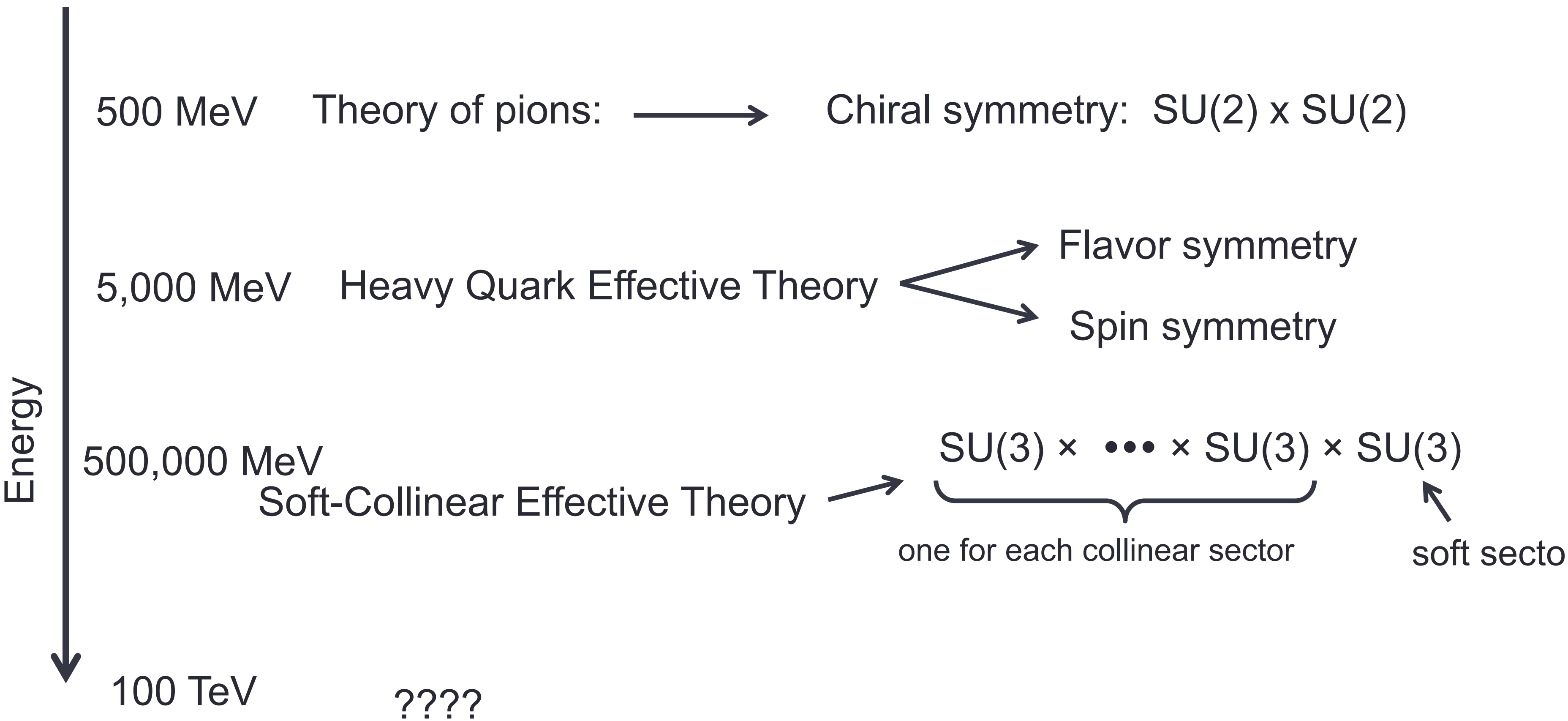


- Charge distribution non-perturbative
- **Scale dependence** of mean and width **calculable in QCD**
- Can be observed for the first time at the LHC
  - Better charge and momentum resolution
  - More particles in the jets
  - Larger range of energies accessible than before

