

Title: New Physics Gets a Boost: Jet Substructure at the Large Hadron Collider

Date: May 03, 2017 02:00 PM

URL: <http://pirsa.org/17050002>

Abstract: <p>Collisions at the Large Hadron Collider (LHC) are dominated by jets, collimated sprays of particles that arise from quantum chromodynamics (QCD) at high energies. With the remarkable performance of the ATLAS and CMS detectors, jets can now be characterized not just by their overall direction and energy but also by their substructure. In this talk, I highlight the increasingly important role that jet substructure is playing in searches for dark matter and other new physics at the LHC, especially when exploring extreme kinematic regimes involving large Lorentz boosts.</p>

<p>I also explain how innovative theoretical studies of jet substructure have taught us surprising lessons about QCD, revealing new probes of hot dense matter and universal features of gauge theories.</p>

New Physics Gets a Boost

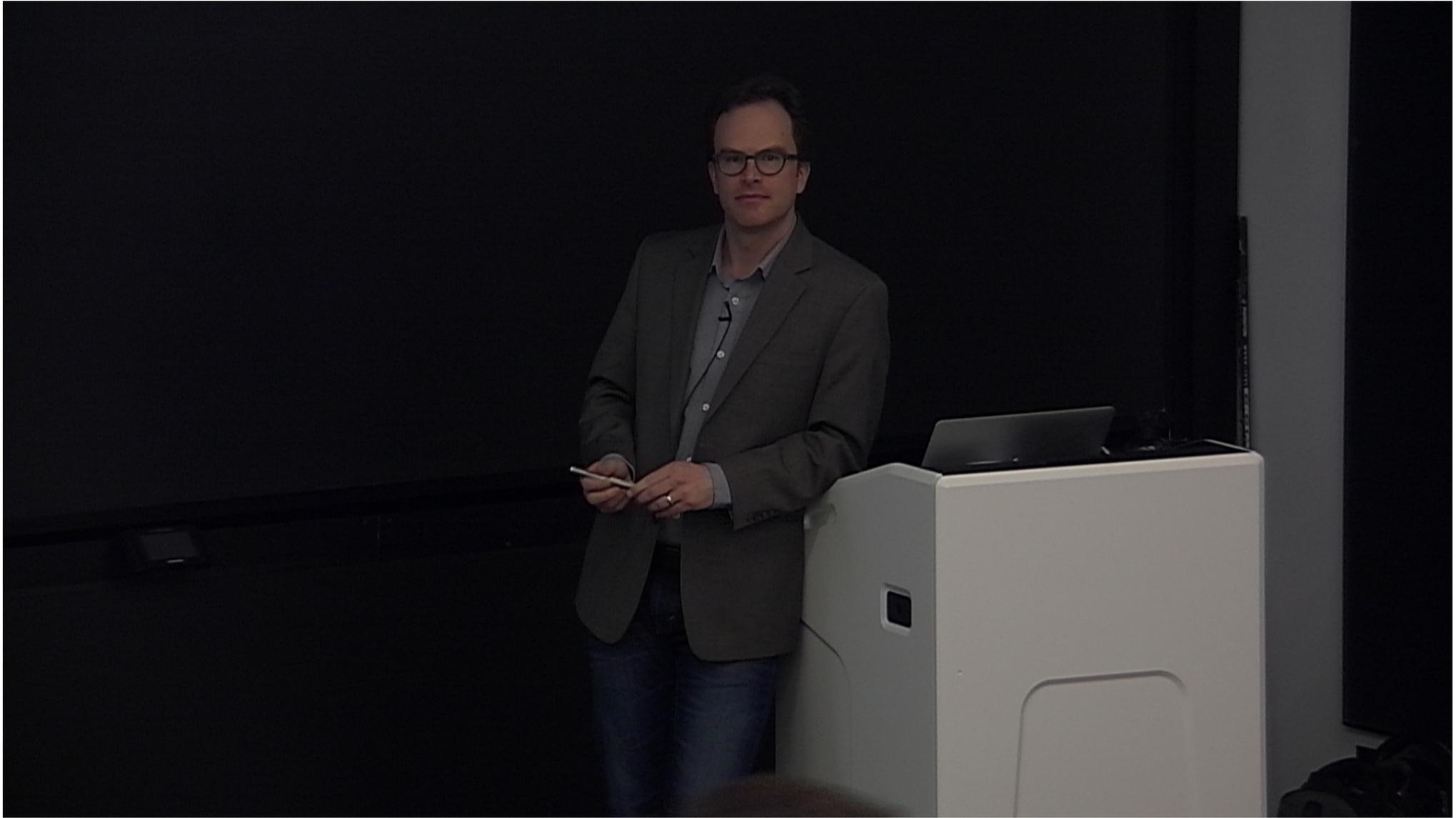
Jet Substructure at the Large Hadron Collider

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

Jesse Thaler

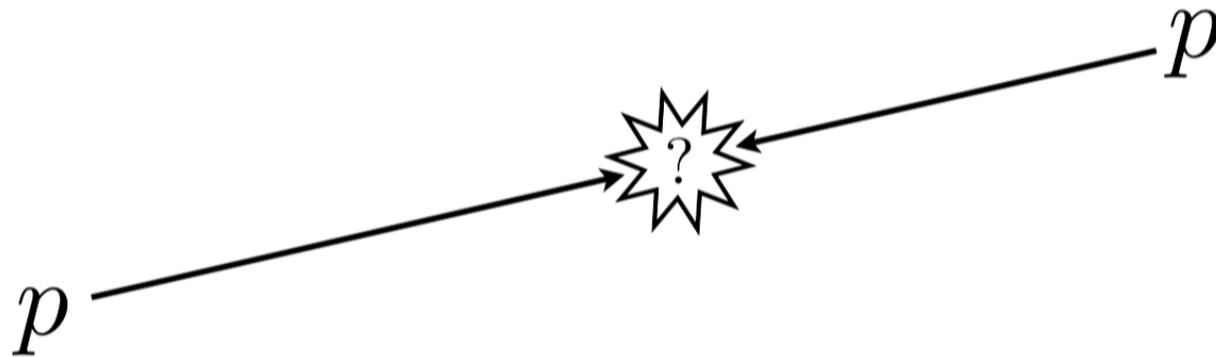


Perimeter Institute Colloquium
May 3, 2017



New Physics Gets a Boost

Jet Substructure at the Large Hadron Collider



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

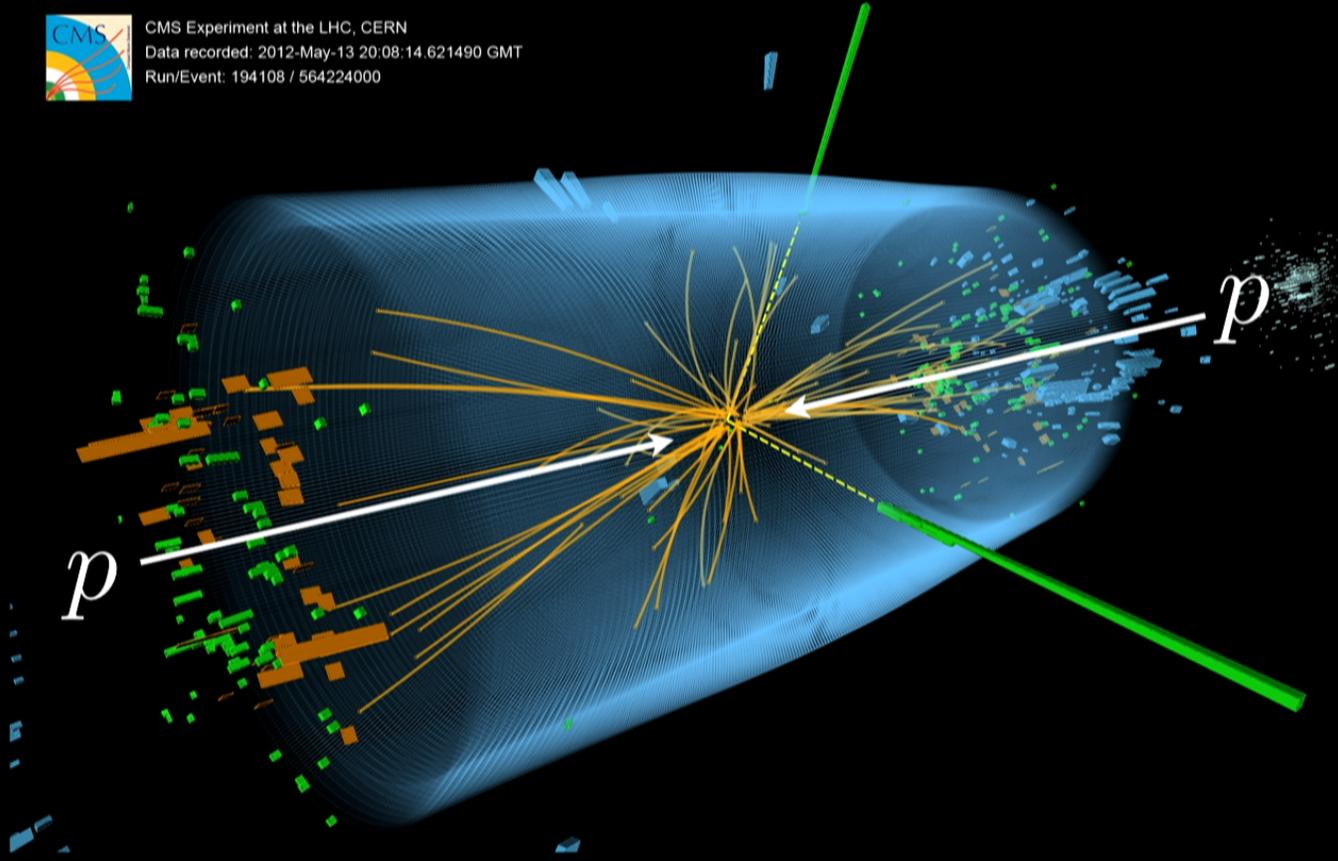
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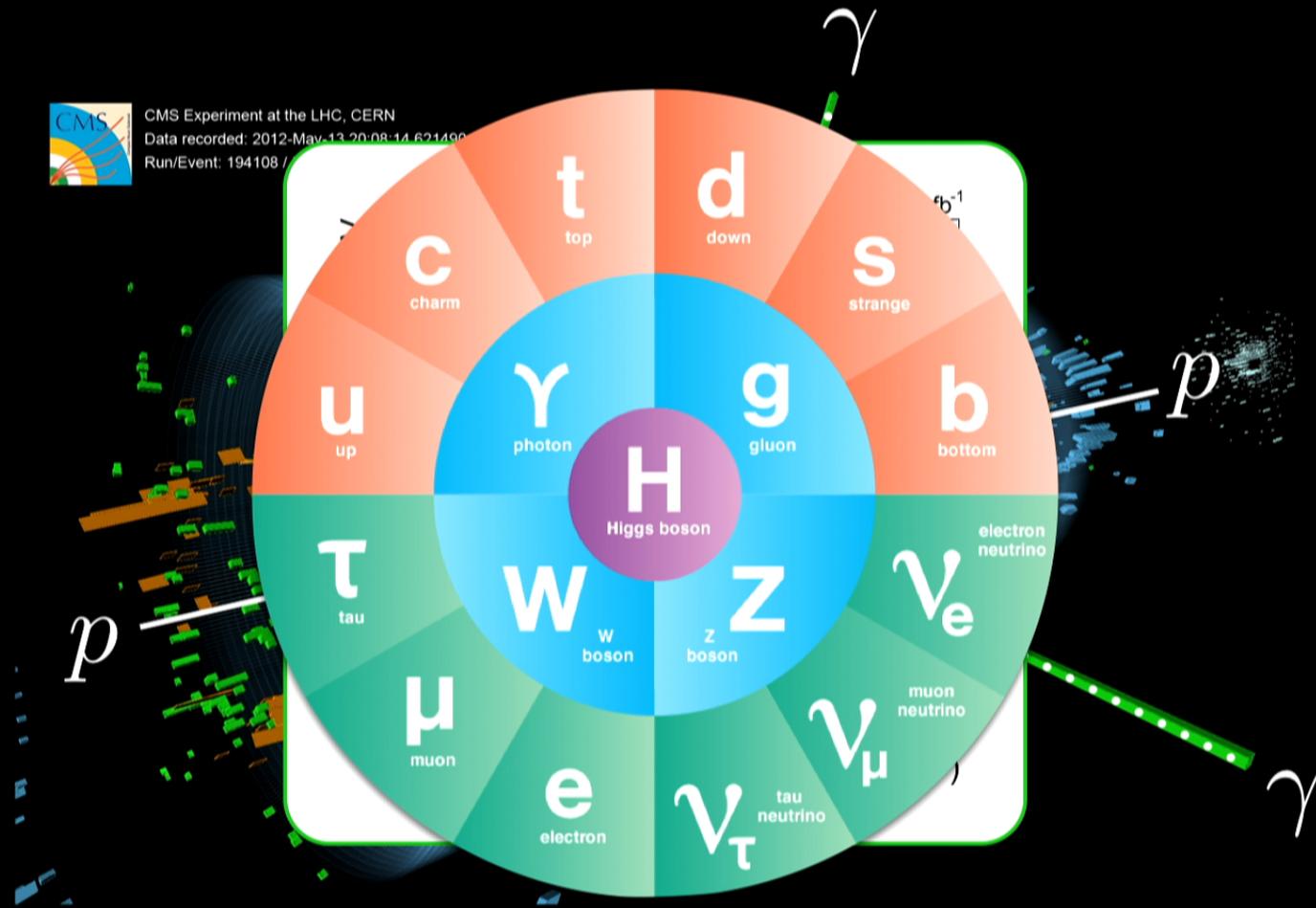


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Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000



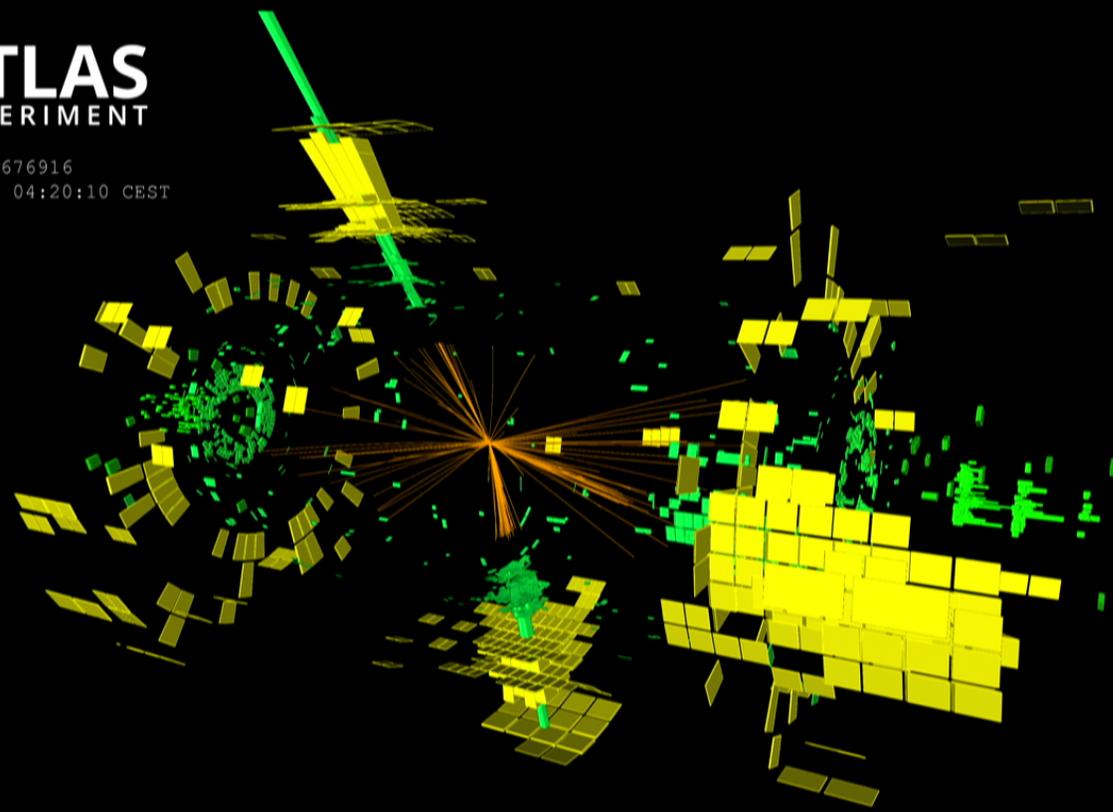


CMS Experiment at the LHC, CERN
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Run/Event: 194108 /





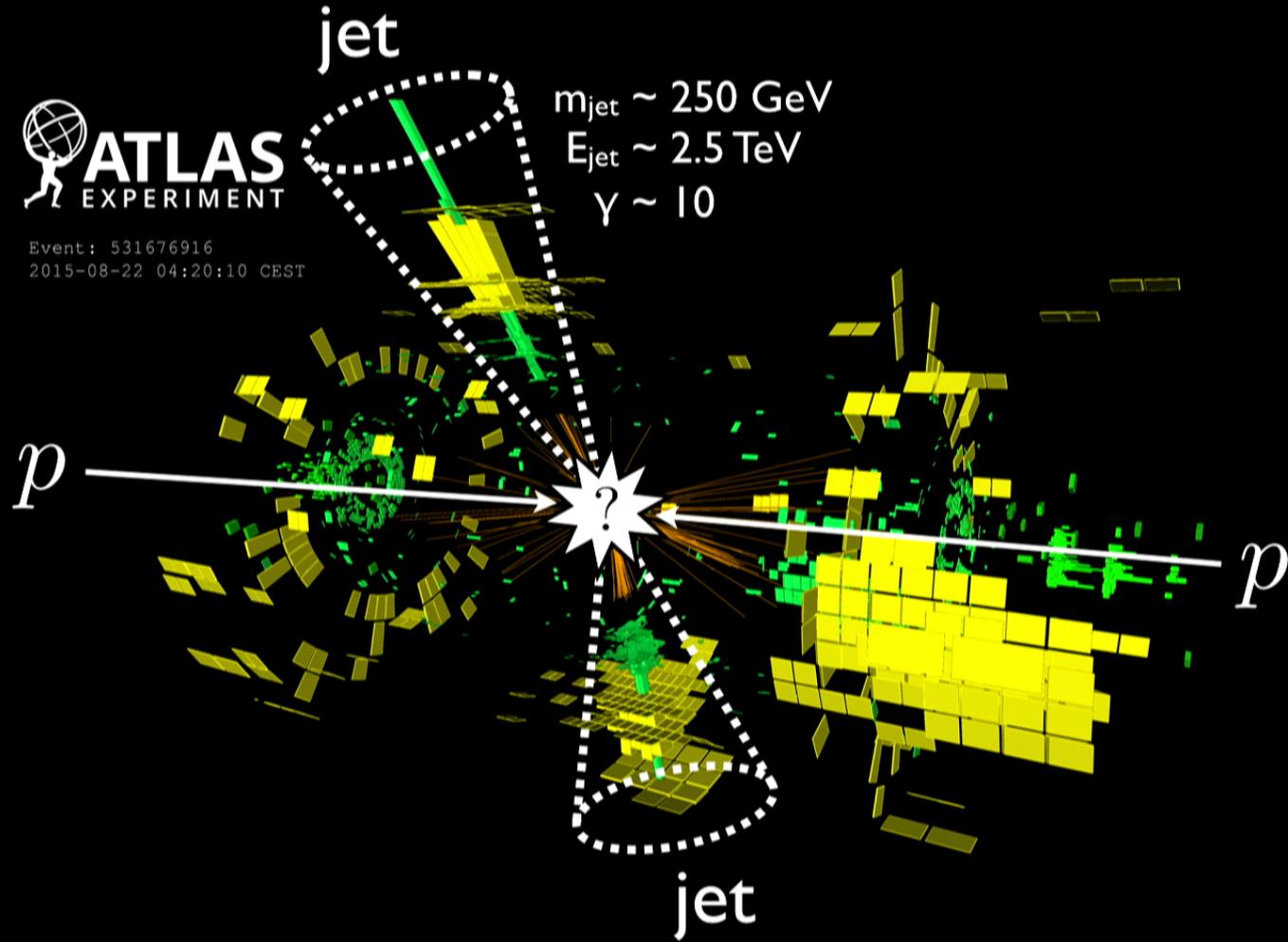
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Event: 531676916
2015-08-22 04:20:10 CEST





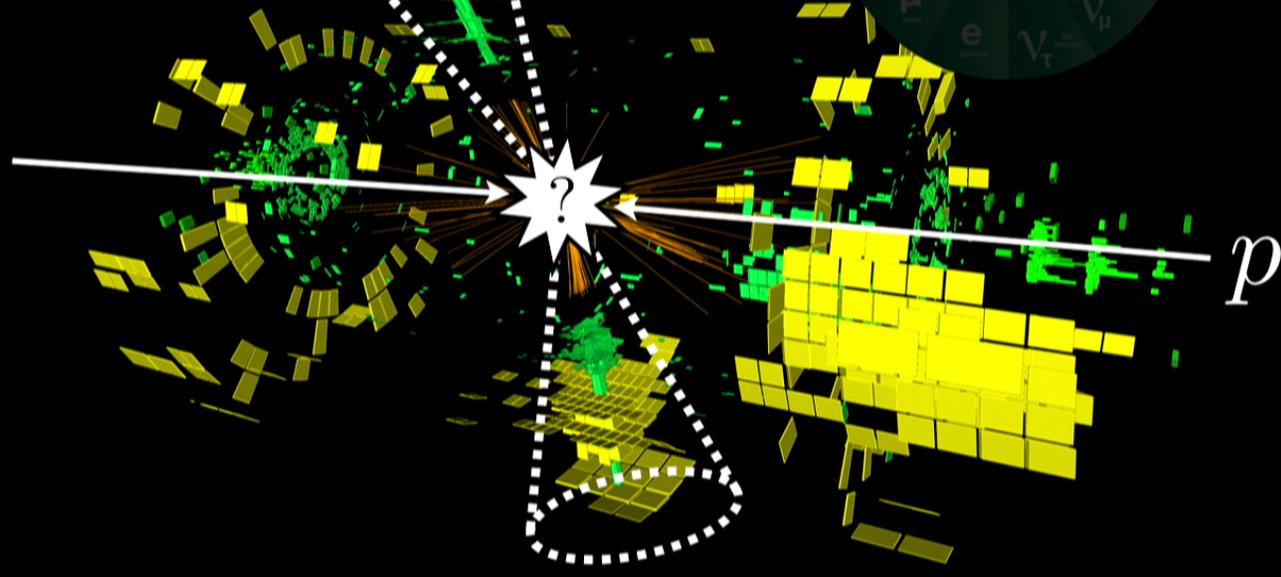
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jet

$m_{\text{jet}} \sim 250 \text{ GeV}$
 $E_{\text{jet}} \sim 2.5 \text{ TeV}$
 $\gamma \sim 10$

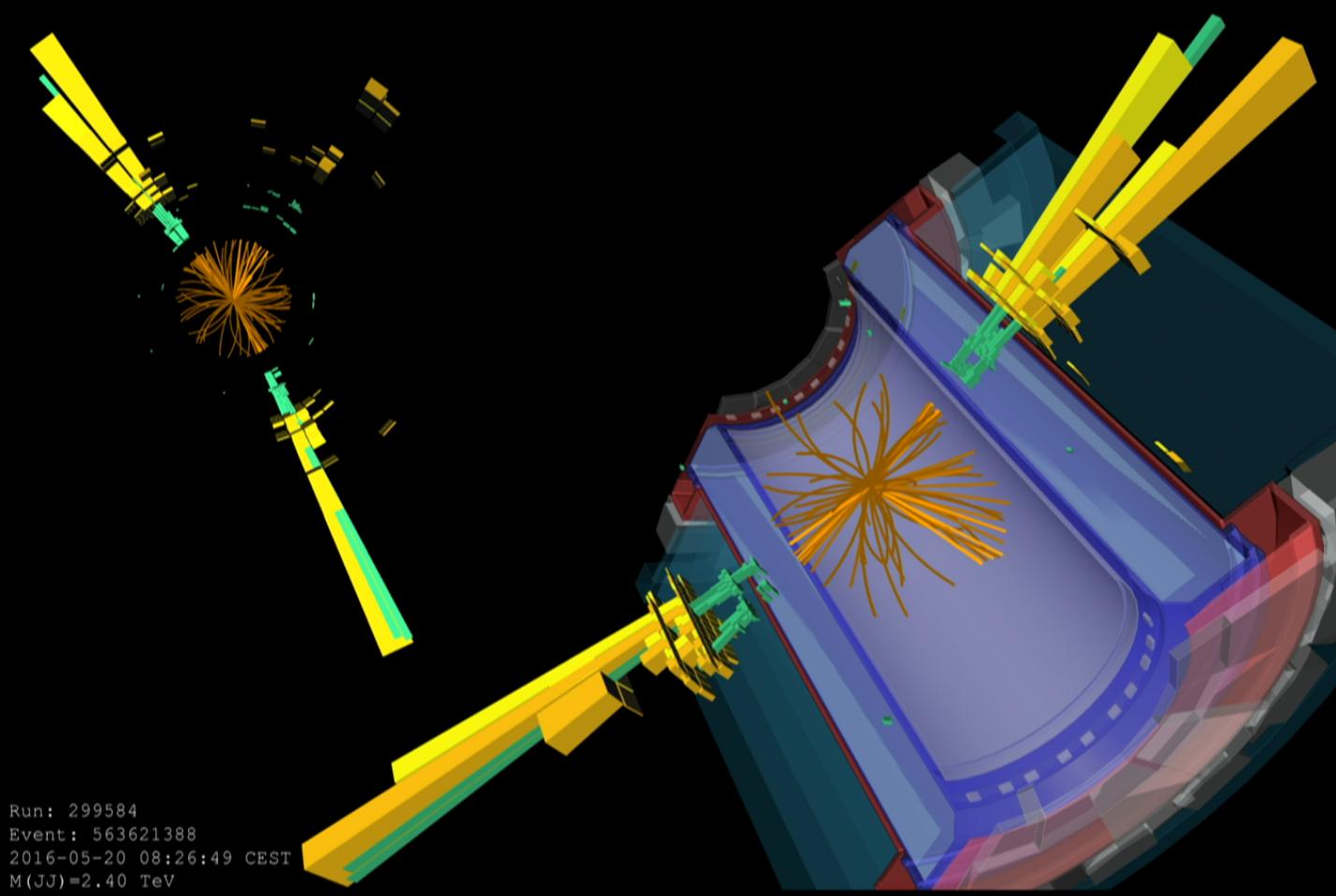


p



p

jet

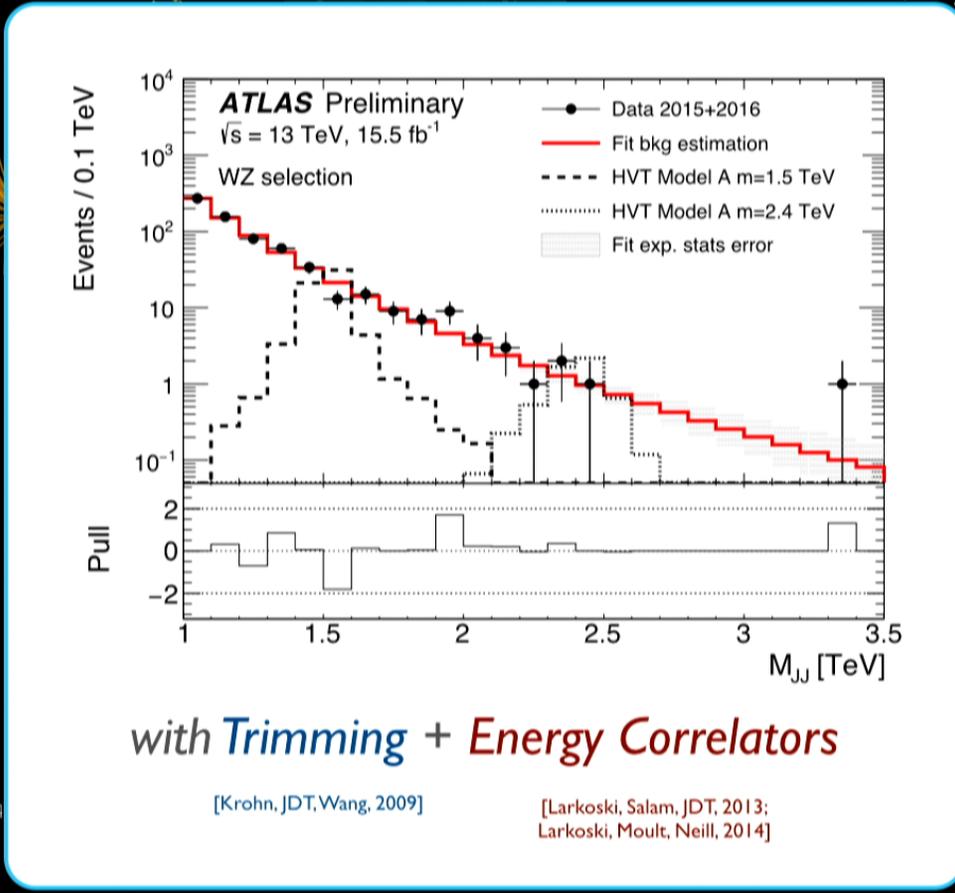
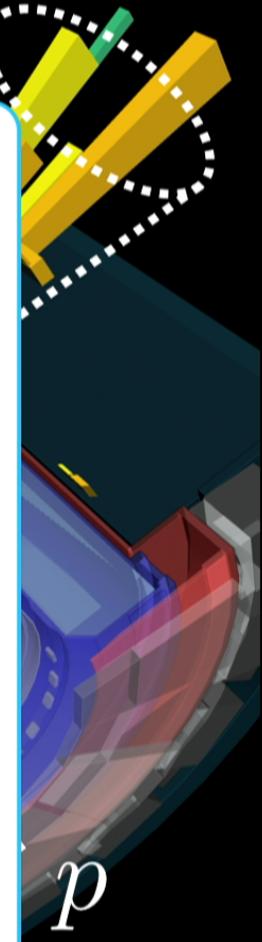


Run: 299584
Event: 563621388
2016-05-20 08:26:49 CEST
M(JJ)=2.40 TeV



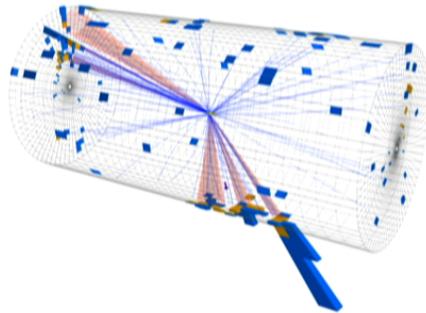
$m_{\text{jet}} \sim 80 \text{ GeV}$
 $E_{\text{jet}} \sim 1.3 \text{ TeV}$

