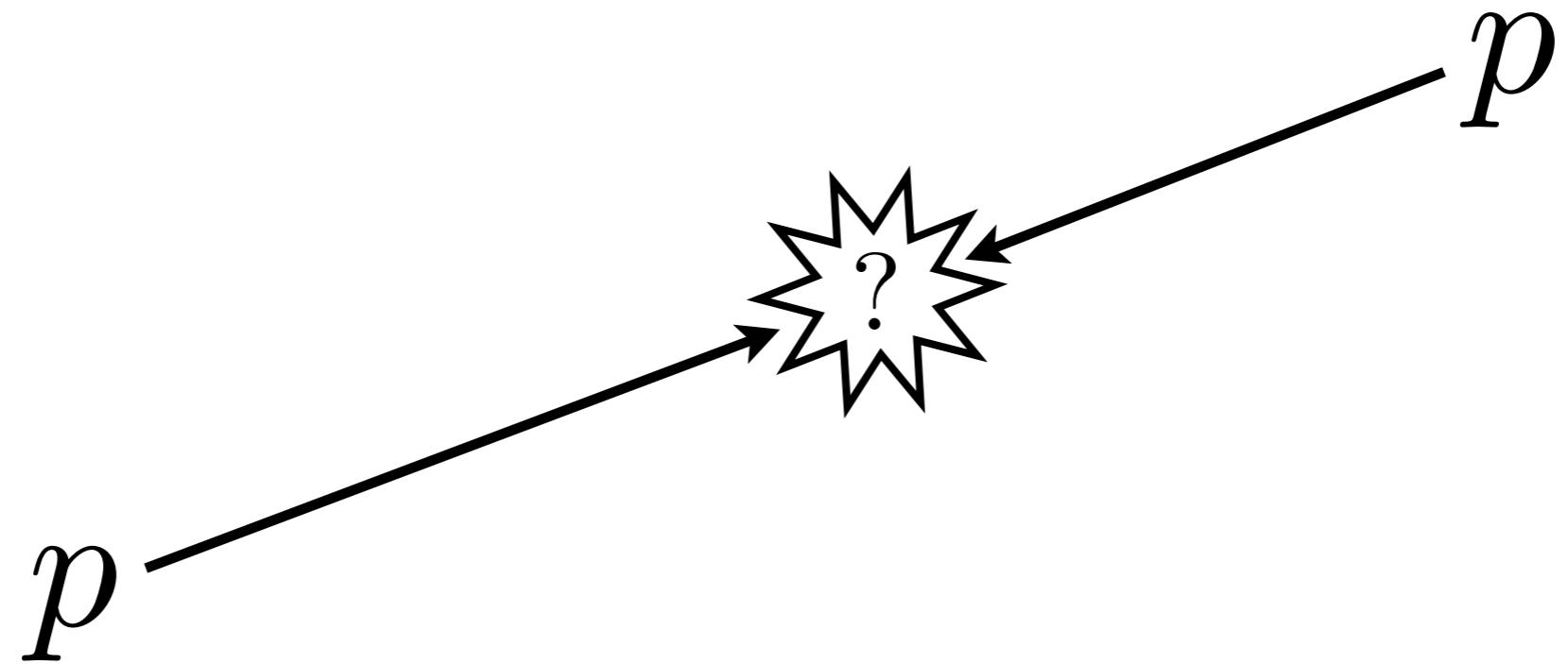


Jet Substructure at the Frontiers of Particle Physics

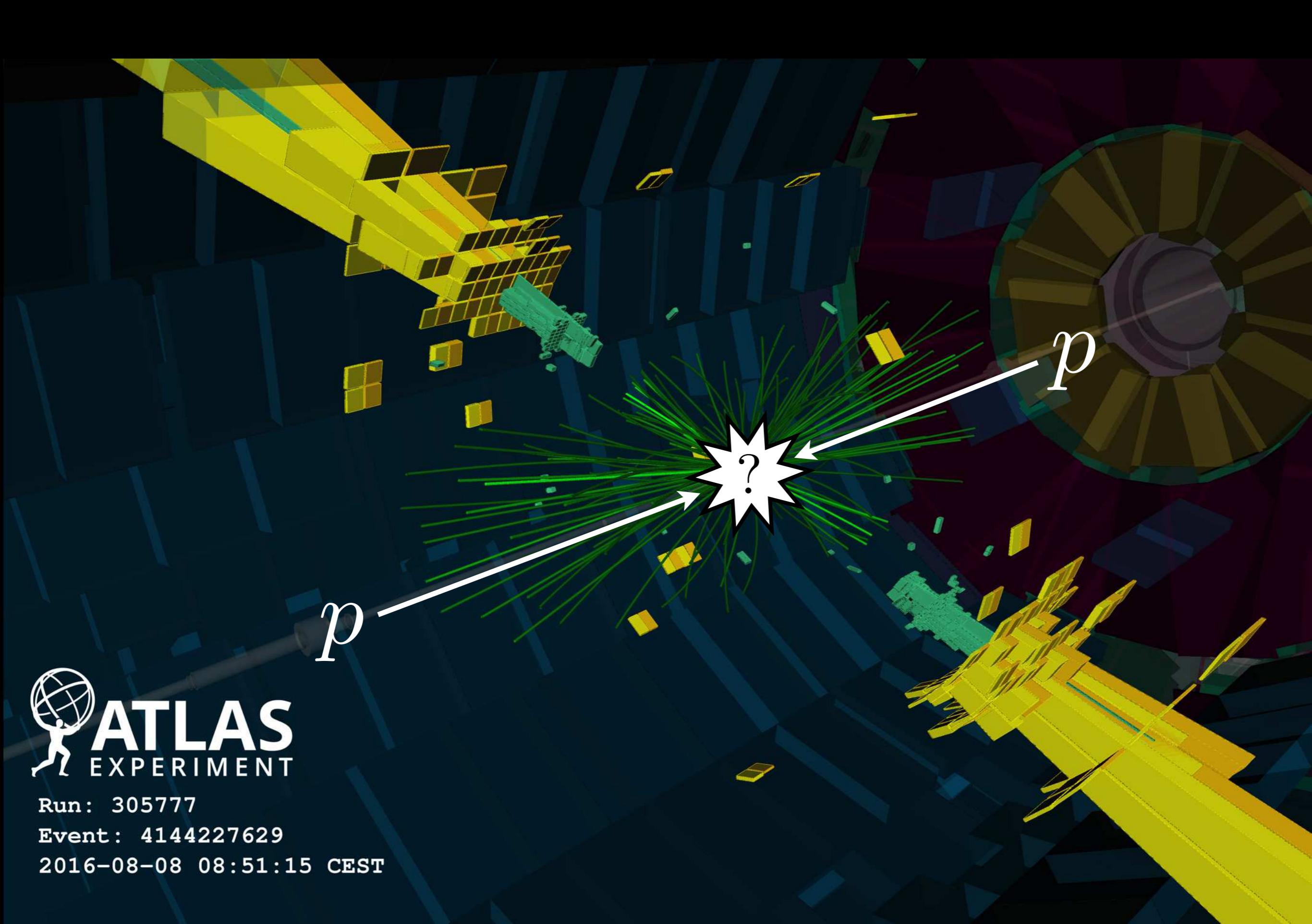


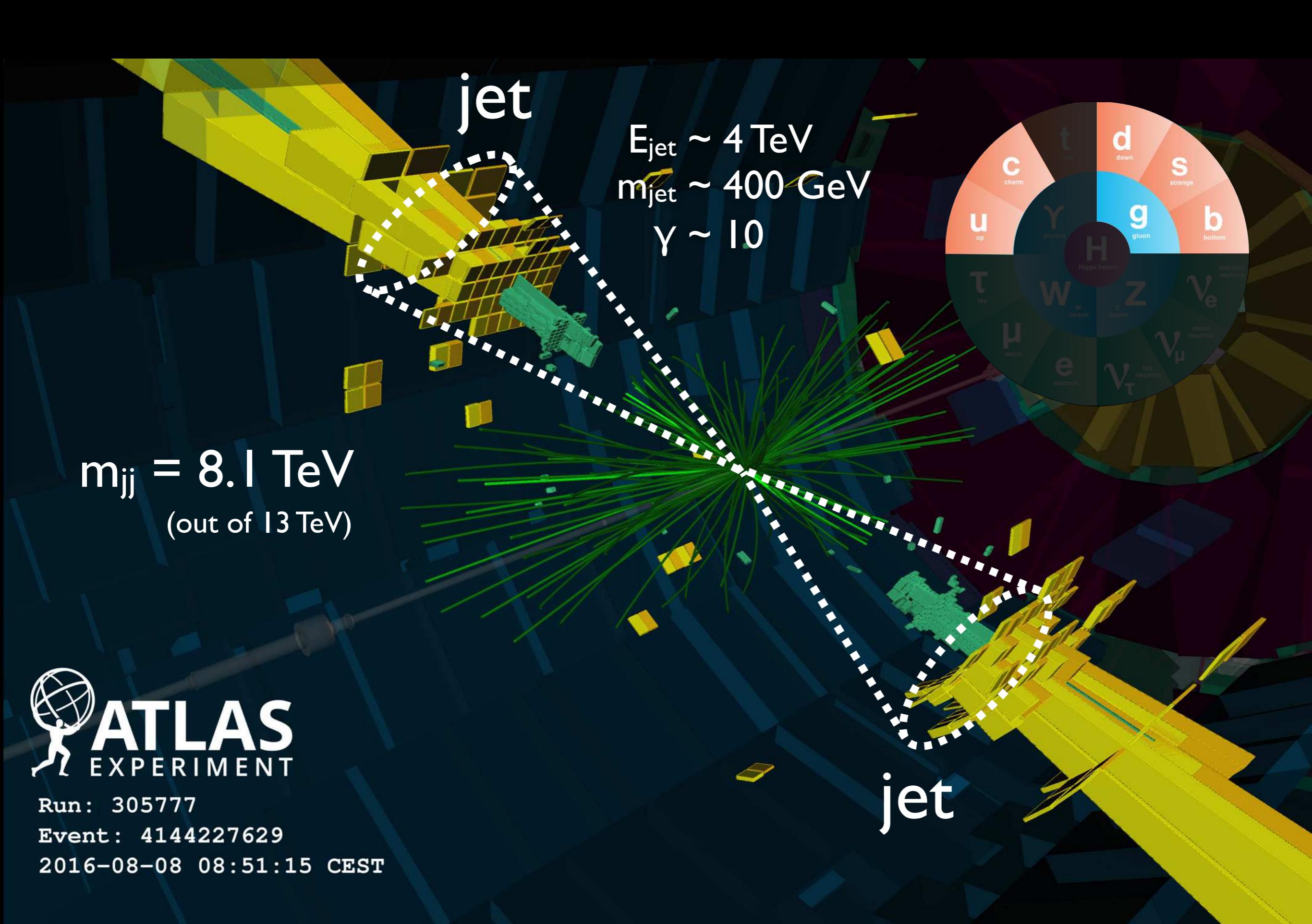
Jesse Thaler

$m_p \sim 0.938 \text{ GeV}$
 $E_p \sim 6.5 \text{ TeV}$
 $\gamma = E/m \sim 7000 (!)$



Milano Physics Colloquium
March 27, 2018





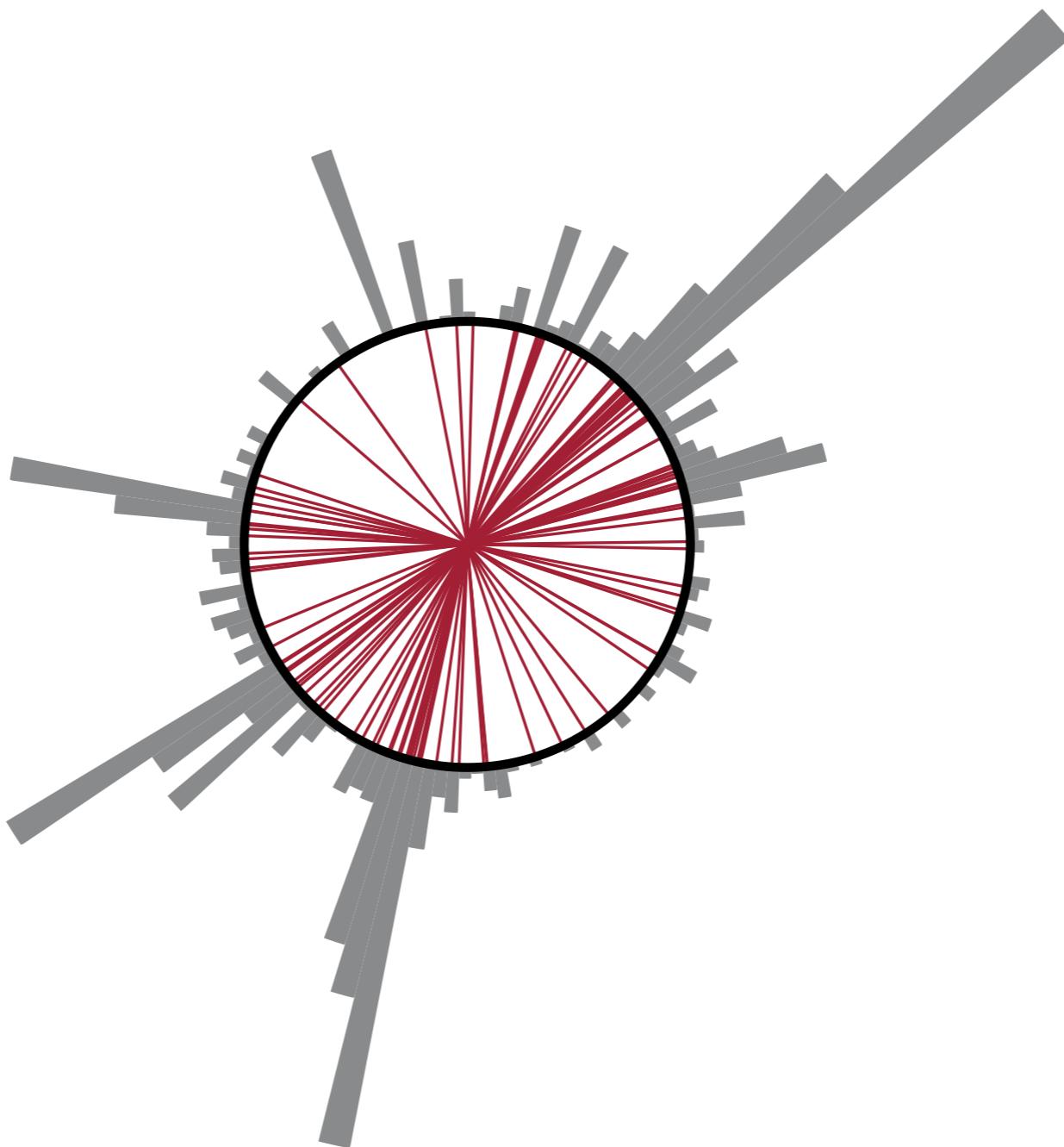
Energy $7 \rightarrow 8 \rightarrow 13 \rightarrow 14 \text{ TeV}$

Luminosity $5 \rightarrow 30 \rightarrow 150 \rightarrow 3000 \text{ fb}^{-1}$

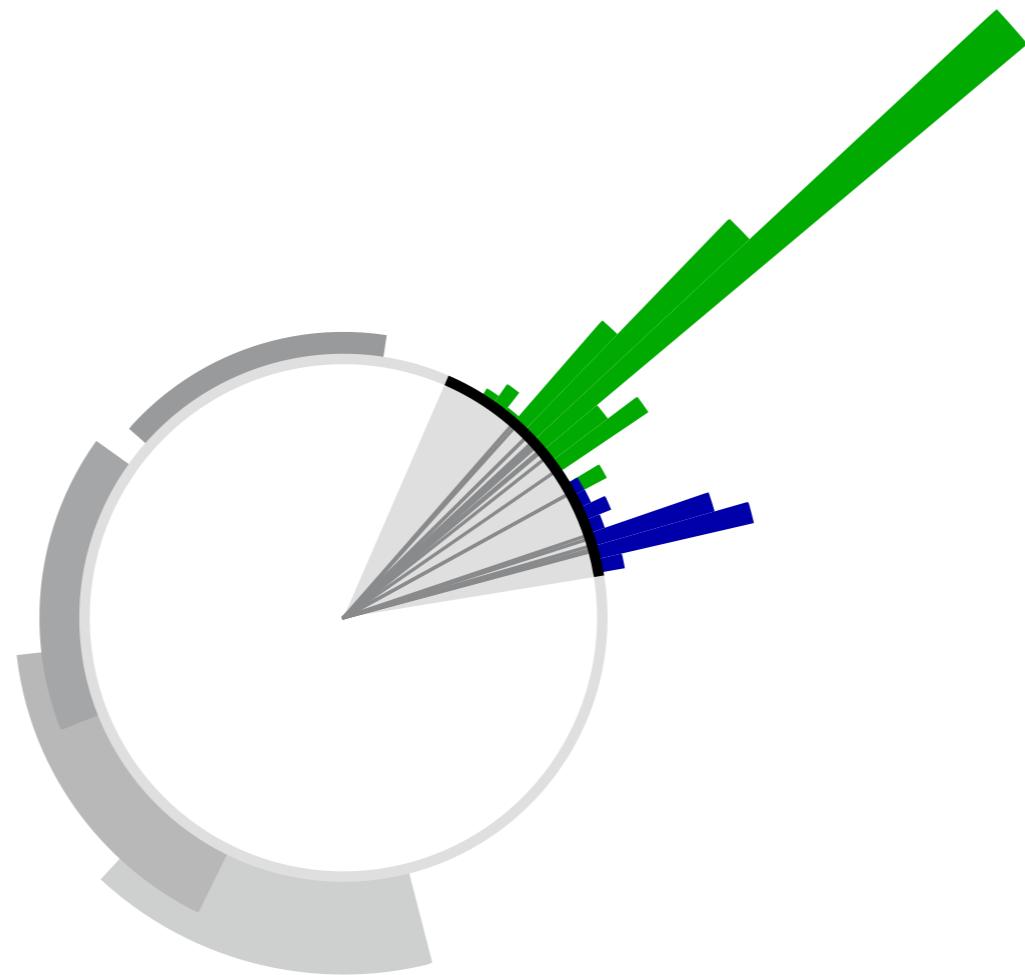
Precision $LO \rightarrow NLO \rightarrow NNLO \rightarrow N^3LO$

Hierarchy $m_{\text{proton}} \ll m_{\text{jet}} \ll m_{\text{collision}}$

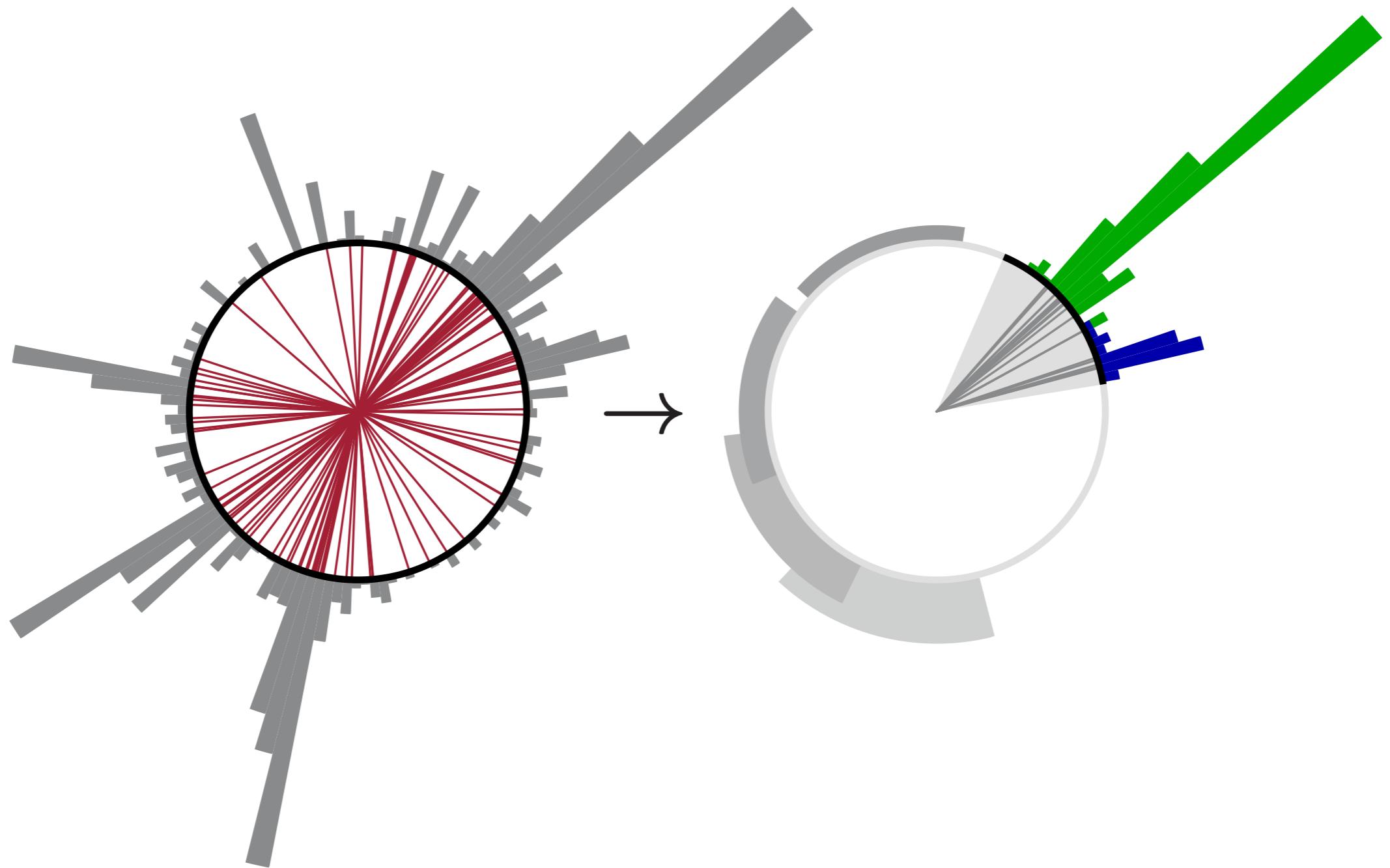
Complexity



Simplicity



“*Simplexity*”





Exposing the QCD Splitting Function with CMS Open Data

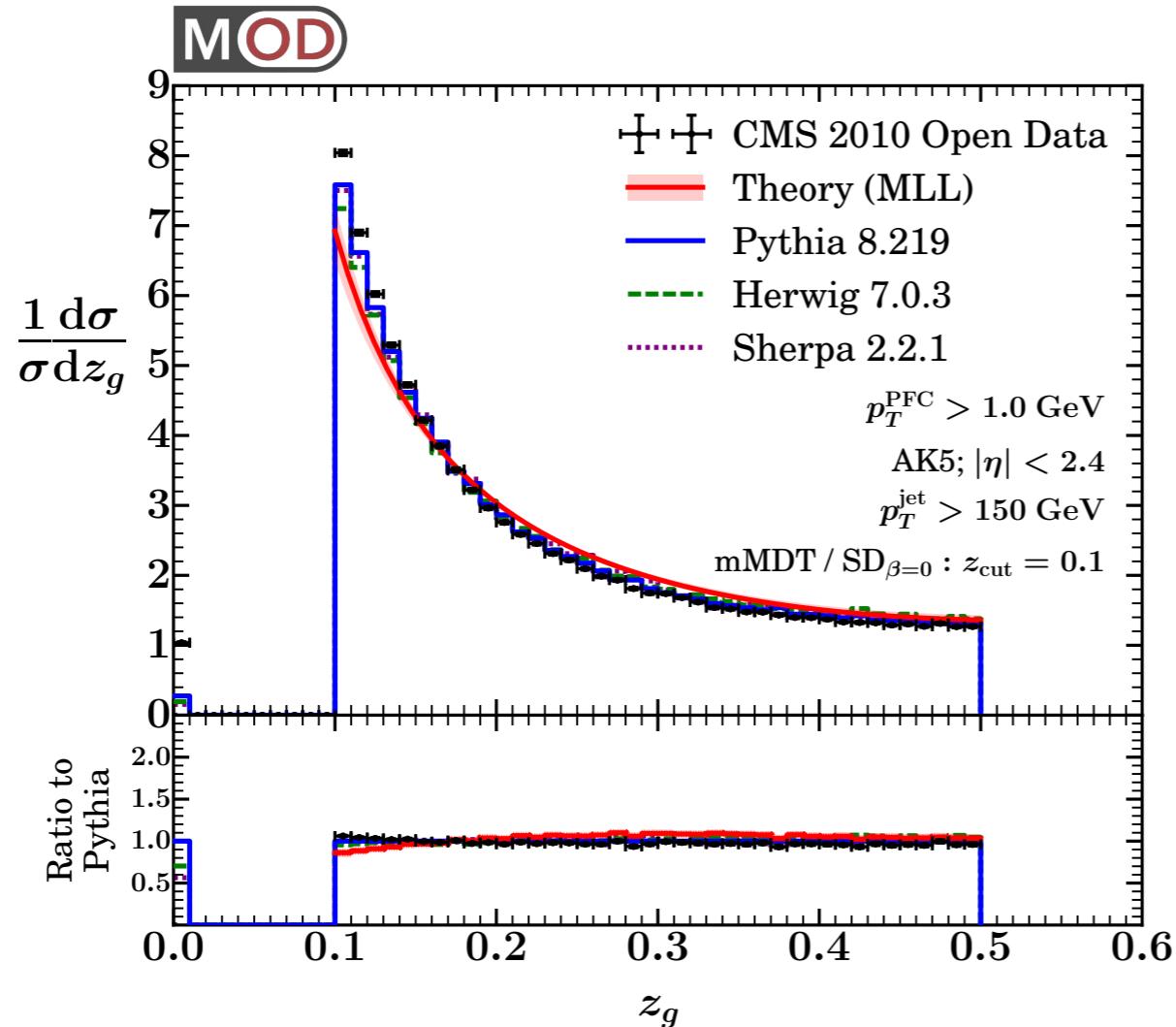
Andrew Larkoski,^{1,*} Simone Marzani,^{2,†} Jesse Thaler,^{3,‡} Aashish Tripathee,^{3,§} and Wei Xue^{3,||}

¹*Physics Department, Reed College, Portland, Oregon 97202, USA*

²*University at Buffalo, The State University of New York, Buffalo, New York 14260-1500, USA*

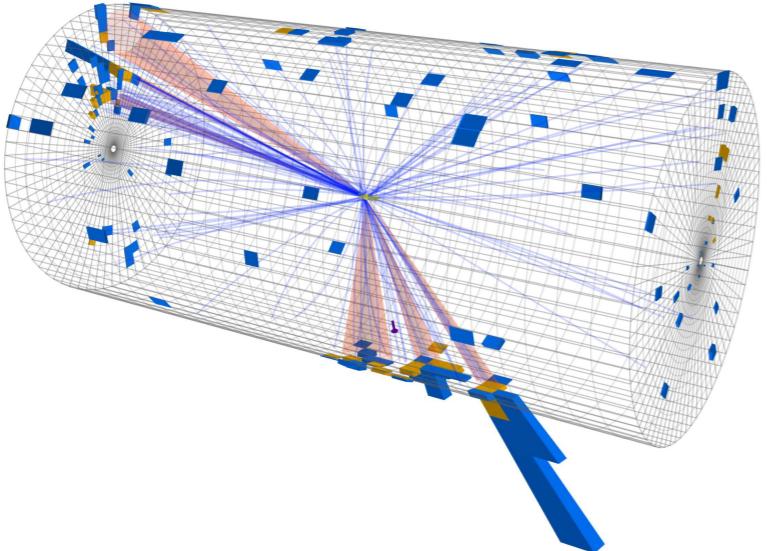
³*Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

(Received 9 May 2017; revised manuscript received 27 July 2017; published 26 September 2017)

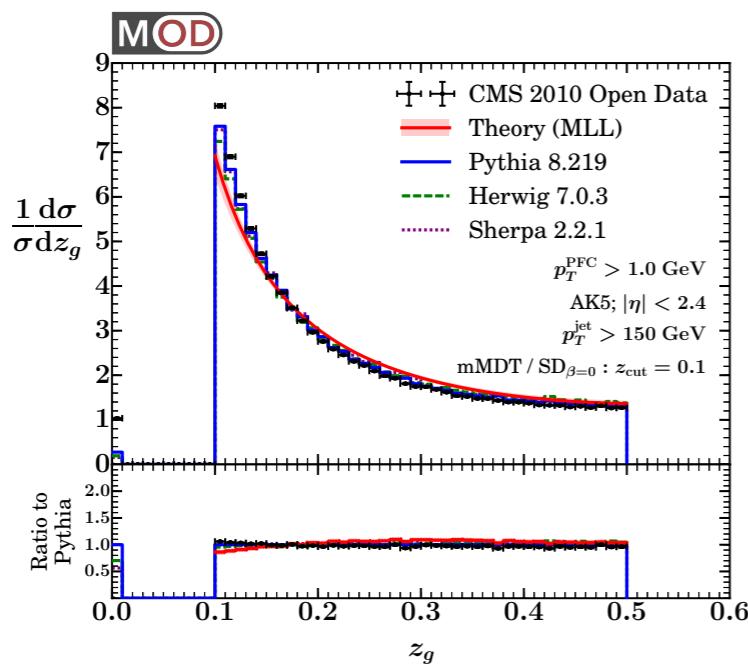


open data
CERN
“Accelerating science
through public data”

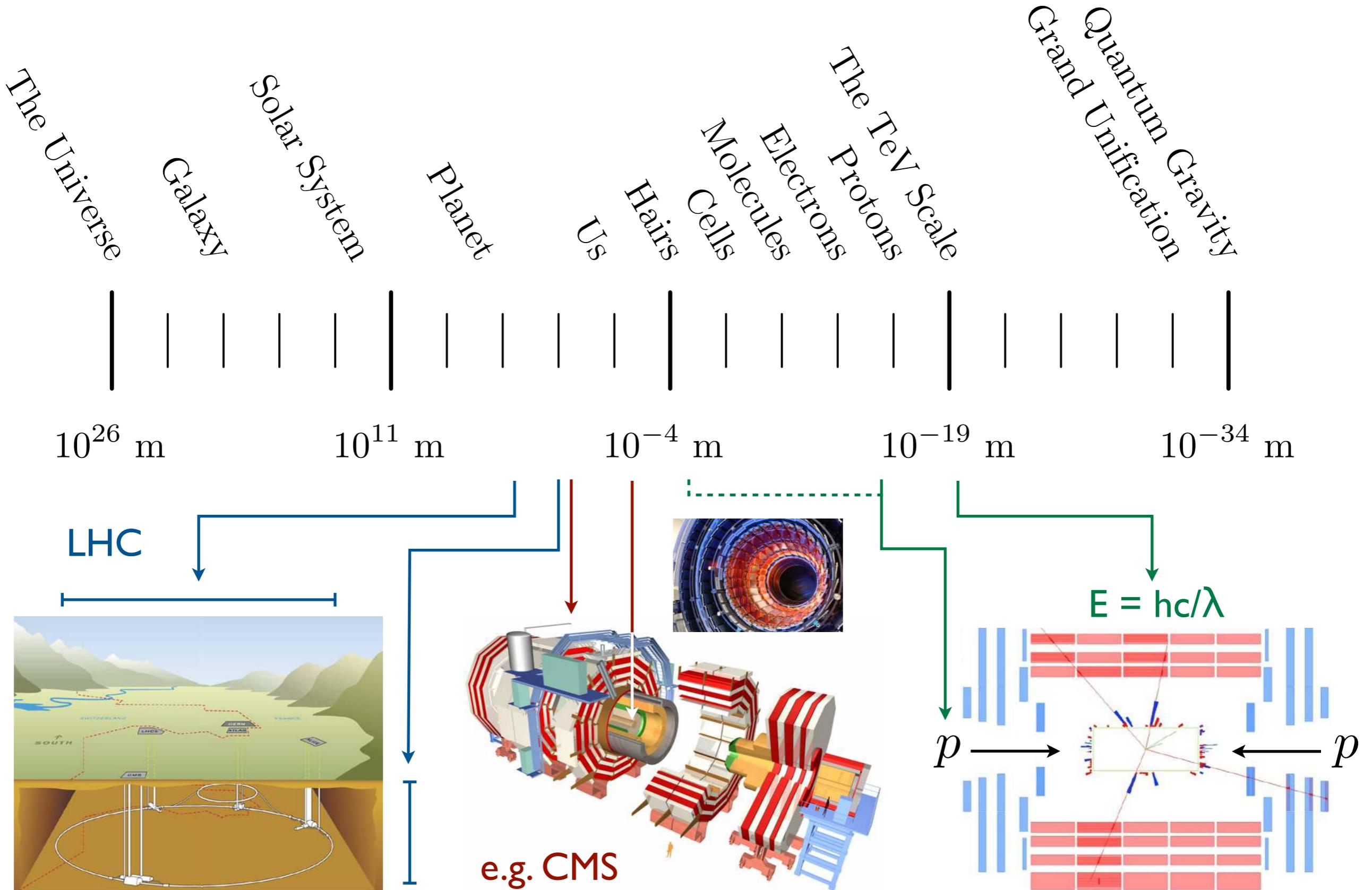
Jet Substructure



*Boosting the Search
for New Phenomena*



*Pushing the Boundaries
of Quantum Field Theory*





Mesons

$\pi^\pm \pi^0 \eta K^\pm K^0 \eta' D^\pm D^0 D_s^\pm \eta_c B^\pm B^0 B_s^0 \eta_b \dots$



Baryons

$p n \Lambda^0 \Sigma^+ \Sigma^0 \Sigma^- \Xi^0 \Xi^- \dots$

$\Delta^{++} \Delta^+ \Delta^0 \Delta^- \Sigma^{*+} \Sigma^{*0} \Sigma^{*-} \Xi^{*0} \Xi^{*-} \Omega^- \dots$



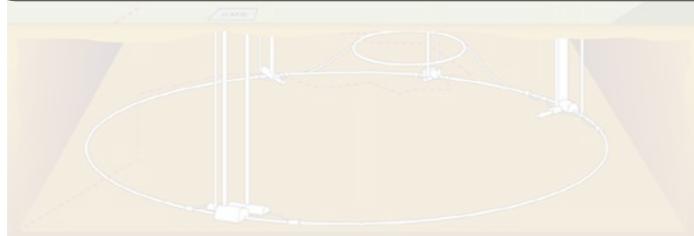
Tetraquarks (?)

$X(3872) Y(4260) Z(4430) \dots$



Pentaquarks (?)

