Jets at Les Houches 2019: *Four decades of gluons*

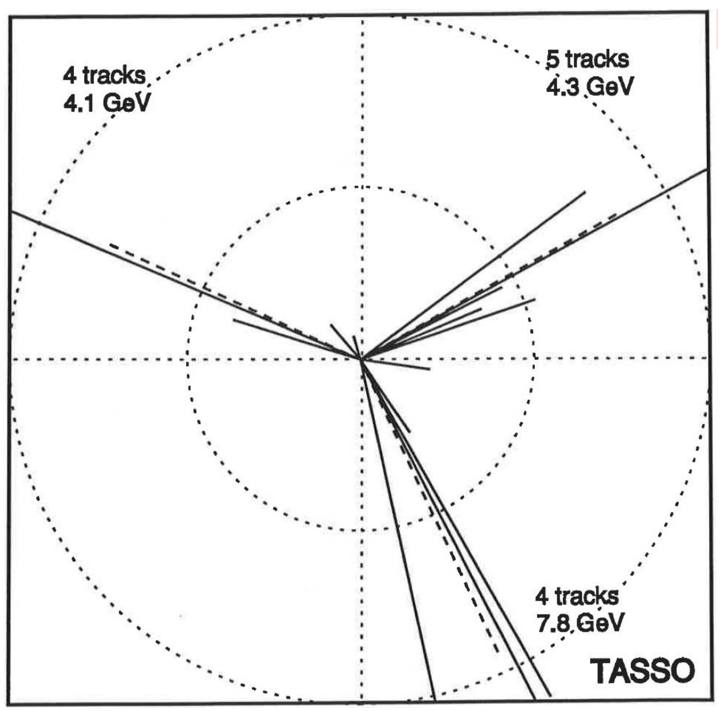
Benjamin Nachman and Simone Marzani

for the jets working group:

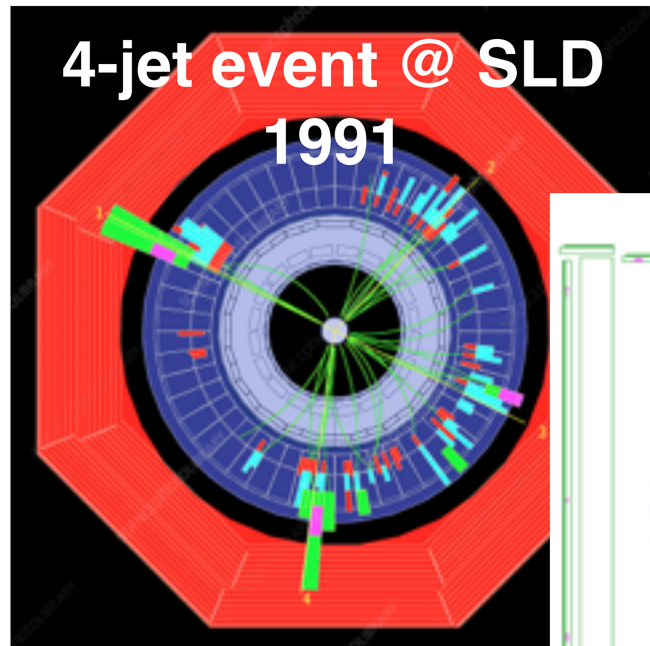
Simone Amoroso, Paolo Azzurri, Helen Brooks, Stefano Forte, Philippe Gras, Yacine Haddad, Joey Huston, Andrew Larkoski, Matt Le Blanc, Peter Loch, Kenneth Long, Eric Metodiev, Davide Napoletano, Stefan Prestel, Peter Richardson, Felix Ringer, Jennifer Roloff, Davison Soper, Gregory Soyez, Vincent Theeuwes,…

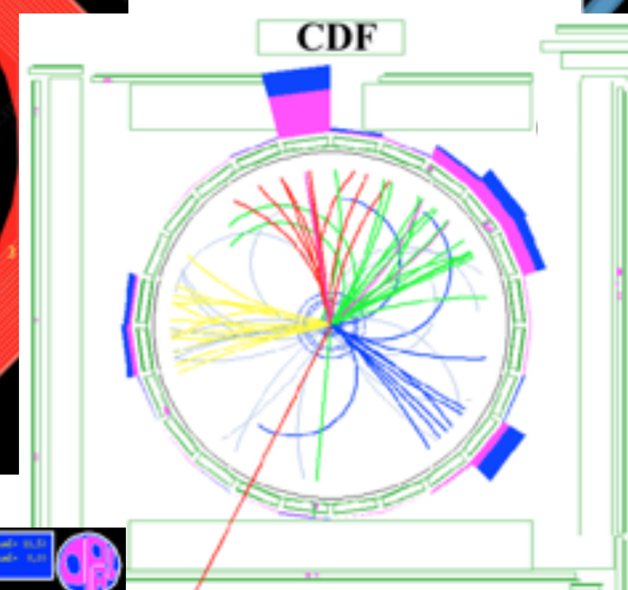
Outline

1979 — **2019**



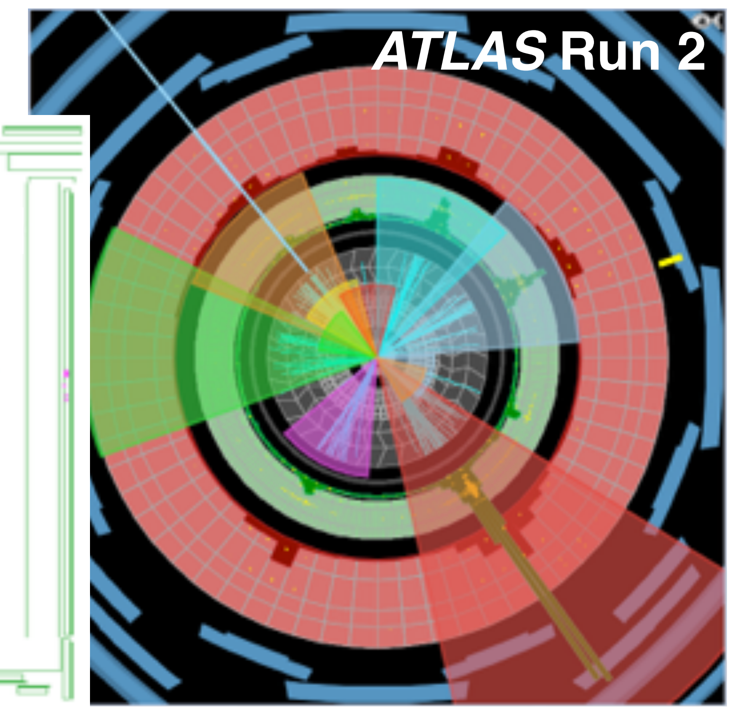
B. Wiik (on behalf of TASSO), Bergen, **June 19, 1979***





Gluino search @ Tevatron **2005**

Event with 11 jets @ 13 TeV



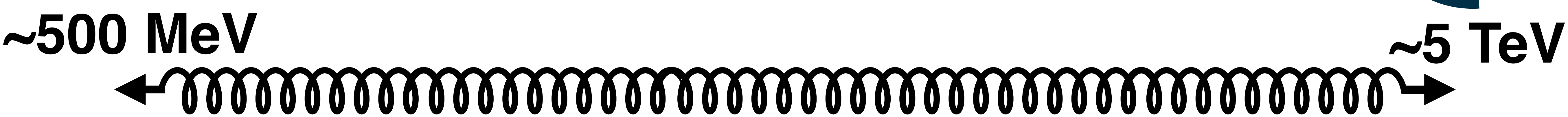
Les Houches
June 19, 2019

+relatives: Tristan, HERA, CLEO, BaBar, BELLE, BES, RHIC,…

(mixing colliders and experiments)

*The conference was June 18-22; I actually have no idea which day Bjørn gave his talk.

Outline



low mass bump

VBF/VBS

X → gg

tuning with jet substructure

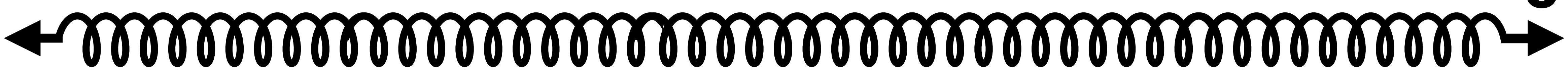
g → bb

higher order parton showers

gluon PDF

Outline

~500 MeV **~5 TeV**



low mass bump

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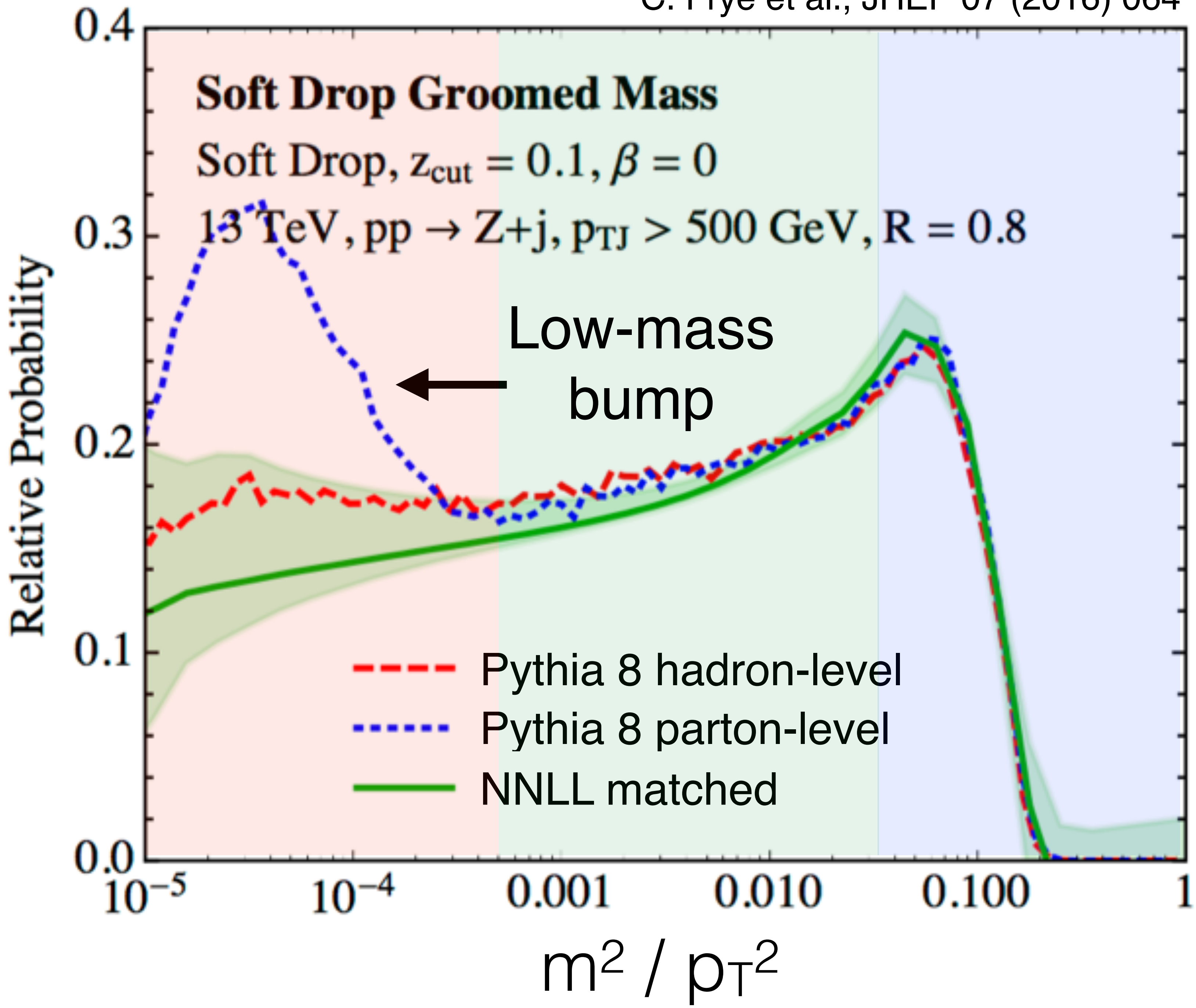
gluon PDF

New Les Houches Observable:
LH multiplicity: n_{LH}

$O(\Lambda_{QCD})$: The low mass bump

C. Frye et al., JHEP 07 (2016) 064



Soft drop grooming parametrically separates **non-perturbative**, **resummation**, and **fixed-order** sensitive regions.

Question:

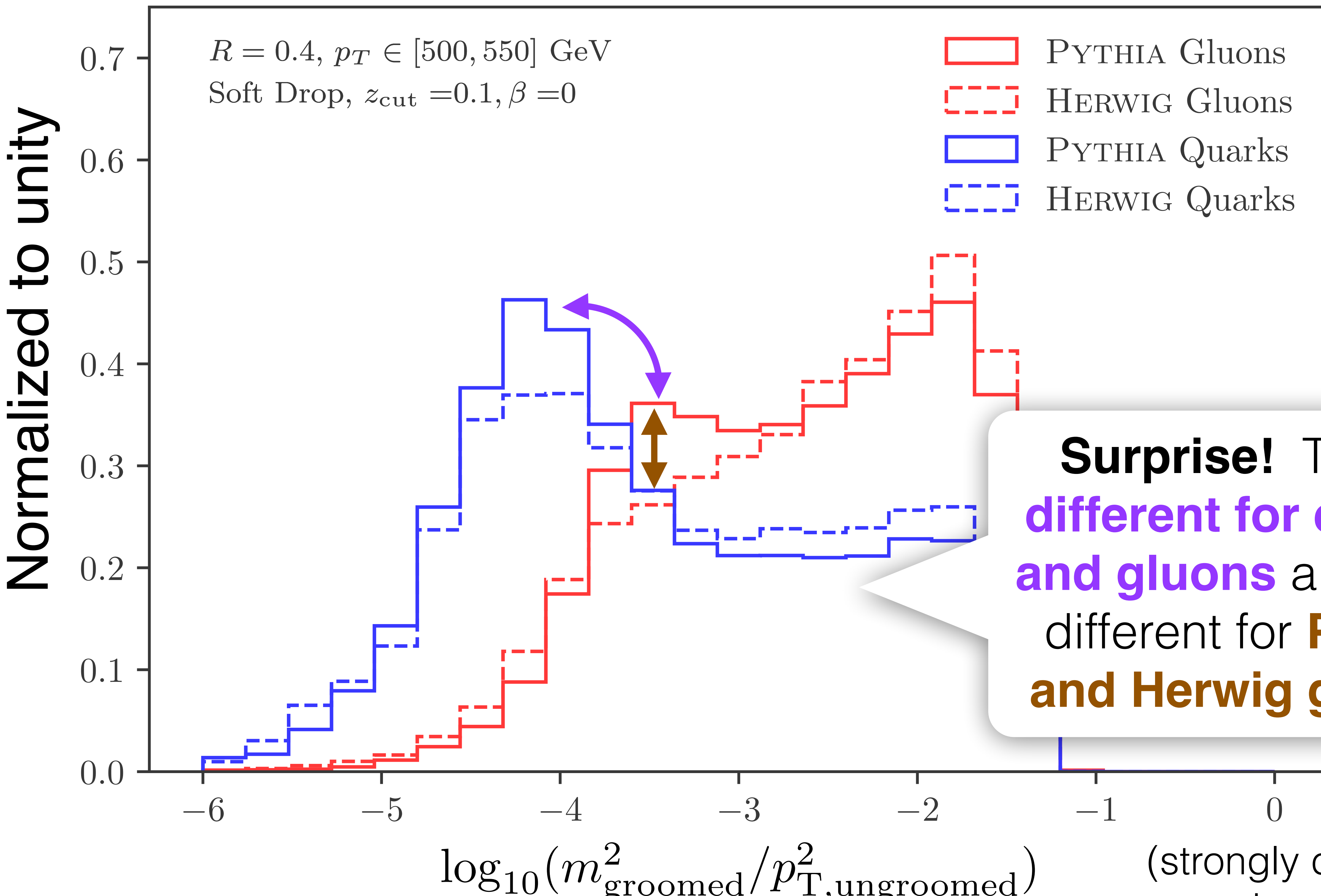
Can we use this for tuning NP at the LHC?

ATLAS measurement: Phys. Rev. Lett. 121 (2018) 092001

CMS measurement: JHEP 11 (2018) 113

For analytic work on the NP region, see A. Pathak et al.

$O(\Lambda_{QCD})$: The low mass bump



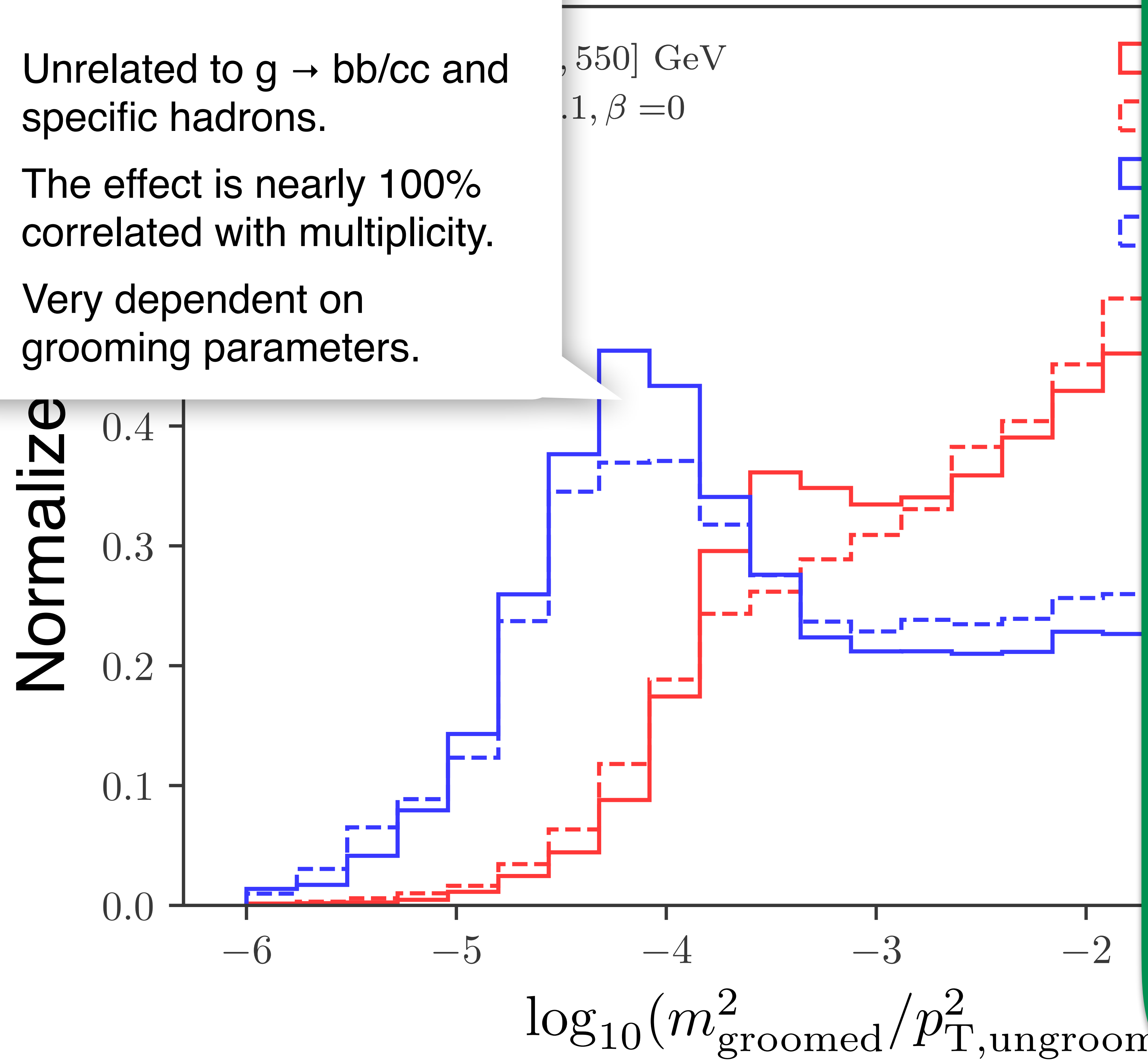
Surprise! Totally **different for quarks and gluons** and very different for **Pythia and Herwig gluons**

