QCD physics at the LHC

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Lawrence Berkeley National Laboratory

HEP Graduate Workshop
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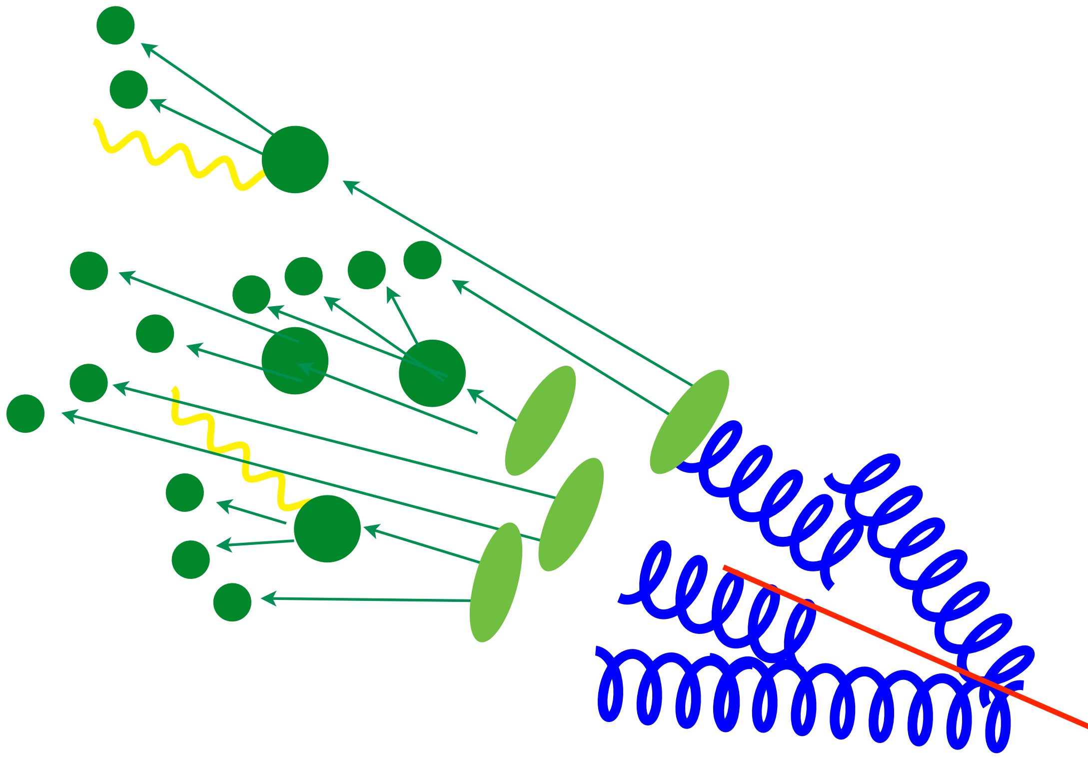
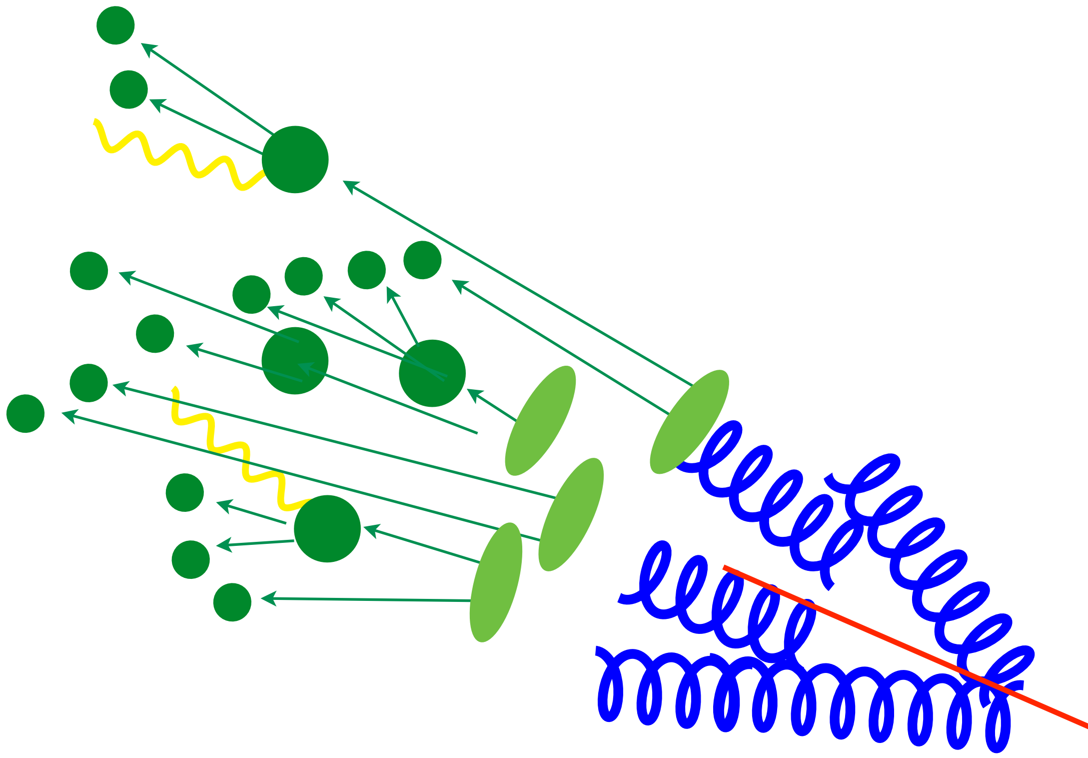


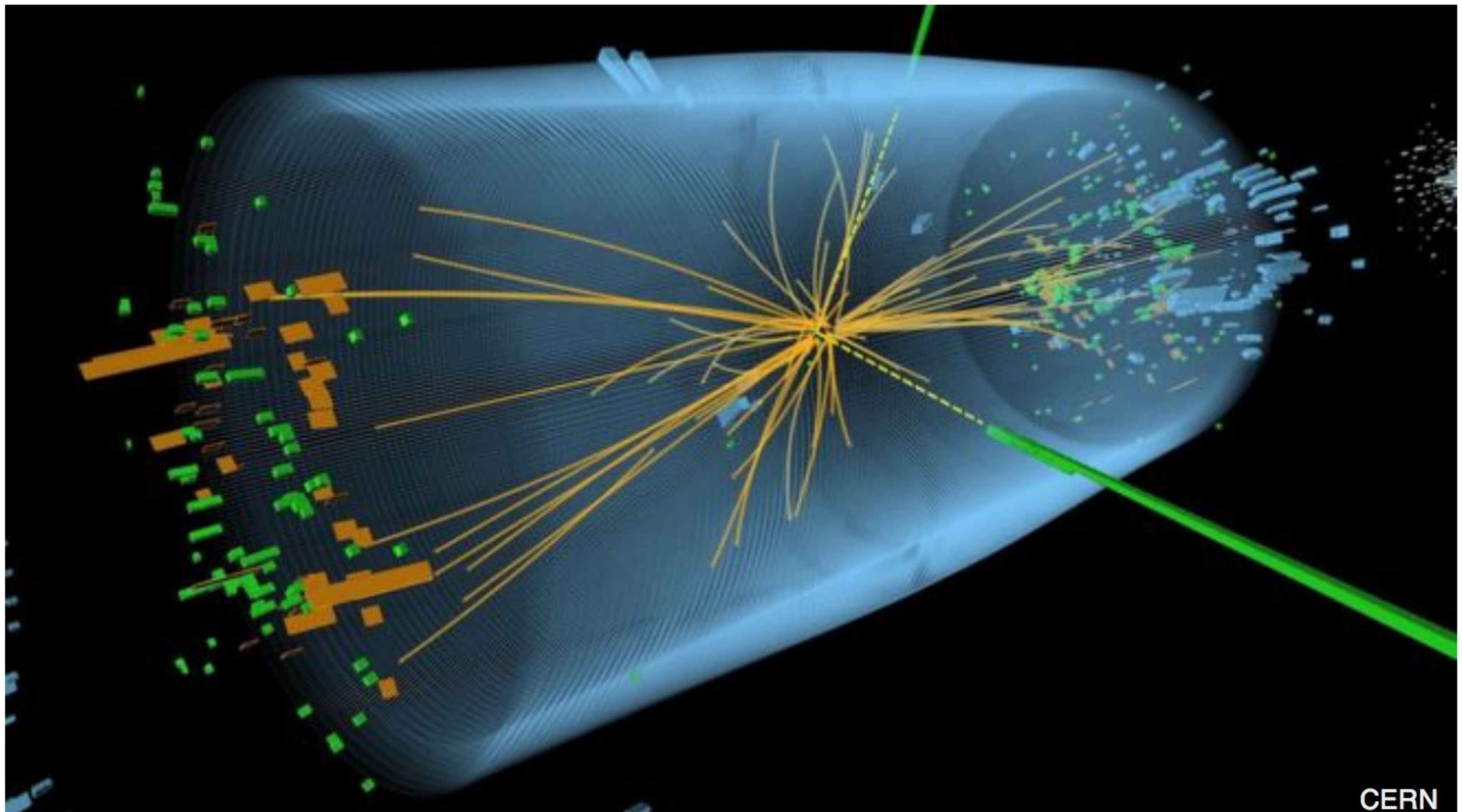
Outline

1. The Large Hadron Collider as a gluon factory
2. Overview of the QCD physics program at the LHC
3. Experimental considerations
    1. Calibration
    2. Unfolding
4. Physics topics
    1. PDFs
    2. α_S
    3. jet substructure
    4. other



What is the goal of the LHC?

BBC, March 2018



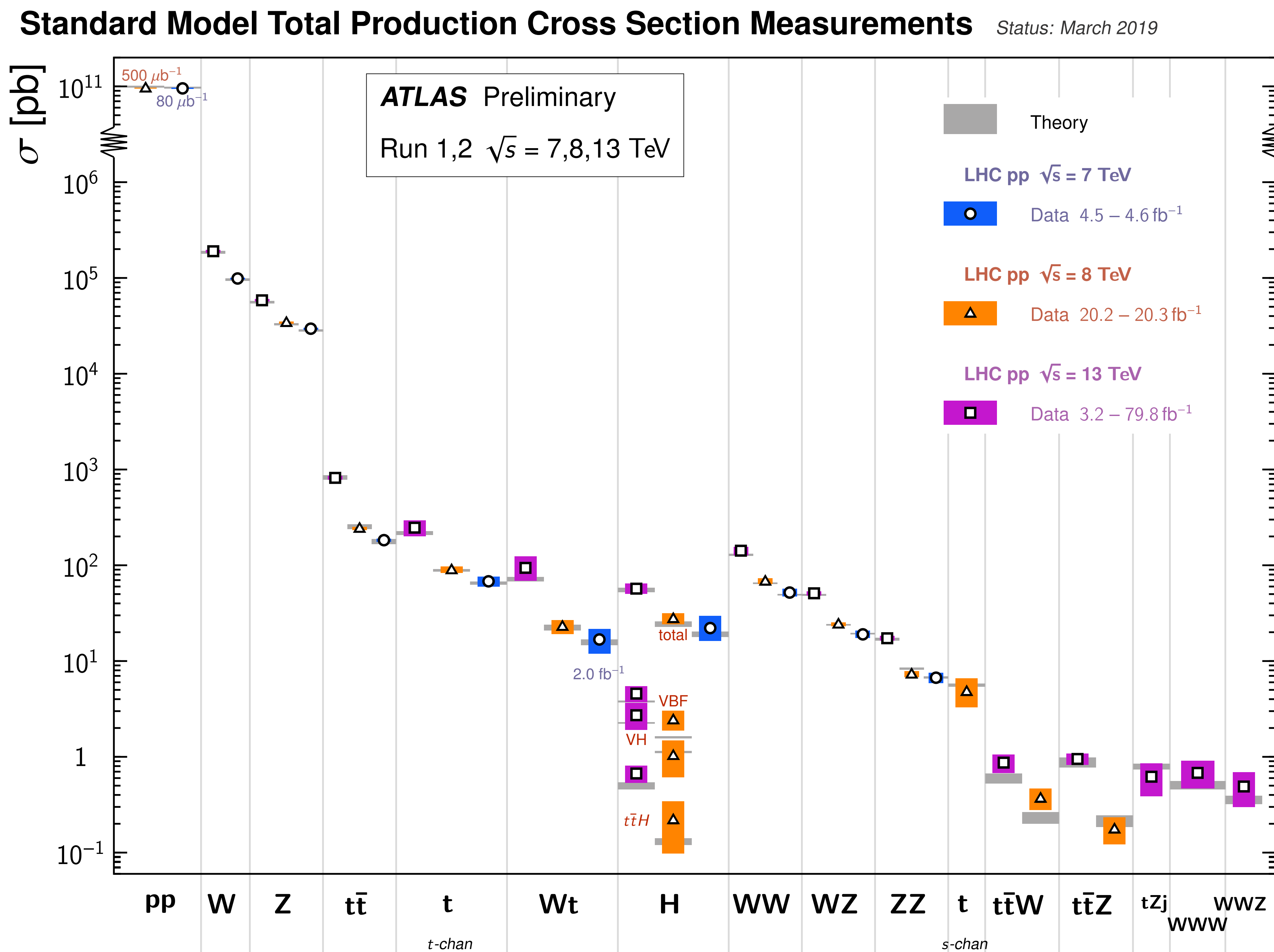
A candidate Higgs boson collision event at CMS, one of the experiments at the Large Hadron Collider

A top physicist says the construction of a "factory" to produce Higgs boson particles is a priority for the science community.

In an exclusive interview, Nigel Lockyer, head of America's premier particle physics lab, said studying the Higgs could hasten major discoveries.

Is the LHC a Higgs factory?

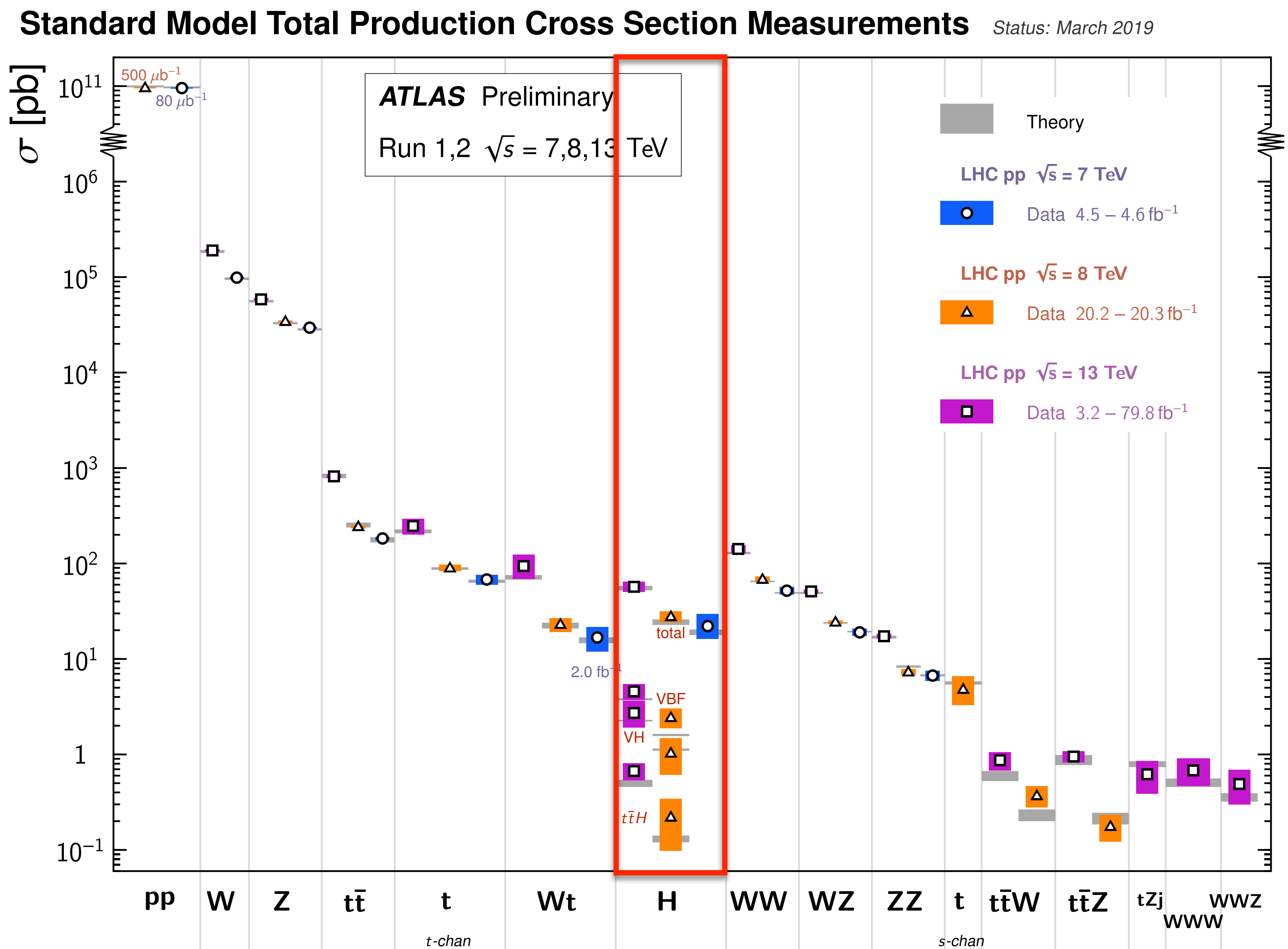
Rate at which processes happen



Process name: proton + proton goes to X

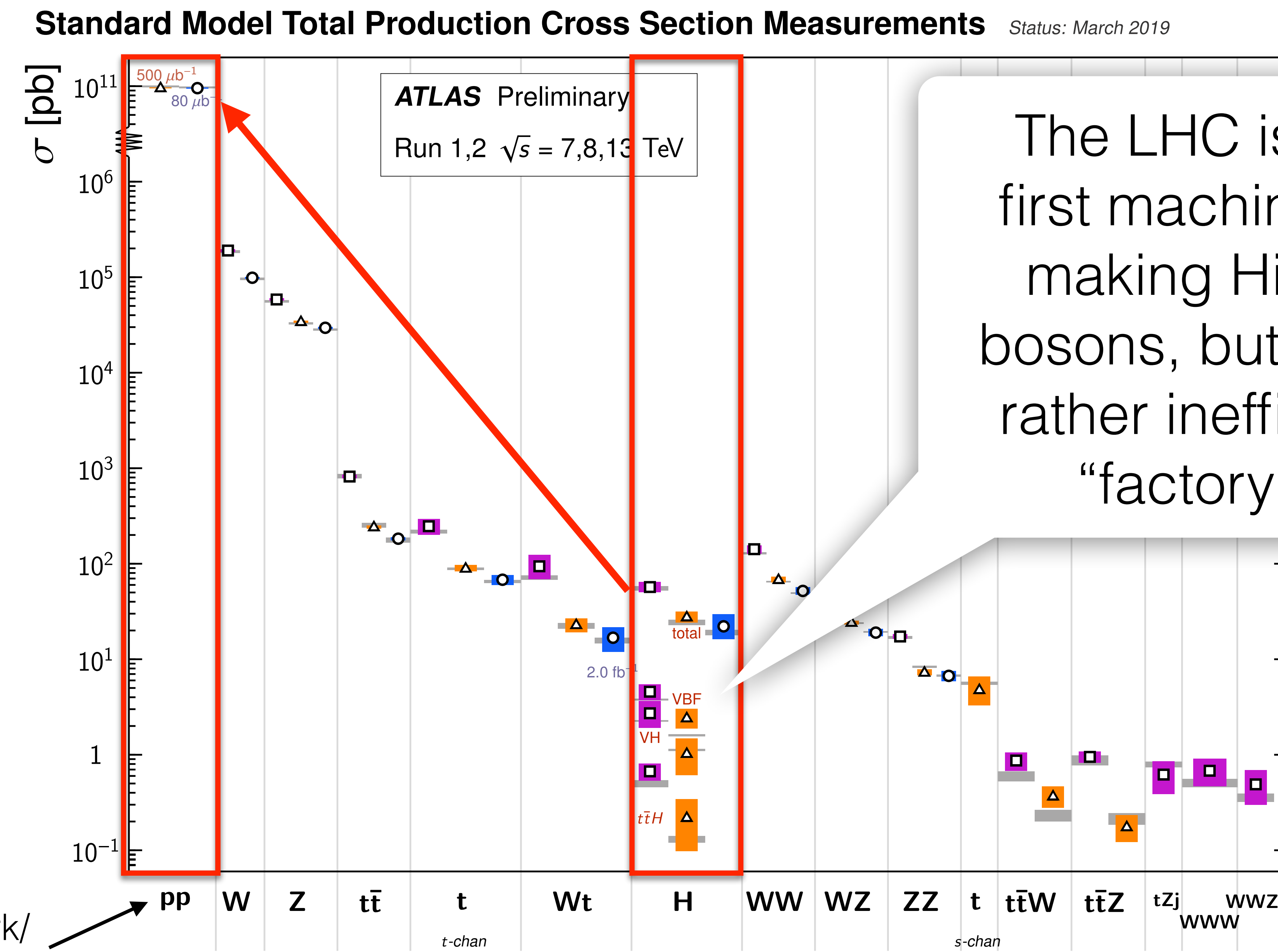
Is the LHC a Higgs factory?

Rate at which processes happen



Process name: proton + proton goes to X

Is the LHC a Higgs factory?



Rate at which processes happen

The LHC is the first machine for making Higgs bosons, but it is a rather inefficient "factory" !

~Generic quark/ gluon scattering

Process name: proton + proton goes to X

Higgs versus gluons

nature. One major ingredient in this model is a hypothetical, ubiquitous quantum field that is supposed to be responsible for giving particles their masses (this field would answer the basic question of why particles have the masses they do--or indeed, why they have any mass at all). This field is called the Higgs field. As a consequence of wave-particle

- Scientific American

Higgs versus gluons

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\- Scientific American

This is true, but it turns out that the gluon is responsible for most of our mass - without them, the proton mass would be many orders of magnitude lighter…

Image credit: JLab

The Higgs-gluon connection

There is a **strong** connection between the Higgs boson and gluons.

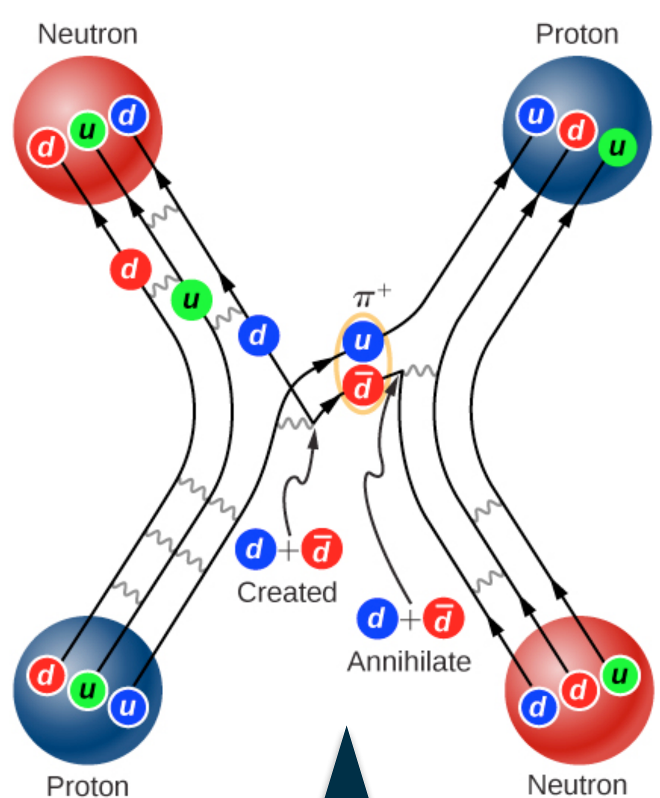
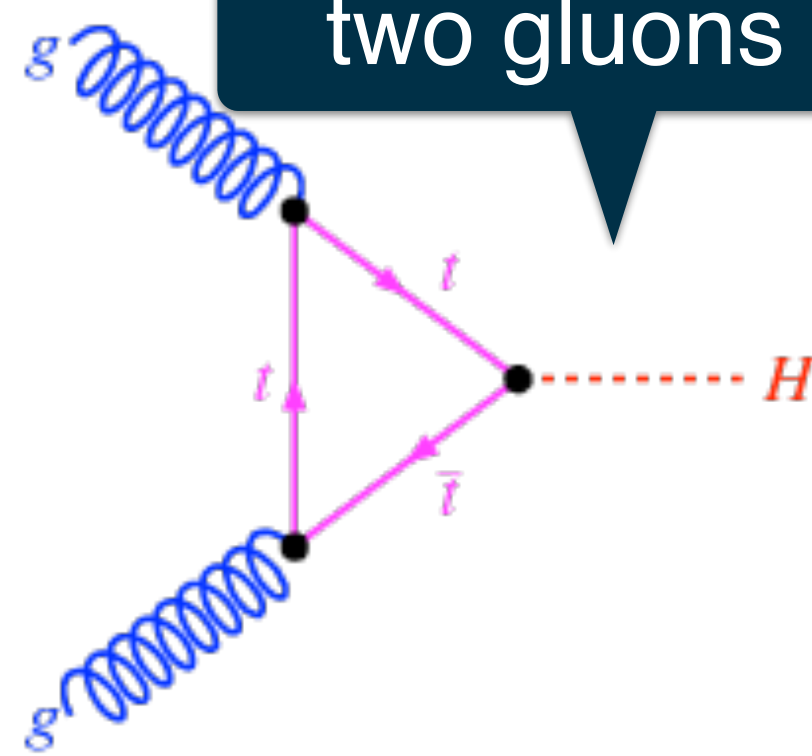


Image credit: University Physics

Due to the Higgs boson, the strong force is short-ranged



Most Higgs bosons are produced when two gluons fuse

…okay, enough about the Higgs boson for now - more about the strong force!

