

Jet Substructure

Boosting the Search for New Physics at the LHC

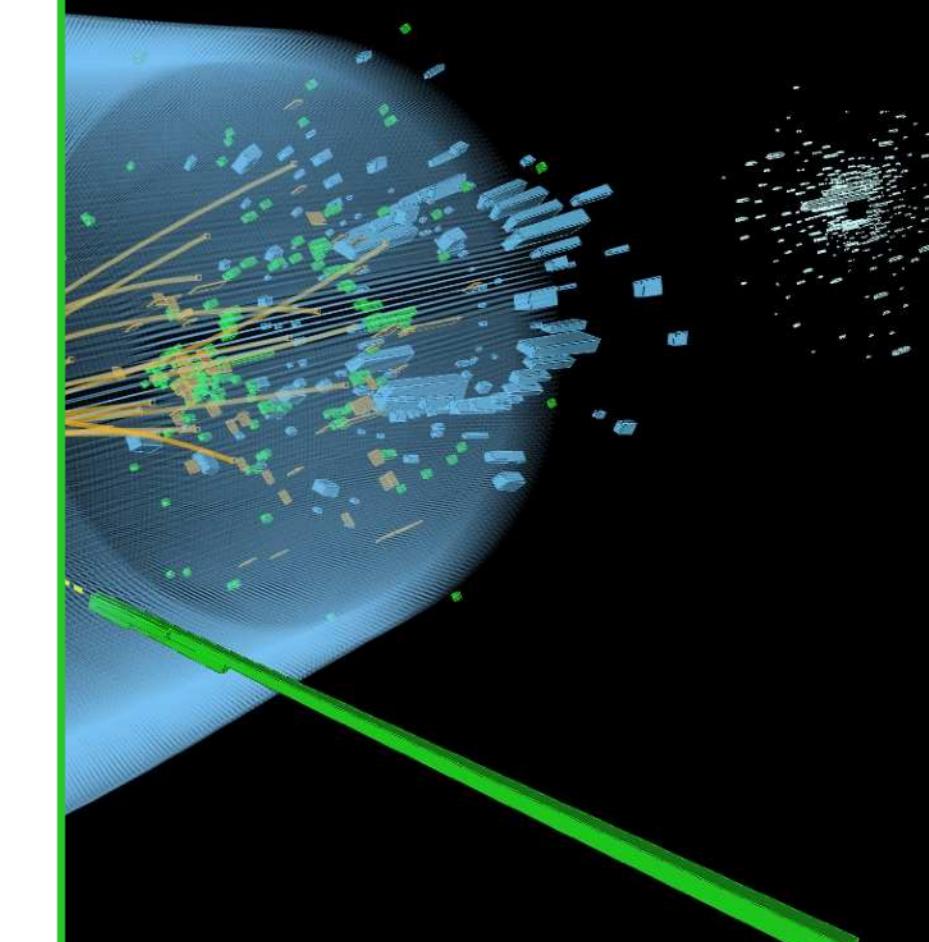
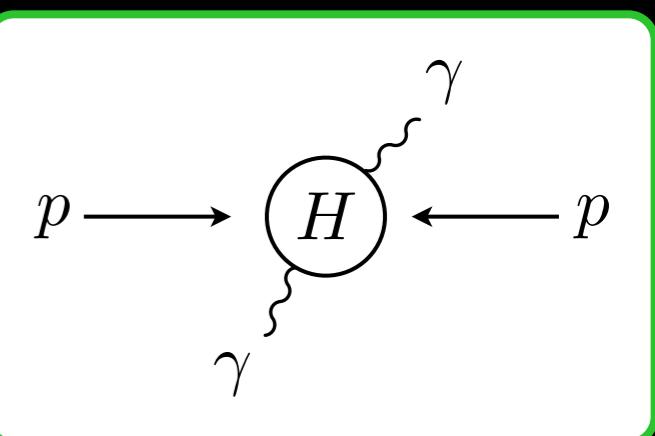
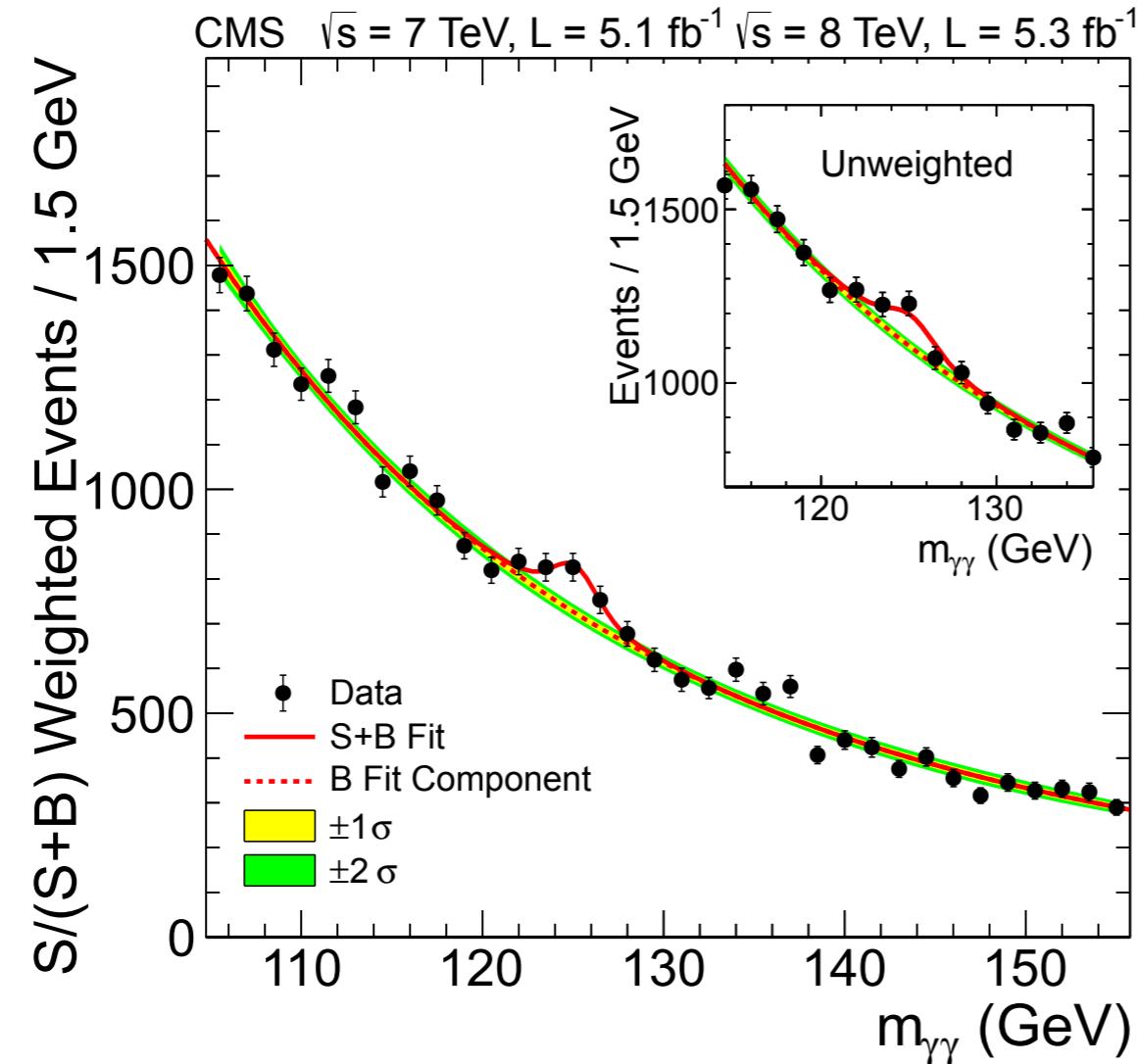
Jesse Thaler



University of Chicago Physics Colloquium — May 5, 2016



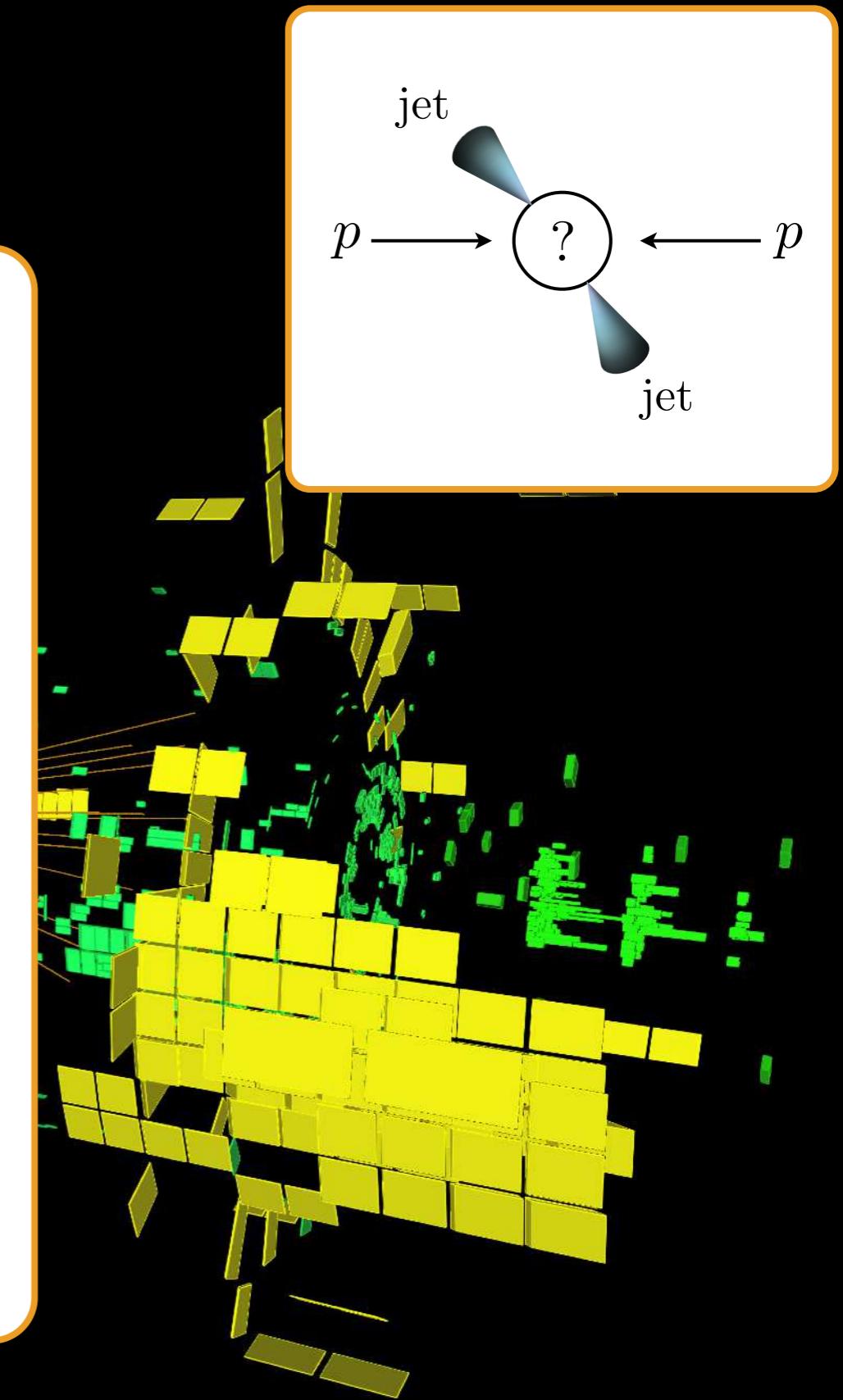
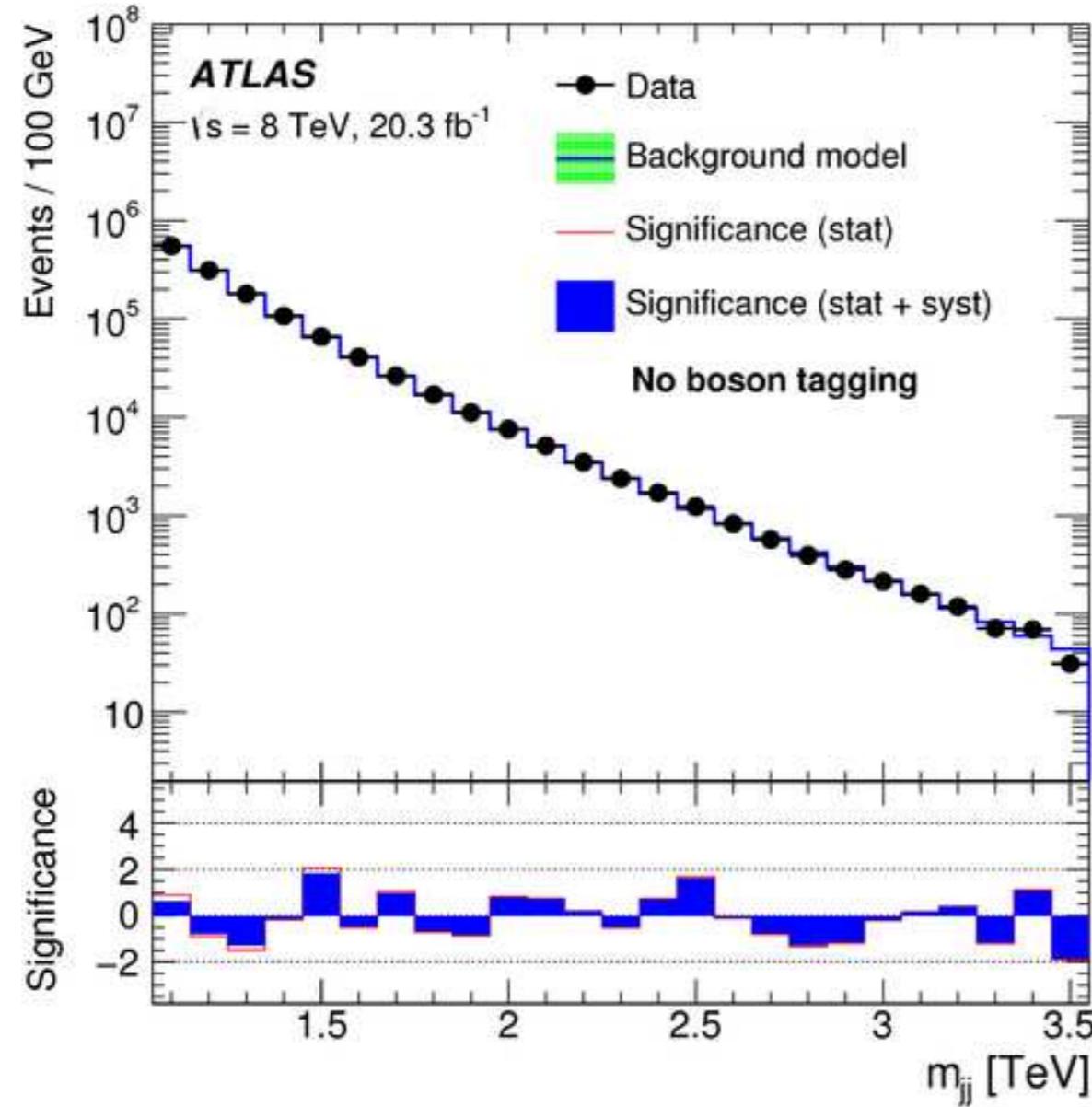
CMS Experiment at the LHC, CERN





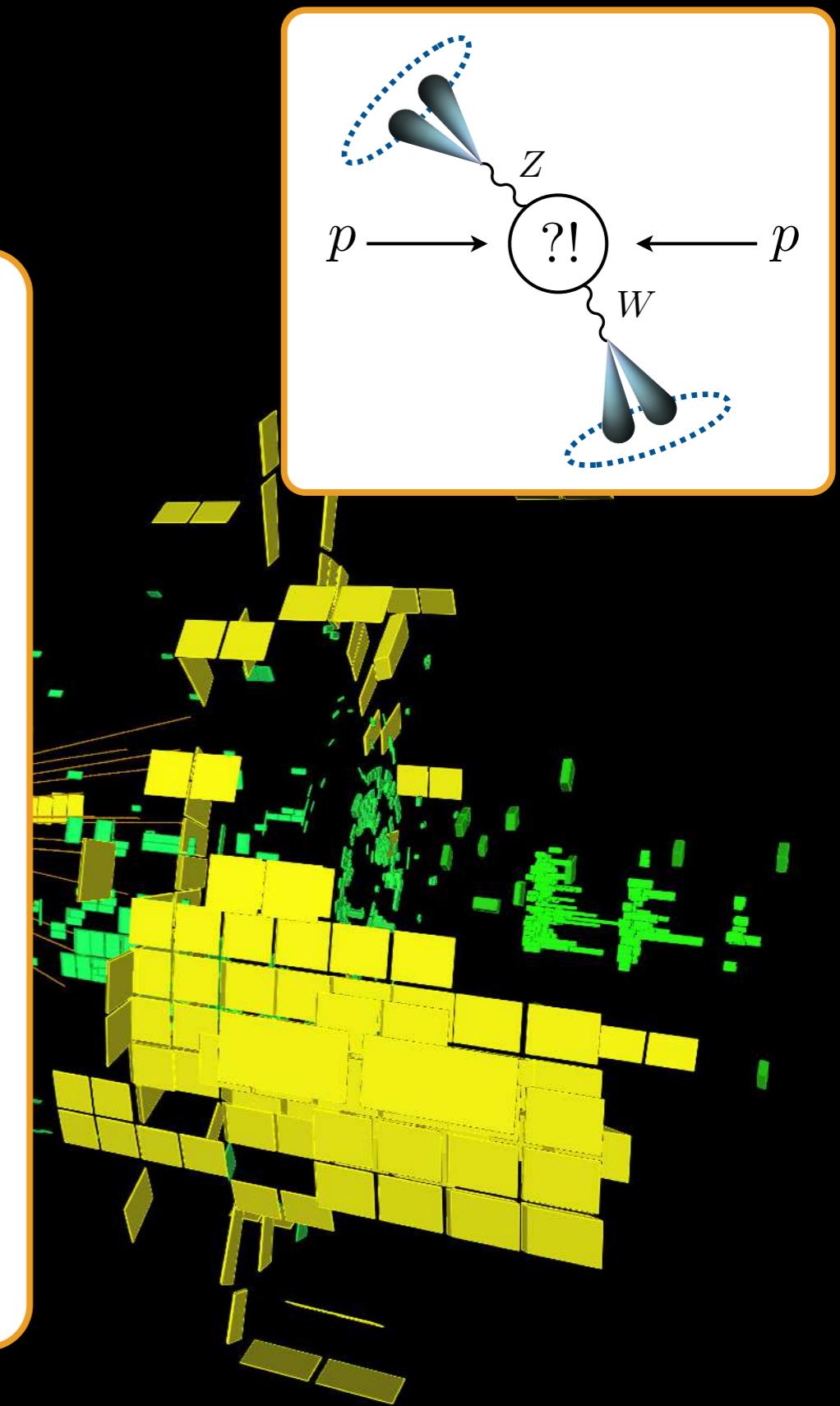
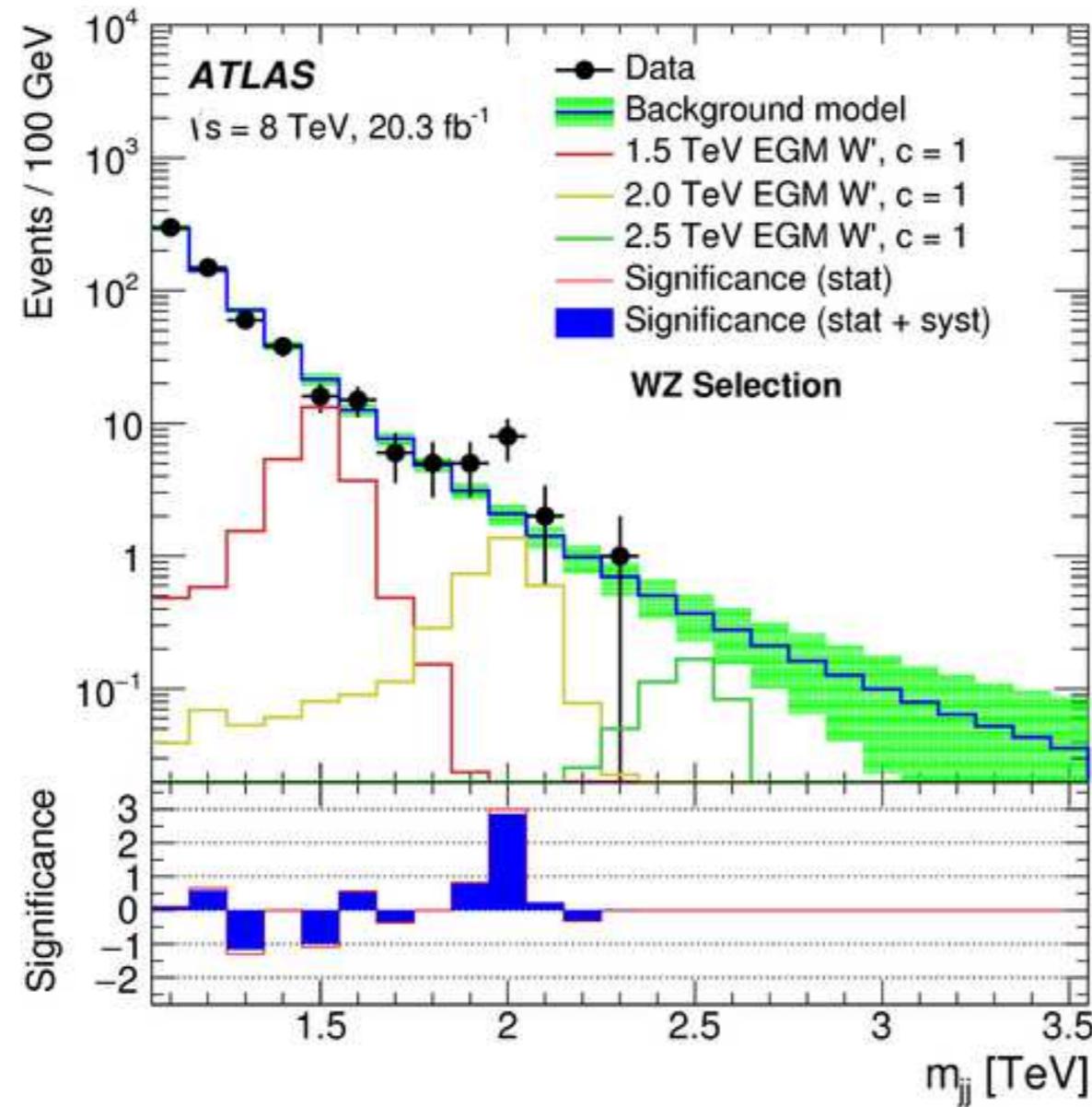
ATLAS

Event:
2015-08

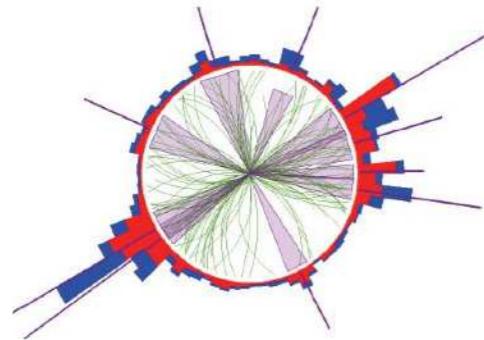




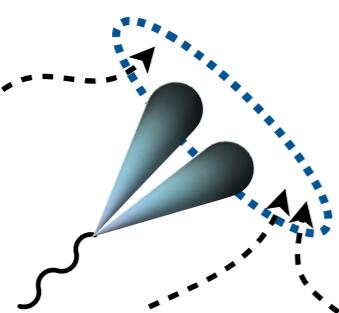
Event:
2015-08



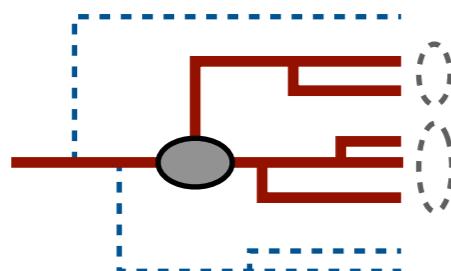
Outline



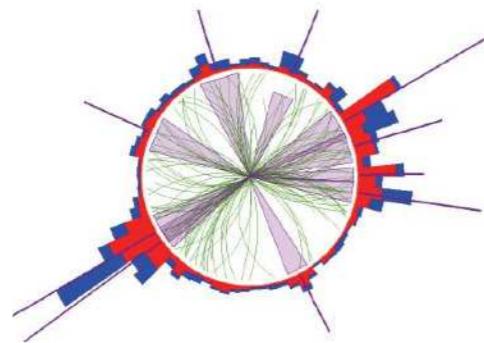
From jets to jet substructure



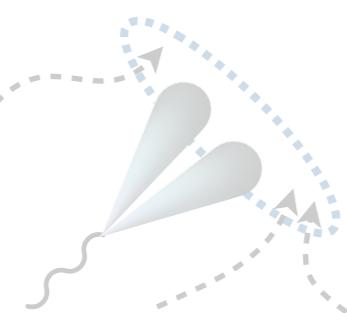
Maximize discovery potential of LHC



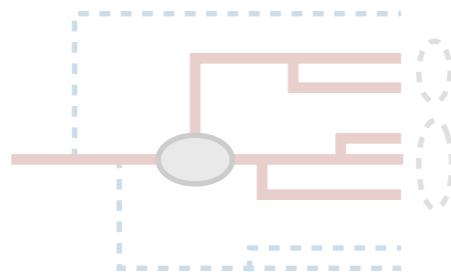
Probe emergent phenomena in QCD



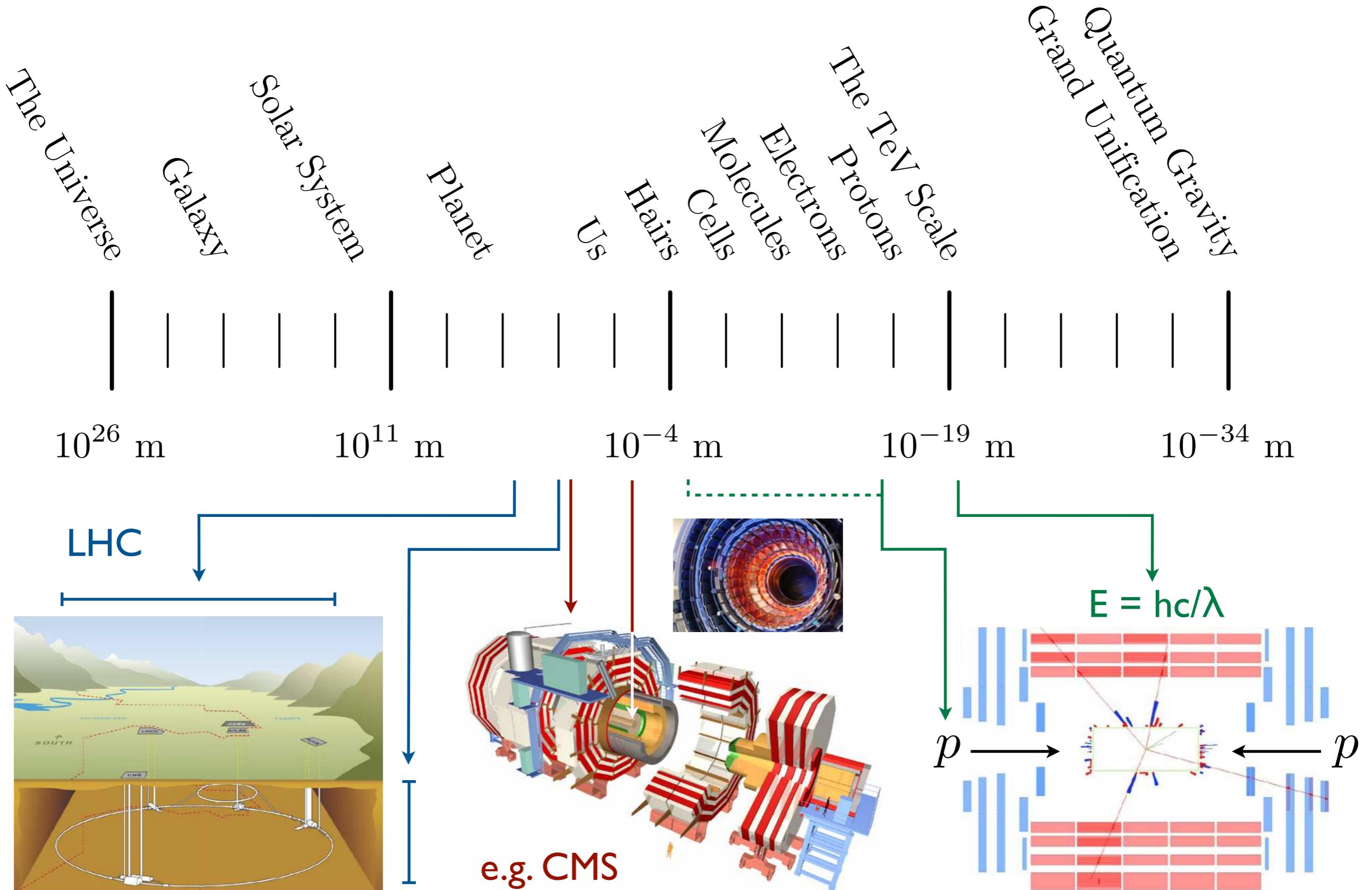
From jets to jet substructure



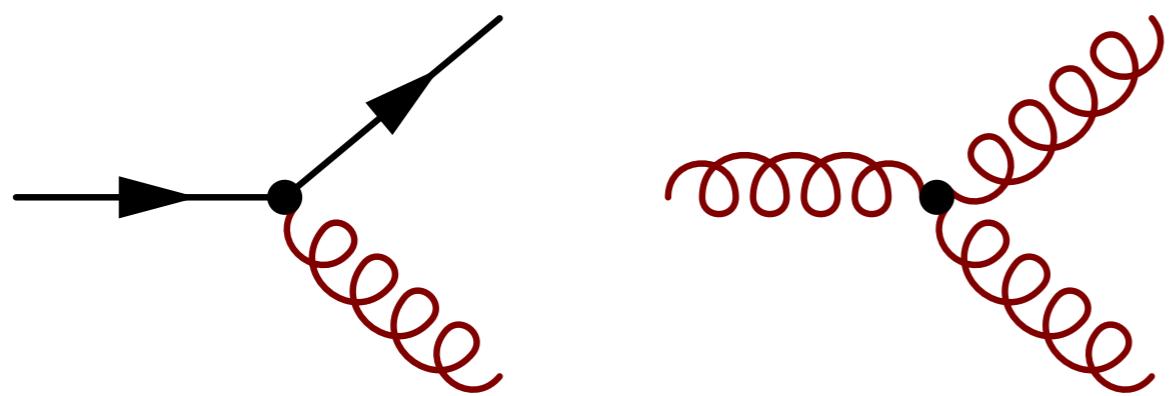
Maximize discovery potential of LHC



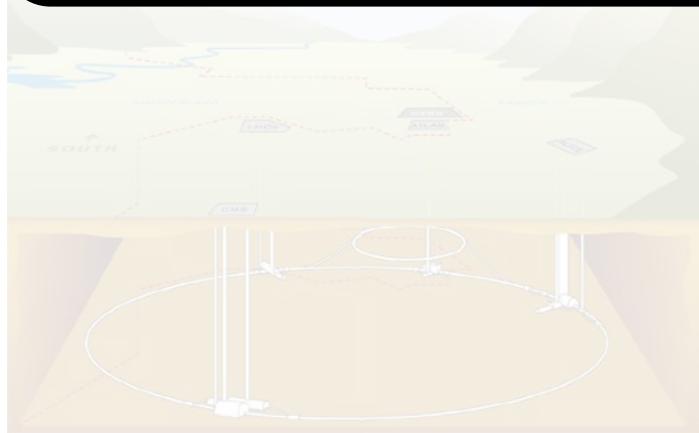
Probe emergent phenomena in QCD



QCD



α_s



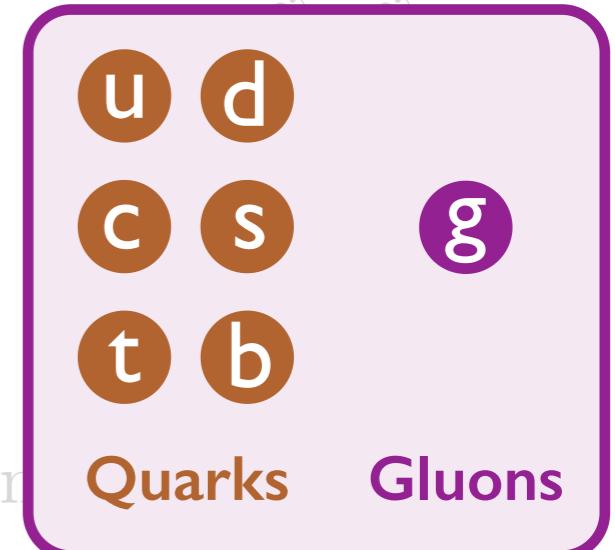
e.g. CMS

The TeV Scale
Protons
Electrons
Positrons

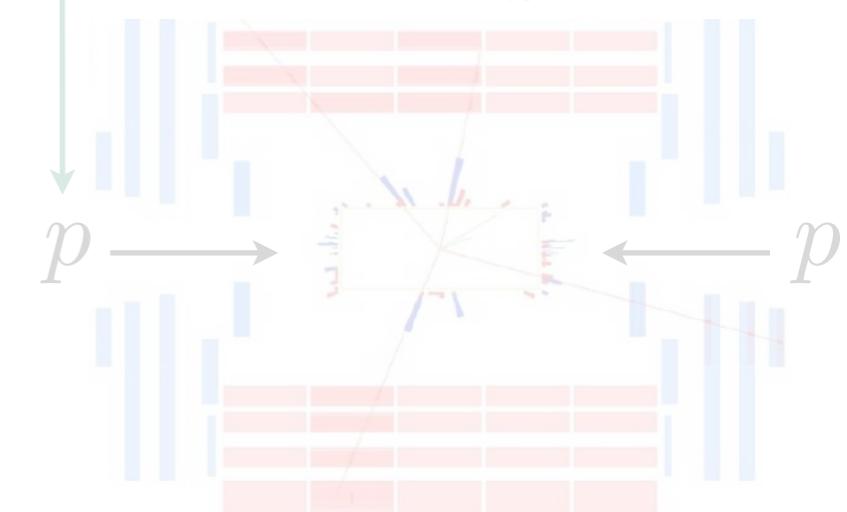
10^{-19} m

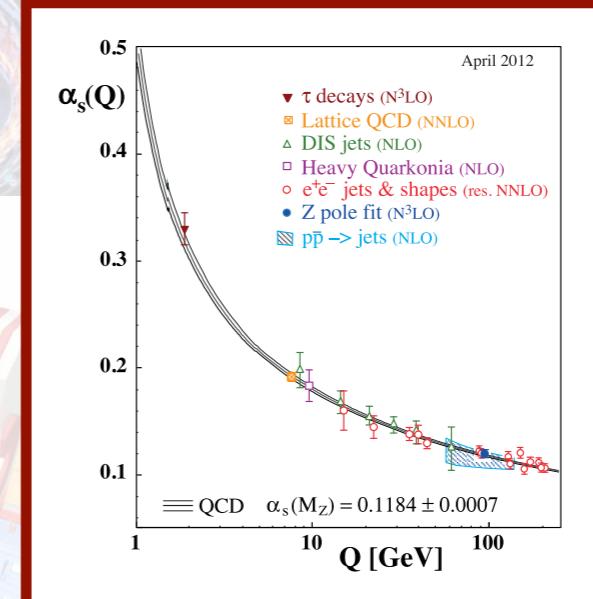
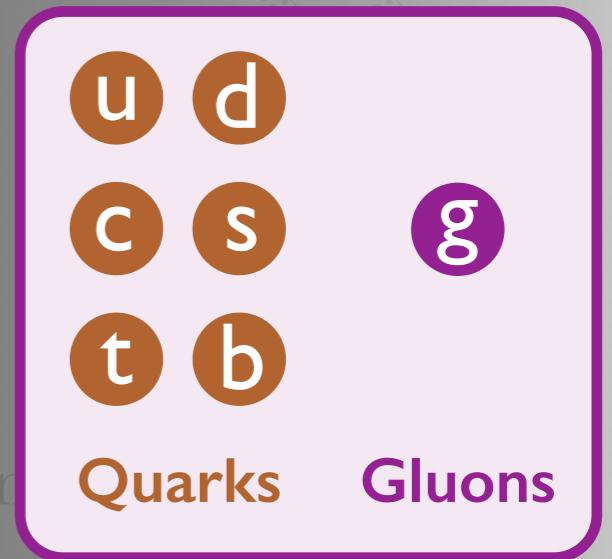
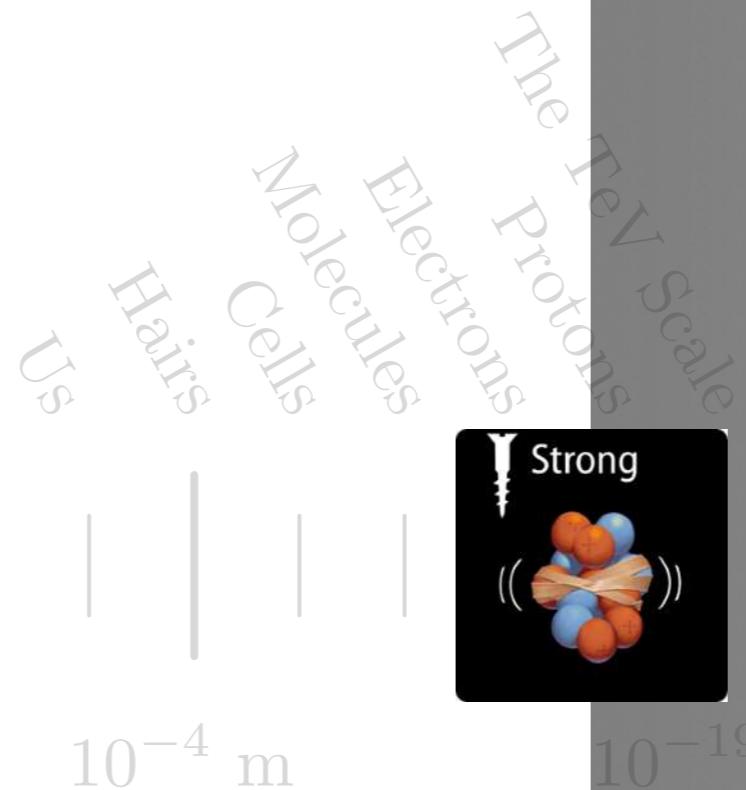
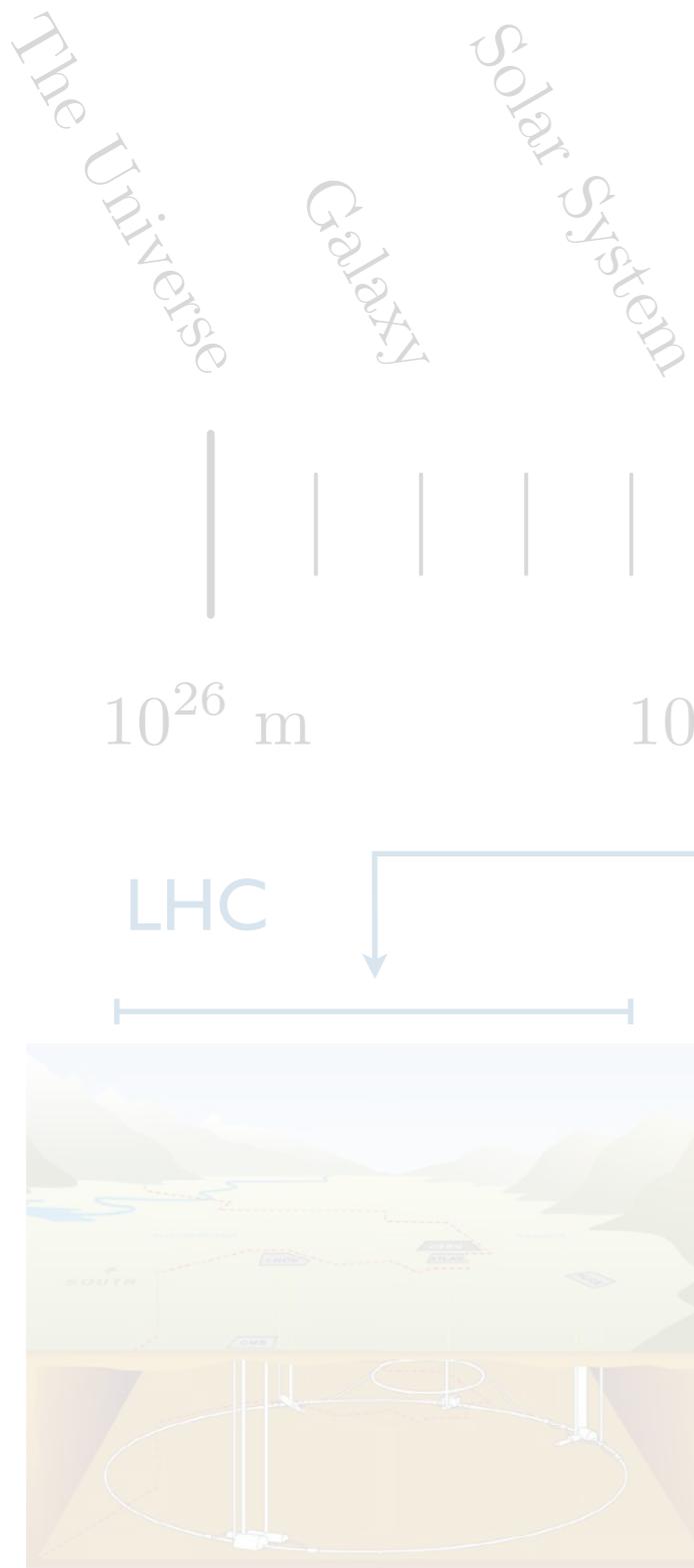


Quantum Grand Unification



$$E = hc/\lambda$$







Mesons

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

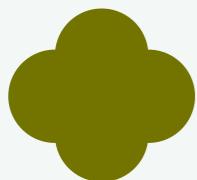
$\rho^\pm \rho^0 \omega K^{*\pm} K^{*0} \phi D^{*\pm} D^{*0} D_s^{*\pm} J/\psi B^{*\pm} B^{*0} B_s^{*0} \Upsilon \dots$



Baryons

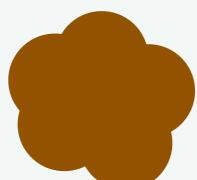
$p n \Lambda^0 \Sigma^+ \Sigma^0 \Sigma^- \Xi^0 \Xi^- \dots$

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



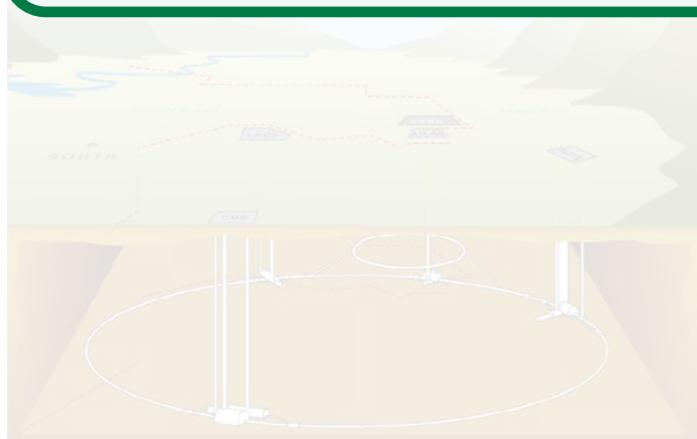
Tetraquarks (?)

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



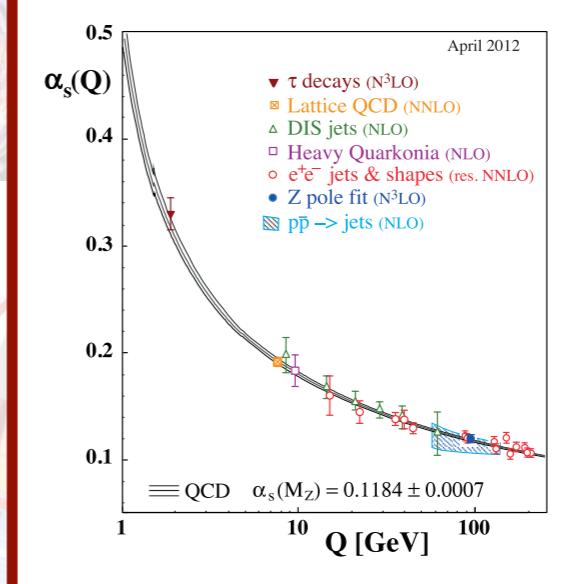
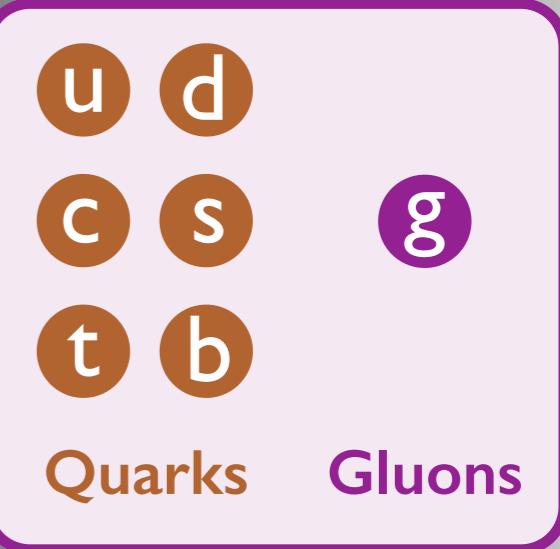
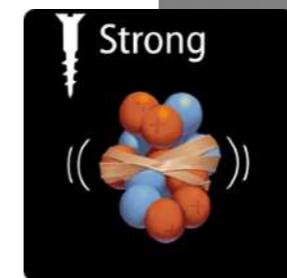
Pentaquarks (?)