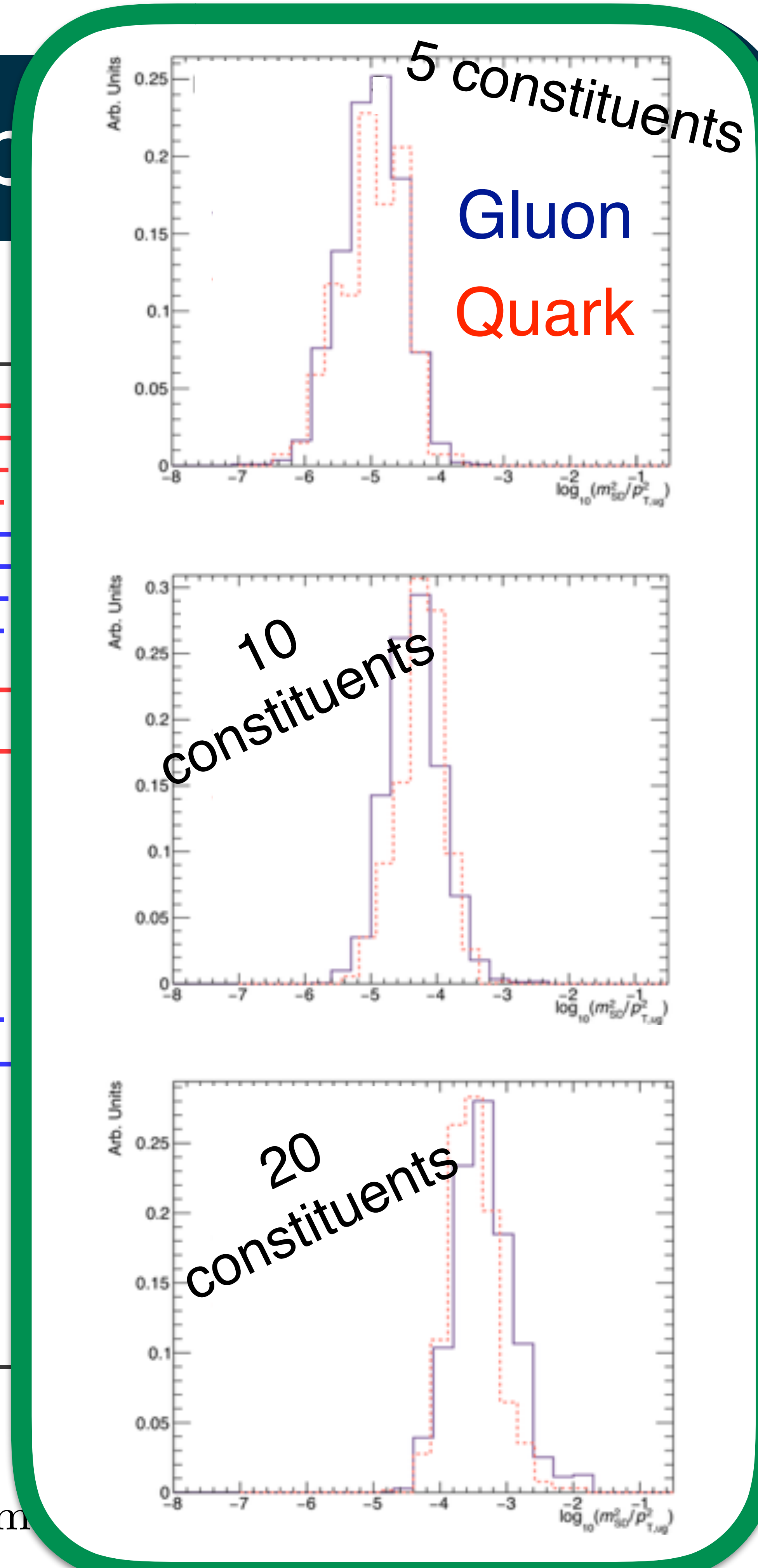
(strongly depends on grooming parameters)

$O(\Lambda_{QCD})$: The low mass bump

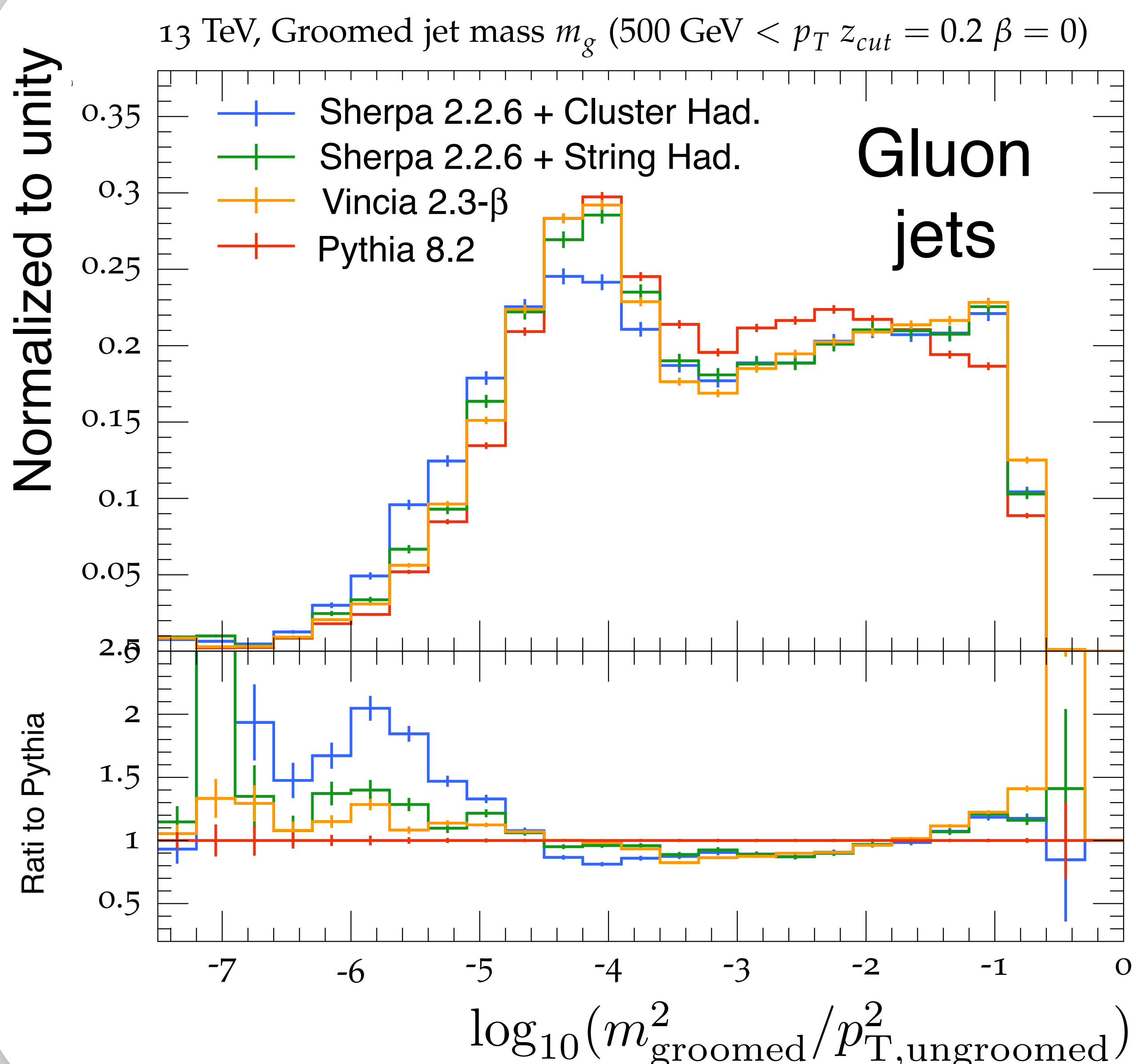
What we have learned:

1. Unrelated to g → bb/cc and specific hadrons.
2. The effect is nearly 100% correlated with multiplicity.
3. Very dependent on grooming parameters.





$O(\Lambda_{QCD})$: The low mass bump



Very sensitive to hadronization model.

string/cluster only change in the NP region (i.e. name make sense)

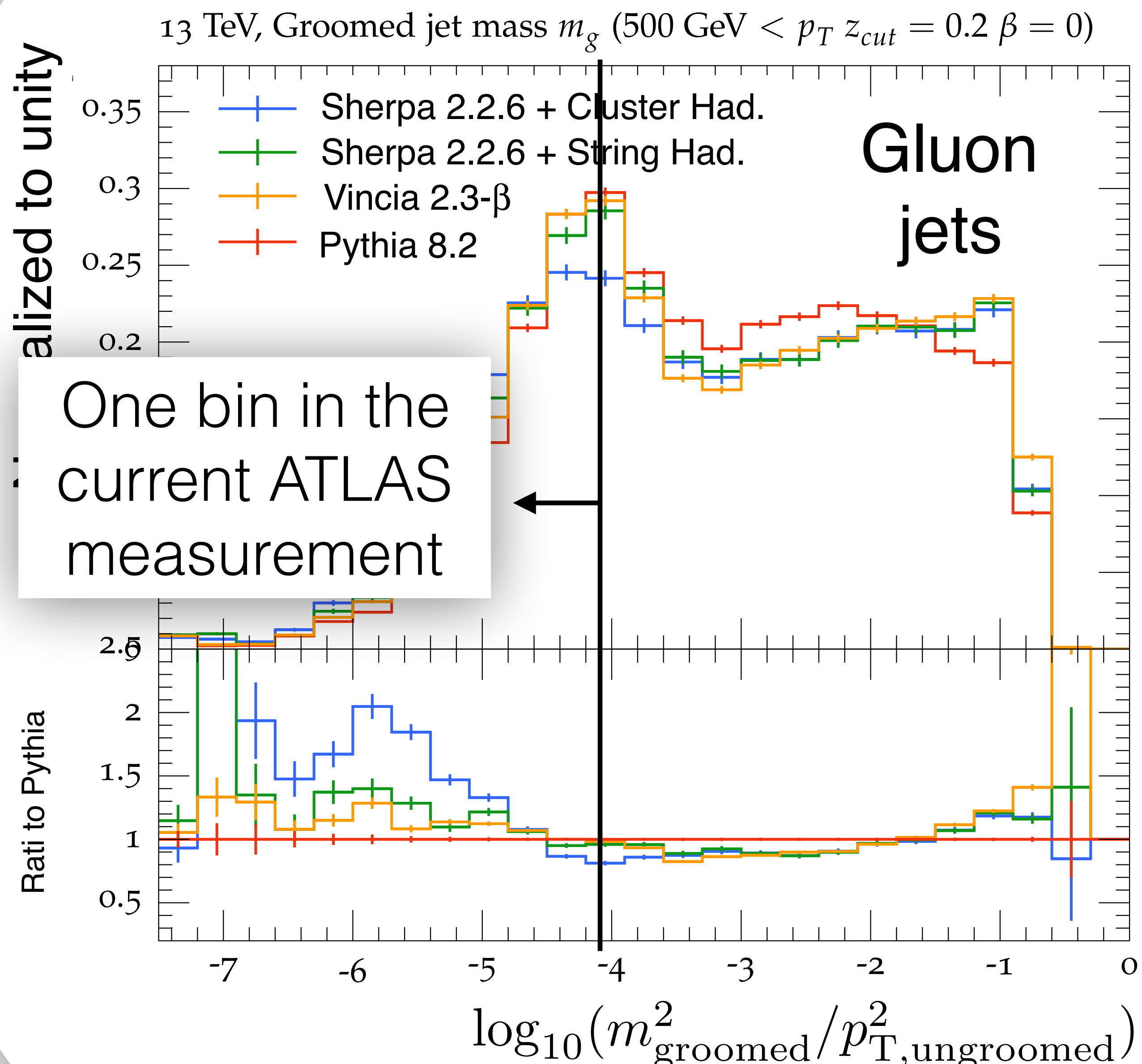
useful for tuning NP with LHC data?

Pythia is qualitatively different at high(er) masses even though it agrees ~well in the NP region.

to reiterate - seems the NP region is doing what it is supposed to!

For the **proceedings**: show NP parameter variations within a model & compare with analytic predictions.

$O(\Lambda_{QCD})$: The low mass bump



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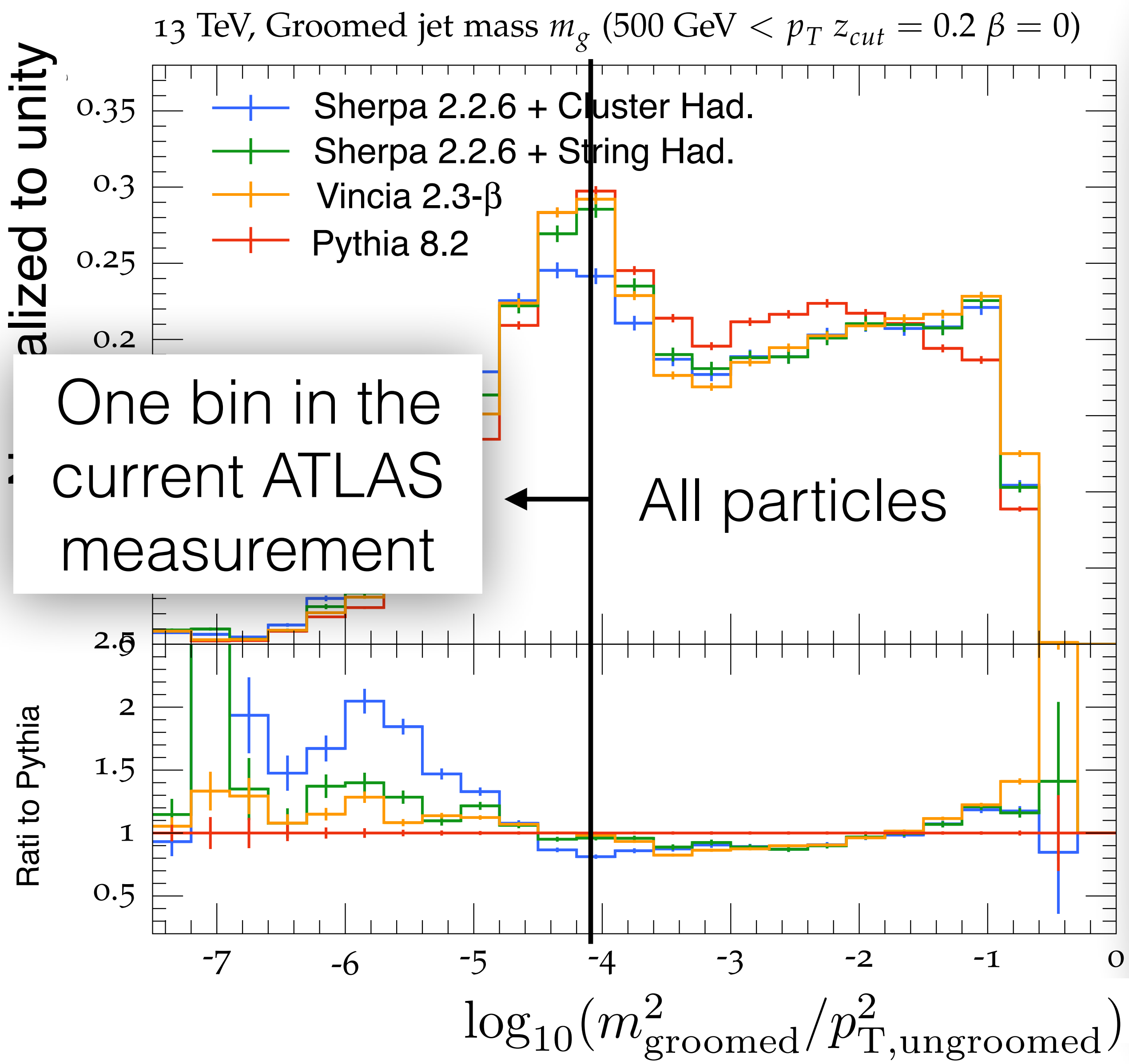

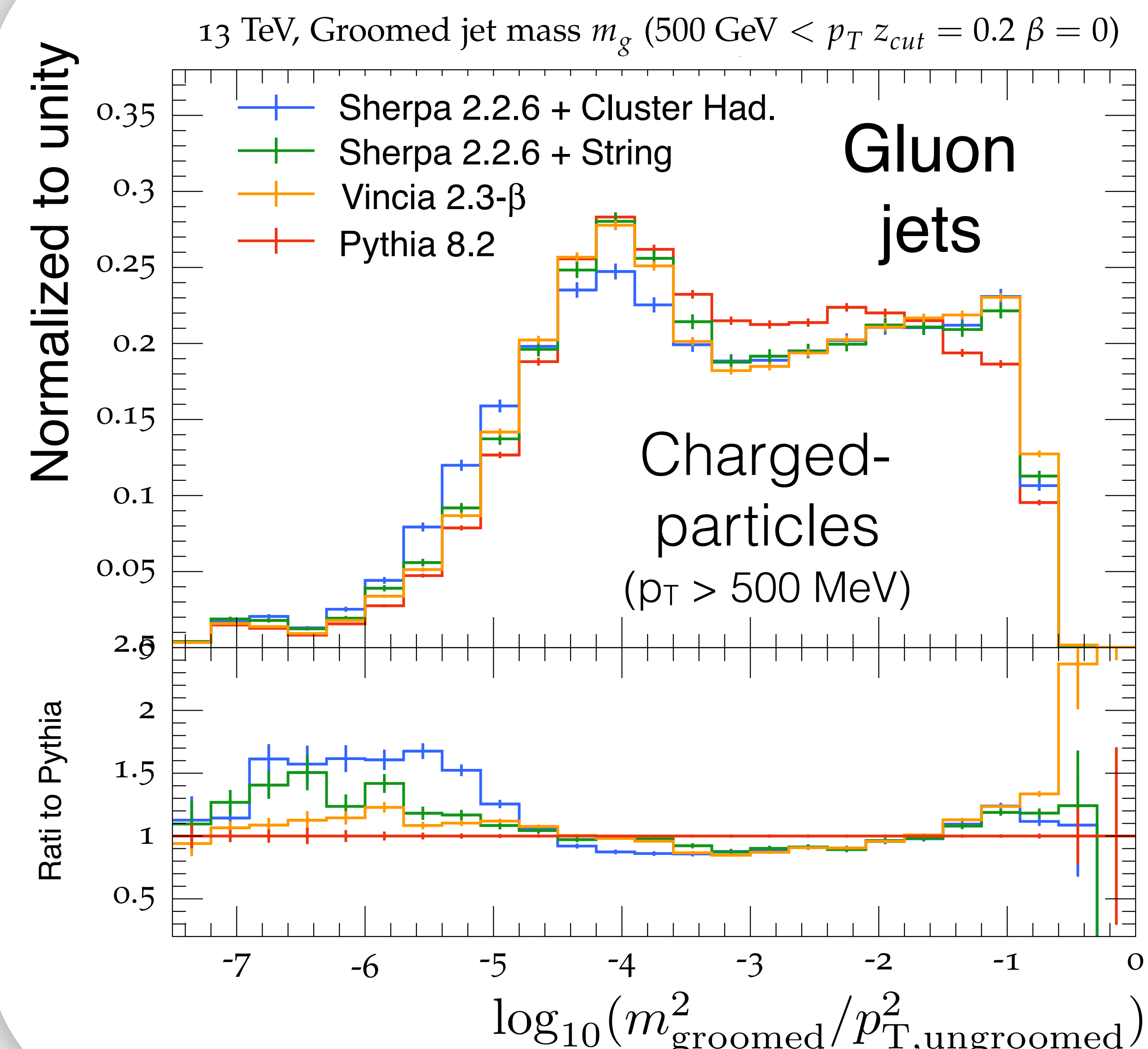

Currently, low mass region limited by angular resolution - can solve with charged particles! …let's zoom in on this region!

$\mathcal{O}$(10 GeV): Tuning with jet substructure

The low mass bump may be an important input to MC tuning.

What else can we do with JSS for tuning? This is often one motivation for our measurements - let's investigate!

We are maintaining a twiki page for JSS measurements in the context of the LHC EW WG:

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCJetSubstructureMeasurements

Many of these measurements have HepData and Rivet routines … we **added two more this week**!