2-prong jet

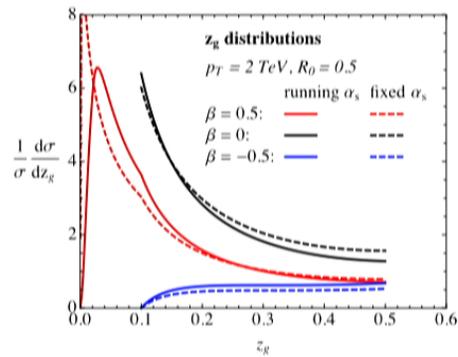


Run: 299584
 Event: 563621388
 2016-05-20 08:26:4
 M(JJ)=2.40 TeV

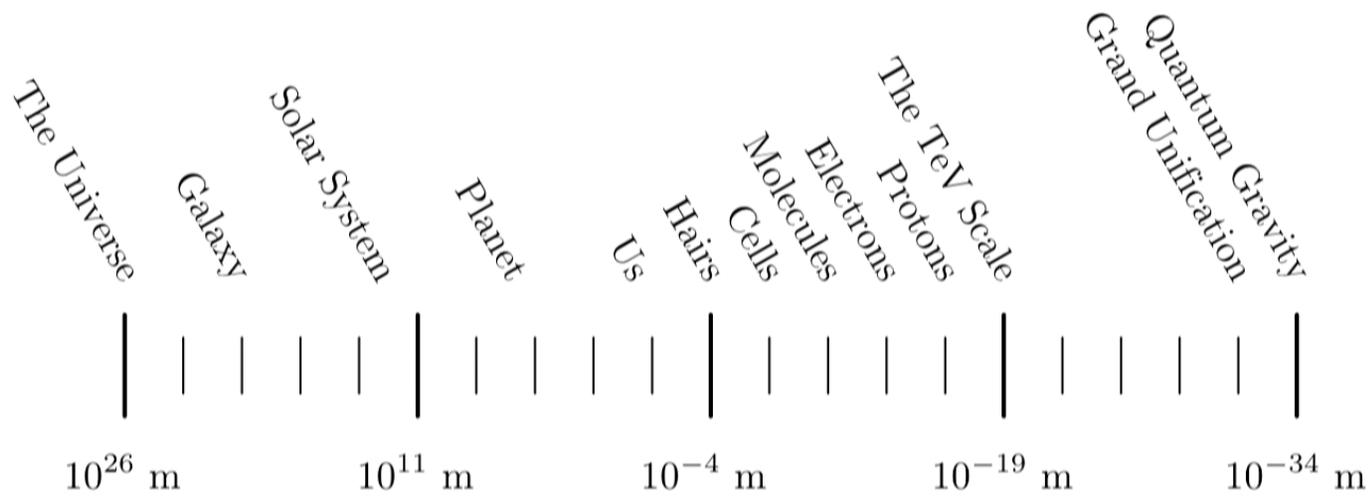
Jet Substructure

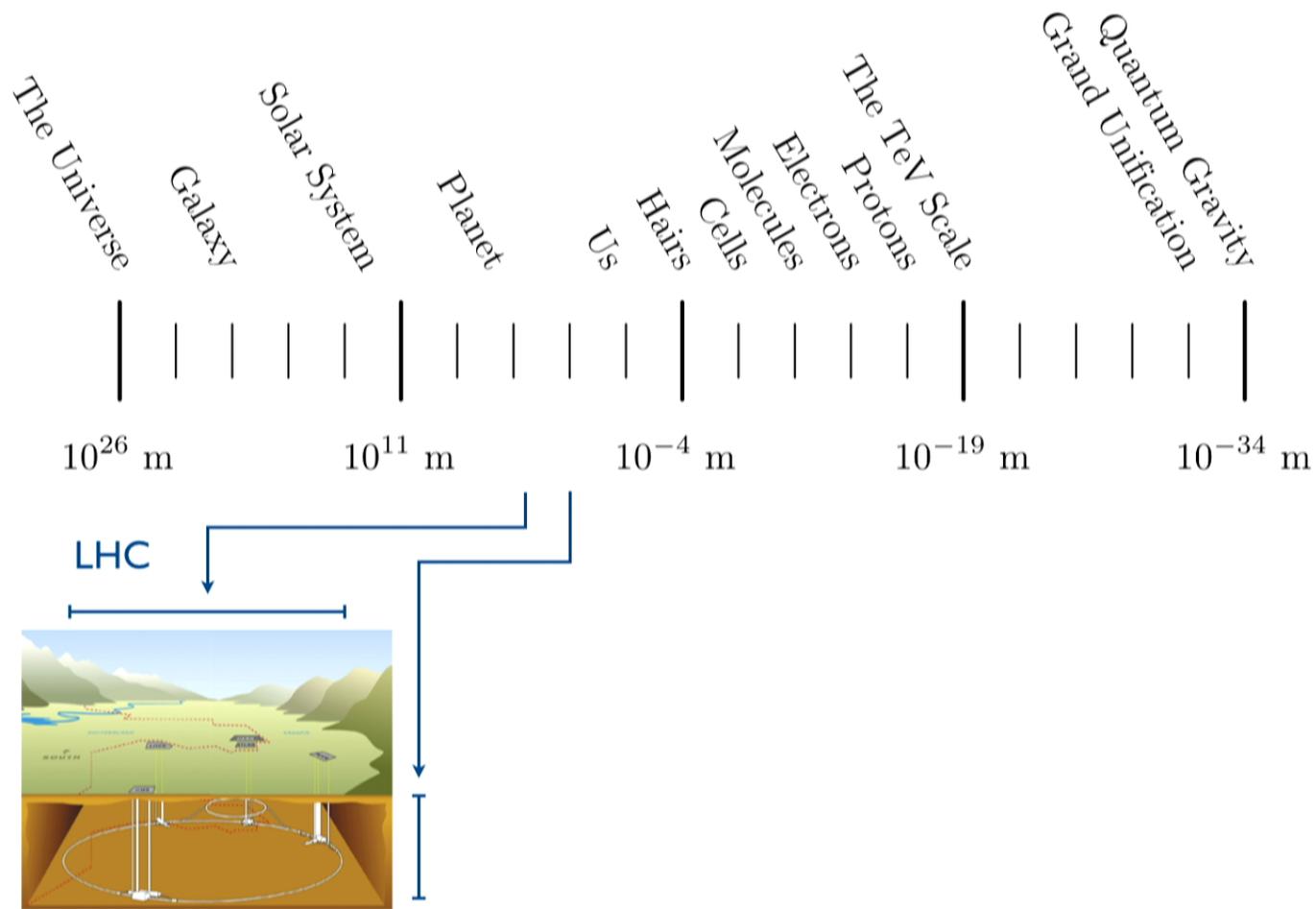


*Boosting the Search
for New Phenomena*

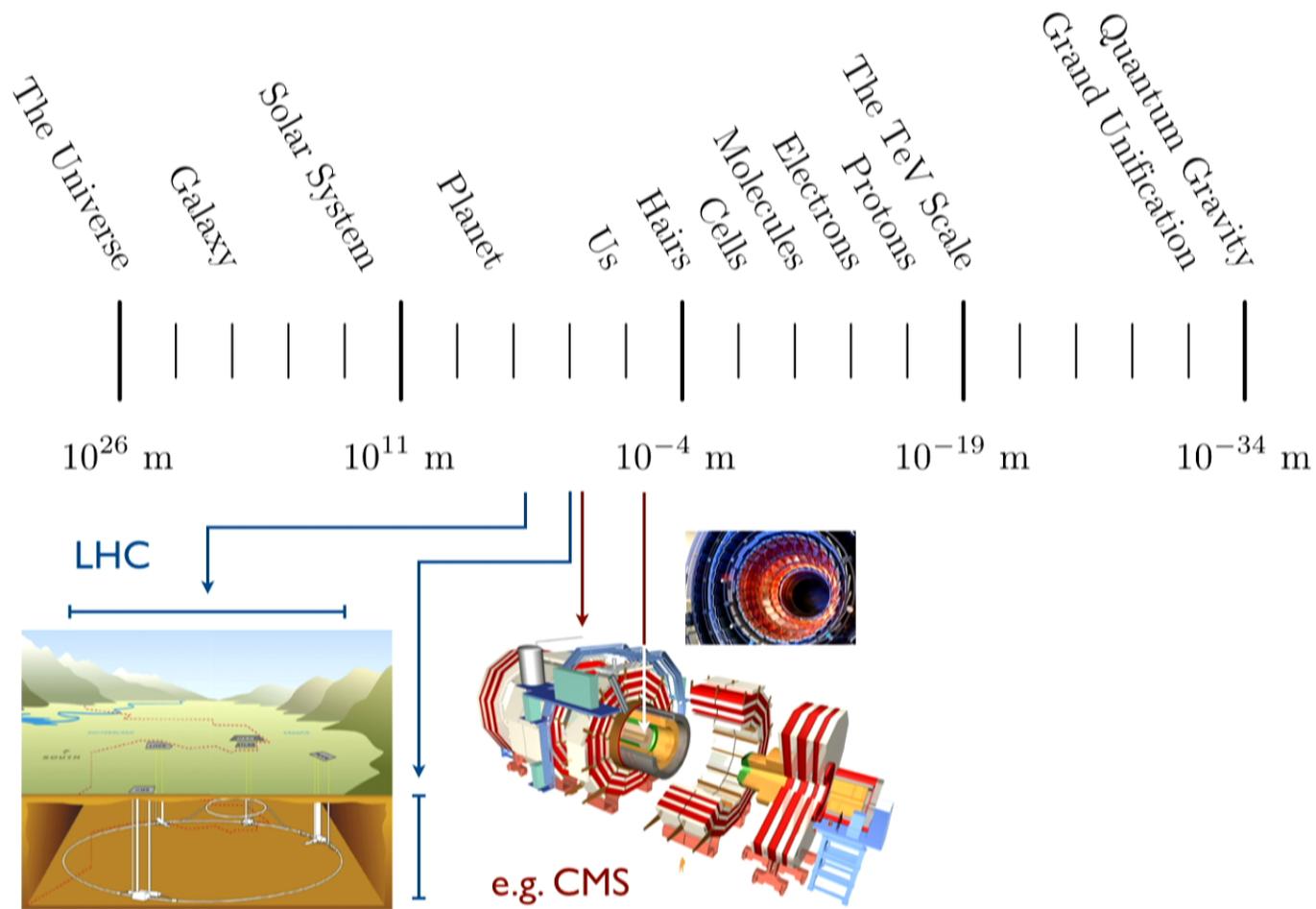


*Pushing the Boundaries
of Quantum Field Theory*

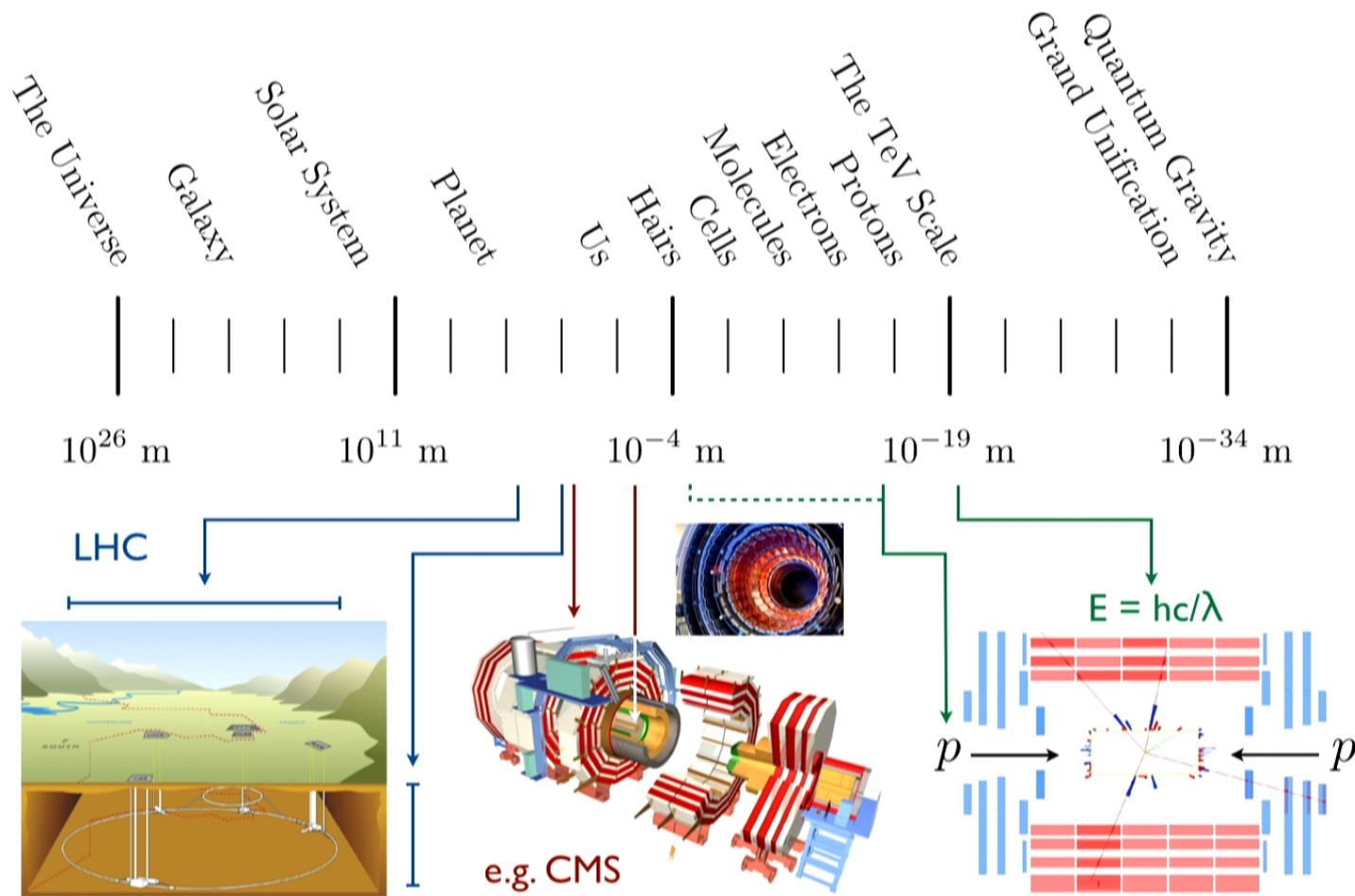




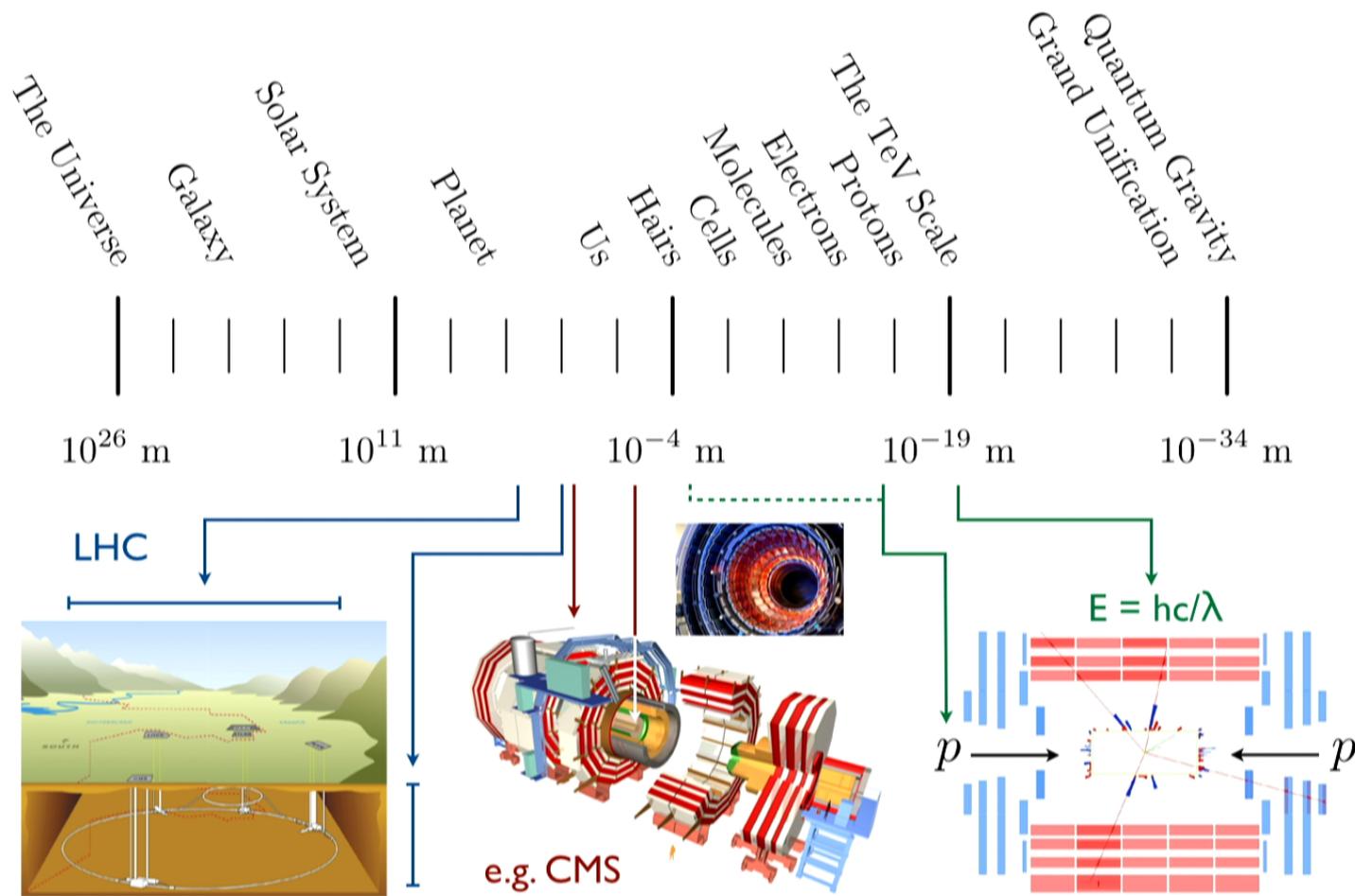
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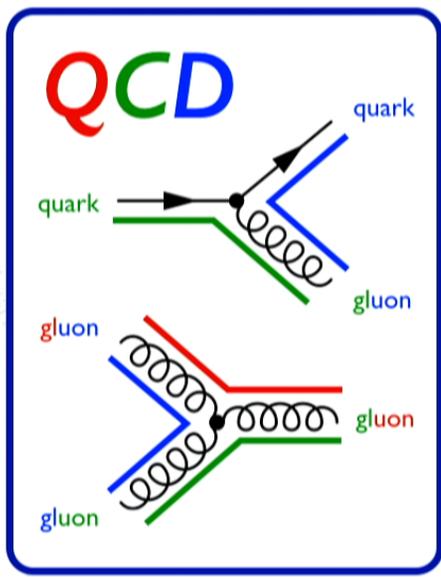
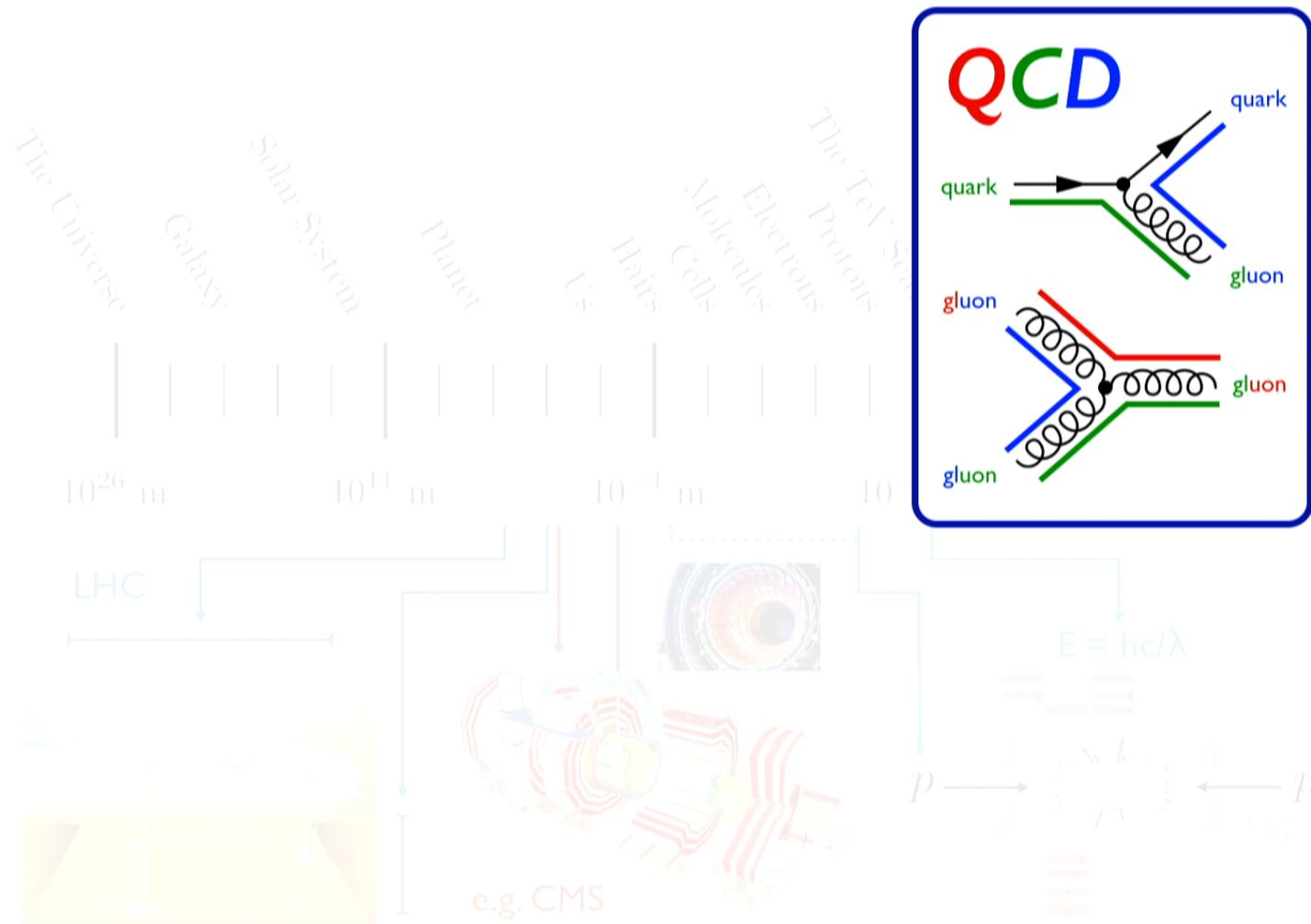
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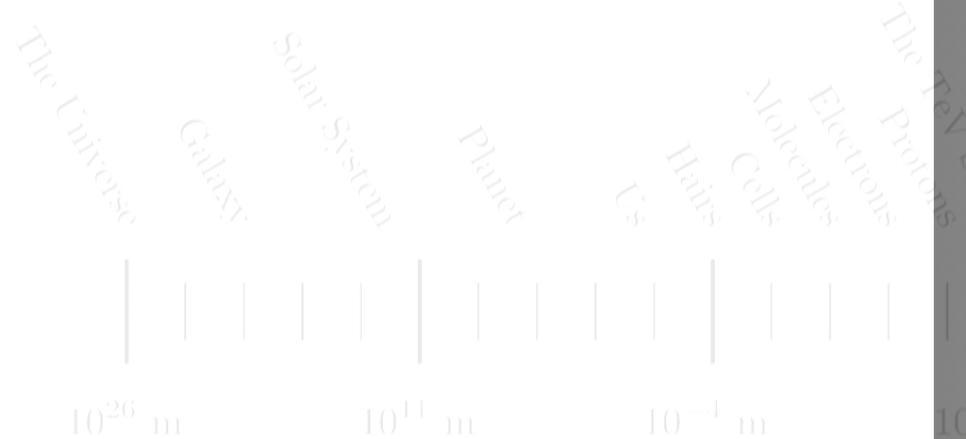


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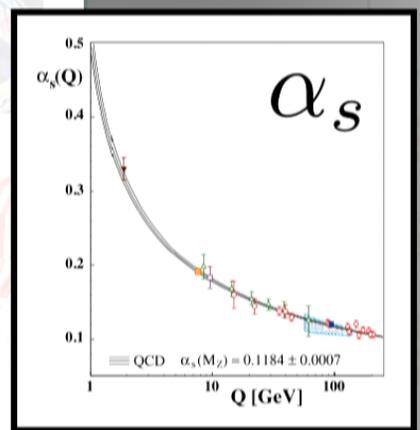
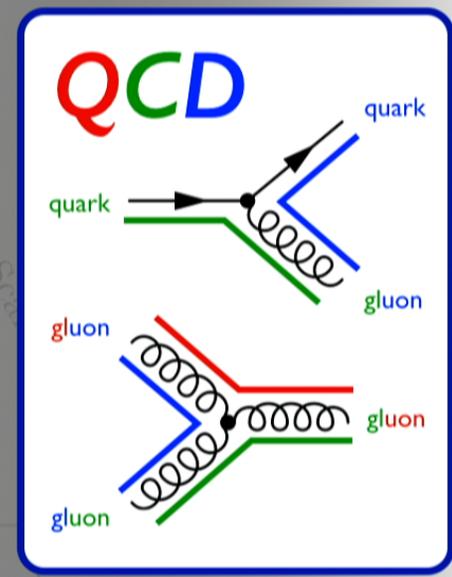




LHC



e.g. CMS



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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

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



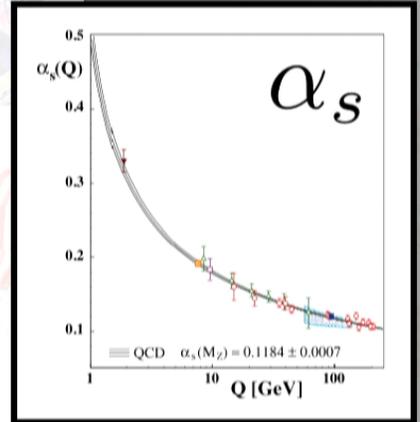
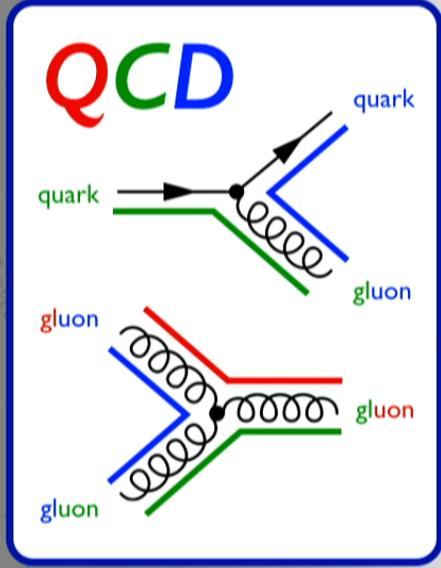
Tetraquarks (?)

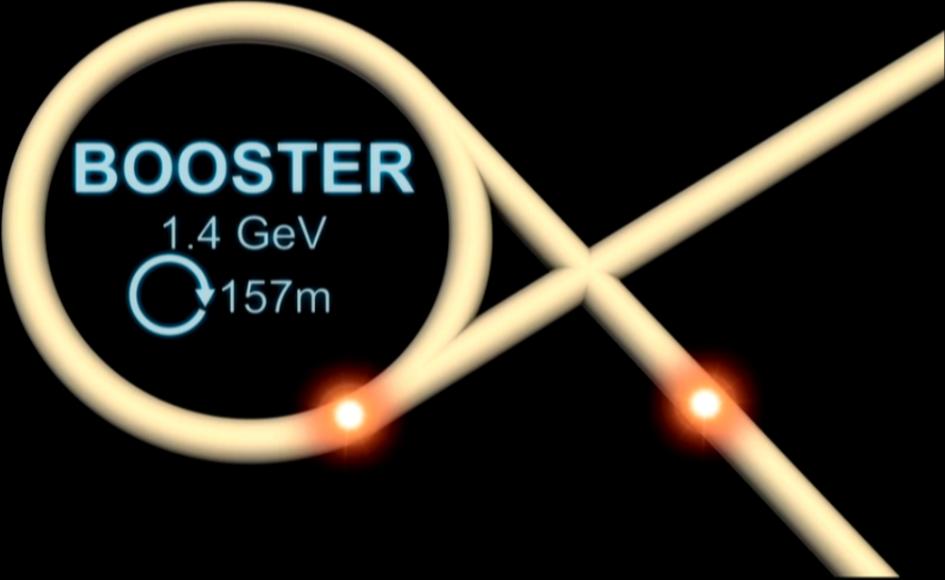
$X(3872) Y(4260) Z(4430) \dots$

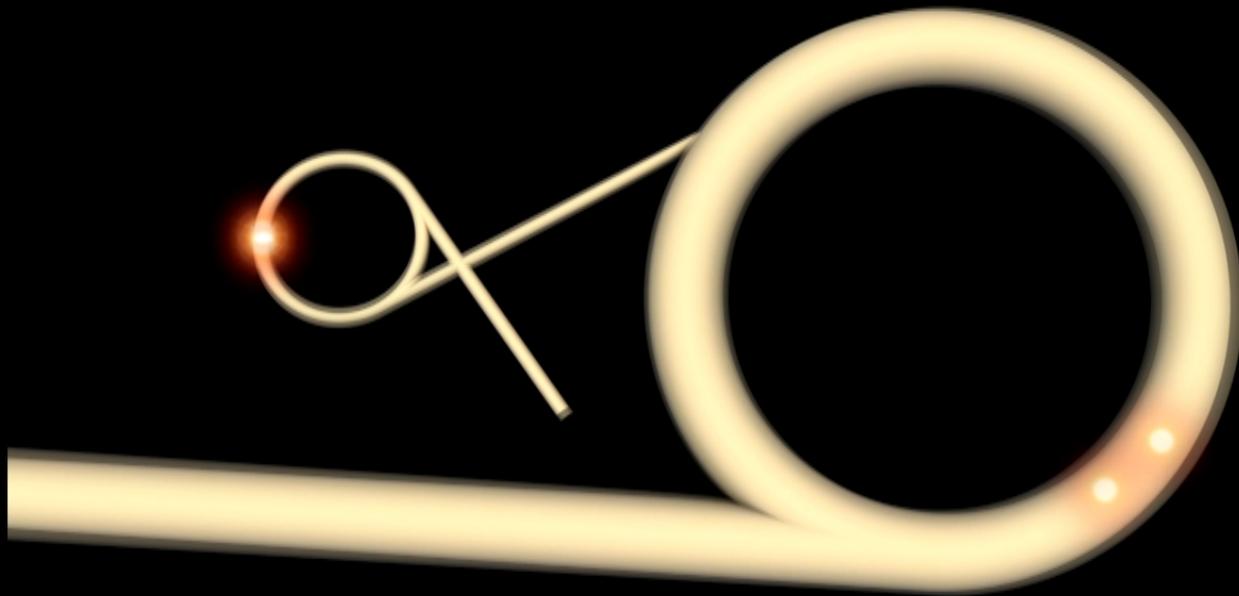


Pentaquarks (?)