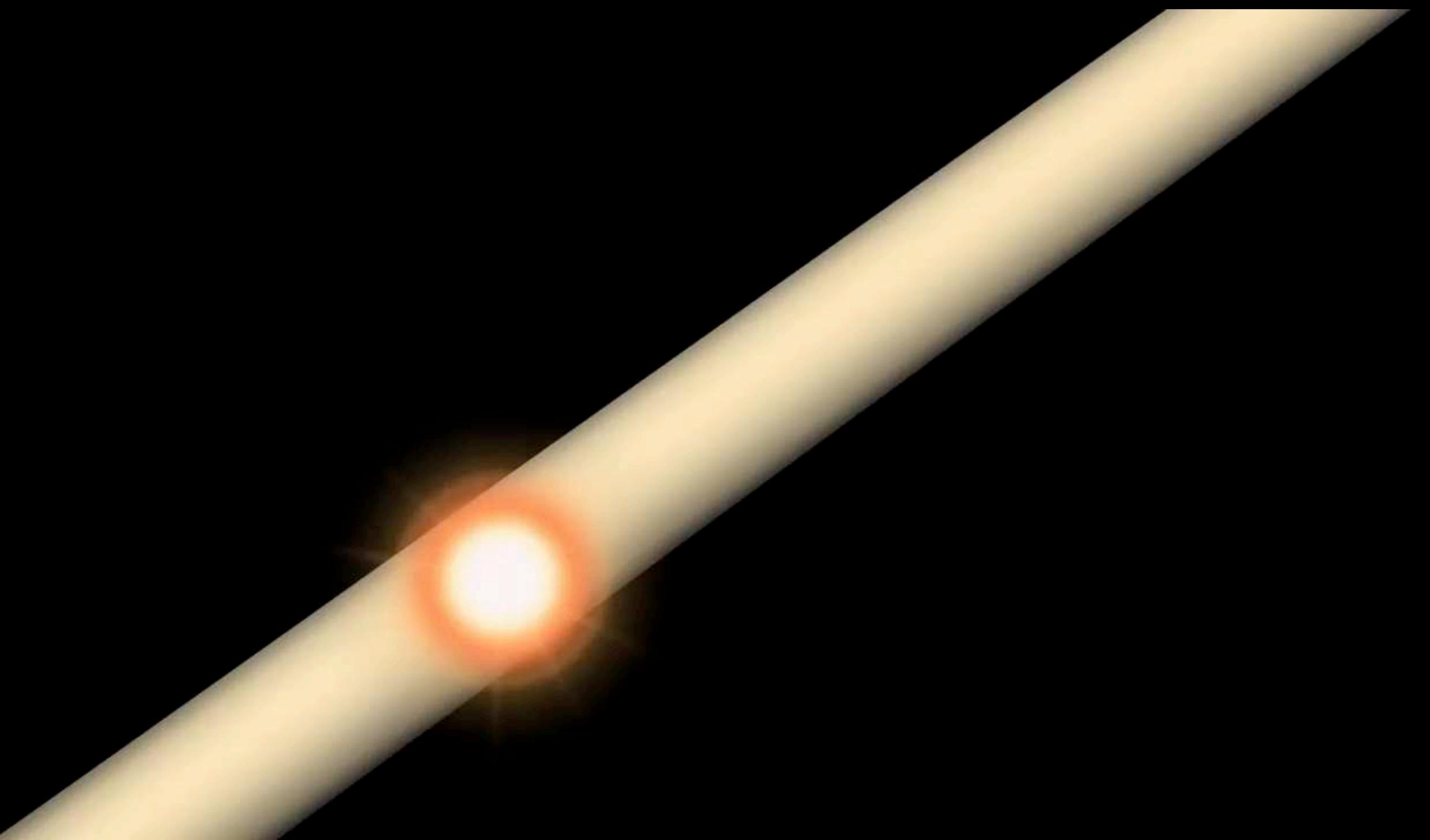
$P_c^+(4450) \dots$

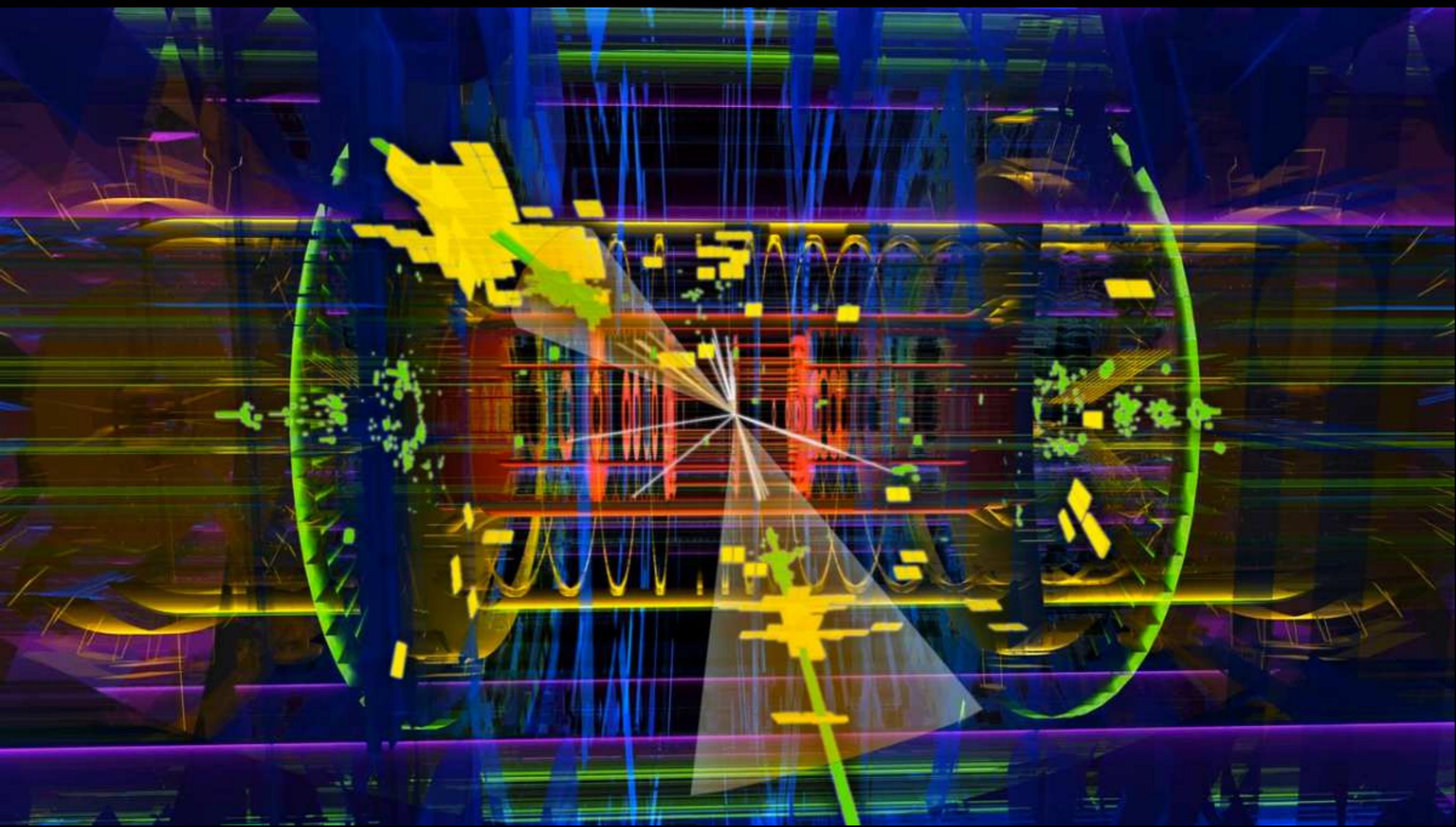


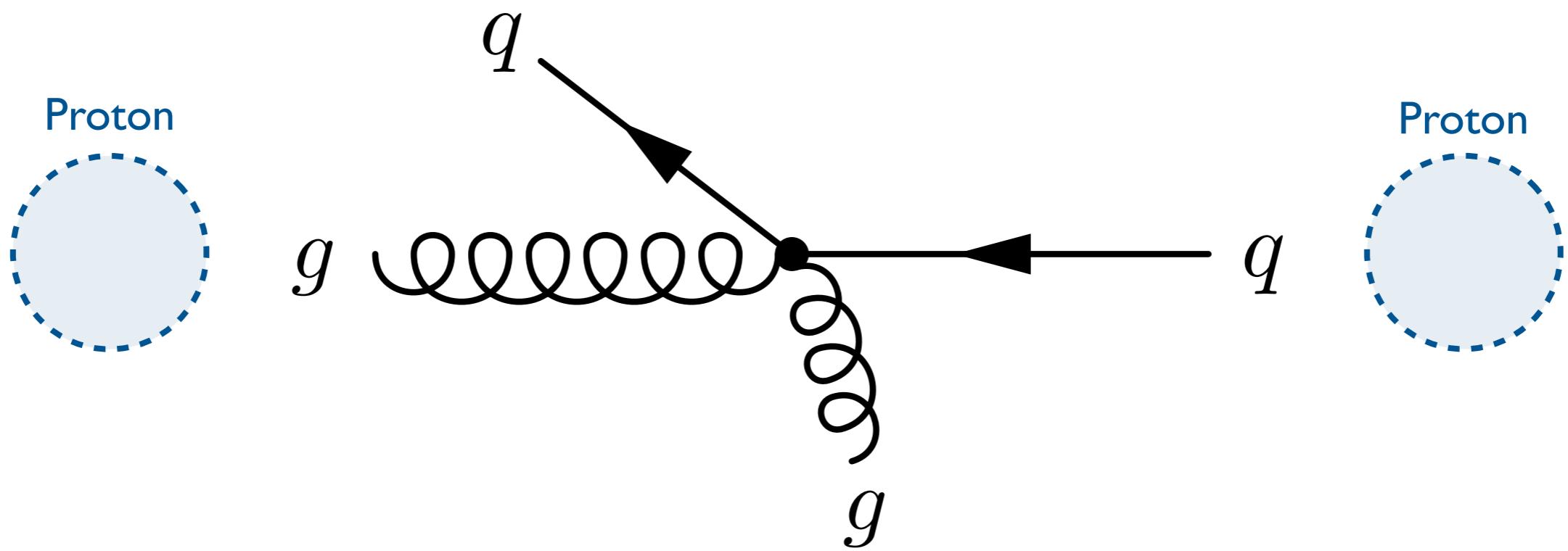
e.g. CMS

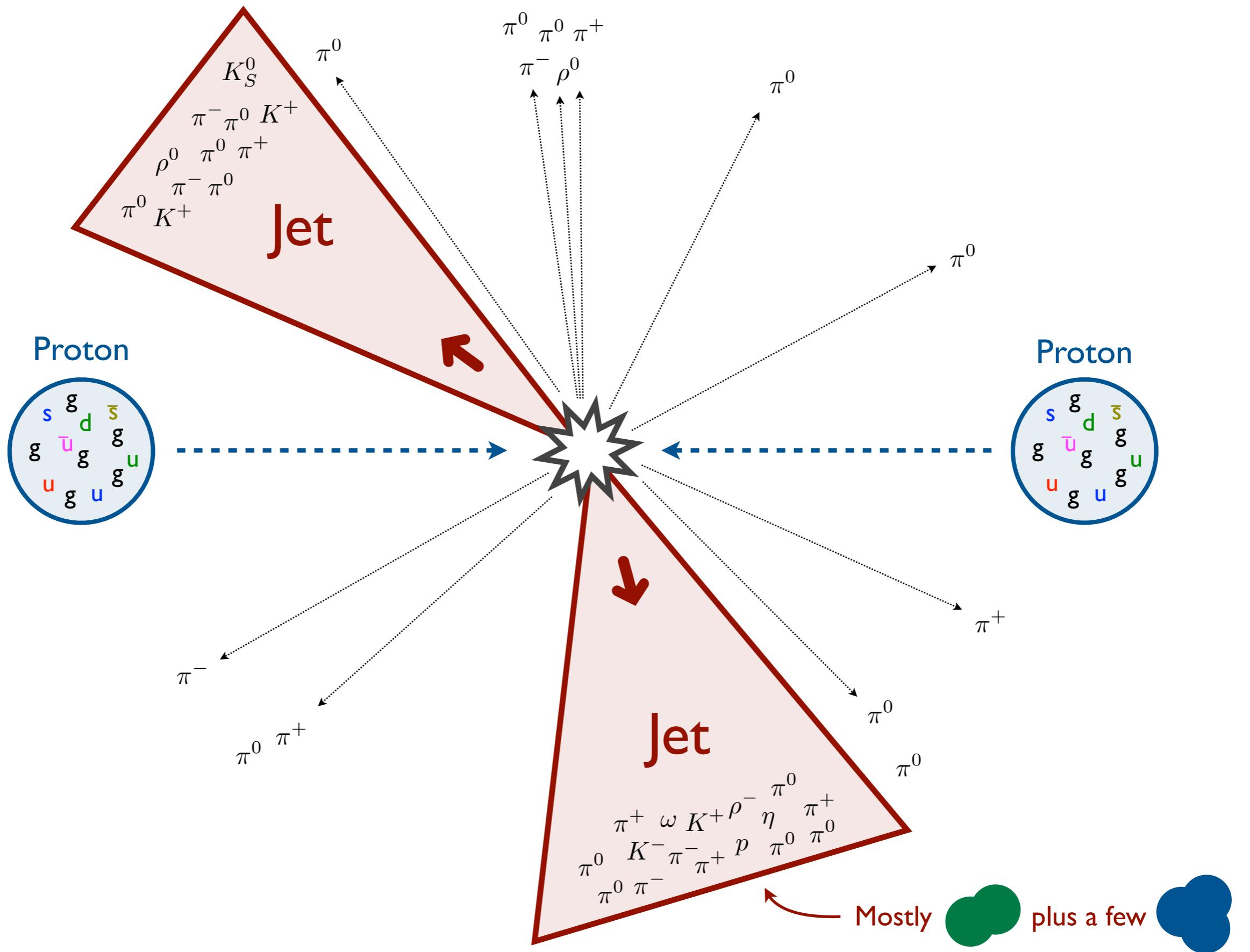
The TeV Scale
Electrons
Protons
Les





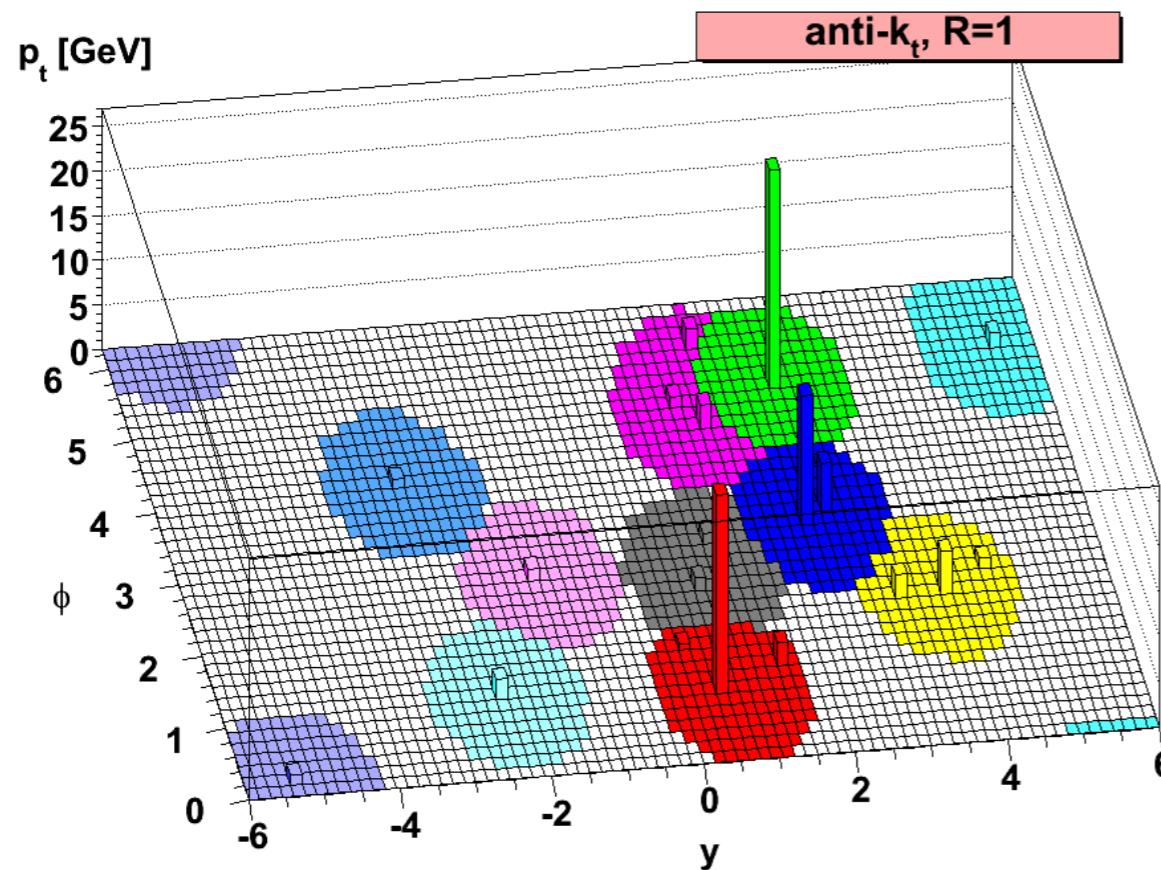




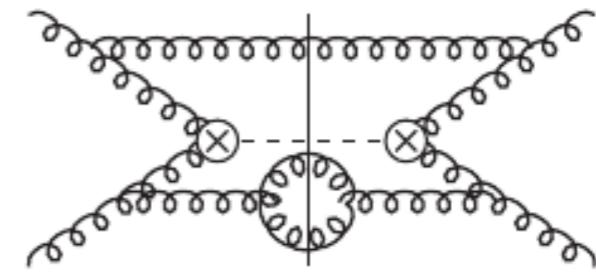


QCD Renaissance

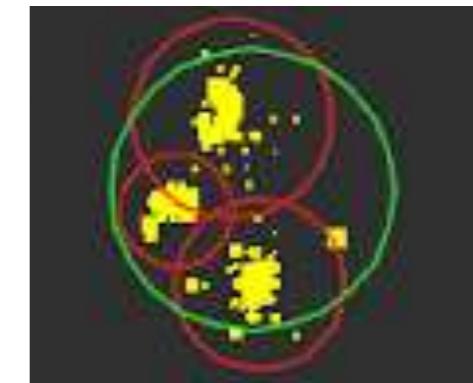
Theory c. 2008–present



New Jet Algorithms



Loop/Leg/Log Explosion



Jet Substructure

[Anti- k_T : Cacciari, Salam, Soyez, 2008; see also Delsart, 2006]

[N^3LO : Anastasiou, Duhr, Dulat, Herzog, Mistlberger, 2015]

[BDRS: Butterworth, Davison, Rubin, Salam, 2008; see also Seymour, 1991, 1994]

Tevatron



LHC

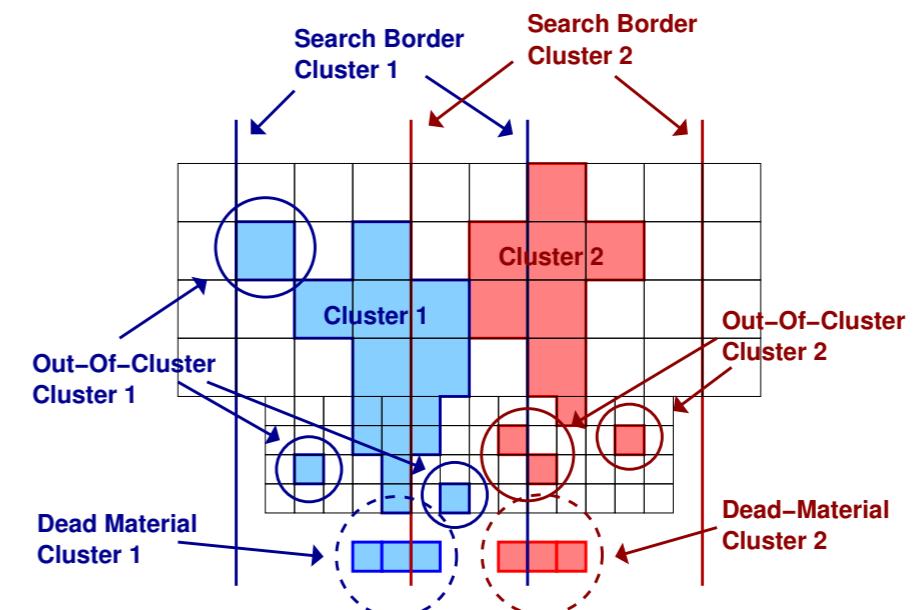
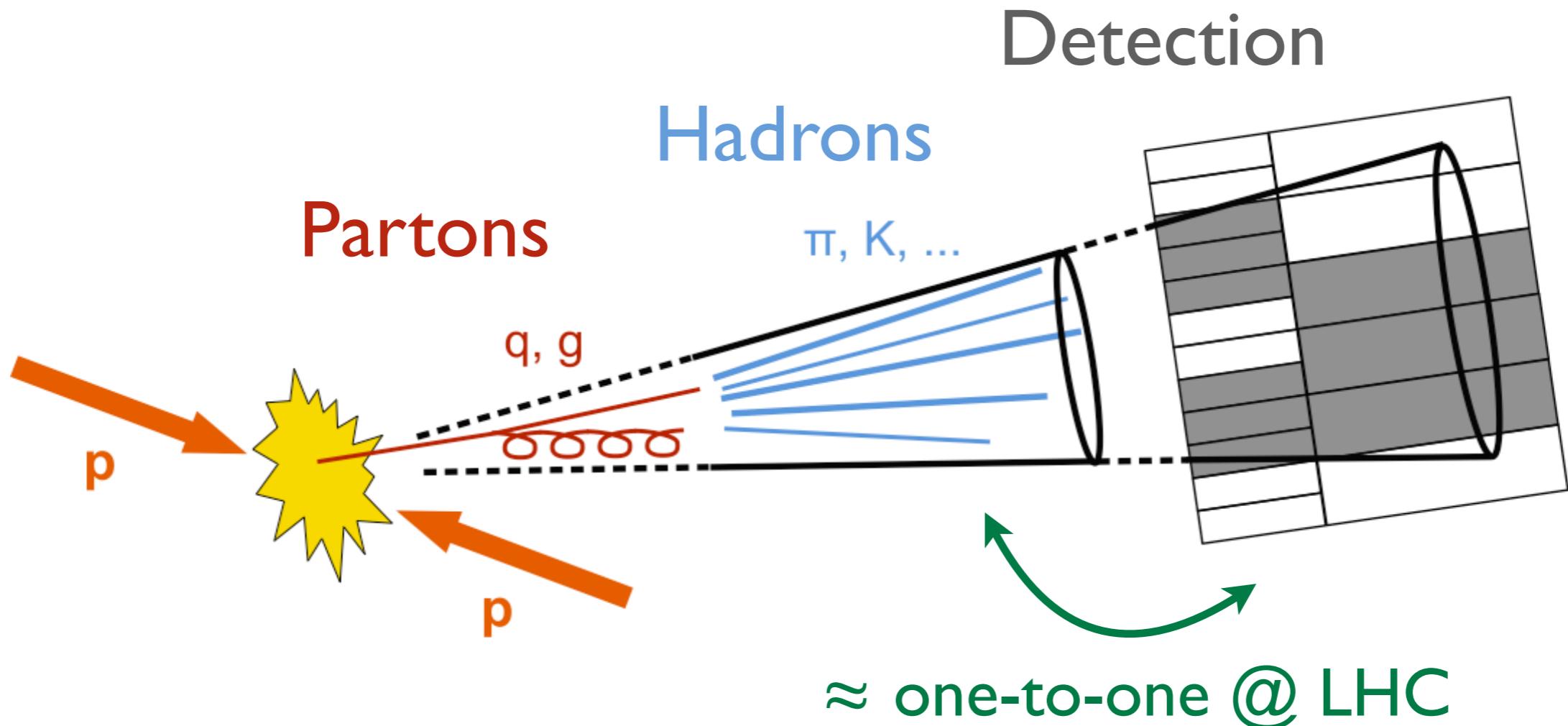


1.9 TeV

12 fb^{-1} total

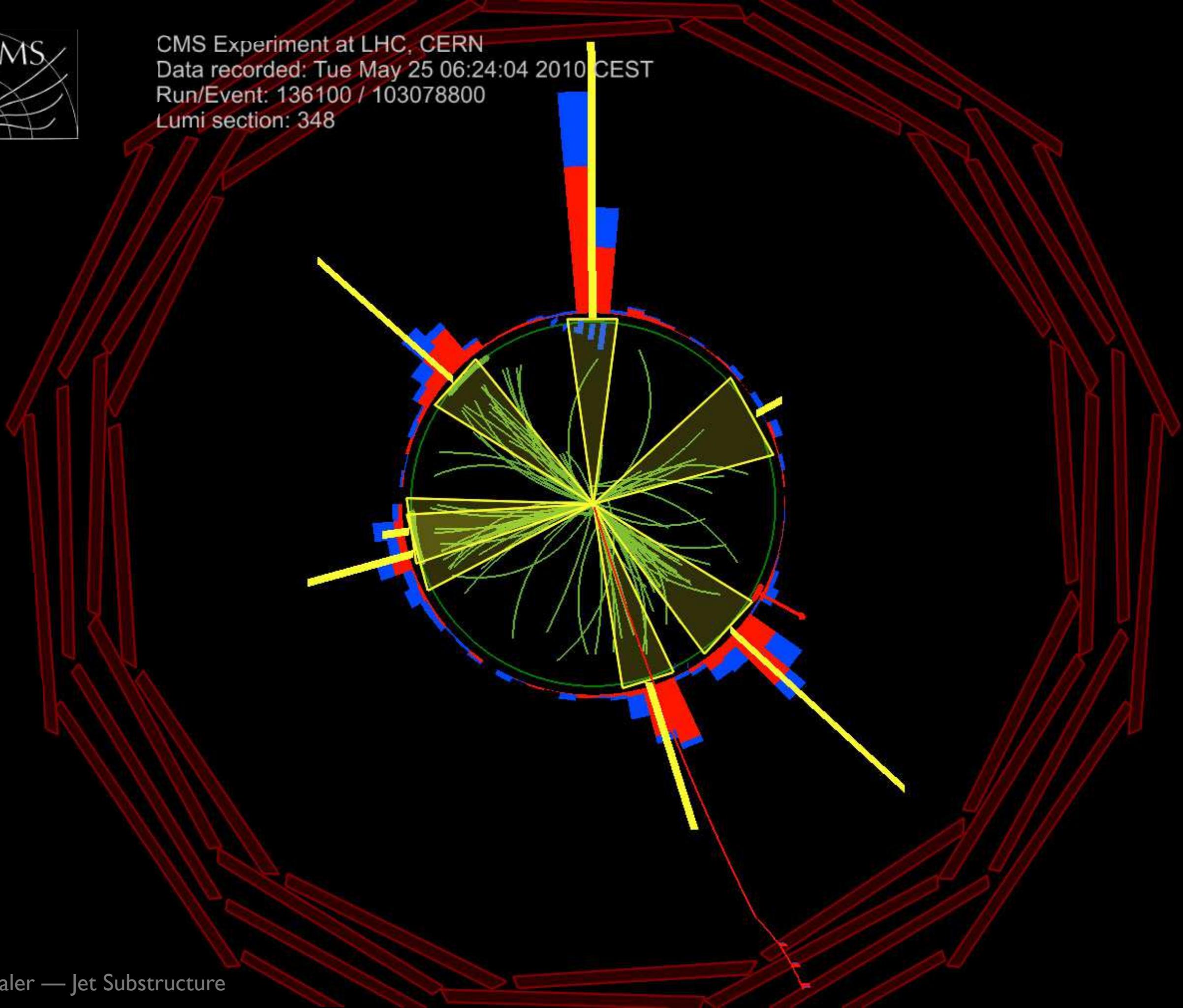
7–8 TeV 13–14 TeV

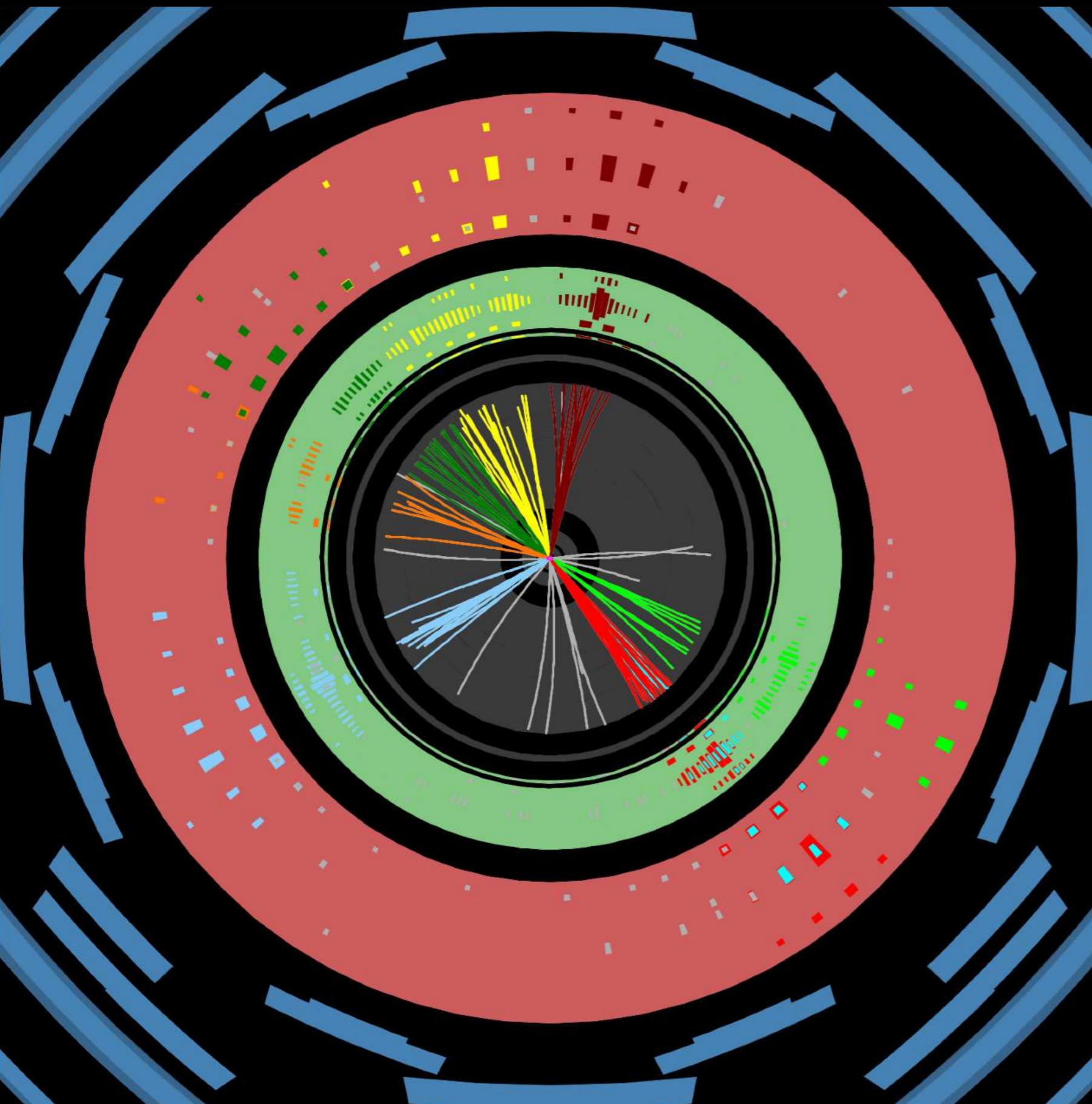
30 fb^{-1} 40 fb^{-1}/yr





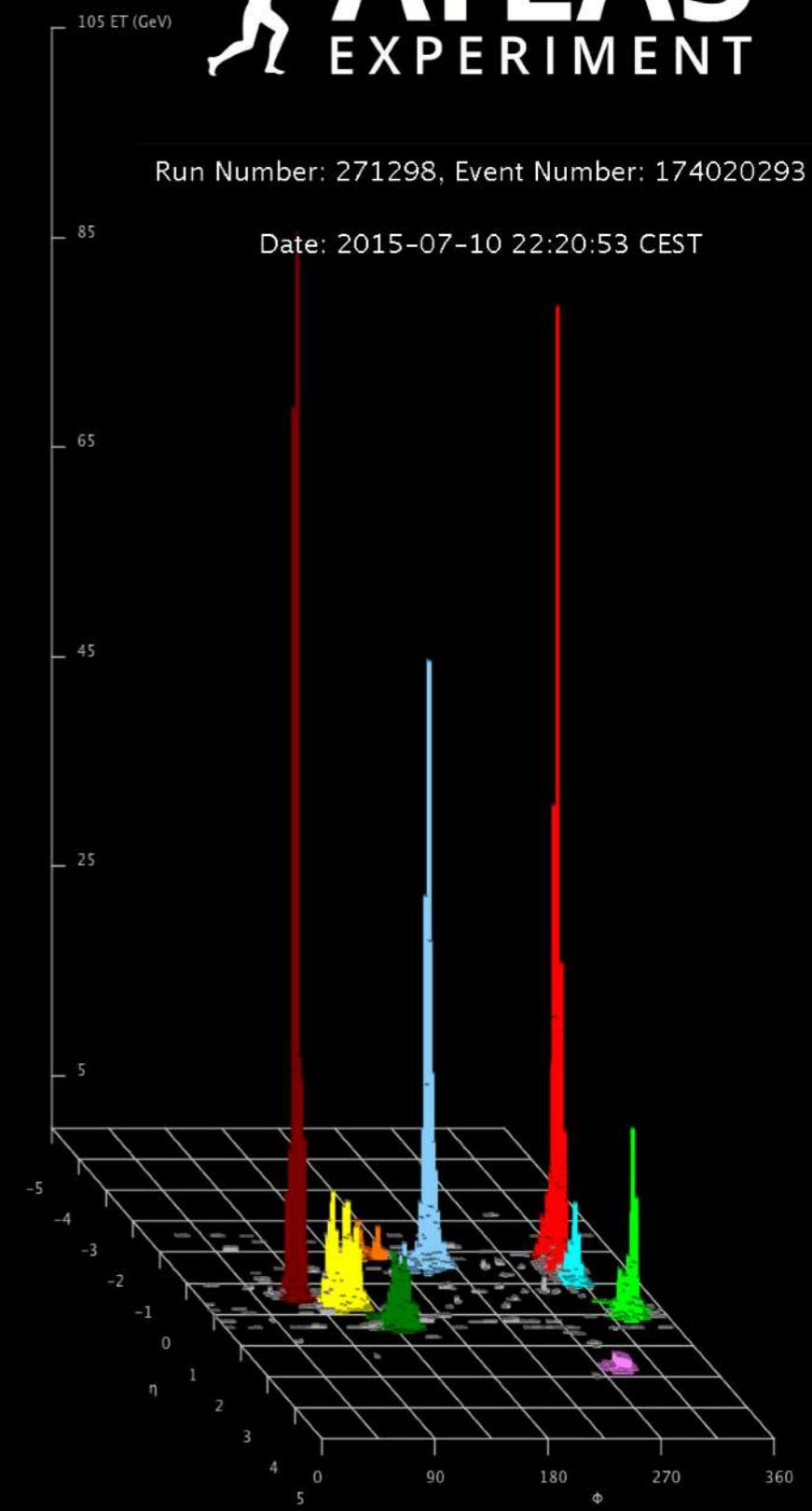
CMS Experiment at LHC, CERN
Data recorded: Tue May 25 06:24:04 2010 CEST
Run/Event: 136100 / 103078800
Lumi section: 348





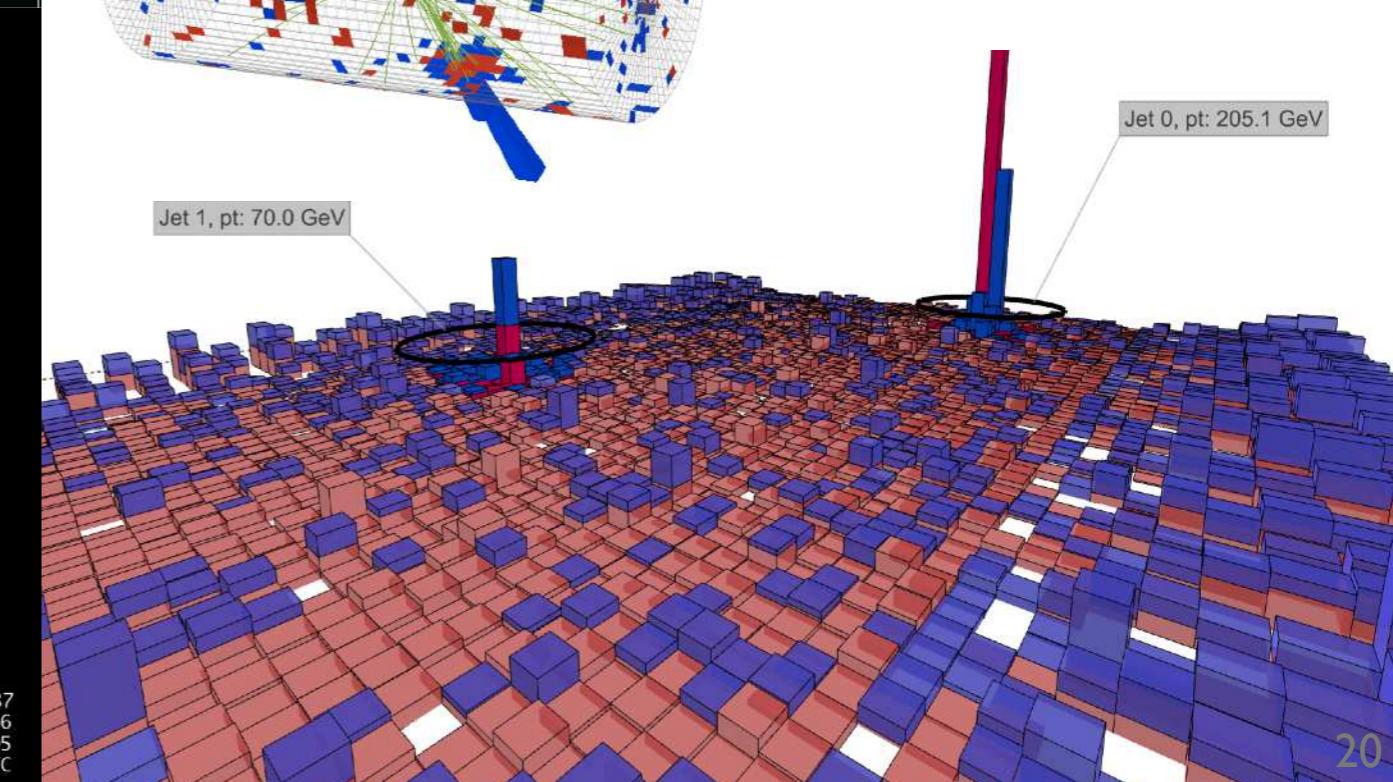
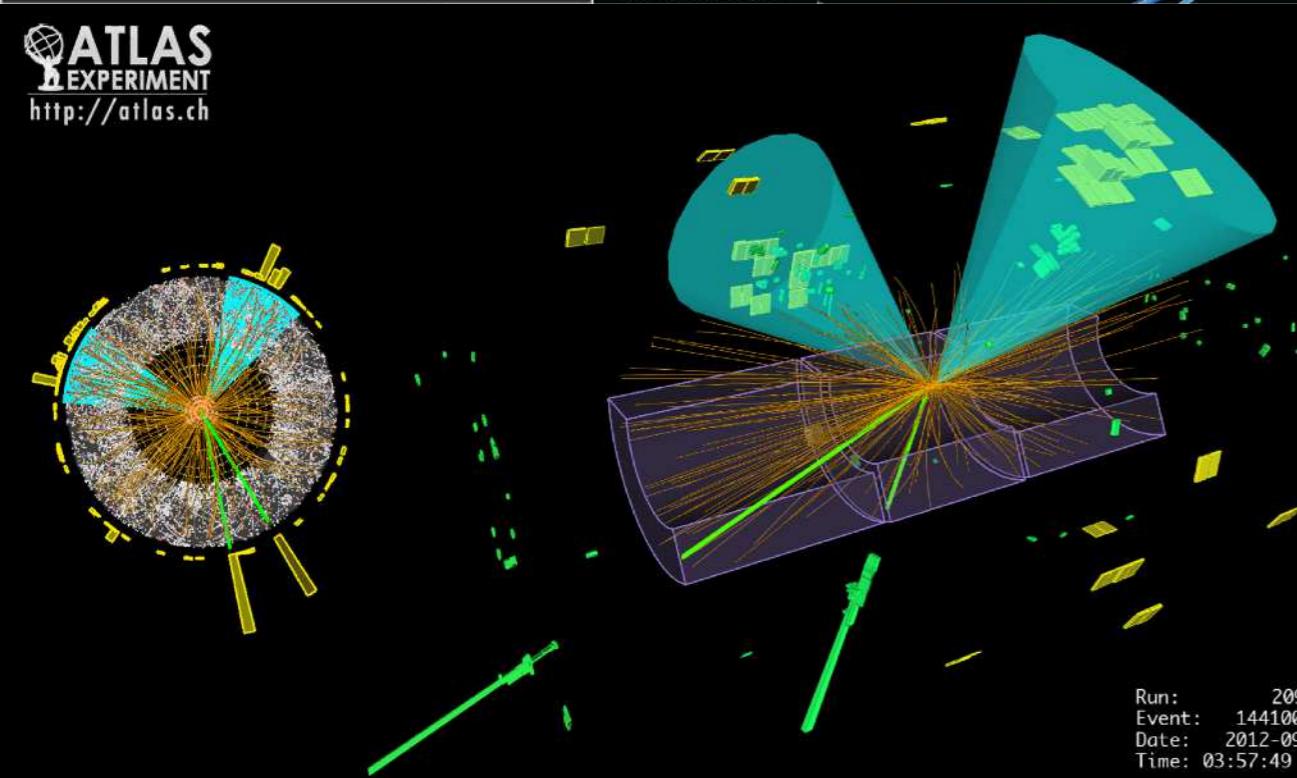
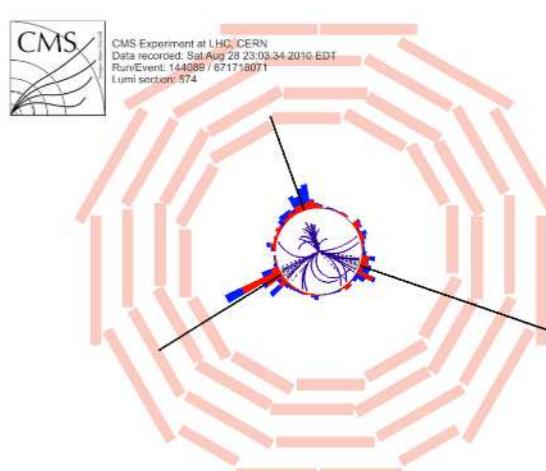
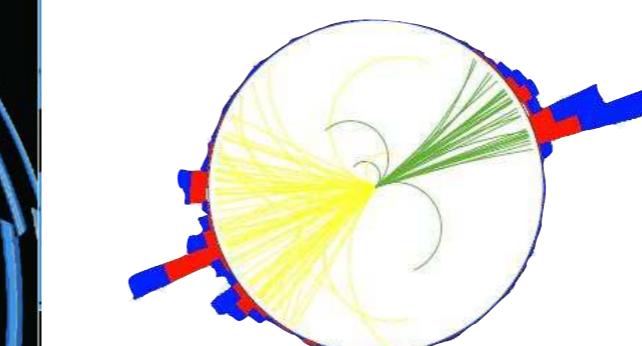
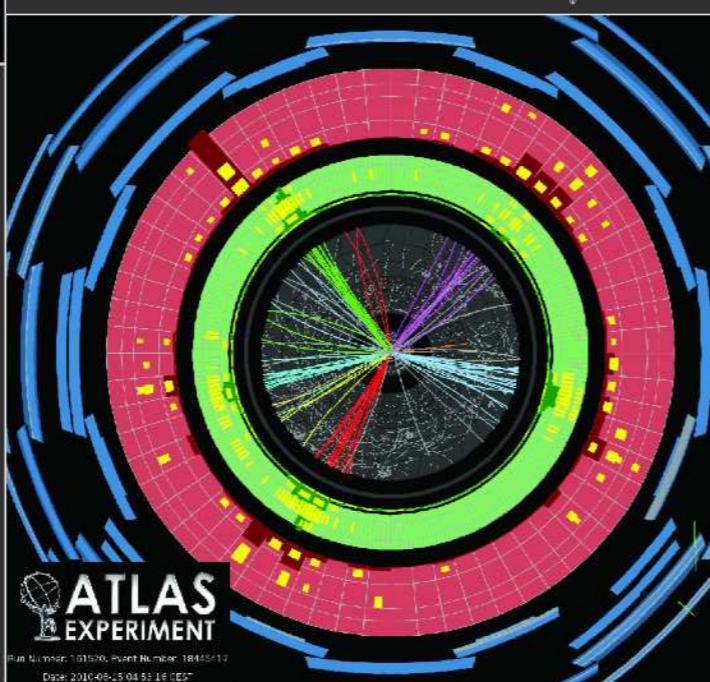
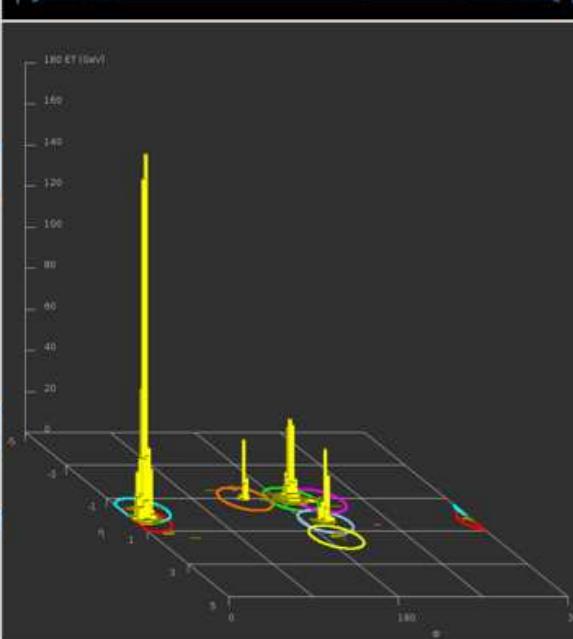
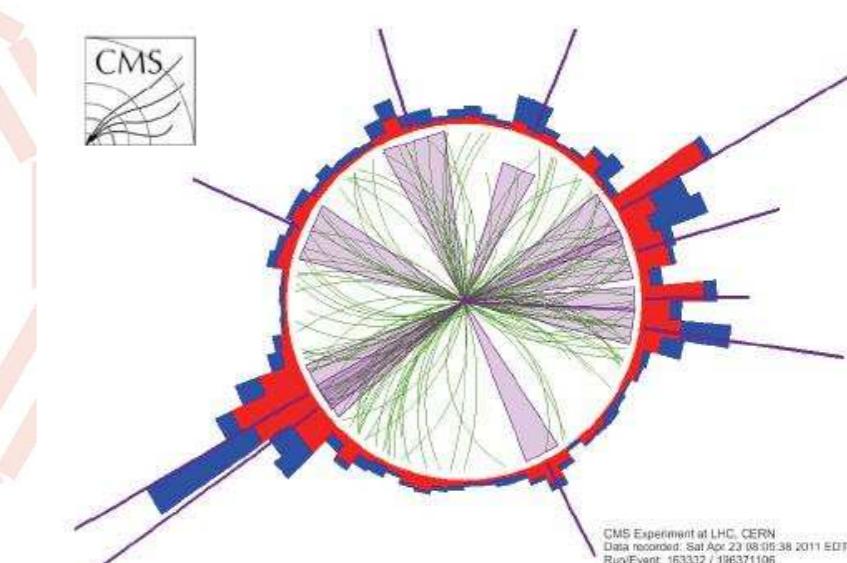
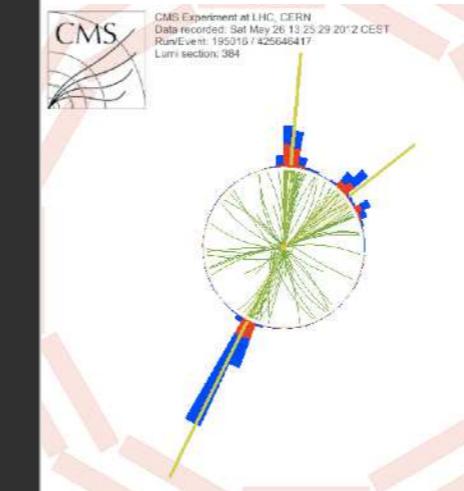
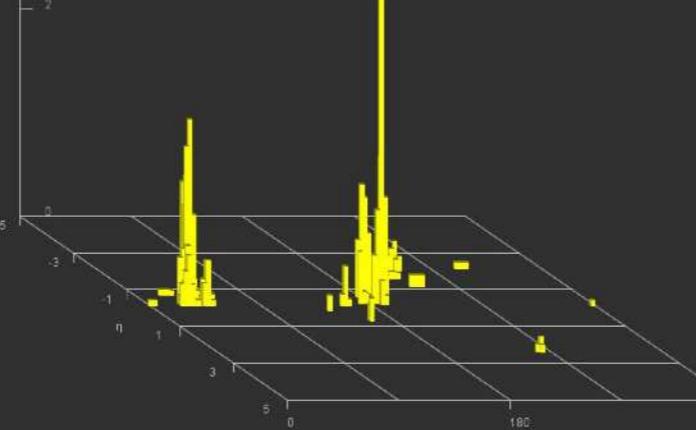
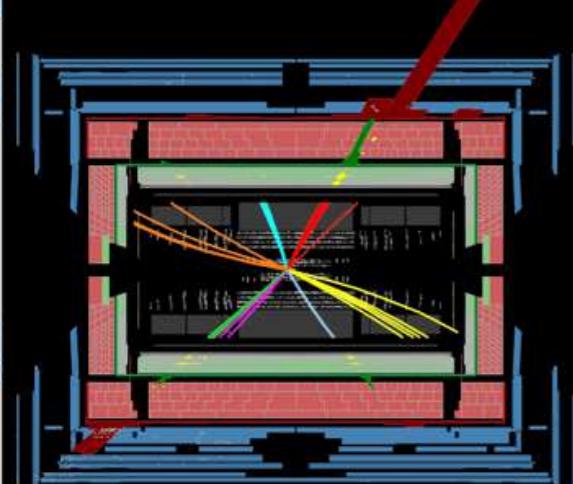
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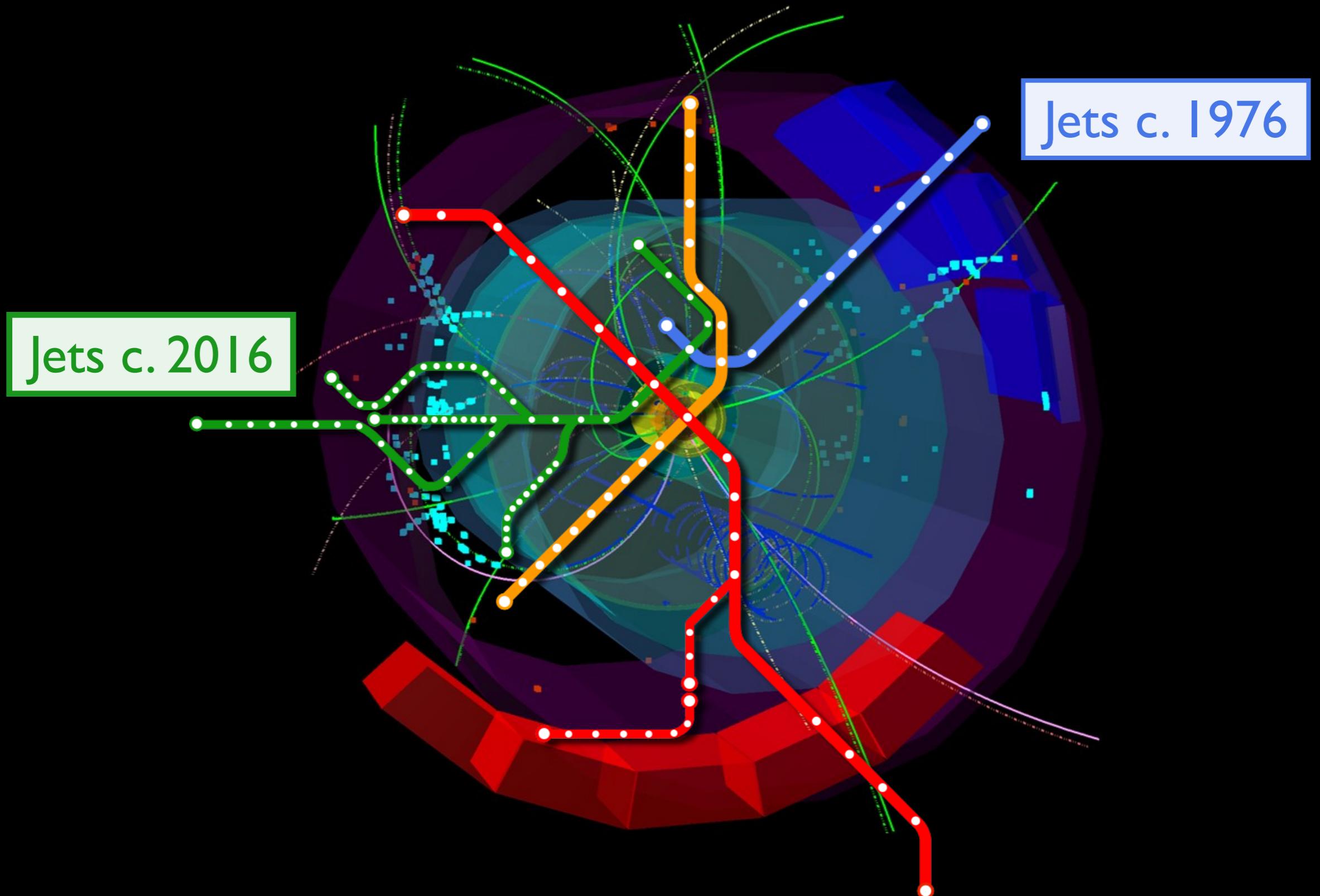
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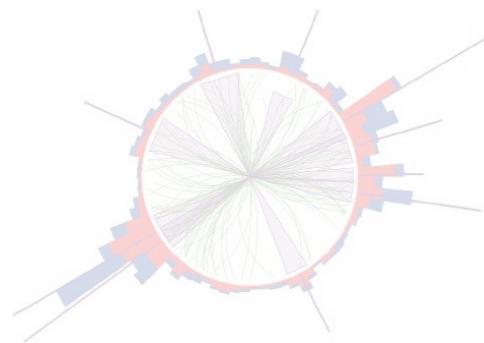


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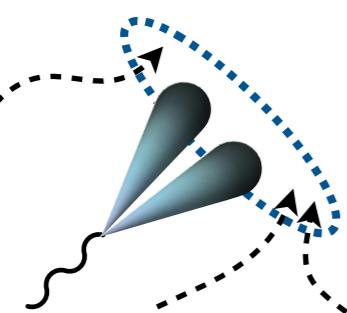
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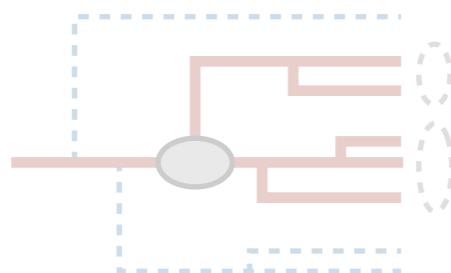




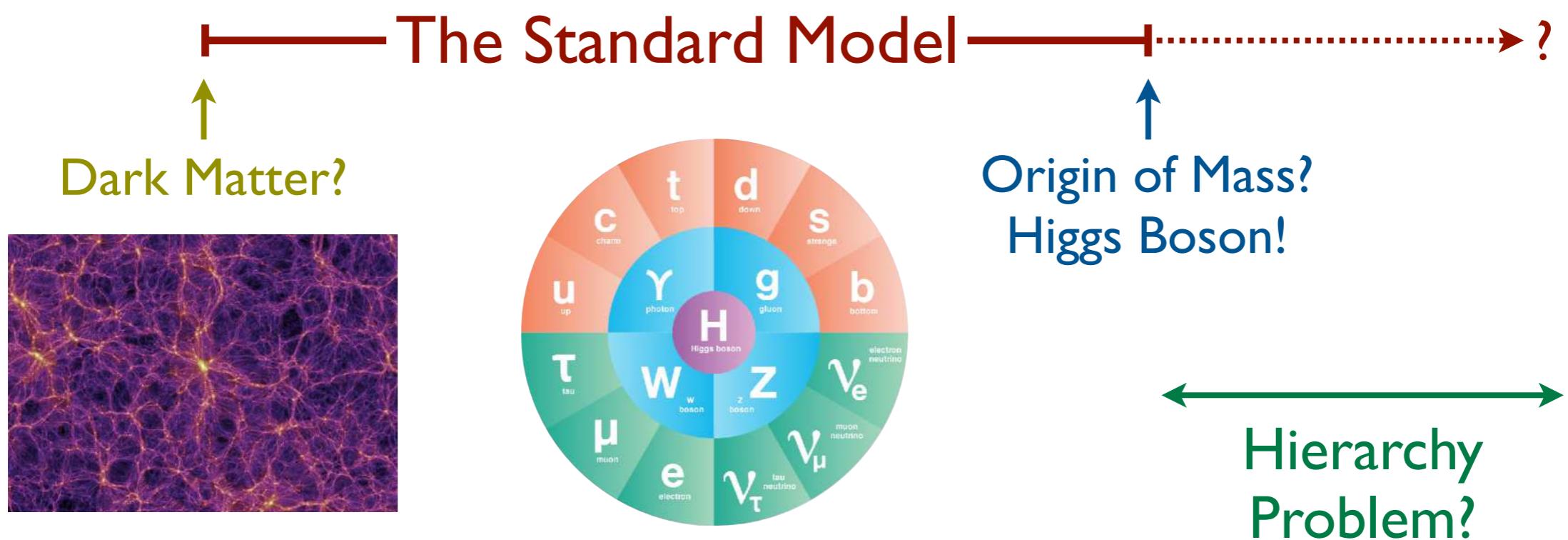
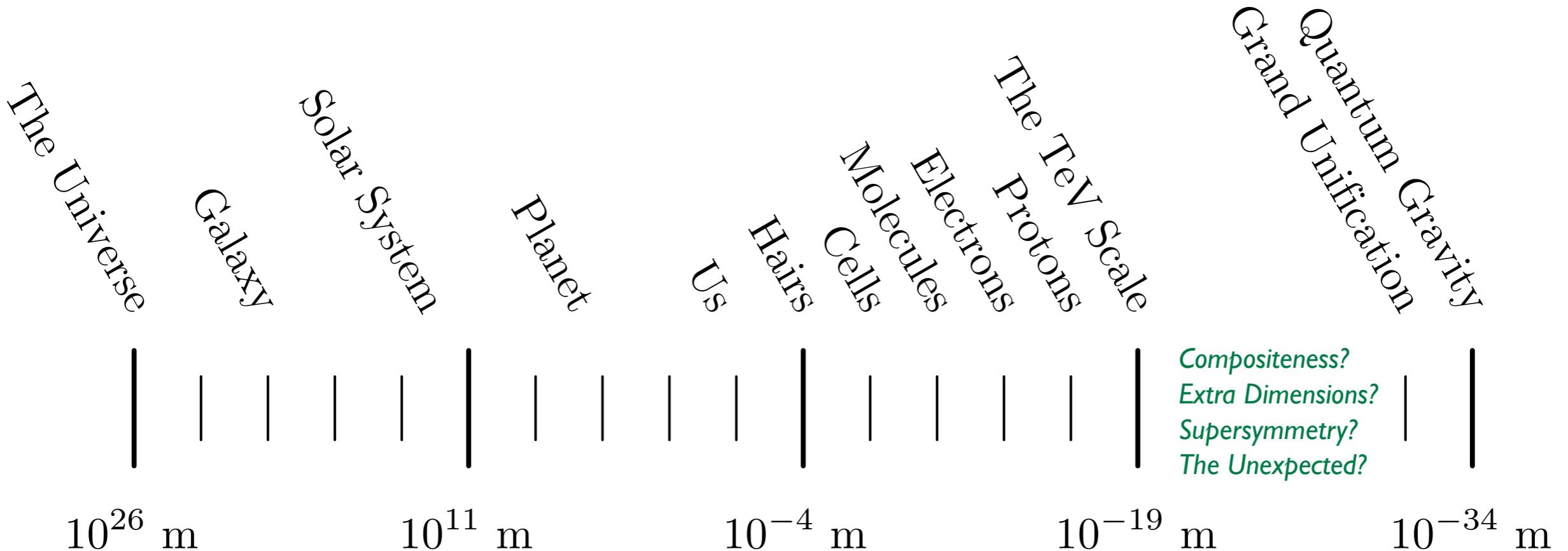
From jets to jet substructure