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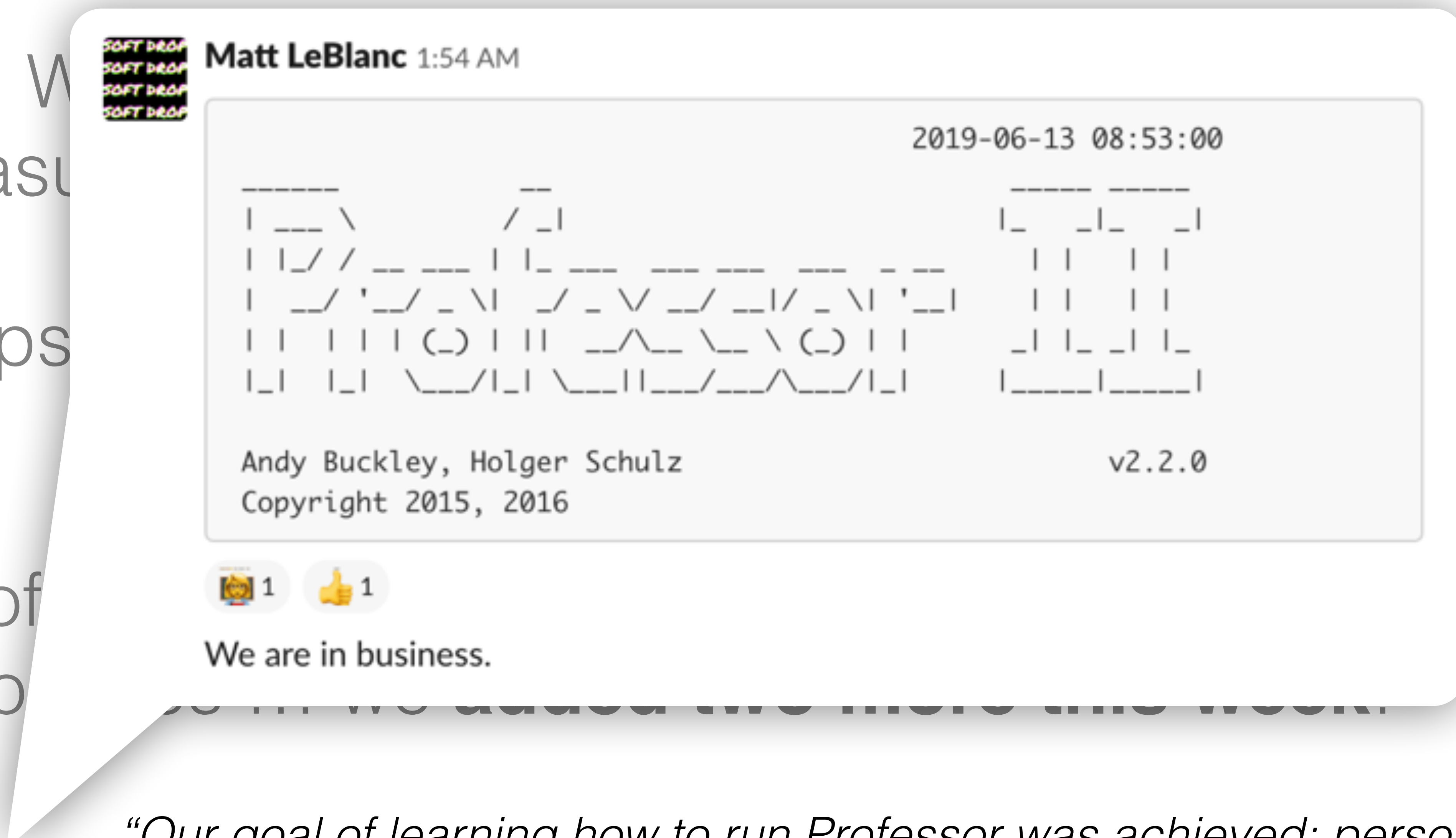
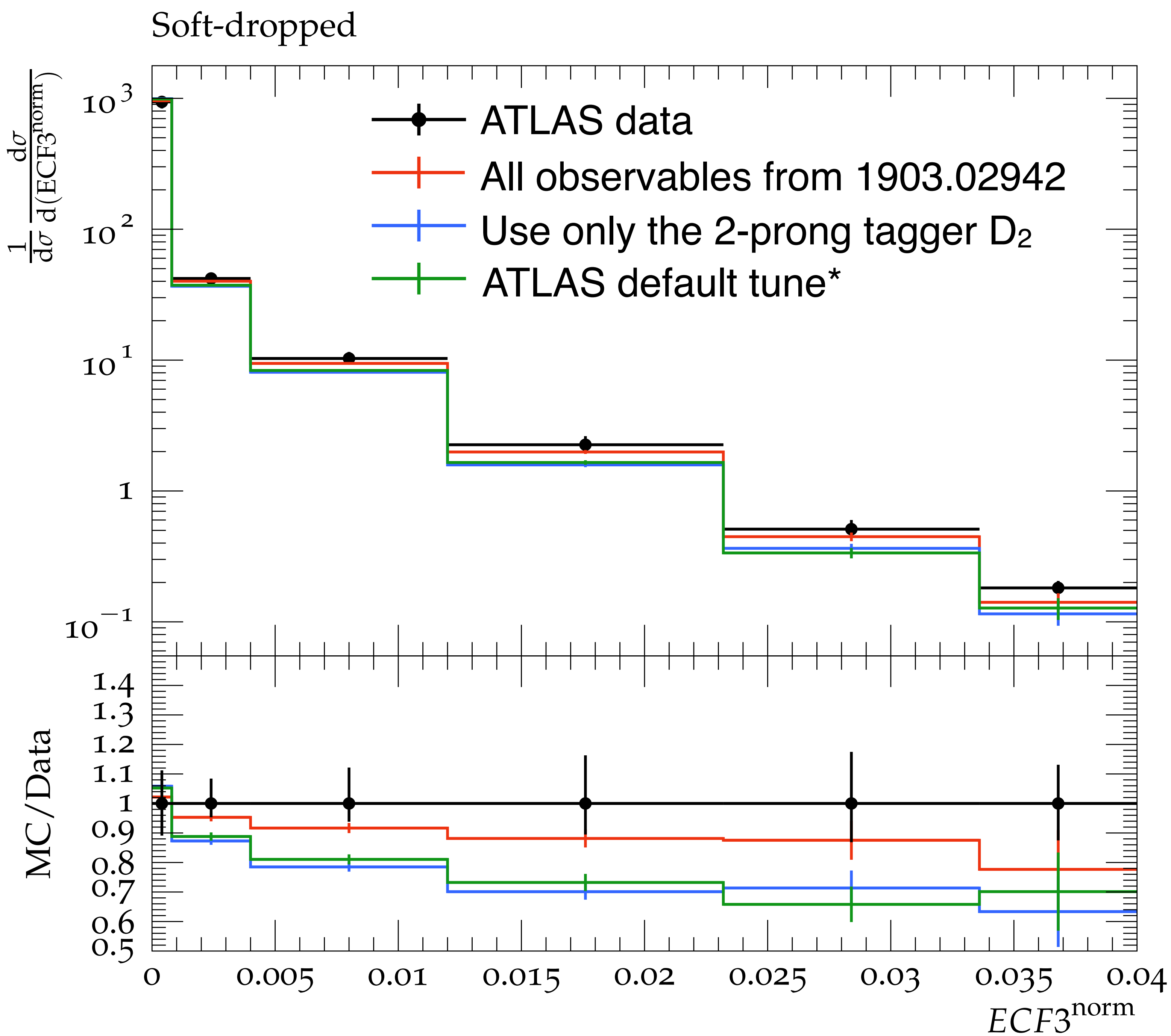


"Our goal of learning how to run Professor was achieved: personal success."

$\mathcal{O}$(10 GeV): Tuning with jet substructure



$$\mathrm{ECF3}^{\mathrm{norm}} = \frac{\sum p_{T,i} p_{T,j} p_{T,k} \Delta R_{ij} \Delta R_{ik} \Delta R_{jk}}{(\sum p_{T,i})^3}$$

The work has just begun…

…but preliminary results indicate that multiple observables a can have a non-negligible impact on FSR parameters.

For the **proceedings**: complete a Les Houches jet substructure tune & determine sensitivity of individual measurements

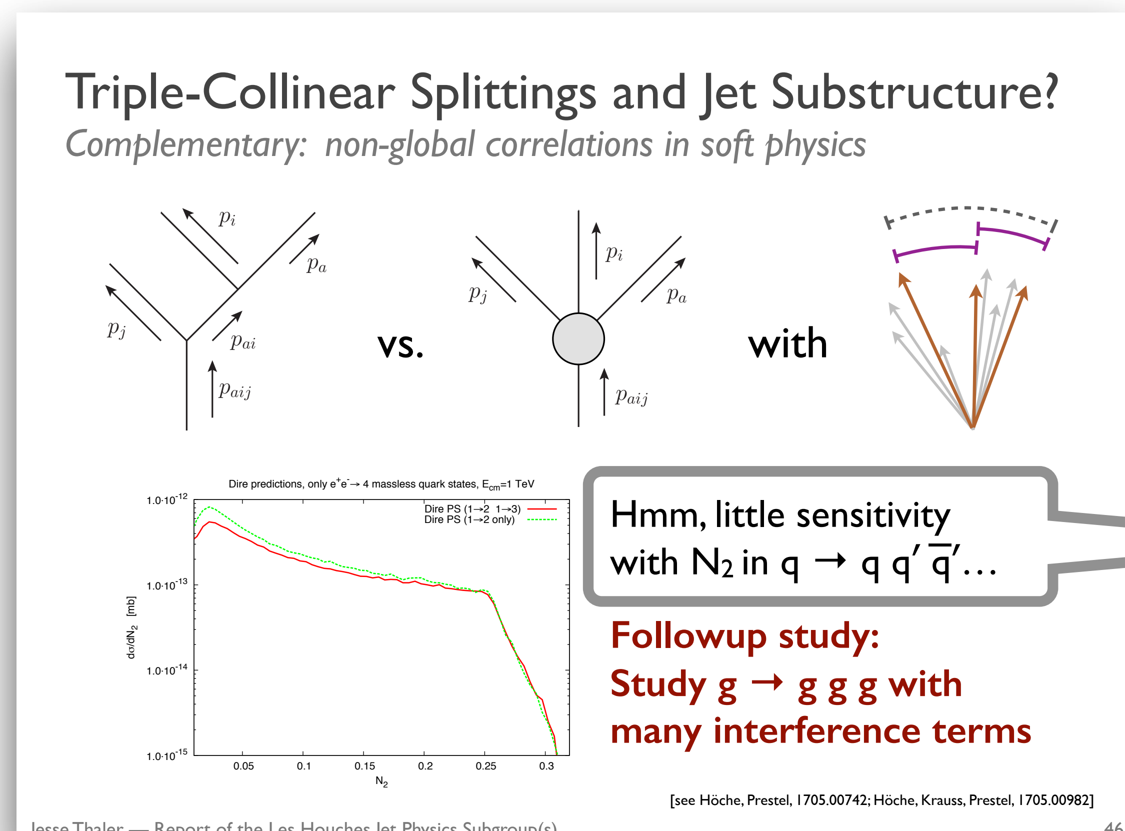
see jet pull in the backup

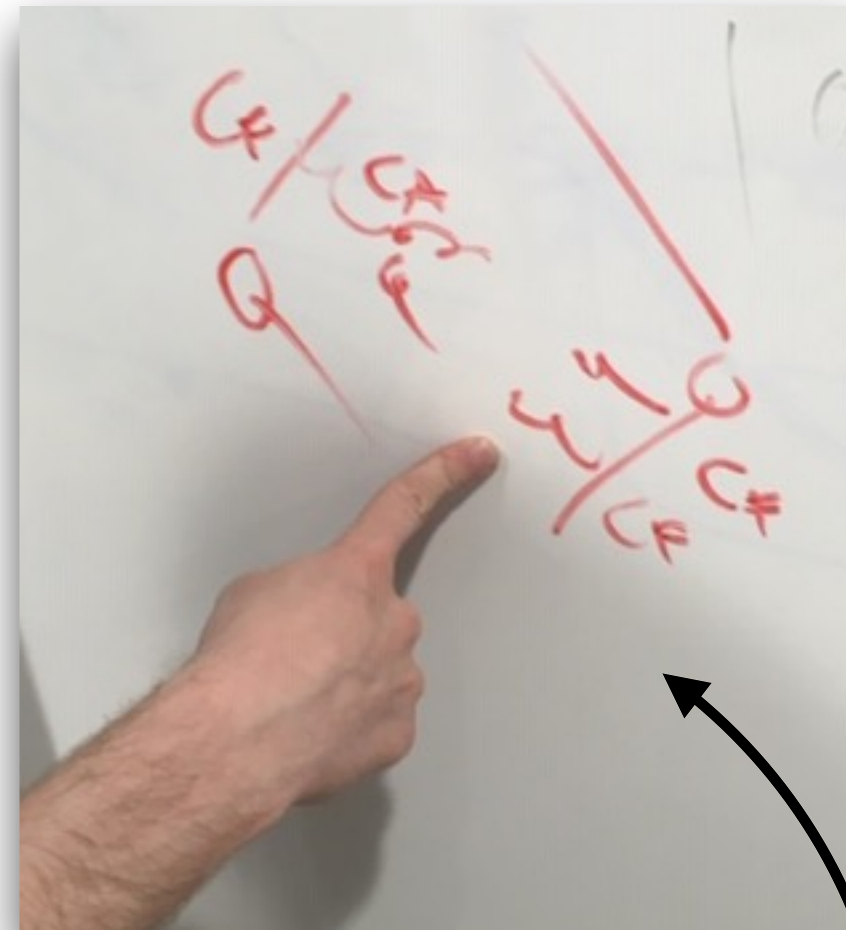
*This is basically the JSS-sensitive parts of A14 and otherwise, Monash.

$\mathcal{O}$(10+ GeV): Higher order showers

There is an impressive effort by the MC community to include higher-order effects in parton showers.

Key question: **what observables are sensitive to these innovations?**



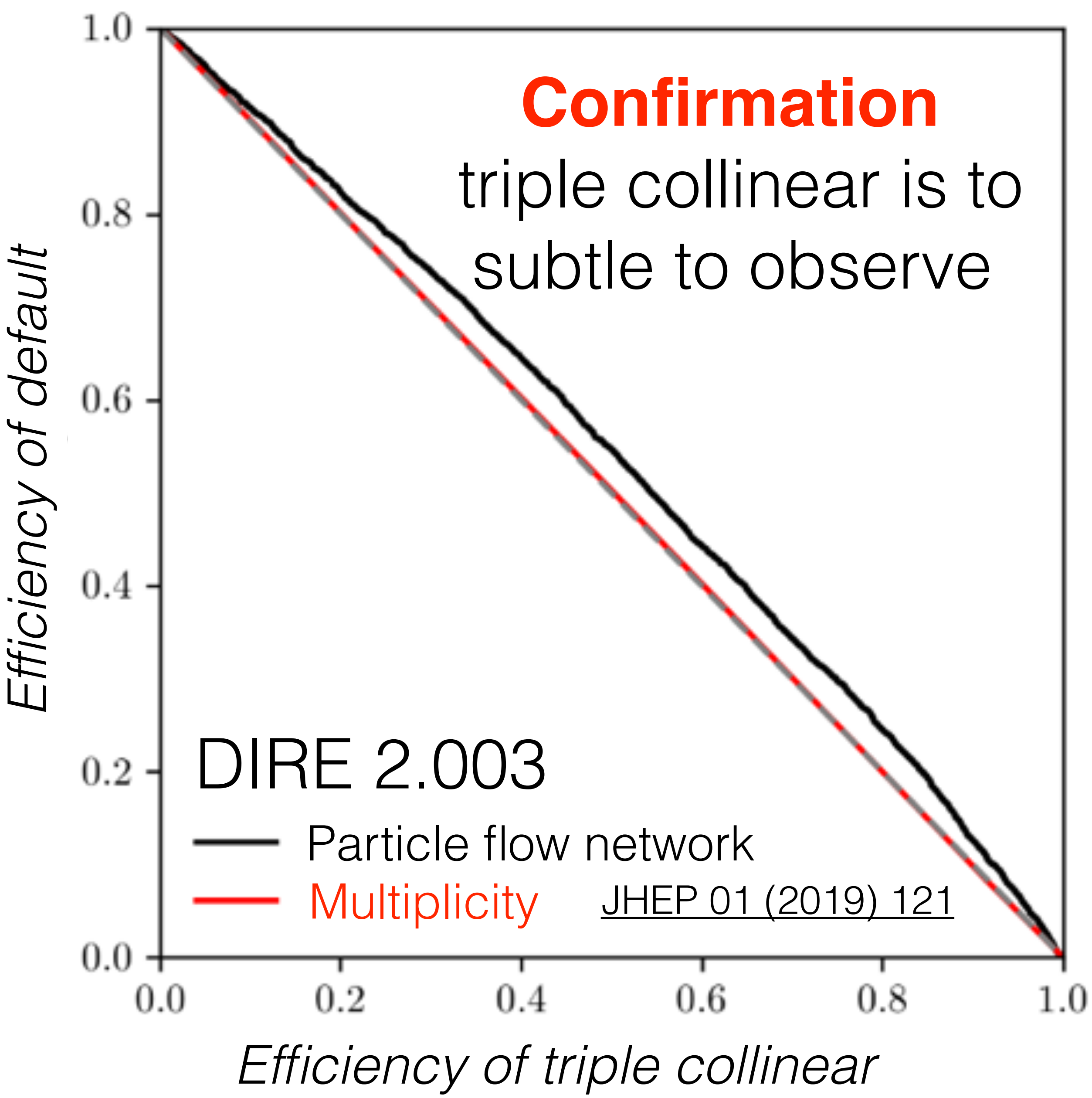


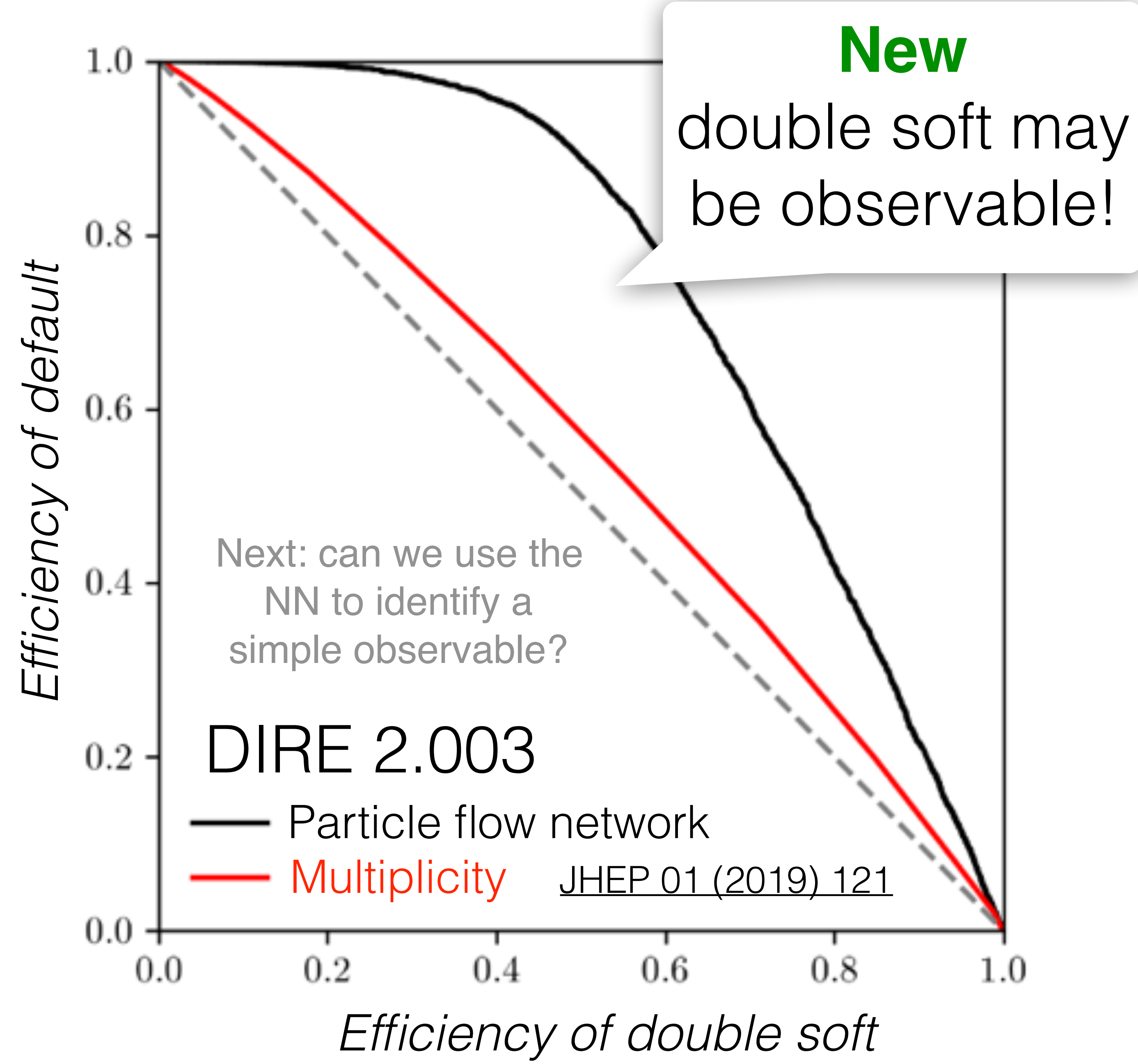
Attempt at LH17 to use jet substructure for probing the triple collinear splitting function … **without much luck**. What about the **double soft** splitting?

O(10+ GeV): Higher order showers

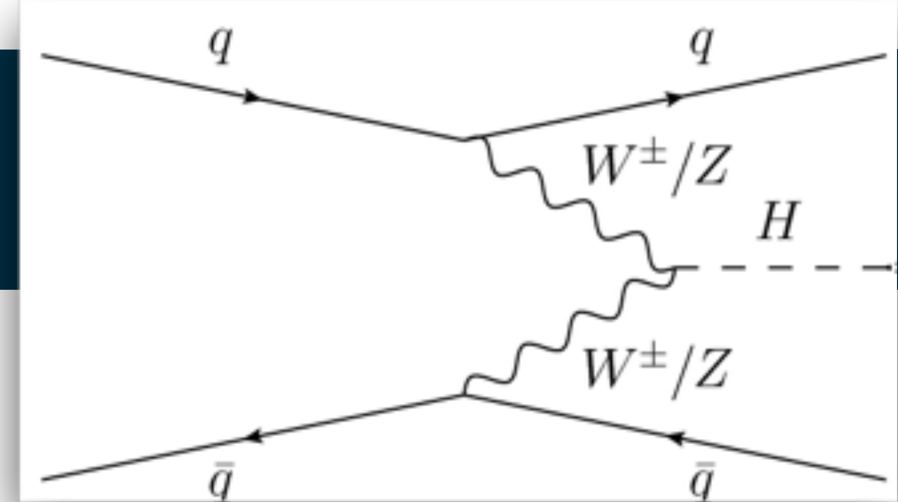
Idea: state-of-the-art neural networks to bound performance

Particle flow networks use all 4-vectors + particle flavor





$\mathcal{O}$(10+ GeV): VBF



Vector boson fusion is an often-discussed testing ground for q/g tagging.