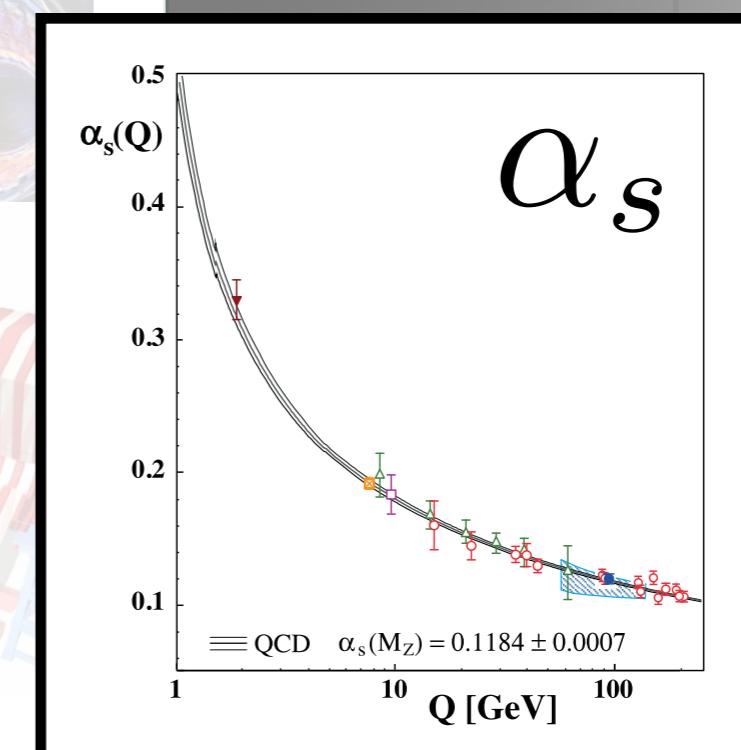
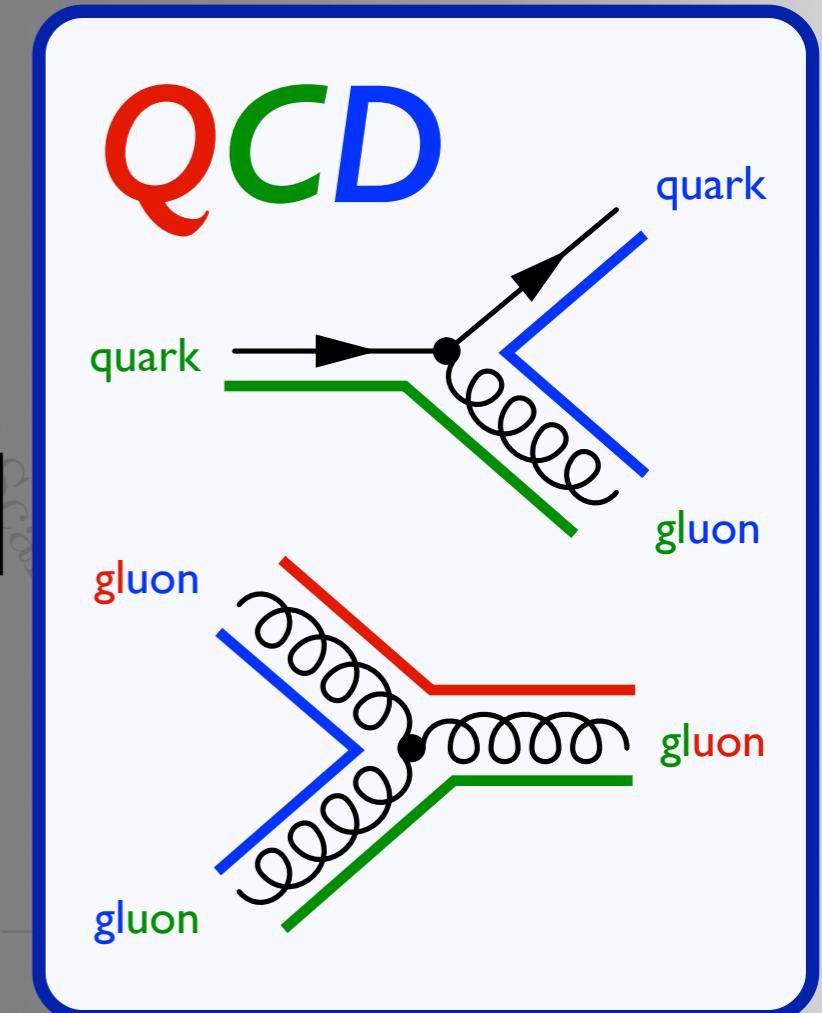
$P_c^+(4450) \dots$

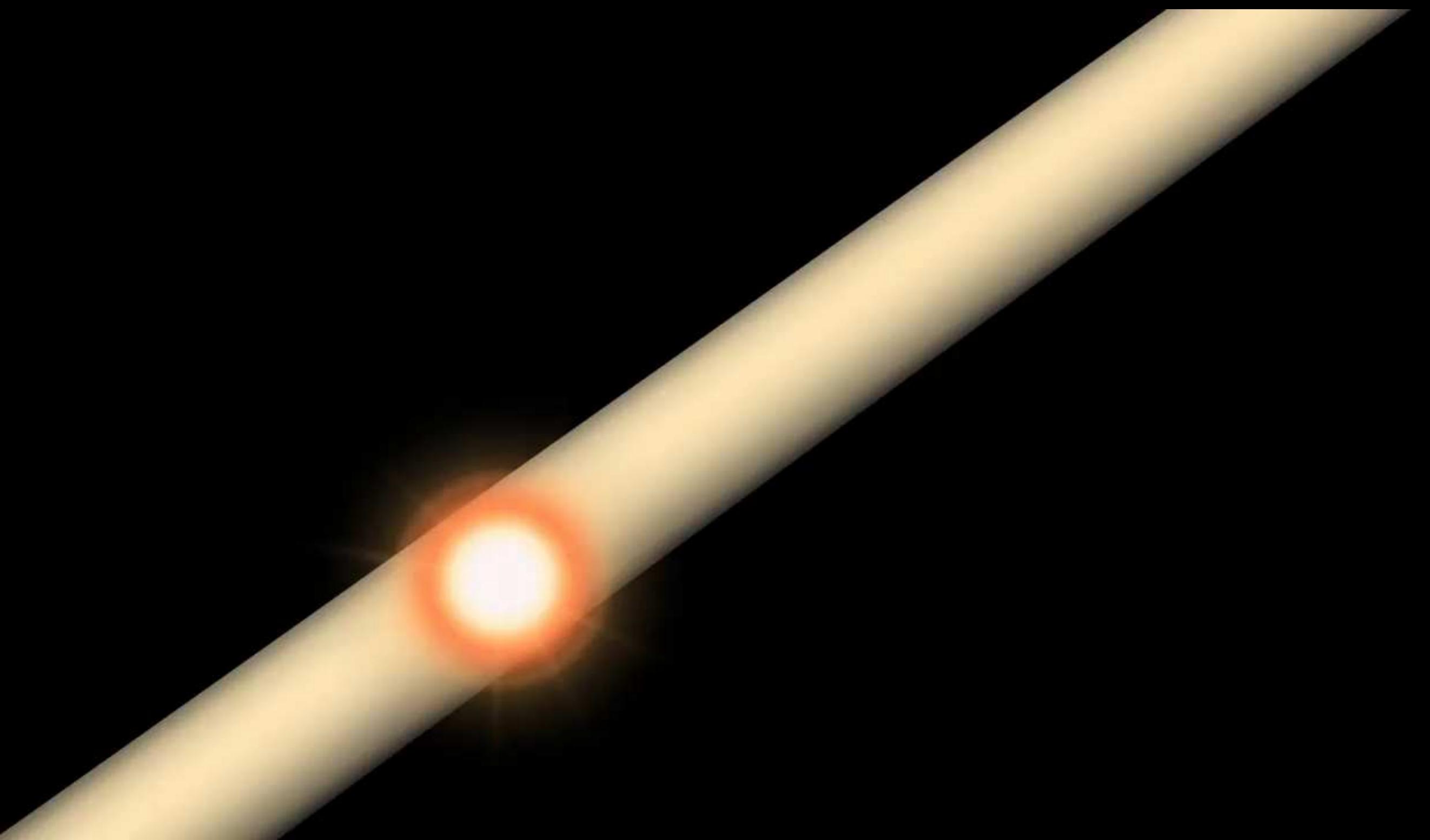


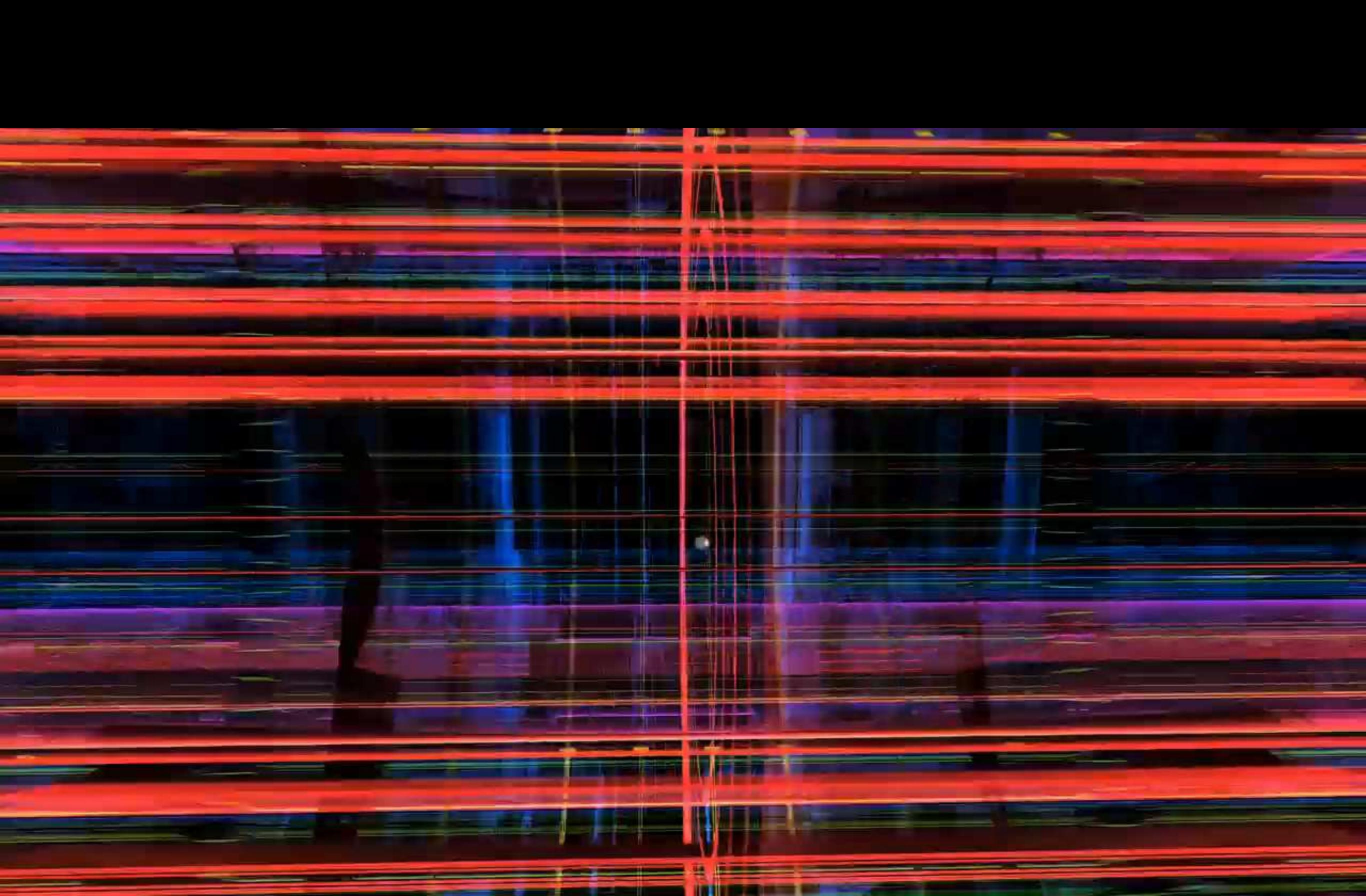
|

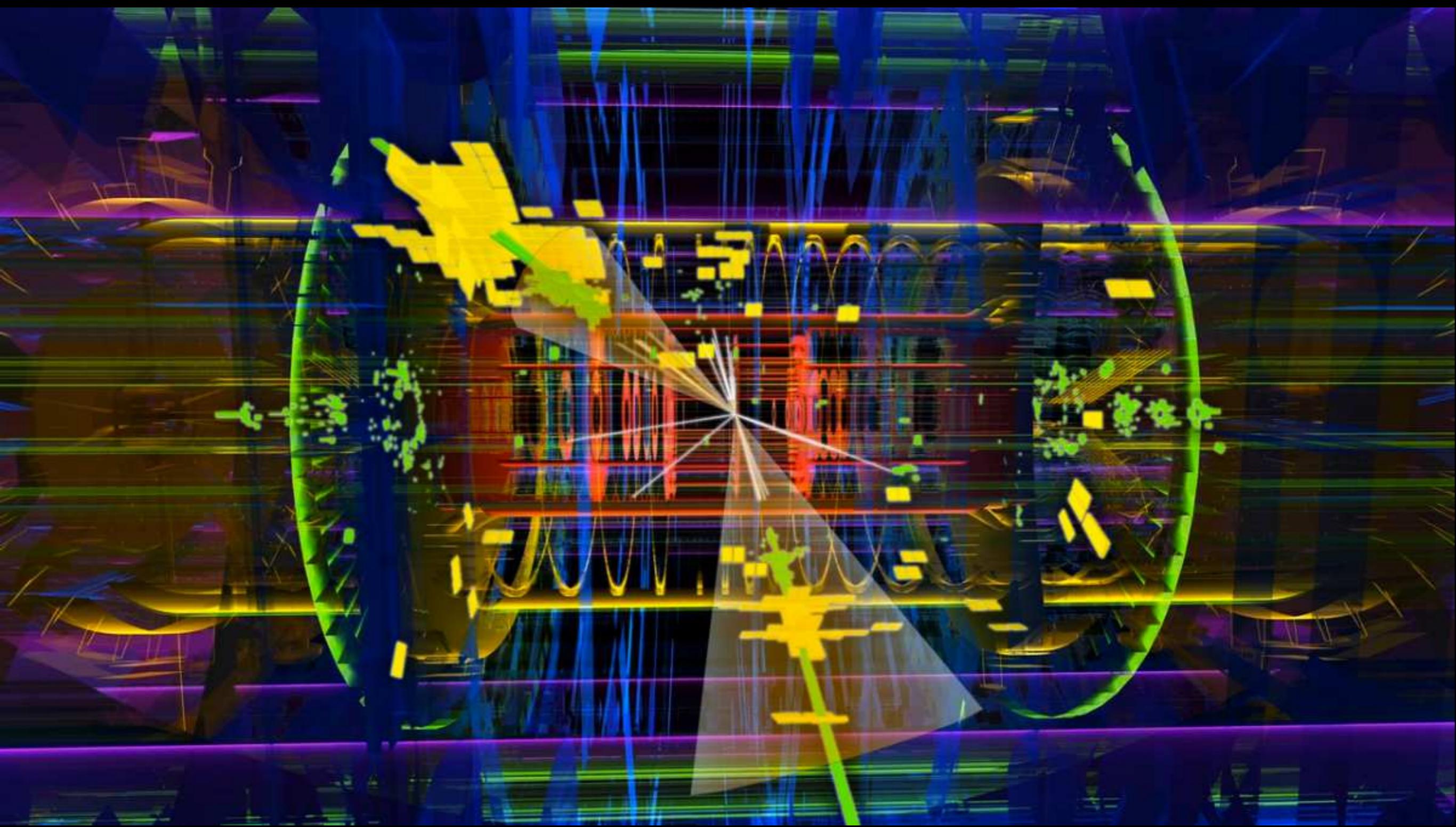
e.g. CMS

Jets



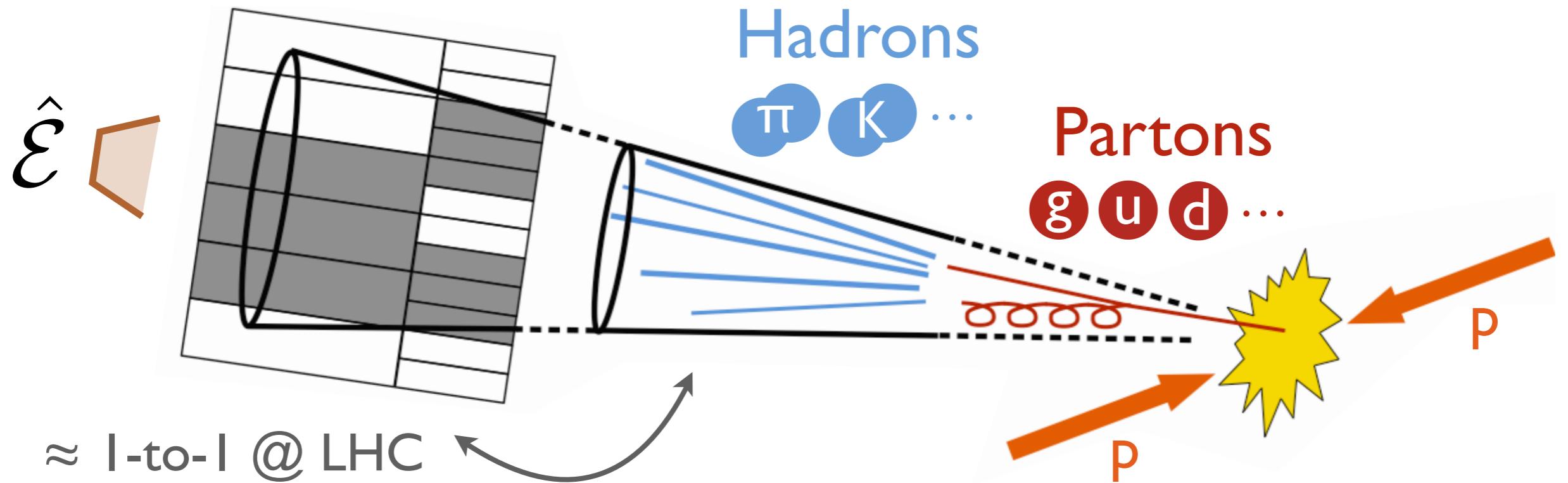






Theory

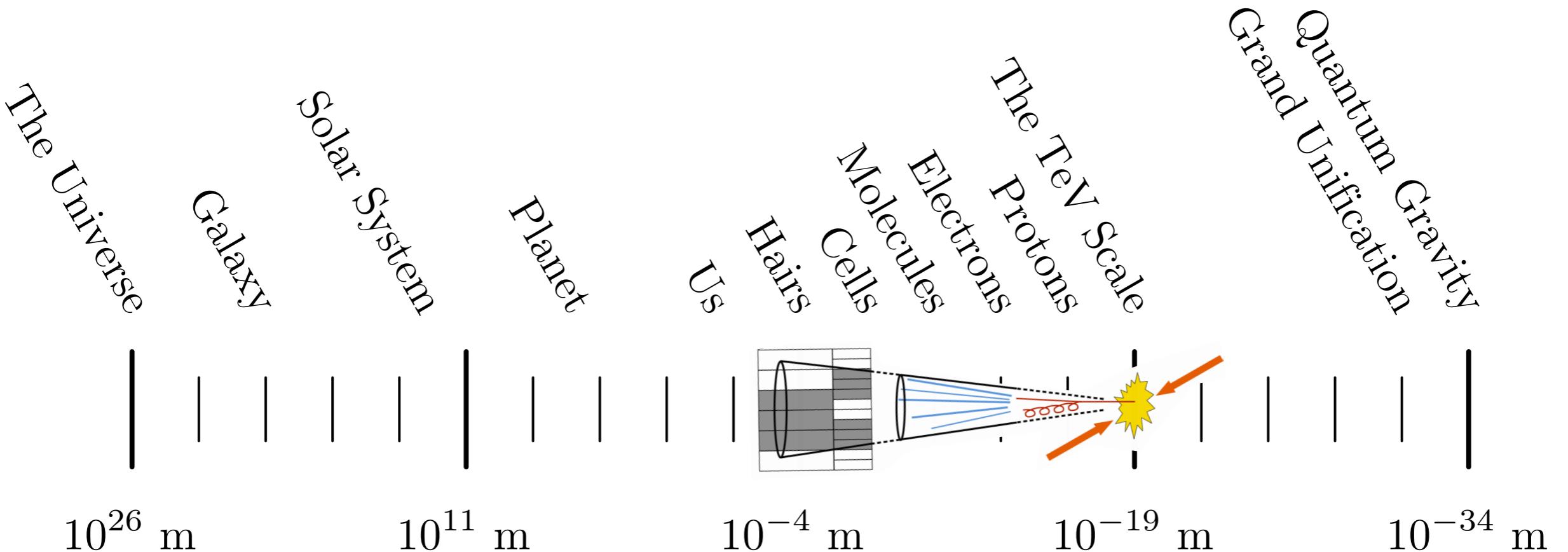
Detection

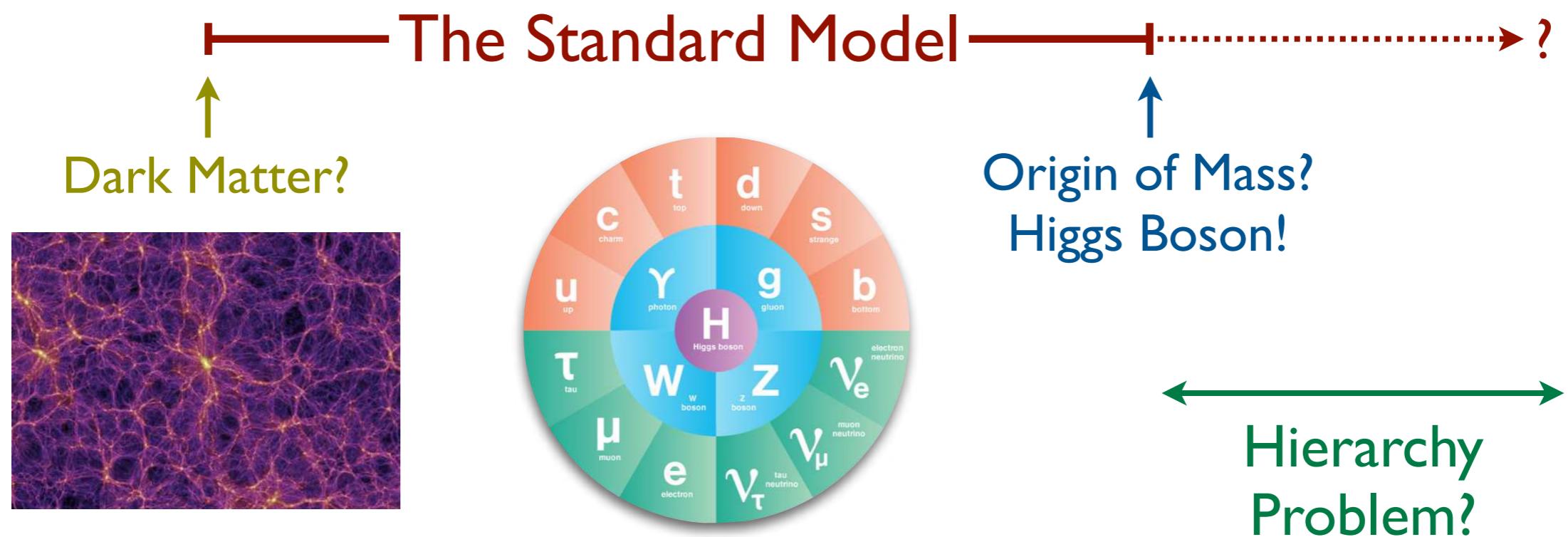
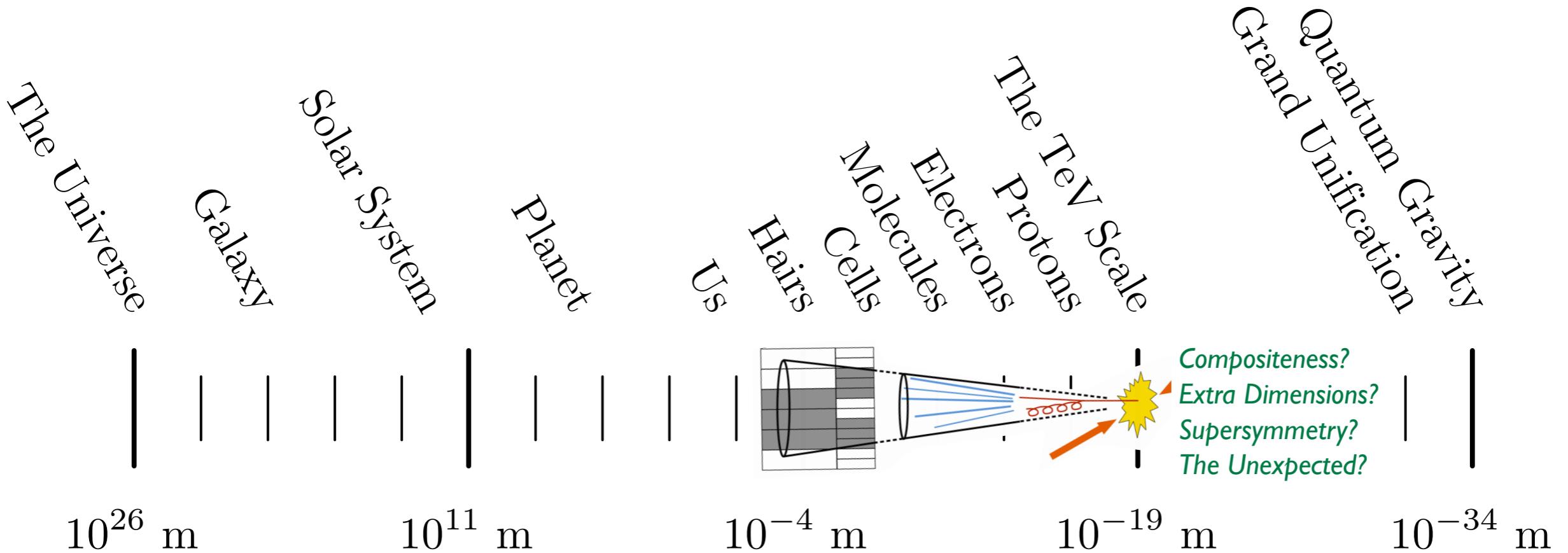


Stress-Energy
Flow Operator:

$$\hat{\mathcal{E}} \simeq \lim_{t \rightarrow \infty} \hat{n}_i T^{0i}(t, vt\hat{n})$$

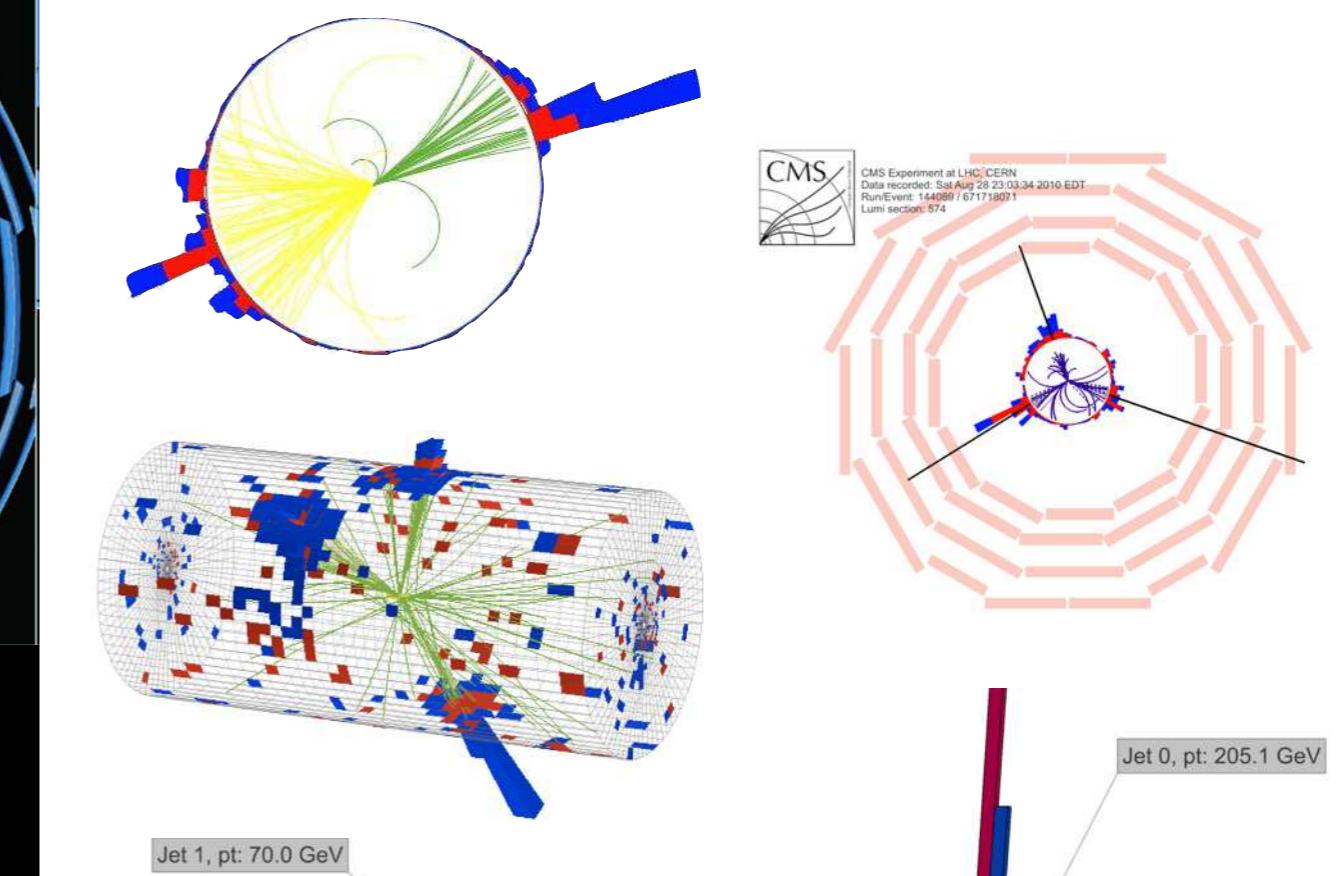
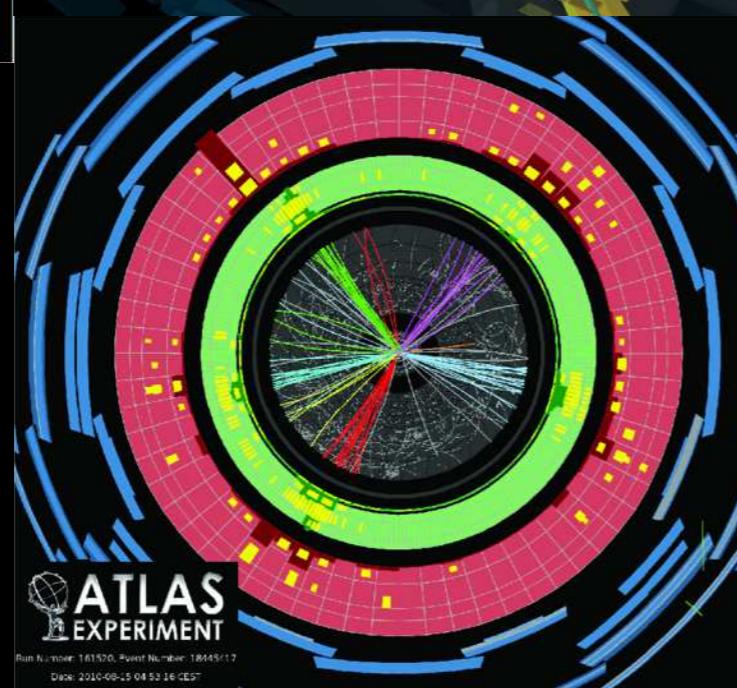
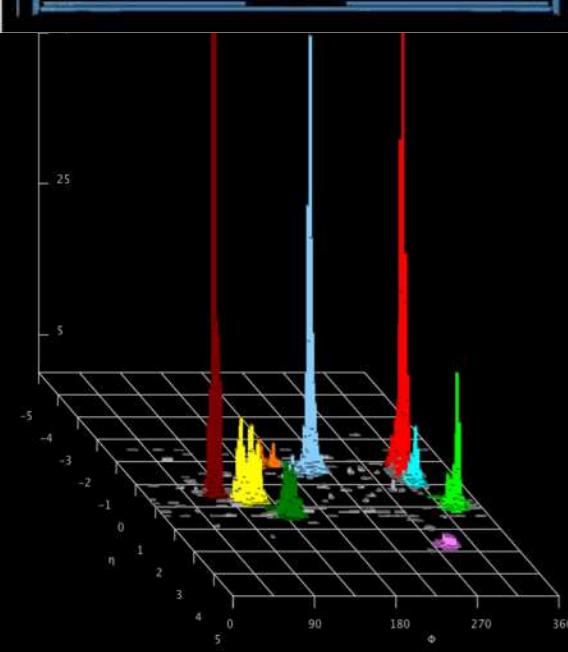
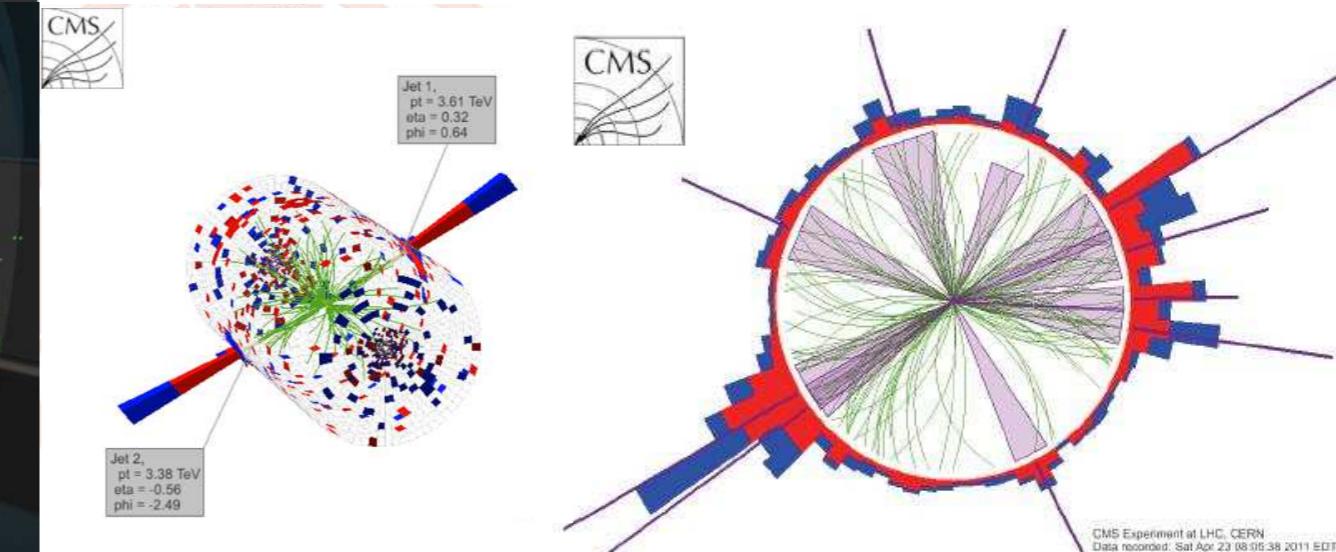
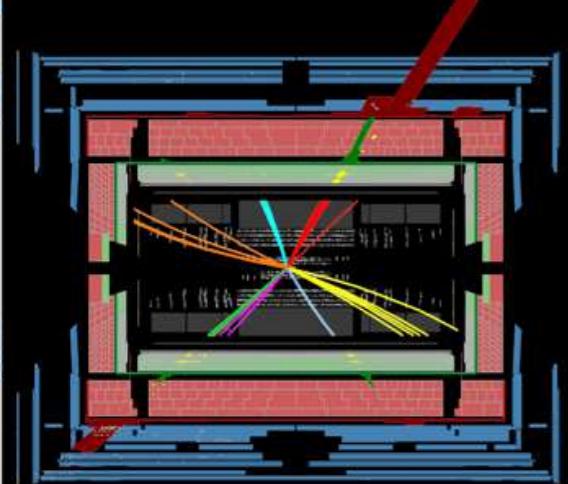
[Sveshnikov, Tkachov, 1995; Mateu, Stewart, JDT, 2012]