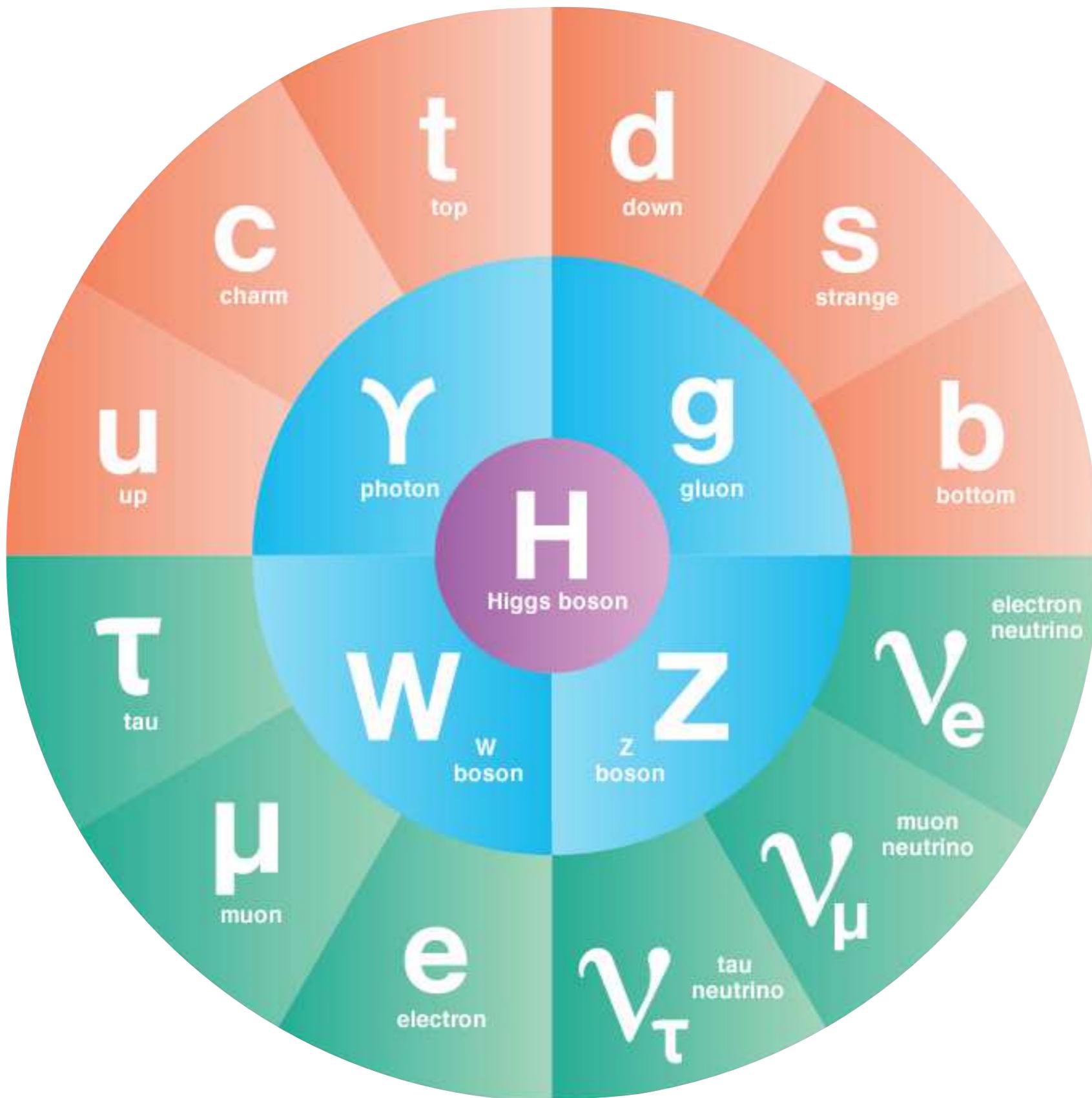


Maximize discovery potential of LHC

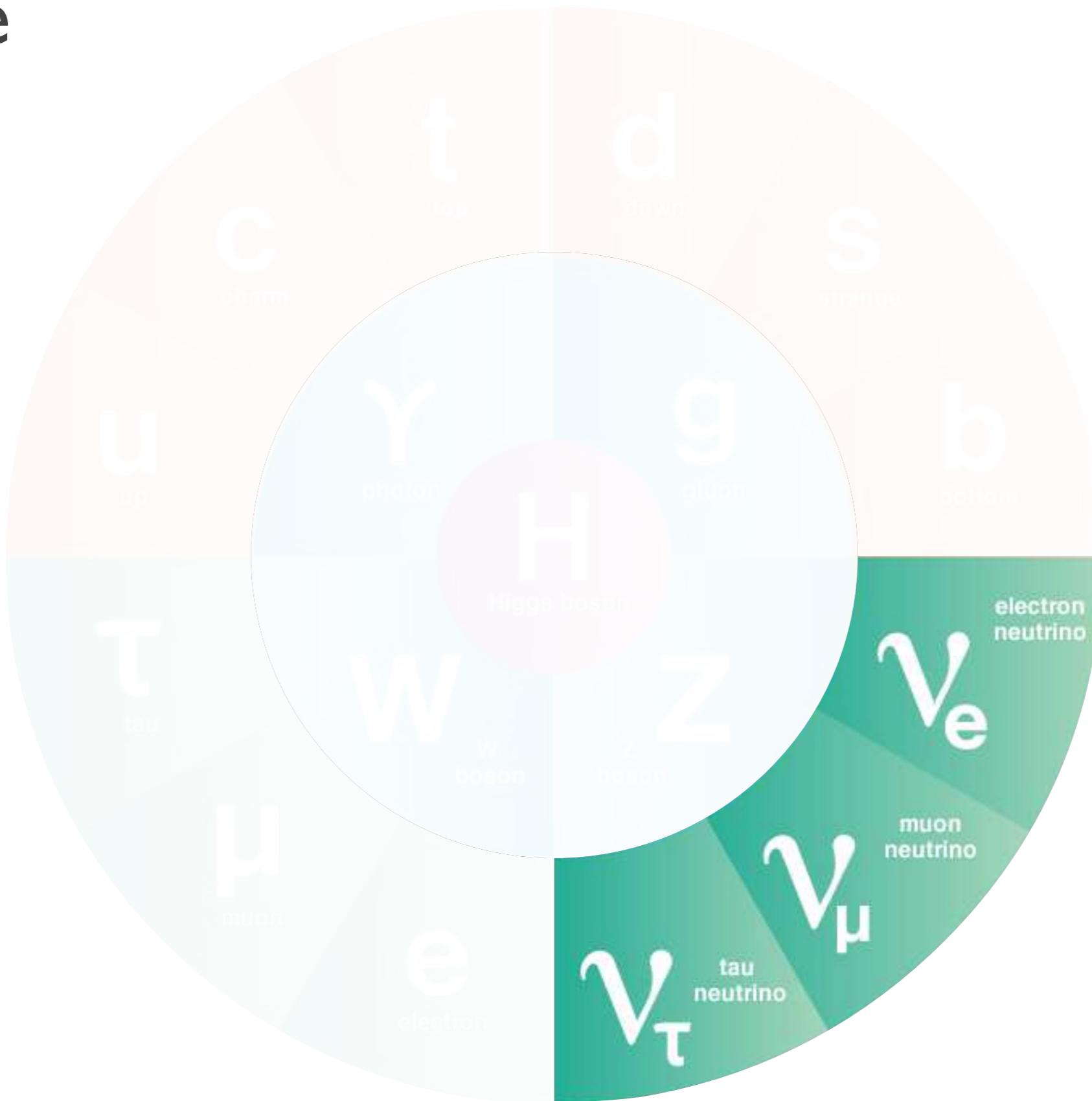


Probe emergent phenomena in QCD

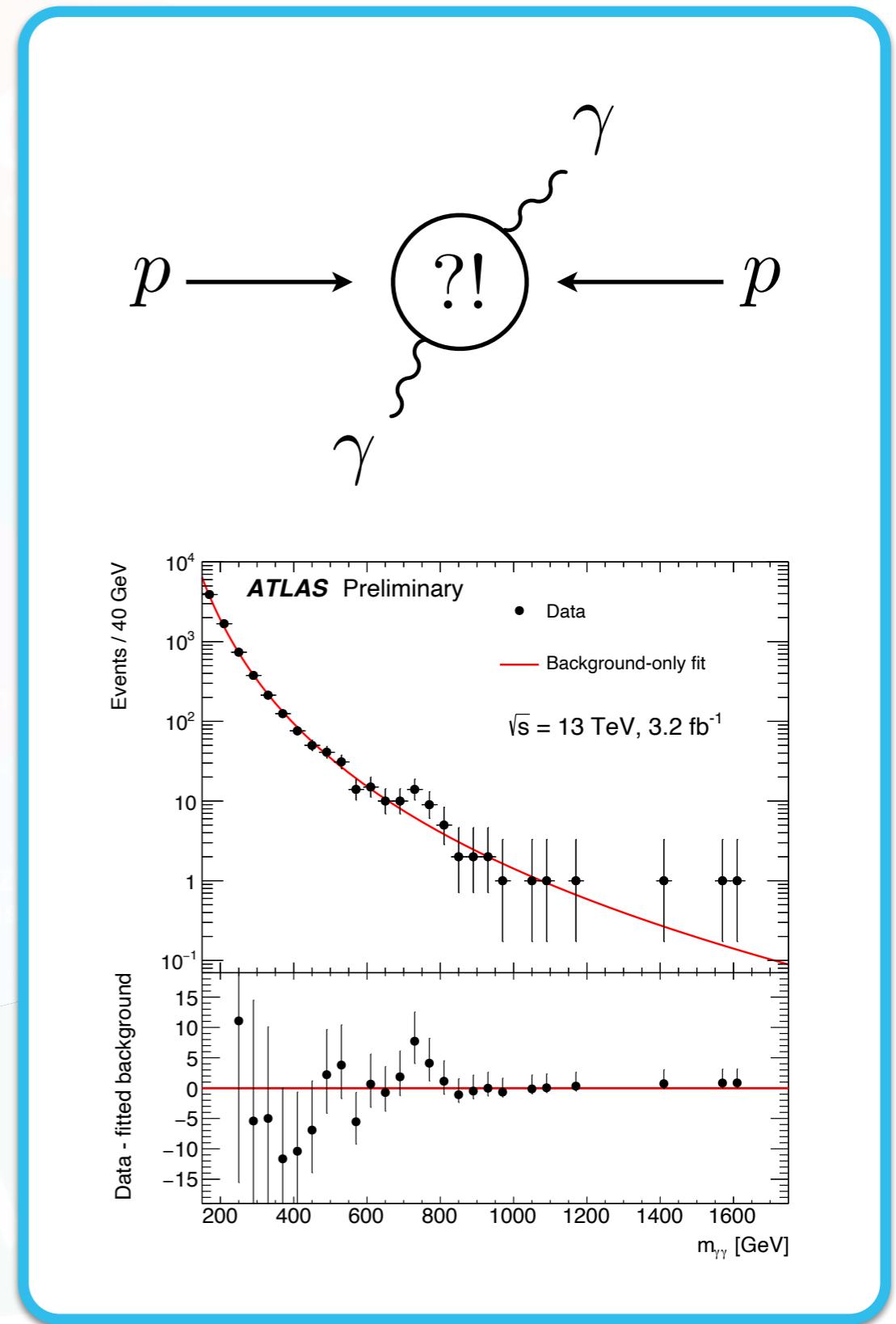
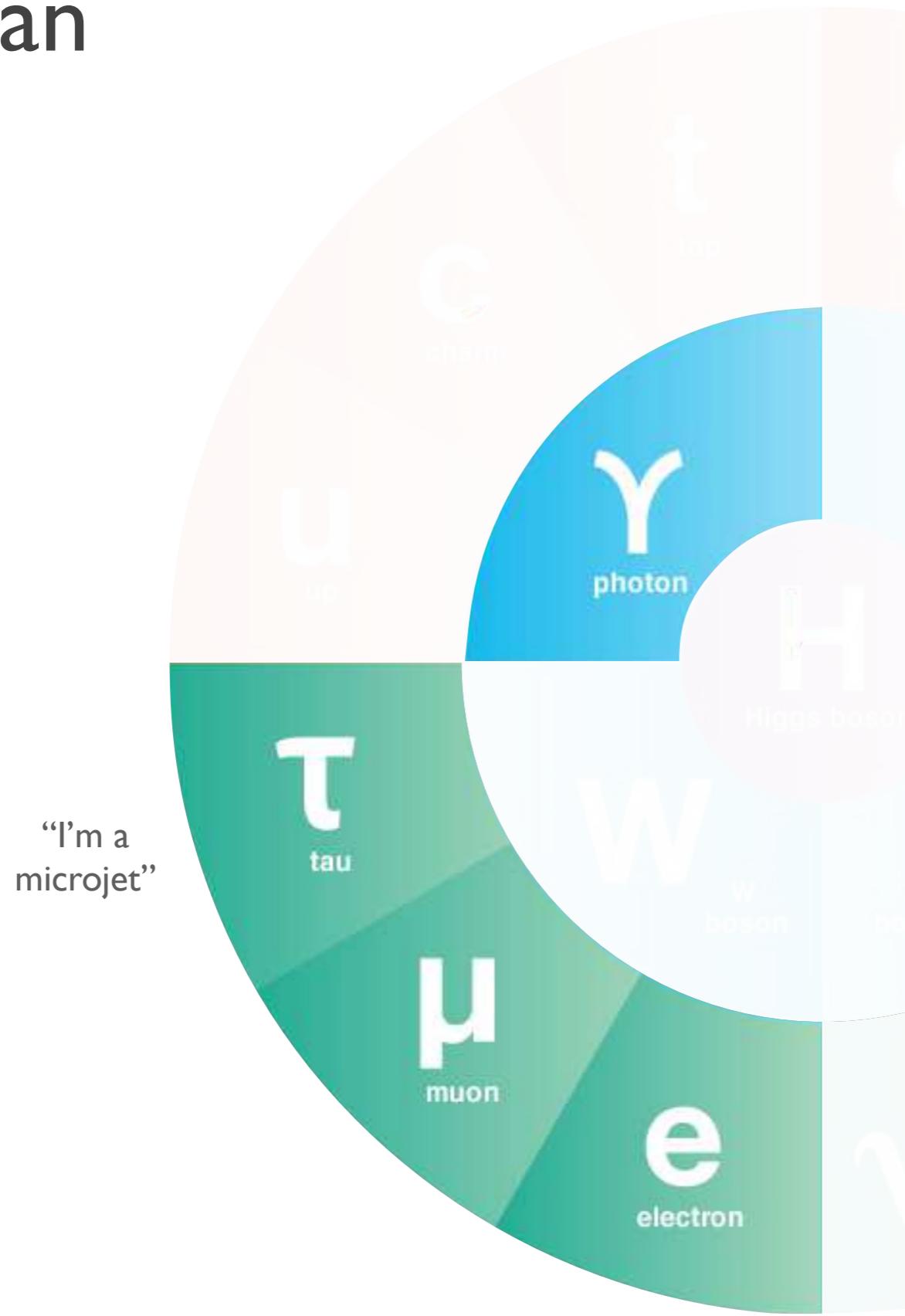




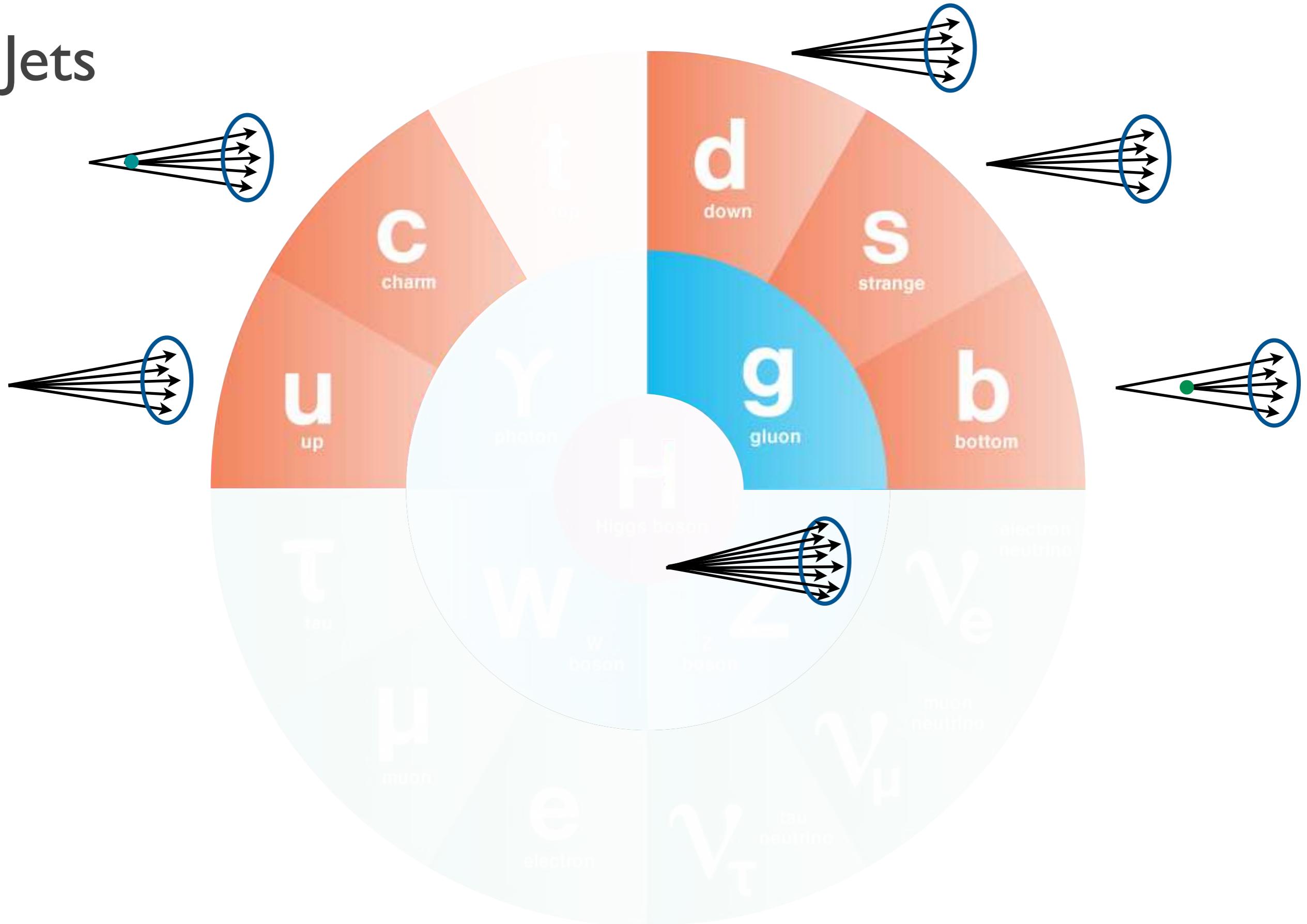
Invisible



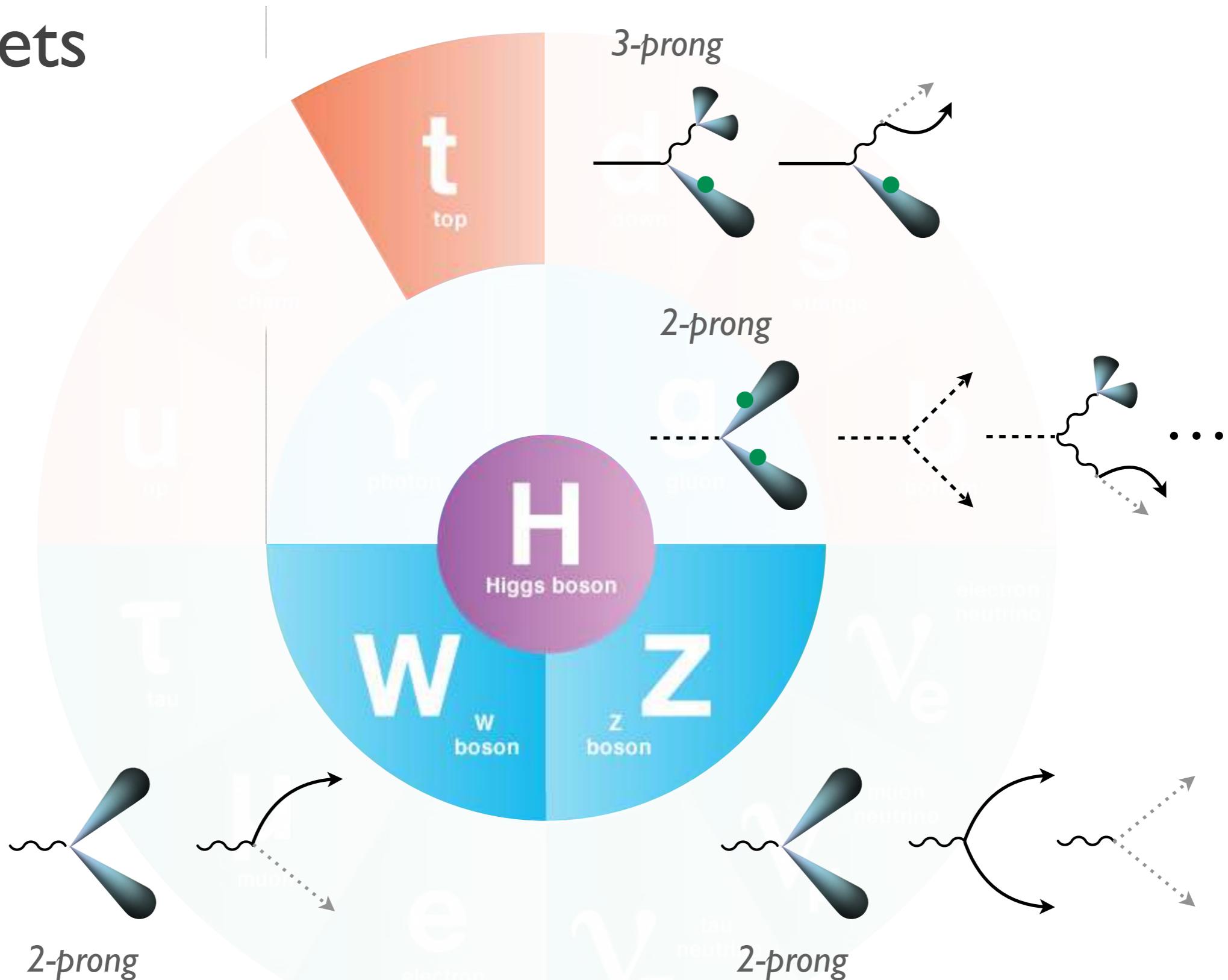
Clean



Jets

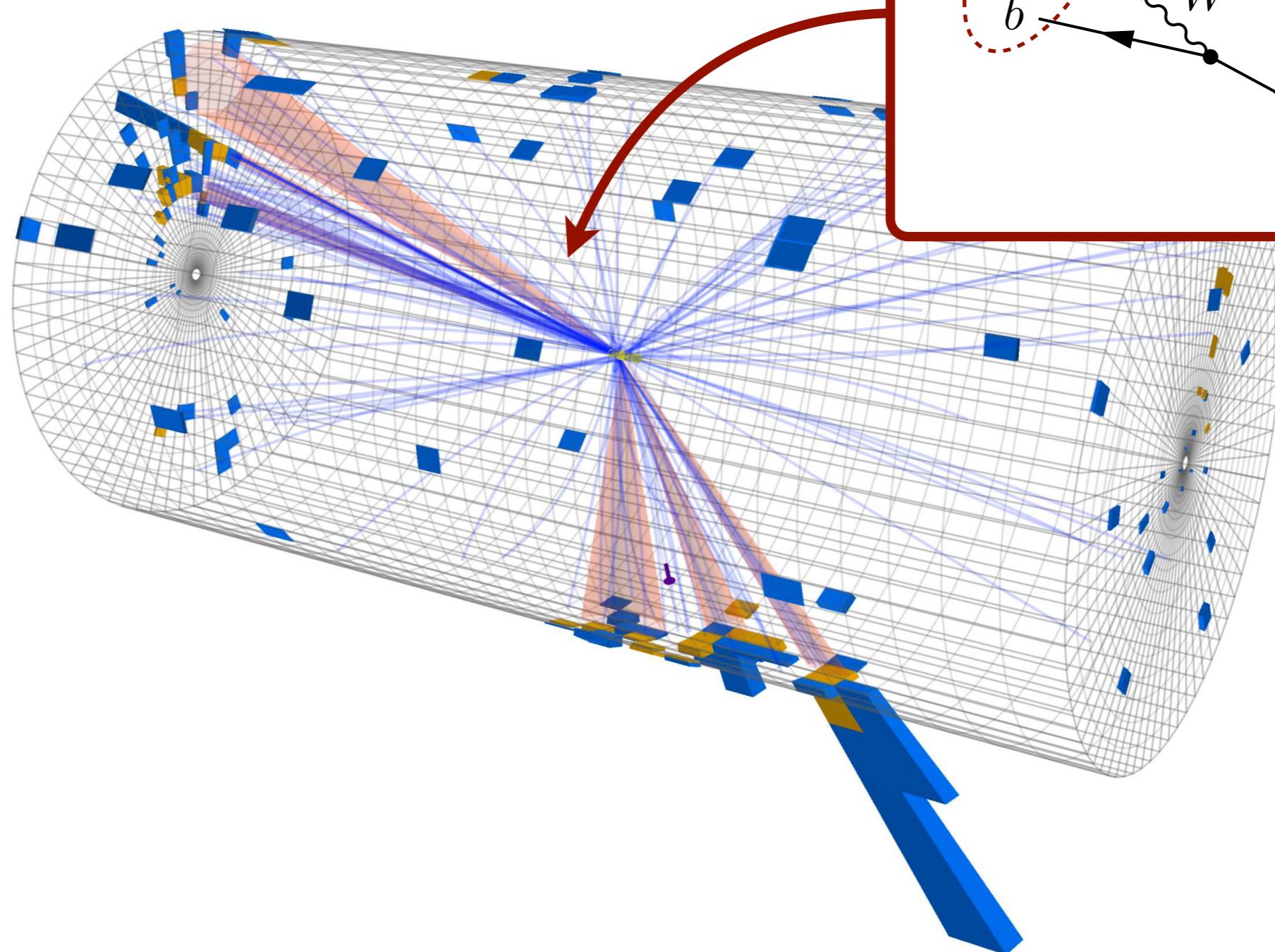


Multi-Jets

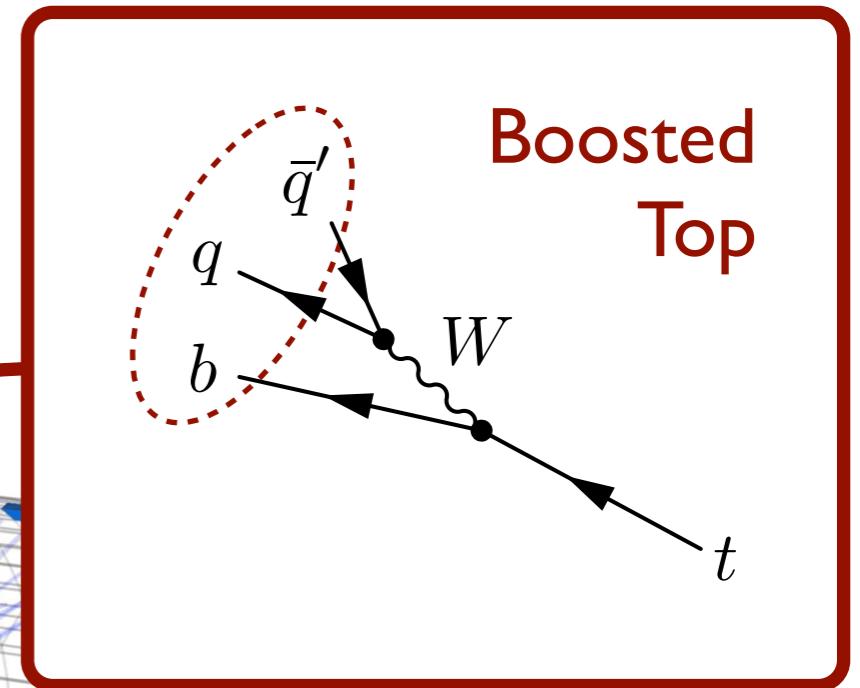




CMS Experiment at LHC, CERN
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Run/Event: 251562 / 111132974
Lumi section: 122
Orbit/Crossing: 31722792 / 2253



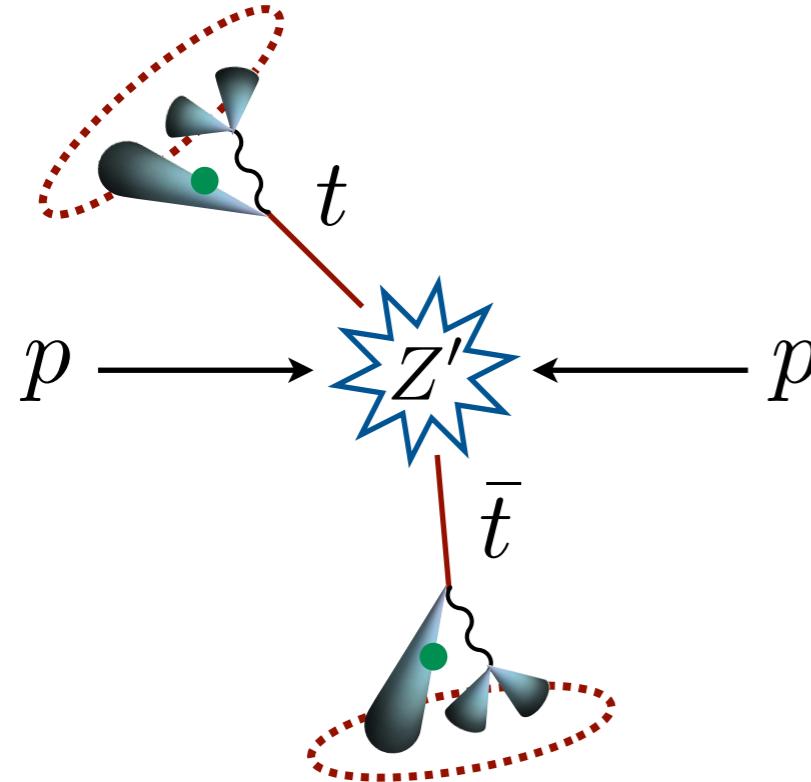
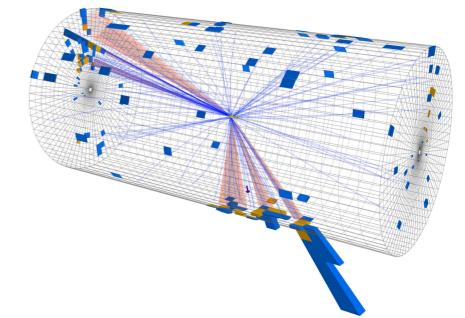
Boosted
Top



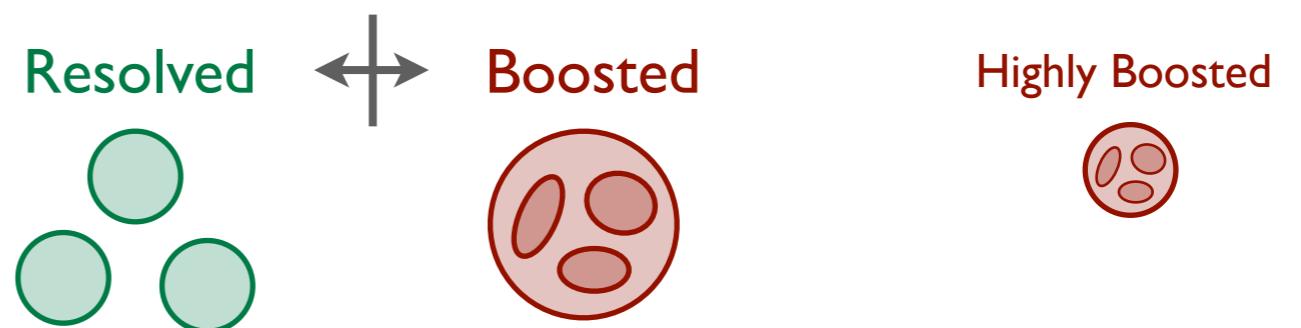
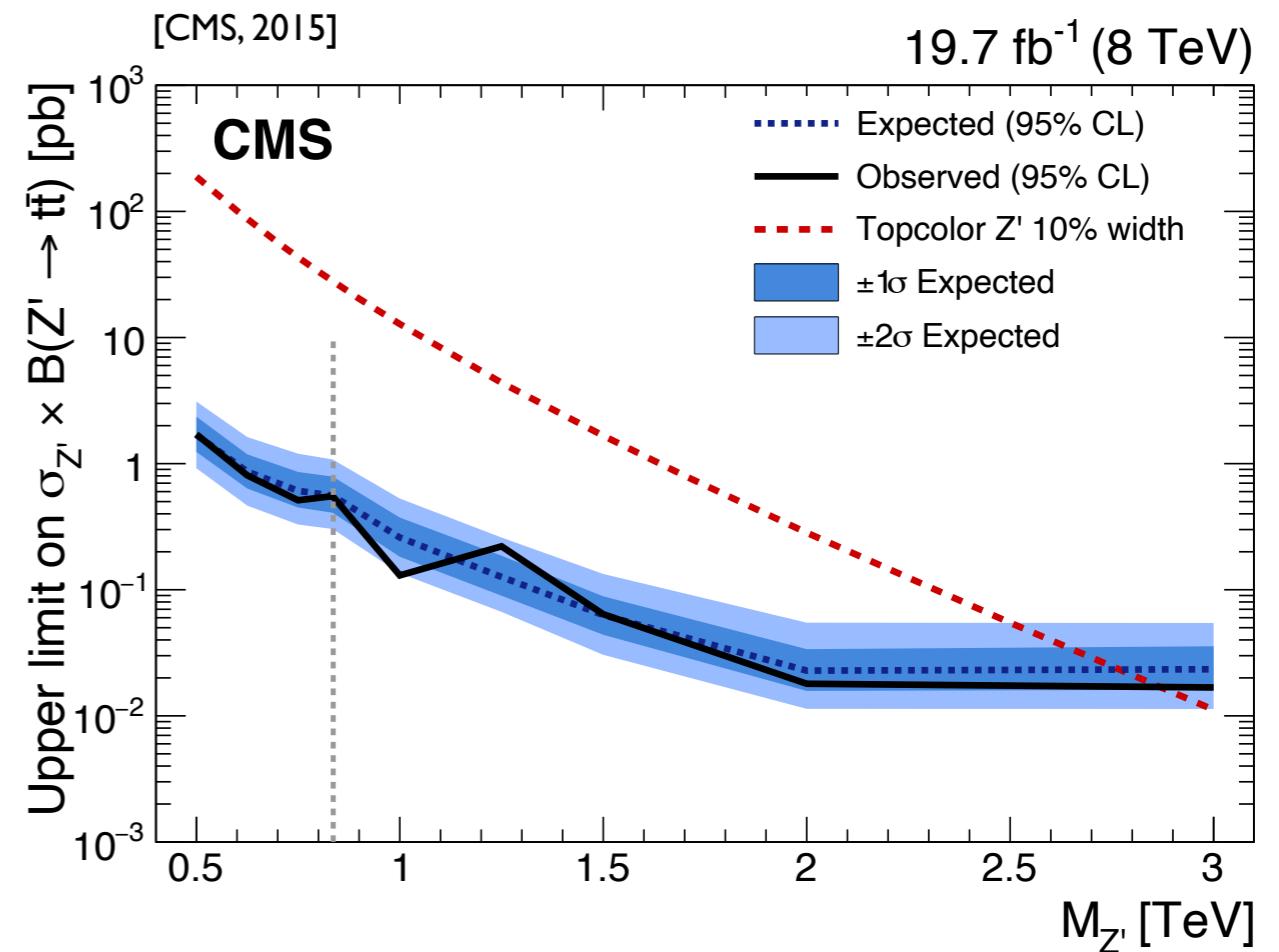
[CMS 2011, 2013, 2015]

[using Kaplan, Rehermann, Schwartz, Tweedie, 2008; using Ellis, Vermilion, Walsh, 2009]

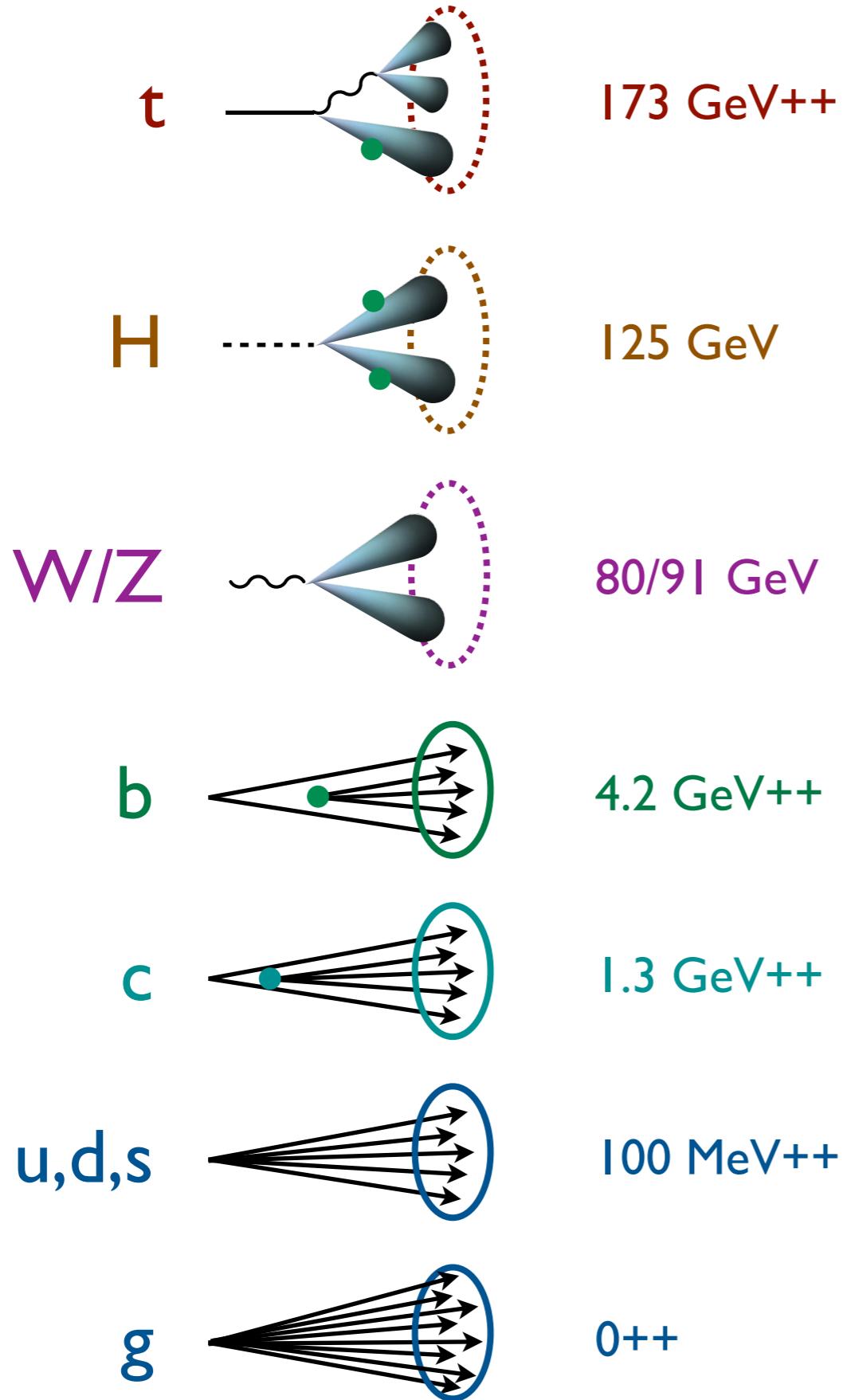
Welcome to the Boosted Regime



$$\Delta R \simeq \frac{2m_{\text{top}}}{p_T}$$

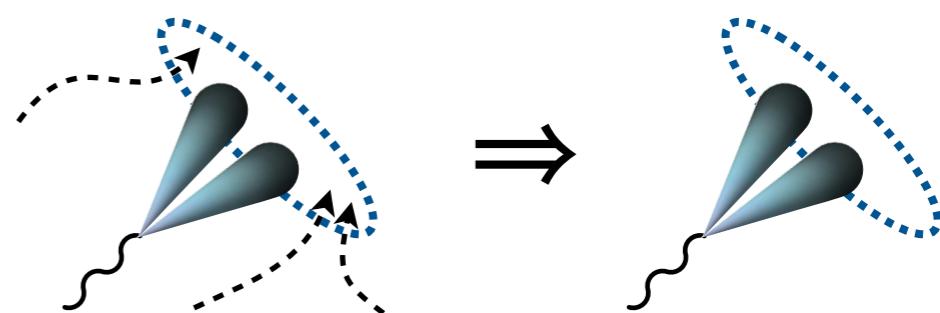






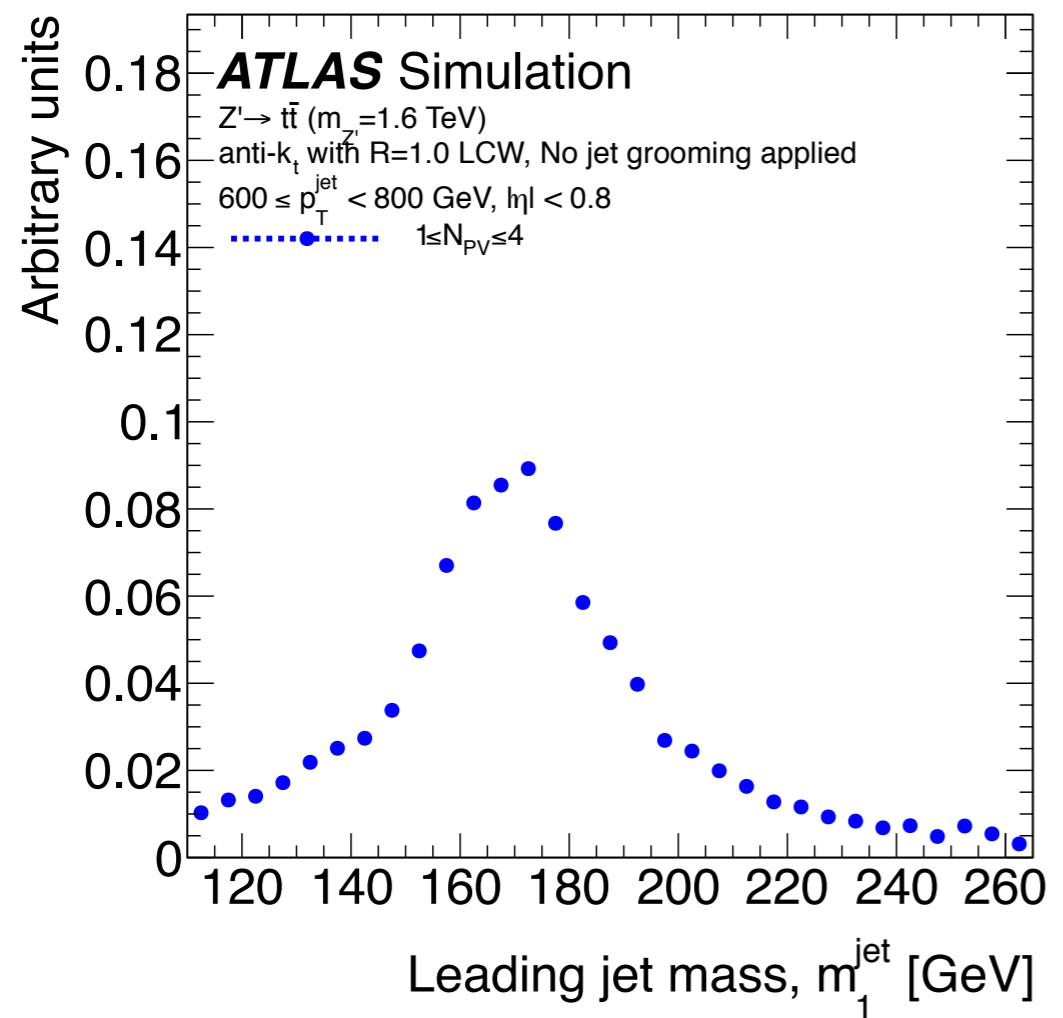
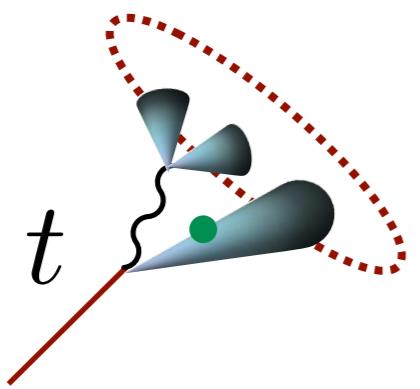
Substructure Toolbox:

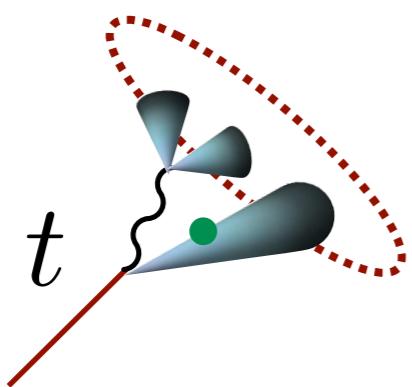
Jet Cleaning



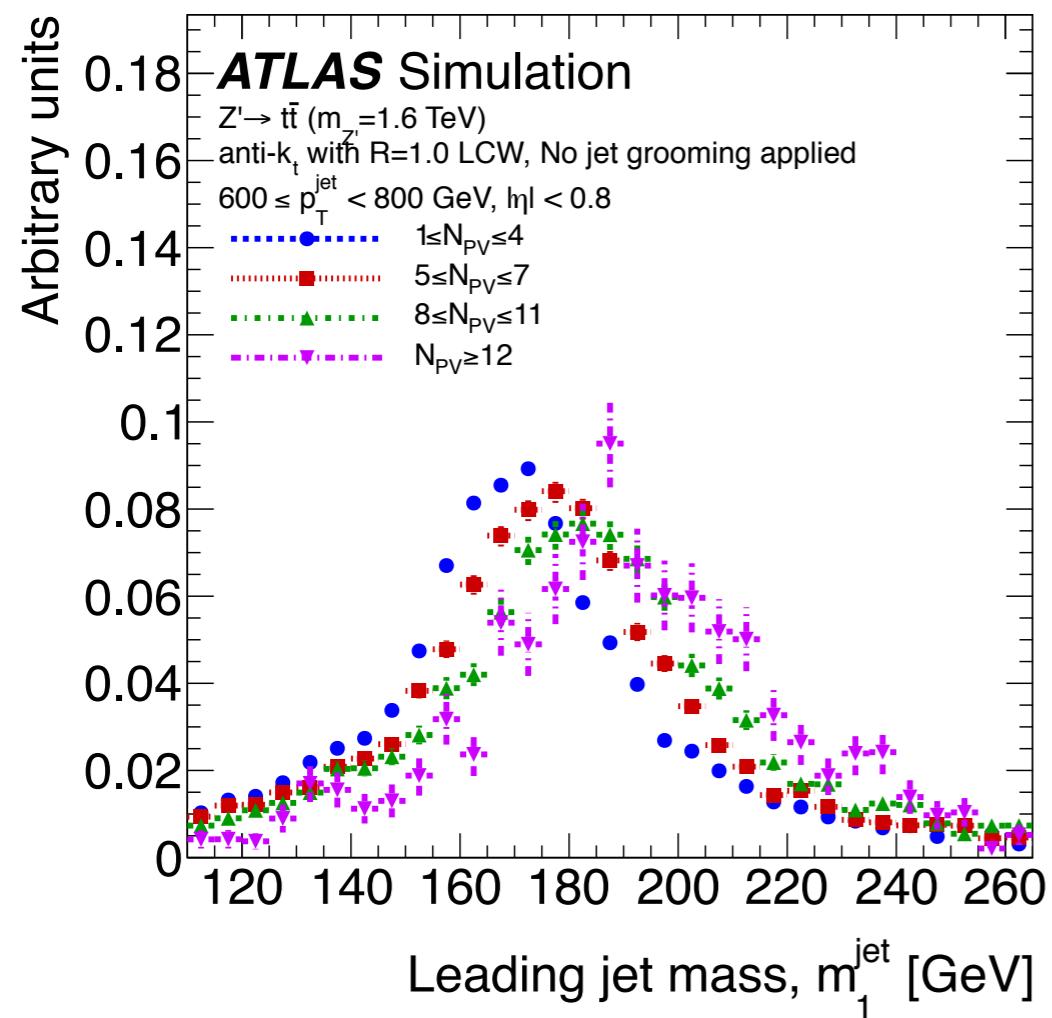
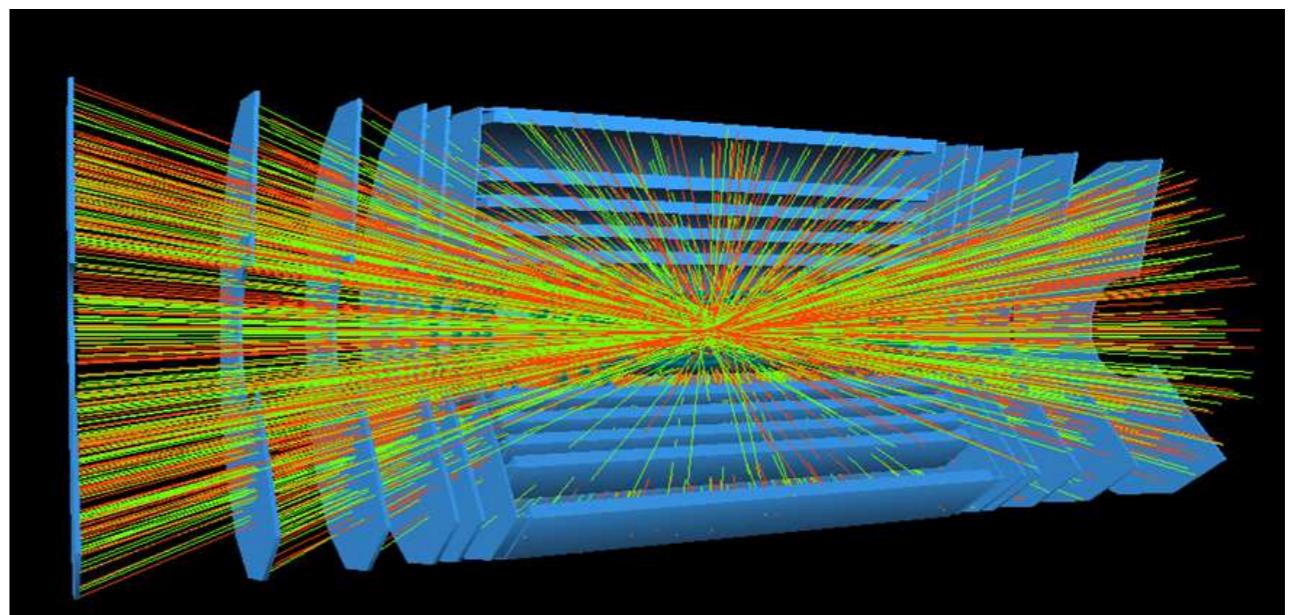
Jet Discrimination

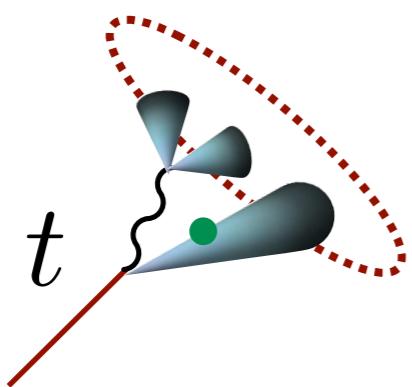




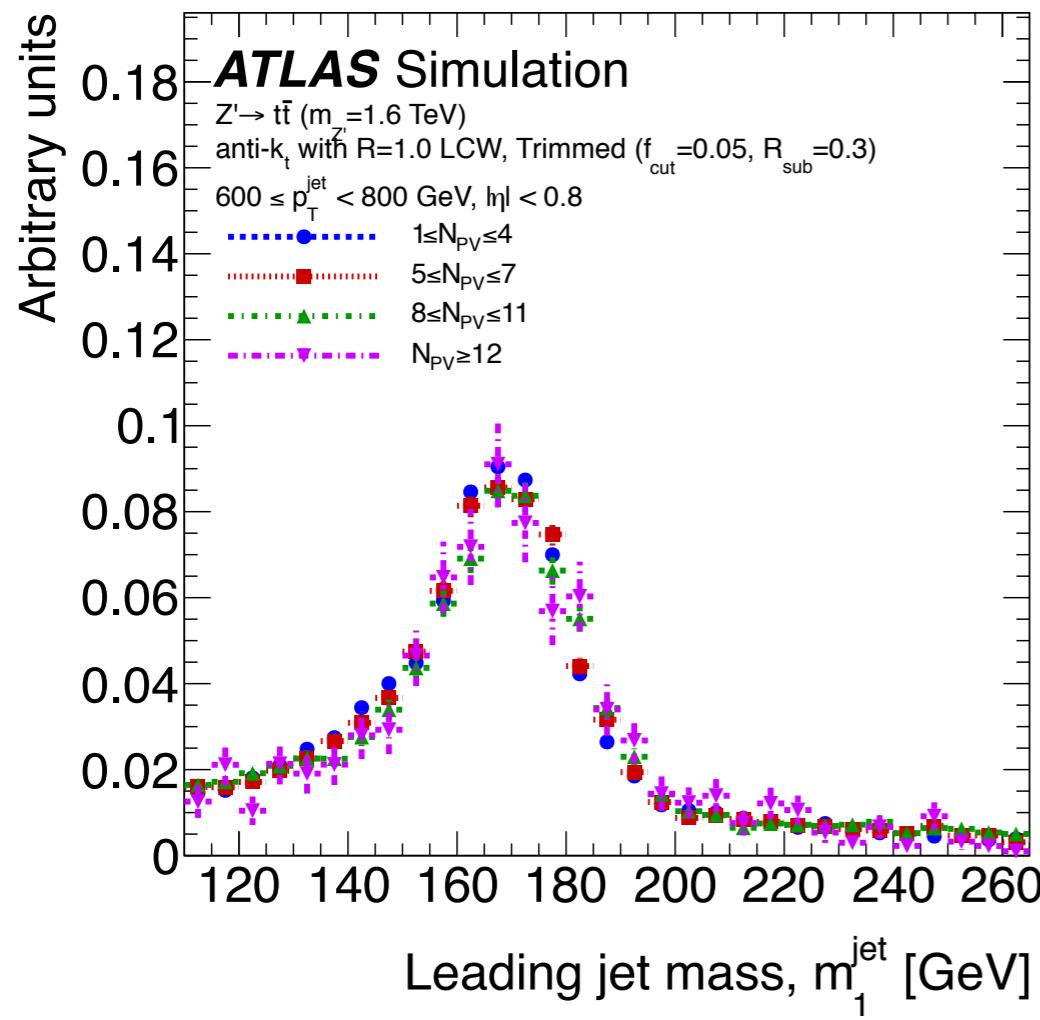
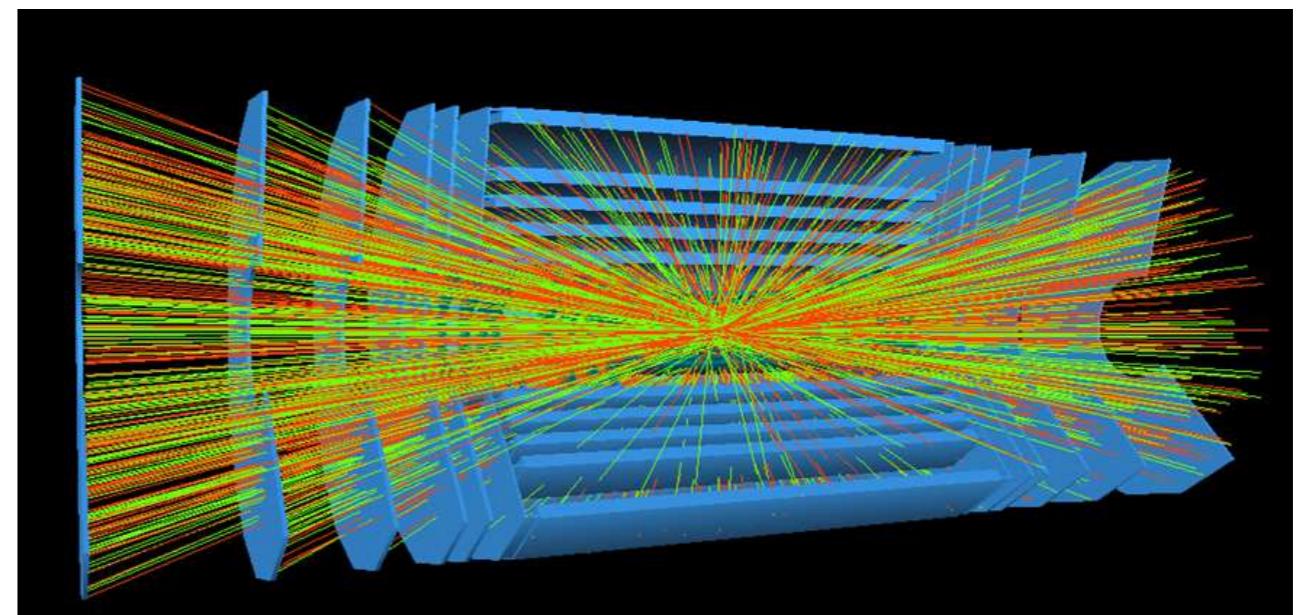