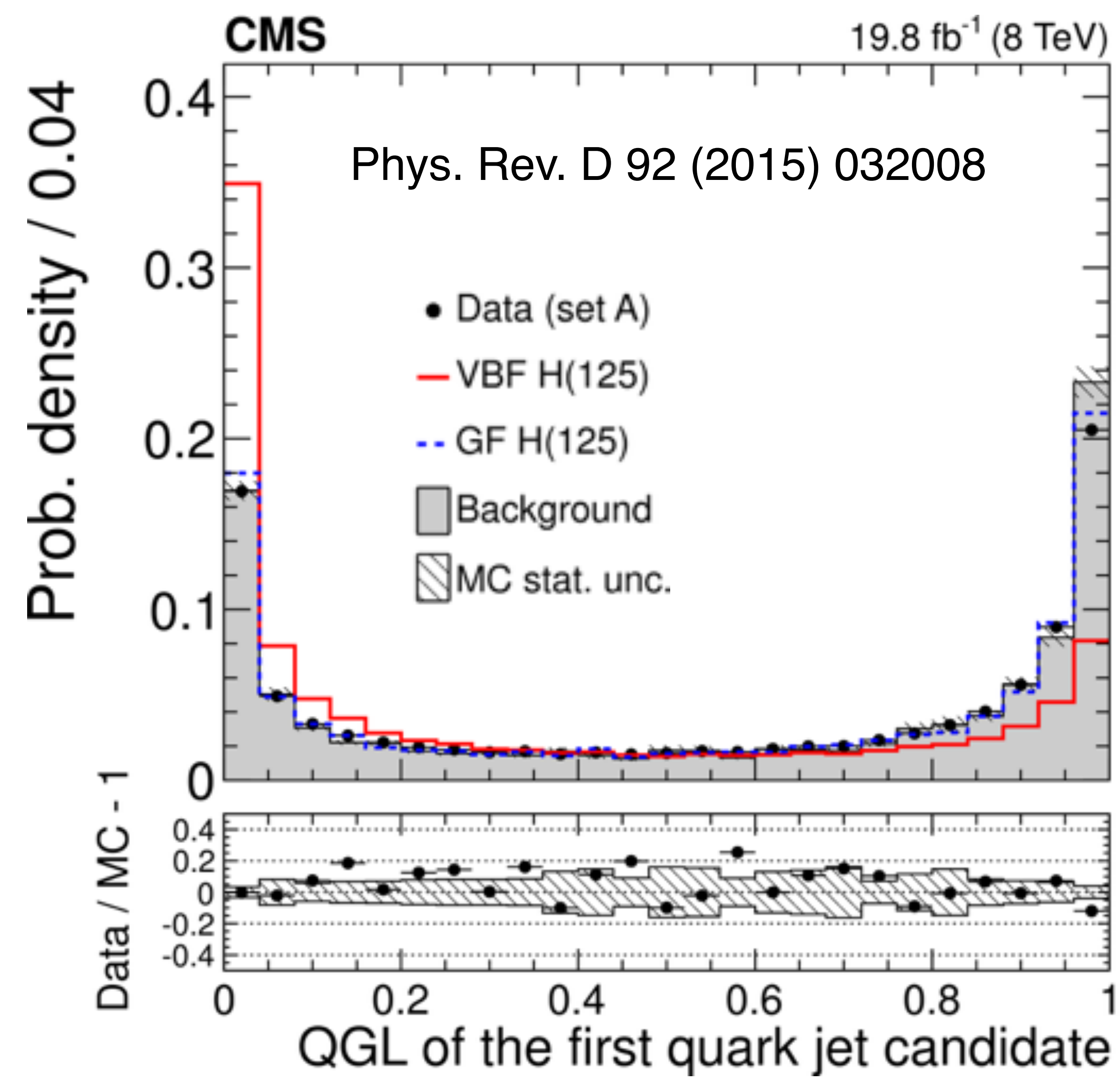
Our study has two components:

Signal versus background.

How useful is q/g tagging & how well is it modeled?

Signal versus signal

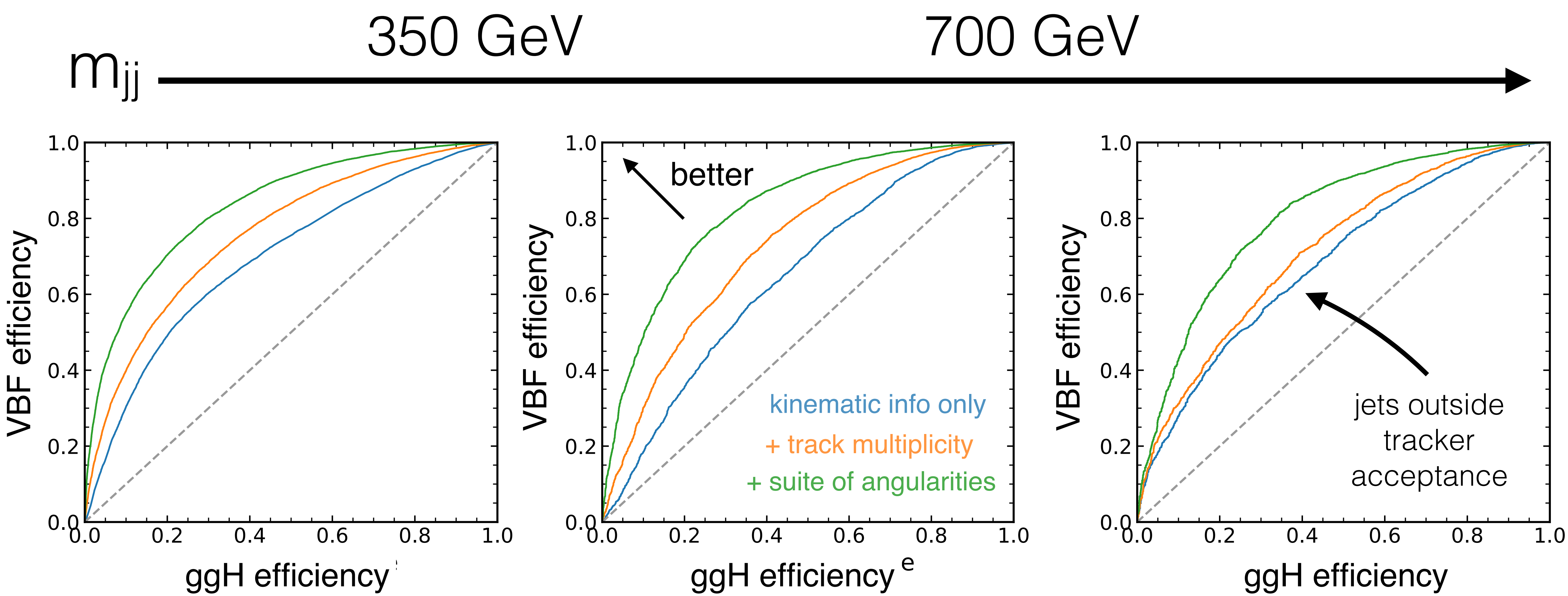
Can q/g tagging be used to disentangle VBF from VH/ggH?



O(10+ GeV): VBF

Case study: can q/g tagging help disentangle VBF from ggH?

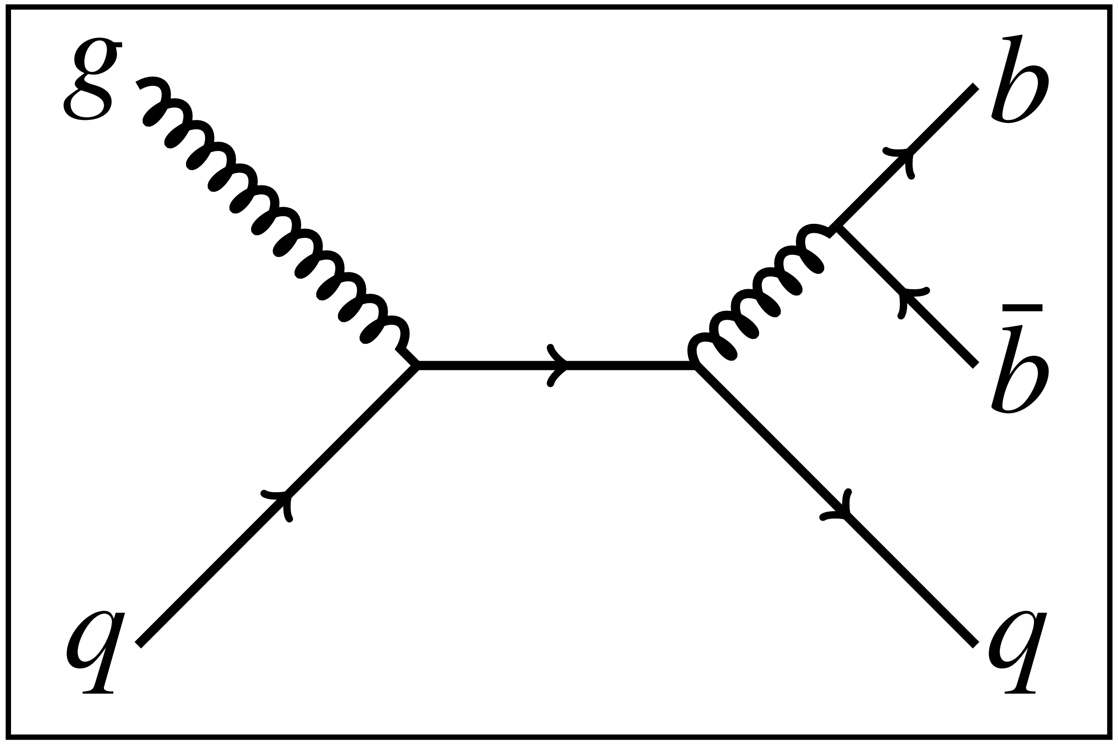
At high m_{jj}, jets from ggH are also quark-like - biggest gains expected at lower mass.



Non-trivial gains seem possible!

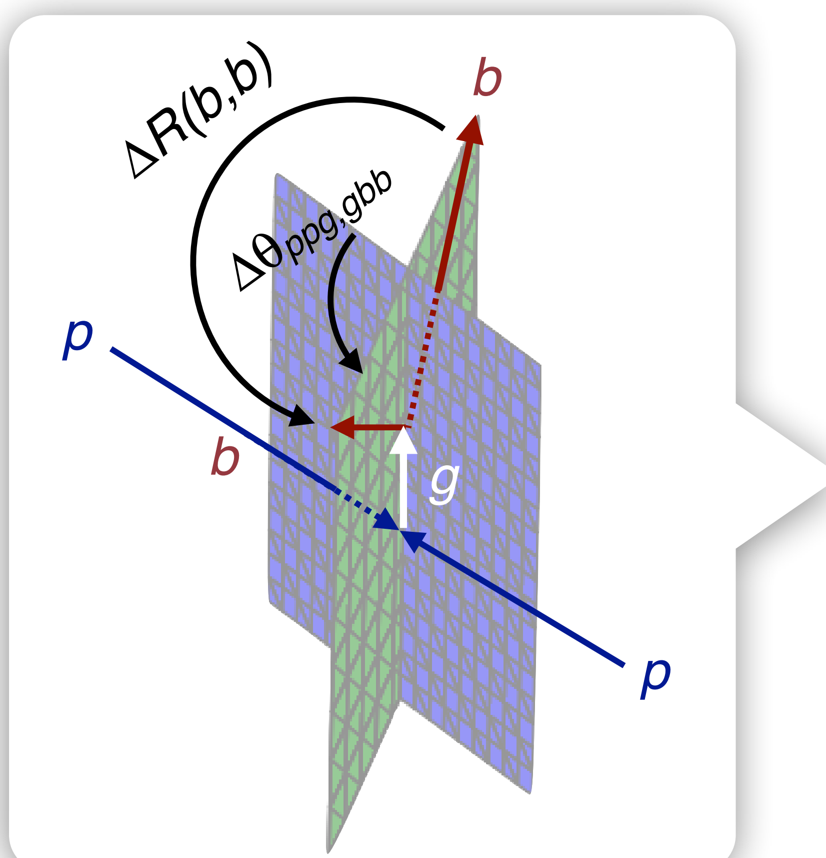
…for the **proceedings**: signal versus background, modeling, etc.

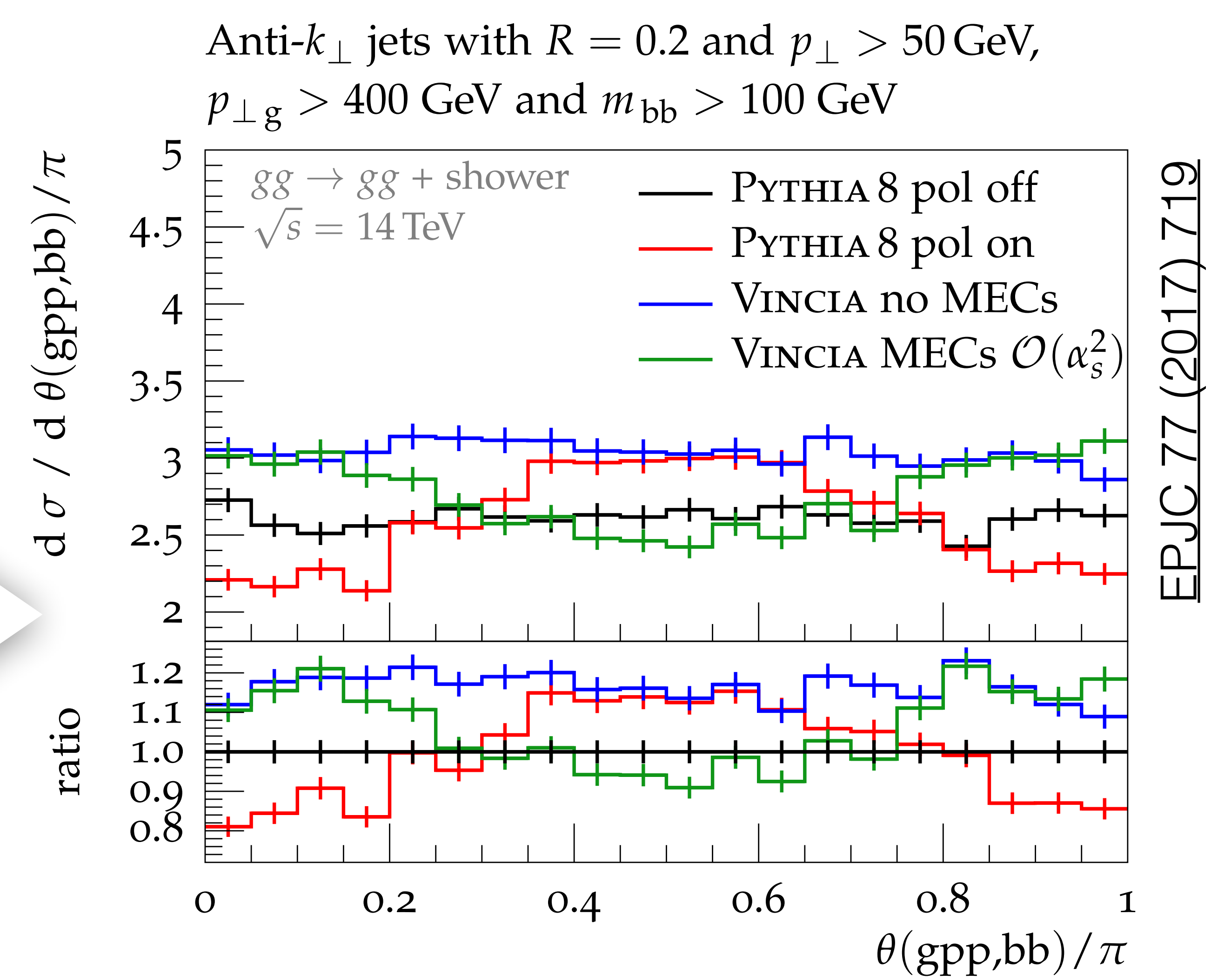
O(100 GeV): g → bb



g → bb provides a unique opportunity to directly probe the (polarized) gluon fragmentation function

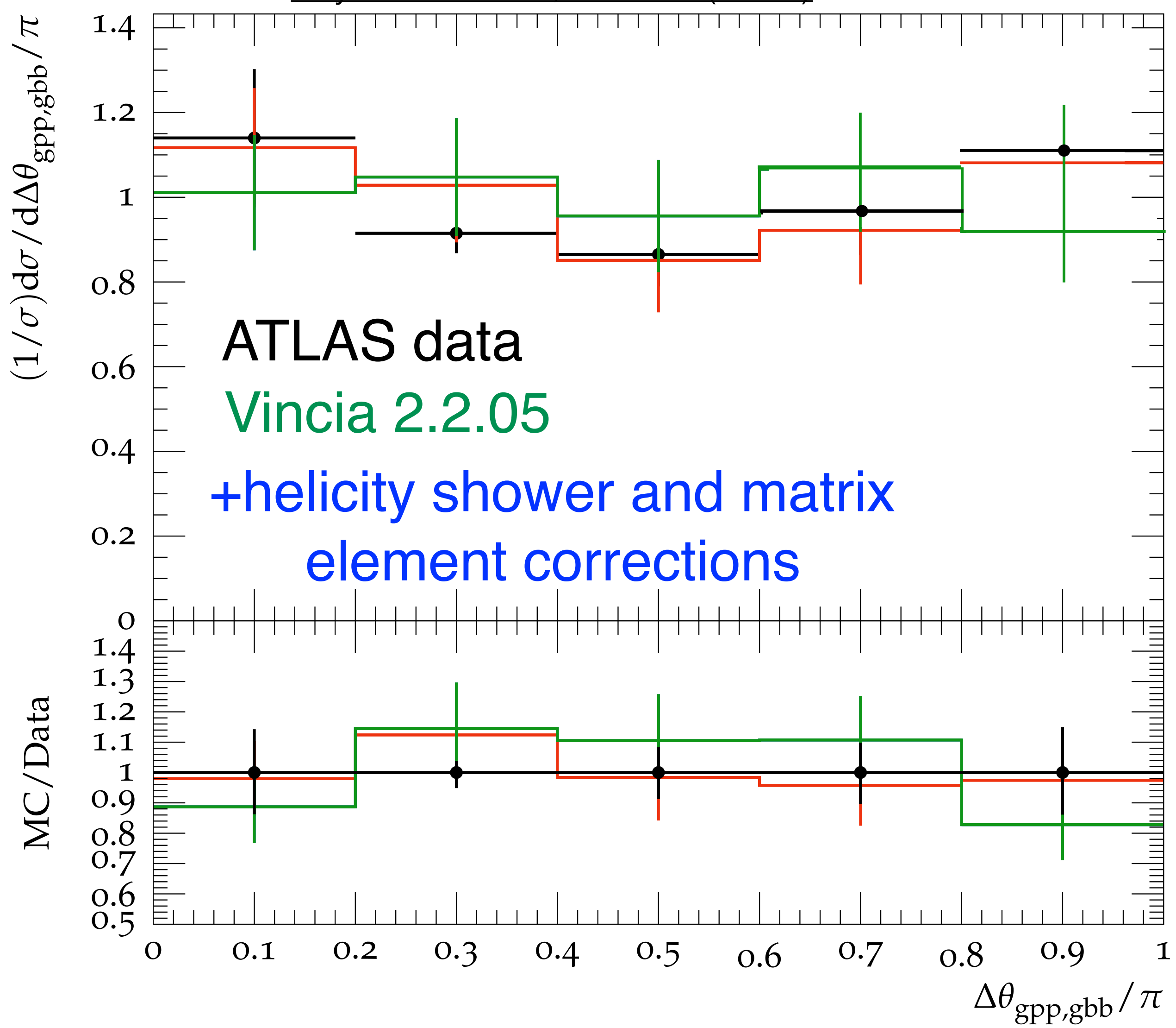
state-of-the-art seemed strange - what does data say?

