New Physics Gets a Boost

Jet Substructure at the Large Hadron Collider

Jesse Thaler

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

UT Austin Physics Colloquium
March 29, 2017

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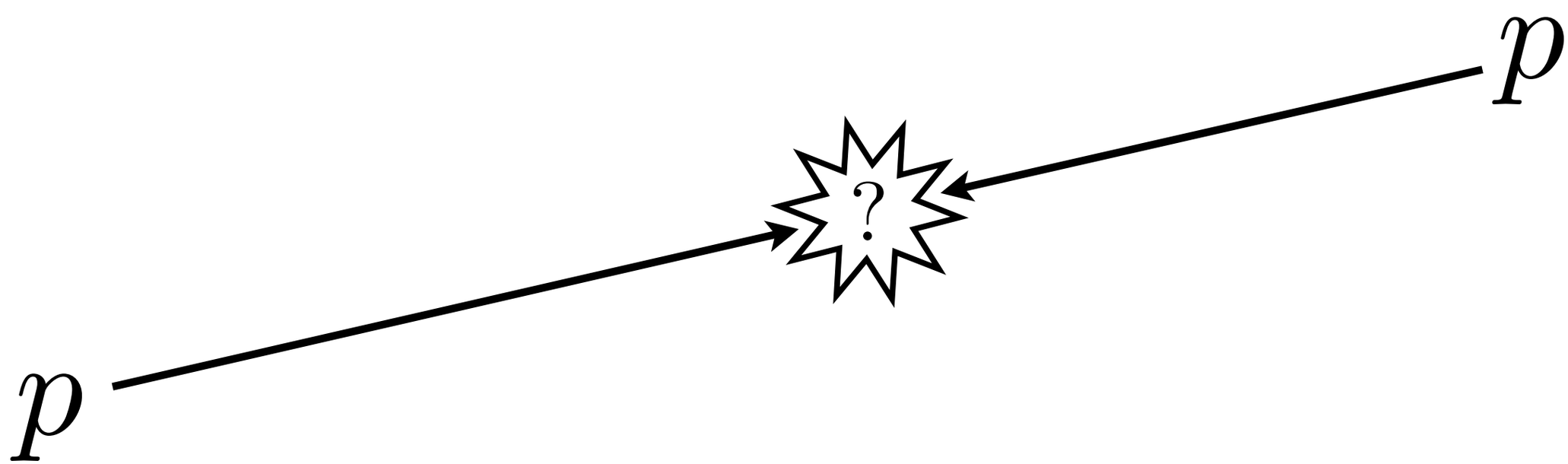

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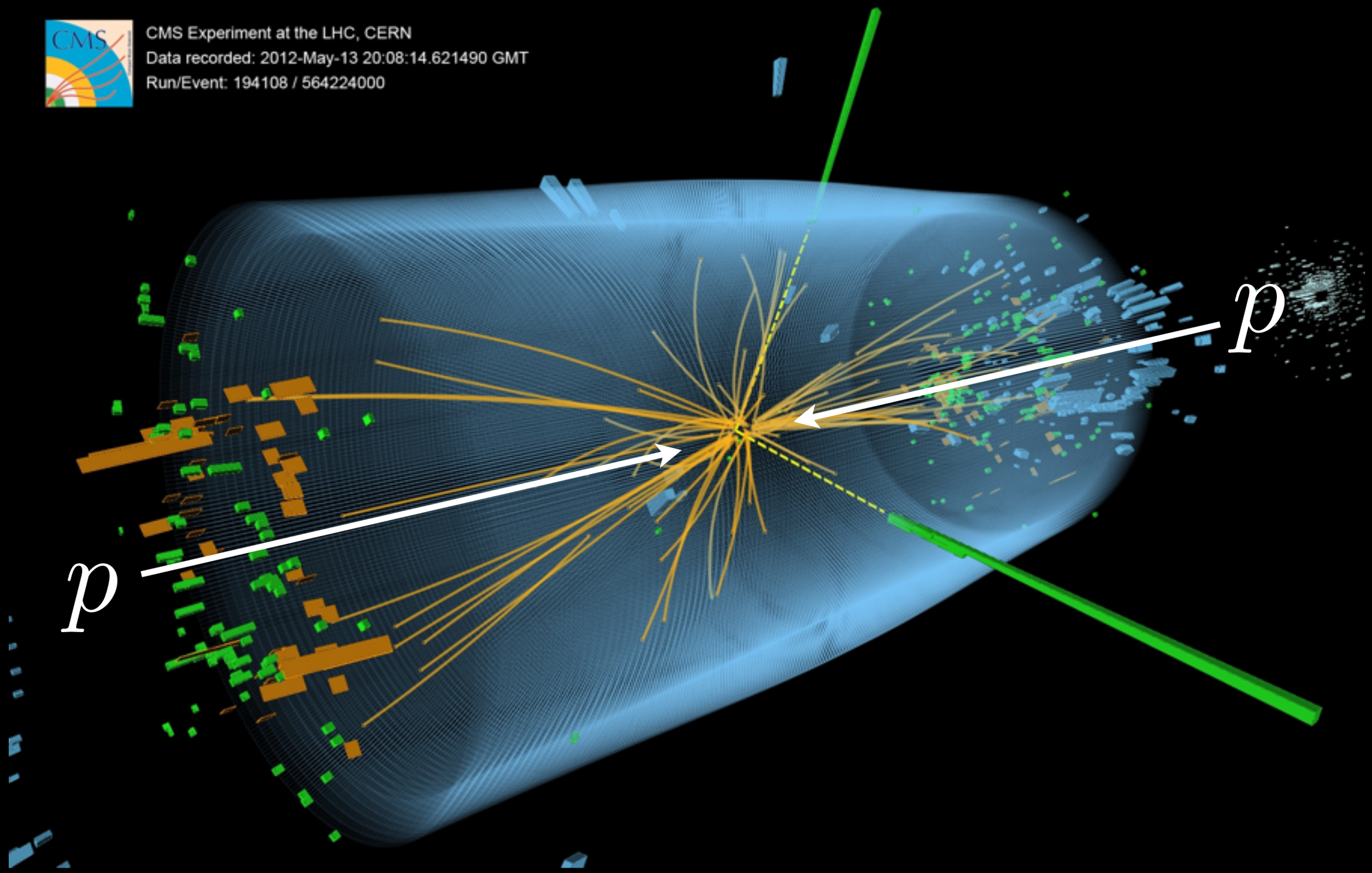
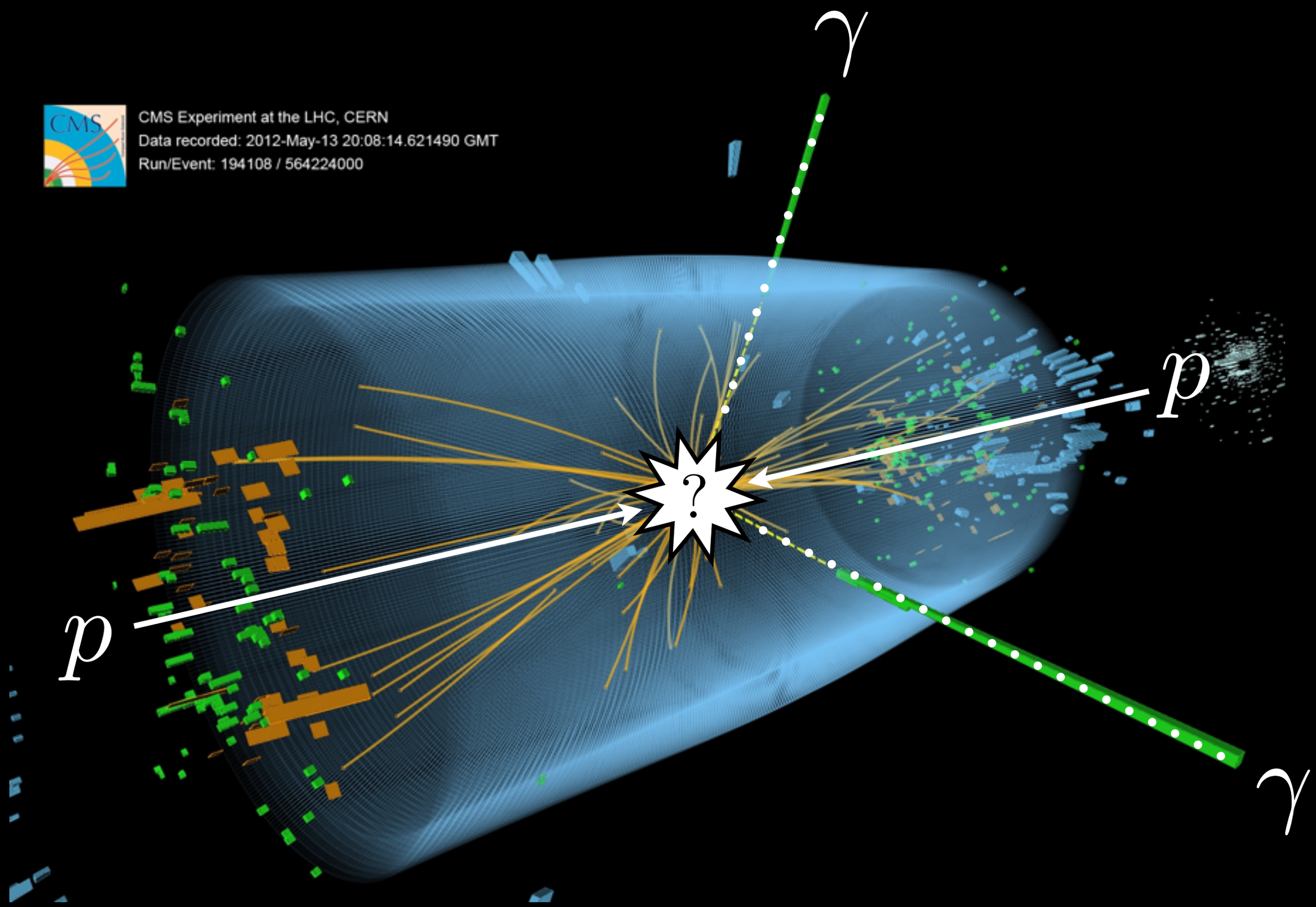

CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000
p
p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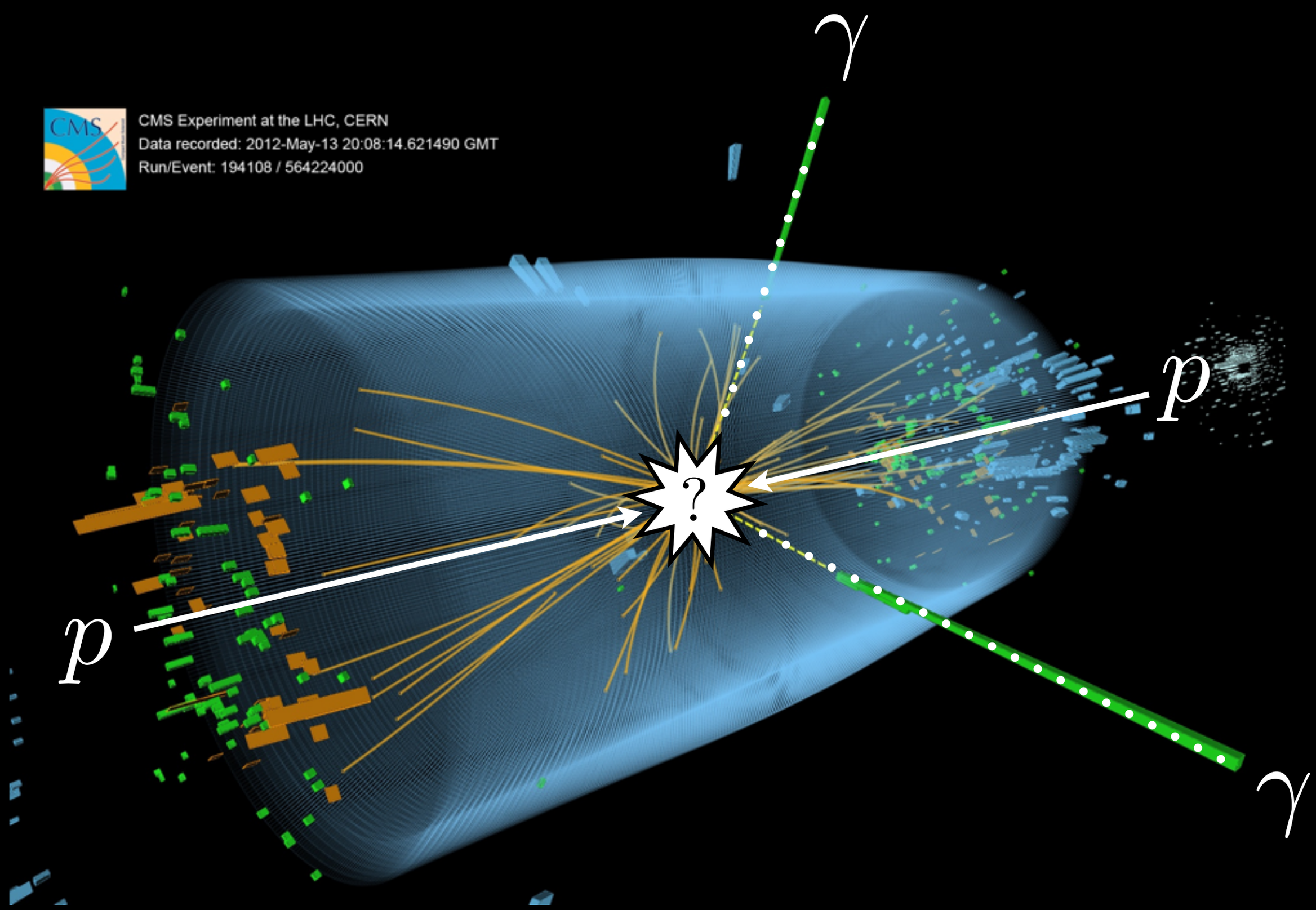
γ
p
?
p
γ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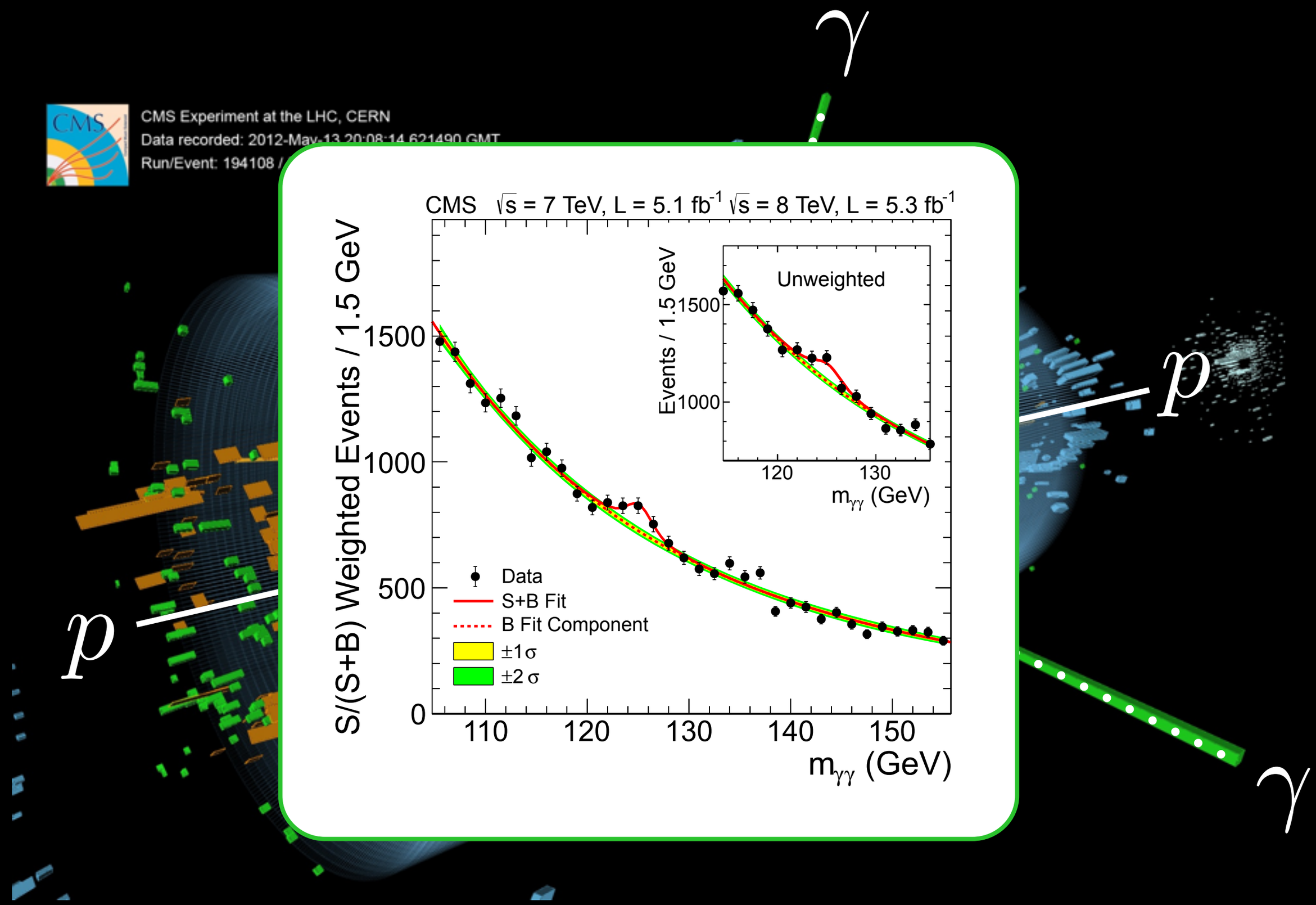
γ
p
?
p
γ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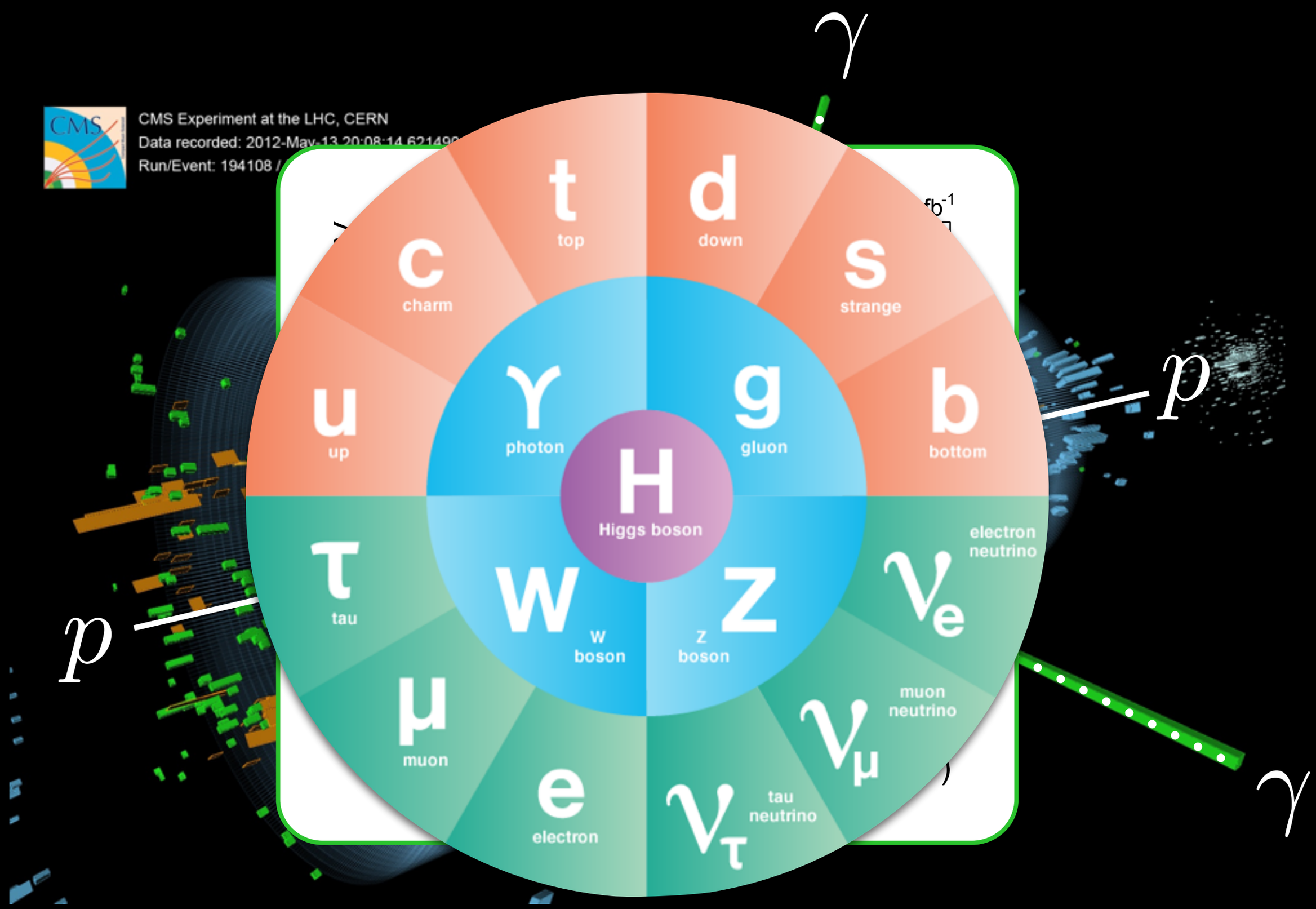
Run/Event: 194108 /
γ
p
p
γ
CMS √s = 7 TeV, L = 5.1 fb-1 √s = 8 TeV, L = 5.3 fb-1
S/(S+B) Weighted Events / 1.5 GeV
0
500
1000
1500
110
120
130
140
150
mγγ (GeV)
Data
S+B Fit
B Fit Component
±1σ
±2 σ
Unweighted
Events / 1.5 GeV
1000
1500
120
130
mγγ (GeV)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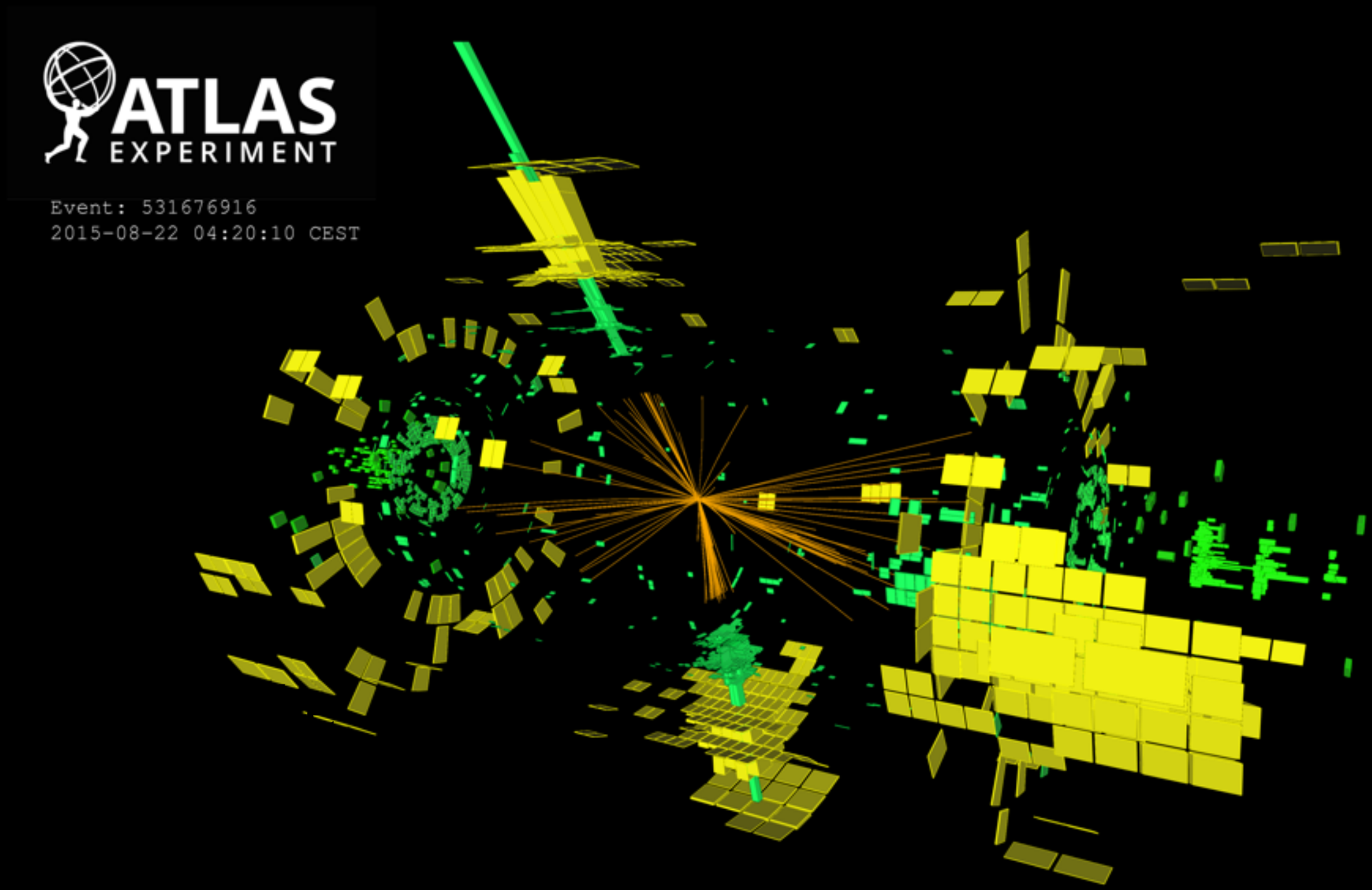
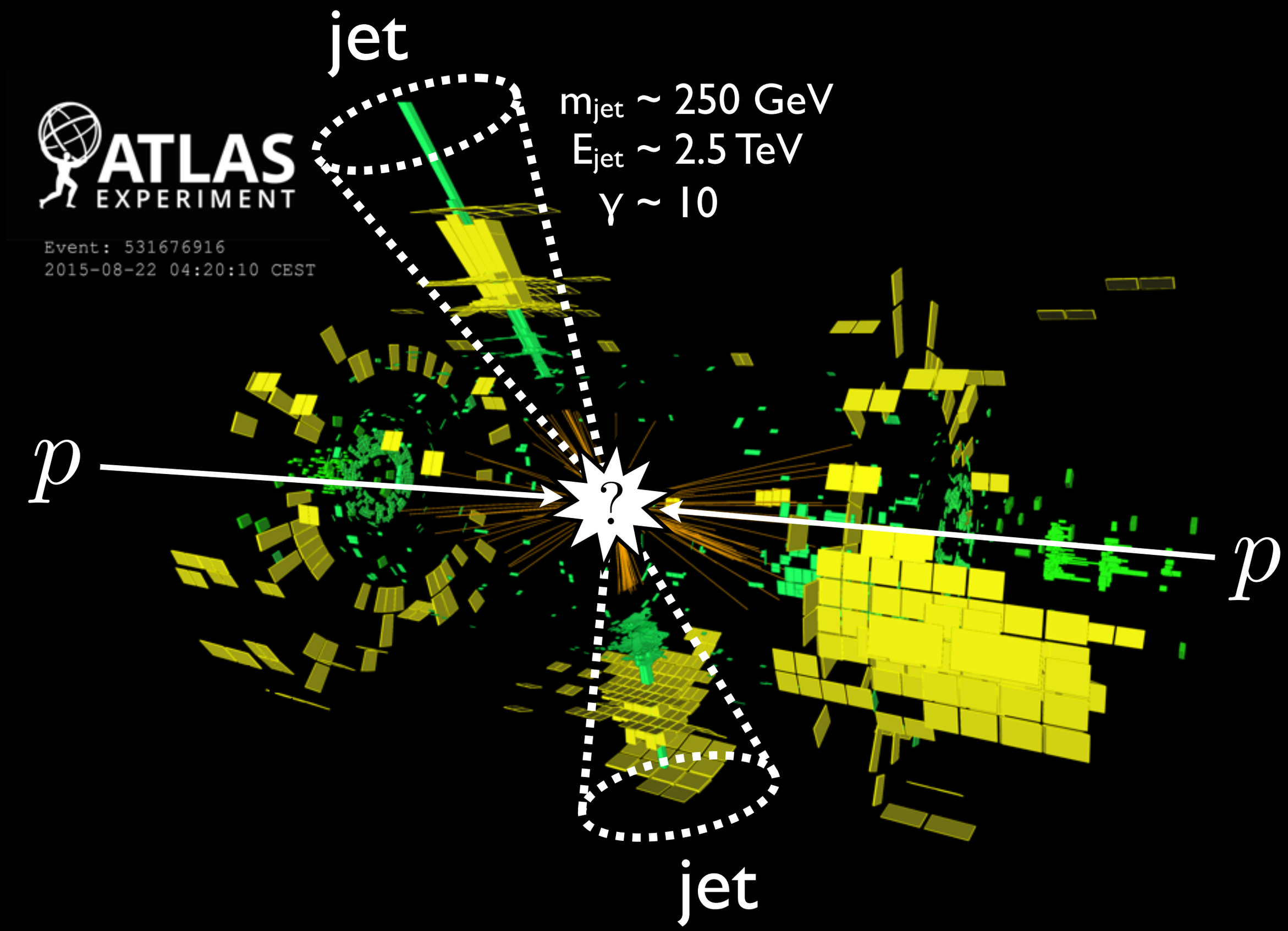
γ
p
p
γ
t
top
d
down
c
charm
s
strange
u
up
γ
photon
g
gluon
b
bottom
H
Higgs boson
τ
tau
W
W boson
Z
Z boson
ν_e
electron neutrino
μ
muon
ν_μ
muon neutrino
e
electron
ν_τ
tau neutrino


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


jet
$m_{jet} \sim 250$ GeV
$E_{jet} \sim 2.5$ TeV
$\gamma \sim 10$
ATLAS
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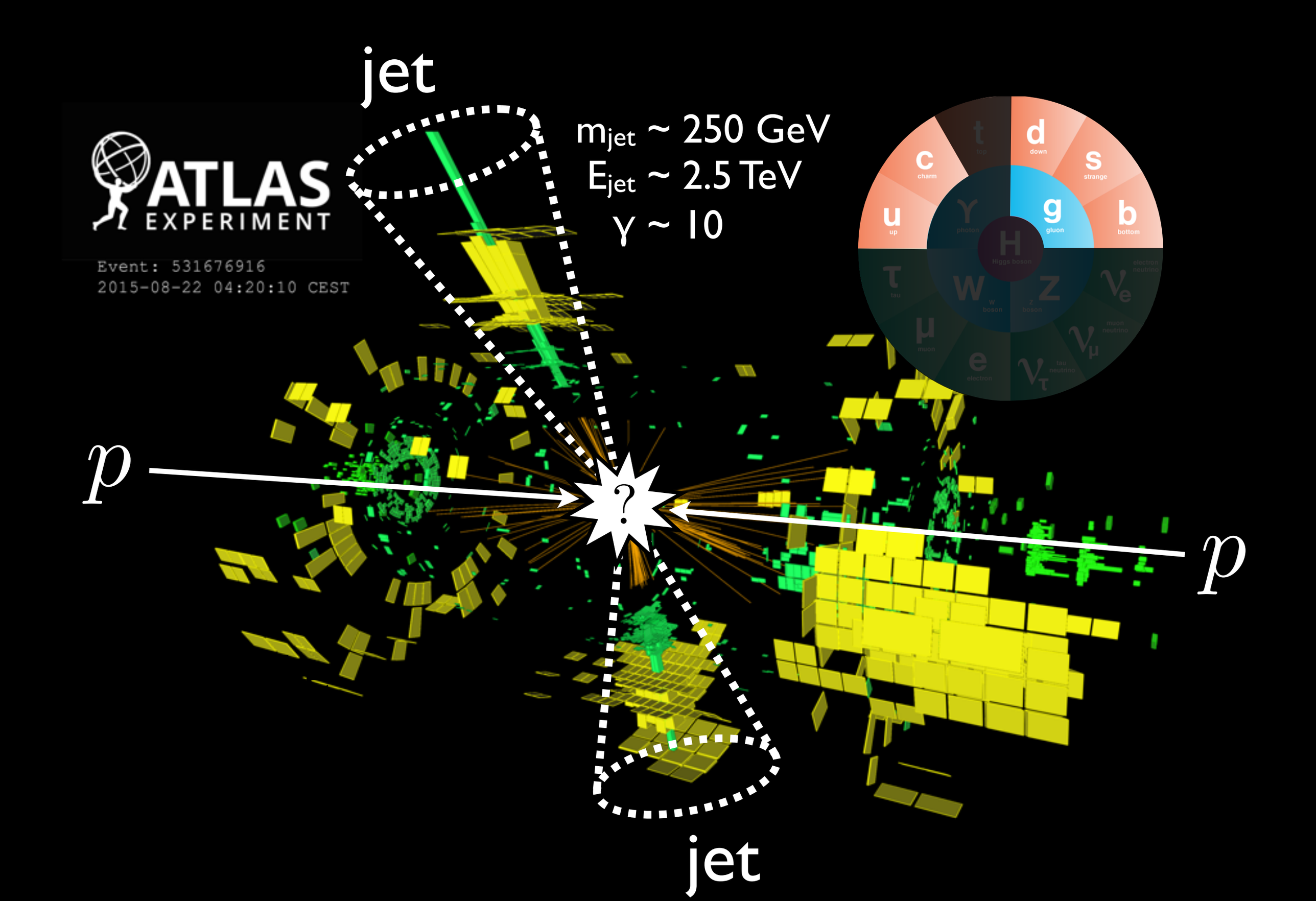
Event: 531676916
2015-08-22 04:20:10 CEST
p
?
p
jet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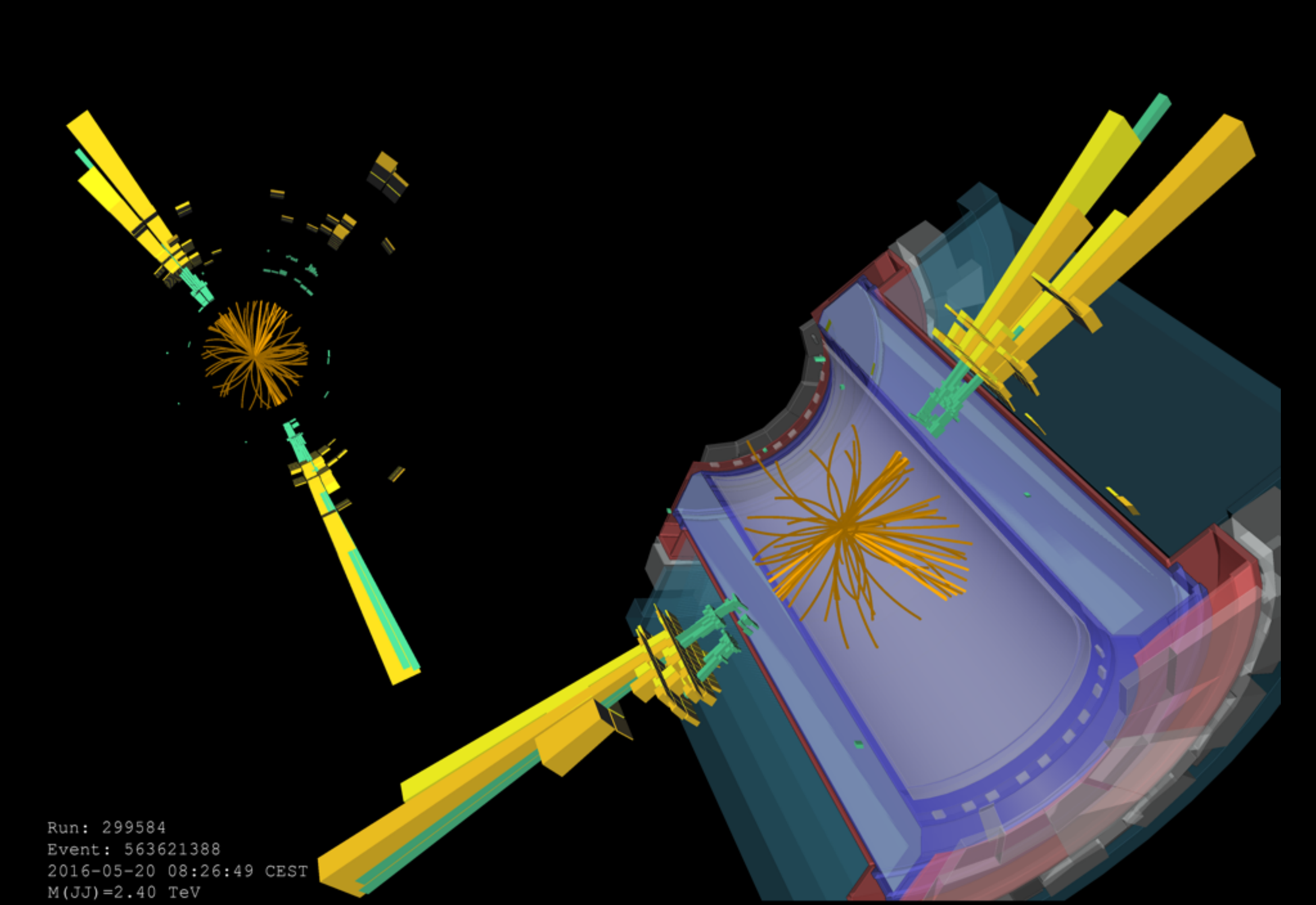
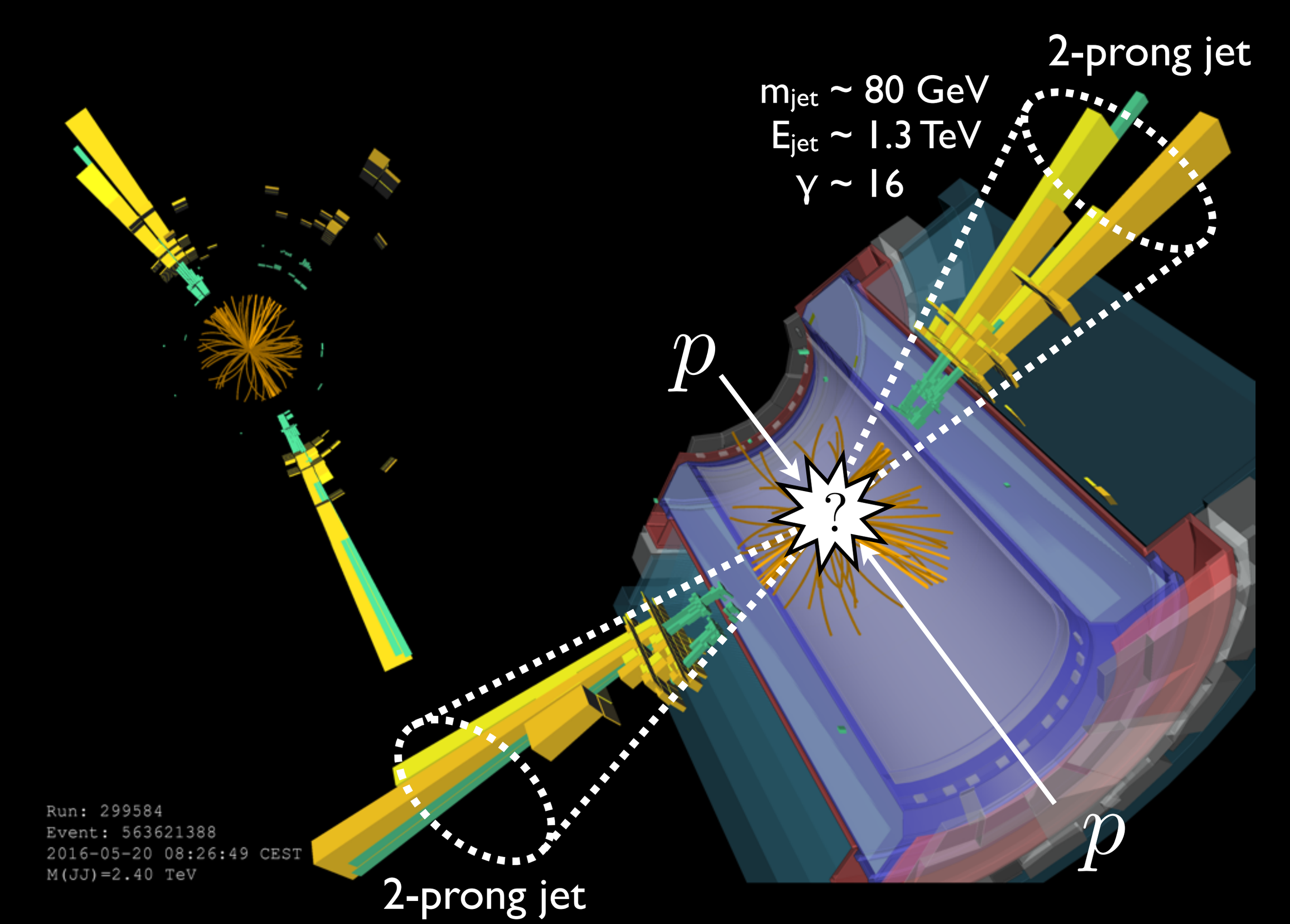

Run: 299584
Event: 563621388
2016-05-20 08:26:49 CEST
M(JJ)=2.40 TeV


2-prong jet
m_{jet} ~ 80 GeV
E_{jet} ~ 1.3 TeV
γ ~ 16
p
?
p
Run: 299584
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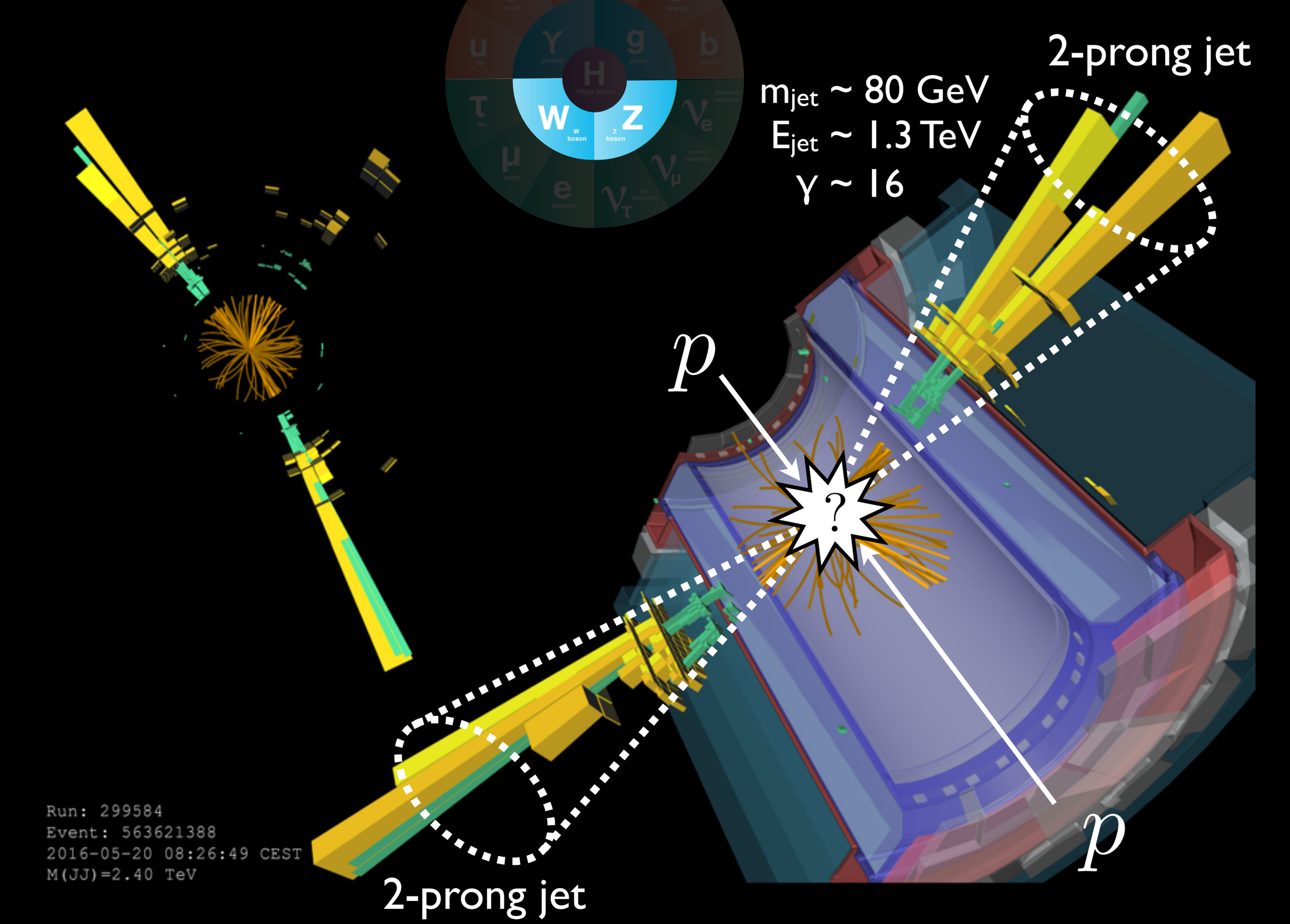
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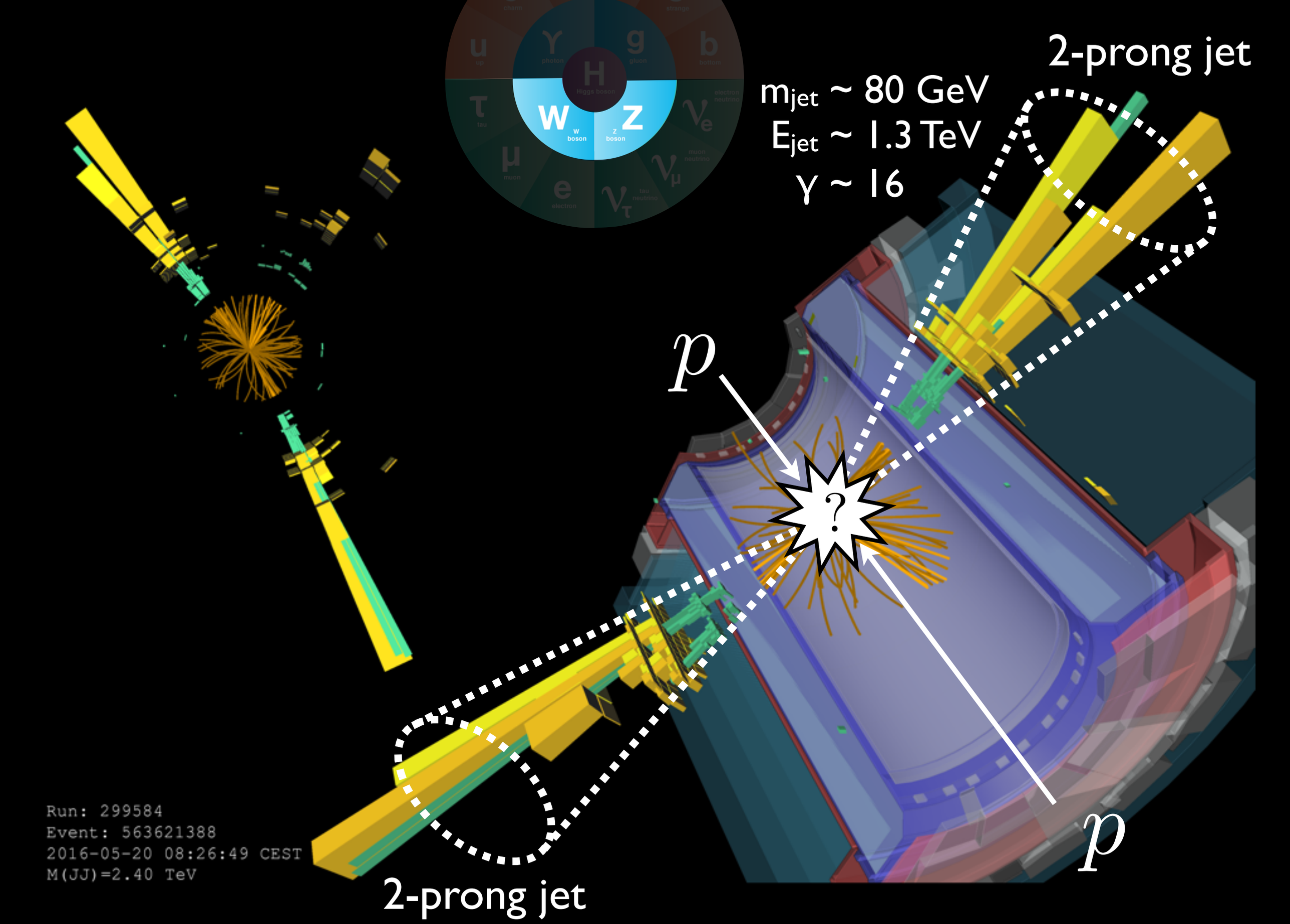
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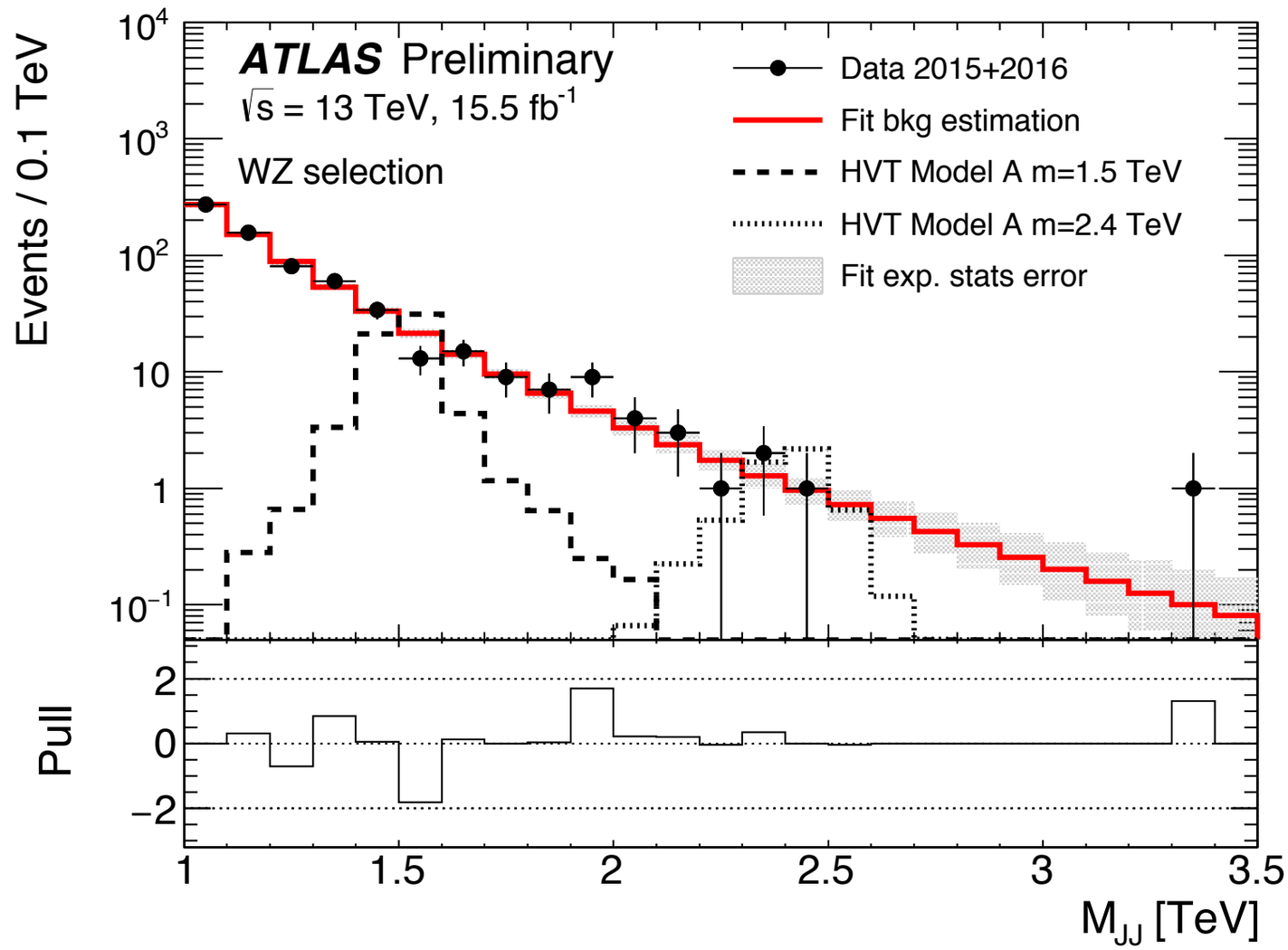


with Trimming + Energy Correlators

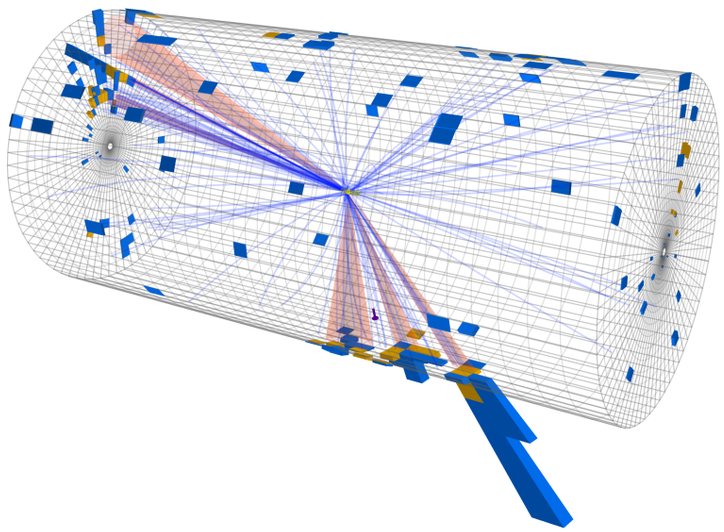
[Krohn, JDT, Wang, 2009]