QCD physics program at the LHC

Parton Distribution Functions (PDFs)

Perturbative QCD / strong coupling

1. Photon/W/Z+jets
2. Jet physics
3. Jet substructure
4. "Soft QCD" & Heavy Ions
5. Quarkonia

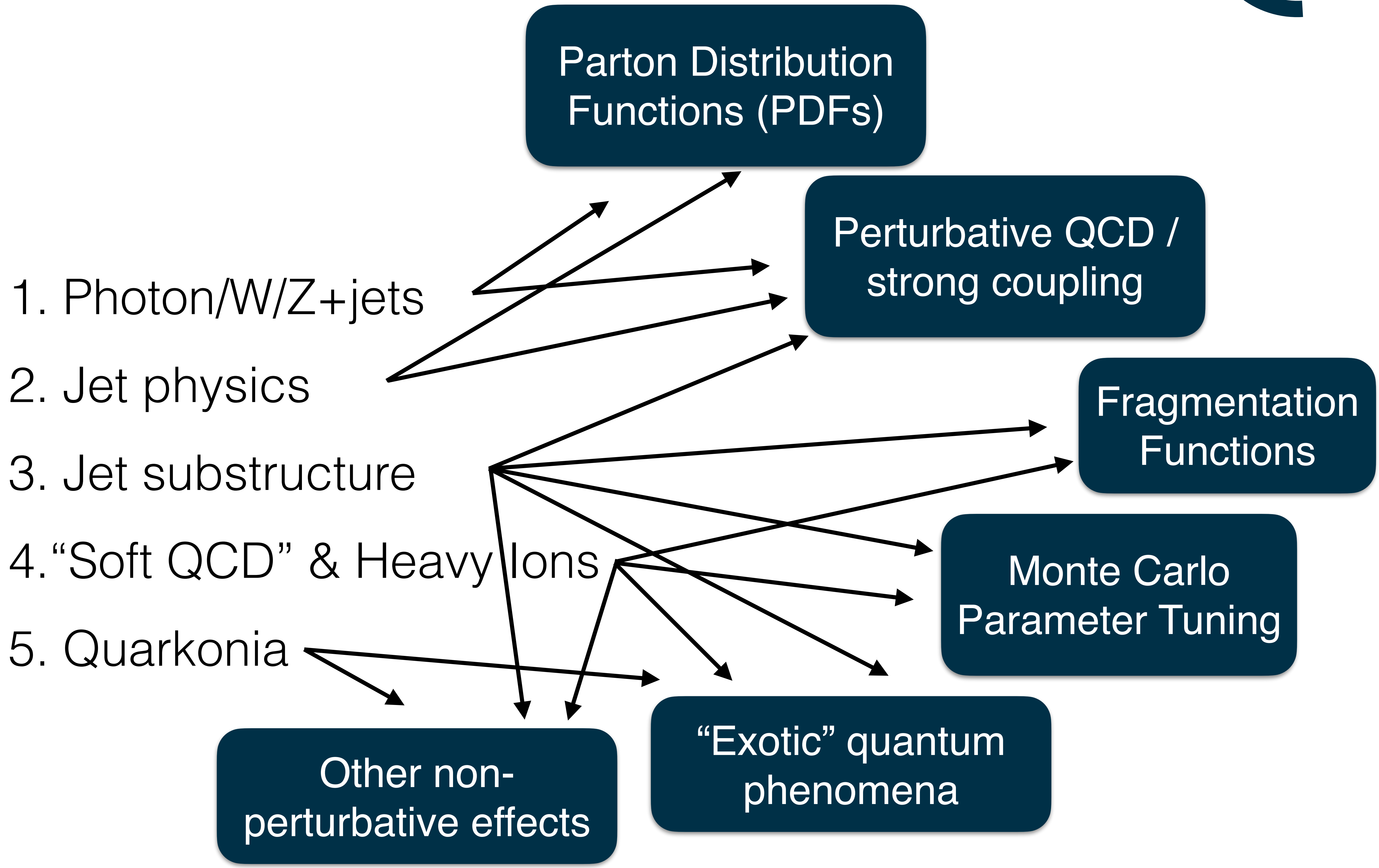
Fragmentation Functions

Monte Carlo Parameter Tuning

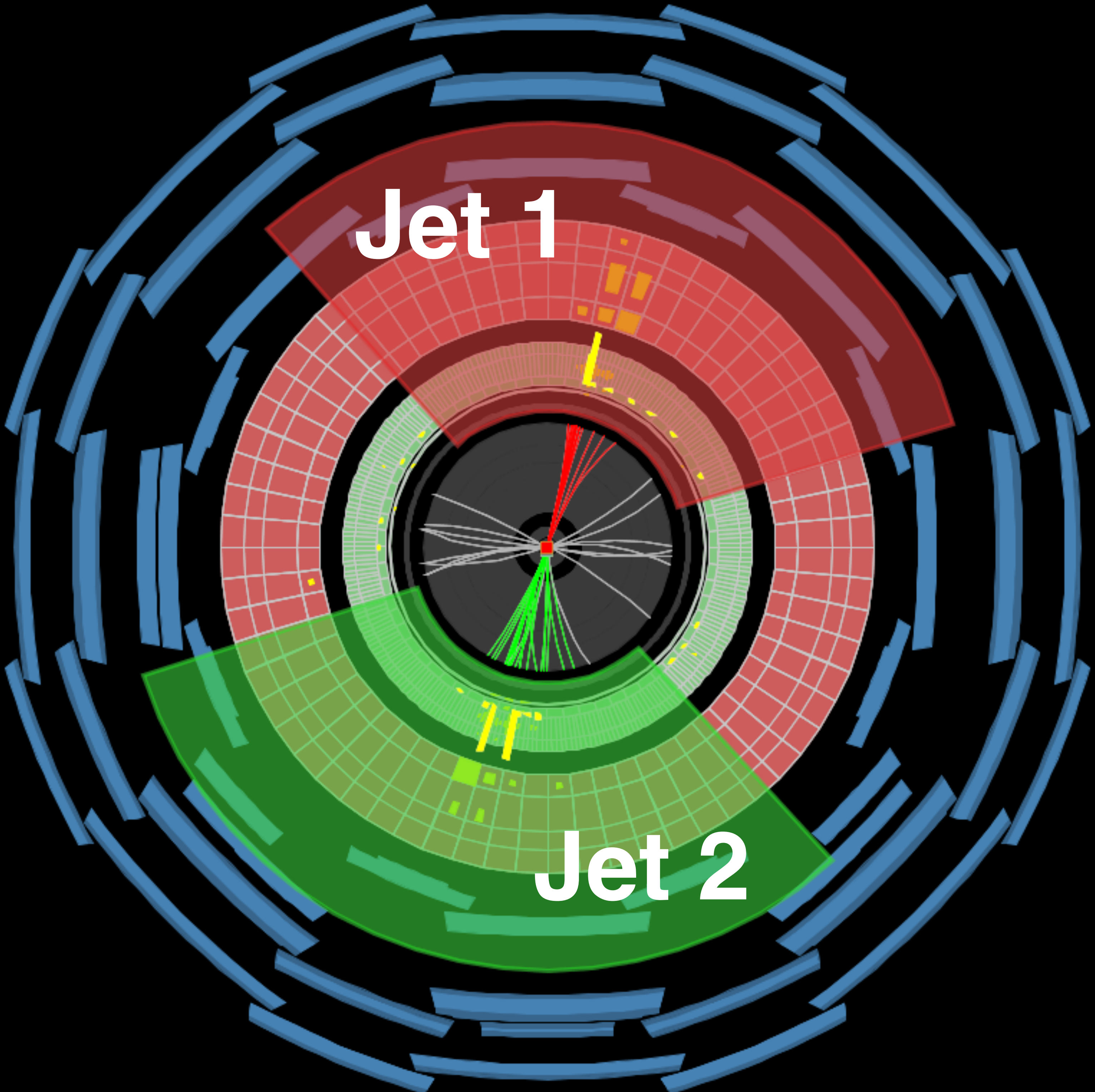
"Exotic" quantum phenomena

Other non-perturbative effects

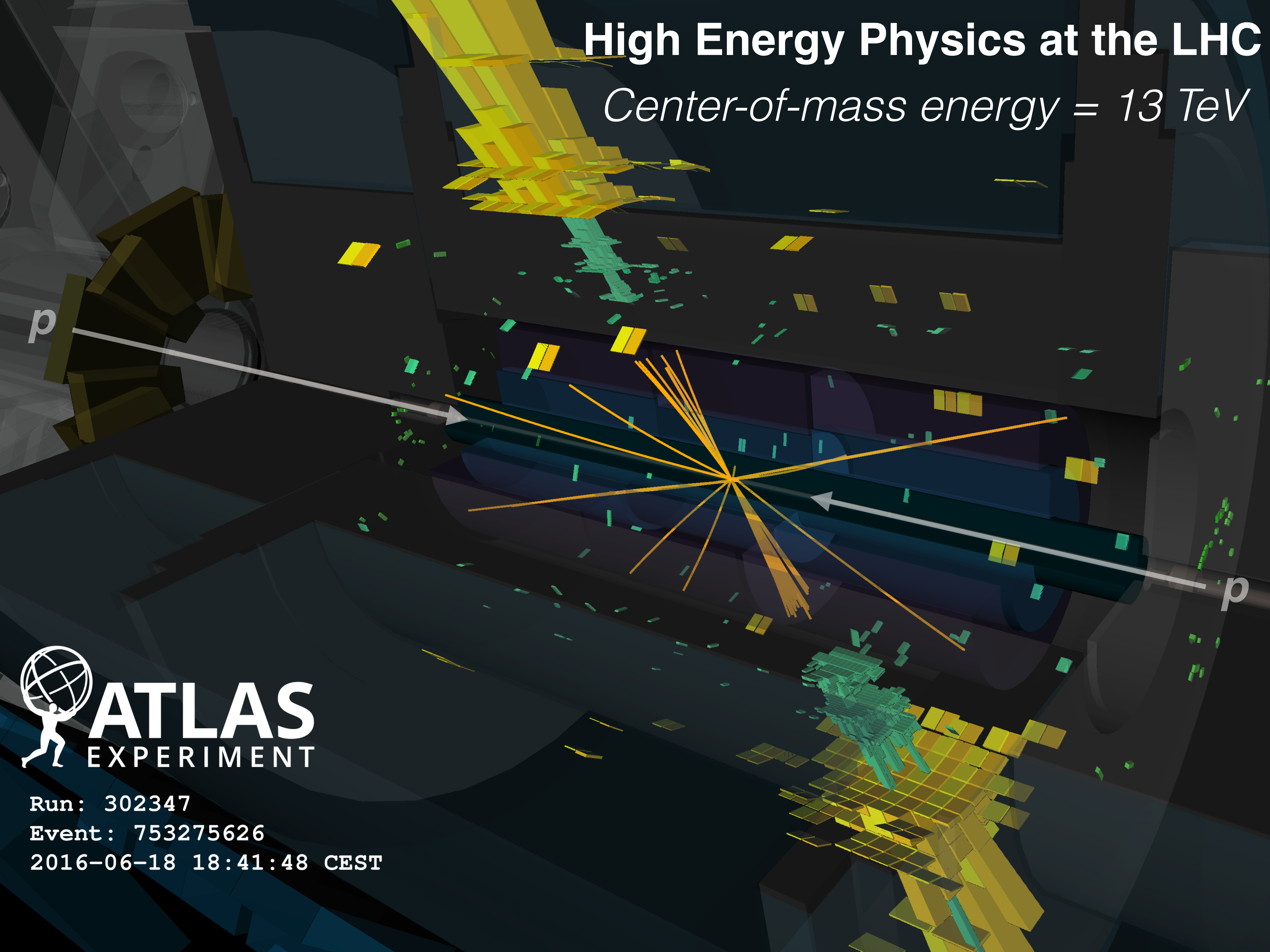
QCD physics program at the LHC



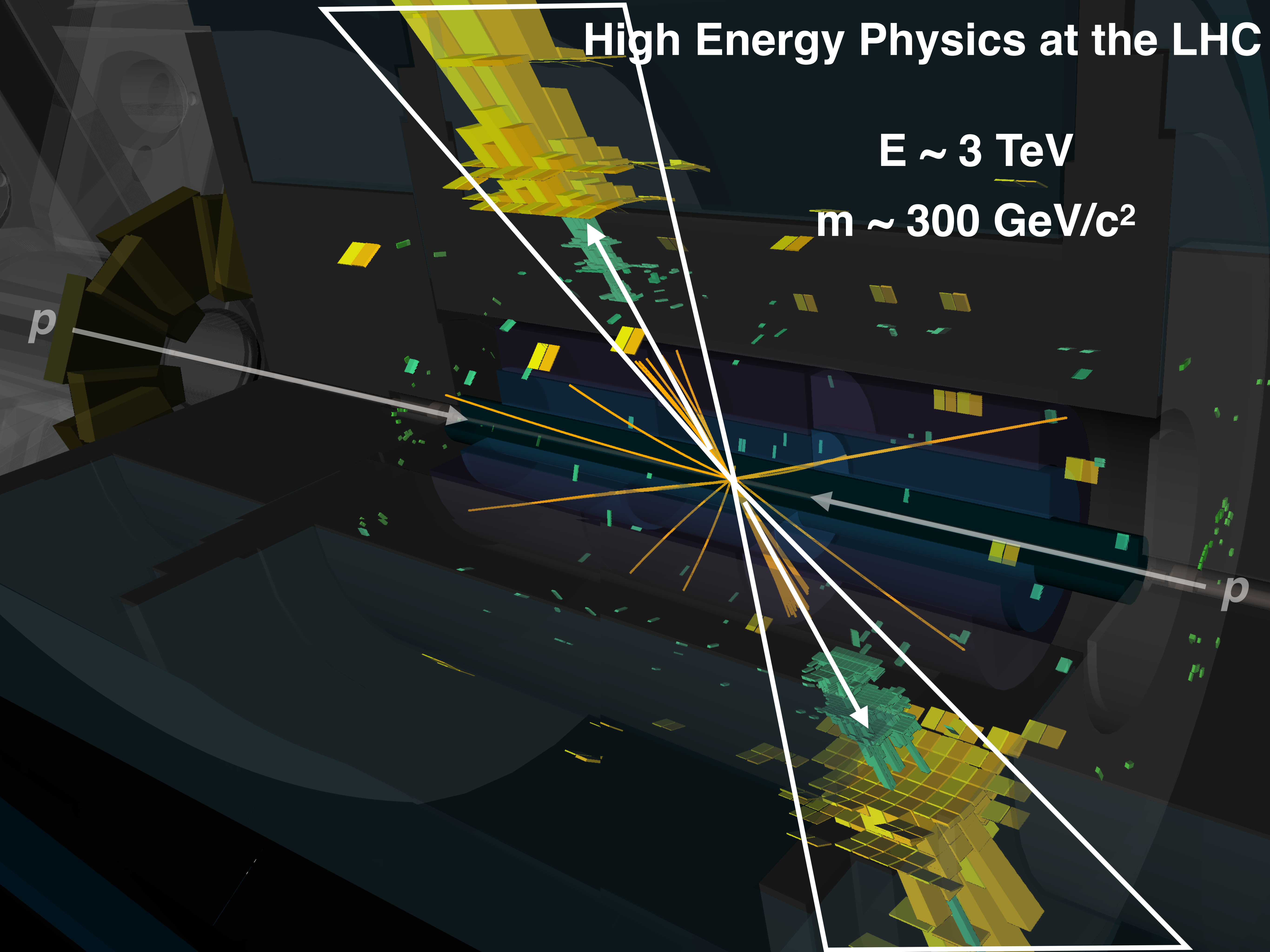
Jets

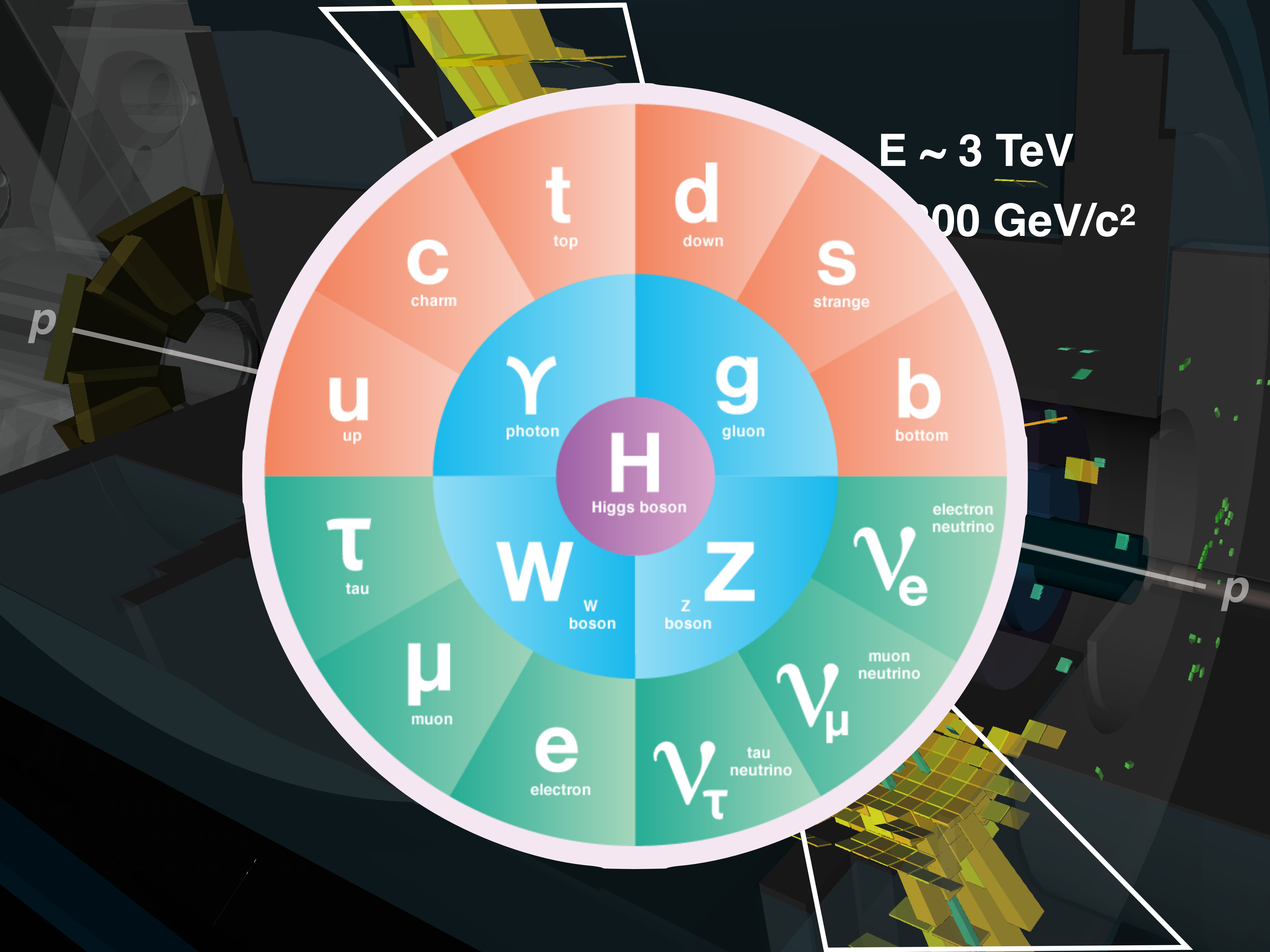


collisions in/out of page


High Energy Physics at the LHC
Center-of-mass energy = 13 TeV
p
p
ATLAS
EXPERIMENT
Run: 302347
Event: 753275626
2016-06-18 18:41:48 CEST

High Energy Physics at the LHC




E ~ 3 TeV
00 GeV/c²
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p
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top
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charm
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γ
photon
g
gluon
H
Higgs boson
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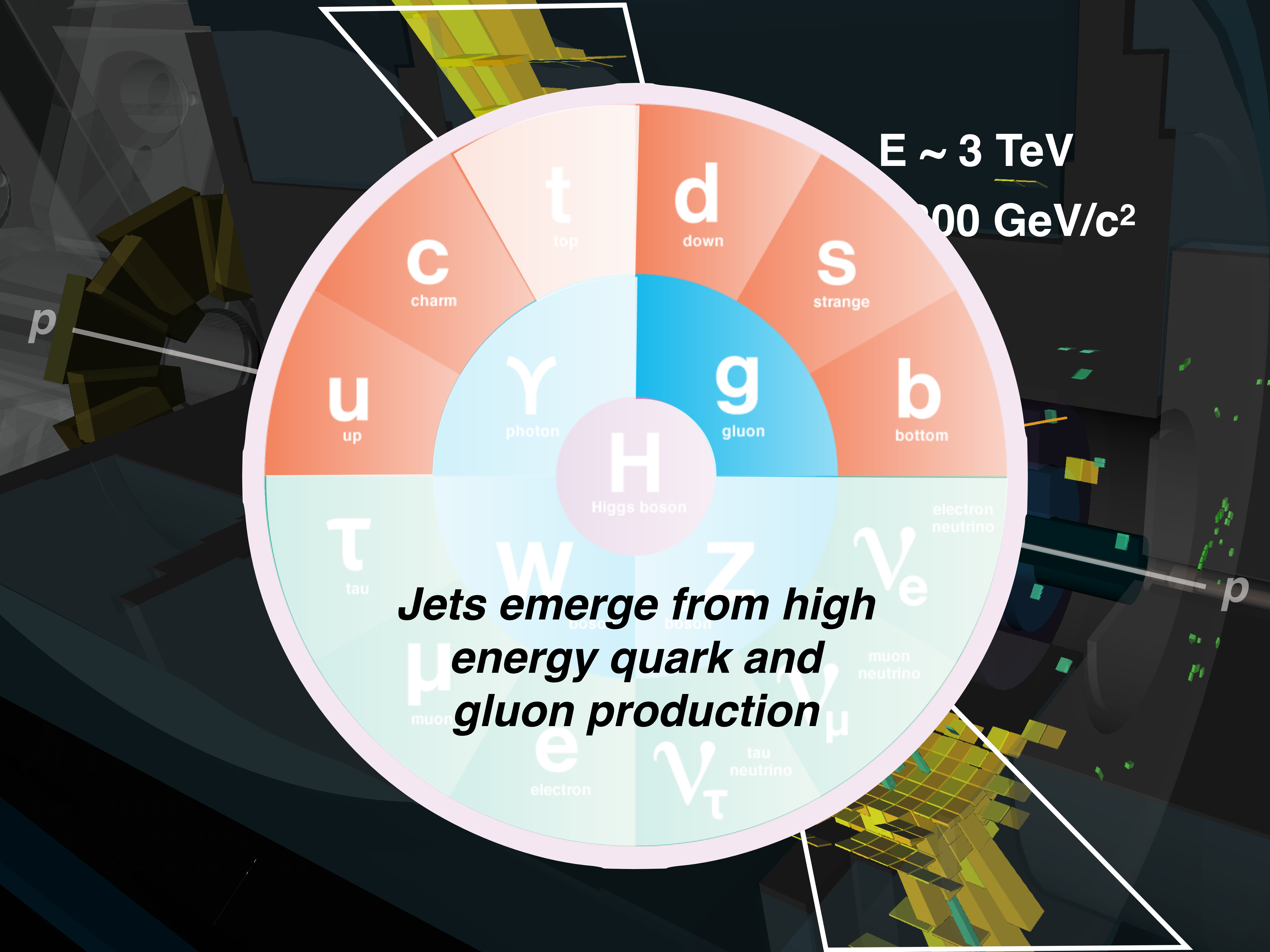
E ~ 3 TeV
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H
Higgs boson
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tau
W
Z
νe
electron neutrino
μ
muon
νμ
muon neutrino
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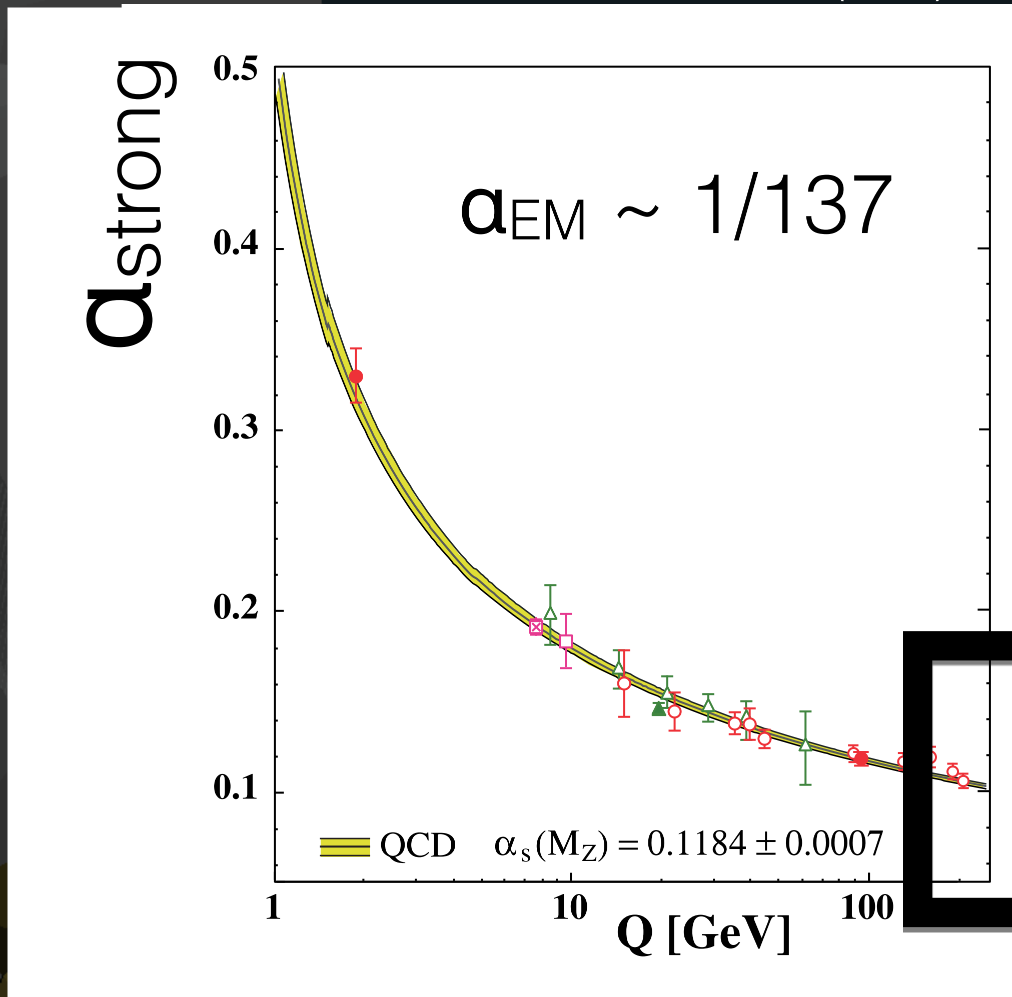
electron
ντ
tau neutrino
Jets emerge from high energy quark and gluon production

The origin of jets

S. Bethke, EPJC 64 (2009) 689



At small distance scales, there are quarks and gluons

They radiate gluons and quarks as they fly away

Quarks and gluons form bound states (like the proton)

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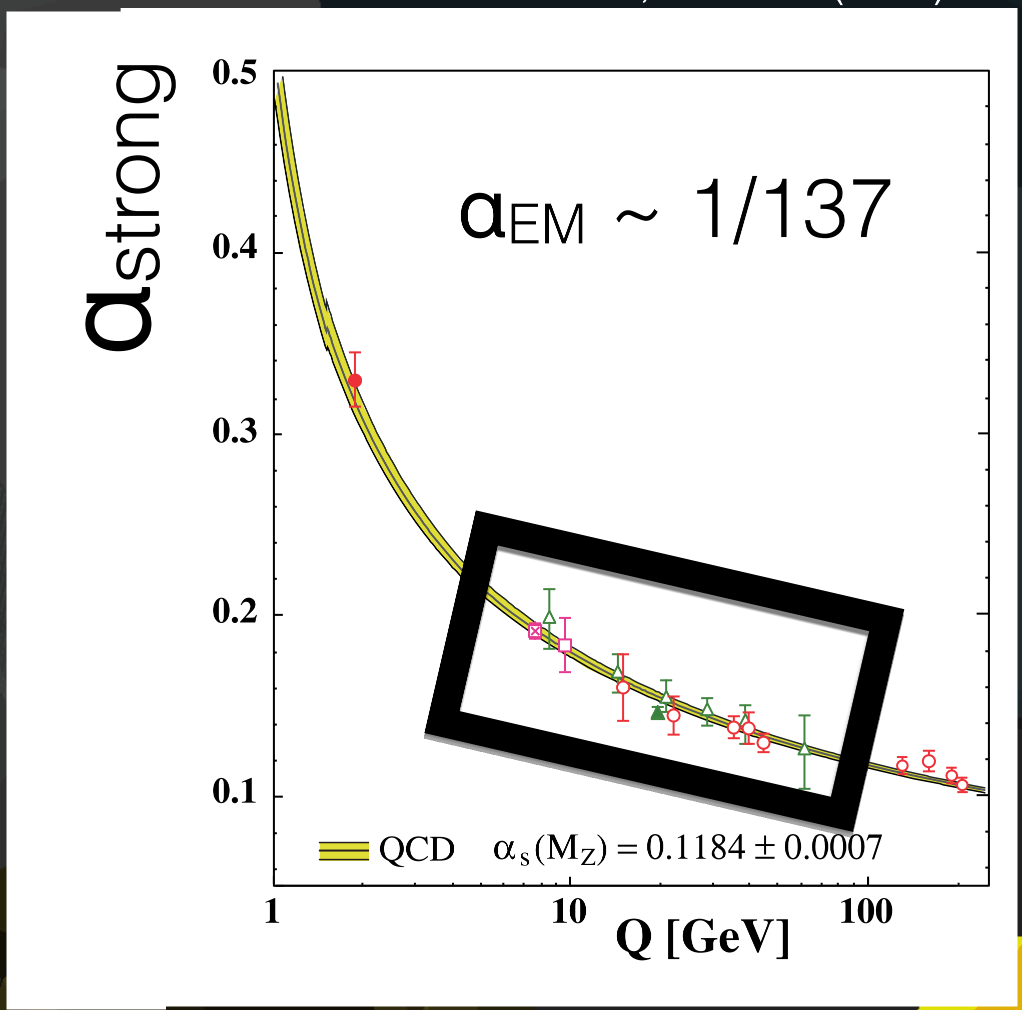

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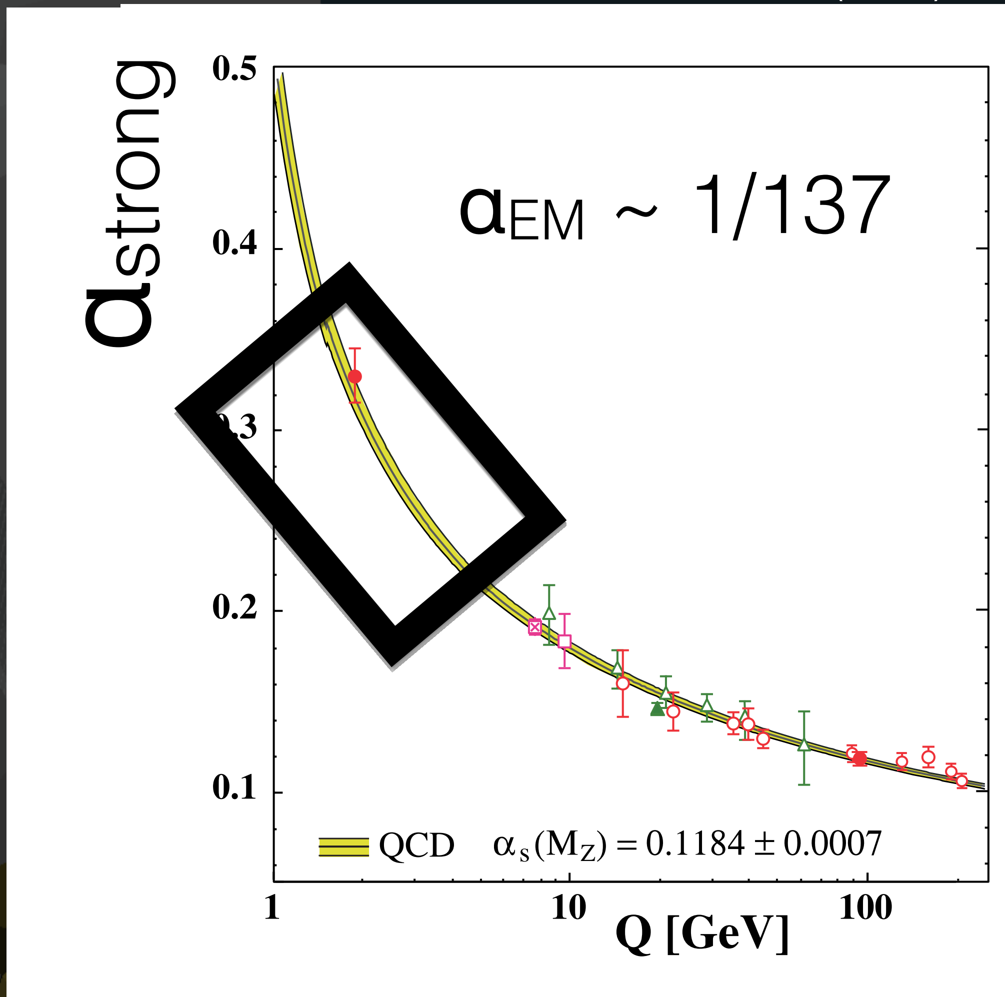