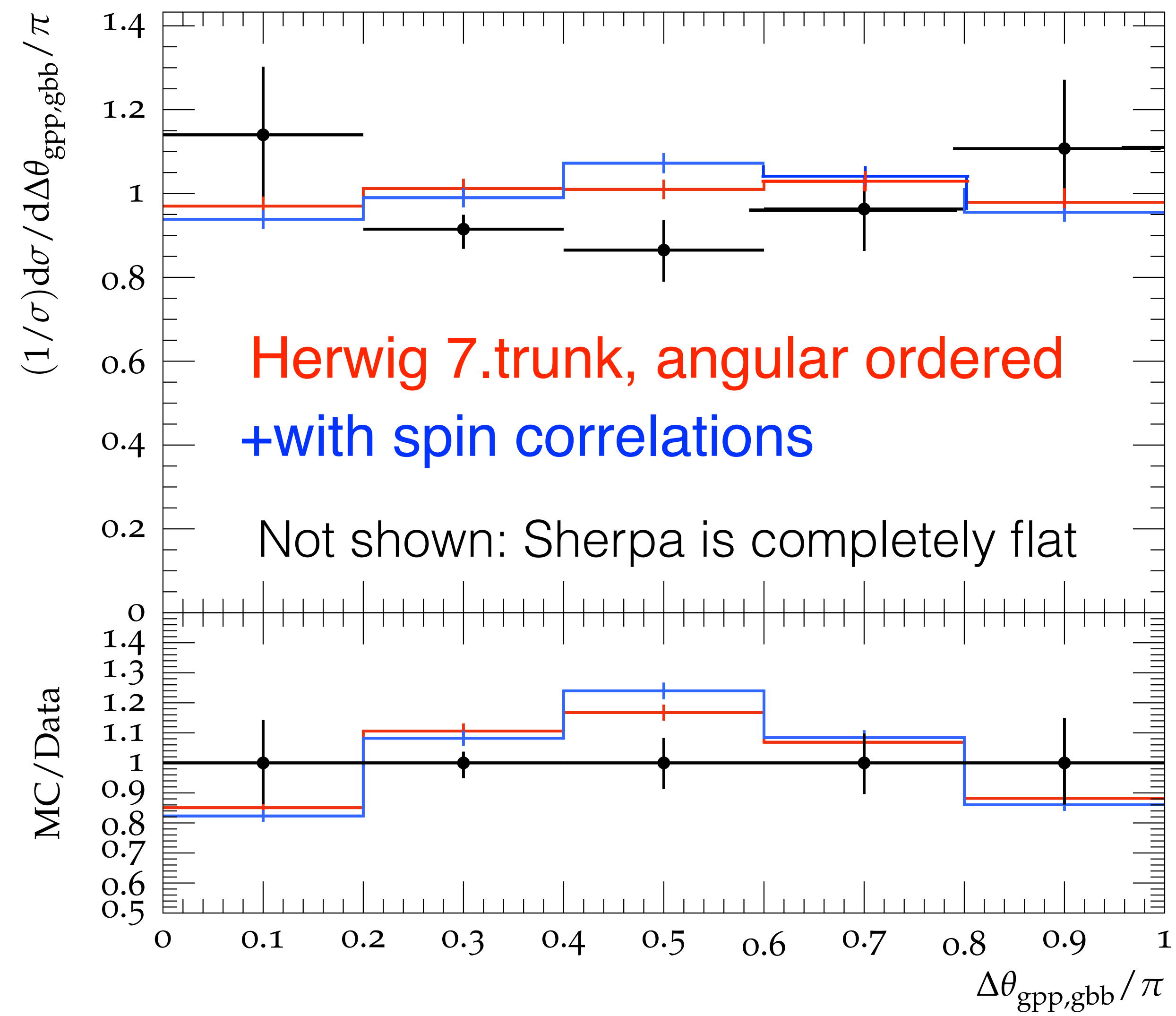




O(100 GeV): g → bb

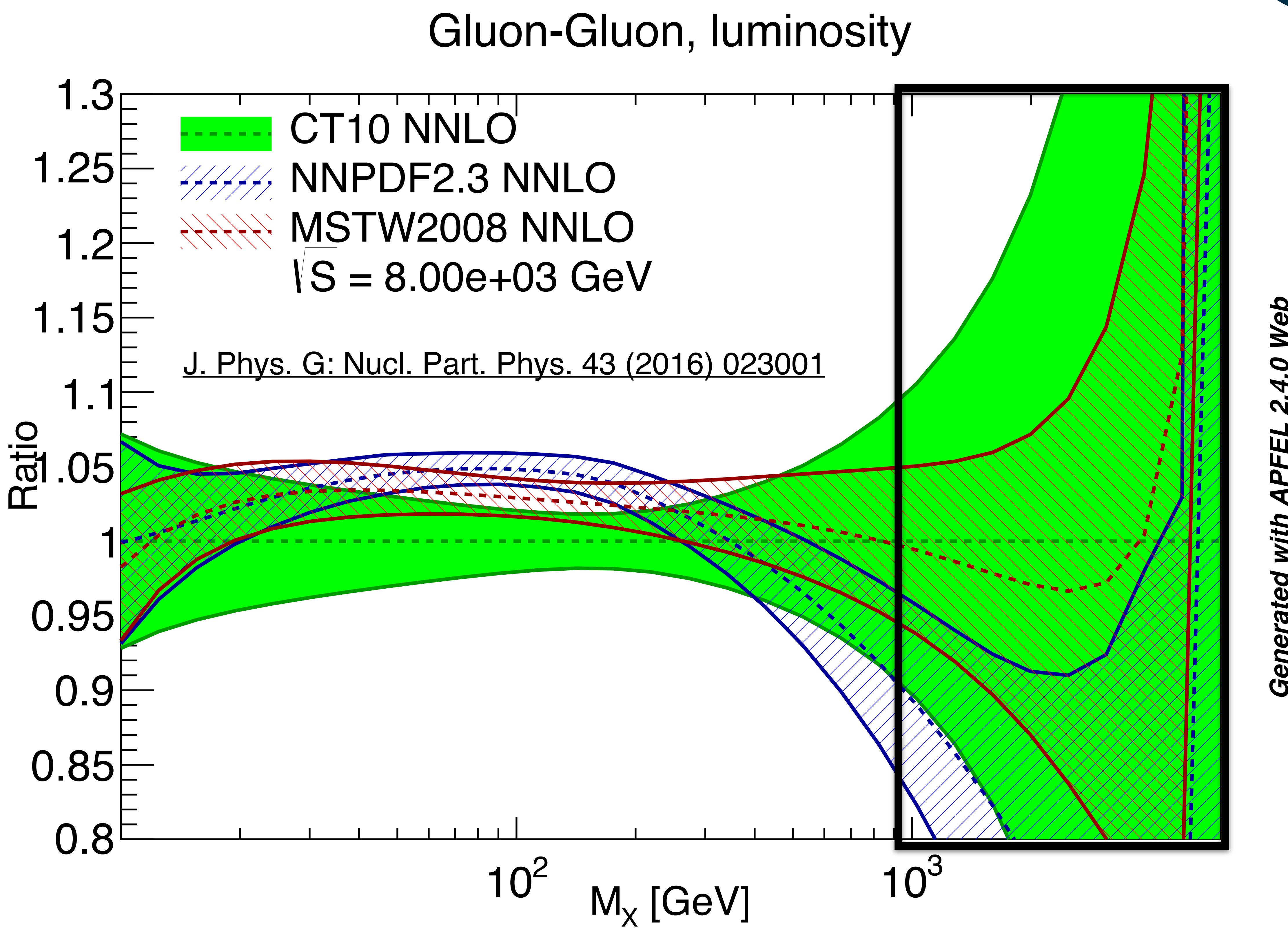
Data = Phys. Rev. D 99, 052004 (2019)





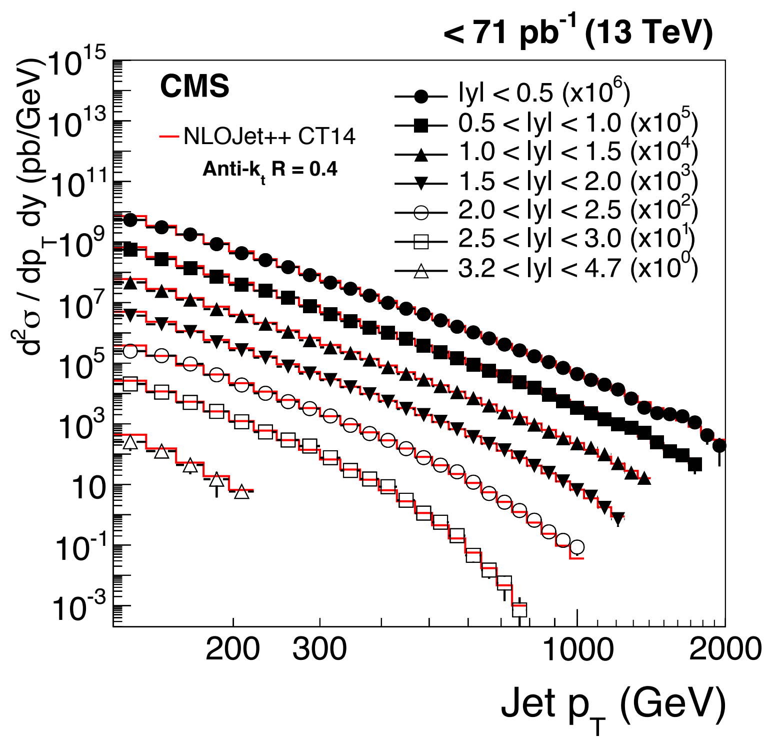
Low-stats indication: Vincia + ME corrections w/ helicity shower show same trend as data - prediction confirmed!

~1-2 TeV: Gluon PDF



*All of the groups have updated, this is for illustration only

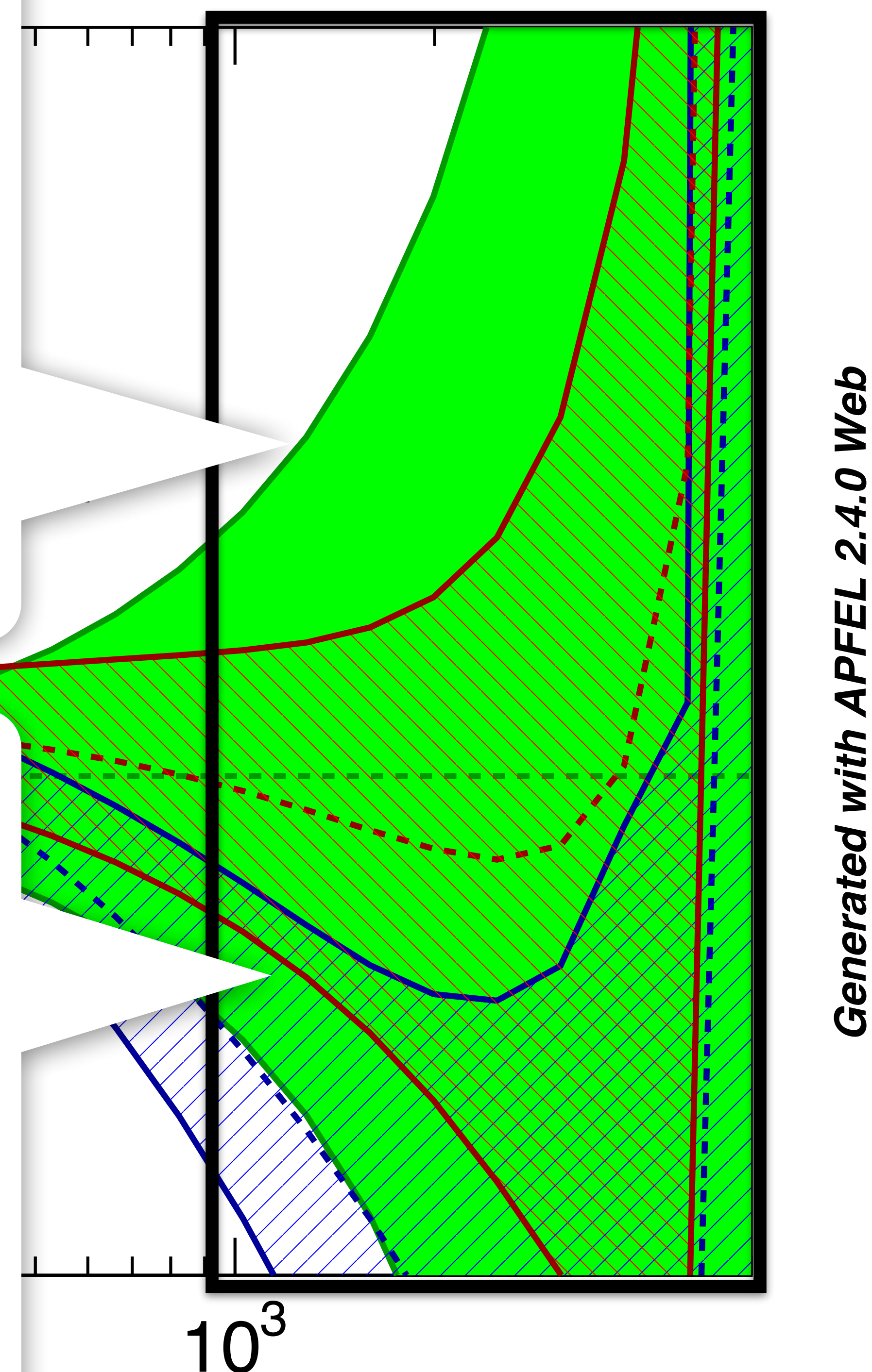
Gluon PDF: current constraints

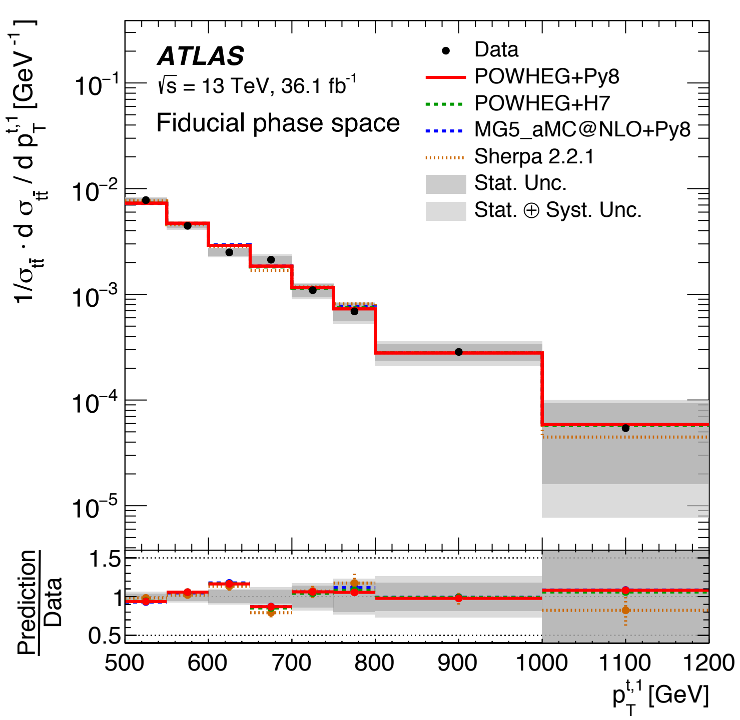


Inclusive jets

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

small gg/qg fraction at high jet p_T





Top quark pairs

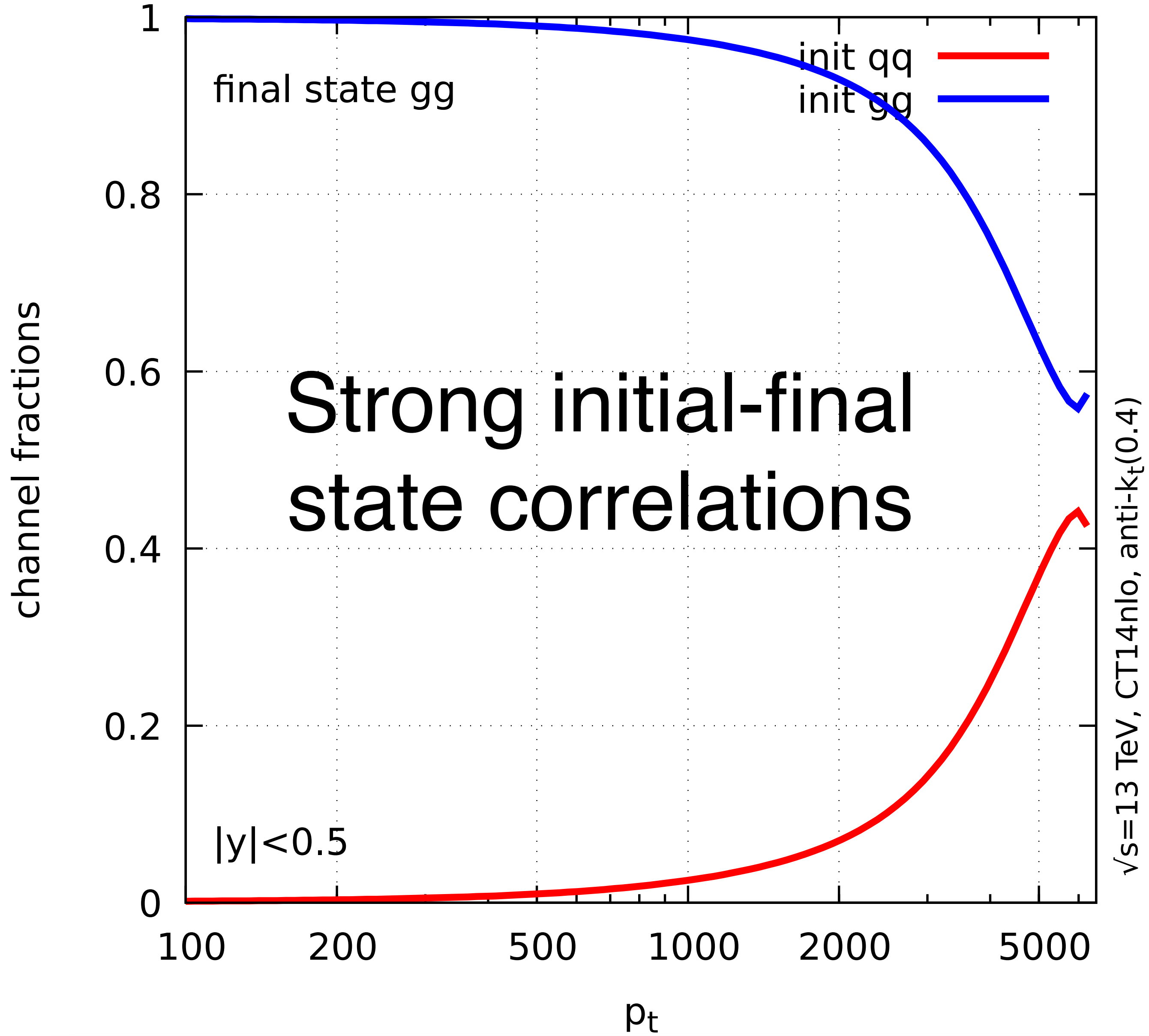
Dominated by gg initial state

run out of statistics much earlier than inclusive jets

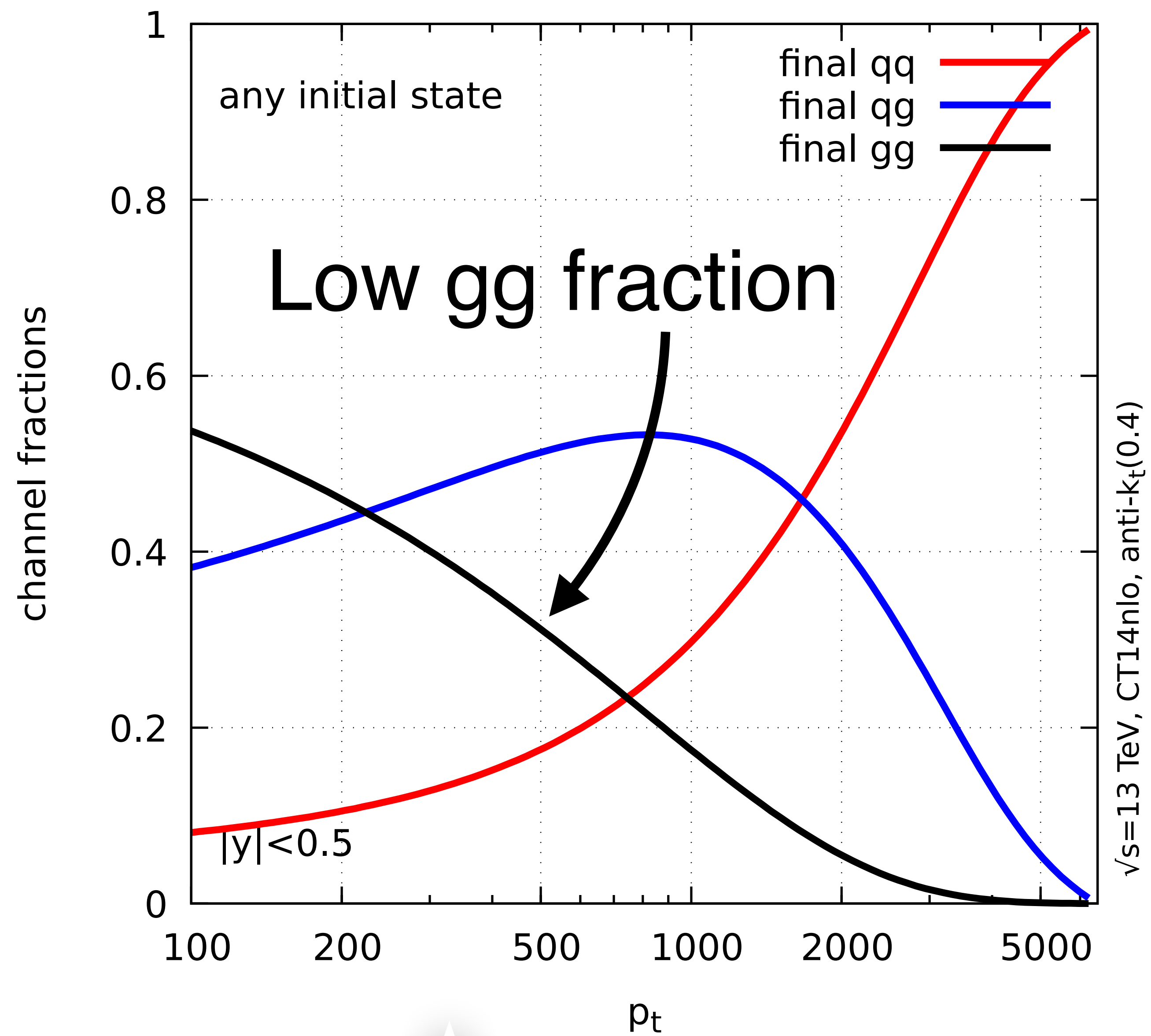
*All of the groups have updated, this is for illustration only

Can we target *gg* from inclusive jets?