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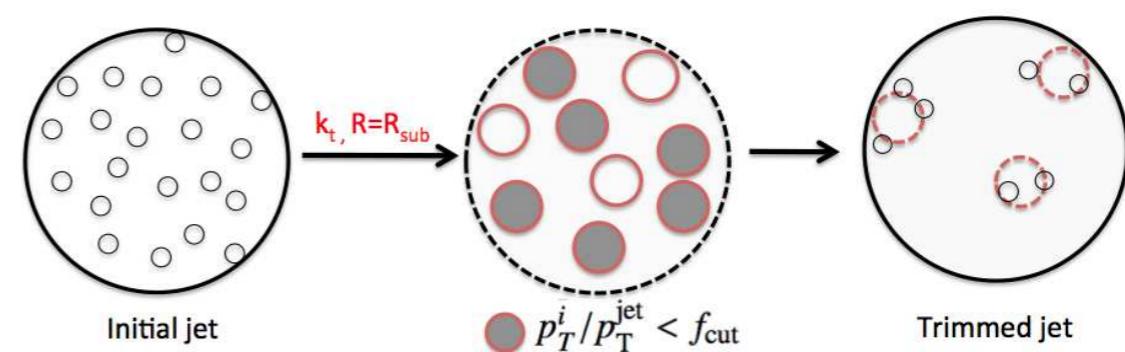


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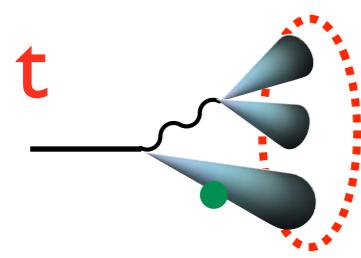


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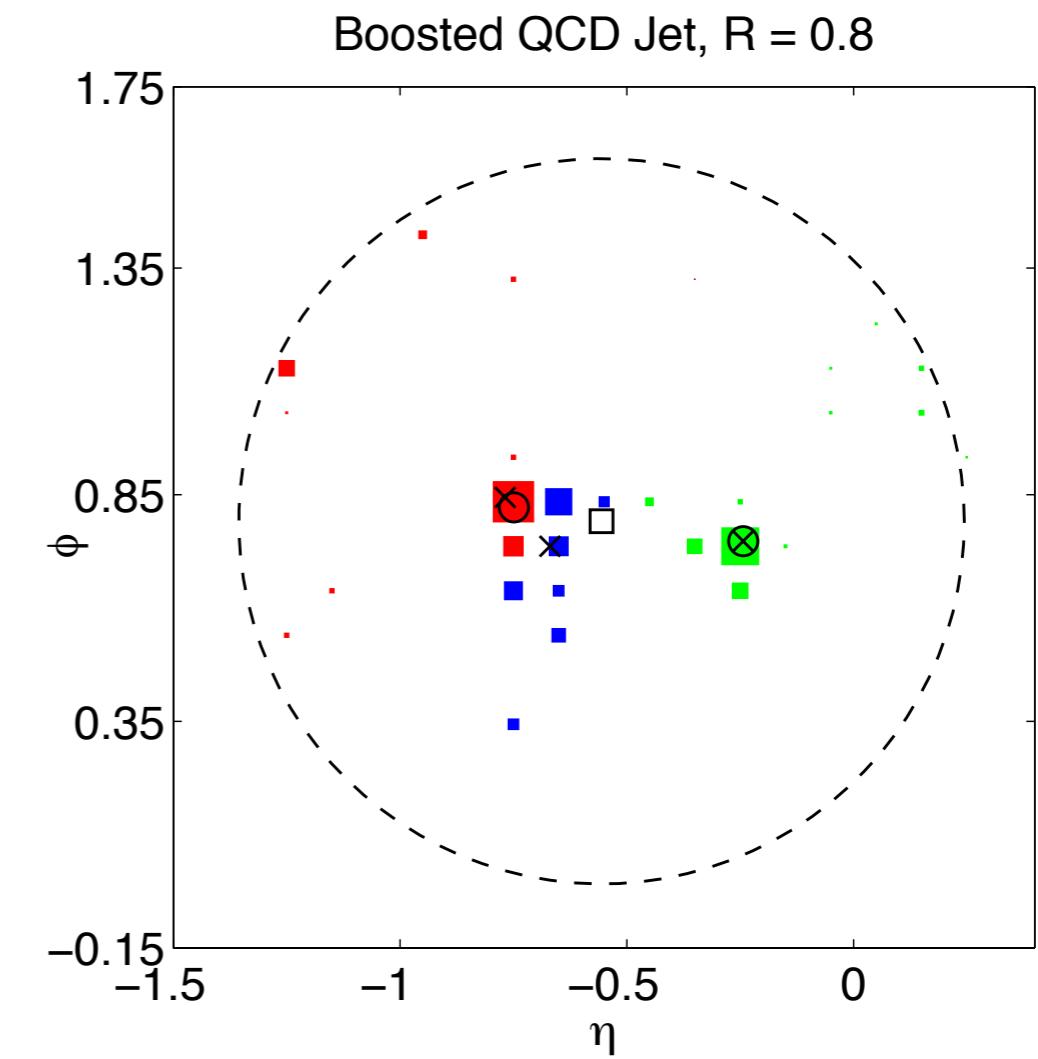
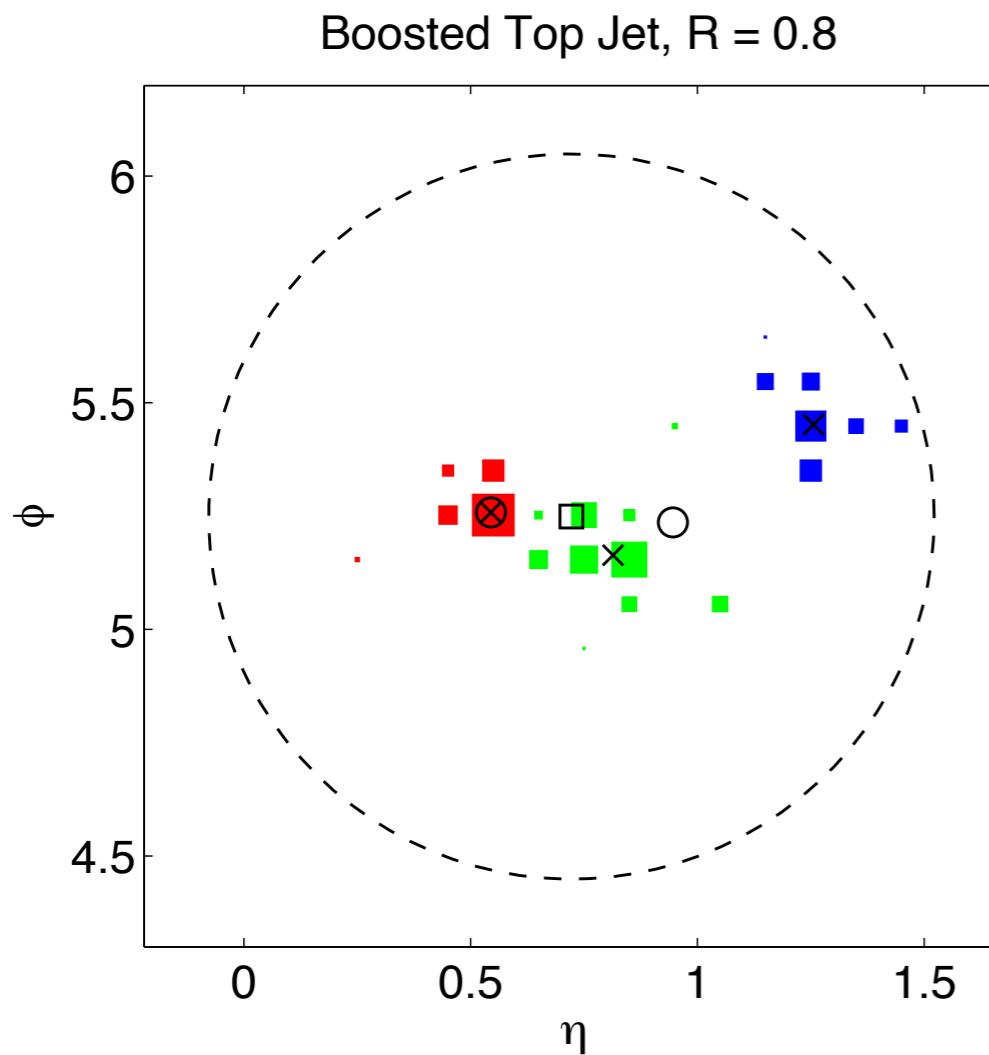
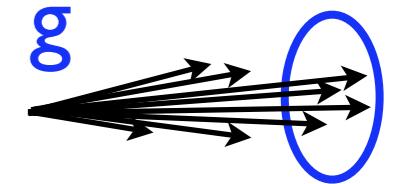
e.g. Jet Trimming



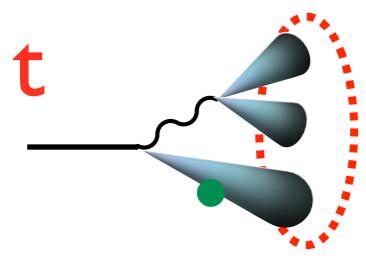
[ATLAS, 2012; using Krohn, JDT, Wang, 2009]



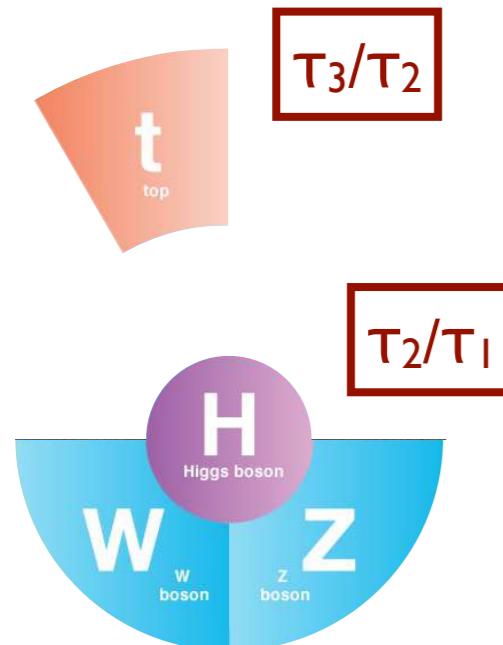
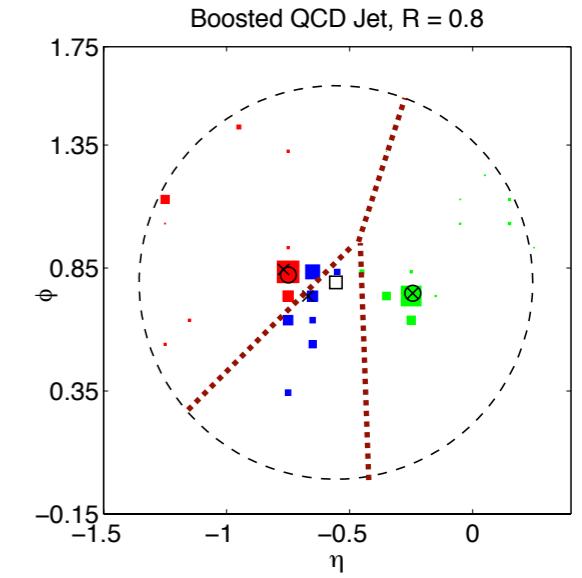
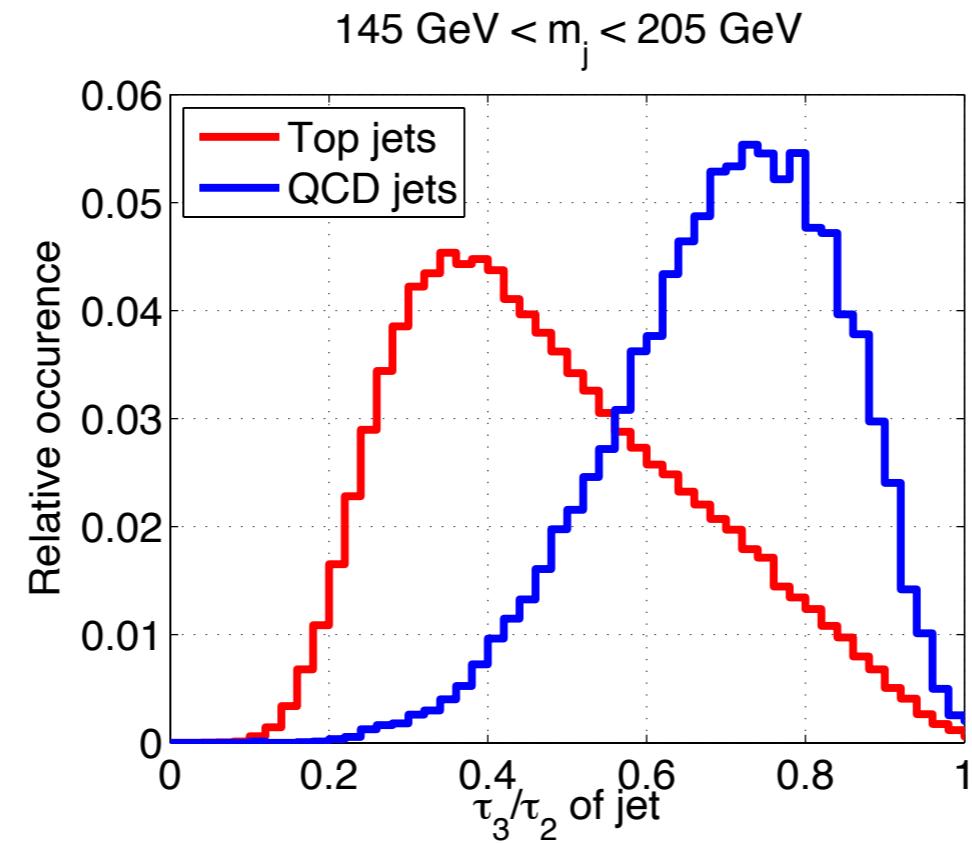
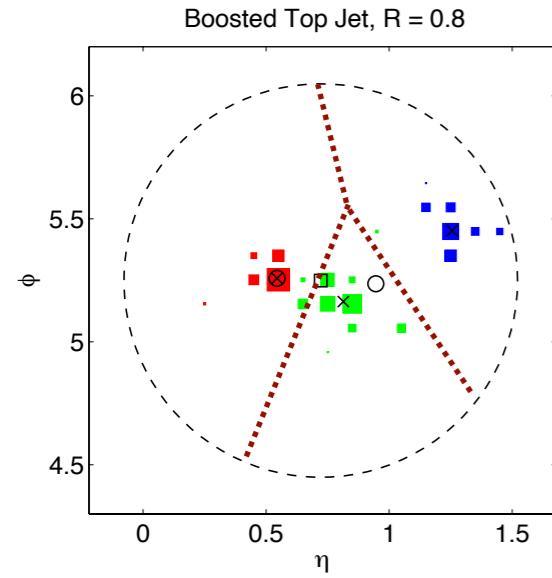
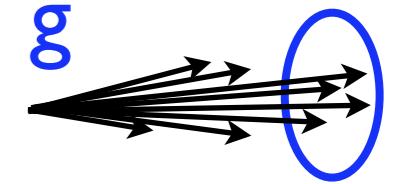
N-Prong vs. I-Prong



Both jets have $m \approx 170$ GeV



N-Prong vs. I-Prong



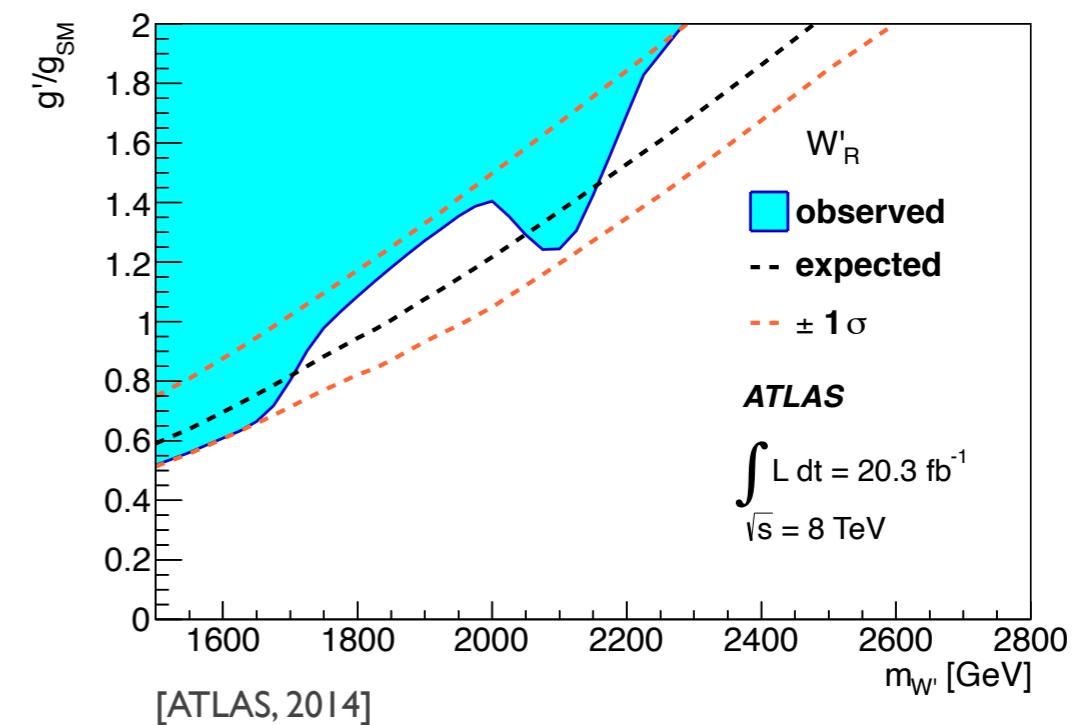
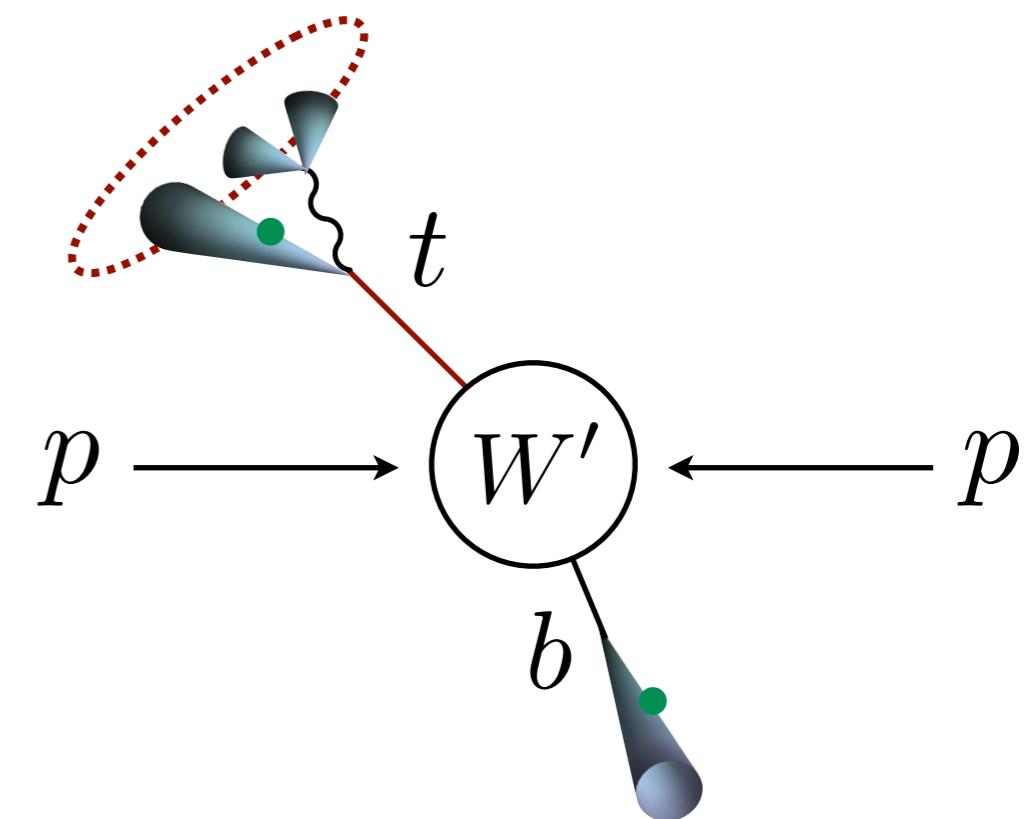
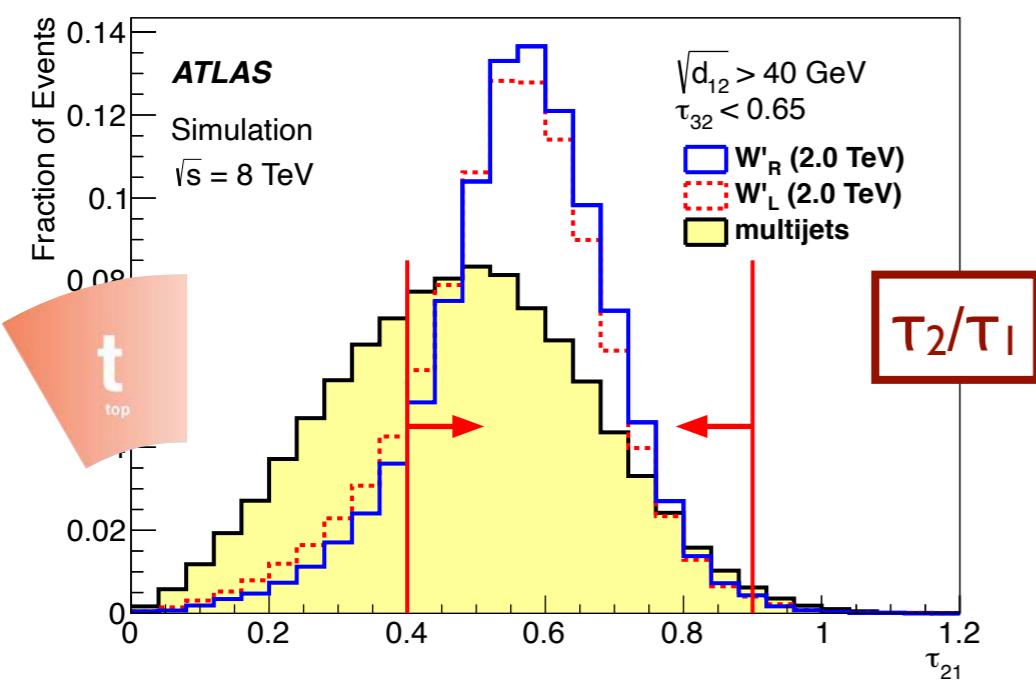
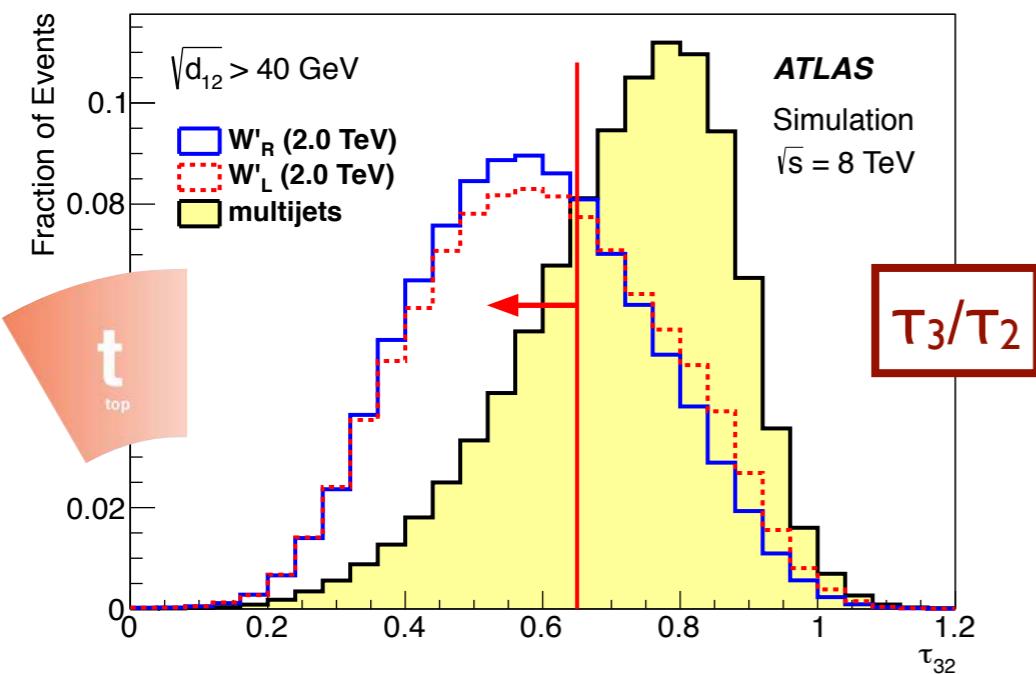
N-subjettiness

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

[JDT, Van Tilburg, 2010, 2011]
 [see also Stewart, Tackmann, Waalewijn, 2010; Larkoski, Moult, Neill, 2014]

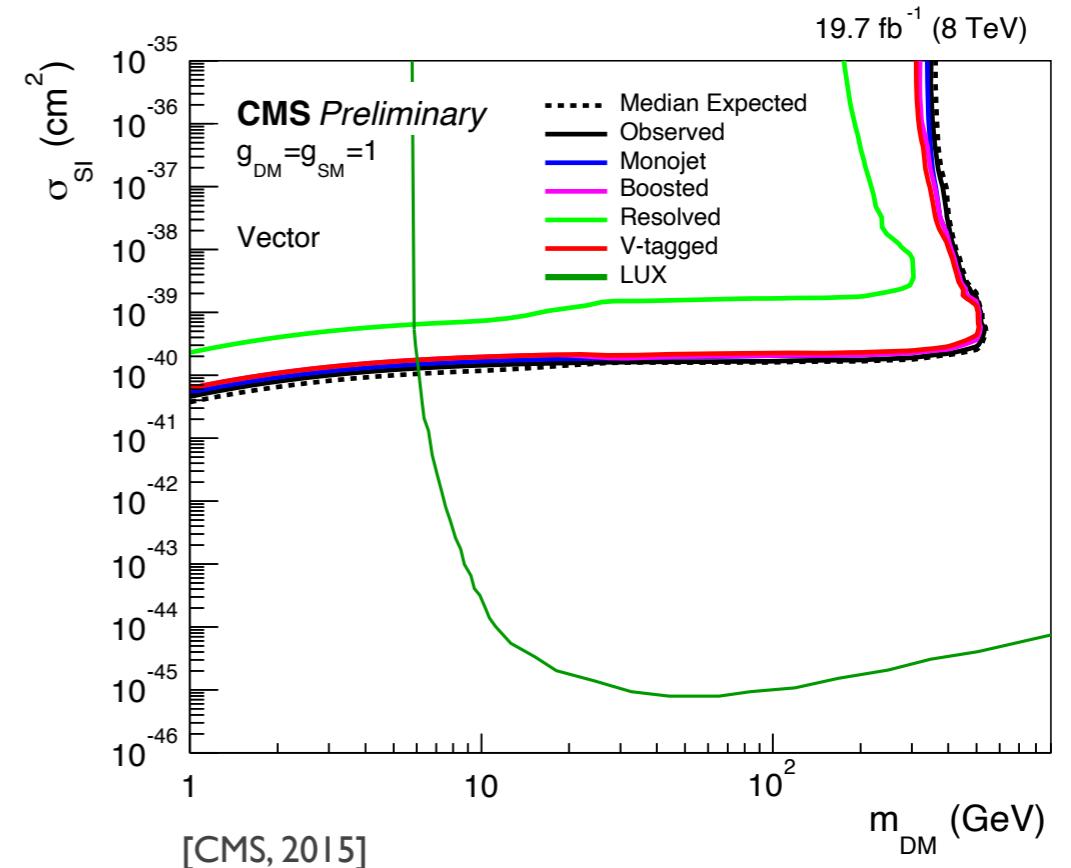
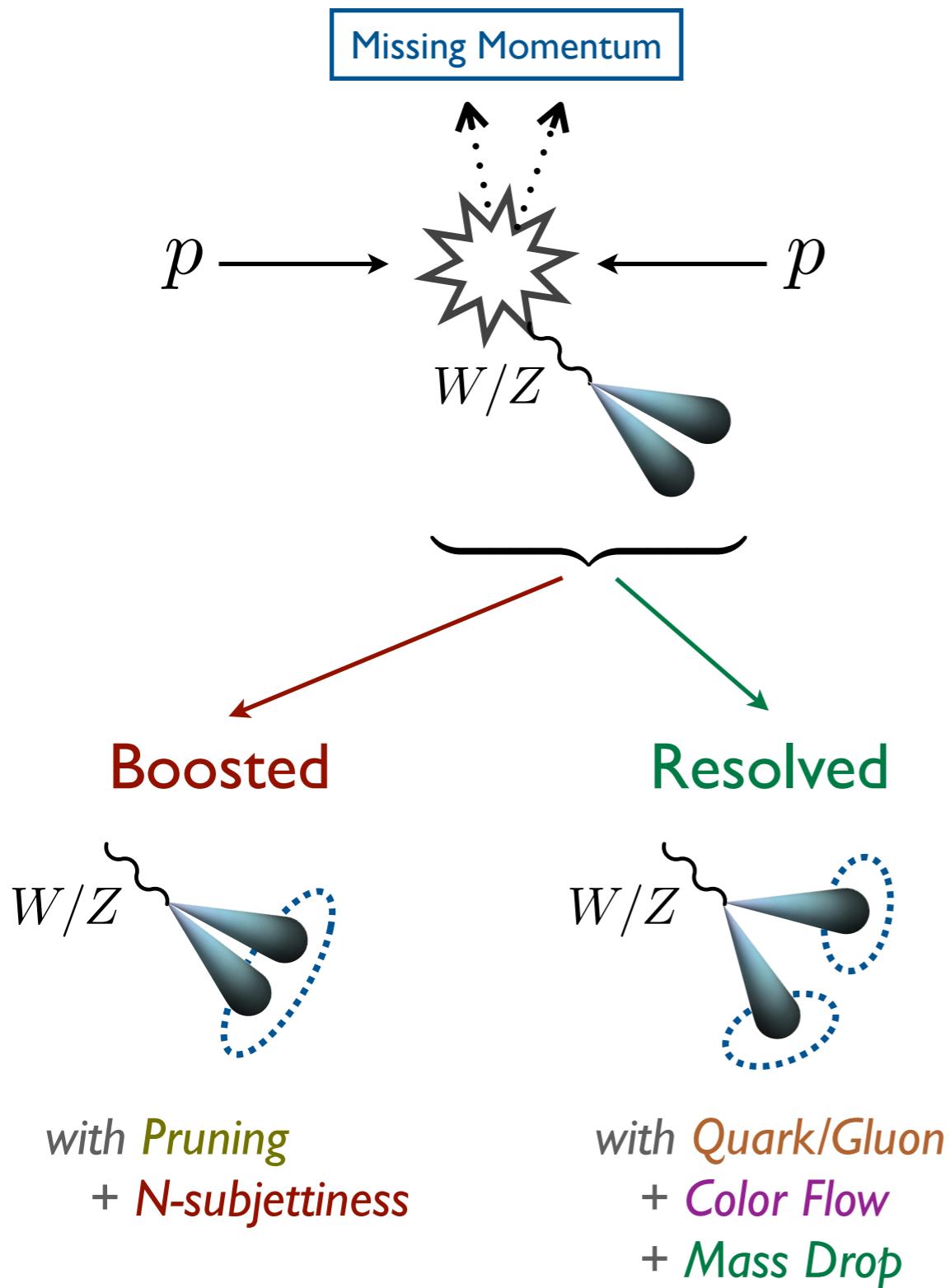
ATLAS: Heavy W Search

N-subjettiness + B-tagging + Trimming

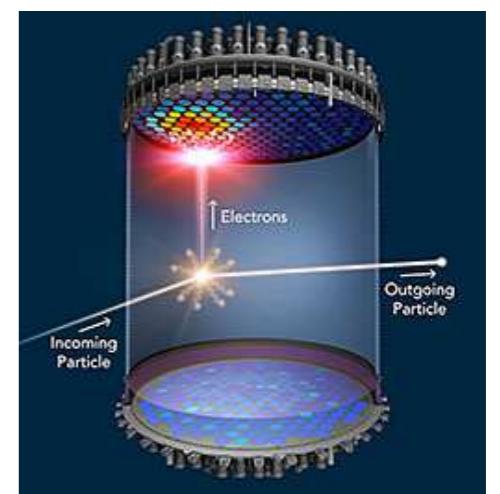


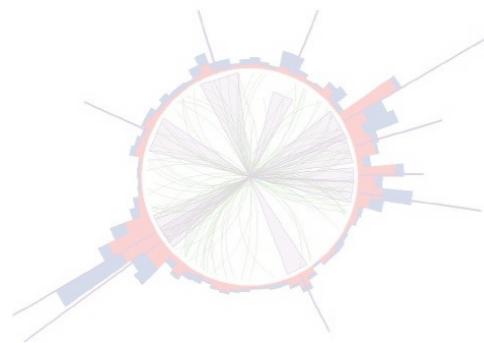
CMS: Dark Matter Search

Hot Topic @ BOOST2015

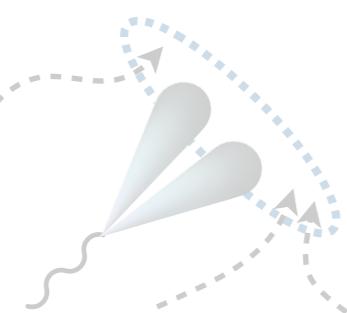


Complementary
to direct dark
matter searches

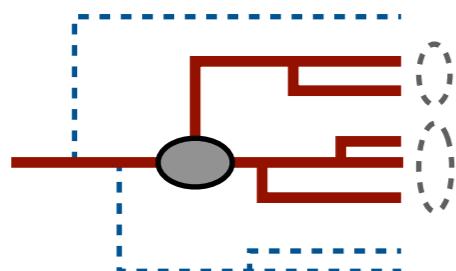




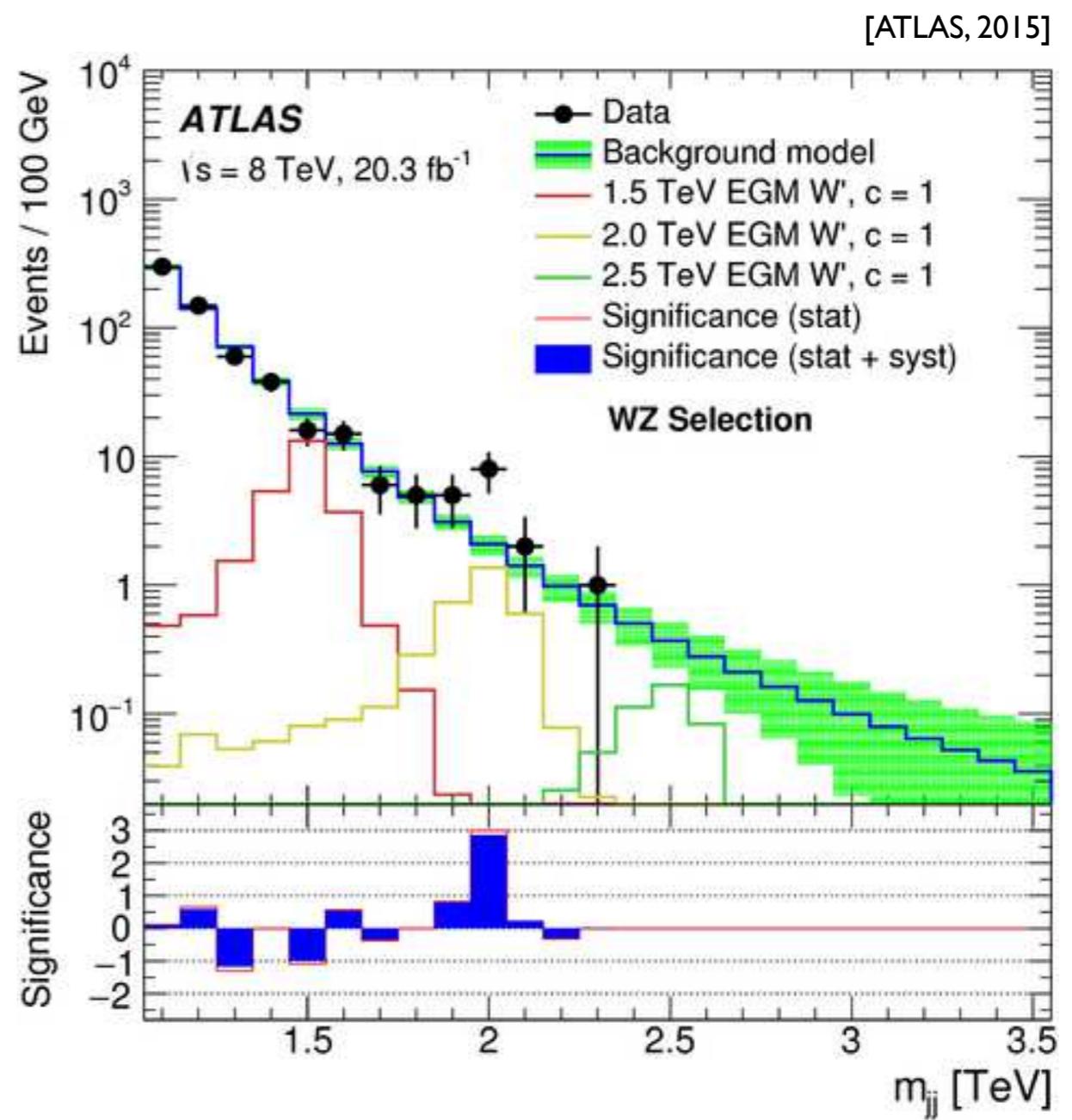
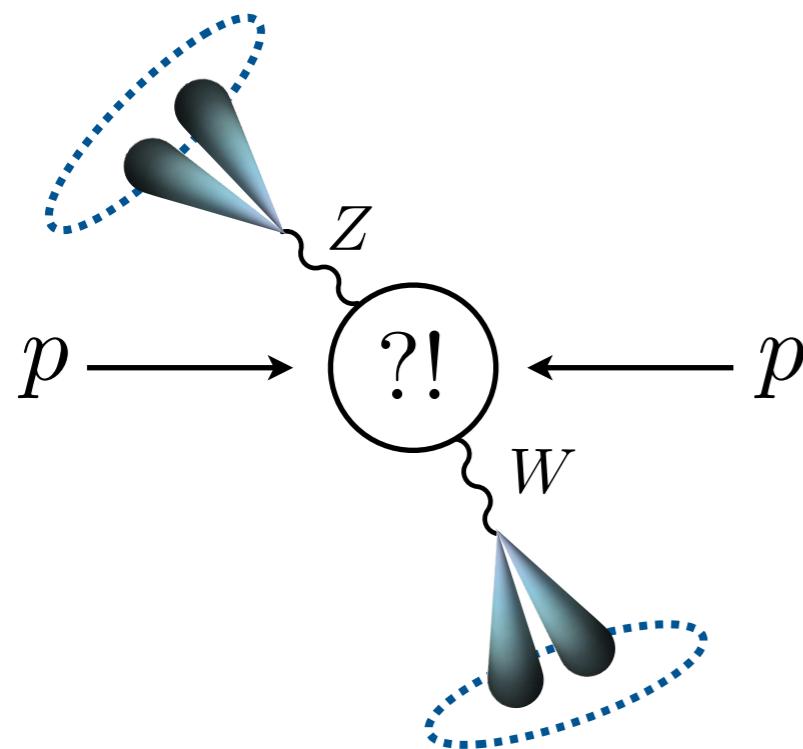
From jets to jet substructure

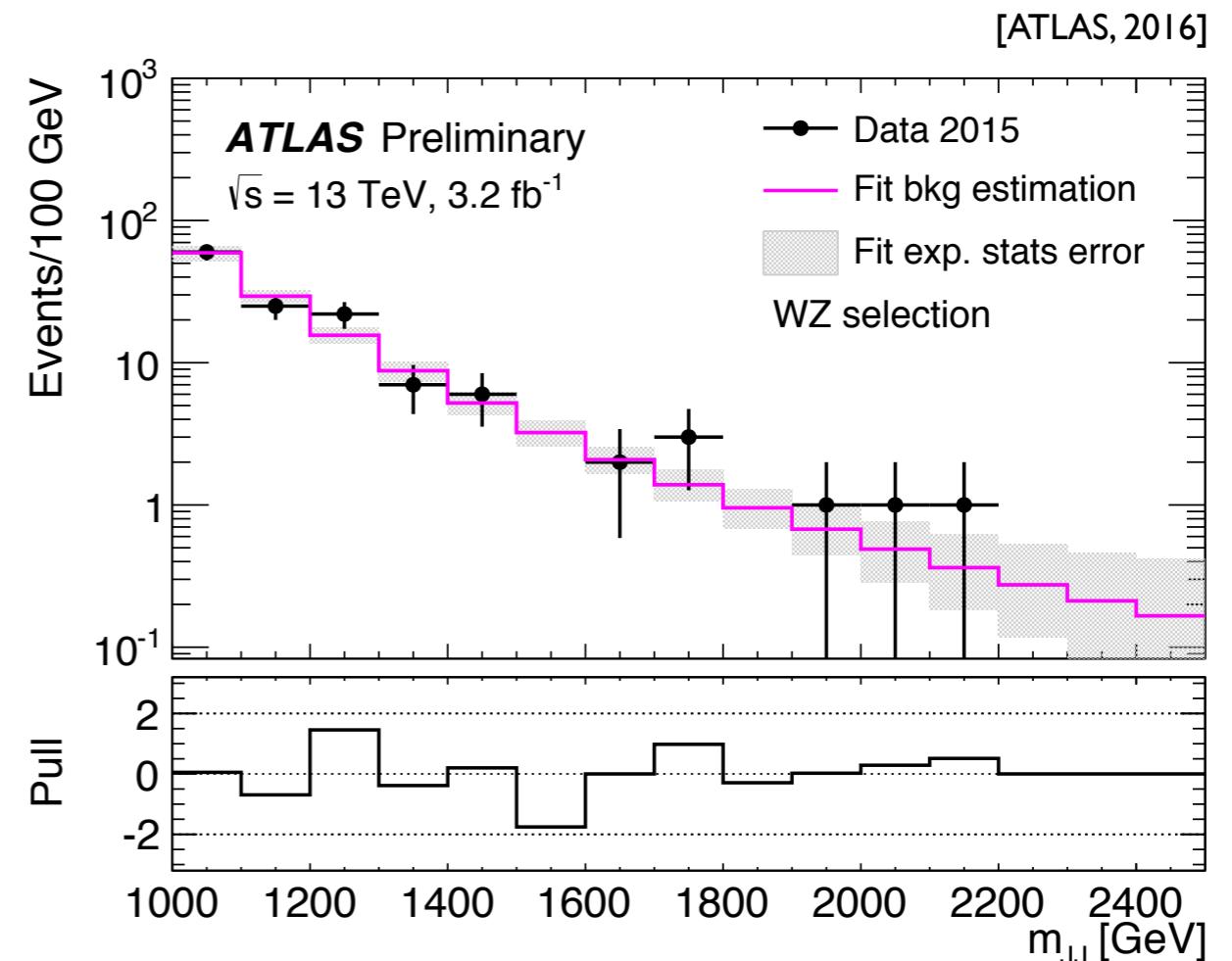
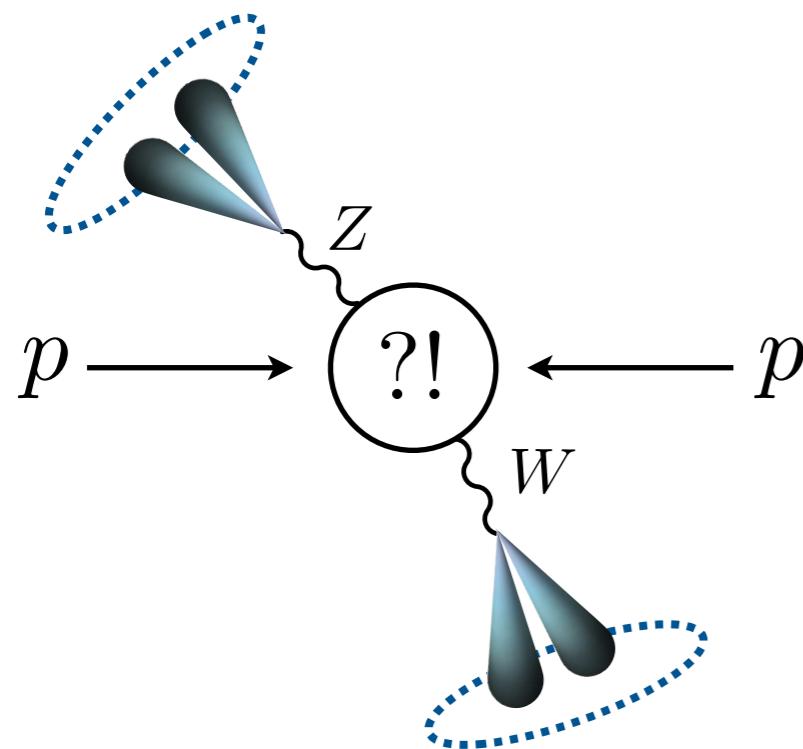


Maximize discovery potential of LHC

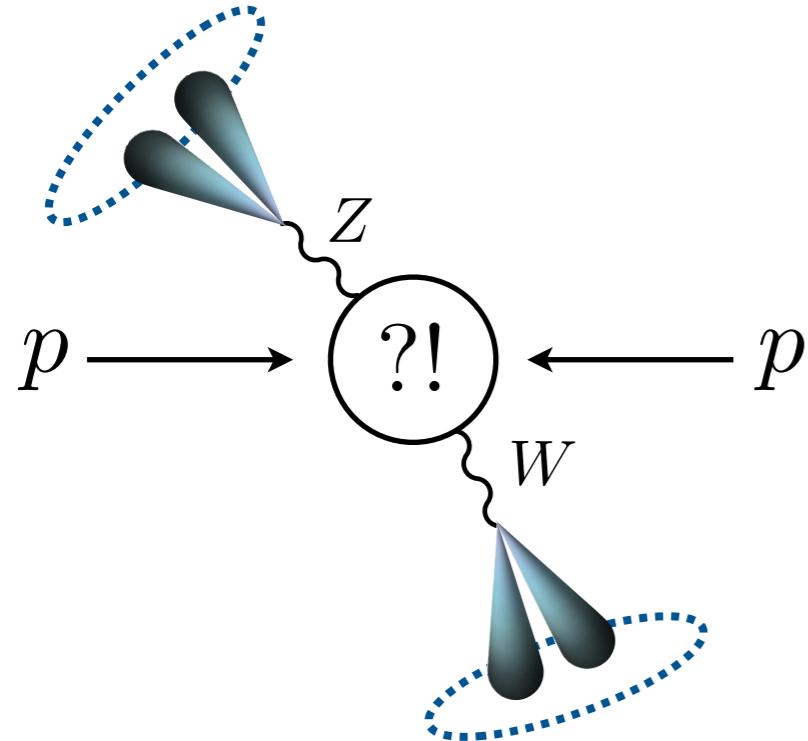


Probe emergent phenomena in QCD

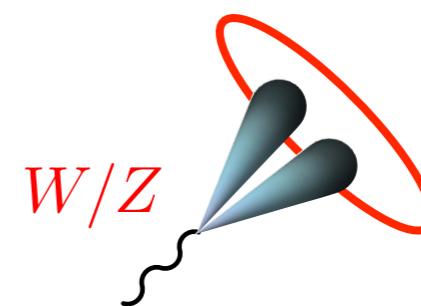




Bumps may come and go...

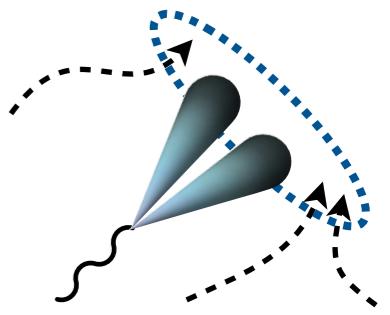


VS.