$P_c^+(4450) \dots$

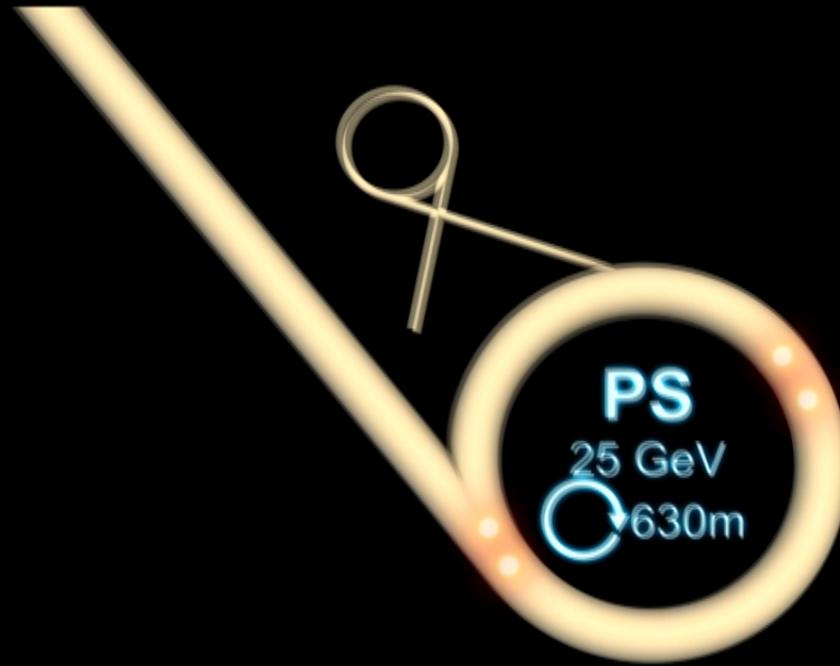


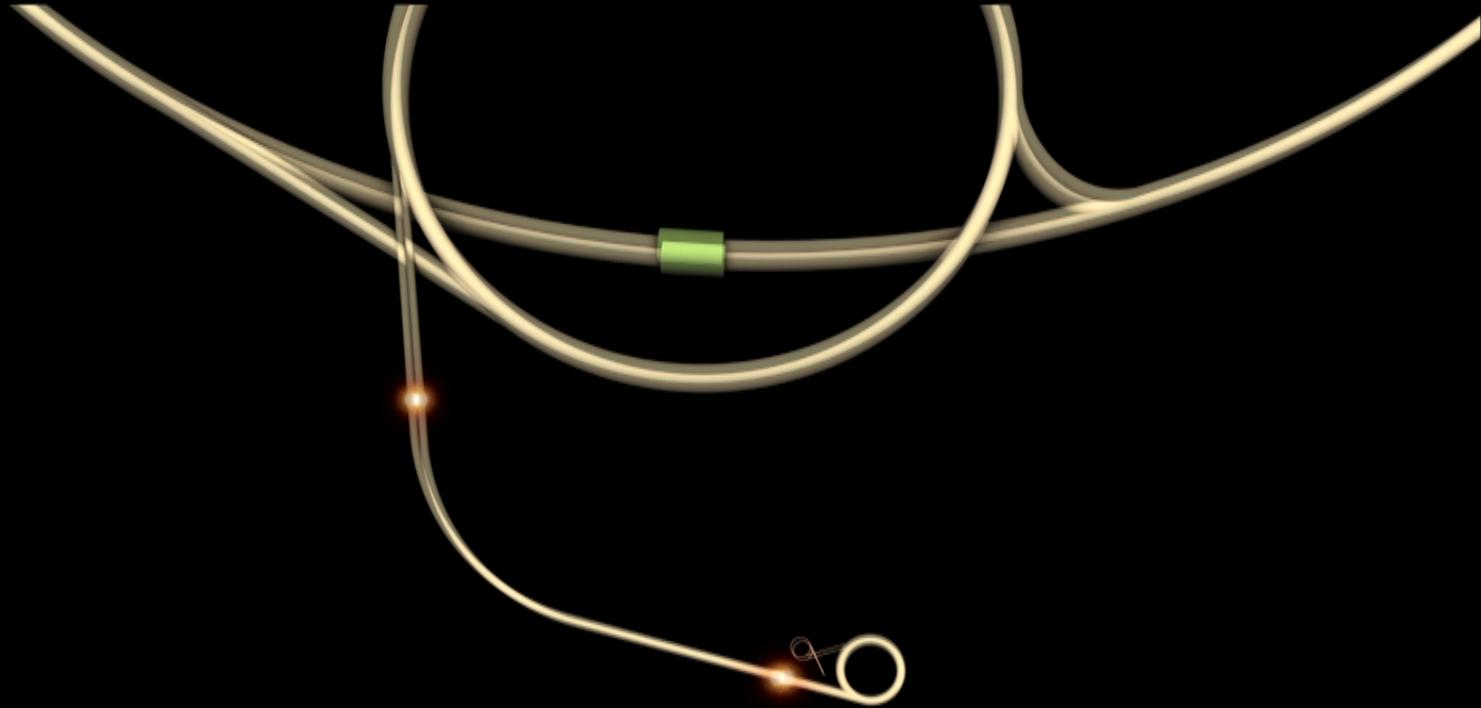




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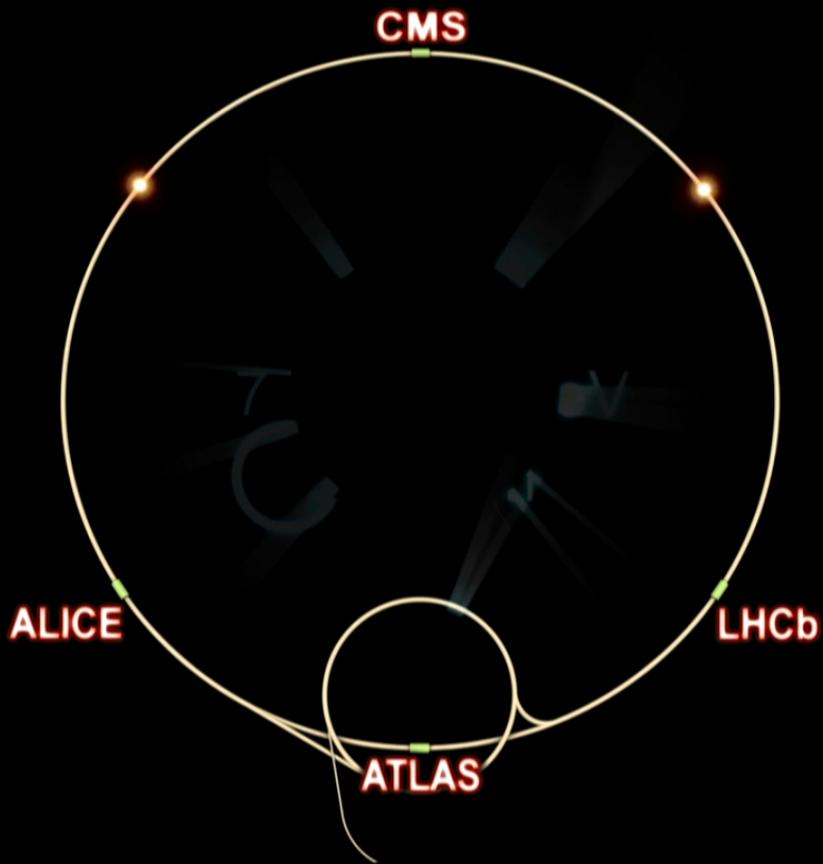


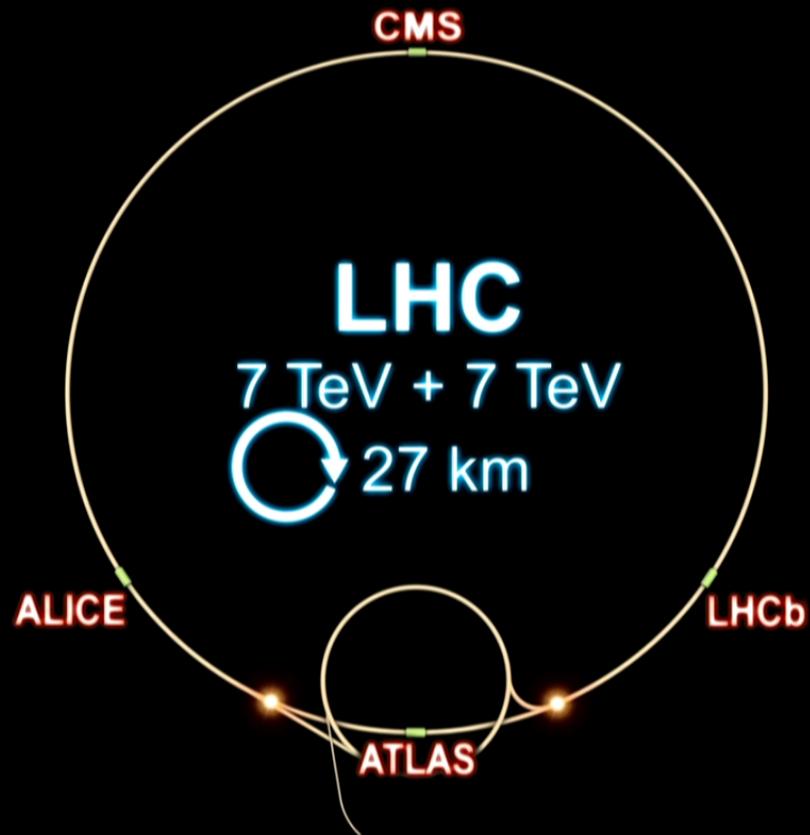


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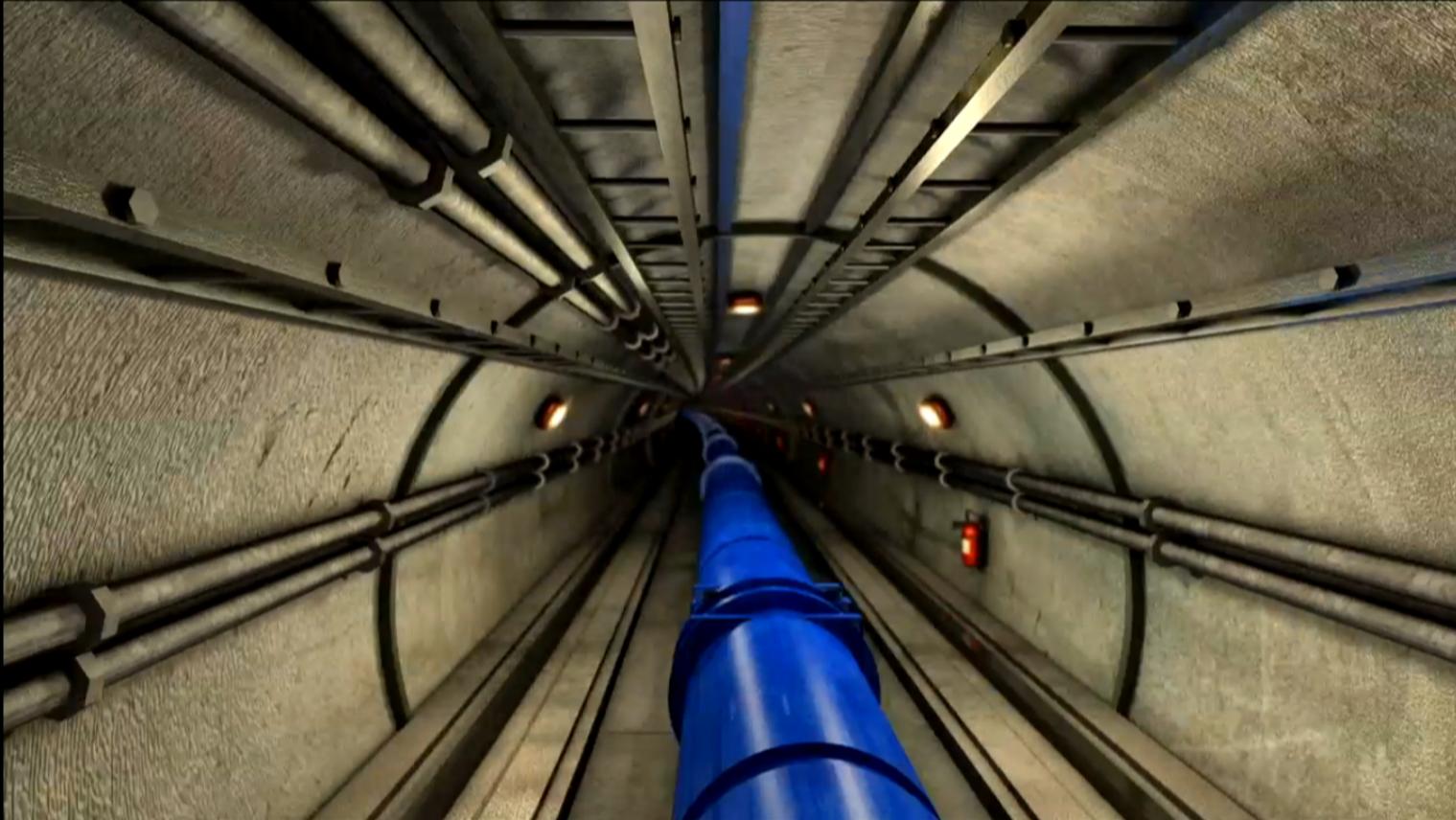








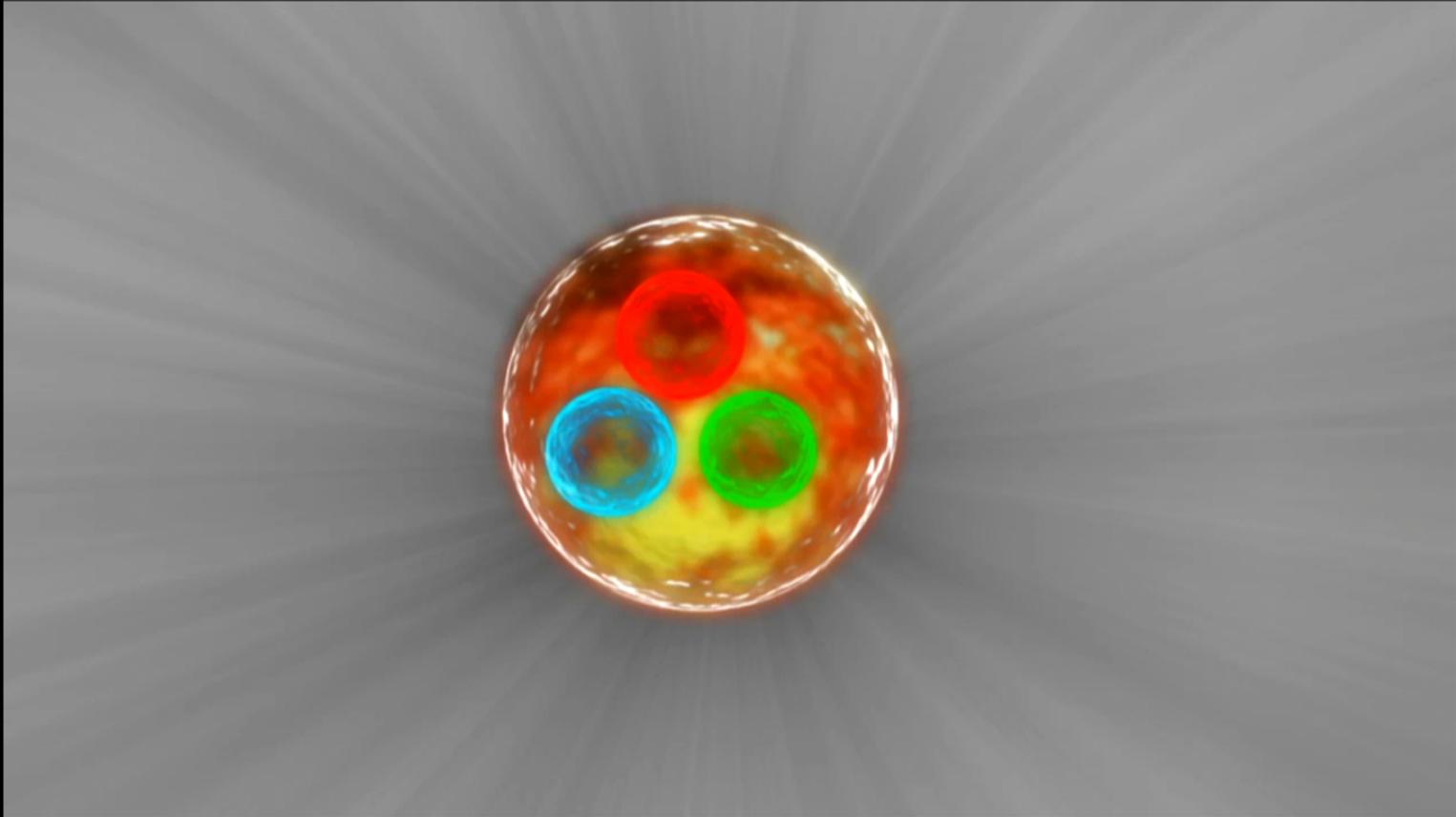
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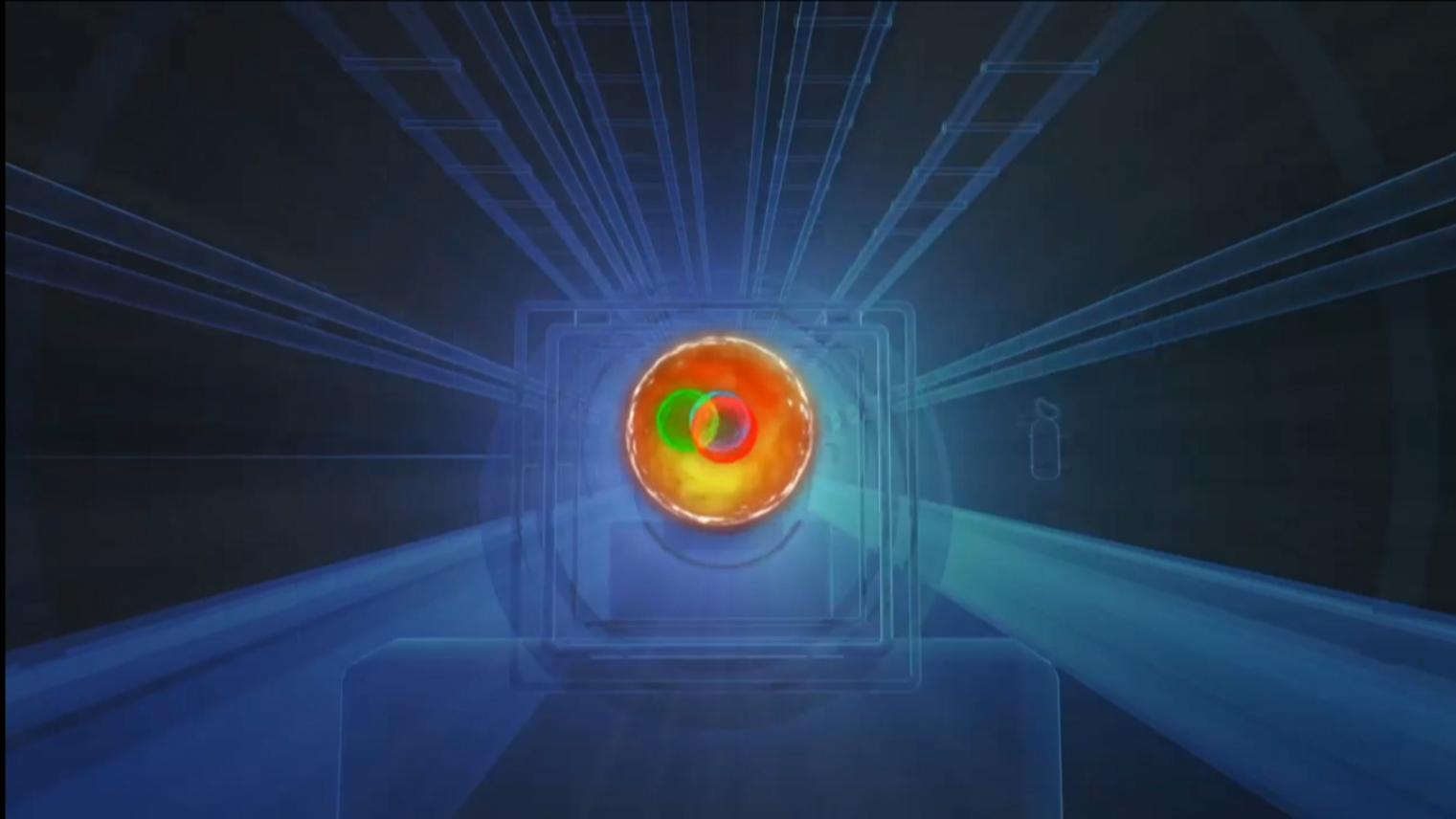


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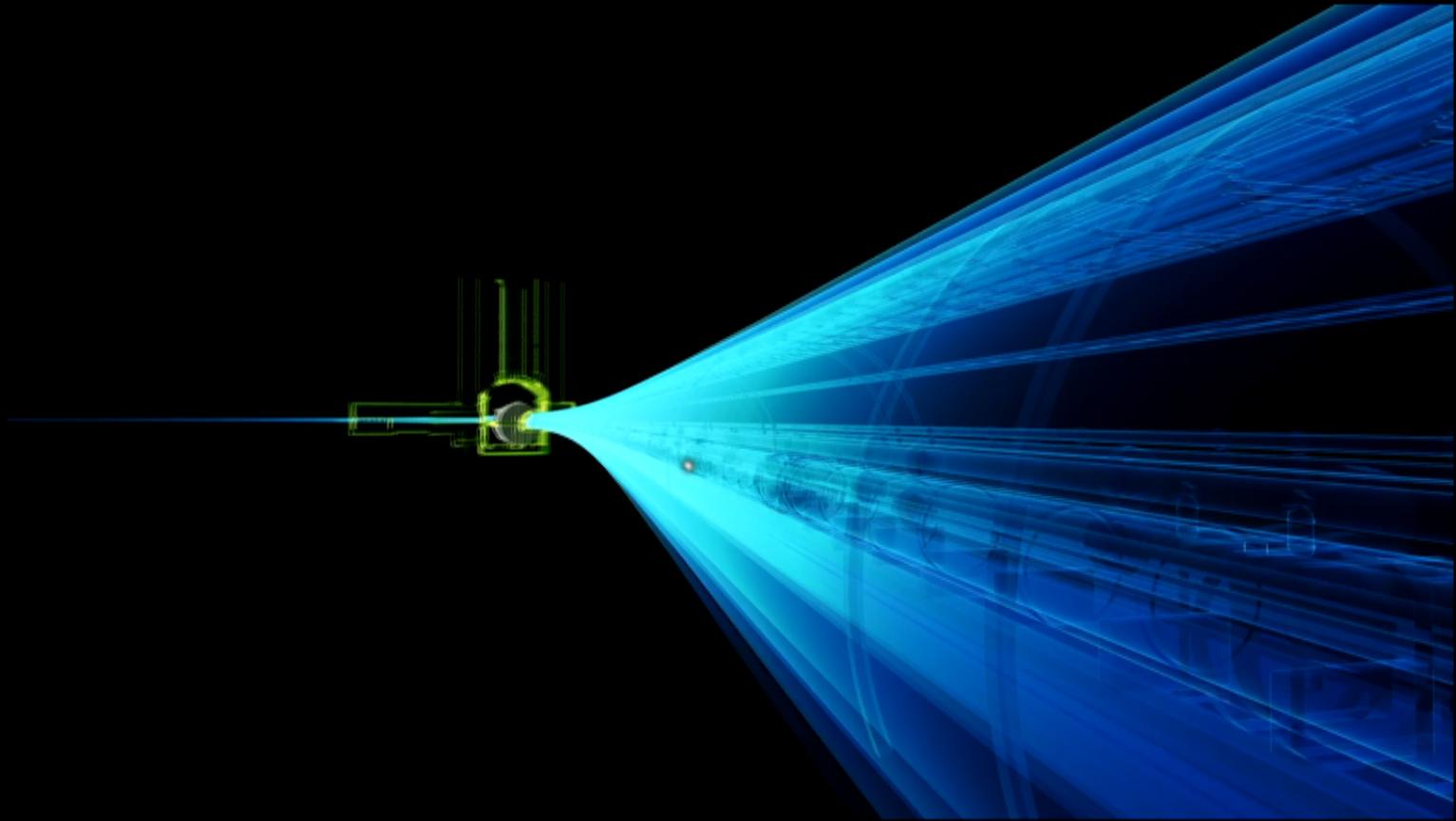
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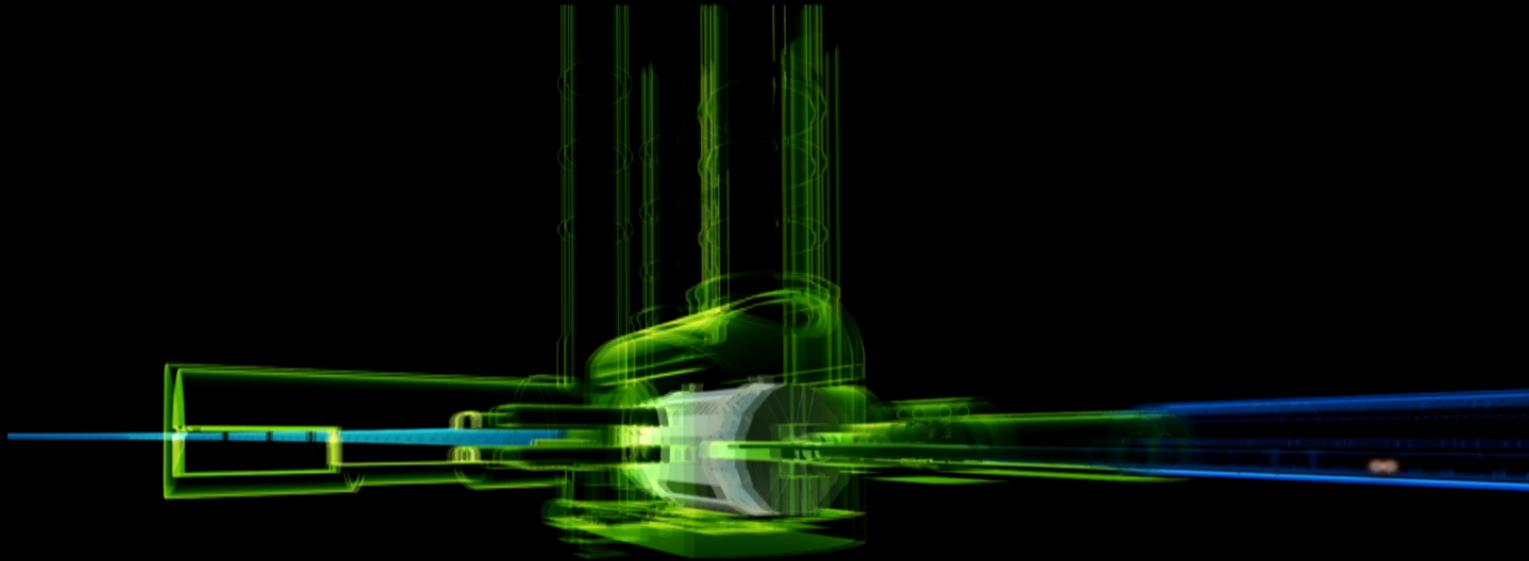
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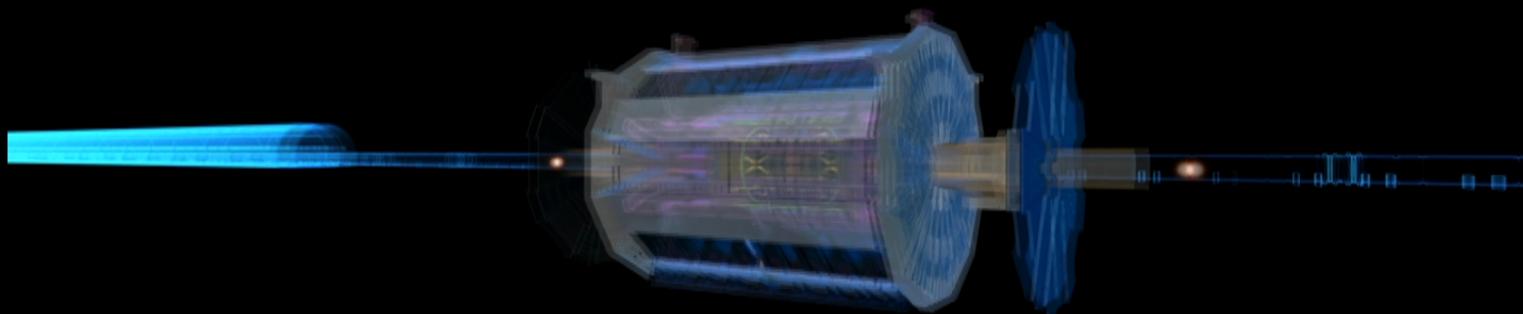
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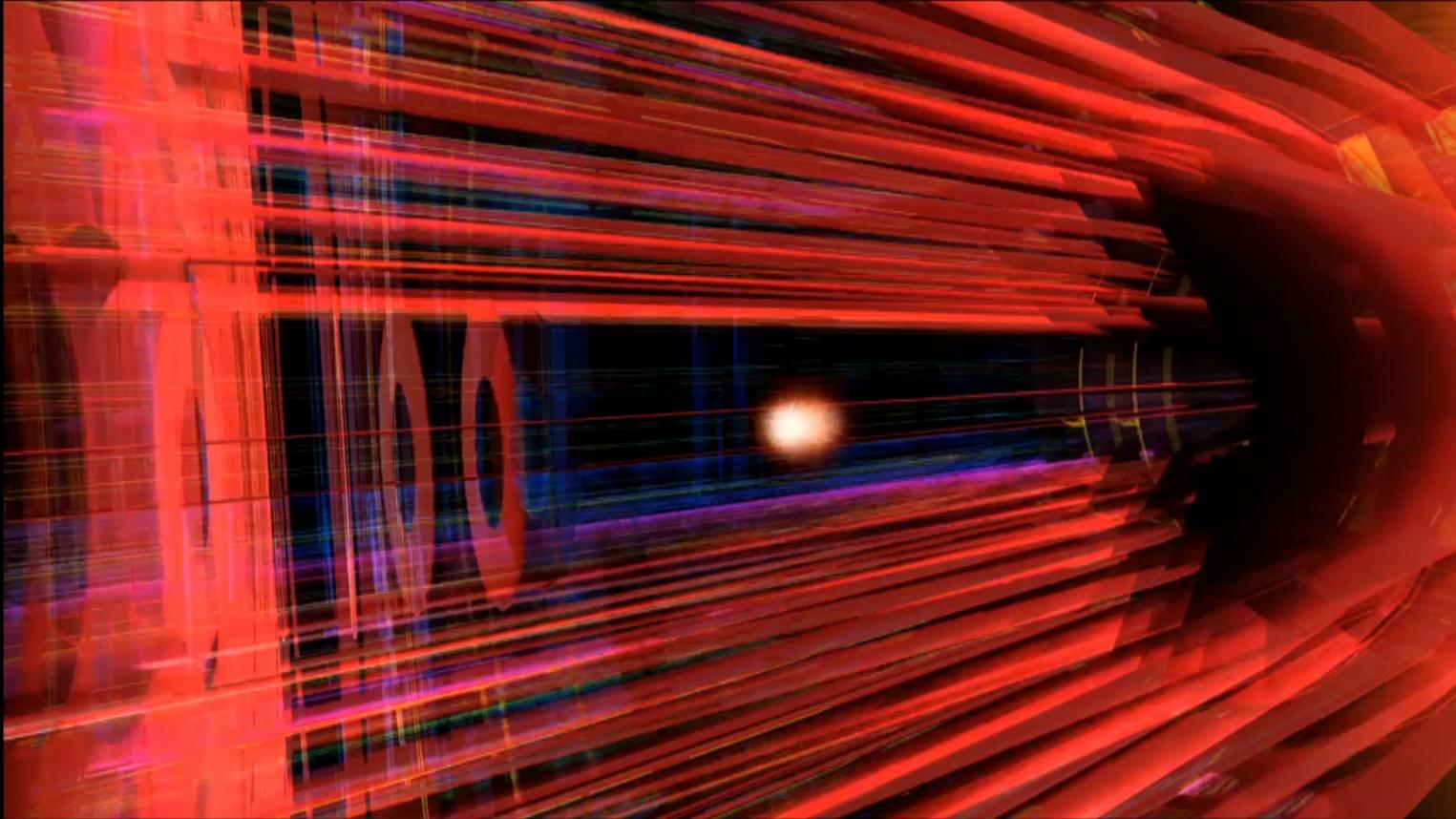
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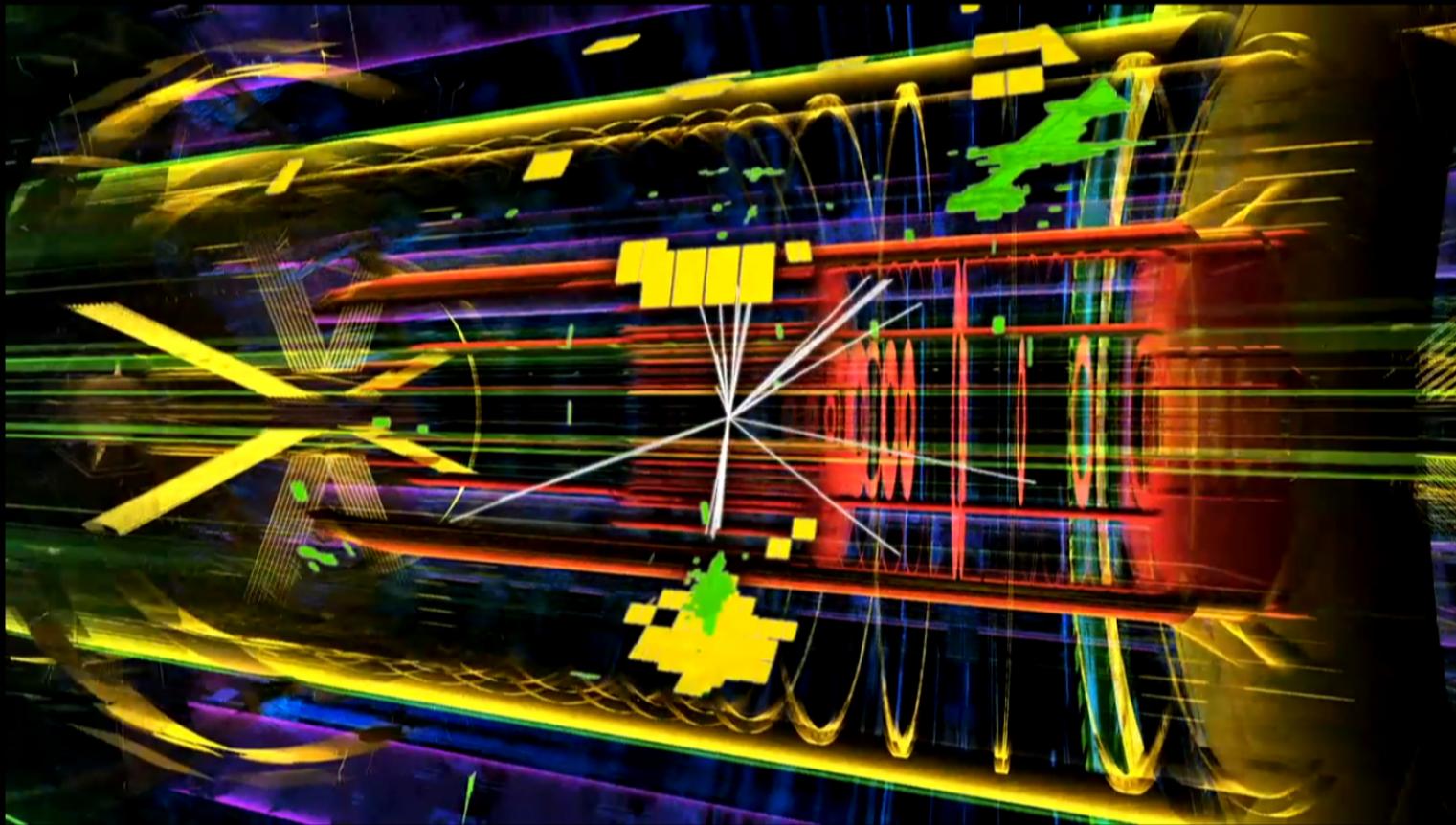