Good

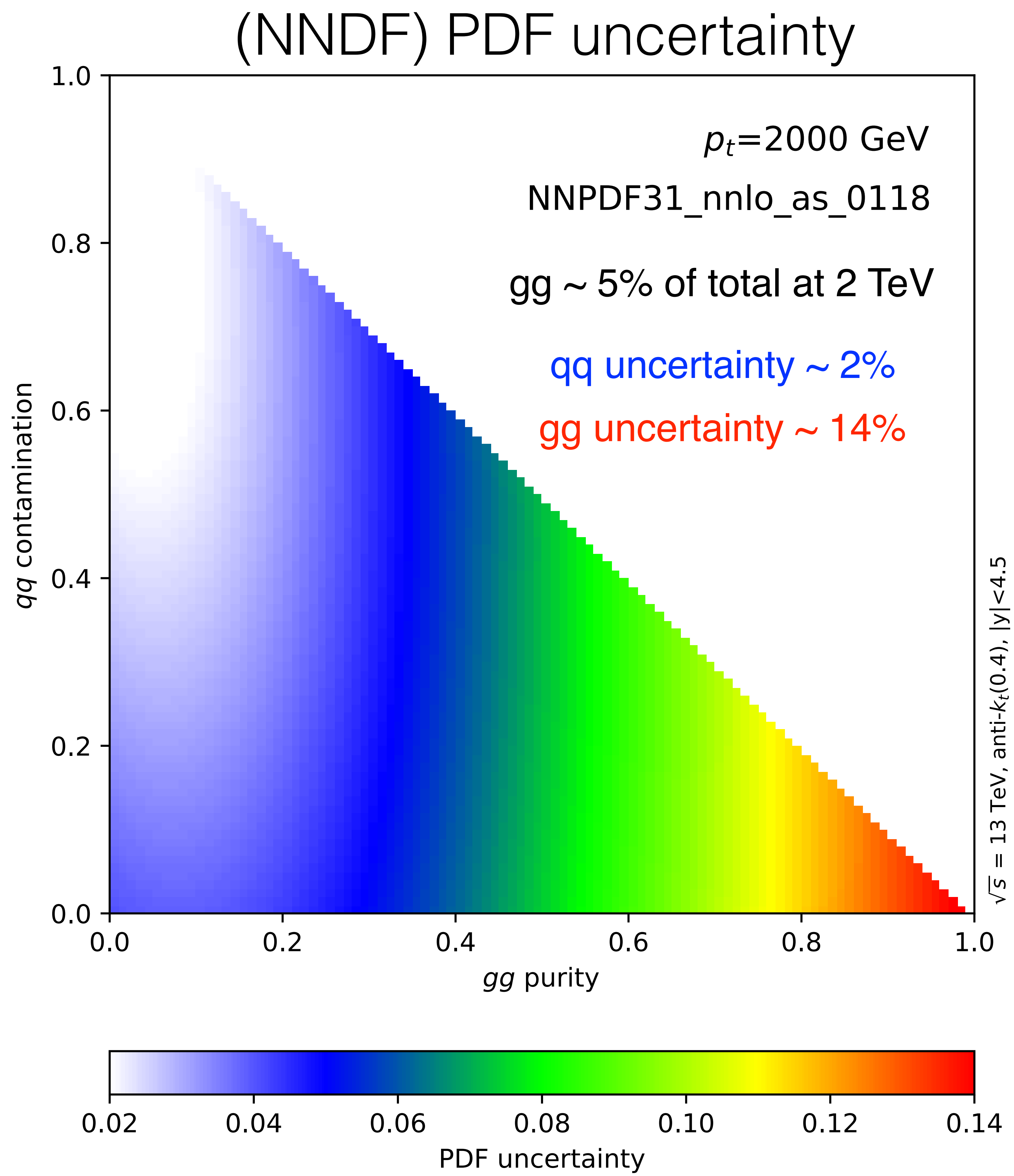


Challenging



How can we suppress quarks in regions of relatively large-x?

PDF uncertainty landscape post-tagging



Before we get too far, let's see what the PDF uncertainty is for a given *gg* purity and *qq* contamination.

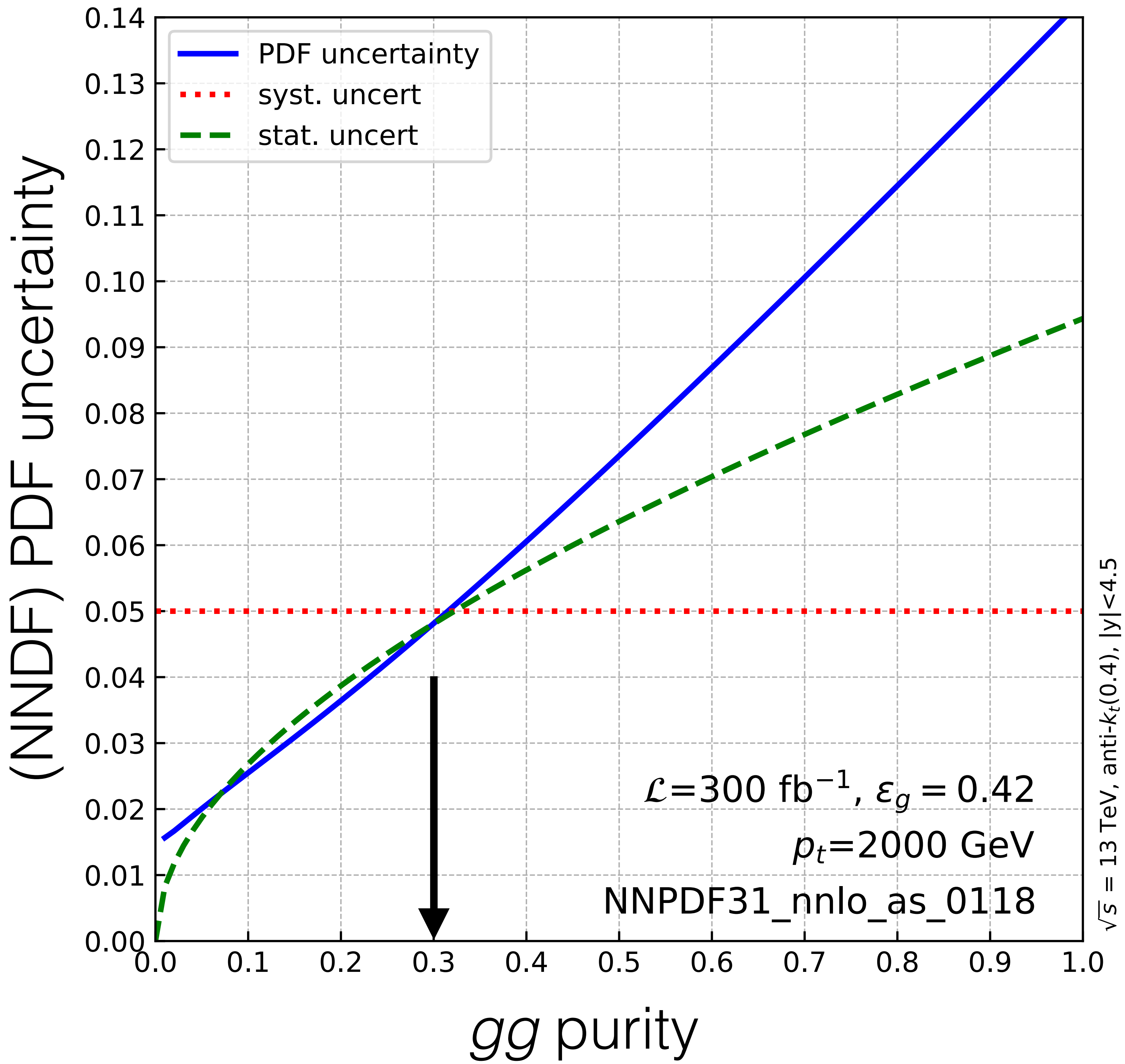
gg purity = *gg* / (*gg* + *gq* + *qq*)

no tagger here - not all of this plane is achievable!

current experimental uncertainty at 2 TeV is ~5%*

*Current cross section uncertainty from early 2015 is 10% but current JES uncertainty is x2 smaller.

How good does the tagging need to be?



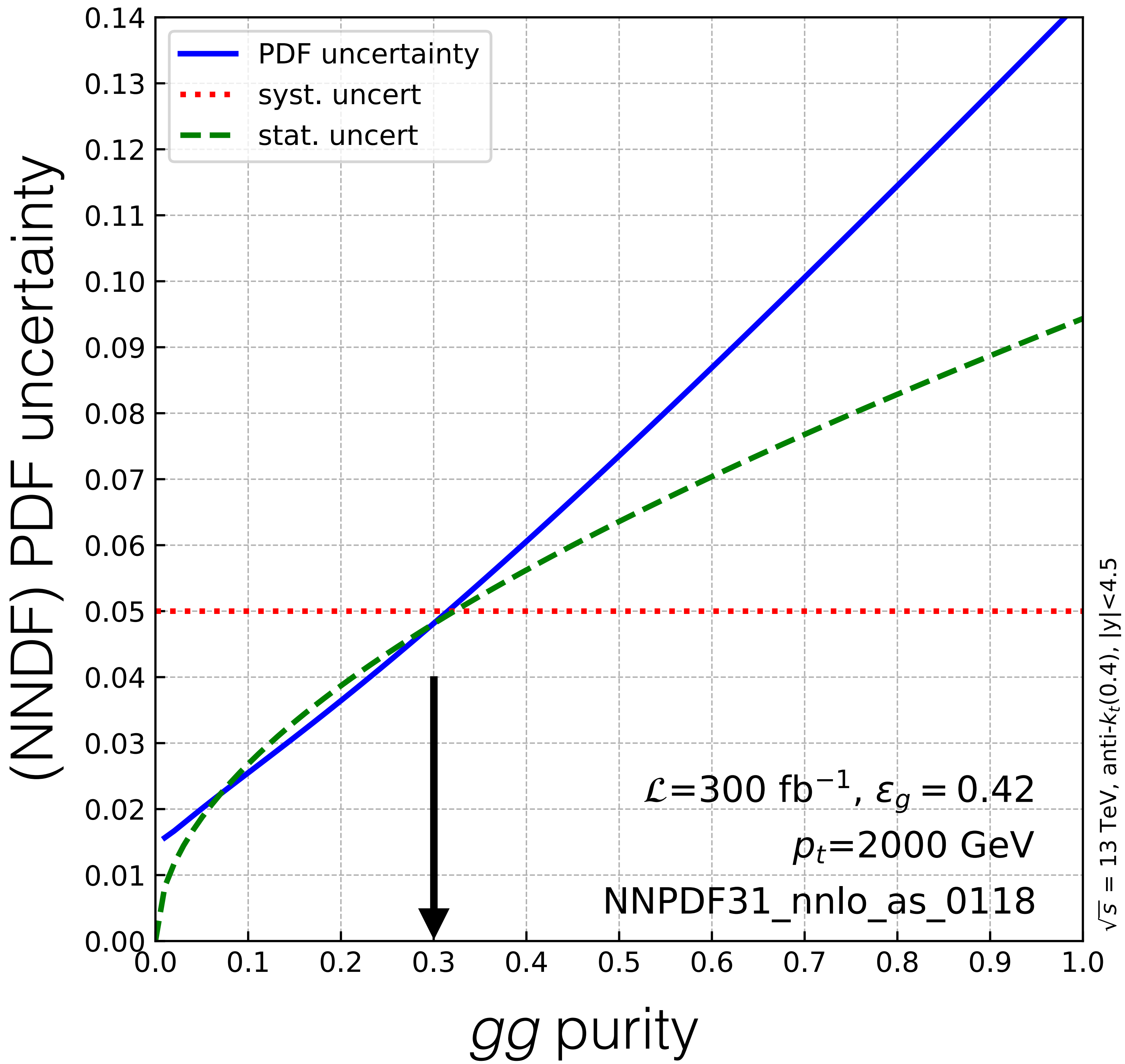
Goal: enrich the *gg* purity with a gluon tagger and hope that

PDF uncertainty $\gtrsim$ other uncertainties

Theory uncertainty on tagging not included!

…need a good q/g tagger that is also calculable!

How good does the tagging need to be?



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IRC safe multiplicity?!

Les Houches Multiplicity*, n_{LH}

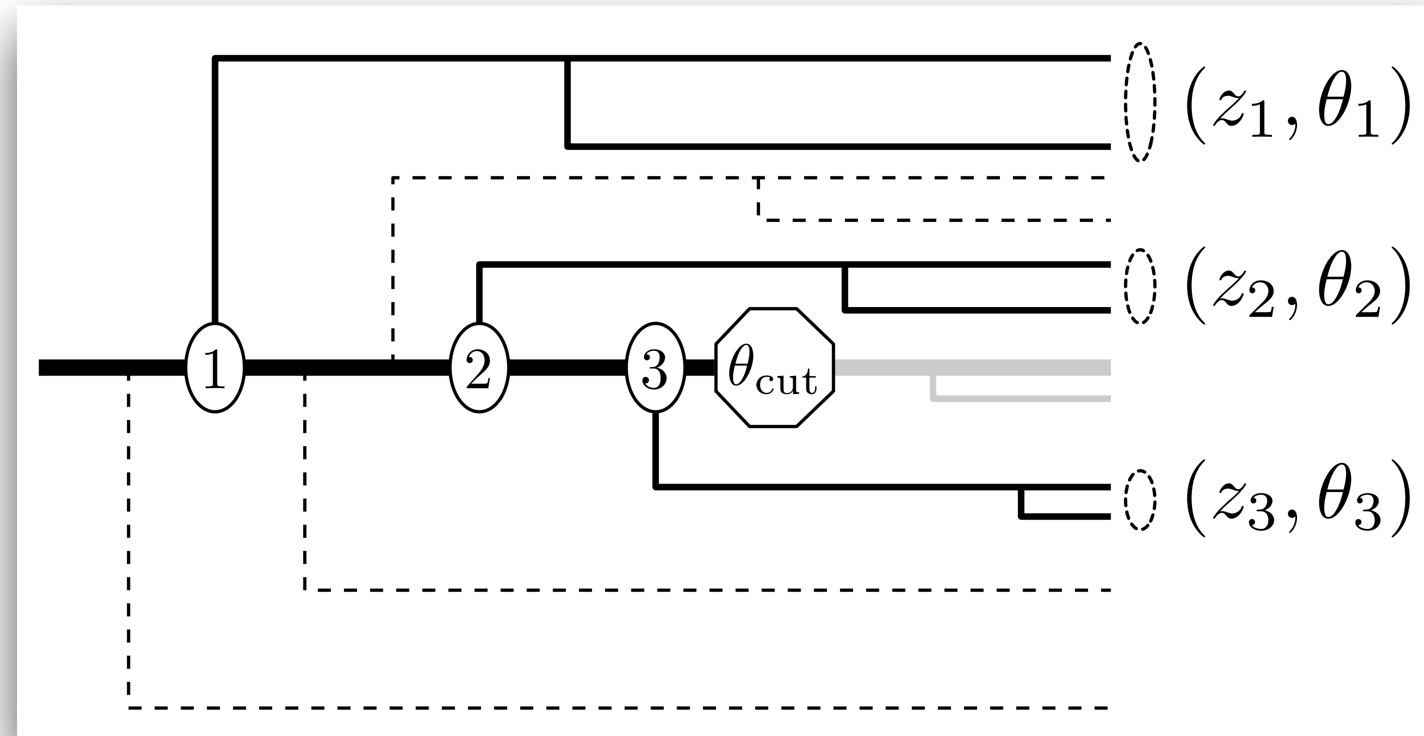
Iterative soft drop multiplicity: JHEP 09 (2017) 083

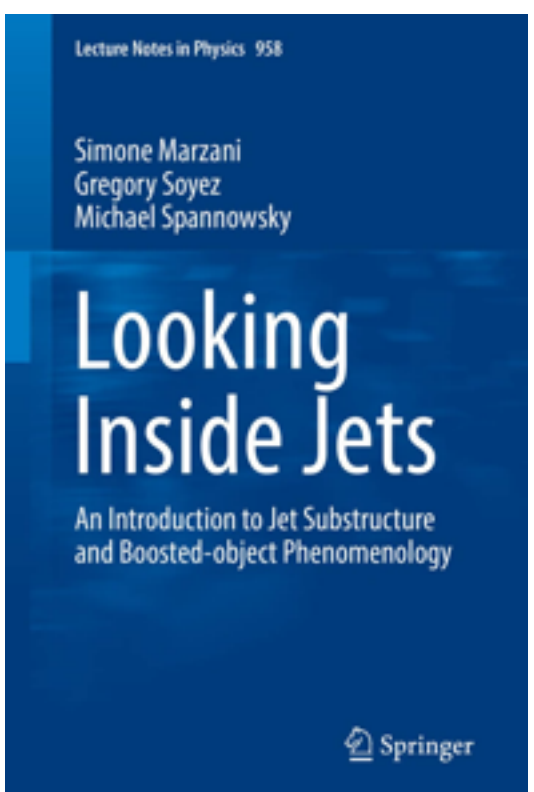
In the jet group, we make observables, not accords!