[Larkoski, Salam, JDT, 2013; Larkoski, Moult, Neill, 2014]

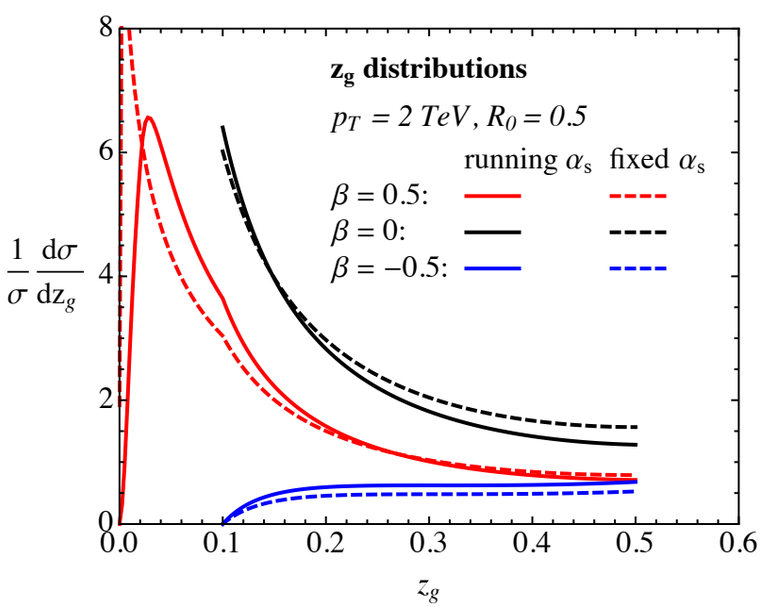
Run: 299584
Event: 563621388
2016-05-20 08:26:4
M(JJ)=2.40 TeV

p

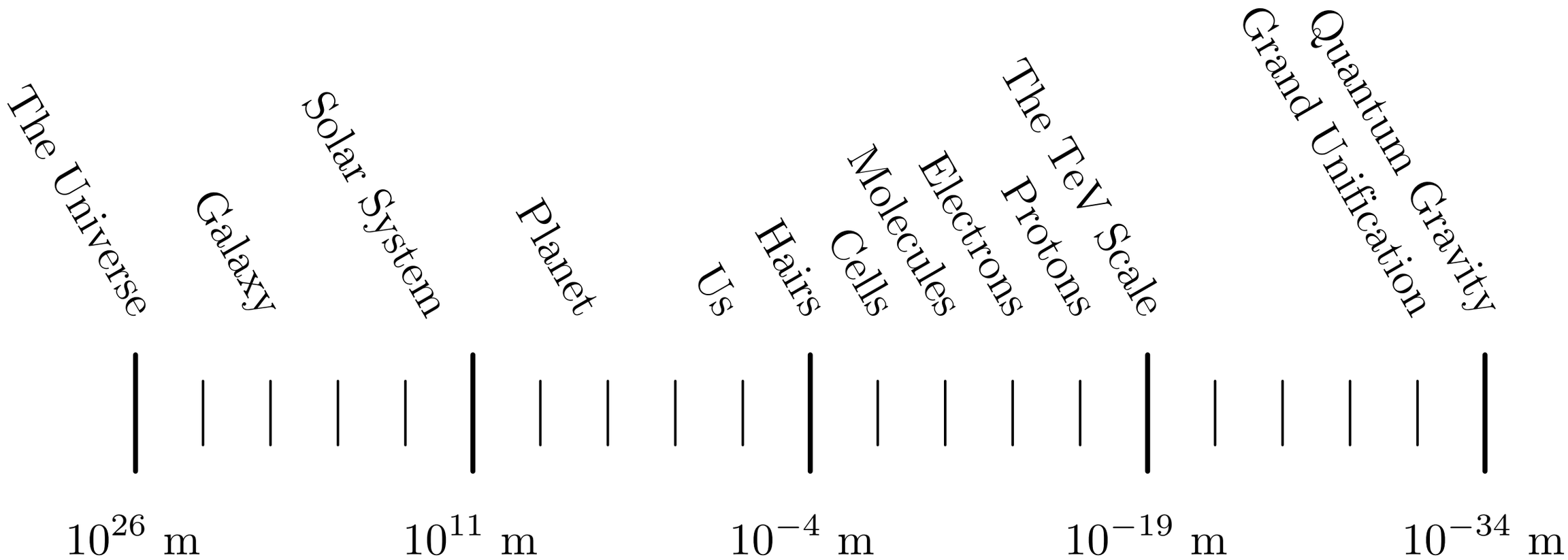
Jet Substructure

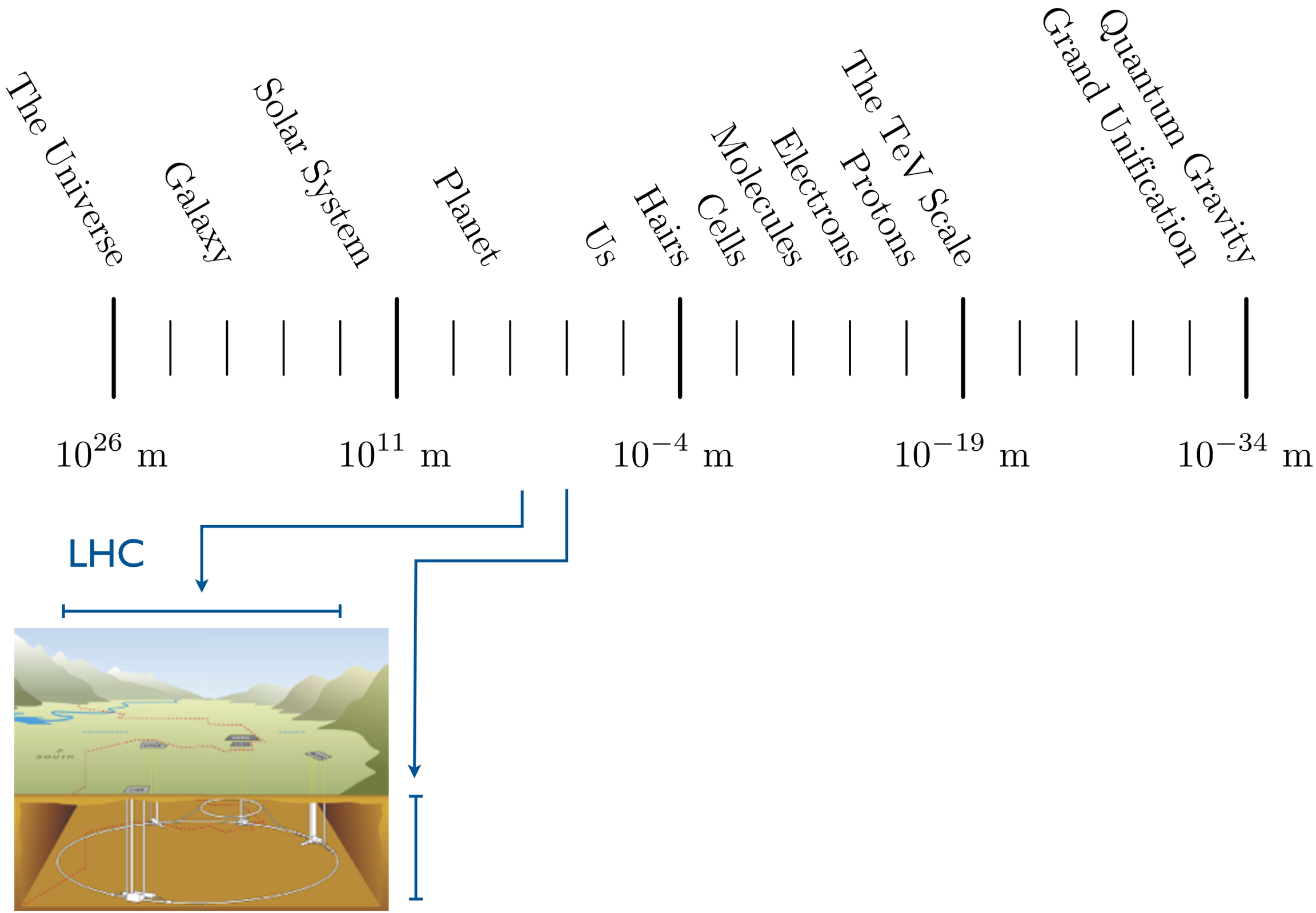


Boosting the Search for New Phenomena



Pushing the Boundaries of Quantum Field Theory


The Universe
Galaxy
Solar System
Planet
Us
Hairs
Cells
Molecules
Electrons
Protons
The TeV Scale
Grand Unification
Quantum Gravity
10^{26} m
10^{11} m
10^{-4} m
10^{-19} m
10^{-34} m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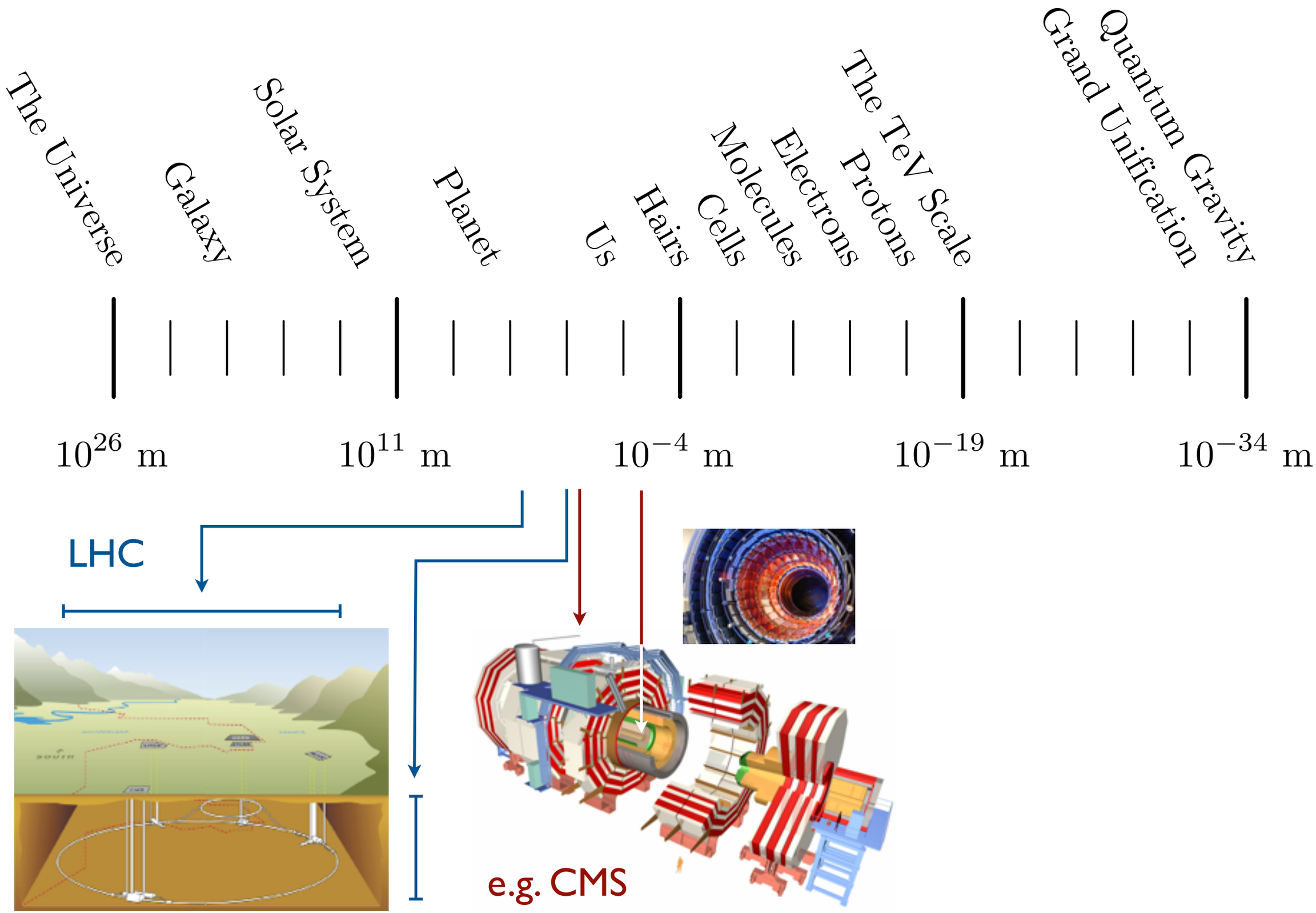
LHC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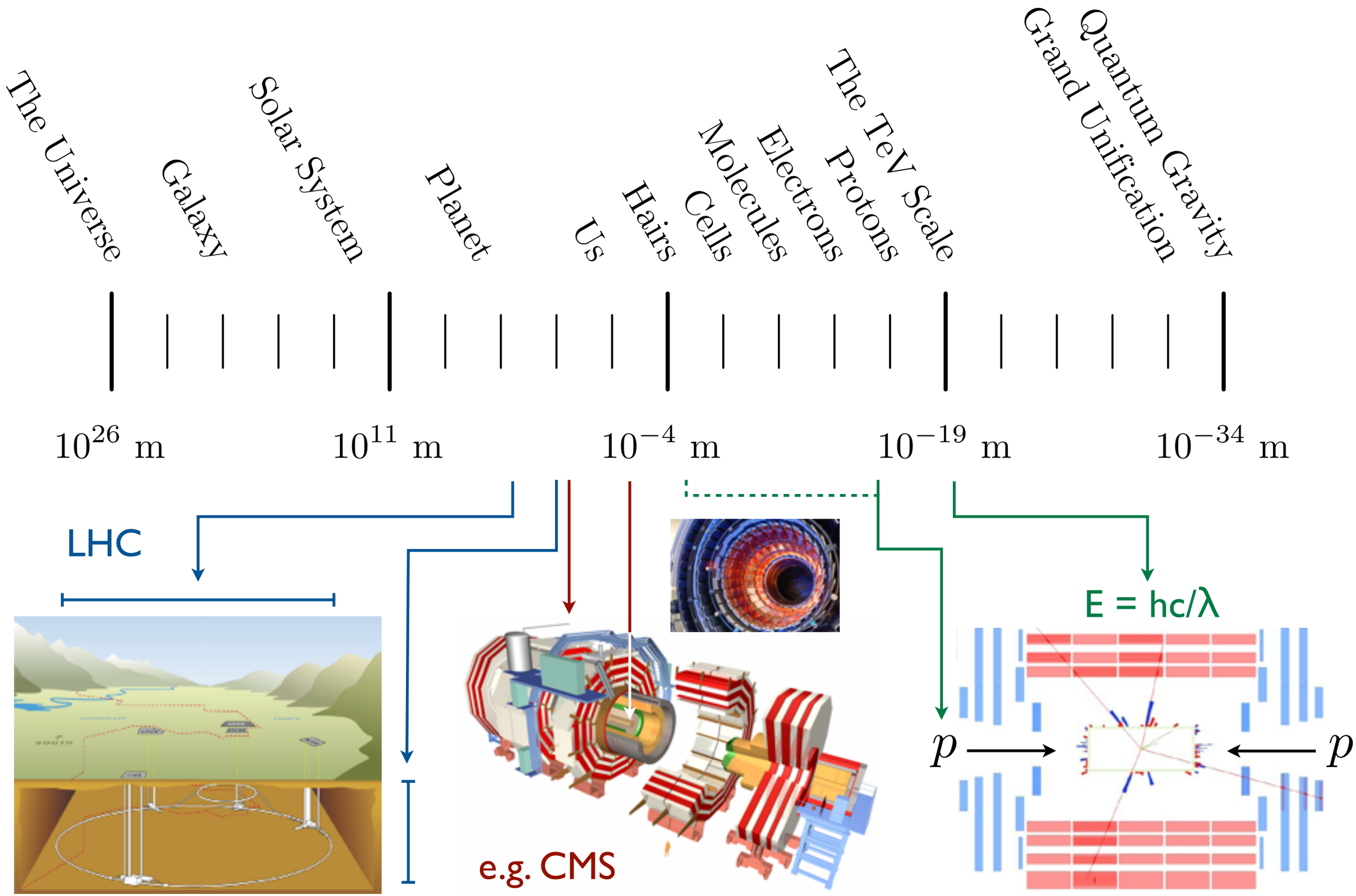
LHC
e.g. CMS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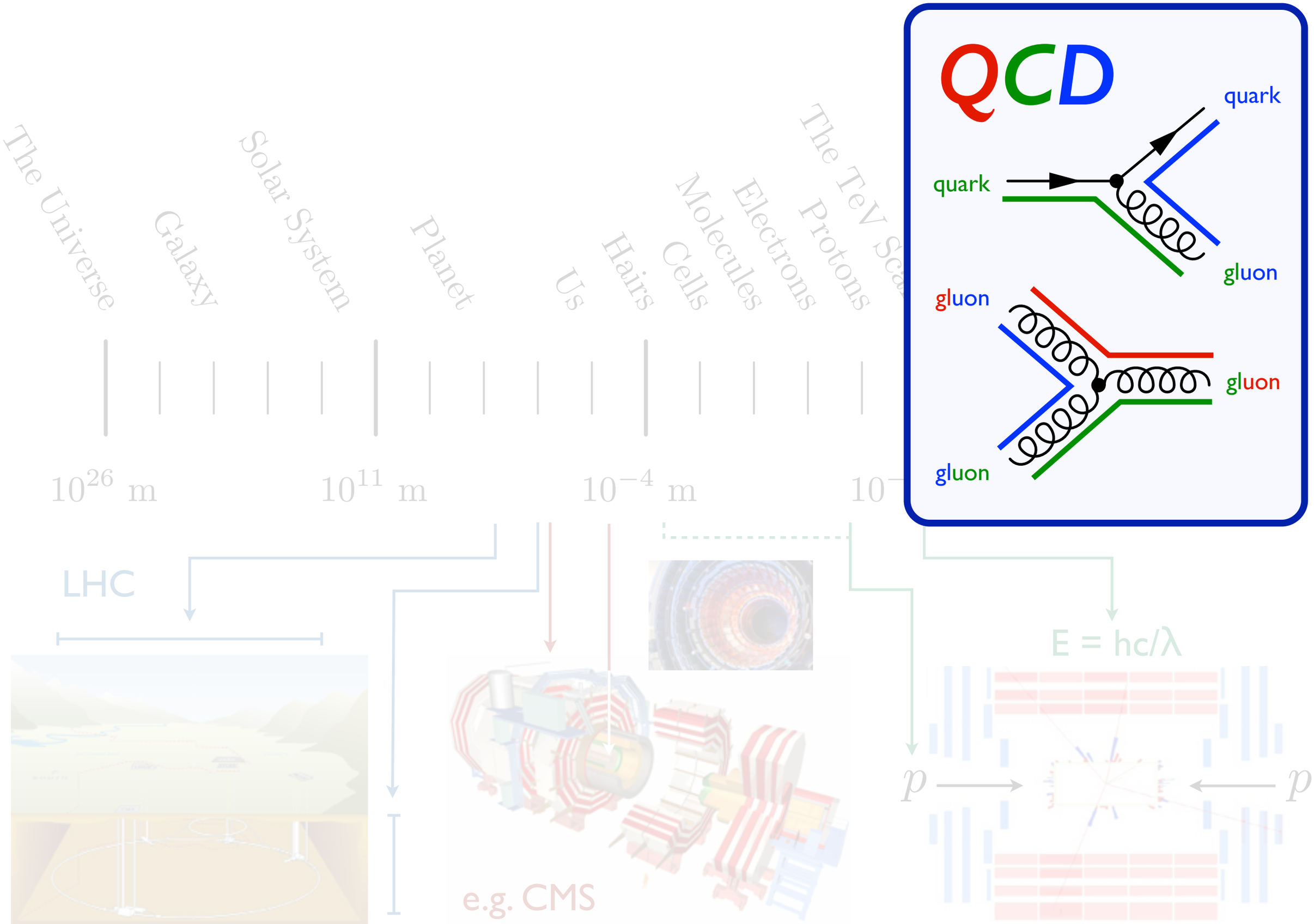
10^{-4} m
10^{-19} m
10^{-34} m
LHC
e.g. CMS
E = hc/λ
p
p


QCD
quark
quark
gluon
gluon
gluon
gluon
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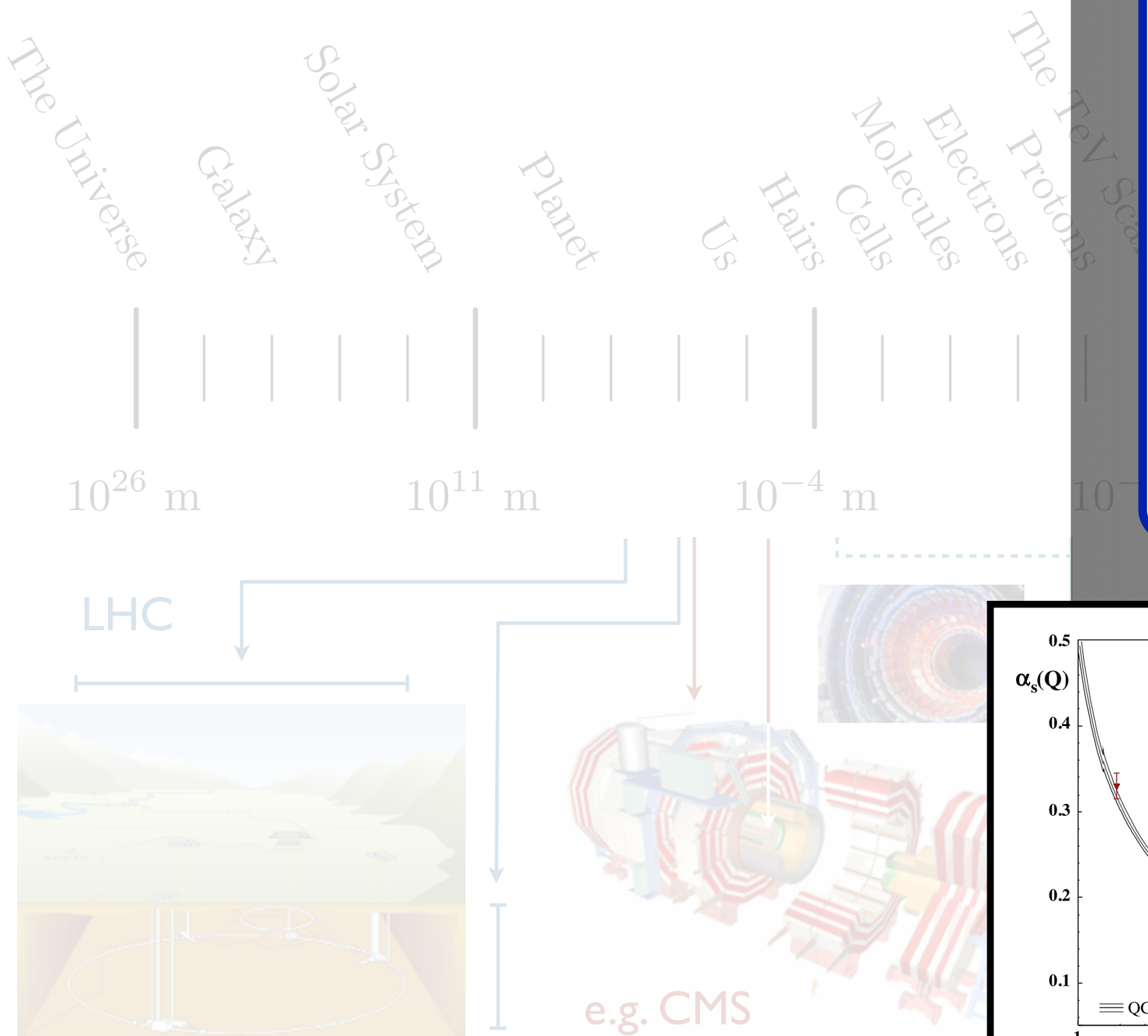
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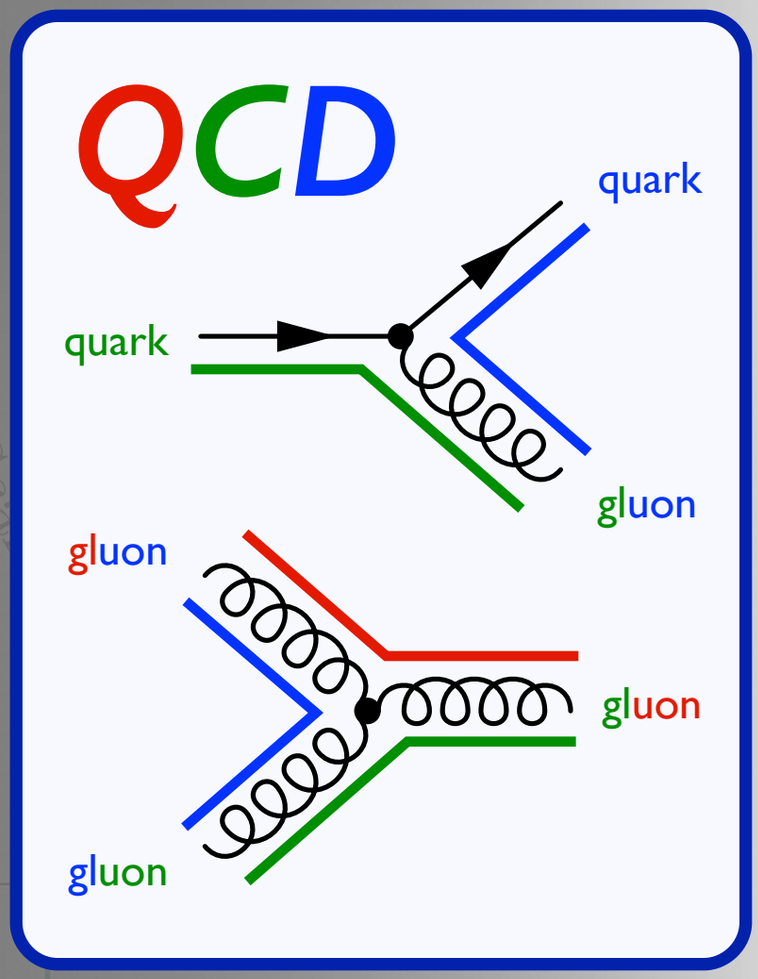
QCD
quark
quark
gluon
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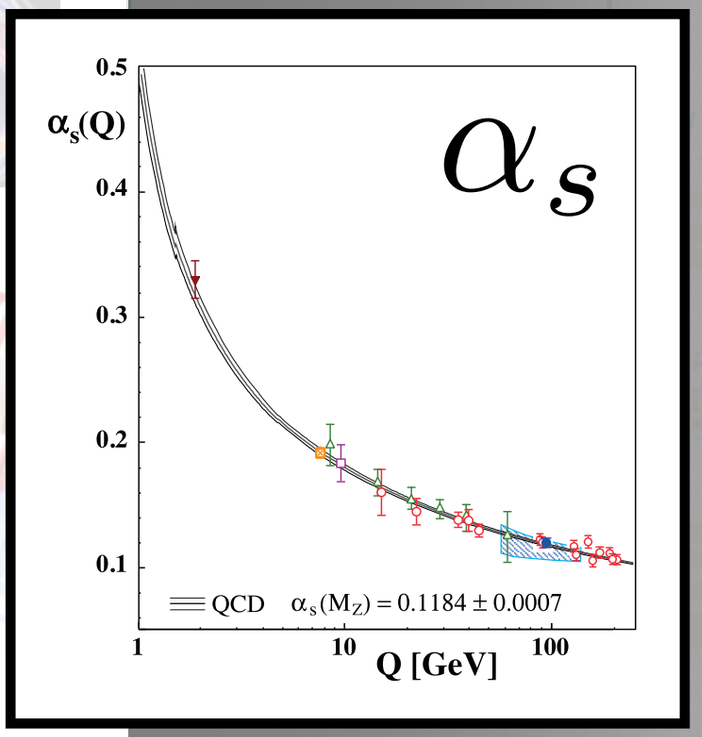

α_s
$\alpha_s(Q)$
0.5
0.4
0.3
0.2
0.1
1
10
100
Q [GeV]
QCD $\alpha_s(M_Z) = 0.1184 \pm 0.0007$

Mesons

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

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

Baryons

$p\, n\, \Lambda^0\, \Sigma^+\, \Sigma^0\, \Sigma^-\, \Xi^0\, \Xi^-\, \ldots$

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

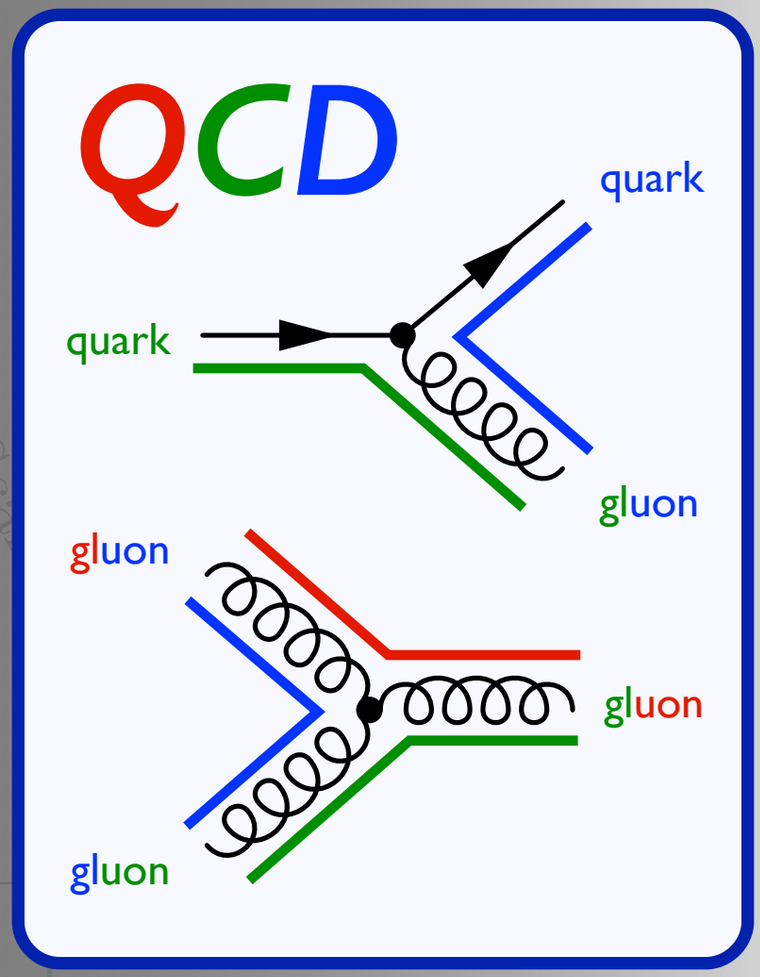
Tetraquarks (?)

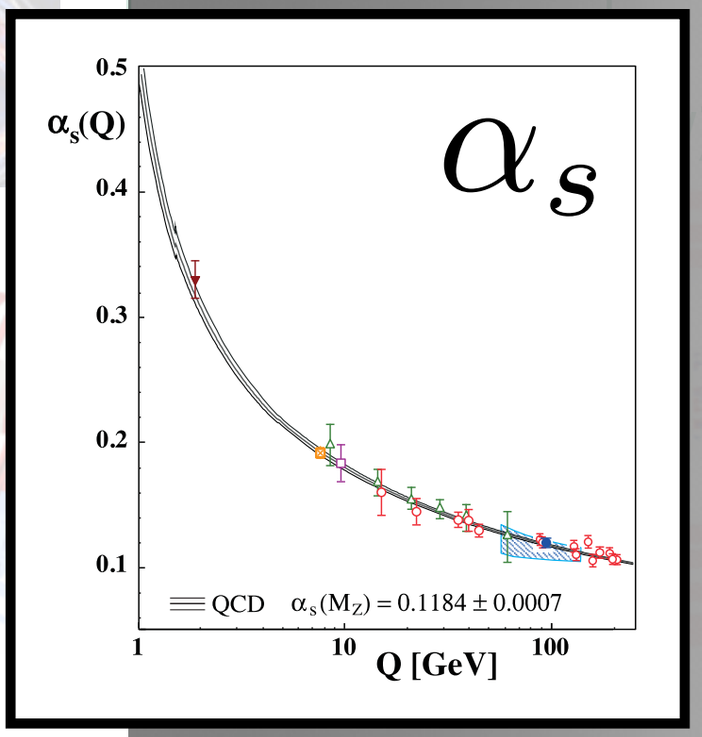
$X(3872)\, Y(4260)\, Z(4430)\, \ldots$

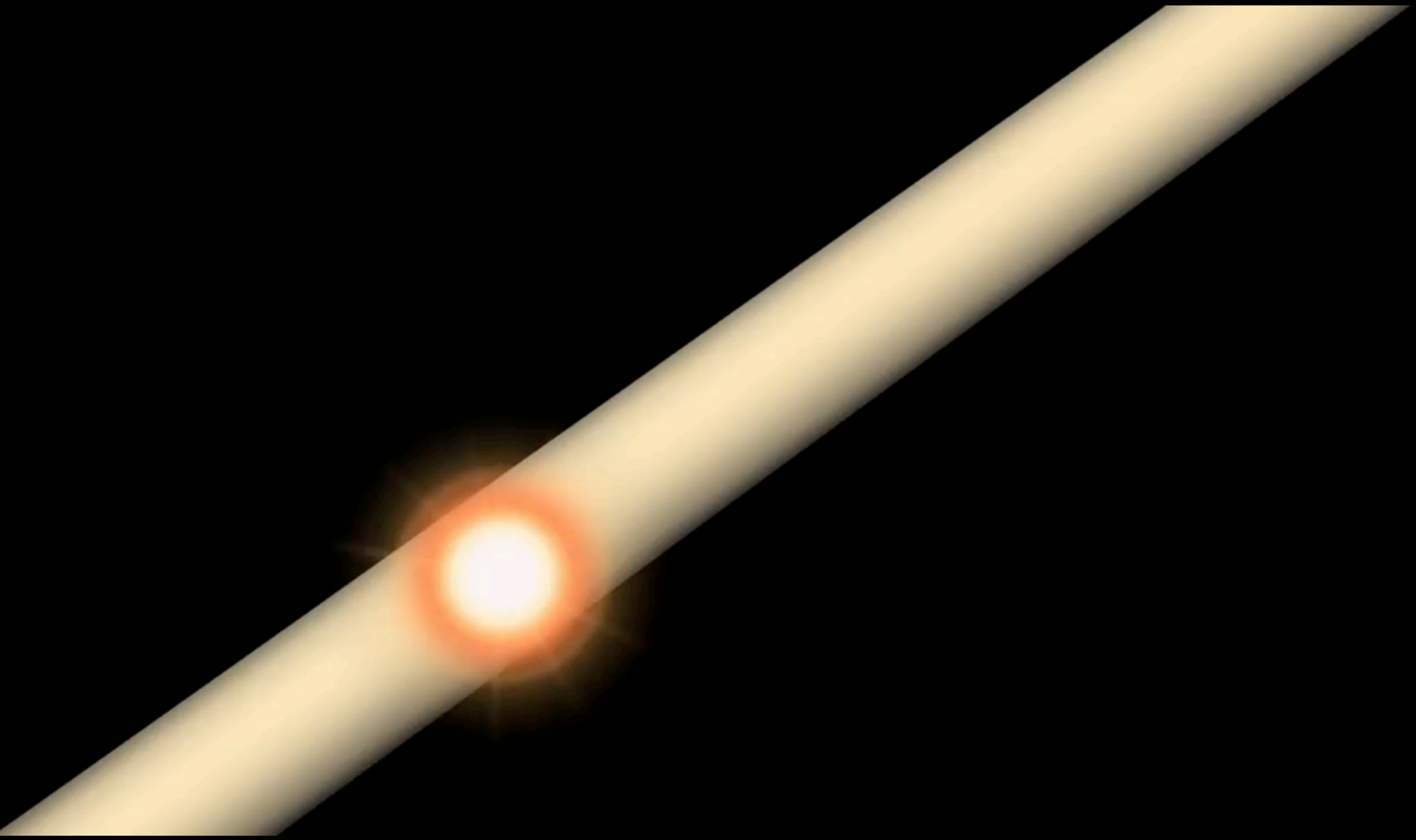
Pentaquarks (?)