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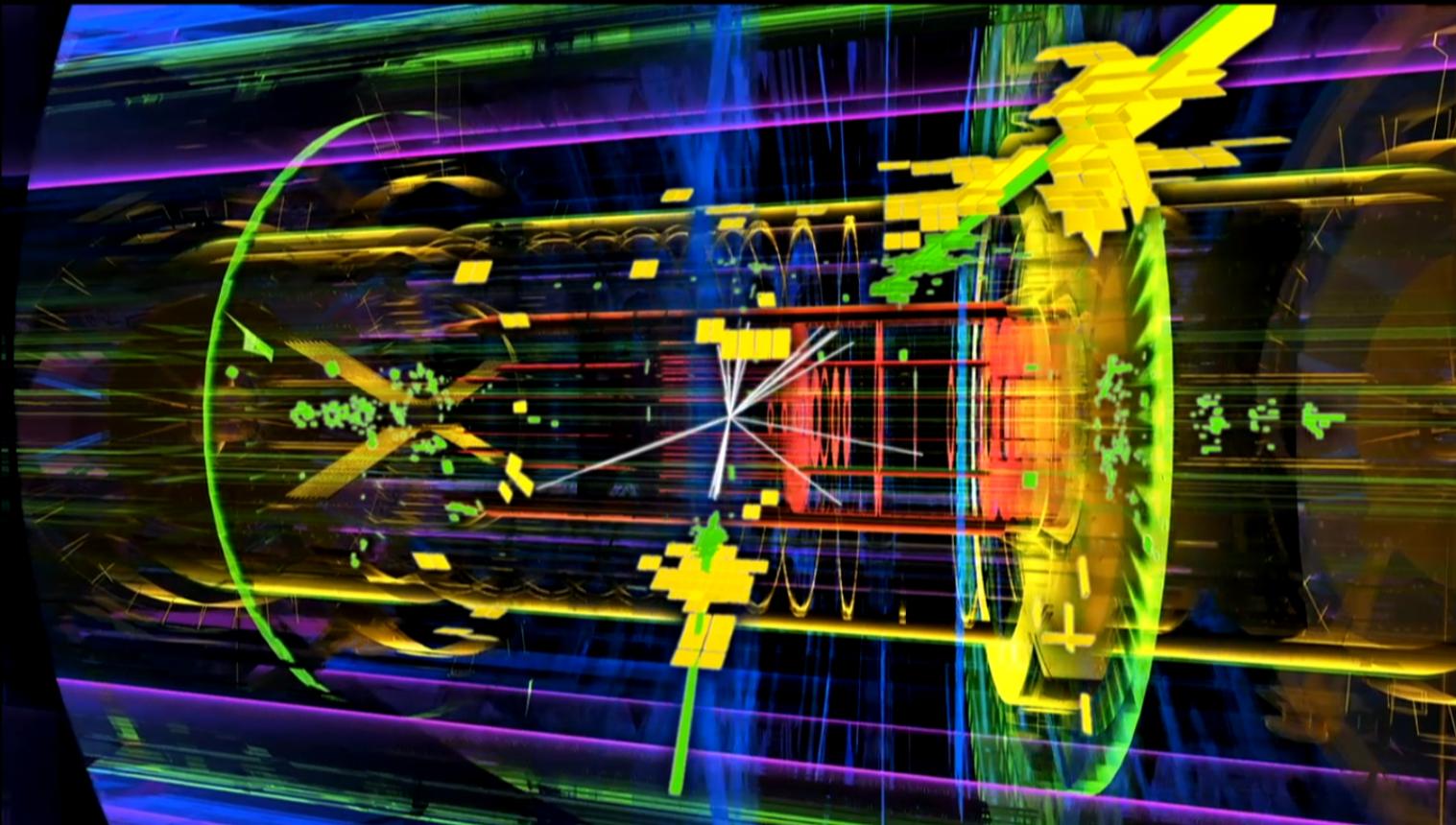


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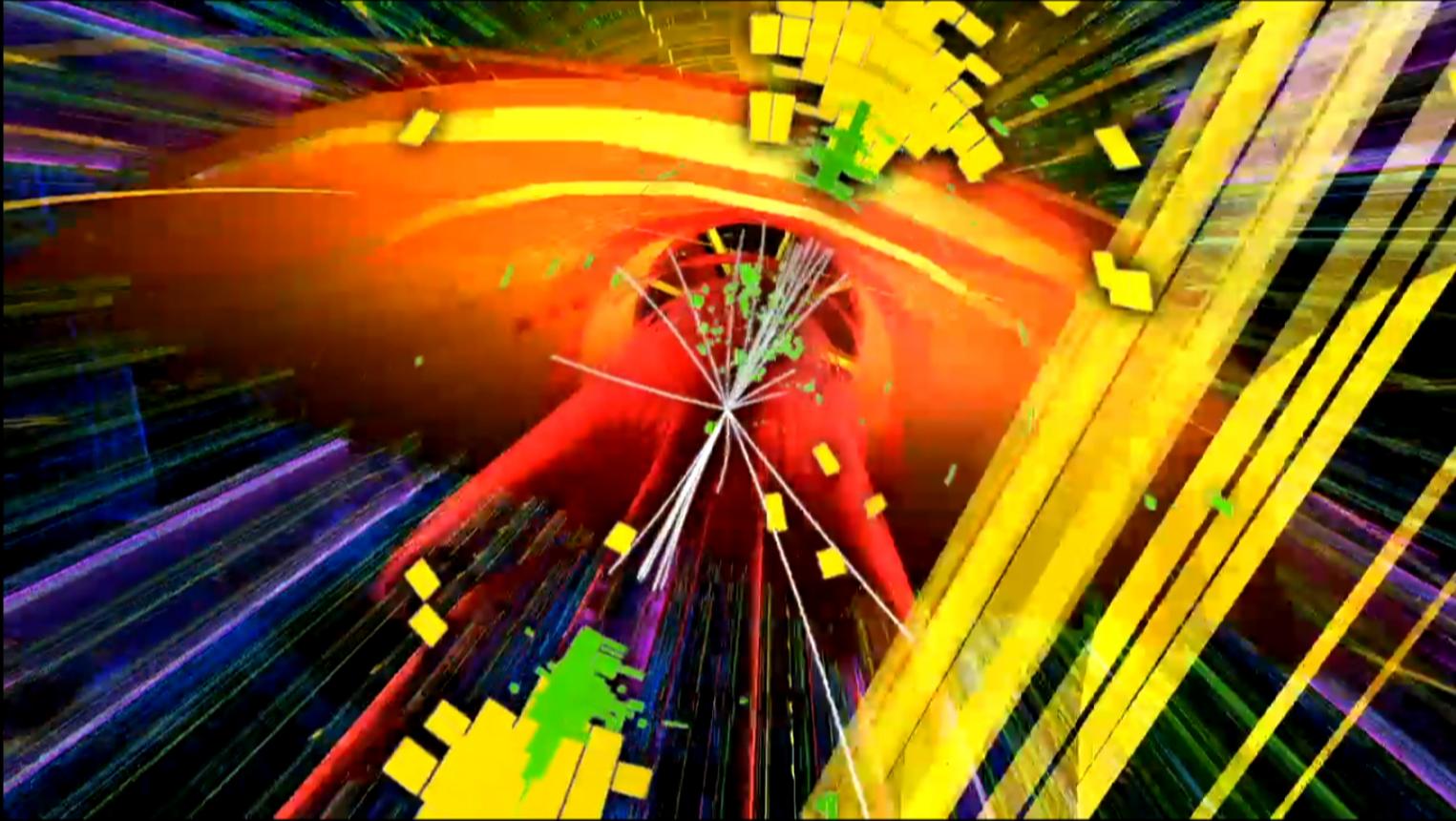
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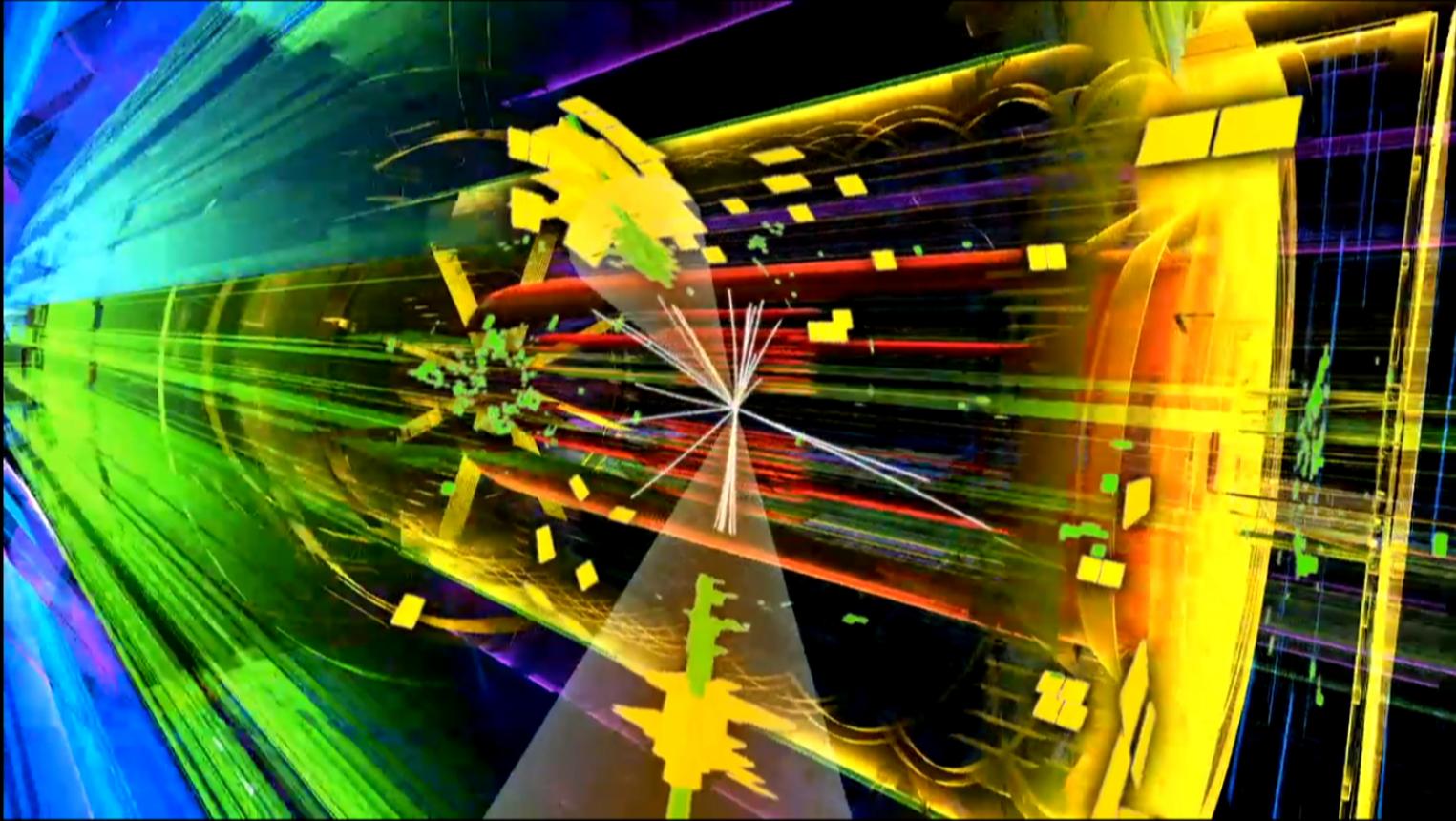
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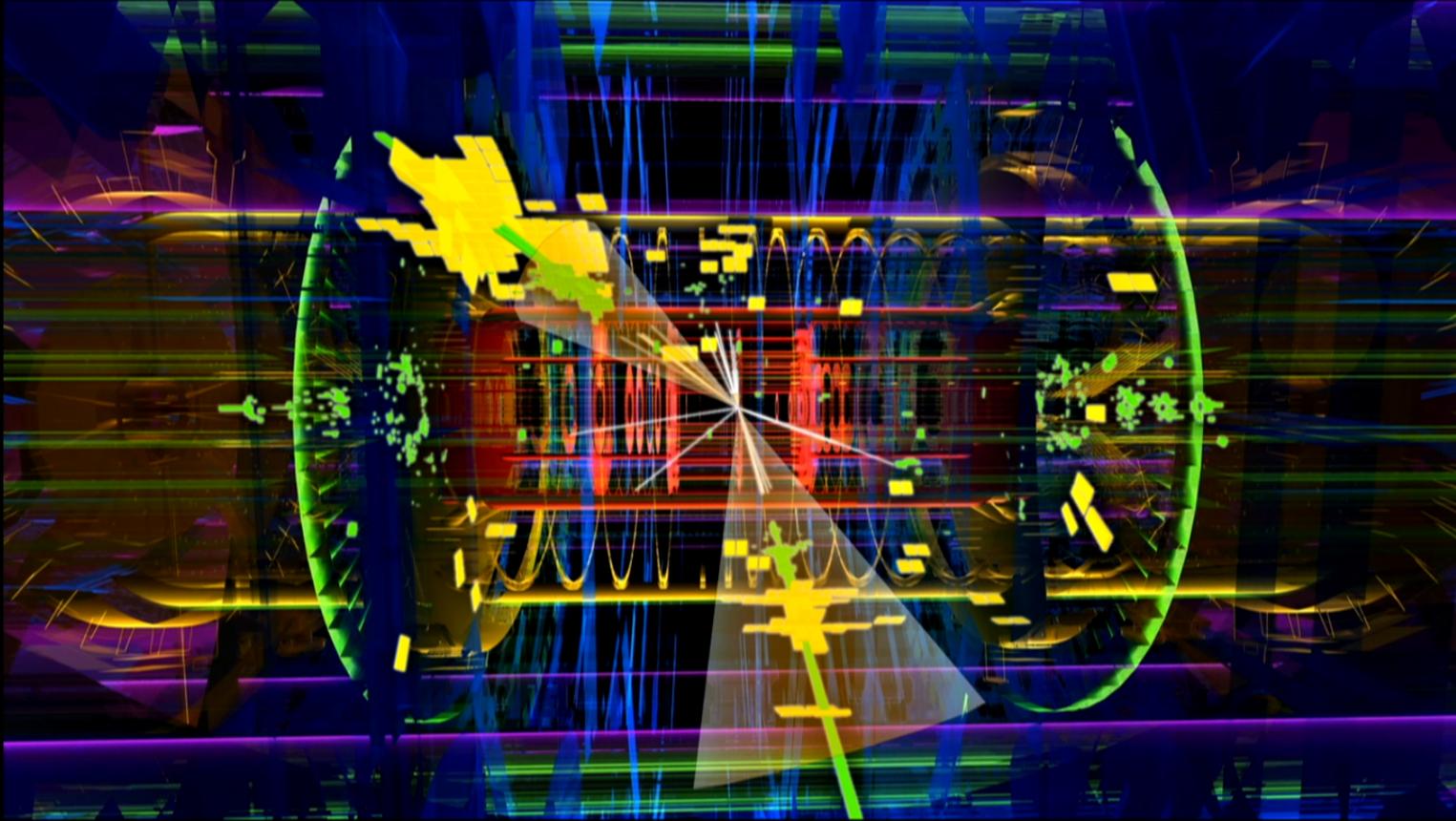
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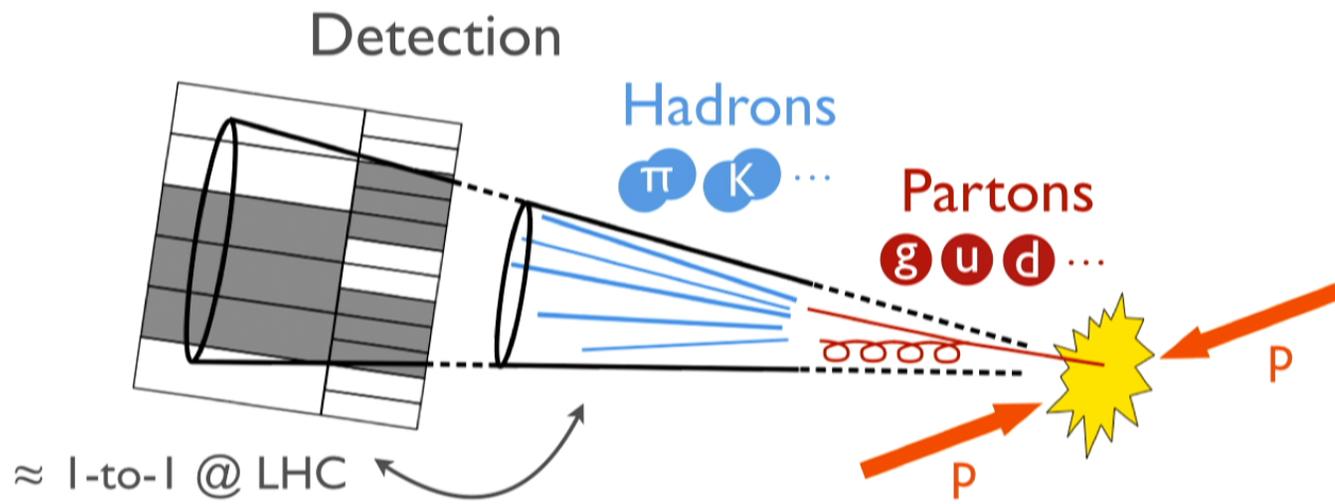
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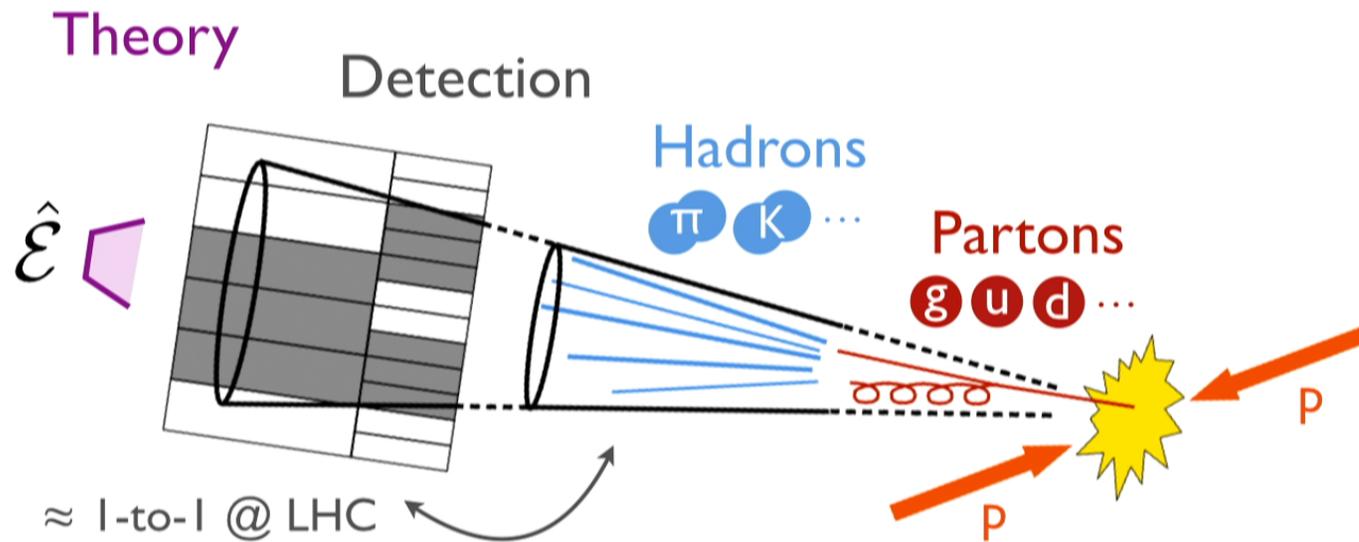
11



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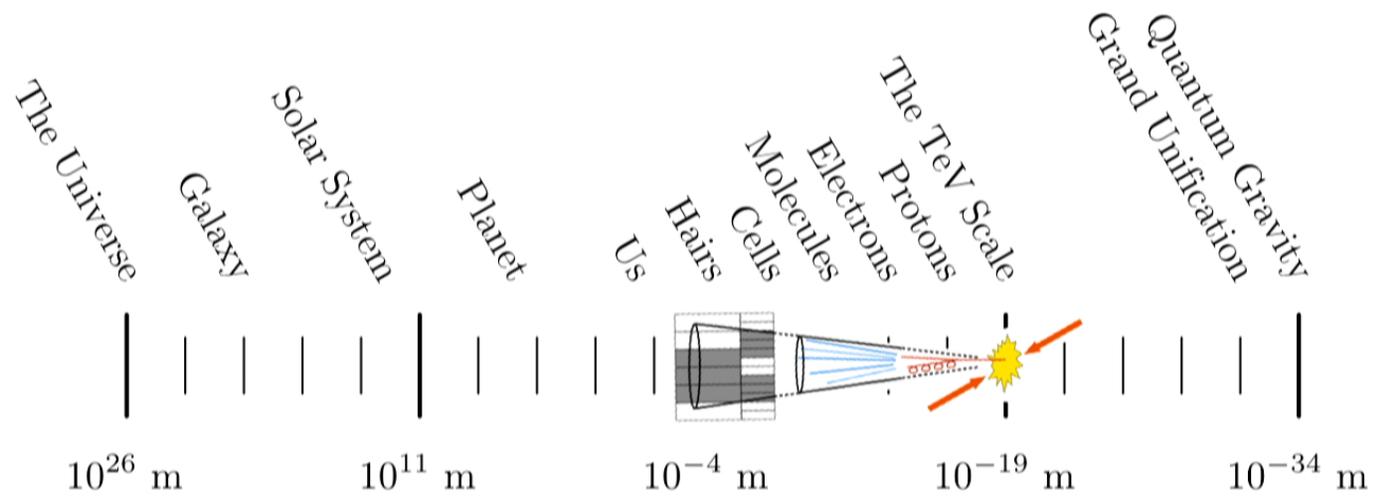


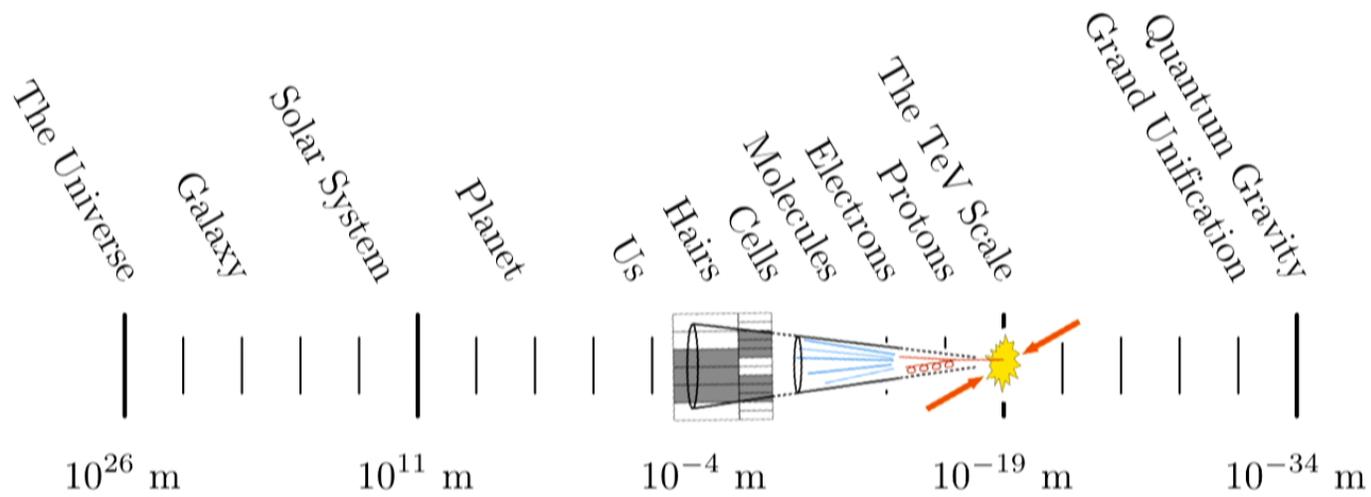


Stress-Energy Flow Operator:

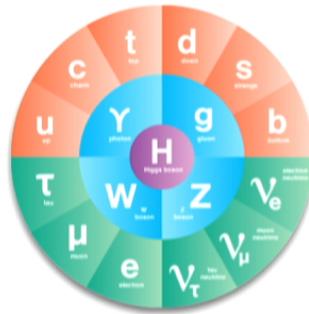
$$\hat{\mathcal{E}} \simeq \lim_{t \rightarrow \infty} \hat{n}_i T^{0i}(t, vt\hat{n})$$

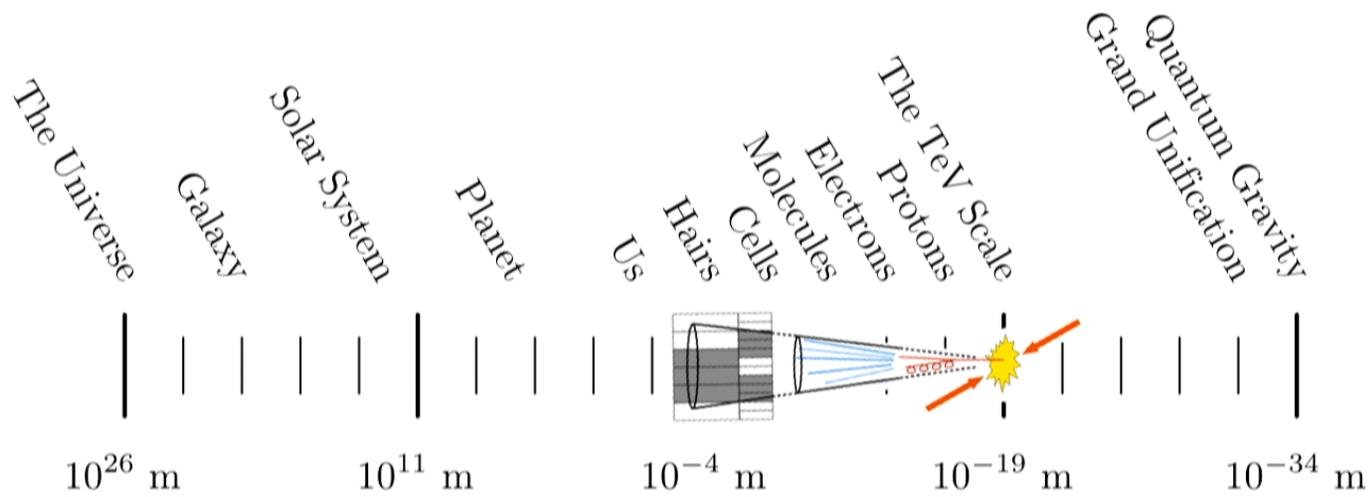
[Sveshnikov, Tkachov, 1995; Mateu, Stewart, JDT, 2012]





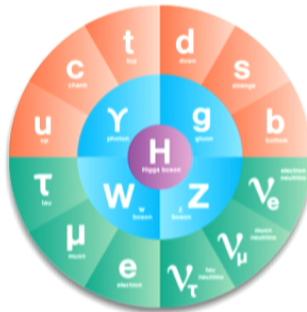
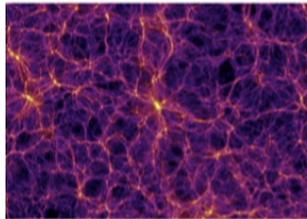
— The Standard Model —

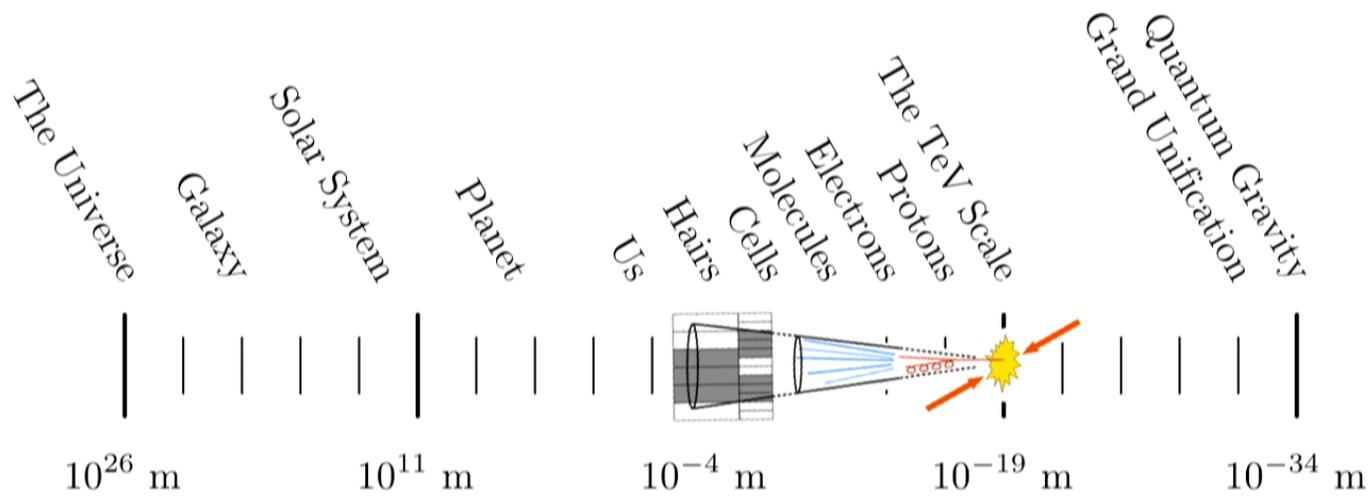




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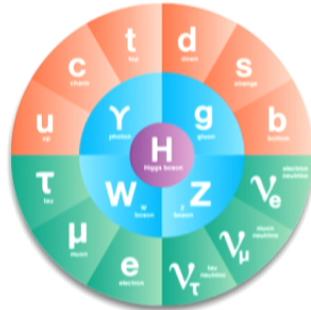
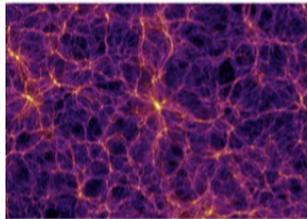
↑
Dark Matter?