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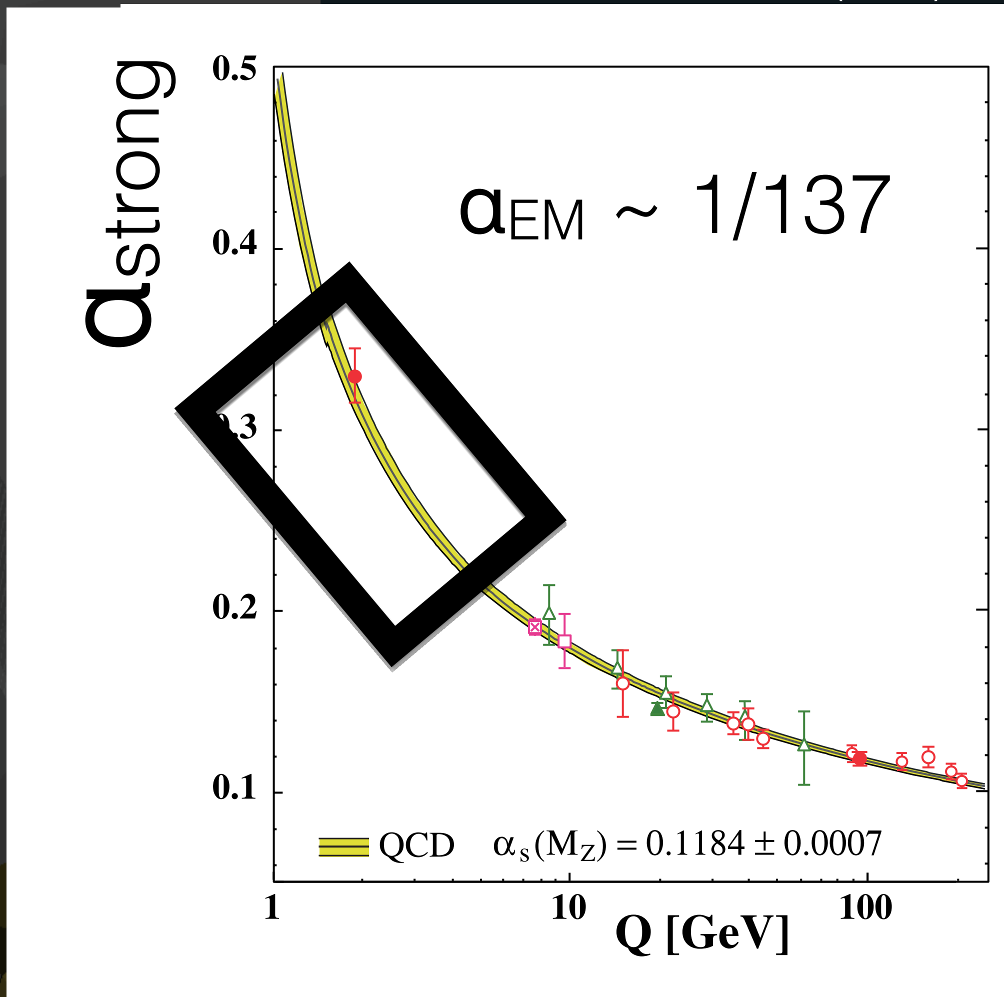


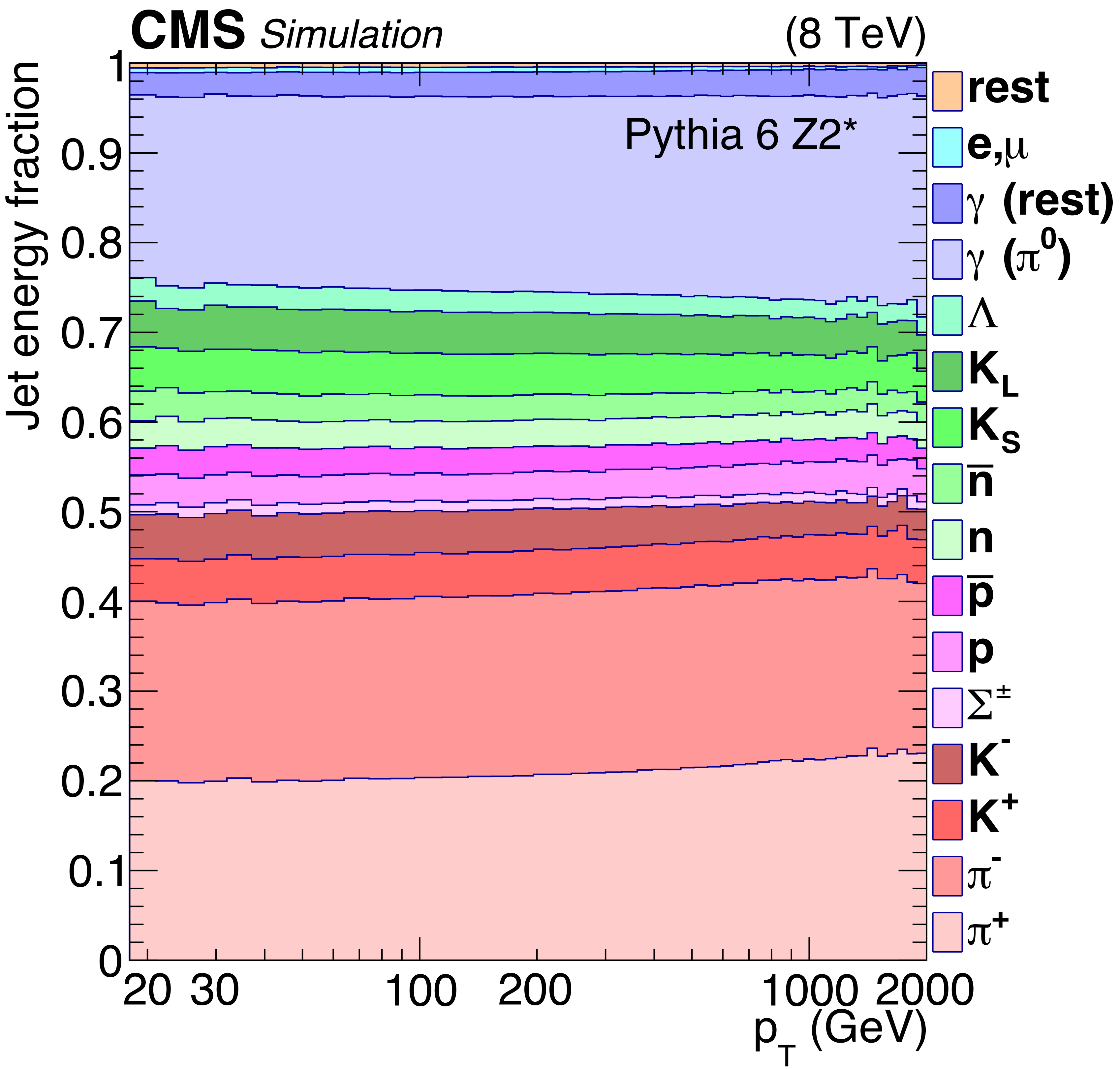
At small distance scales, there are quarks and gluons

They radiate gluons and quarks as they fly away

Quarks and gluons form bound states (like the proton)

We measure these bound-states flying into our detector

Jet constituents



Experimental considerations

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Calibration

We don't measure particles, we measure energy deposits and then infer particle properties.

Single-particle objects (e.g. muons)	Composite objects (e.g. jets)
Energy and angular biases	Energy and angular biases
	Particles in inactive material
	Particles bent out of cone
	Secondary particles
	Punchthrough

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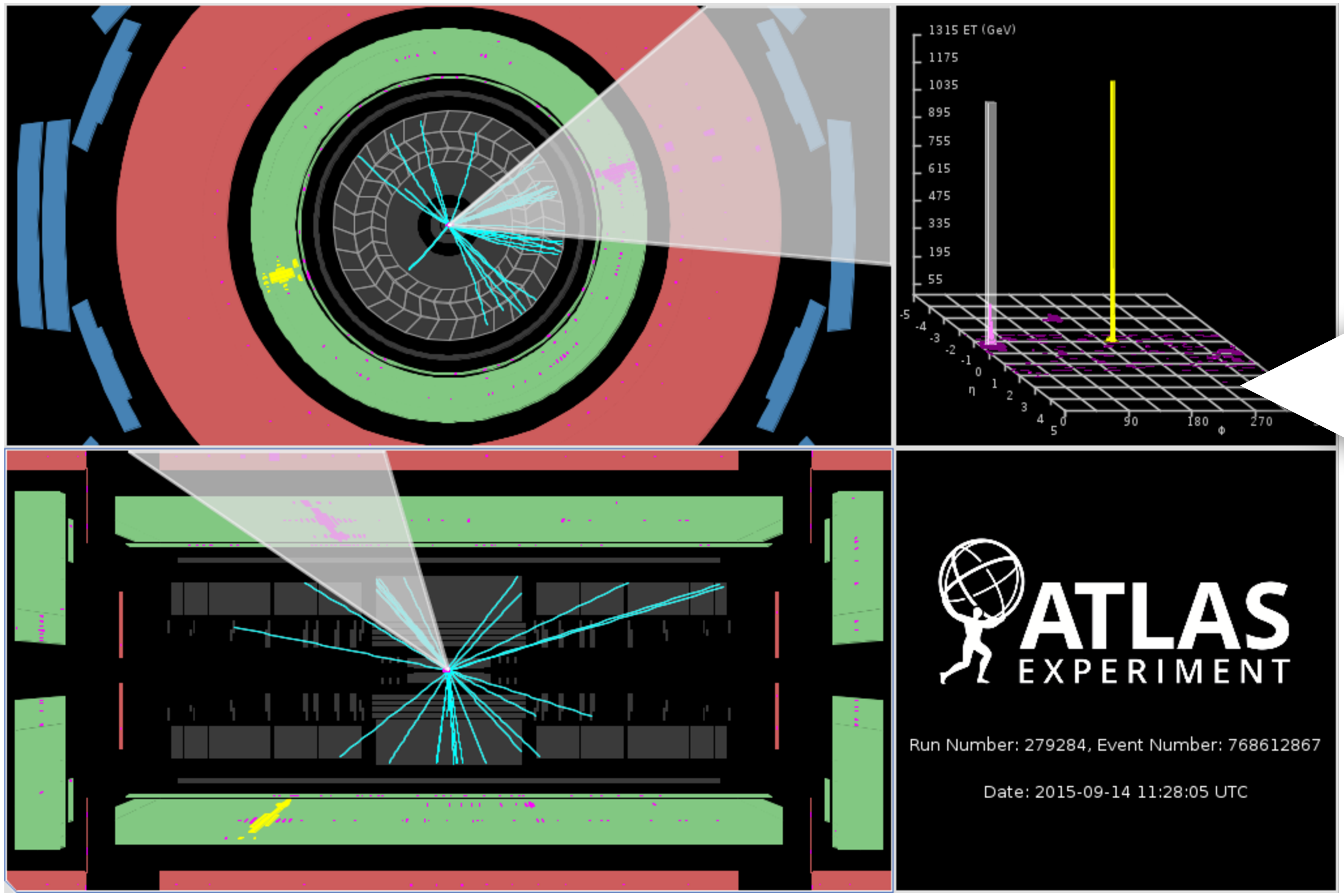
Usually one "bulk" correction

Food for thought: how would you do this without depending on the prior spectrum?

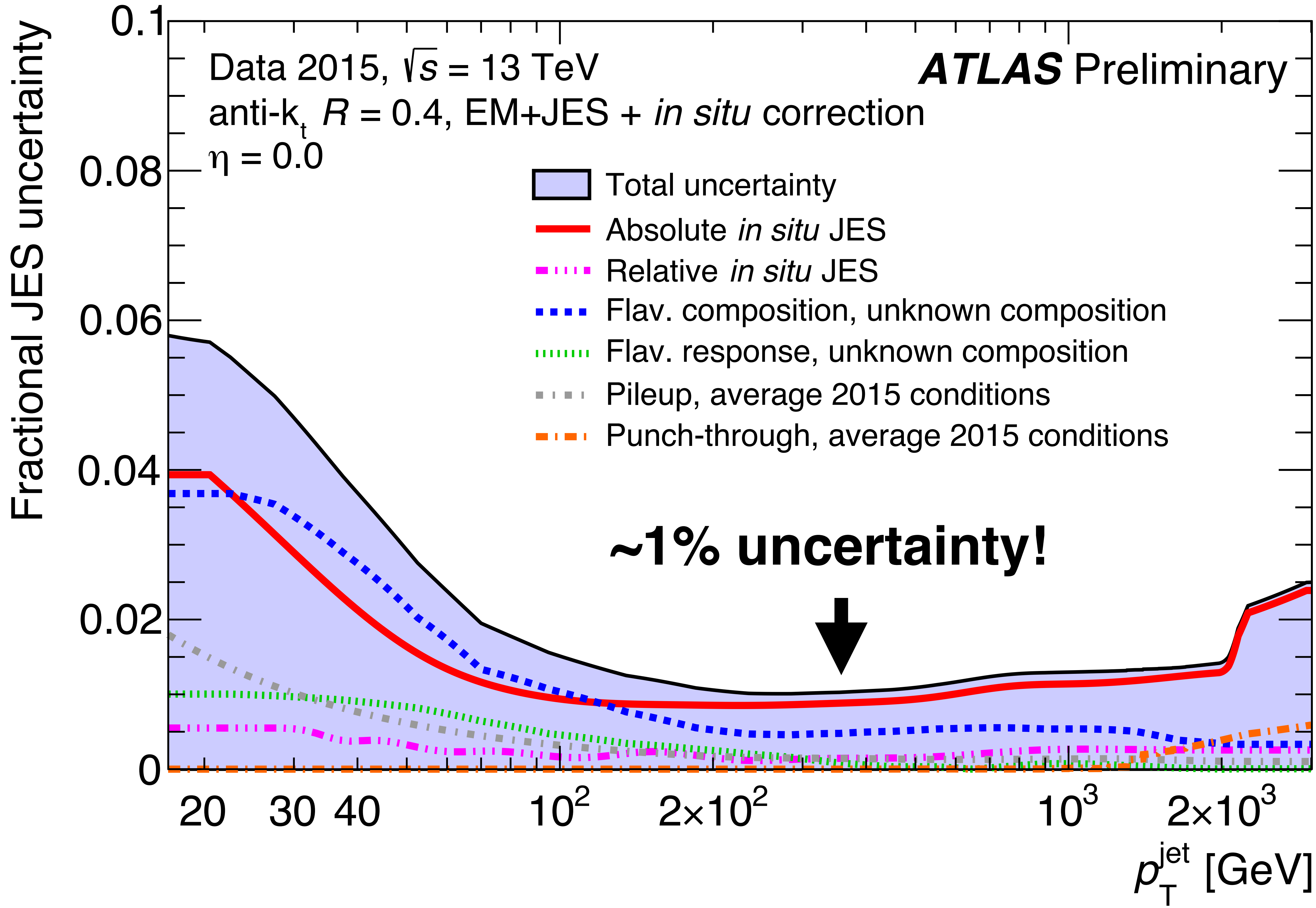
Calibration

The nominal calibration is derived using simulation and then a residual calibration accounts for differences between data and simulation (derived using data).

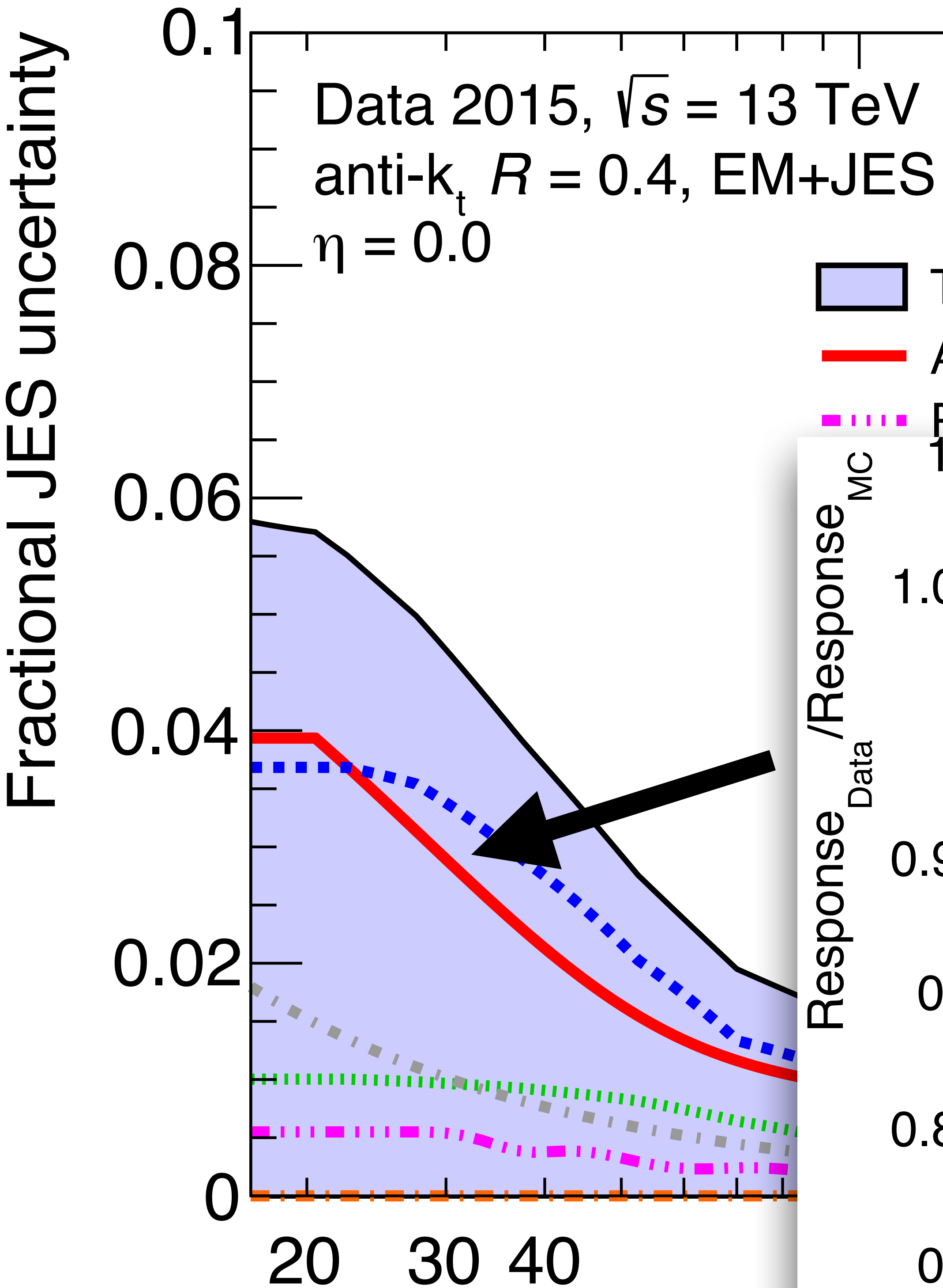


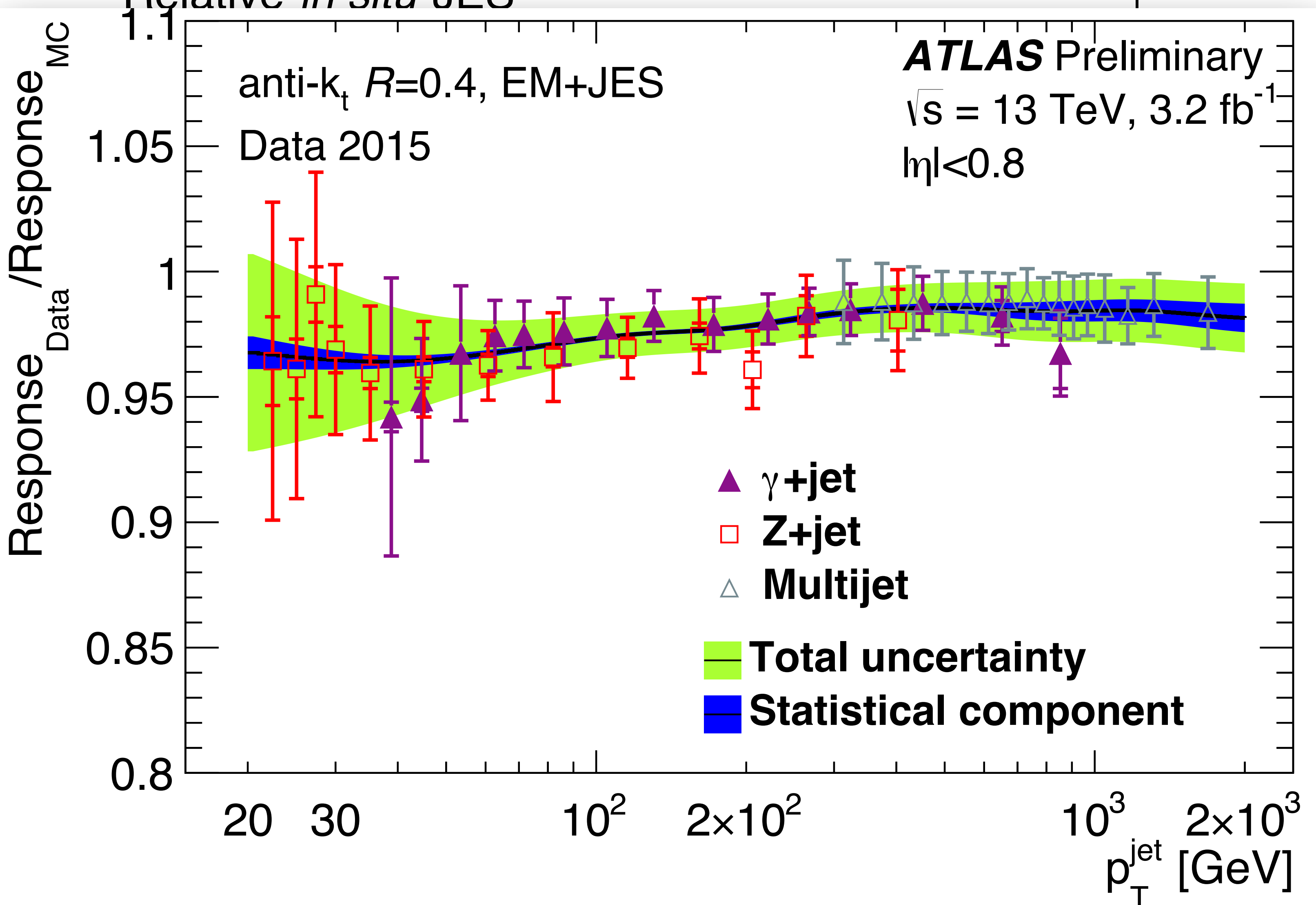
Can use the balance of well-measured objects (e.g. photons) with jets to study the bias in data.