Surely many similar opportunities at 100 TeV

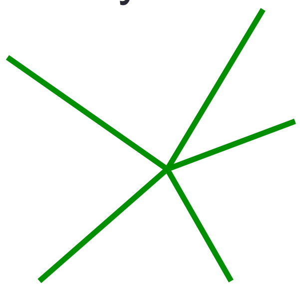
4. SYMMETRIES

New energies, new symmetries



Other hidden symmetries

Soft limit of QCD
described by Wilson lines



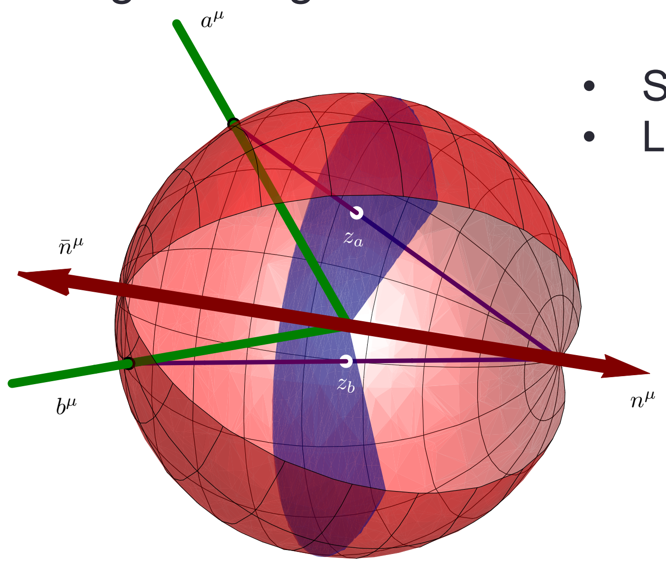
Anomalous dimension has surprising features

$$\Gamma(\{\underline{p}\},\mu) = \sum_{(i,j)} \frac{\boldsymbol{T}_i \cdot \boldsymbol{T}_j}{2}\, \gamma_{\text{cusp}}(\alpha_s)\, \ln\frac{\mu^2}{-s_{ij}} + \sum_i \gamma^i(\alpha_s)\,,$$

Universal pairwise structure?

Becher, Neubert, Gardi, Magnea 2009

Non-global logarithms



- Similarities to BFKL and BK equations
- Leading non-global logarithms have
  PSL(2,R) symmetry of Poincare disk

Hatta, Ueda (2013), MDS, Zhu (2014)

Wilson lines may relate to iterative structures
in scattering amplitudes
(e.g. Bern, Dixon, Smirnov conjecture)

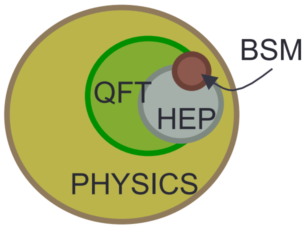
Much is not understood…

PART 2:
WHY EFT NEEDS 100 TEV

Four Questions

- Is Standard Model physics interesting if there is no experimentally accessible **BSM** physics?
- Do we need **new experiments** if we already know the Lagrangian?
- Will 100 TeV tell us something about the SM that we do not already know?
- Can Standard Model physics **motivate** 100 TeV?

- Is Standard Model physics interesting without BSM?
  - Yes.
  - Many mysteries:
    - non-perturbative effects
    - scattering amplitudes
    - infrared structure
    - factorization properties
    - hidden symmetries
    - finite temperature
    - vacuum stability
- Do we need new experiments if we already know the Lagrangian?
  - Yes.
  - Does condensed matter physics = QED?
  - Effective field theories isolate the relevant physics



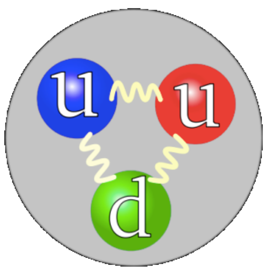
- Will 100 TeV tell us something new about the SM?
  - Logically unanswerable.
  - Almost certainly yes. Every other experiment since 1974 has.
- Can SM physics motivate 100 TeV
  - Yes.
  - SM physicists are not good at marketing.