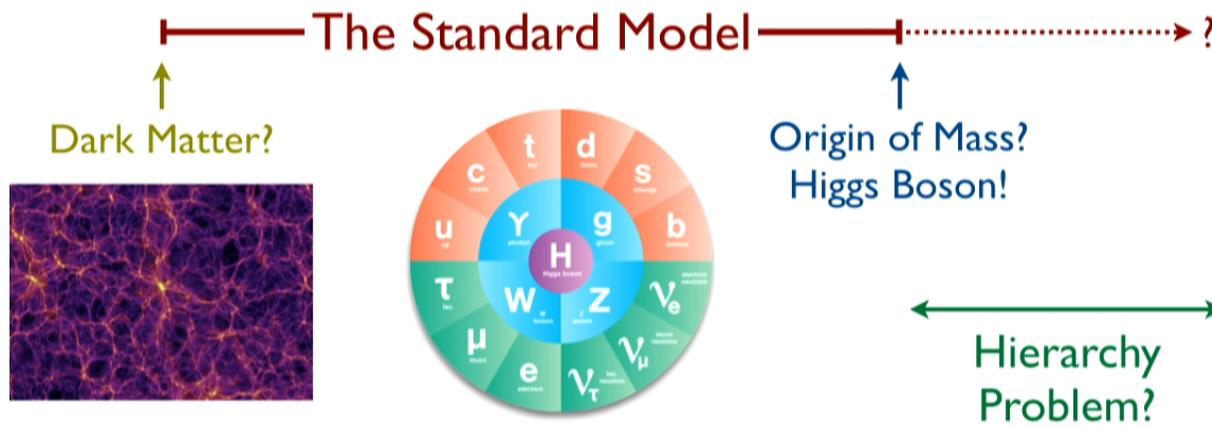
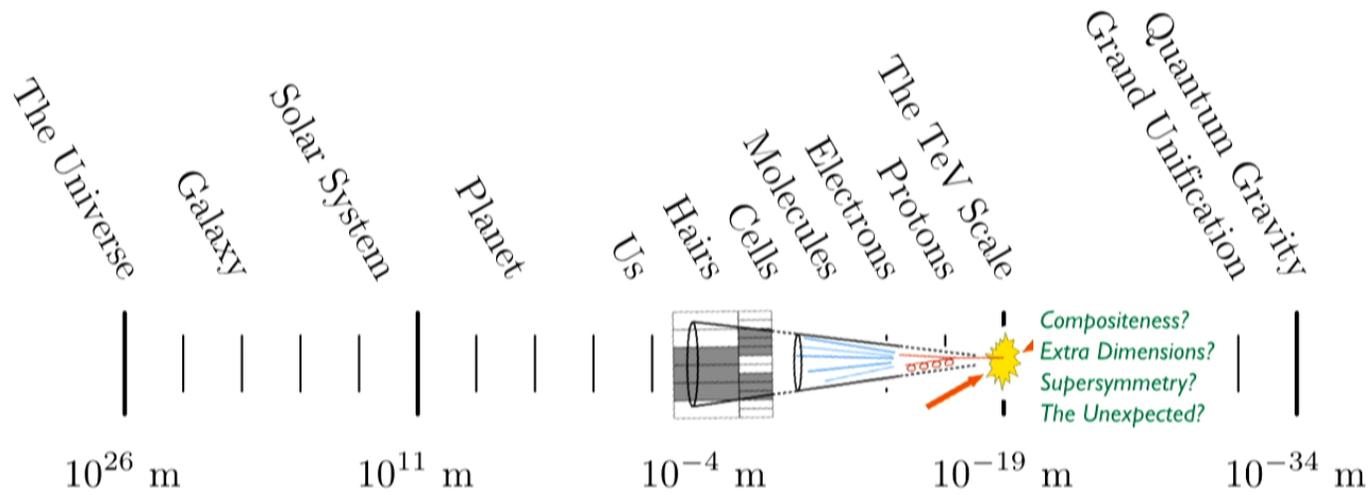


— The Standard Model —

↑
Dark Matter?

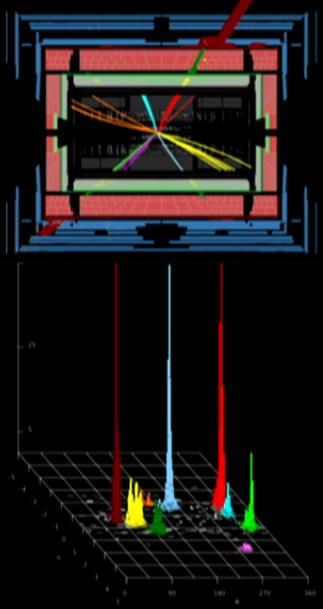


↑
Origin of Mass?
Higgs Boson!



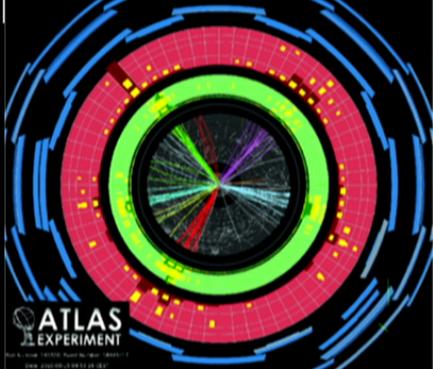
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Date: 2010-07-18 11:05:54 CEST



ATLAS
EXPERIMENT

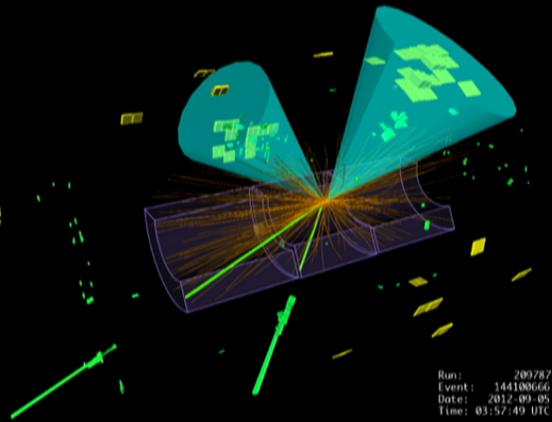
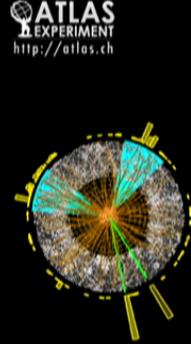
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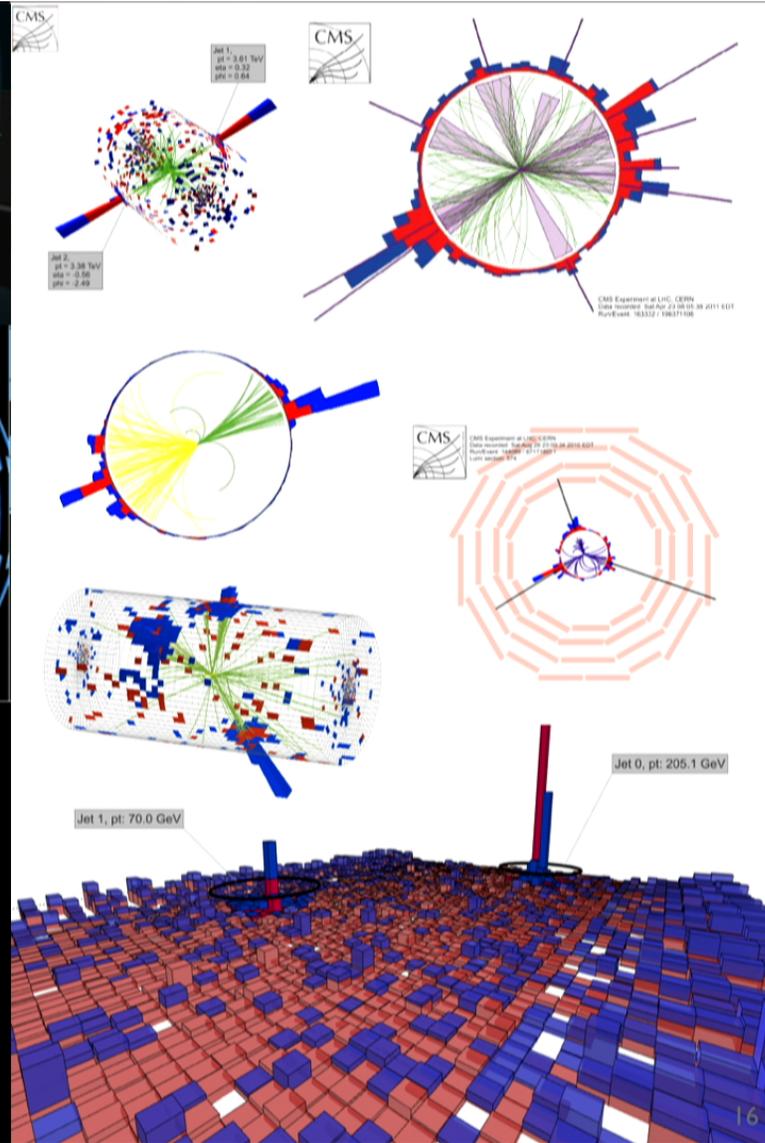
ATLAS
EXPERIMENT

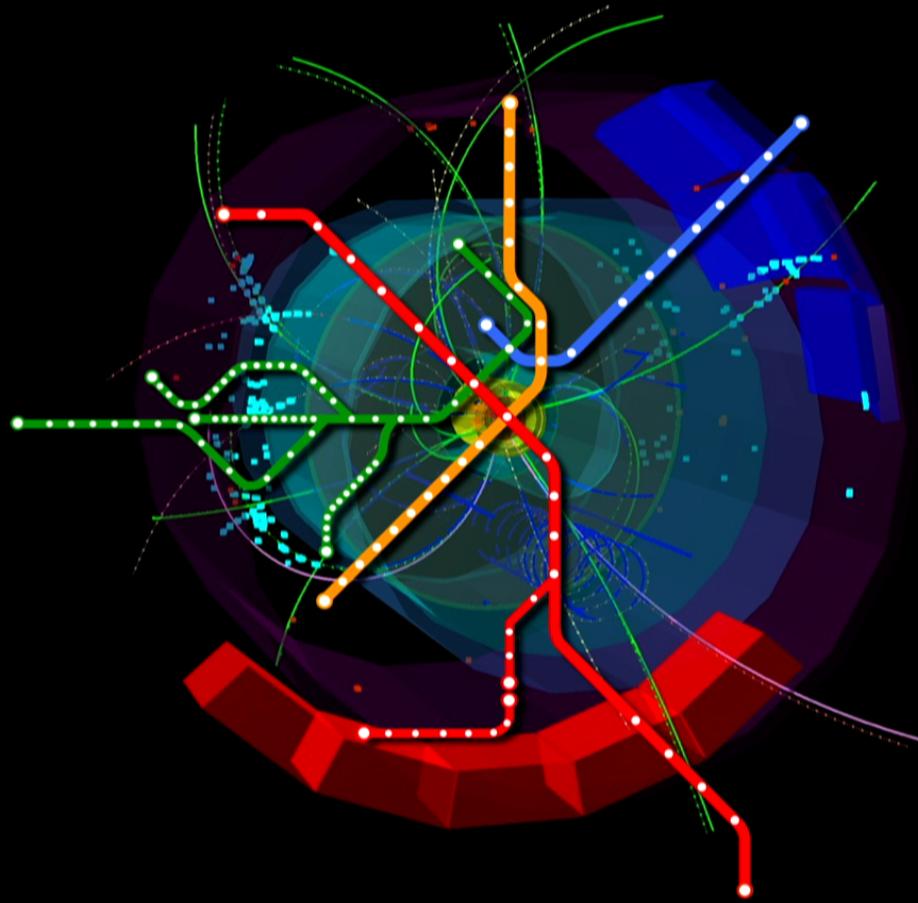
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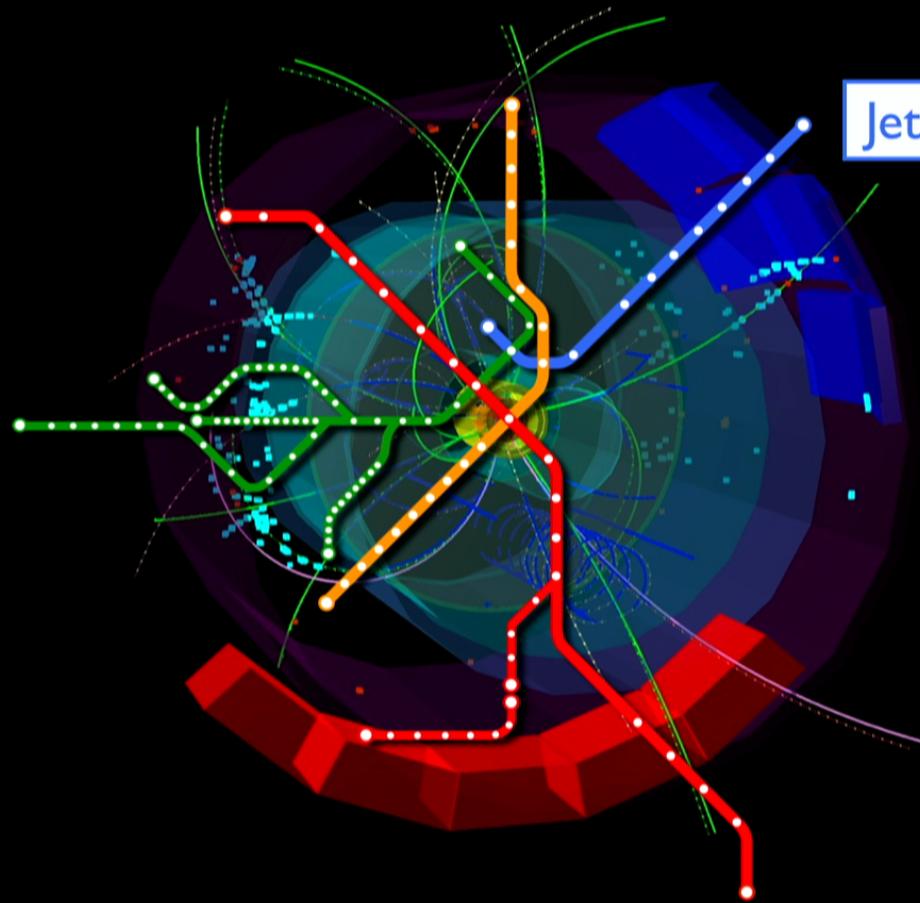
ATLAS
EXPERIMENT
<http://atlas.ch>



Run: 209787
Event: 144100666
Date: 2012-09-05
Time: 03:57:49 UTC



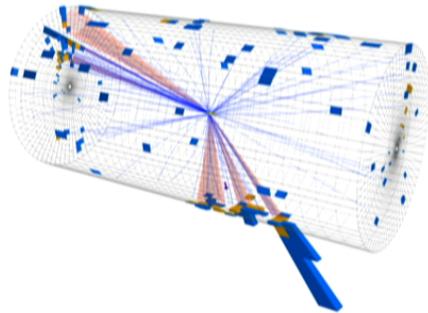




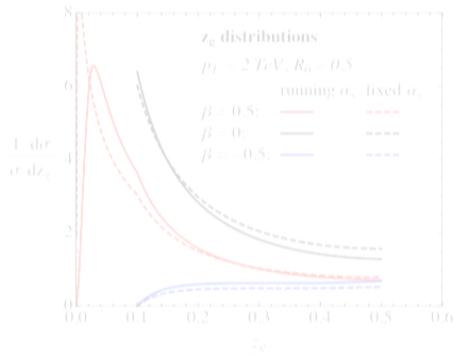
Jets c. 1975

[Hanson, et al.]

Jet Substructure



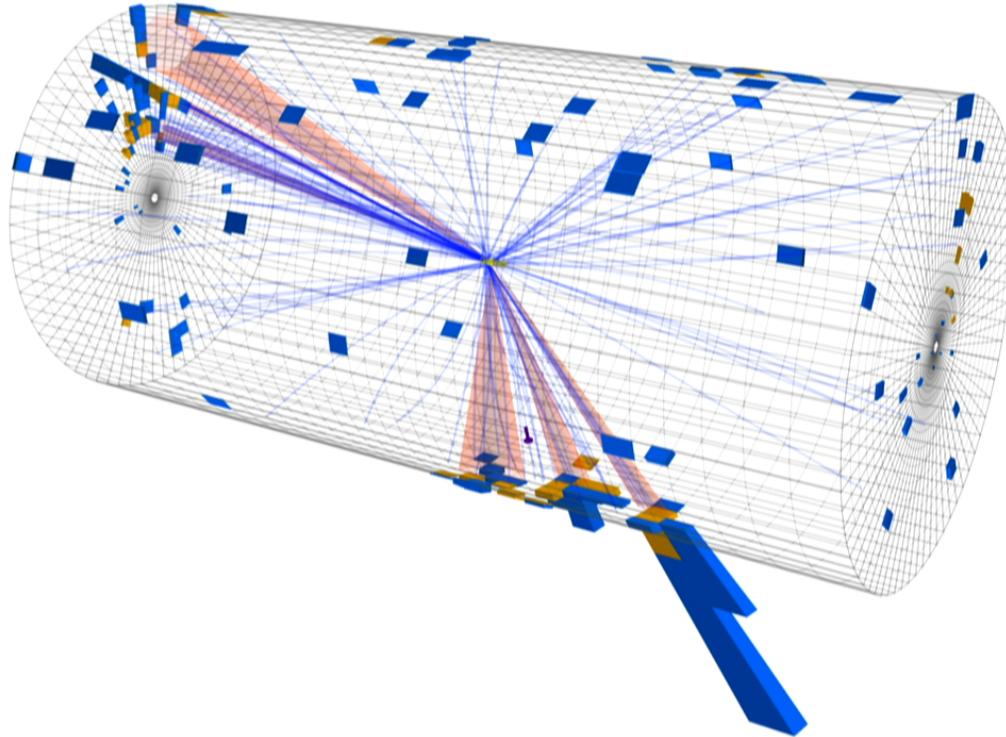
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for New Phenomena*



*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

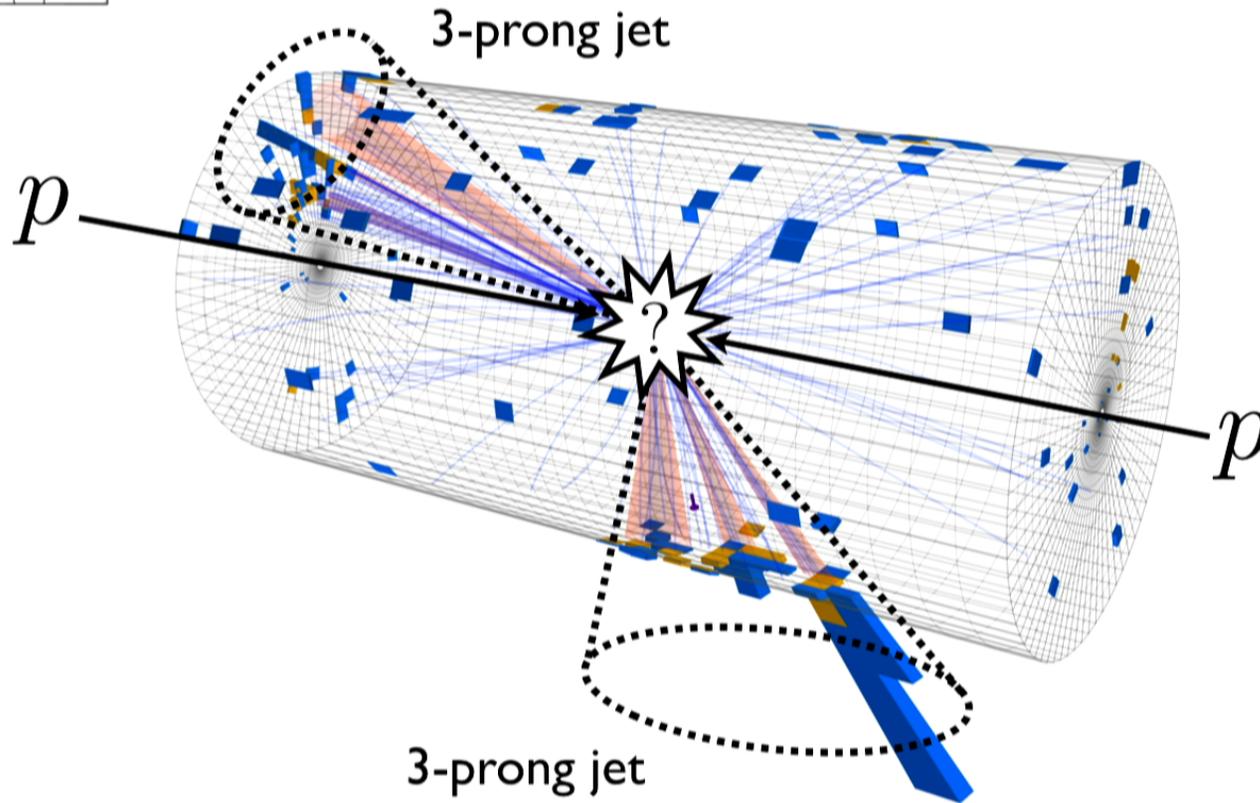


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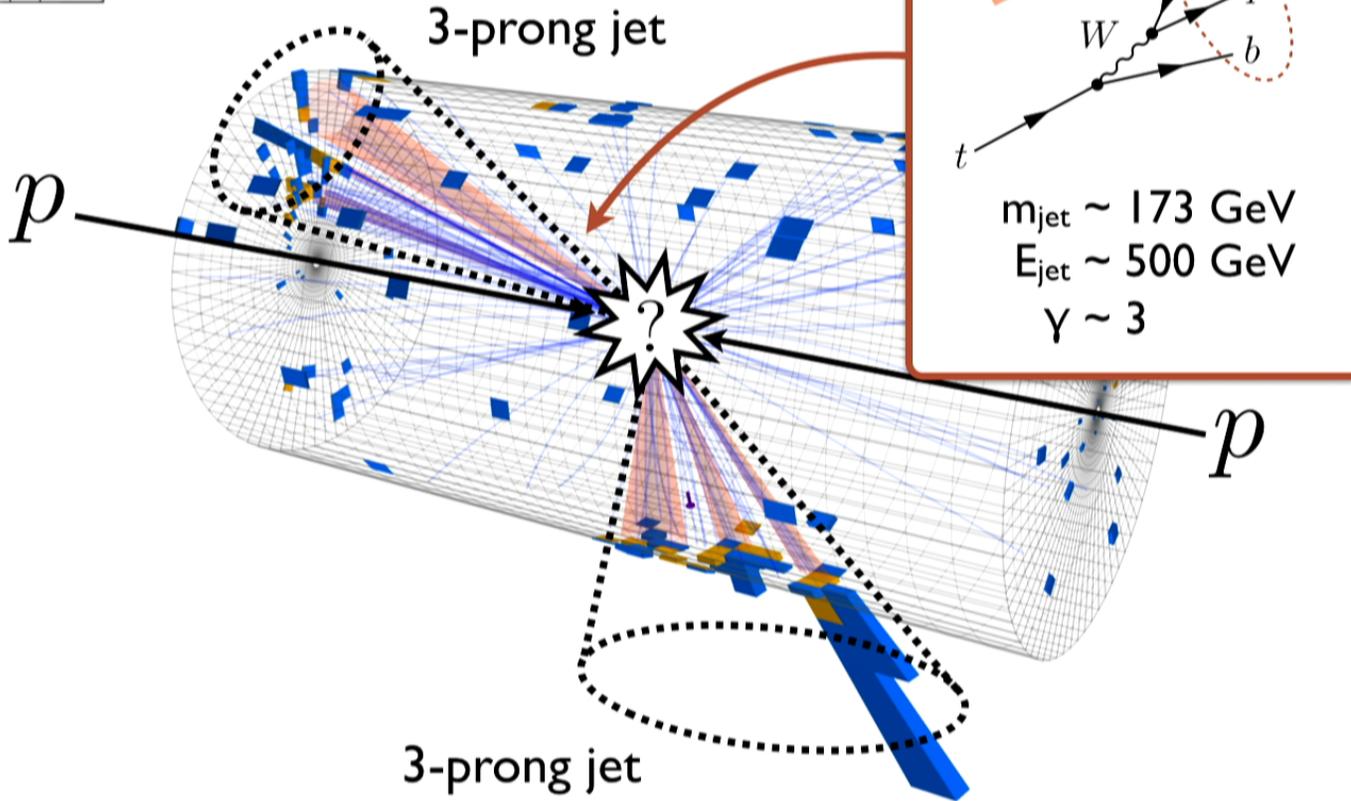


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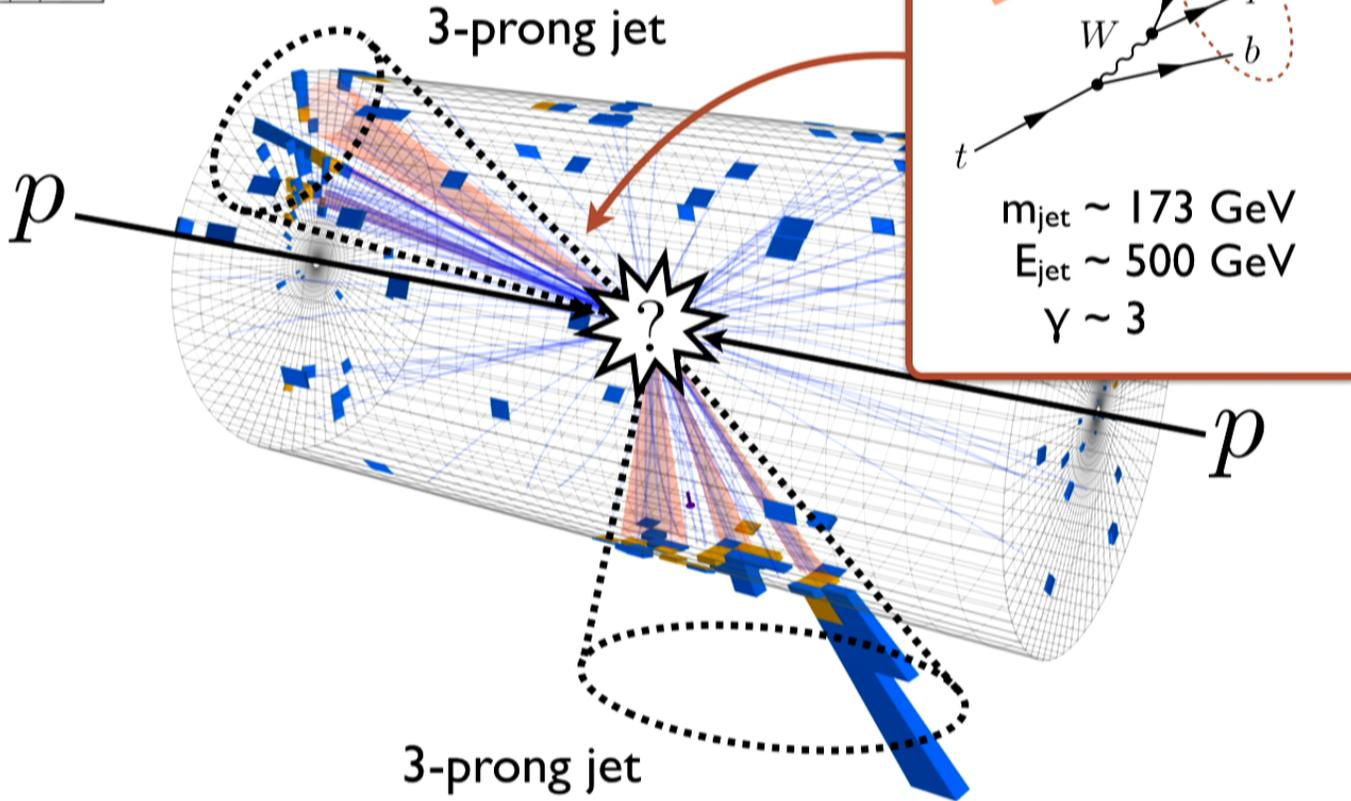


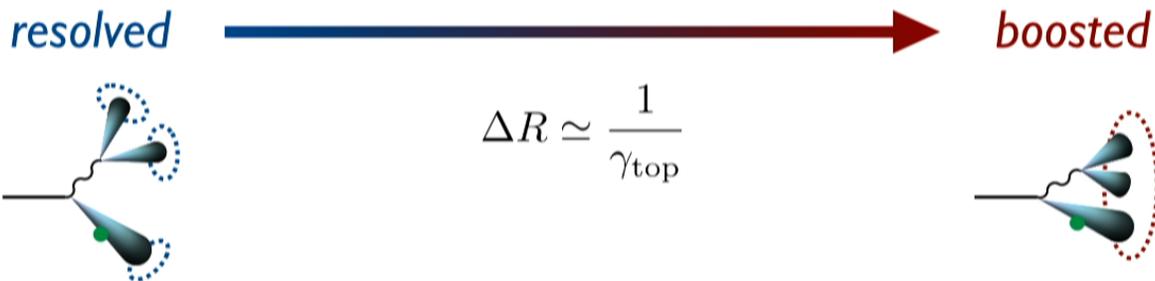
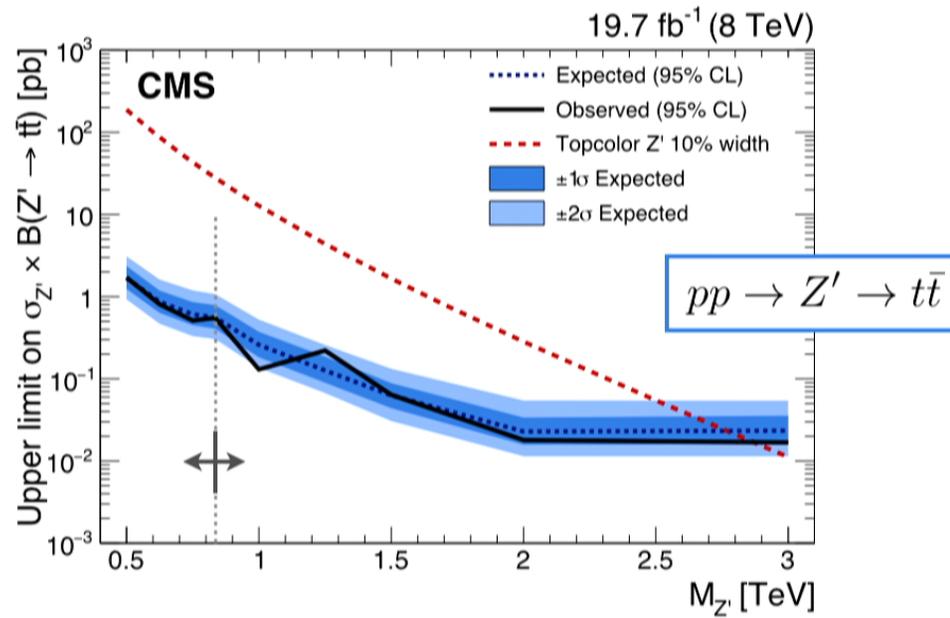
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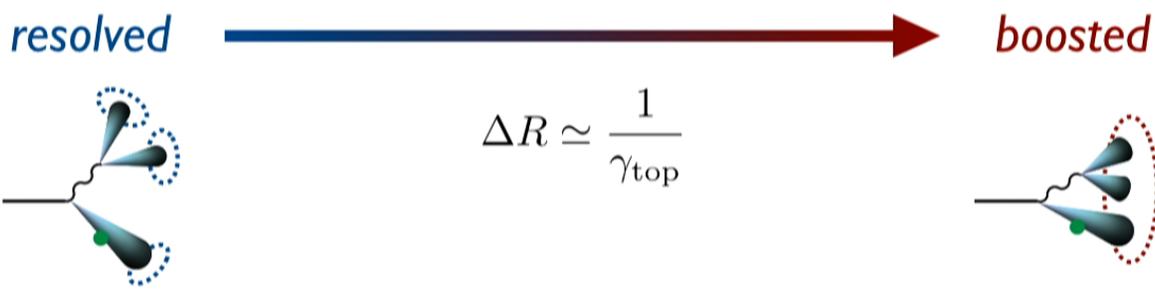
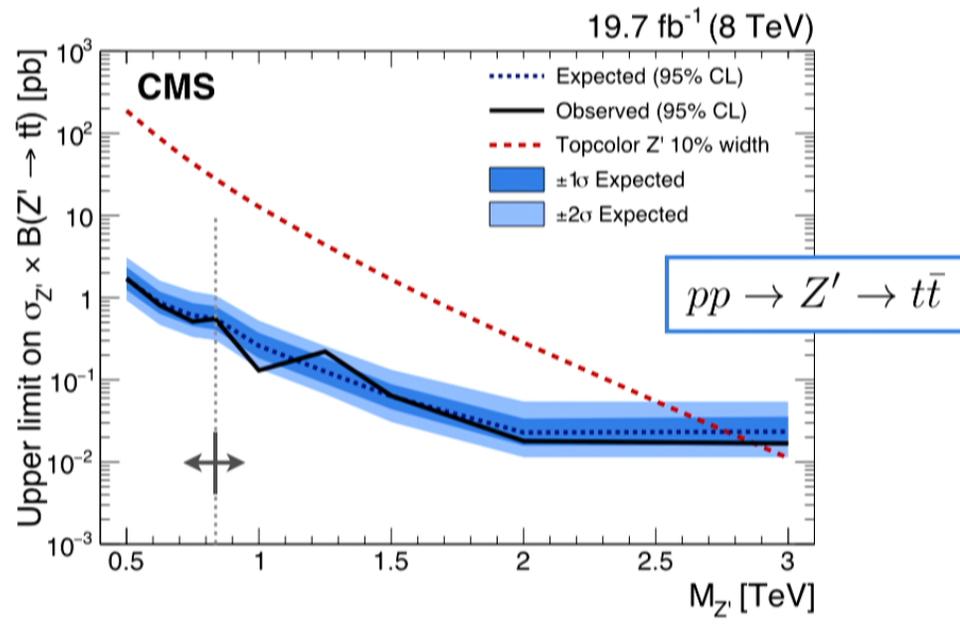