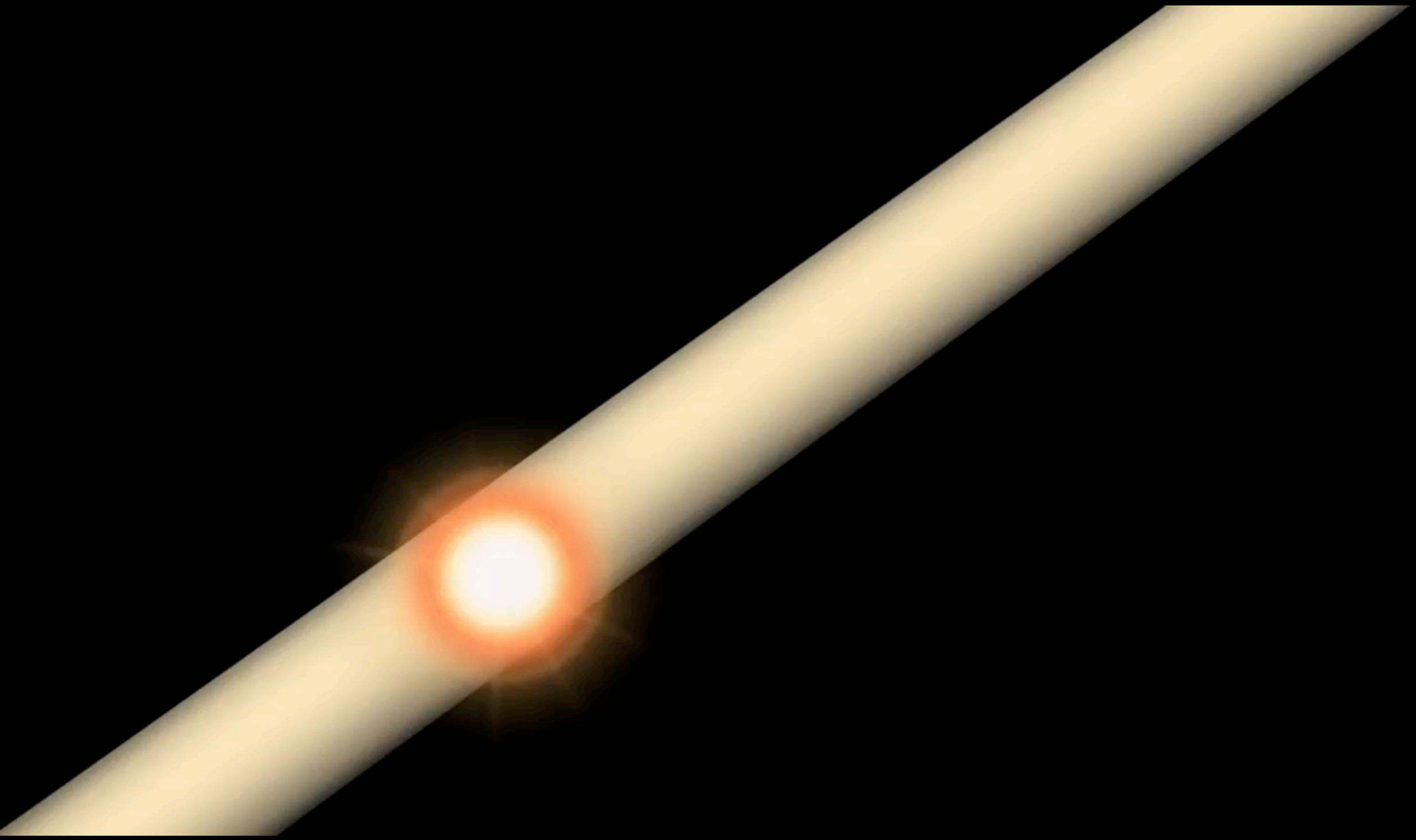
$P_c^+(4450)\, \ldots$

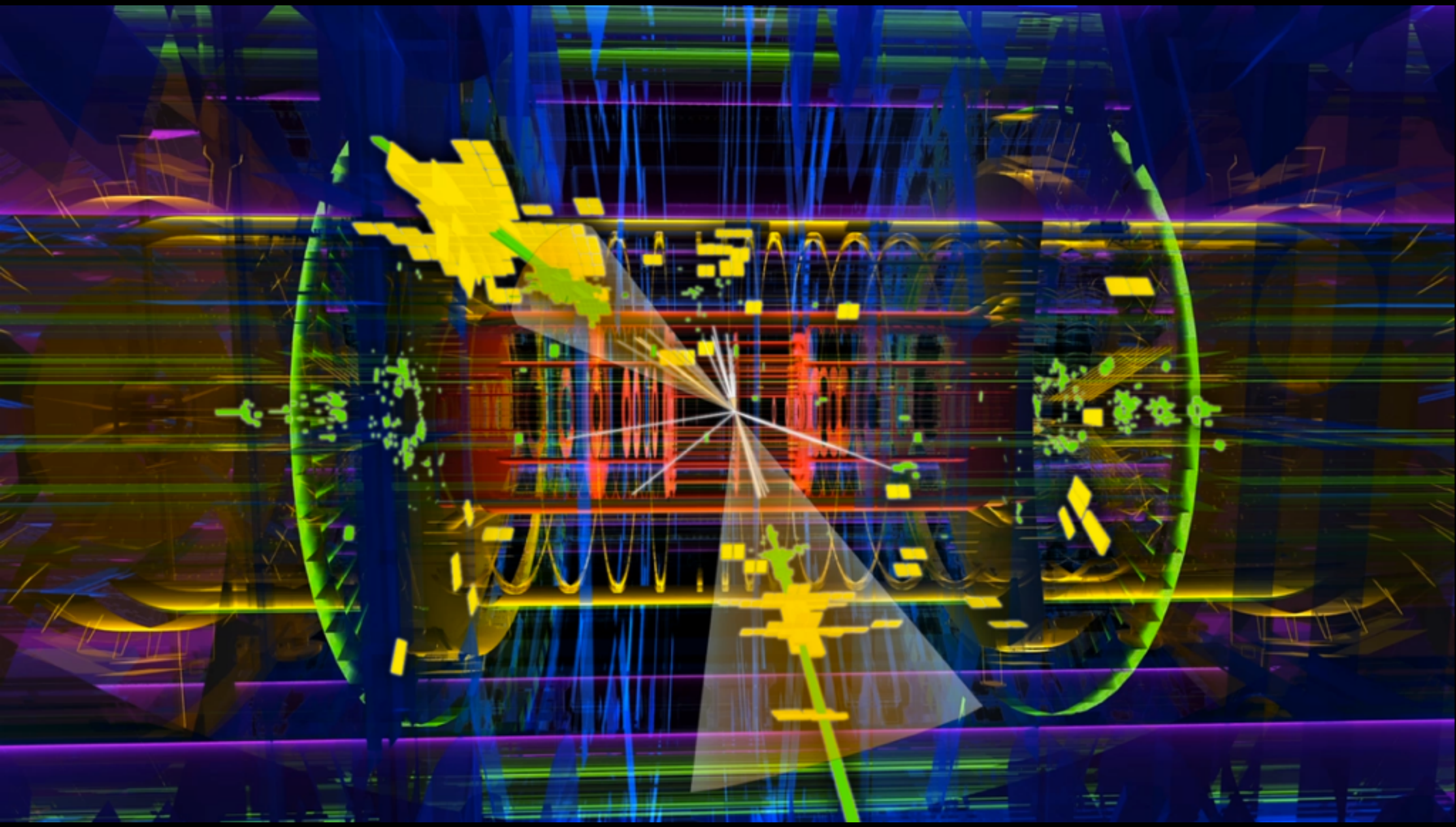
Jets

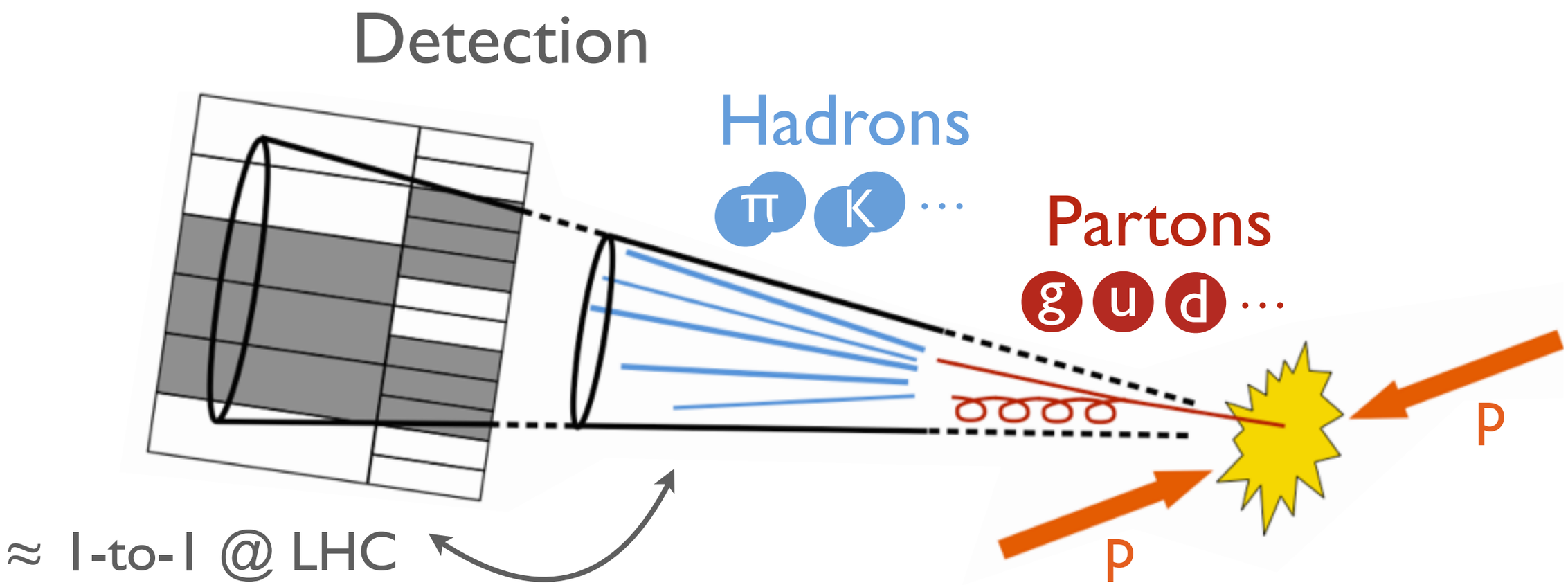


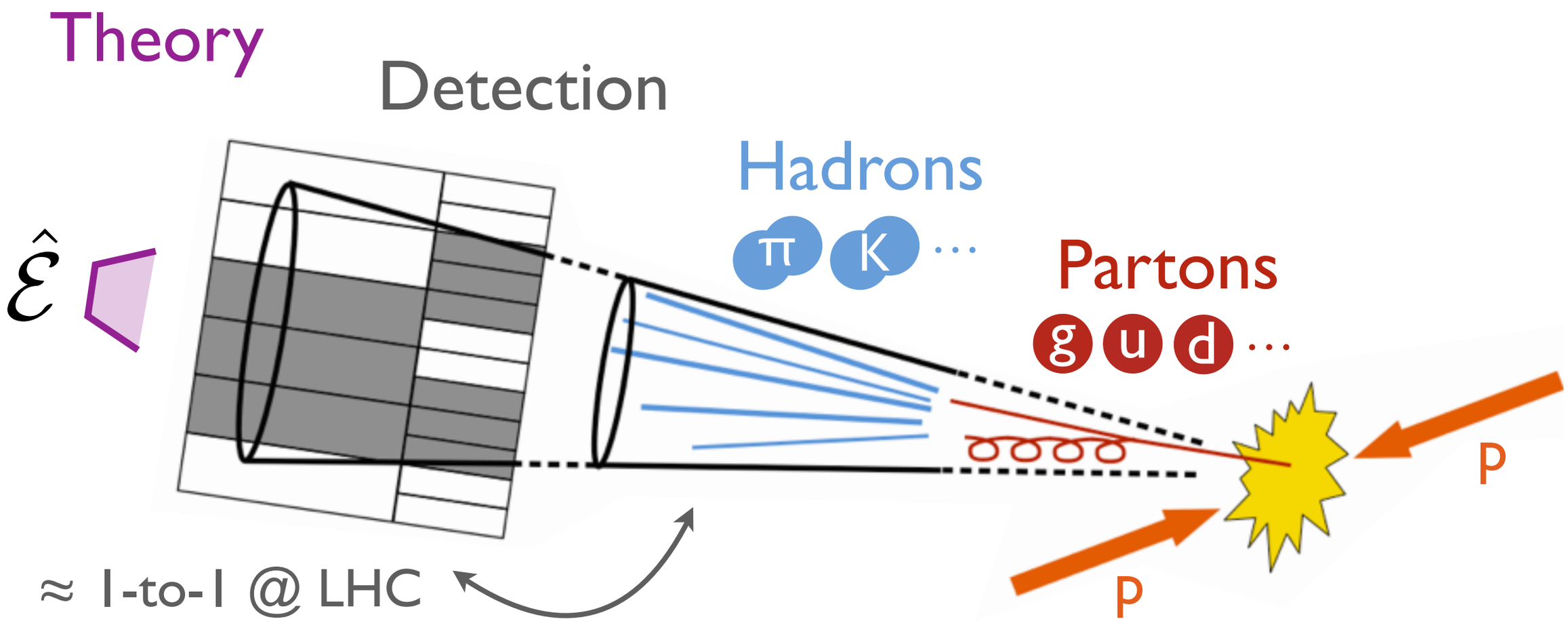









Detection
Hadrons
π K ...
Partons
g u d ...
p
p
≈ 1-to-1 @ LHC


Theory
Detection
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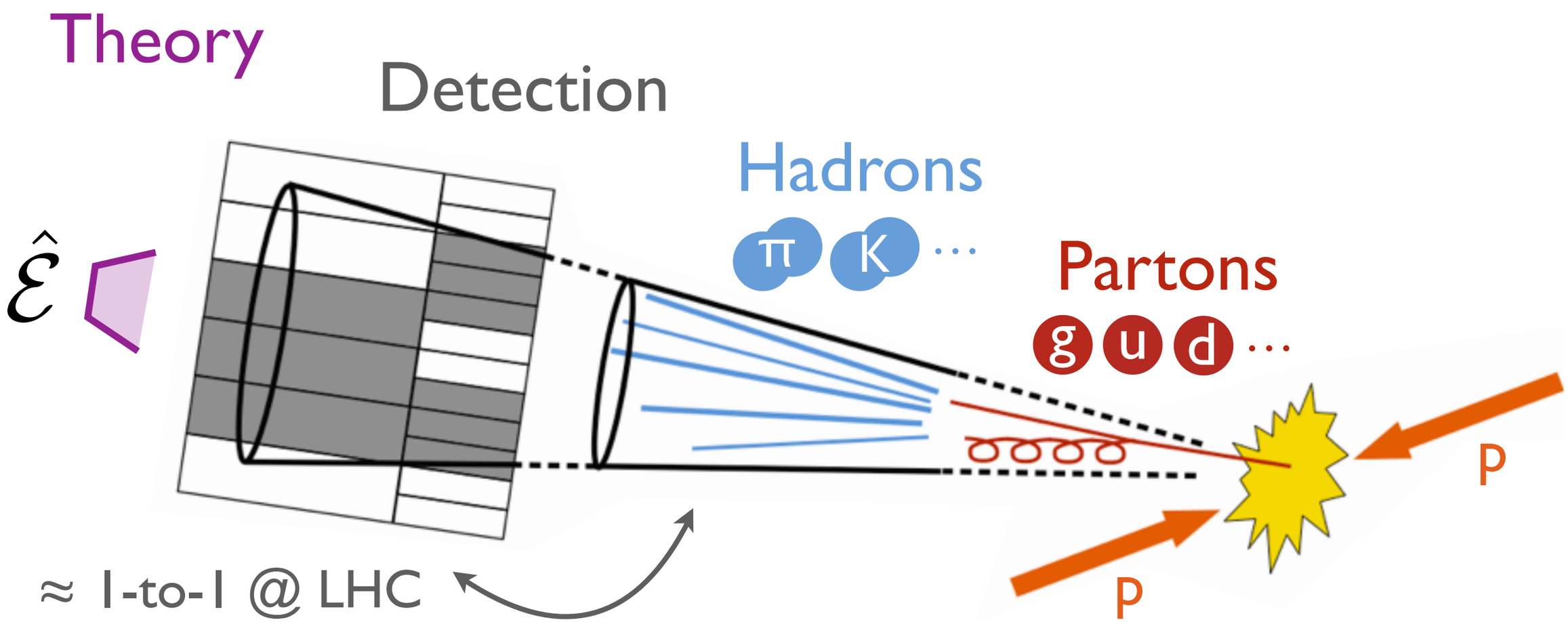
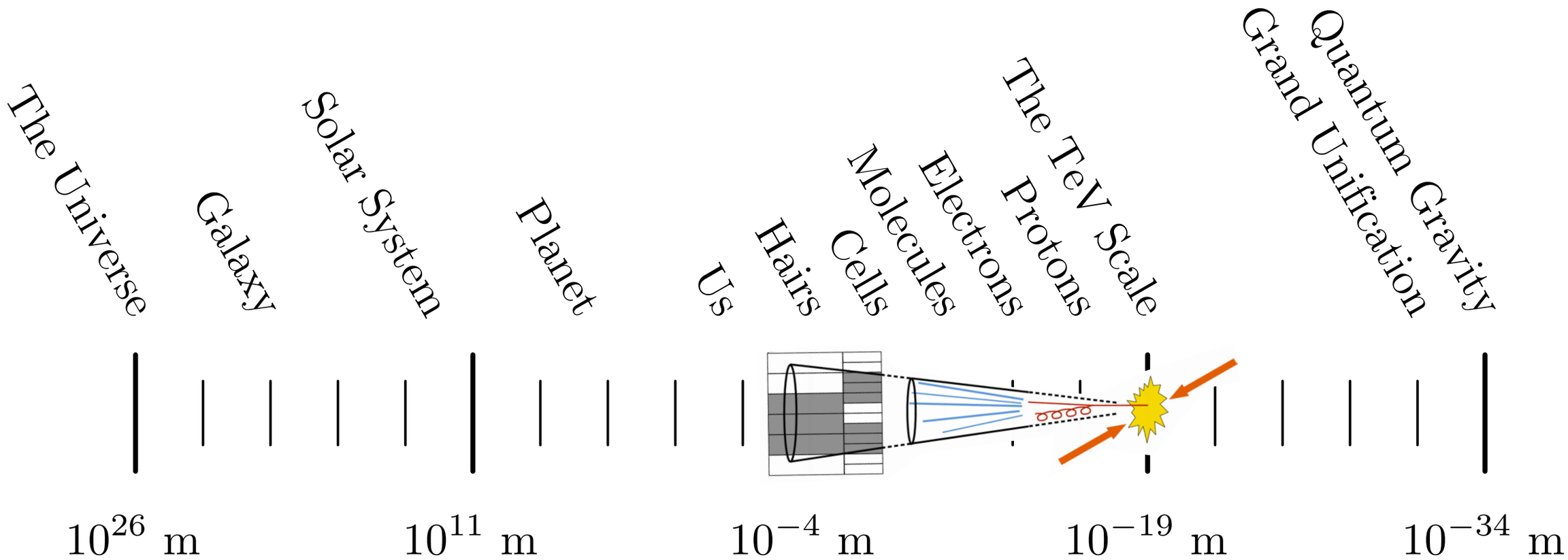
π K …
Partons
g u d …
$\hat{\mathcal{E}}$
p
p
≈ 1-to-1 @ LHC



Stress-Energy Flow Operator:

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

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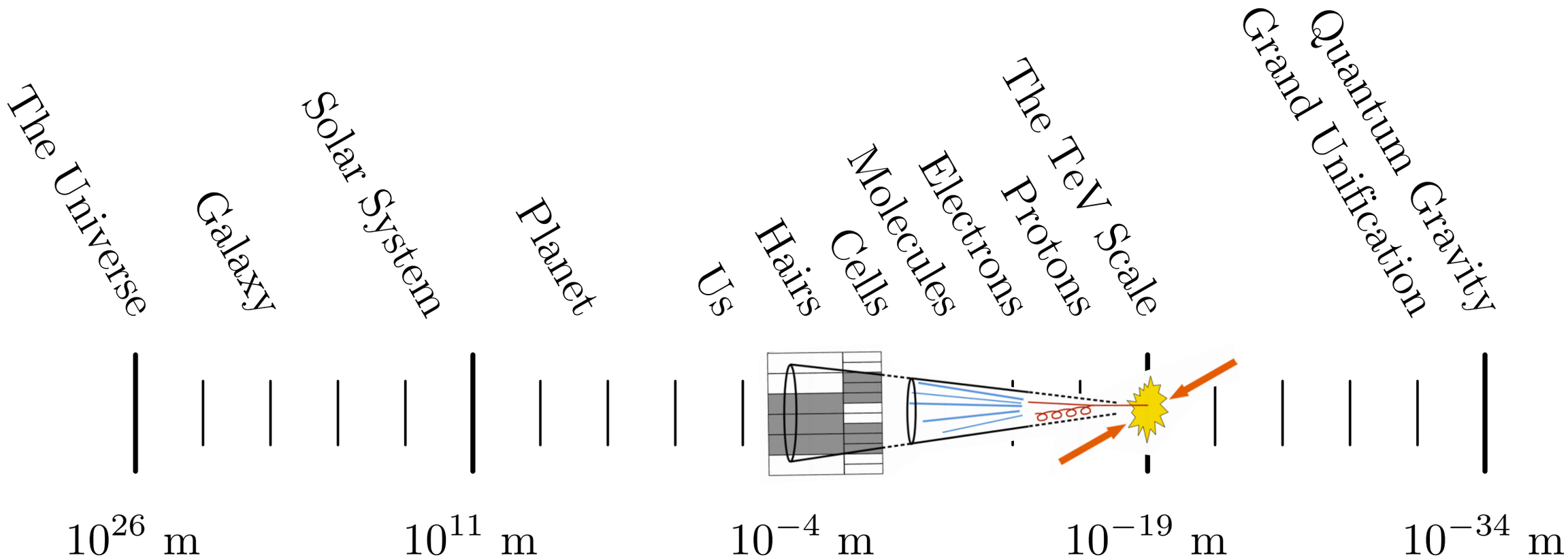
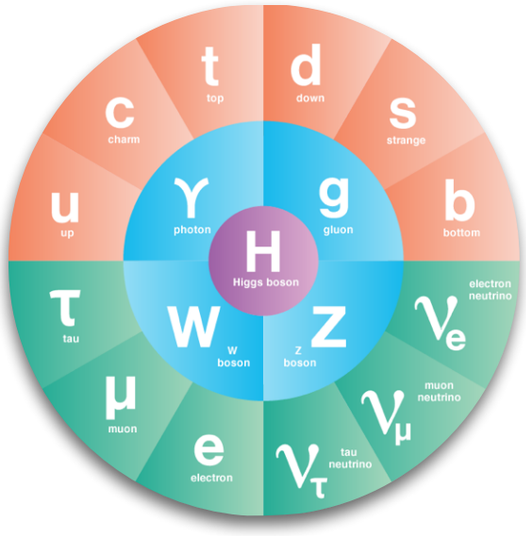
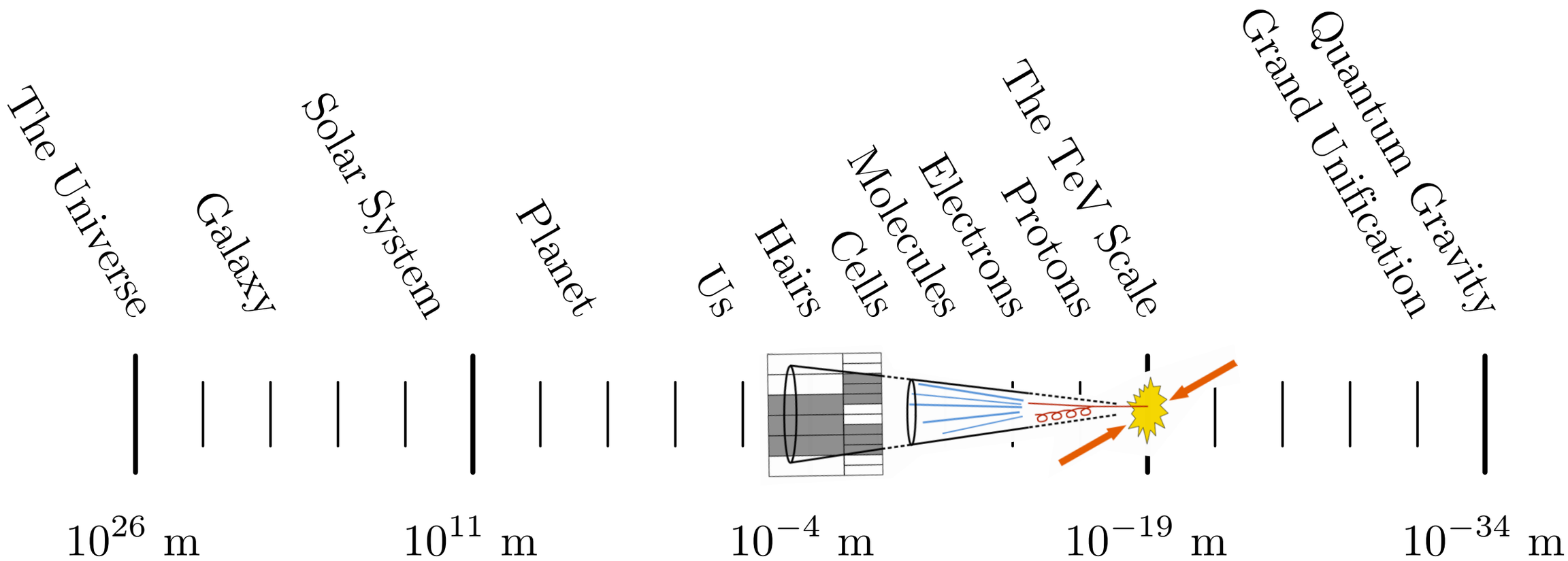


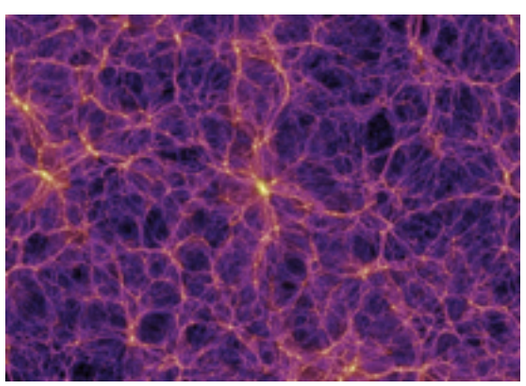
The Standard Model

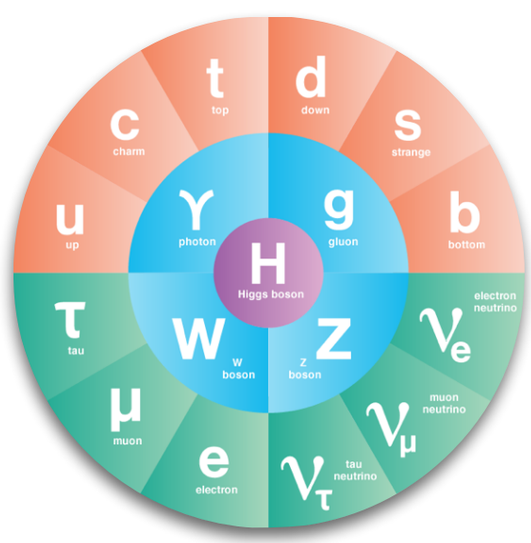


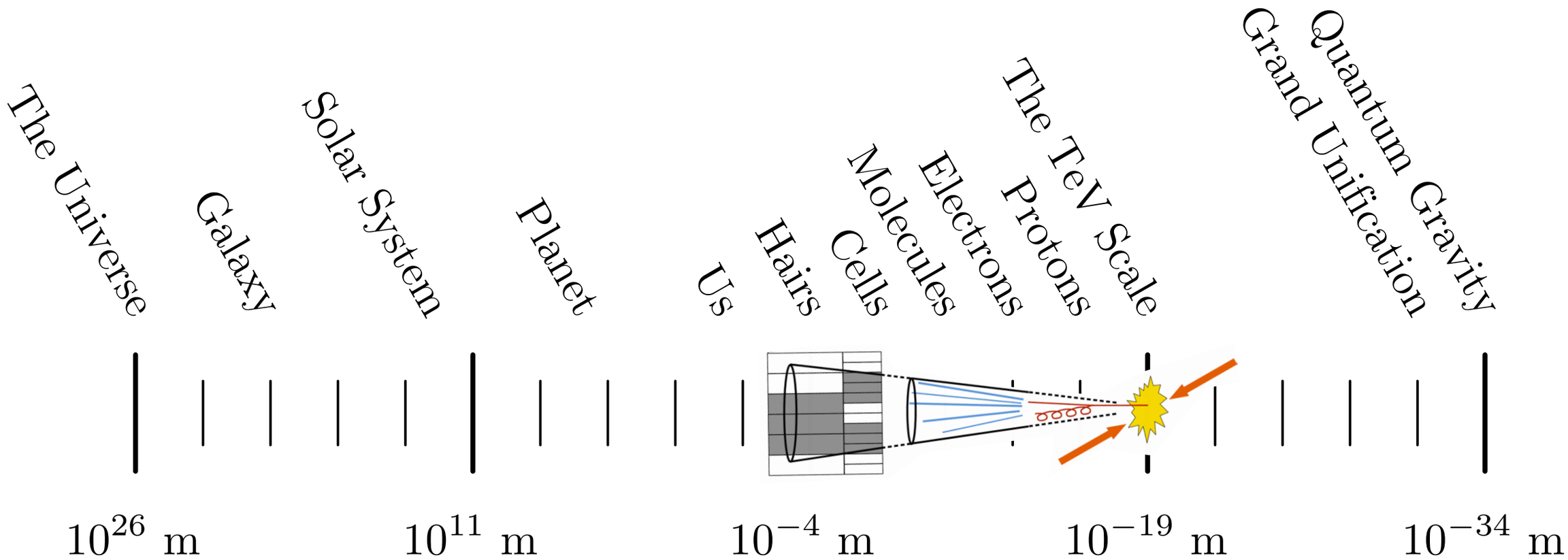


The Standard Model

Dark Matter?

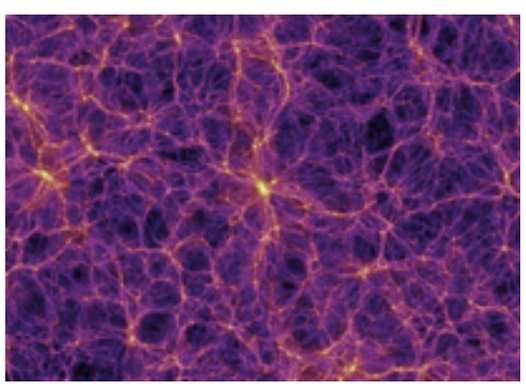


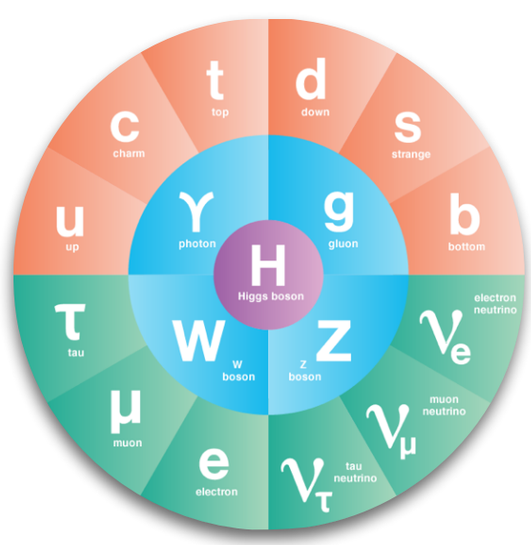




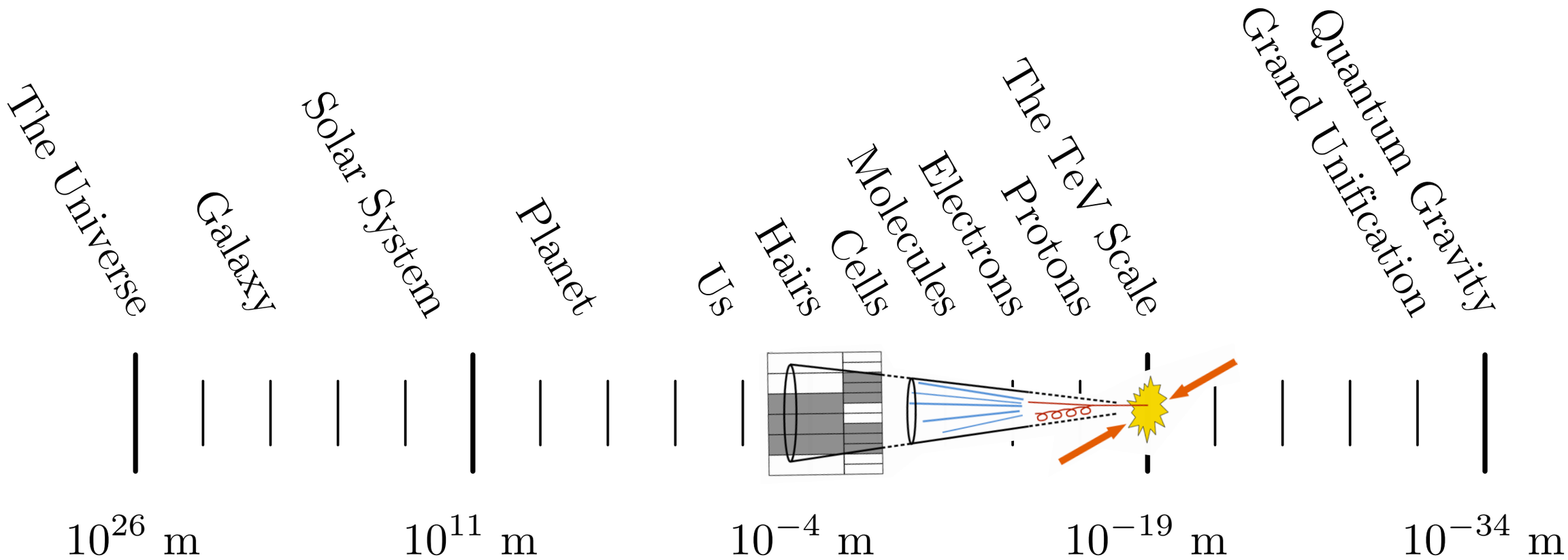
The Standard Model

Dark Matter?



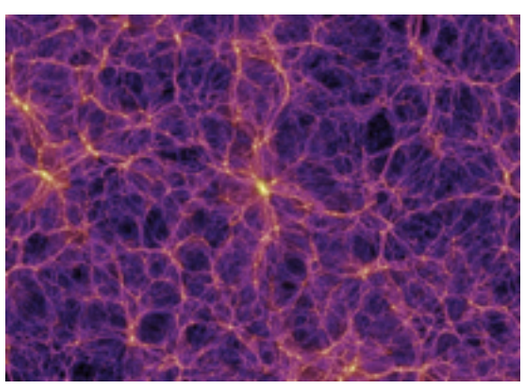


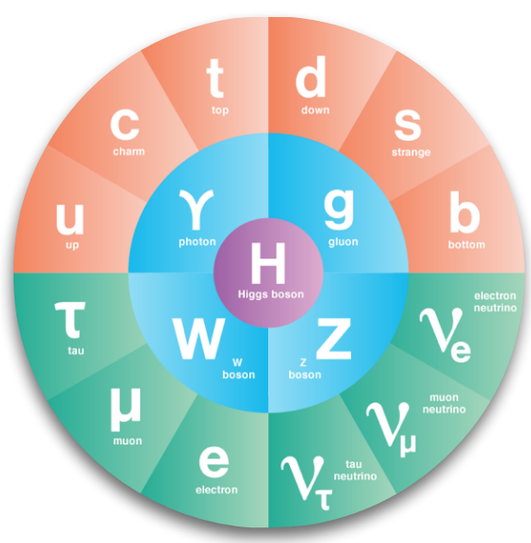
Origin of Mass?
Higgs Boson!



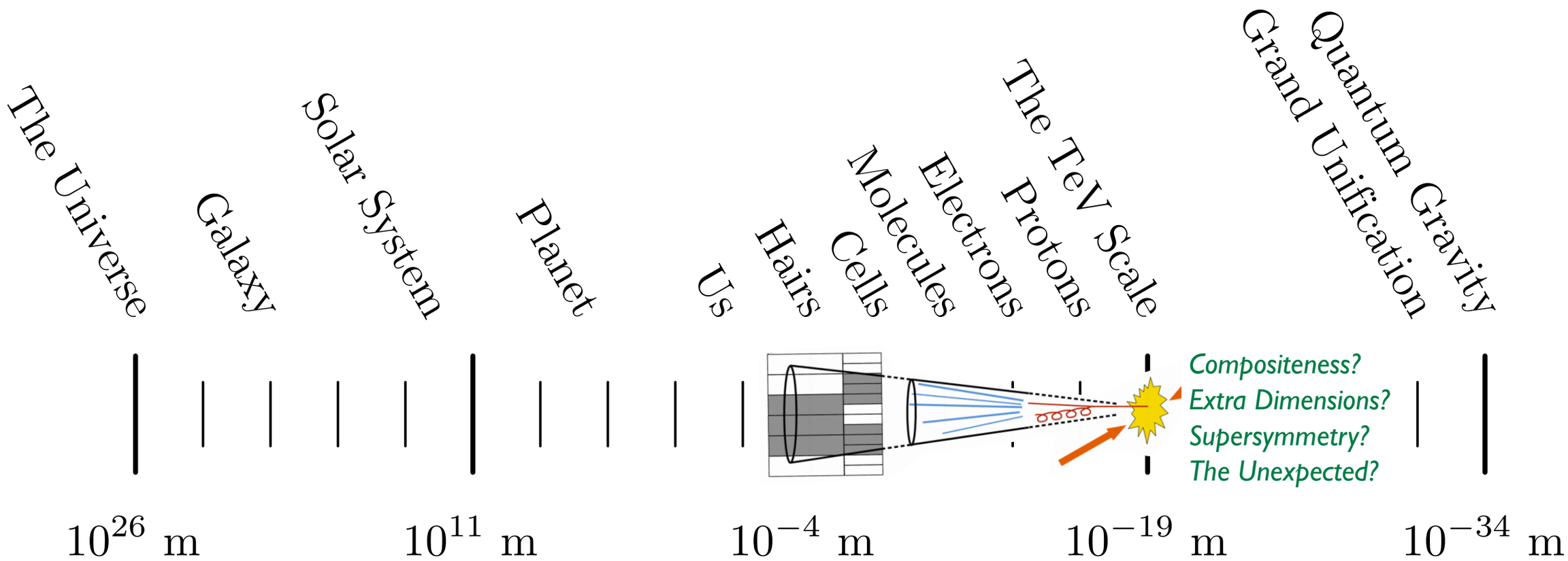
The Standard Model → ?

Dark Matter?



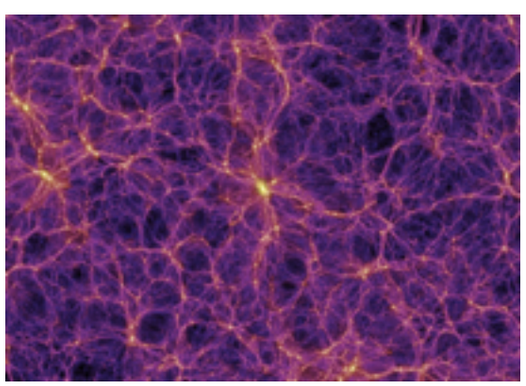


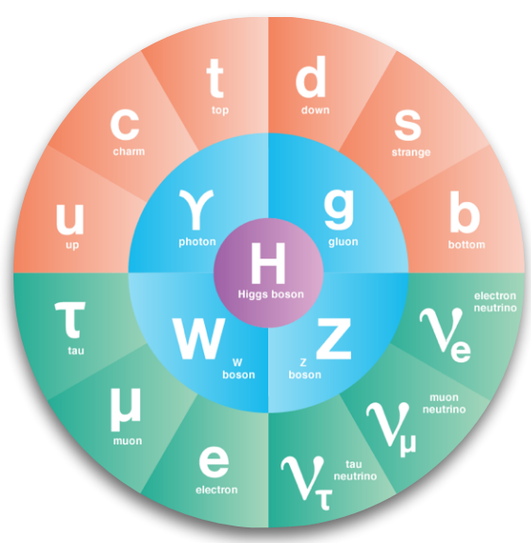
Origin of Mass?
Higgs Boson!



The Standard Model → ?

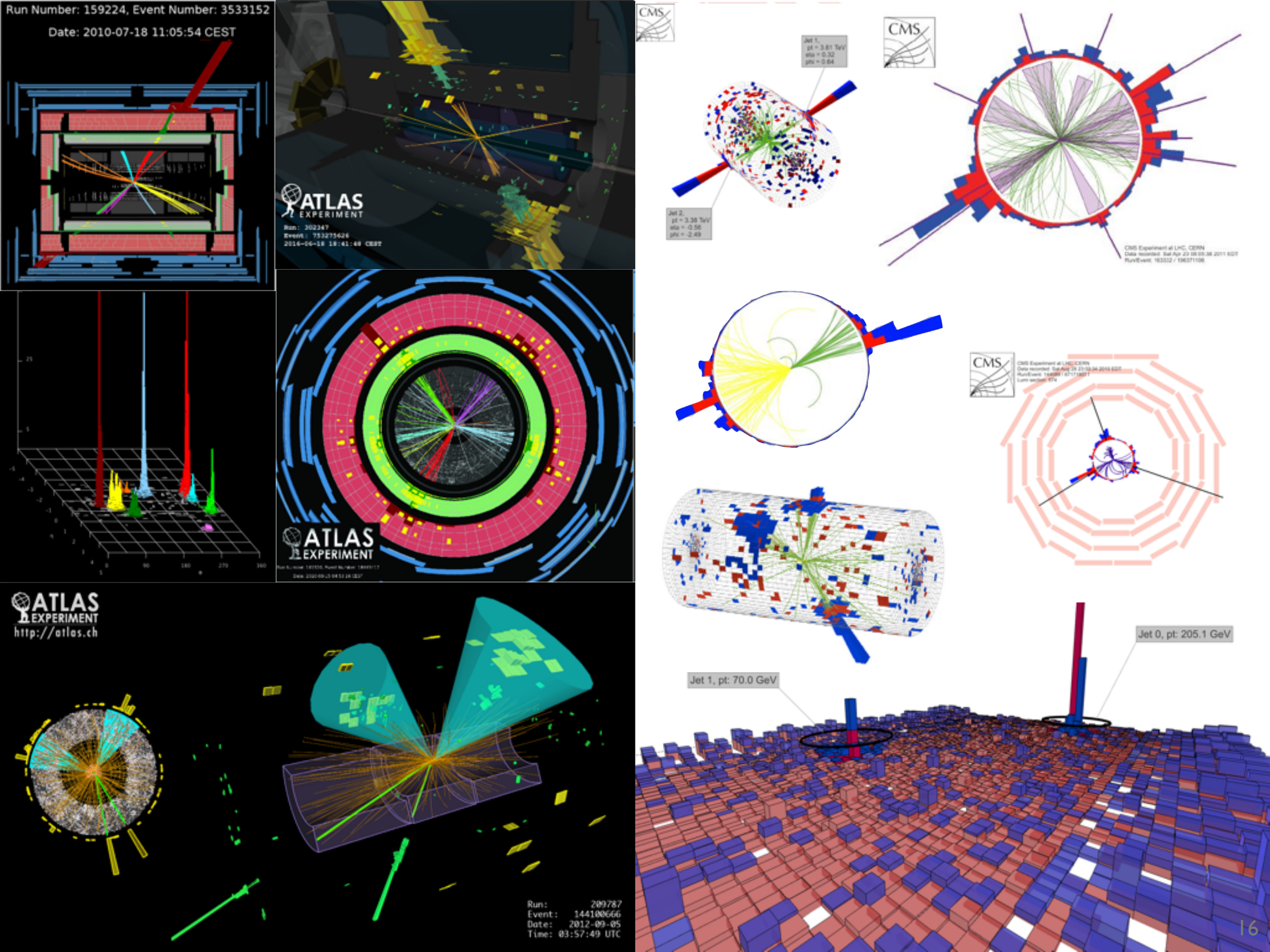
Dark Matter?

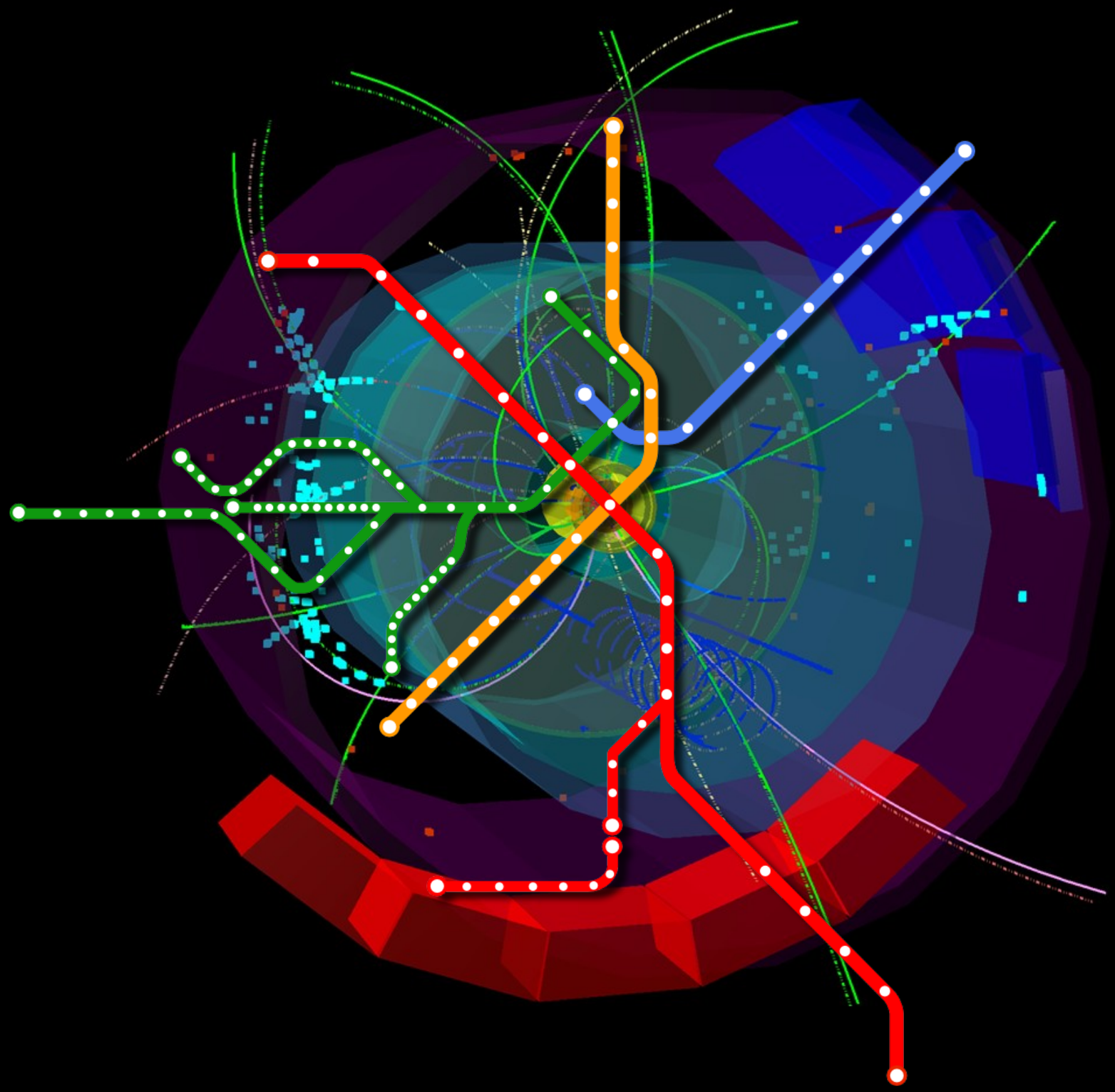


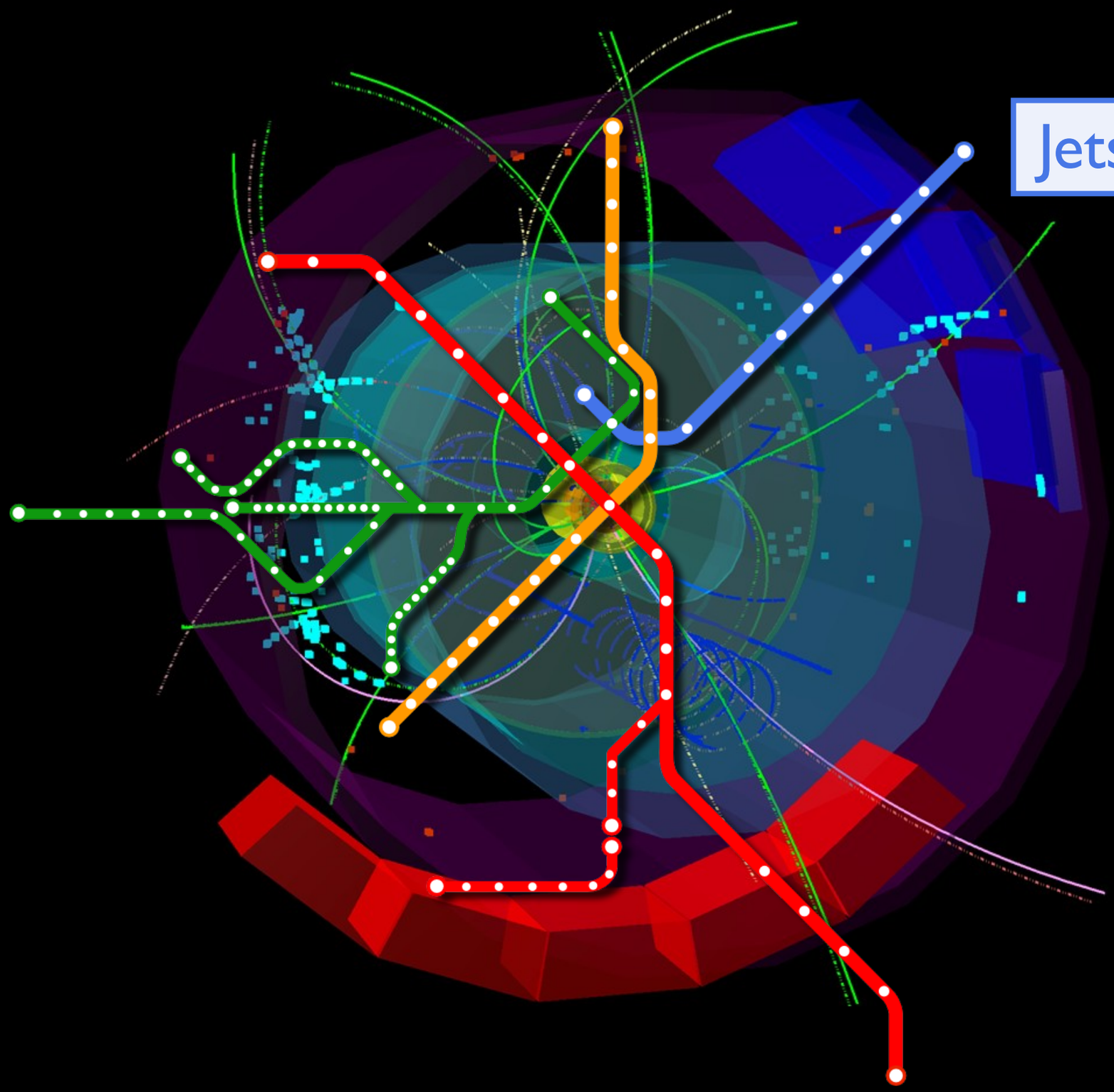


Origin of Mass?
Higgs Boson!

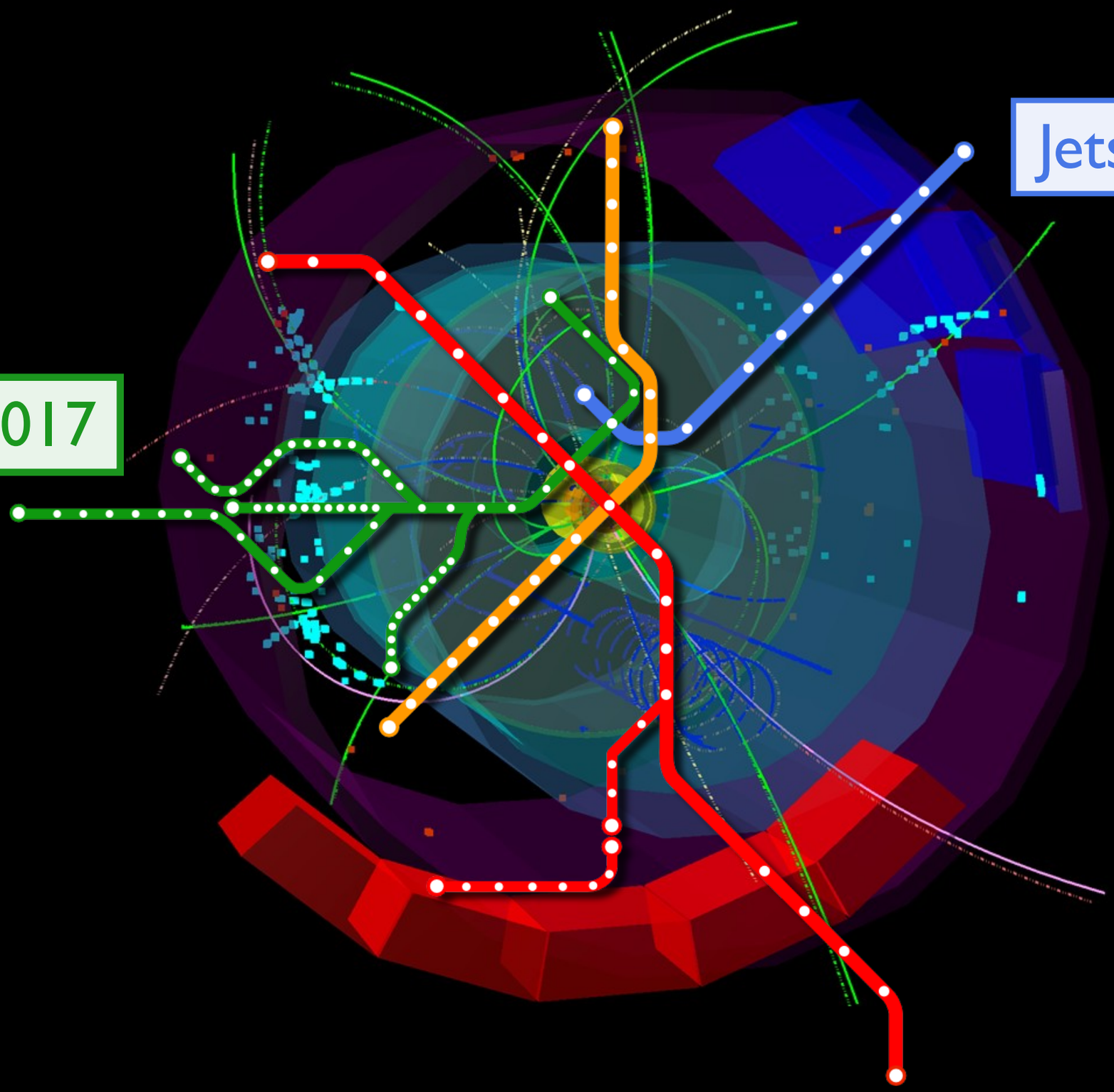
Hierarchy Problem?