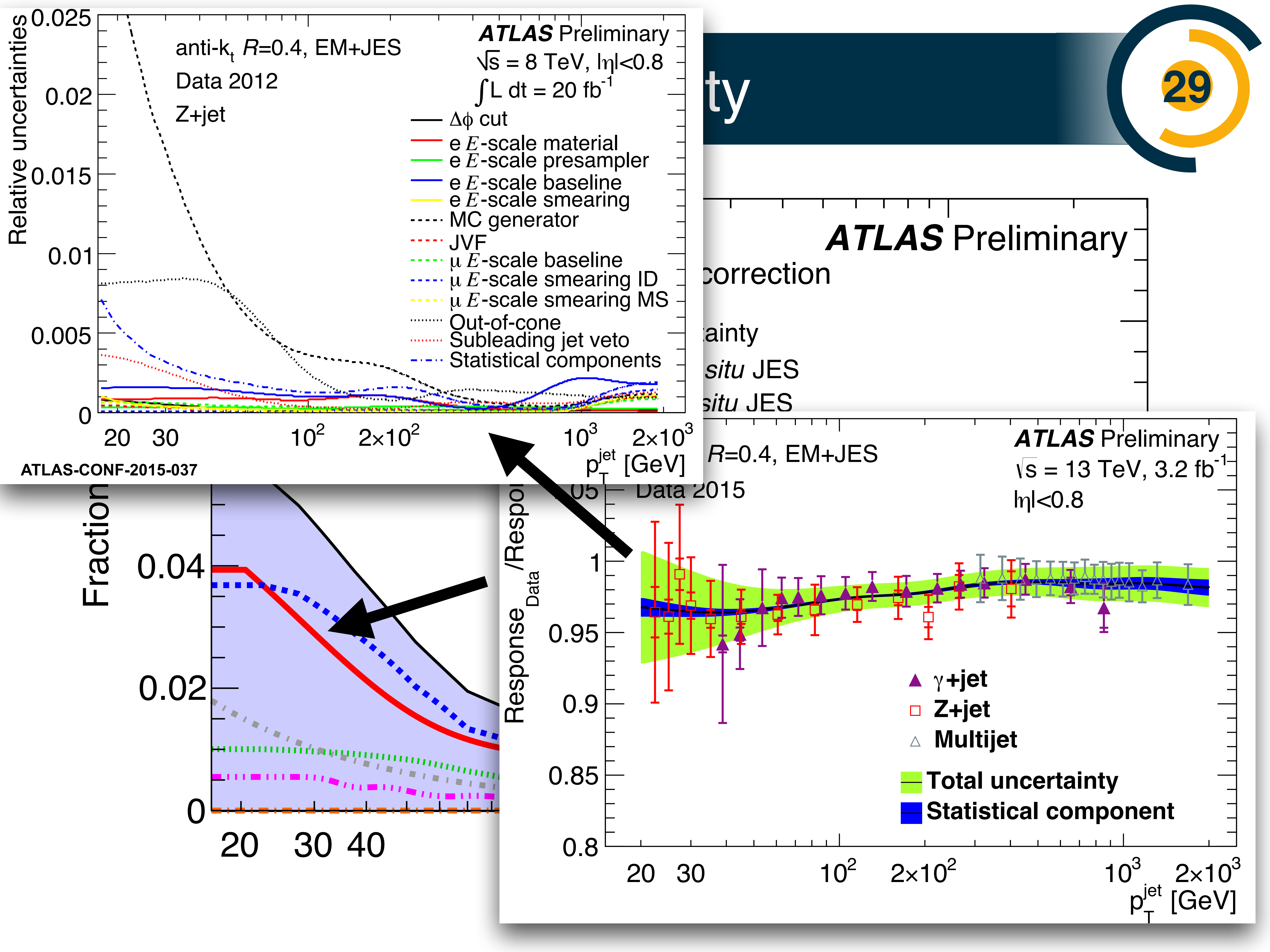
Jet energy bias uncertainty



Jet energy bias uncertainty






ATLAS Preliminary
anti-kt R=0.4, EM+JES
Data 2012
Z+jet
√s = 8 TeV, |η|<0.8
∫L dt = 20 fb-1
Δφ cut
e E-scale material
e E-scale presampler
e E-scale baseline
e E-scale smearing
MC generator
JVF
μ E-scale baseline
μ E-scale smearing ID
μ E-scale smearing MS
Out-of-cone
Subleading jet veto
Statistical components
Relative uncertainties
pT jet [GeV]
ATLAS-CONF-2015-037
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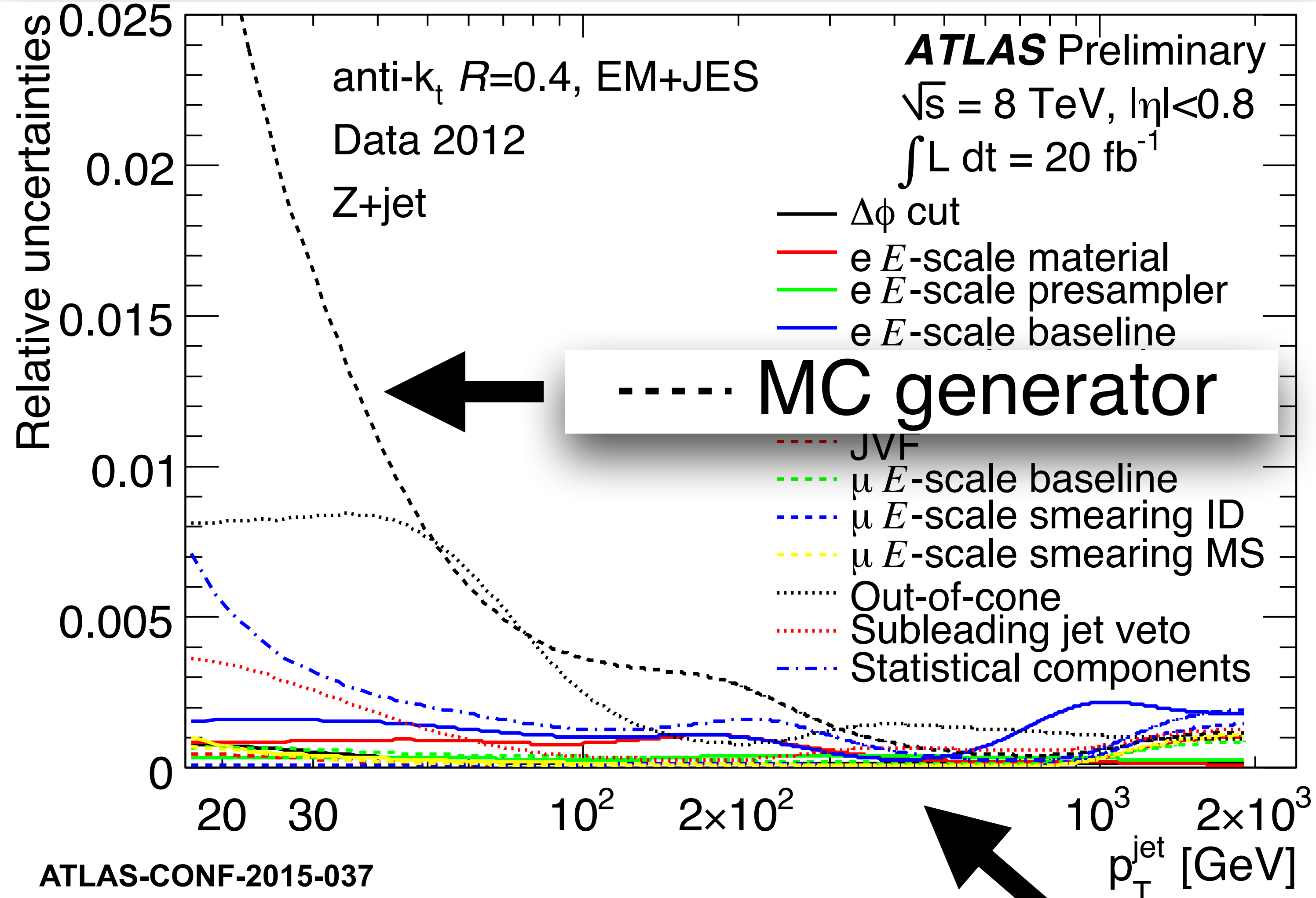
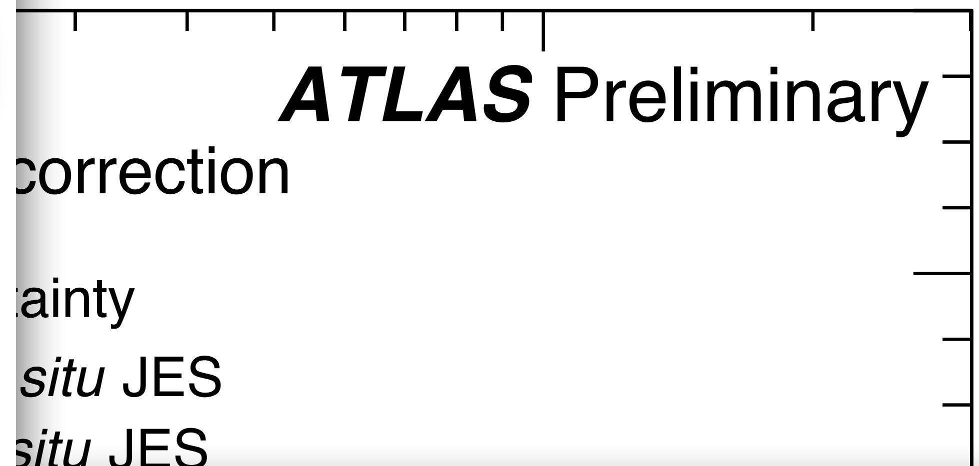
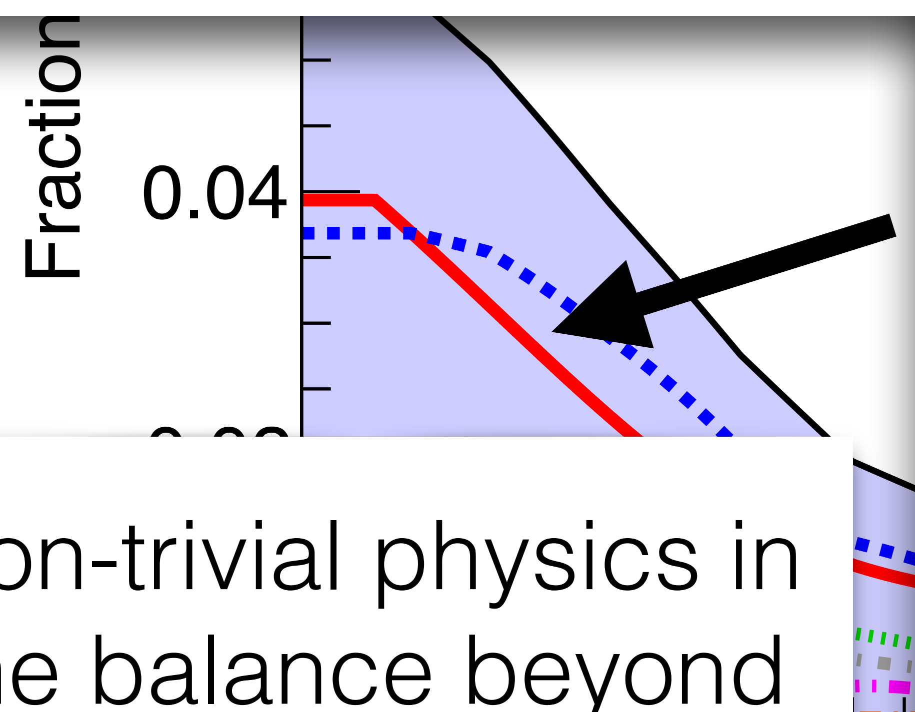
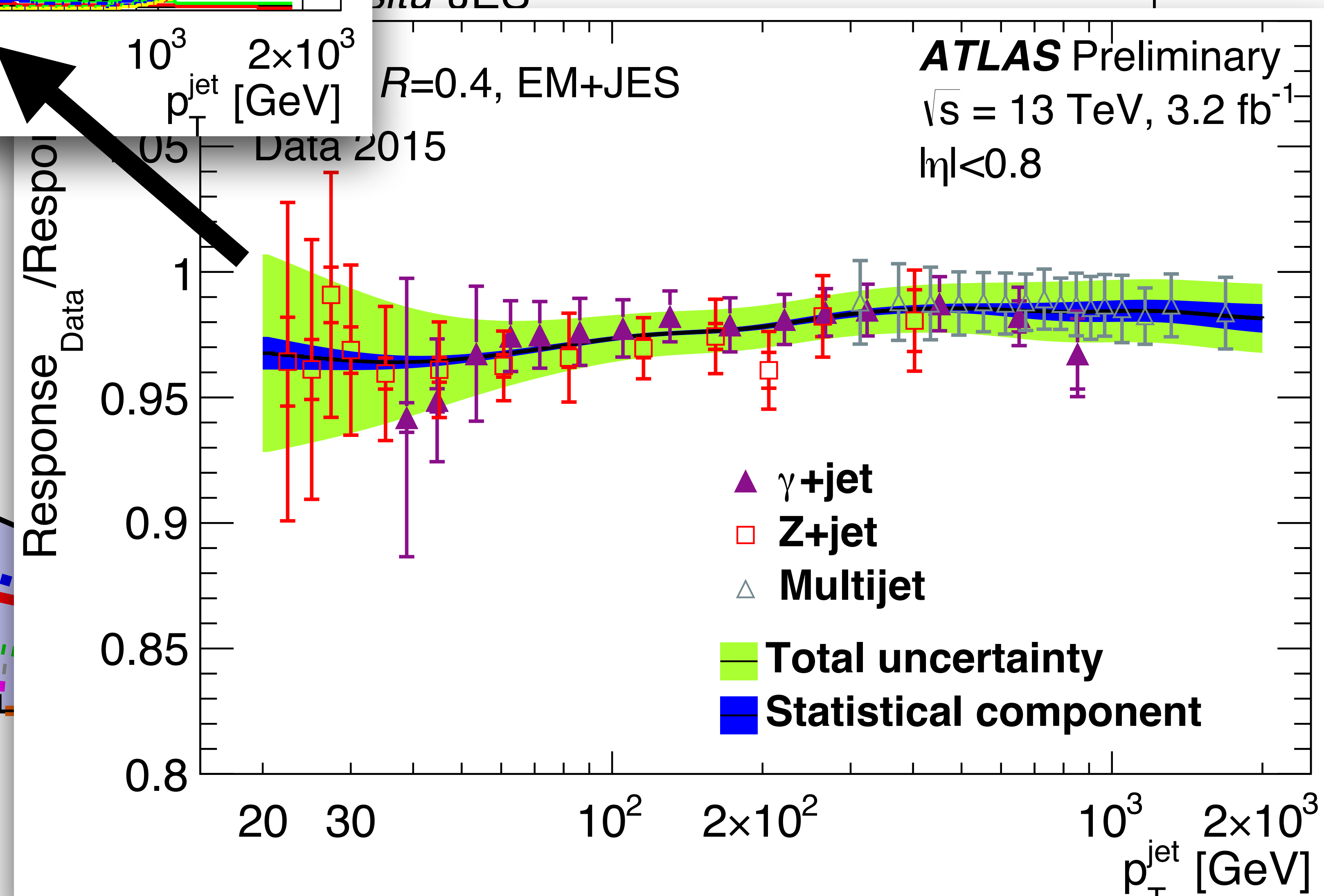
ATLAS Preliminary
correction
ainty
situ JES
situ JES
Fraction
ATLAS Preliminary
R=0.4, EM+JES
Data 2015
√s = 13 TeV, 3.2 fb-1
|η|<0.8
γ+jet
Z+jet
Multijet
Total uncertainty
Statistical component
Response Data /Respo
pT jet [GeV]



MC generator







Non-trivial physics in the balance beyond leading order!

Unfolding

When someone says they have measured a differential cross-section, they mean that it has been **unfolded**.

Unfolding corrects for detector effects so that our data can be directly compared with theory predictions.

It is not valid to directly compare theory predictions to detector-level data !!

Either the theory or the data must be corrected. Correcting the data is more general and can allow for multiple theory groups to reuse the same measurement.

What does unfolding do?

In general, unfolding needs to correct for interrelated effects:

- Acceptance and efficiency
  - ➡ Particles produced may not be measured
- Detector noise
  - ➡ Particles measured may not be from real particles
- Background processes
  - ➡ If you want to measure process X, need to remove Y
- Combinatorics
  - ➡ If N particles, chance that detector can change order
- Detector distortions
  - ➡ Bias and resolution effects

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← I'll briefly illustrate this

Illustrative toy example

$$m = Rt$$

m = measured; ***t*** = true

We usually call ***R*** the "response matrix" because ***m*** and ***t*** are binned (and thus vectors).

We (usually) get ***R*** from detailed detector simulations.

e.g. Geant4 (particle propagation and energy deposition) + custom code for analg and digital signal emulation.

Illustrative toy example

$$m = Rt$$

m = measured; *t* = true

I know what you want to do here is $t = R^{-1} m$.

Illustrative toy example

$$m = Rt$$

m = measured; *t* = true

I know what you want to do here is $t = R^{-1} m$.

In the next slides, I hope to convince you that this is not usually a good idea.

Illustrative toy example

$$m = Rt$$

m = measured; *t* = true

$$R = \begin{pmatrix} 1-\epsilon & \epsilon \\ \epsilon & 1-\epsilon \end{pmatrix}$$

Consider this case, where $0 \leq \epsilon \leq 0.5$

Illustrative toy example

$$m = Rt$$

m = measured; *t* = true

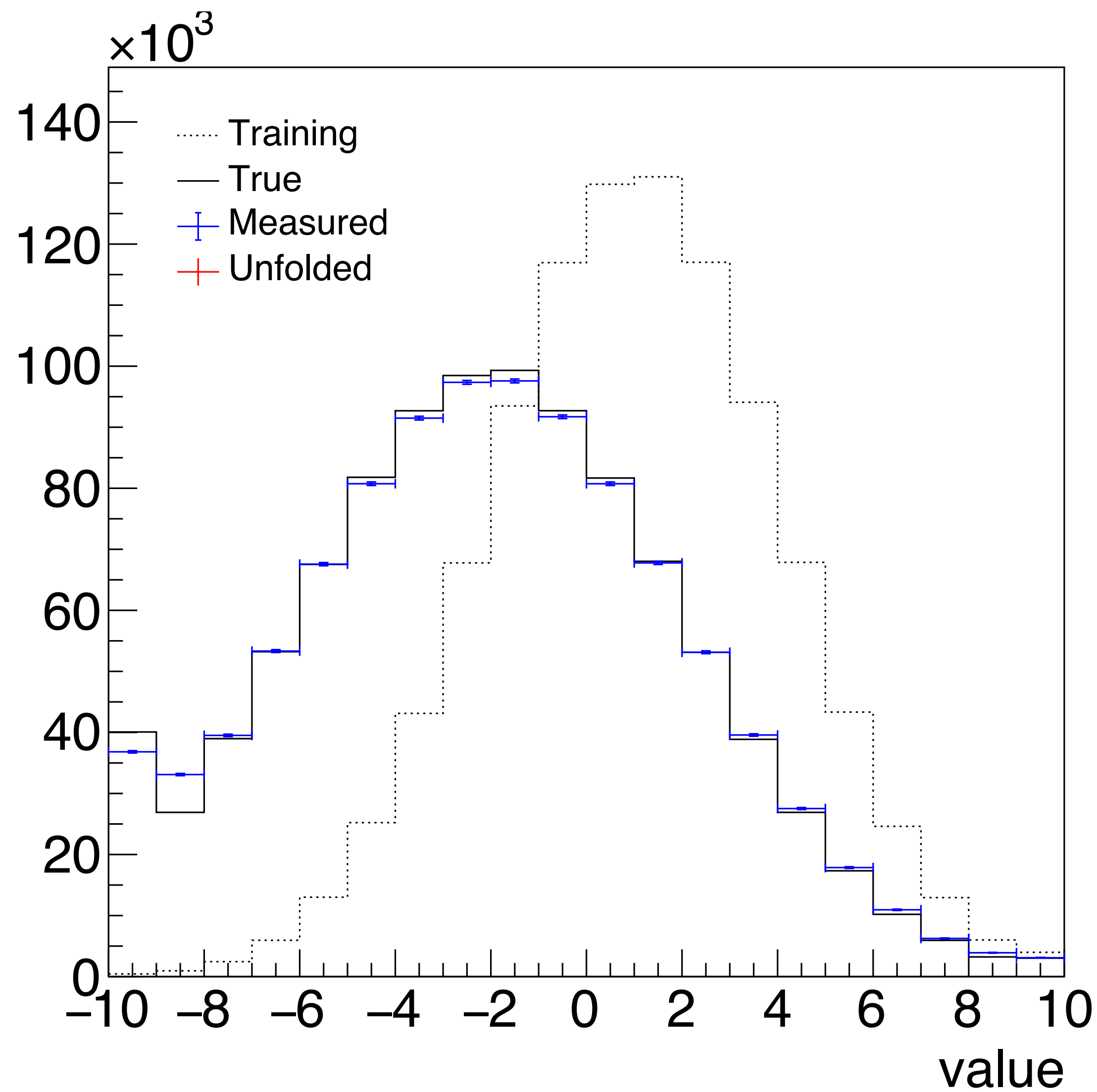
$$R = \begin{pmatrix} 1-\epsilon & \epsilon \\ \epsilon & 1-\epsilon \end{pmatrix}$$

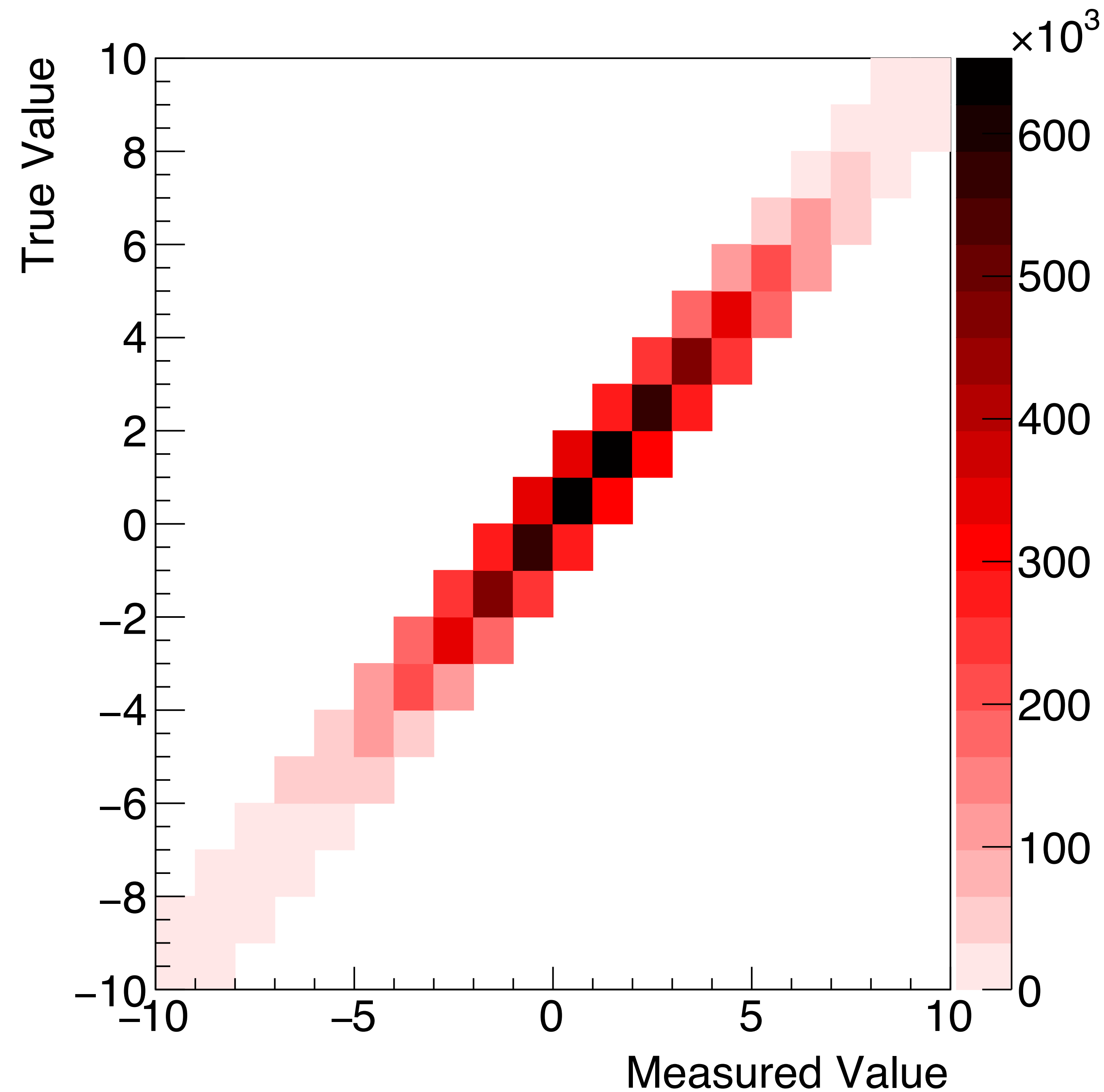
$$\mathrm{Var}(R^{-1}m) \propto 1/\mathrm{Det}(R) = 1 - 2\epsilon$$

Statistical uncertainty blows up as **e** → 0.5

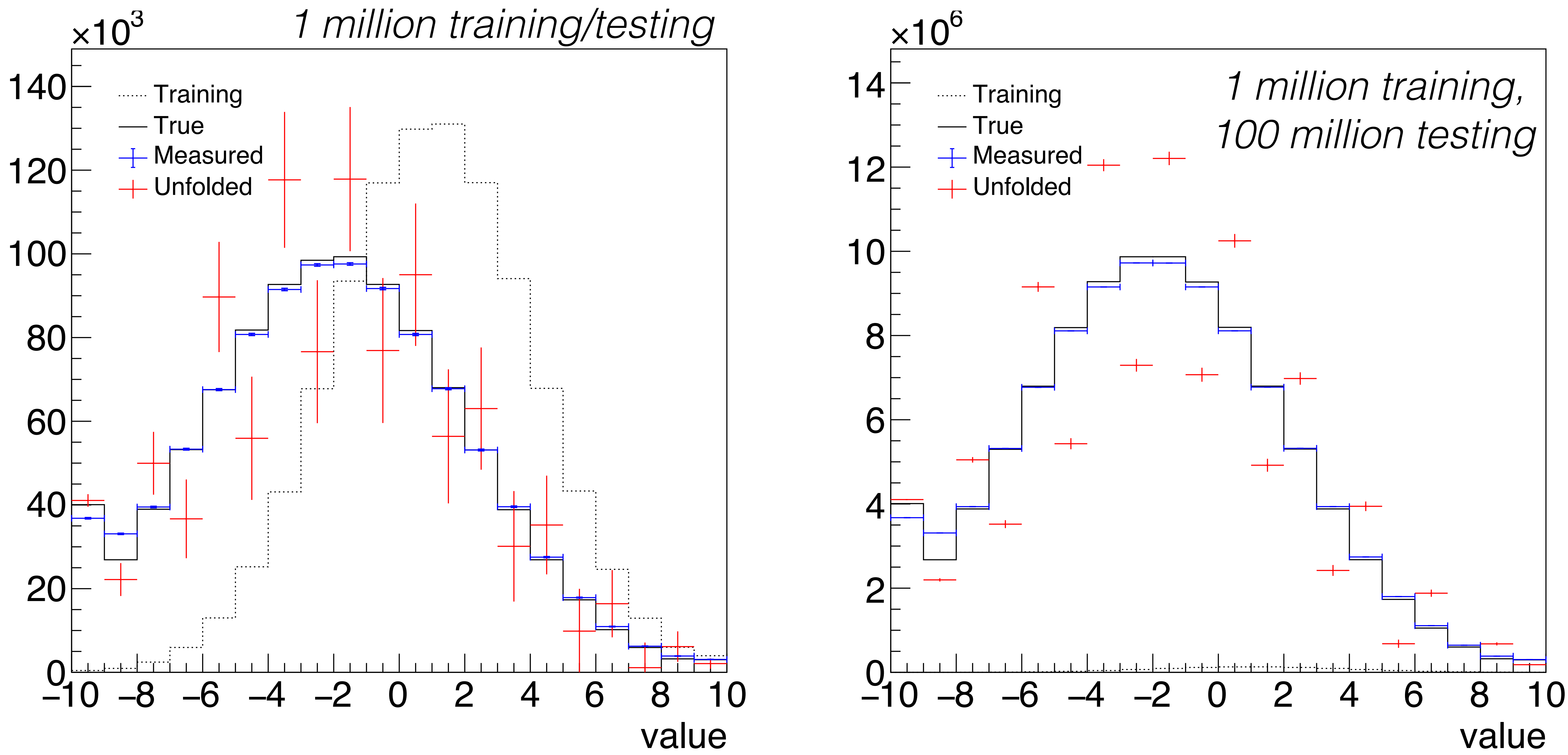
A more realistic example

$$R_{\mathrm{norm}} = \begin{pmatrix} 0.75 & 0.25 & 0 & & & \\ 0.25 & 0.50 & 0.25 & 0 & & \\ 0 & 0.25 & 0.50 & 0.25 & 0 & \\ & 0 & 0.25 & 0.50 & 0.25 & \\ & & 0 & 0.25 & 0.50 & \\ & & & & & \ddots \end{pmatrix}$$





Unfolding by Matrix Inversion



Stat. uncertainty is large and there is a bias when training dataset is too small.

The HEP solution

Our solution is to do regularized matrix inversion.

There are two main techniques that we use:

"Iterative Bayesian Unfolding"

$$\theta_{ij} = \frac{\Pr(m_j|t_i)\cdot\Pr(t_i)}{\sum_i \Pr(m_j|t_i)\cdot\Pr(t_i)}$$

response matrix

regularization
= number of iterations

$$\Pr_{k+1}(t_i) = \sum_j \theta_{ij}\Pr_k(t_i)$$

Nucl. Inst. Meth. A 362 (1995) 487

"Singular Value Decomposition (SVD) Unfolding"

$$R = USV^T$$

U, *V*, orthogonal, *S* diagonal & non-negative

$$d = U^T m \qquad z_i(\tau) = \frac{d_i}{s_i}\cdot\frac{s_i^2}{s_i^2+\tau}$$

$$t = Vz$$

regularization parameter

Nucl. Inst. Meth. A 372 (1995) 469

Main tool: RooUnfold (ROOT-based C++ code)

The HEP solution

Our solution is to do regularized matrix inversion.

Note: regularized matrix inversion depends on unphysical irregularization parameters

There are two main techniques that we use:

One choses parameters to tradeoff bias and uncertainty.

IBU Unfolding

- depend on prior
- depends on # of iterations

Nucl. Inst. Meth. A 362 (1995) 487

SVD Unfolding

- depend on t

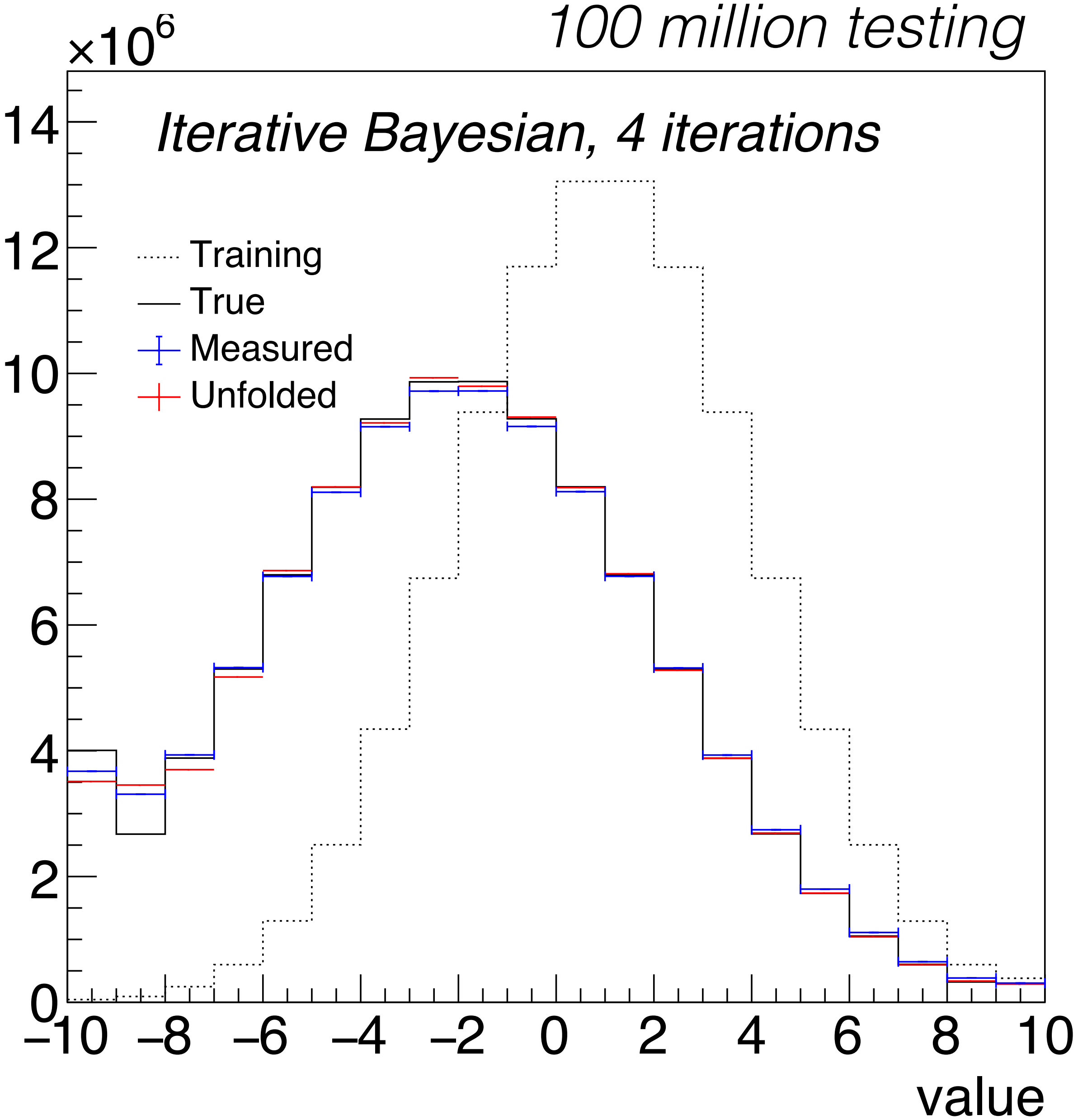
Nucl. Inst. Meth. A 372 (1995) 469

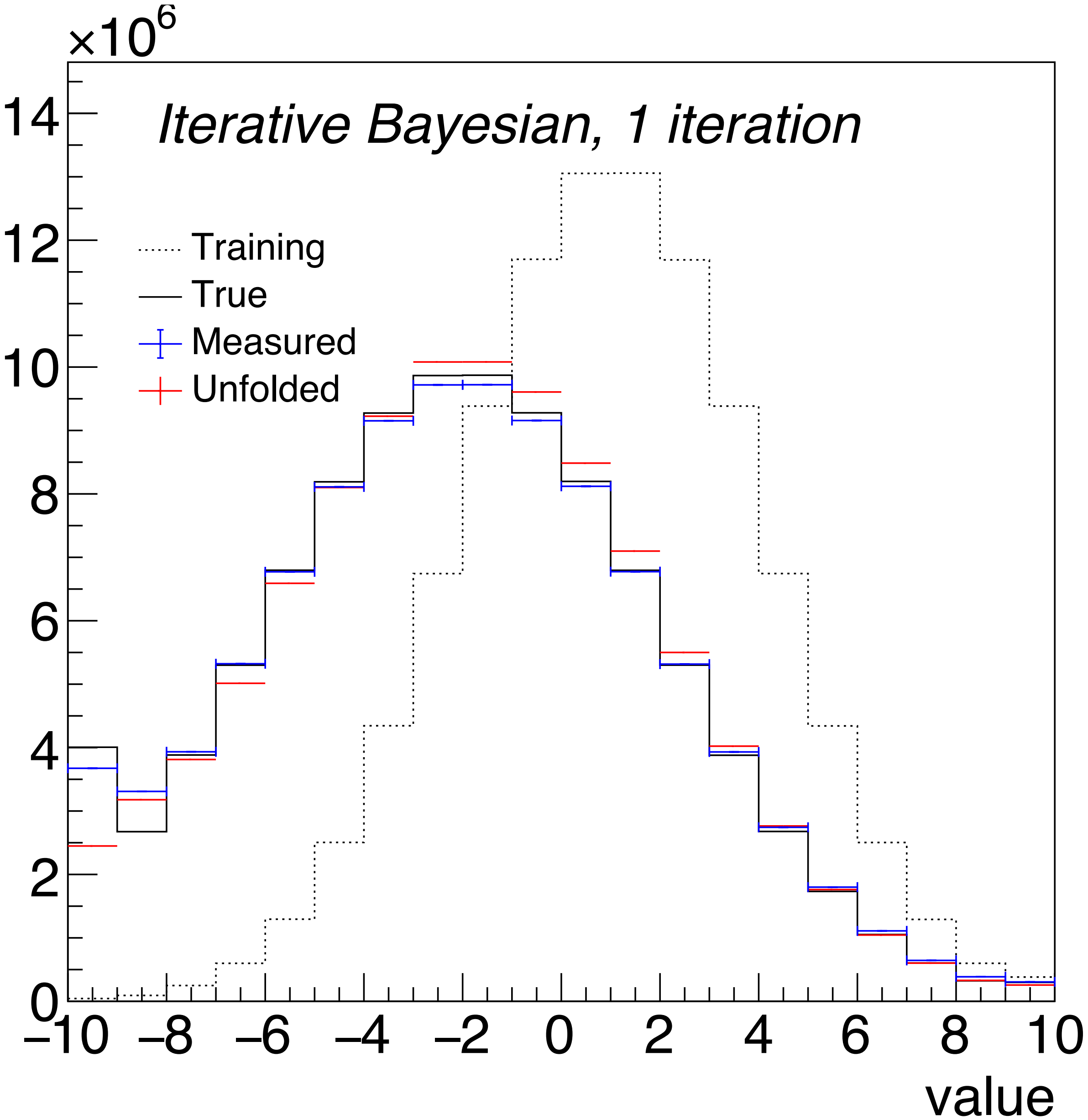
~1000 citations each

Main tool: RooUnfold (ROOT-based C++ code)

Example: Iterative Bayesian Unfolding

1 million training, 100 million testing





One last comment: phase space def.