Les Houches Angularity '15

+ JHEP 1707 (2017) 091

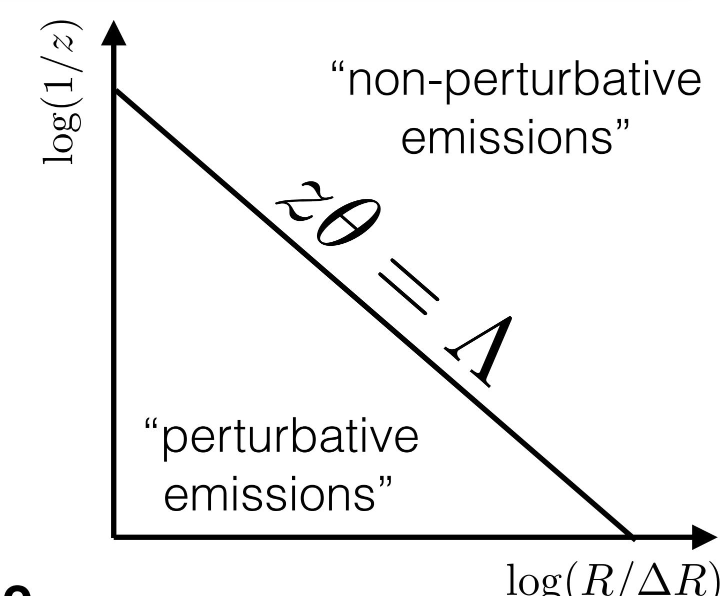
$$\sum_{i\in\text{jet}}(p_{T,i}/p_{T,\text{jet}})\Delta R_{i,\text{jet}}^{1/2}$$





n_{LH}: (a variation of iterative soft drop multiplicity)

- Recluster a jet using Cambridge/Aachen (same start as soft drop)
- follow the hardest branch and count the number of branches with zθ > cut

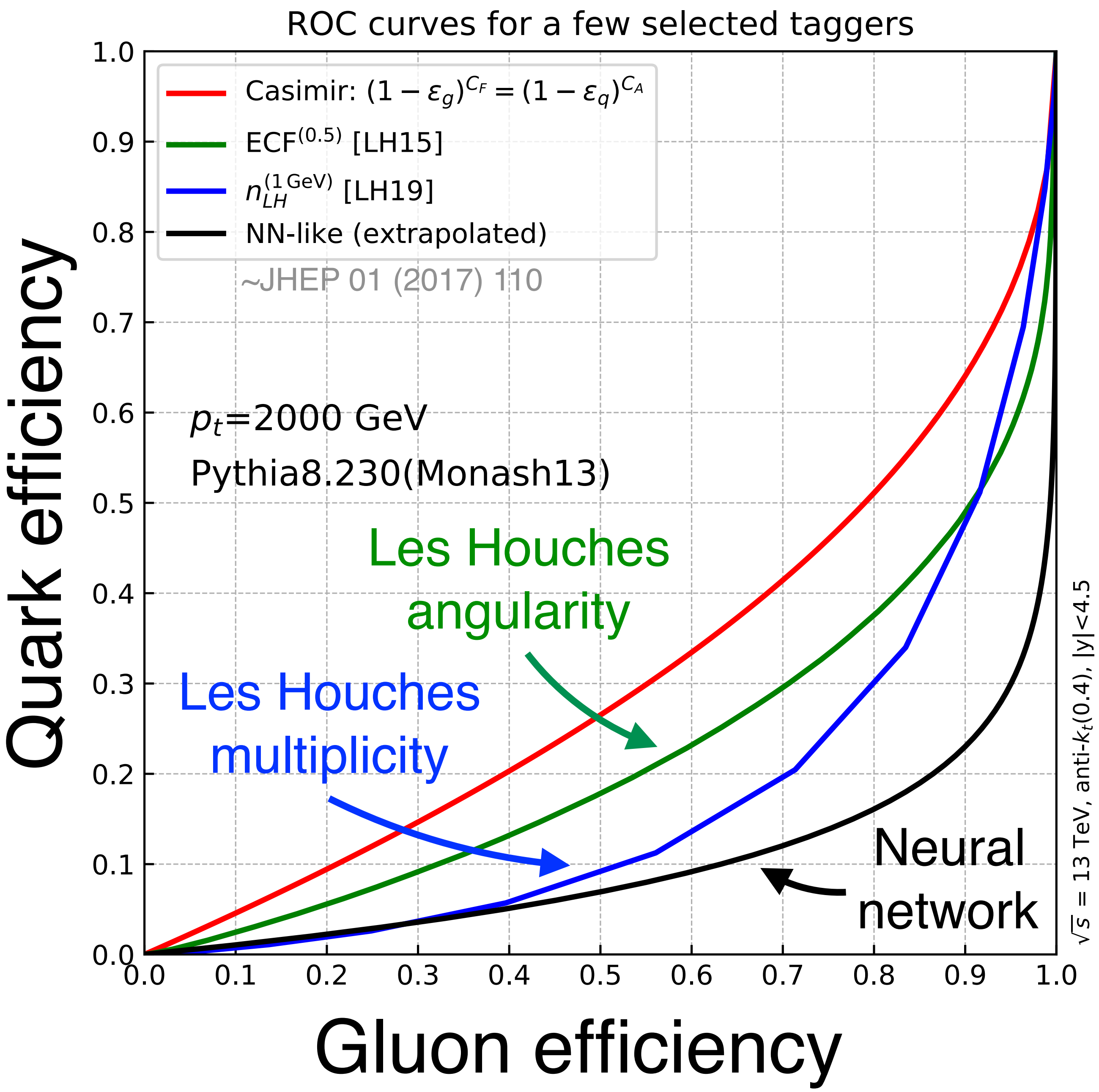


i.e. fill Lund plane and count emissions in the triangle

*first introduced in the book by Simone, Gregory, and Michael

Reconstruct the Lund plane: JHEP 12 (2018) 064

Gluon PDF with JSS: dead or alive?



For 50% gluon efficiency, save only 10% quarks.

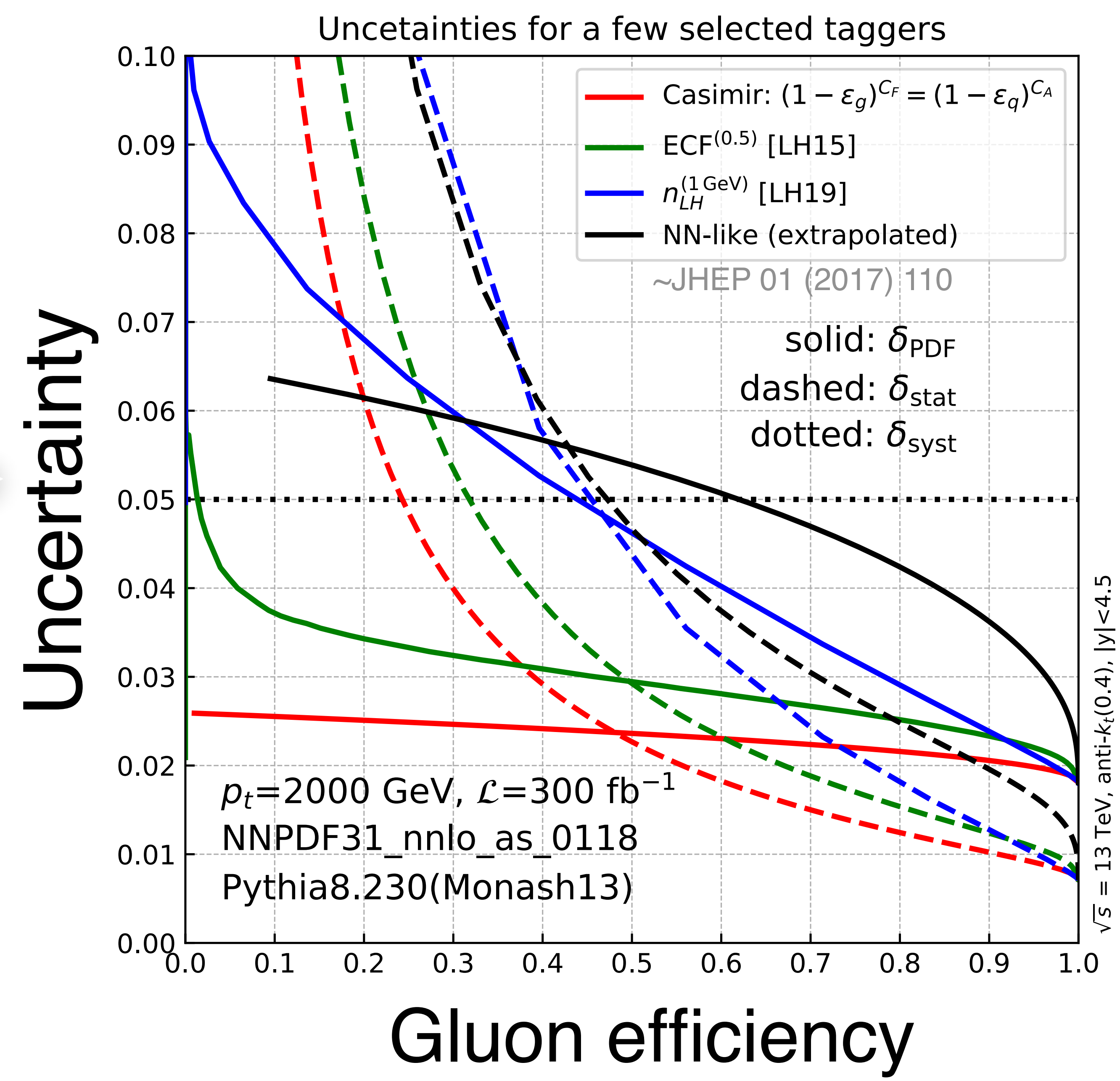
At low efficiency, multiplicity (e.g. n_{LH}) is not much worse than **NN**.

We have two jets, so we get to tag twice.

Gluon PDF with JSS: dead or alive?

Fold in the actual achievable uncertainty:

want solid $\gtrsim$ dashed, dotted (for same color)



We have studied many combinations of grooming and observables…

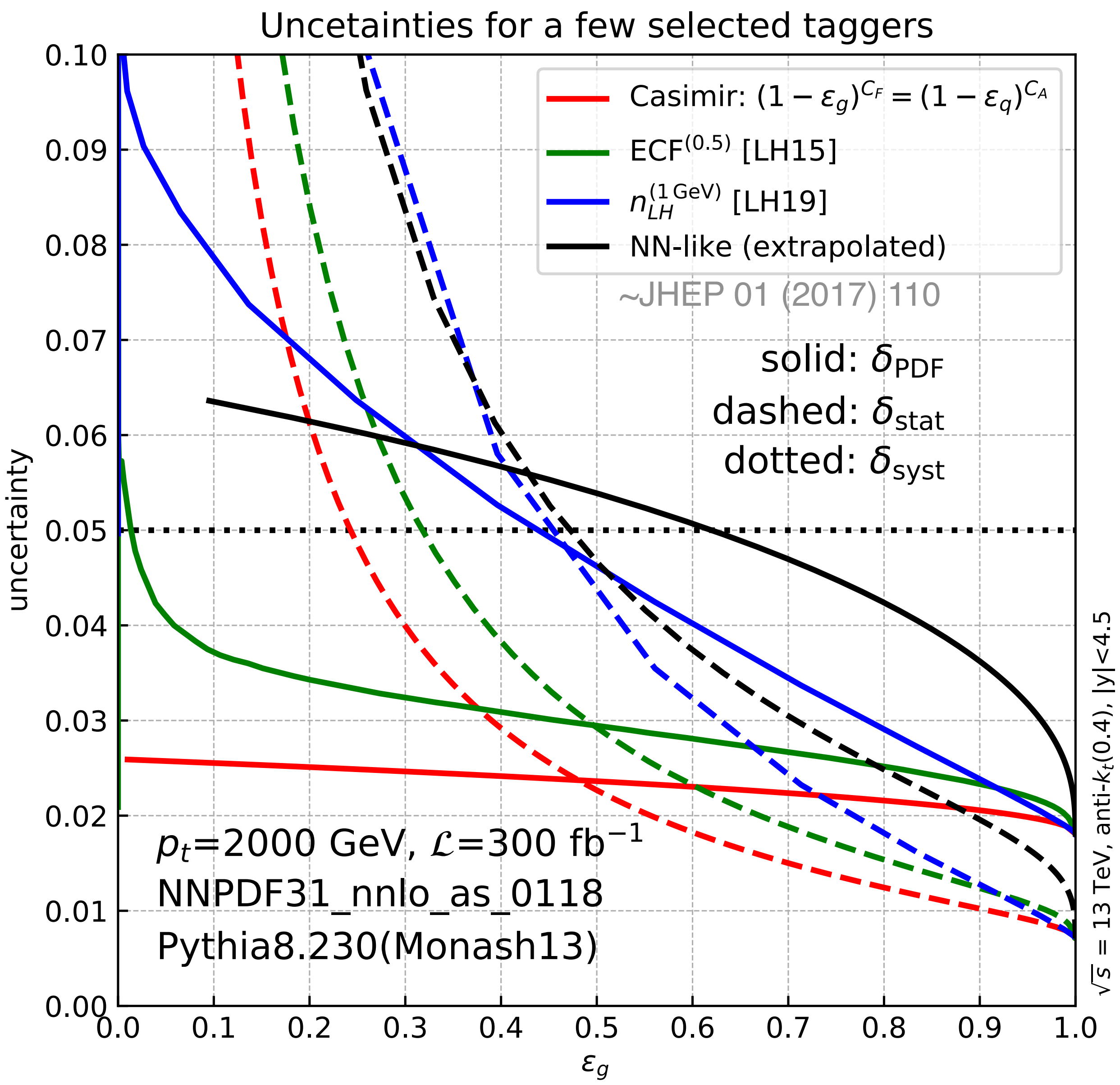
Seems like $\mathbf{n_{LH}}$ has nearly the correct properties !

Gluon PDF with JSS: **not dead yet !**

For the **proceedings**:

Think about / explore other possibilities:

- Performance
  - *Weight instead of cut*
  - *η cut / Z+jets / etc.*
  - *Jet vetos*
  - *Non-square cuts*
- Uncertainties
  - *LL/MC (done)*
  - *Relative q/g*
  - *p_T dependence*



Kinematic limit *O*(many TeV): X → gg

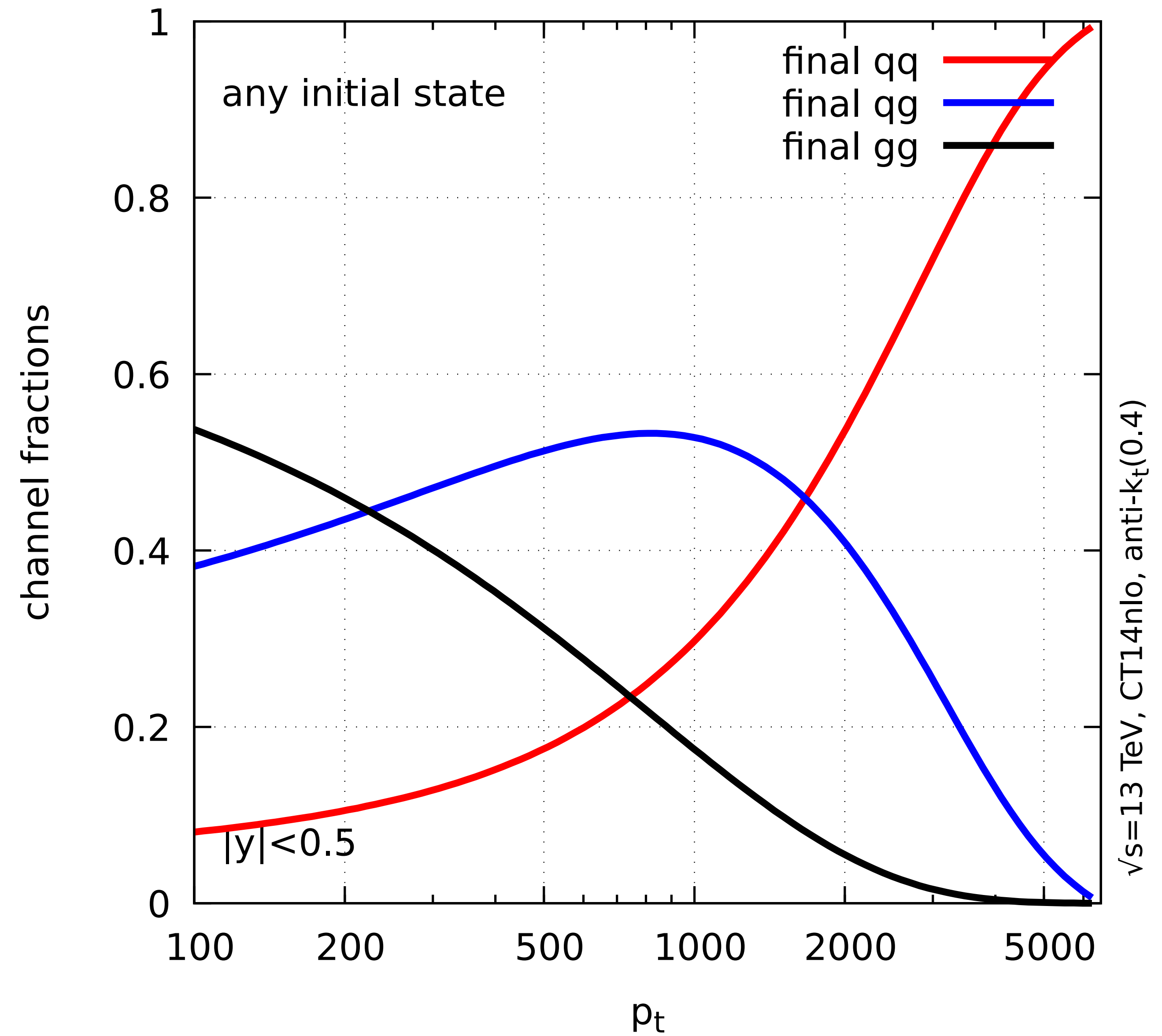
We reach the end and exhaust the phase space.

q/g tagging improves with p_T

quark backgrounds dominate at high p_T

50%² / sqrt(10%) = 2.5

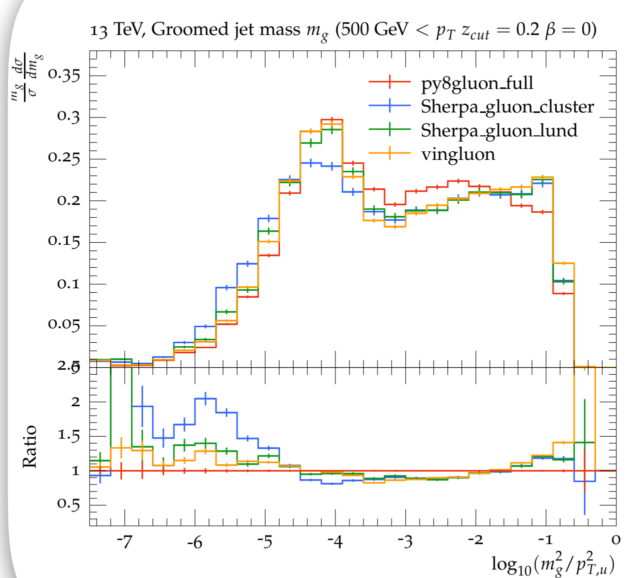
When all else fails, let's pack our bags for **q/g 4 BSM !**

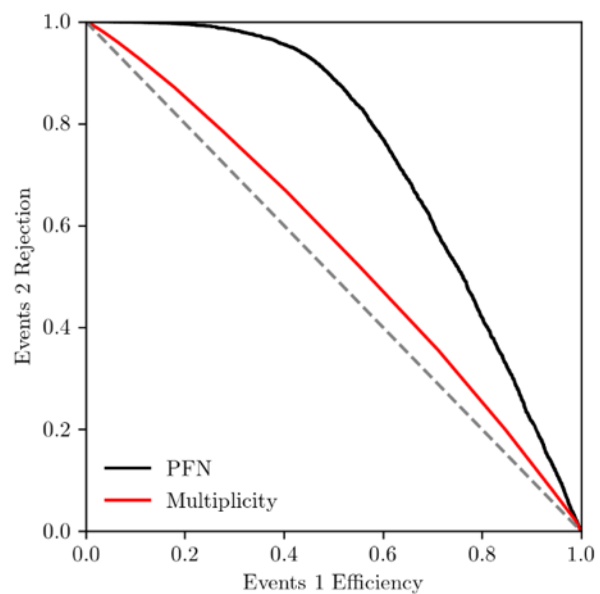


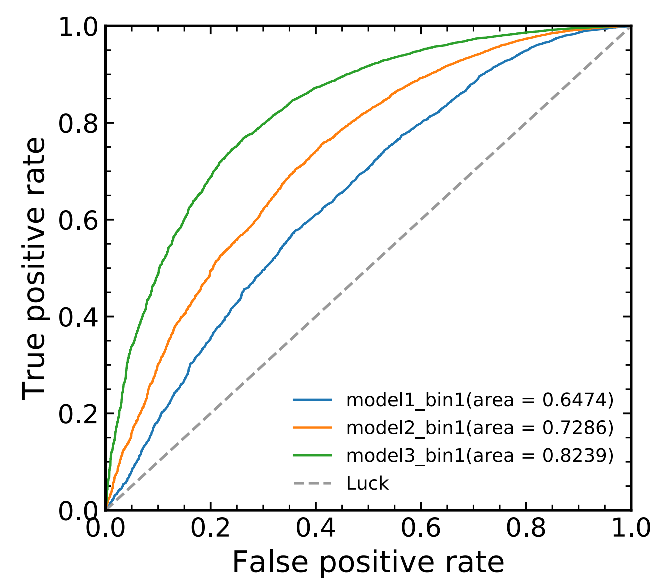
Conclusions / outlook

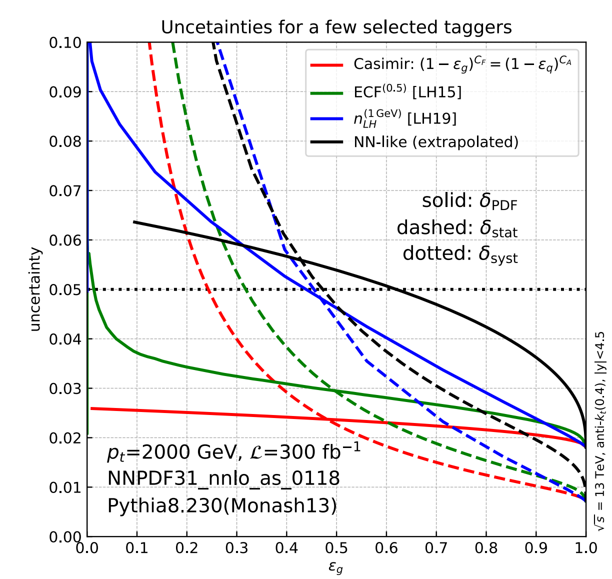
Studies of gluon jets have a long and rich history!

At this Les Houches, we have studied many aspects of gluon jets, spanning scales ranging from below 1 GeV all the way to the kinematic limit.