Run Number: 159224, Event Number: 3533152
Date: 2010-07-18 11:05:54 CEST
ATLAS EXPERIMENT
ATLAS EXPERIMENT
ATLAS EXPERIMENT
http://atlas.ch
Run: 209787
Event: 144100666
Date: 2012-09-05
Time: 03:57:49 UTC
CMS
CMS
CMS
CMS
Jet 0, pt: 205.1 GeV
Jet 1, pt: 70.0 GeV

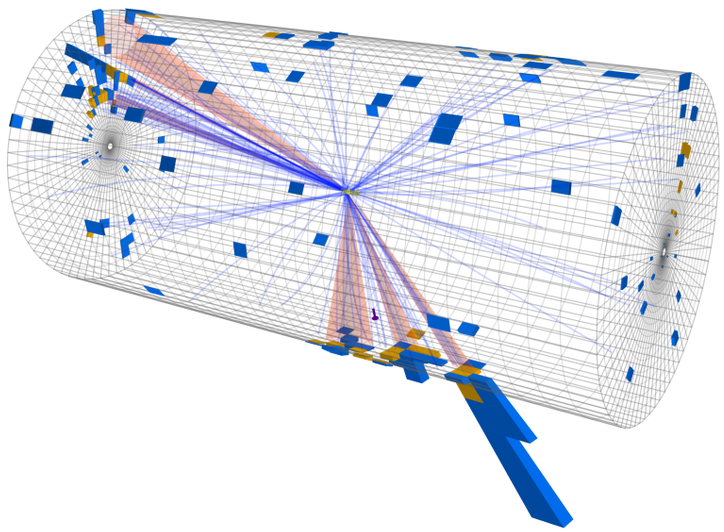




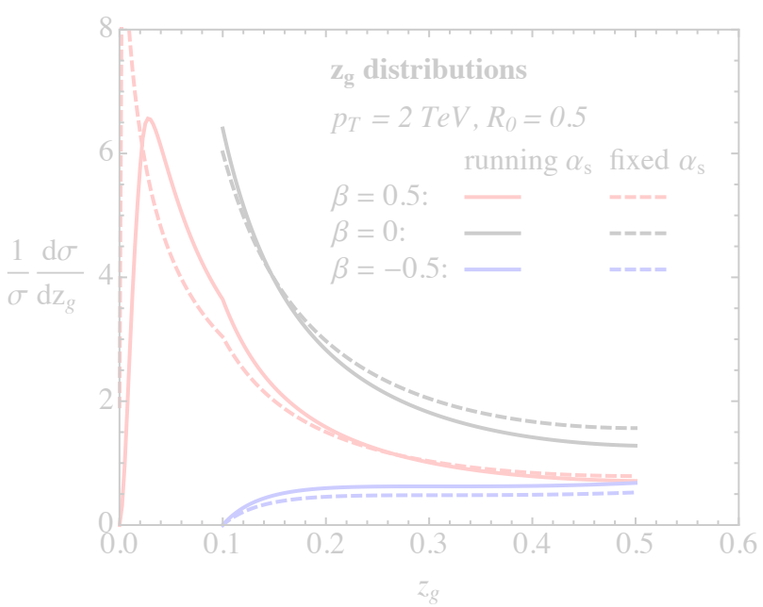
Jets c. 1977


Jets c. 1977
Jets c. 2017

Jet Substructure

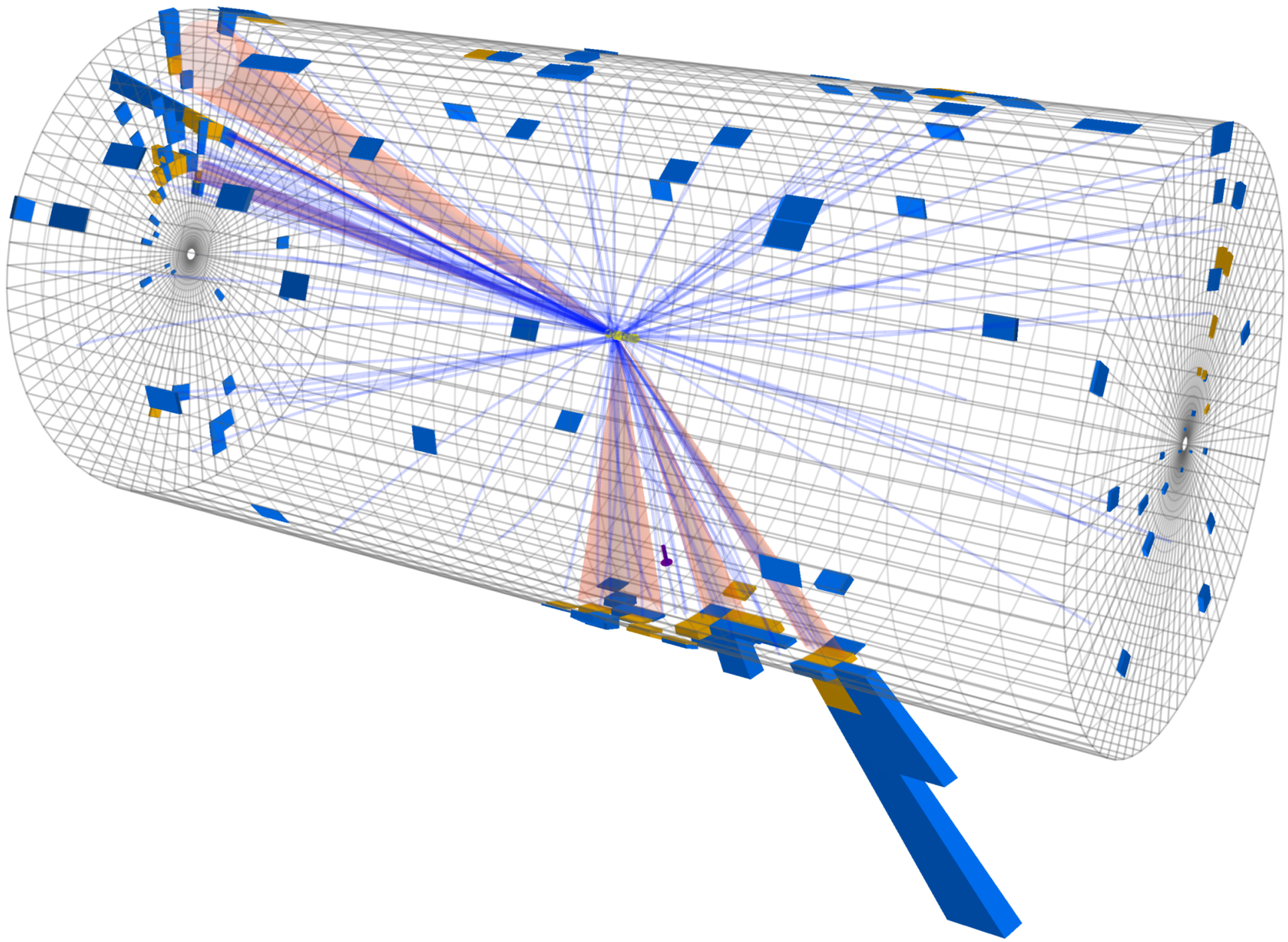


Boosting the Search for New Phenomena



Pushing the Boundaries of Quantum Field Theory

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



CMS Experiment at LHC, CERN
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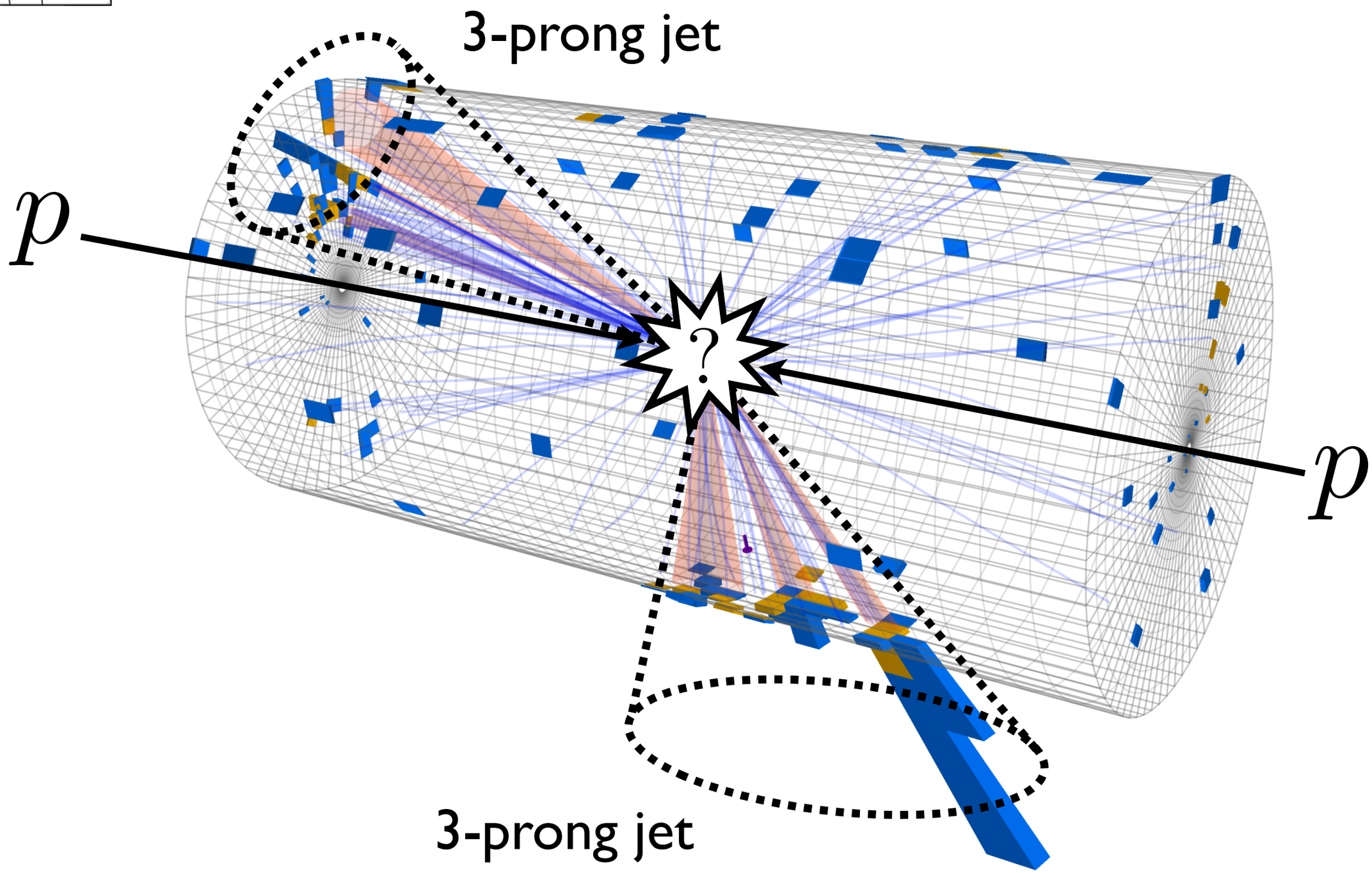

CMS Experiment at LHC, CERN
Data recorded: Sun Jul 12 07:25:11 2015 CEST
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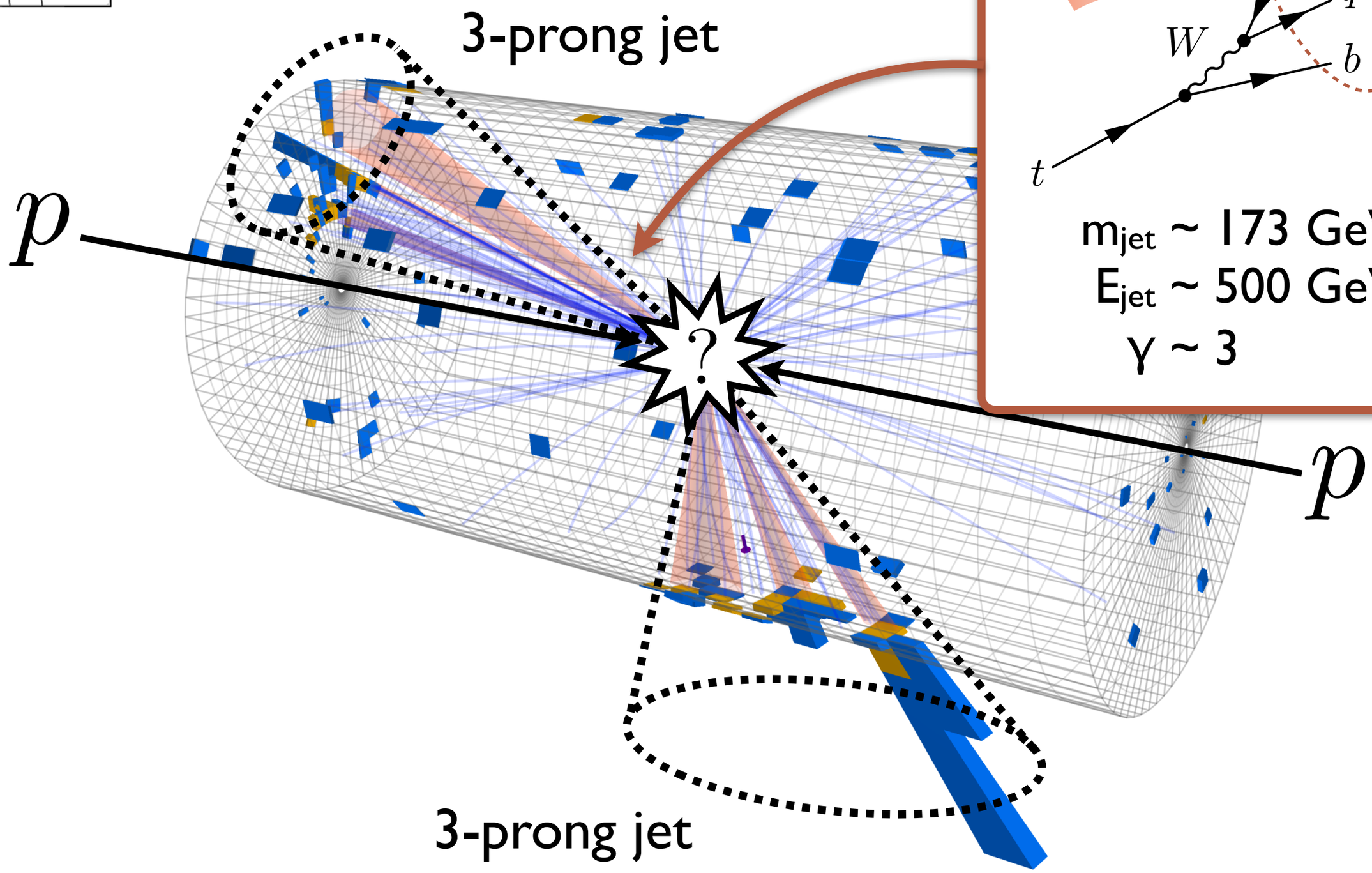
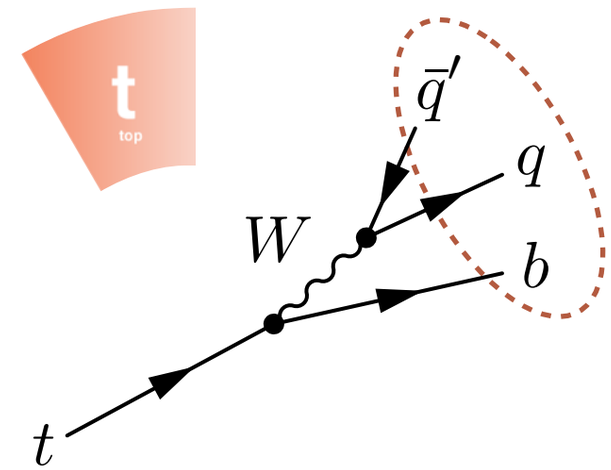
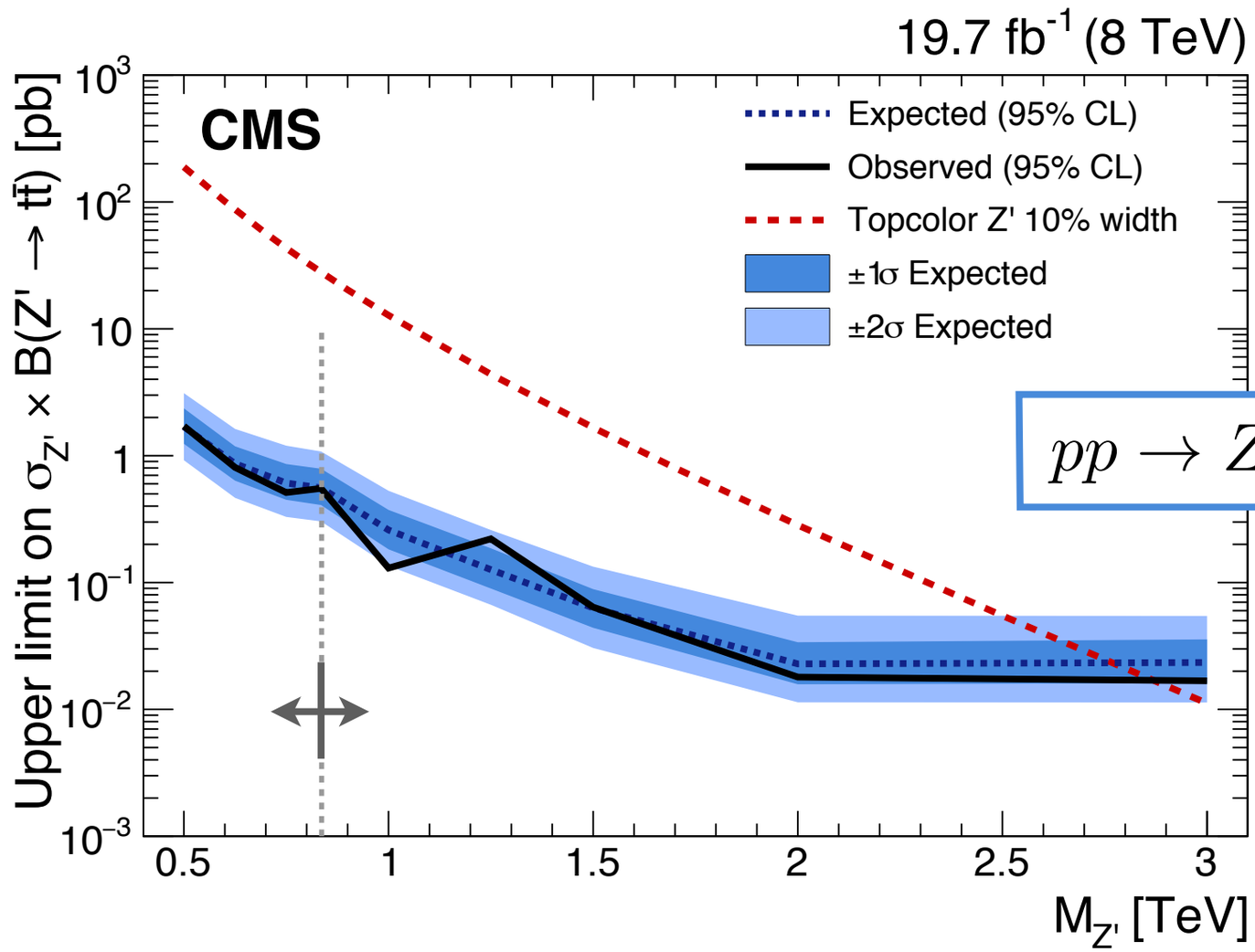


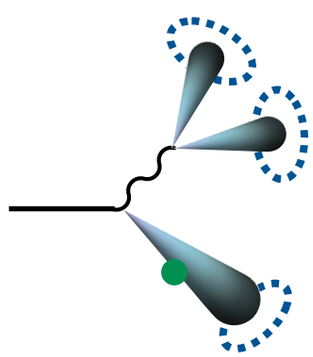


$m_{jet} \sim 173$ GeV
$E_{jet} \sim 500$ GeV
$\gamma \sim 3$

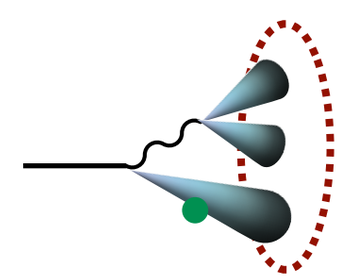


$$pp \to Z' \to t\bar{t}$$

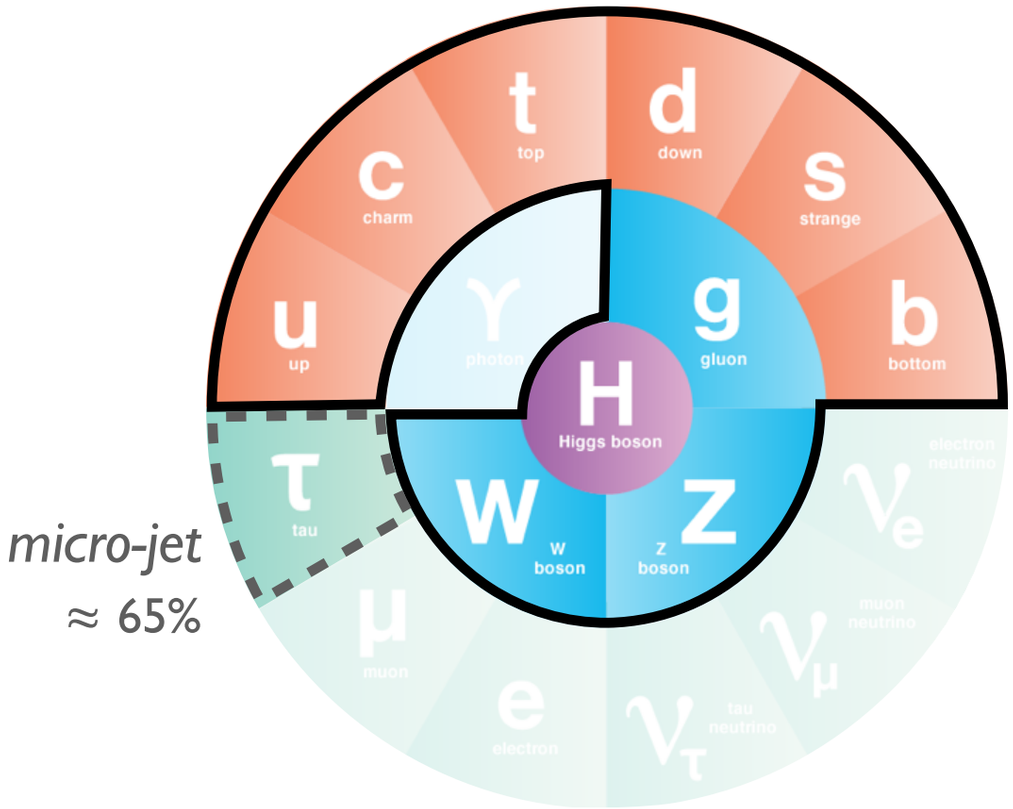
resolved → *boosted*



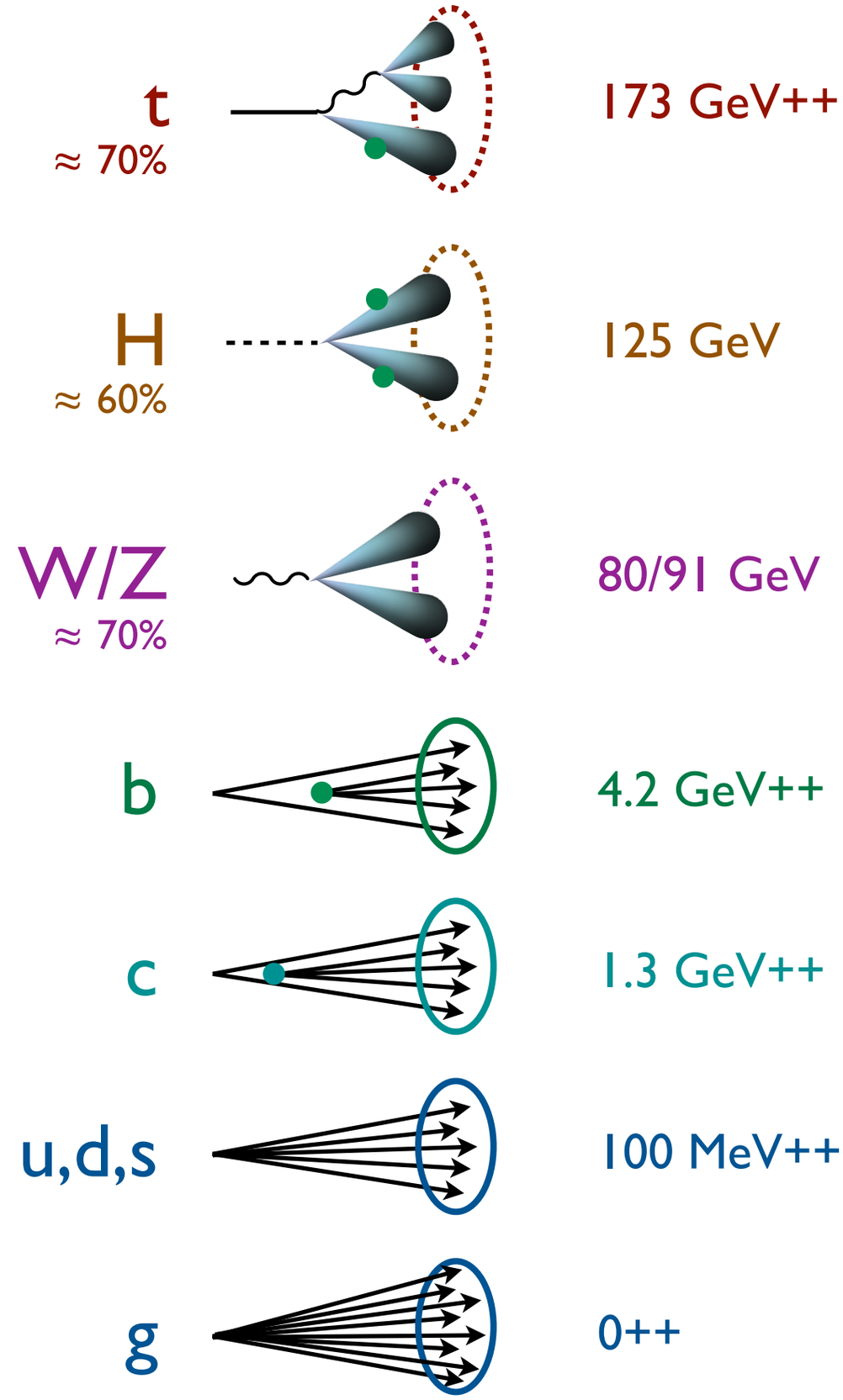
$$\Delta R \simeq \frac{1}{\gamma_{\text{top}}}$$

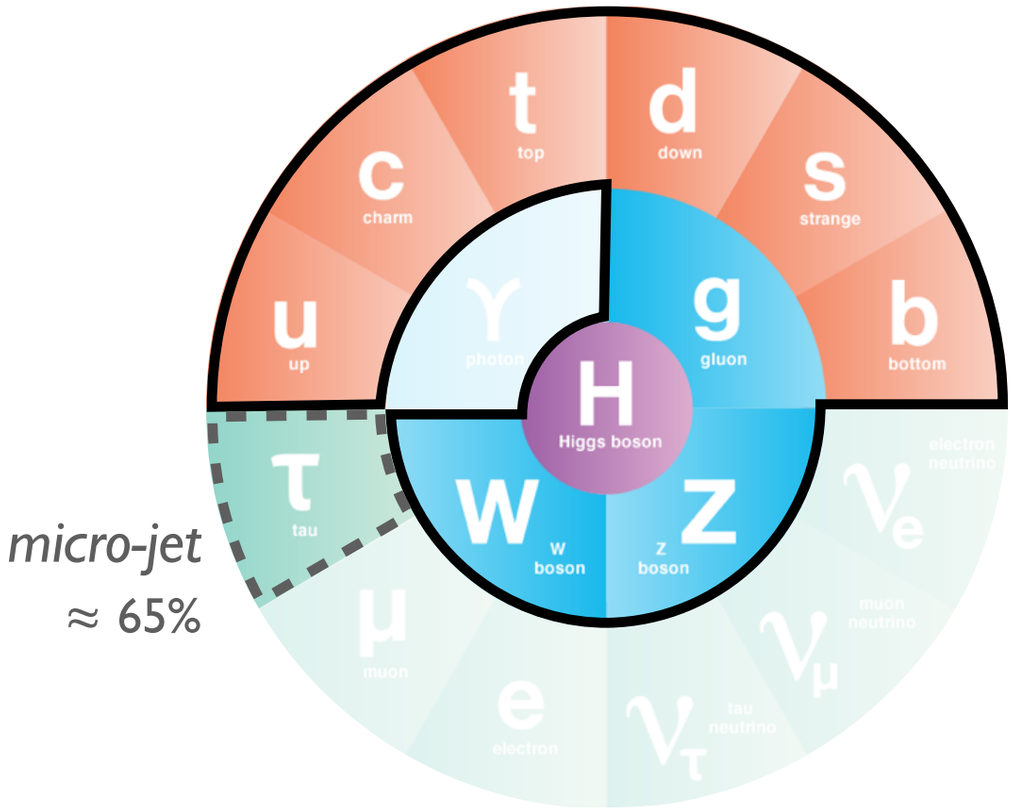


[CMS 2011, 2013, 2015; using Kaplan, Rehermann, Schwartz, Tweedie, 2008; Ellis, Vermilion, Walsh, 2009]



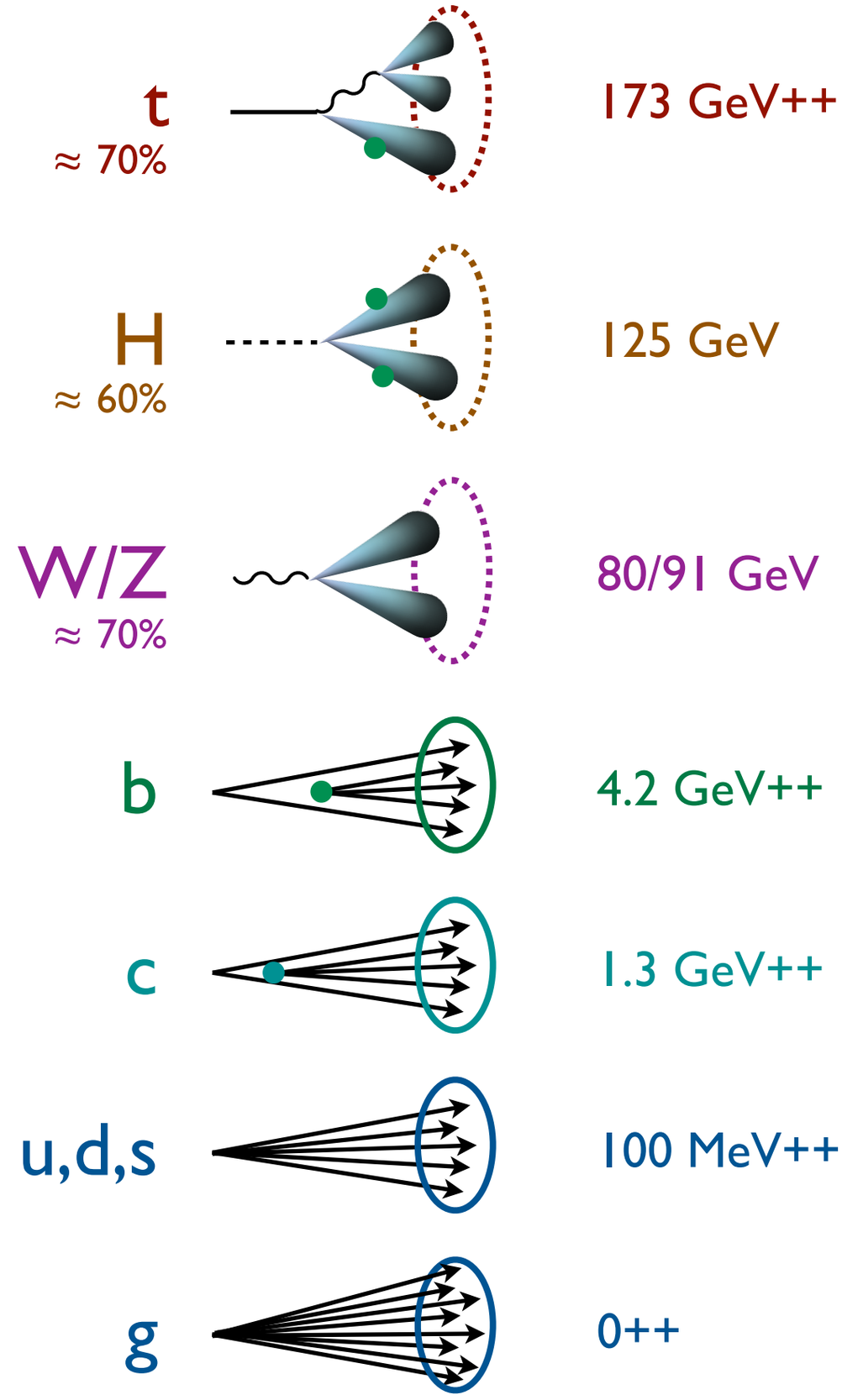
Jets from the Standard Model





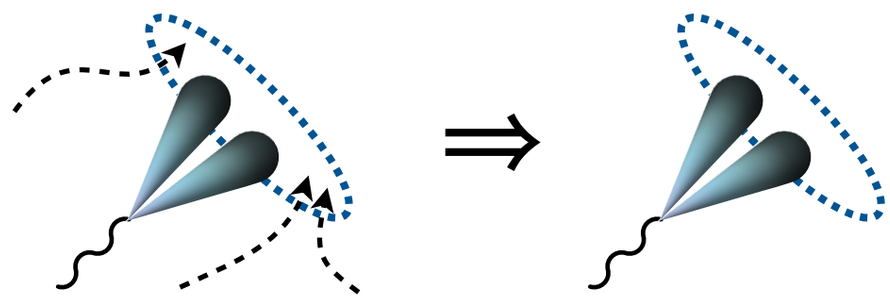
micro-jet
≈ 65%

Jets from the Standard Model

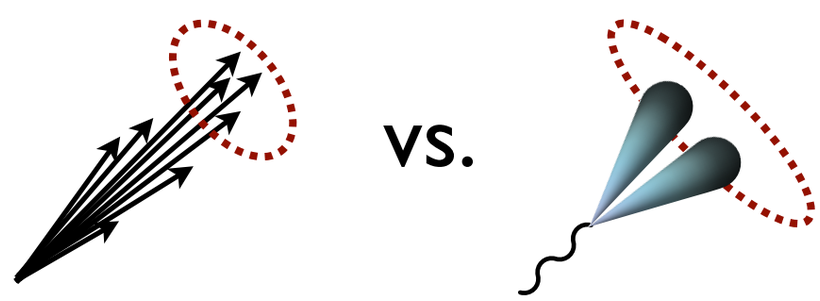


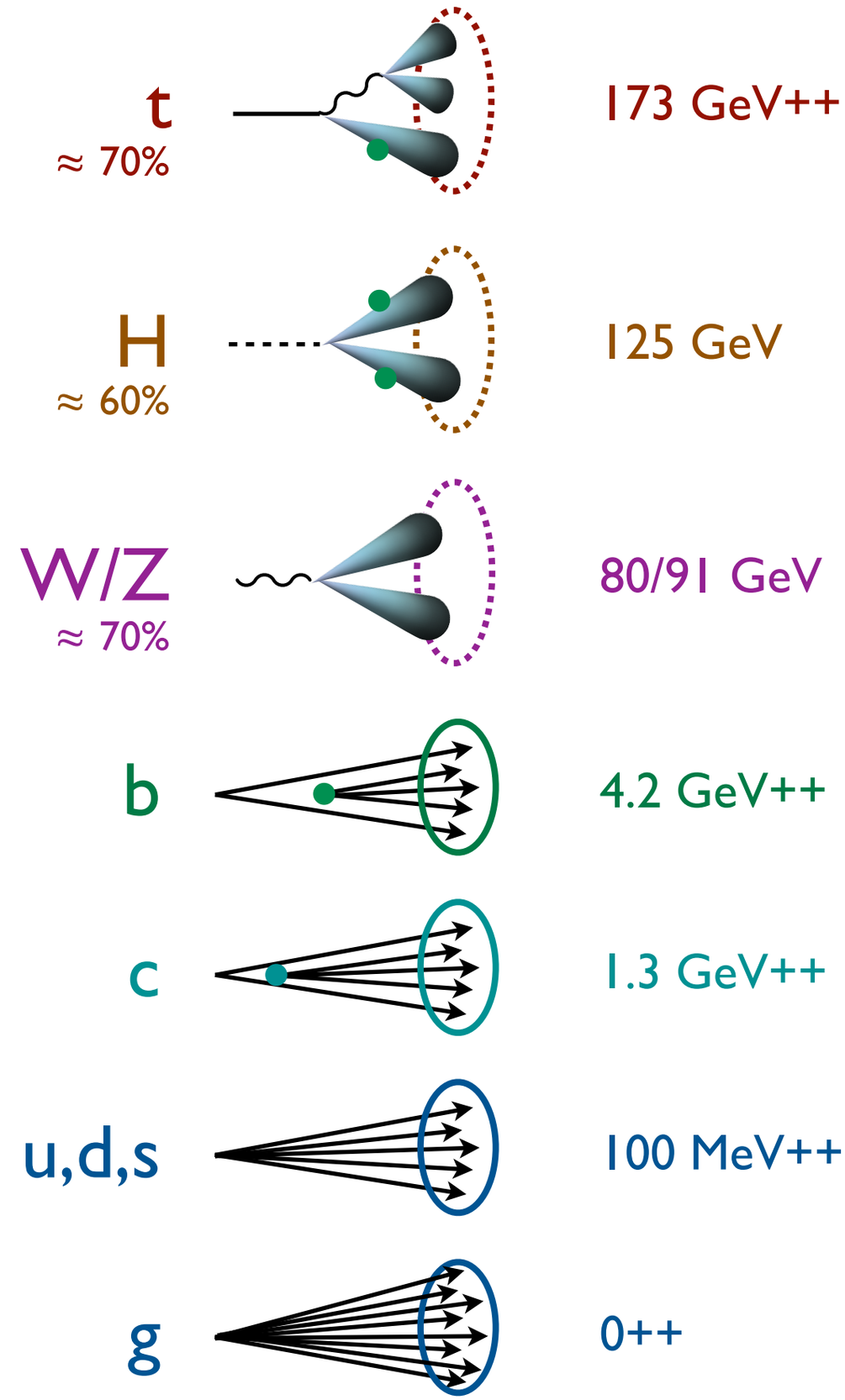
Substructure Toolbox:

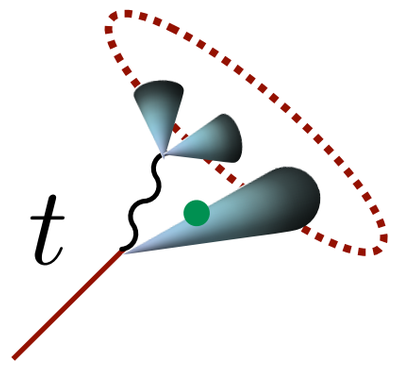
Jet Grooming



Jet Discrimination



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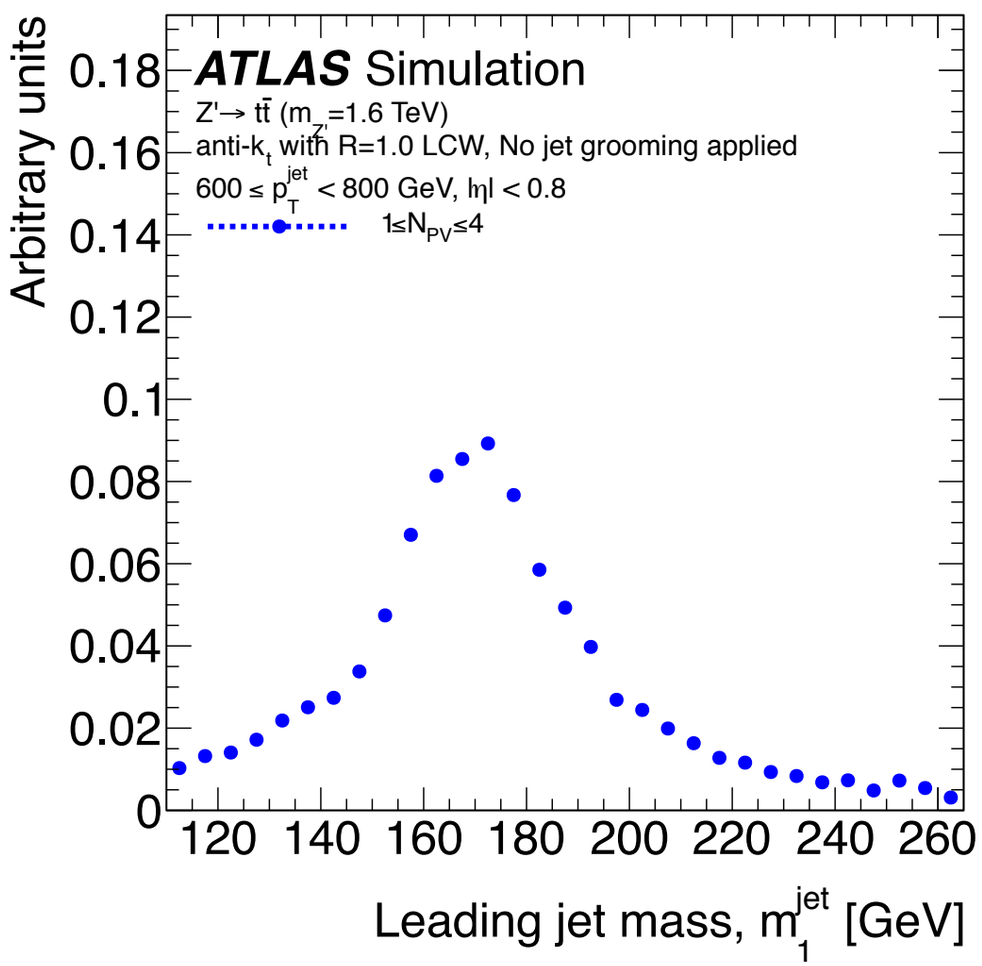
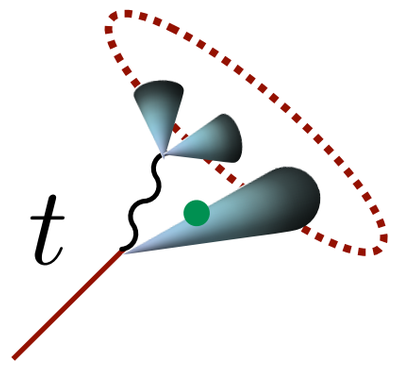

ATLAS Simulation
Z'→ tt̄ (m_Z'=1.6 TeV)
anti-k_t with R=1.0 LCW, No jet grooming applied
600 ≤ p_T^jet < 800 GeV, |η| < 0.8
1≤N_PV≤4
Arbitrary units
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
120 140 160 180 200 220 240 260
Leading jet mass, m_1^jet [GeV]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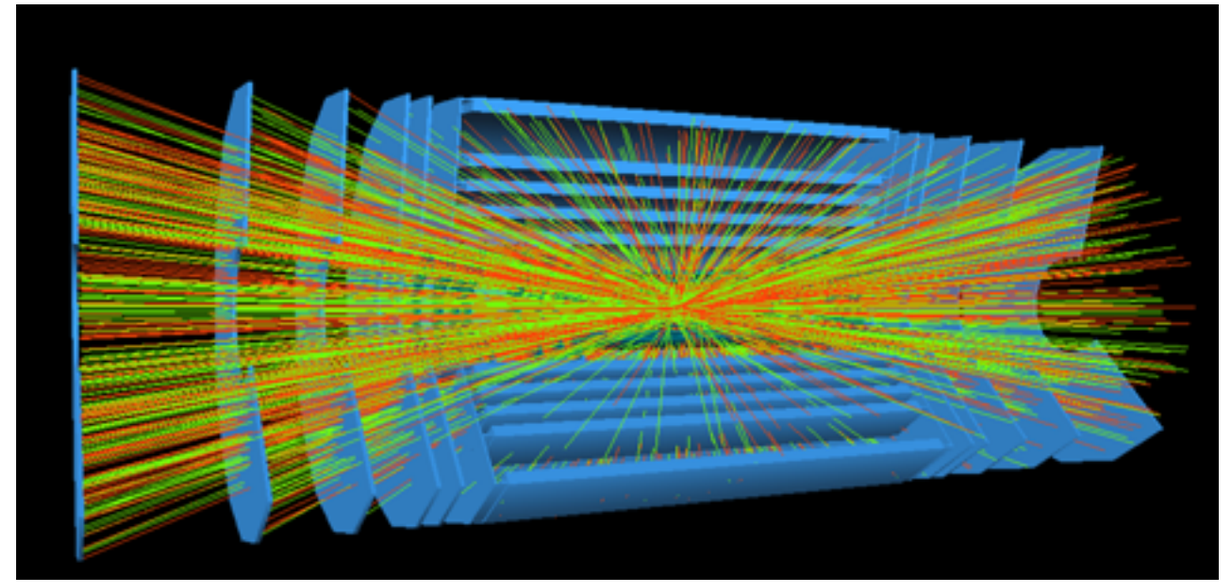
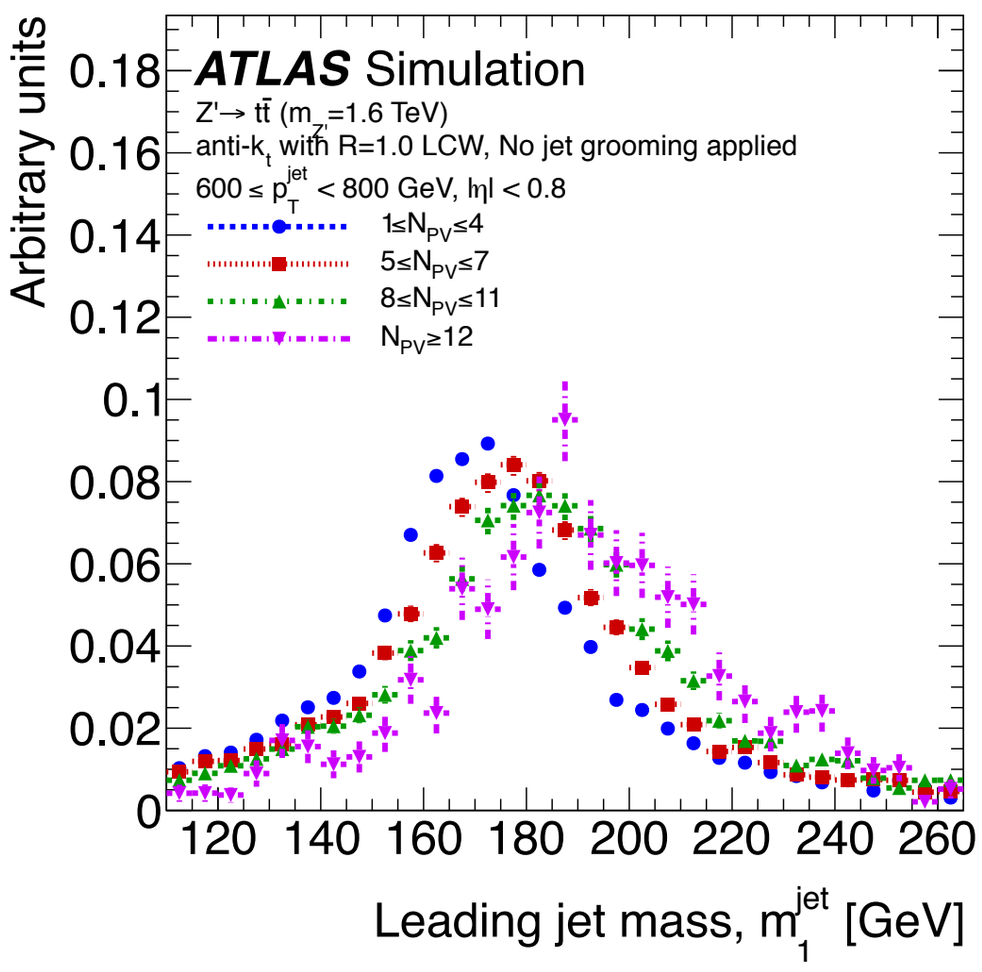
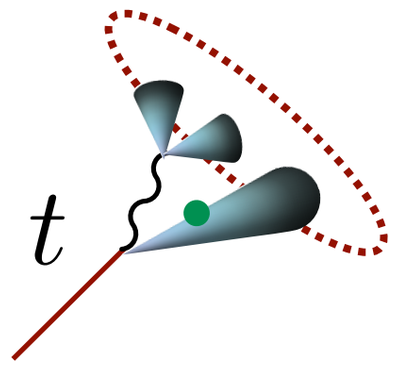



ATLAS Simulation
Z'→ tt̄ (m_Z'=1.6 TeV)
anti-k_t with R=1.0 LCW, No jet grooming applied
600 ≤ p_T^jet < 800 GeV, |η| < 0.8
1≤N_PV≤4
5≤N_PV≤7
8≤N_PV≤11
N_PV≥12
Arbitrary units
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
120
140
160
180
200
220
240
260
Leading jet mass, m_1^jet [GeV]



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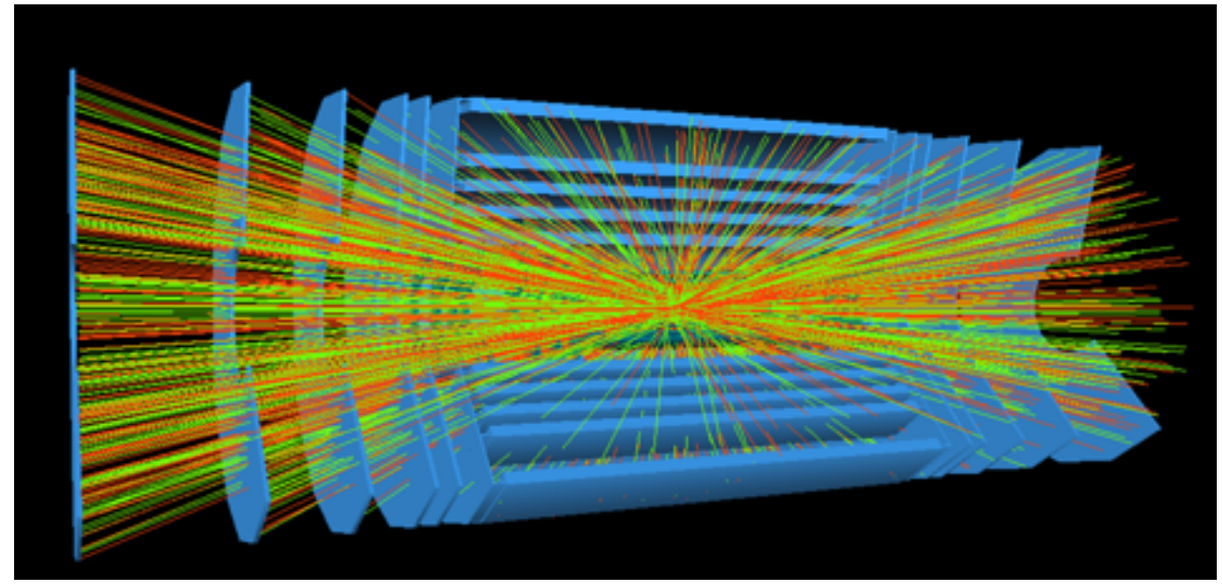

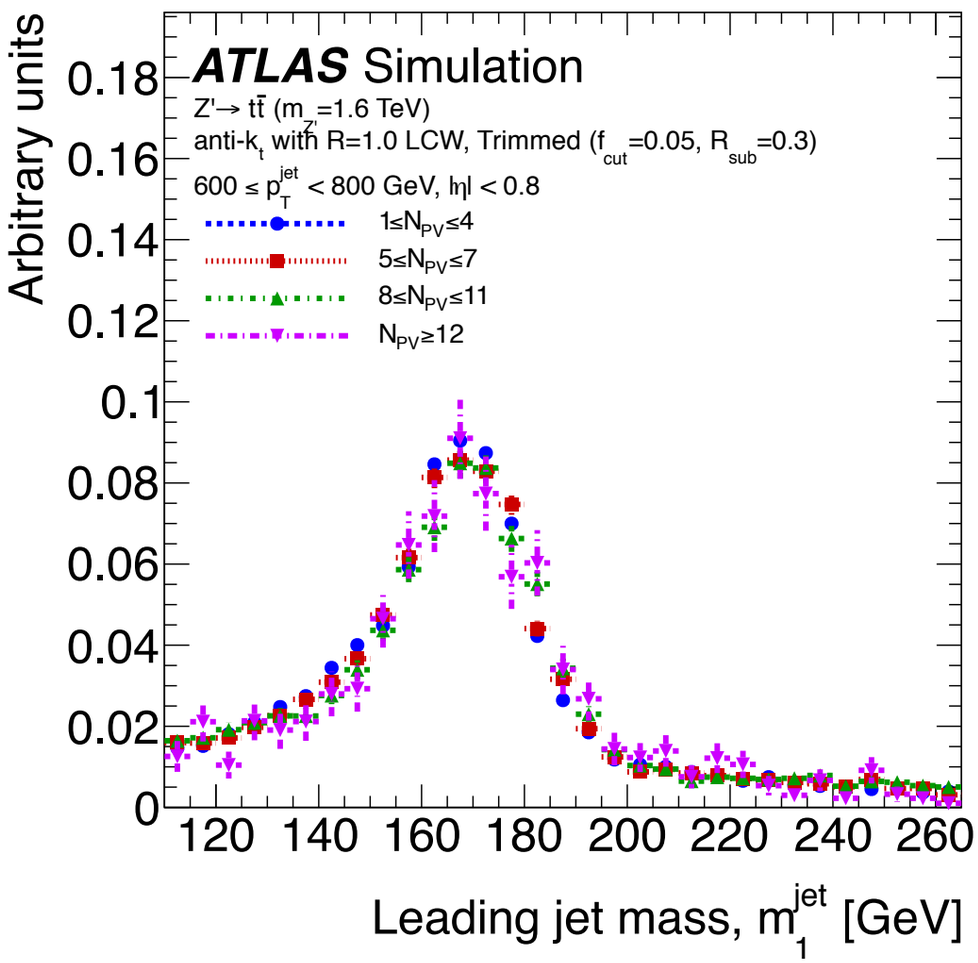

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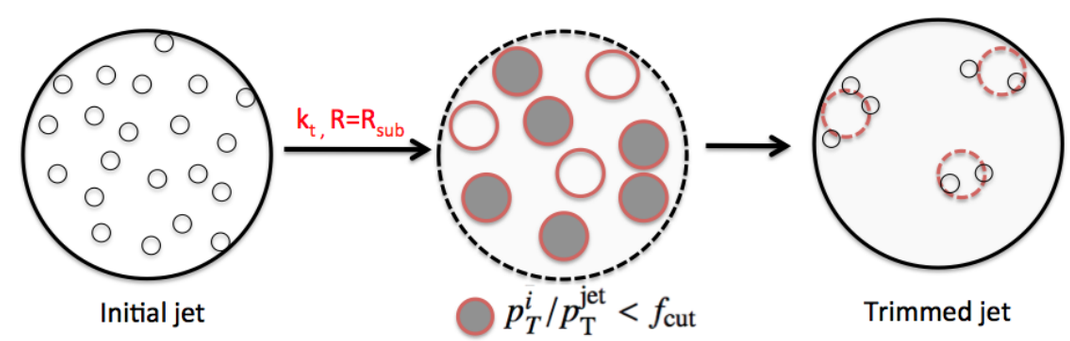
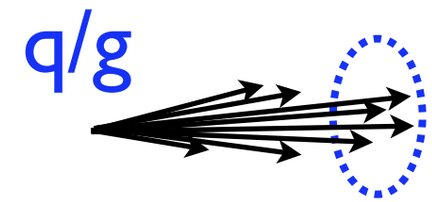
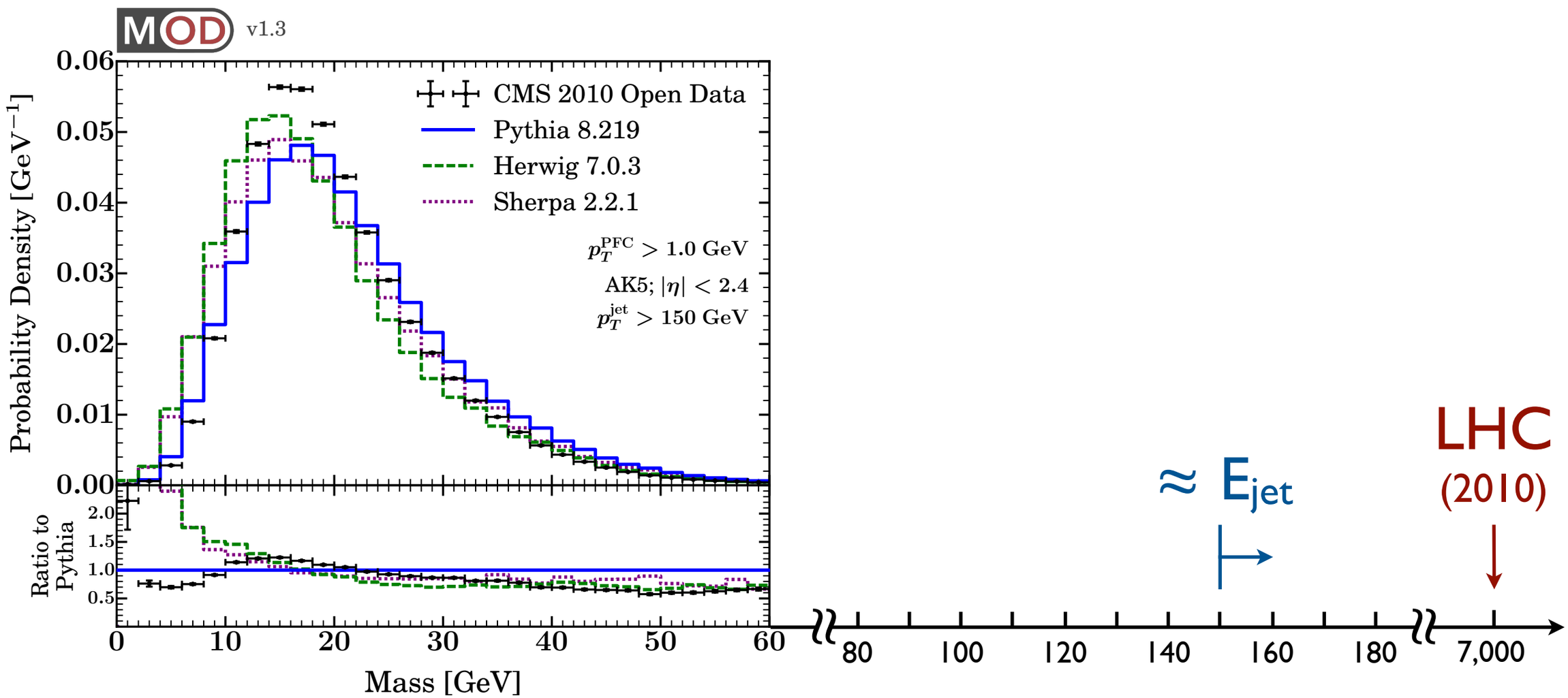
Jet Trimming