Need to decide what to unfold to, called the "fiducial volume"

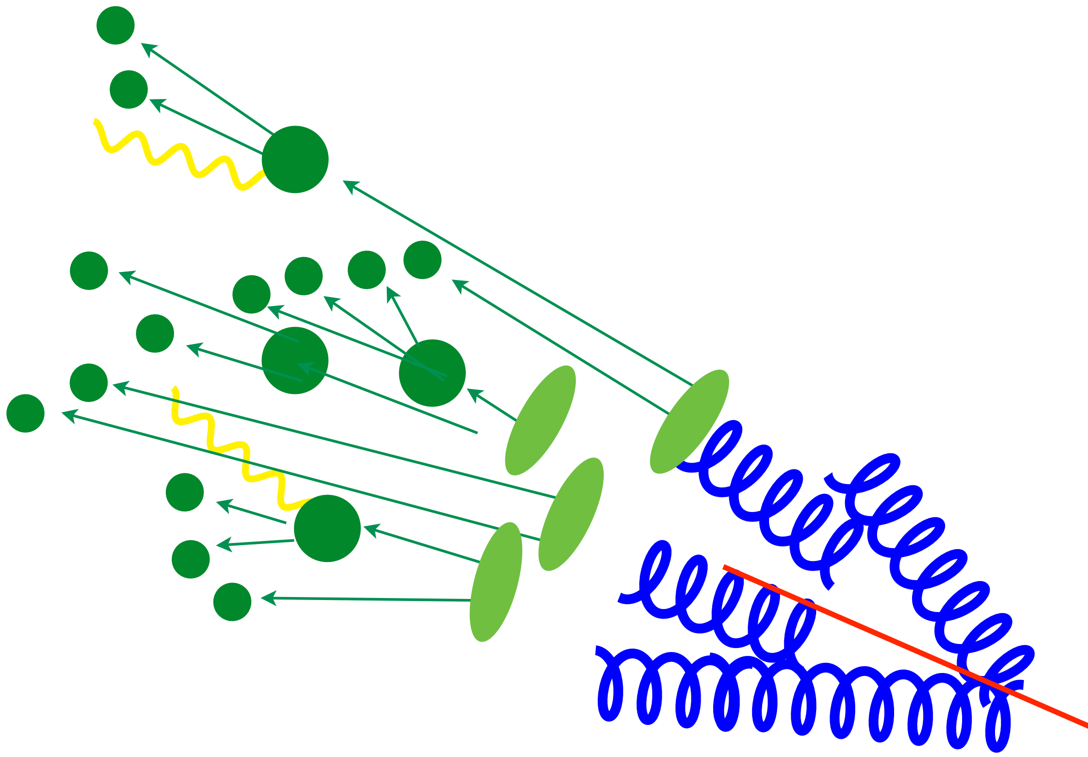
Calculations are often at the level of "born-level partons"

Measurements are at the level of hadrons.

+Non-perturbative corrections

+Resummation ("dressed")

Born-level parton



One last comment: phase space def.

Need to decide what to unfold to, called the "fiducial volume"

Calculations are often at the level of "born-level partons"

Measurements are at the level of hadrons.

The closer the target is to the observable, the less the unfolding has to do and the smaller the modeling uncertainty.

Please don't unfold to "born-level partons". Better to "dress" the calculations with resummation and hadronization.

(fortunately, born measurements is becoming less fashionable these days)

Physics topics

PDFs

$$\sigma = \sum_{ij \in \{q,\bar{q},g\}} \int dx_1 dx_2 f_i(x_1,\mu) f_j(x_2,\mu) \hat{\sigma}_{ij}(x_1 E, x_2 E)$$

PDFs

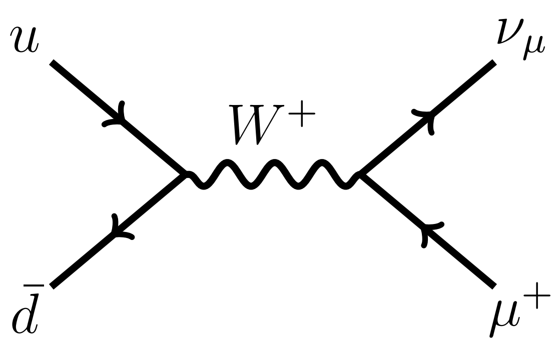
Every* LHC measurement is sensitive to PDFs - the ones that are most useful for constraining them can be (1) measured precisely, (2) predicted precisely (see last term), and (3) mostly sensitive to ~one partonic channel

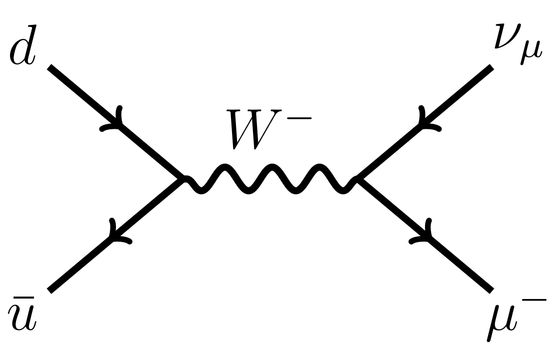
*Except when the protons interact coherently.

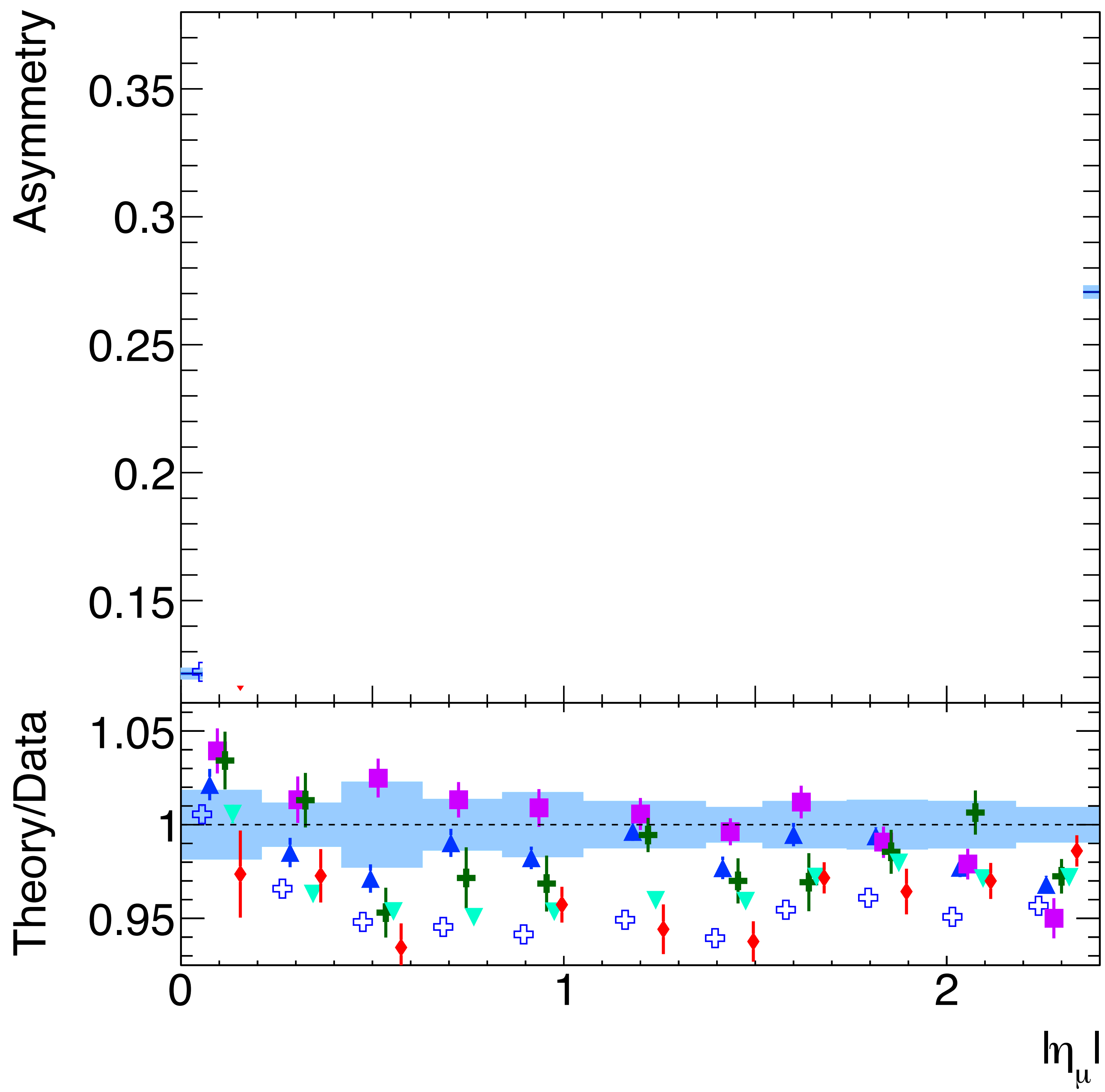
Valence quarks at moderate x

W+jets is a precise probe of the u/d content of the proton.

At a *pp* collide, more W+ than W-







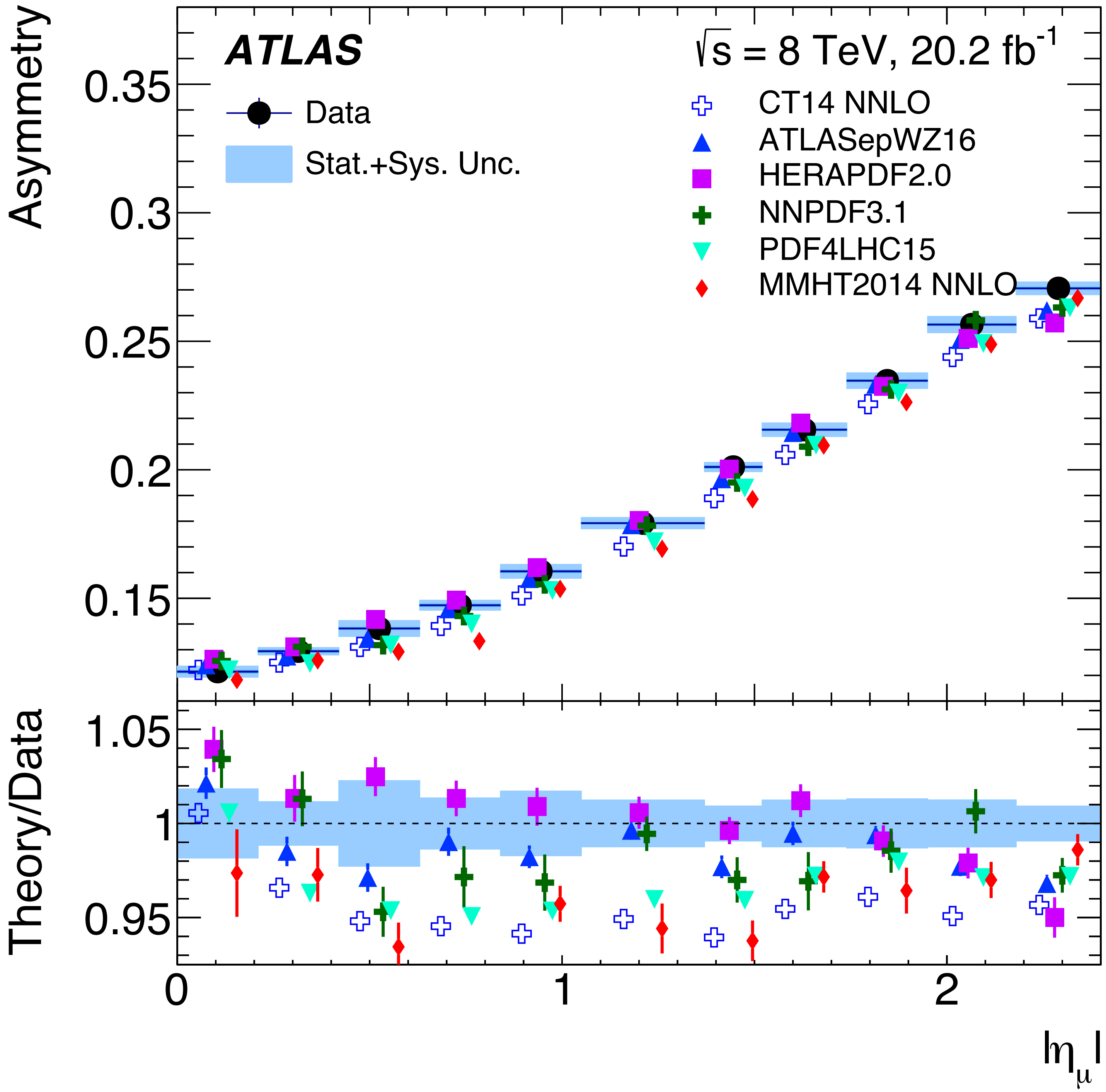
Valence quarks at moderate x

W+jets is a precise probe of the u/d content of the proton.

At a *pp* collide, more W^+ than W^-

$$A_\mu = \frac{d\sigma_{W_{\mu^+}}/d\eta_\mu - d\sigma_{W_{\mu^-}}/d\eta_\mu}{d\sigma_{W_{\mu^+}}/d\eta_\mu + d\sigma_{W_{\mu^-}}/d\eta_\mu}$$

Why not 1/3?

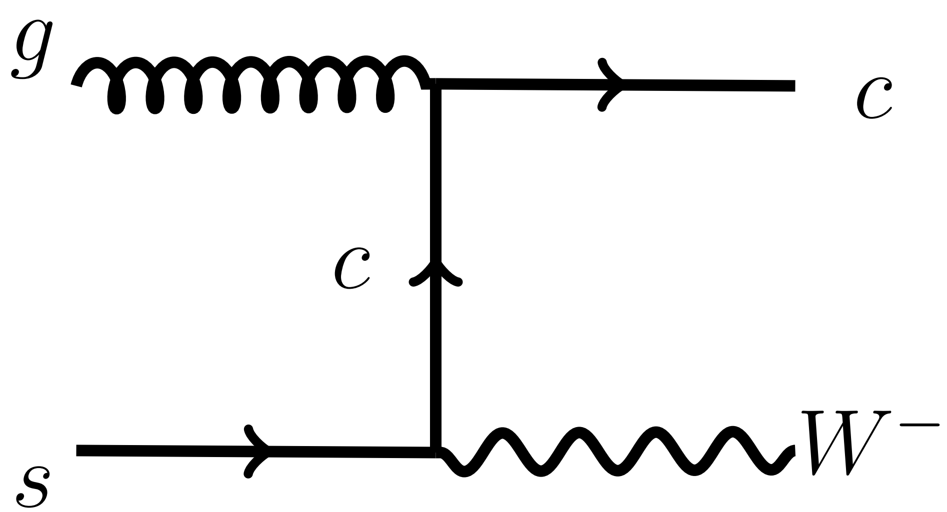


Heavier quarks

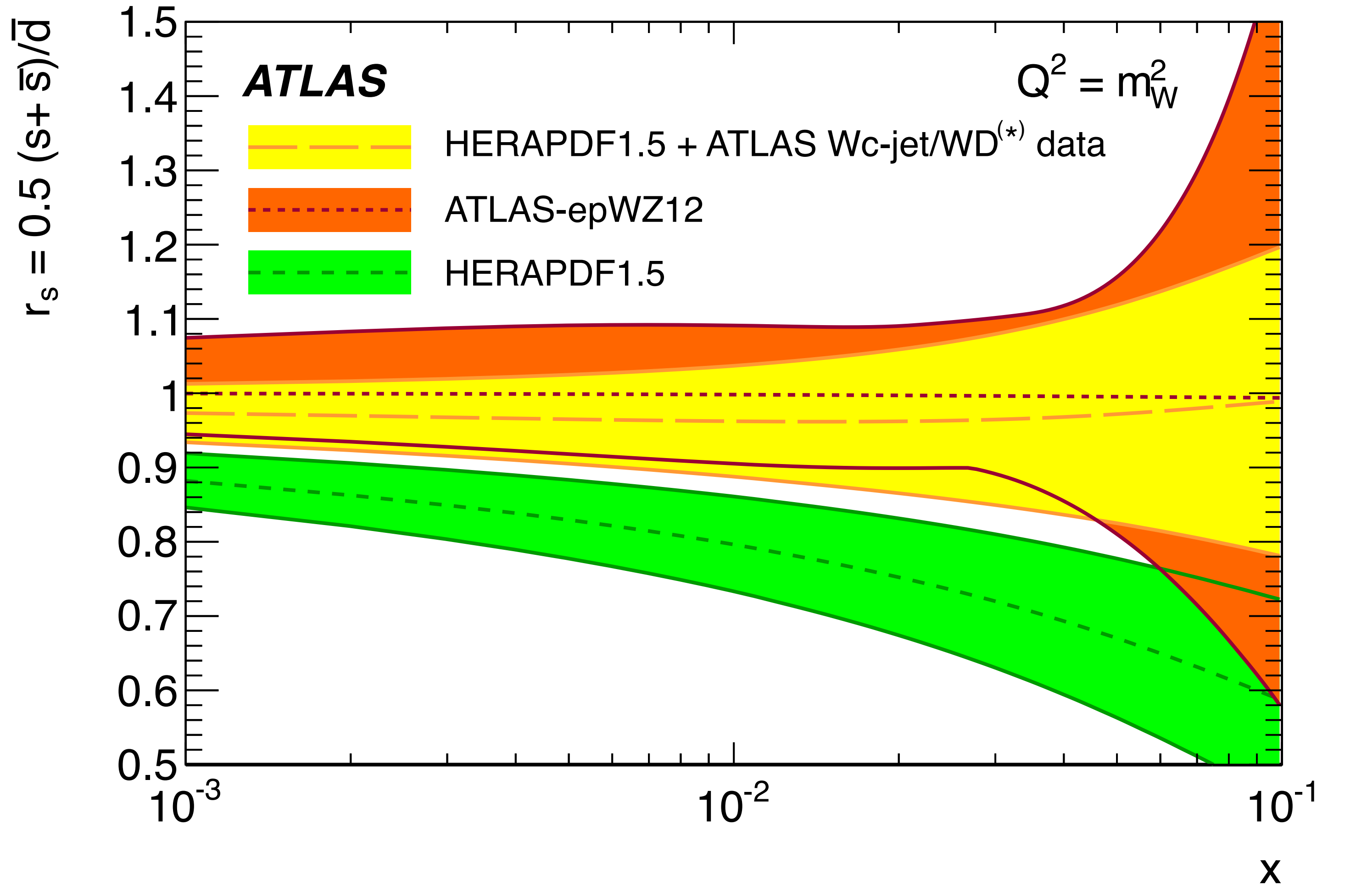
Various measurements are constructed to be sensitive to the s-, c-, and even b-component of the proton.

For example, W+charm measurement can constrain the sea strangeness.

(ATLAS and to a lesser extent CMS find s ~ other sea contributions)

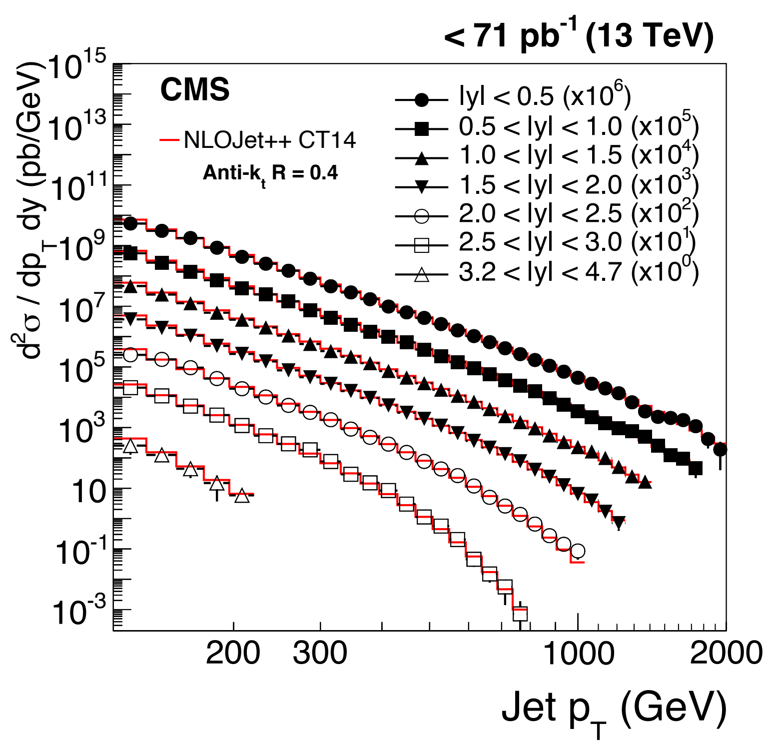


Question: how would you identify the c-quark?



Gluons

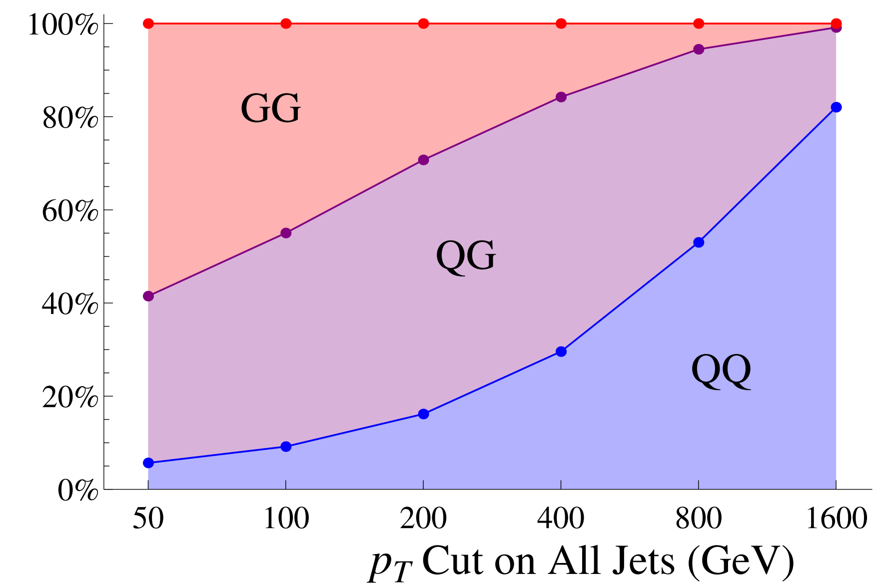
Gluon PDF at moderate - high *x* is constrained by two sources:

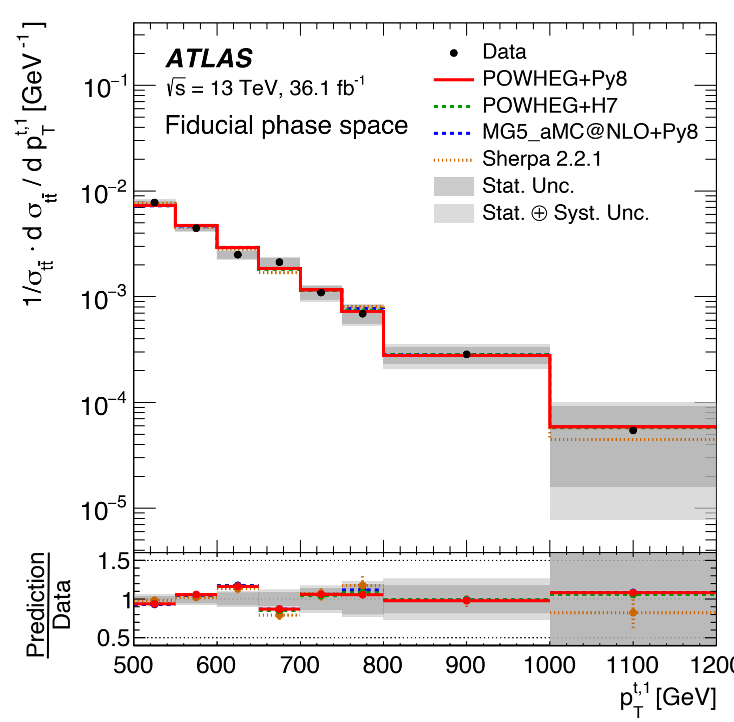


Dijets

High stats, ~10% precision across a wide kinematic range

small gg/qg fraction at high jet p_T



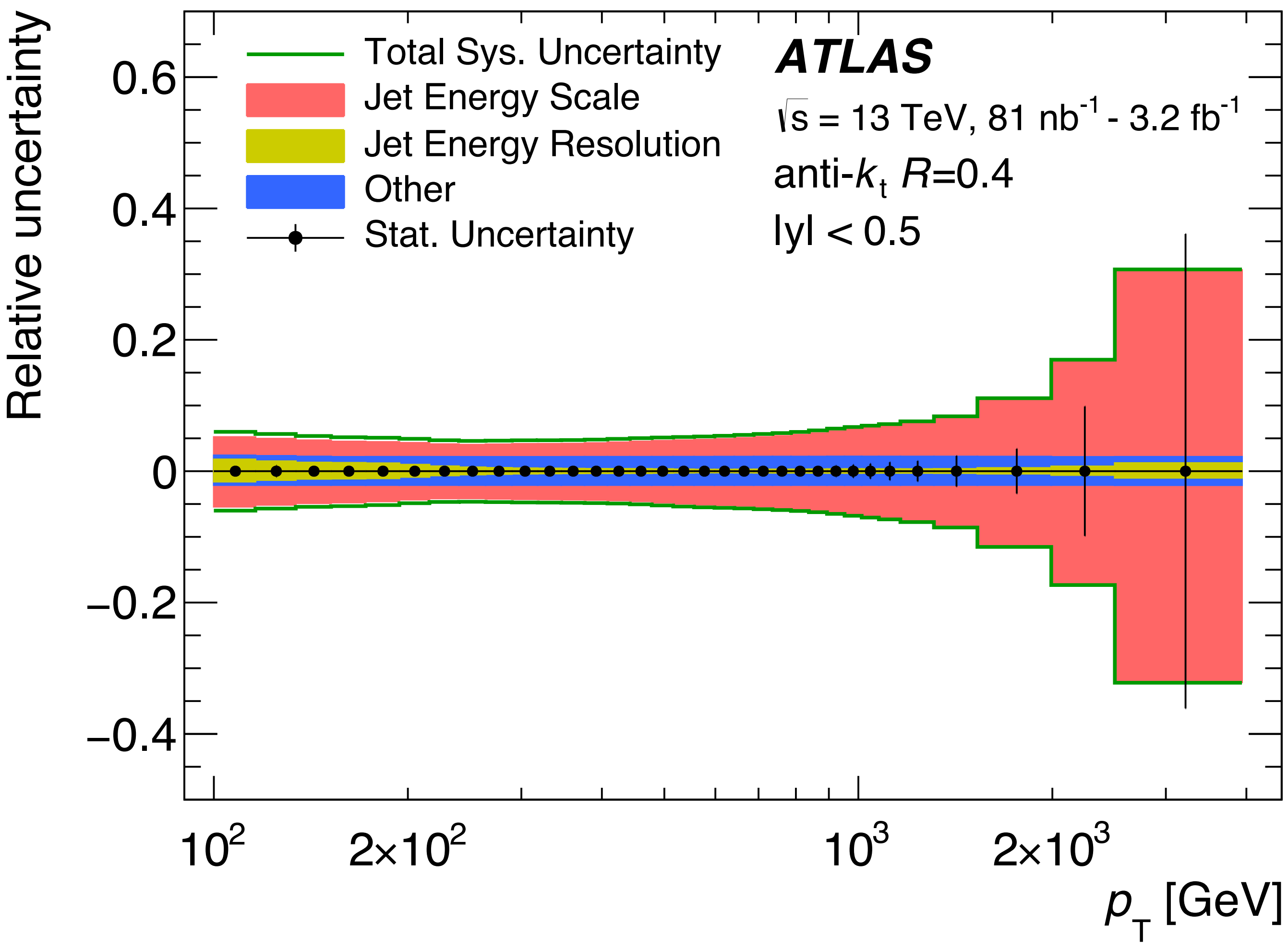


Top quark pairs

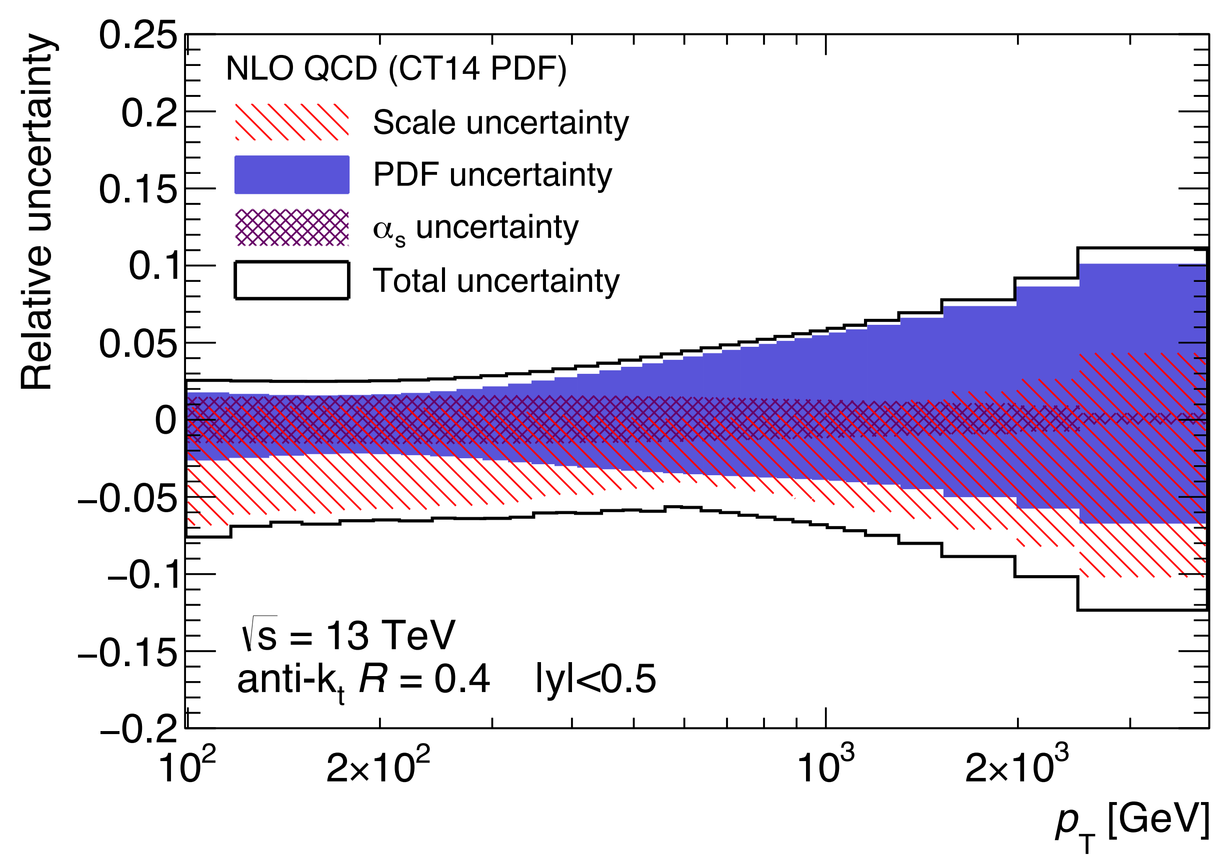
Dominated by gg initial state

run out of statistics much earlier than inclusive jets

Dijets (gluons at low p_T, quarks at high p_T)