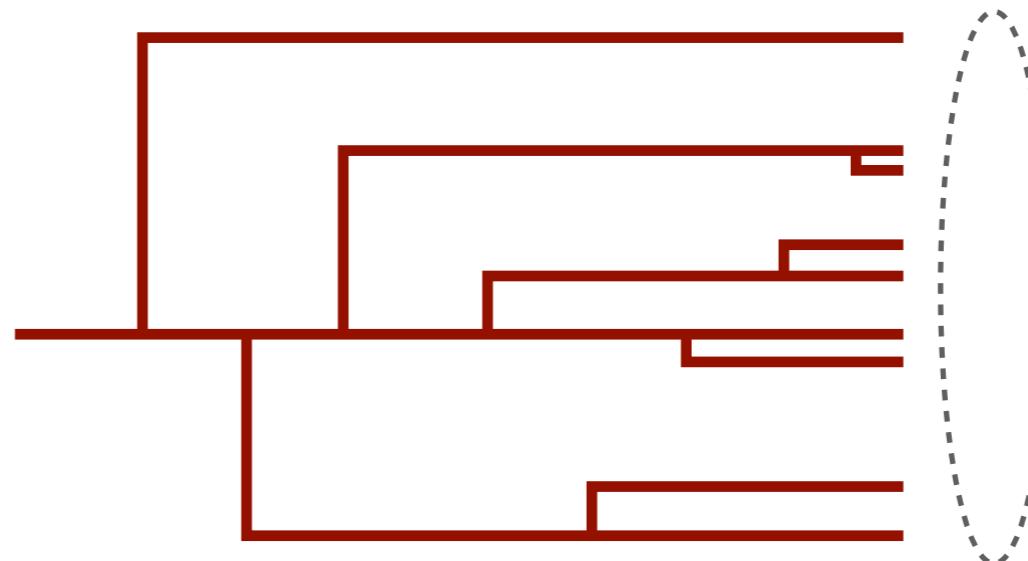
Simple discriminant requires
new calculational techniques

ATLAS: W/Z Boson Tagging

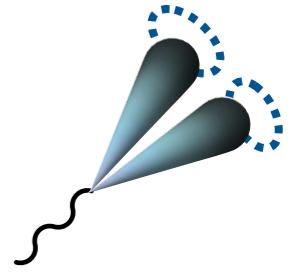


Angular-ordered
clustering tree:

[Butterworth, Davison, Rubin, Salam, 2008]

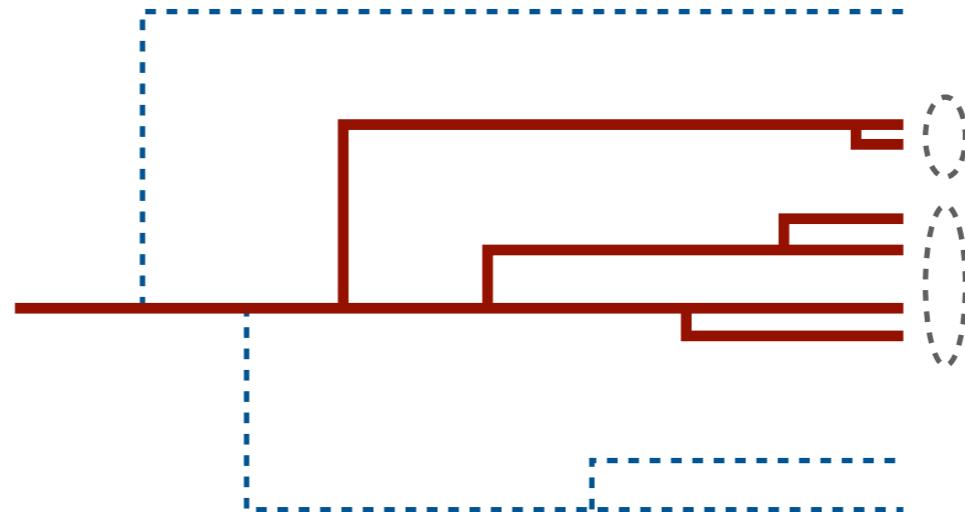


ATLAS: W/Z Boson Tagging

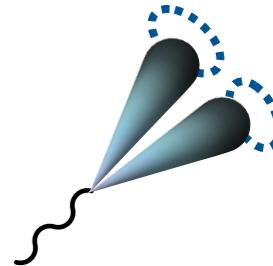


Groomed
angular-ordered
clustering tree:

[Butterworth, Davison, Rubin, Salam, 2008]

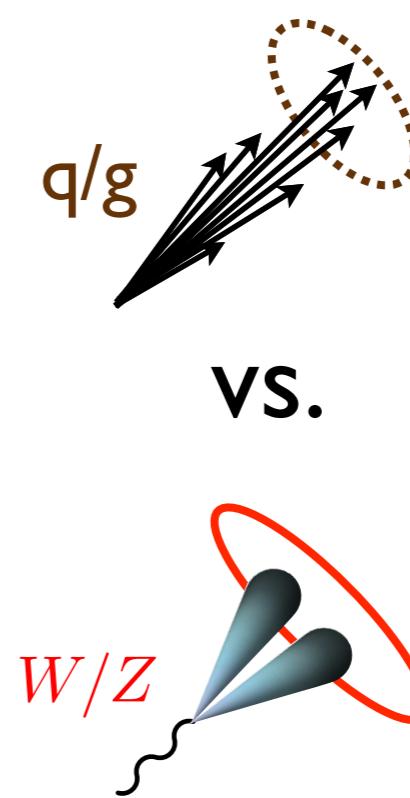
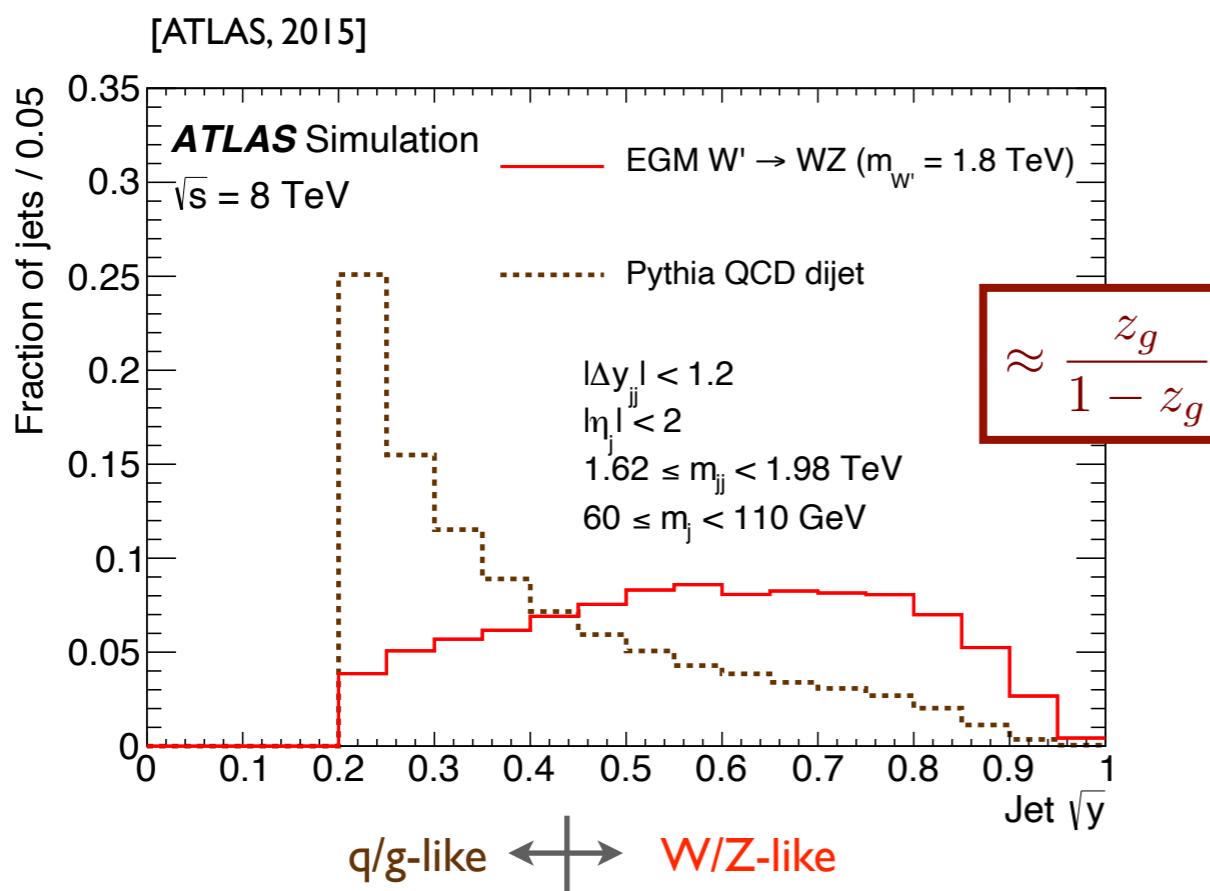
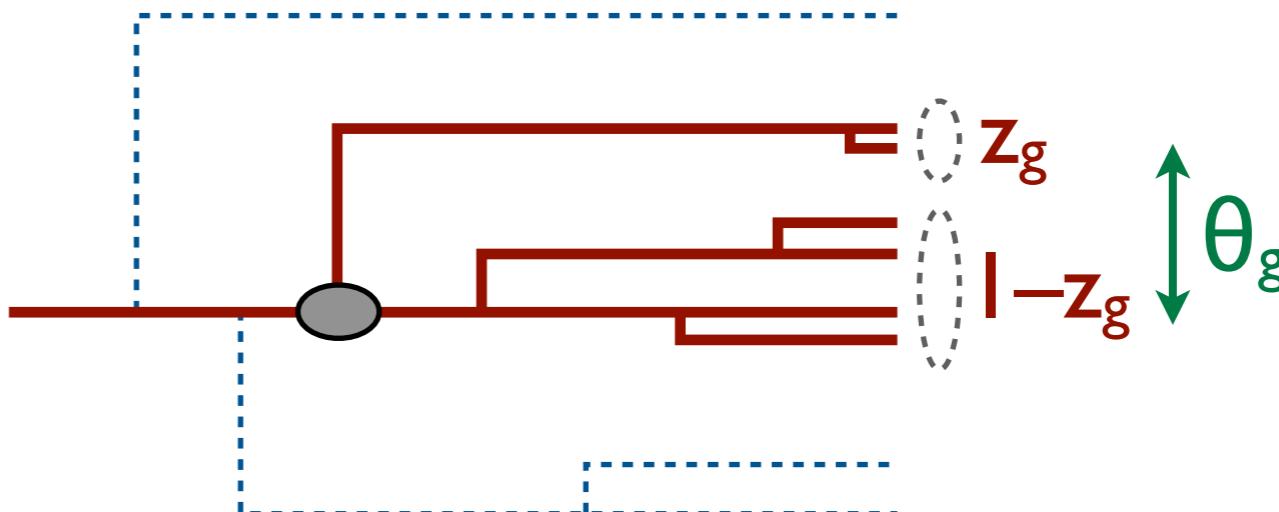


ATLAS: W/Z Boson Tagging

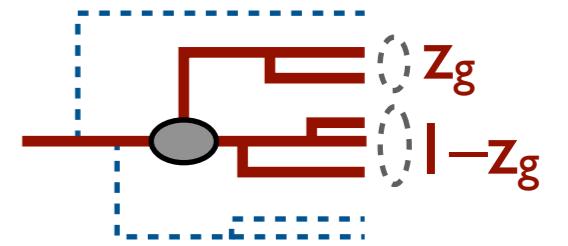


Groomed
angular-ordered
clustering tree:

[Butterworth, Davison, Rubin, Salam, 2008]



Calculating Momentum Balance?



Unsafe

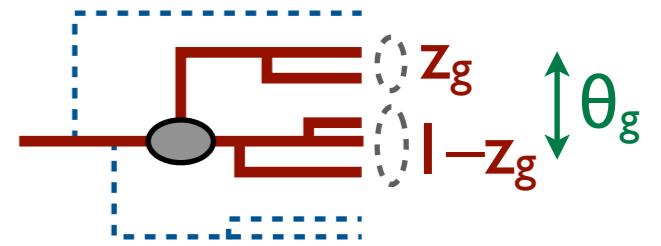


$$p(z_g)$$

$$\longrightarrow z_g ??$$

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

Calculating Momentum Balance?



Unsafe



$$p(z_g)$$

Calculable
order-by-order in α_s



$$p(z_g | \theta_g)$$

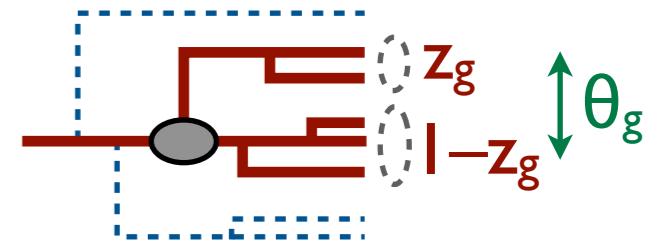
$\longrightarrow z_g ??$

vs.

$\longrightarrow z_g$ $\longrightarrow |z_g|$ $\longrightarrow \theta_g$

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

Calculating Momentum Balance?

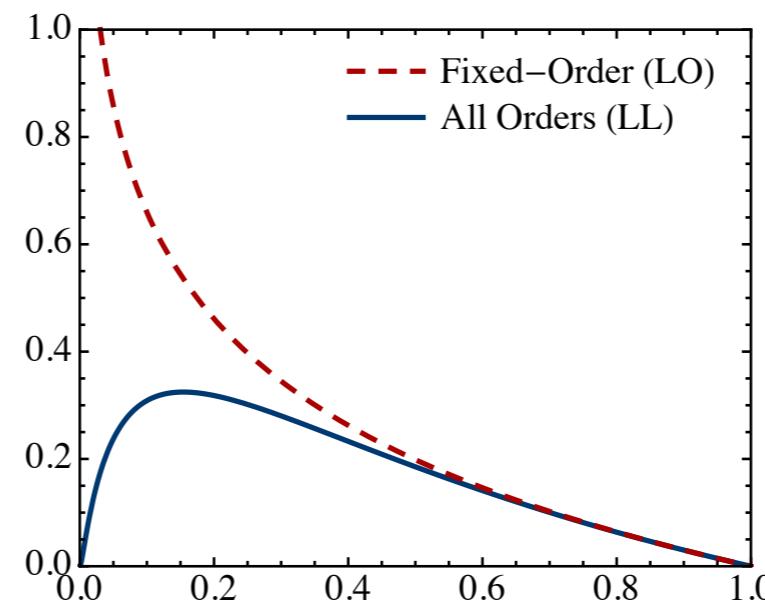


“Sudakov Safe”

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

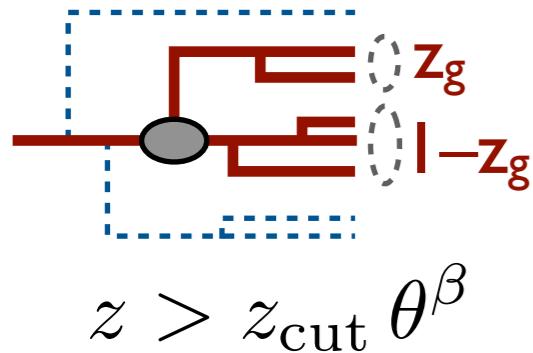
Calculable
order-by-order in α_s

Form factor
suppresses singularities
at all orders in α_s

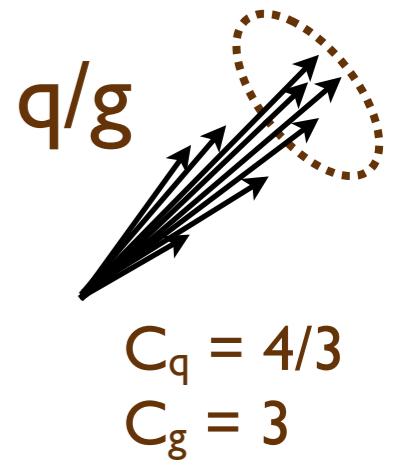
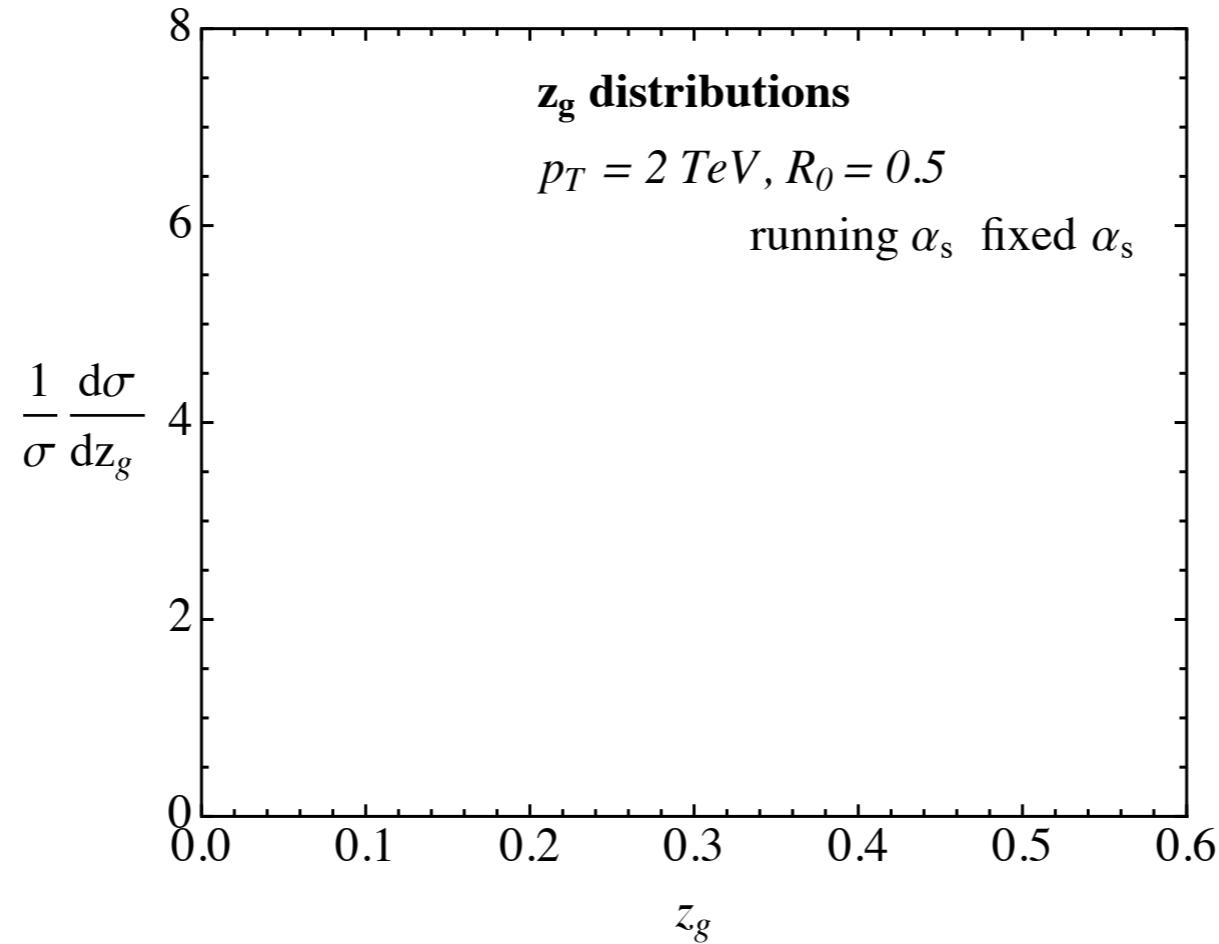


[Larkoski, JDT, 2013;
Larkoski, Marzani, JDT, 2015]

Soft Drop



First-Principles QCD



ATLAS 8 TeV
Diboson Search

More Grooming

$\beta \rightarrow -\infty$

$\beta < 0$

$\beta = 0$

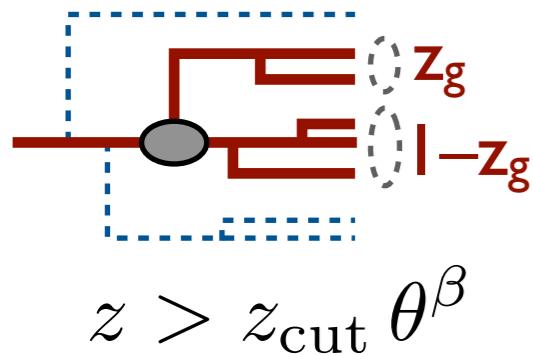
$\beta > 0$

Less Grooming

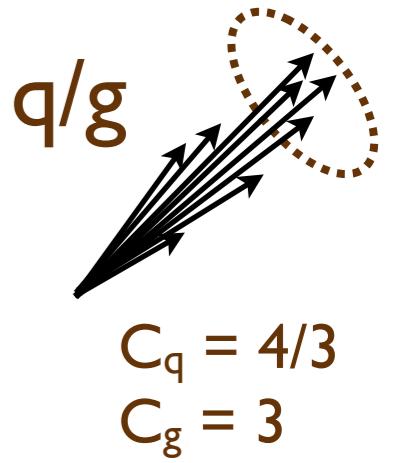
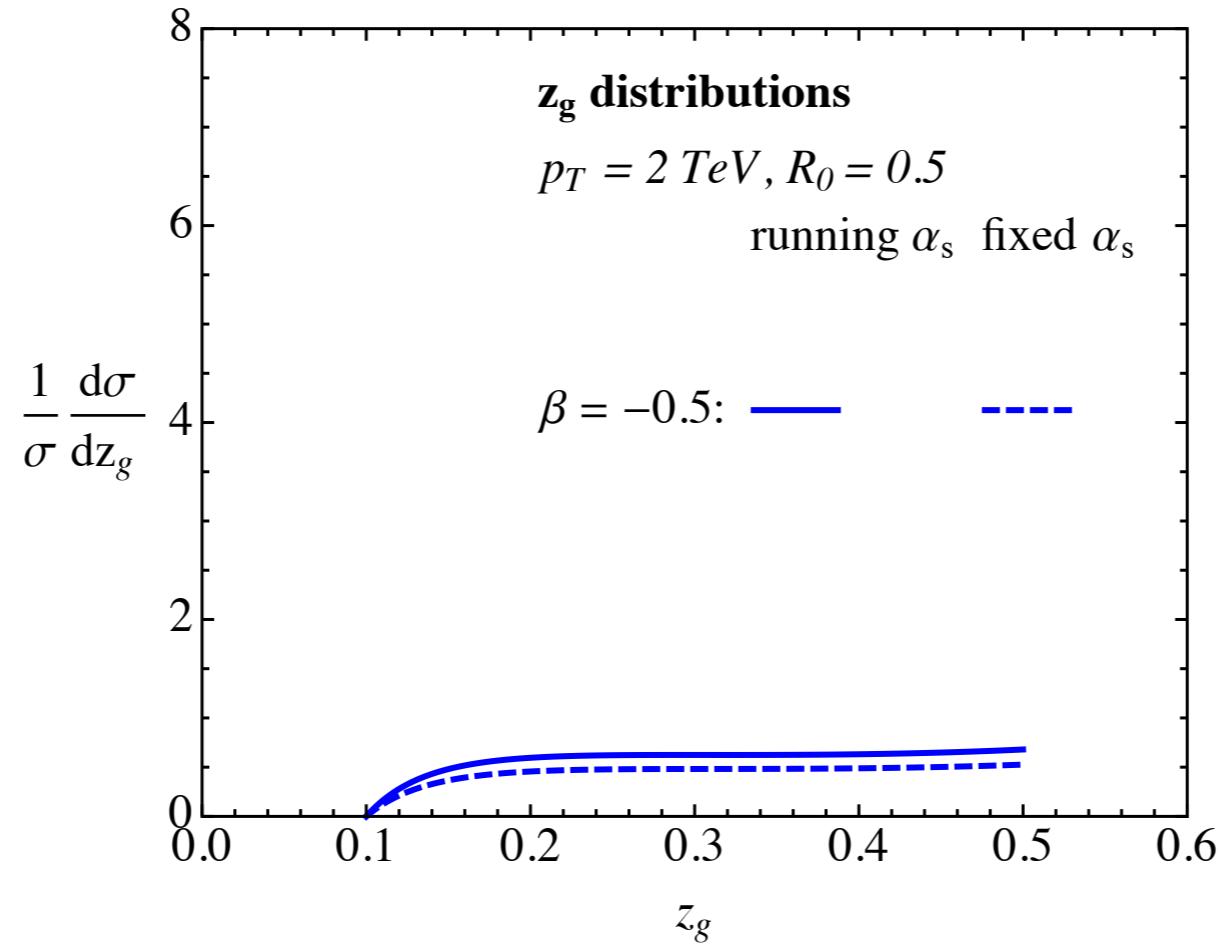
$\beta \rightarrow \infty$

[Larkoski, Marzani, JDT, 2015; using techniques in Dasgupta, Fregoso, Marzani, Salam, 2013; Larkoski, JDT, 2013; Larkoski, Marzani, Soyez, JDT, 2014]

Soft Drop



First-Principles QCD



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

More Grooming



$\beta \rightarrow -\infty$

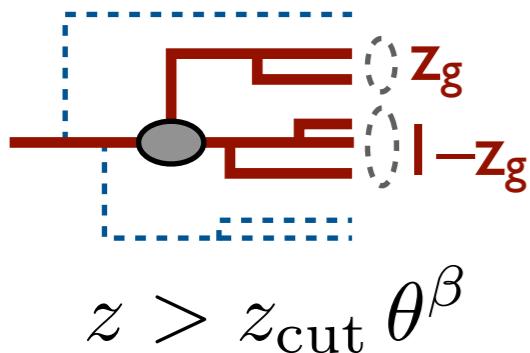
$\beta < 0$

$\beta = 0$

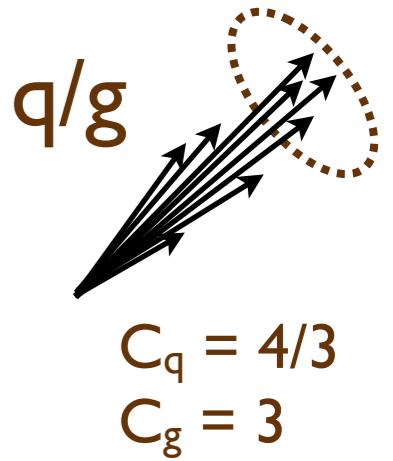
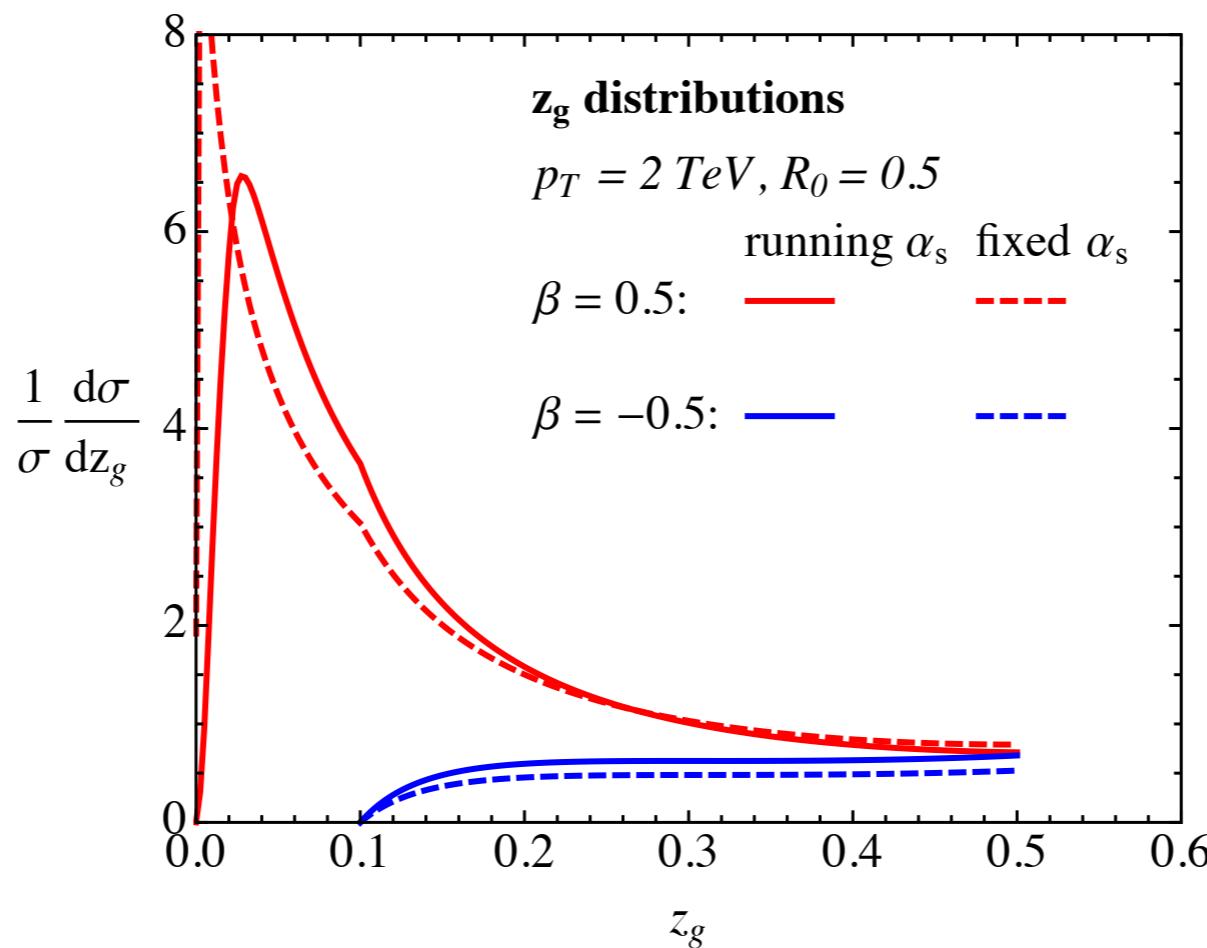
$\beta > 0$

Less Grooming

Soft Drop



First-Principles QCD



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

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

Beyond traditional perturbation theory
(Sudakov safe)

More Grooming

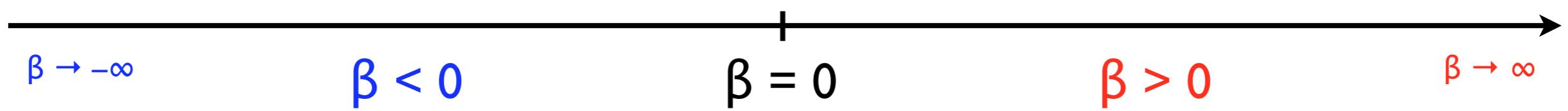
$\beta \rightarrow -\infty$

$\beta < 0$

$\beta = 0$

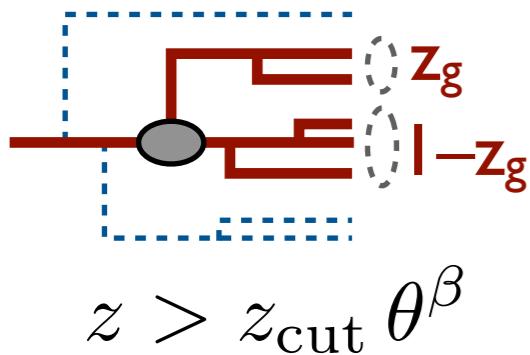
$\beta > 0$

$\beta \rightarrow \infty$

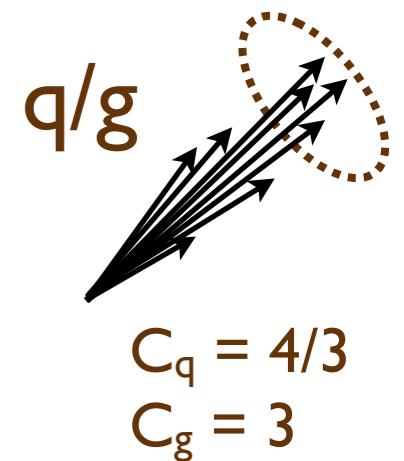
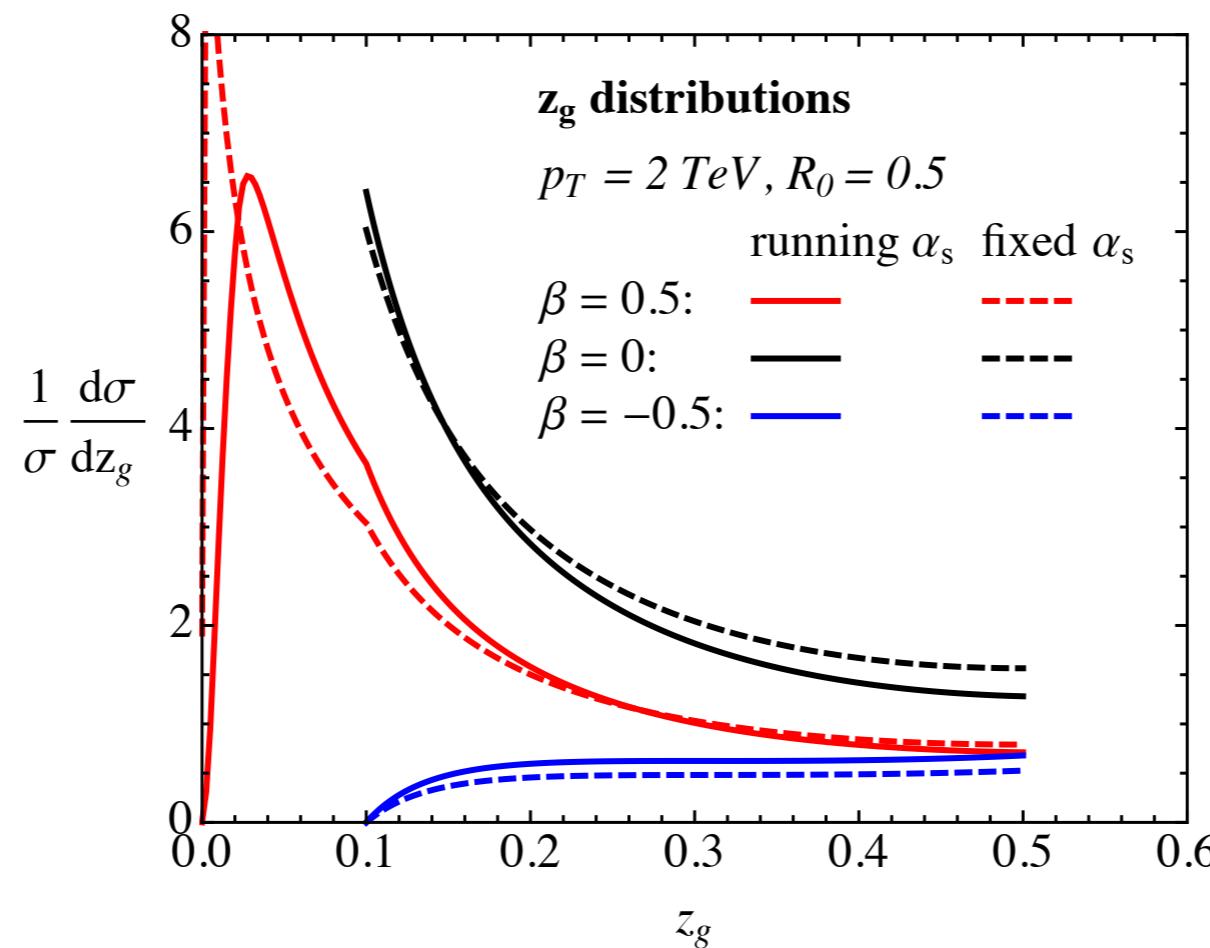


[Larkoski, Marzani, JDT, 2015; using techniques in Dasgupta, Fregoso, Marzani, Salam, 2013; Larkoski, JDT, 2013; Larkoski, Marzani, Soyez, JDT, 2014]

Soft Drop



First-Principles QCD



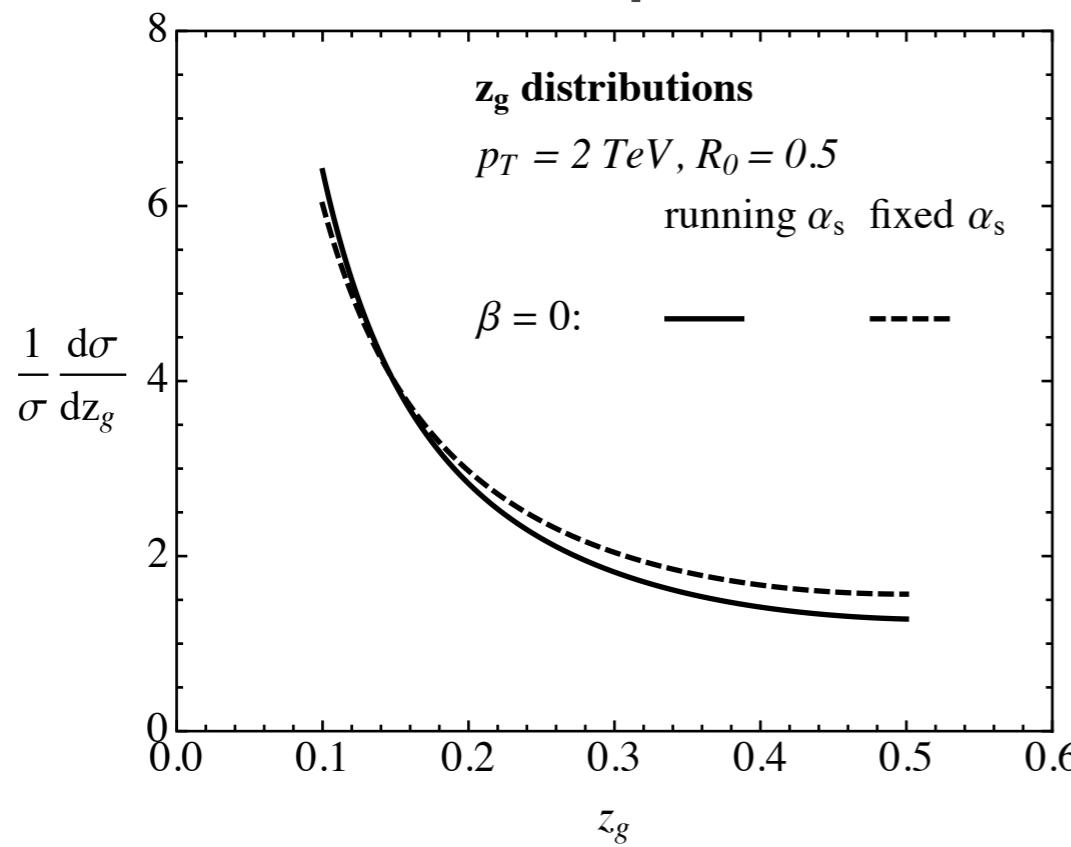
$\simeq \frac{2\alpha_s C_i}{\pi |\beta|} \frac{1}{z_g} \log \frac{z_g}{z_{\text{cut}}}$ $\simeq \frac{1}{z_g} (!)$ $\simeq \sqrt{\frac{\alpha_s C_i}{\beta}} \frac{1}{z_g}$ Beyond traditional perturbation theory (Sudakov safe)

More Grooming $\beta < 0$ $\beta = 0$ $\beta > 0$ Less Grooming

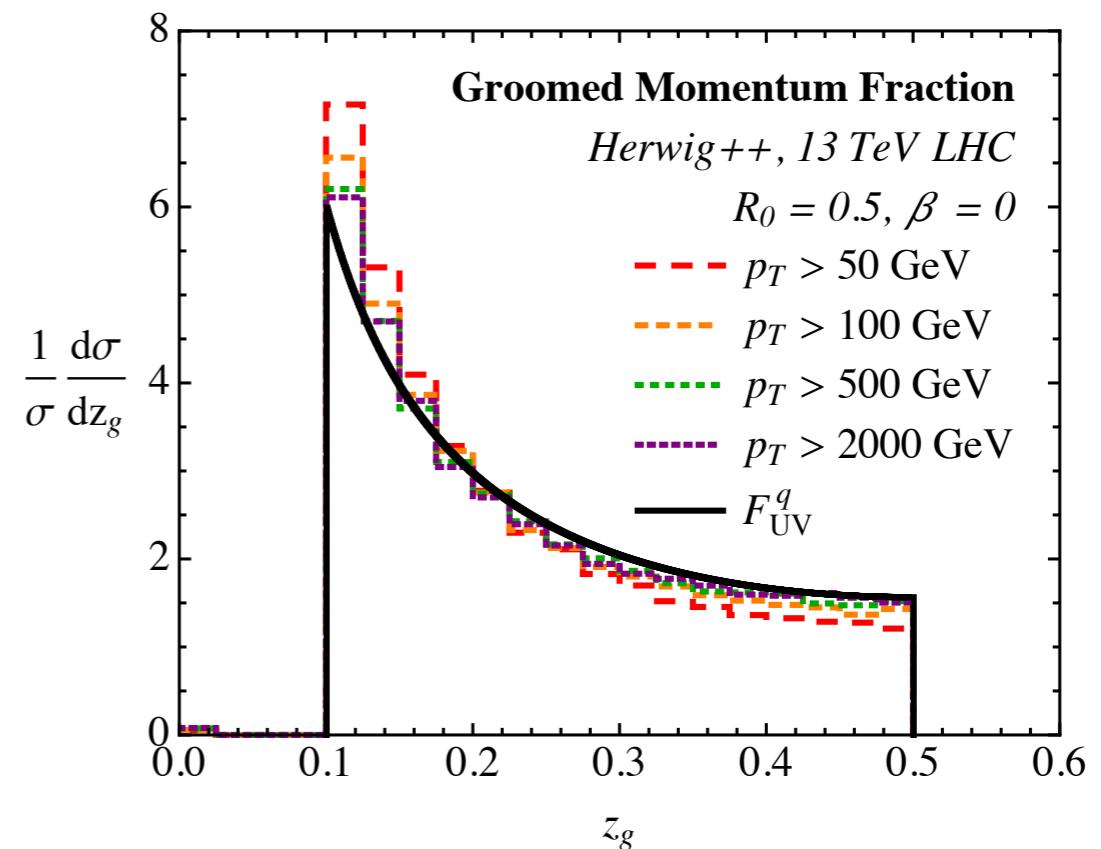
$\beta \rightarrow -\infty$ $\beta < 0$ $\beta = 0$ $\beta > 0$ $\beta \rightarrow \infty$

[Larkoski, Marzani, JDT, 2015; using techniques in Dasgupta, Fregoso, Marzani, Salam, 2013; Larkoski, JDT, 2013; Larkoski, Marzani, Soyez, JDT, 2014]

First-Principles QCD



Simulated LHC Data



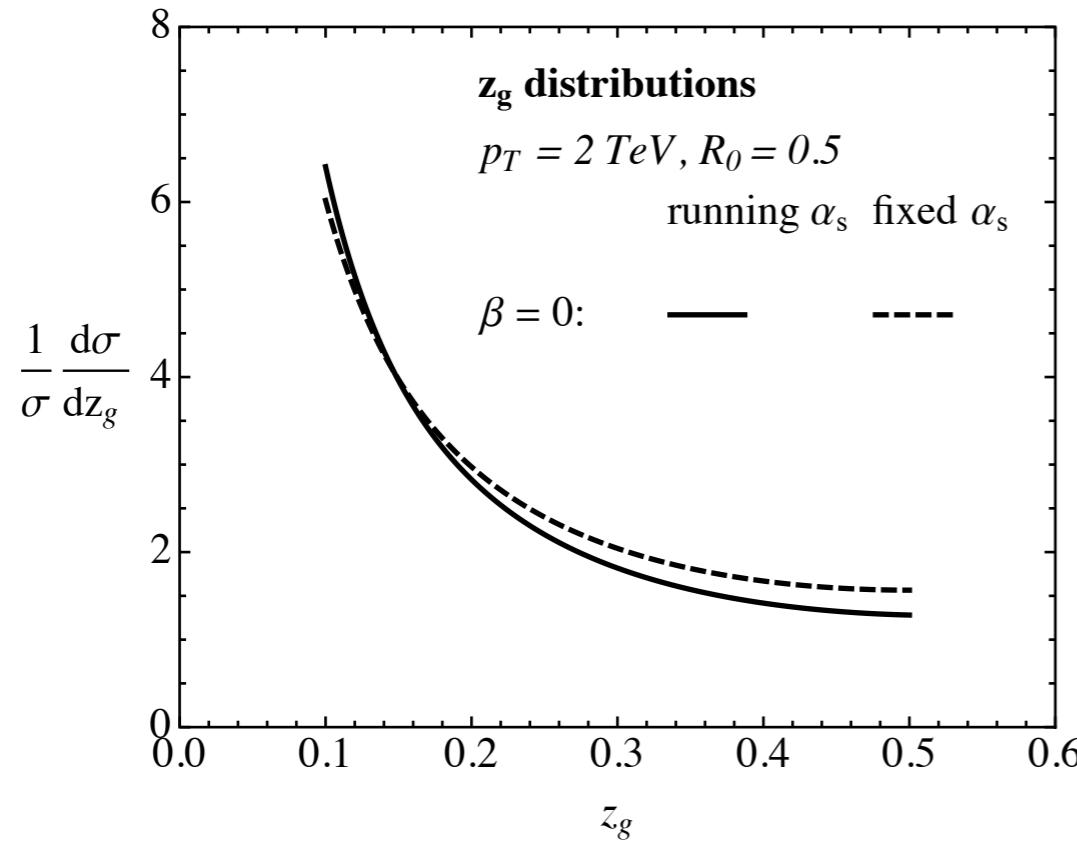
Core Feature of QCD:

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

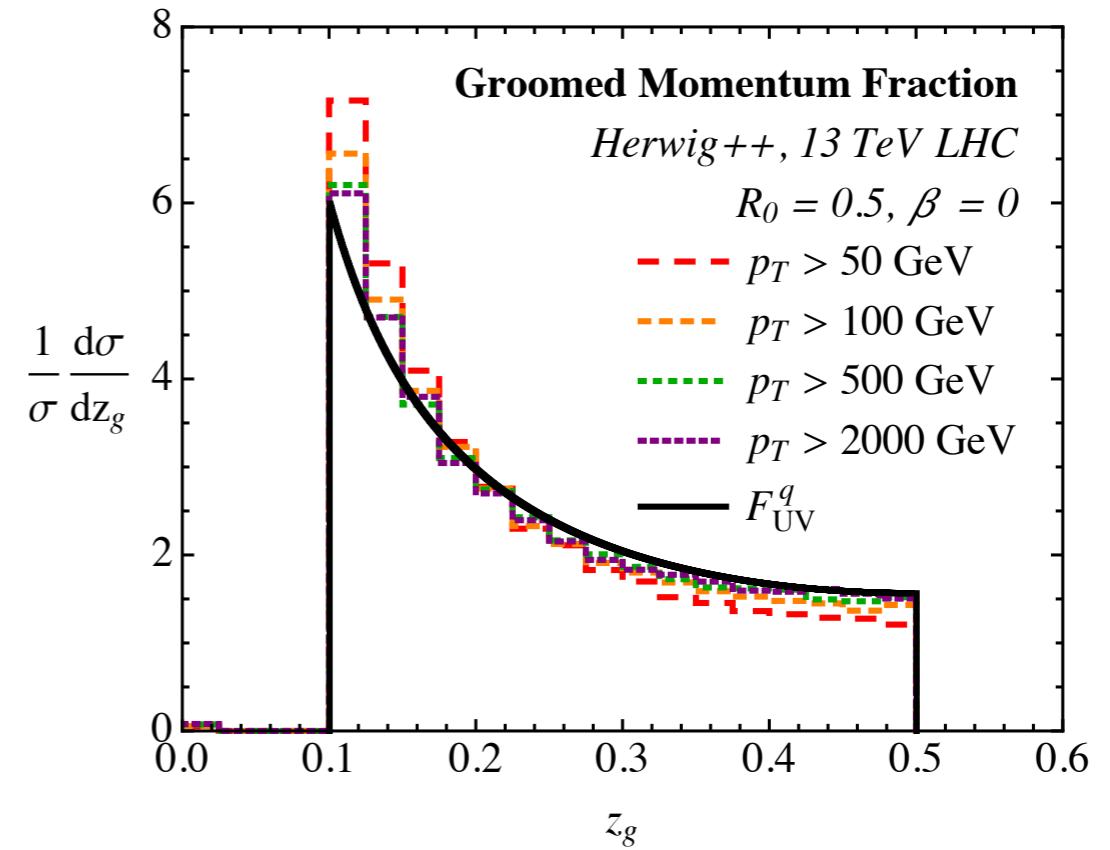
- ≈ independent of α_s (!)
- ≈ independent of jet energy/radius
- ≈ same for quarks/gluons

$$\text{cf. } \left| \begin{array}{c} z \\ \theta \\ -z \end{array} \right|^2$$

First-Principles QCD

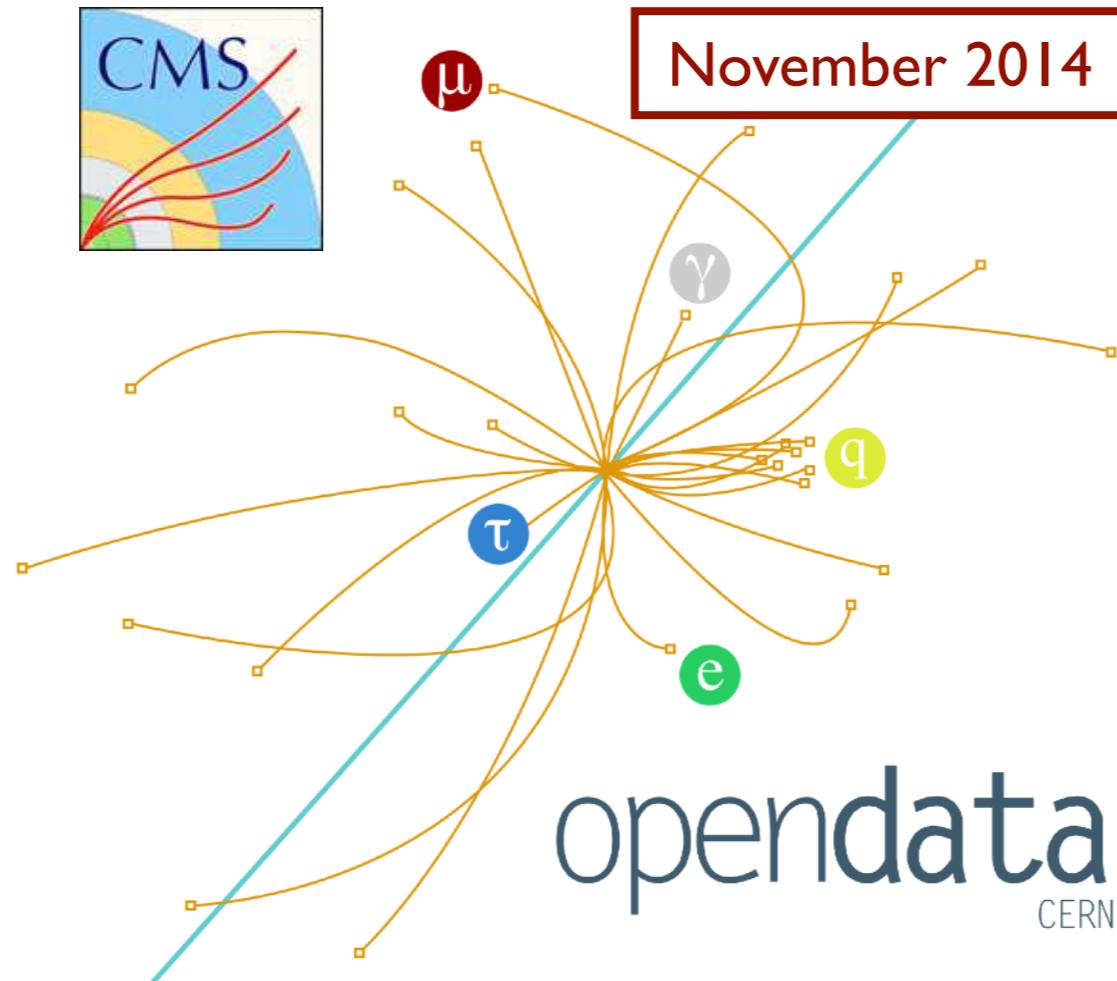


Simulated LHC Data



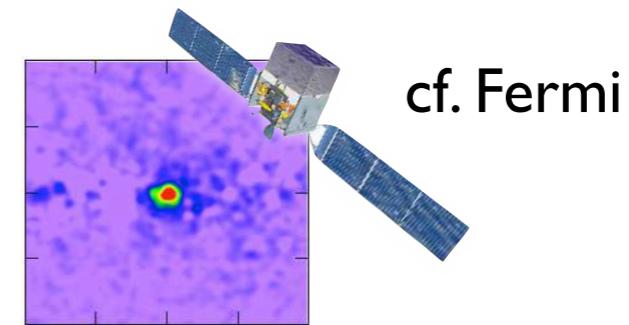
*Actual
LHC Data?*

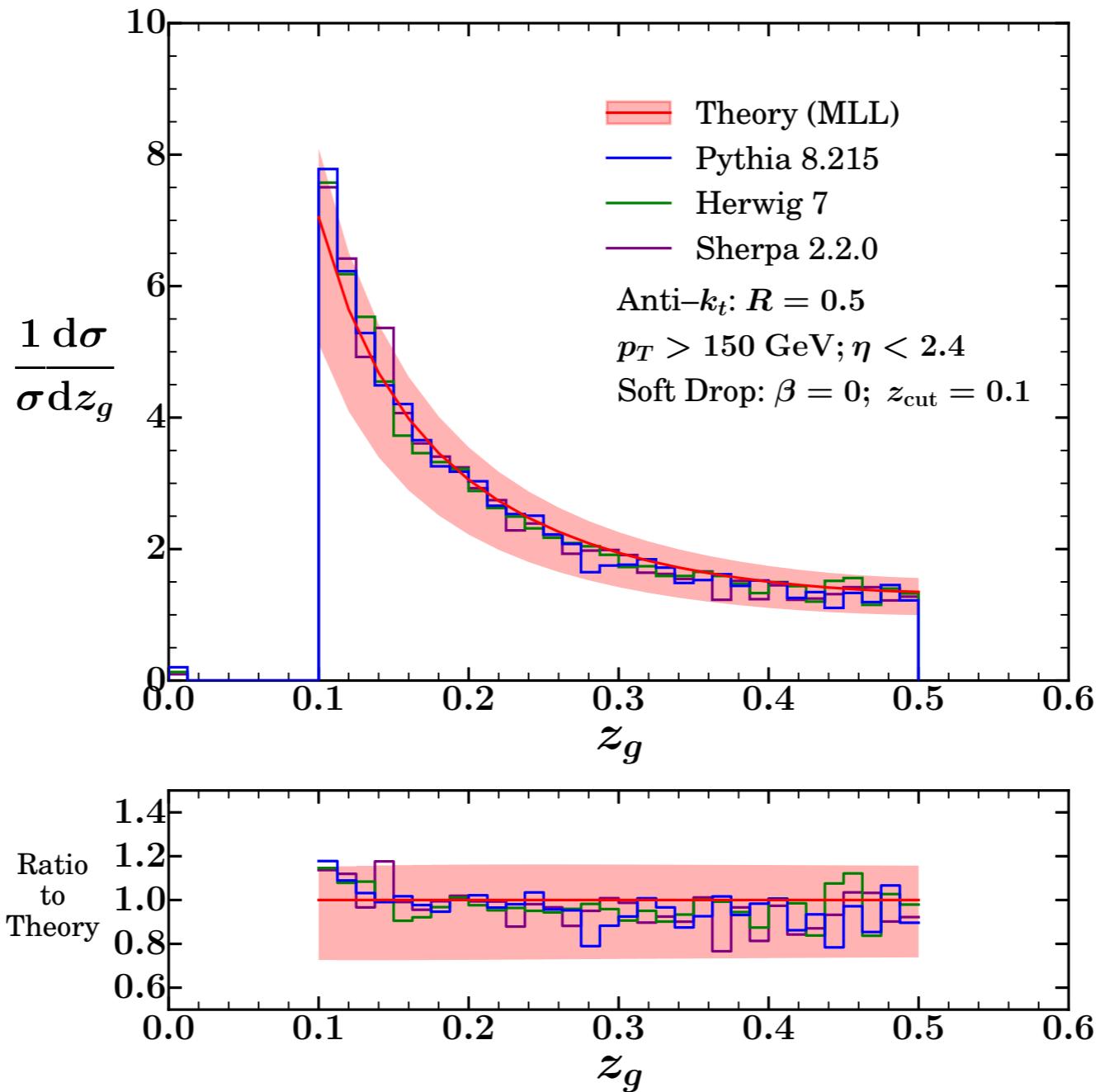
The Future is Open



*Accelerating science
through public data*

CMS 2010:
Unique data set
with very low pileup





Andrew Larkoski



Simone Marzani



Alexis Romero



Aashish Tripathee

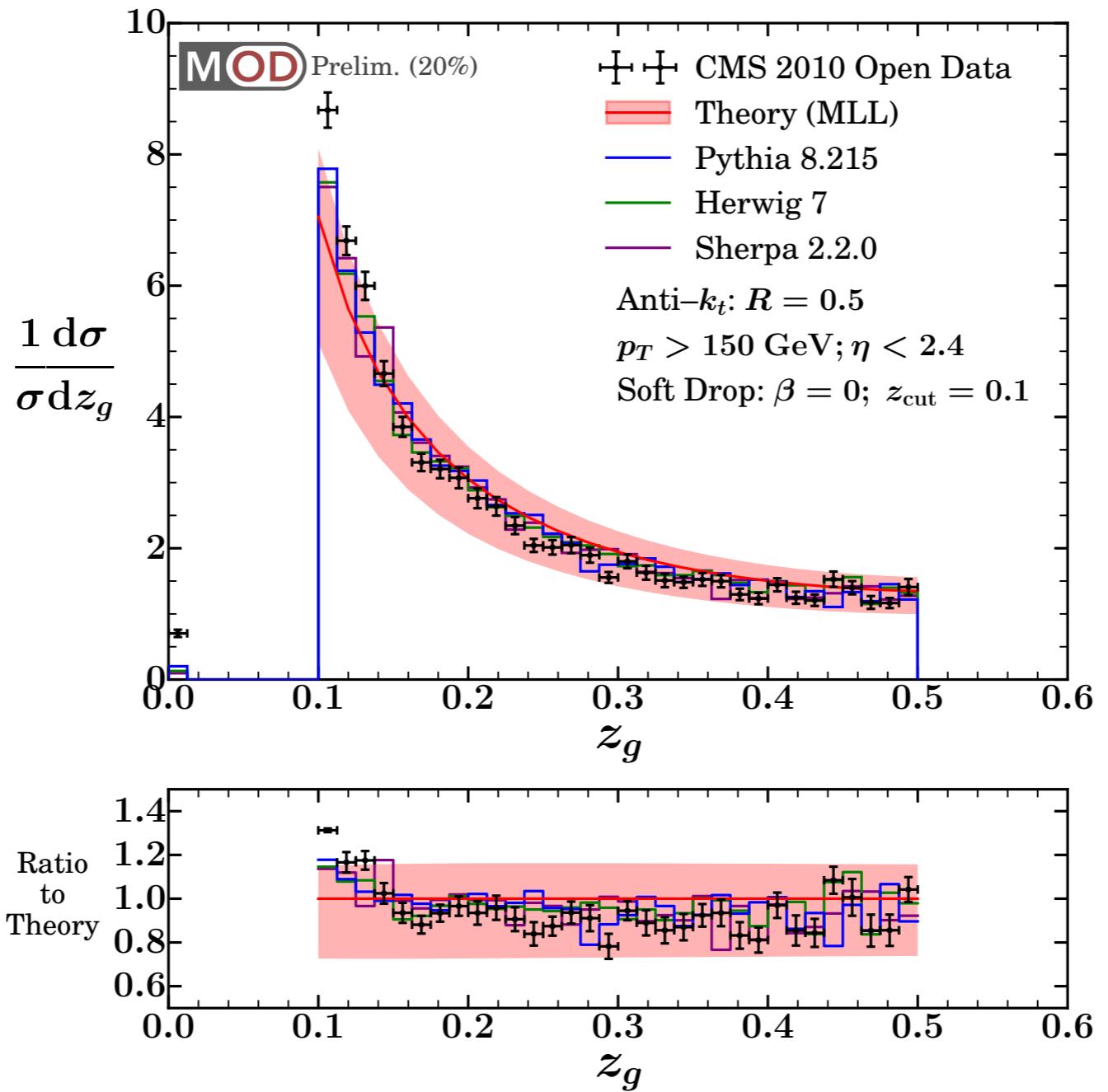


Wei Xue



CMS advice from
Sal Rappoccio





Andrew Larkoski



Simone Marzani



Alexis Romero



Aashish Tripathee



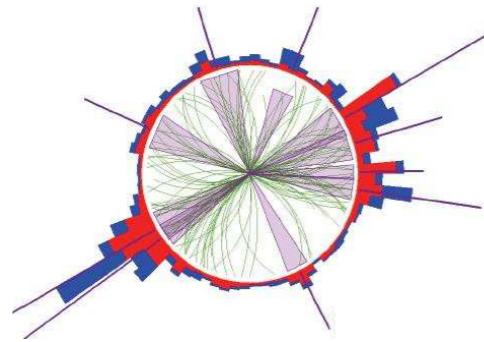
Wei Xue



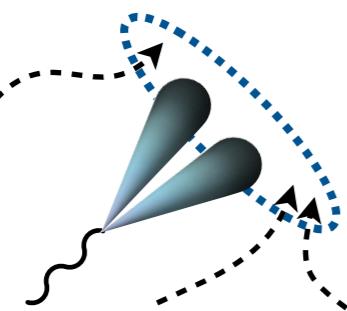
CMS advice from
Sal Rappoccio



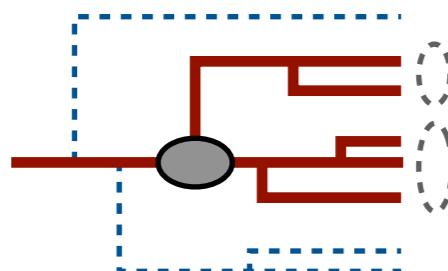
Boosting the Search for New Physics



From jets to jet substructure
Exceptional LHC performance + (B)SM physics



Maximize discovery potential of LHC
Creative analysis strategies to handle high energy/luminosity