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

Regular Jets Have Mass, Too

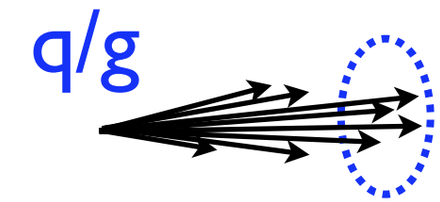


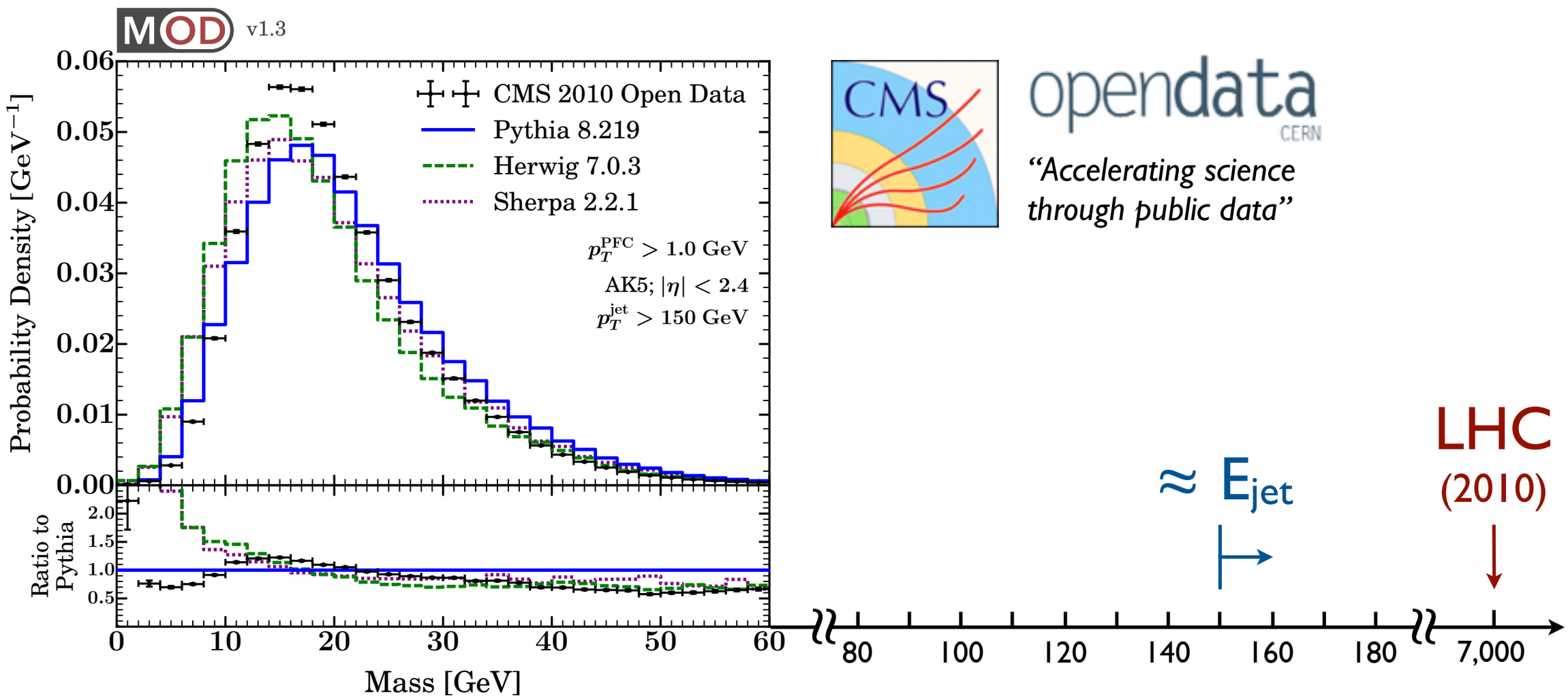


g u d s c b

[Tripathee, Xue, Larkoski, Marzani, JDT, in progress]

Regular Jets Have Mass, Too





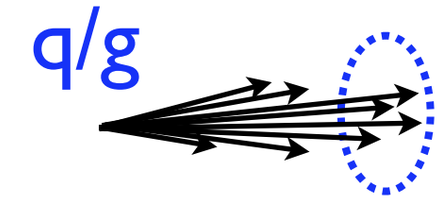
CMS opendata CERN

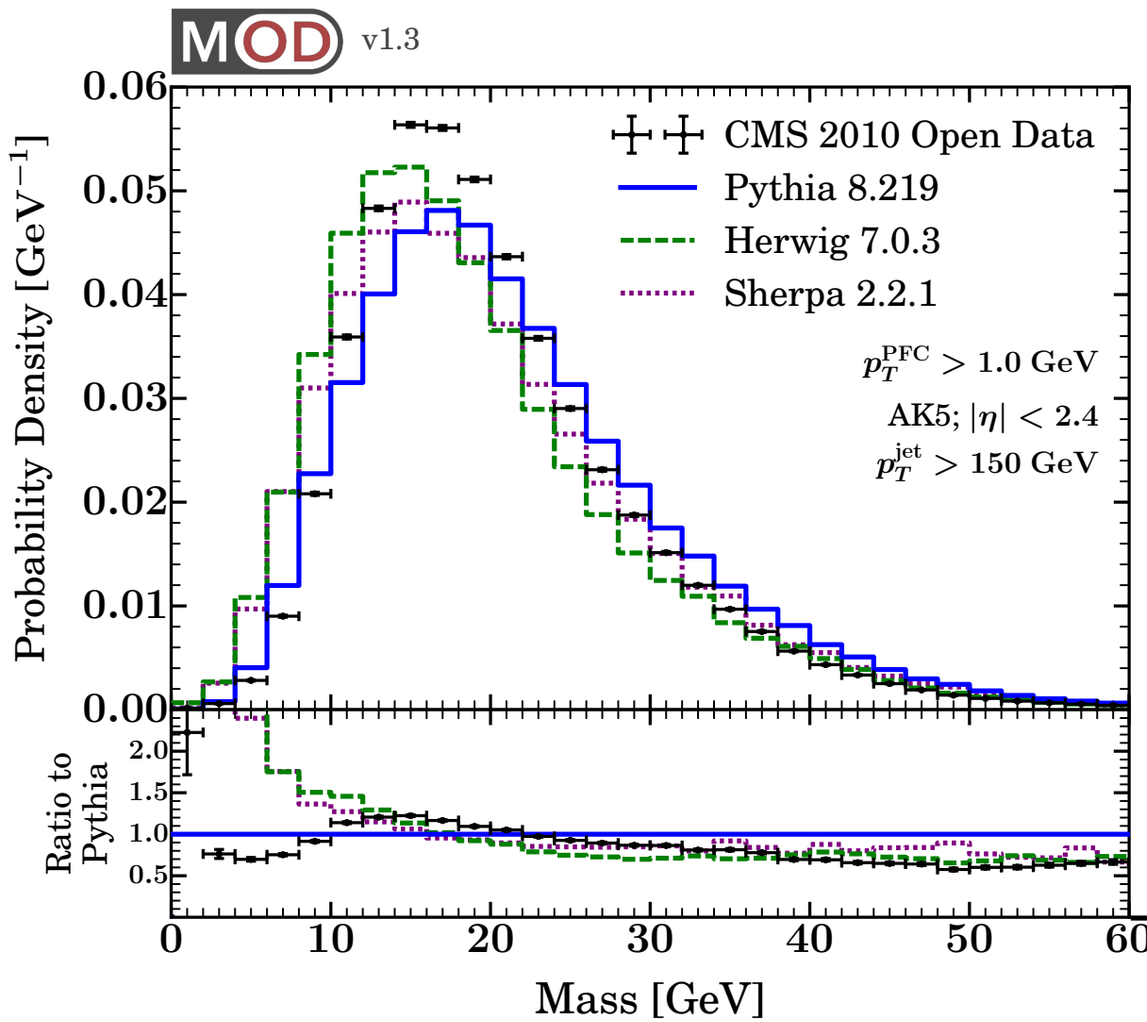
"Accelerating science through public data"

g u d s c b

[Tripathee, Xue, Larkoski, Marzani, JDT, in progress]

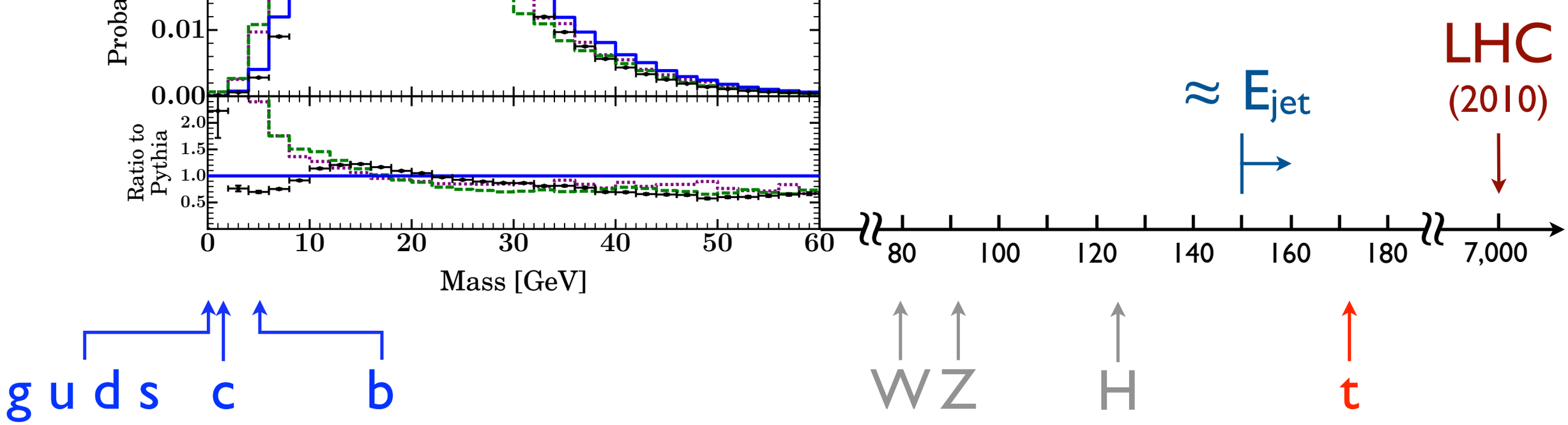
Regular Jets Have Mass, Too



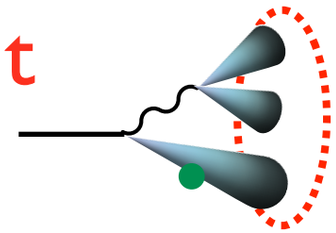


opendata CERN

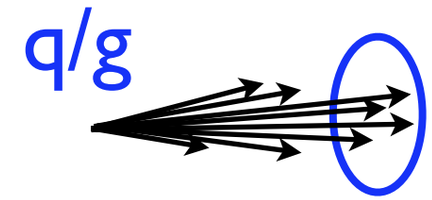
"Accelerating science through public data"

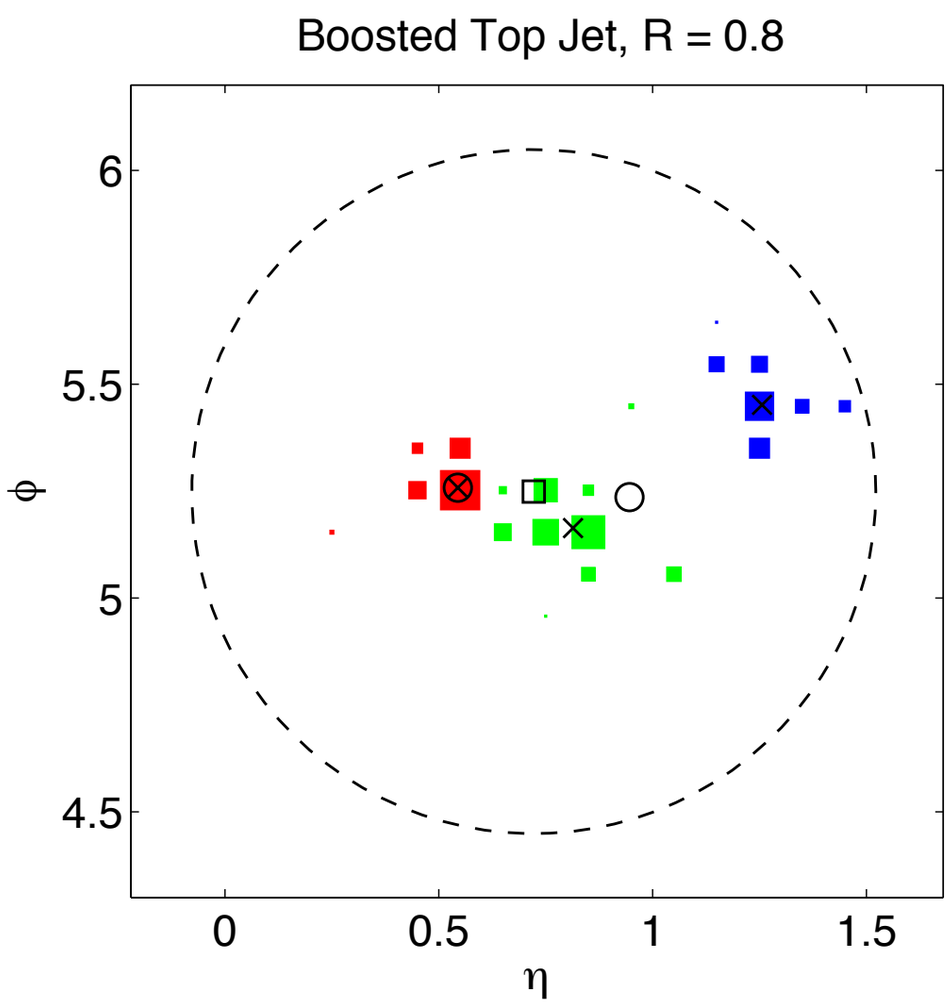


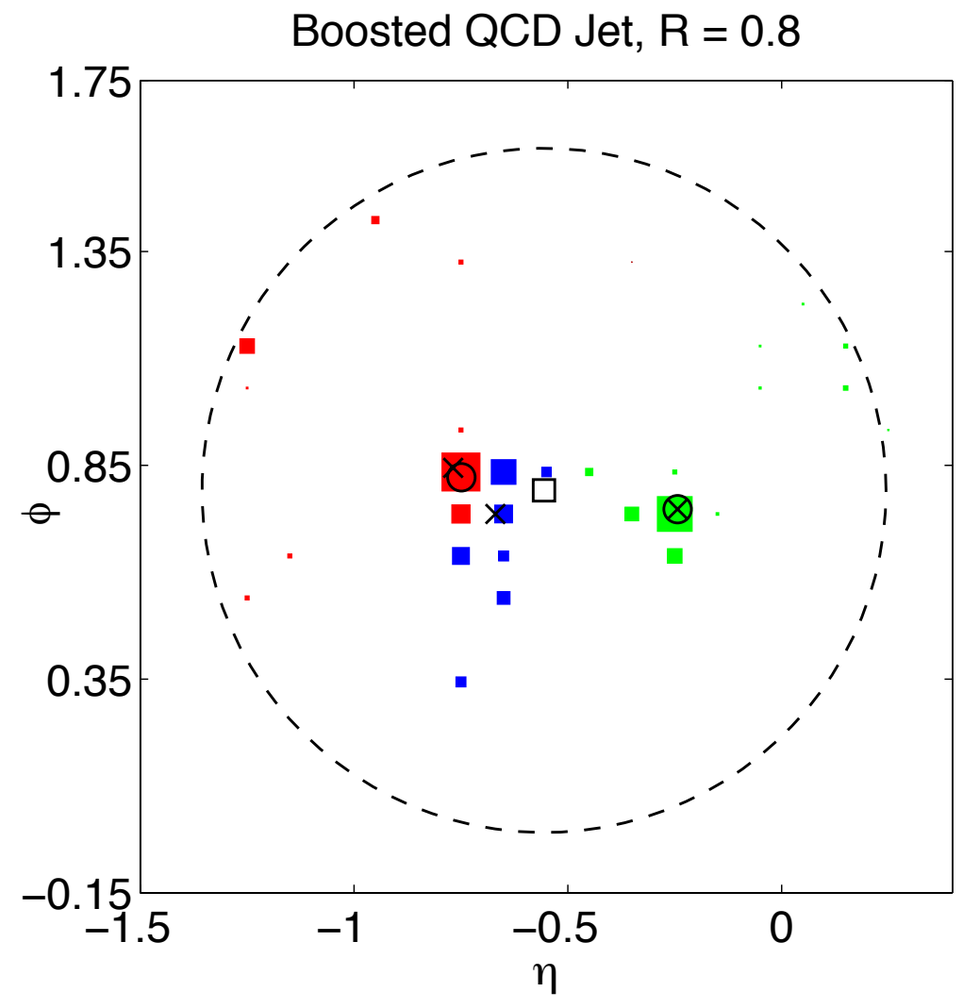
[Tripathee, Xue, Larkoski, Marzani, JDT, in progress]



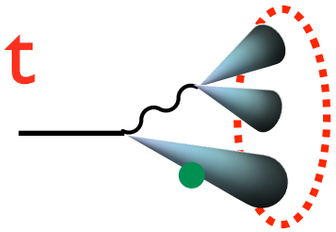
N-Prong vs. 1-Prong



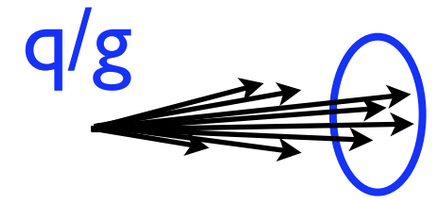


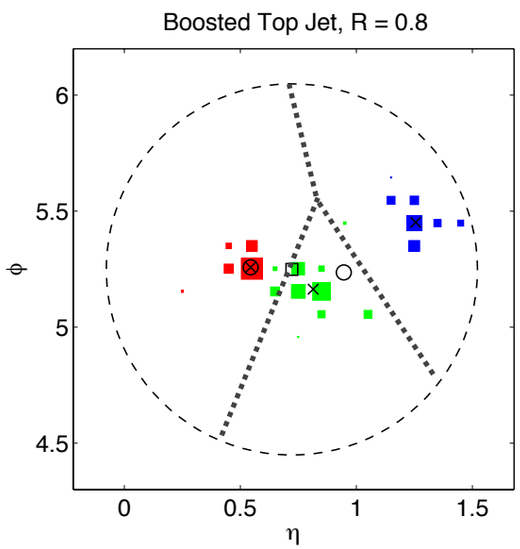


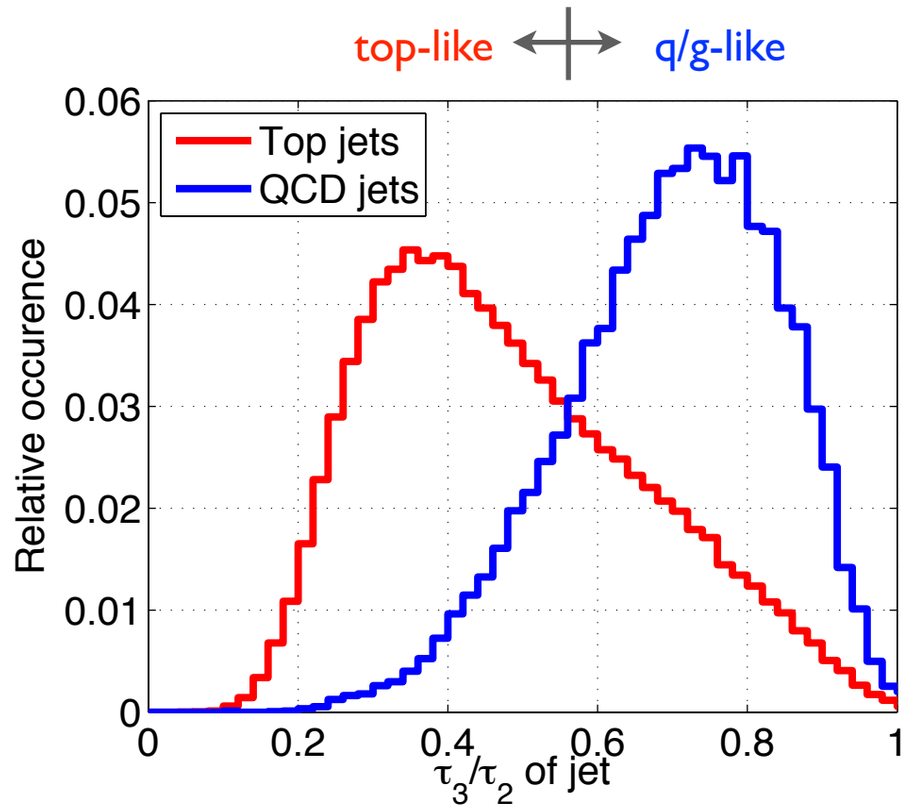
Both jets have m ≈ 173 GeV

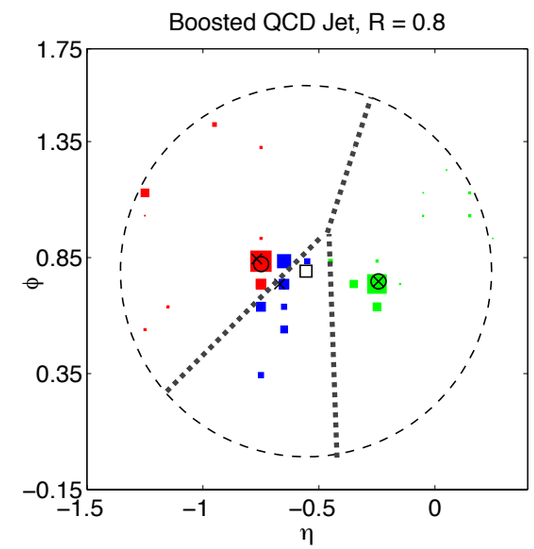


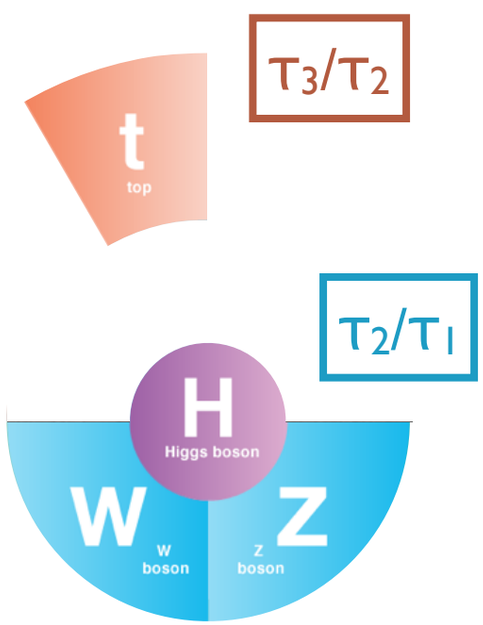
N-Prong vs. 1-Prong









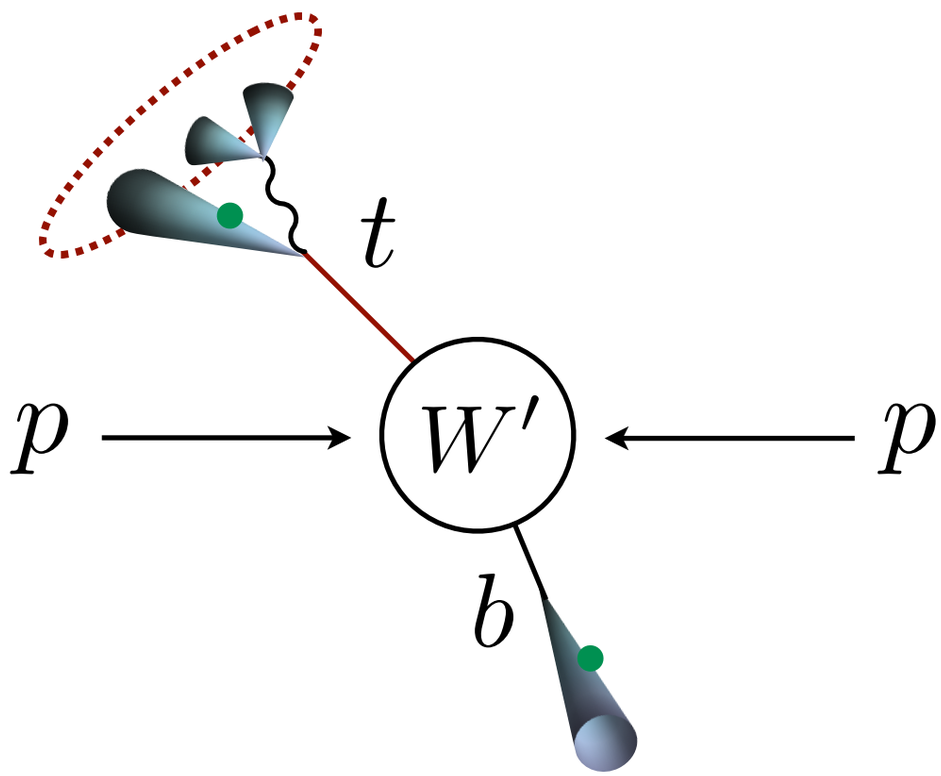


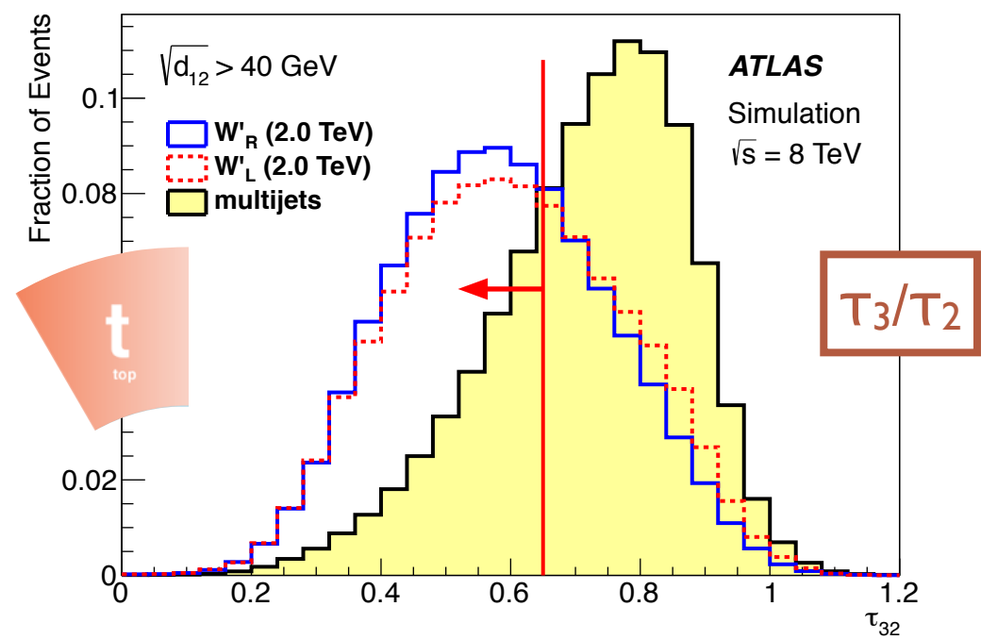
N-subjettiness

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

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

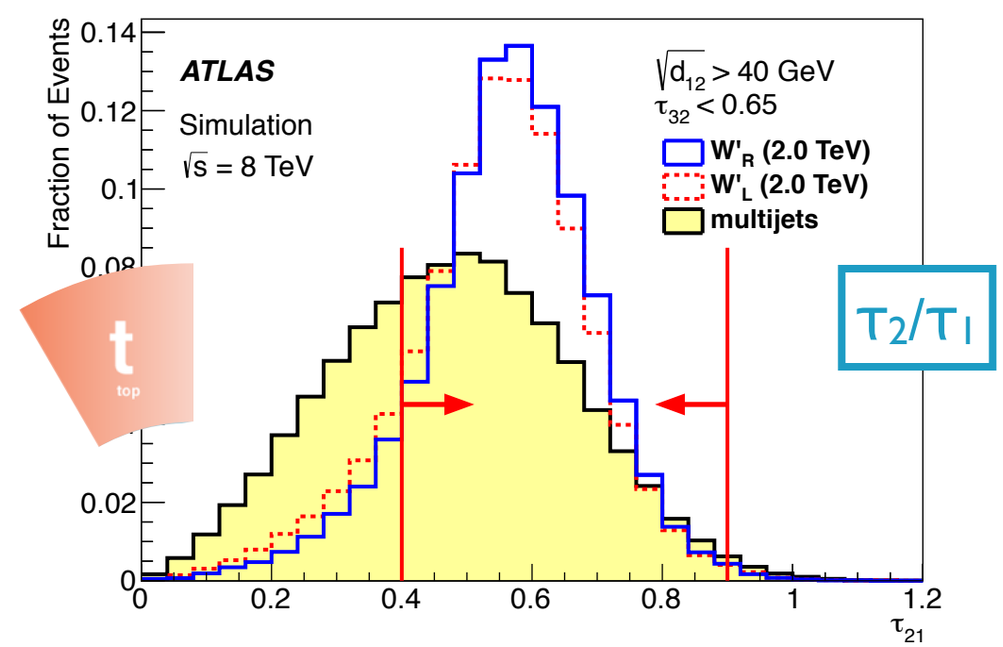
ATLAS: Heavy W Search





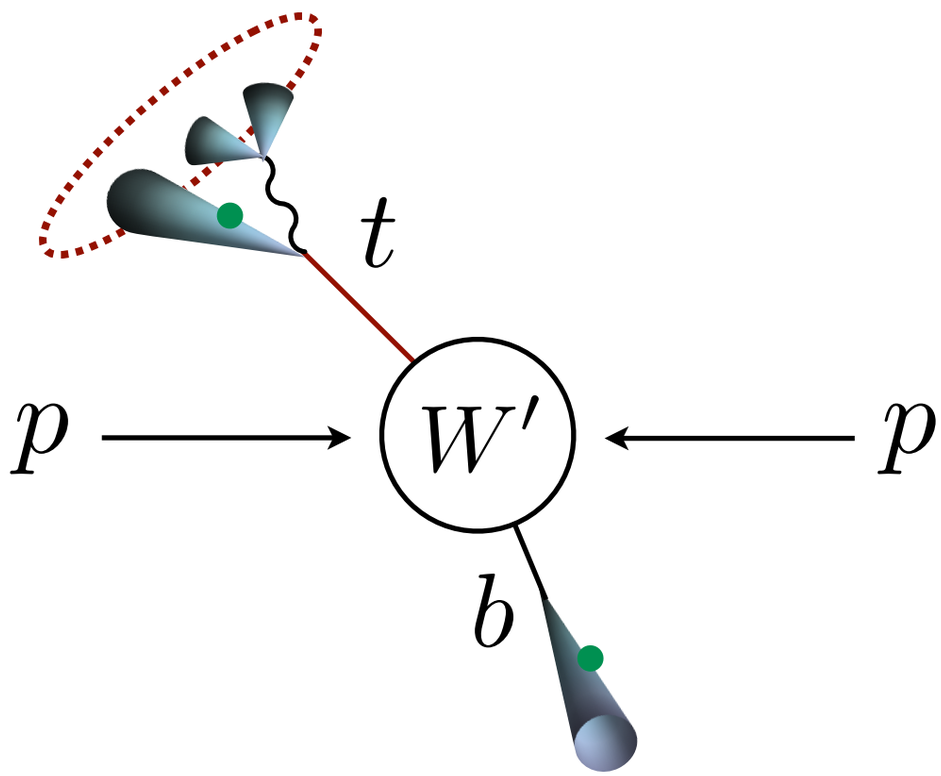
with B-tagging
+ Trimming
+ N-subjettiness

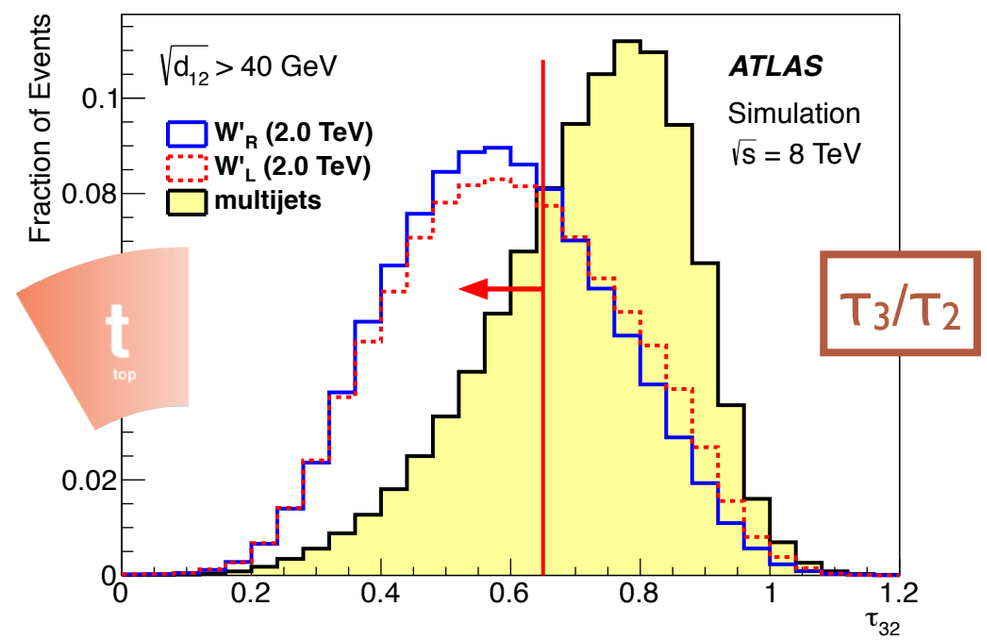
≈100x background rejection
@ 50% signal efficiency



[ATLAS, 2014]

ATLAS: Heavy W Search





with B-tagging
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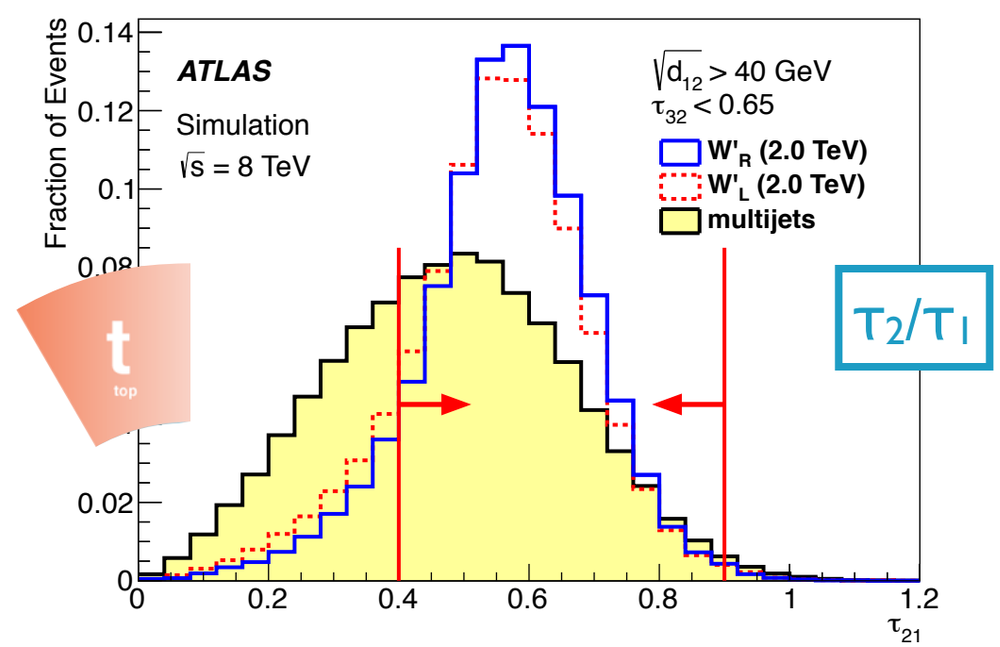
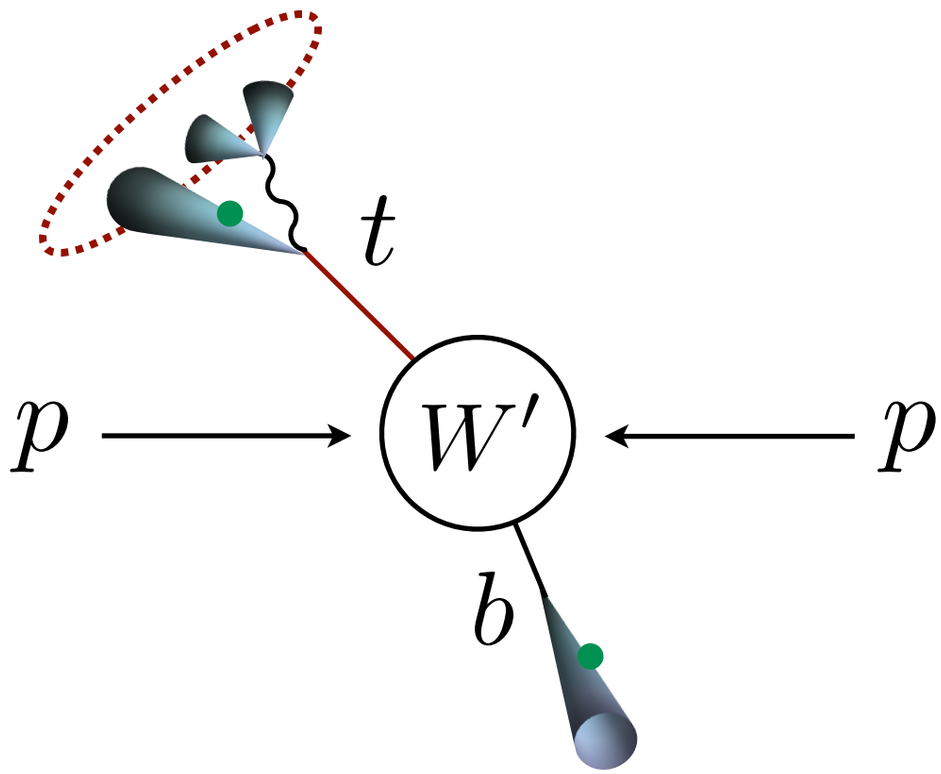


[ATLAS, 2014]

ATLAS: Heavy W Search



with B-tagging
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≈100x background rejection
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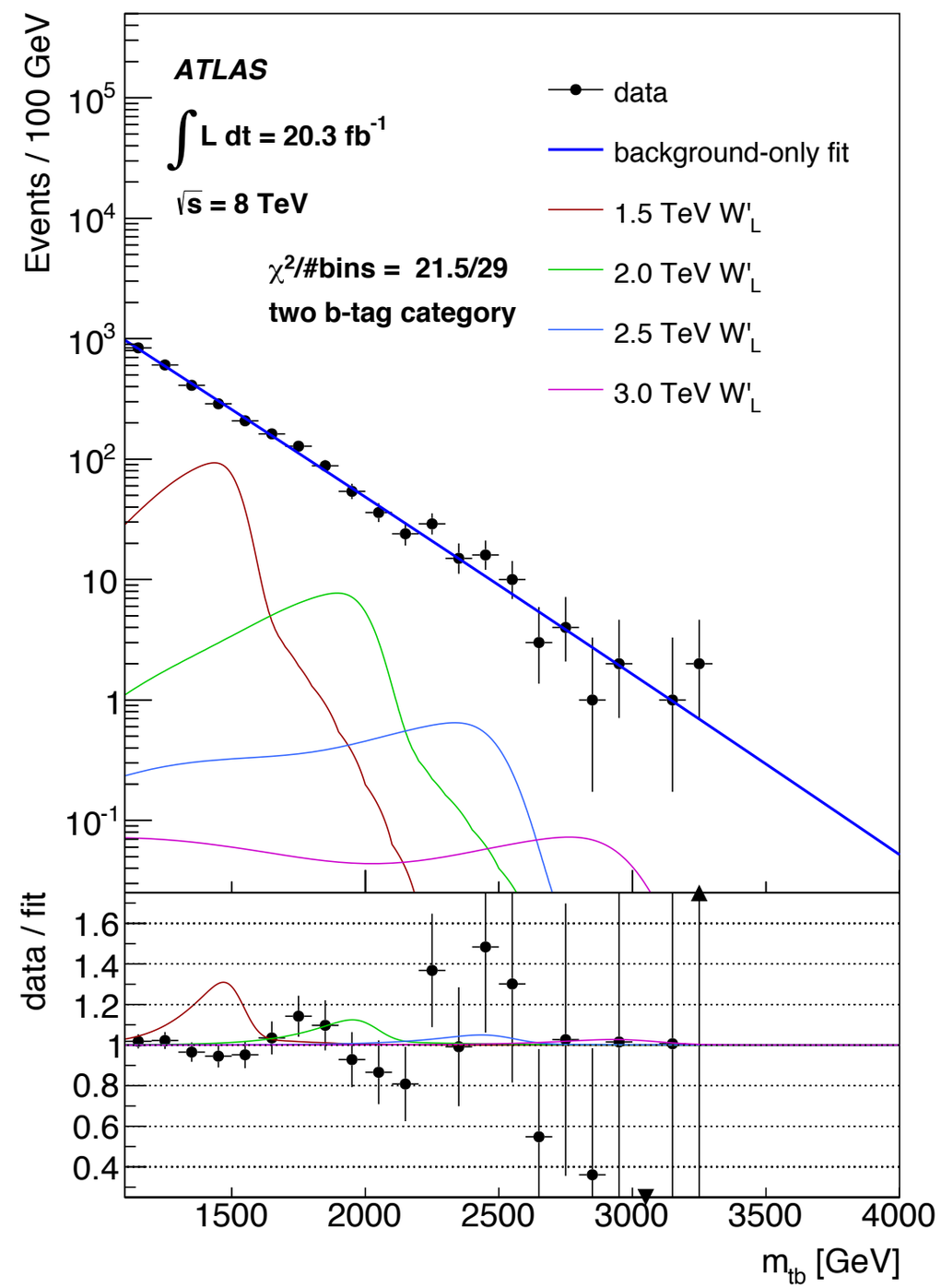

BOOST 2013
BOOST
BOOST 2015
BOOST 2012
BOOST 2014

BOOST 2015
CHICAGO

BOOST 2015
CHICAGO
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2017

BOOST 2015
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Boost'17
RENCONTRES DE MORIOND
50
since 1966
ASPEN
CENTER
FOR
PHYSICS
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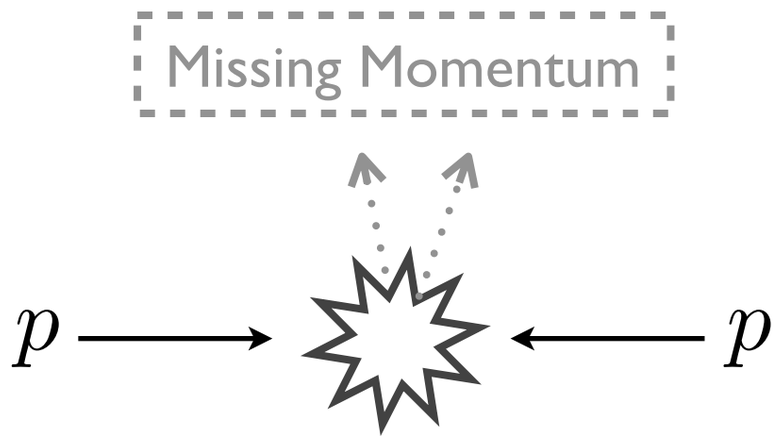
00st
2017

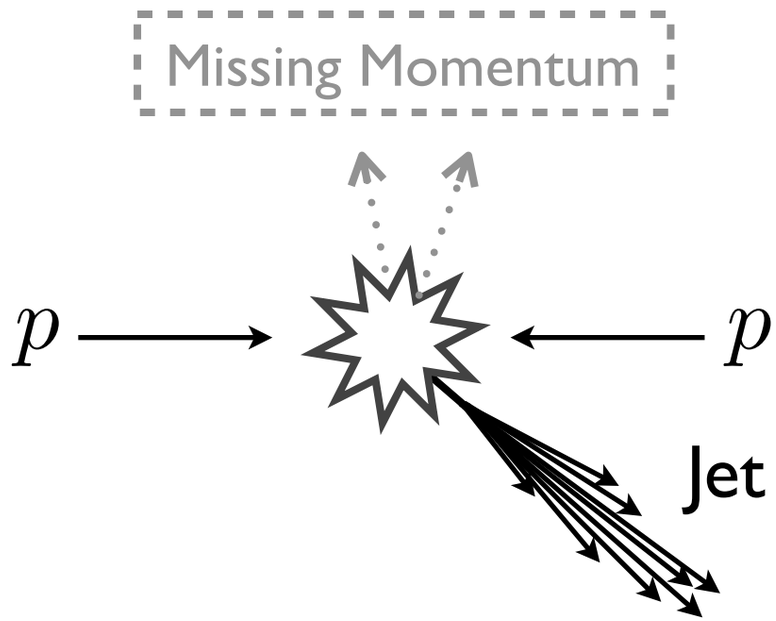
CMS: Dark Matter Search



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

CMS: Dark Matter Search

Hot topic @



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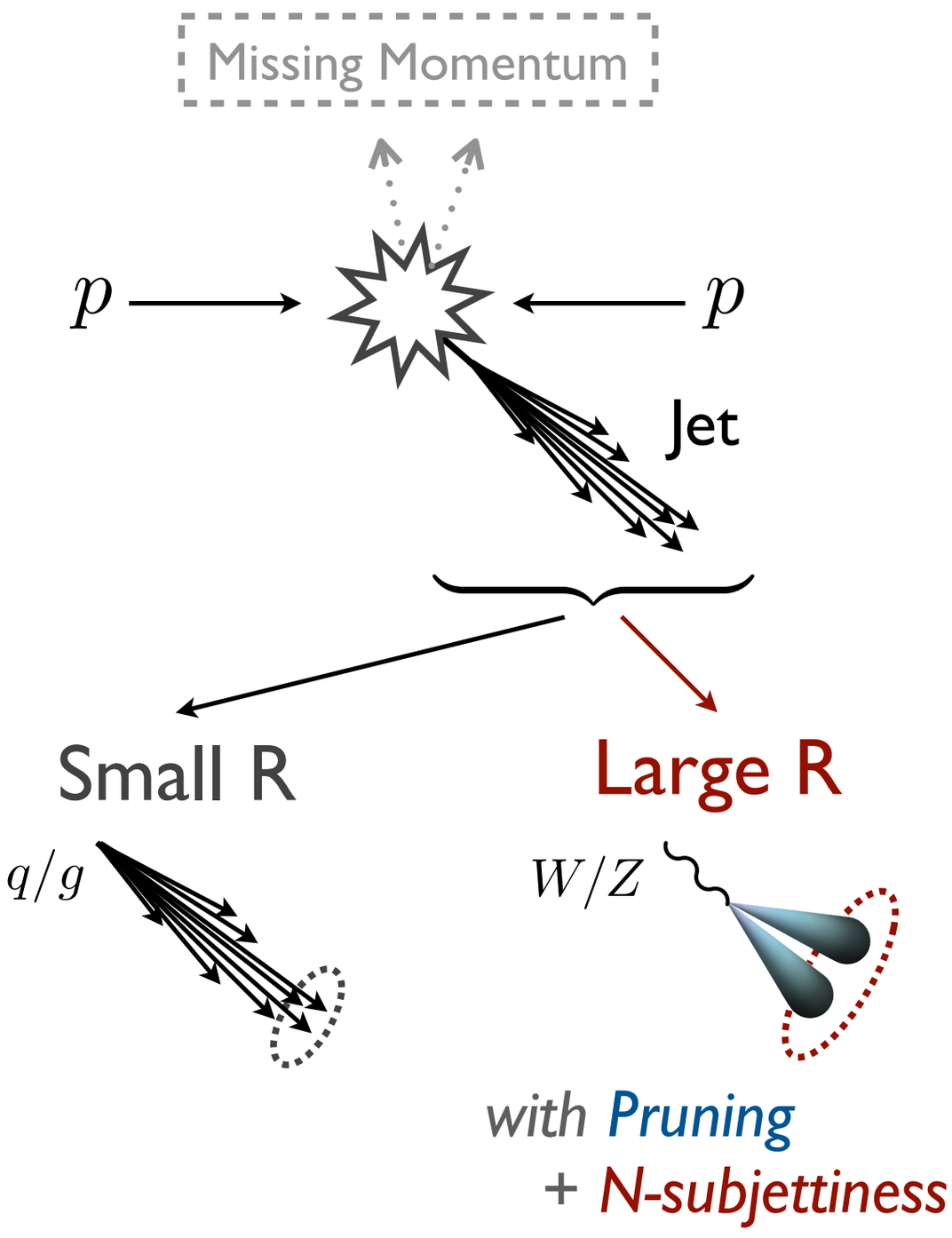
CMS: Dark Matter Search