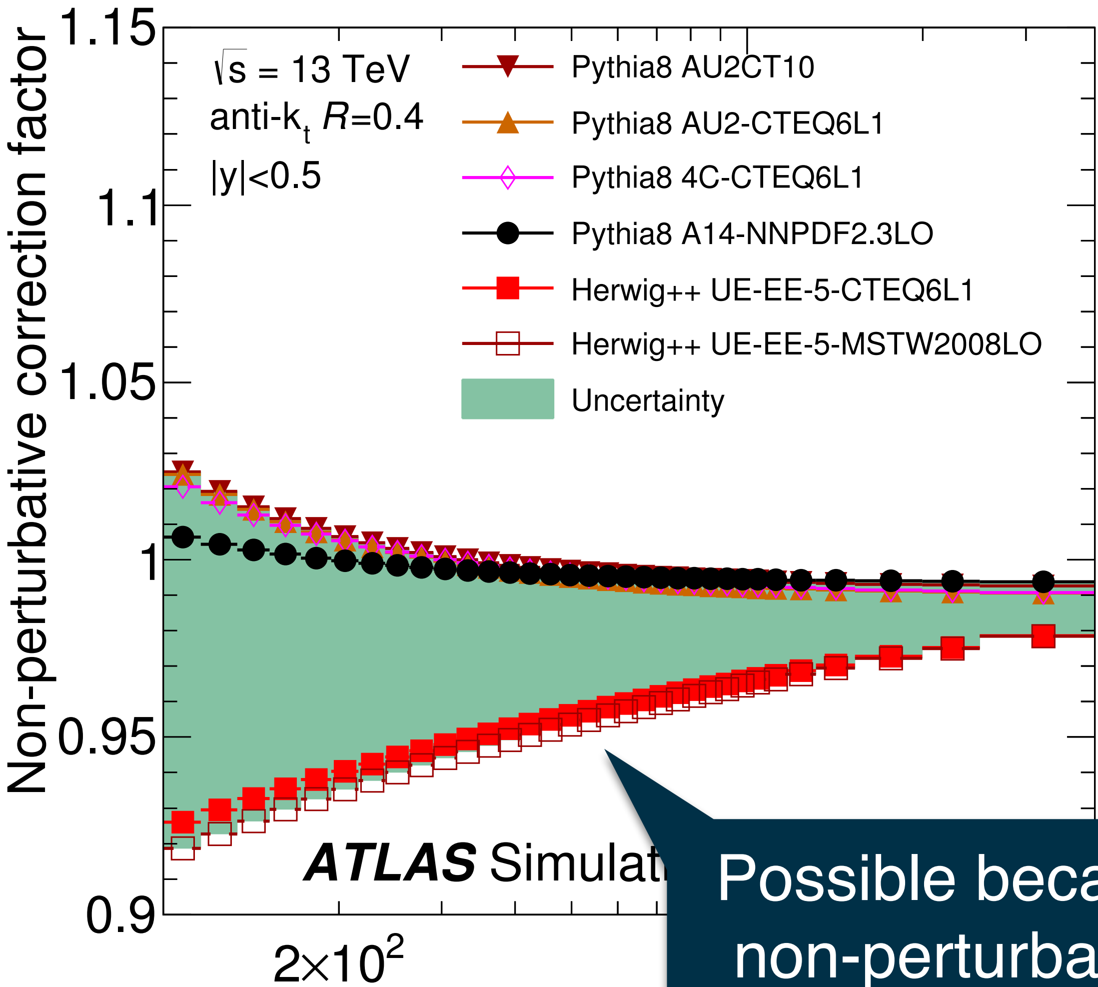
The PDF uncertainty is comparable to the measurement uncertainty at ~O(100) GeV
→ constraining power!



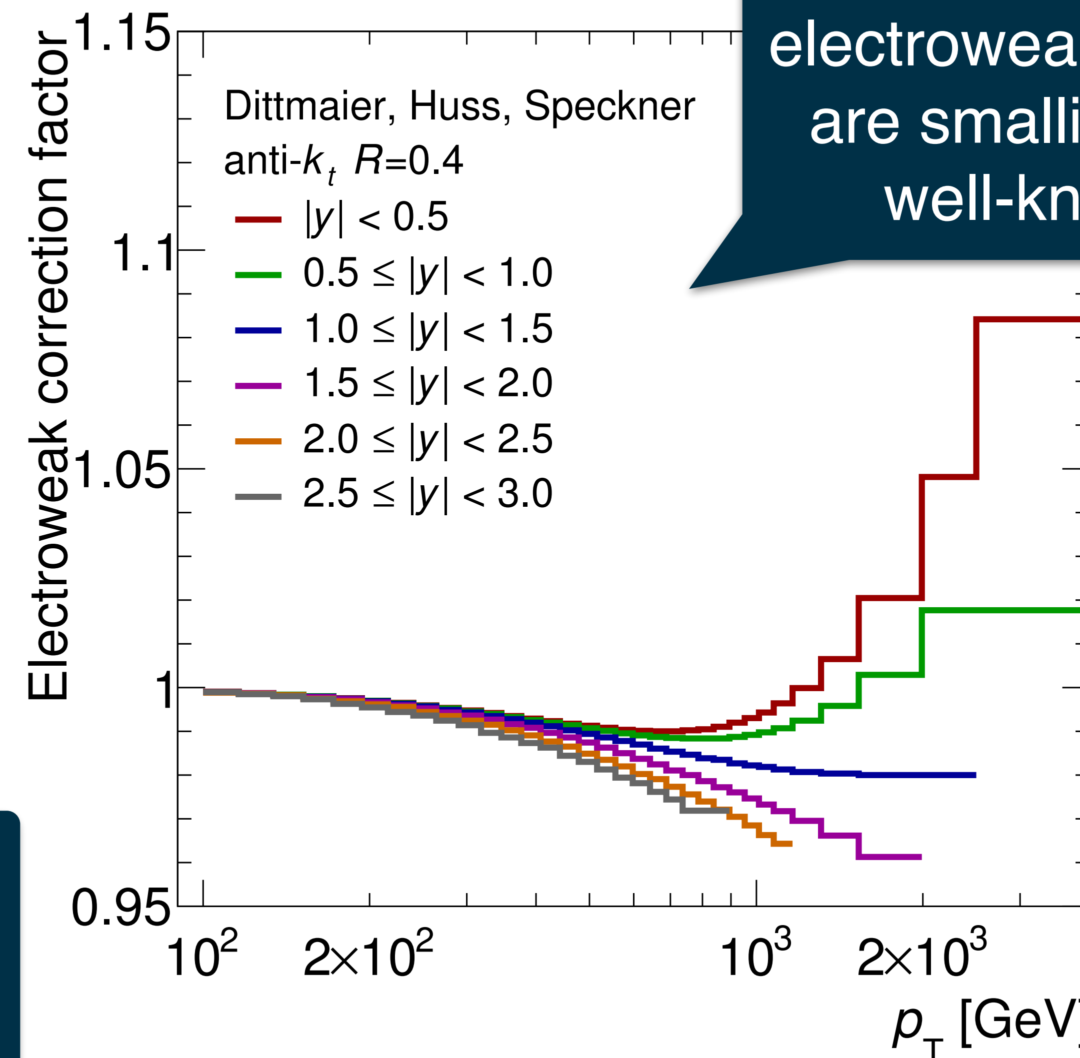
If the energy uncertainty is 1%, why is the cross-section uncertainty much larger?

Fixed-order pQCD

Precise measurements and predictions can do more than provide input to PDFs - they also provide a powerful consistency test of QCD in new energy regimes.



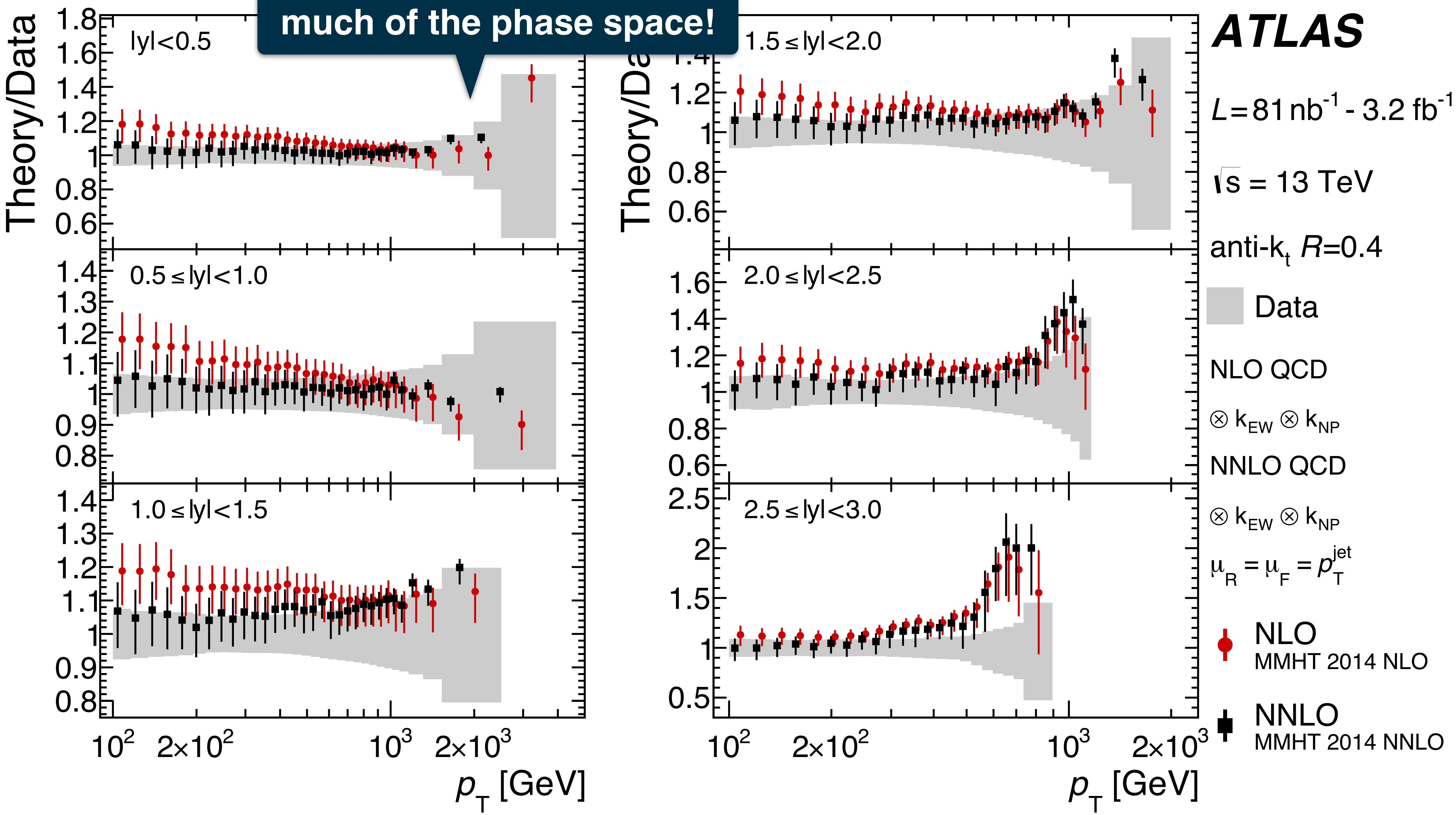
Possible because non-perturbative effects are small



Possible because electroweak effects are smallish and well-known

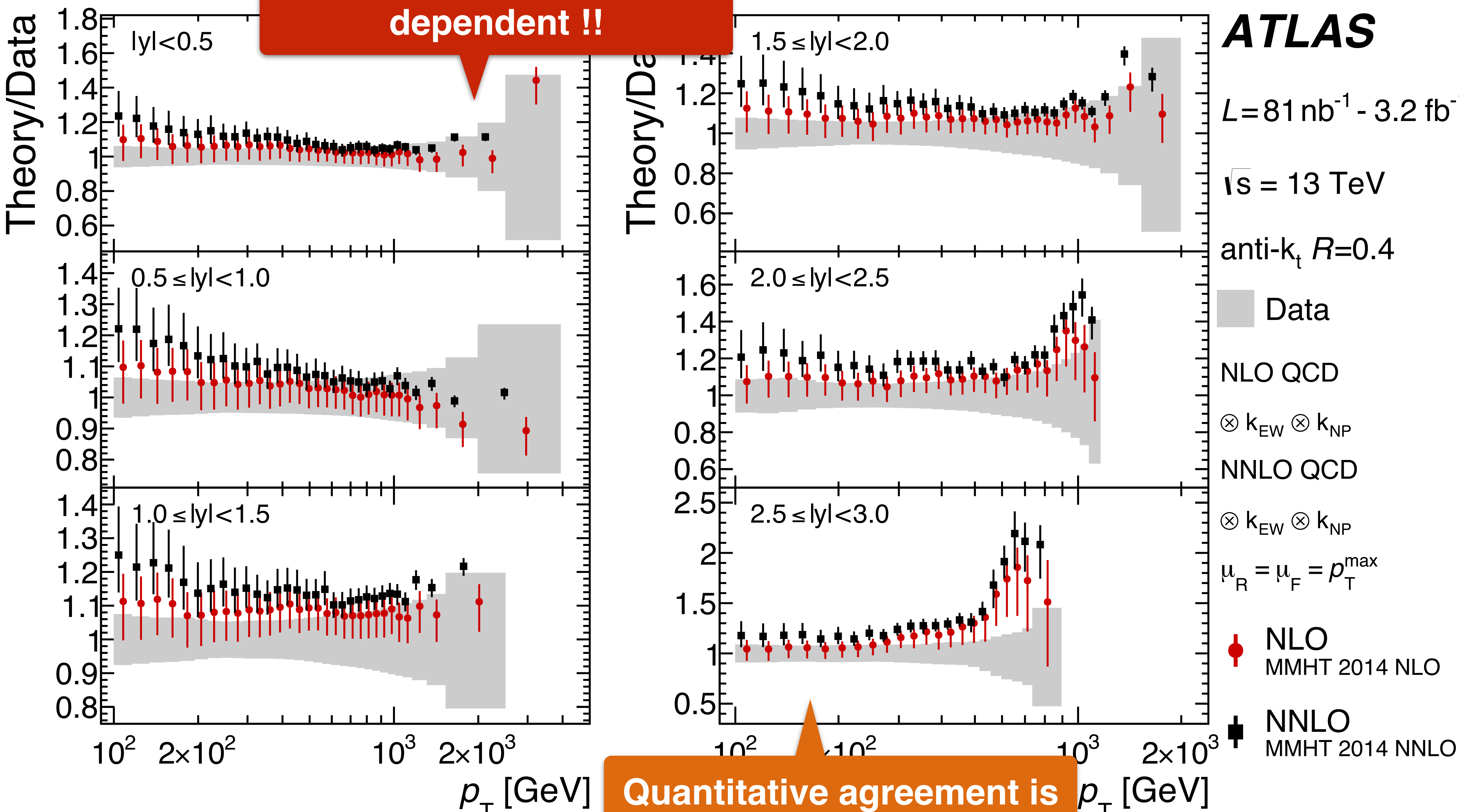
Fixed-order pQCD

Impressive agreement over much of the phase space!



Fixed-order pQCD

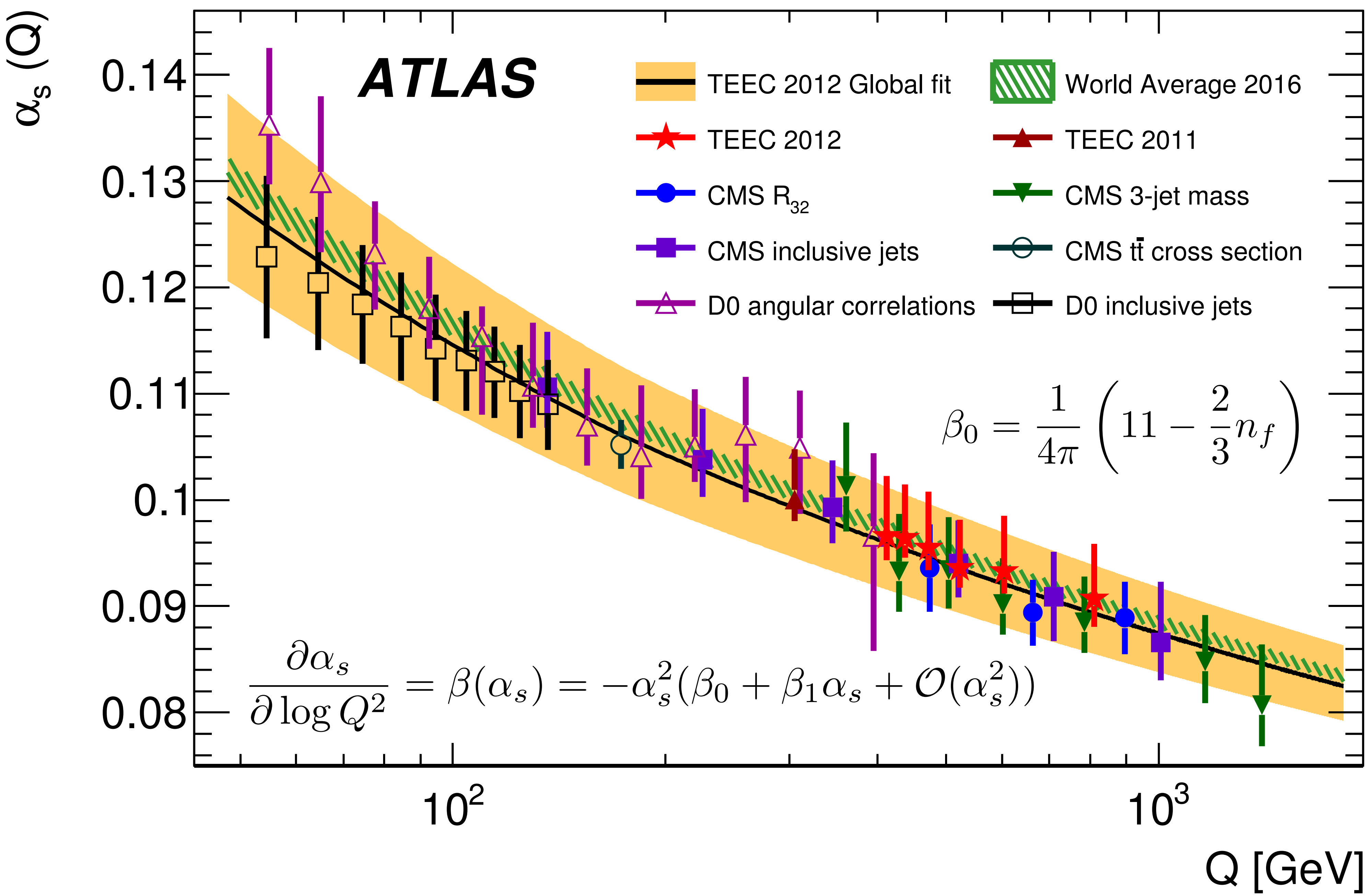
Caution: story is scale-dependent !!



Quantitative agreement is less good for all y-bins.

Strong coupling constant

Scale challenges aside, one can use these data to test the running of the strong coupling at the highest energies.



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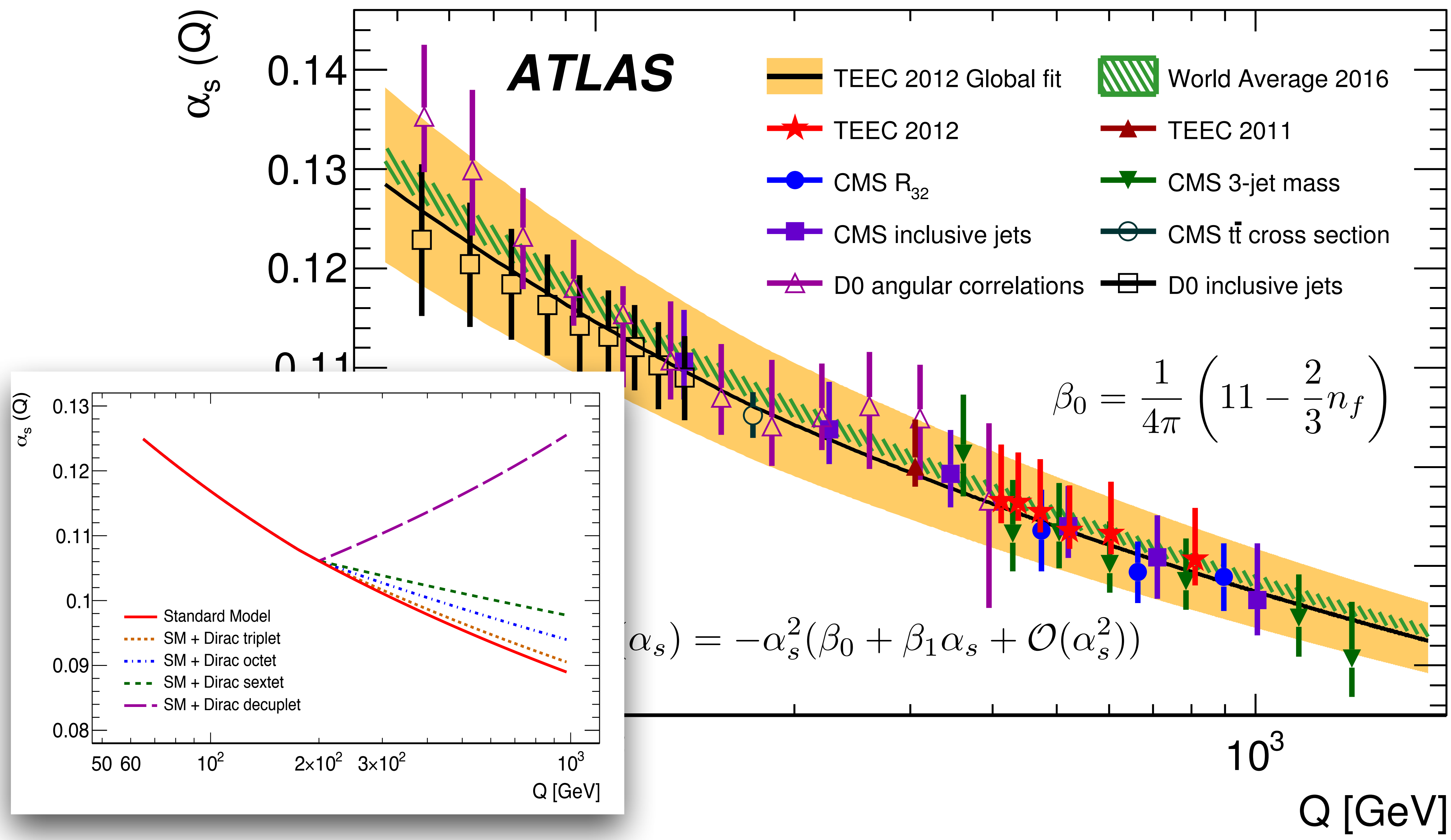
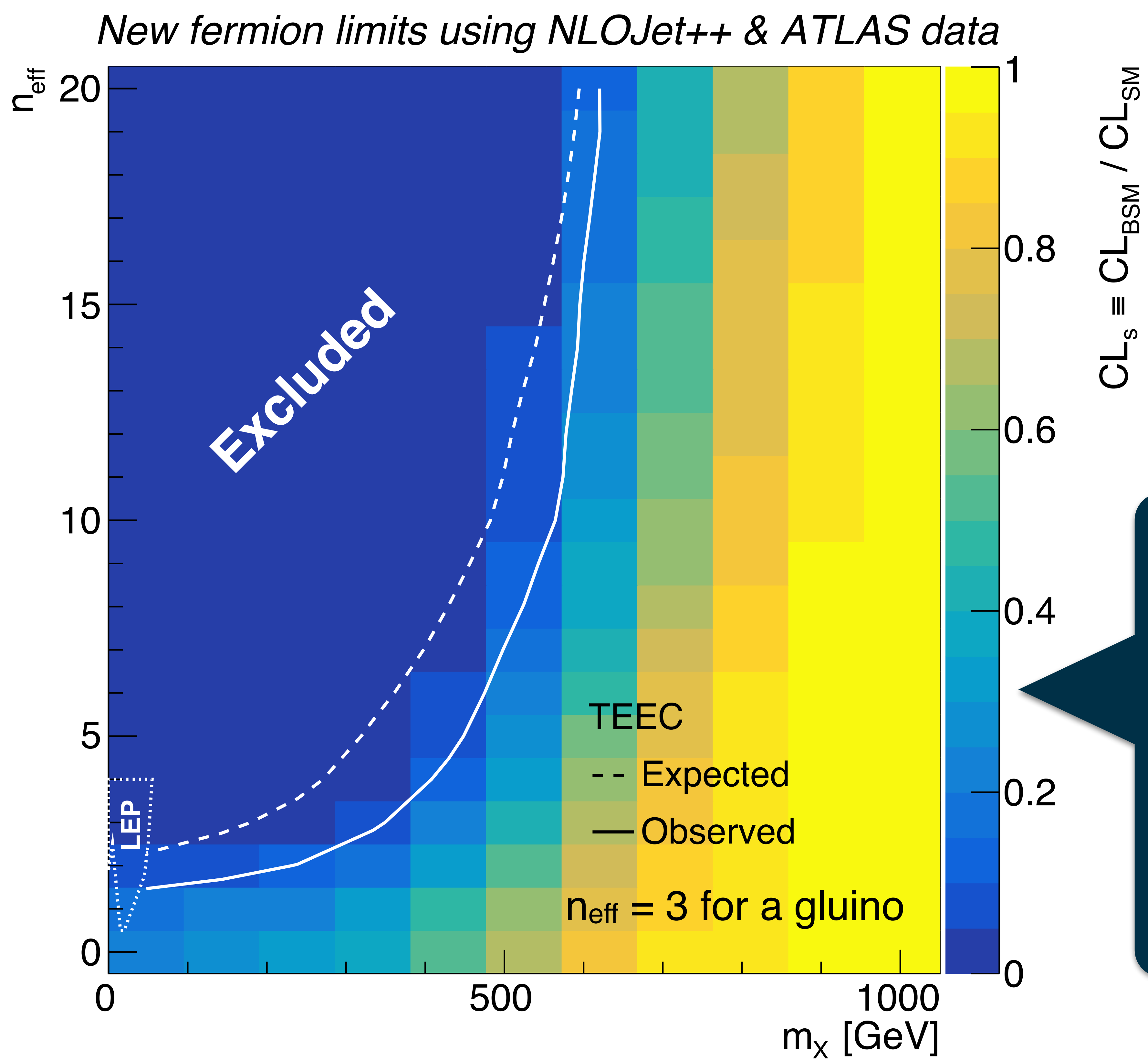


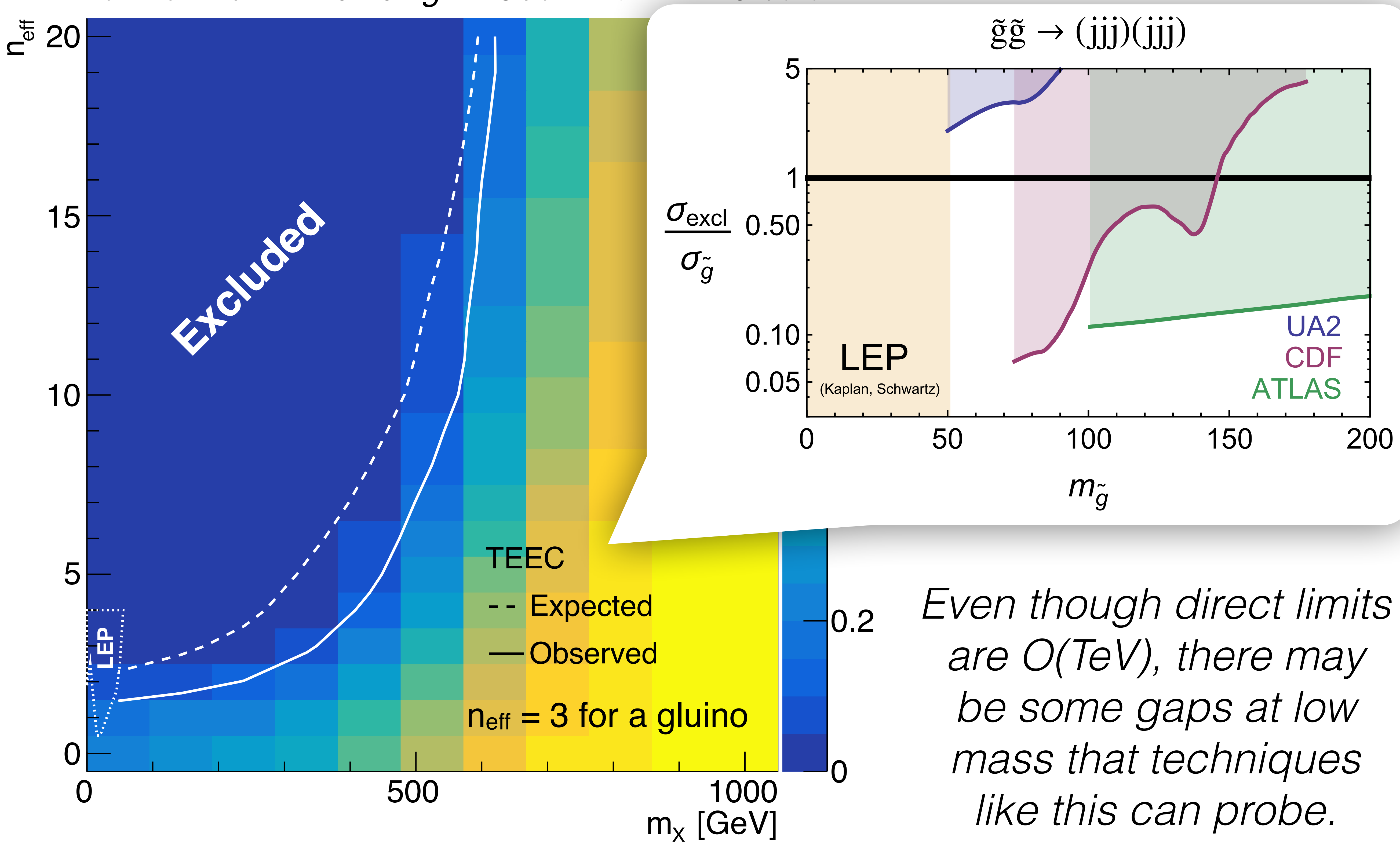
BSM from the running of a_S



Complimentary to direct searches because ~agnostic to the decay of the new particles.