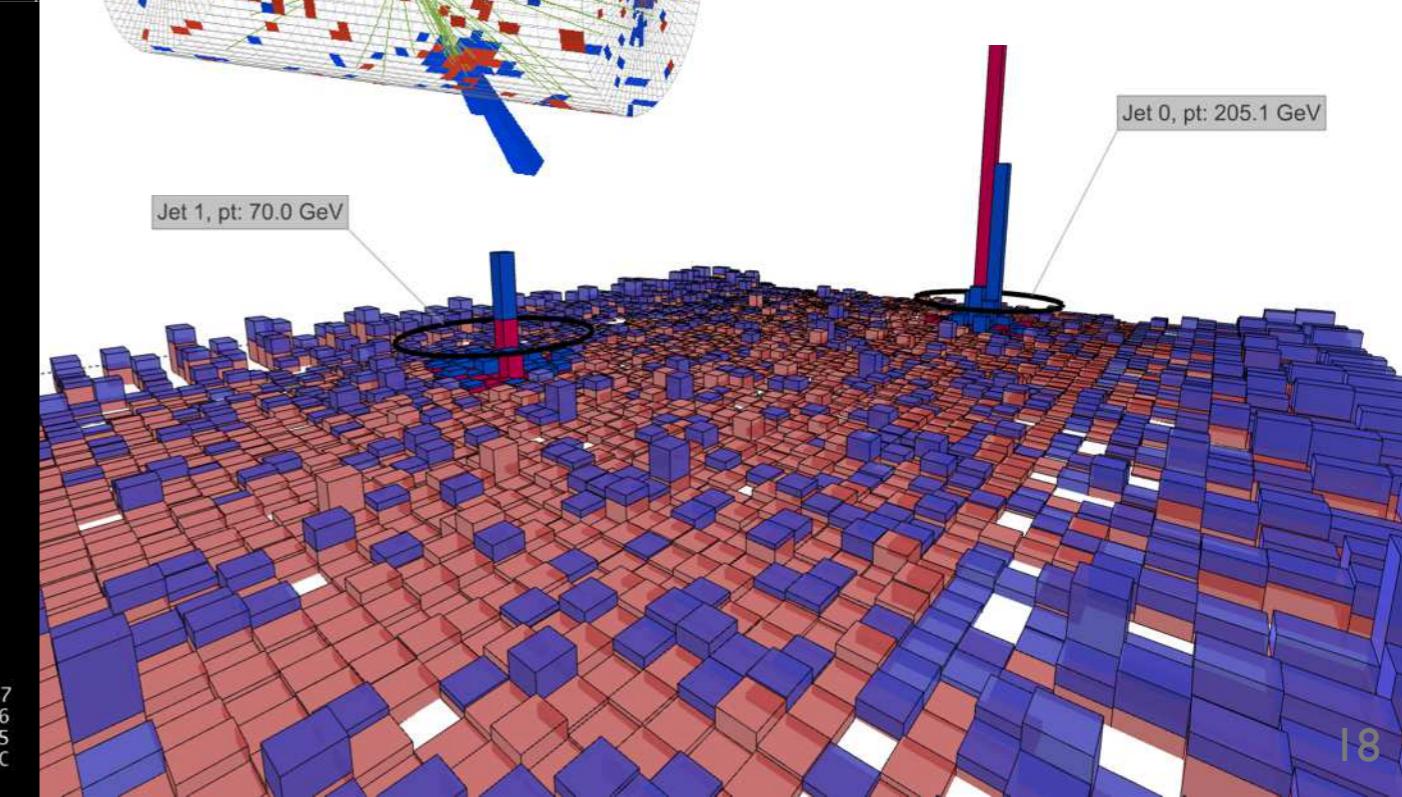
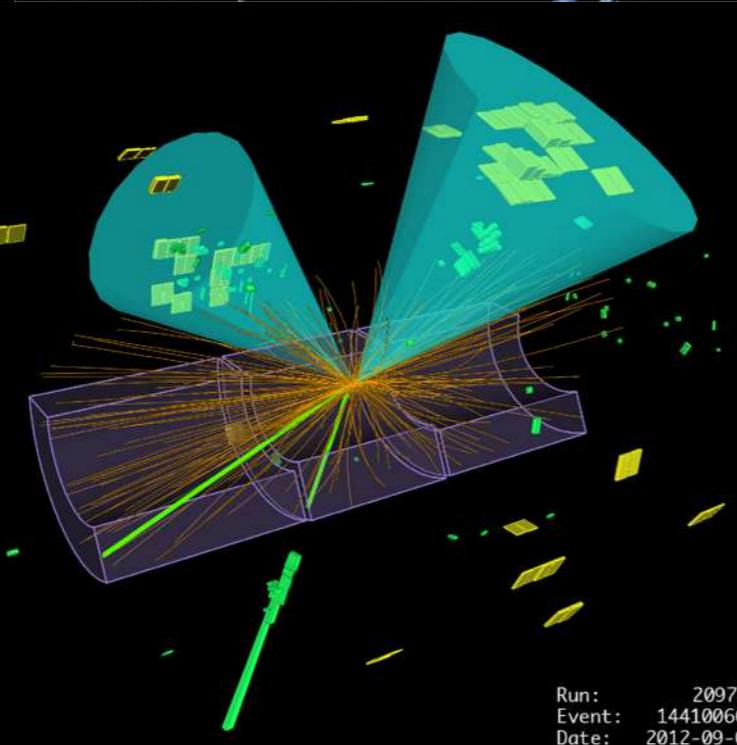


Run Number: 159224, Event Number: 3533152

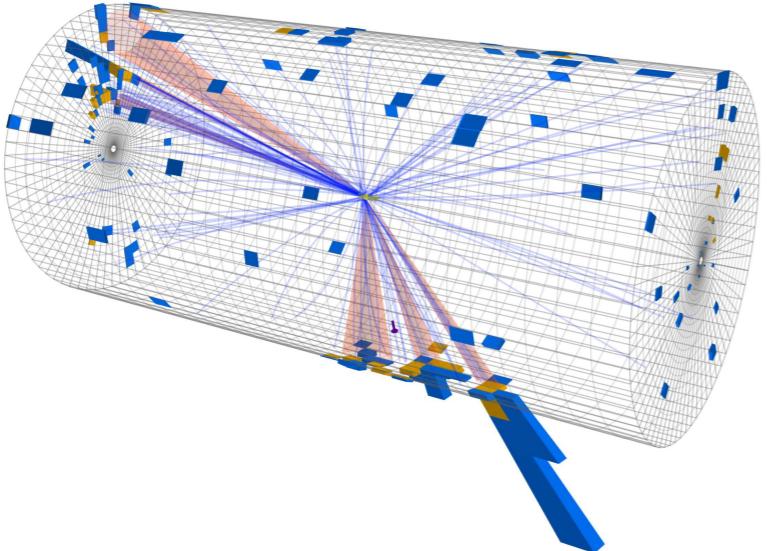
Date: 2010-07-18 11:05:54 CEST



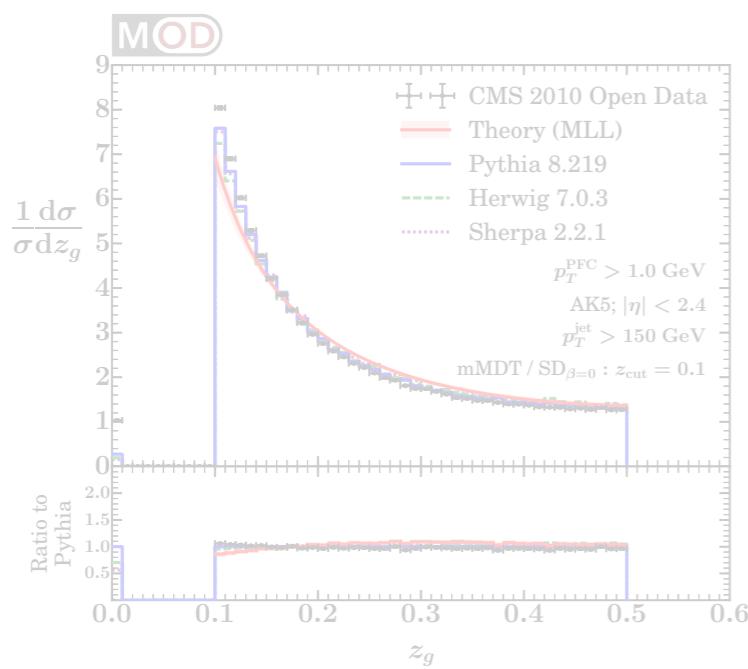
ATLAS
EXPERIMENT
<http://atlas.ch>



Jet Substructure



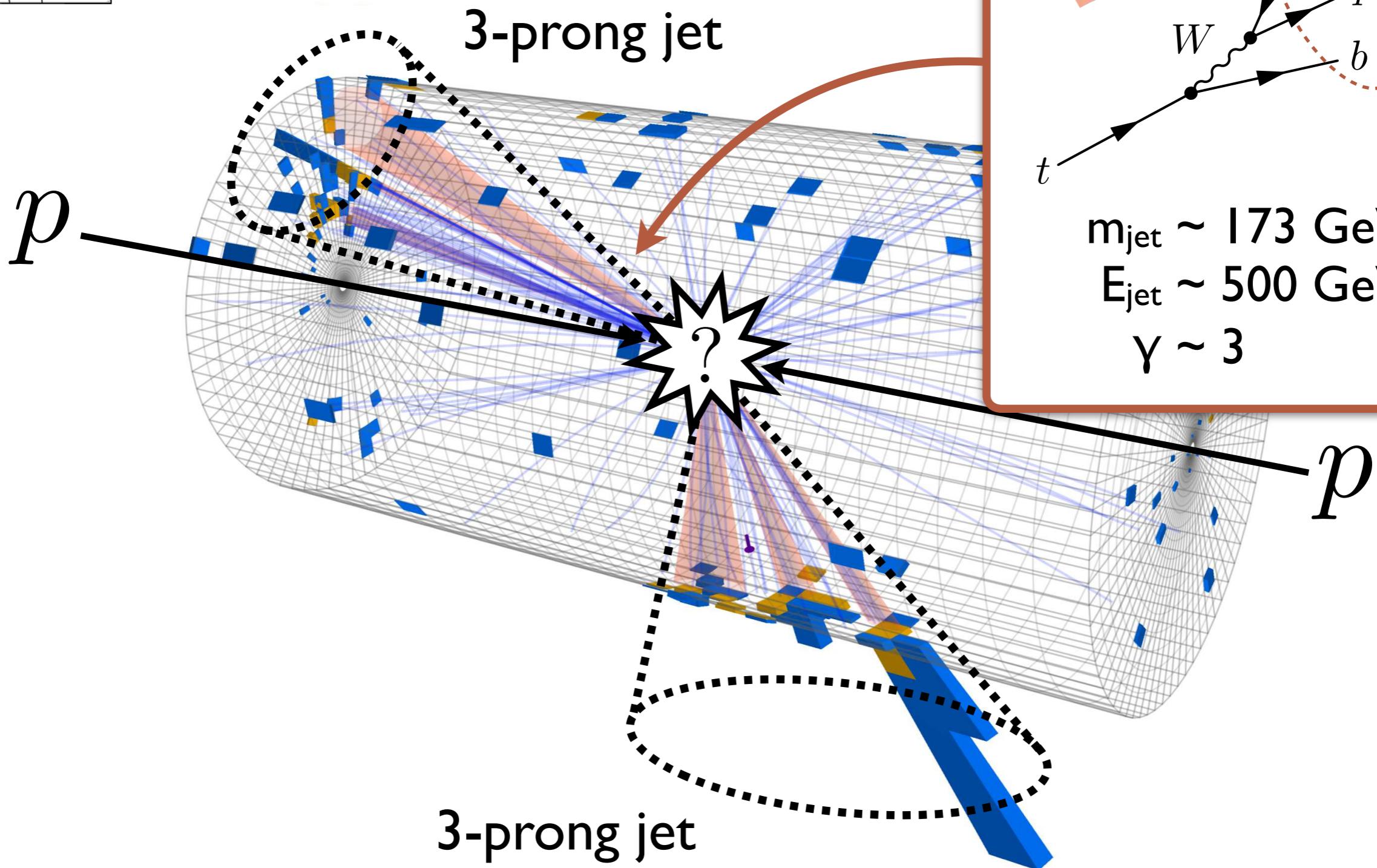
*Boosting the Search
for New Phenomena*



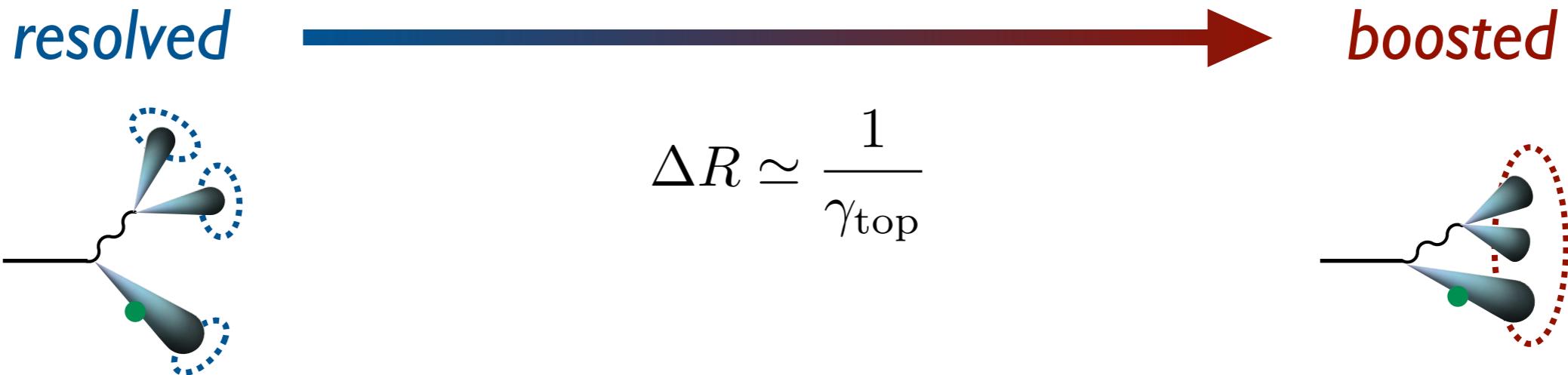
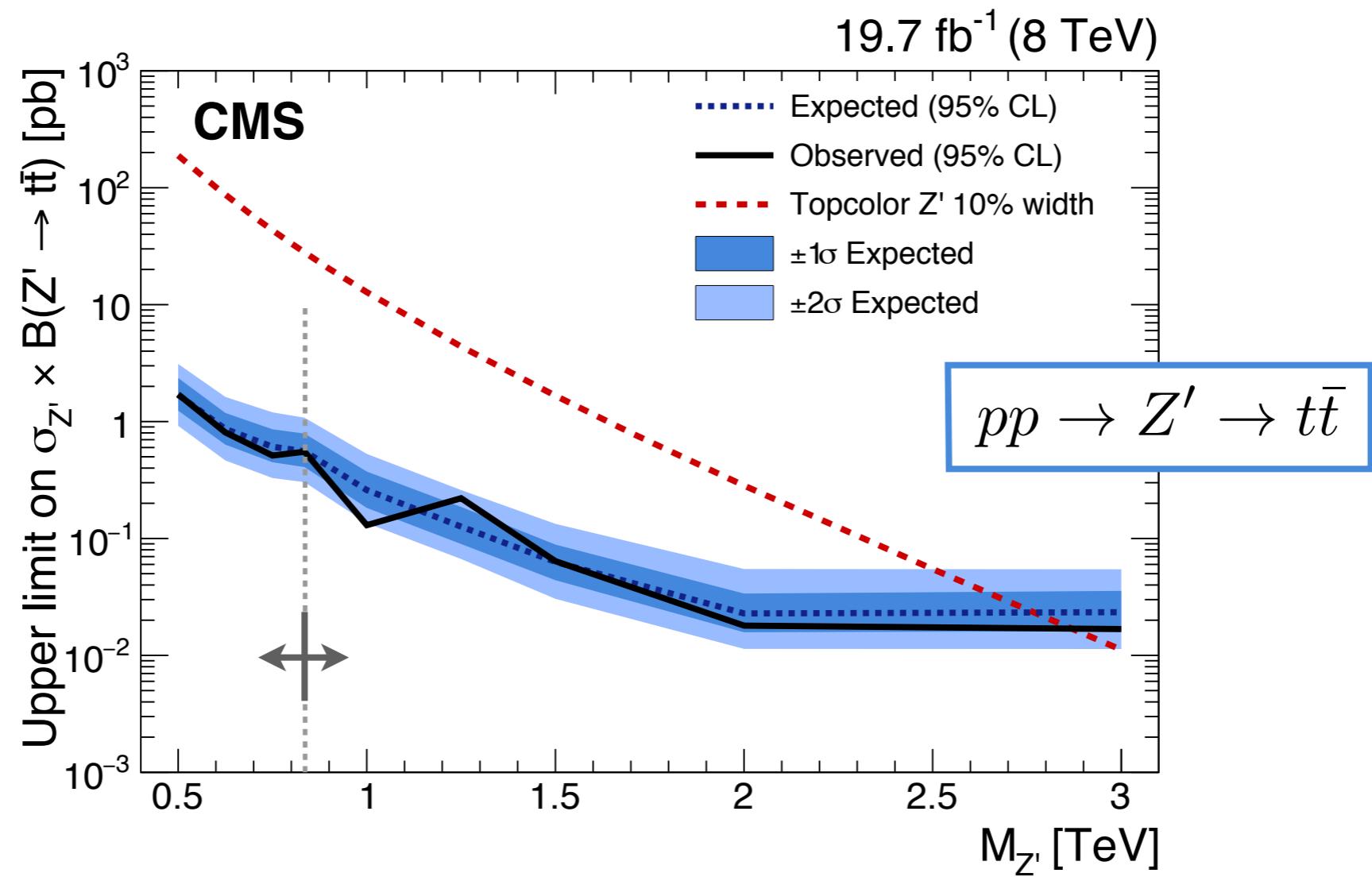
*Pushing the Boundaries
of Quantum Field Theory*



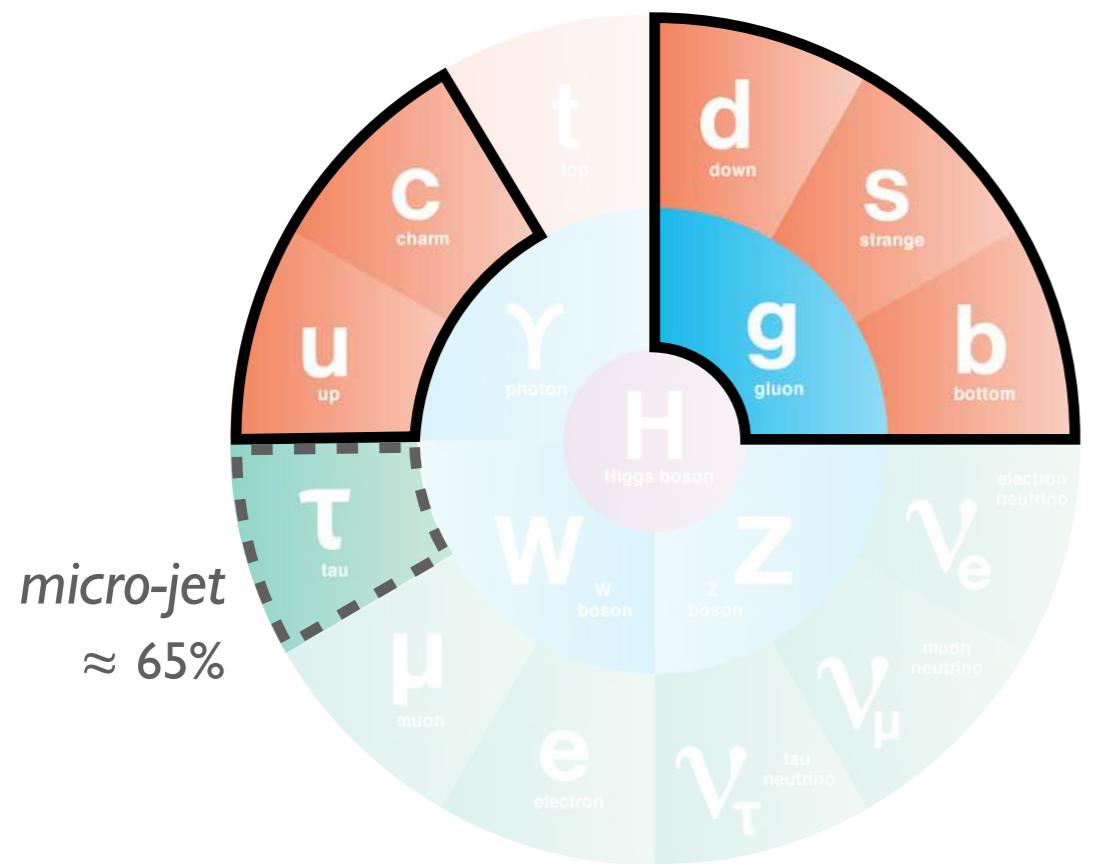
CMS Experiment at LHC, CERN
Data recorded: Sun Jul 12 07:25:11 2015 CEST
Run/Event: 251562 / 111132974
Lumi section: 122
Orbit/Crossing: 31722792 / 2253



$m_{\text{jet}} \sim 173 \text{ GeV}$
 $E_{\text{jet}} \sim 500 \text{ GeV}$
 $\gamma \sim 3$

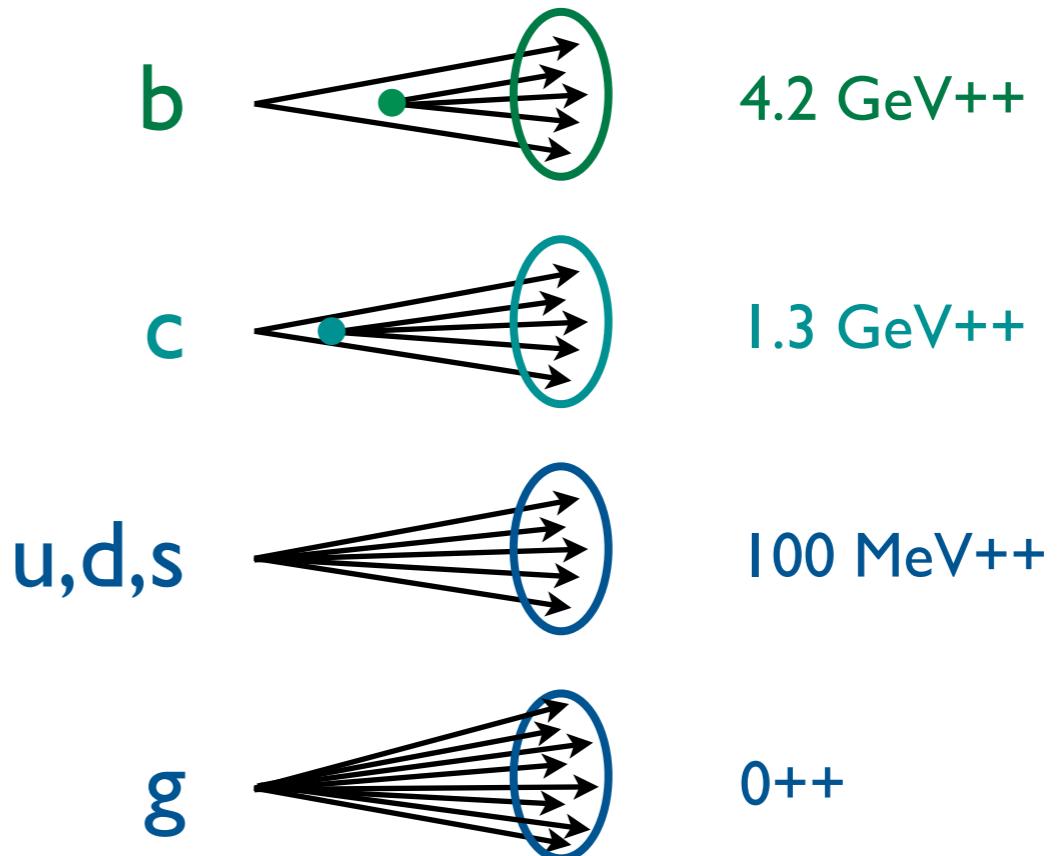


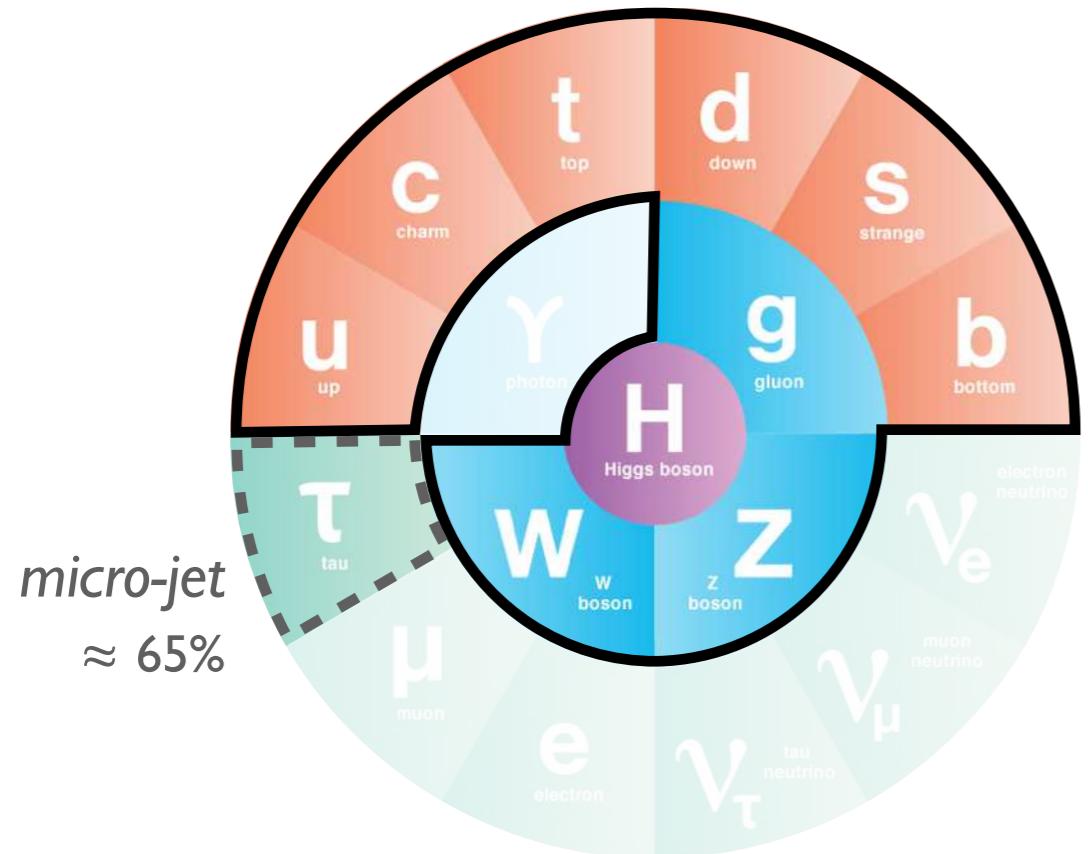
[CMS 2011, 2013, 2015; using Kaplan, Rehermann, Schwartz, Tweedie, 2008; Ellis, Vermilion, Walsh, 2009]



Jets from the Standard Model

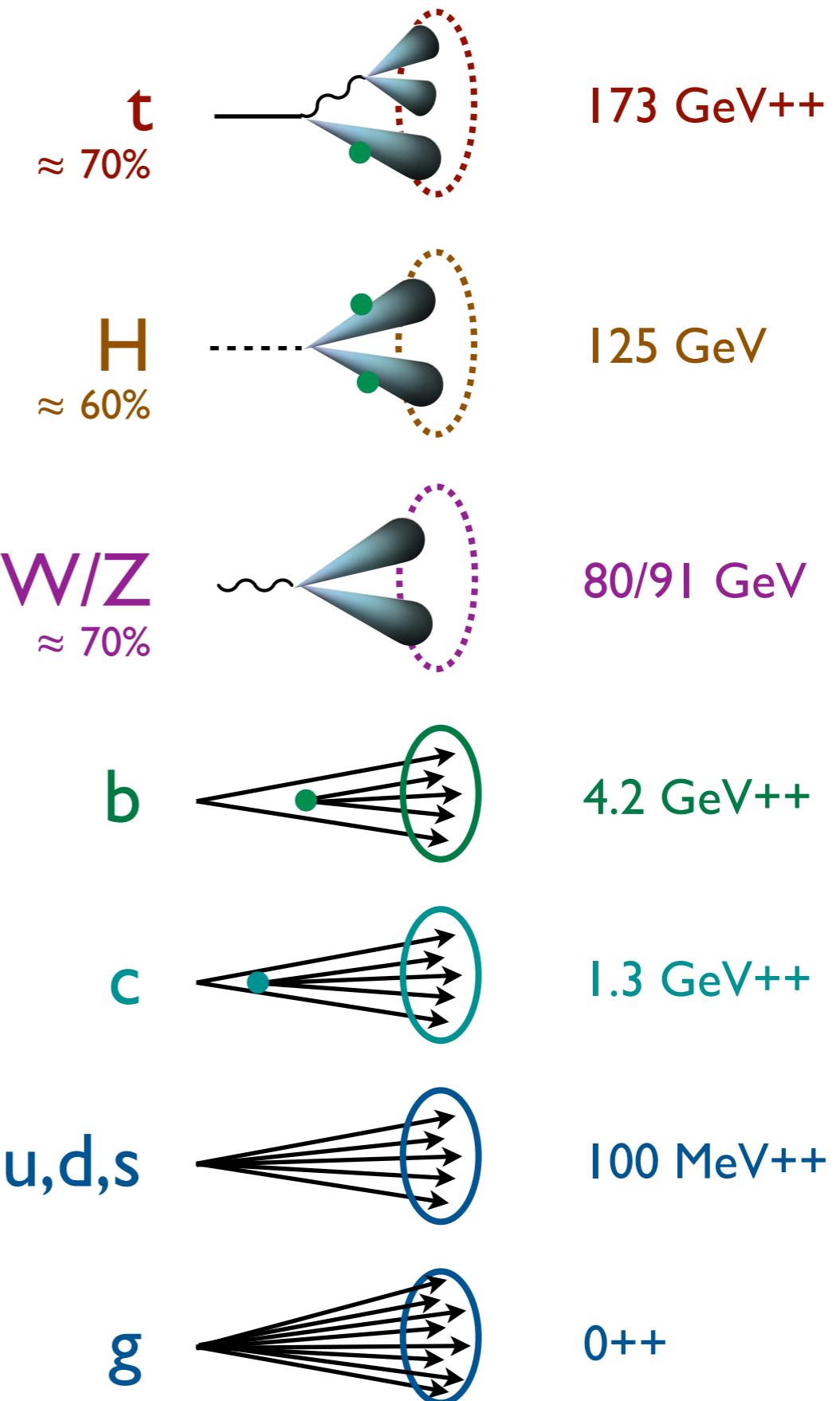
\leftrightarrow = Mass from QCD Radiation

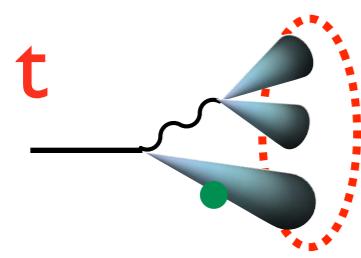




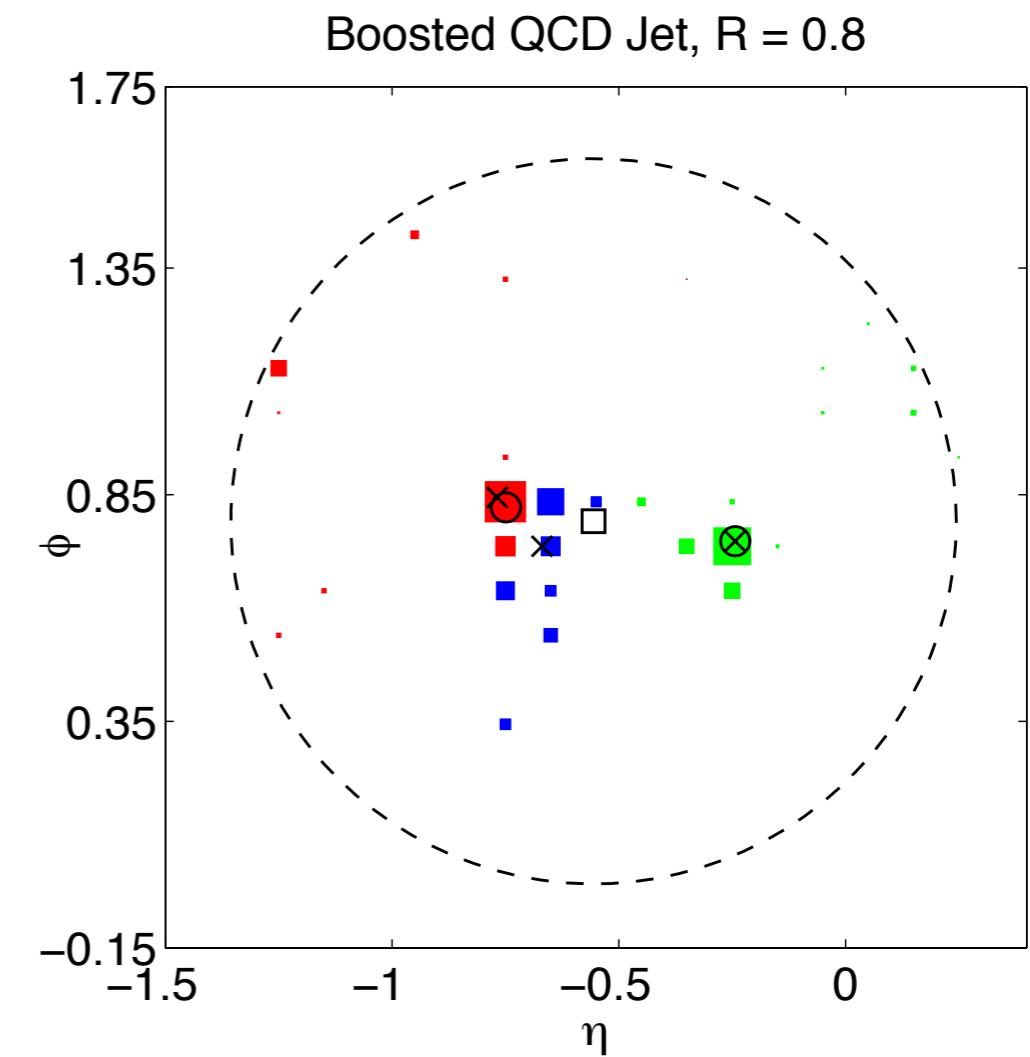
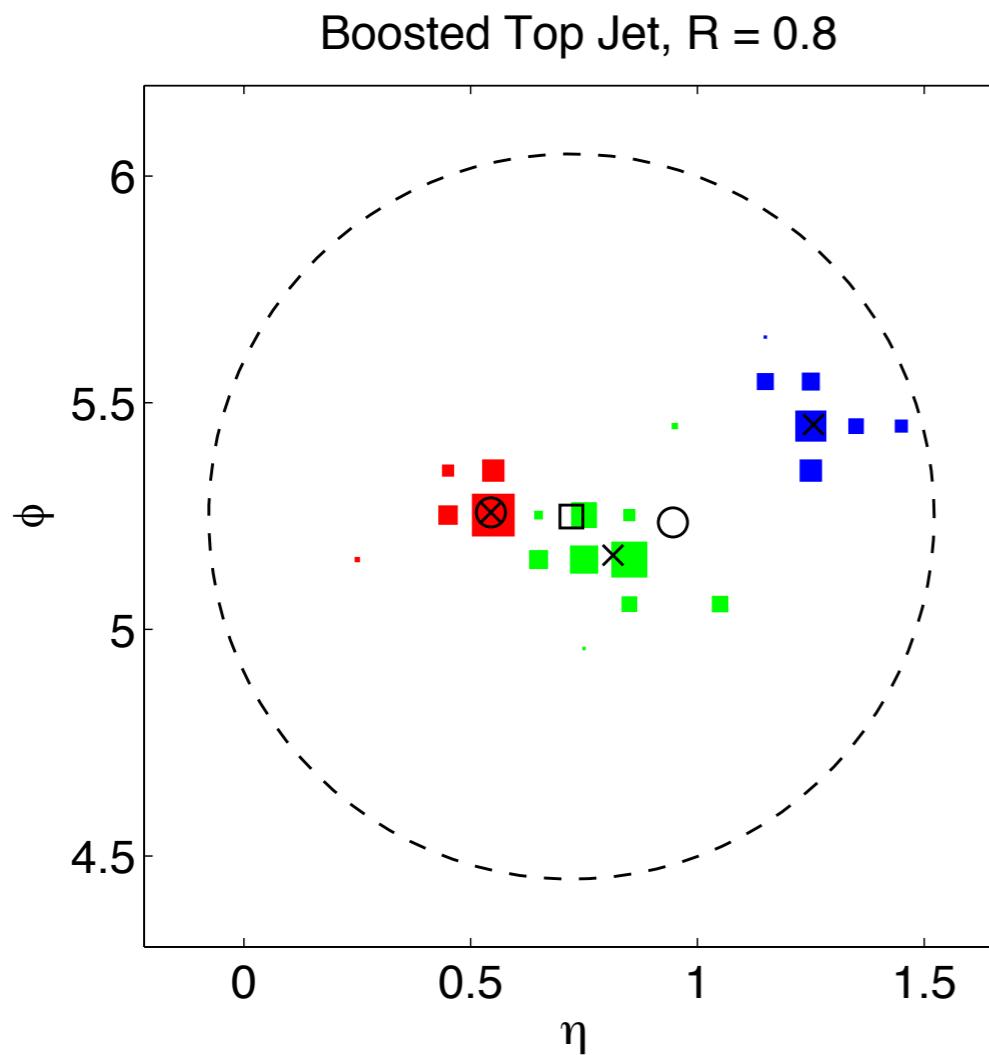
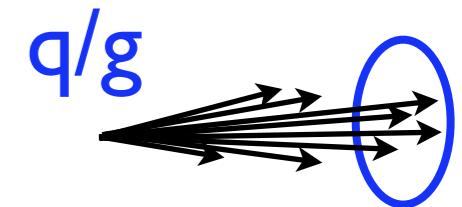
Jets from the Standard Model