Quantum chromodyanmics

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^2 + i\bar{\psi}\,(\partial\!\!\!/ + i g_s A\!\!\!/ - m)\psi$$

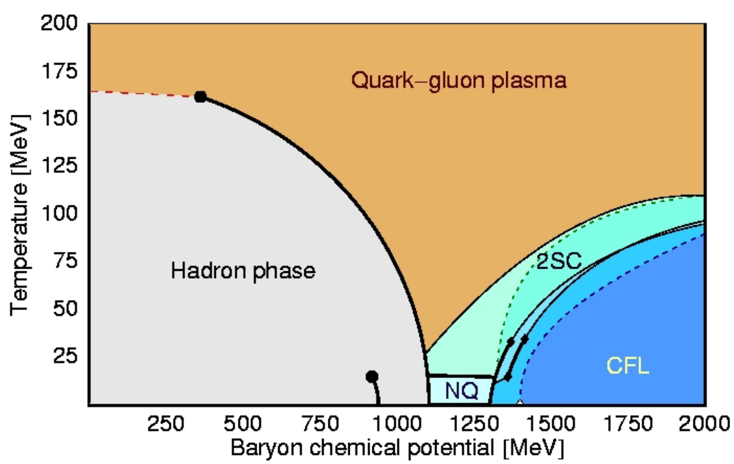
Emergent phenomena

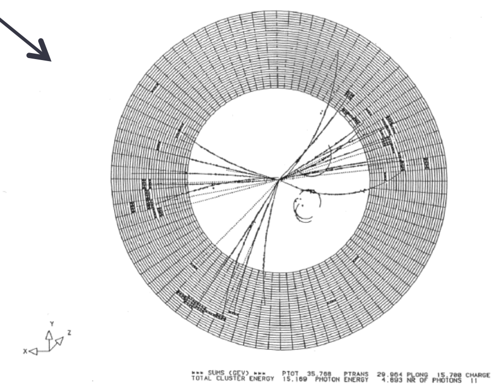
Bound states
Hadron spectroscopy



Proton

Intricate Phase diagram

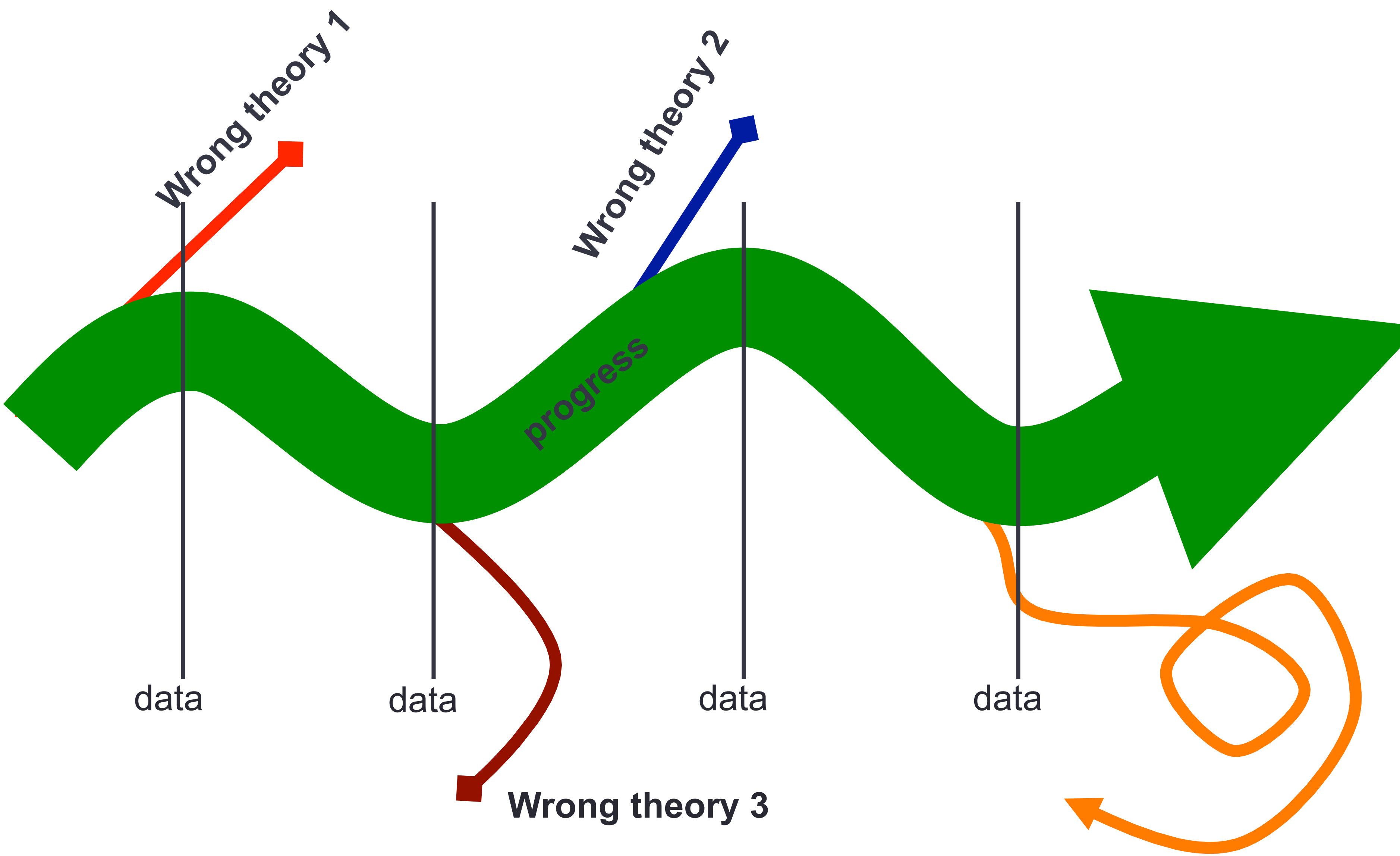




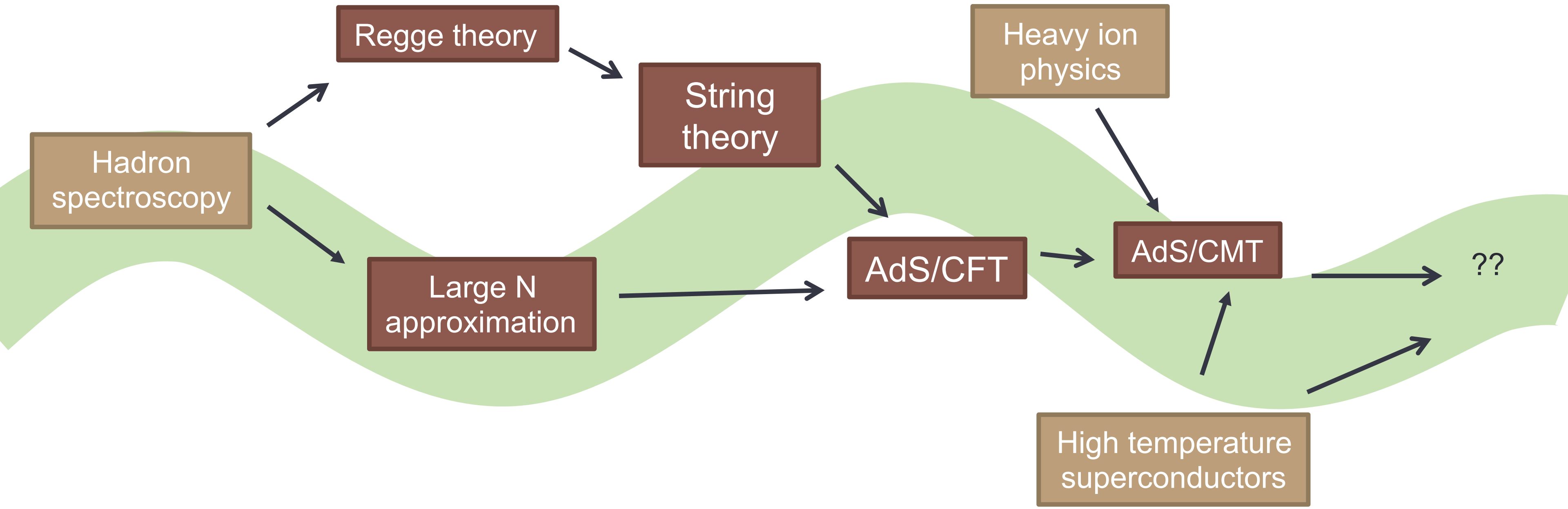
Jets at high energy

- We have learned a tremendous amount about QFT from QCD
- How much could we have figured out by thinking alone (without data)?

Progress in fundamental physics



Example



Regge theory
Heavy ion physics
String theory
Hadron spectroscopy
AdS/CFT
AdS/CMT
??
Large N approximation
High temperature superconductors

100 TeV for Effective Field Theories

- Non-perturbative effects smaller
- QCD becomes truly weakly coupled

Tevatron → LHC → 100 TeV

What are the right effective degrees of freedom for perturbative QCD?

Quarks and gluons	Jets	Something else?
Scattering amplitudes	SCET	

My personal view:

much beauty in the perturbative **S-matrix**
→ zero (Sudakov suppressed)
→ infinite (IR divegent)

→ maybe 100 TeV will force us to rewrite QFT to describe the data …