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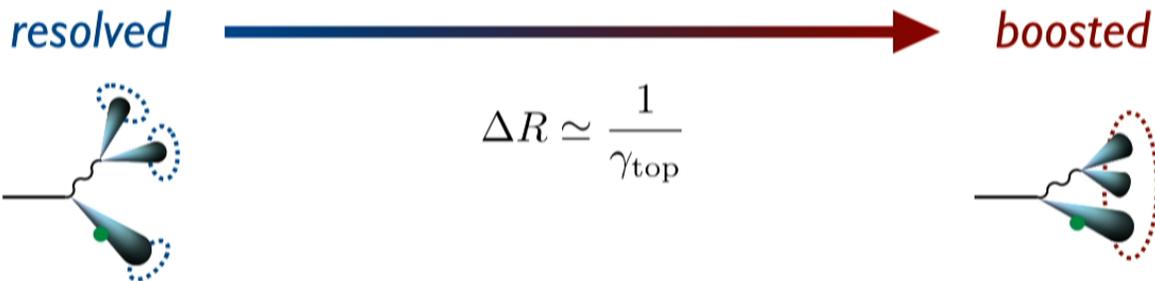
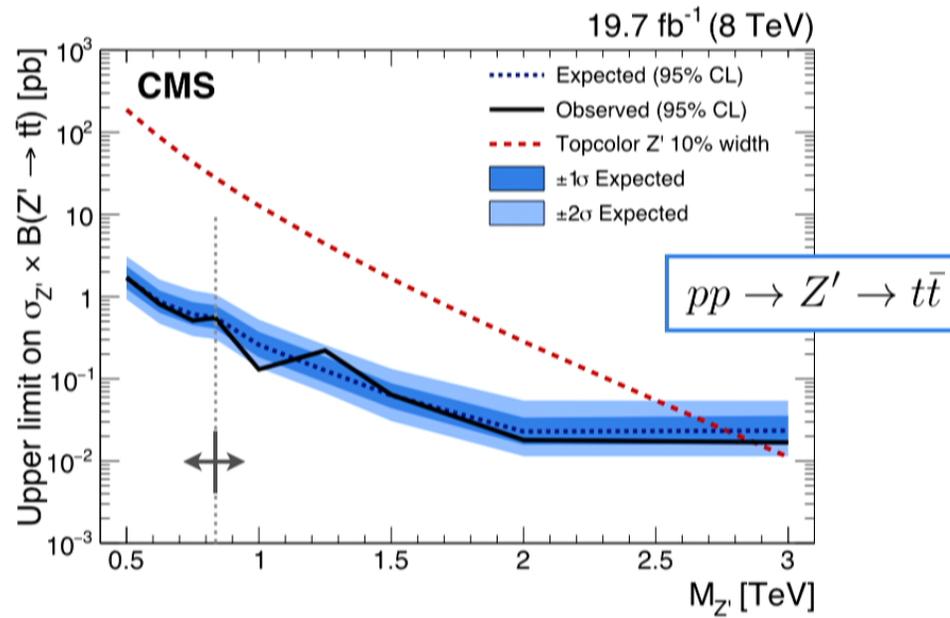




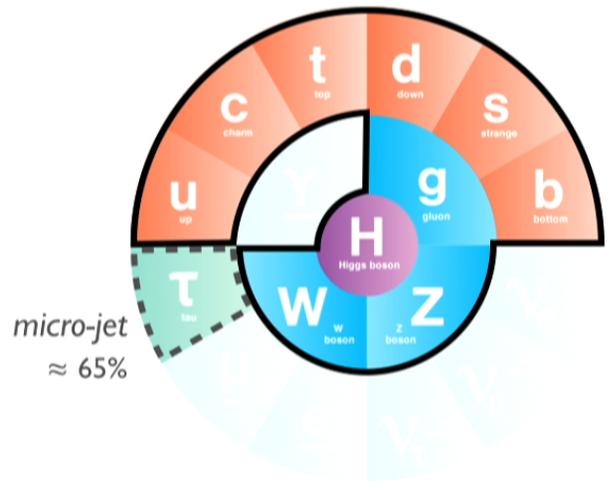
[CMS 2011, 2013, 2015; using Kaplan, Rehermann, Schwartz, Tweedie, 2008; Ellis, Vermilion, Walsh, 2009]



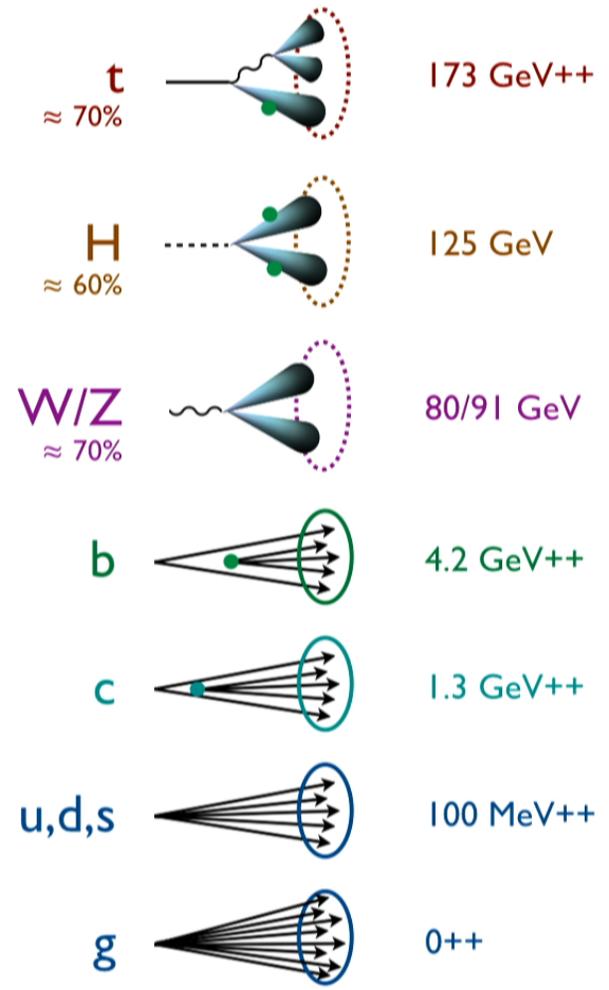
[CMS 2011, 2013, 2015; using Kaplan, Rehermann, Schwartz, Tweedie, 2008; Ellis, Vermilion, Walsh, 2009]



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

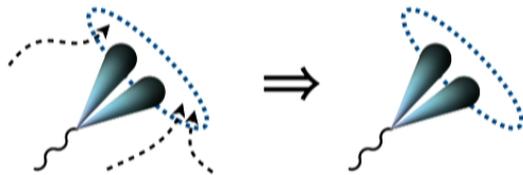


Jets from the Standard Model



Substructure Toolbox:

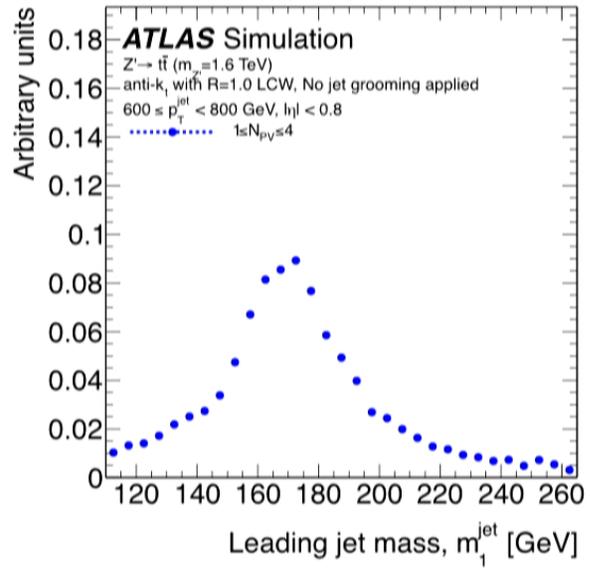
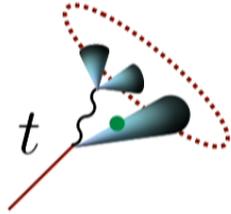
Jet Grooming

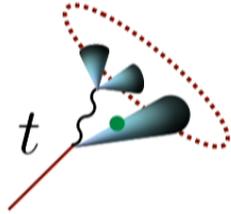


Jet Discrimination

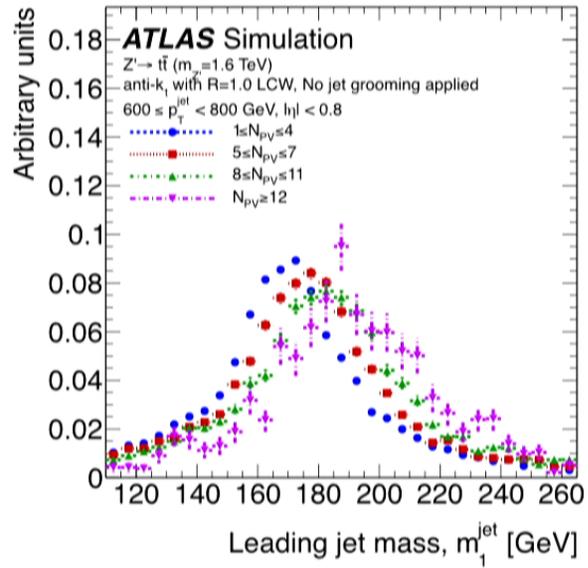
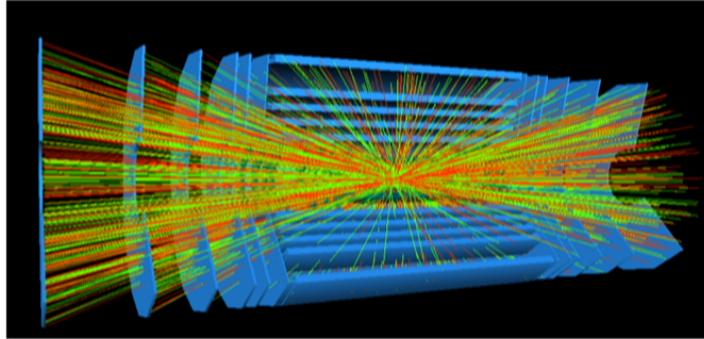


t $\approx 70\%$		173 GeV++
H $\approx 60\%$		125 GeV
W/Z $\approx 70\%$		80/91 GeV
b		4.2 GeV++
c		1.3 GeV++
u,d,s		100 MeV++
g		0++



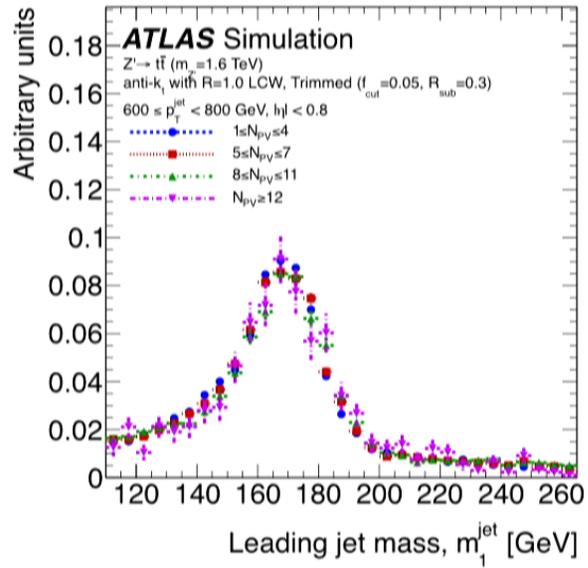
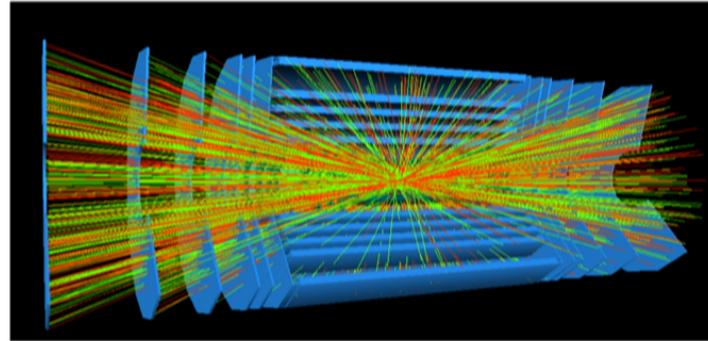
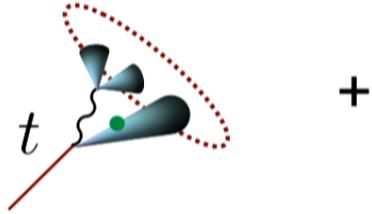


+

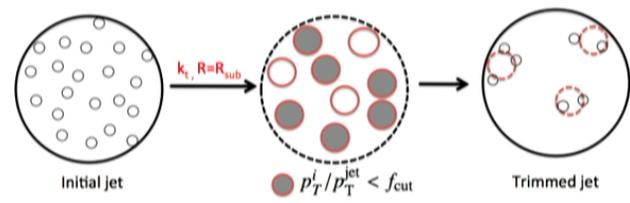


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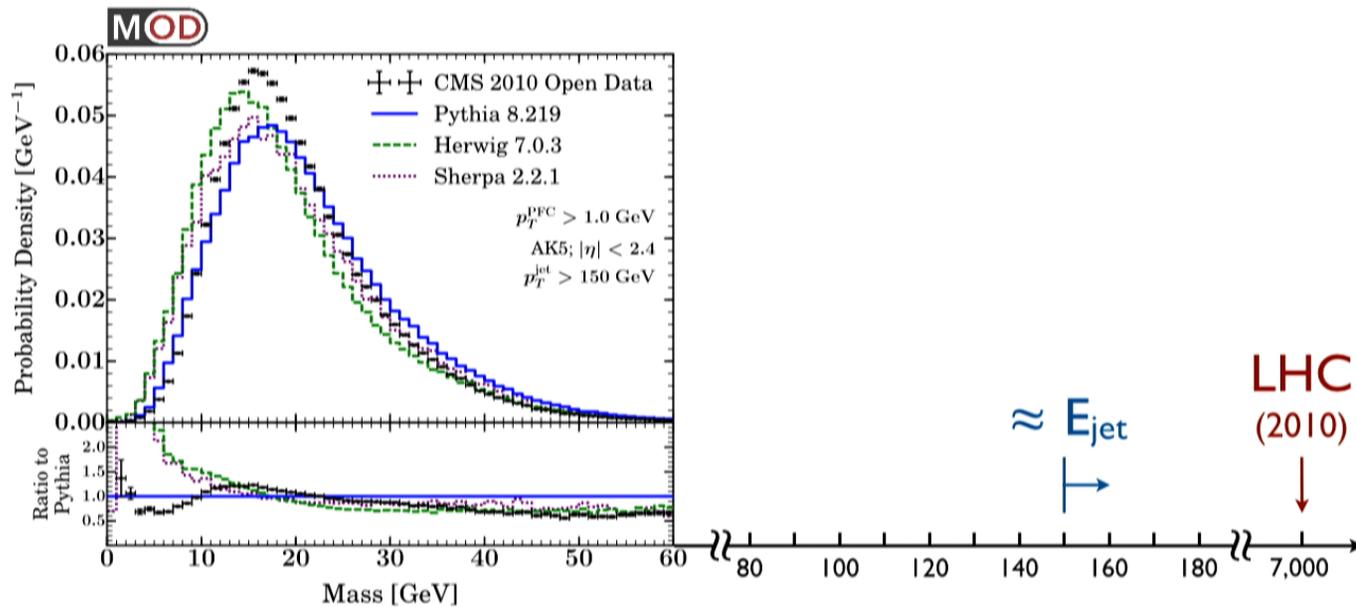
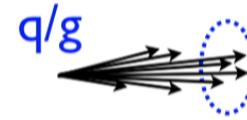


+
Jet Trimming



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

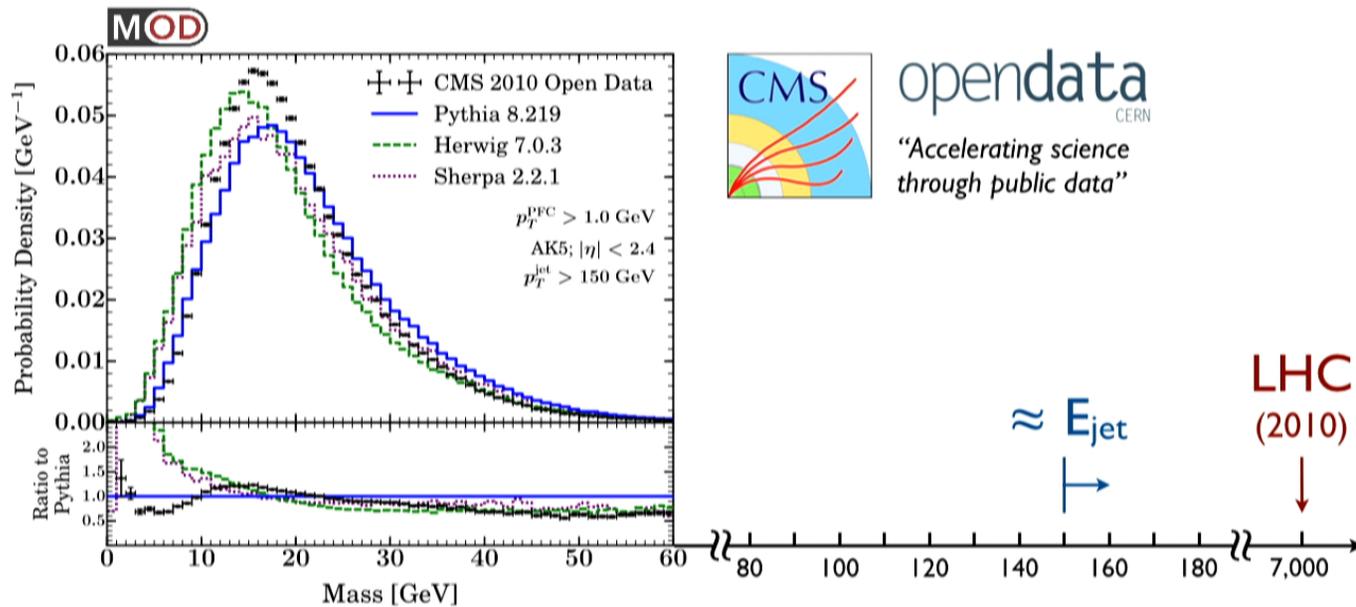
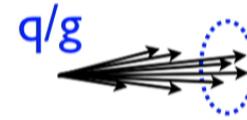
Regular Jets Have Mass, Too



g u d s c b

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

Regular Jets Have Mass, Too

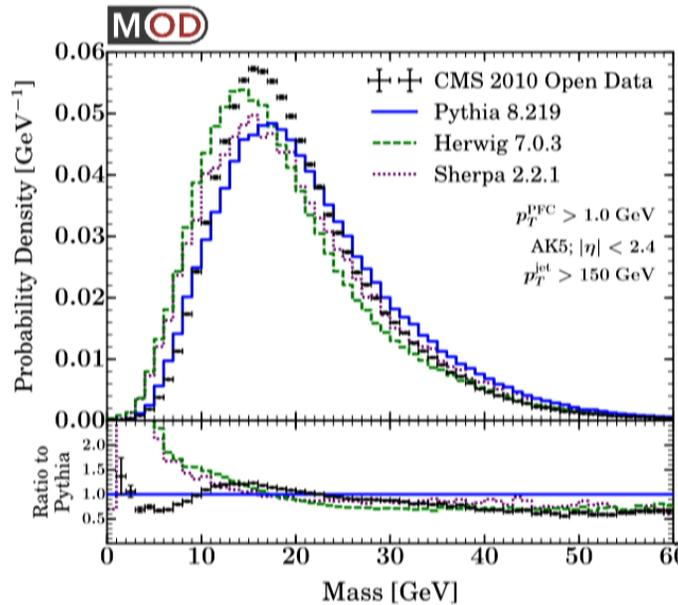
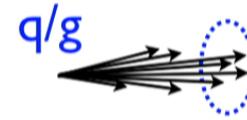


opendata
CERN
 "Accelerating science through public data"

g u d s c b

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

Regular Jets Have Mass, Too



opendata
CERN
"Accelerating science through public data"

g u d s c b

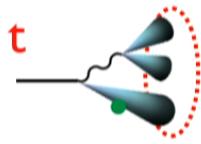
W Z H t

$\approx E_{\text{jet}}$
LHC (2010)

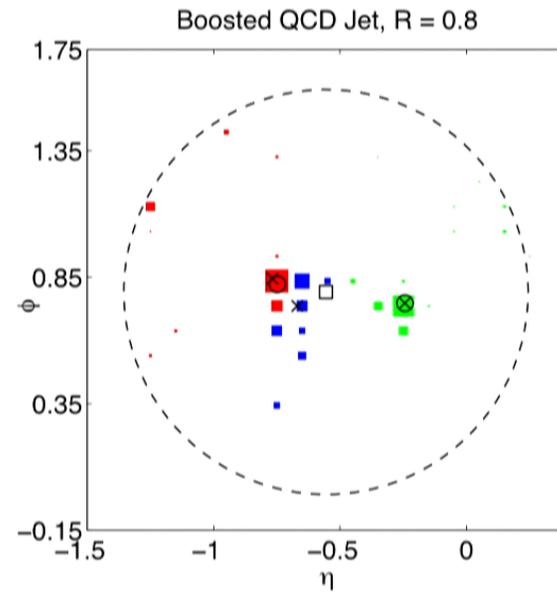
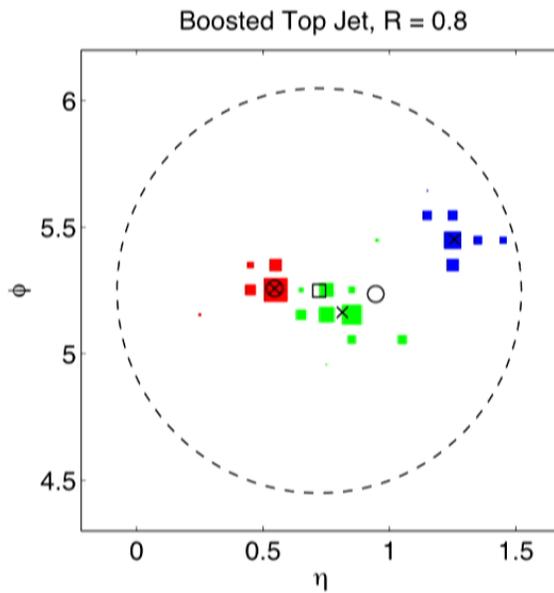
[Tripathee, Xue, Larkoski, Marzani, JDT, 2017]

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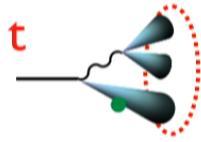
26



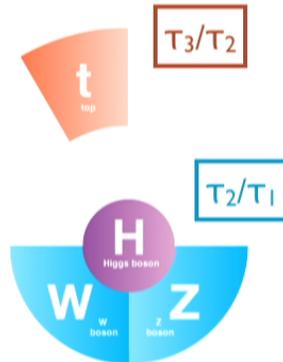
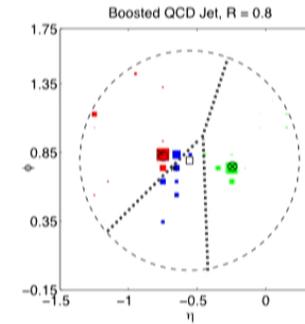
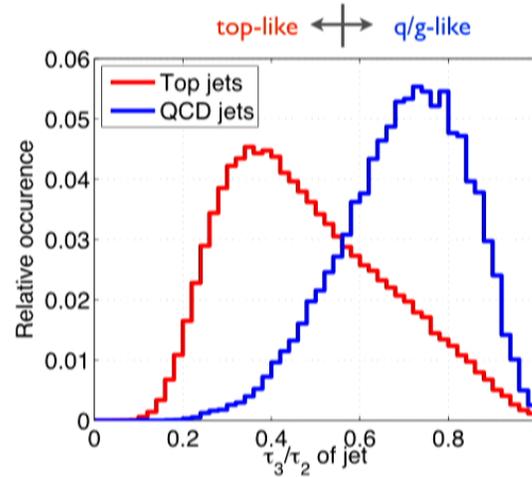
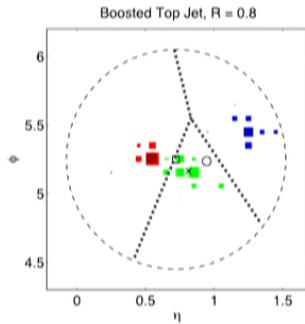
N-Prong vs. I-Prong



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



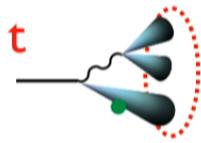
N-Prong vs. I-Prong



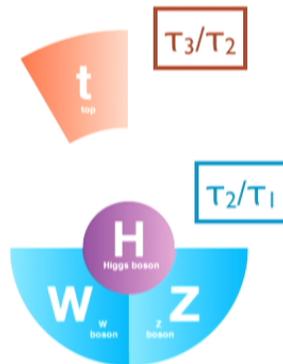
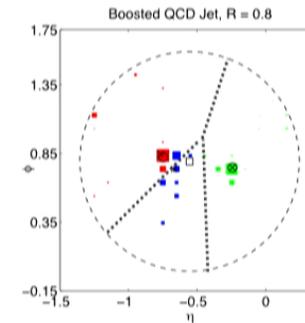
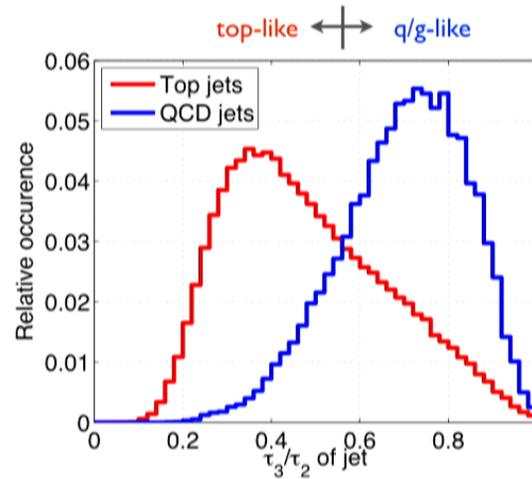
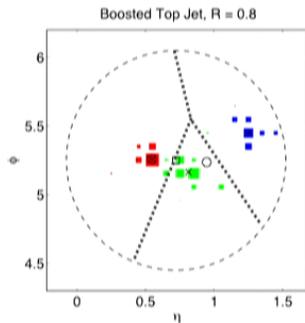
N-subjettiness

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

[JDT, Van Tilburg, 2010, 2011; see also Stewart, Tackmann, Waalewijn, 2010; Kim, 2010]



N-Prong vs. I-Prong

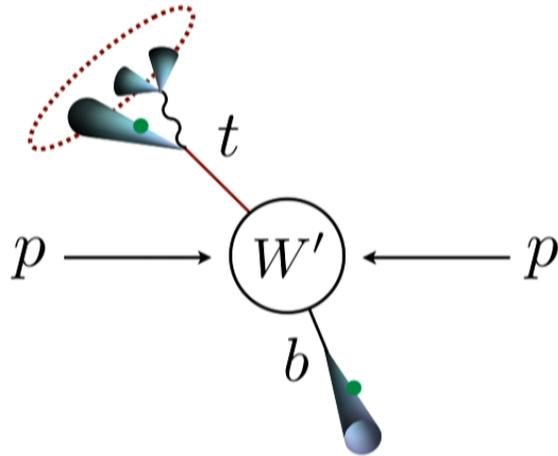


N-subjettiness

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

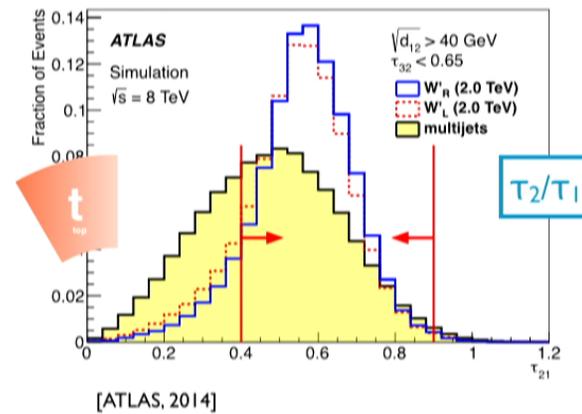
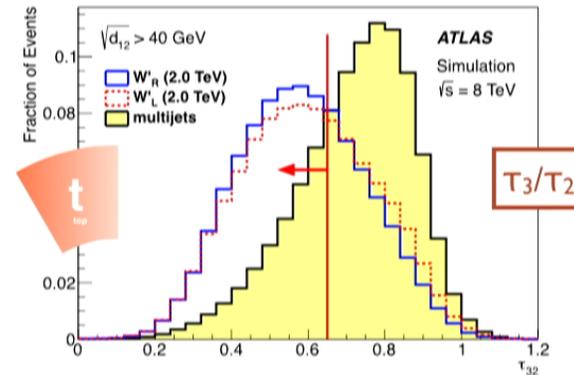
[JDT, Van Tilburg, 2010, 2011; see also Stewart, Tackmann, Waalewijn, 2010; Kim, 2010]