Probe emergent phenomena in QCD
Studying jets to push boundaries of quantum field theory



University of
Zurich

ETH Zurich

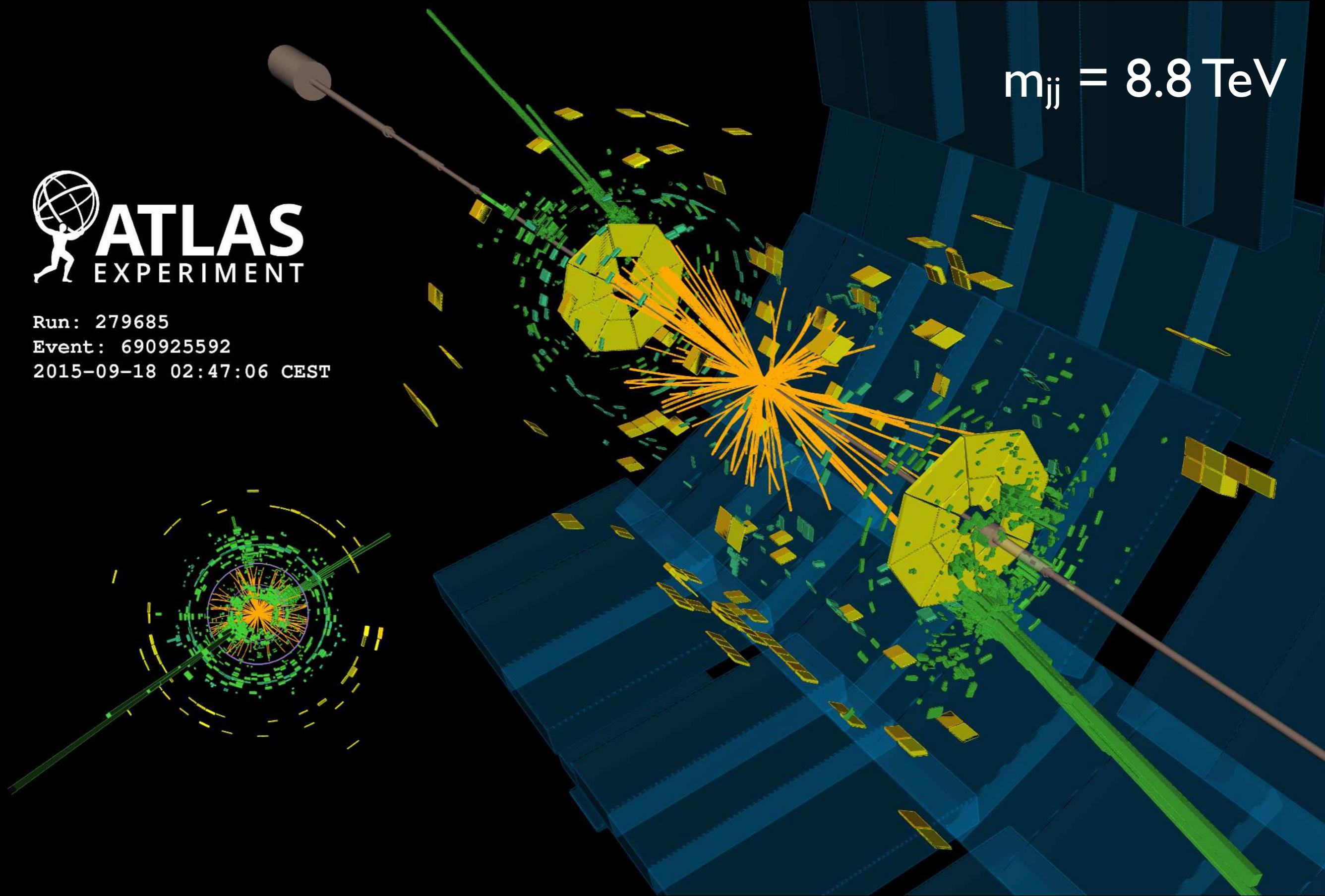
ZURICH
www.boost2016.ch

July 18–22, 2016



Run: 279685
Event: 690925592
2015-09-18 02:47:06 CEST

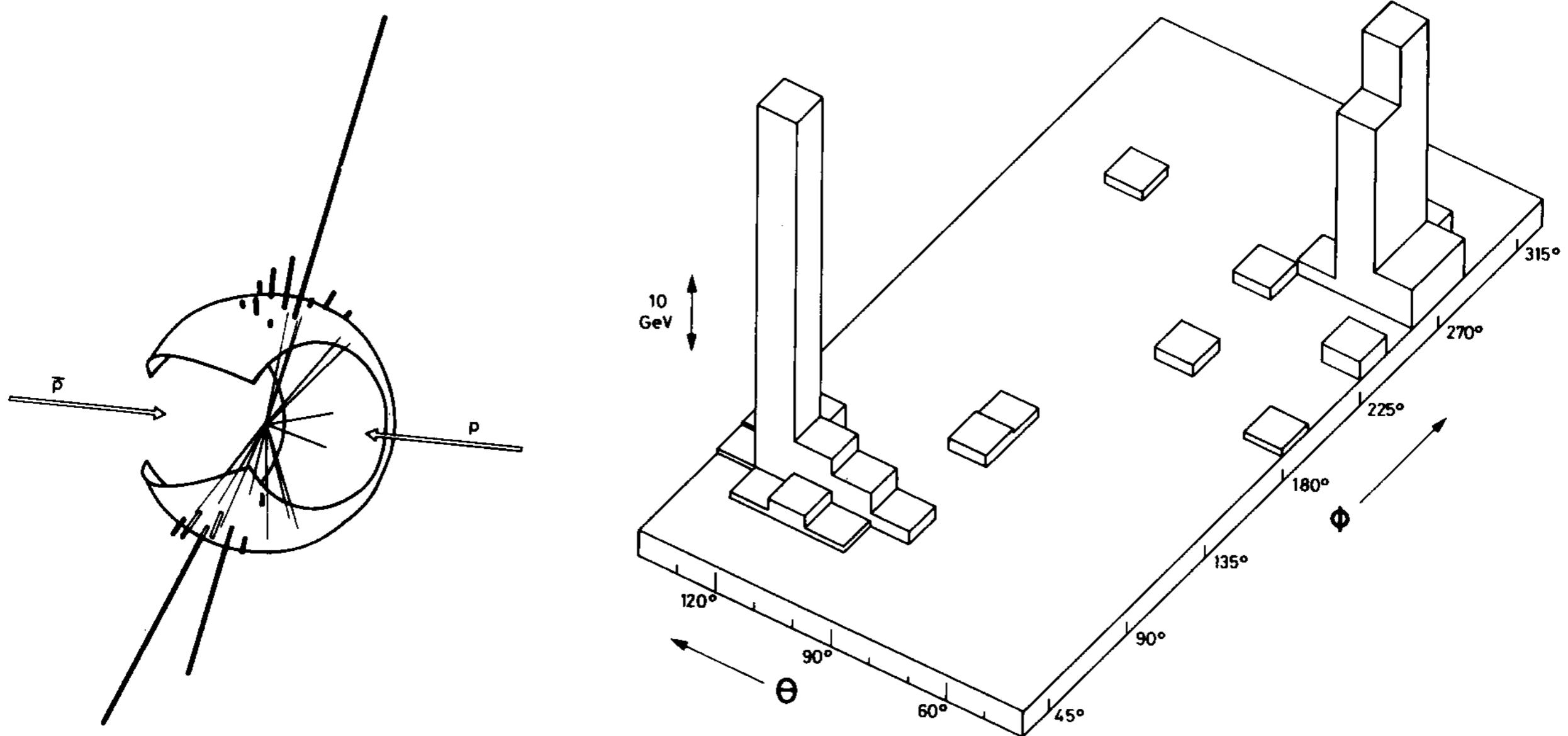
$m_{jj} = 8.8 \text{ TeV}$



Backup Slides

Four Decades of Jets

UA2, 1982



[see also SPEAR, 1975; PETRA, 1979]

Pushing Collision Frontiers

1987 → 2009

Tevatron



LHC



Energy?

1.9 TeV

7–8 TeV 13–14 TeV

Luminosity?

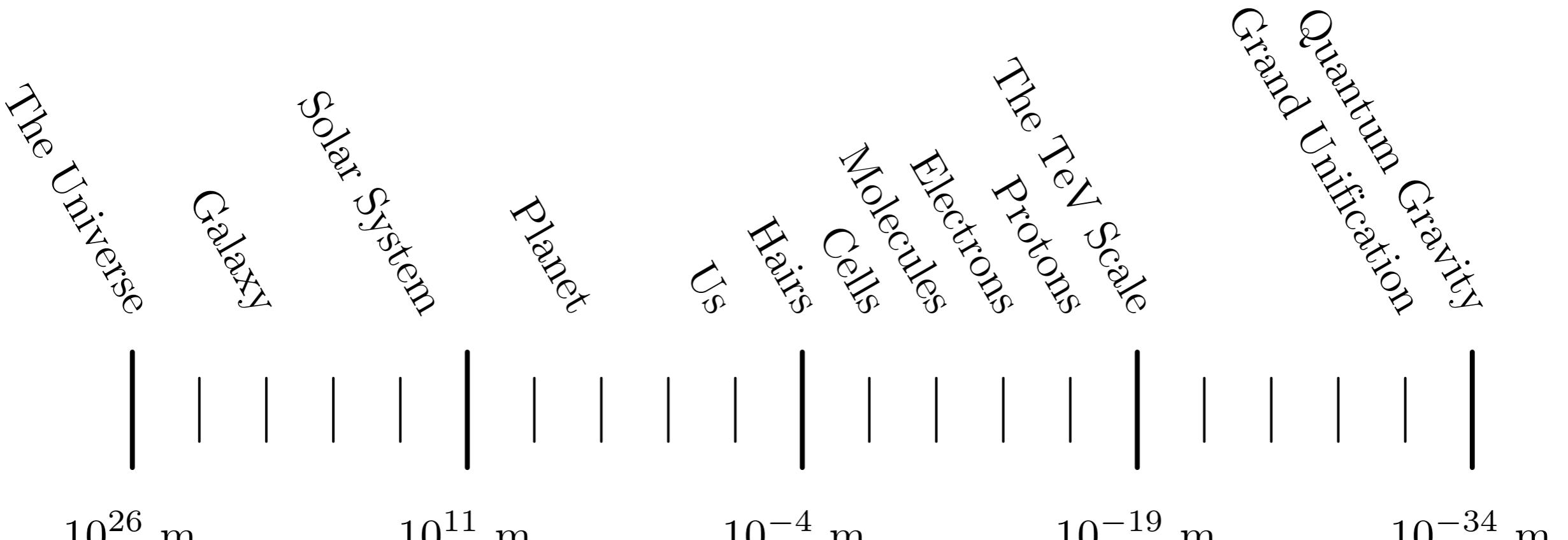
12 fb^{-1} total

30 fb^{-1} 40 fb^{-1}/yr

Resolution?

$\approx 0.1 \times 0.1$

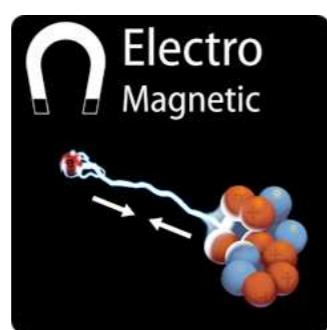
$\approx 0.02 \times 0.02$



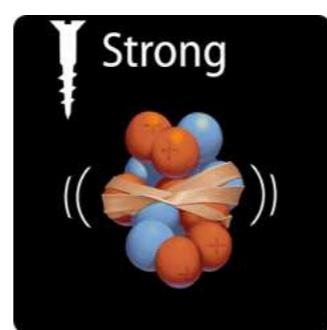
The Standard Model



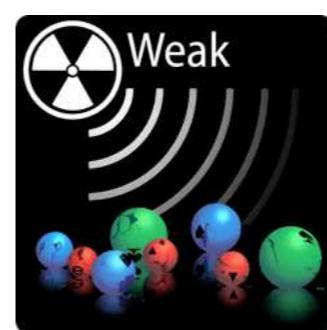
Graviton



Photon



Gluon



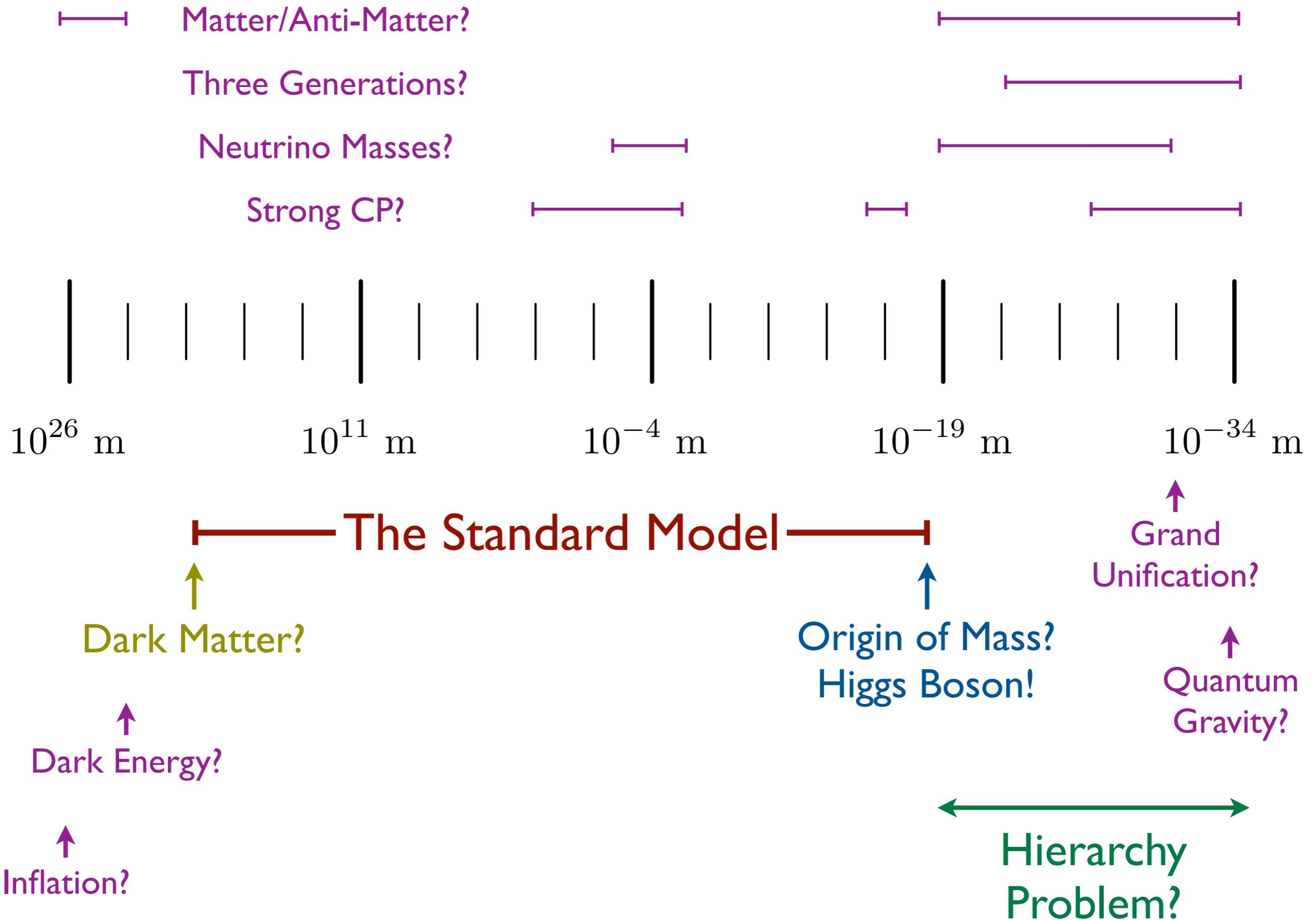
W/Z Bosons

+

u d
s c
t b

e ν_e
 μ ν_μ
 τ ν_τ

Quarks Leptons

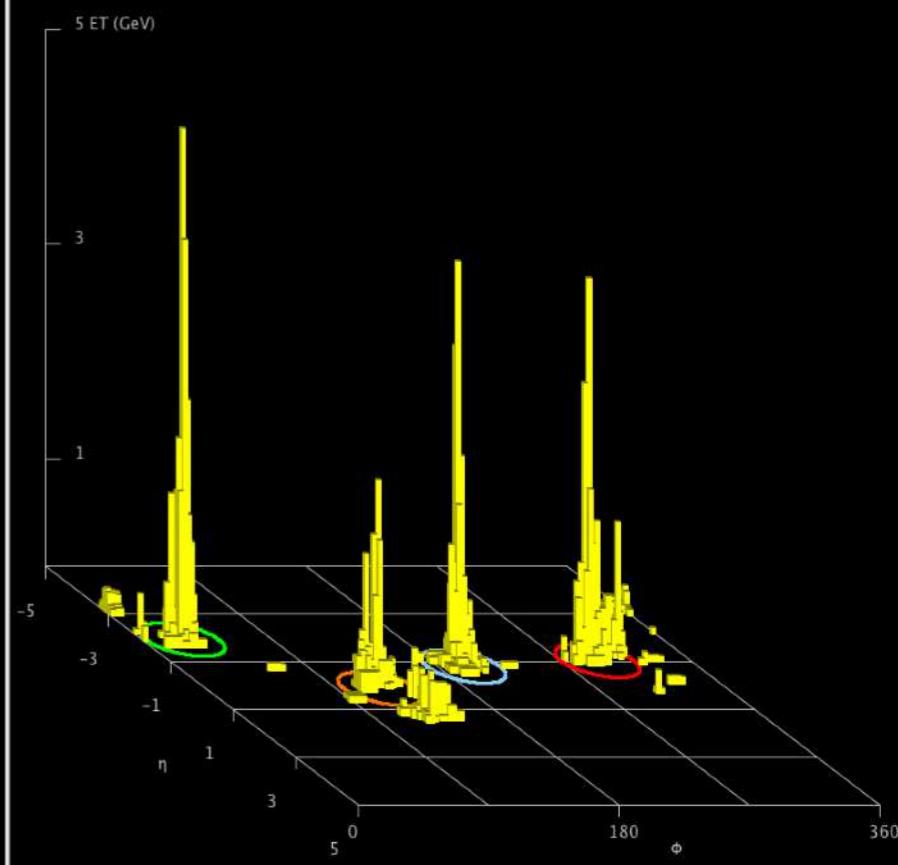
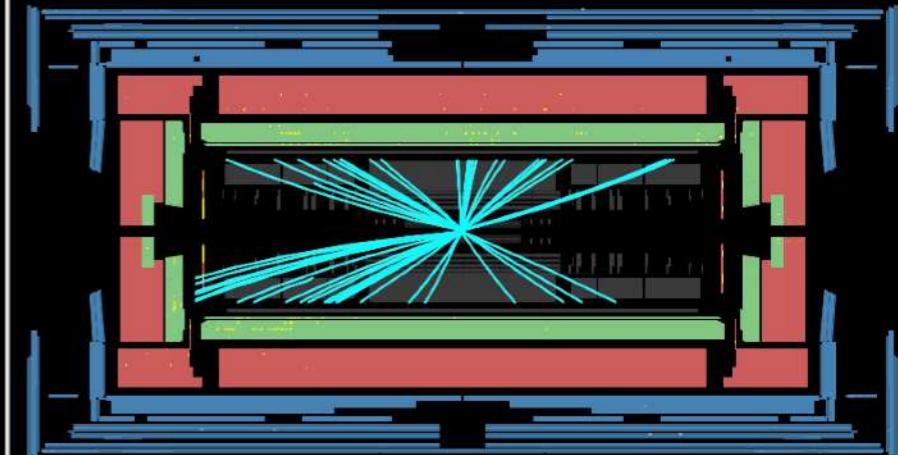
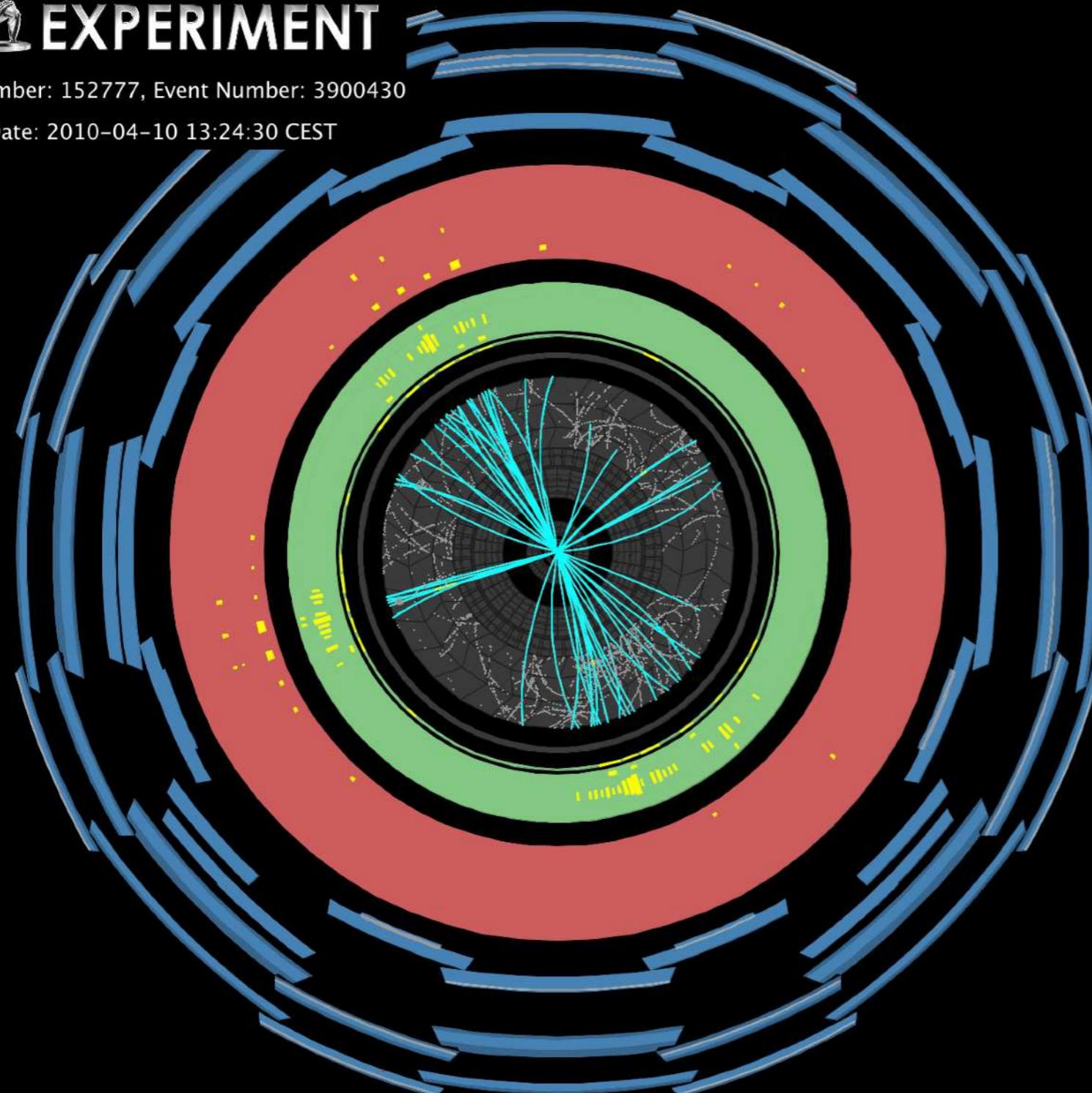




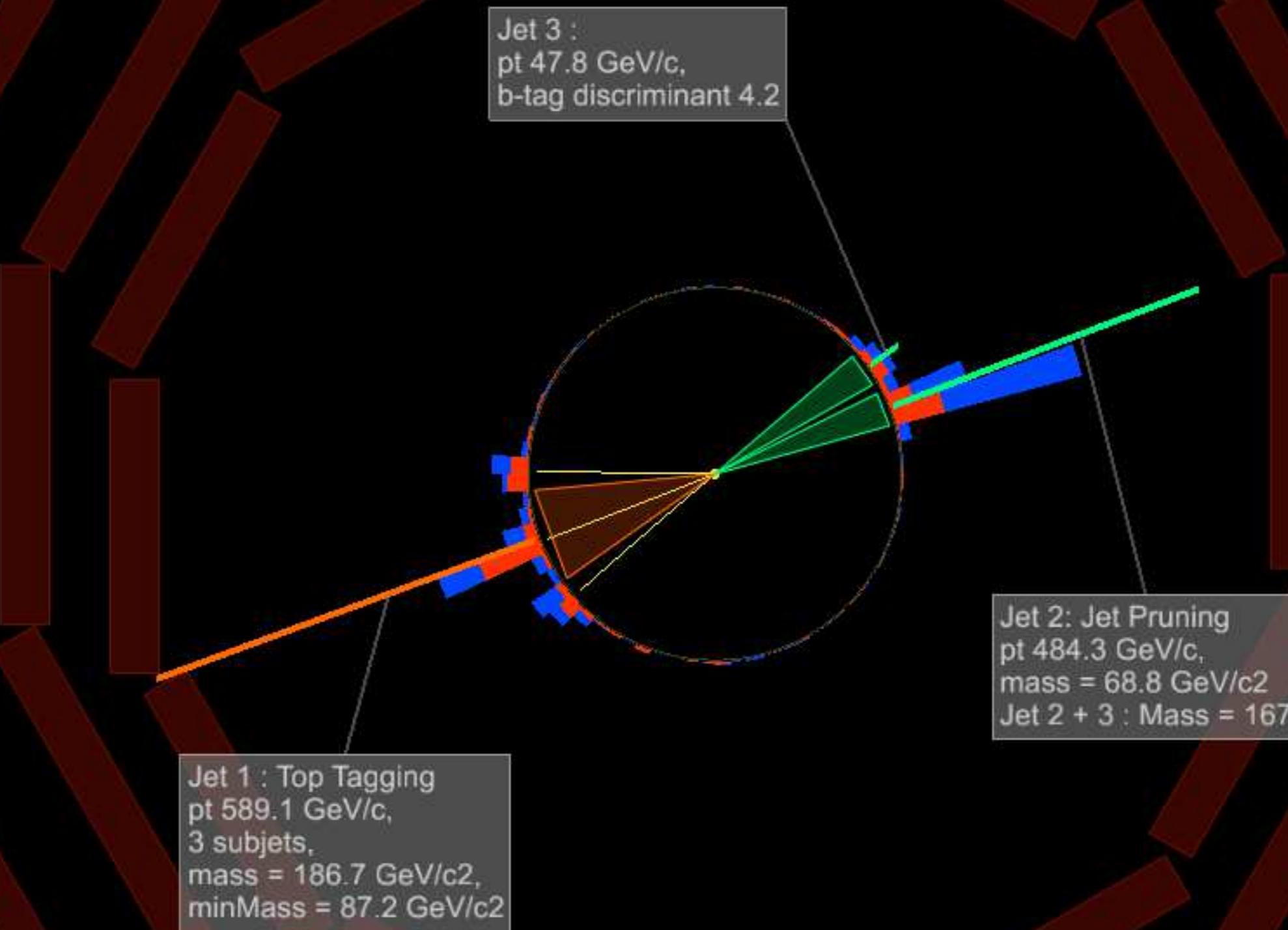
ATLAS EXPERIMENT

Run Number: 152777, Event Number: 3900430

Date: 2010-04-10 13:24:30 CEST



Jets or Jet Substructure?



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

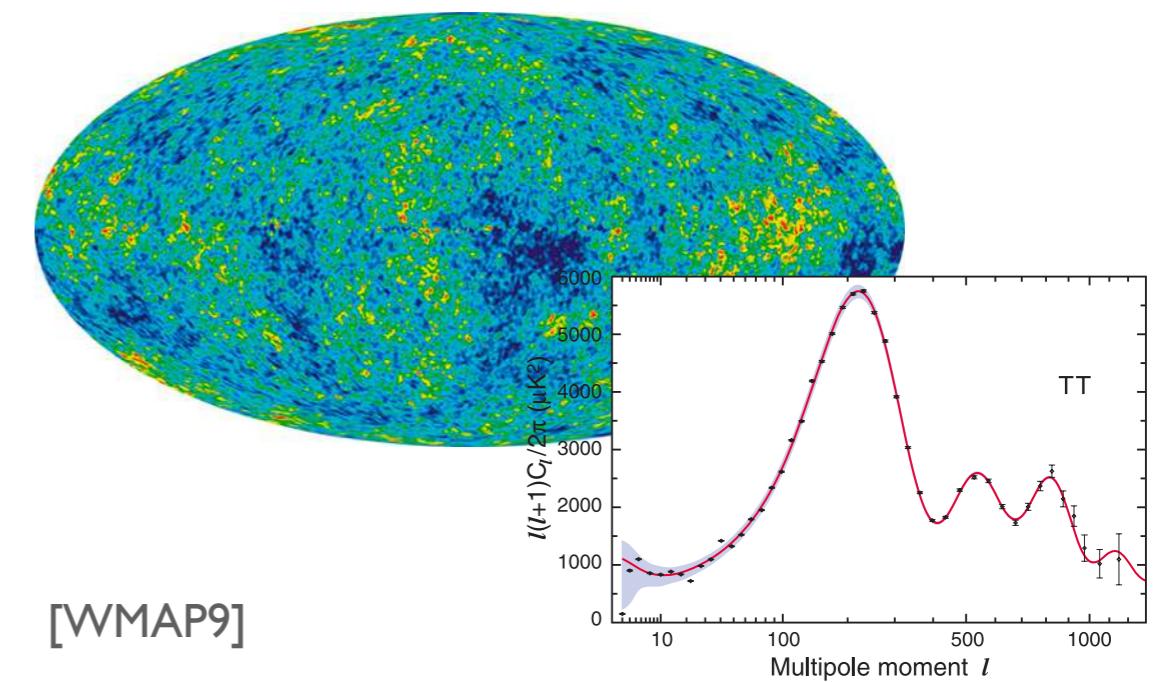
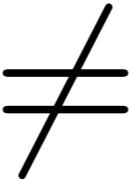
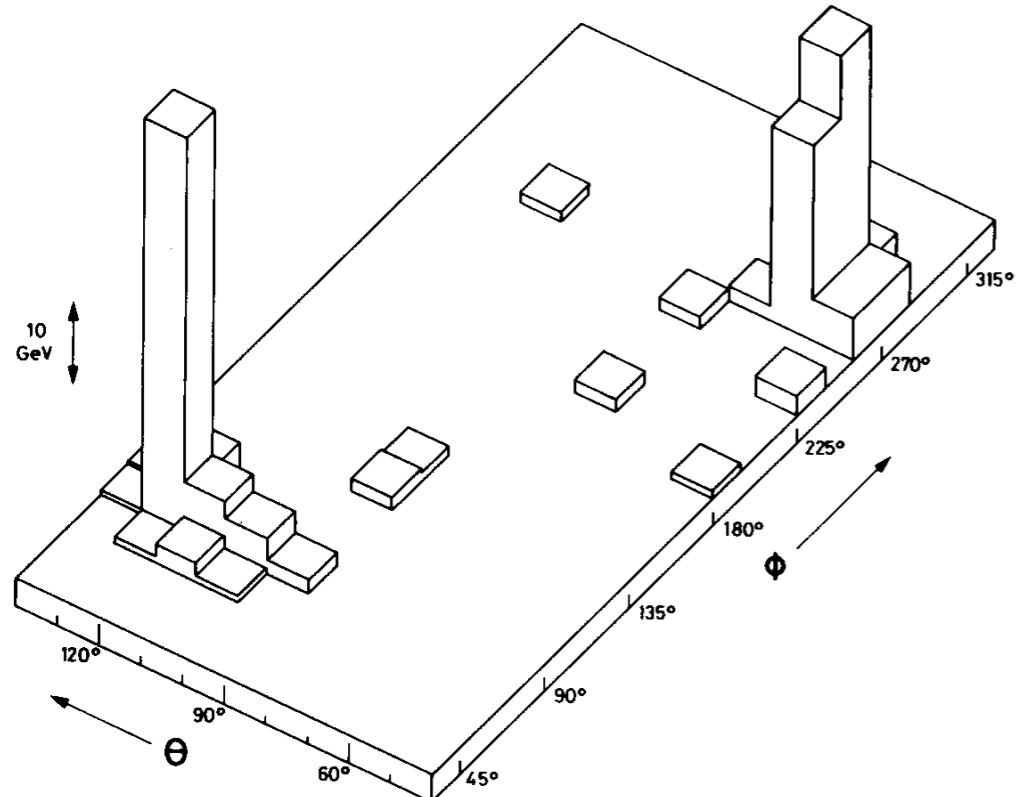
JOSHUA BATSON SCIENCE 01.23.15 6:45 AM

HOW THREE GUYS WITH \$10K AND DECADES-OLD DATA ALMOST FOUND THE HIGGS BOSON FIRST



“Figuring out what happened in a collider is like trying to figure out what your dog ate at the park yesterday. You can find out, but you have to sort through a lot of shit to do it.”

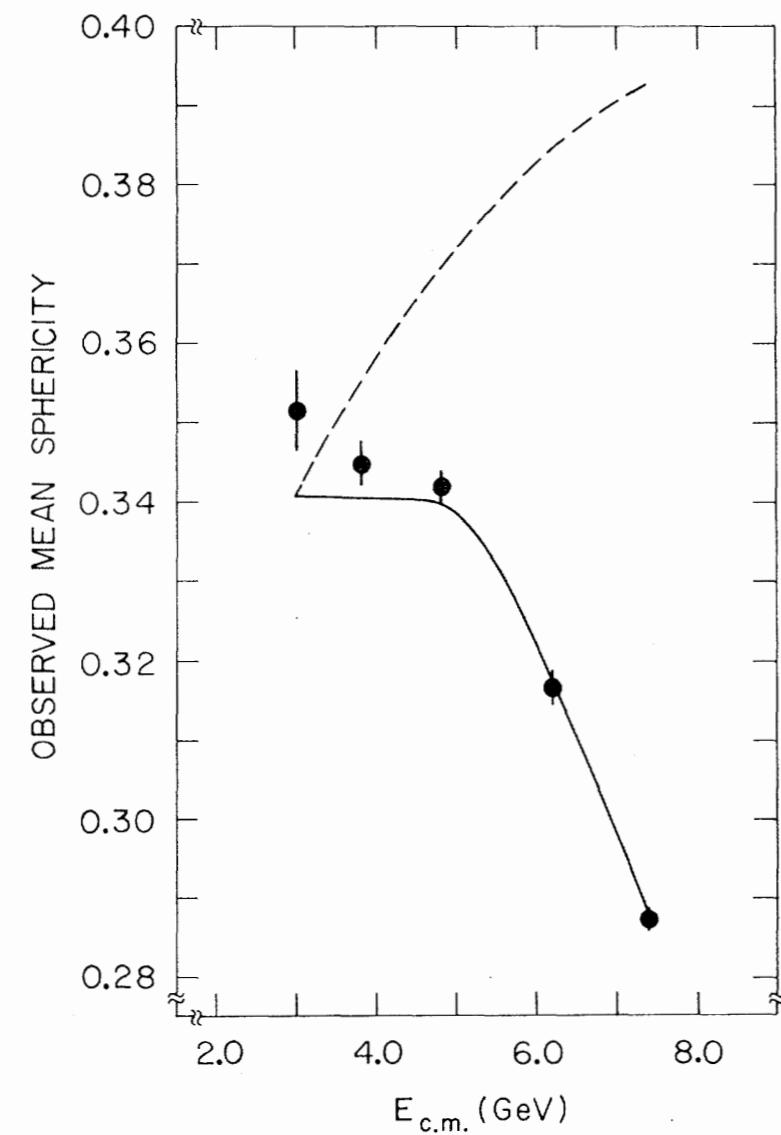
Identification of Jets



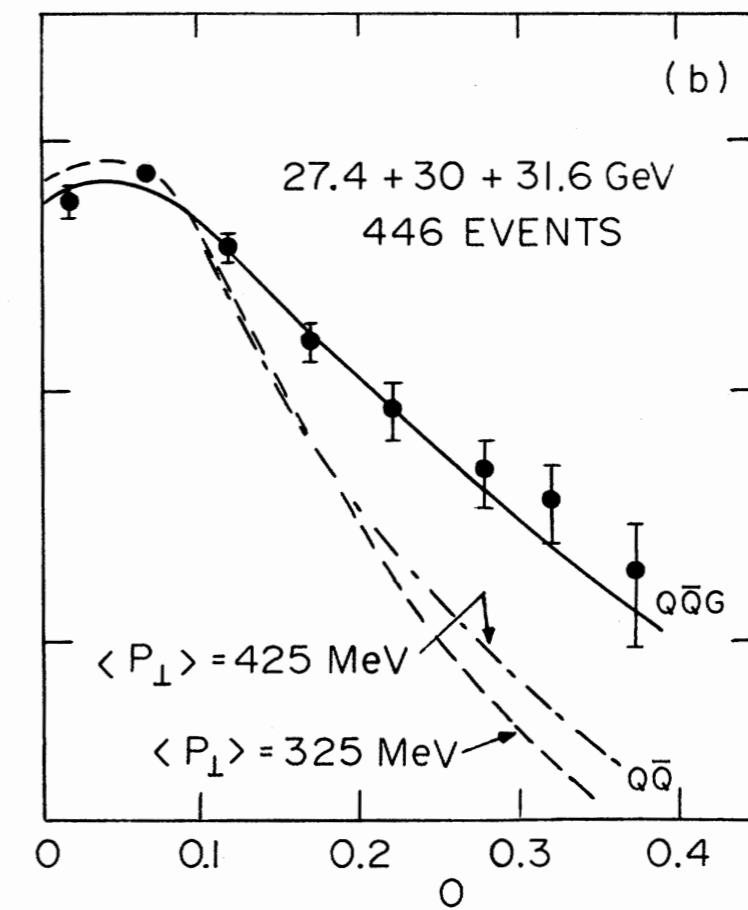
[WMAP9]

First Light on Jets

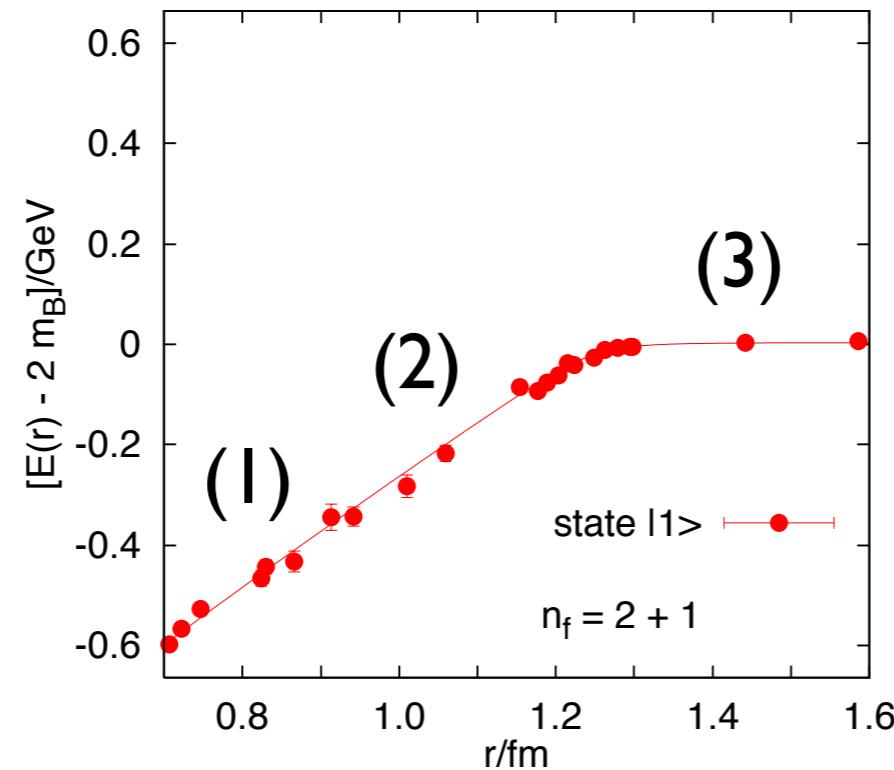
Jets @ SPEAR, 1975



Gluons @ PETRA, 1979



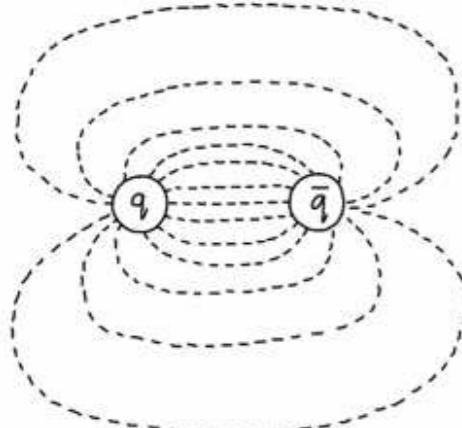
Confinement/Liberation



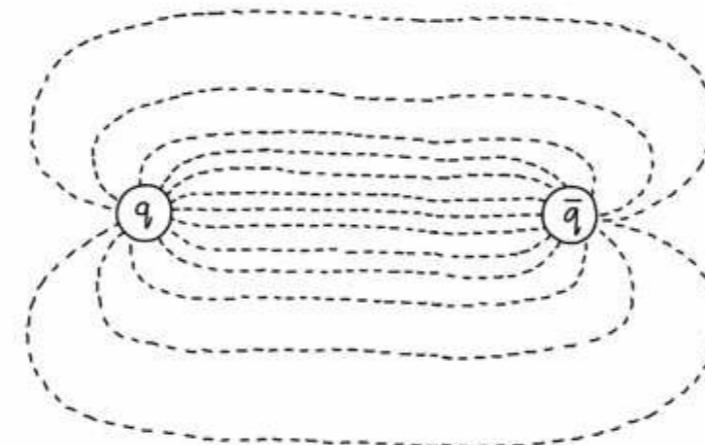
Potential between
two heavy quarks
(from lattice calculation)

[SESAM, 2005]

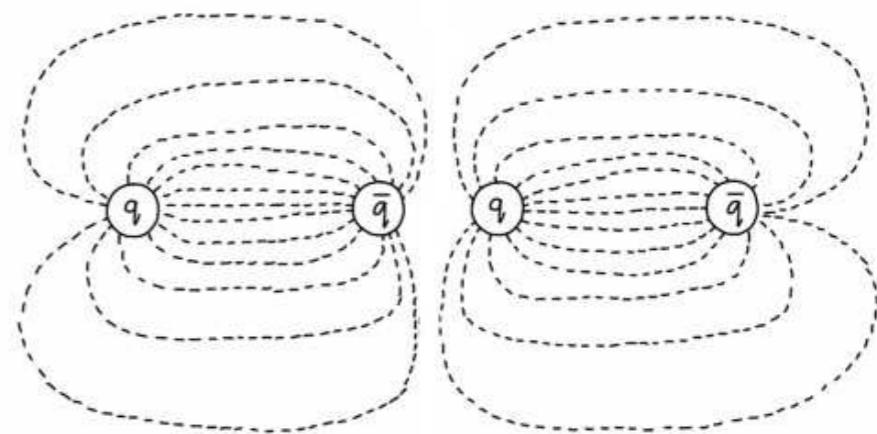
(1)



(2) = linear confinement

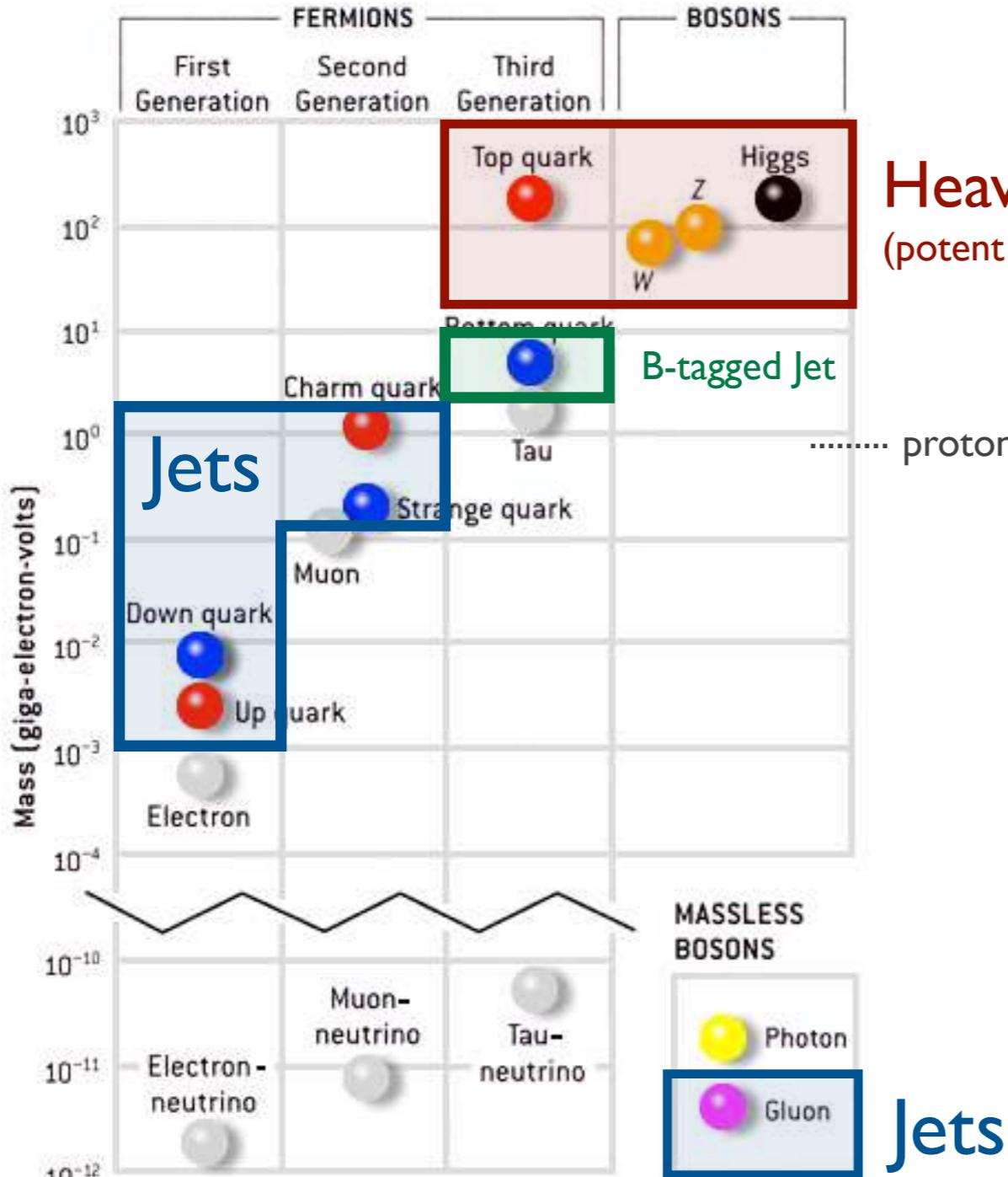


(3) = string breaking

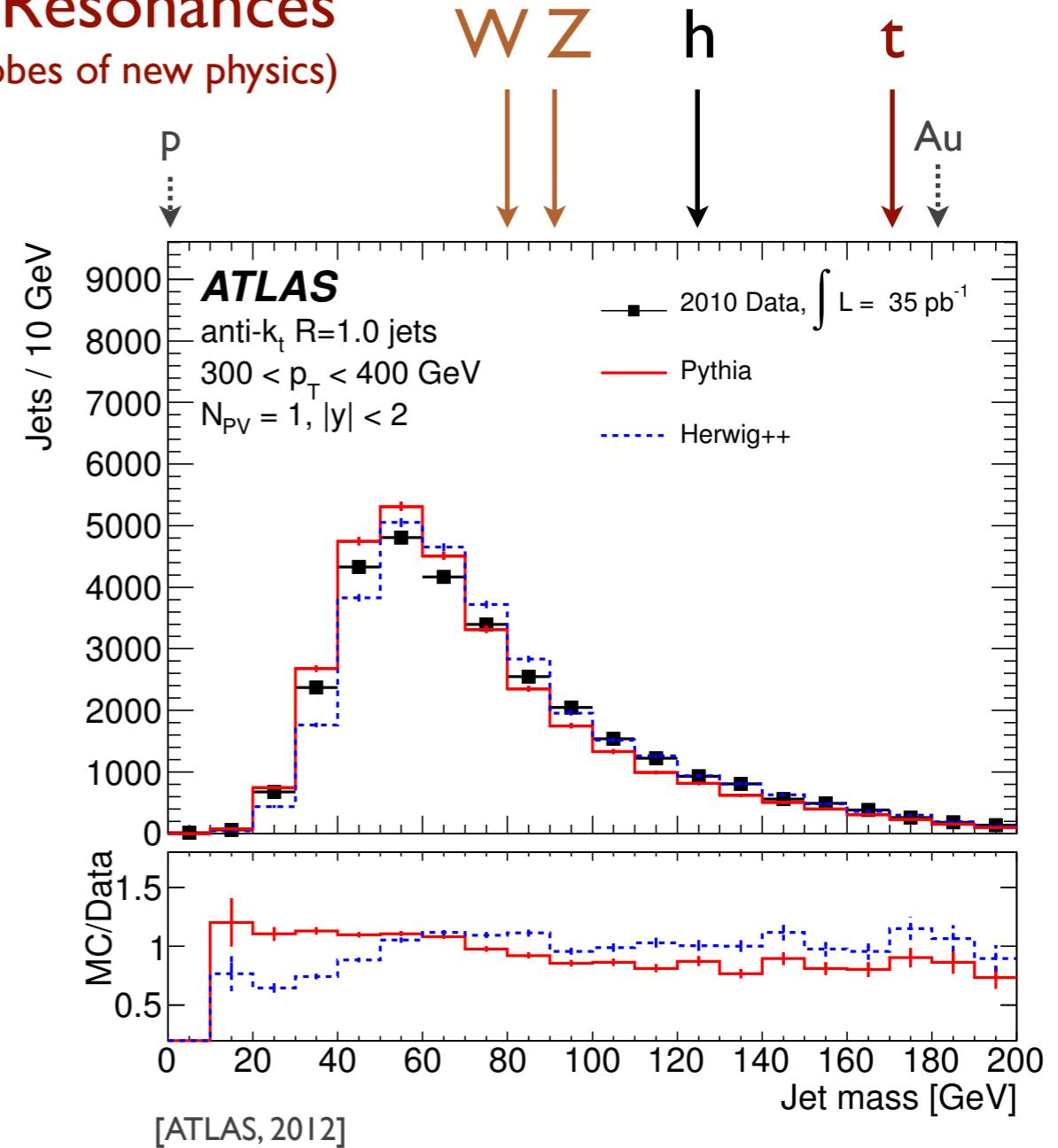


[pictures from coffeeshopphysics.com]