++ = Mass from QCD Radiation



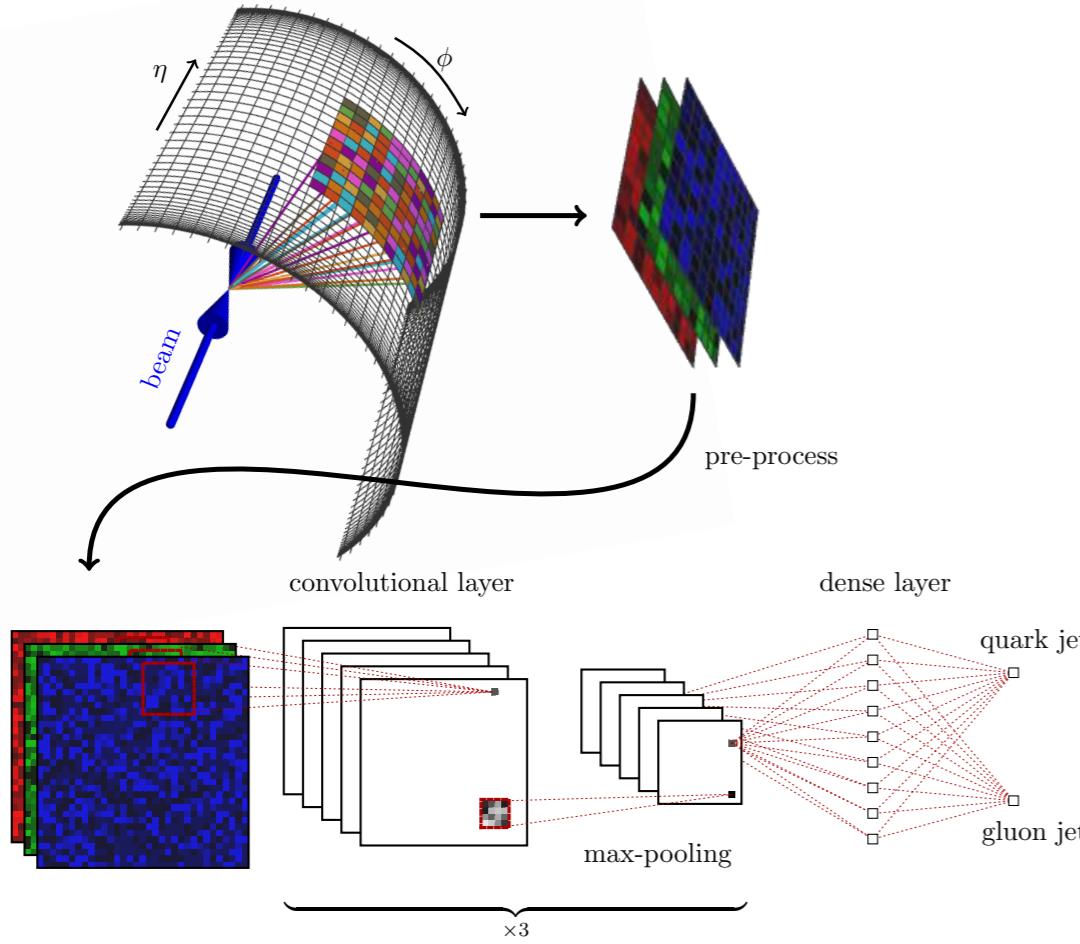


N-Prong vs. I-Prong



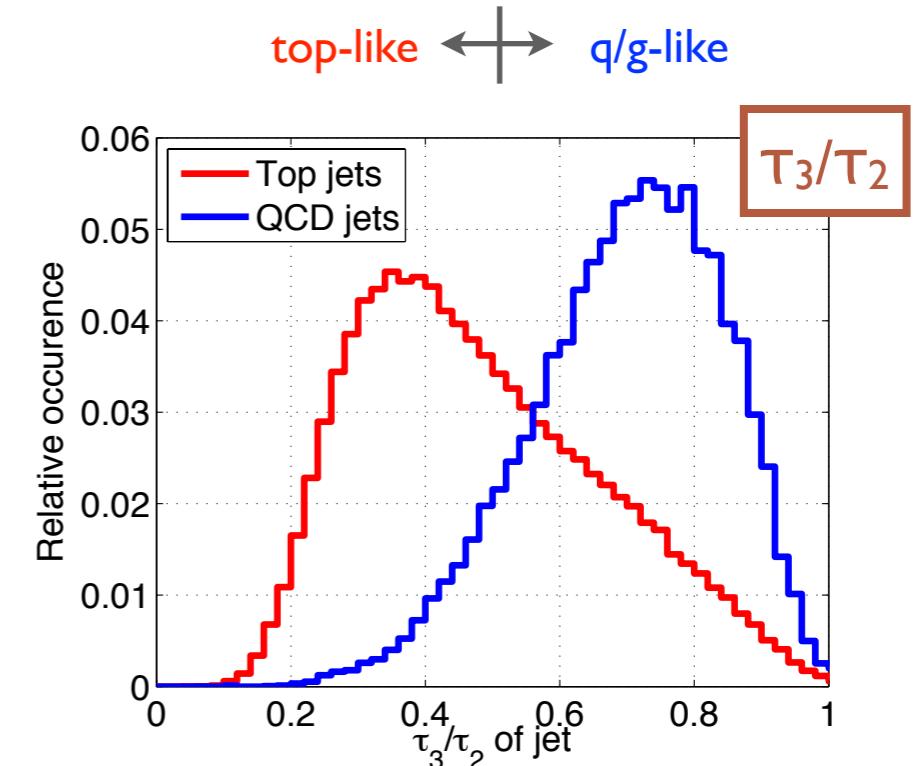
Both jets have $m \approx 173 \text{ GeV}$

Complexity?



e.g. CNNs/DNNs

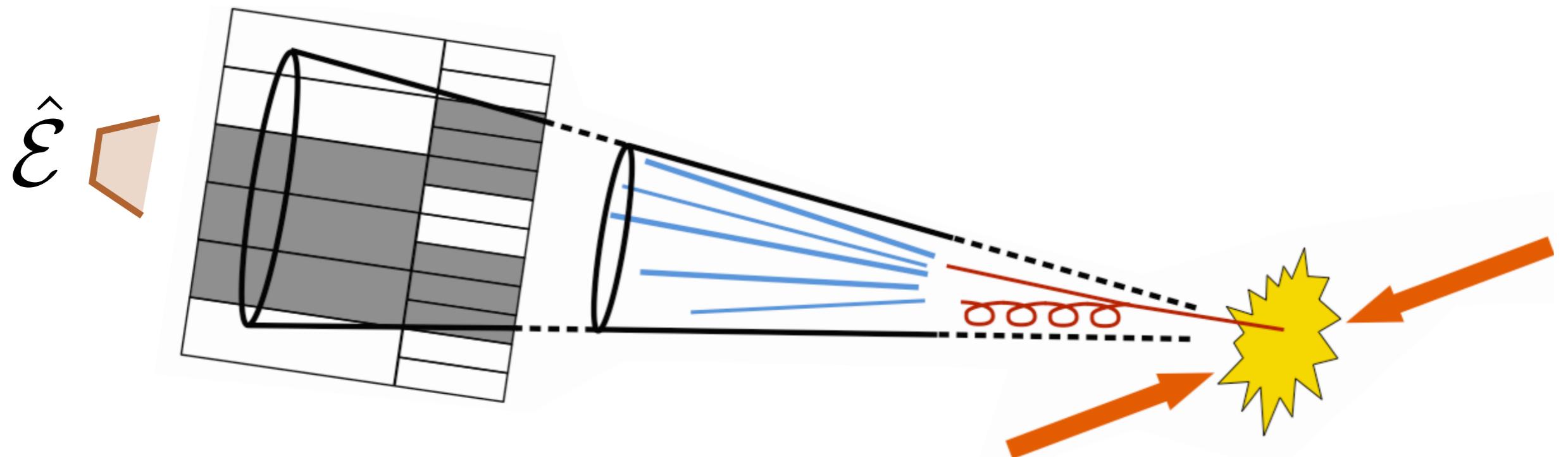
Simplicity?

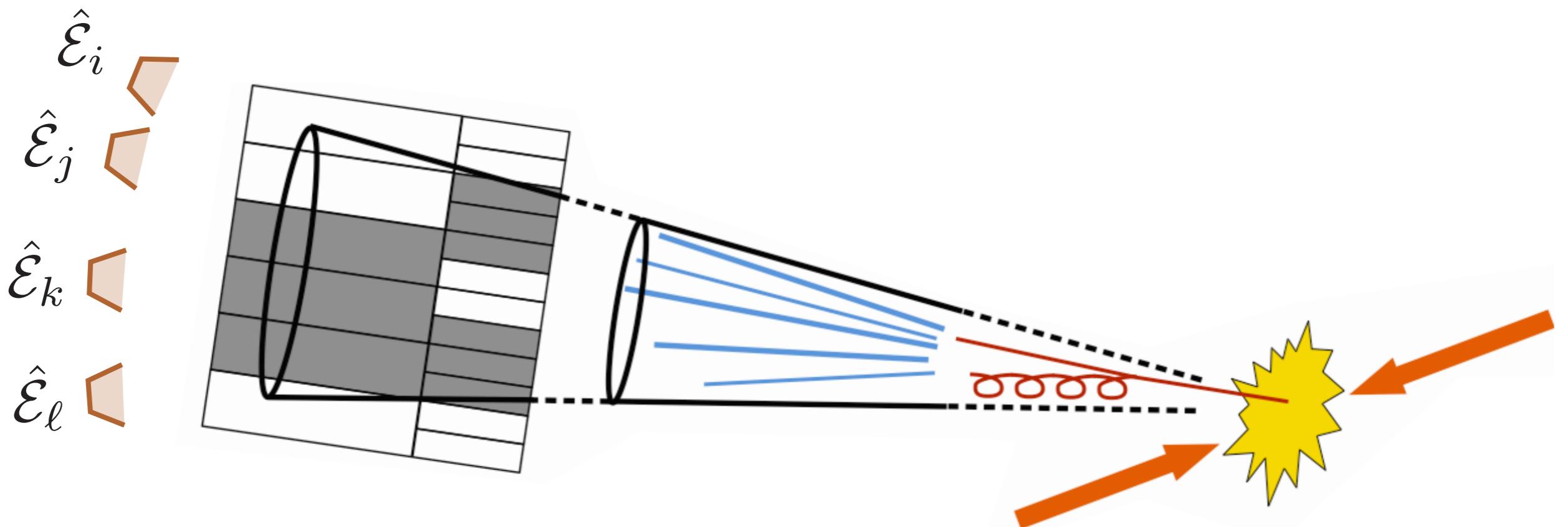


$$\tau_N = \sum_k p_{T,k} \min \{ \Delta R_{k,1}, \Delta R_{k,2}, \dots, \Delta R_{k,N} \}$$

e.g. N-subjettiness

[e.g. Komiske, Metodiev, Schwartz, 2016; e.g. JDT, Van Tilburg, 2010, 2011]



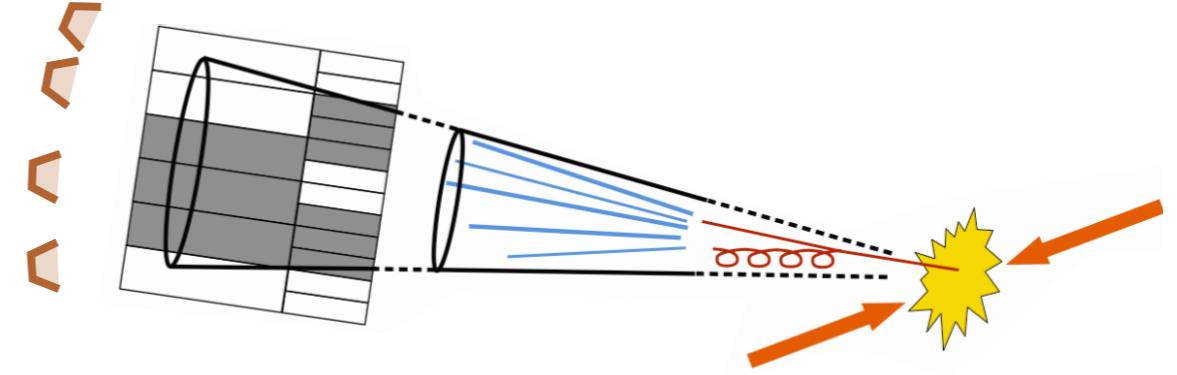


e.g.

$$\begin{array}{c}
 i \quad j \quad k \\
 \text{---} \quad \text{---} \quad \text{---} \\
 | \quad \quad \quad |
 \end{array}
 = \sum_{ijkl} E_i E_j E_k E_\ell \theta_{ij} \theta_{jk} \theta_{jl}^2 \theta_{kl}$$

Energies Pairwise Angles

Energy Flow Polynomials



Linear Basis for
Any* Jet Observable

$$\mathcal{S} = \sum_{\text{Graphs}} s_G \text{EFP}_G$$

e.g.

$$\text{EFP}_G = \sum_{\text{all } N} E_{i_1} \cdots E_{i_N} \prod_{(k,\ell) \in G} \theta_{i_k i_\ell}$$

$$= \sum_{ijkl} E_i E_j E_k E_\ell \theta_{ij} \theta_{jk} \theta_{jl}^2 \theta_{kl}$$

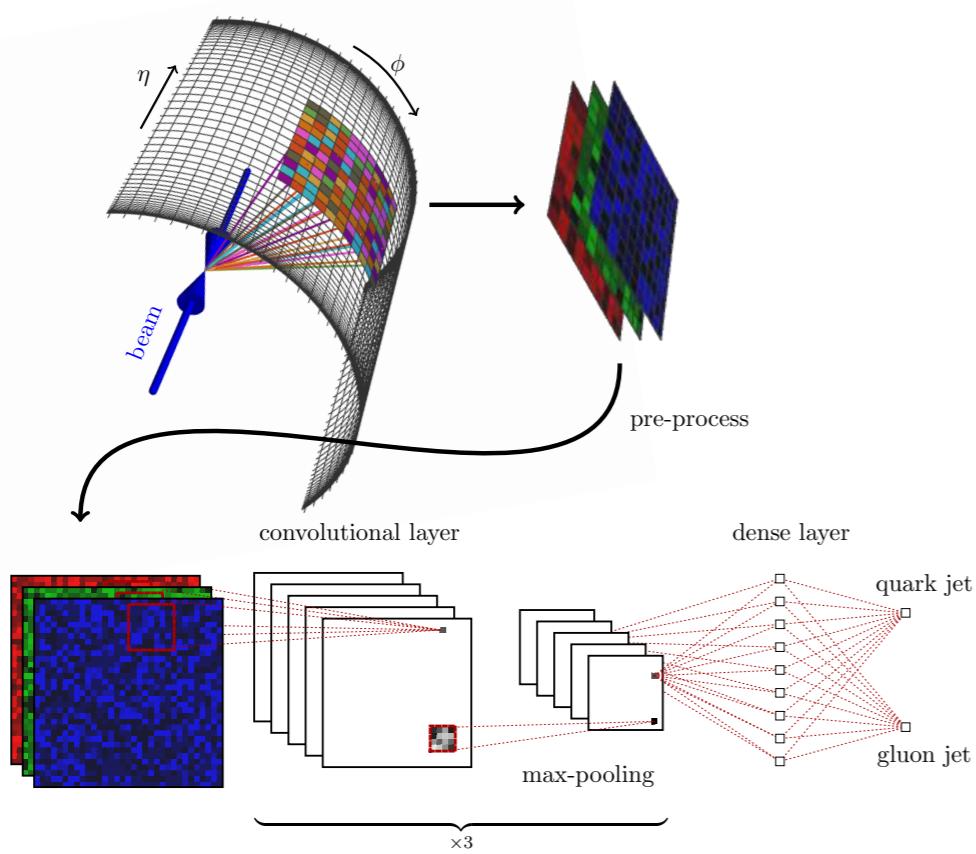
Energies Pairwise Angles

[Komiske, Metodiev, JDT, 2017]

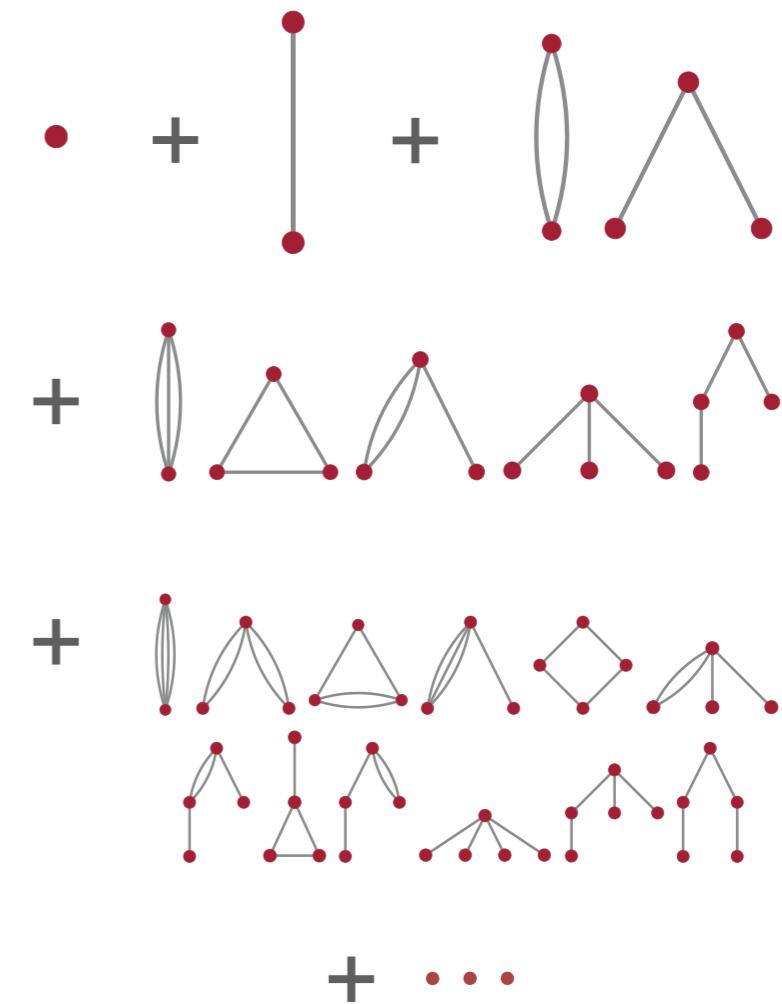
“Deep Learning”

vs.

“Deep Thinking”



Complex Combination
of Simple Inputs

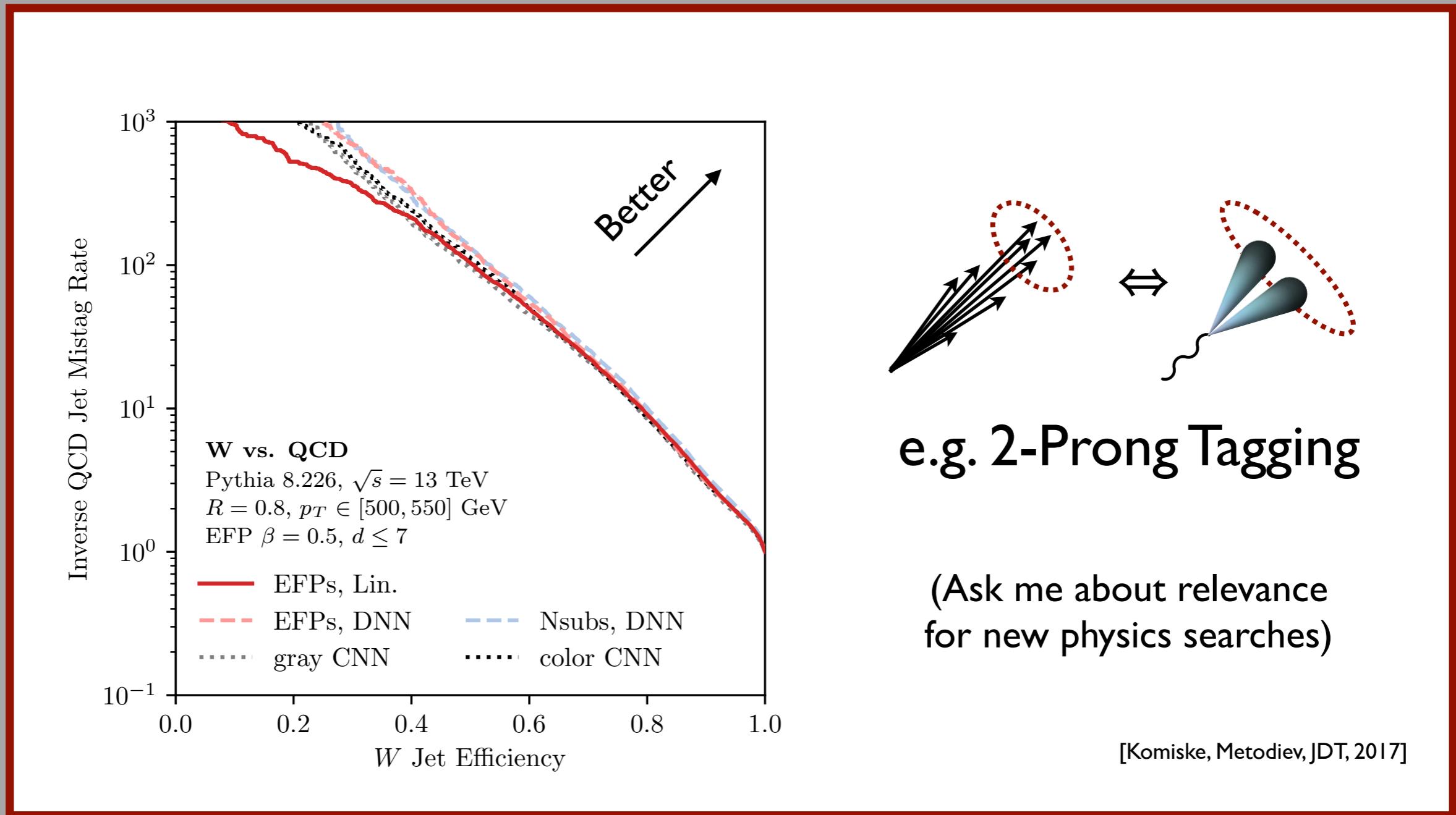


Simple Combination
of Complex Inputs

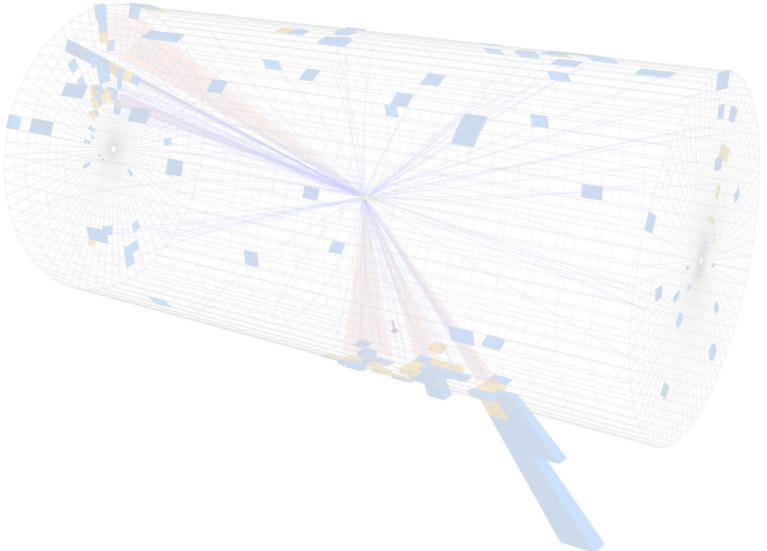
“Deep Learning”

vs.

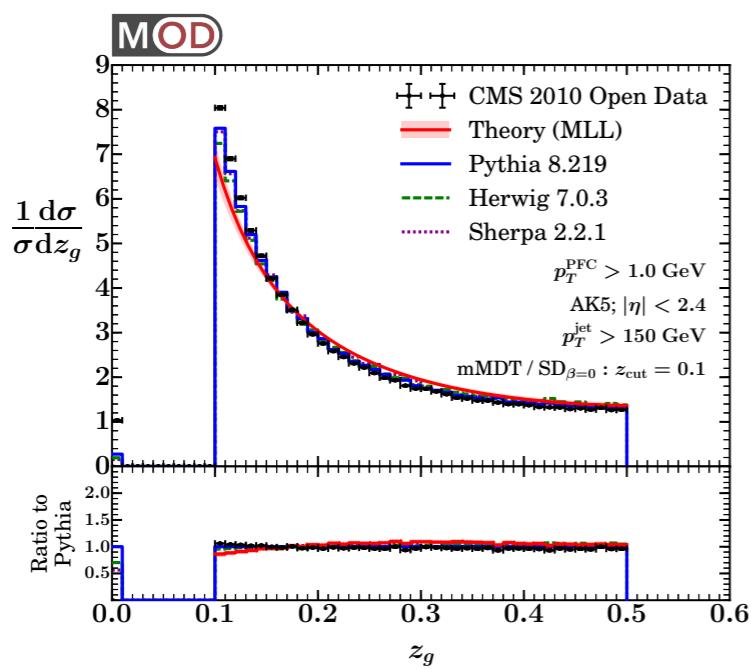
“Deep Thinking”



Jet Substructure



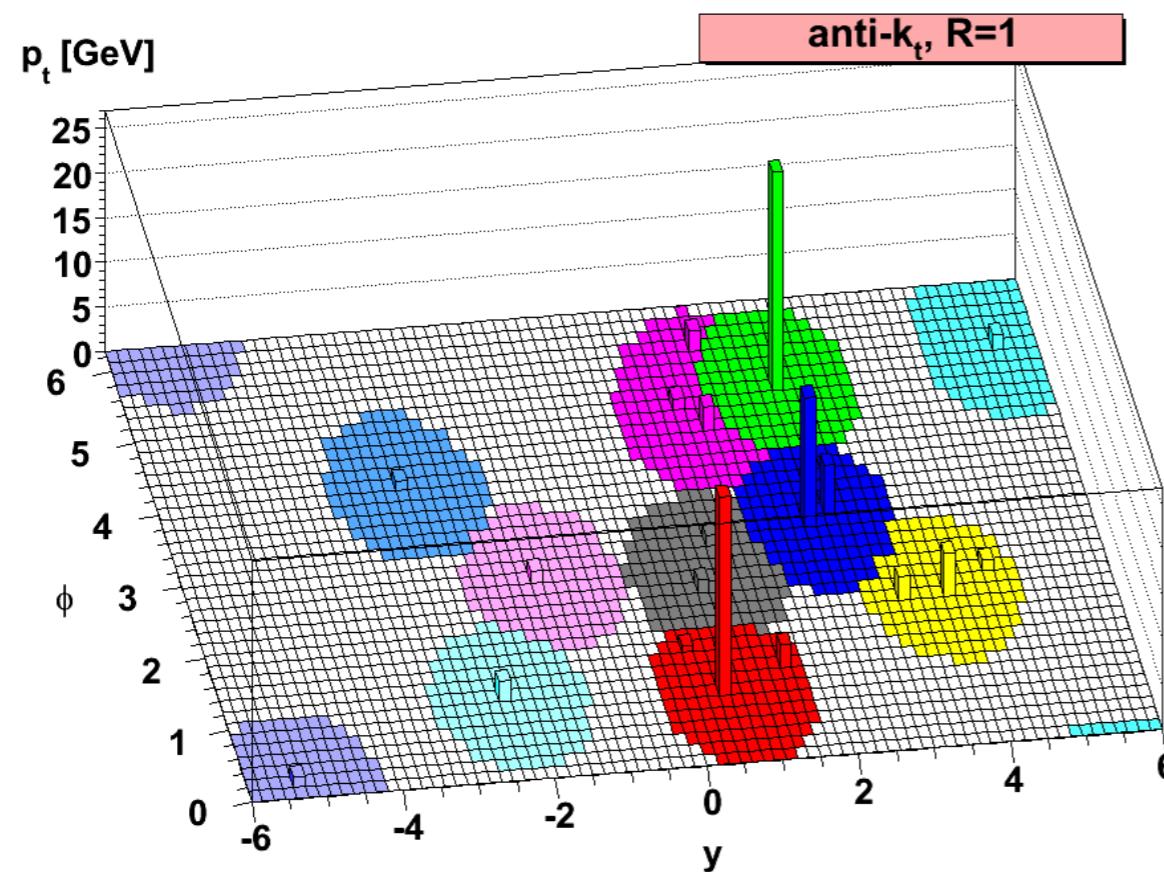
*Boosting the Search
for New Phenomena*



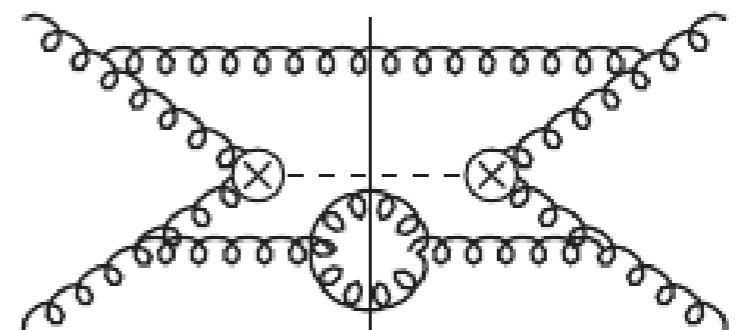
*Pushing the Boundaries
of Quantum Field Theory*

QCD Renaissance

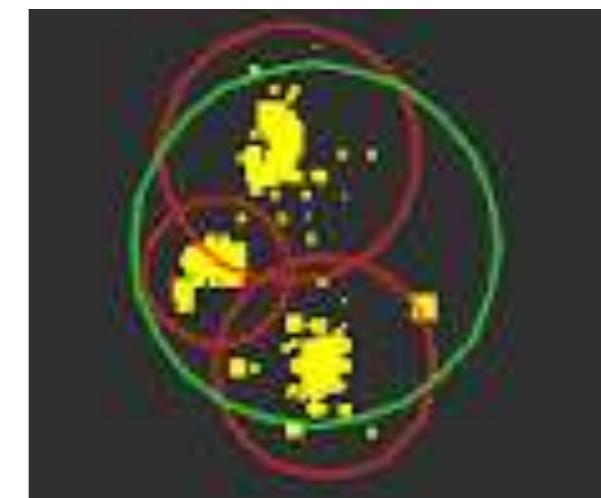
Theory c. 2008–present



New Jet Algorithms



Loop/Leg/Log Explosion



Jet Substructure

[Anti- k_t : Cacciari, Salam, Soyez, 2008; see also Delsart, 2006] [N³LO: Anastasiou, Duhr, Dulat, Herzog, Mistlberger, 2015]
[BDRS: Butterworth, Davison, Rubin, Salam, 2008; see also Seymour, 1991, 1994]