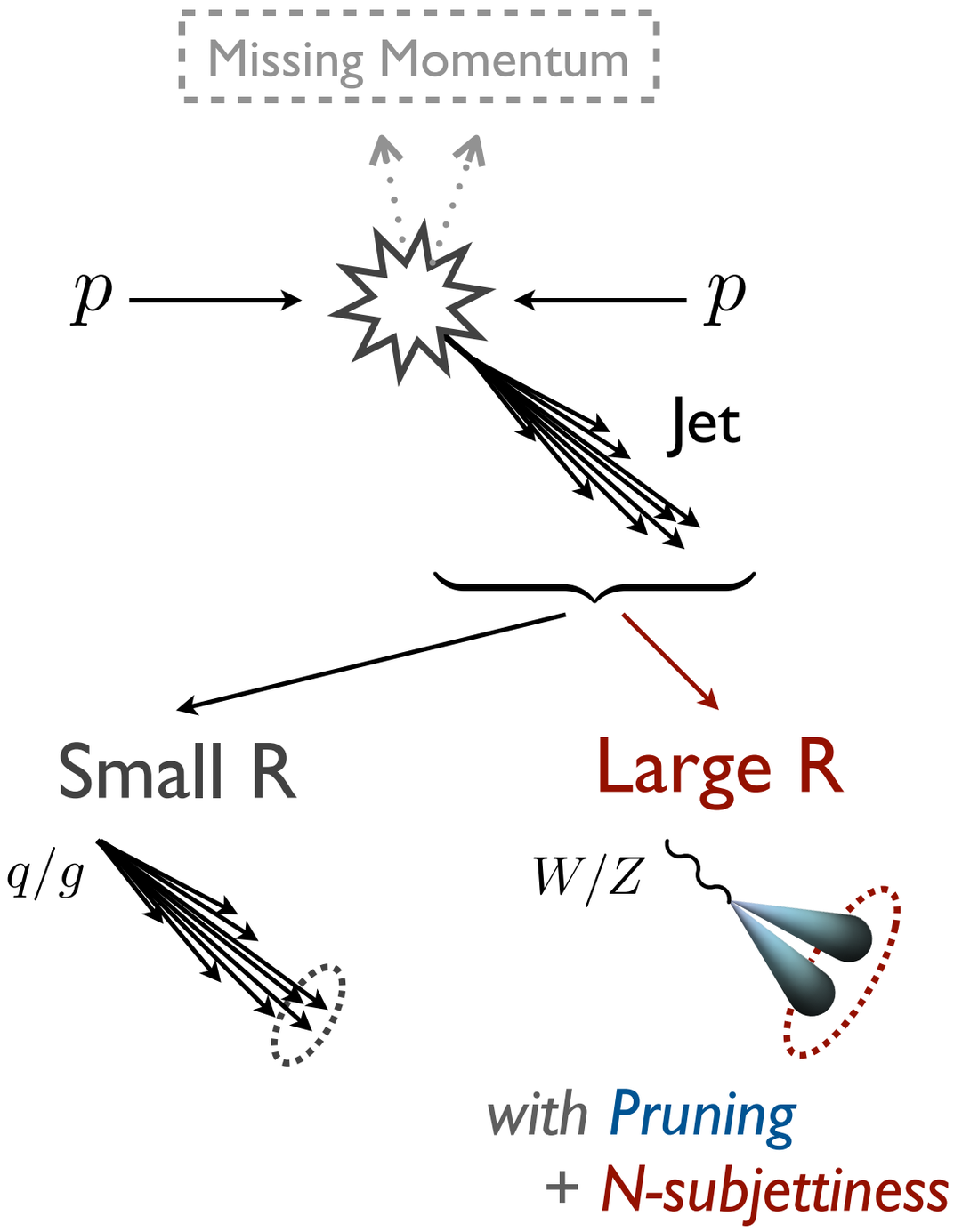
Hot topic @

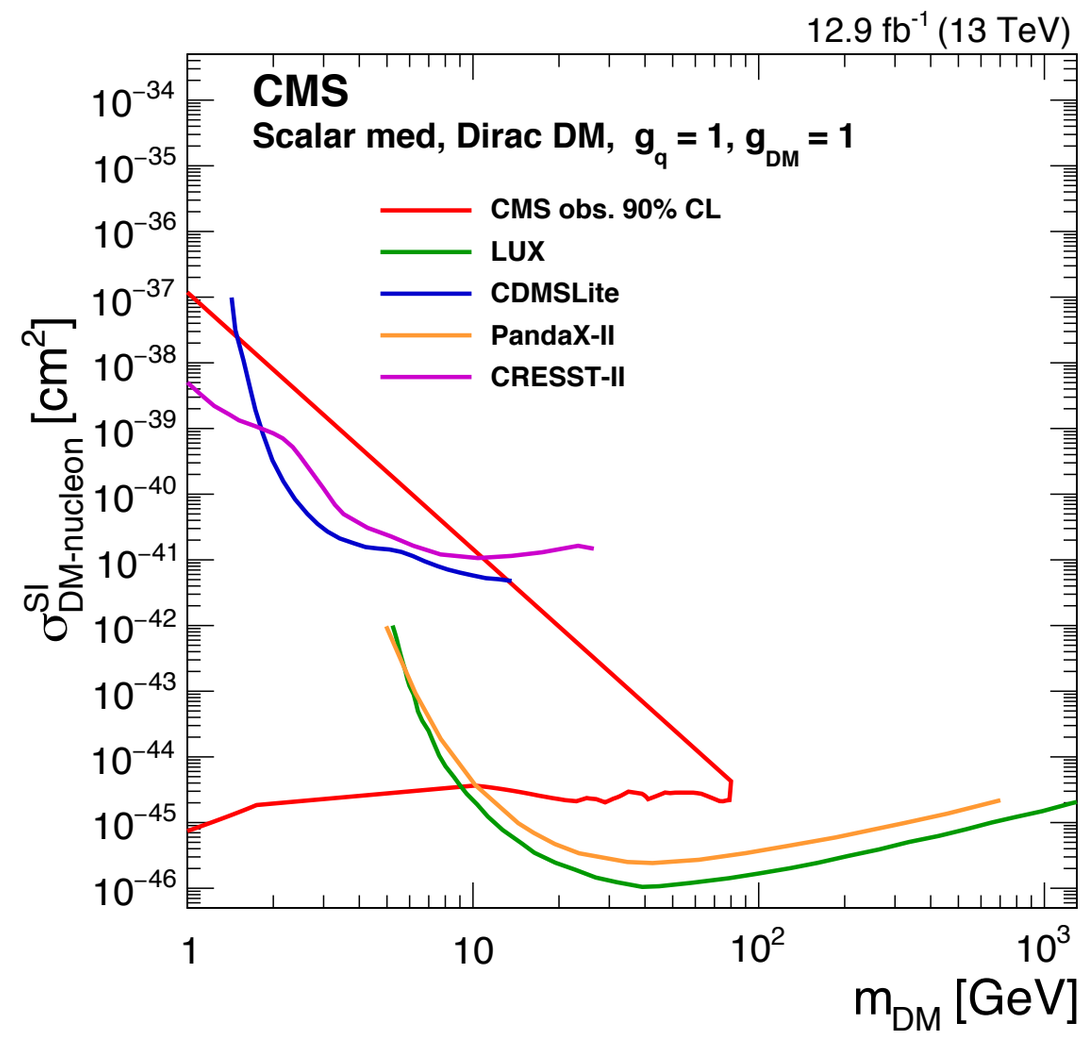


[CMS, 2017; using Ellis, Vermilion, Walsh, 2009; JDT, Van Tilburg, 2010, 2011]

CMS: Dark Matter Search

Hot topic @

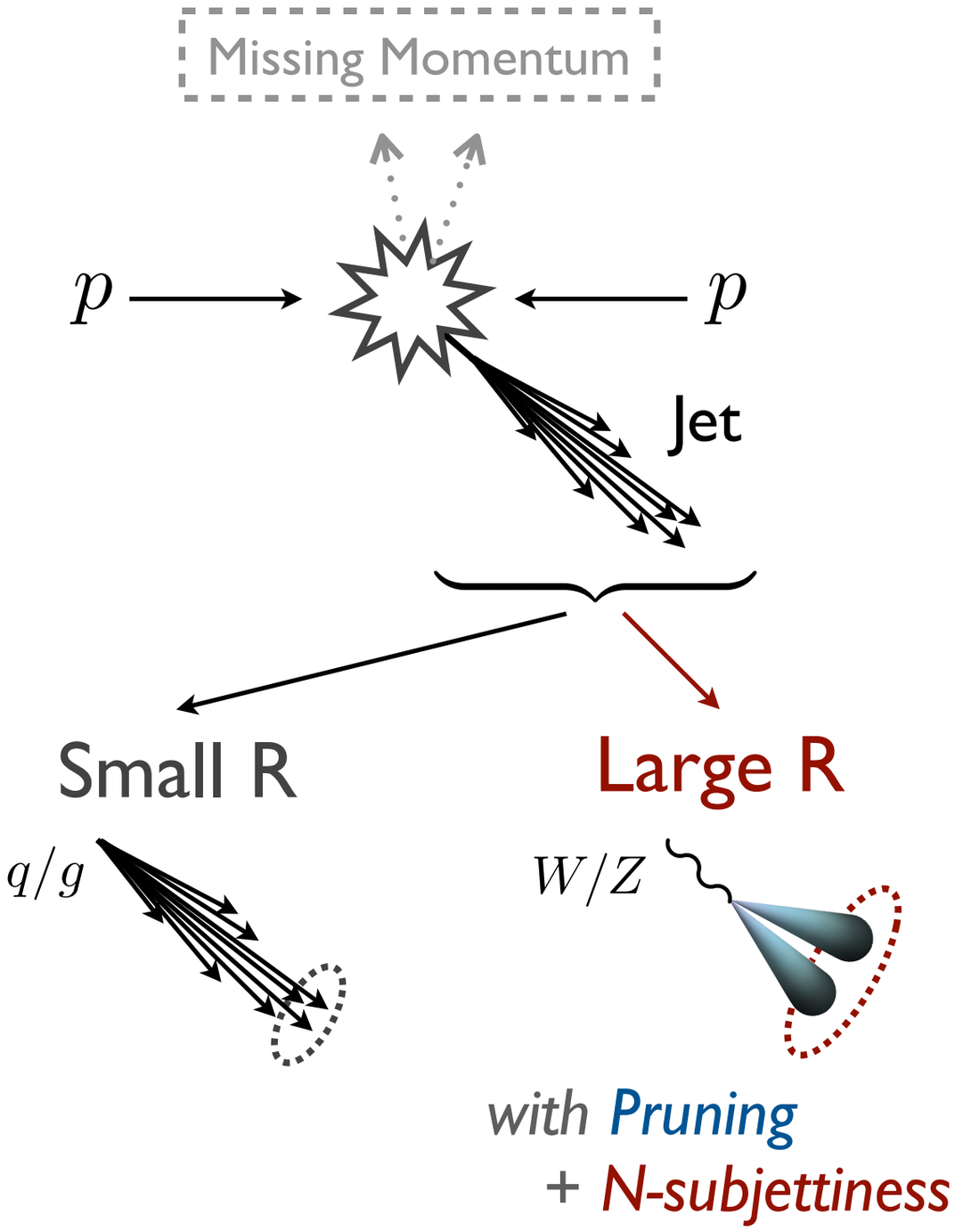


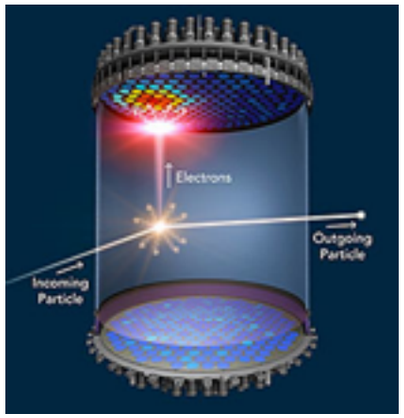


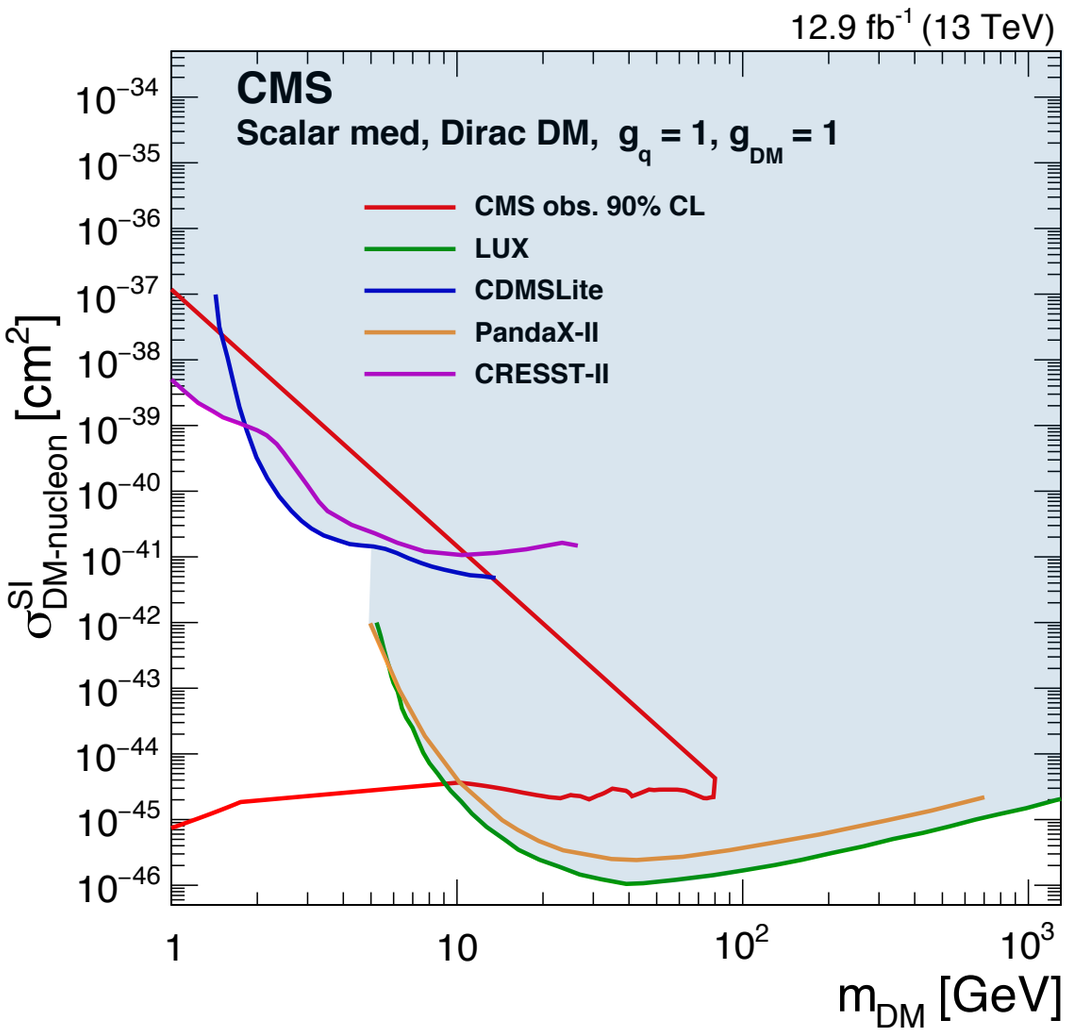
[CMS, 2017; using Ellis, Vermilion, Walsh, 2009; JDT, Van Tilburg, 2010, 2011]

CMS: Dark Matter Search

Hot topic @







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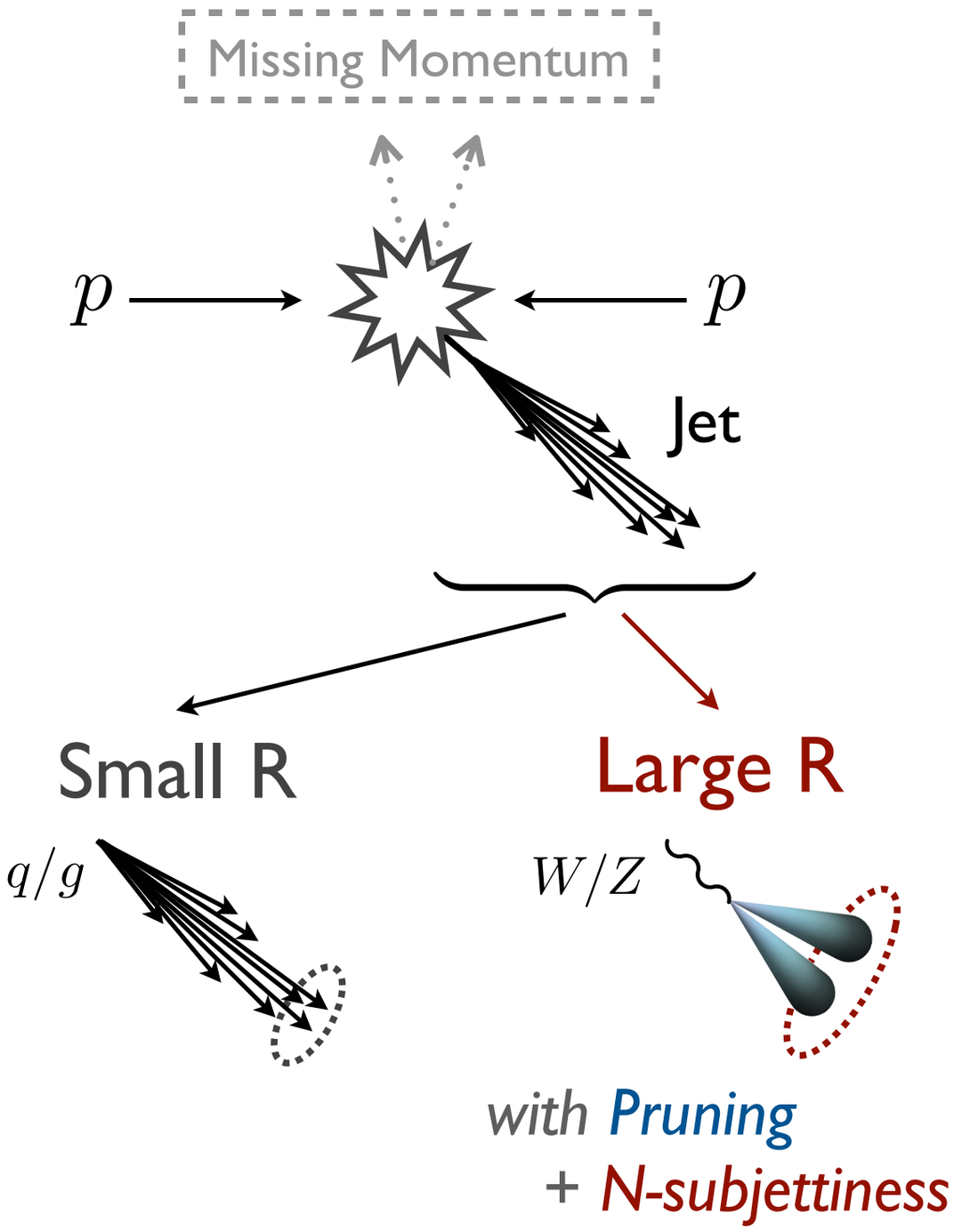
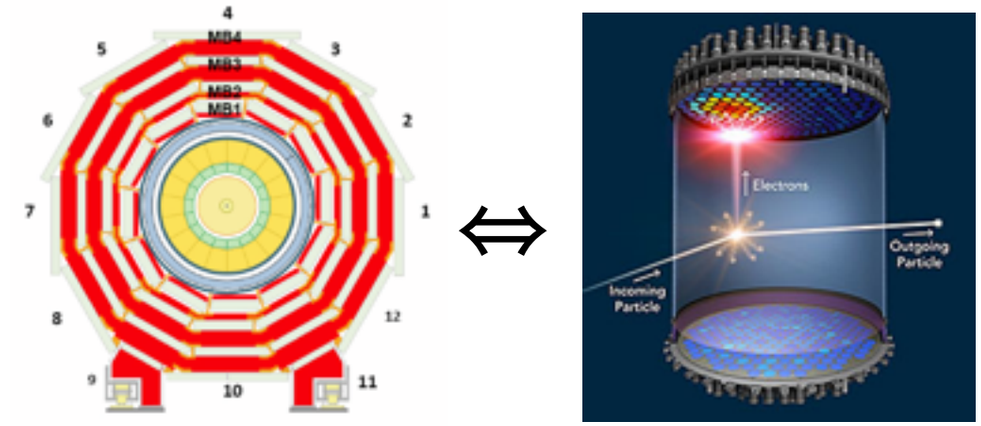
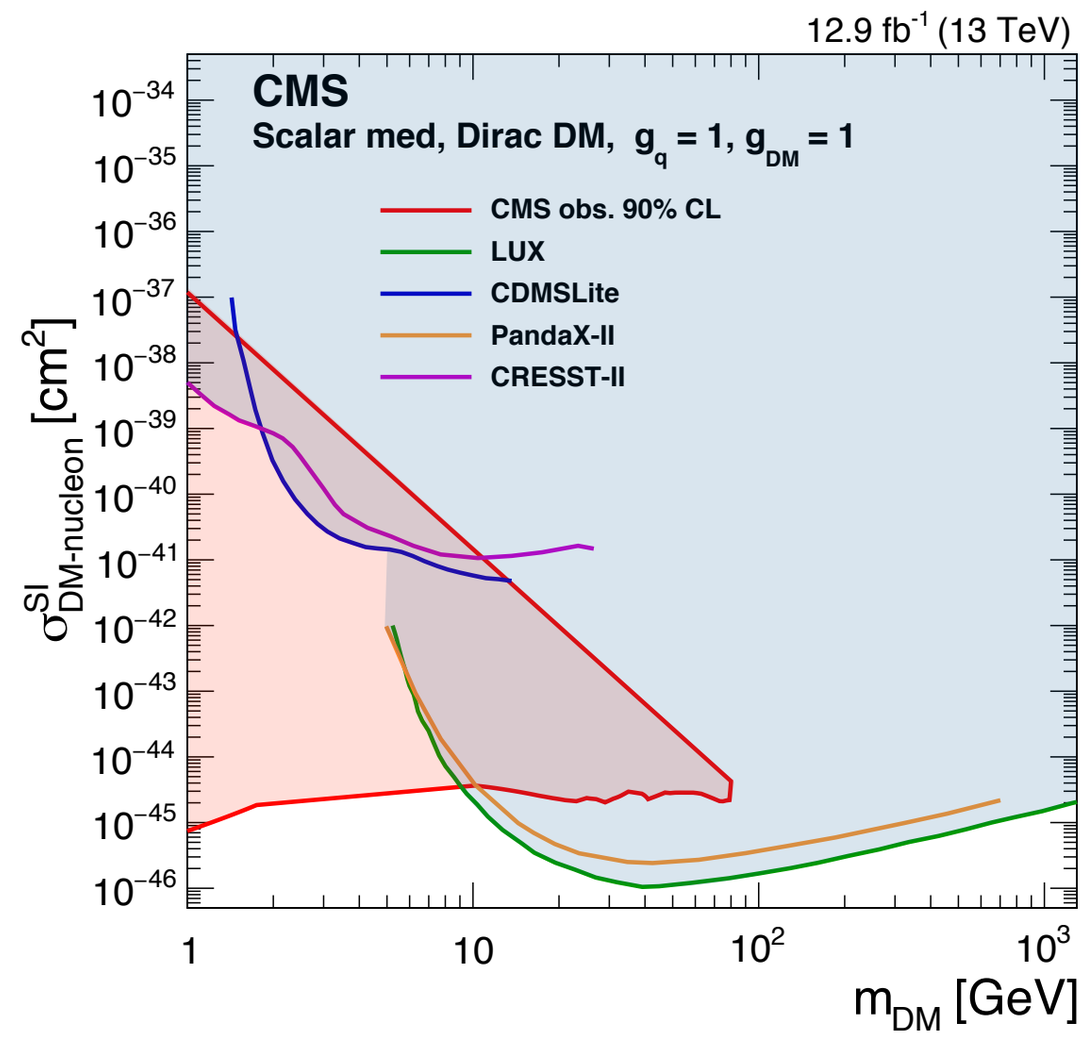
CMS: Dark Matter Search

Hot topic @



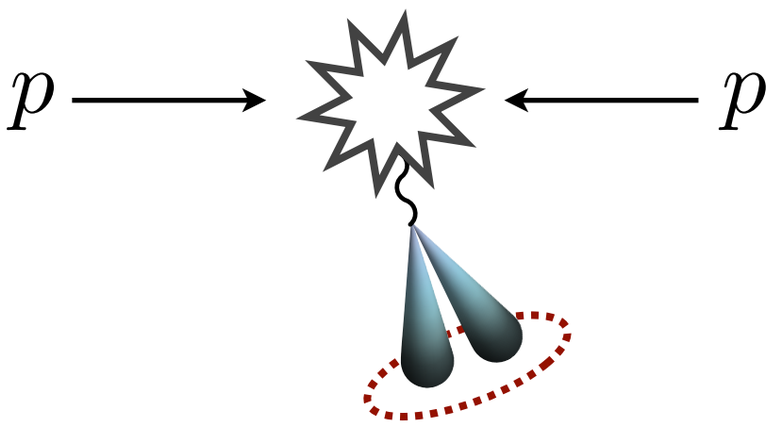




[CMS, 2017; using Ellis, Vermilion, Walsh, 2009; JDT, Van Tilburg, 2010, 2011]

CMS: Boosted Z' Search

Hot topic @

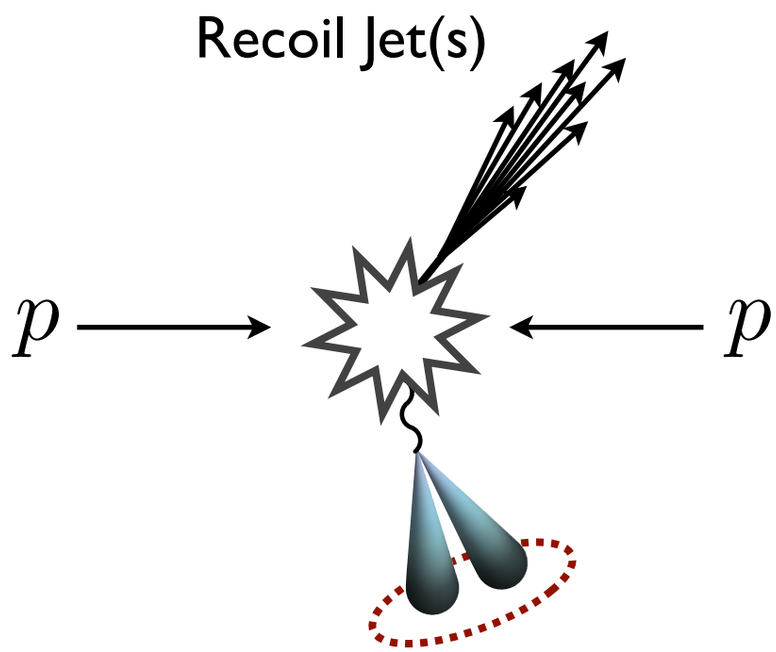


Z or Z' ?

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

CMS: Boosted Z' Search

Hot topic @



Z or Z' ?

with Soft Drop
+ N-subjettiness
+ Decorrelation

[CMS, 2016; using Larkoski, Marzani, Soyez, JDT, 2014;
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CMS: Boosted Z' Search

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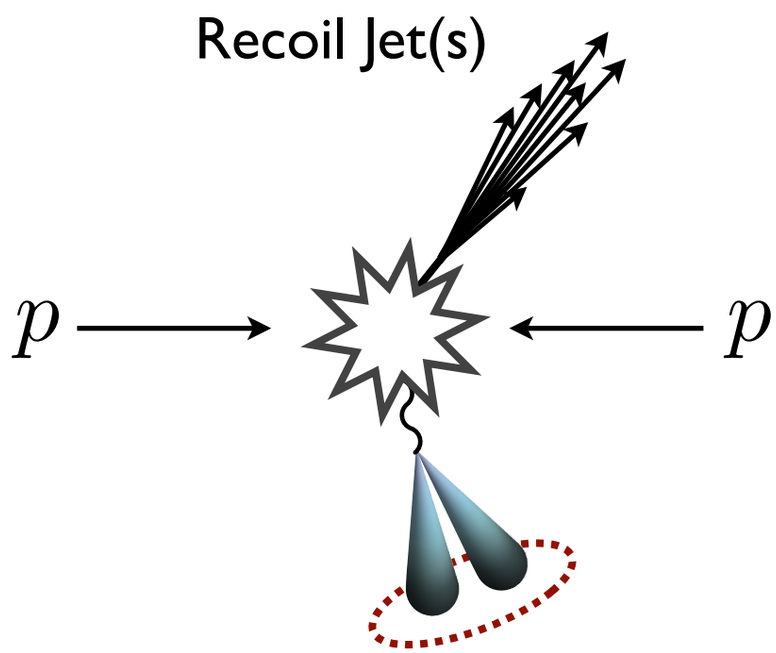

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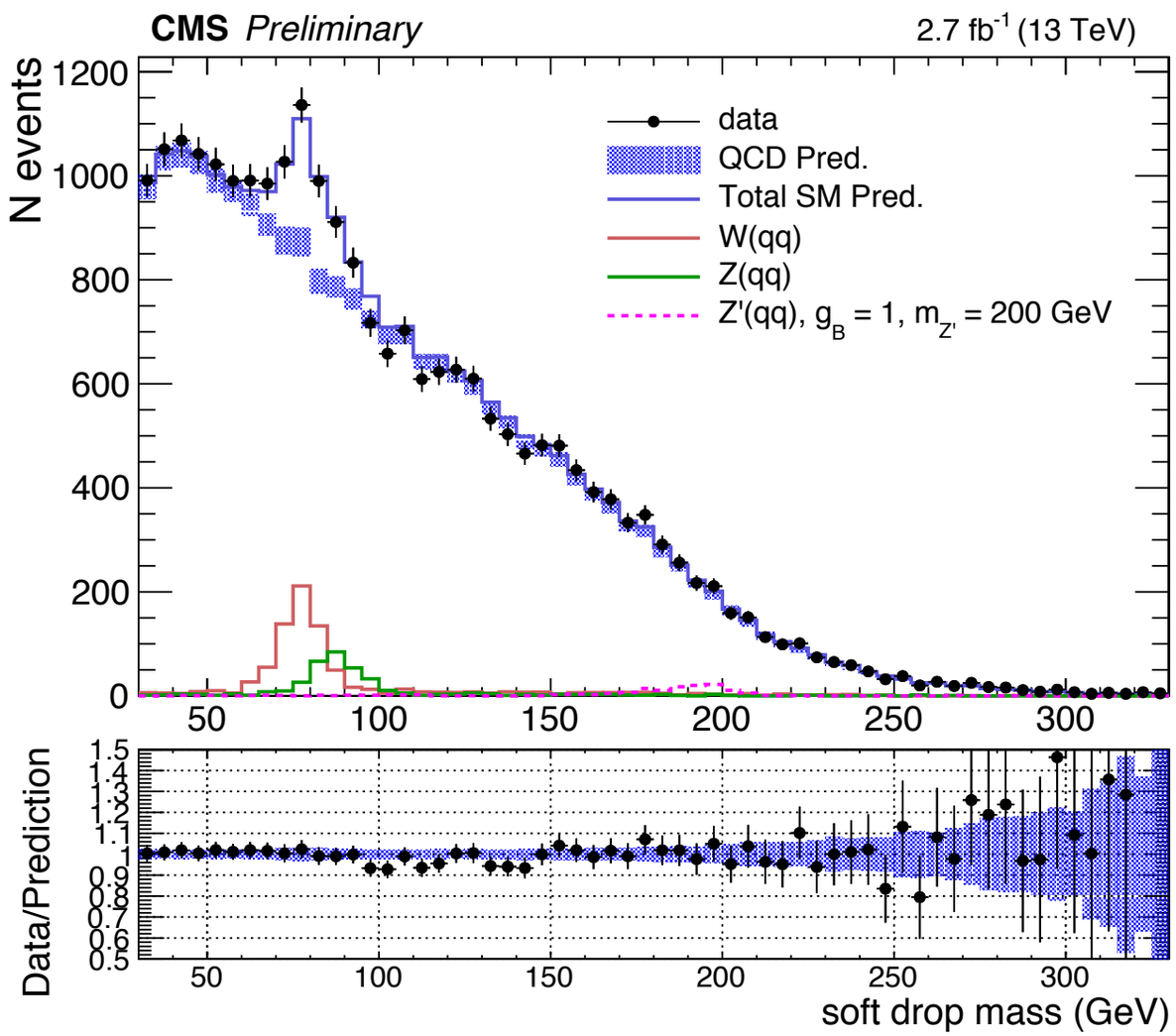
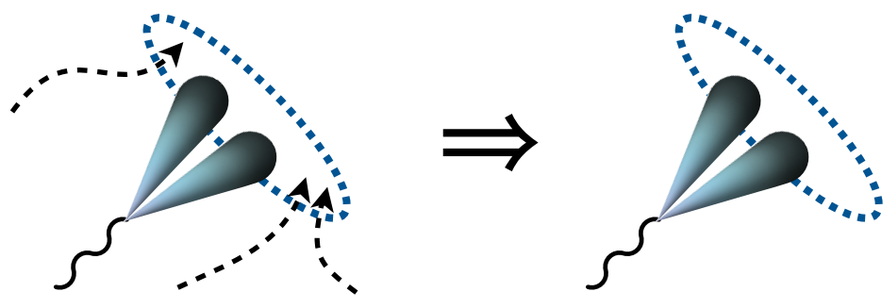


Discovered at SPS

Strongest bounds since SPS (!)

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

W/Z Tagging for Winter 2017

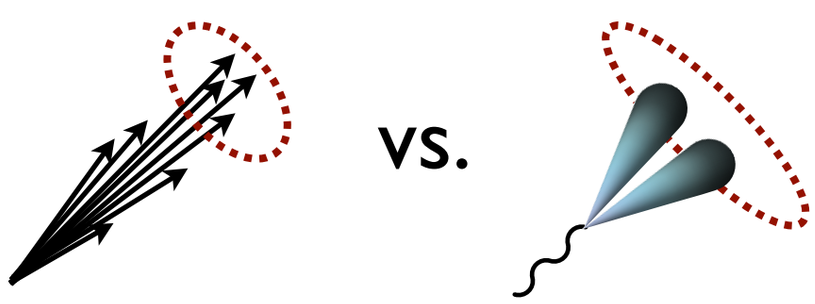


Soft Drop

[Larkoski, Marzani, Soyez, JDT, 2014;
see also Dasgupta, Fregoso, Marzani, Salam, 2013]

Trimming

[Krohn, JDT, Wang, 2009]



N-subjettiness

before grooming, after decorrelation

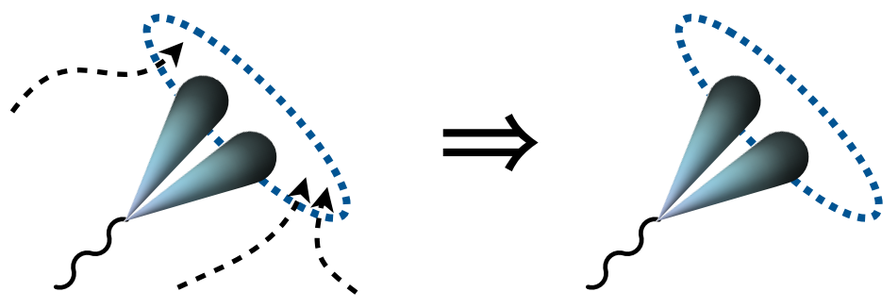
[JDT, Van Tilburg, 2010, 2011;
Dolen, Harris, Marzani, Rappoccio, Tran, 2016]

D_2

after grooming

[Larkoski, Moult, Neill, 2014;
based on Larkoski, Salam, JDT, 2013]

W/Z Tagging for Winter 2017



Soft Drop

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before grooming, after decorrelation

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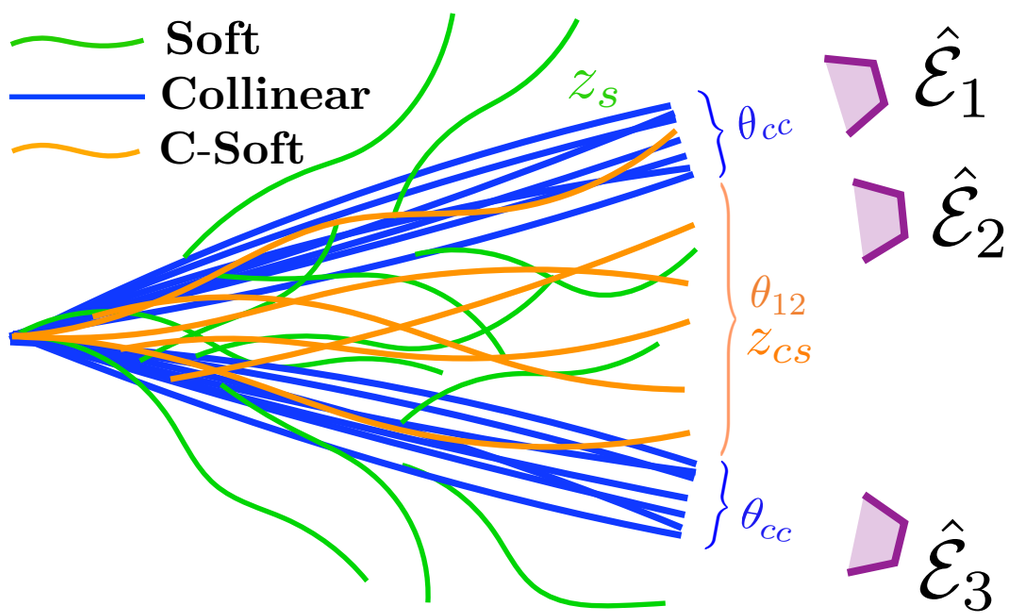
after grooming

[Larkoski, Moult, Neill, 2014;
based on Larkoski, Salam, JDT, 2013]

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

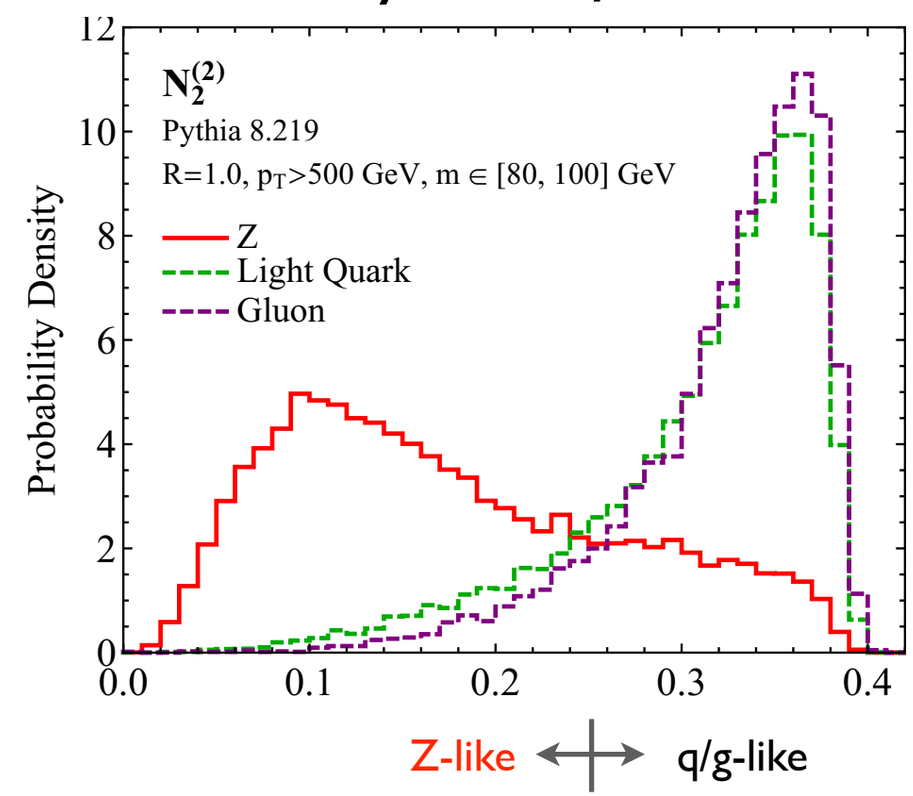
[Moult, Necib, JDT, 2016]

W/Z Tagging for Summer 2017?



$\Rightarrow$

Stability & Performance

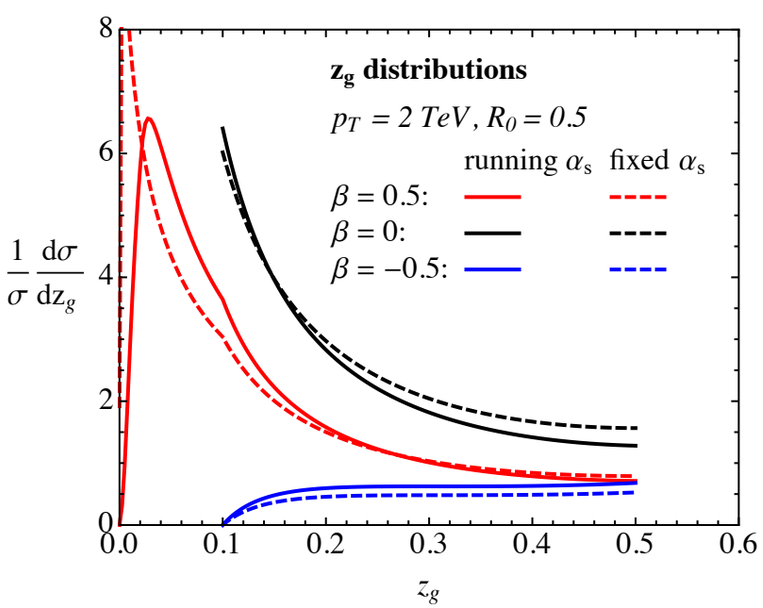


$$\boxed{N_2} = \frac{\sum_{i<j<k} p_{Ti}\, p_{Tj}\, p_{Tk} \min\left\{(R_{ij}R_{jk})^2, (R_{jk}R_{ki})^2, (R_{ki}R_{ij})^2\right\}}{\left(\sum_{i<j} p_{Ti}\, p_{Tj}\, R_{ij}^2\right)^2 \Big/ \sum_i p_{Ti}}$$

[Moult, Necib, JDT, 2016]

Jet Substructure

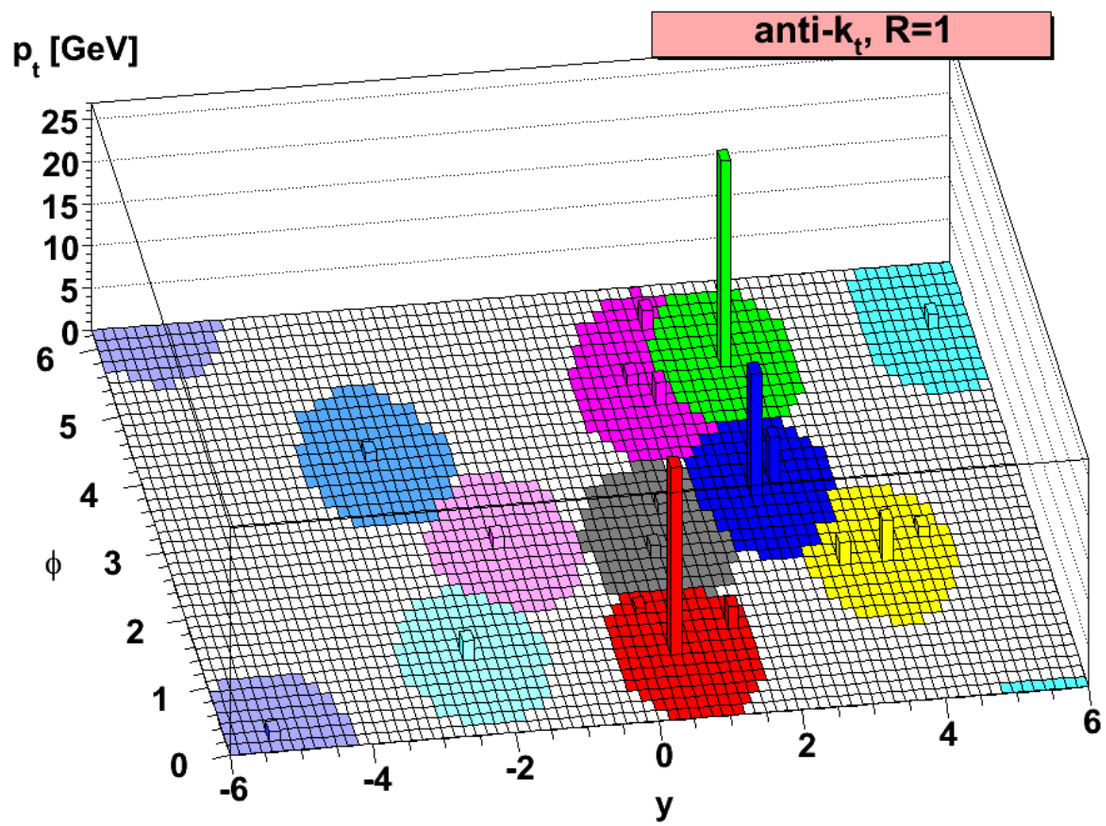
Boosting the Search for New Phenomena



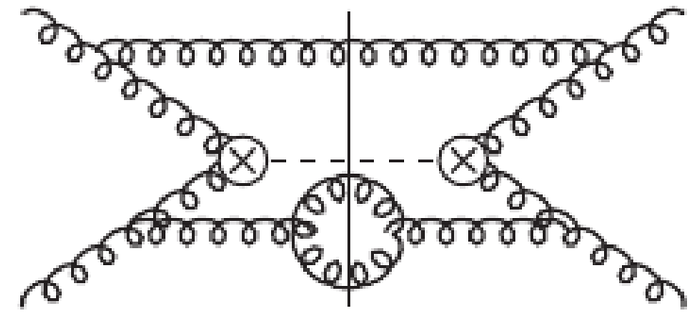
Pushing the Boundaries of Quantum Field Theory

QCD Renaissance

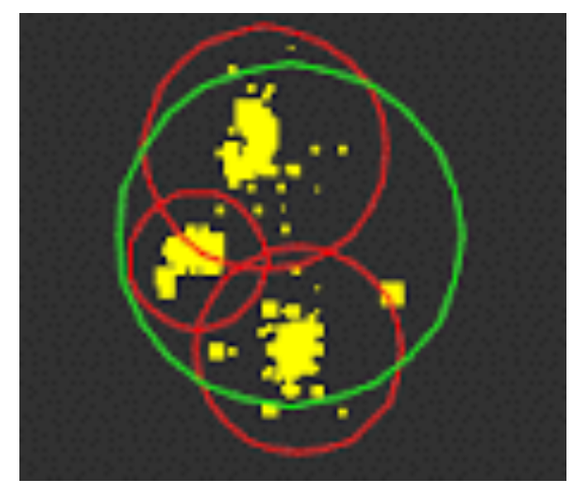
Theory c. 2008–present



New Jet Algorithms



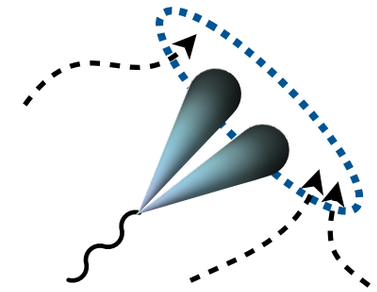
Loop/Leg/Log Explosion



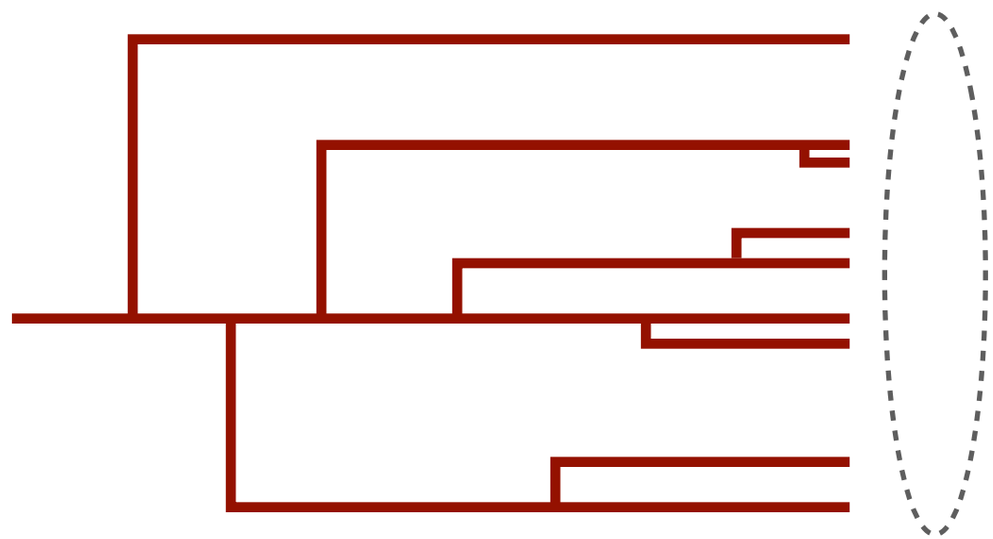
Jet Substructure

[Anti-k_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]