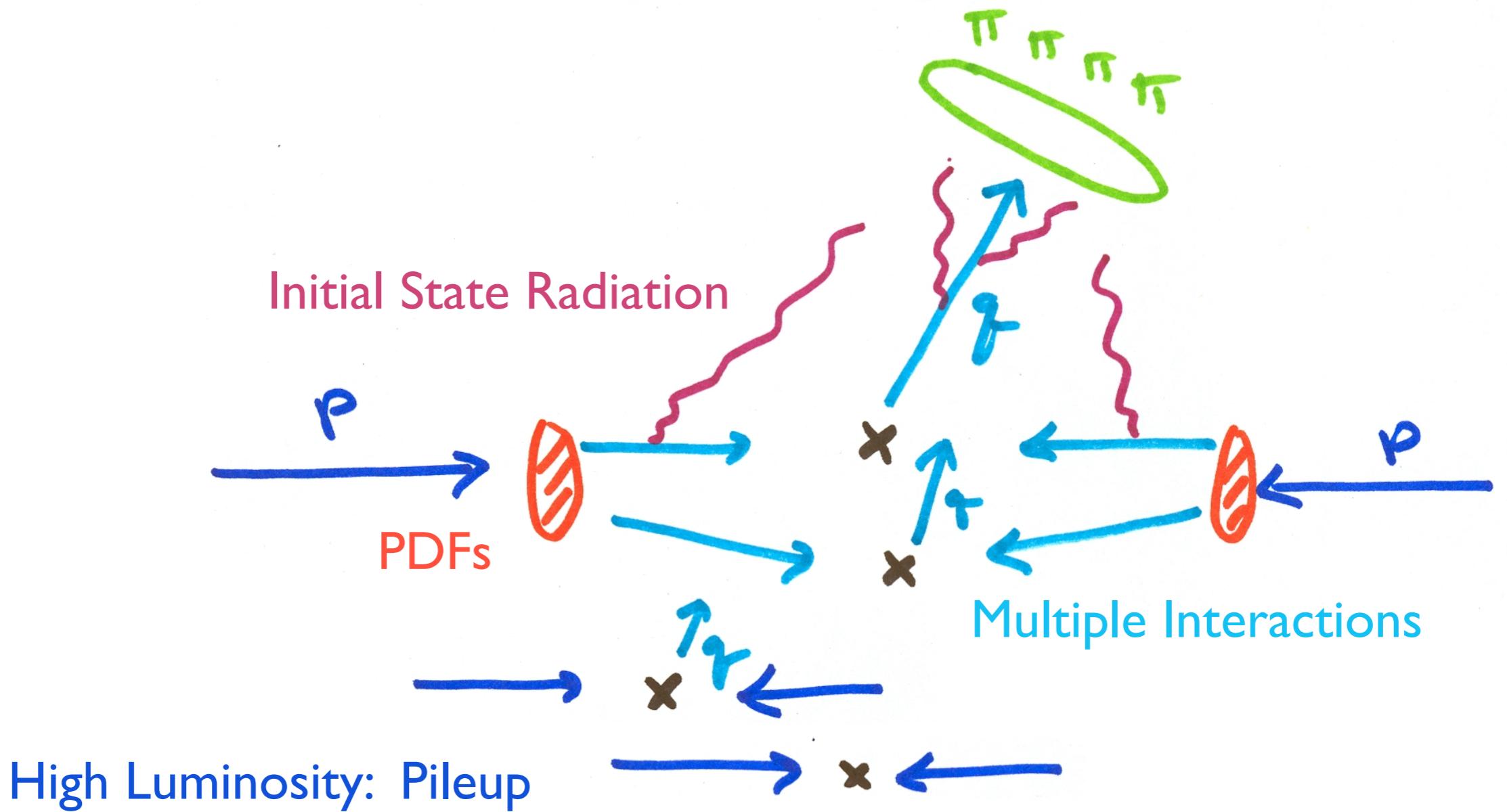
Jets Have Mass



Heavy Resonances
(potent probes of new physics)

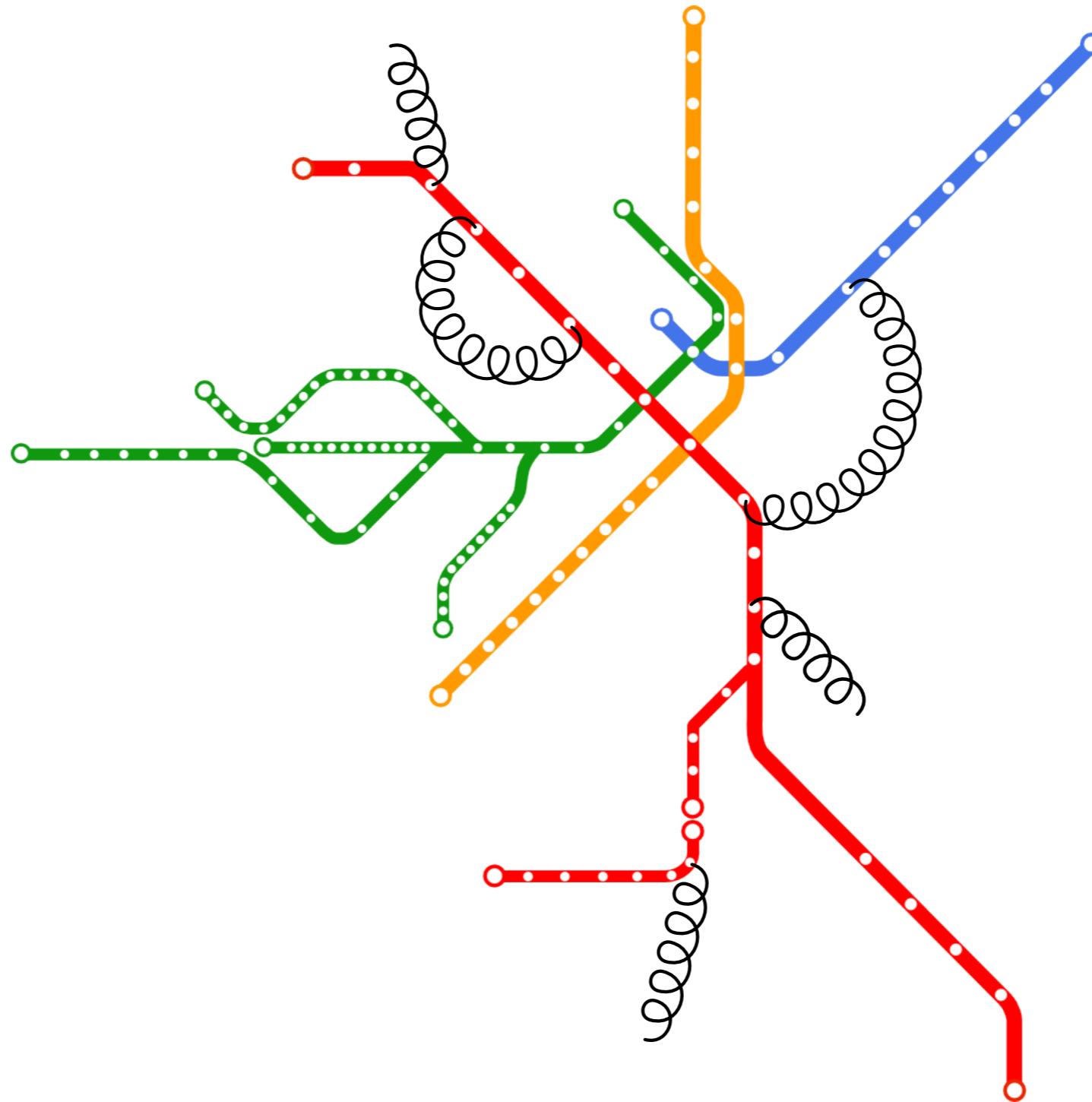


Jets are Complicated

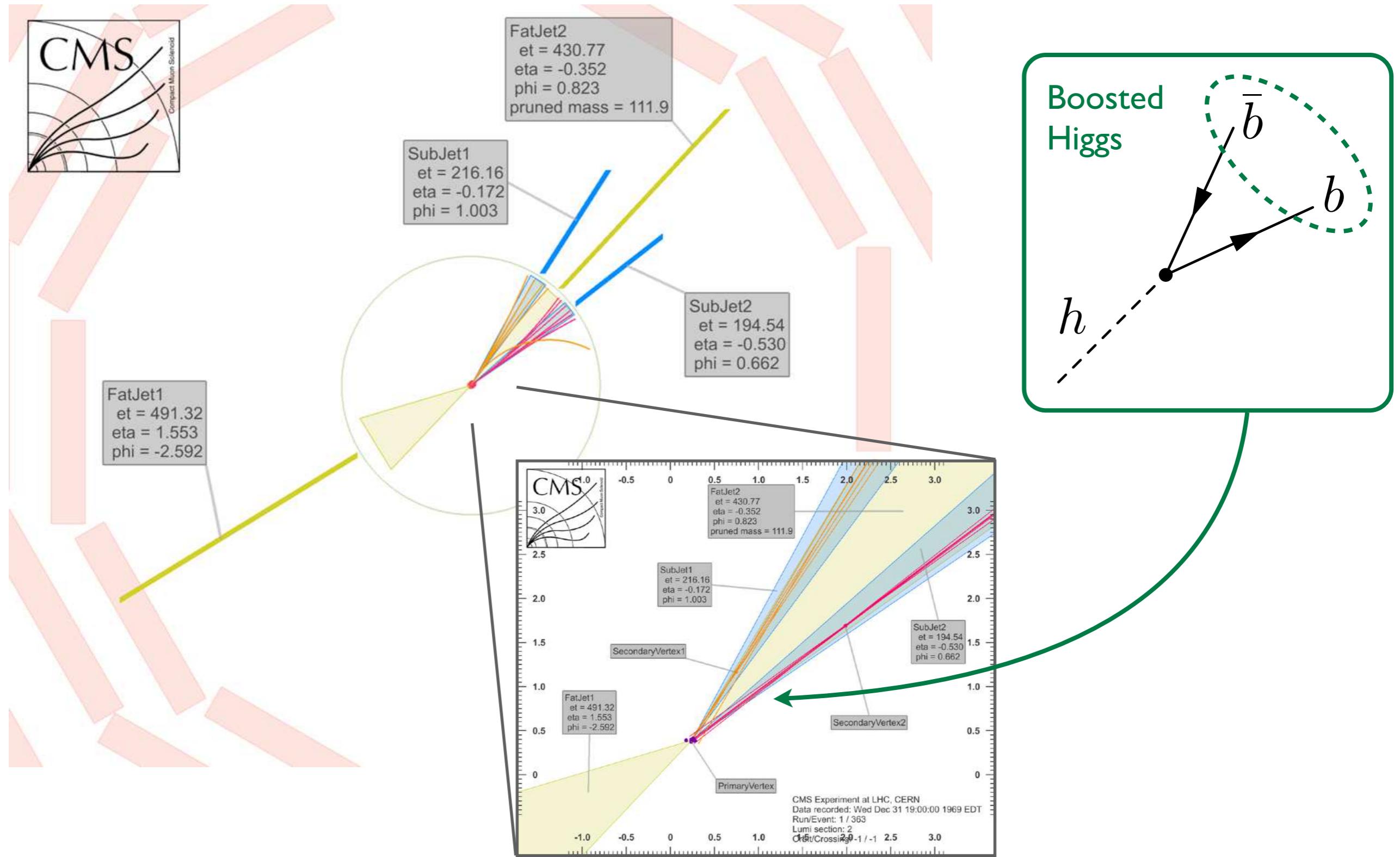


Jet = Desired Radiation + Contamination

MBTA Beyond LO

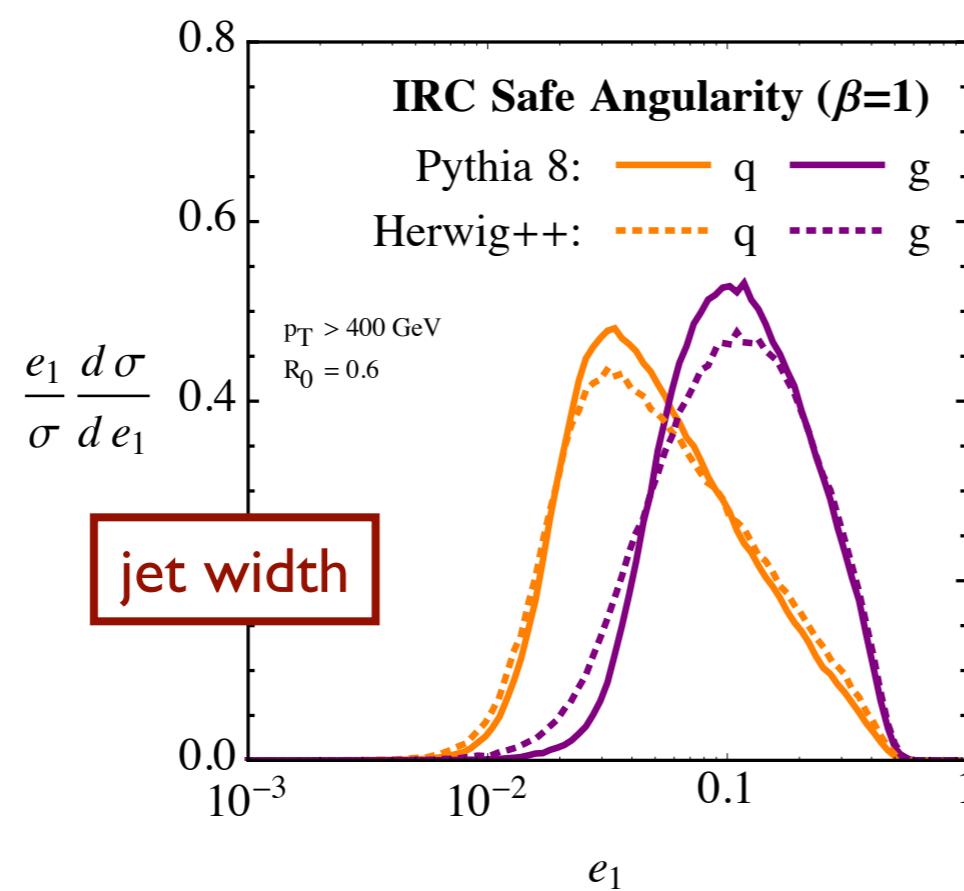
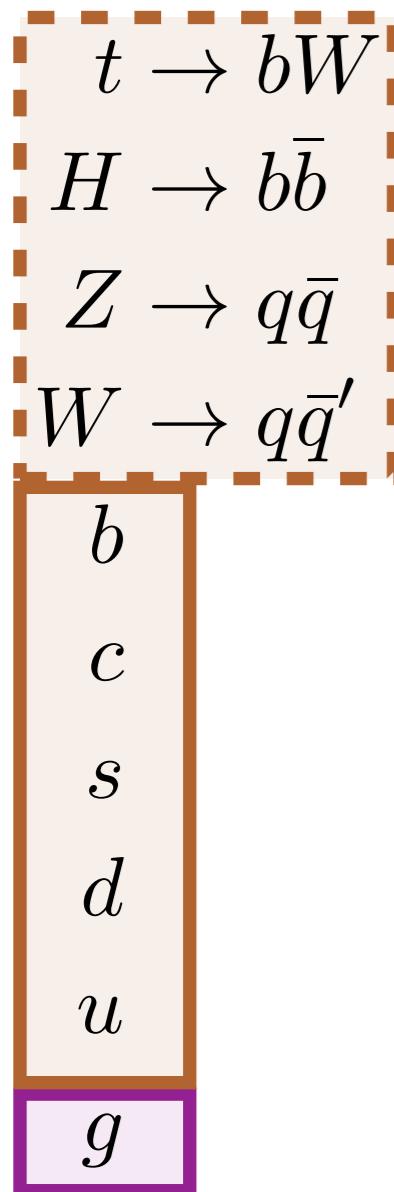


Finer Resolution: Cleverness is Inevitable

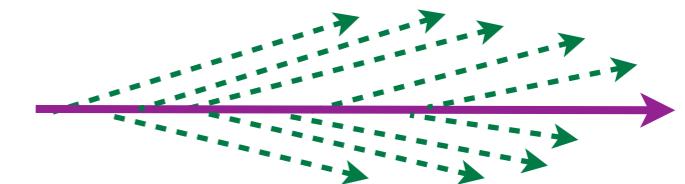


[CMS, 2013]

Quark-like vs. Gluon-like



$$C_F = 4/3$$



$$C_A = 3$$

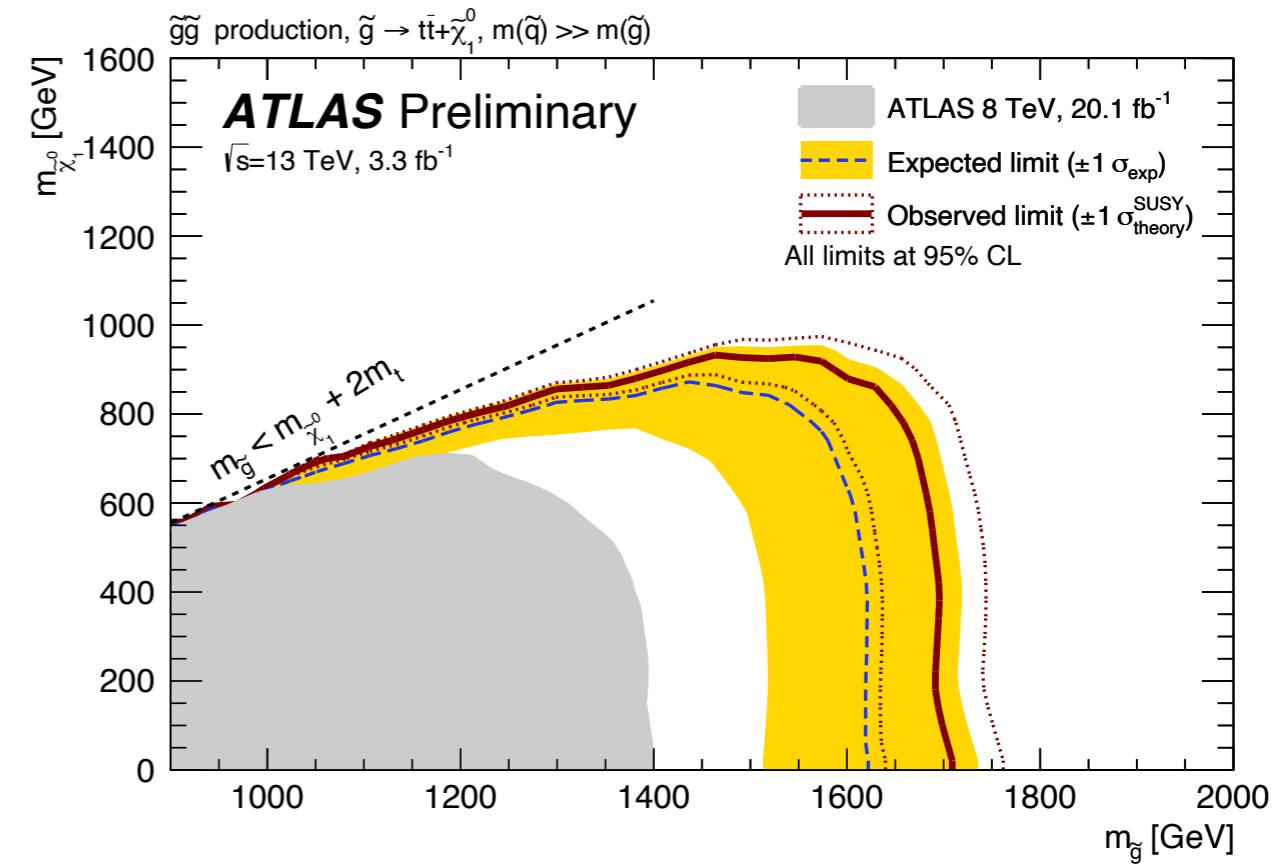
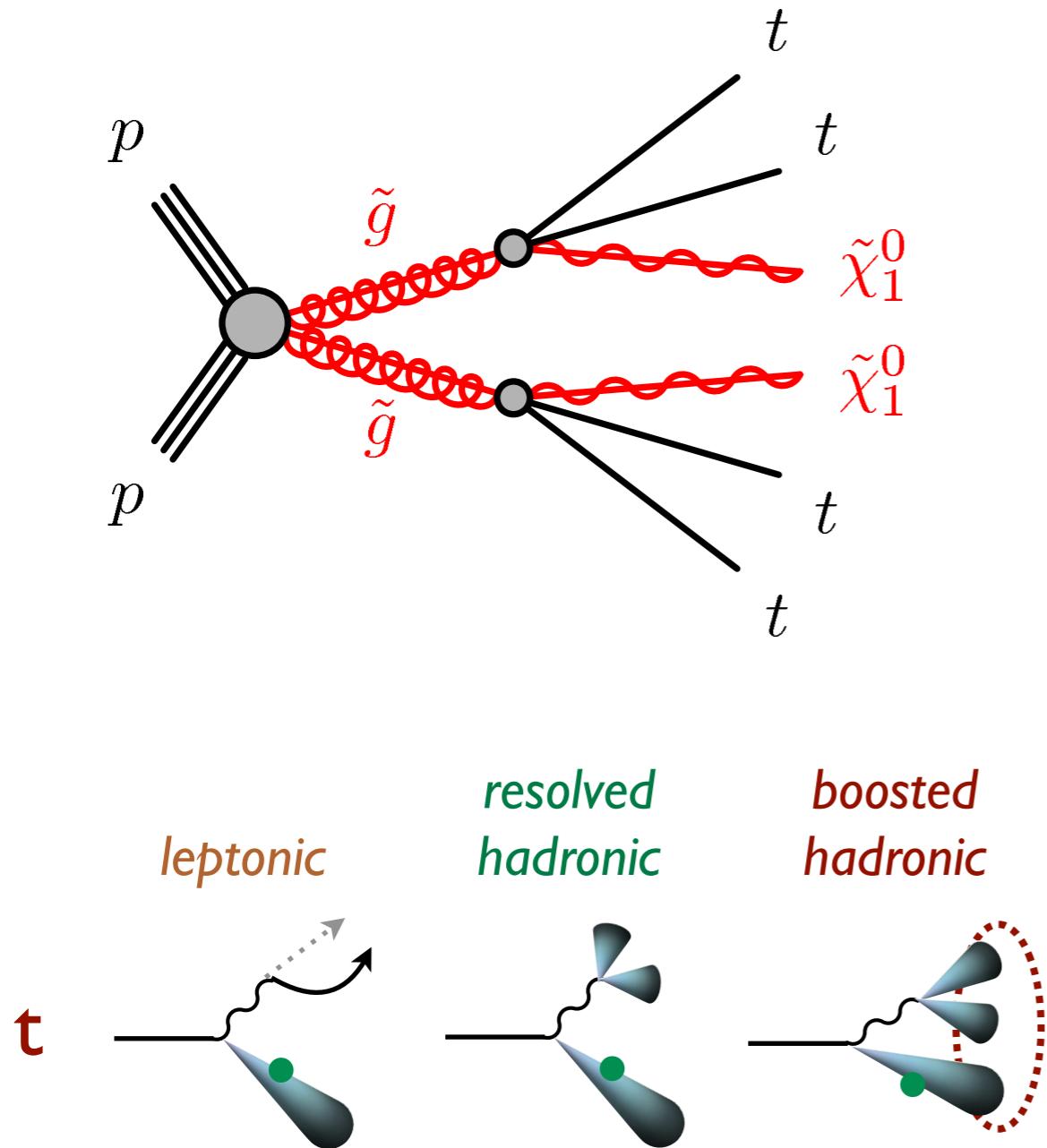
Angularities



[Berger, Kucs, Sterman, 2003; Ellis, Vermilion, Walsh, Hornig, Lee, 2010]
 [improved versions: Larkoski, Salam, JDT, 2013; Larkoski, Neill, JDT, 2014]

Hot off the Press: ATLAS SUSY Search

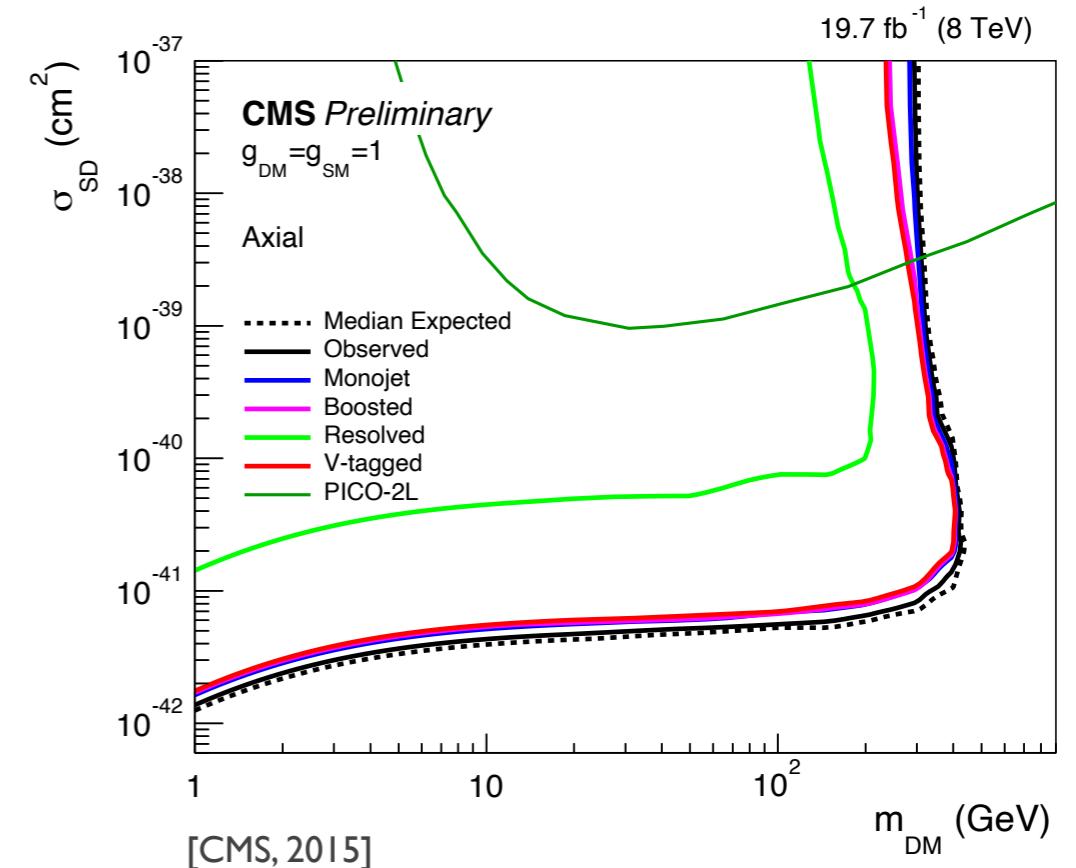
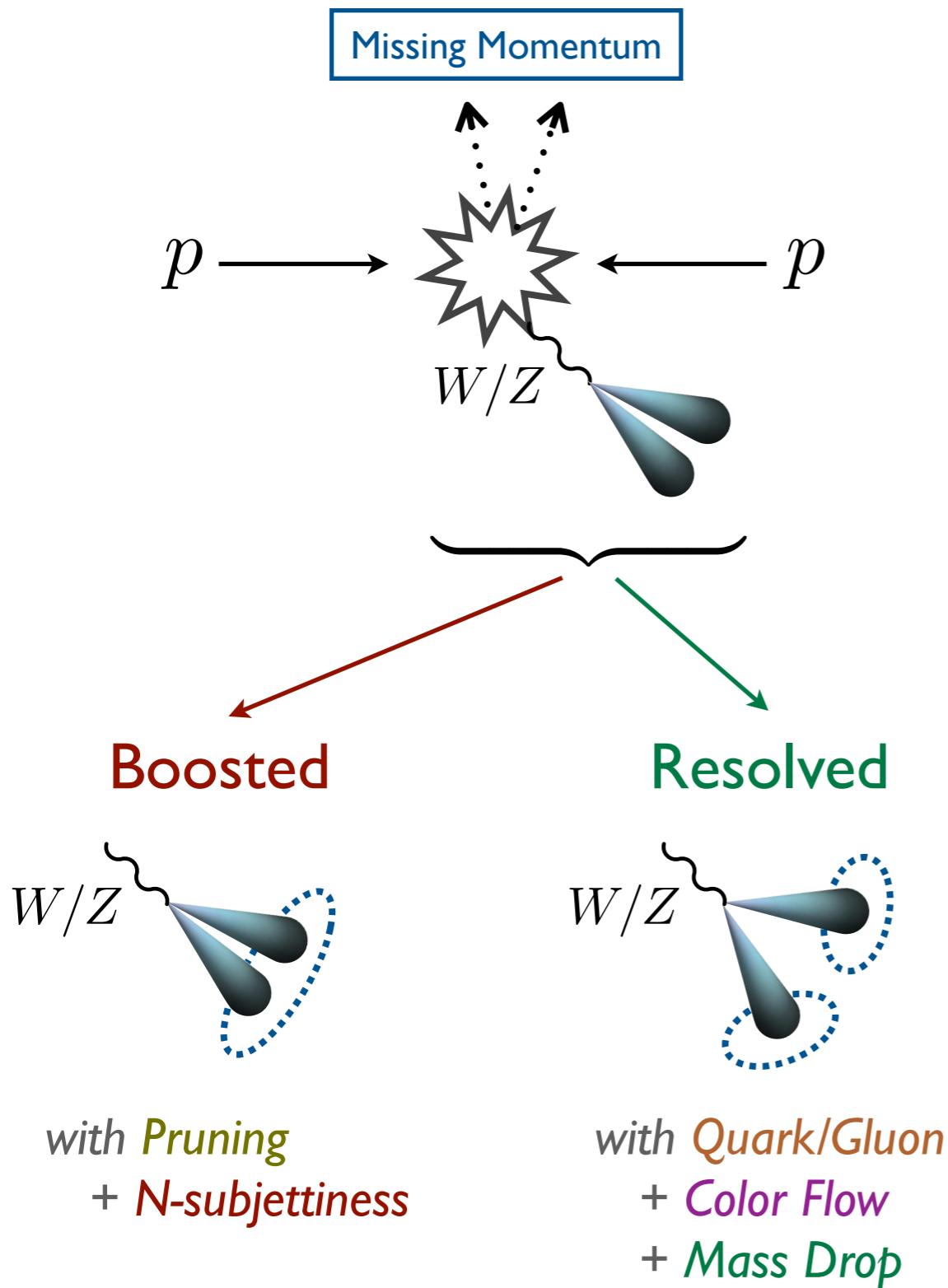
Missing Momentum + Leptons + B-tagging + Trimming + ...



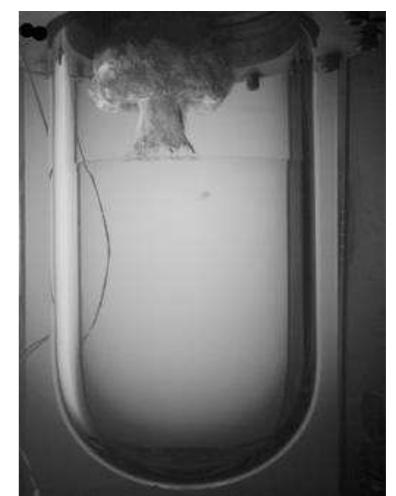
[ATLAS, 2016]

CMS: Dark Matter Search

Hot Topic @ **BOOST2015**

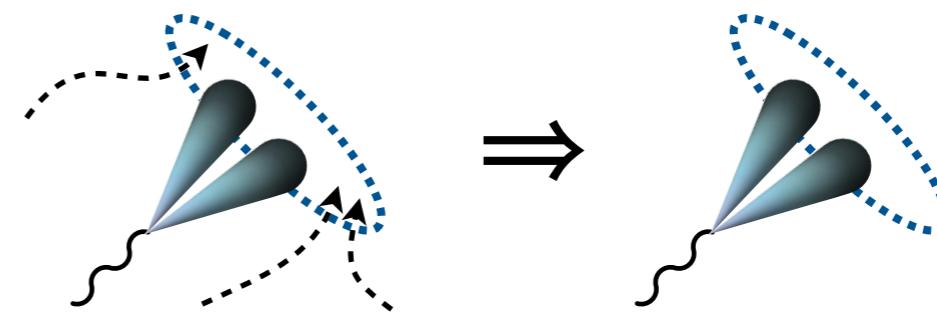


Complementary
to direct dark
matter searches

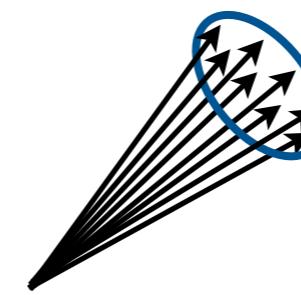


Key Substructure Techniques

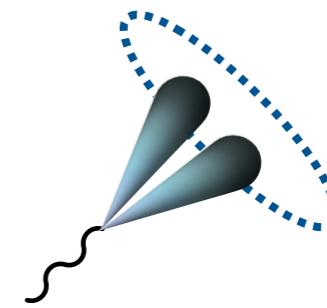
Jet Cleaning:



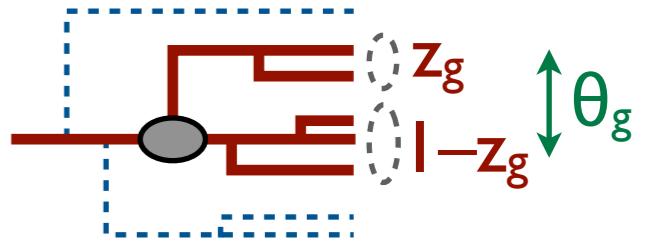
Jet Discrimination:



vs.



I. Explicit Computation



Master Formula: $p(z_g) = \int d\theta_g p(\theta_g) p(z_g | \theta_g)$

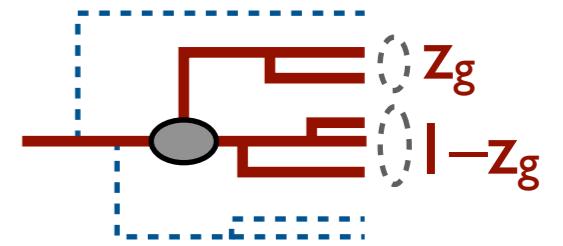
$$p(\theta_g) \simeq \frac{d}{d\theta_g} \exp \left[-\frac{\alpha_s C_i}{\pi} \left(\beta \log^2 \frac{1}{\theta_g} + 2 \log \frac{1}{\theta_g} \log \frac{1}{2 z_{\text{cut}}} \right) \right]$$

$$p(z_g | \theta_g) \simeq \frac{1}{\text{norm}} \frac{1}{z_g} \Theta(z_g - z_{\text{cut}} \theta_g^\beta)$$

$$\begin{aligned} p(z_g) &\simeq \sqrt{\frac{\alpha_s C_i}{\beta}} \frac{1}{z_g} \exp \left[\frac{\alpha_s C_i}{\pi \beta} \log^2 \frac{1}{2 z_{\text{cut}}} \right] \operatorname{erfc} \left[\sqrt{\frac{\alpha_s C_i}{\pi \beta}} \log \frac{1}{\min[2 z_{\text{cut}}, 2 z_g]} \right] \\ &\Rightarrow \frac{1}{\text{norm}} \frac{1}{z_g} \Theta(z_g - z_{\text{cut}}) \quad (\beta = 0) \end{aligned}$$

[Larkoski, Marzani, JDT, 1502.01719;
using Larkoski, JDT, 1307.1699; Larkoski, Marzani, Soyez, JDT, 1402.2657]

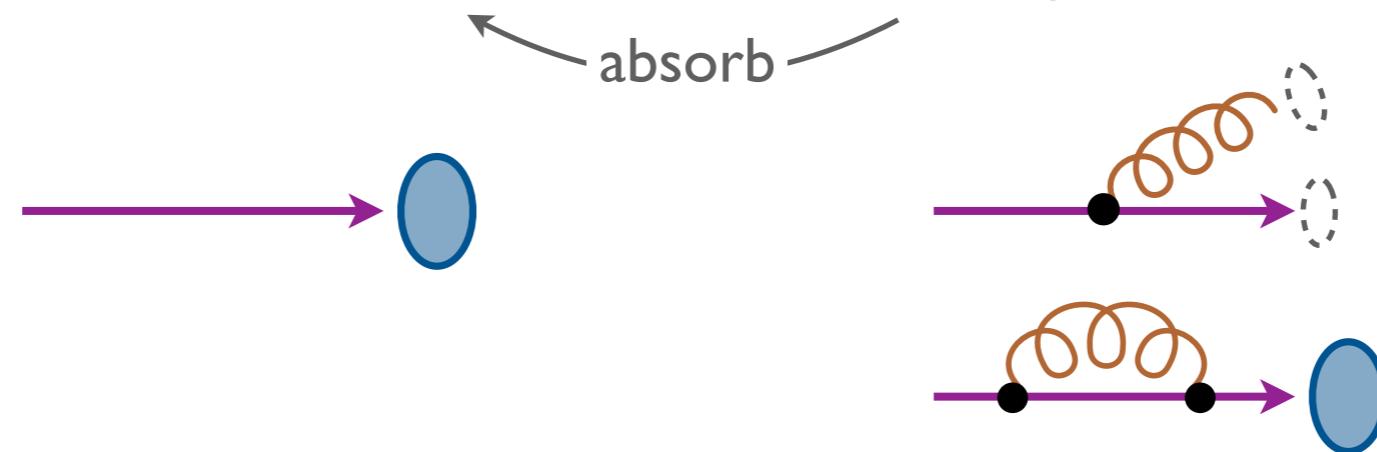
2. Renormalization Group Flow



Collinear Unsafe?

Absorb singularities into universal nonperturbative function (cf. PDFs)

$$\frac{d\sigma}{dz_g} = \left(\begin{array}{c} \text{fragmentation} \\ \text{function} \end{array} \right) + \alpha_s \left(\begin{array}{c} \text{collinear} \\ \text{singularities} \end{array} \right) + \mathcal{O}(\alpha_s^2)$$

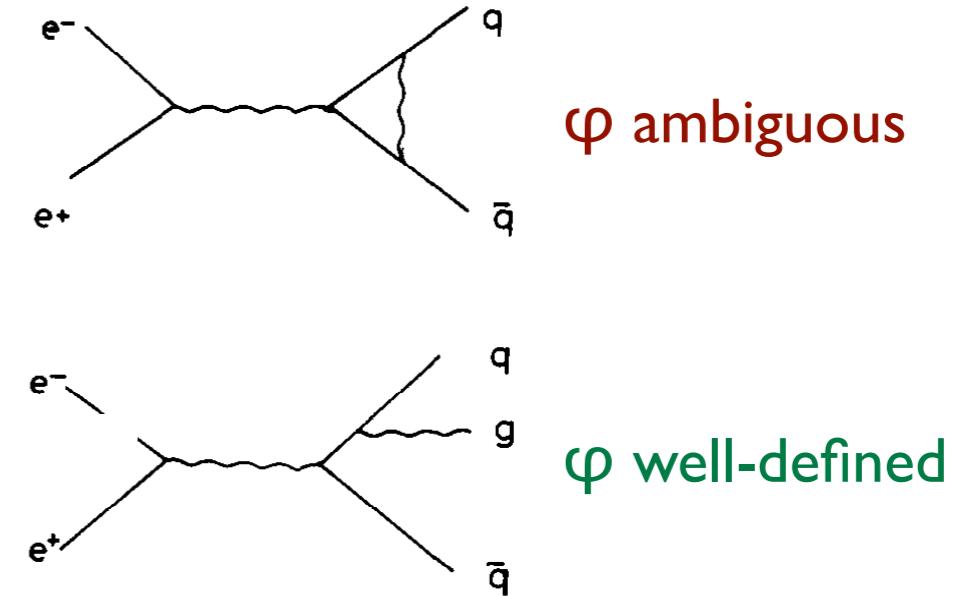
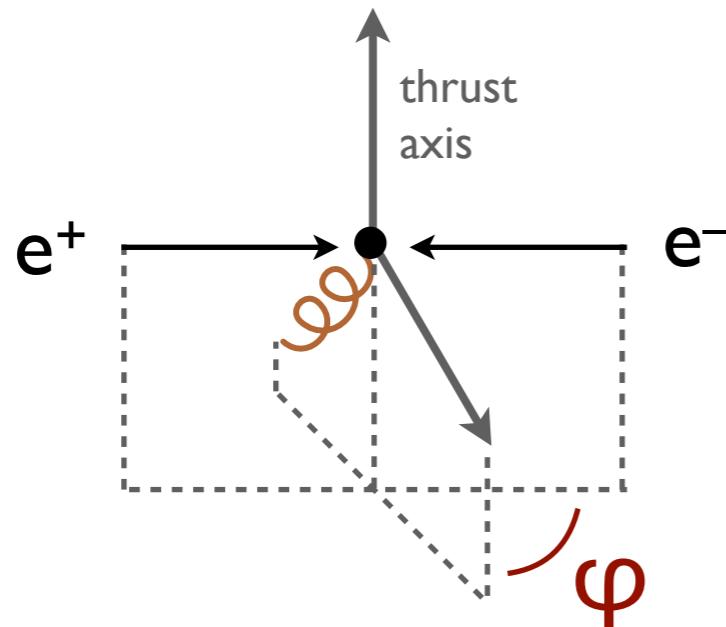


$$\mu \frac{\partial}{\partial \mu} F_i(z_g; \mu) \simeq \frac{\alpha_s C_i}{\pi} \left(p(z_g) - F_i(z_g; \mu) \right)$$

UV fixed point

[Larkoski, Marzani, JDT, 1502.01719]

3. Learn from our Elders



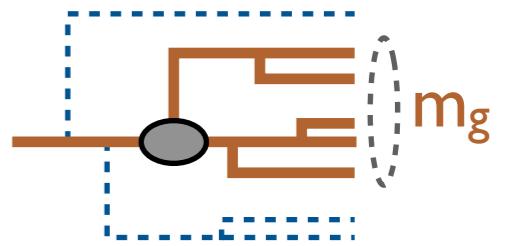
$$\frac{2\pi}{\sigma_0} \frac{d\sigma}{d\varphi} = 1 + O(\alpha_s(Q^2)) + \frac{\alpha_s(Q^2)}{\pi} \left(\frac{16}{3} \ln \frac{3}{2} - 2 \right) \cos 2\varphi$$

↗ Born cross section despite ambiguity (!)

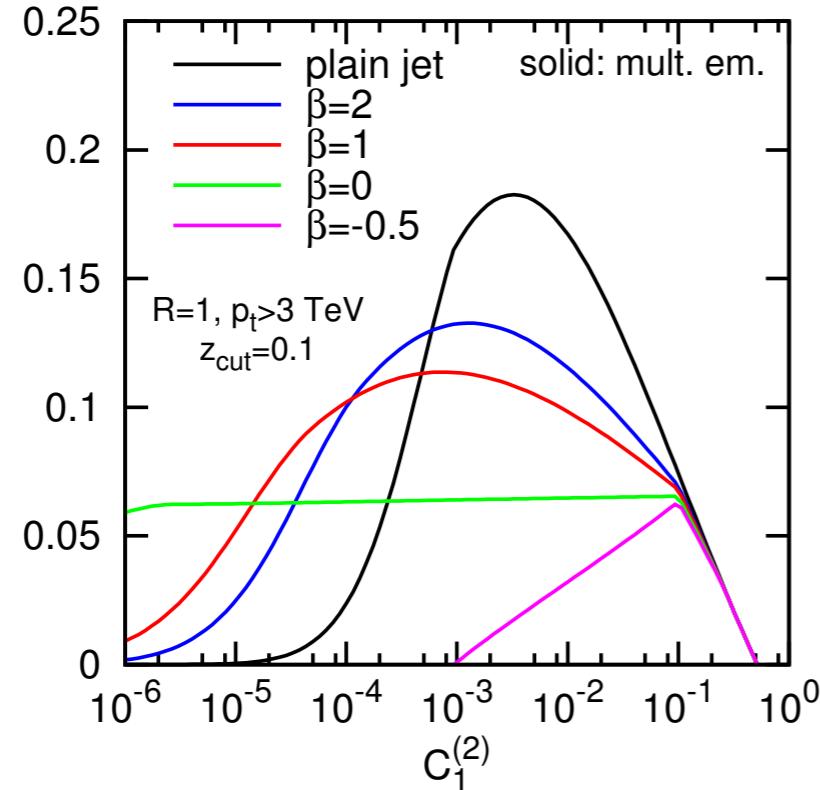
Exploits generalized notion of “observable”

[Pi, Jaffe, Low, 1978; Kramer, Schierholz, Willrodt, 1978]

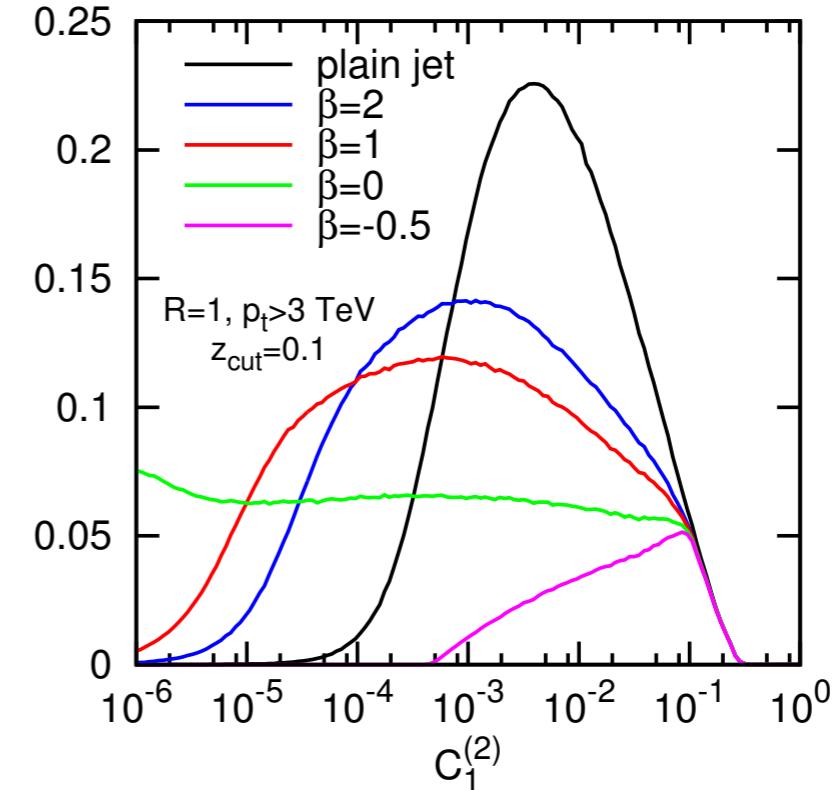
Soft-Dropped Jet Mass



First-principles QCD



Simulated LHC Data



More Grooming

$\beta \rightarrow -\infty$

$\beta < 0$

$\beta = 0$

$\beta > 0$

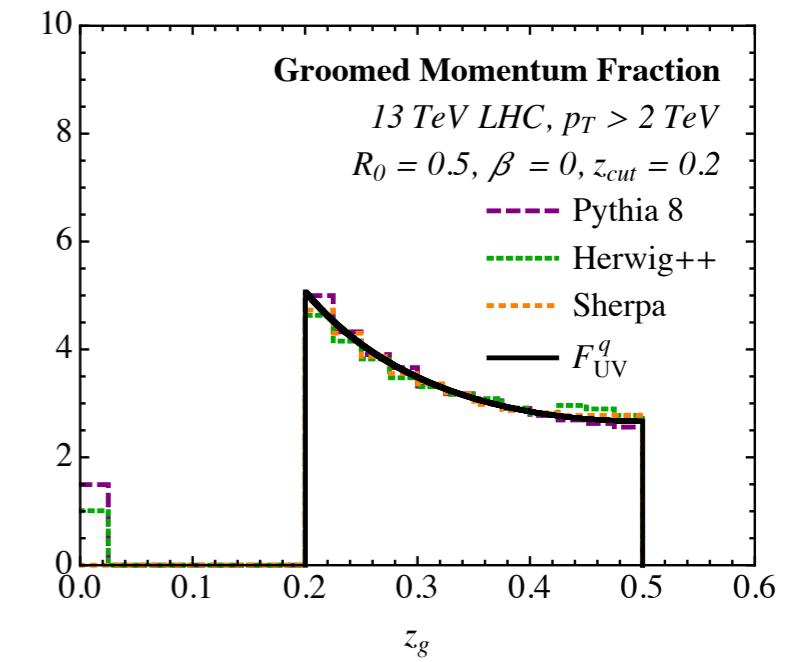
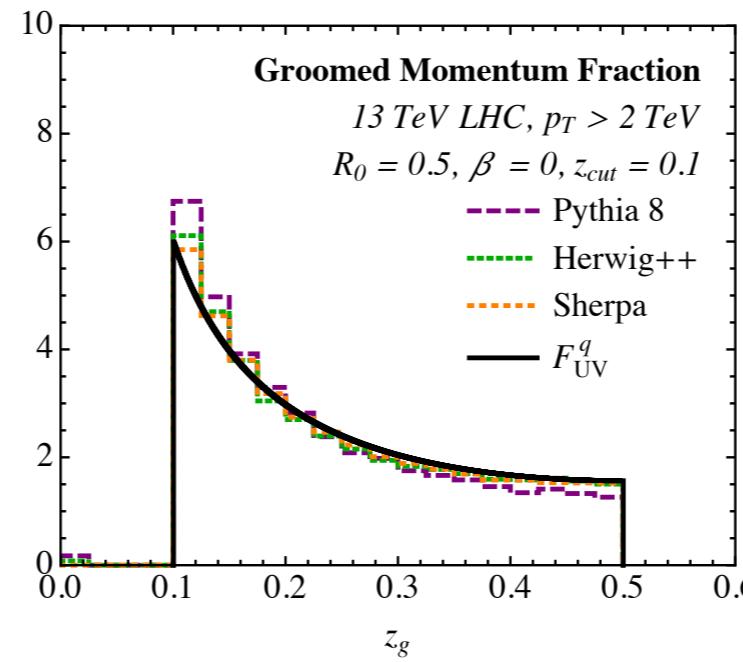
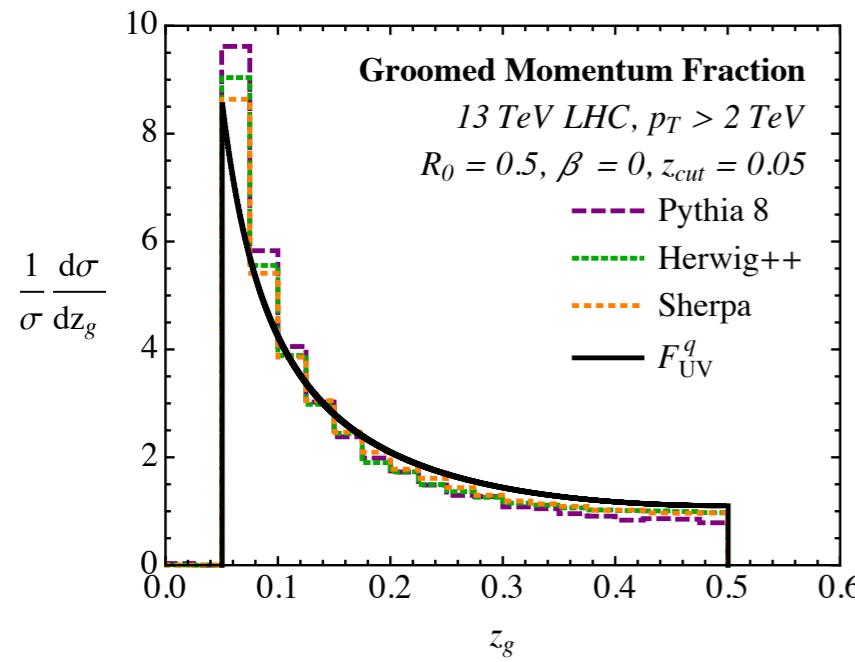
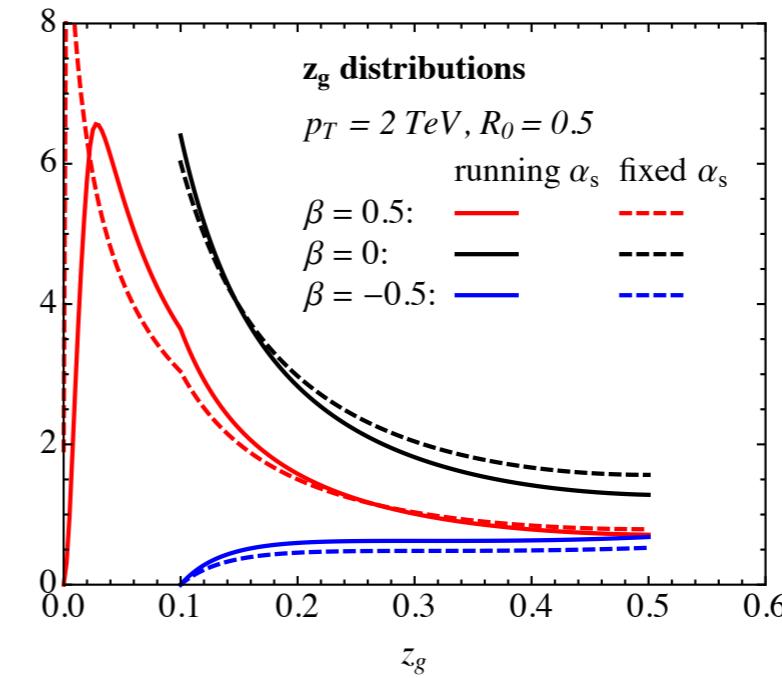
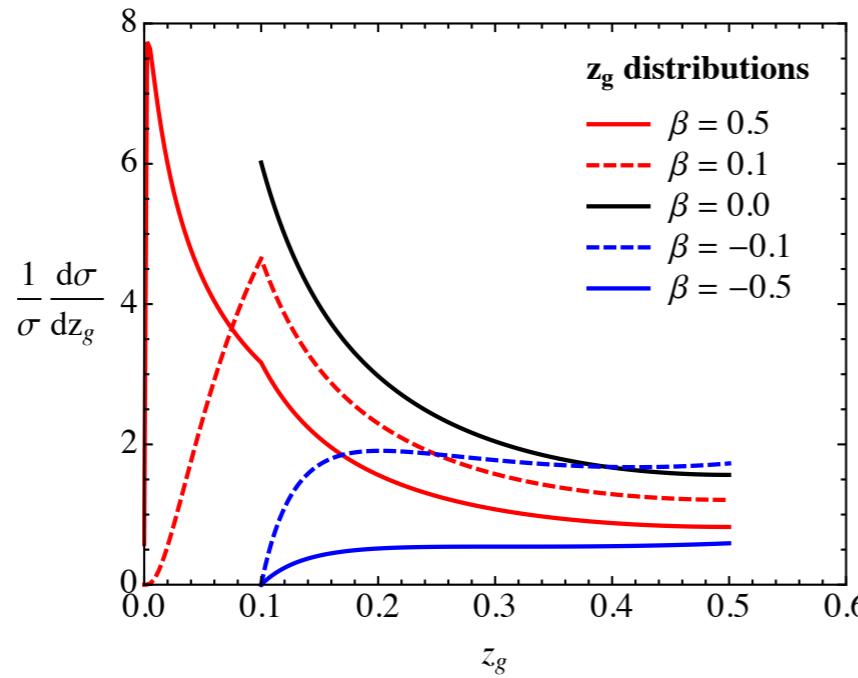
$\beta \rightarrow \infty$