ATLAS: Heavy W Search

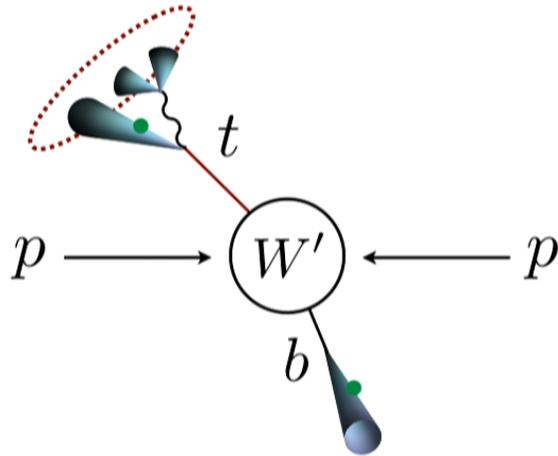


with *B*-tagging
 + Trimming
 + *N*-subjettiness

≈ 100x background rejection
 @ 50% signal efficiency

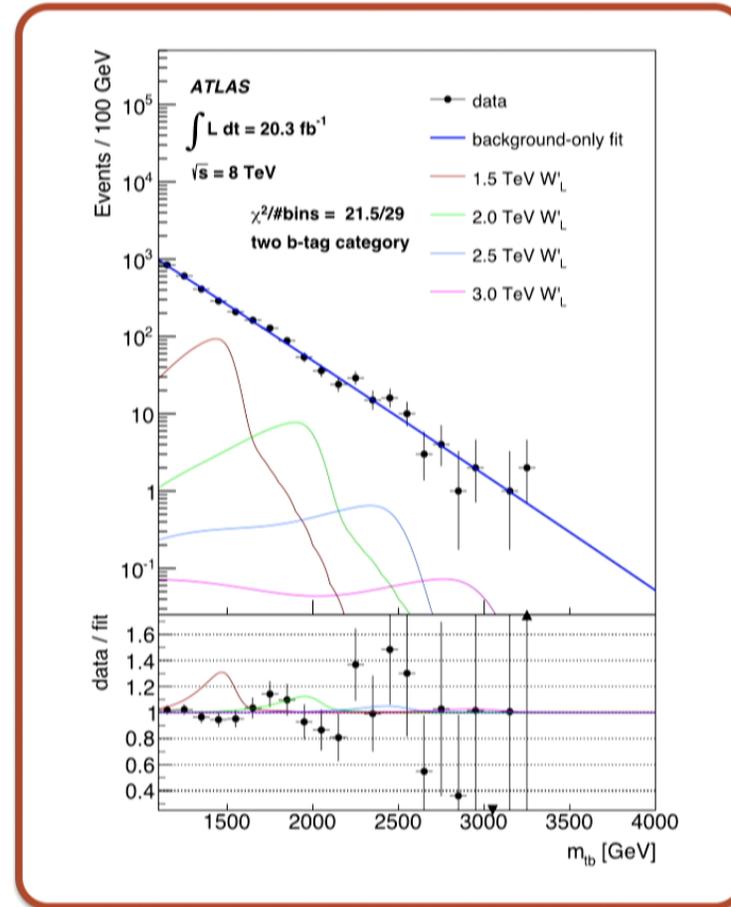


ATLAS: Heavy W Search



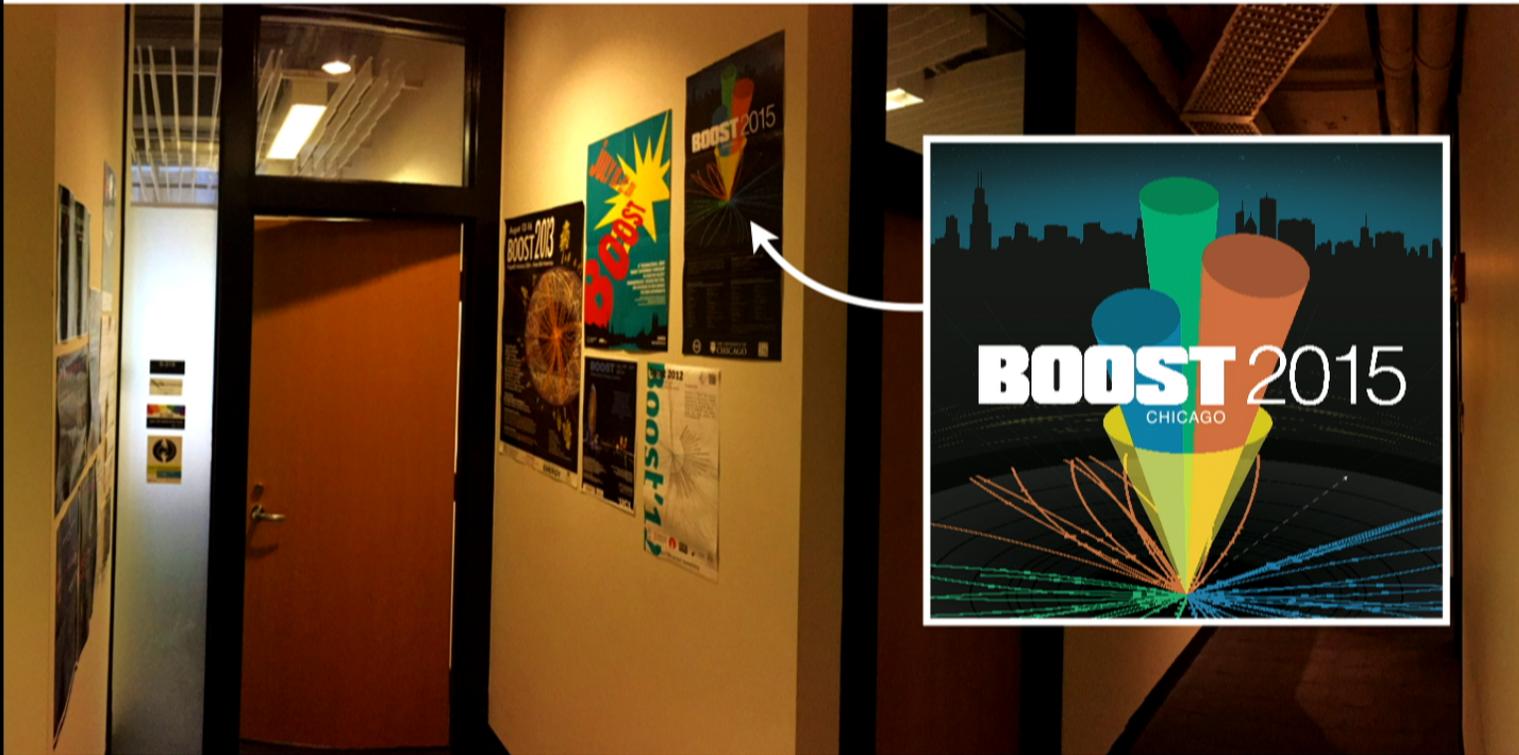
with **B-tagging**
 + **Trimming**
 + **N-subjettiness**

≈ 100x background rejection
 @ 50% signal efficiency





Jesse Thaler — New Physics Gets a Boost



Jesse Thaler — New Physics Gets a Boost

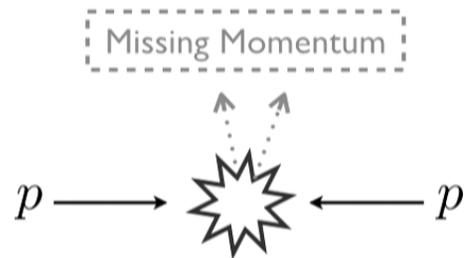


Jesse Thaler — New Physics Gets a Boost



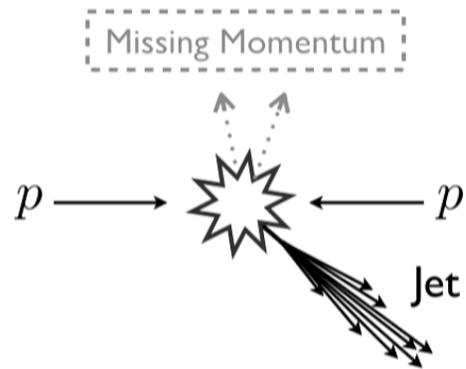
Jesse Thaler — New Physics Gets a Boost

CMS: Dark Matter Search



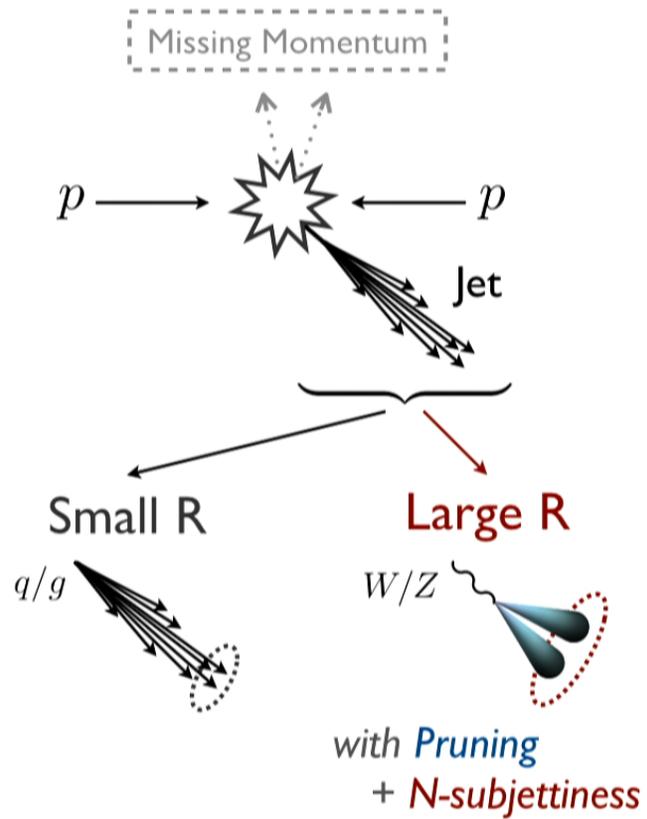
[CMS, 2017; using [Ellis, Vermilion, Walsh, 2009](#); [JDT, Van Tilburg, 2010, 2011](#)]

CMS: Dark Matter Search



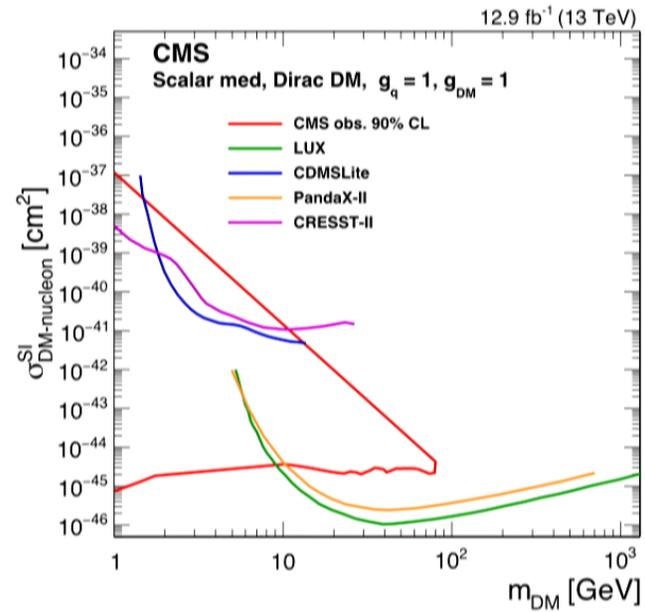
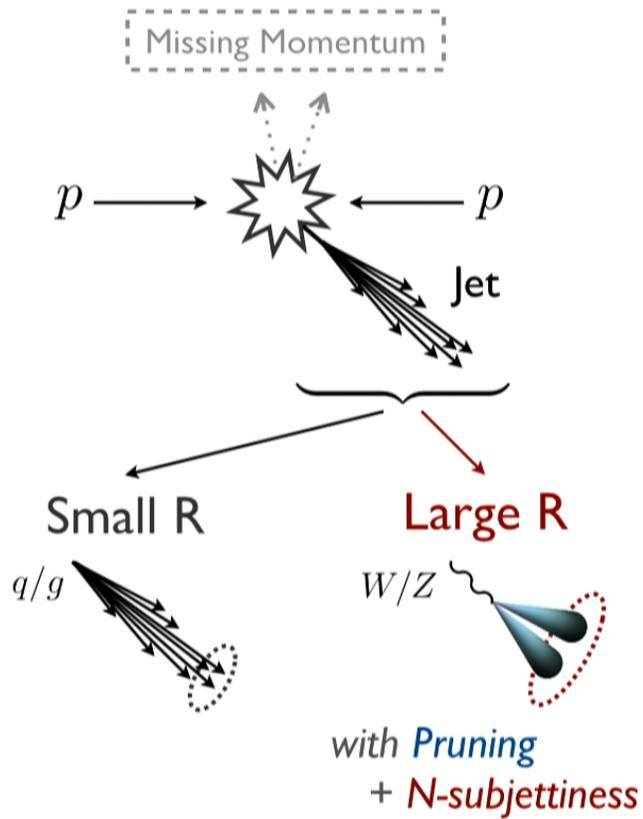
[CMS, 2017; using [Ellis, Vermilion, Walsh, 2009](#); [JDT, Van Tilburg, 2010, 2011](#)]

CMS: Dark Matter Search



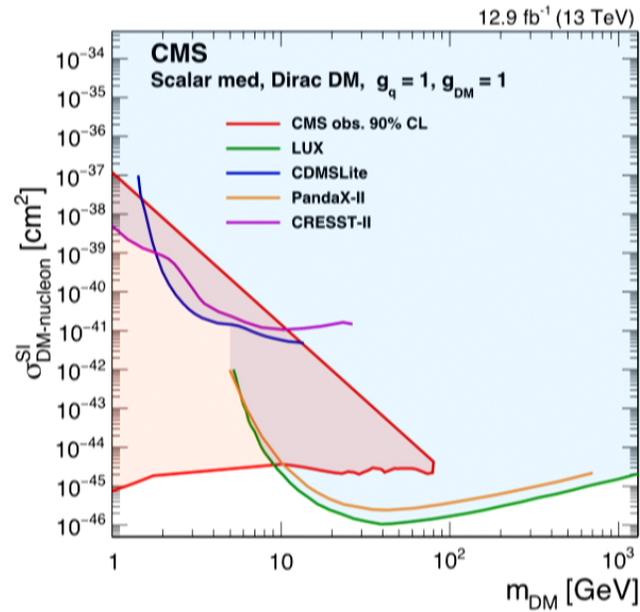
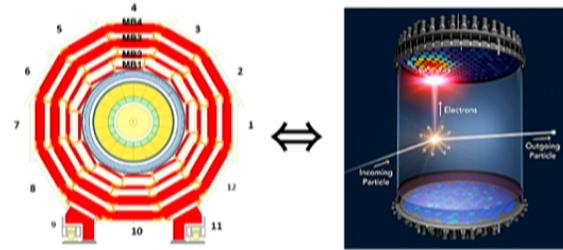
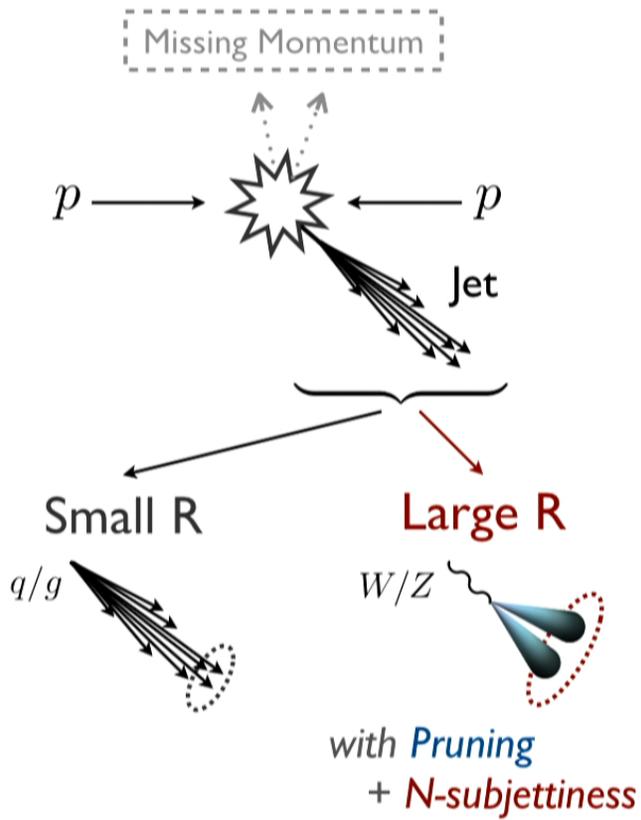
[CMS, 2017; using Ellis, Vermilion, Walsh, 2009; JDT, Van Tilburg, 2010, 2011]

CMS: Dark Matter Search



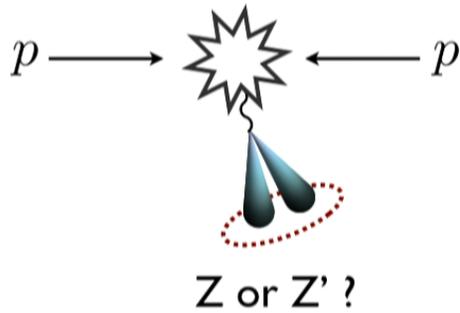
[CMS, 2017; using Ellis, Vermilion, Walsh, 2009; JDT, Van Tilburg, 2010, 2011]

CMS: Dark Matter Search



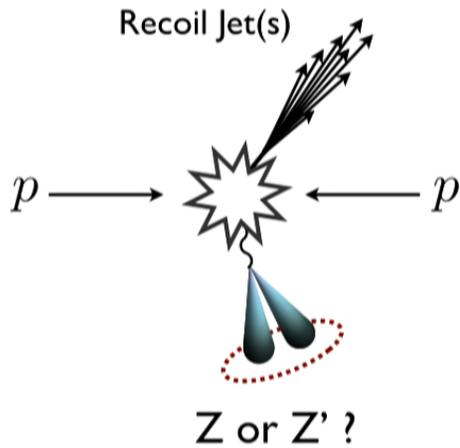
[CMS, 2017; using Ellis, Vermilion, Walsh, 2009; JDT, Van Tilburg, 2010, 2011]

CMS: Boosted Z' Search

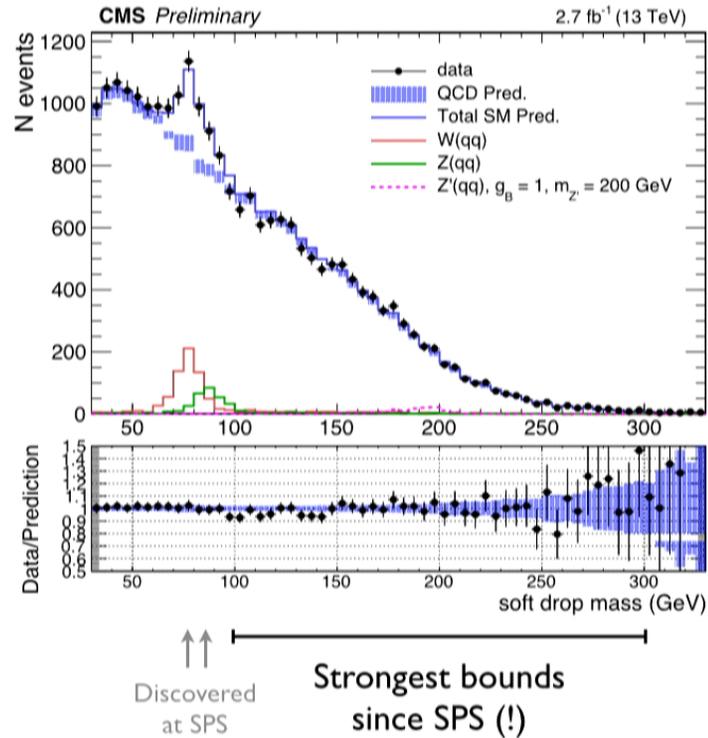


[CMS, 2016; using Larkoski, Marzani, Soyez, JDT, 2014;
JDT, Van Tilburg, 2010, 2011; Dolen, Harris, Marzani, Rappoccio, Tran, 2016]

CMS: Boosted Z' Search



with *Soft Drop*
 + *N-subjettiness*
 + *Decorrelation*

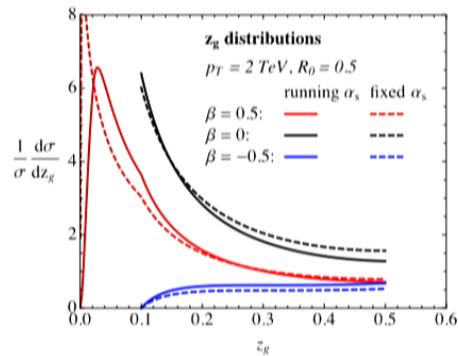


[CMS, 2016; using Larkoski, Marzani, Soyez, JDT, 2014; JDT, Van Tilburg, 2010, 2011; Dolen, Harris, Marzani, Rappoccio, Tran, 2016]

Jet Substructure



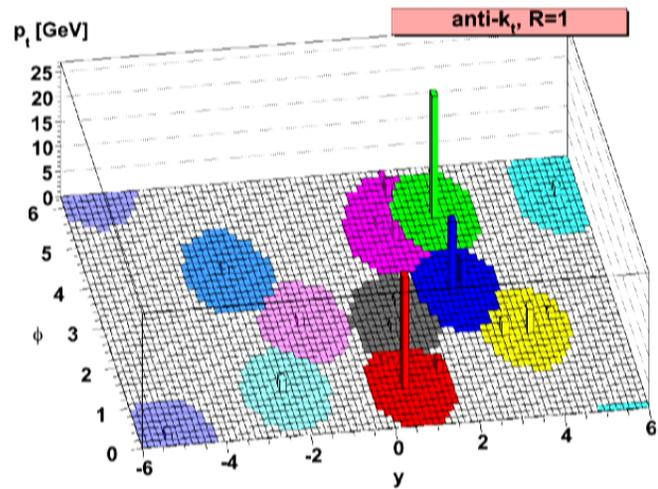
*Boosting the Search
for New Phenomena*



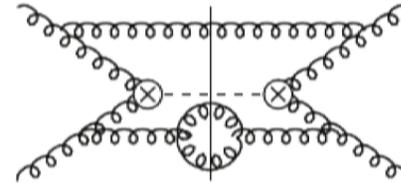
*Pushing the Boundaries
of Quantum Field Theory*

QCD Renaissance

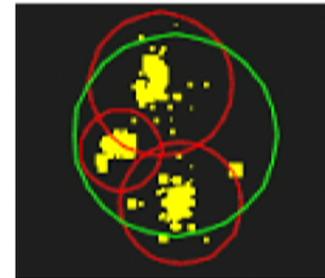
Theory c. 2008–present



New Jet Algorithms



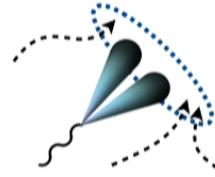
Loop/Leg/Log Explosion



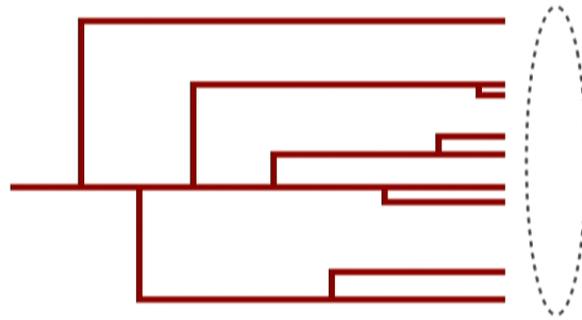
Jet Substructure

[Anti-k: 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]

Soft Drop

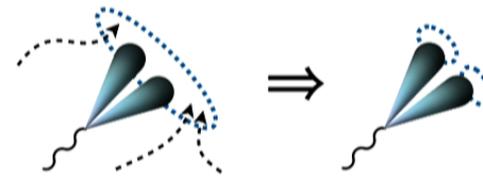


Clustering Tree

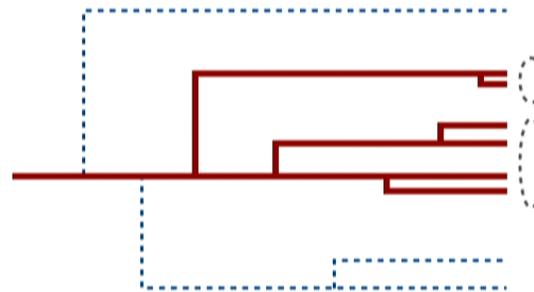


[Larkoski, Marzani, Soyez, JDT, 2014; see also Butterworth, Davison, Rubin, Salam, 2008; Dasgupta, Fregoso, Marzani, Salam/Powling, 2013]

Soft Drop

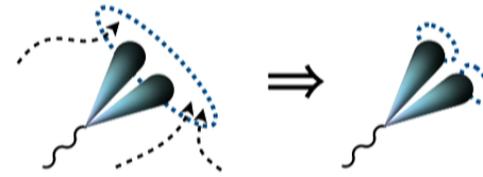


Groomed Clustering Tree

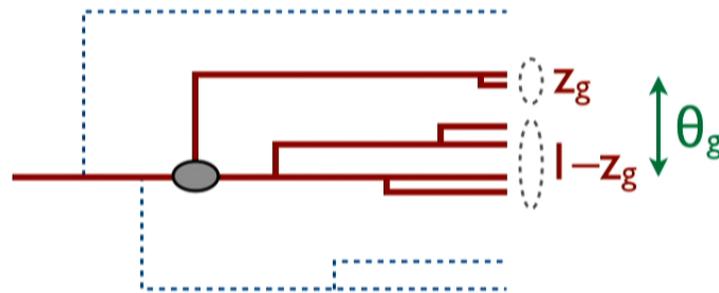


[Larkoski, Marzani, Soyez, JDT, 2014; see also Butterworth, Davison, Rubin, Salam, 2008; Dasgupta, Fregoso, Marzani, Salam/Powling, 2013]

Soft Drop



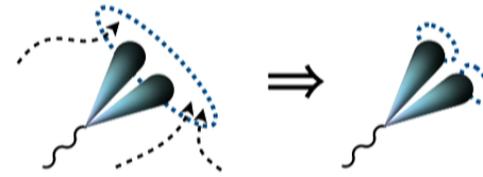
Groomed
Clustering Tree



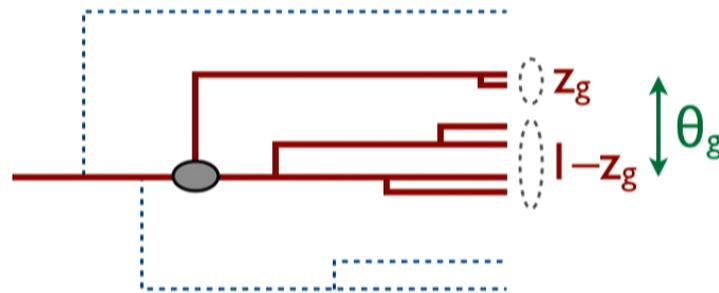
$$z_g > z_{\text{cut}} \theta_g^\beta$$

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

Soft Drop



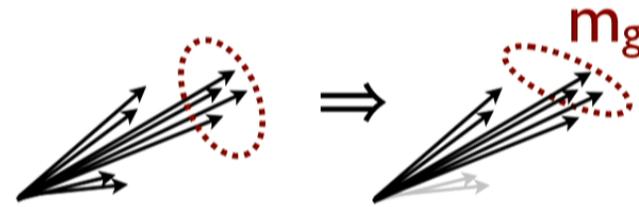
Groomed
Clustering Tree



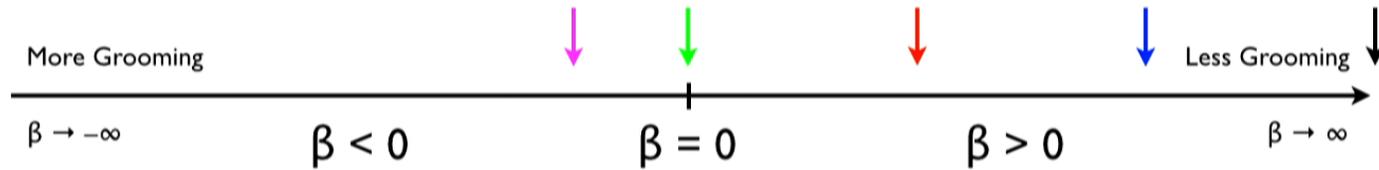
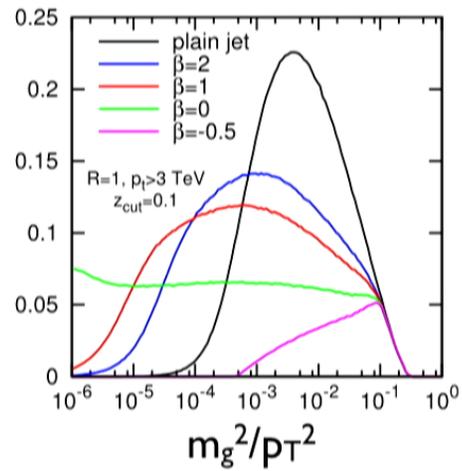
$$z_g > z_{\text{cut}} \theta_g^\beta$$

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

Calculating Mass?

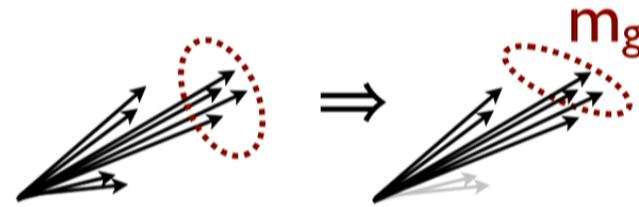


Simulated LHC Data

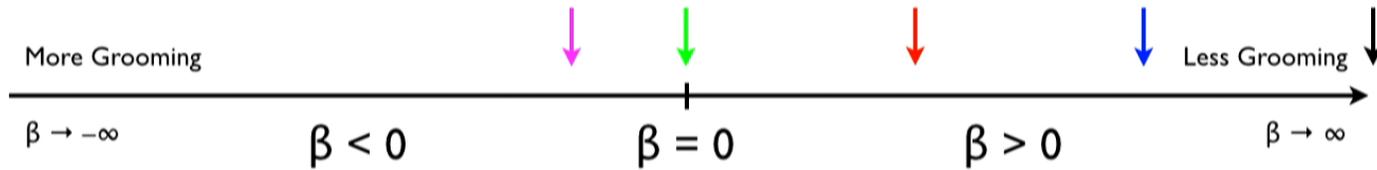
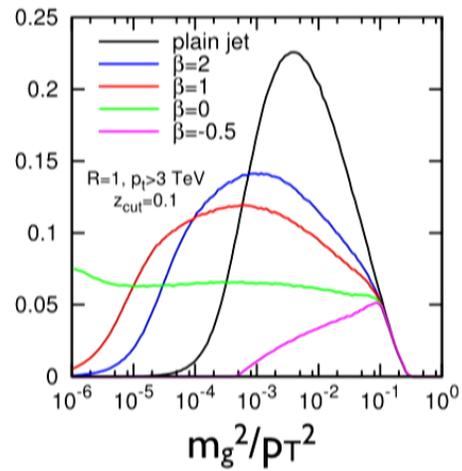


[Larkoski, Marzani, Soyez, JDT, 2014; see also Frye, Larkoski, Schwartz, Yan, 2016]

Calculating Mass?

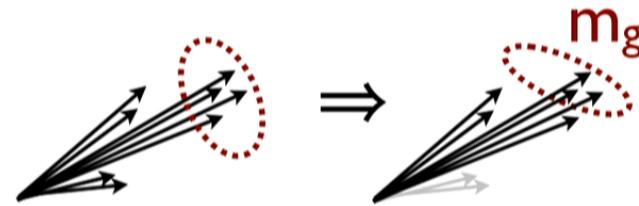


Simulated LHC Data

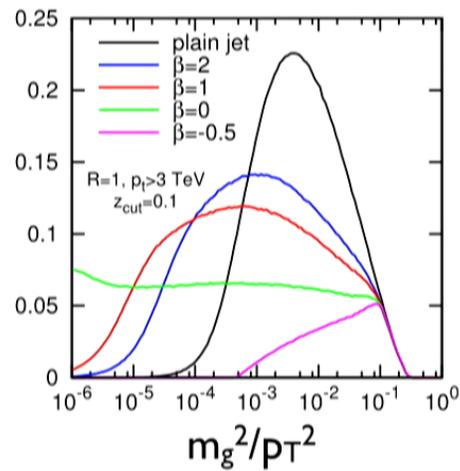


[Larkoski, Marzani, Soyez, JDT, 2014; see also Frye, Larkoski, Schwartz, Yan, 2016]

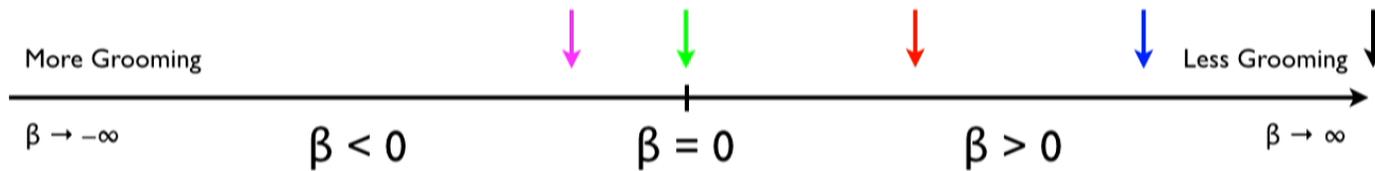
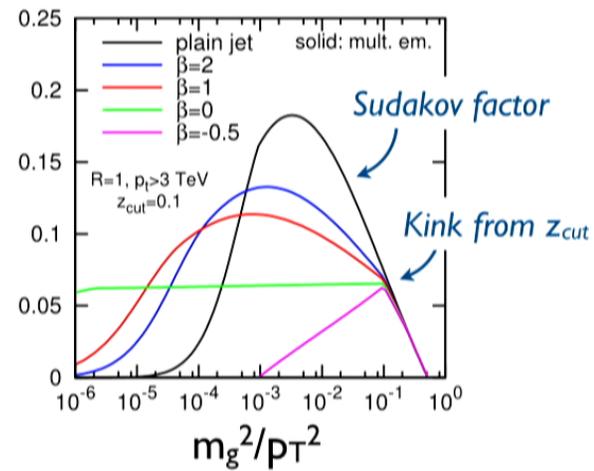
Calculating Mass?