Soft Drop

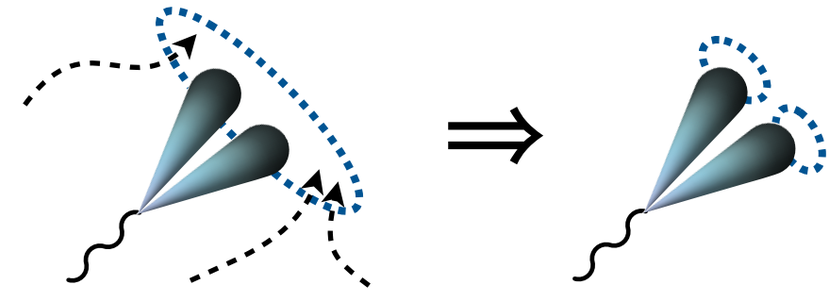


Clustering Tree

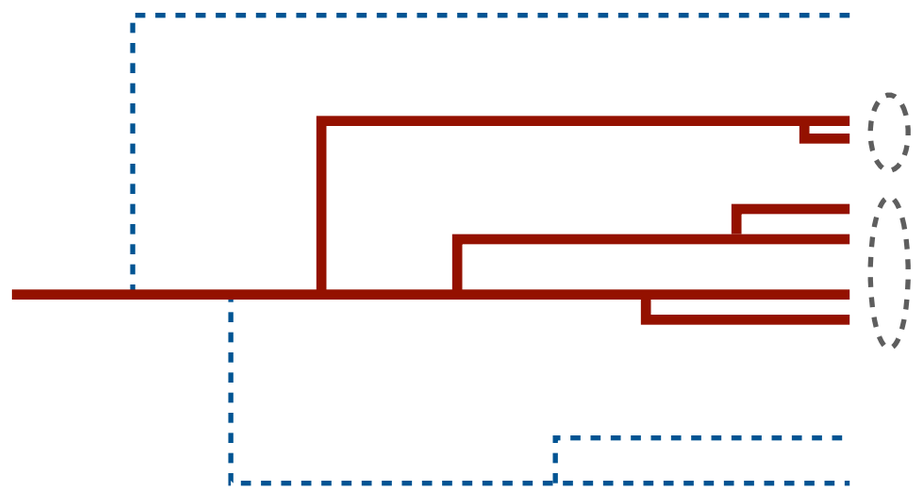


[Larkoski, Marzani, Soyez, JDT, 2014; see also Butterworth, Davison, Rubin, Salam, 2008; Dasgupta, Fregoso, Marzani, Salam/Powling, 2013]

Soft Drop



Groomed
Clustering Tree



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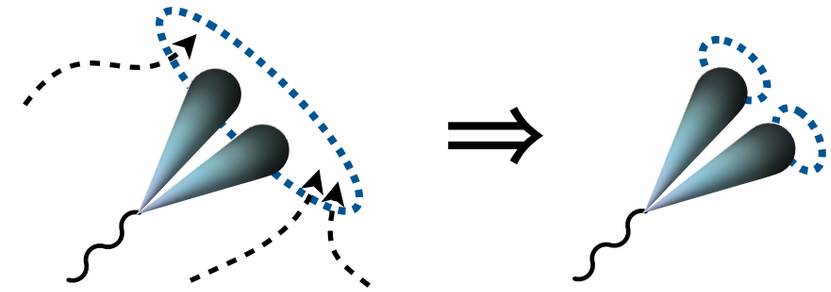
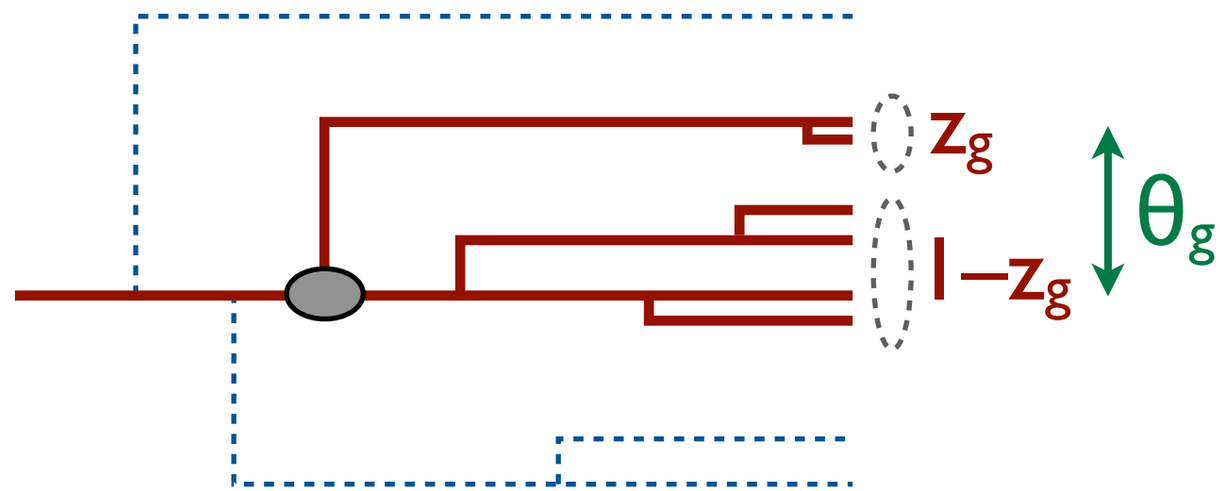


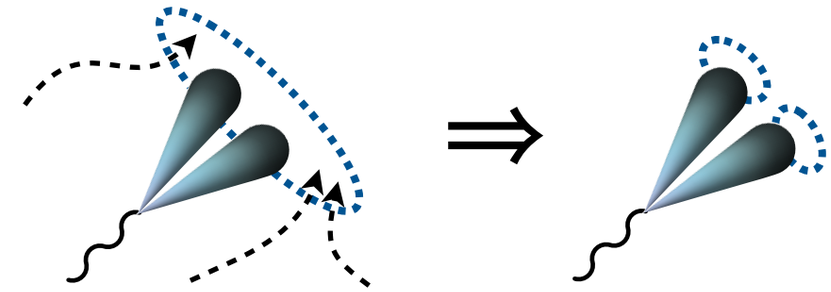
Groomed
Clustering Tree



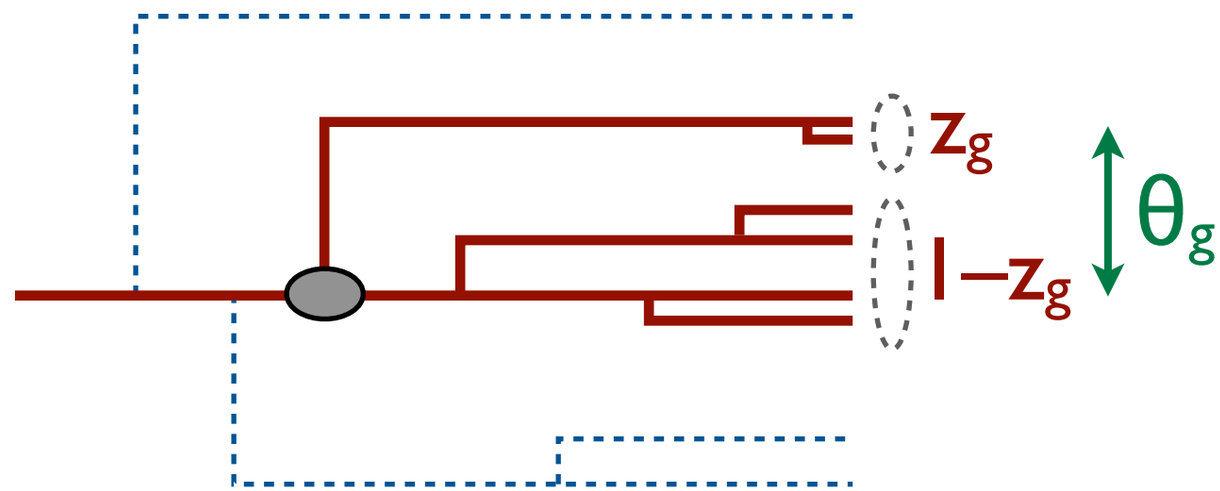
$$z_g > z_{cut}\,\theta_g^{\beta}$$

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

Soft Drop



Groomed
Clustering Tree

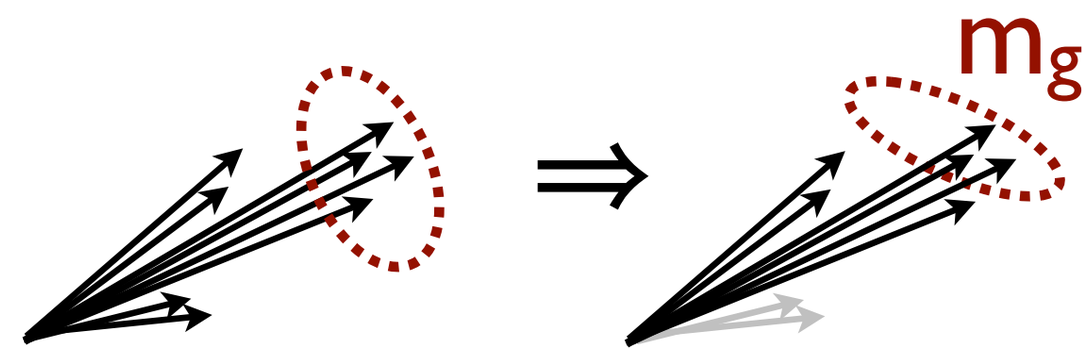


$$z_g > z_{cut}\,\theta_g^{\beta}$$

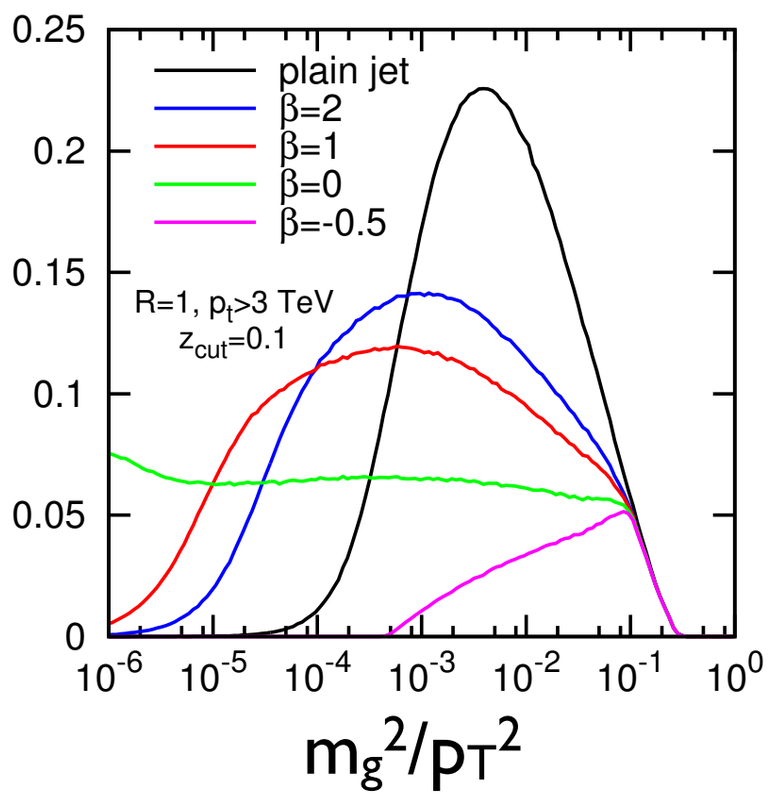
More Grooming — Less Grooming

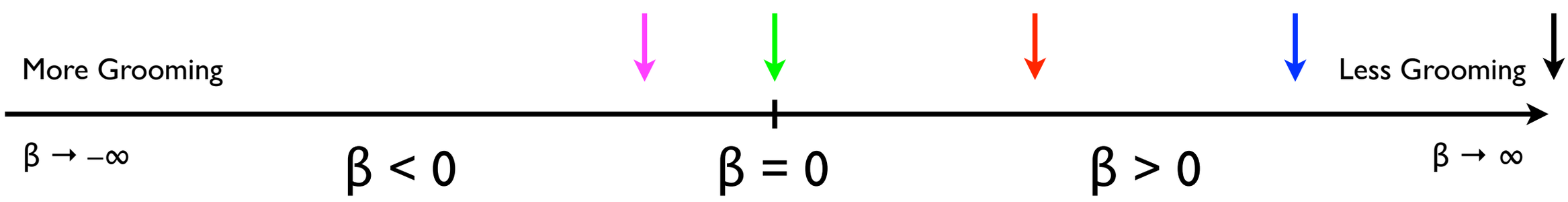
$\beta \to -\infty$ | $\beta < 0$ | $\beta = 0$ | $\beta > 0$ | $\beta \to \infty$

Calculating Mass?



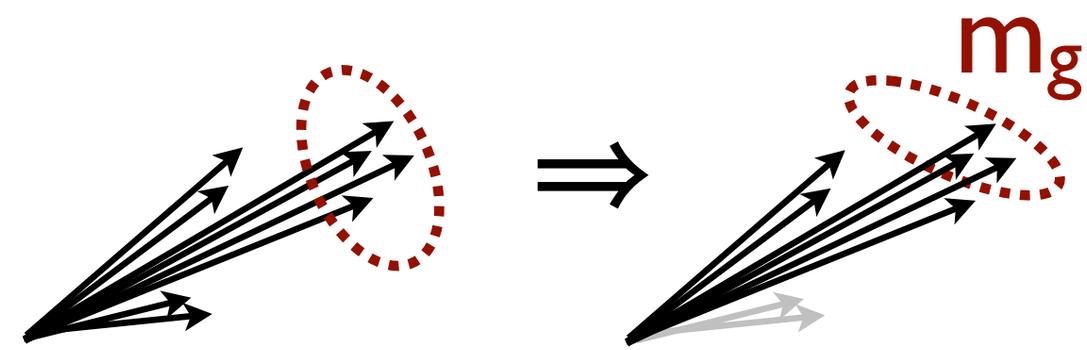
Simulated LHC Data



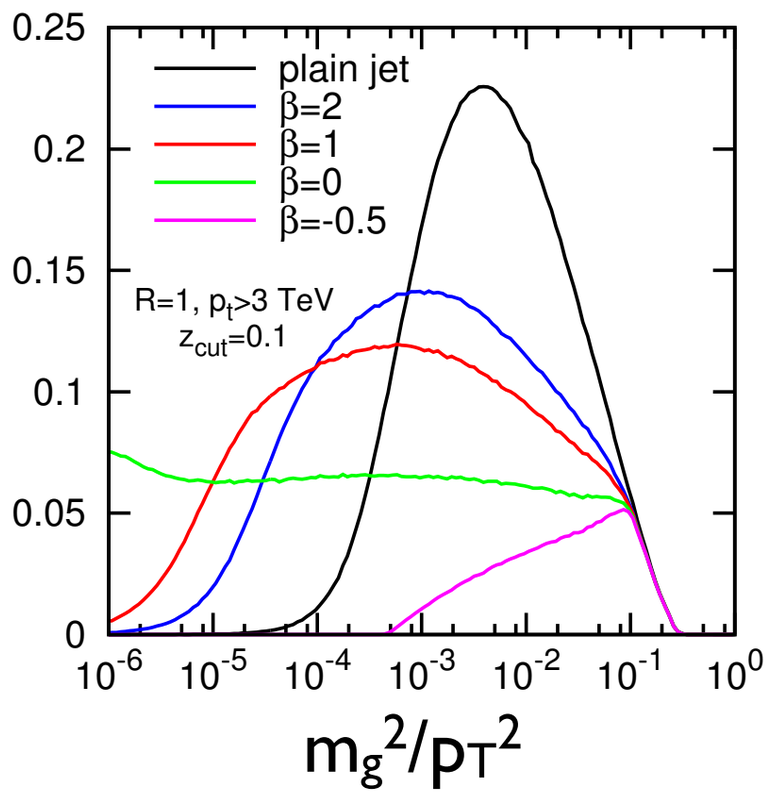


[Larkoski, Marzani, Soyez, JDT, 2014; see also Frye, Larkoski, Schwartz, Yan, 2016]

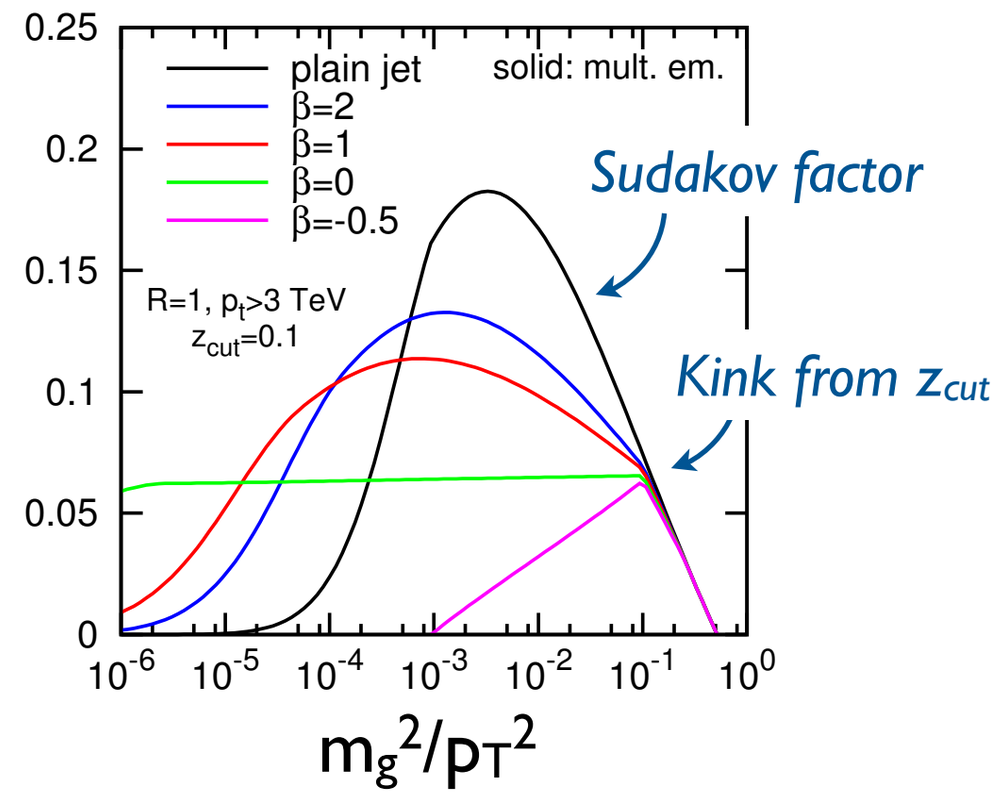
Calculating Mass?

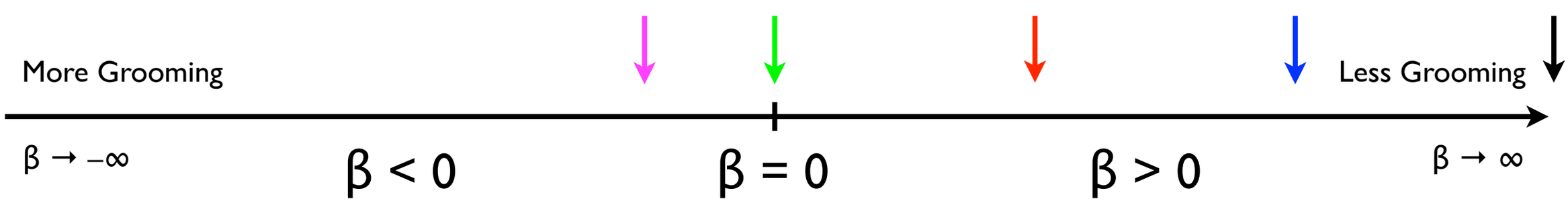


Simulated LHC Data



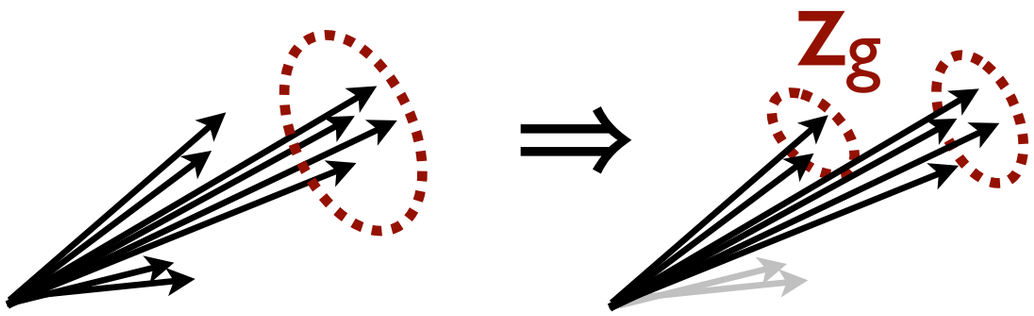
First-principles QCD



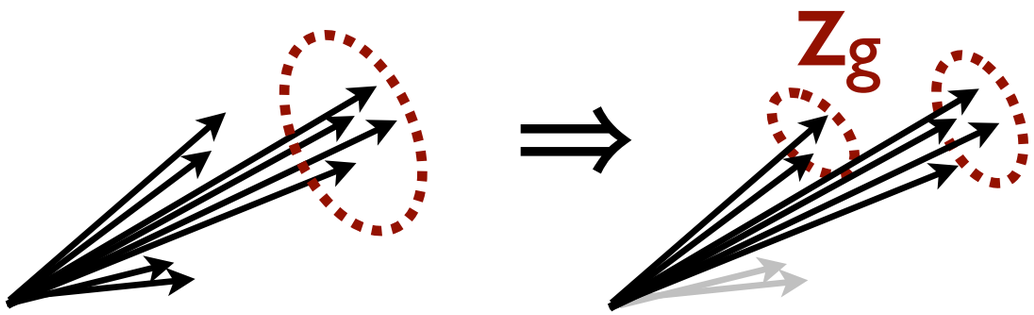


[Larkoski, Marzani, Soyez, JDT, 2014; see also Frye, Larkoski, Schwartz, Yan, 2016]

Calculating z_g?

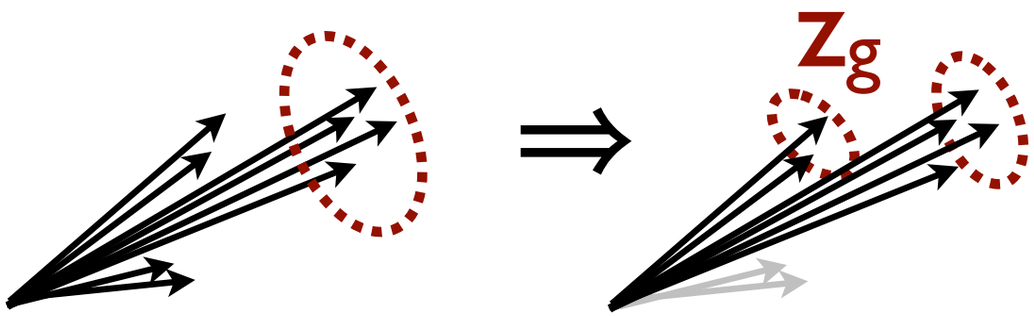


Calculating z_g?



$$p(z_g) = \Big(\qquad \Big) + \alpha_s \Big(\qquad \Big) + \alpha_s^2 \Big(\qquad \Big) + \ldots$$

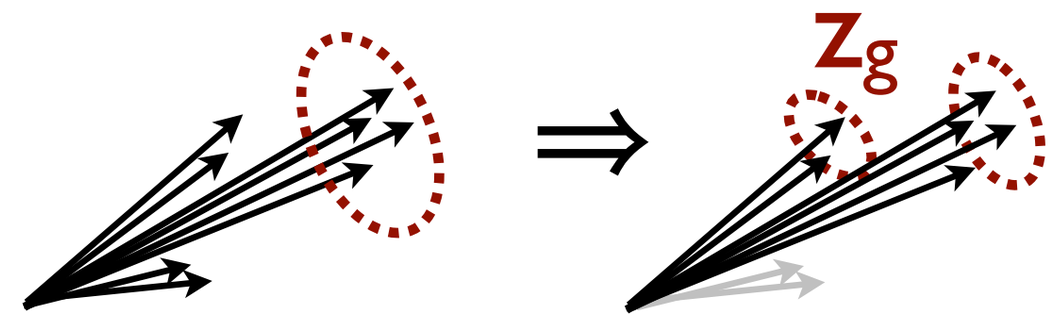
Calculating z_g?



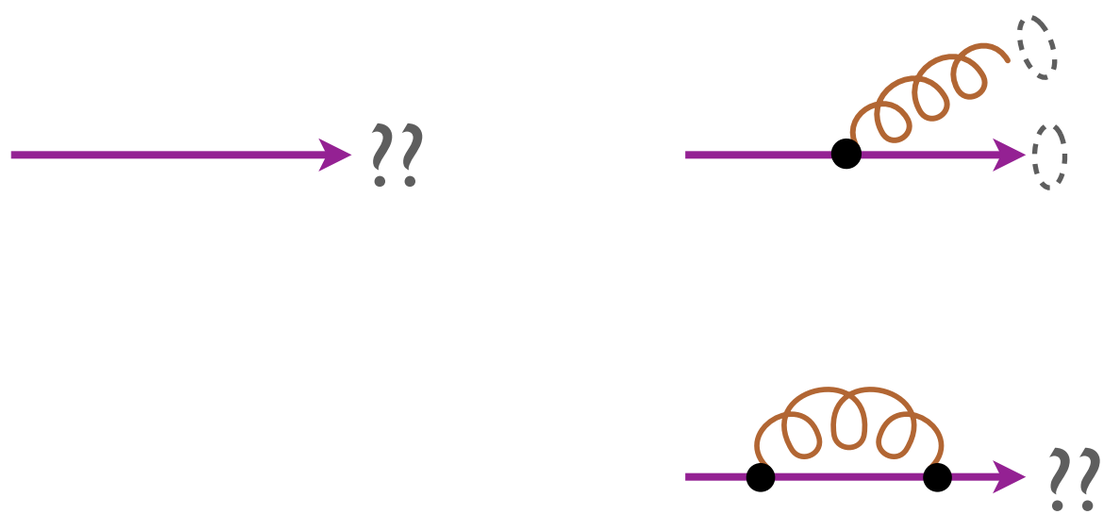
$$p(z_g) = \Big(\textit{undefined}\Big) + \alpha_s\Big(\qquad\qquad\Big) + \alpha_s^2\Big(\qquad\qquad\Big) + \ldots$$

$\longrightarrow$??

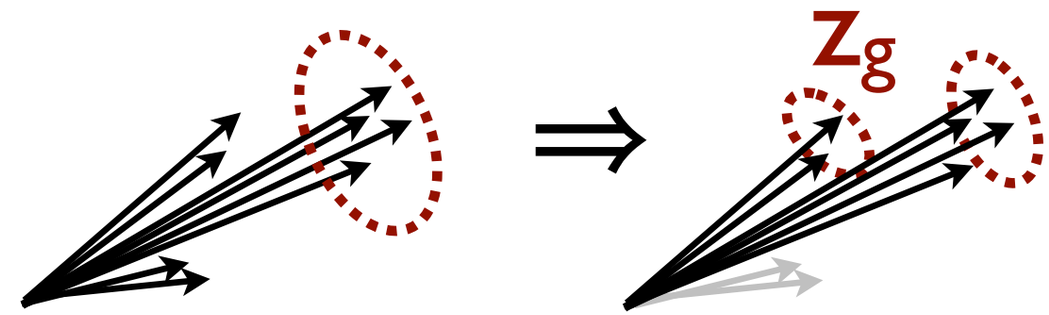
Calculating z_g?



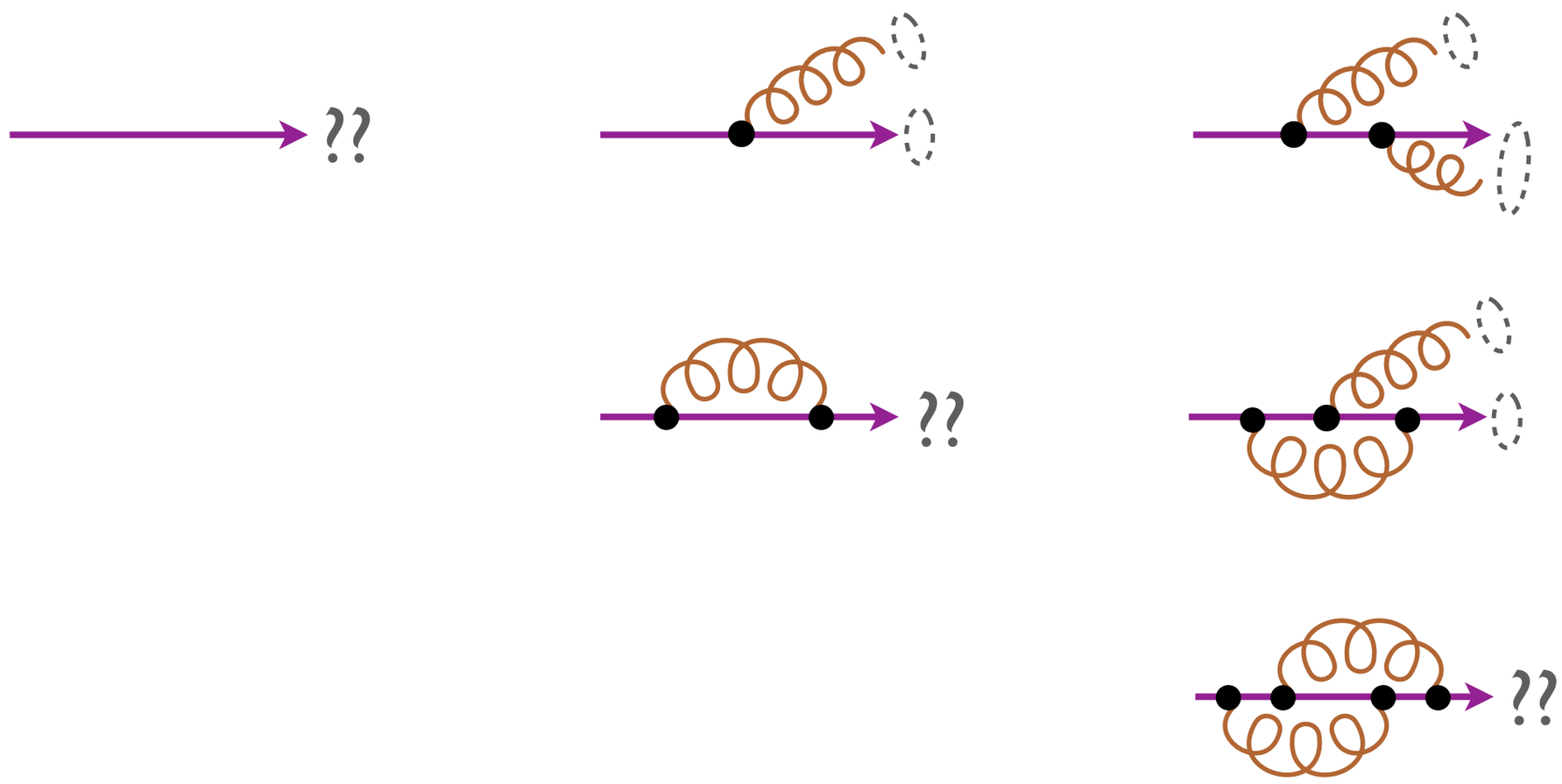
$$p(z_g) = \Big(\textit{undefined}\Big) + \alpha_s\Big(\textit{infinity}\Big) + \alpha_s^2\Big(\qquad\qquad\Big) + \ldots$$



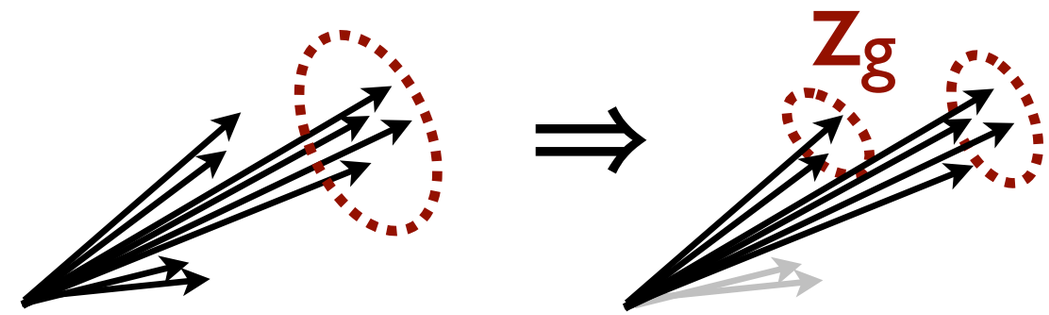
Calculating z_g?



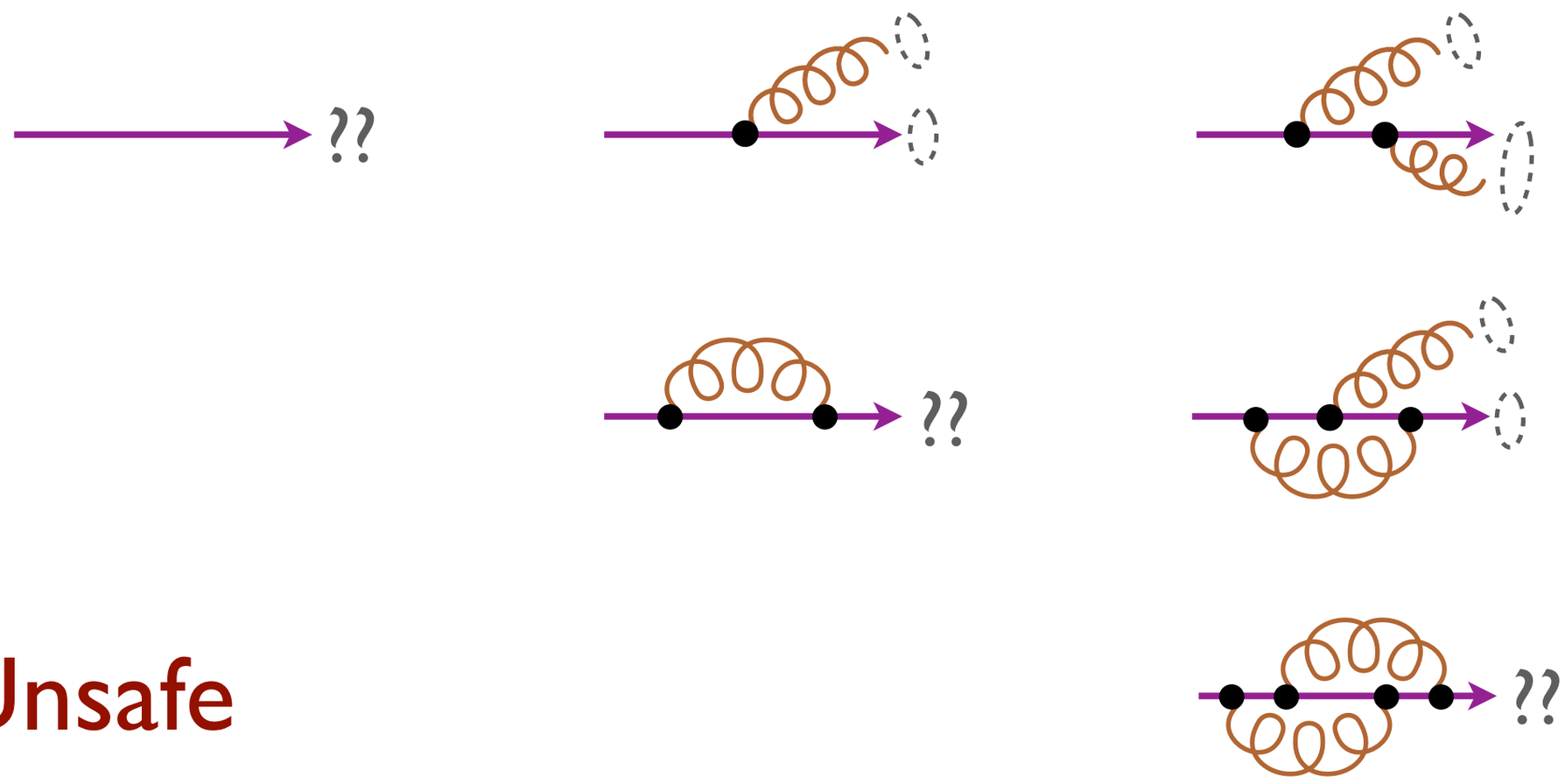
$$p(z_g) = \Big(\textit{undefined}\Big) + \alpha_s\Big(\textit{infinity}\Big) + \alpha_s^2\Big(\textit{infinity}^2\Big) + \ldots$$



Calculating z_g?

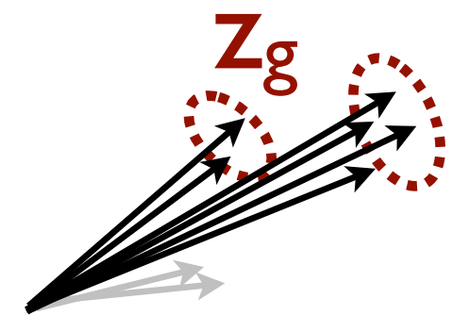


$$p(z_g) = \Big(\textit{undefined}\Big) + \alpha_s\Big(\textit{infinity}\Big) + \alpha_s^2\Big(\textit{infinity}^2\Big) + \ldots$$



z_g Unsafe

The Puzzle



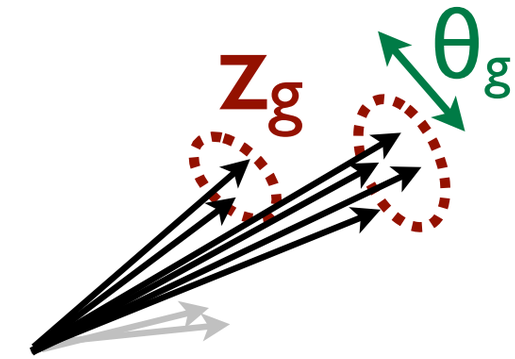
Unsafe

↓

$$p(z_g)$$

→ z_g ??

The Puzzle



Unsafe

↓

$$p(z_g)$$

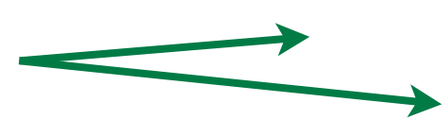
Calculable
order-by-order in α_s

↓

$$p(z_g|\theta_g)$$

z_g ??

vs.

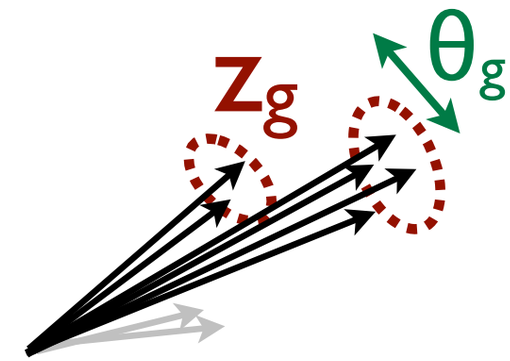


z_g

$1-z_g$

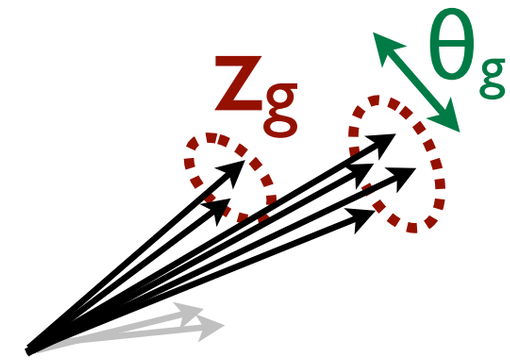
θ_g

The Puzzle



$$p(z_g) \overset{?!}{=} \int \mathrm{d}\theta_g \, p(\theta_g) \, p(z_g|\theta_g)$$

The Resolution



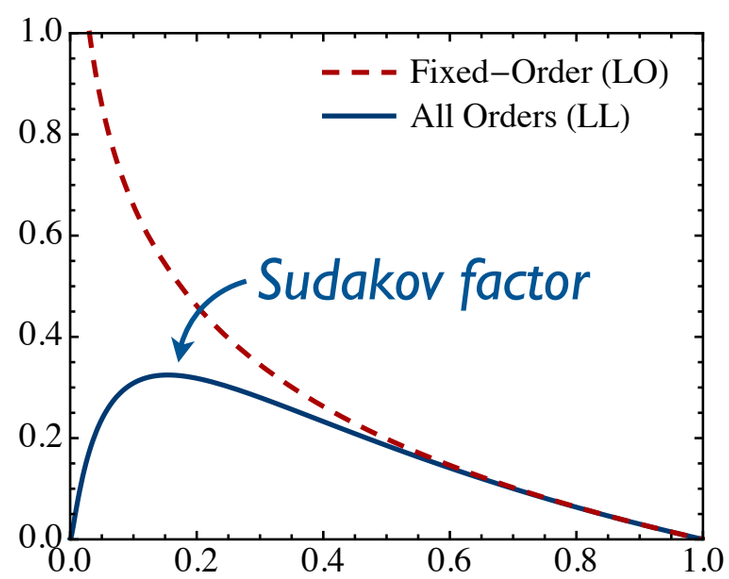
"Sudakov Safe"

Calculable order-by-order in α_s

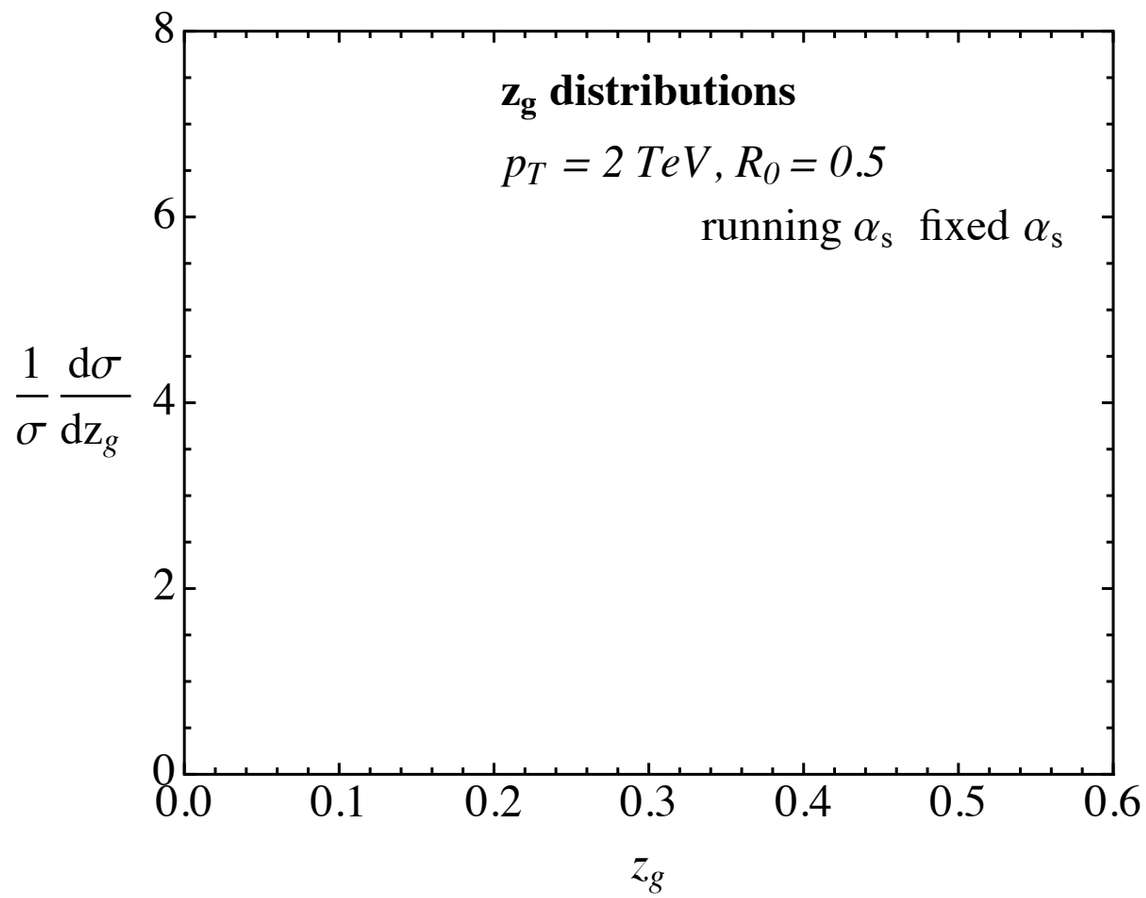
$$p(z_g) = \int \mathrm{d}\theta_g \, p(\theta_g) \, p(z_g|\theta_g)$$

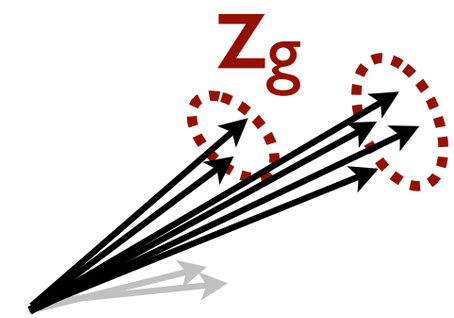
[Larkoski, JDT, 2013; Larkoski, Marzani, JDT, 2015]

Suppresses singularities at all orders in α_s



First-Principles QCD





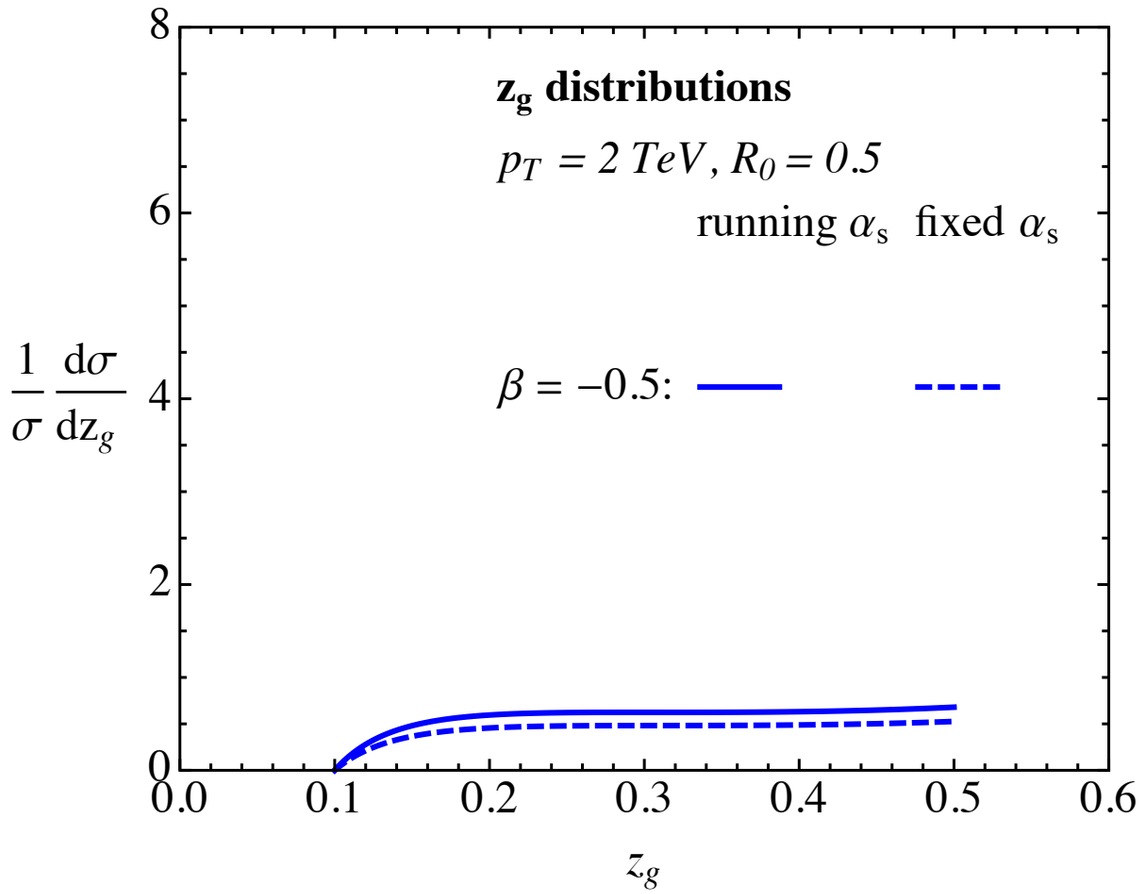
More Grooming

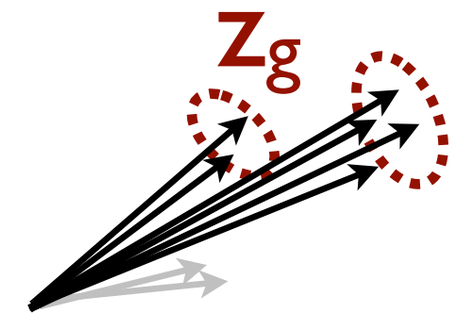
Less Grooming

$\beta \to -\infty$ $\quad$ $\beta < 0$ $\quad$ $\beta = 0$ $\quad$ $\beta > 0$ $\quad$ $\beta \to \infty$

[Larkoski, Marzani, JDT, 2015]

First-Principles QCD





$C_q = 4/3$
$C_g = 3$

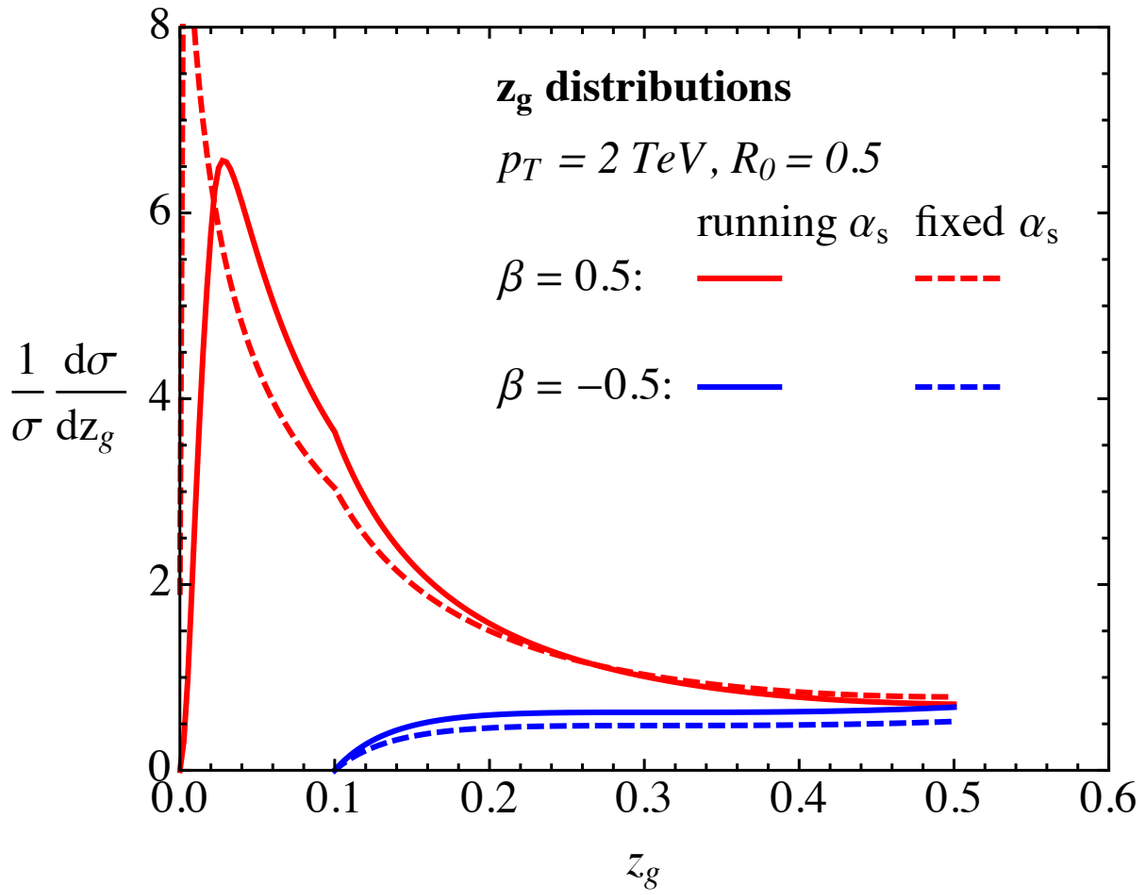
$$\simeq \frac{2\alpha_s C_i}{\pi|\beta|}\frac{1}{z_g}\log\frac{z_g}{z_{\rm cut}}$$