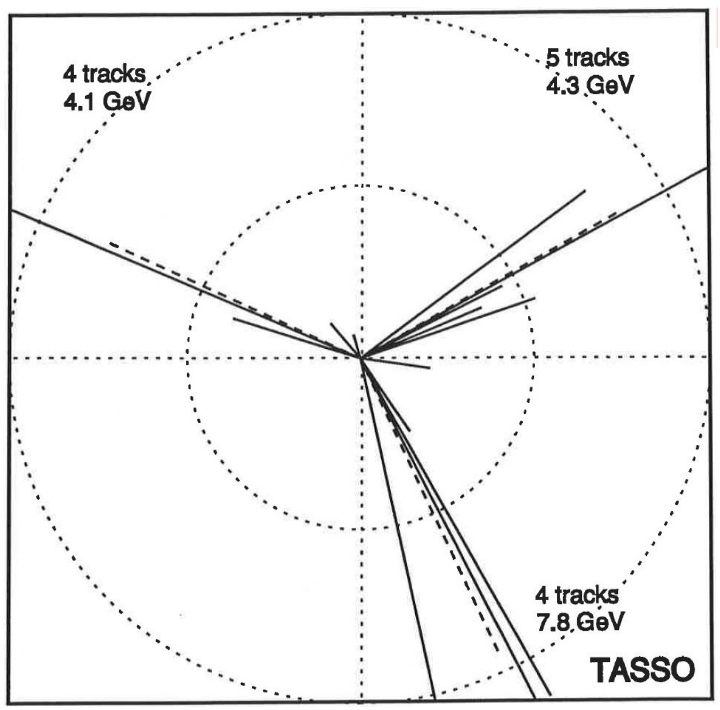


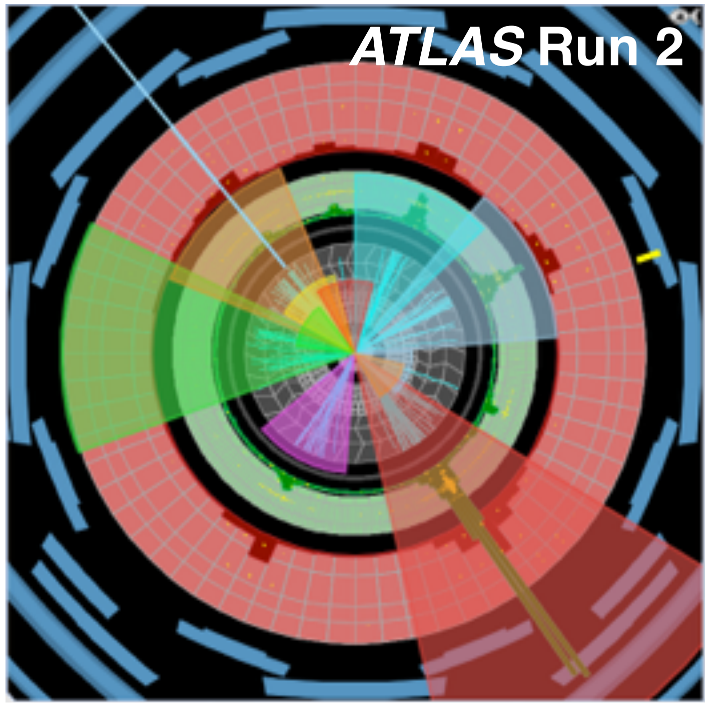


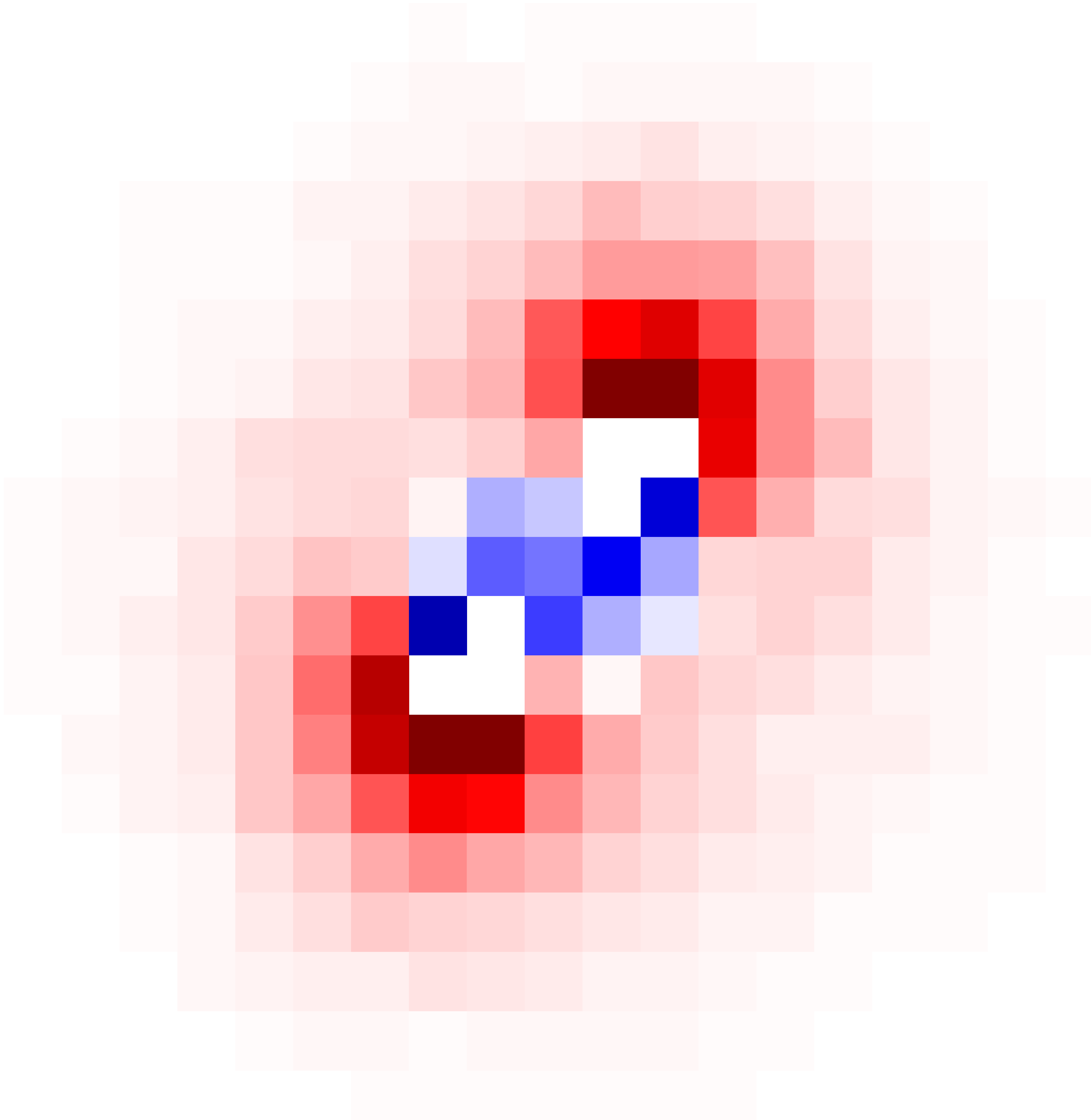


Want to get involved for the proceedings? Join us:

Joyeux anniversaire gluons!

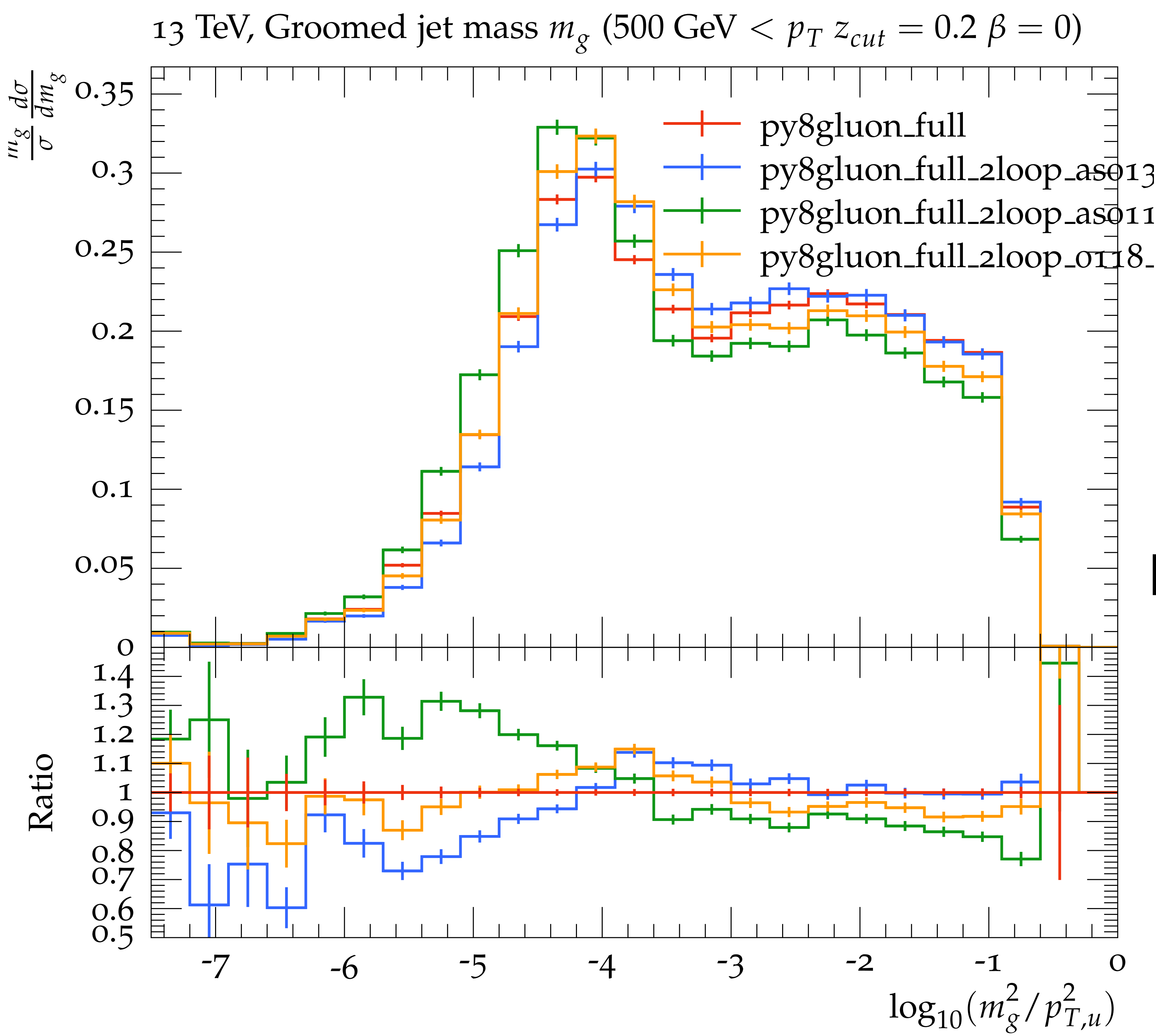






Fin.

$O(\Lambda_{QCD})$: The low mass bump



Important interplay between α_S and NP region: with (re)tuning, potentially (first?) observable at LHC for NP studies a la p227 in LH2015 proceedings.

Professor setup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# LH19 JSS Tuning Studies
# Limits:

   SigmaProcess:alphaSvalue             0.120618 0.149944
   BeamRemnants:primordialKThard        1.506325 1.992728
   SpaceShower:pT0Ref                   0.794576 2.477560
   SpaceShower:pTmaxFudge               0.510417 1.490886
   SpaceShower:pTdampFudge              1.001718 1.497595
   SpaceShower:alphaSvalue              0.100282 0.147812
   TimeShower:alphaSvalue               0.100117 0.149883
   StringPT:sigma                       0.302527 0.368393
   MultipartonInteractions:pT0Ref       1.510489 2.975495
   MultipartonInteractions:alphaSvalue  0.100536 0.148252
```

66 samplings
25k Pythia events each

```
# D2 (DTune)

# GOF 4.344819
# UNITGOF 4.344819
# NDOF -1.000000

SigmaProcess:alphaSvalue             0.149943
BeamRemnants:primordialKThard        1.506331
SpaceShower:pT0Ref                   2.477553
SpaceShower:pTmaxFudge               1.490885
SpaceShower:pTdampFudge              1.001720
SpaceShower:alphaSvalue              0.147812
TimeShower:alphaSvalue               0.128572
StringPT:sigma                       0.302527
MultipartonInteractions:pT0Ref       2.975367
MultipartonInteractions:alphaSvalue  0.130993
```

```
# All-JSS Tune

# Minimisation result:
#
# GOF 29.146527
# UNITGOF 29.146527
# NDOF 98.000000

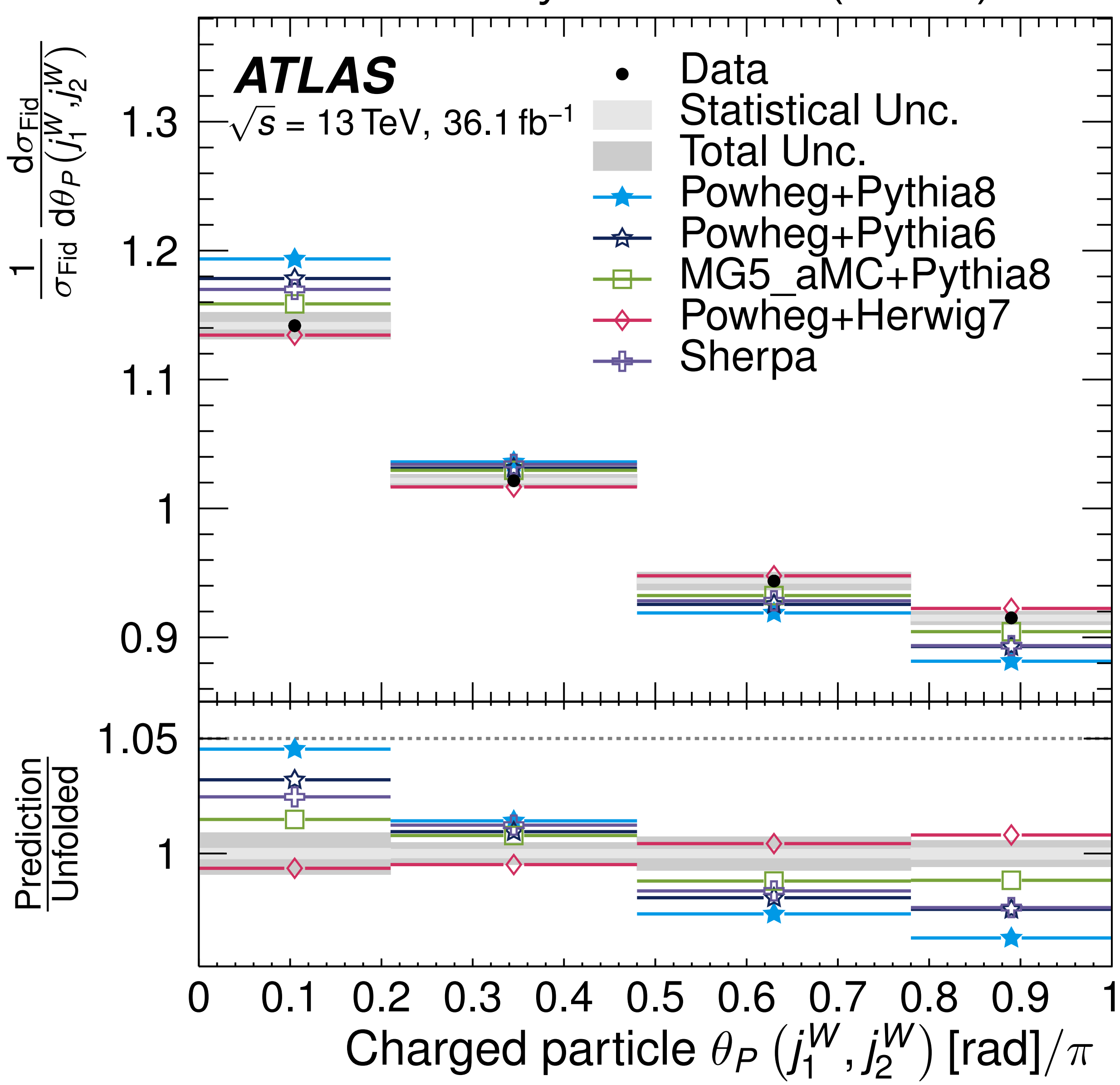
SigmaProcess:alphaSvalue             0.136386
BeamRemnants:primordialKThard        1.506326
SpaceShower:pT0Ref                   2.224143
SpaceShower:pTmaxFudge               1.490886
SpaceShower:pTdampFudge              1.471304
SpaceShower:alphaSvalue              0.147812
TimeShower:alphaSvalue               0.135299
StringPT:sigma                       0.302527
MultipartonInteractions:pT0Ref       2.695938
MultipartonInteractions:alphaSvalue  0.148251
```

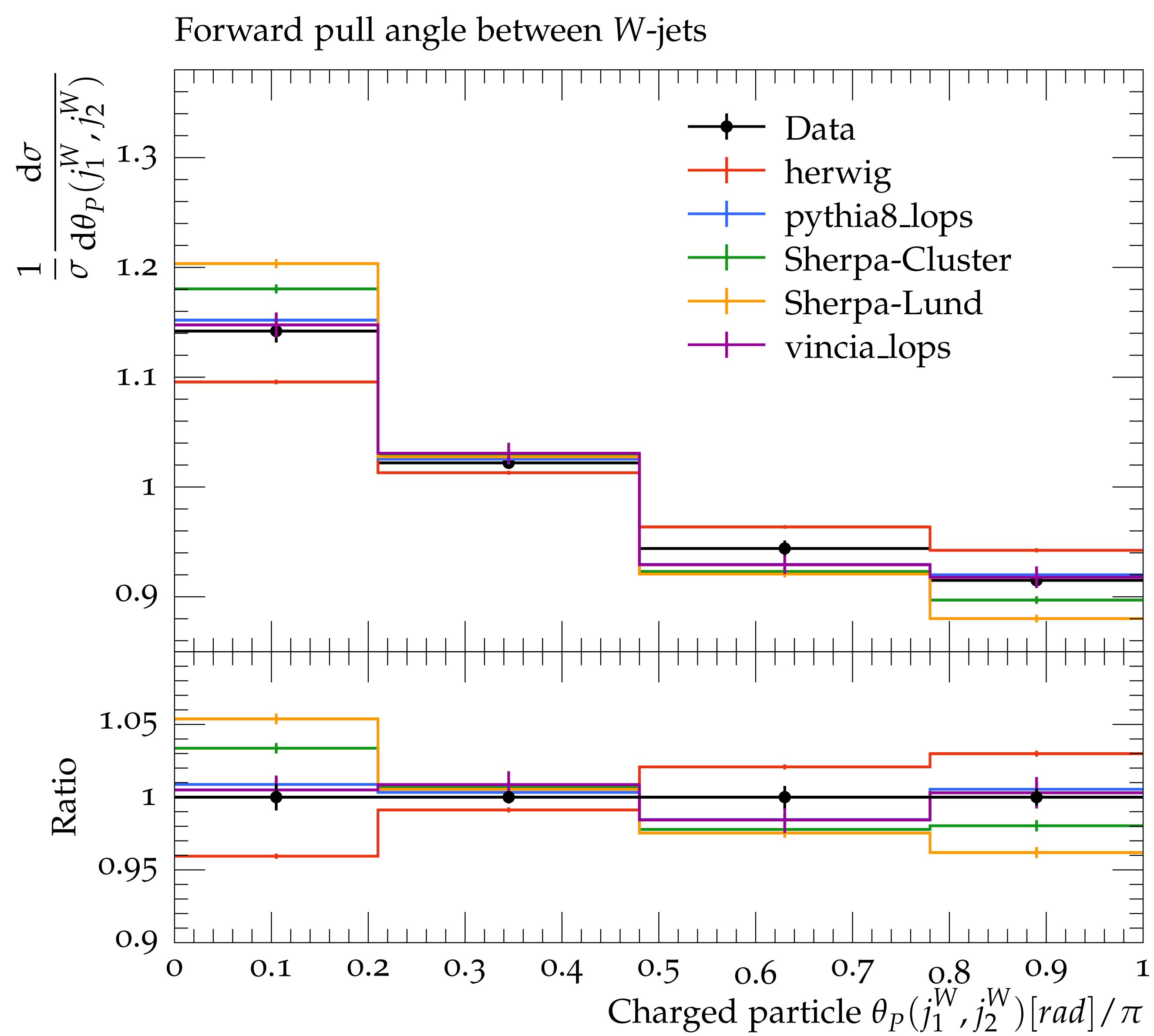
```
# Not really A14


SigmaProcess:alphaSvalue             0.144
BeamRemnants:primordialKThard        1.72
SpaceShower:pT0Ref                   1.30
SpaceShower:pTmaxFudge               0.95
SpaceShower:pTdampFudge              1.21
SpaceShower:alphaSvalue              0.125
TimeShower:alphaSvalue               0.126
MultipartonInteractions:pT0Ref       1.98
MultipartonInteractions:alphaSvalue  0.118
```

O(10 GeV): Jet Pull

Eur. Phys. J. C 78 (2018) 847





O(10 GeV): Jet Pull

Eur. Phys. J. C 78 (2018) 847