BSM from the running of as

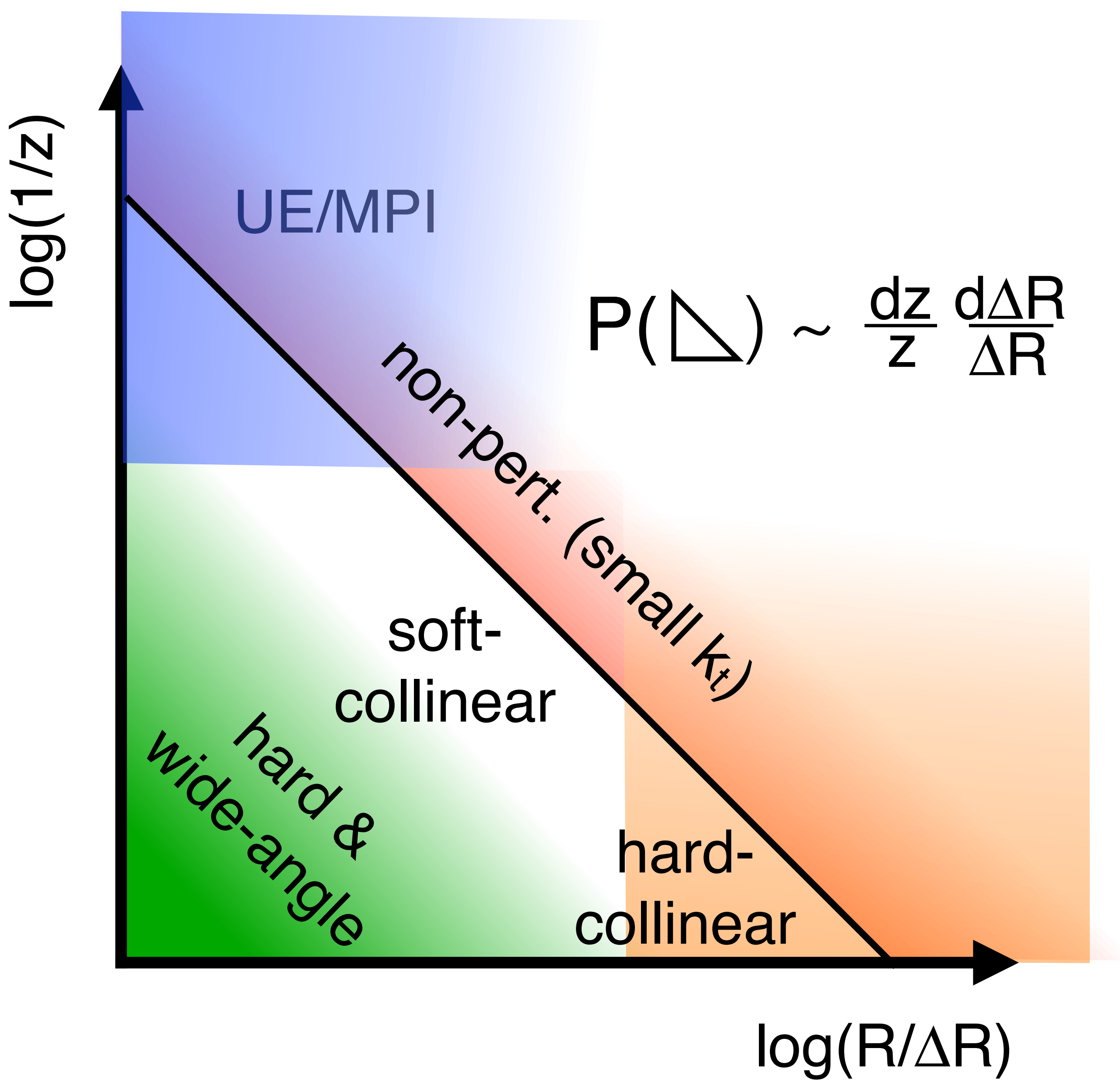
New fermion limits using NLOJet++ & ATLAS data



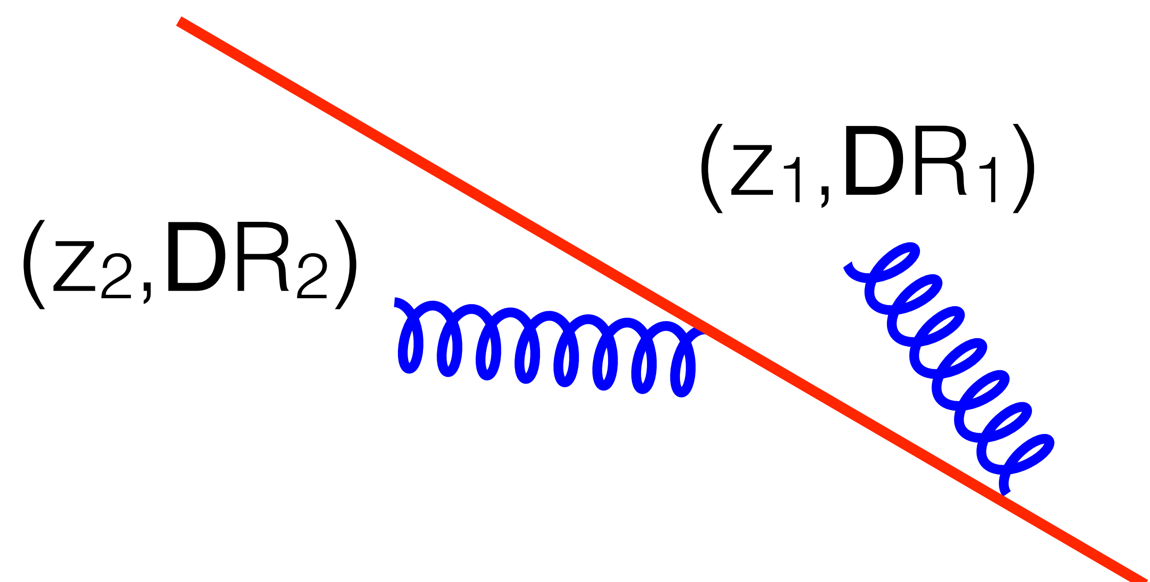
Even though direct limits are O(TeV), there may be some gaps at low mass that techniques like this can probe.

Resumed pQCD and jet substructure

Well-separated jets can be described by fixed-order pQCD but the radiation pattern **inside jets** requires resummation.



A useful way of thinking about radiation inside the jet is in the context of the *Lund plane*



Resumed pQCD and jet substructure

Well-separated jets can be described by fixed-order pQCD but the radiation pattern inside jets requires resummation.

For example, the jet mass is approximately

$m^2/p_T^2 \sim z\Delta R^2$ which is a line in the Lund plane:

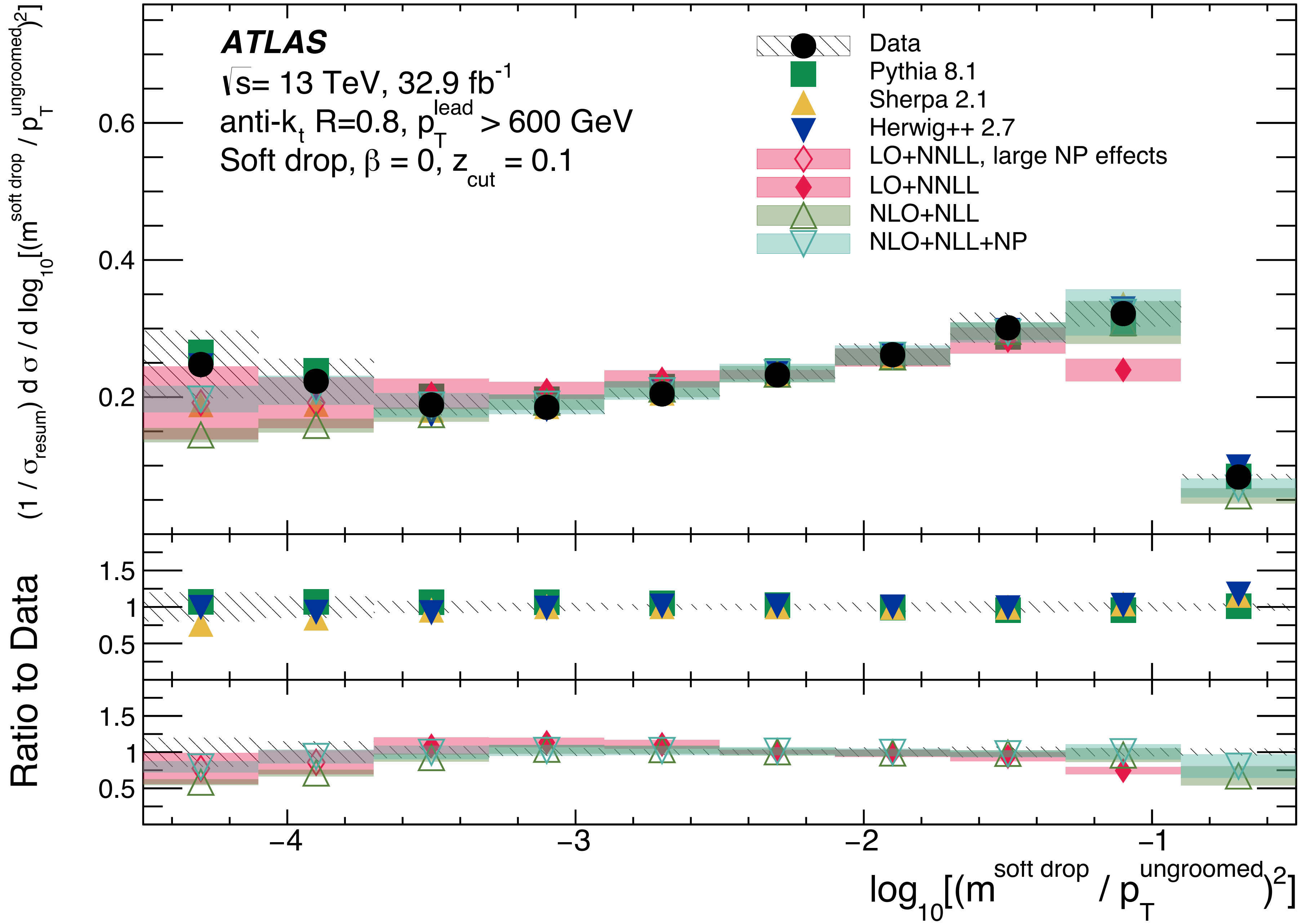
(where did this come from?)

$$\log(1/z) = \text{constant} - 2\log(R/\Delta R)$$

One can use this to derive the probability distribution at leading logarithm accuracy.

Jet Mass

In fact, the jet mass has been calculated to higher accuracy and precisely measured!



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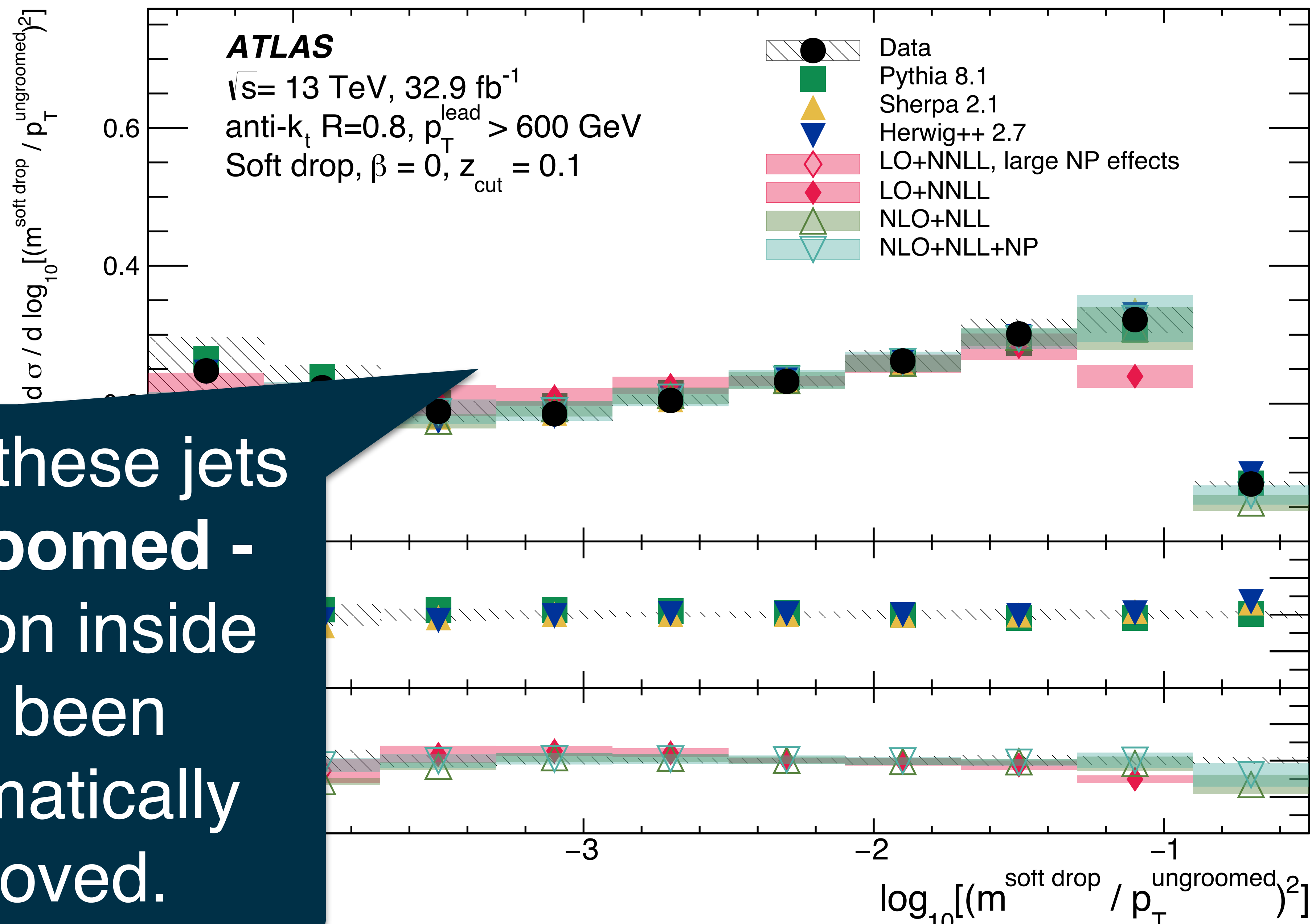
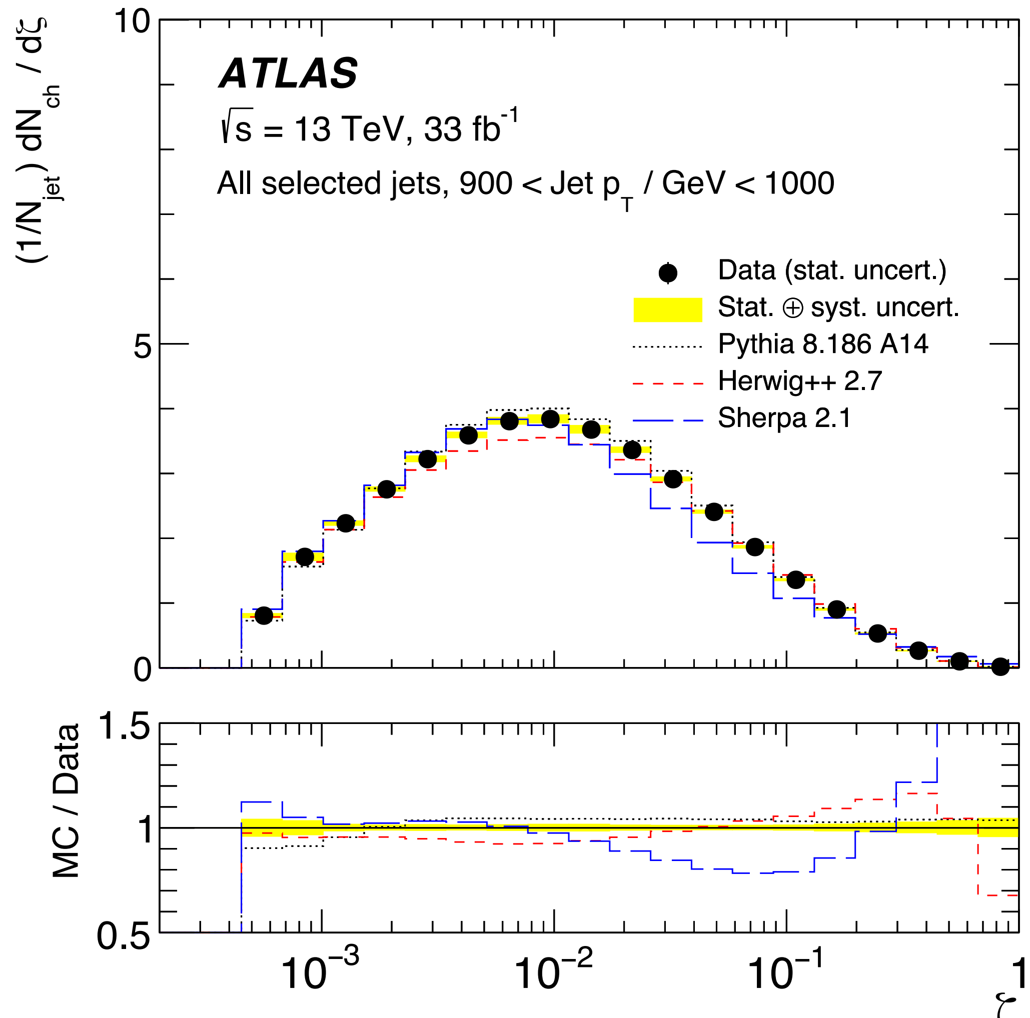


Subtly: these jets are **groomed** - radiation inside has been systematically removed.

Fragmentation

While jet substructure nowadays typically refers to observables like the jet mass and Lund plane coordinates,

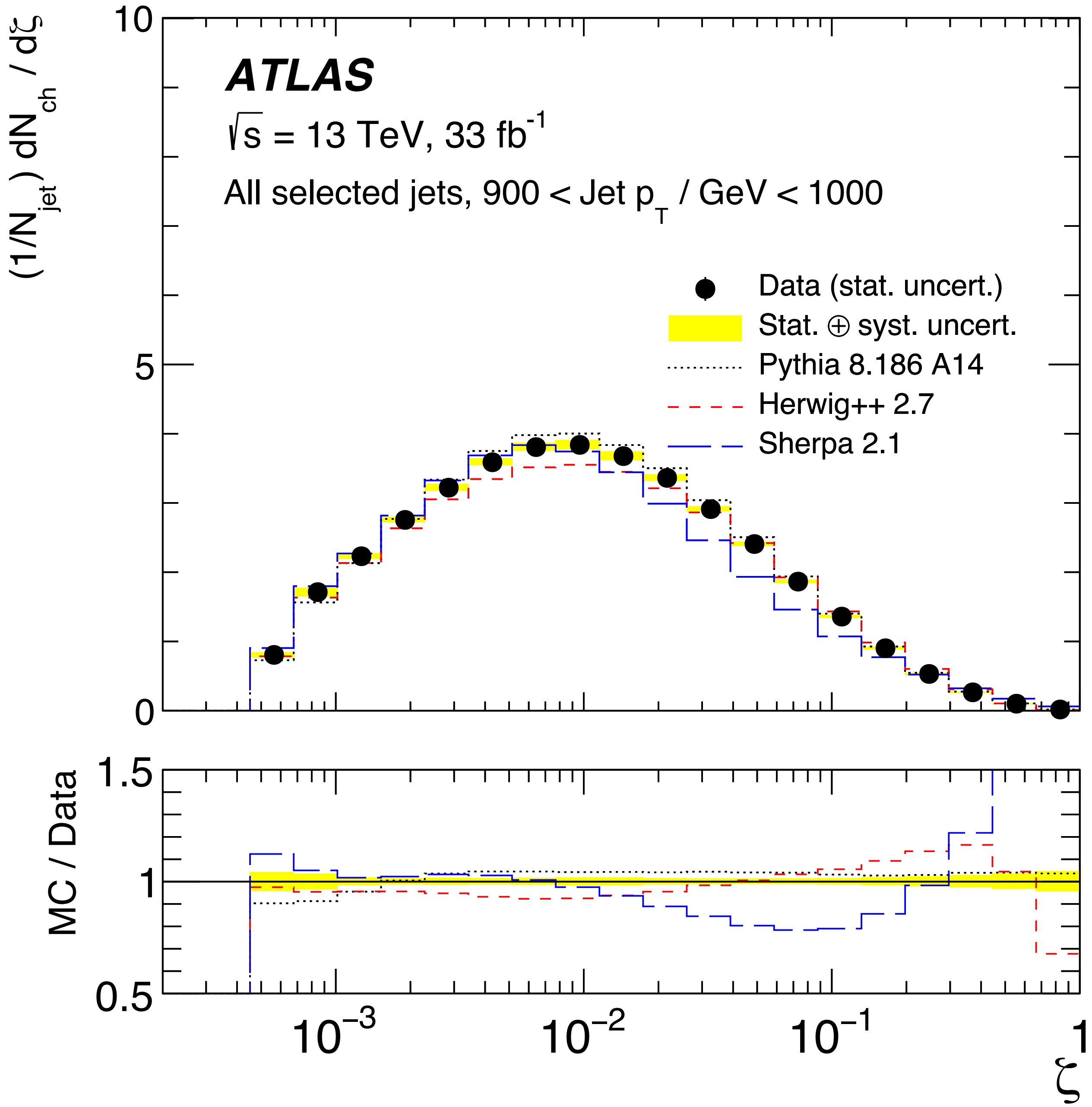
there is a long history of more traditional "fragmentation function" measurements which probe similar physical regimes.



These studies are crucial inputs to tuning Parton Shower Monte Carlo algorithms, but can also be used to study pQCD.

← p_T(particle) / p_T(jet)

Fragmentation: generic q/g jets



p_T(particle) / p_T(jet)

We can't generally measure individual particles, but we can for charged particles.

With charged-only, we can't predict this distribution from first principles. But for a given jet type (q/g) we can predict how it depend on jet p_T.

How can we extract just the gluon (or quark) contribution?

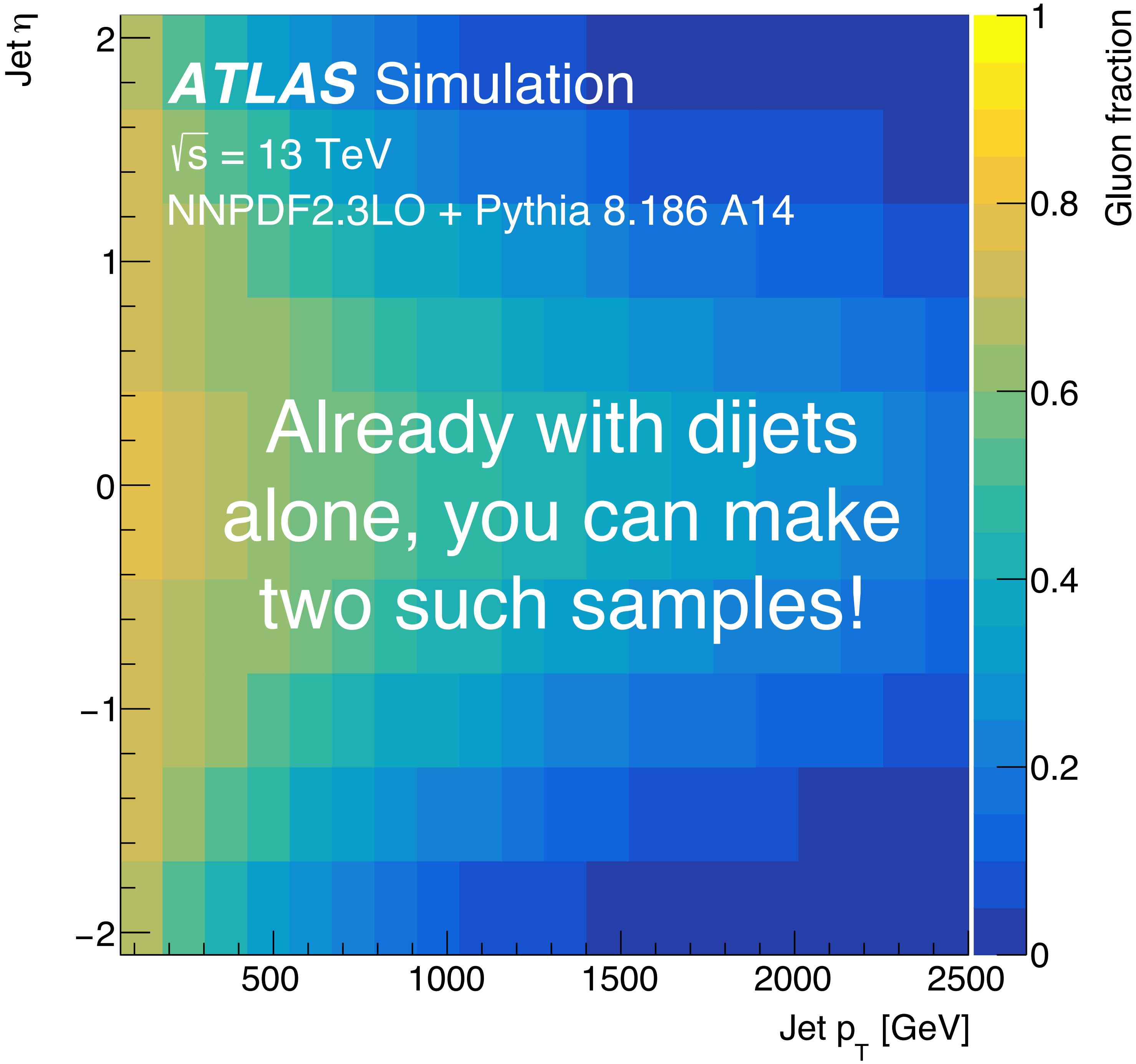
The rapidity trick

One way is to find two event samples (f and c) with different q/g compositions.