[Dasgupta, Fregoso, Marzani, Salam, I307.0007; Larkoski, Marzani, Soyez, JDT, I402.2657]

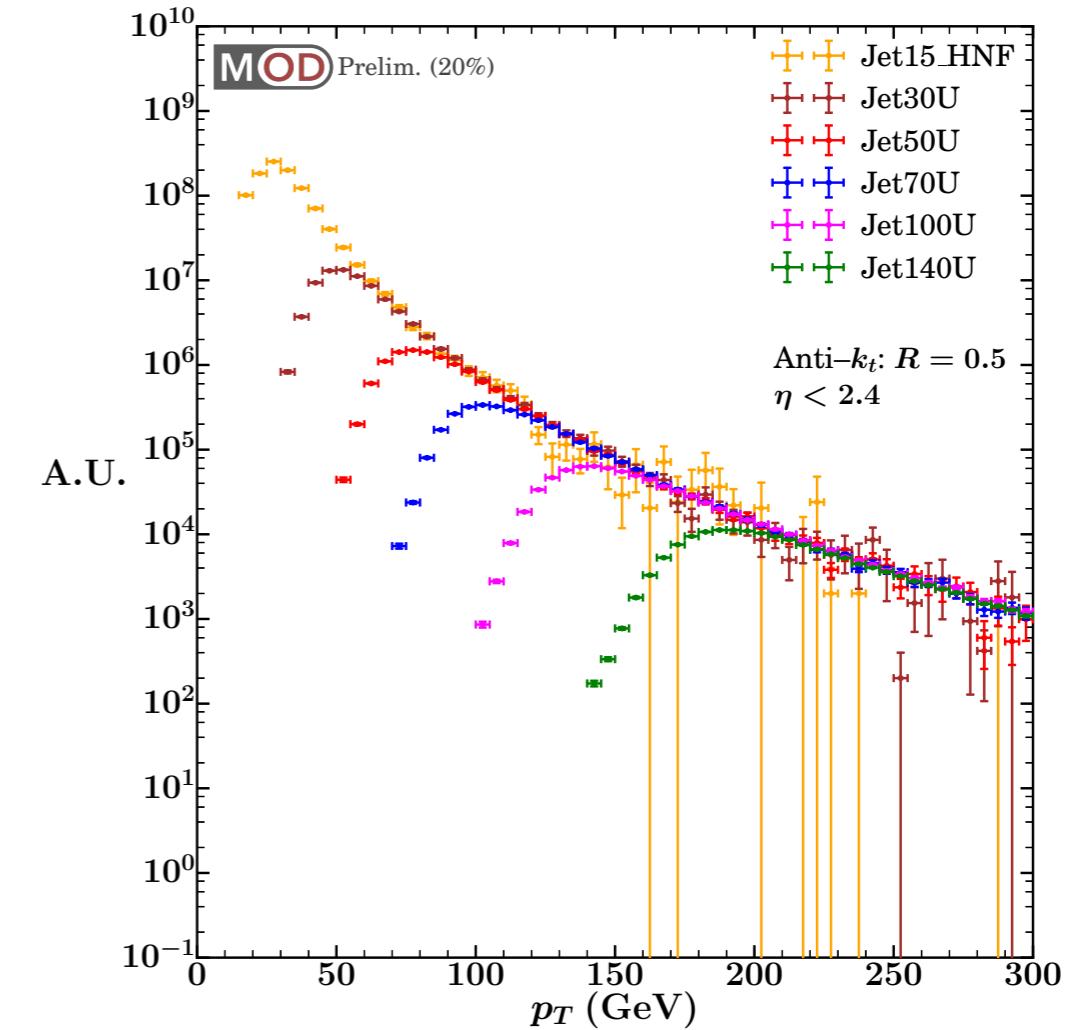
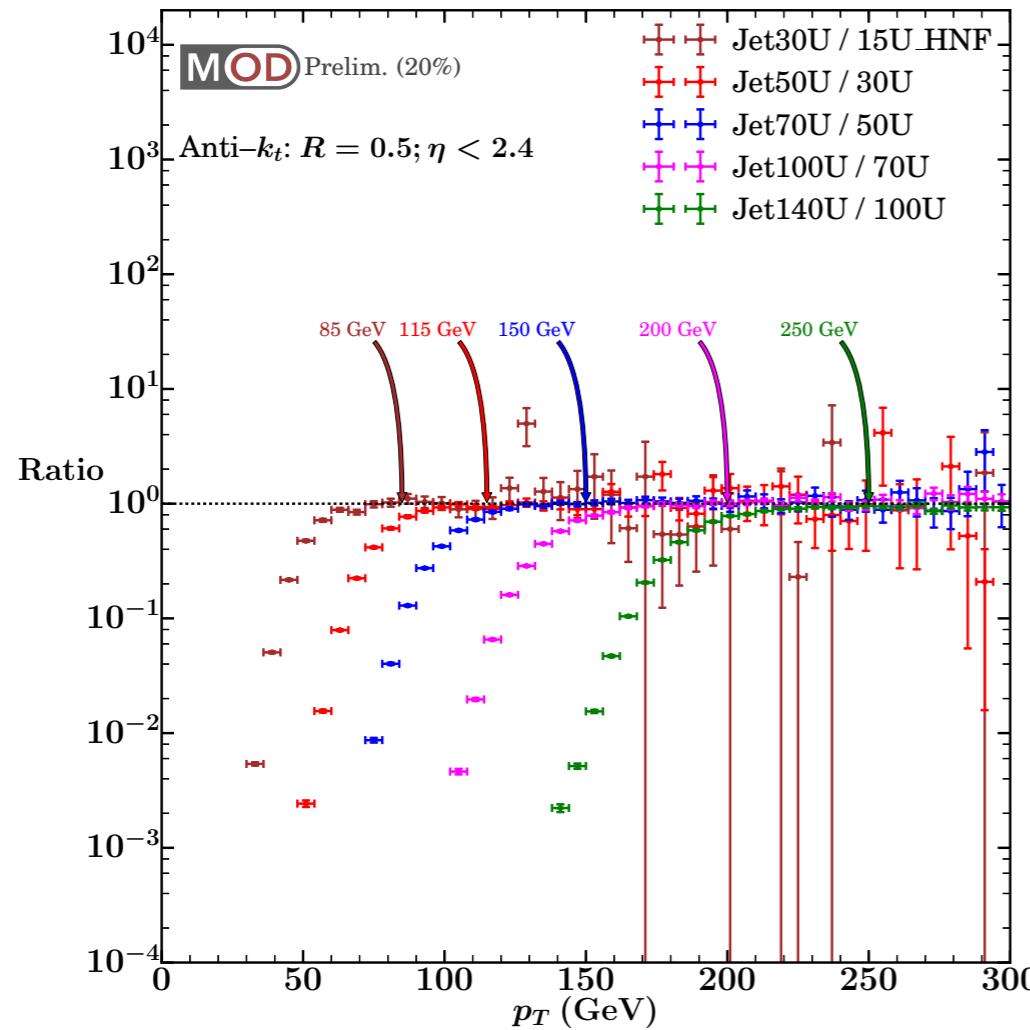
More About Open Data

Additional z_g Theory Plots



[Larkoski, Marzani, JDT, 1502.01719]

CMS Jet Primary Data Set Triggers

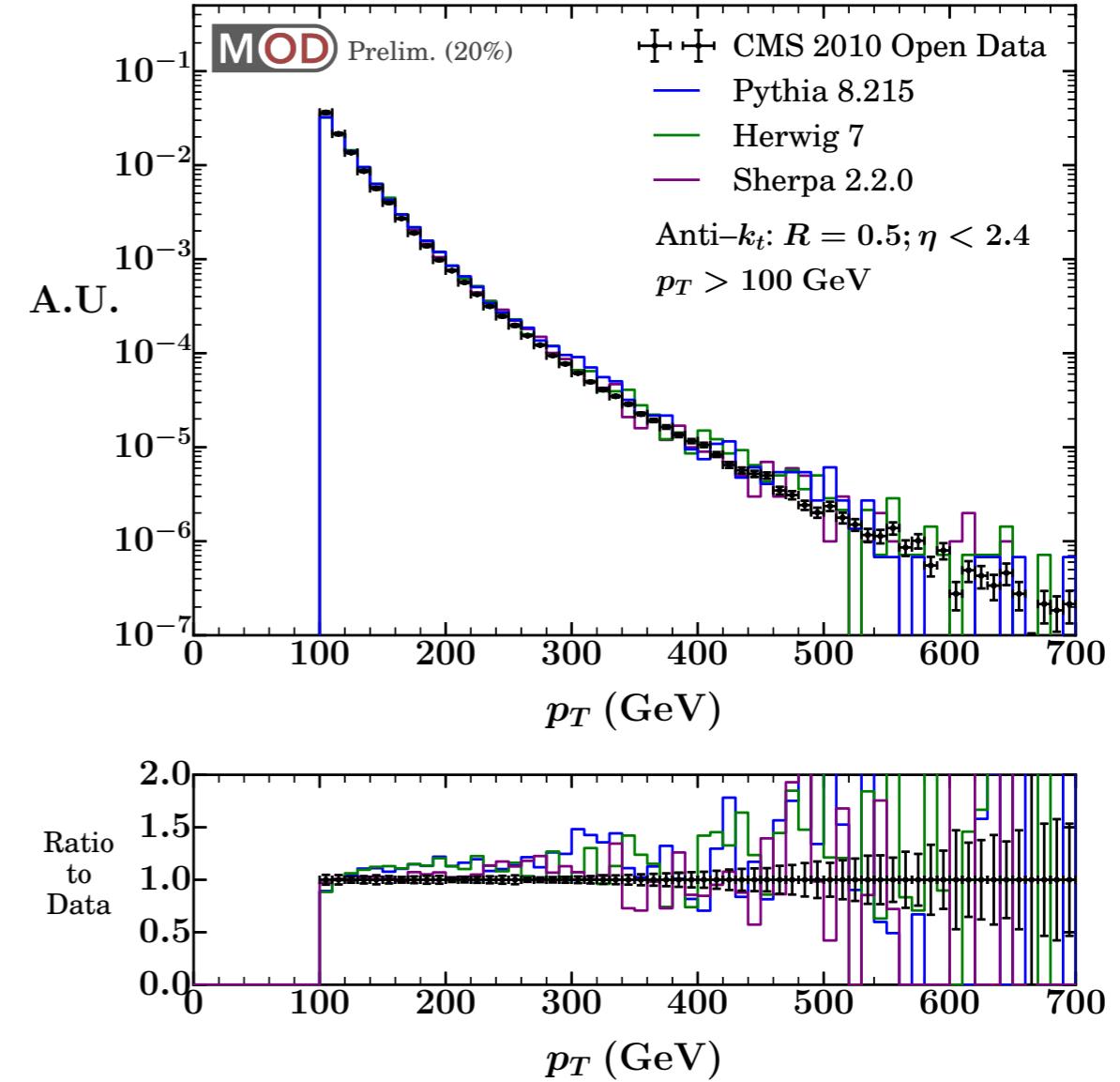
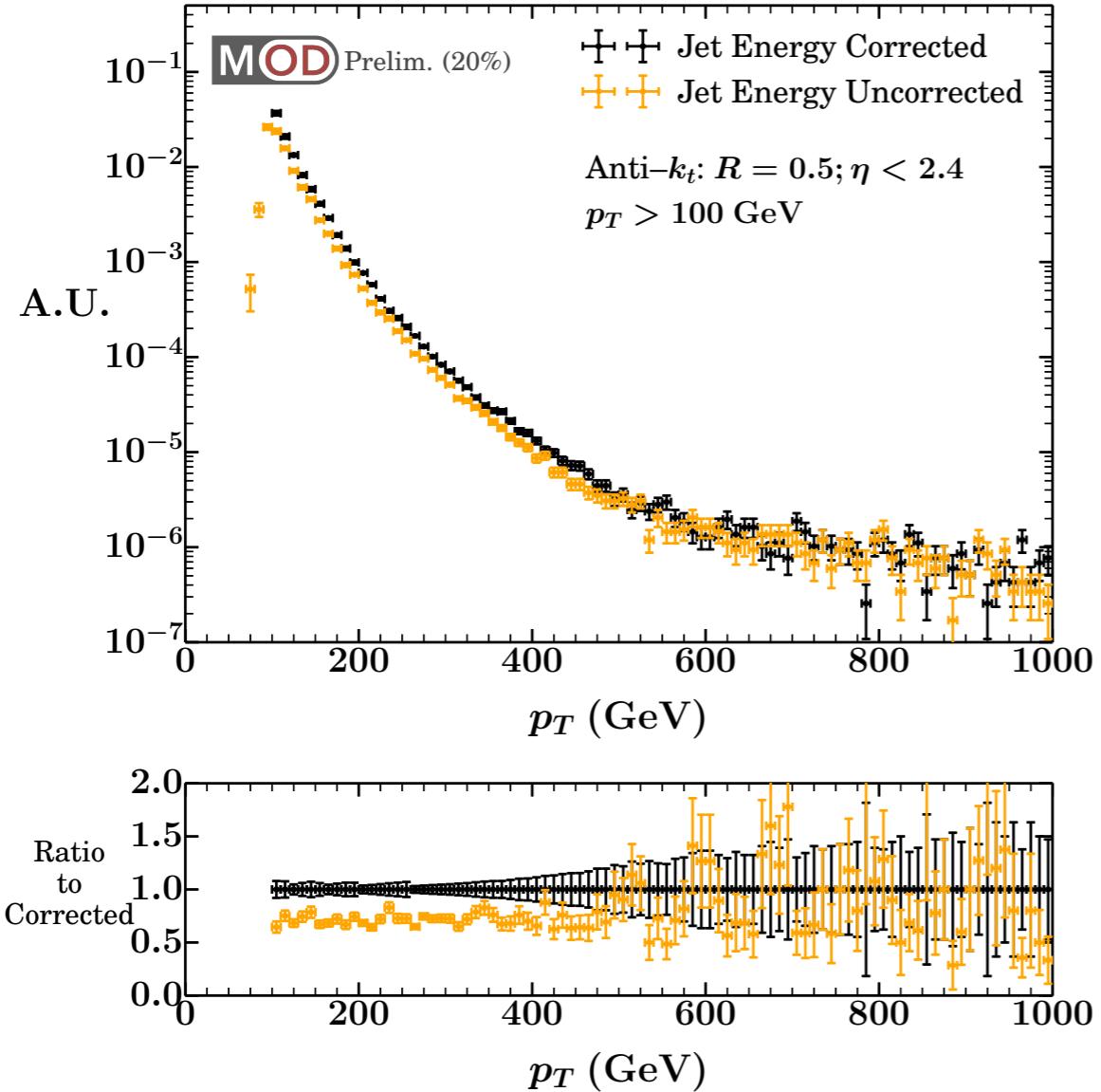


- HLT_Jet15U + _v3
- HLT_Jet15U_HcalNoiseFiltered + _v3
- HLT_Jet30U + _v3**
- HLT_Jet50U + _v3
- HLT_Jet70U + _v2 + _v3
- HLT_Jet100U + _v2 + _v3
- HLT_Jet140U_v1 + _v3
- HLT_Jet180U_v3

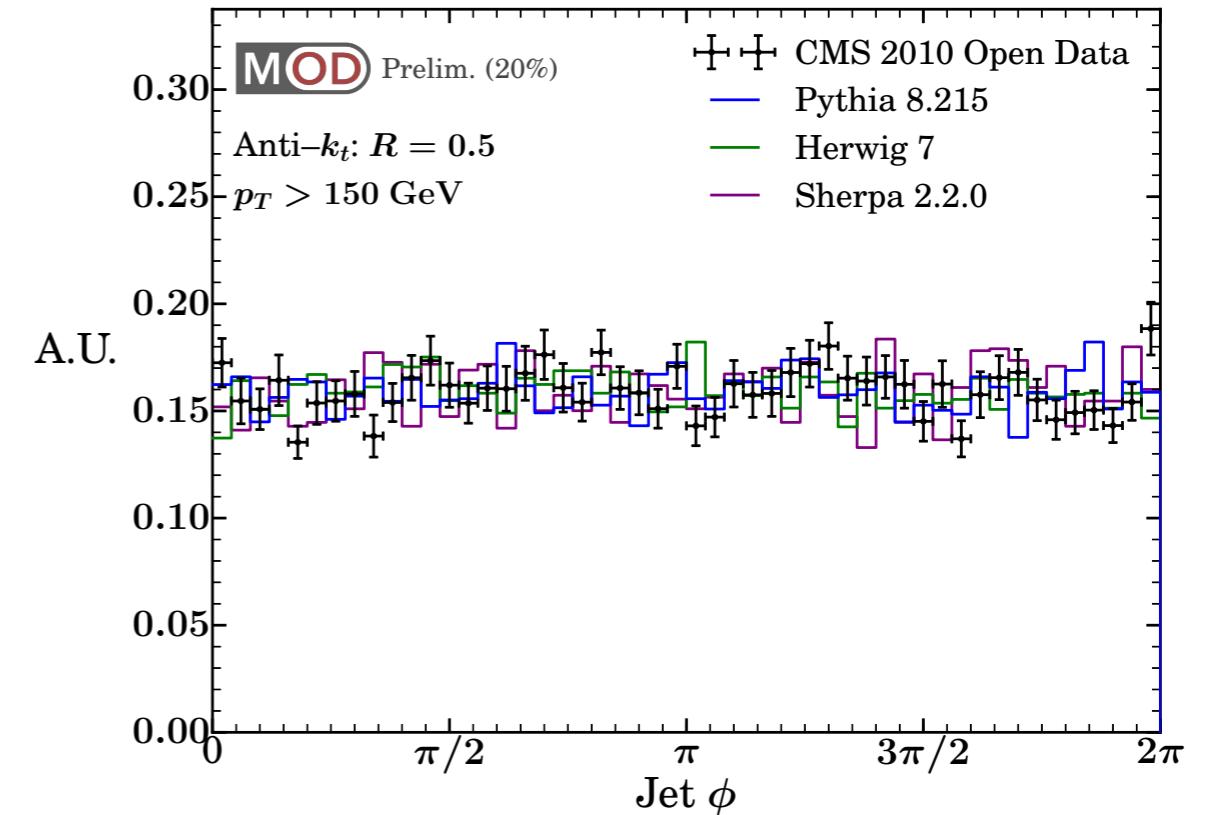
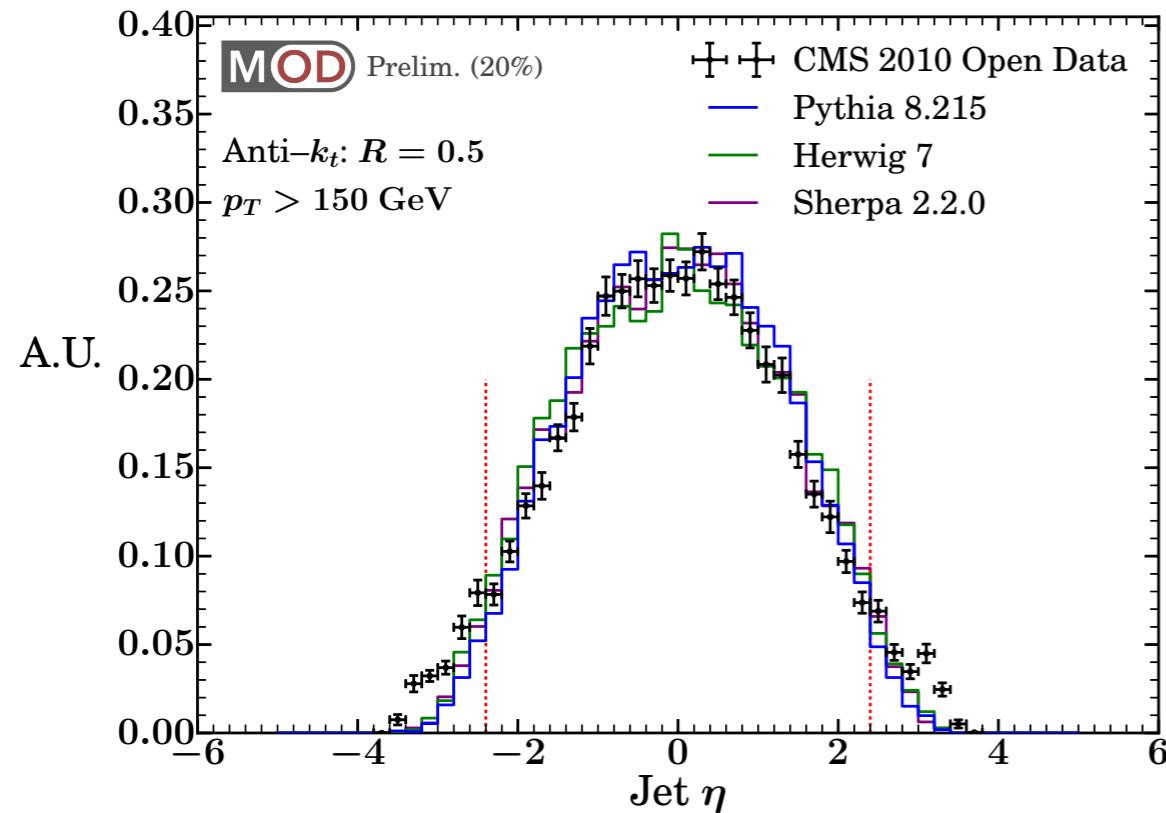
- HLT_DiJetAve15U + _v3
- HLT_DiJetAve30U + _v3
- HLT_DiJetAve50U + _v3
- HLT_DiJetAve70U + _v2 + _v3
- HLT_DiJetAve100U_v1 + _v3
- HLT_DiJetAve140U_v3

- HLT_QuadJet20U
- HLT_QuadJet25U
- HLT_HT100U
- HLT_HT120U
- HLT_HT140U
- HLT_EcalOnly_SumEt160

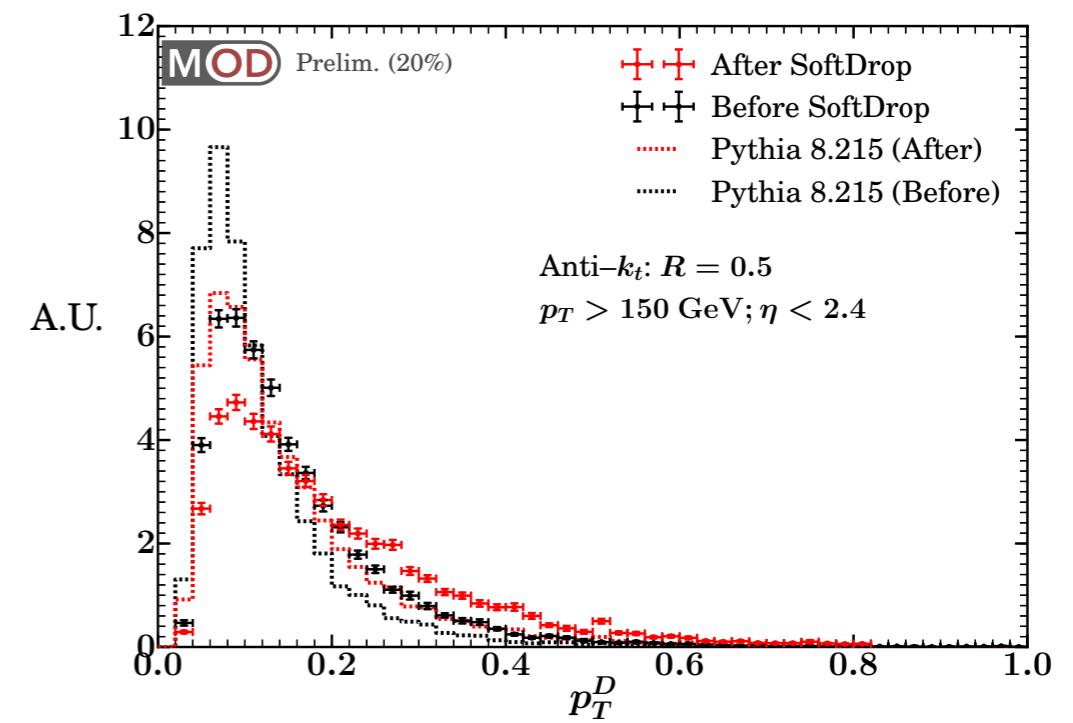
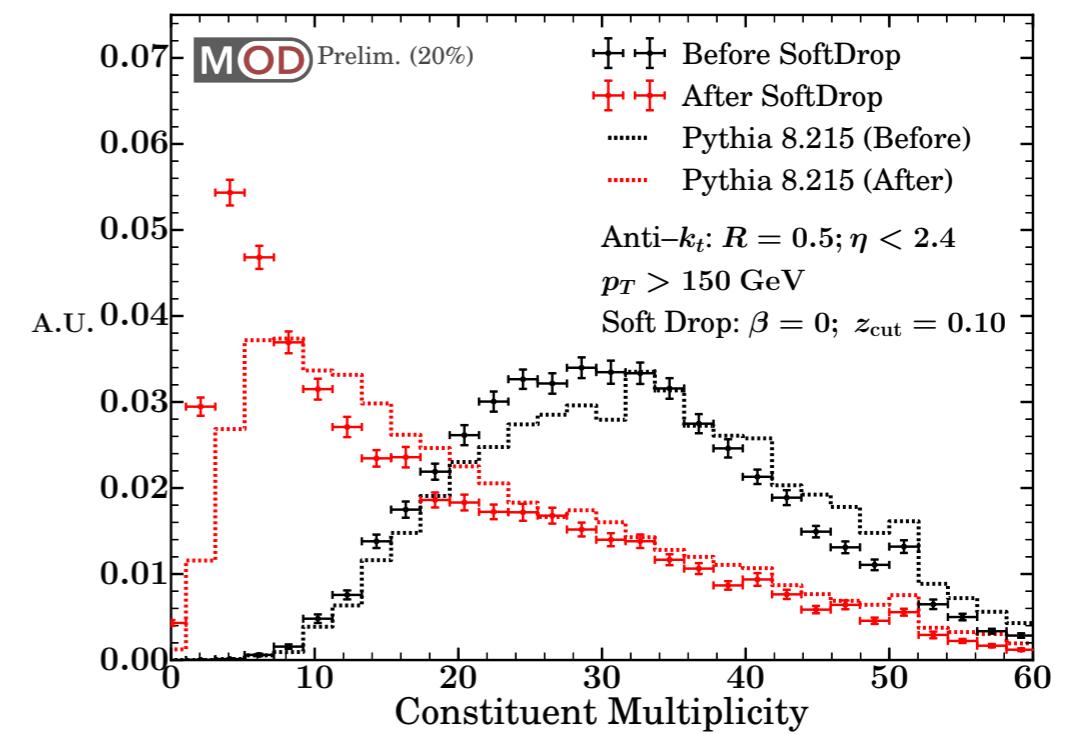
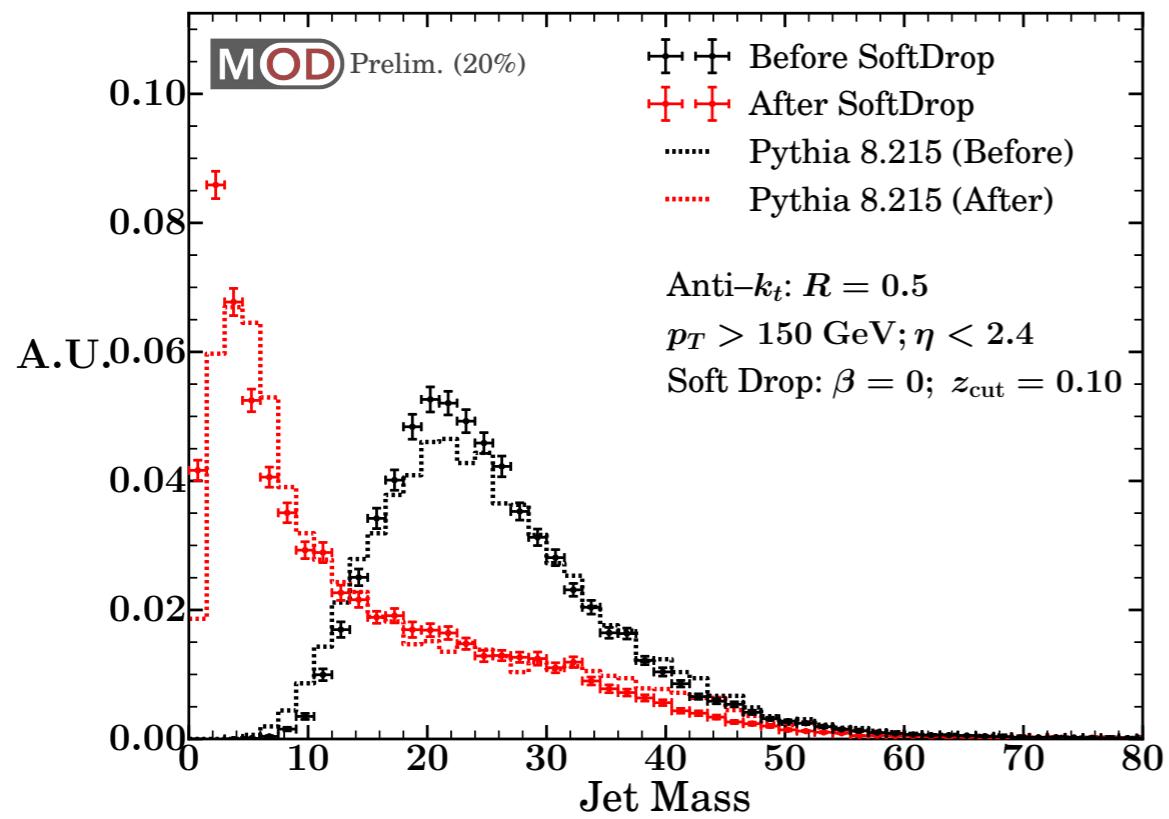
Corrected Jet p_T Spectrum



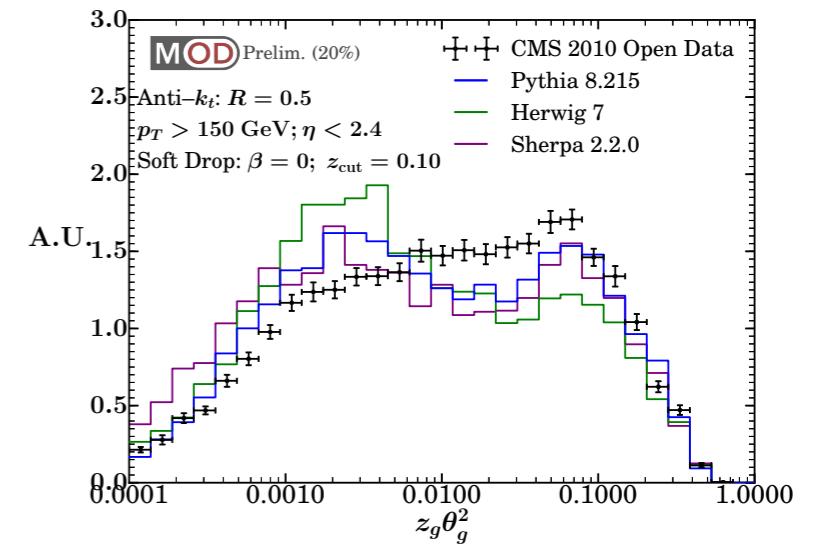
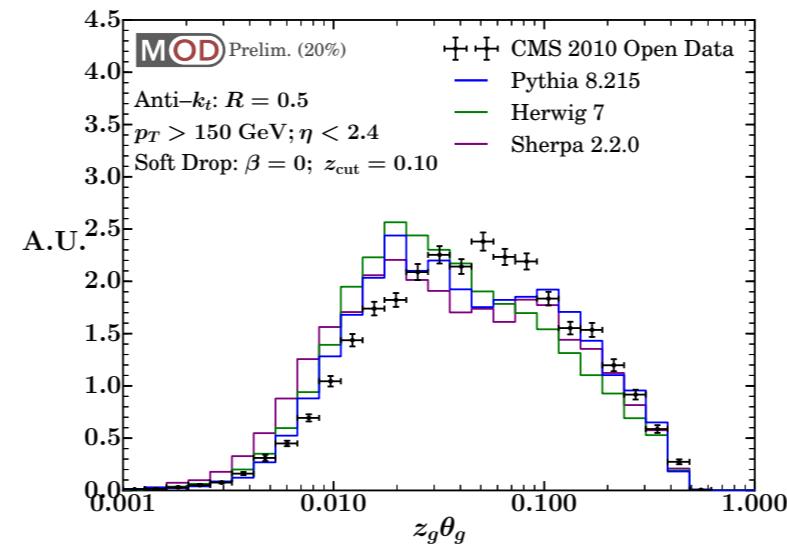
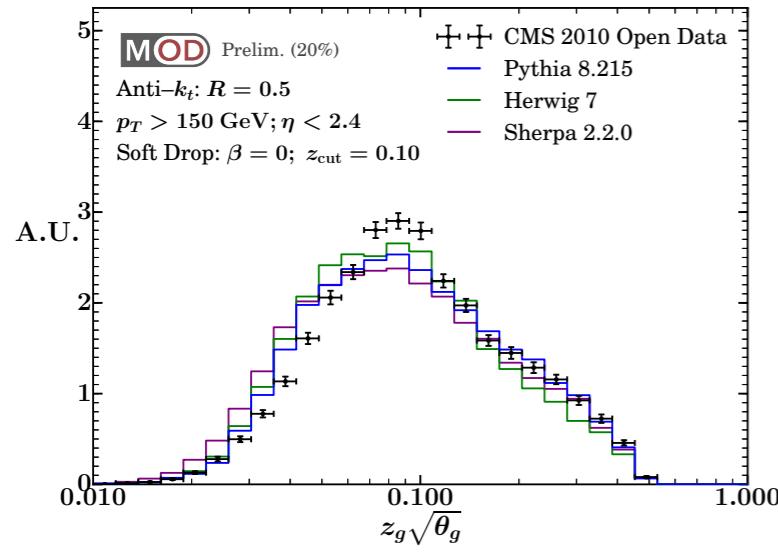
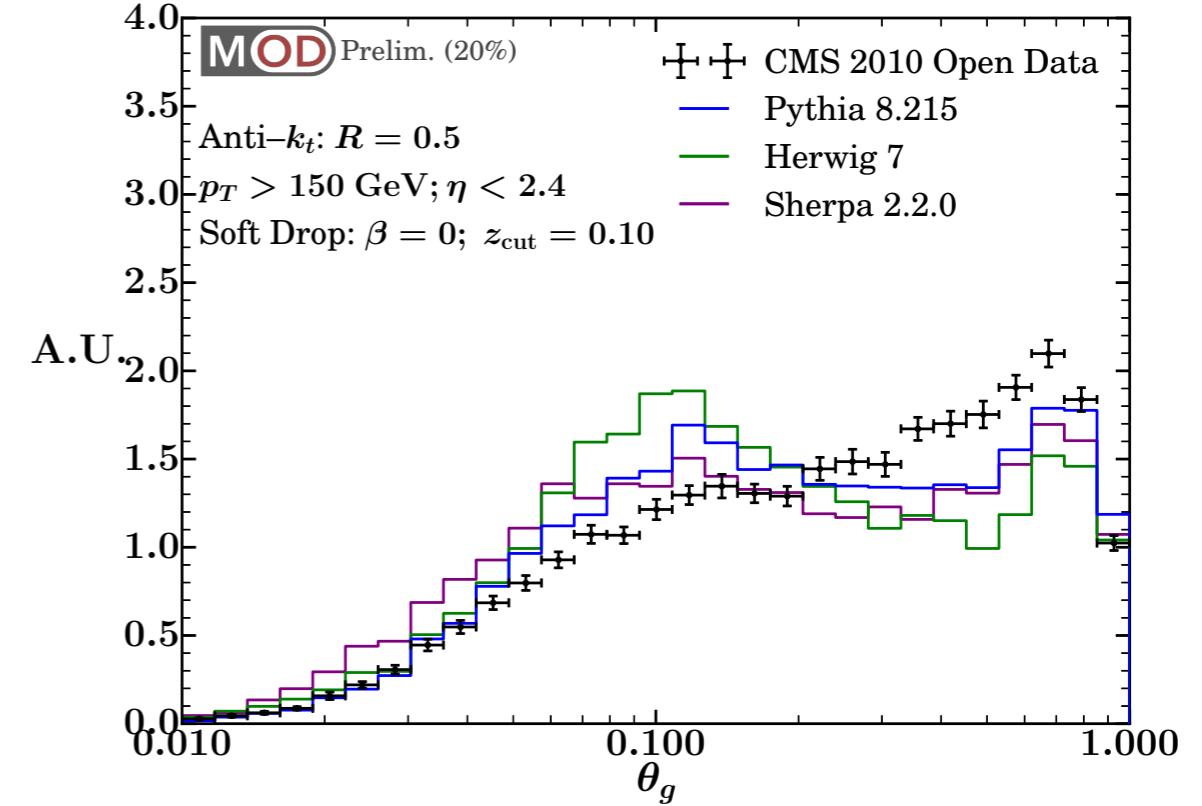
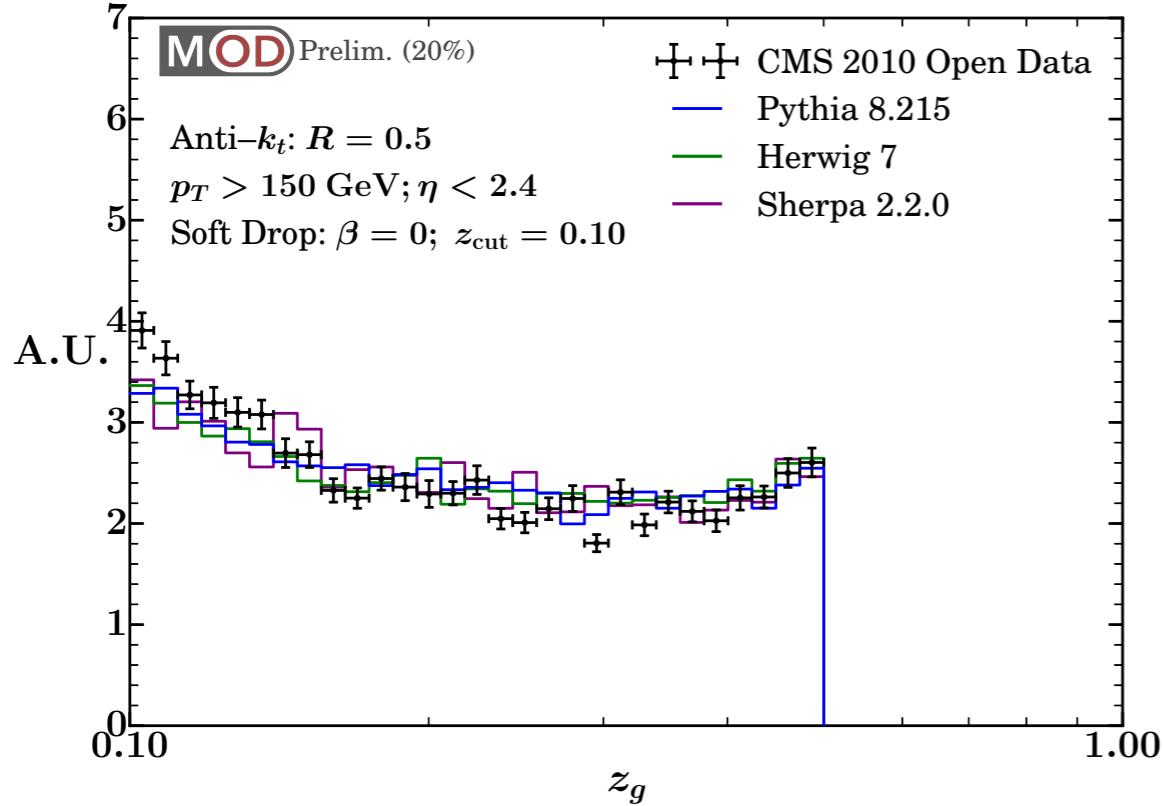
Jet Kinematics



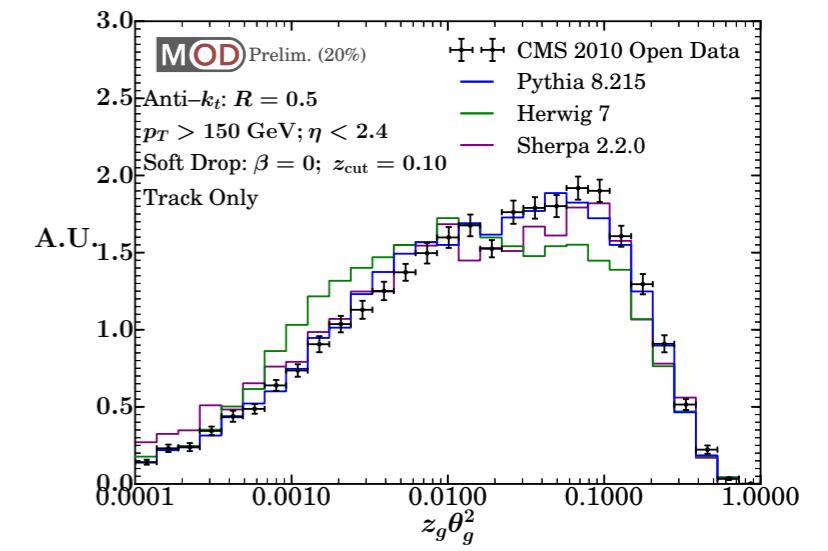
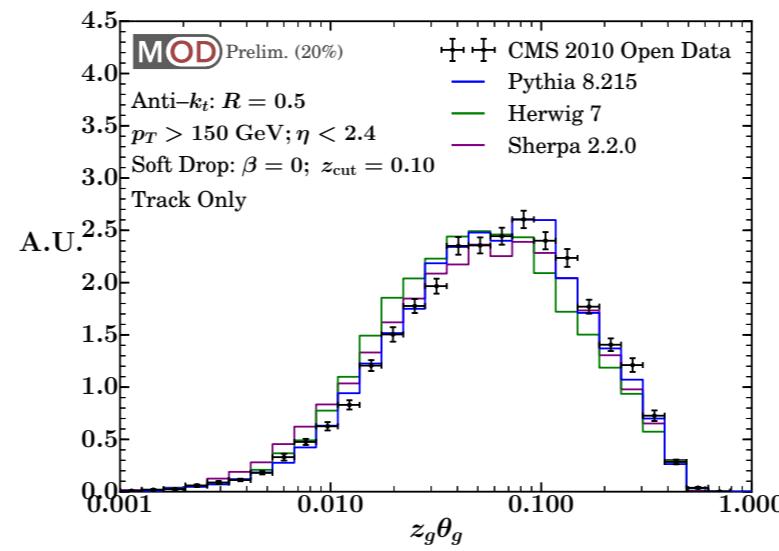
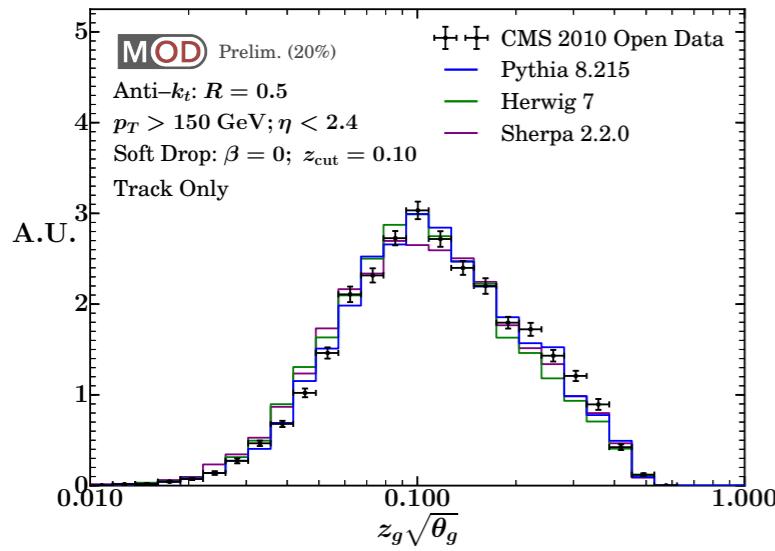
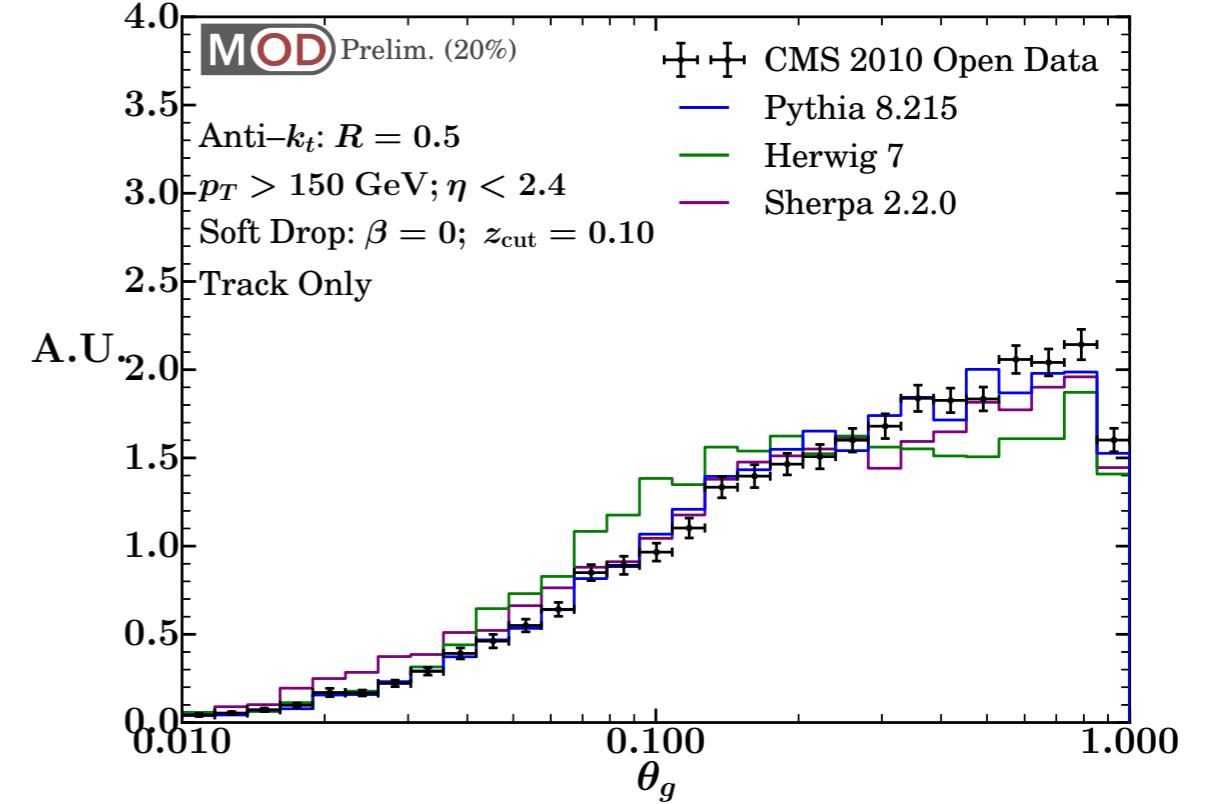
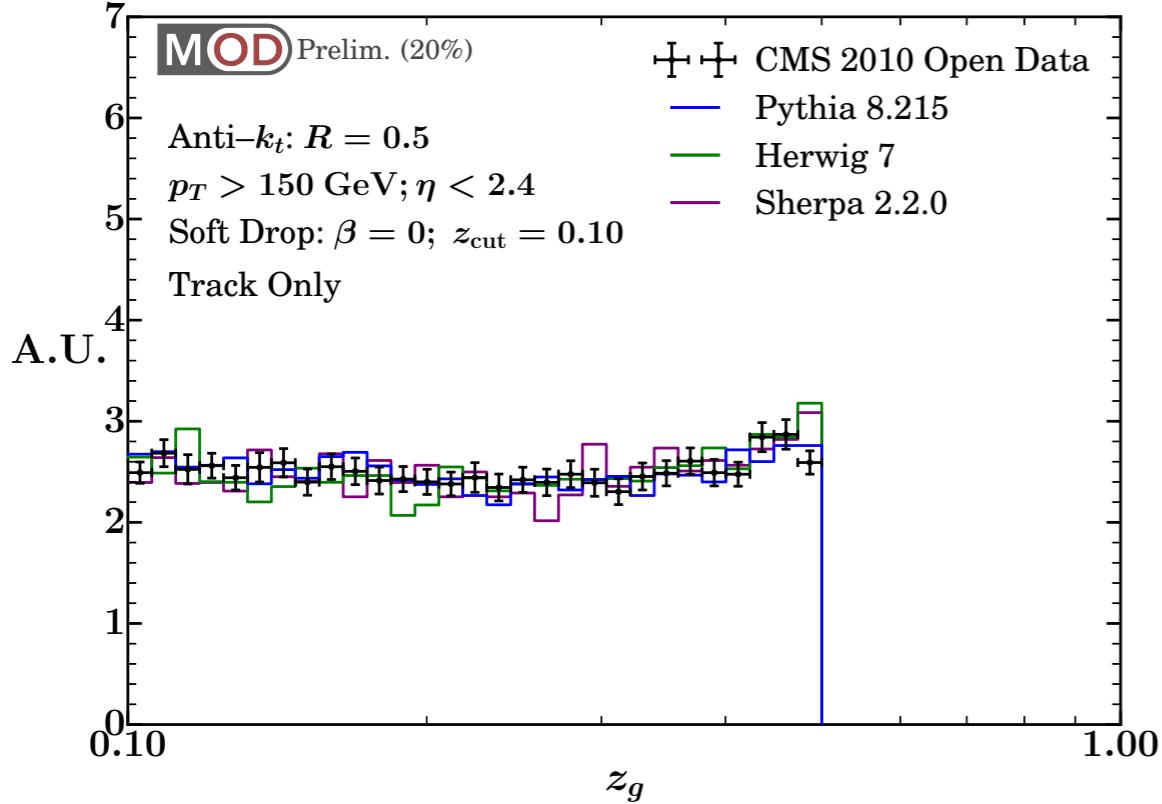
Simple Substructure



2-prong Substructure



Track-Only Substructure



Changing z_{cut}