\approx Three Years on One Slide

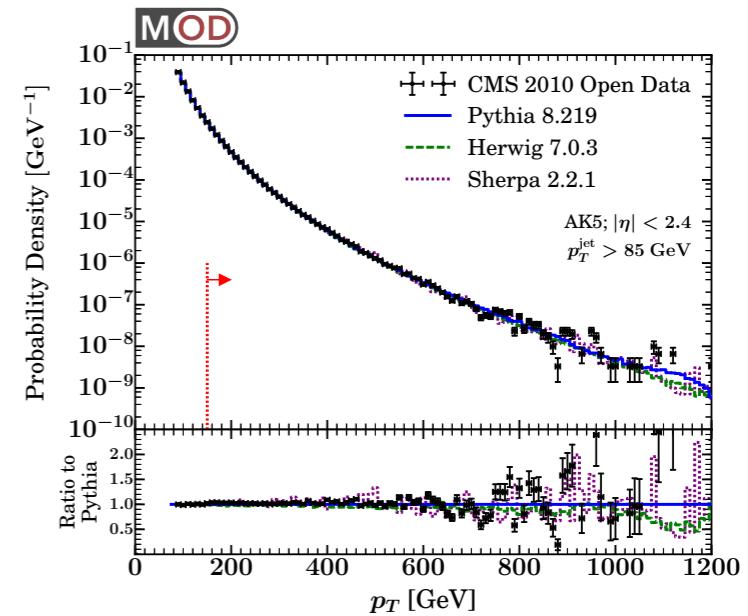
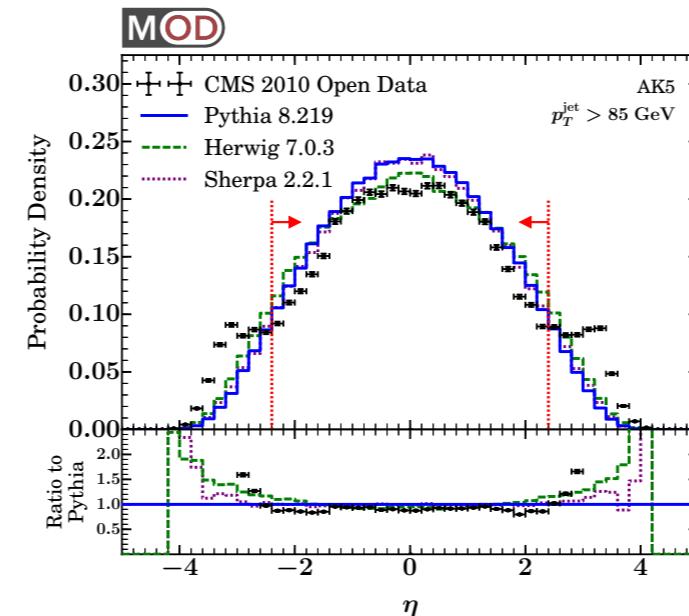
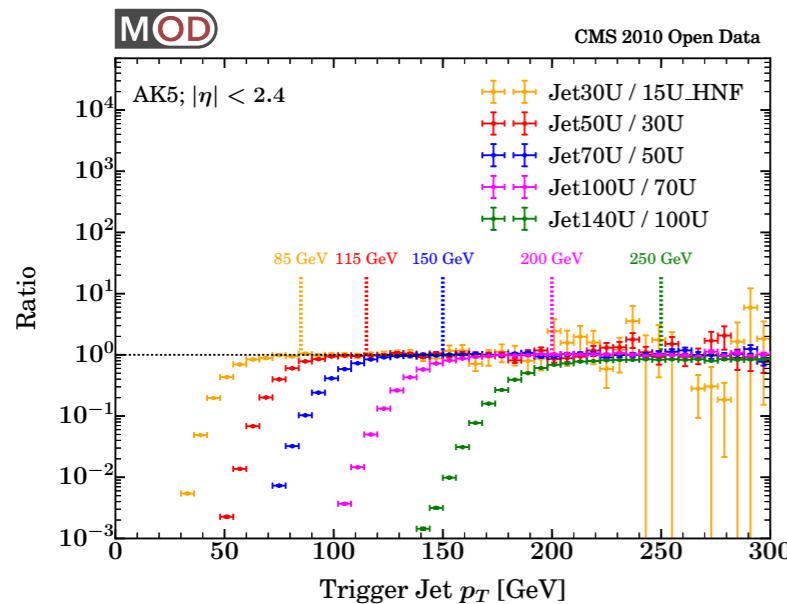
November
2014



opendata
CERN
“Accelerating science
through public data”



September
2017



Andrew Larkoski



Simone Marzani



Alexis Romero



Aashish Tripathee

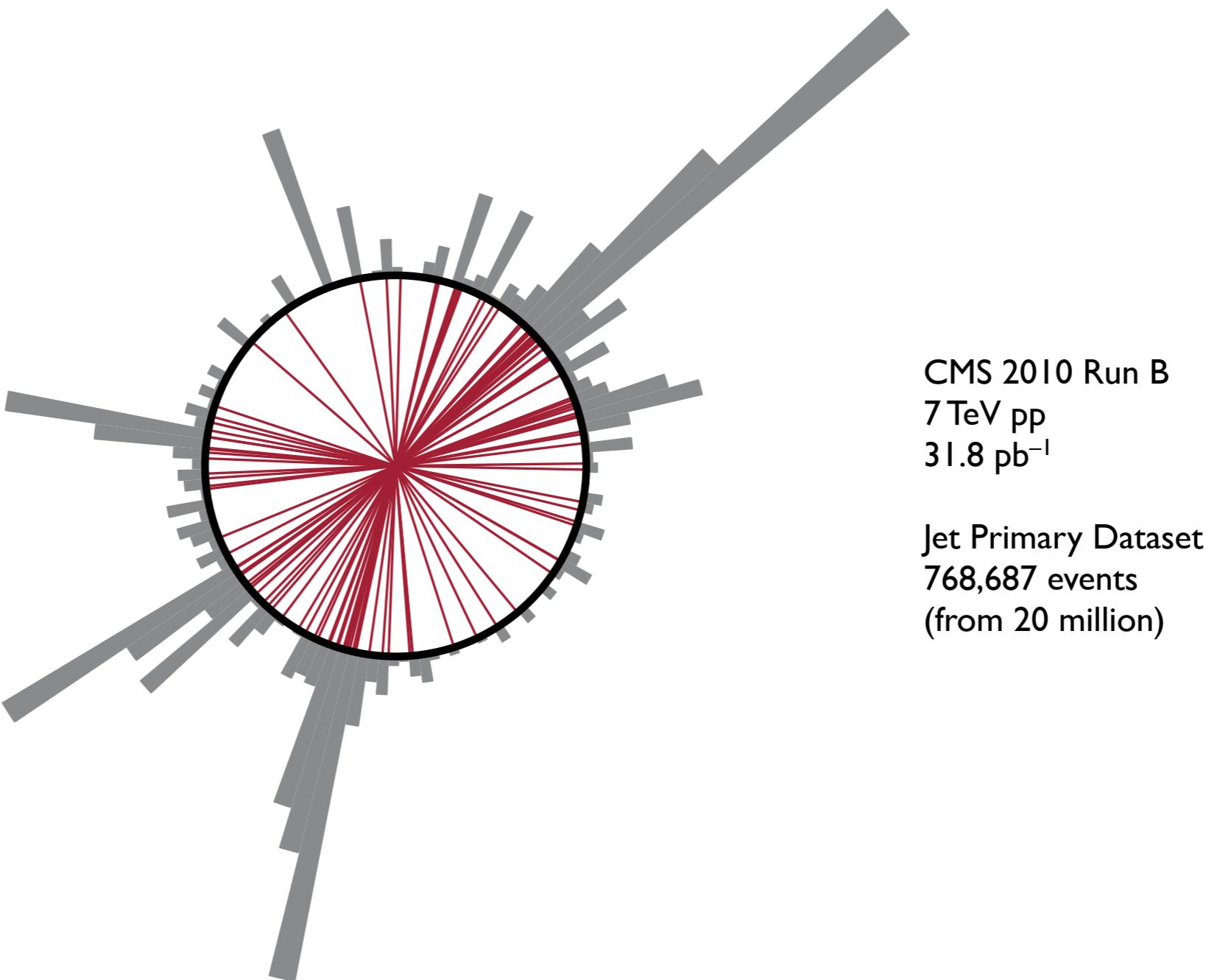


Wei Xue



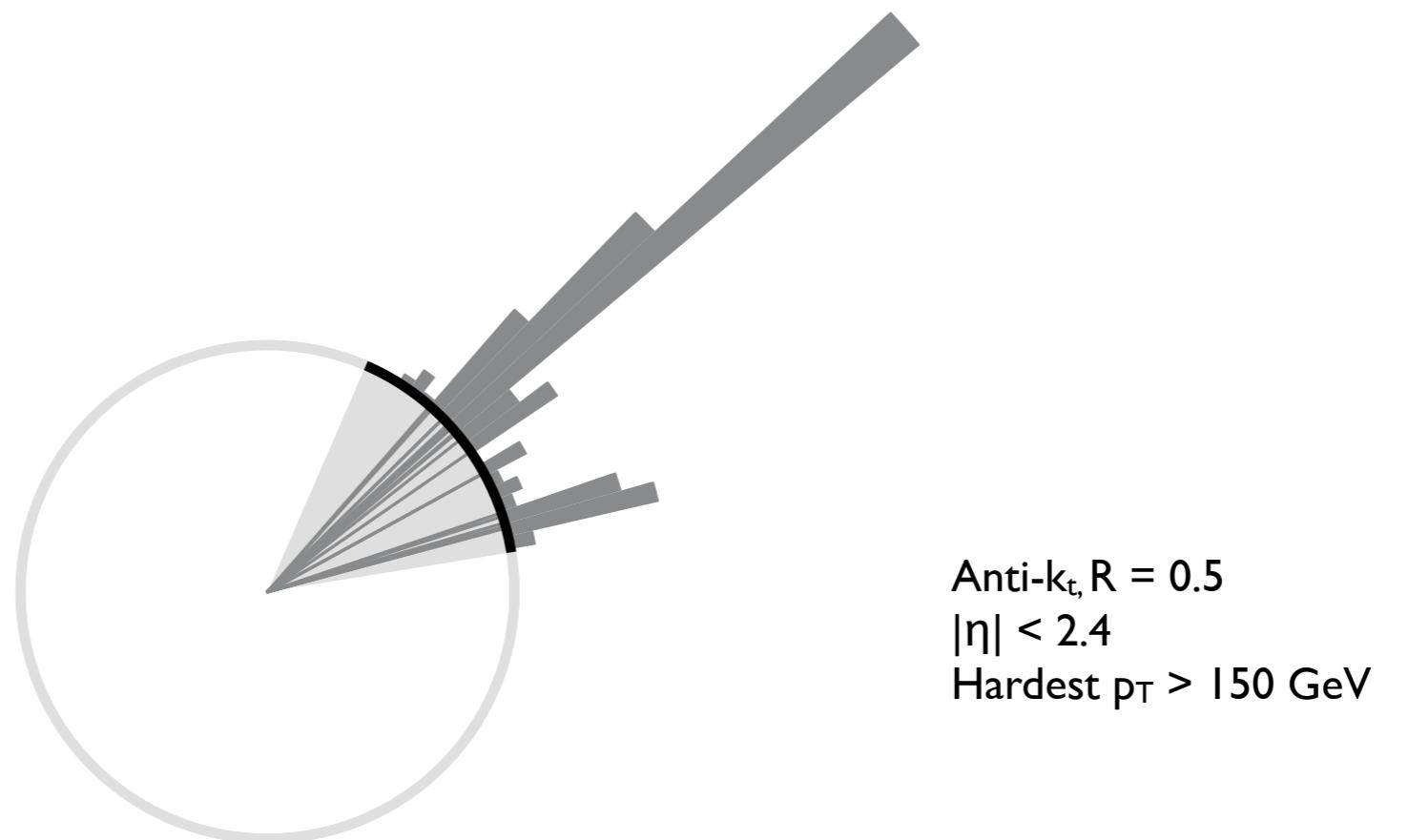
CMS advice from
Sal Rappoccio



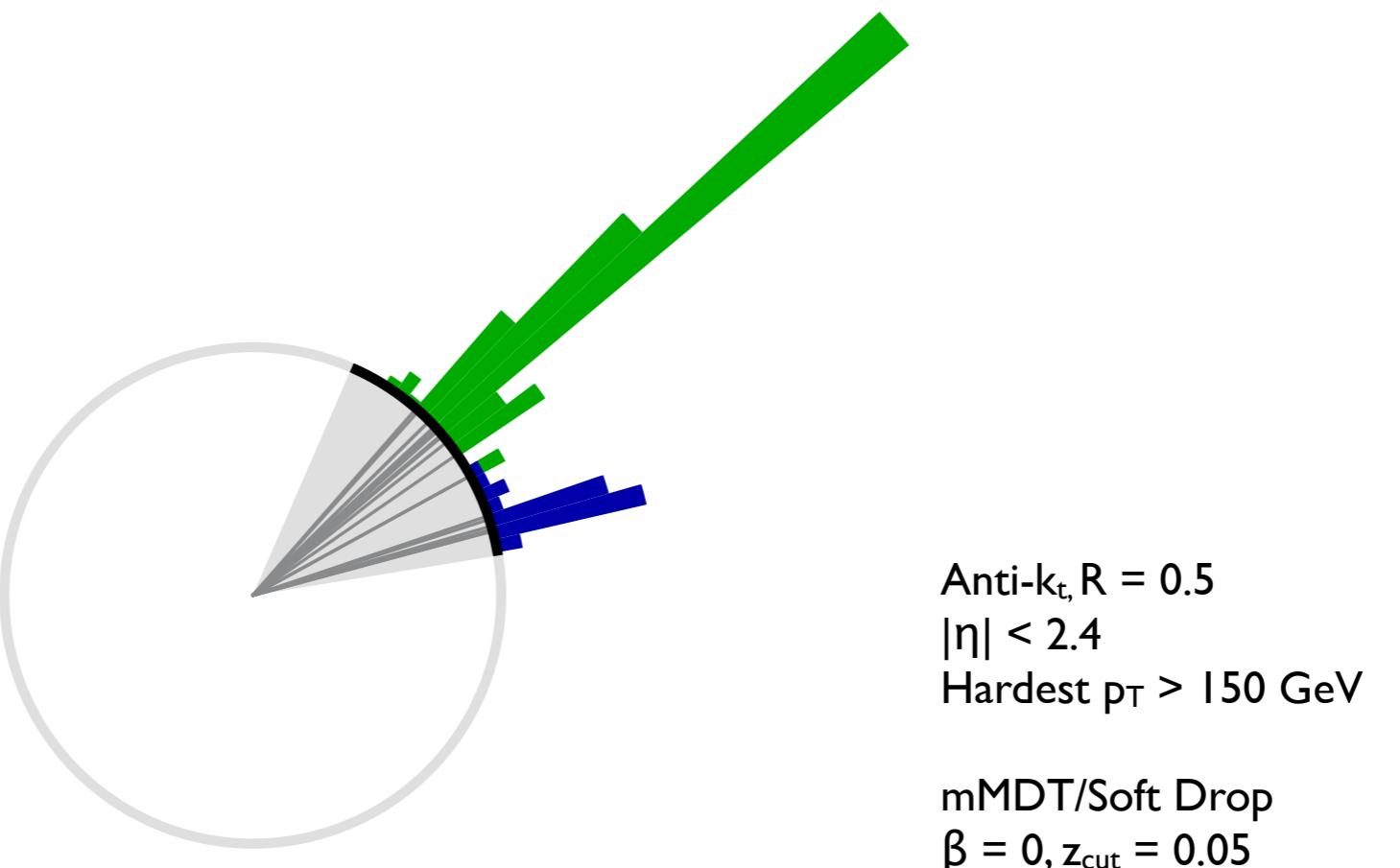




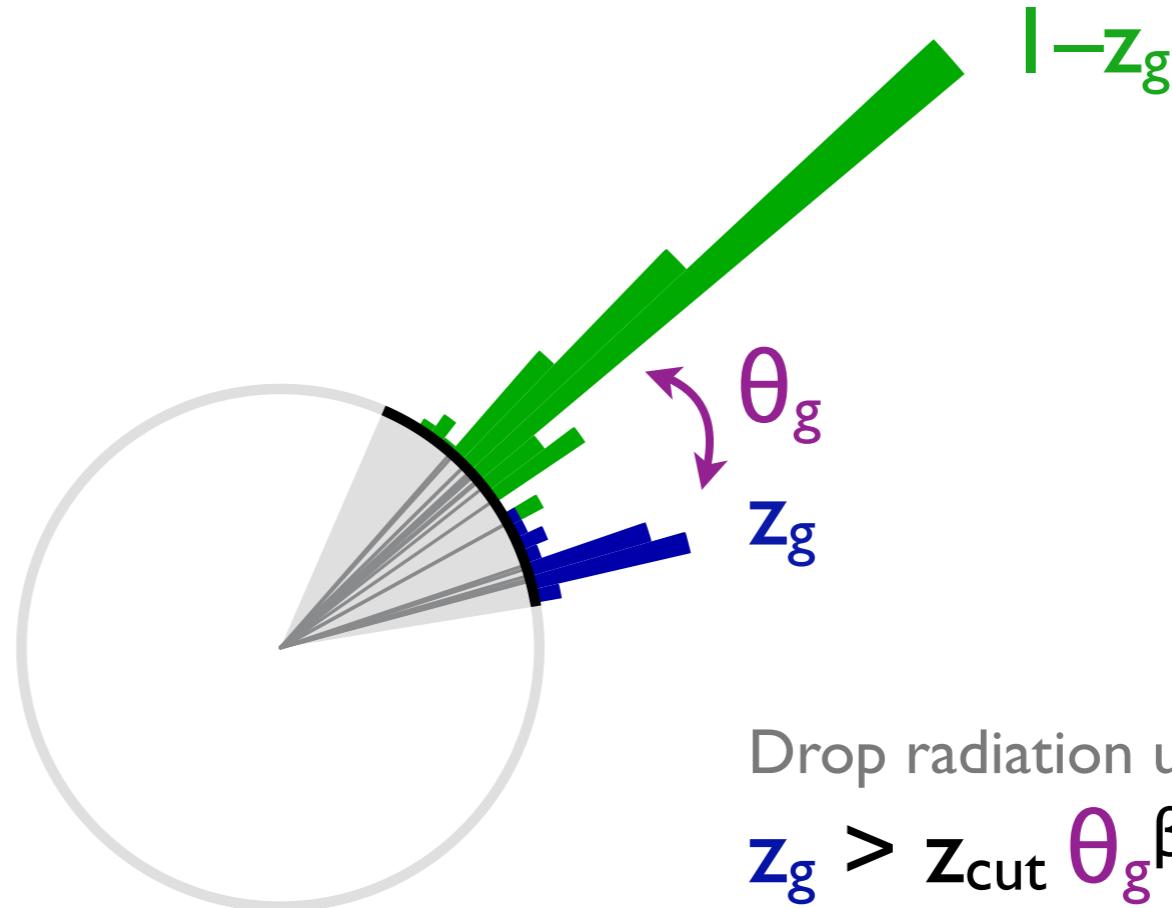
Anti- k_t , $R = 0.5$
 $|\eta| < 2.4$
 $p_T > 20 \text{ GeV}$



Anti- k_t , $R = 0.5$
 $|\eta| < 2.4$
Hardest $p_T > 150$ GeV



Soft Drop Grooming



Drop radiation until:
 $z_g > z_{\text{cut}} \theta_g \beta$

This study

More Grooming

$\beta \rightarrow -\infty$

$\beta < 0$

$\beta = 0$

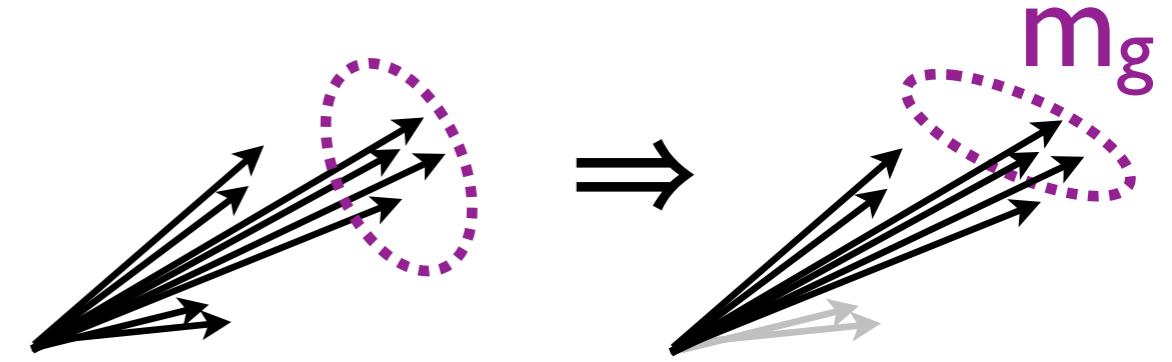
$\beta > 0$

Less Grooming

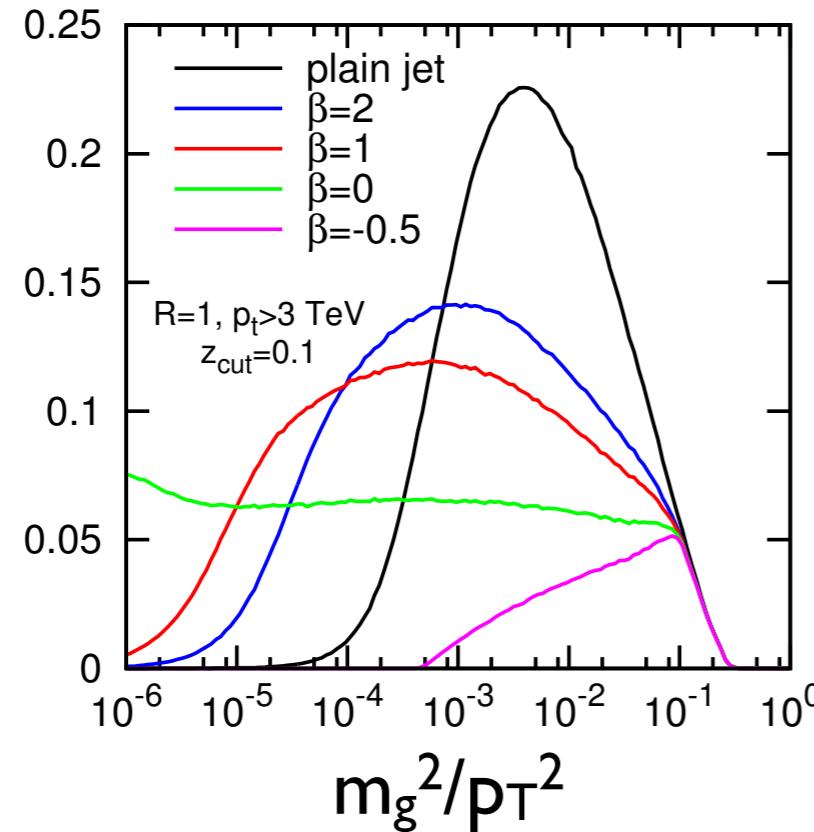
38

[Larkoski, Marzani, Soyez, JDT, 2014; see also Butterworth, Davison, Rubin, Salam, 2008; Dasgupta, Fregoso, Marzani, Salam/Powling, 2013]

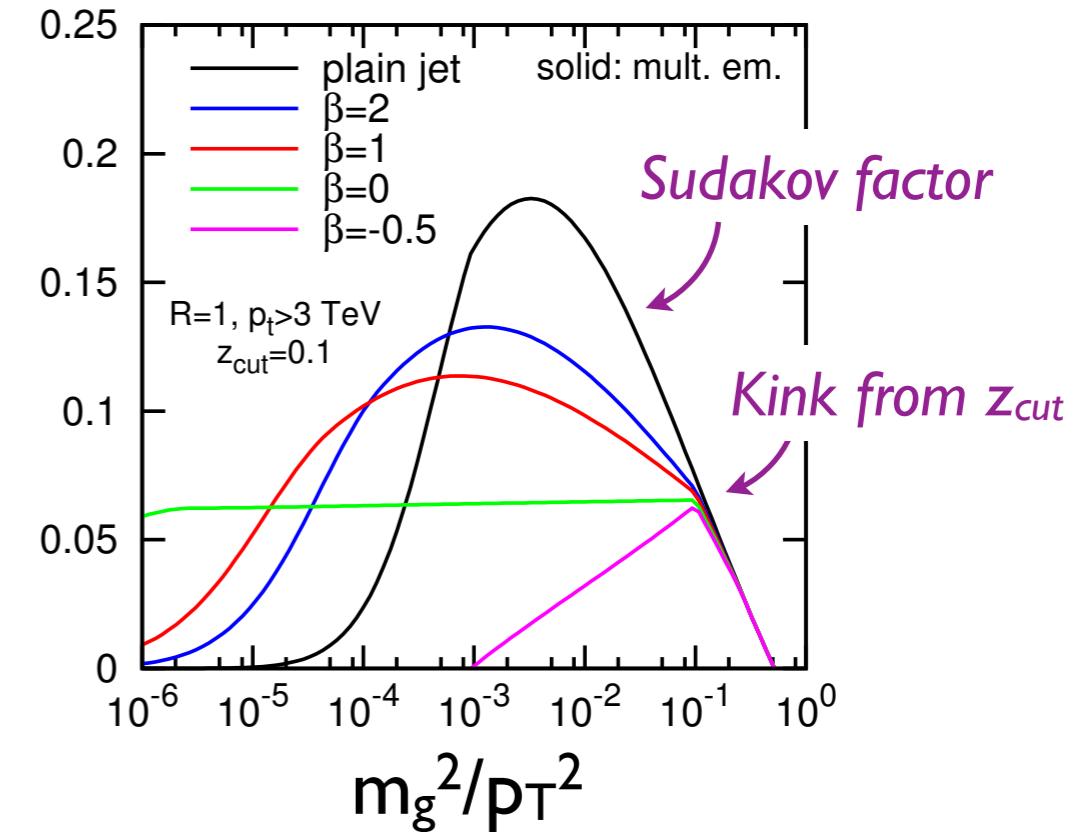
Calculating Mass?



Simulated LHC Data



First-principles QCD



More Grooming

$\beta \rightarrow -\infty$

$\beta < 0$

$\beta = 0$

$\beta > 0$

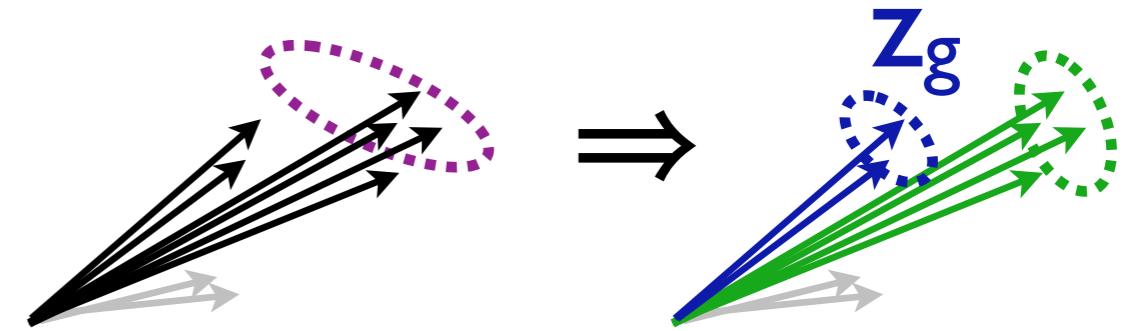
$\beta \rightarrow \infty$



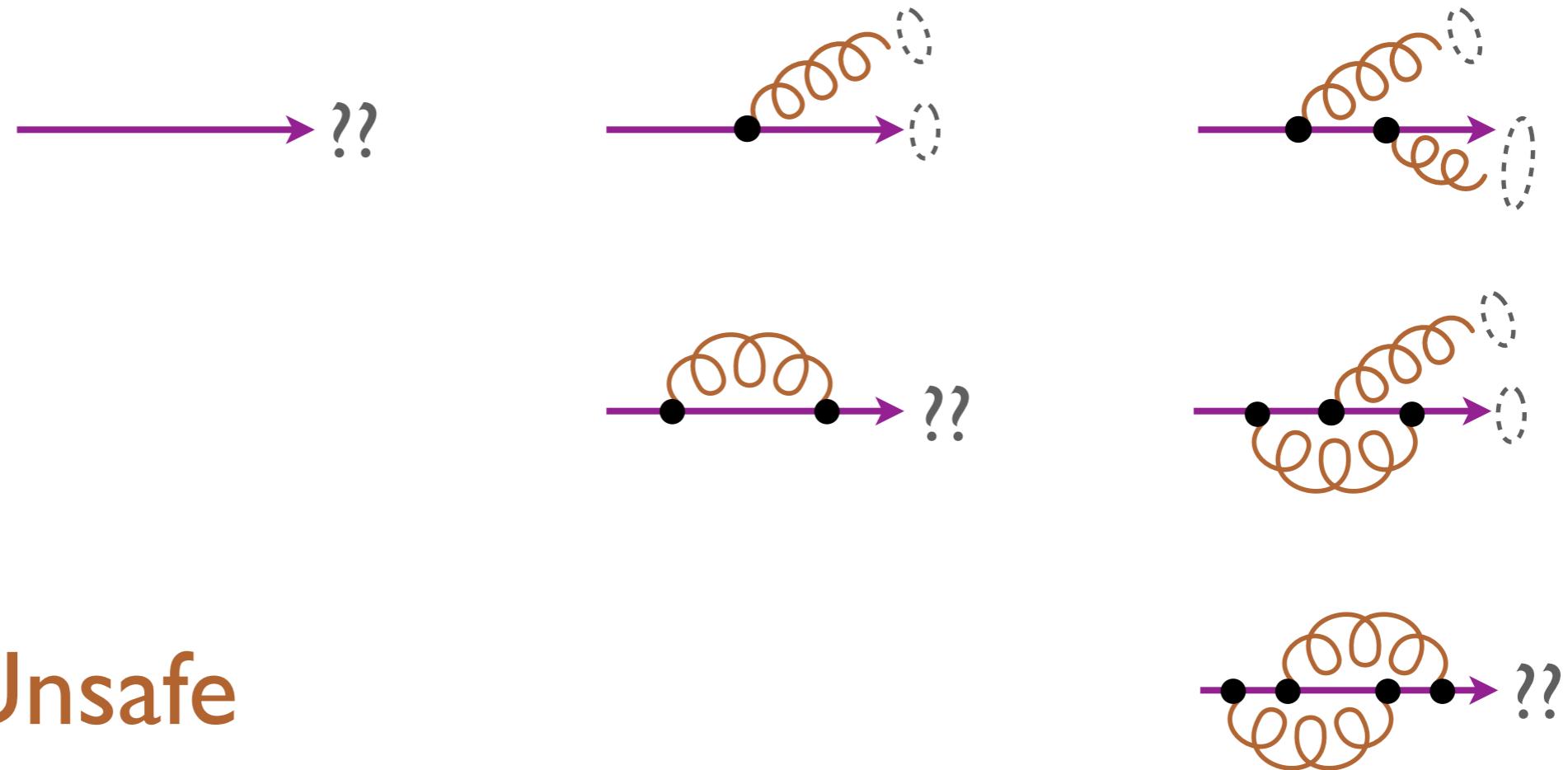
Less Grooming

[Larkoski, Marzani, Soyez, JDT, 2014; see also Frye, Larkoski, Schwartz, Yan, 2016; Marzani, Schunk, Soyez, 2017]

Calculating z_g ?



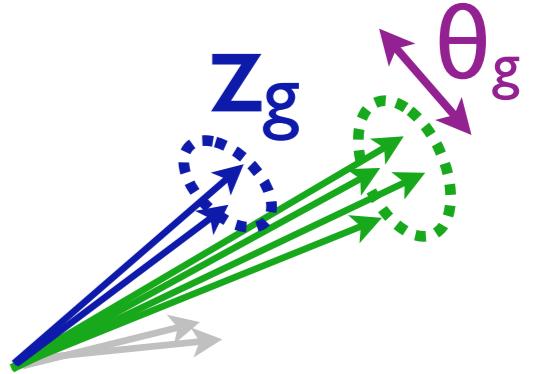
$$p(z_g) = \left(\text{undefined} \right) + \alpha_s \left(\text{infinity} \right) + \alpha_s^2 \left(\text{infinity}^2 \right) + \dots$$



z_g

Unsafe

The Puzzle



Unsafe



$$p(z_g)$$

→ $z_g ??$

VS.

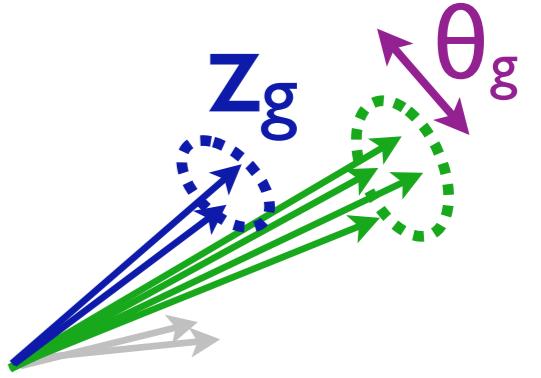
→ z_g $| -z_g \uparrow \theta_g$

Calculable
order-by-order in α_s



$$p(z_g | \theta_g)$$

The Puzzle

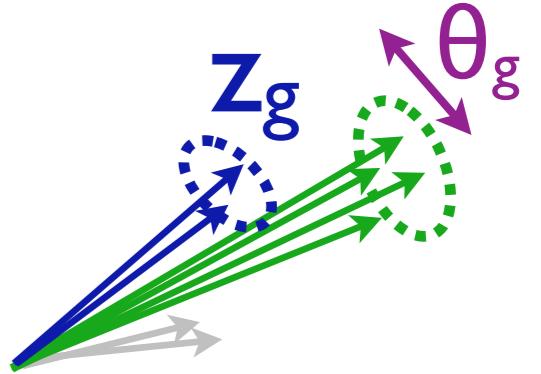


$$p(z_g) = \int d\theta_g p(\theta_g) p(z_g | \theta_g)$$

??