Simulated LHC Data

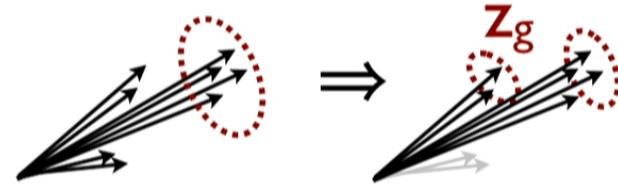


First-principles QCD



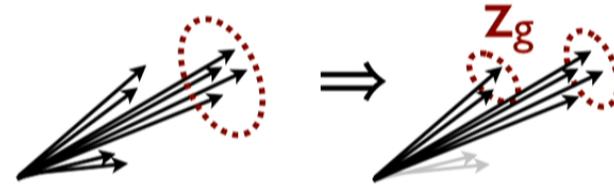
[Larkoski, Marzani, Soyez, JDT, 2014; see also Frye, Larkoski, Schwartz, Yan, 2016]

Calculating z_g ?



$$p(z_g) = \left(\quad \right) + \alpha_s \left(\quad \right) + \alpha_s^2 \left(\quad \right) + \dots$$

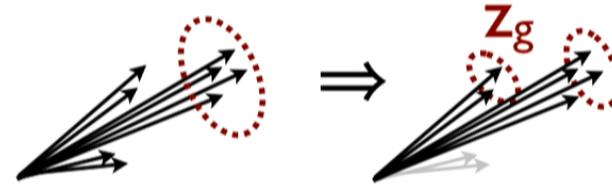
Calculating z_g ?



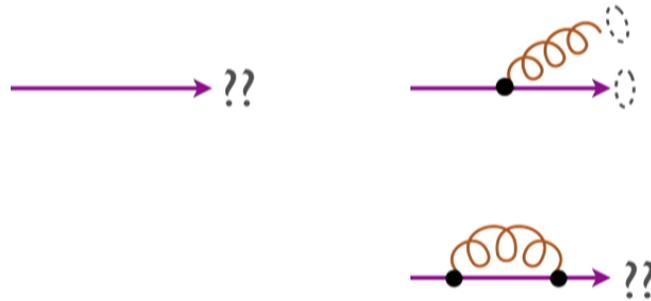
$$p(z_g) = \left(\text{undefined} \right) + \alpha_s \left(\quad \right) + \alpha_s^2 \left(\quad \right) + \dots$$

—————> ??

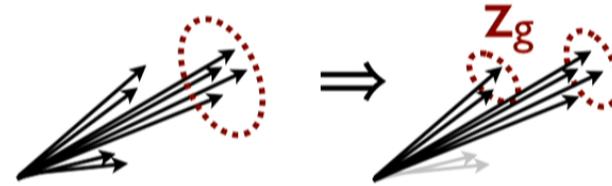
Calculating z_g ?



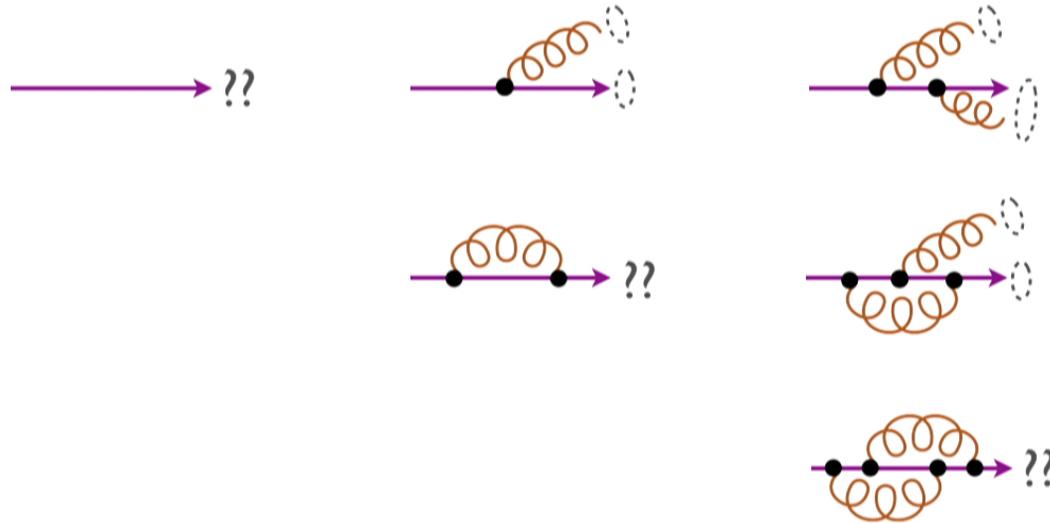
$$p(z_g) = \left(\text{undefined} \right) + \alpha_s \left(\text{infinity} \right) + \alpha_s^2 \left(\quad \right) + \dots$$



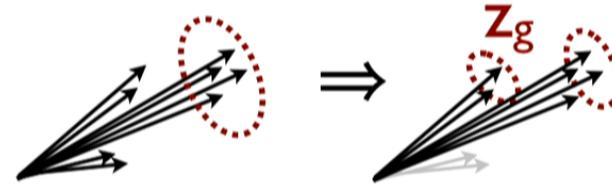
Calculating z_g ?



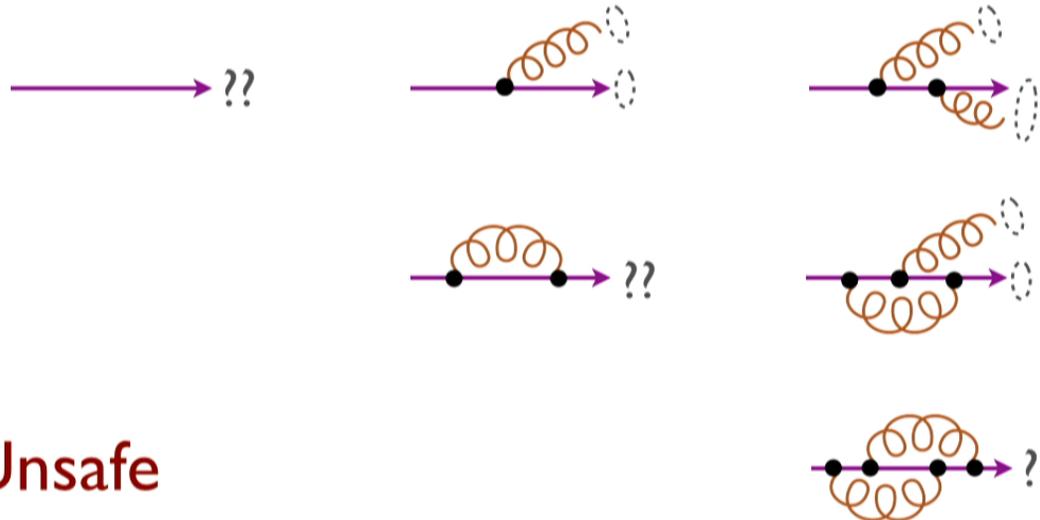
$$p(z_g) = \left(\text{undefined} \right) + \alpha_s \left(\text{infinity} \right) + \alpha_s^2 \left(\text{infinity}^2 \right) + \dots$$



Calculating z_g ?

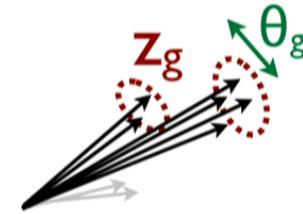


$$p(z_g) = \left(\text{undefined} \right) + \alpha_s \left(\text{infinity} \right) + \alpha_s^2 \left(\text{infinity}^2 \right) + \dots$$



z_g **Unsafe**

The Puzzle



Unsafe
↓
 $p(z_g)$

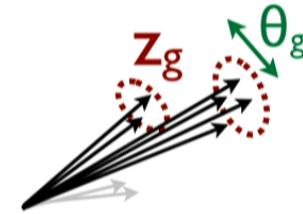
Calculable
order-by-order in α_s
↓
 $p(z_g | \theta_g)$

→ $z_g ??$

vs.

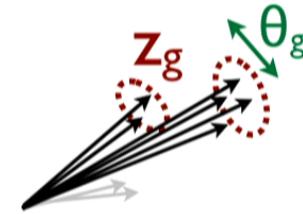
→ z_g
↕ θ_g
→ $1 - z_g$

The Puzzle



$$p(z_g) \stackrel{?!}{=} \int d\theta_g p(\theta_g) p(z_g | \theta_g)$$

The Resolution



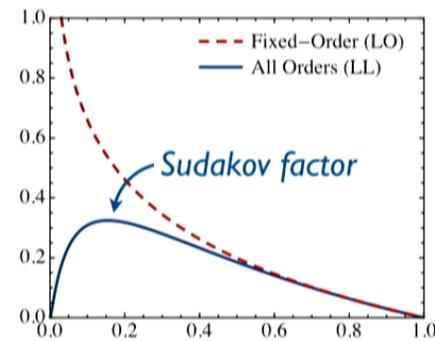
“Sudakov Safe”

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

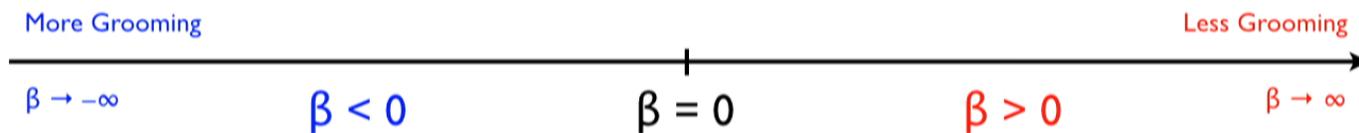
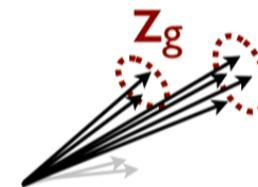
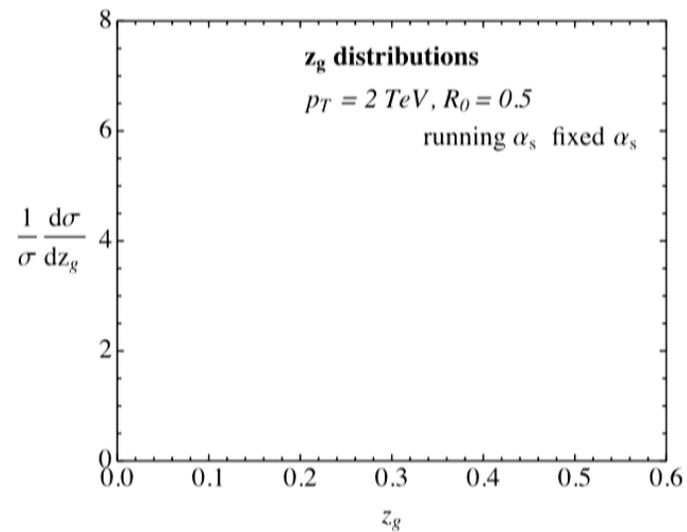
[Larkoski, JDT, 2013;
Larkoski, Marzani, JDT, 2015]

Calculable
order-by-order in α_s

Suppresses singularities
at all orders in α_s

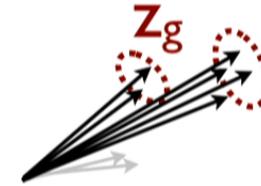
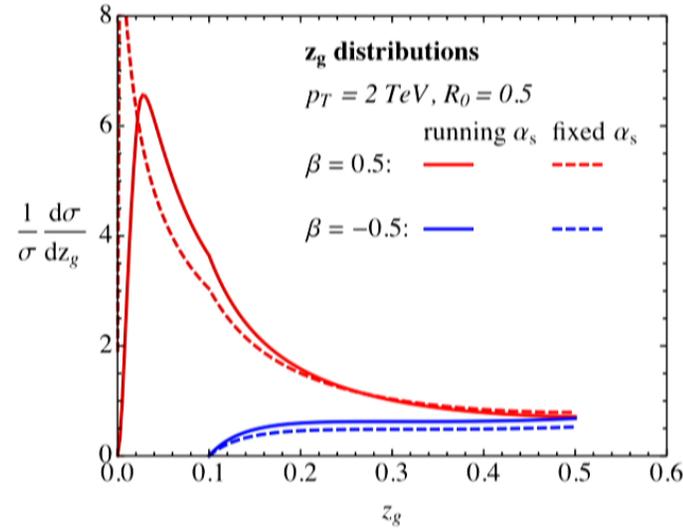


First-Principles QCD



[Larkoski, Marzani, JDT, 2015]

First-Principles QCD



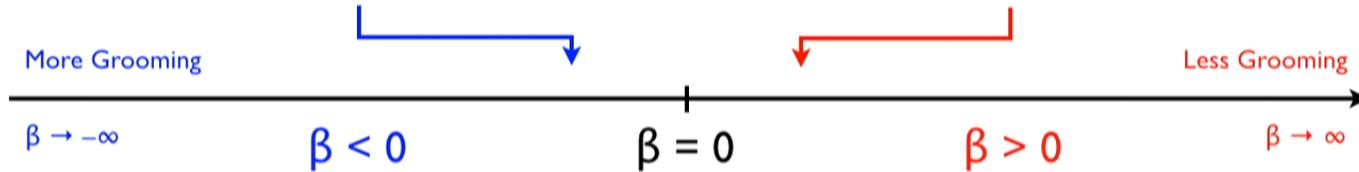
$$C_q = 4/3$$

$$C_g = 3$$

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

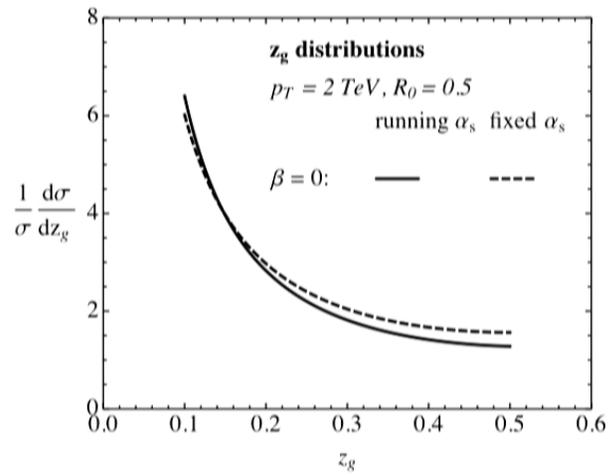
$$\simeq \sqrt{\frac{\alpha_s C_i}{\beta}} \frac{1}{z_g}$$

Beyond traditional
perturbation theory
(Sudakov safe)

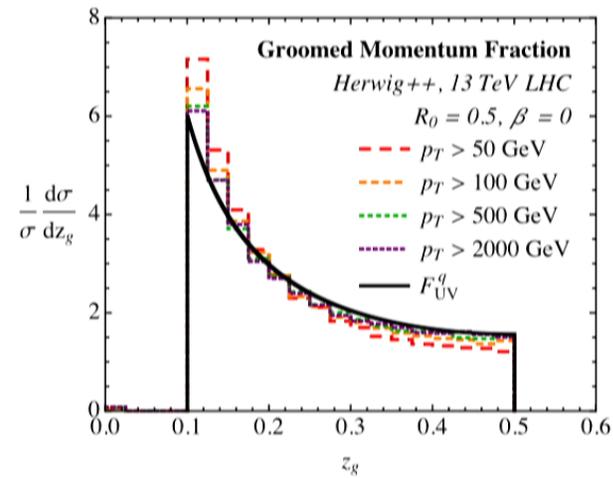


[Larkoski, Marzani, JDT, 2015]

Unsafe but Calculable



Simulated LHC Data

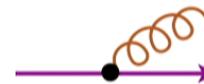


“Standard Candle”
for Jets in QCD:

$$\simeq \frac{1}{z_g}$$

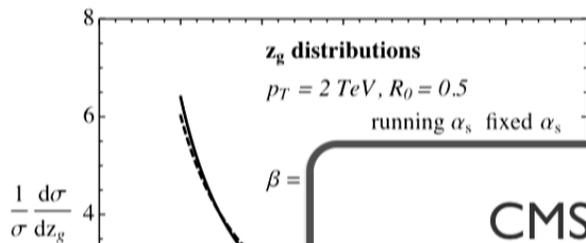


$$dP_{i \rightarrow ig} \simeq \frac{2\alpha_s}{\pi} C_i \frac{d\theta}{\theta} \frac{dz}{z}$$

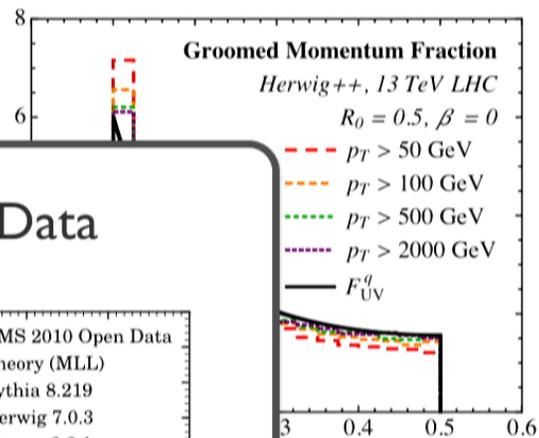


[Larkoski, Marzani, JDT, 2015]

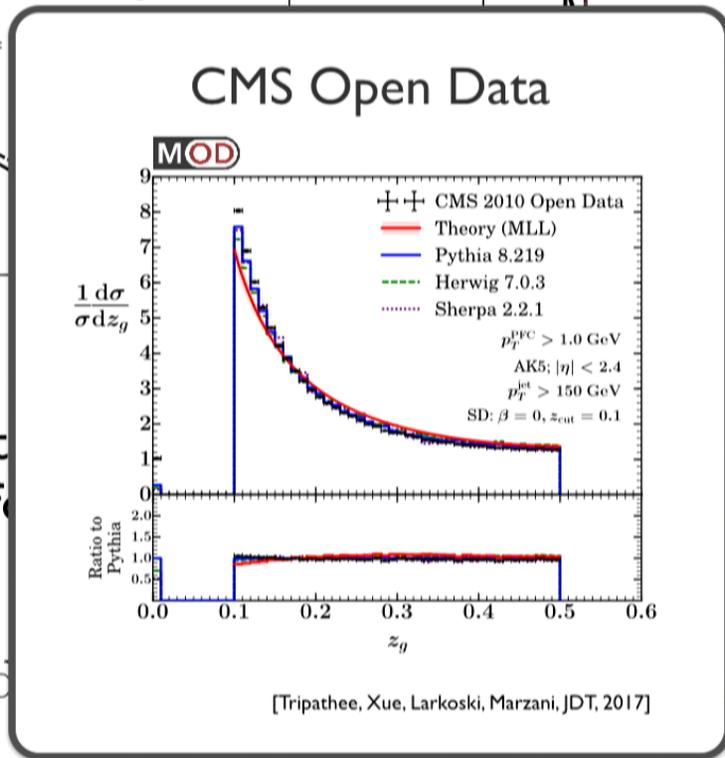
Unsafe but Calculable



Simulated LHC Data



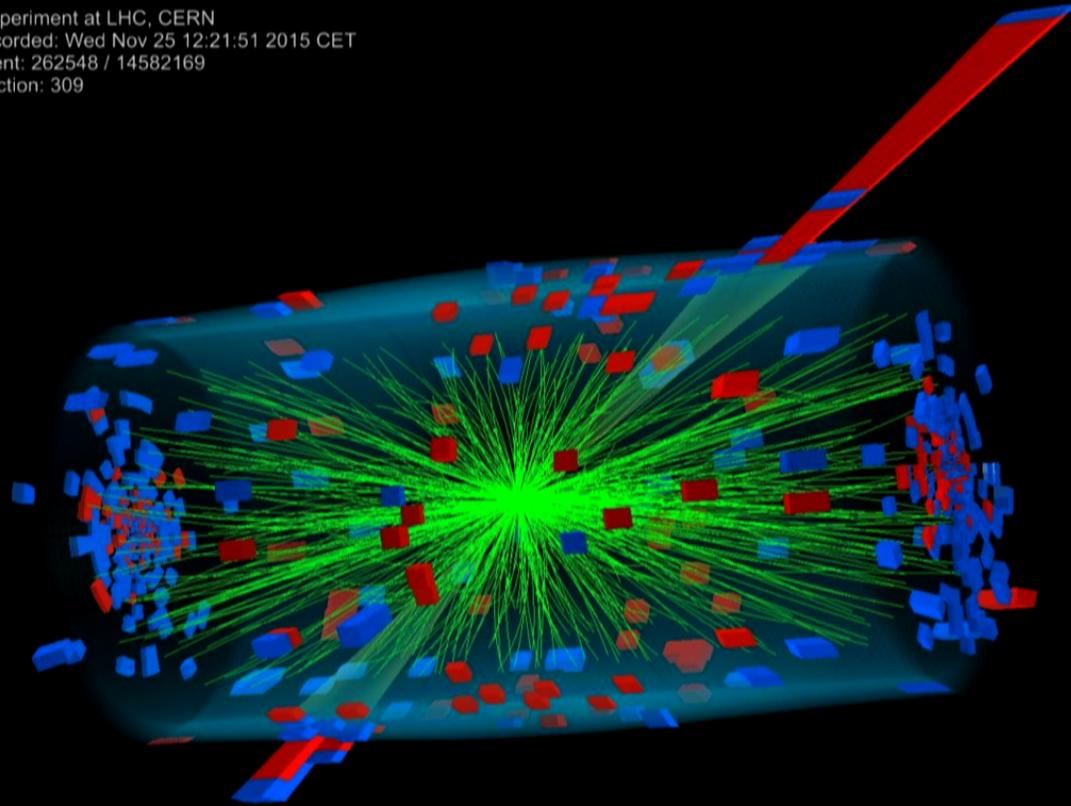
“St
f



[Larkoski, Marzani, JDT, 2015]

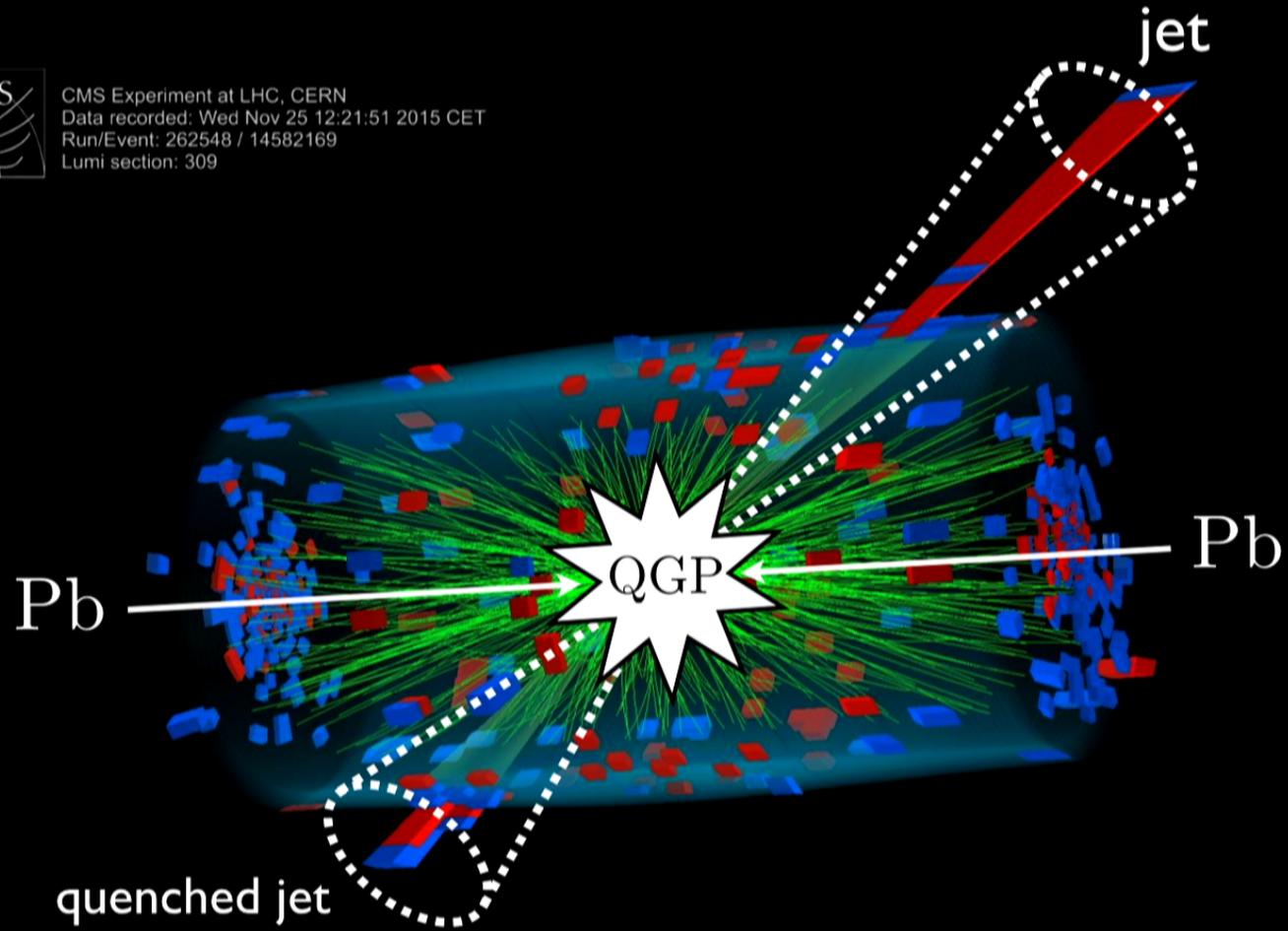


CMS Experiment at LHC, CERN
Data recorded: Wed Nov 25 12:21:51 2015 CET
Run/Event: 262548 / 14582169
Lumi section: 309





CMS Experiment at LHC, CERN
Data recorded: Wed Nov 25 12:21:51 2015 CET
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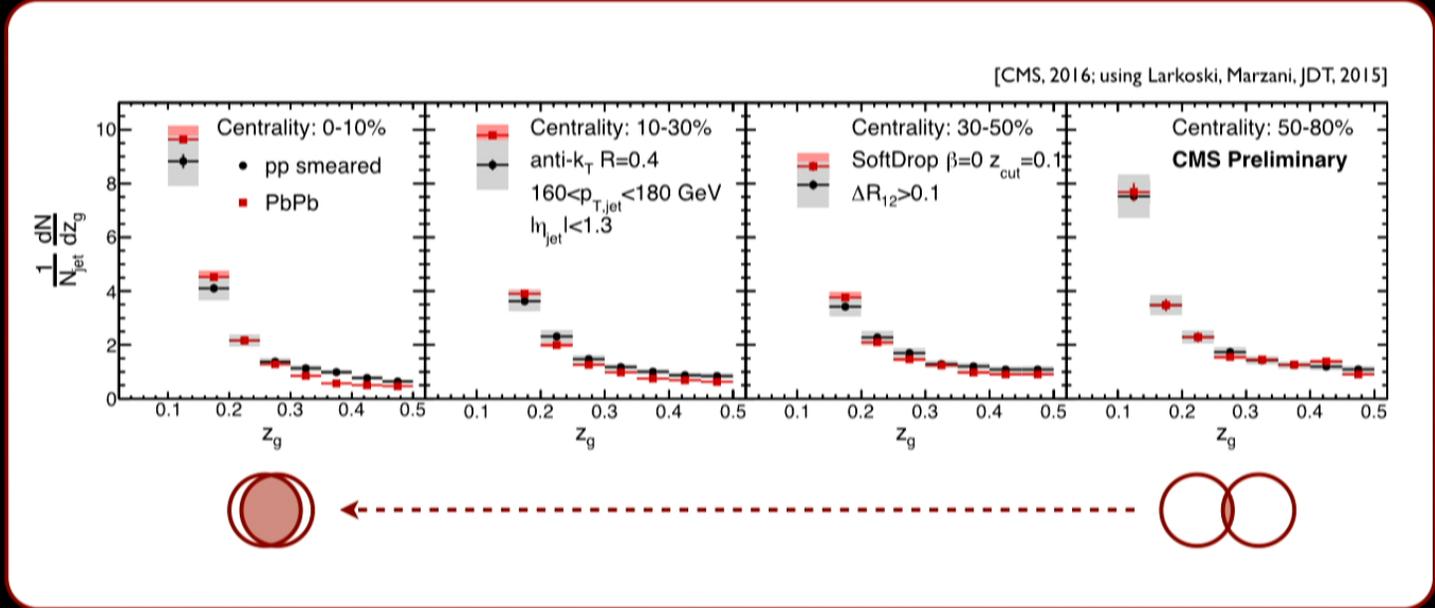




CMS Experiment at LHC, CERN
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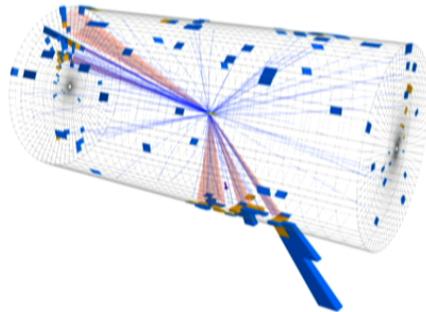
jet



quenched jet

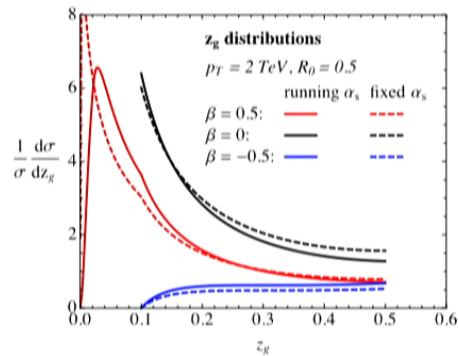


Jet Substructure



Boosting the Search for New Phenomena

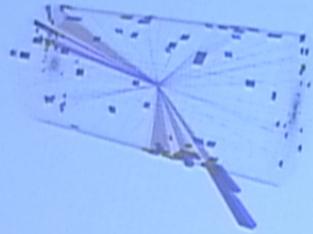
Planar Flow, Trimming, Variable R, N-subjettiness, Energy Correlators, Winner-Take-All Axes, Soft Drop, Jets Without Jets, X Cone, Generalized Correlators, ...



Pushing the Boundaries of Quantum Field Theory

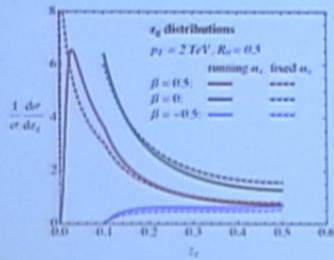
Boosted Event Shapes, Transverse Velocity Flow, Track Functions, Recoil-Free Observables, Sudakov Safety, Quark/Gluon Mutual Information, ...

Jet Substructure



Boosting the Search for New Phenomena

Planar Flow, **Trimming**, Variable R, N-subjettiness, Energy Correlators, Winner-Take-All Axes, Soft Drop, Jets Without Jets, X Cone, **Generalized Correlators**, ...



Pushing the Boundaries of Quantum Field Theory

Boosted Event Shapes, Transverse Velocity Flow, Track Functions, Recoil-Free Observables, **Sudakov Safety**, Quark/Gluon Mutual Information, ...