Final thoughts I

1998

Cosmic acceleration

Supernovae

Cosmological constant problem

10^{120} tuning

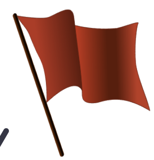
2012

Light scalar Higgs boson

ATLAS and CMS

Hierarchy problem

10^{30} tuning



2014

Transplanckian inflation

BICEP 2

Lyth bound

10^{2} tuning

Fine-tuning problem problem??

Psst... something is wrong

Is this a crisis for effective field theory?

- Wilsonian EFT picture may be in trouble

Will 100 TeV really convince us?

Panel discussion today…

Final thoughts II

Maybe we've just been lucky with Pythia/Herwig

What if Pythia regularly fails at 100 TeV??

→ Standard Model physics becomes much more interesting

→ 100 TeV would be super exciting!

- High energy physics becomes more like condensed matter physics or astrophysics.
- Maybe you don't find CM physics exciting, but it has no shortage of funding.
- What is different about high energy physics and the rest of physics?
  - Can BSM be a bonus, not the main goal?

Conclusions

"There are more things in Heaven and in Earth than are dreamt of in our philosophy"

-- Ernest Rutherford, 1914, quoting Hamlet

- Effective field theories are important at the LHC
  - Resummation
  - Determining relevant scales
  - Factorization properties
  - Hidden symmetries
  - …

- Insights will continue
- Necessity of EFTs more acute at 100 TeV

Standard Model physics is fun!

Already fun at the LHC
- New measurements, new insights
- Theory and experiment teach each other

100 TeV is a mystery
- What is the right effective description?
- Crisis in effective field theory?

1. It's hard to solve problems just by thinking. Data is absolutely **critical**.
2. Standard Model physics at 100 TeV is a **no-lose proposition**. BSM is a **gamble**.
3. Can we incorporate SM physics into the marketing strategy for 100 TeV?

BACKUP SLIDES

From M. Peskin's talk

Physics:

We now have much experience with physics at 7-8 TeV.

Is physics at 100 TeV a simple extension of this, or do essential new phenomena come into play ?

3 possible examples:

- top quark becomes a parton → Fleming et al. (arXiv:0711.2079, …)
- electroweak Sudakov and radiative effects are order 1 → Chiu et al. (arXiv:0806.1240, …)
- W, Z, top, Higgs are typically highly boosted

Already being studied with EFT

What do I mean by EFT?