↓

The Resolution



“Sudakov Safe”

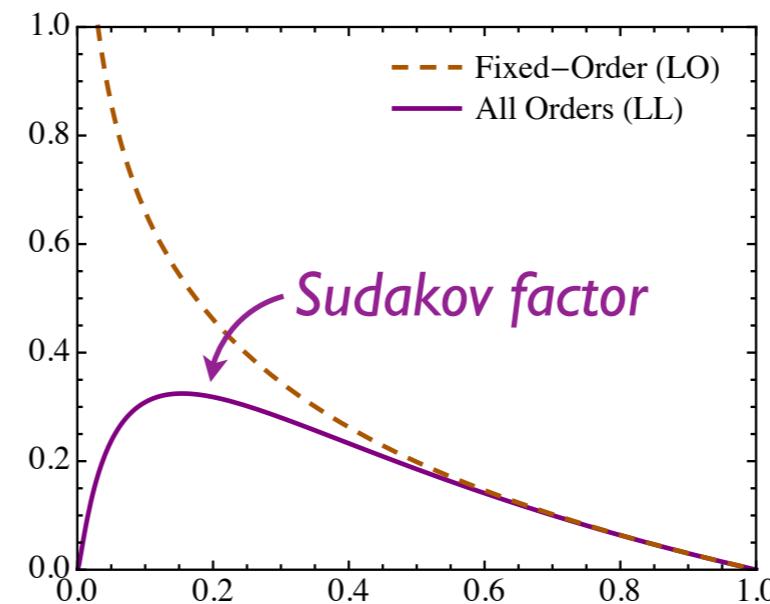


$$p(z_g) = \int d\theta_g p(\theta_g) p(z_g | \theta_g)$$

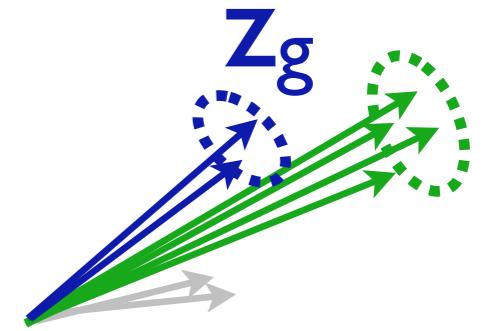
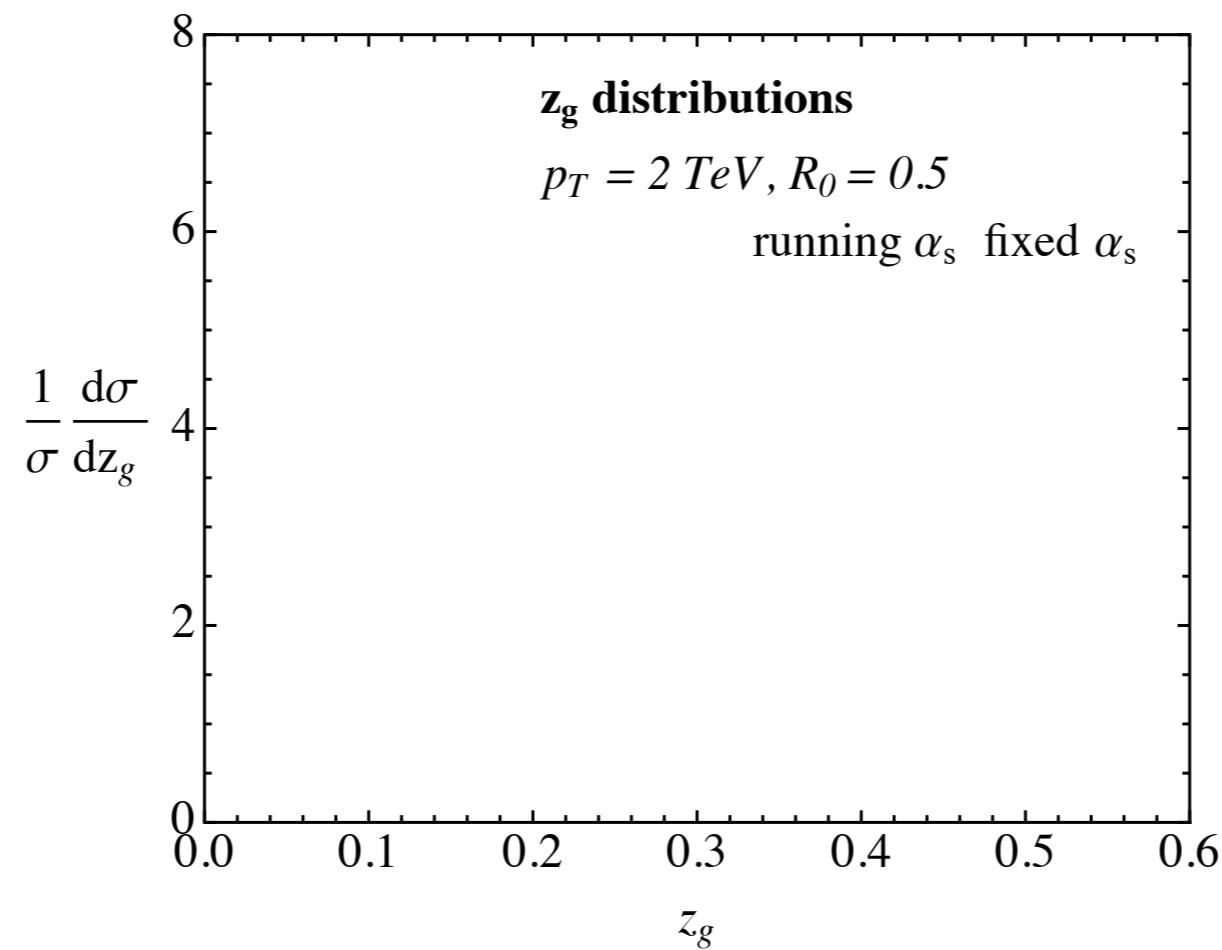
[Larkoski, JDT, 2013;
Larkoski, Marzani, JDT, 2015]

*Suppresses singularities
at all orders in α_s*

*Calculable
order-by-order in α_s*



First-Principles QCD



More Grooming

Less Grooming

$\beta \rightarrow -\infty$

$\beta < 0$

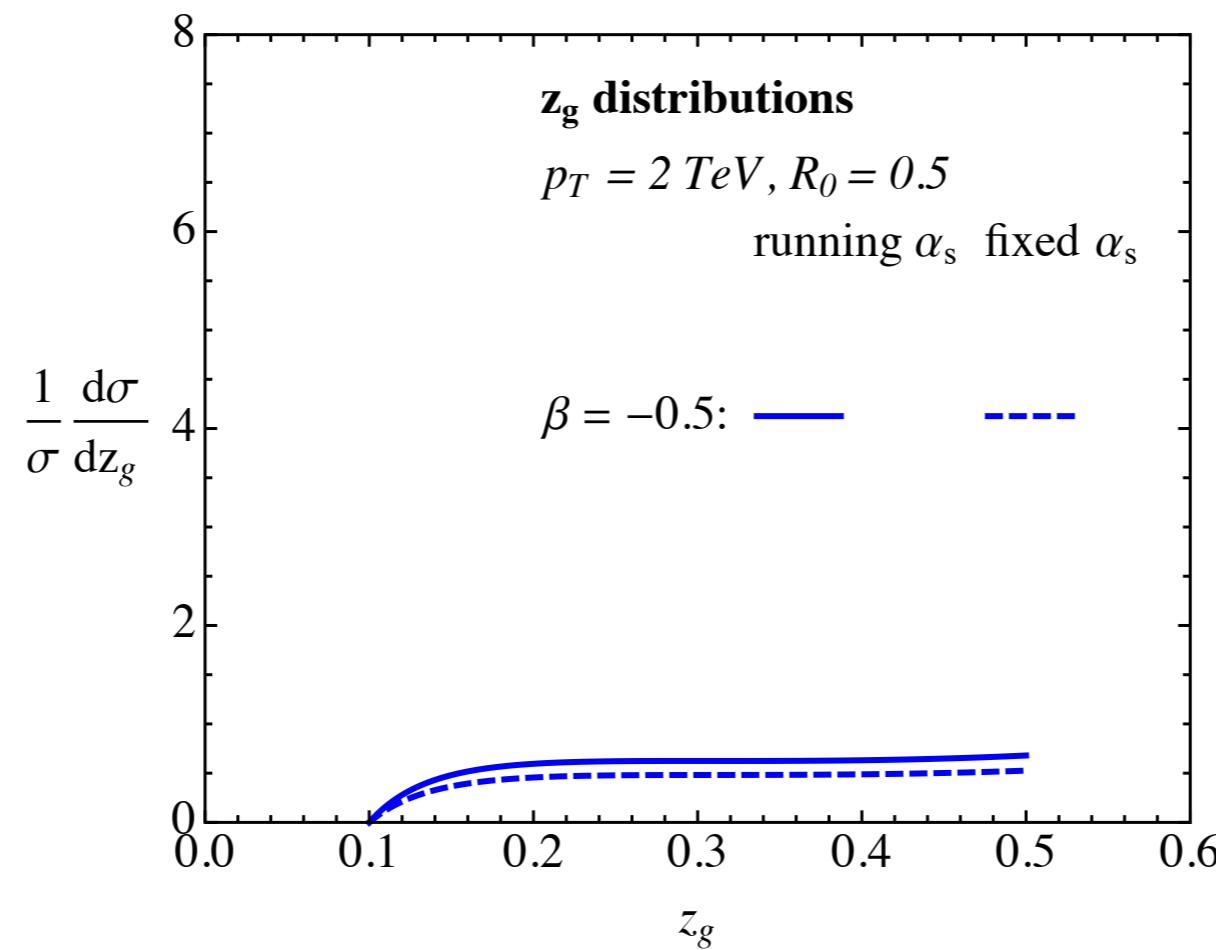
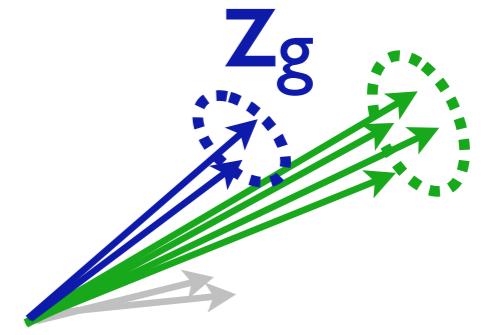
$\beta = 0$

$\beta > 0$

$\beta \rightarrow \infty$

[Larkoski, Marzani, JDT, 2015]

First-Principles QCD



$$C_q = 4/3$$

$$C_g = 3$$



$$\simeq \frac{2\alpha_s C_i}{\pi |\beta|} \frac{1}{z_g} \log \frac{z_g}{z_{cut}}$$

More Grooming



$\beta \rightarrow -\infty$

$\beta < 0$

$\beta = 0$

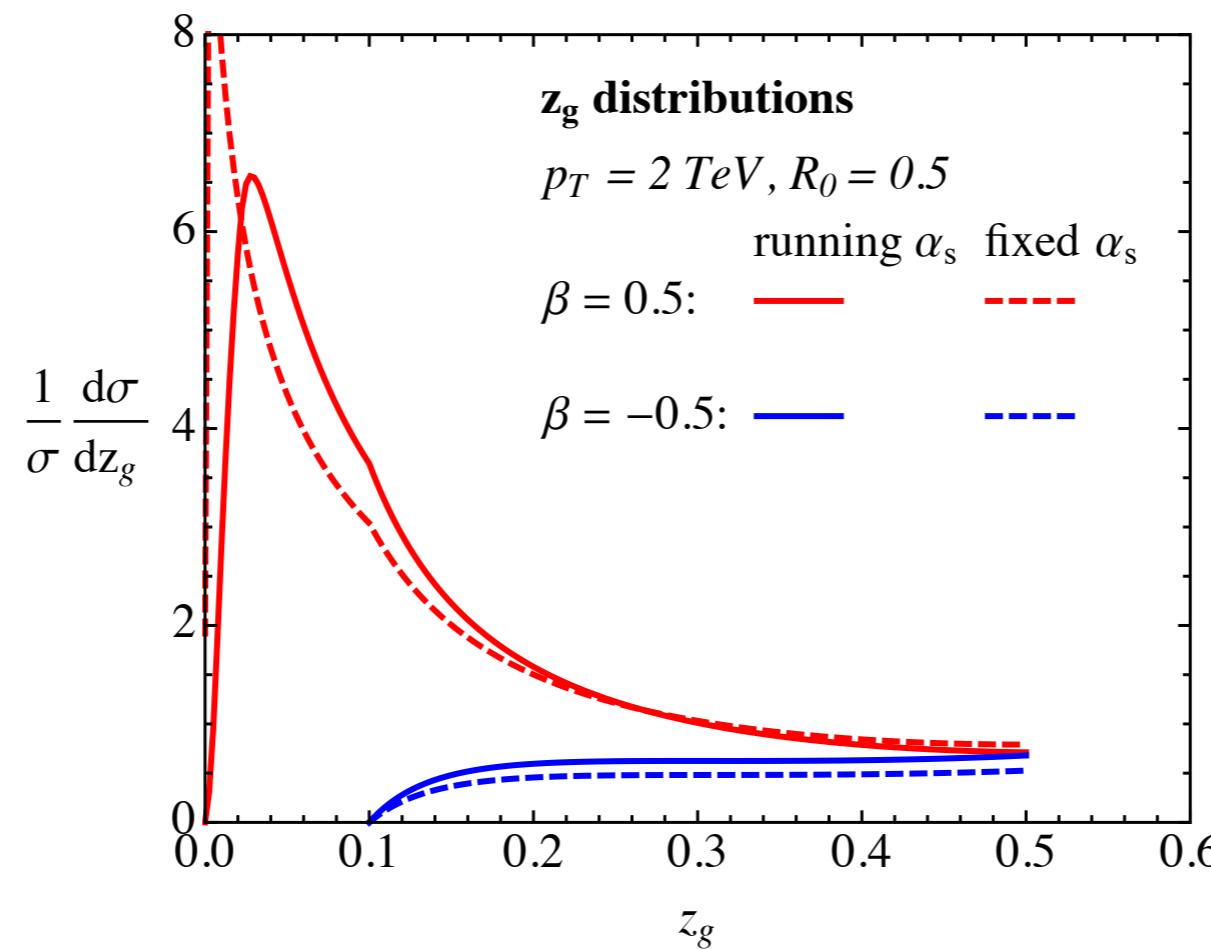
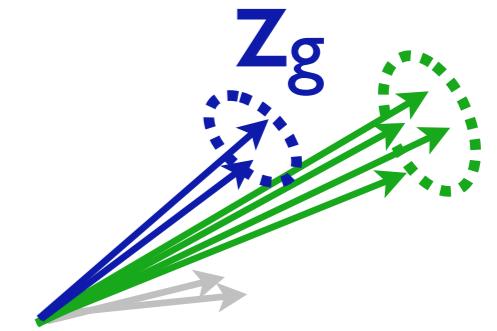
$\beta > 0$

$\beta \rightarrow \infty$

Less Grooming

[Larkoski, Marzani, JDT, 2015]

First-Principles QCD



$$C_q = 4/3$$

$$C_g = 3$$

$$\simeq \frac{2\alpha_s C_i}{\pi |\beta|} \frac{1}{z_g} \log \frac{z_g}{z_{\text{cut}}}$$

$$\simeq \sqrt{\frac{\alpha_s C_i}{\beta}} \frac{1}{z_g}$$

Beyond traditional perturbation theory (Sudakov safe)

More Grooming

$\beta \rightarrow -\infty$

$\beta < 0$

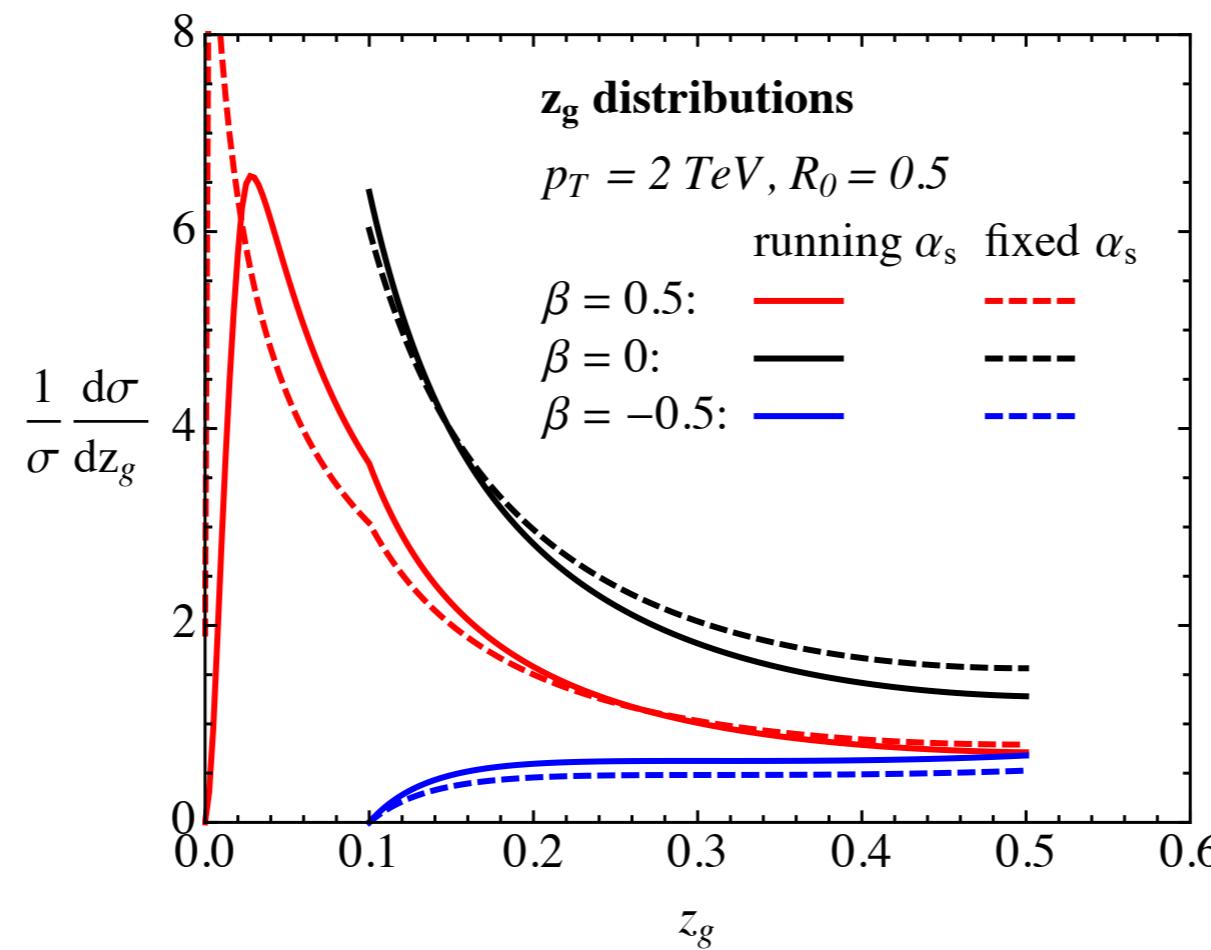
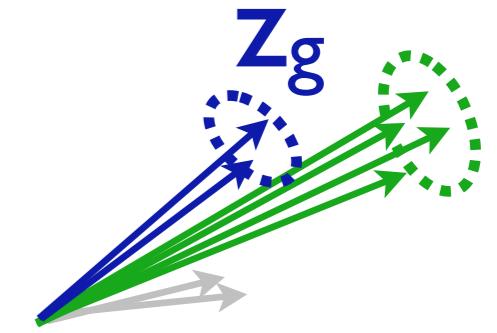
$\beta = 0$

$\beta > 0$

$\beta \rightarrow \infty$

[Larkoski, Marzani, JDT, 2015]

First-Principles QCD



$$C_q = 4/3$$

$$C_g = 3$$

$$\simeq \frac{2\alpha_s C_i}{\pi |\beta|} \frac{1}{z_g} \log \frac{z_g}{z_{cut}}$$

$$\simeq \frac{1}{z_g} (!)$$

$$\simeq \sqrt{\frac{\alpha_s C_i}{\beta}} \frac{1}{z_g}$$

Beyond traditional
perturbation theory
(Sudakov safe)

More Grooming

$\beta \rightarrow -\infty$

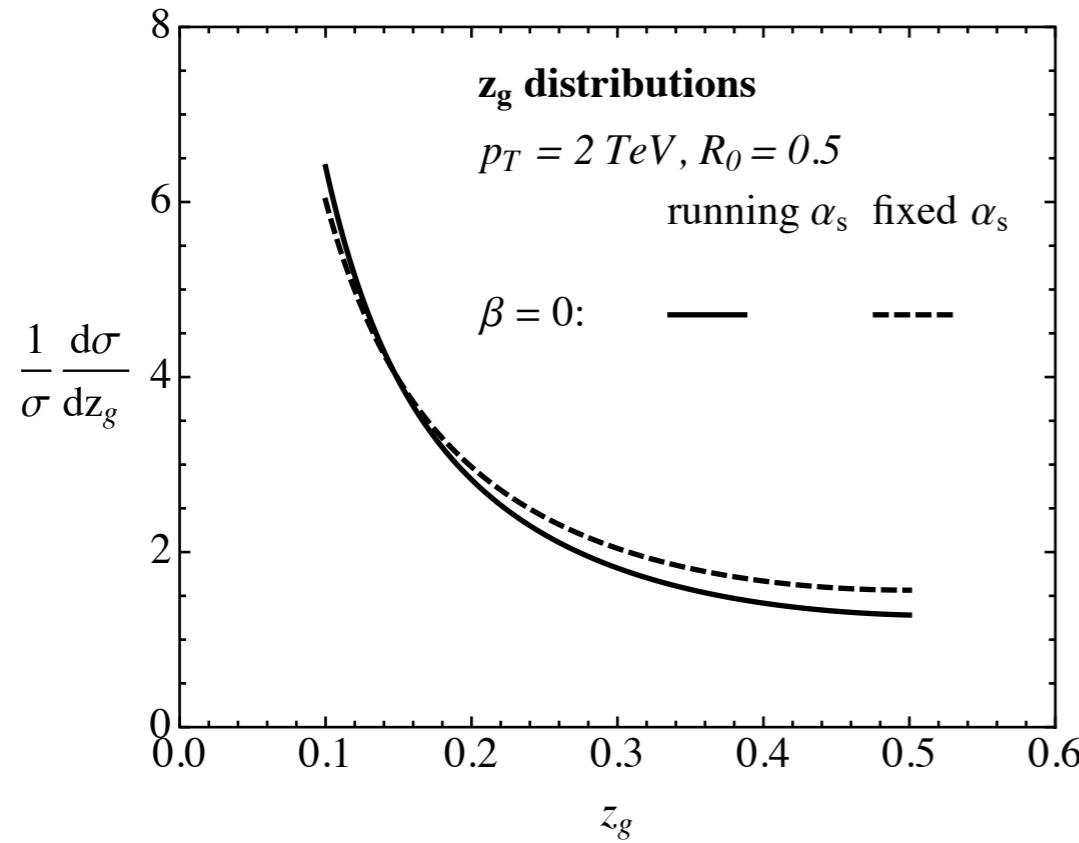
$\beta < 0$

$\beta = 0$

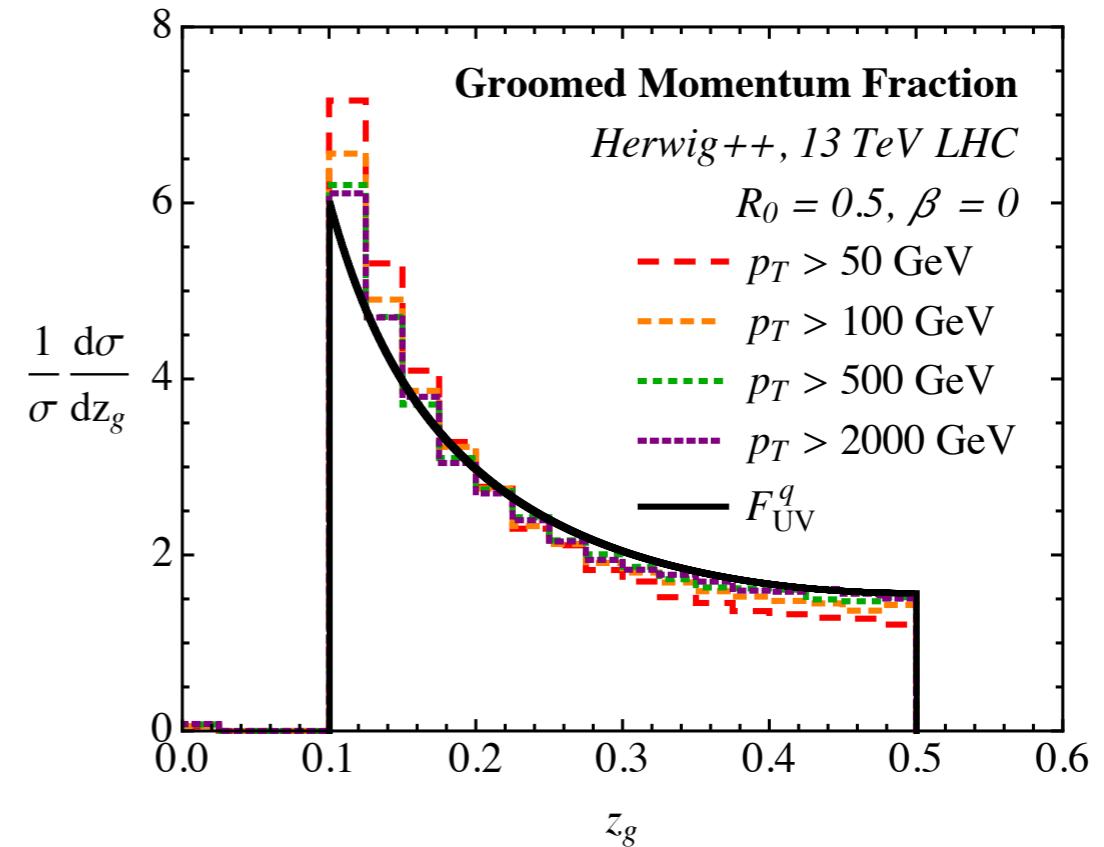
$\beta > 0$

$\beta \rightarrow \infty$

Unsafe but Calculable



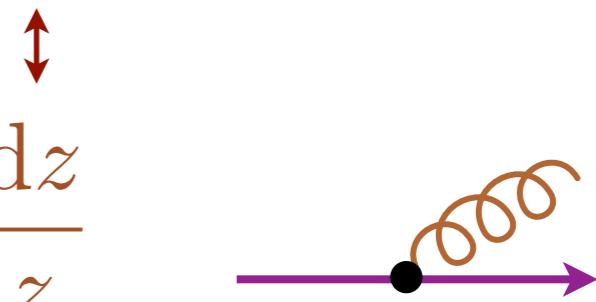
Simulated LHC Data



“Standard Candle”
for Jets in QCD: $\simeq \frac{1}{z_g}$

Altarelli-Parisi
Splitting Function

$$dP_{i \rightarrow ig} \simeq \frac{2\alpha_s}{\pi} C_i \frac{d\theta}{\theta} \frac{dz}{z}$$



[Larkoski, Marzani, JDT, 2015]



Exposing the QCD Splitting Function with CMS Open Data

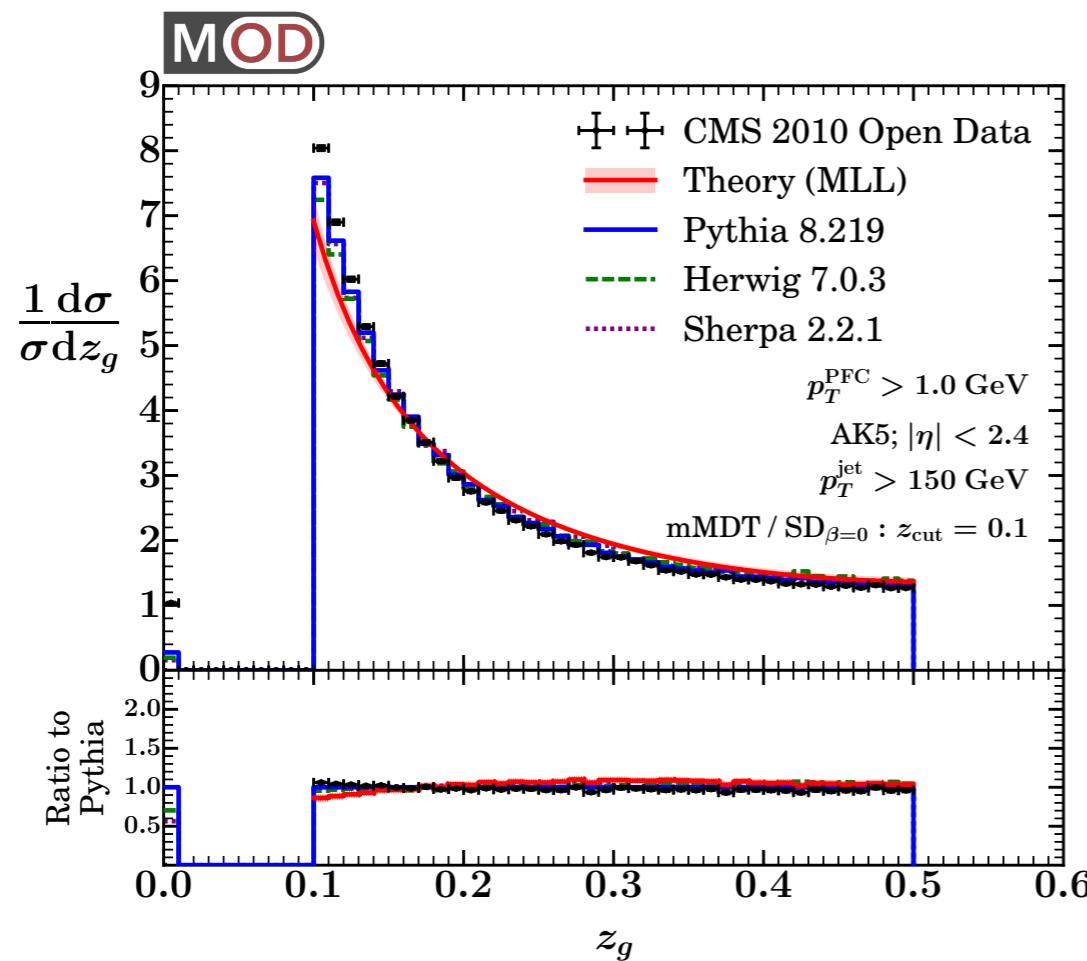
Andrew Larkoski,^{1,*} Simone Marzani,^{2,†} Jesse Thaler,^{3,‡} Aashish Tripathee,^{3,§} and Wei Xue^{3,||}

¹*Physics Department, Reed College, Portland, Oregon 97202, USA*

²*University at Buffalo, The State University of New York, Buffalo, New York 14260-1500, USA*

³*Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

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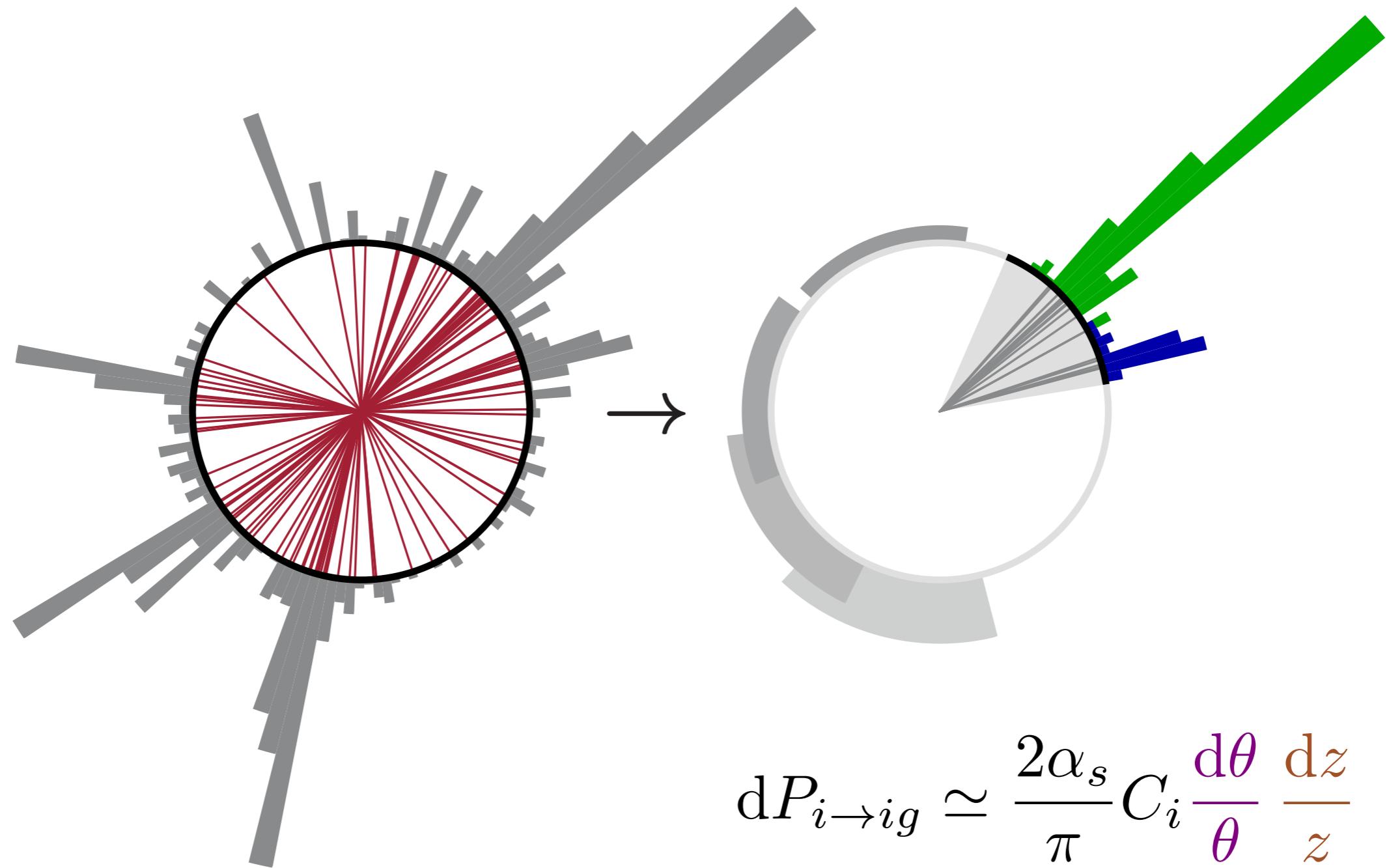


opendata
CERN

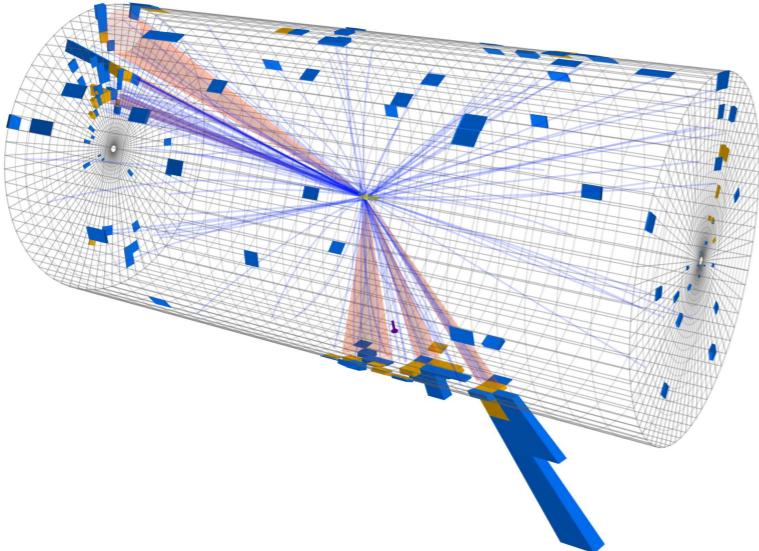
$$dP_{i \rightarrow ig} \sim \frac{2\alpha_s}{\pi} C_i \frac{d\theta}{\theta} \frac{dz}{z}$$

(Ask me about modification
from quark gluon plasma)

Distill Complex Phenomena to Simple Physical Principles

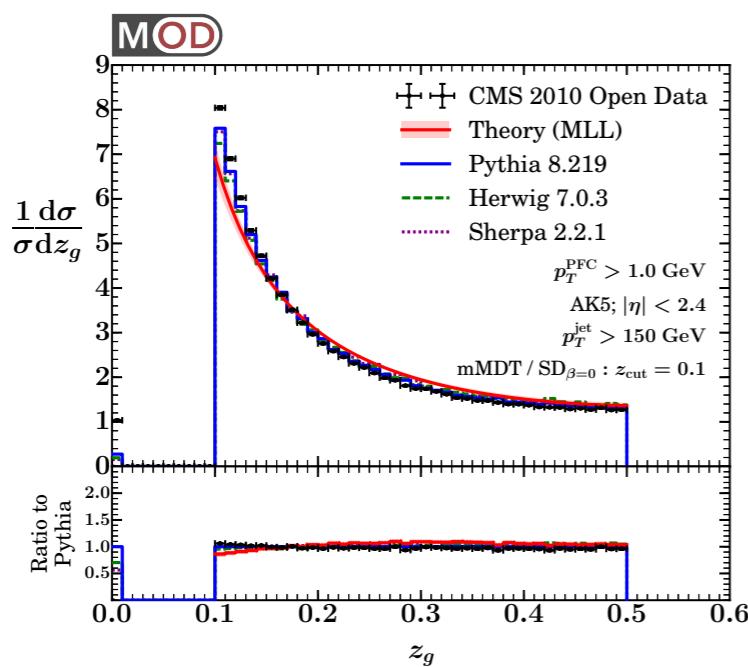


Jet Substructure



Boosting the Search for New Phenomena

Planar Flow, Trimming, Variable R, N-subjettiness, Generalized Correlators, Winner-Take-All Axes, Soft Drop, Jets Without Jets, XCone, [Energy Flow Polynomials](#), Classification Without Labels, Jet Topics, ...



Pushing the Boundaries of Quantum Field Theory

Boosted Event Shapes, Transverse Velocity Flow, Track-Based Observables, Recoil-Free Observables, [Sudakov Safety](#), Quark/Gluon Mutual Information, Generalized Fragmentation Functions, ...