Given the fractions f_q, you can extract the q/g bin contents h:

$$h_i^f = f_q^f h_i^q + (1 - f_q^f) h_i^g$$
$$h_i^c = f_q^c h_i^q + (1 - f_q^c) h_i^g$$

The rapidity trick



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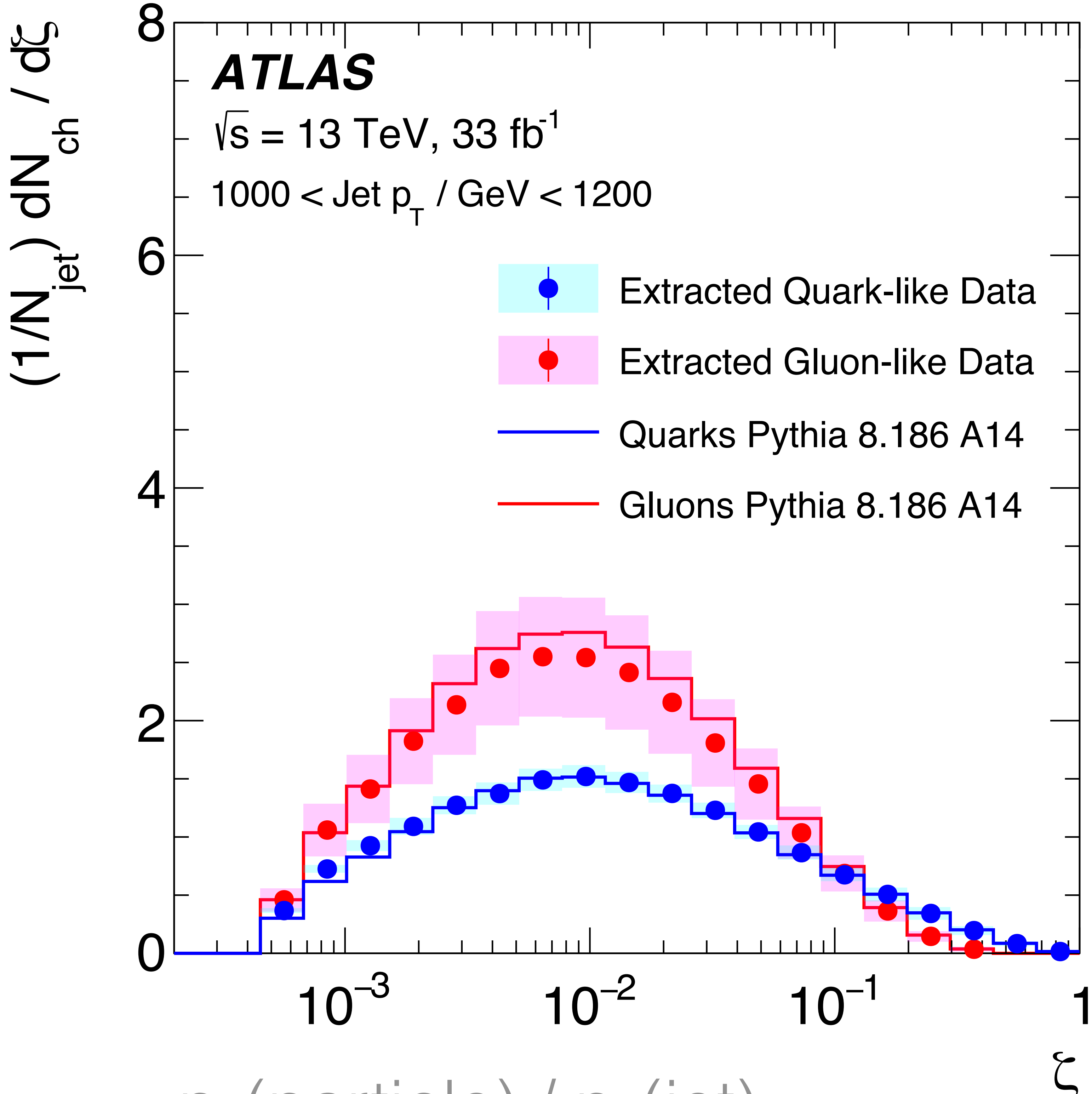


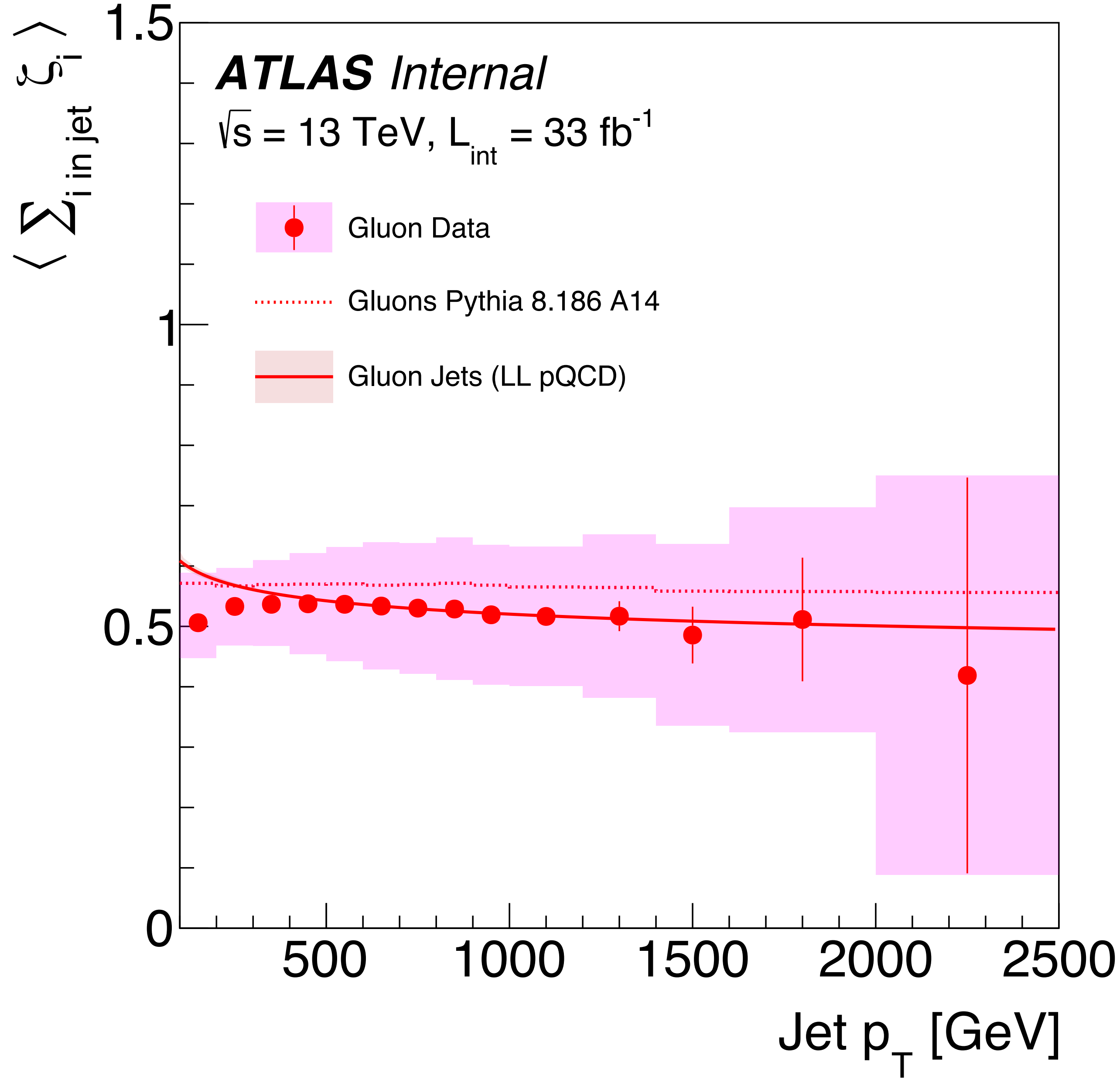
p_T(particle) / p_T(jet)

Gluons have more, softer particles than quarks.

roughly gluons have 2x the particles as quarks since they have ~twice as much color charge

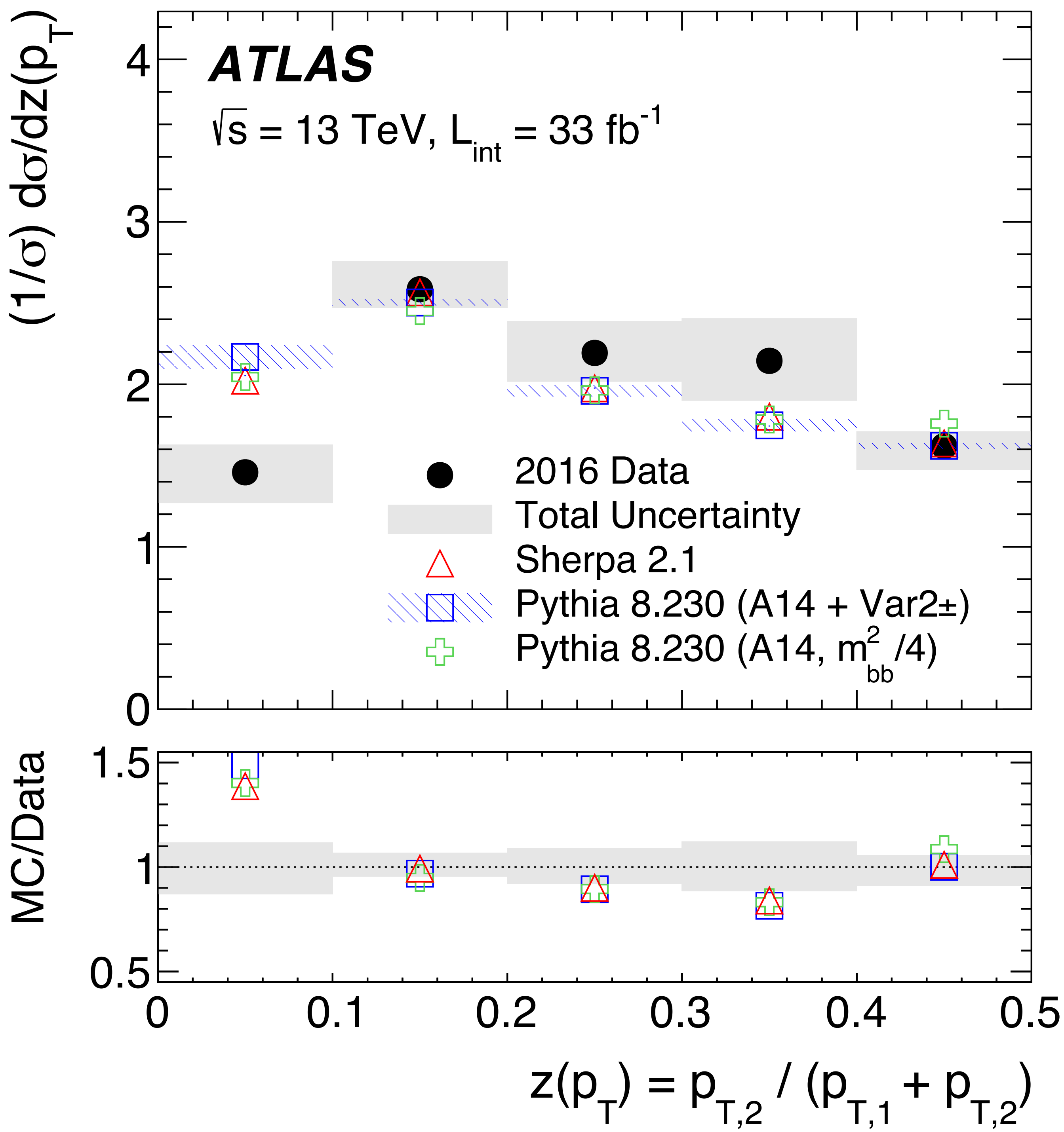
The p_T dependence

One can predict the p_T dependence of these observables, but let's just do a quick sanity check:

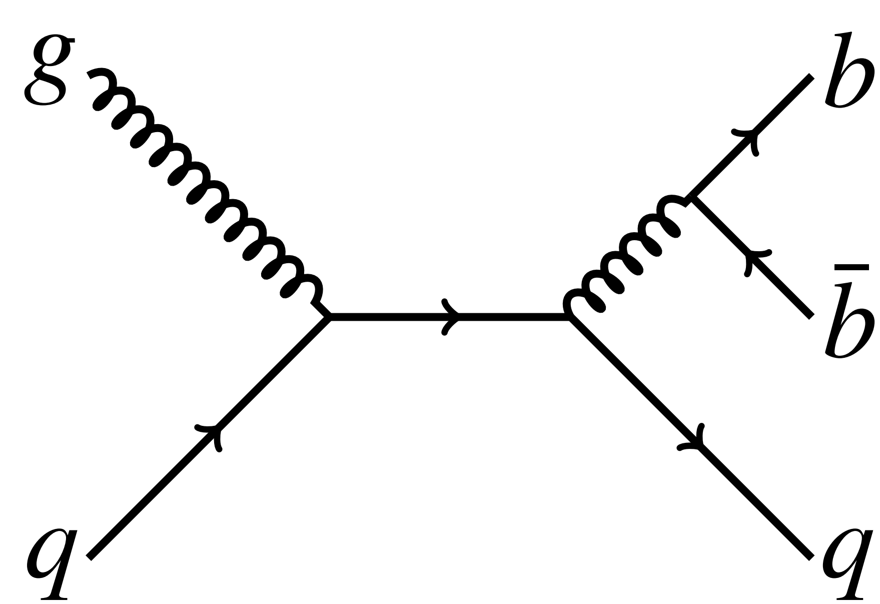


Why is the value ~constant and a bit above 1/2?

One last note on gluon fragmentation



Gluon splitting to *b*-quarks offers a unique opportunity to directly probe gluon fragmentation.



Question: why did I pick this diagram?

QCD has much more to offer

I've offered a (biased) collection of results,
but there are many more!

More on PDFs, fixed-order effects, …

…Resummation, non-global effects ("entanglement"), …

…Quark and gluon properties, W/Z/H hadronic decays, …

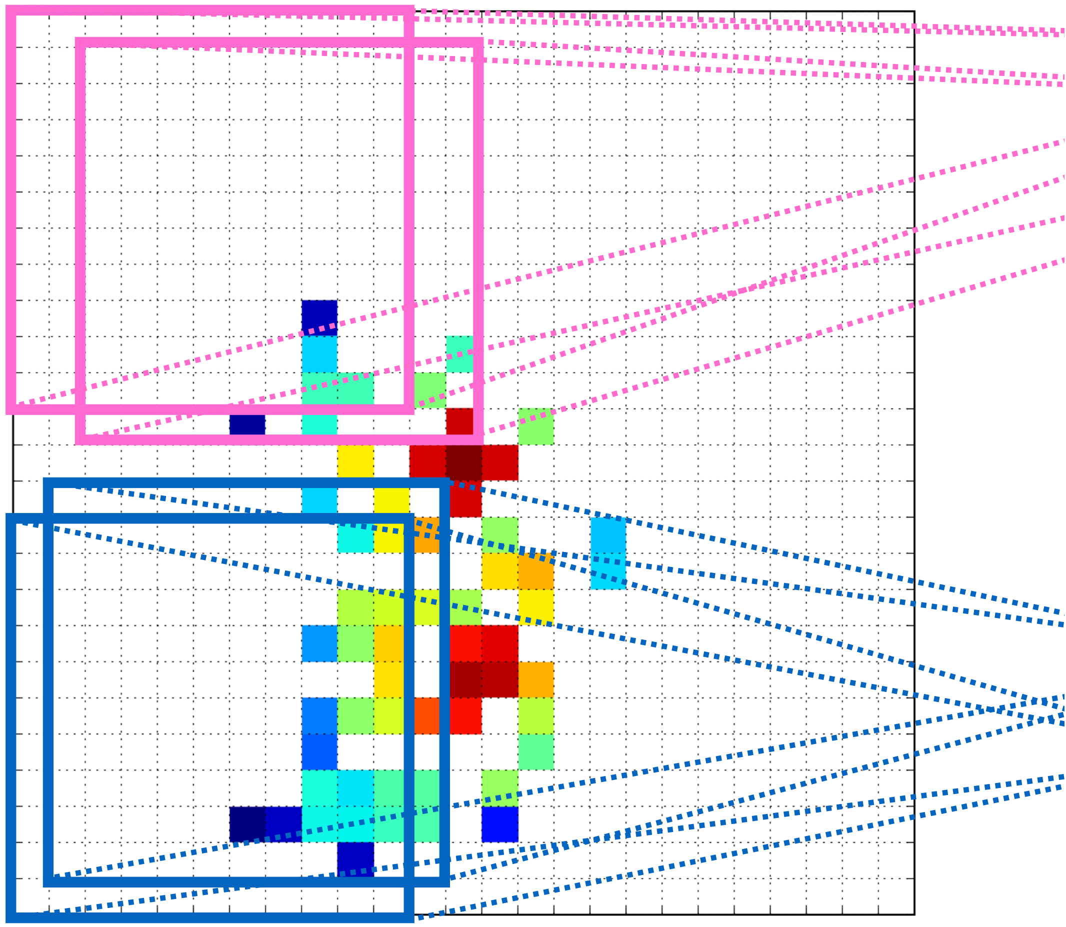
…Collective effects, connections with heavy ions, …

…However, I stand between you and
the end of the day, so let's wrap up!

Summary and overview

Even though QCD has only ~1 free parameter, it is a **rich theory with various regimes** that we can probe at the LHC.

Studying QCD is **inherently interesting** as a quantum theory of nature. Understanding it is also critical for direct and indirect **new particles searches**.



…there are also many exciting connections to modern machine learning that I did not have time to discuss - consider attending ML4Jets2022!

Questions?

Soft drop procedure

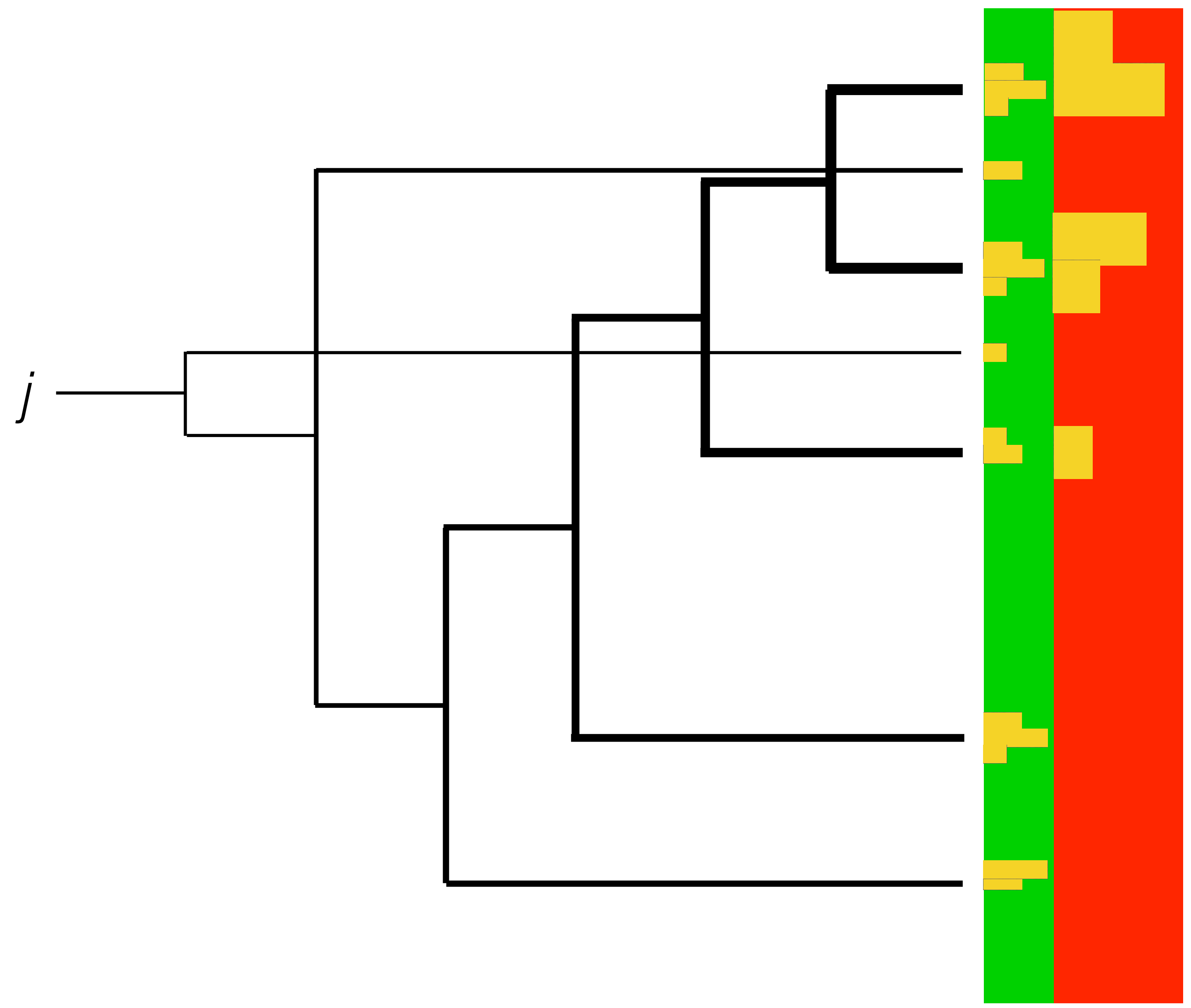
Take a jet clustered with e.g. anti-k_t

Re-cluster it with C/A

Traverse the clustering tree backwards

If a branch point satisfies the soft drop condition, stop.

Otherwise remove the softer branch and continue down the harder branch.



clusters hardest radiation first

Soft drop procedure

Take a jet clustered with e.g. anti-k_t

↓

Re-cluster it with C/A

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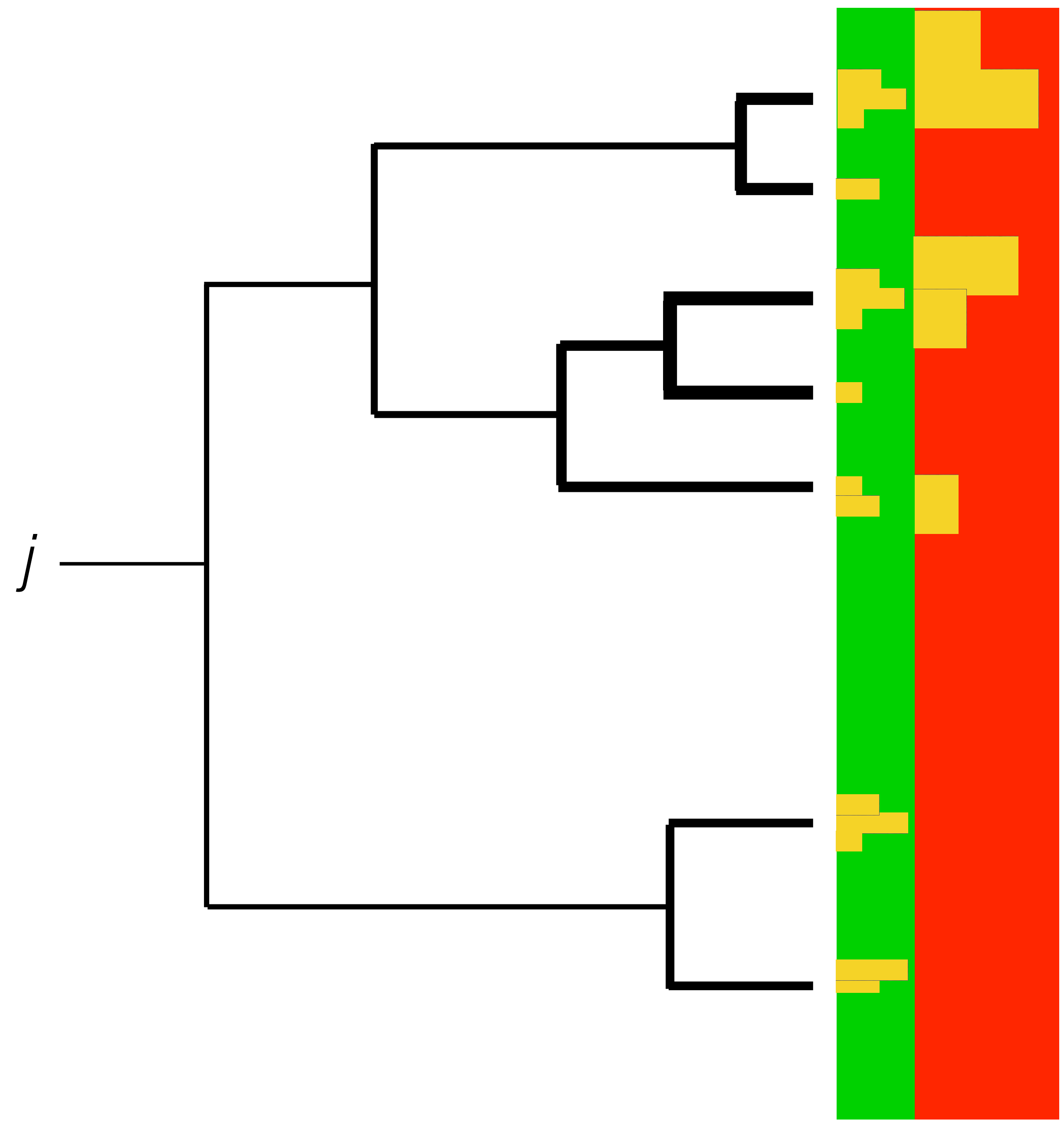

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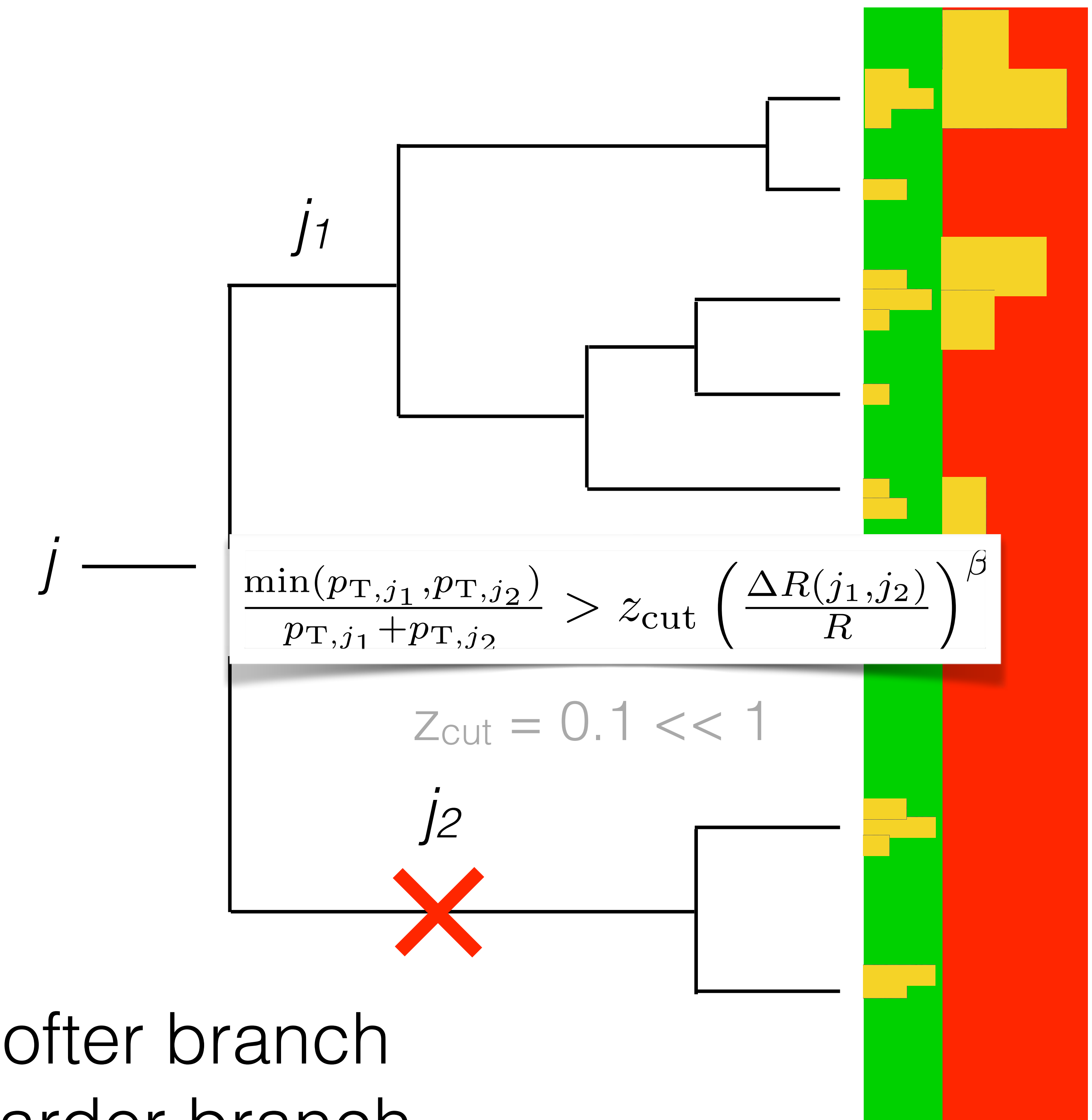

$$\frac{\min(p_{T,j_1}, p_{T,j_2})}{p_{T,j_1} + p_{T,j_2}} > z_{\rm cut} \left(\frac{\Delta R(j_1, j_2)}{R}\right)^{\beta}$$

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