BOOST 2018

10th International Workshop on Boosted Objects
Phenomenology, Reconstruction and Searches

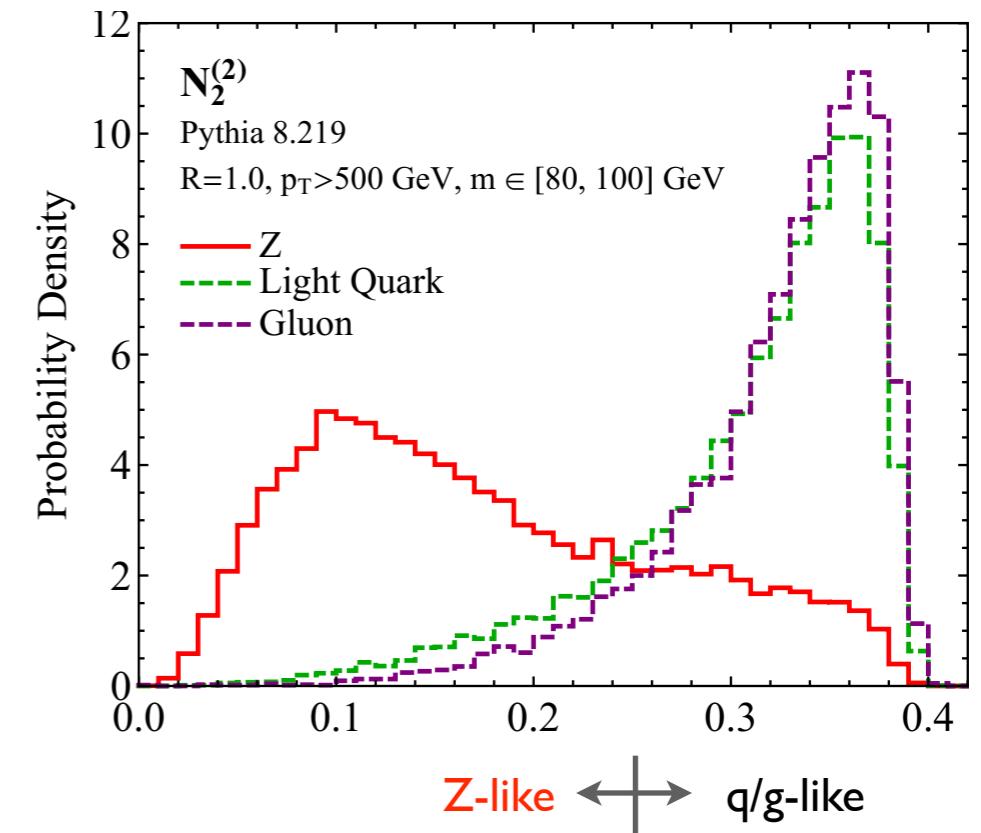
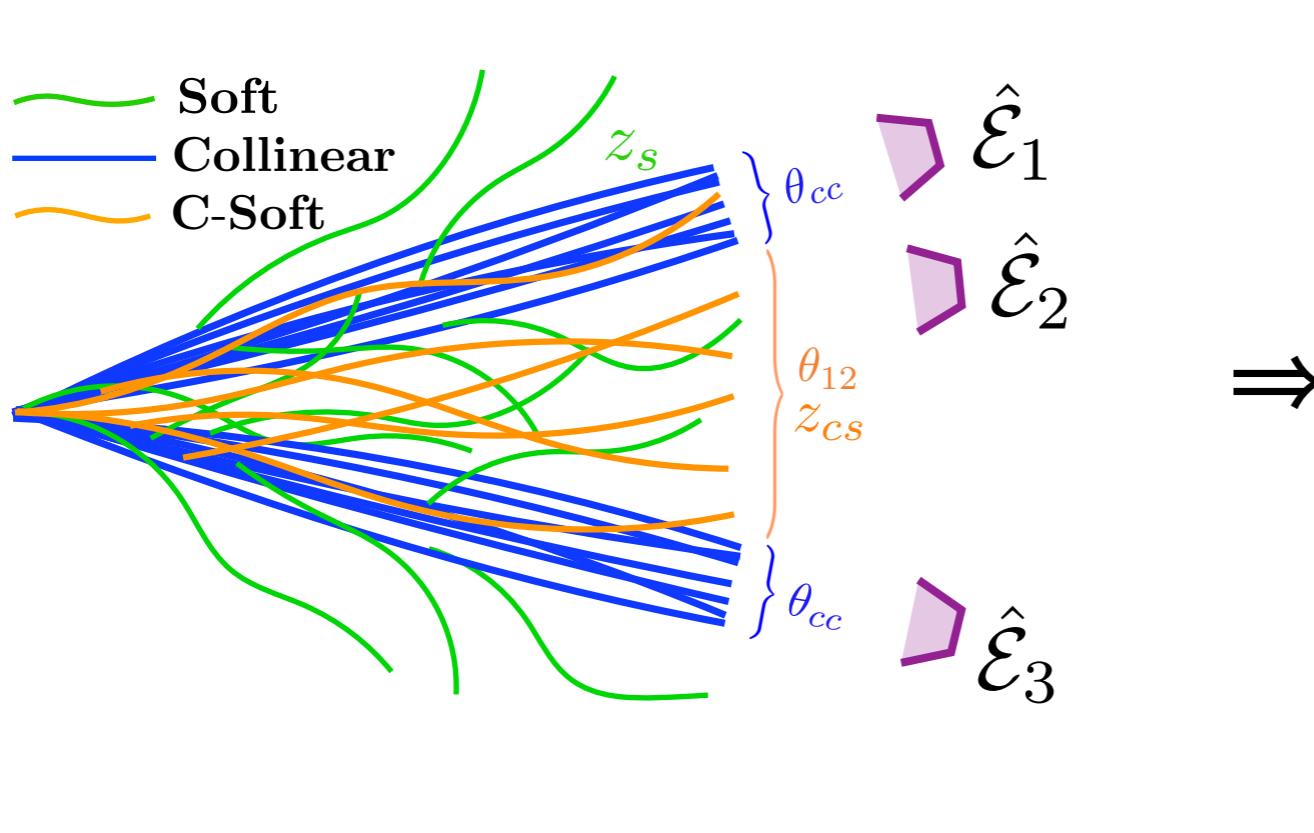
Paris 16-20 July 2018



Backup Slides

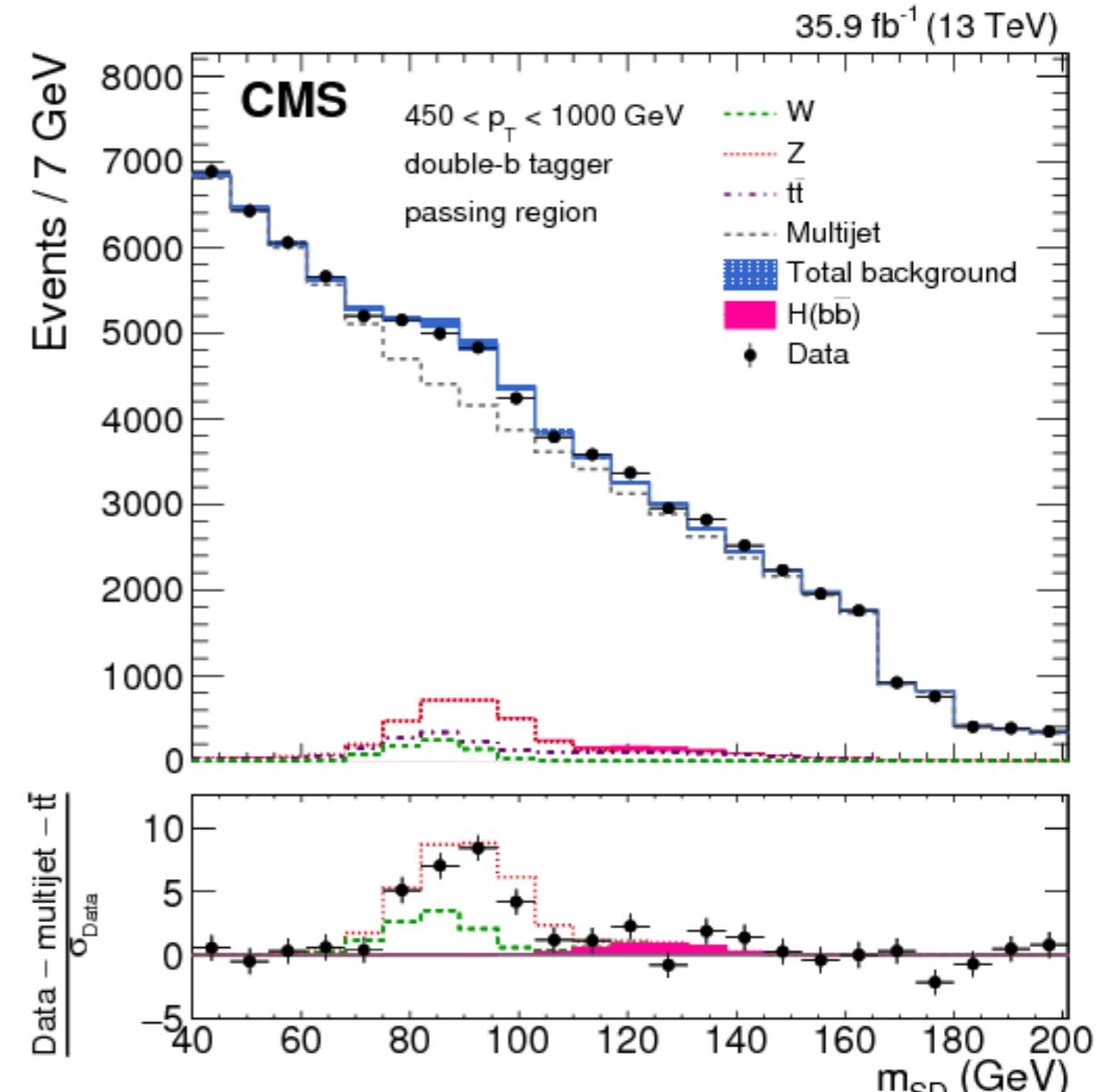
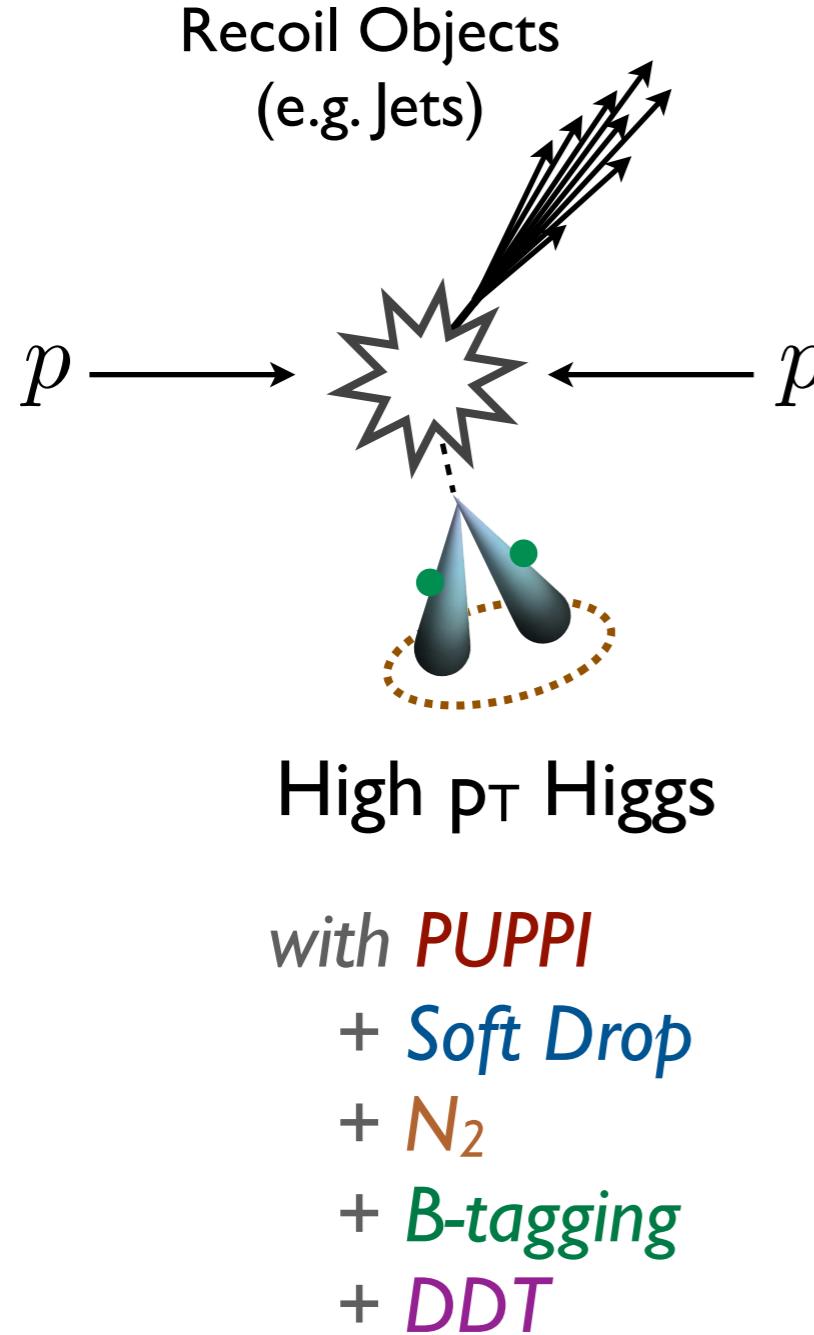
Simplicity: 2-Prongs from Energy Correlators

$$N_2 = \frac{\sum_{i < j < k} p_{Ti} p_{Tj} p_{Tk} \min \left\{ (R_{ij} R_{jk})^2, (R_{jk} R_{ki})^2, (R_{ki} R_{ij})^2 \right\}}{\left(\sum_{i < j} p_{Ti} p_{Tj} R_{ij}^2 \right)^2 / \sum_i p_{Ti}}$$



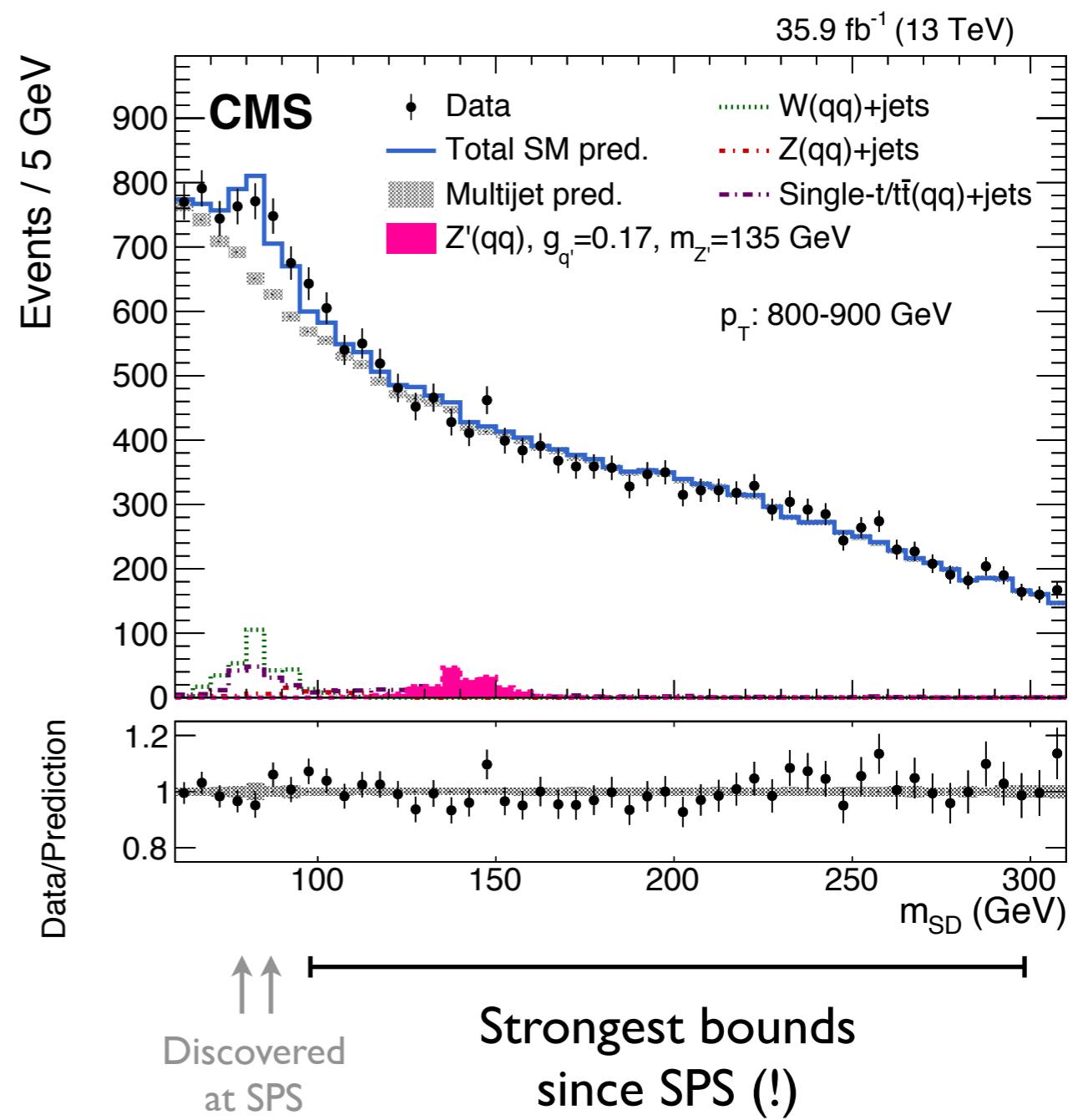
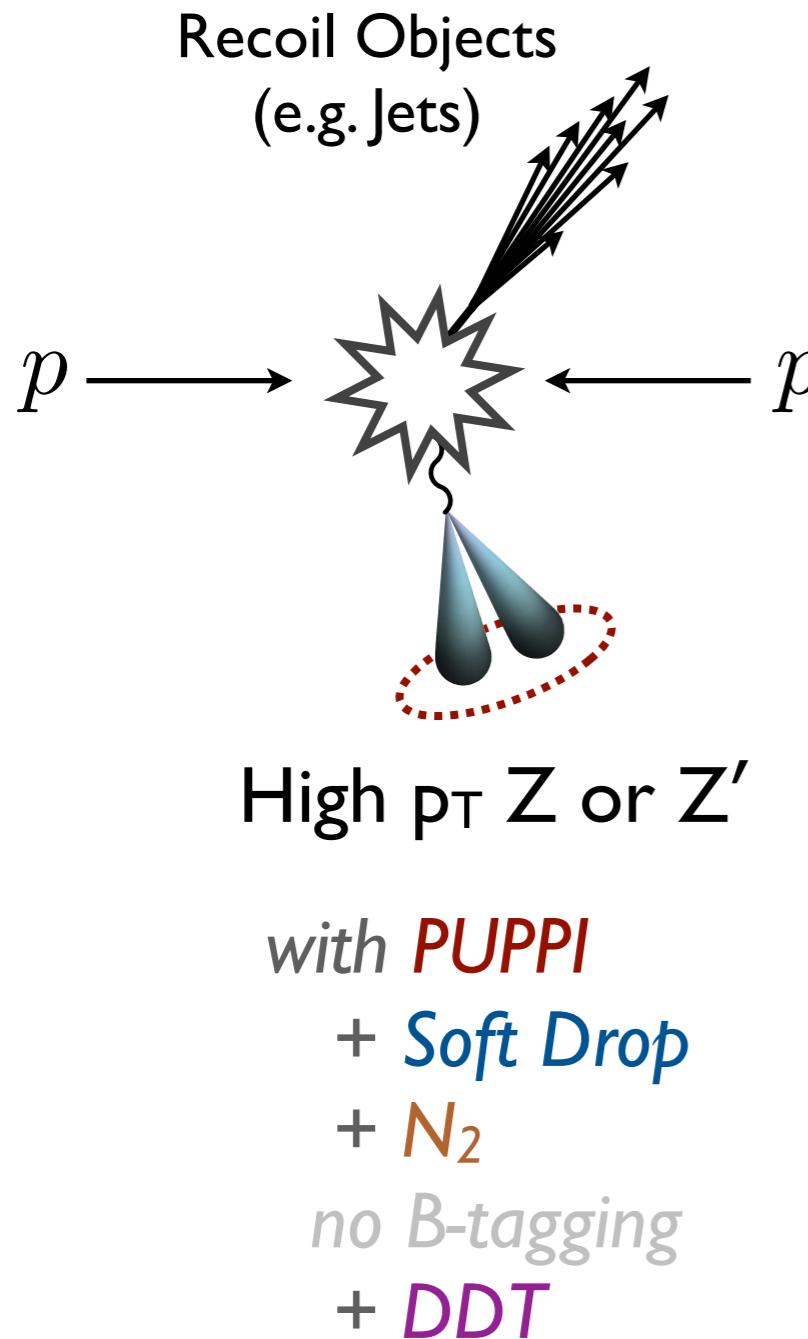
[Moult, Necib, JDT, 2016; based on Larkoski, Salam, JDT, 2013]

CMS: Boosted Higgs...



[CMS, 2017; using Bertolini, Harris, Low, Tran, 2014; Larkoski, Marzani, Soyez, JDT, 2014;
Moult, Necib, JDT, 2016; CMS, 2015; Dolen, Harris, Marzani, Rappoccio, Tran, 2016]

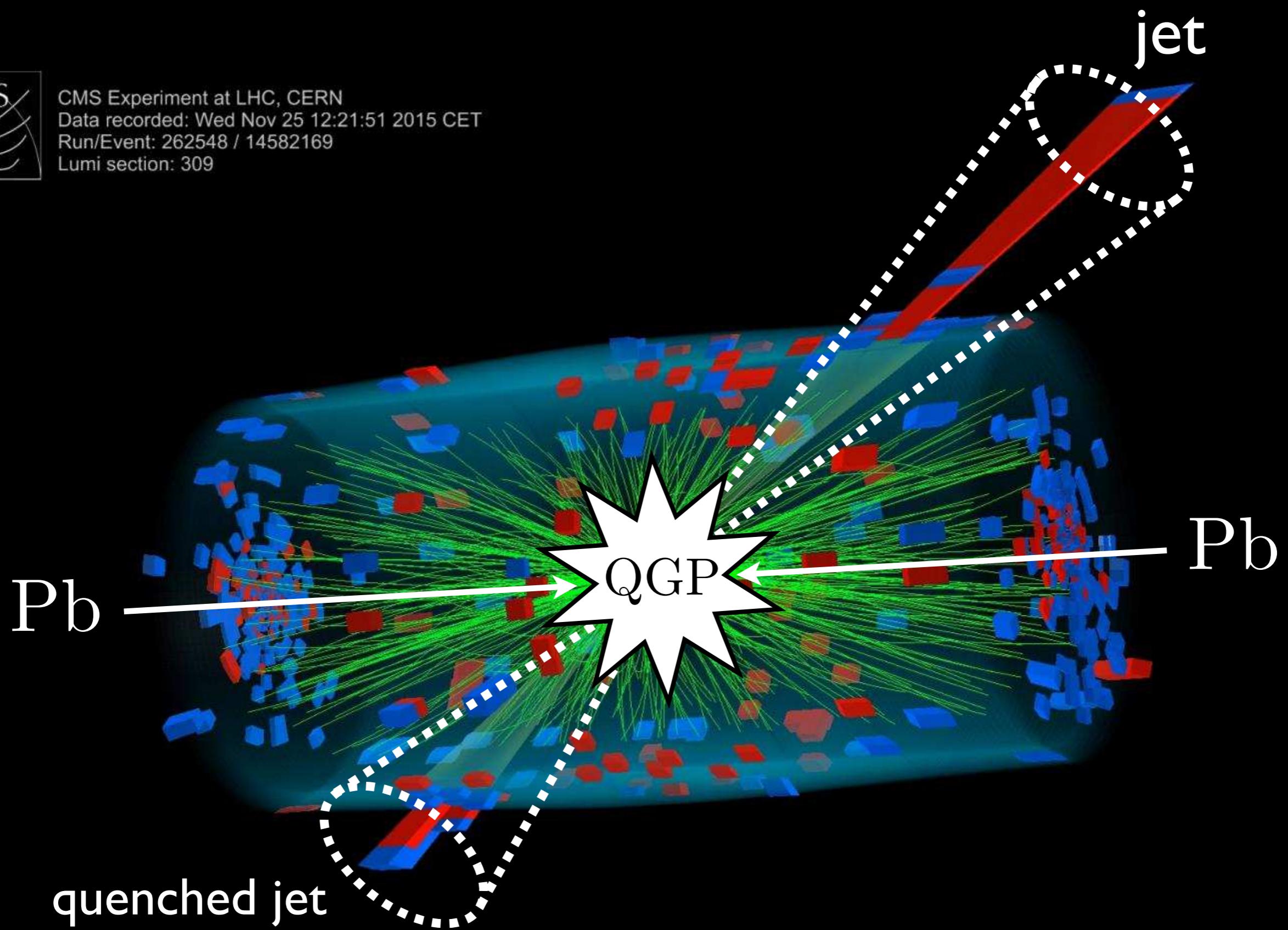
CMS: Boosted Higgs... & Beyond



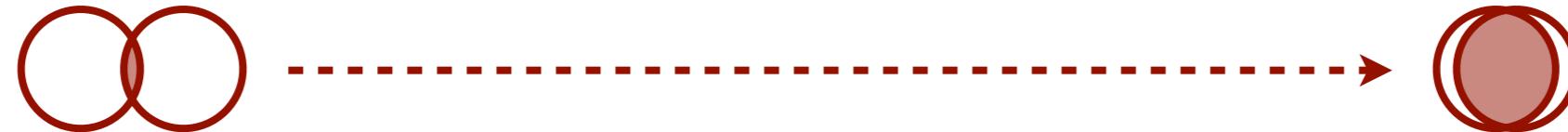
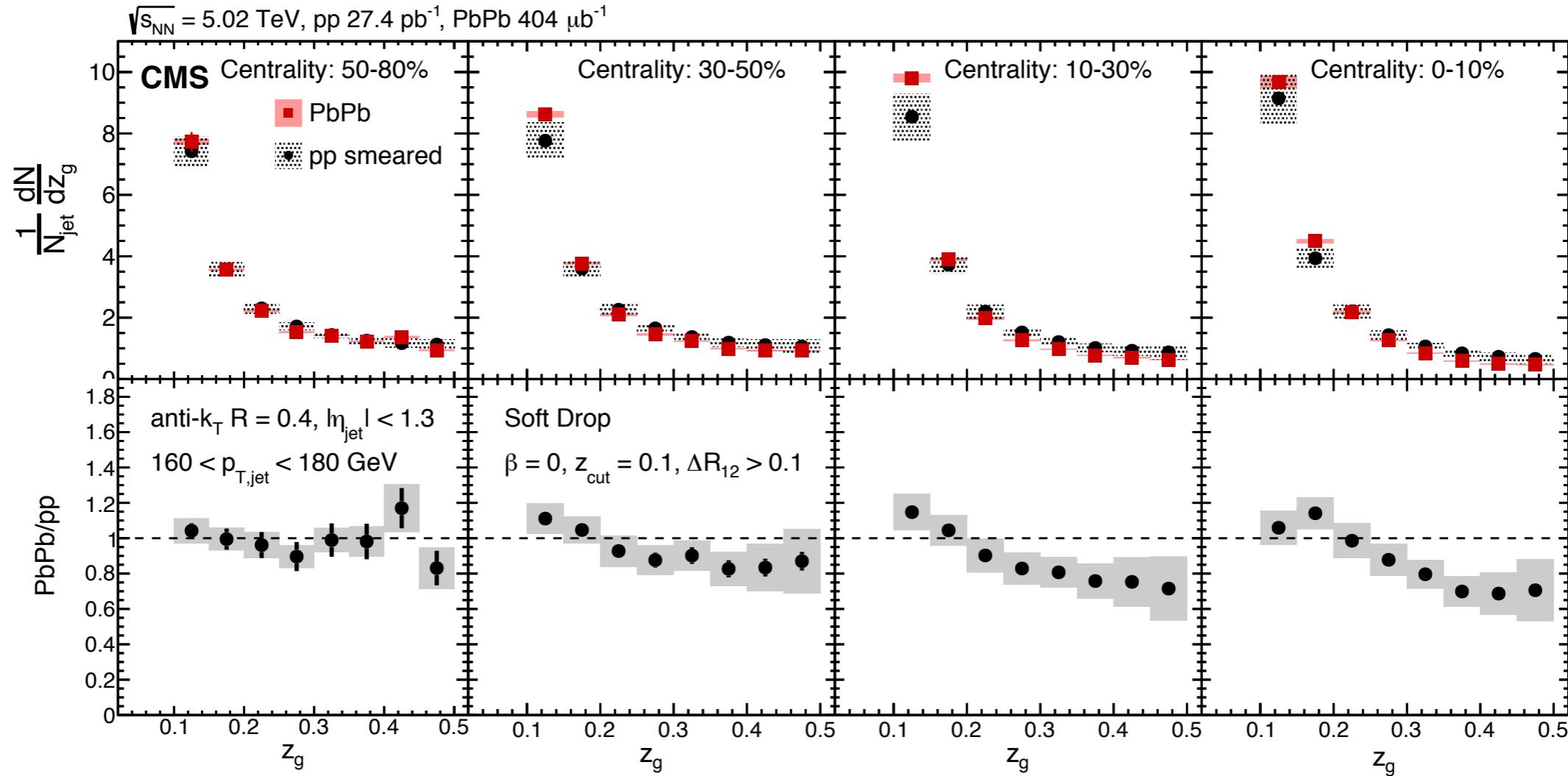
[CMS, 2017; using Bertolini, Harris, Low, Tran, 2014; Larkoski, Marzani, Soyez, JDT, 2014; Moult, Necib, JDT, 2016; CMS, 2015; Dolen, Harris, Marzani, Rappoccio, Tran, 2016]



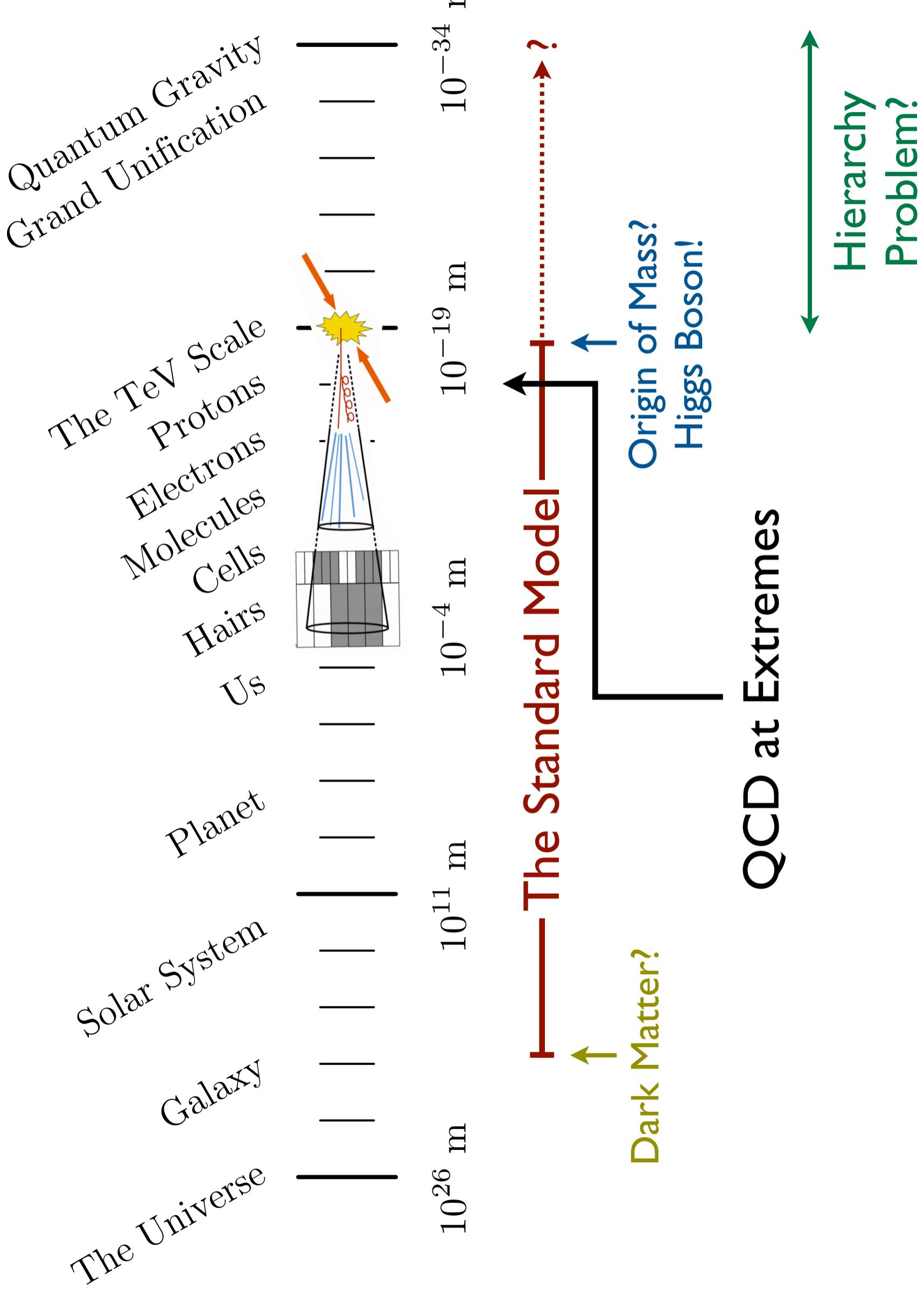
CMS Experiment at LHC, CERN
Data recorded: Wed Nov 25 12:21:51 2015 CET
Run/Event: 262548 / 14582169
Lumi section: 309



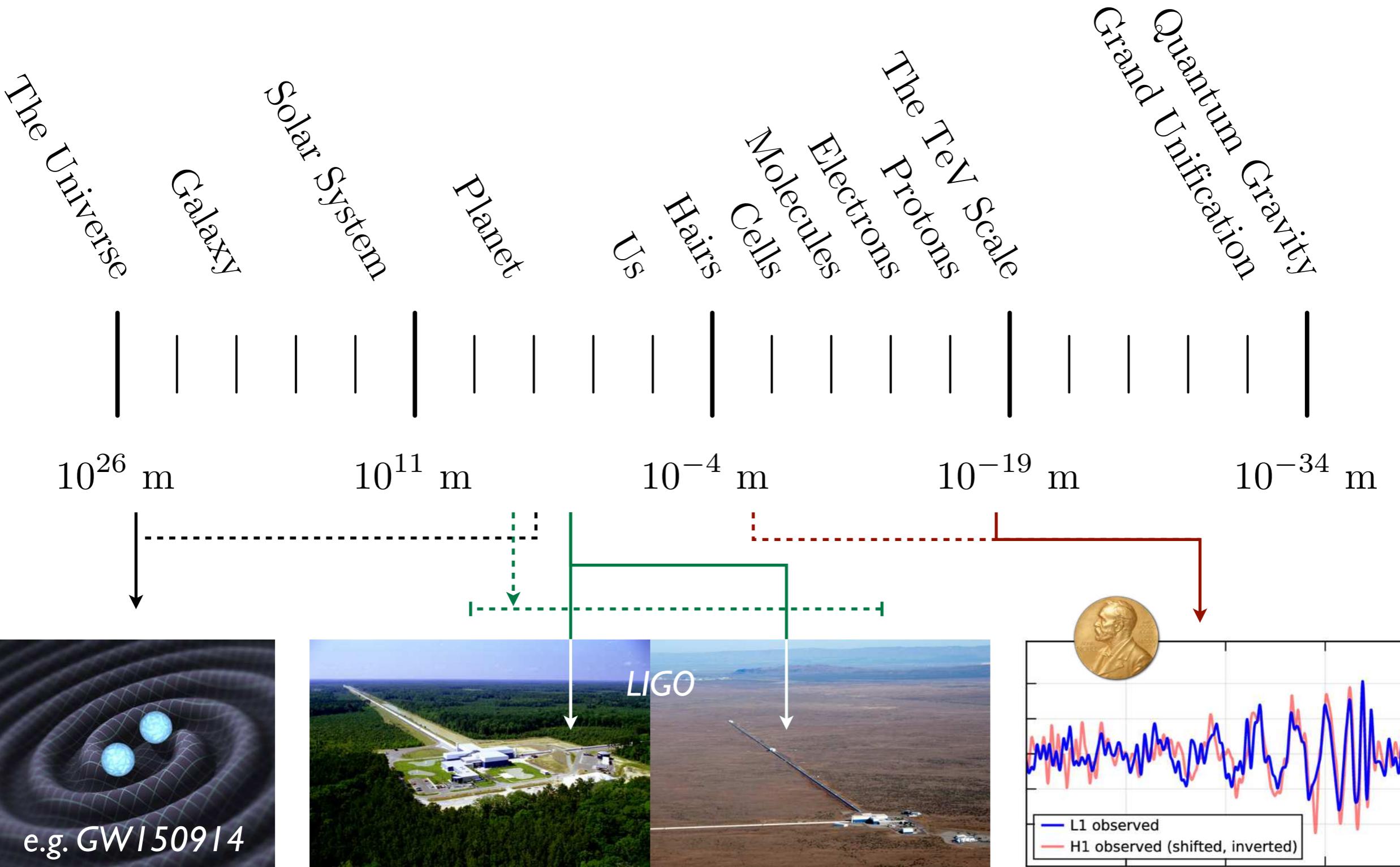
Medium Modifications?

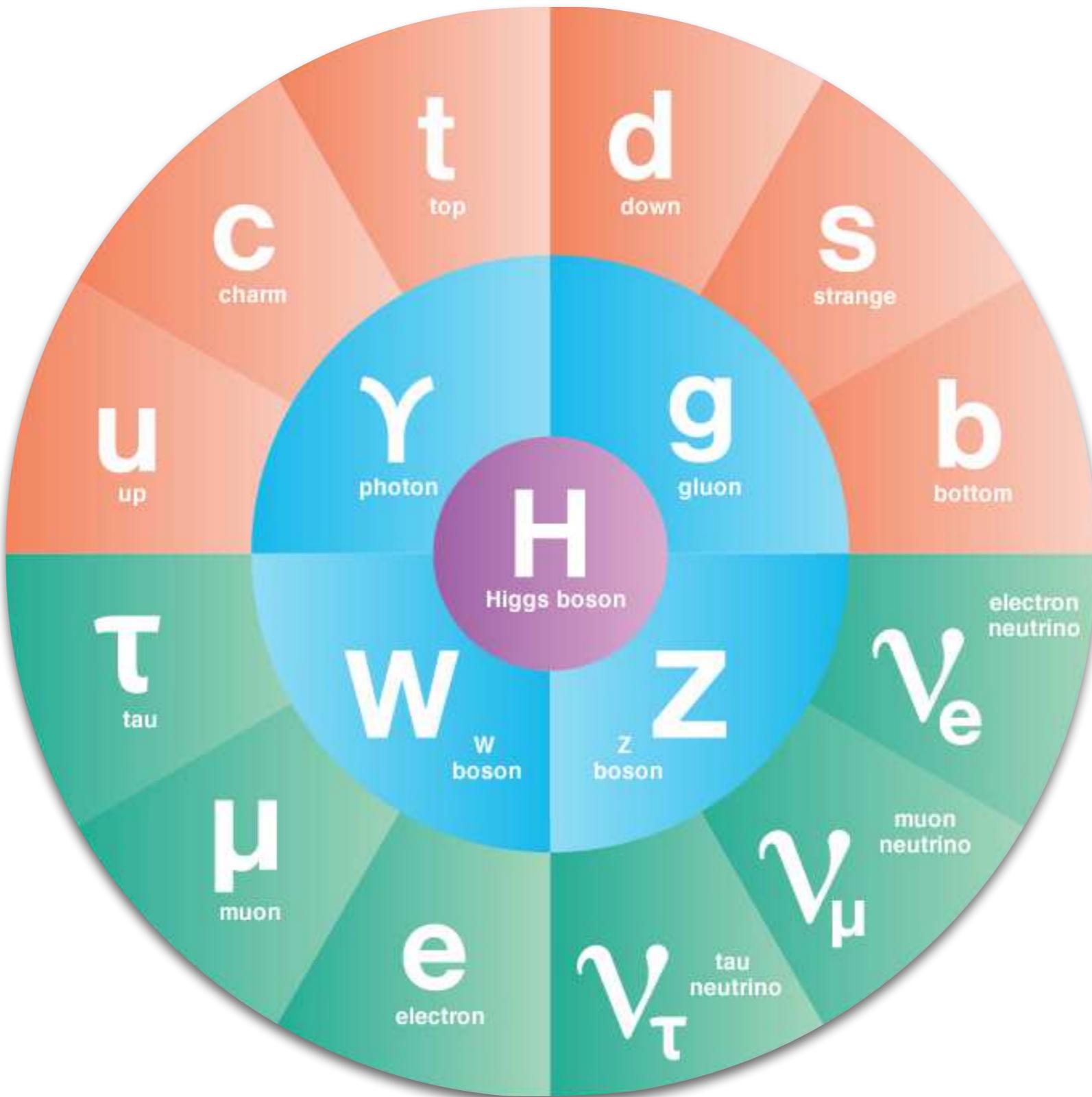


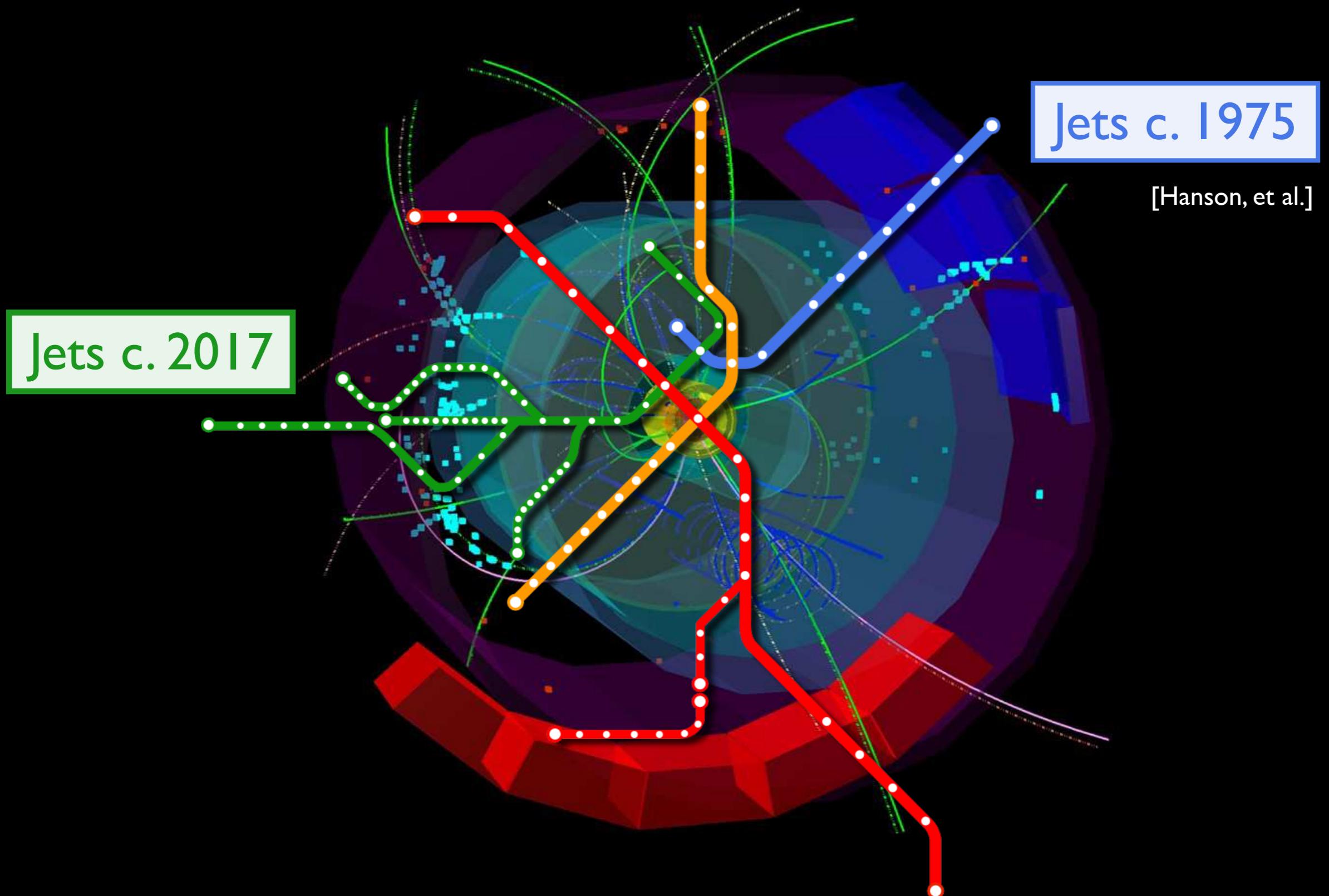
[CMS, 2017; using Larkoski, Marzani, JDT, 2015]

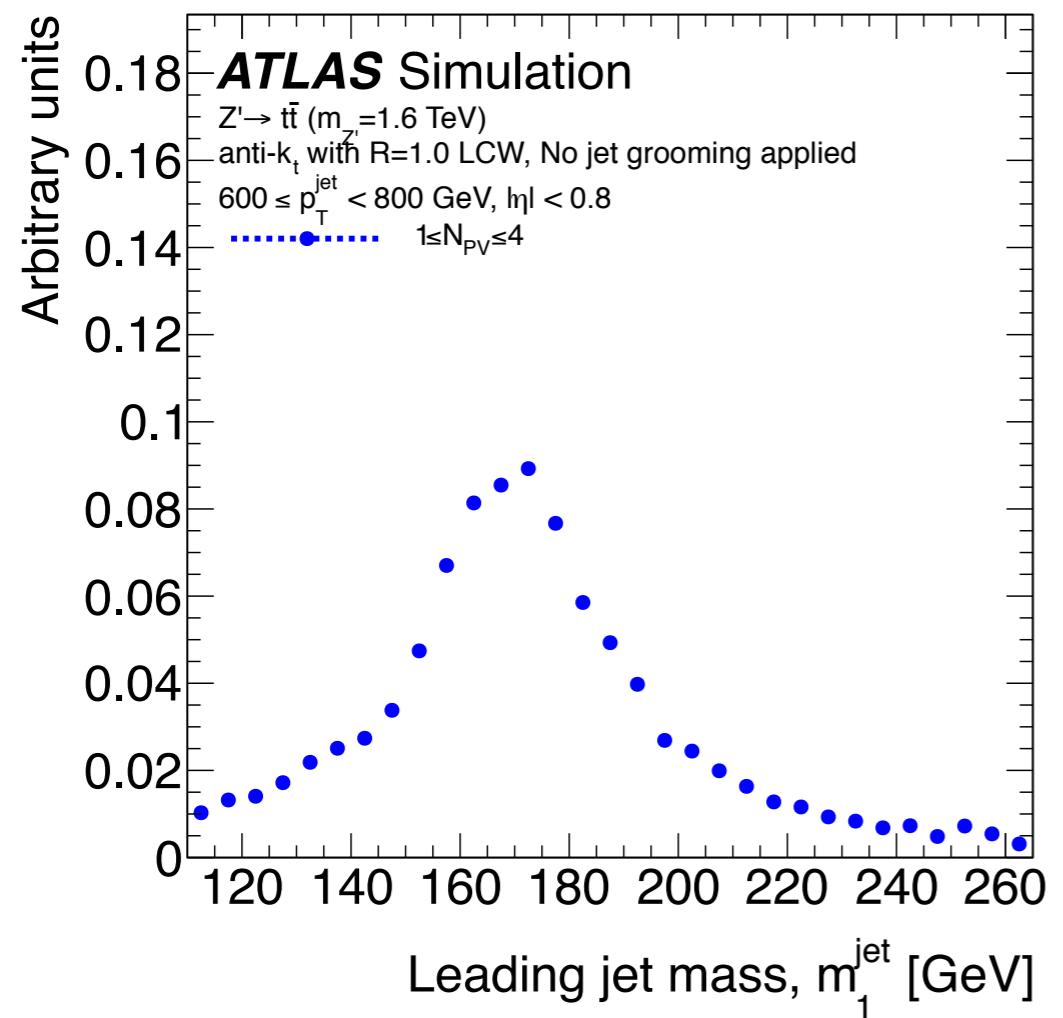
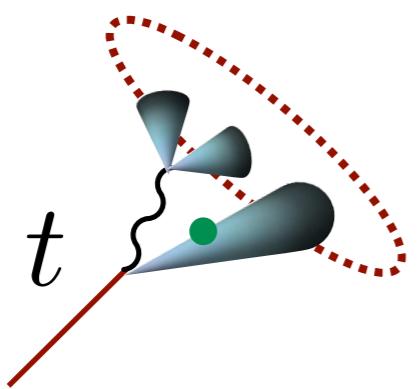


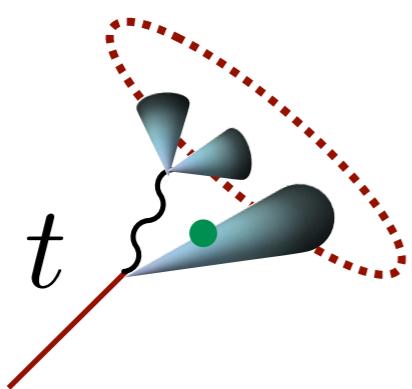
Even More Backup Slides



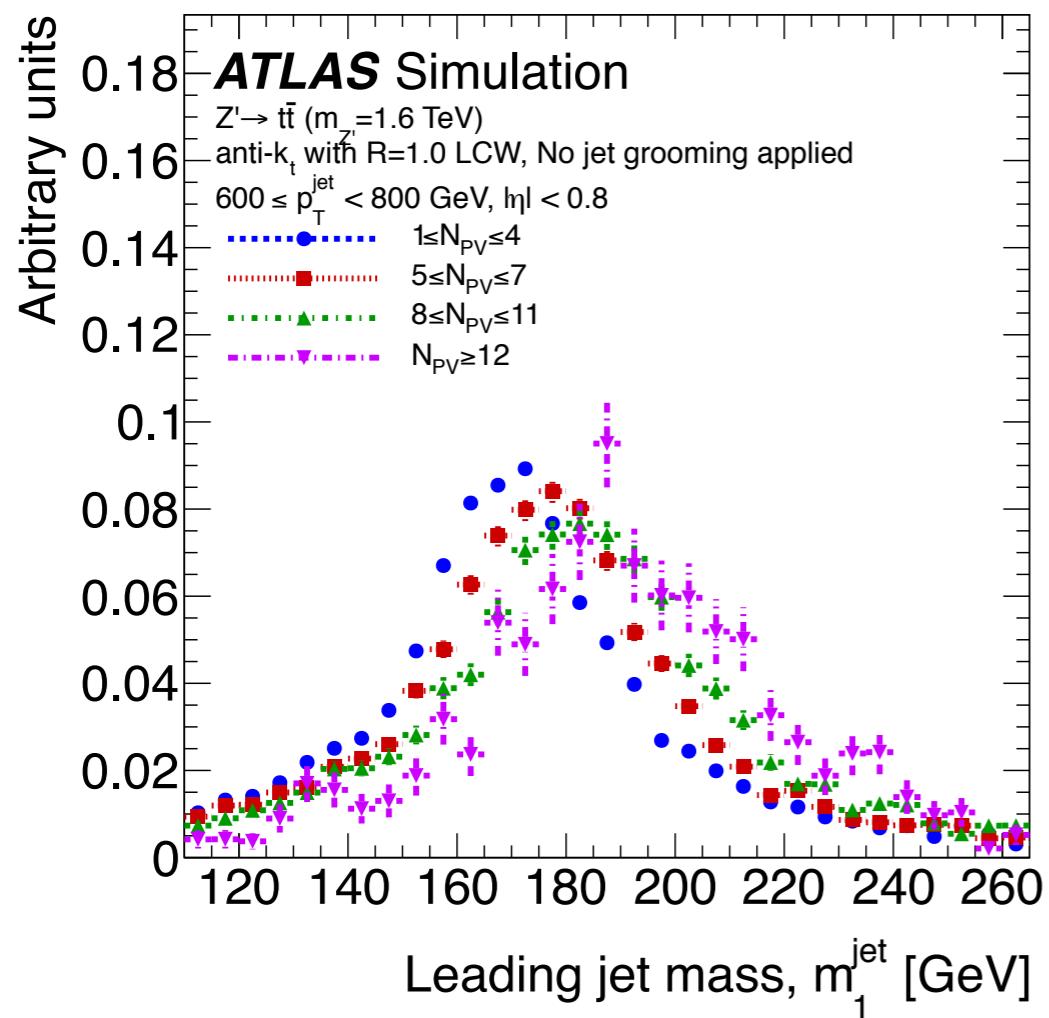
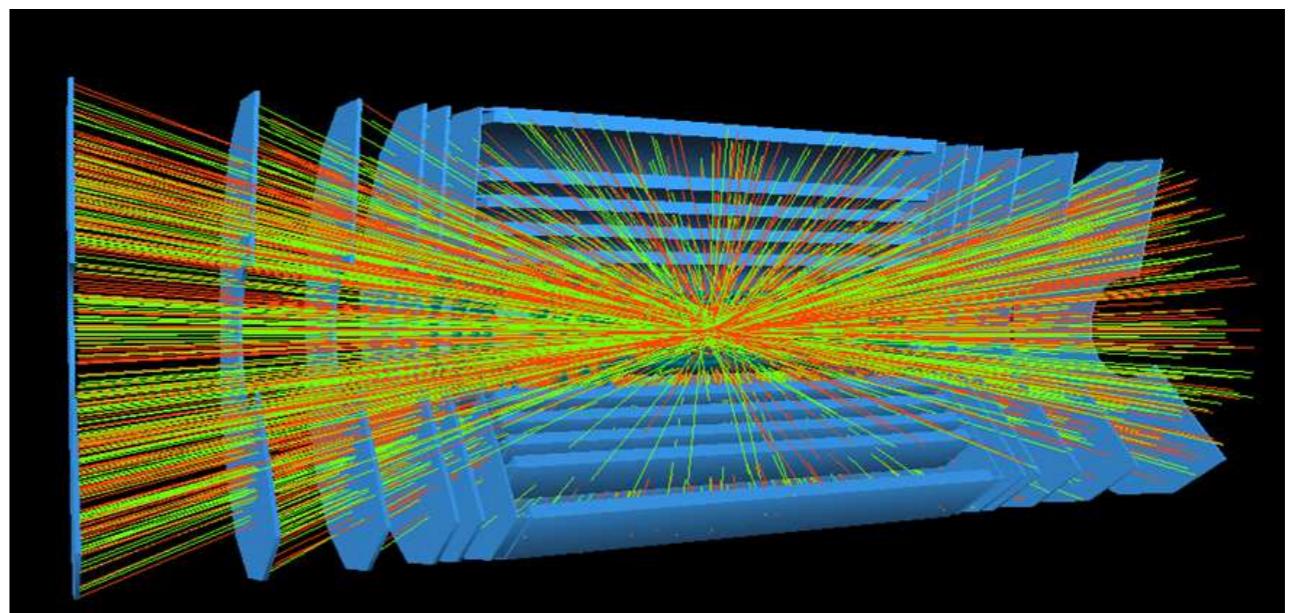


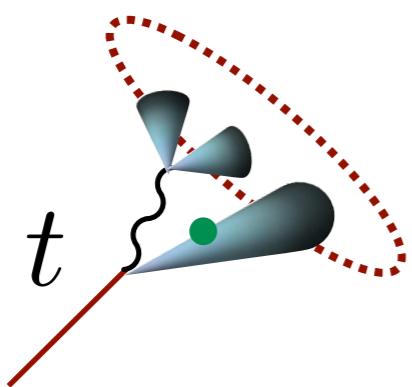




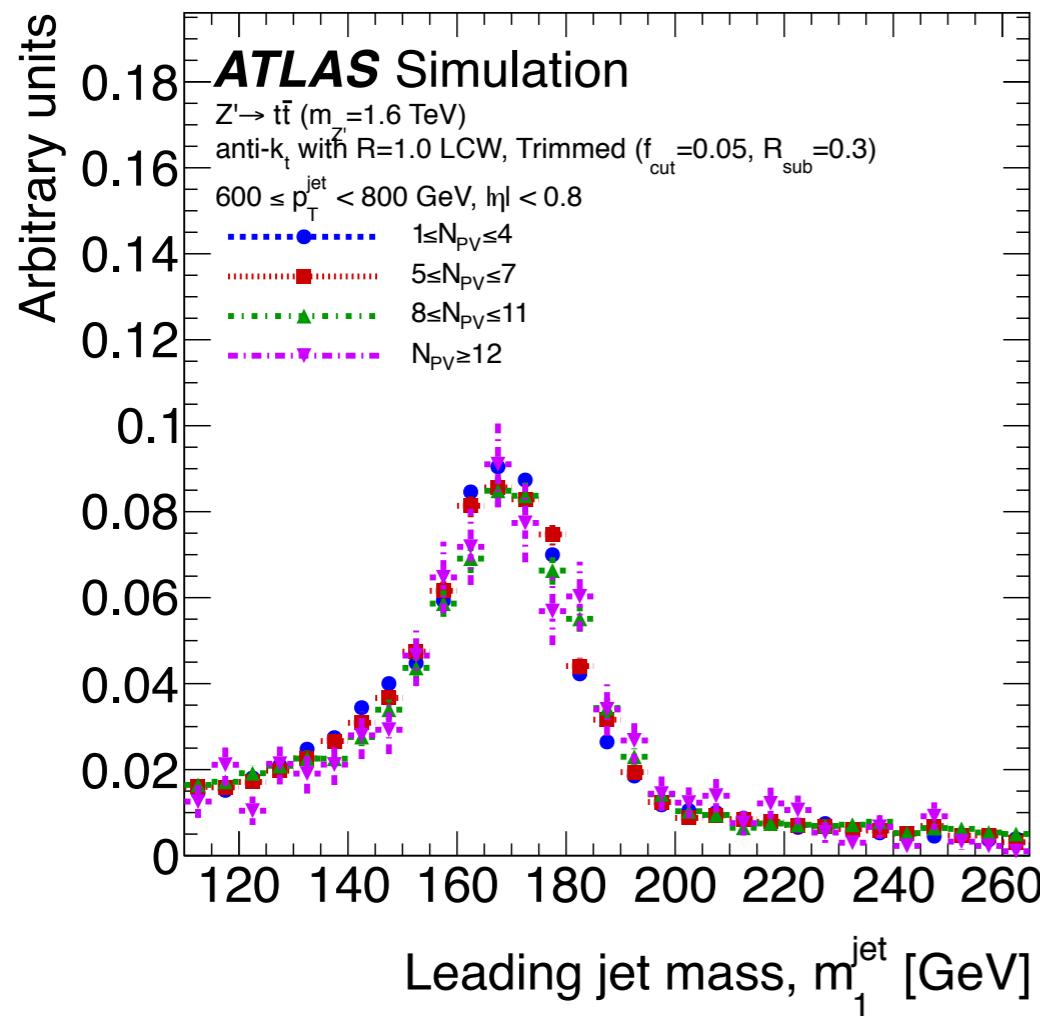
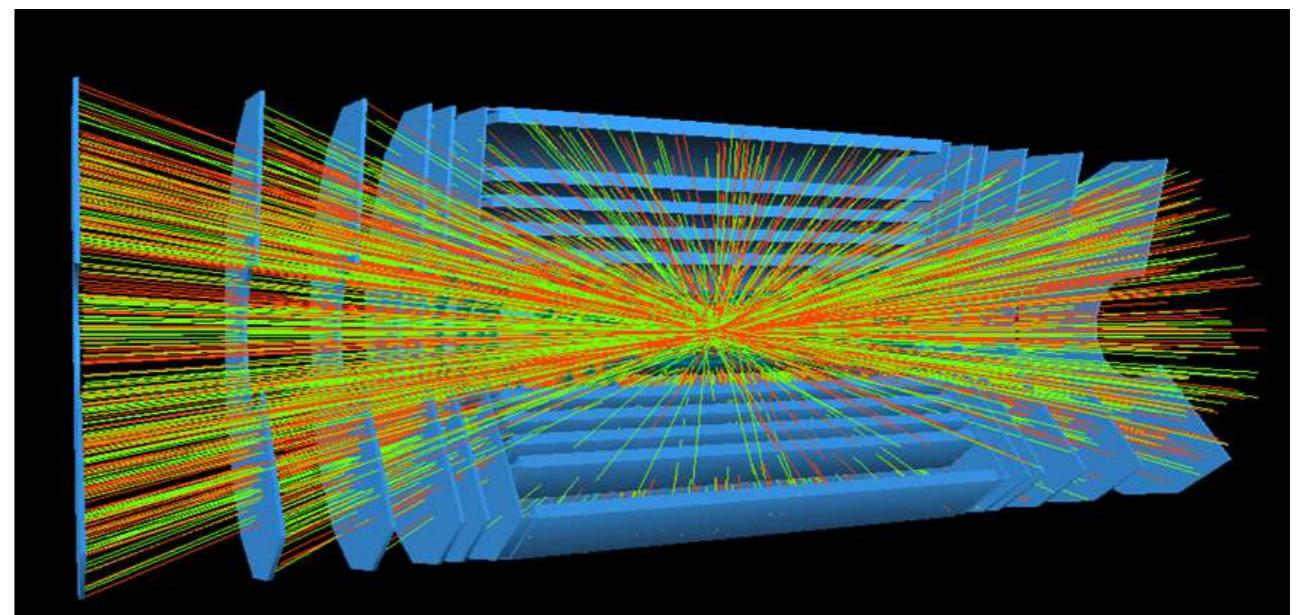


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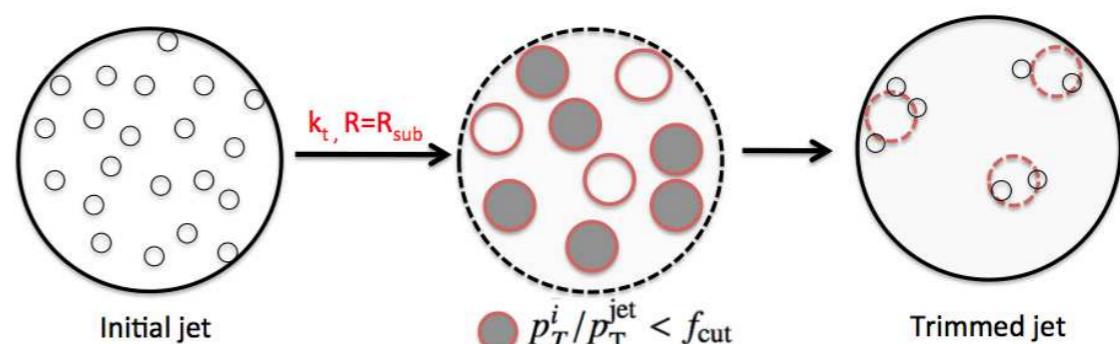


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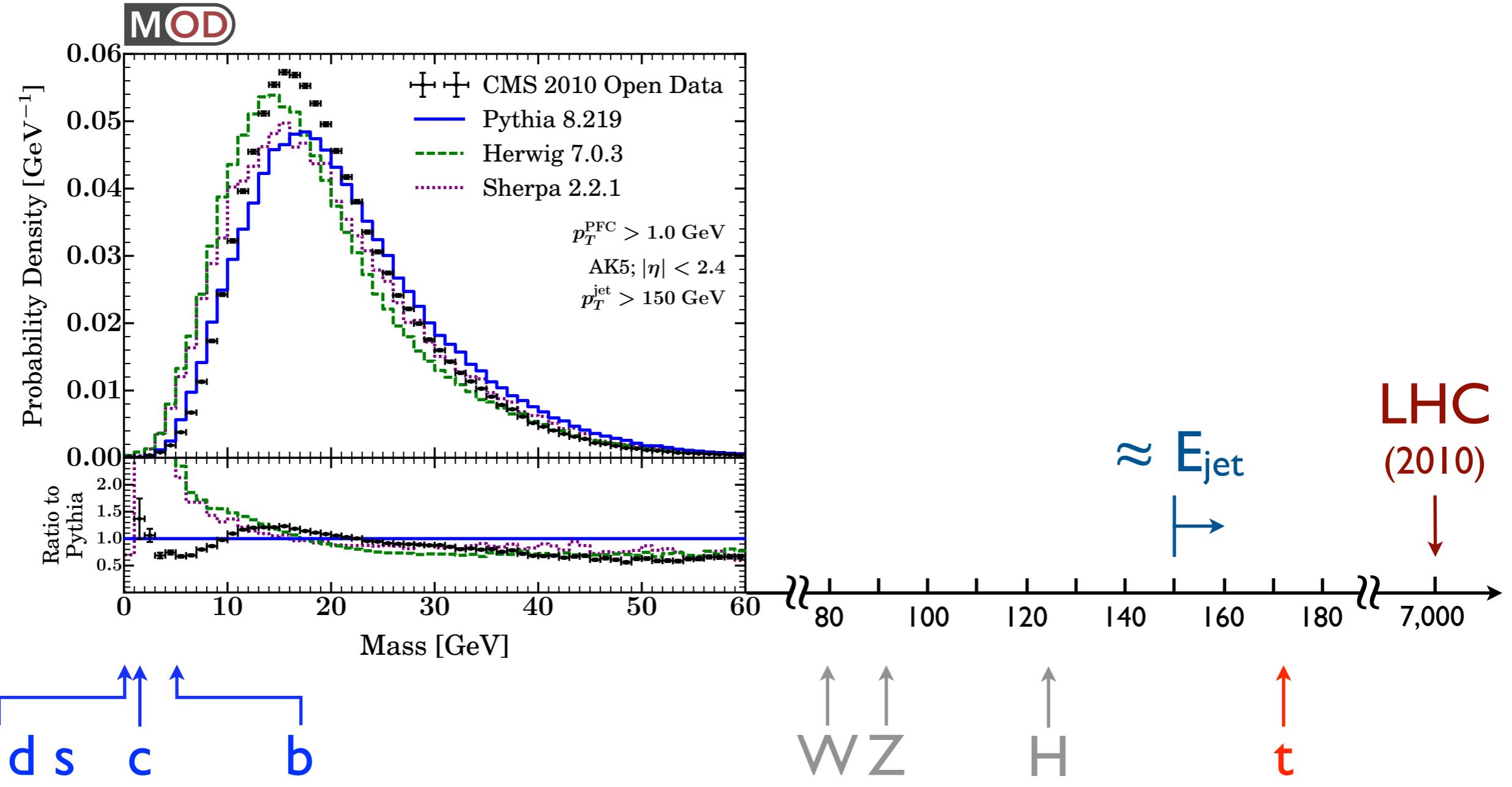
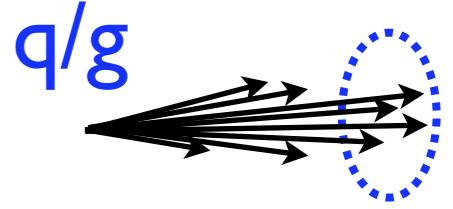
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e.g. Jet Trimming



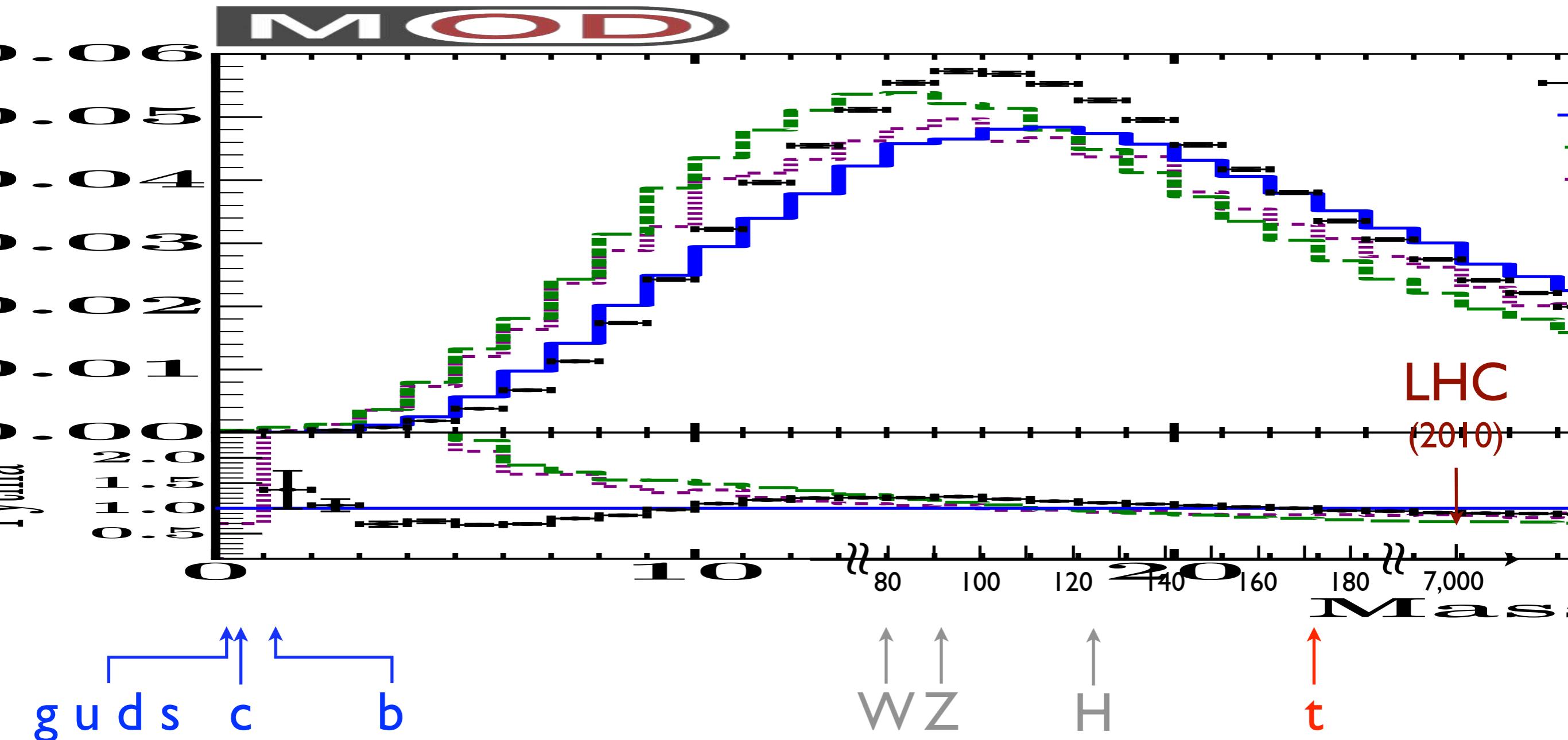
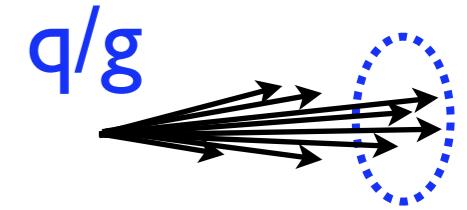
[ATLAS, 2012; Krohn, JDT, Wang, 2009]
[see also Butterworth, Davison, Rubin, Salam, 2008; Ellis, Vermilion, Walsh, 2009]

Regular Jets Have Mass, Too



[Tripathee, Xue, Larkoski, Marzani, JDT, 2017]

Regular Jets Have Mass, Too



[Tripathee, Xue, Larkoski, Marzani, JDT, 2017]