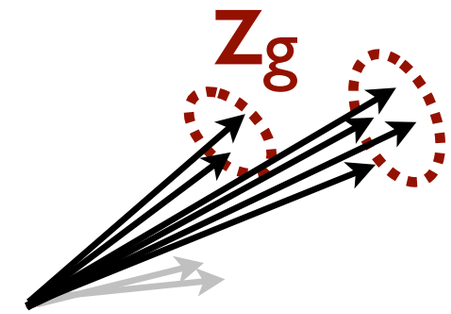
More Grooming — Less Grooming

$\beta \to -\infty$ — $\beta < 0$ — $\beta = 0$ — $\beta > 0$ — $\beta \to \infty$

[Larkoski, Marzani, JDT, 2015]

First-Principles QCD





$C_q = 4/3$
$C_g = 3$

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

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

Beyond traditional perturbation theory (Sudakov safe)

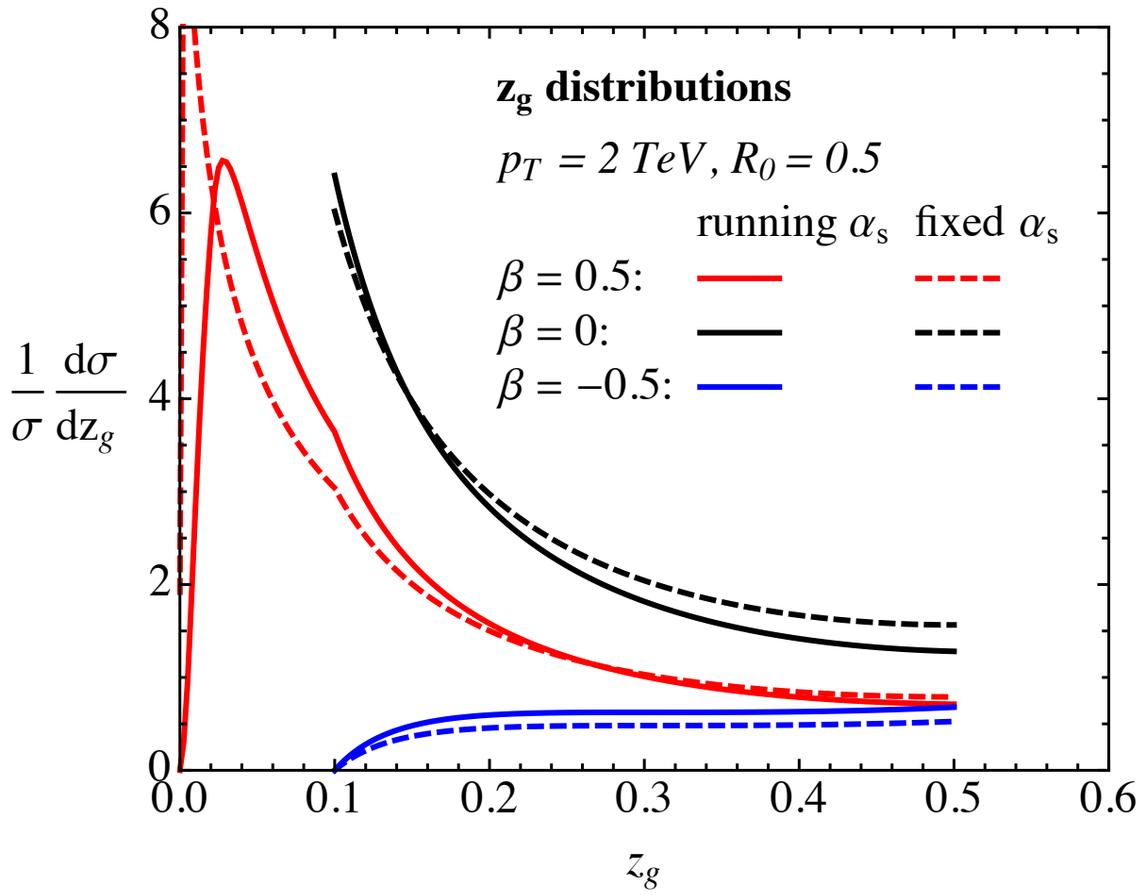
More Grooming

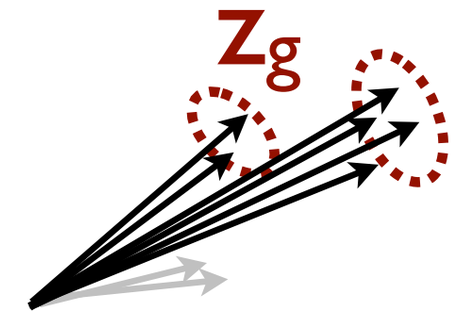
Less Grooming

$\beta \to -\infty$ $\quad$ $\beta < 0$ $\quad$ $\beta = 0$ $\quad$ $\beta > 0$ $\quad$ $\beta \to \infty$

[Larkoski, Marzani, JDT, 2015]

First-Principles QCD





$C_q = 4/3$
$C_g = 3$

$$\simeq \frac{2\alpha_s C_i}{\pi|\beta|}\frac{1}{z_g}\log\frac{z_g}{z_{\rm cut}} \qquad \simeq \frac{1}{z_g}\ (!) \qquad \simeq \sqrt{\frac{\alpha_s C_i}{\beta}}\frac{1}{z_g}$$

Beyond traditional perturbation theory (Sudakov safe)

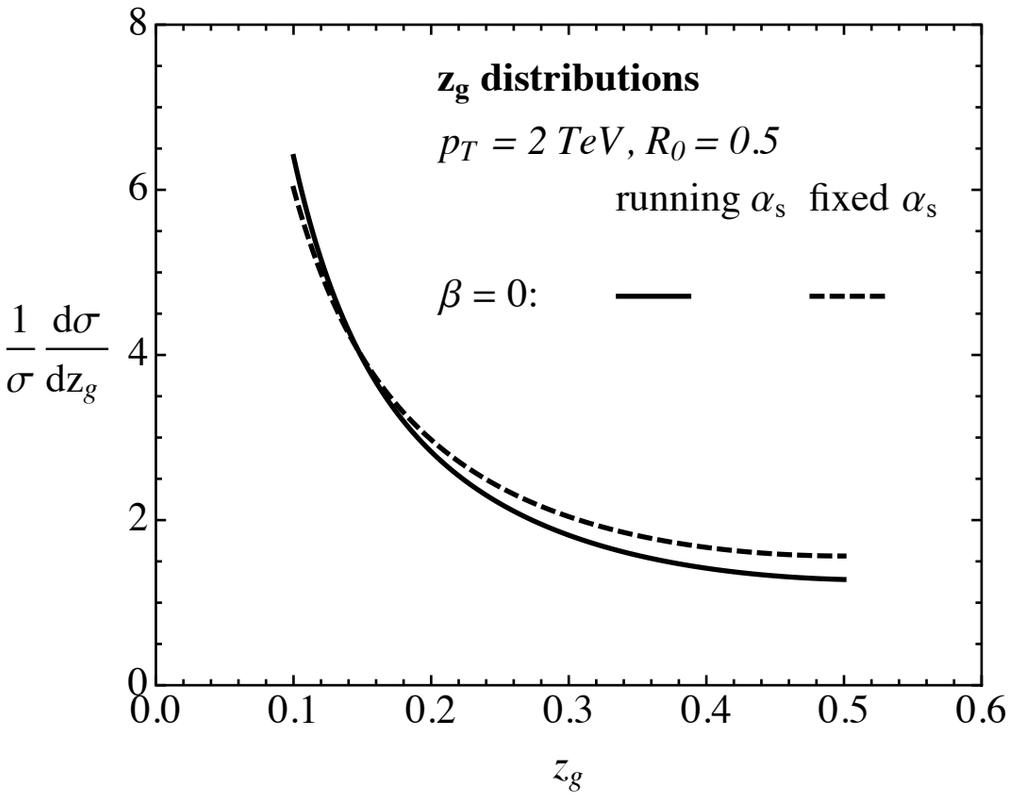
More Grooming

Less Grooming

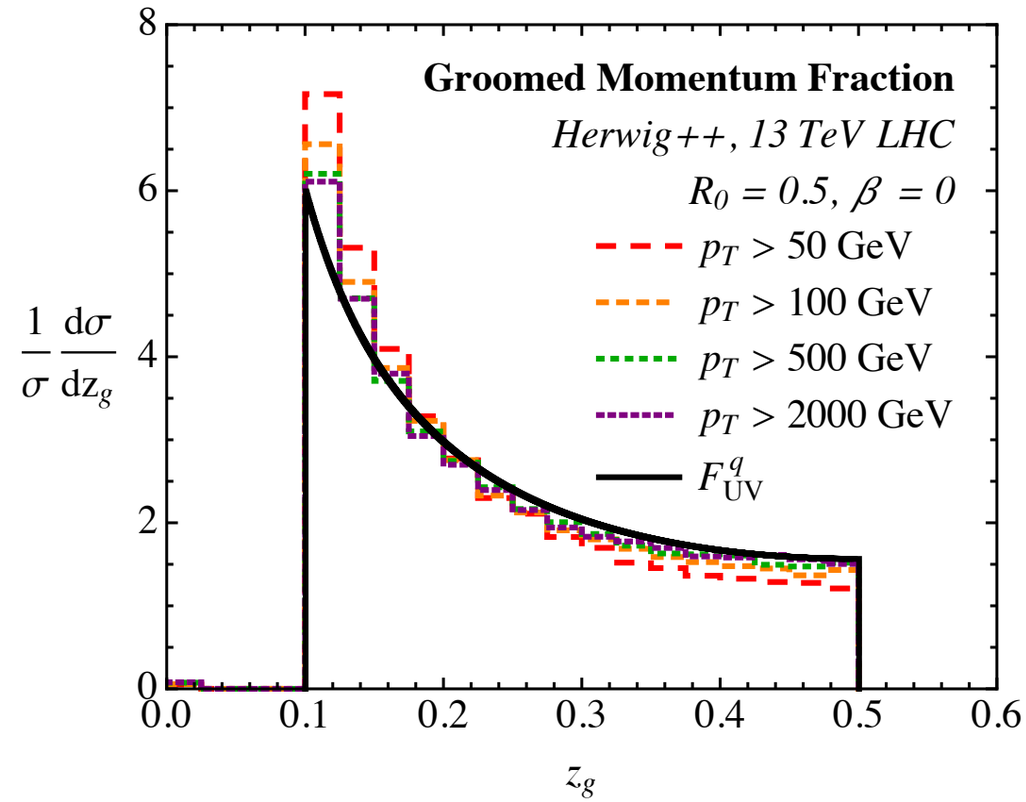
$\beta \to -\infty$ $\quad$ $\beta < 0$ $\quad$ $\beta = 0$ $\quad$ $\beta > 0$ $\quad$ $\beta \to \infty$

[Larkoski, Marzani, JDT, 2015]

Unsafe but Calculable



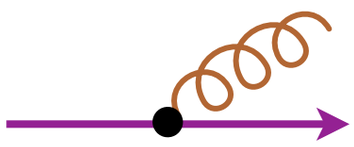
Simulated LHC Data



"Standard Candle" for Jets in QCD: $\simeq \dfrac{1}{z_g}$

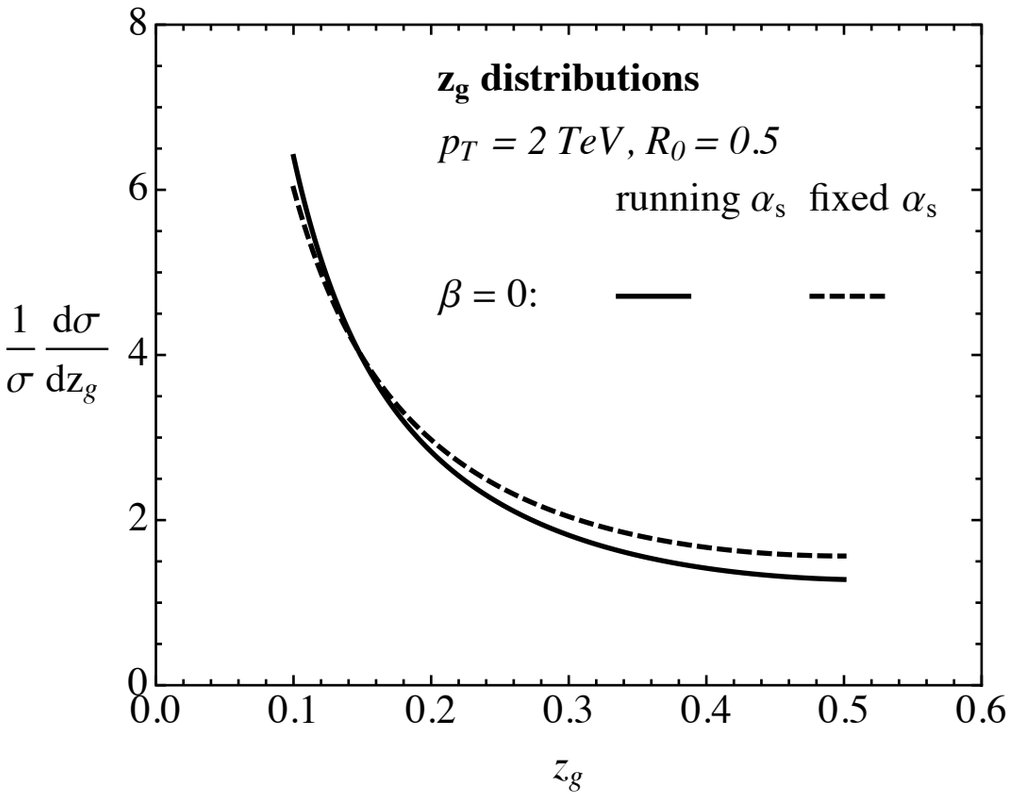
$$\updownarrow$$

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

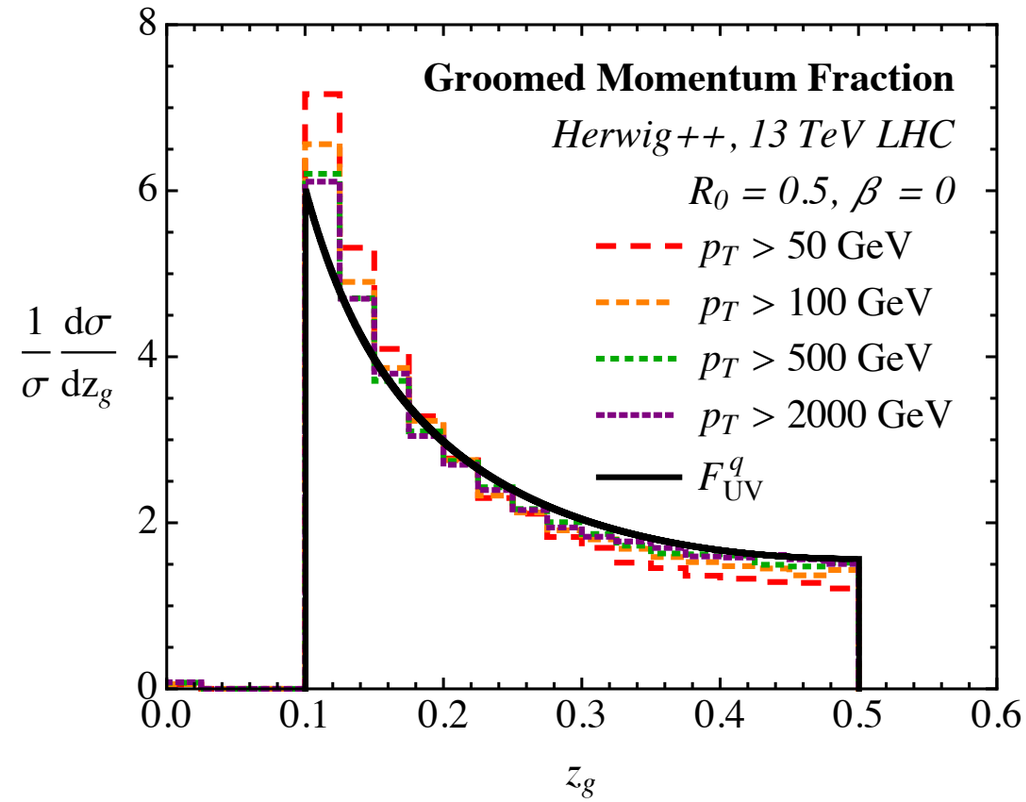


[Larkoski, Marzani, JDT, 2015]

Unsafe but Calculable

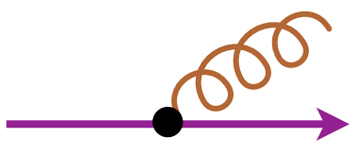


Simulated LHC Data



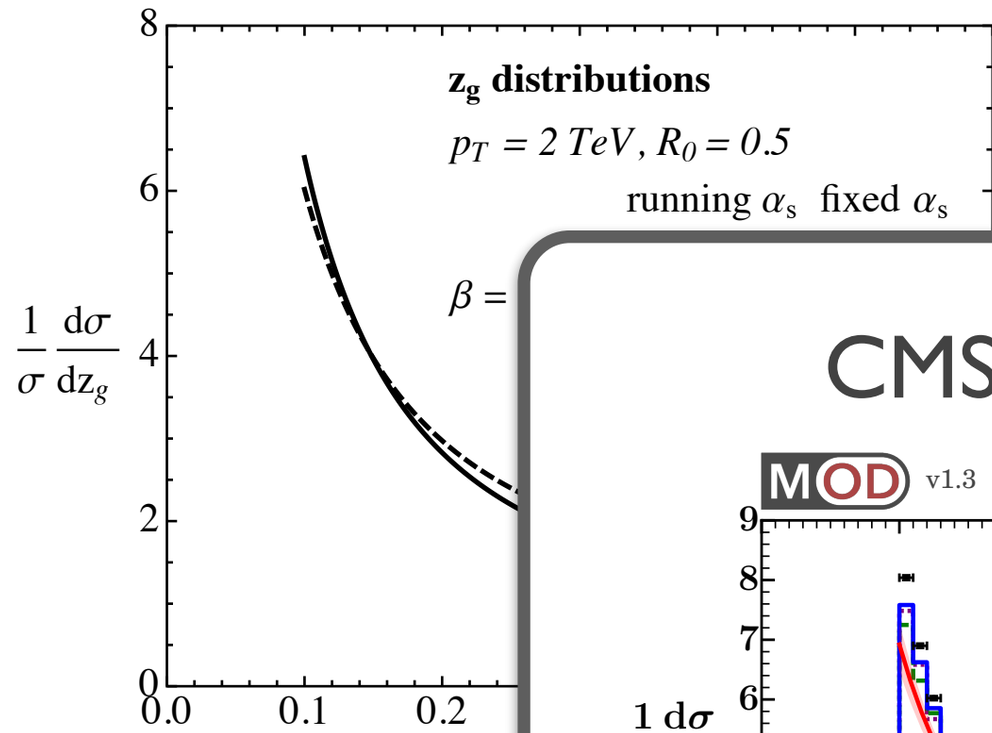
"Standard Candle" for Jets in QCD: $\simeq \dfrac{1}{z_g}$

$$\mathrm{d}P_{i\to ig} \simeq \frac{2\alpha_s}{\pi} C_i \frac{\mathrm{d}\theta}{\theta}\frac{\mathrm{d}z}{z}$$

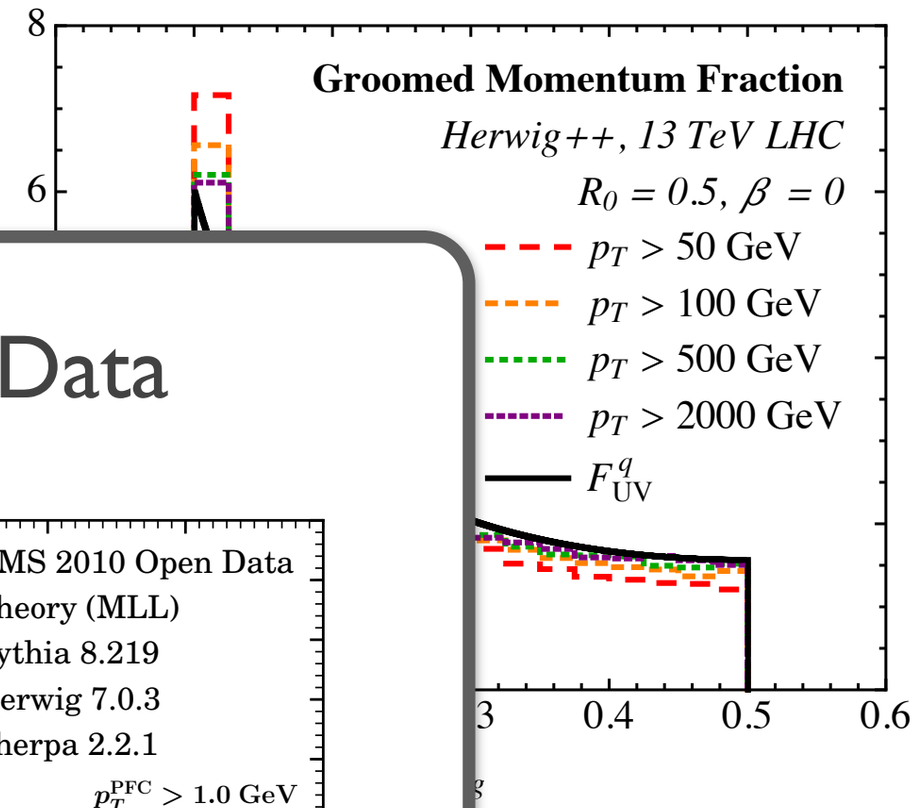


[Larkoski, Marzani, JDT, 2015]

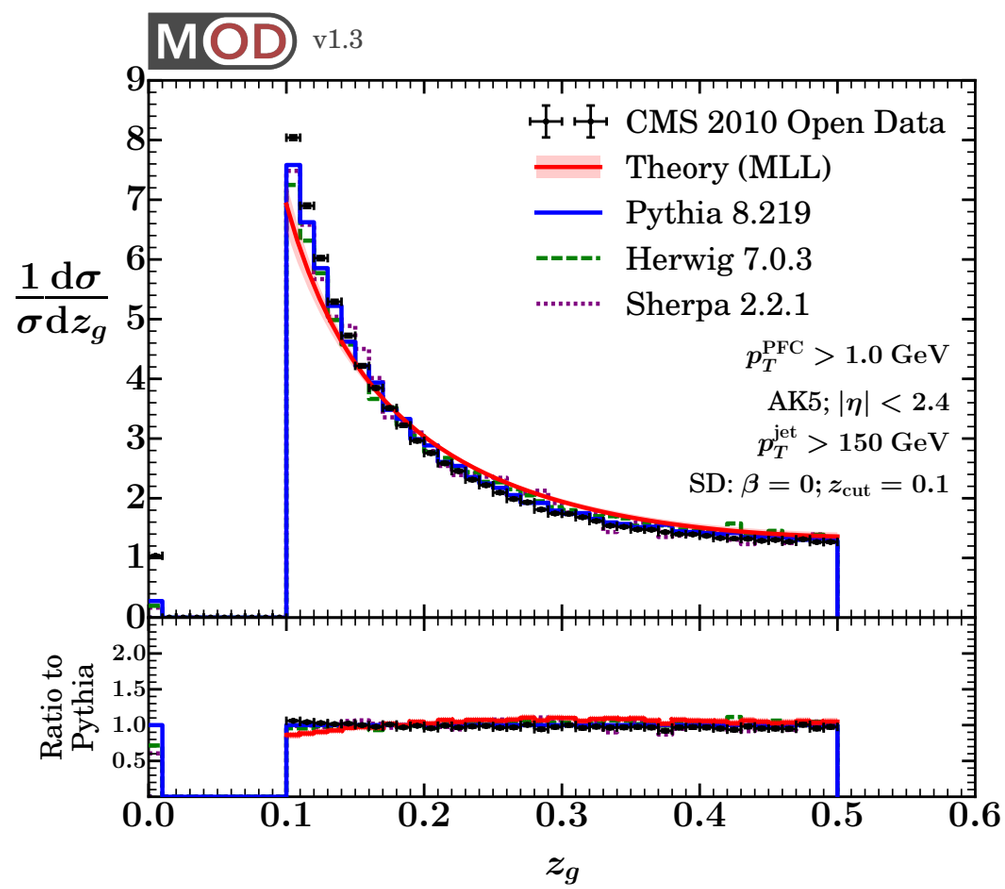
Unsafe but Calculable



Simulated LHC Data



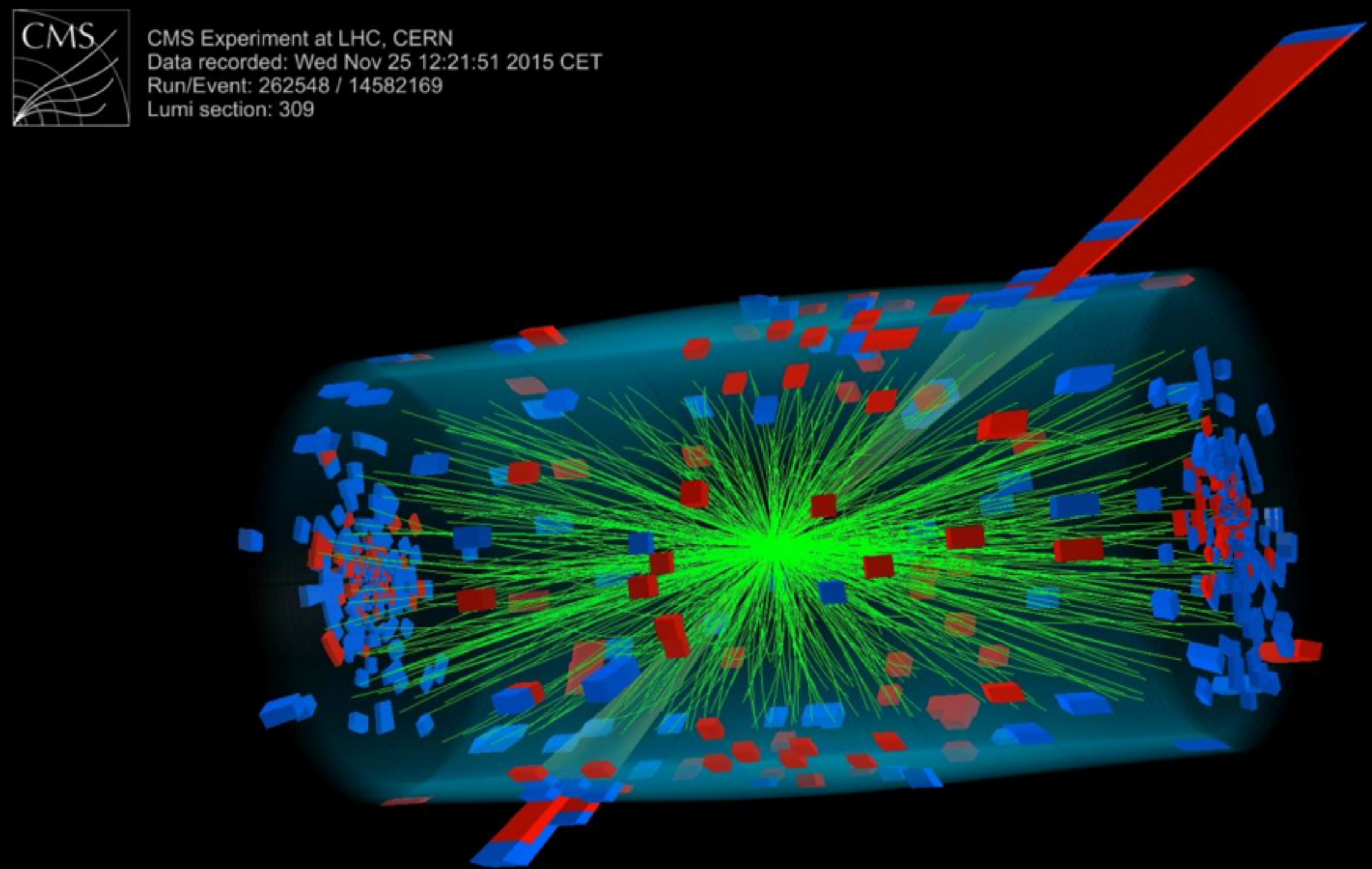
CMS Open Data



[Tripathee, Xue, Larkoski, Marzani, JDT, in progress]

"St
f

[Larkoski, Marzani, JDT, 2015]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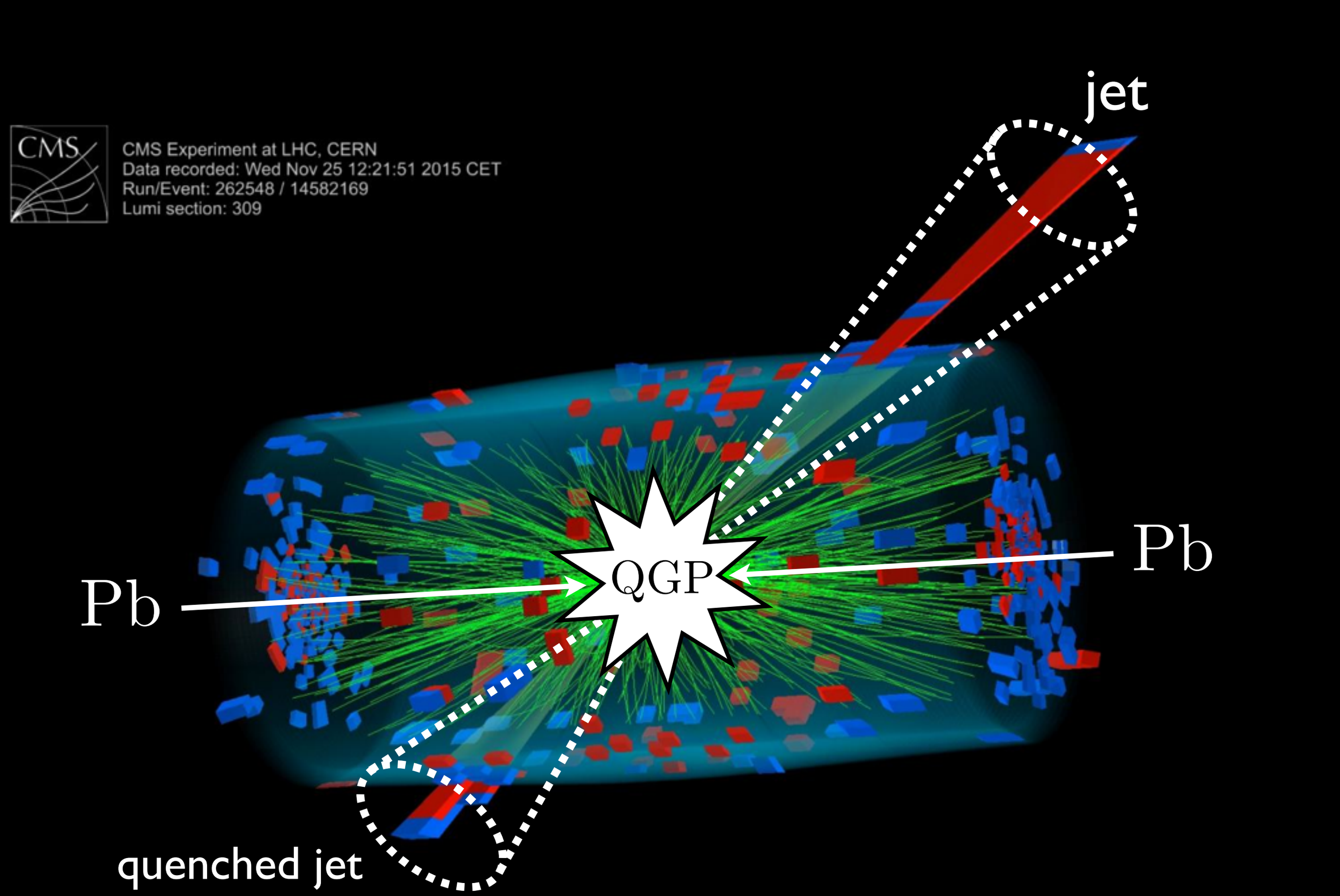
CMS Experiment at LHC, CERN
Data recorded: Wed Nov 25 12:21:51 2015 CET
Run/Event: 262548 / 14582169
Lumi section: 309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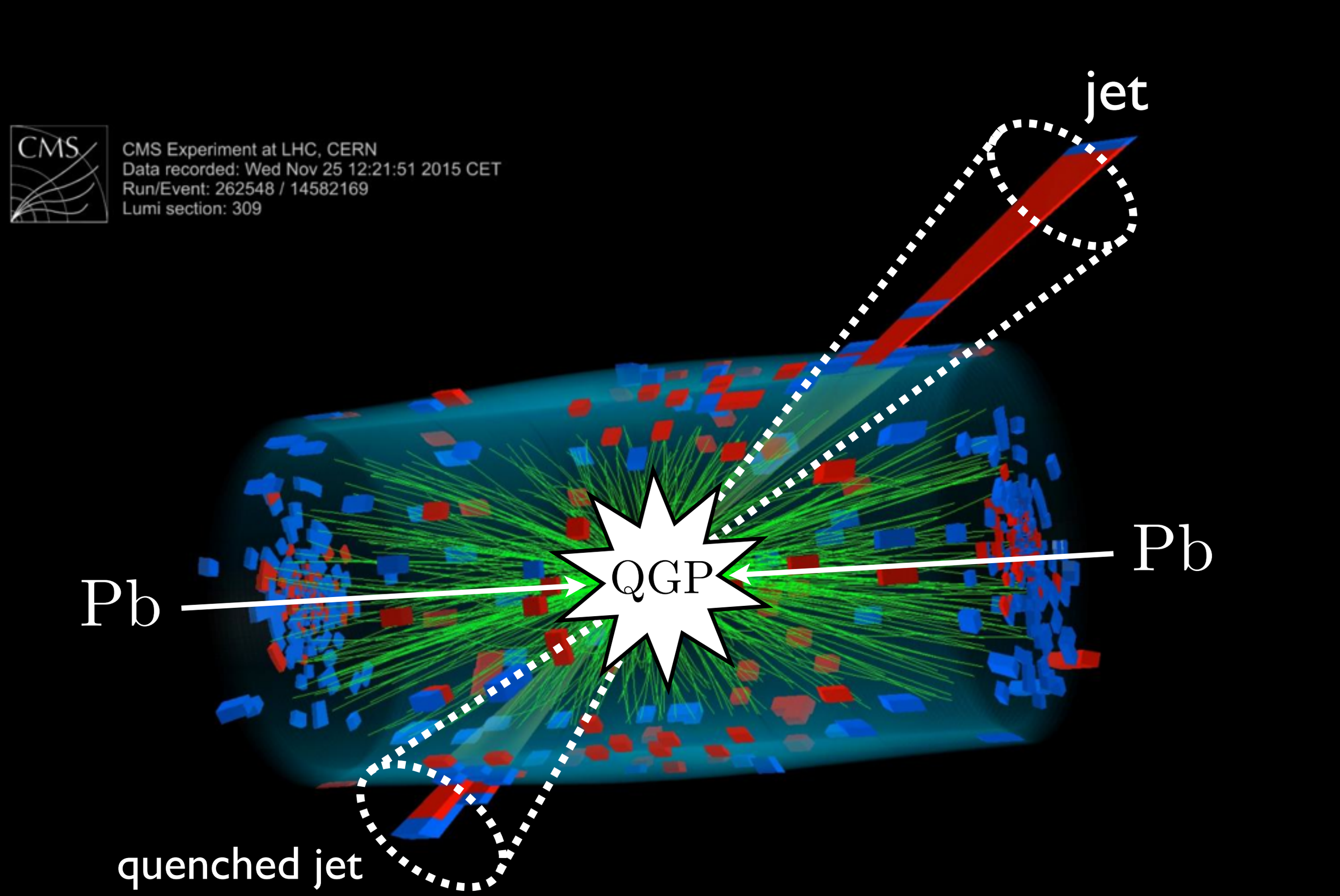
Run/Event: 262548 / 14582169
Lumi section: 309
jet
Pb
QGP
Pb
quenched jet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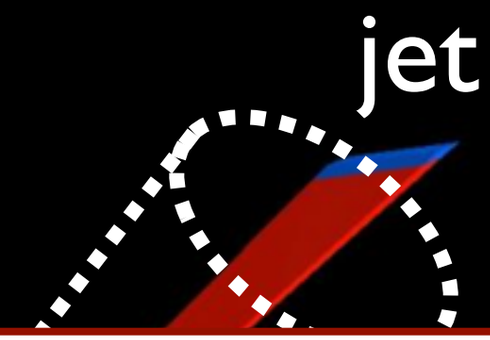
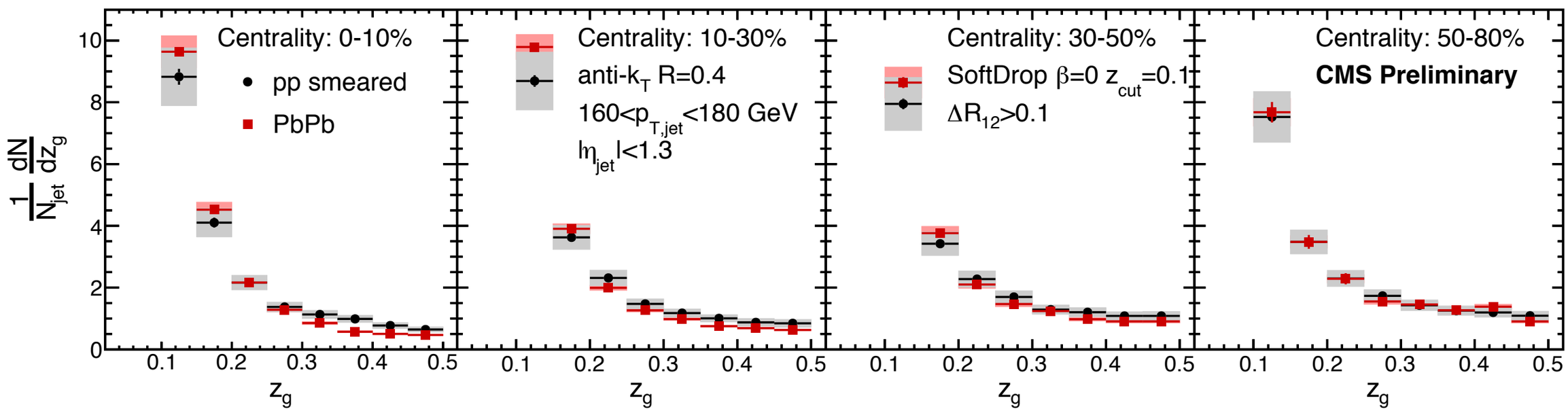
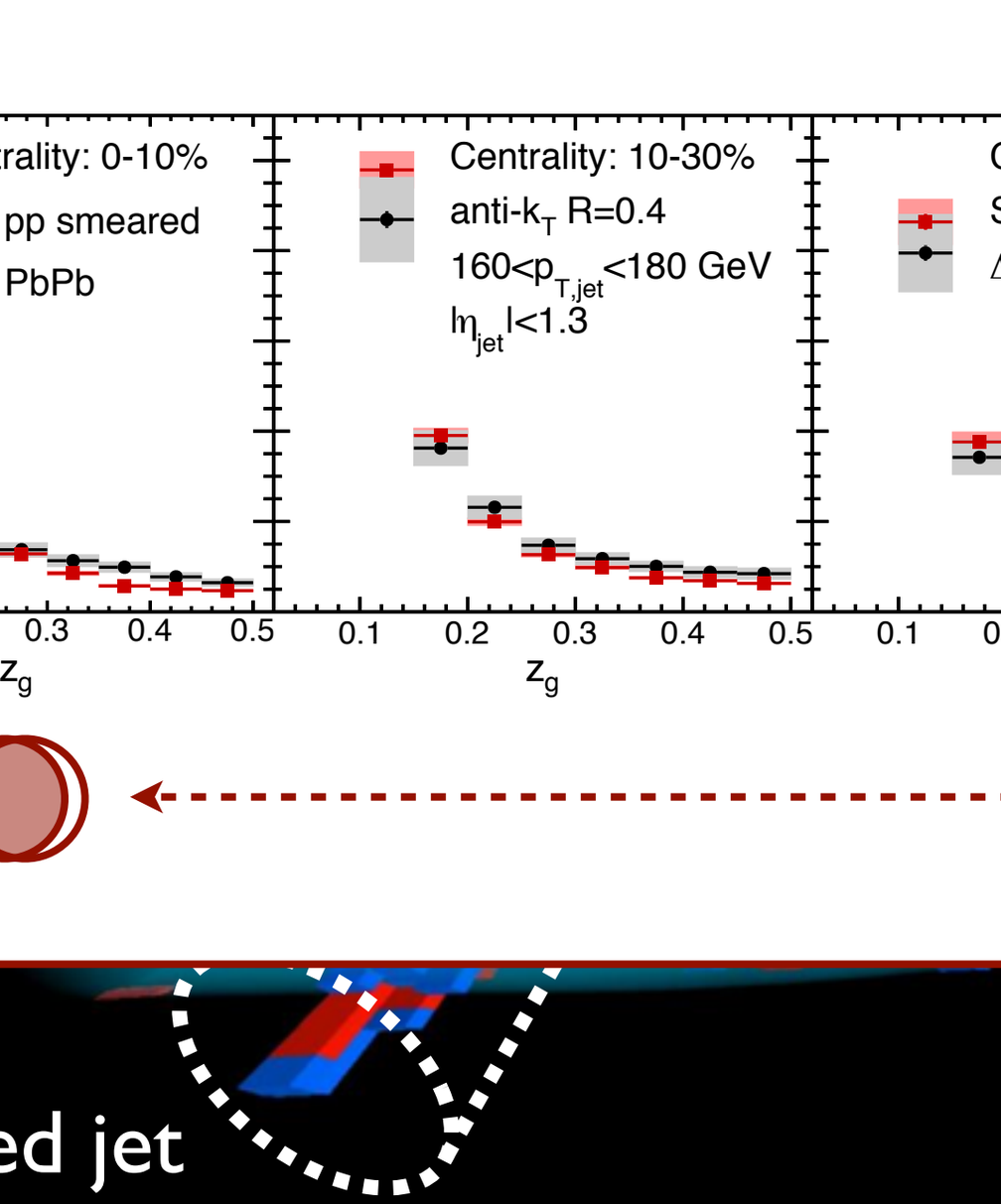
Run/Event: 262548 / 14582169
Lumi section: 309

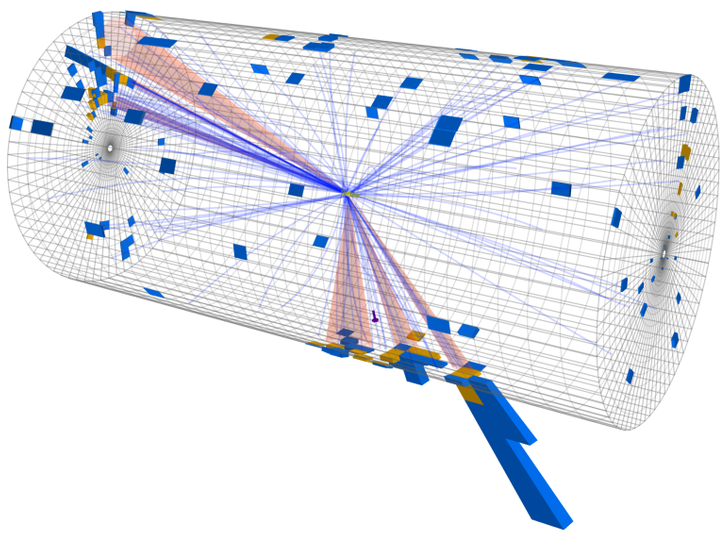


[CMS, 2016; using Larkoski, Marzani, JDT, 2015]



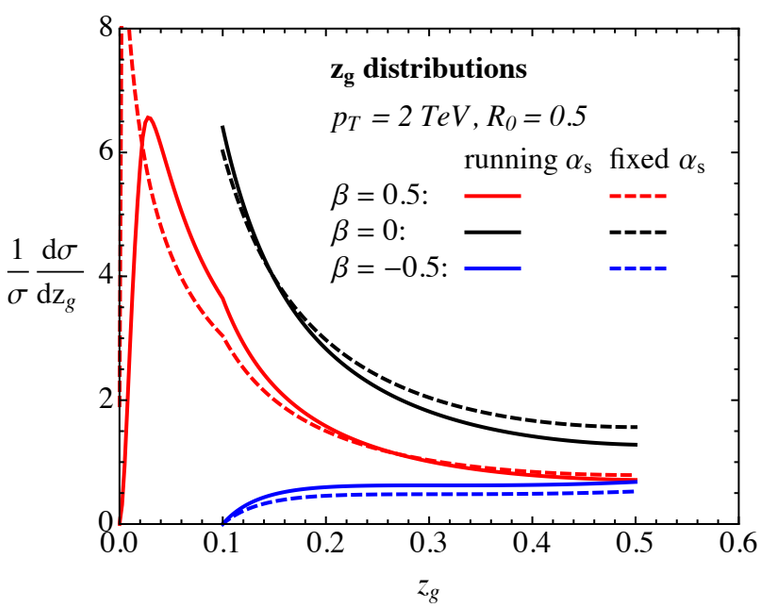


Jet Substructure



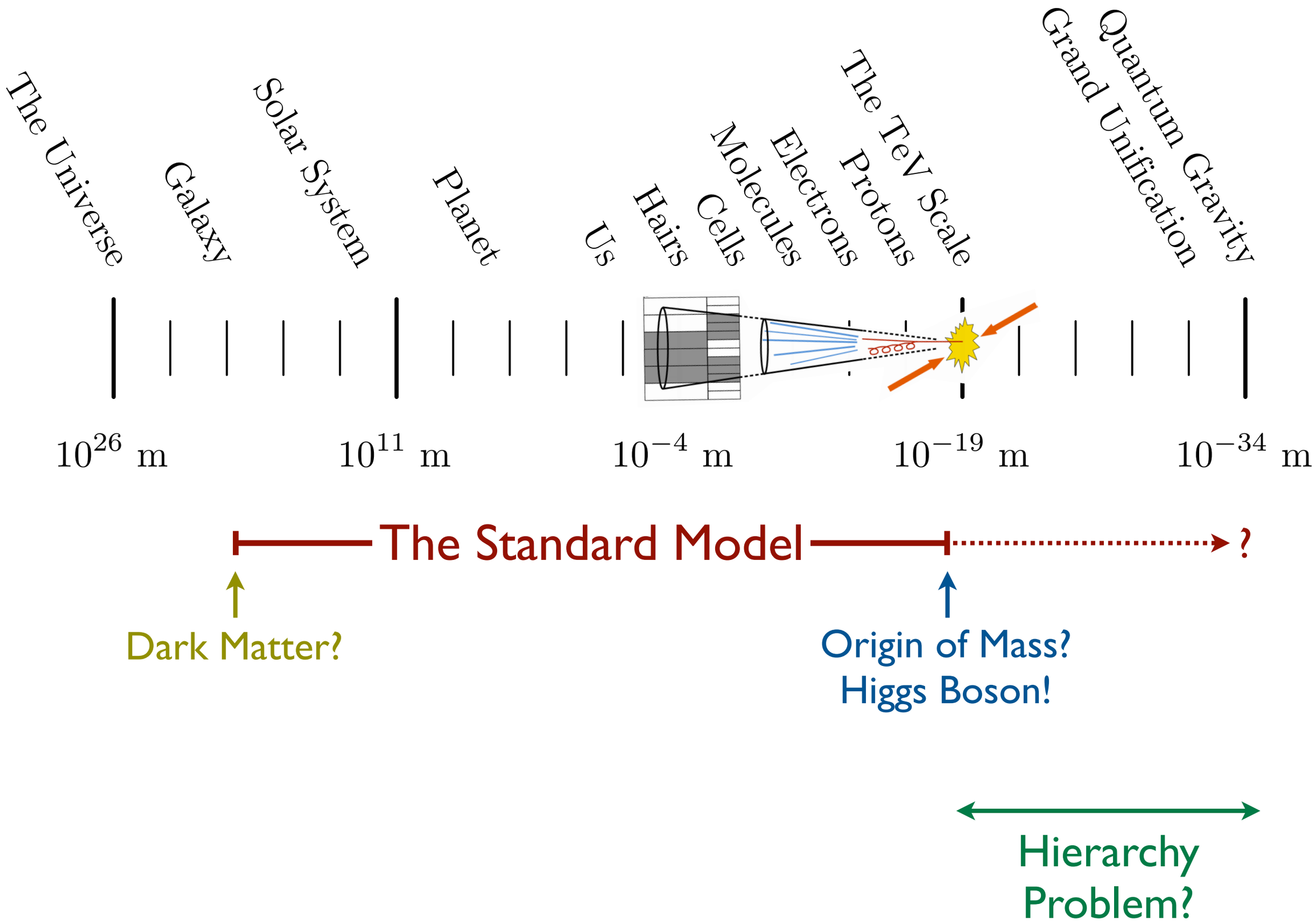
Boosting the Search for New Phenomena

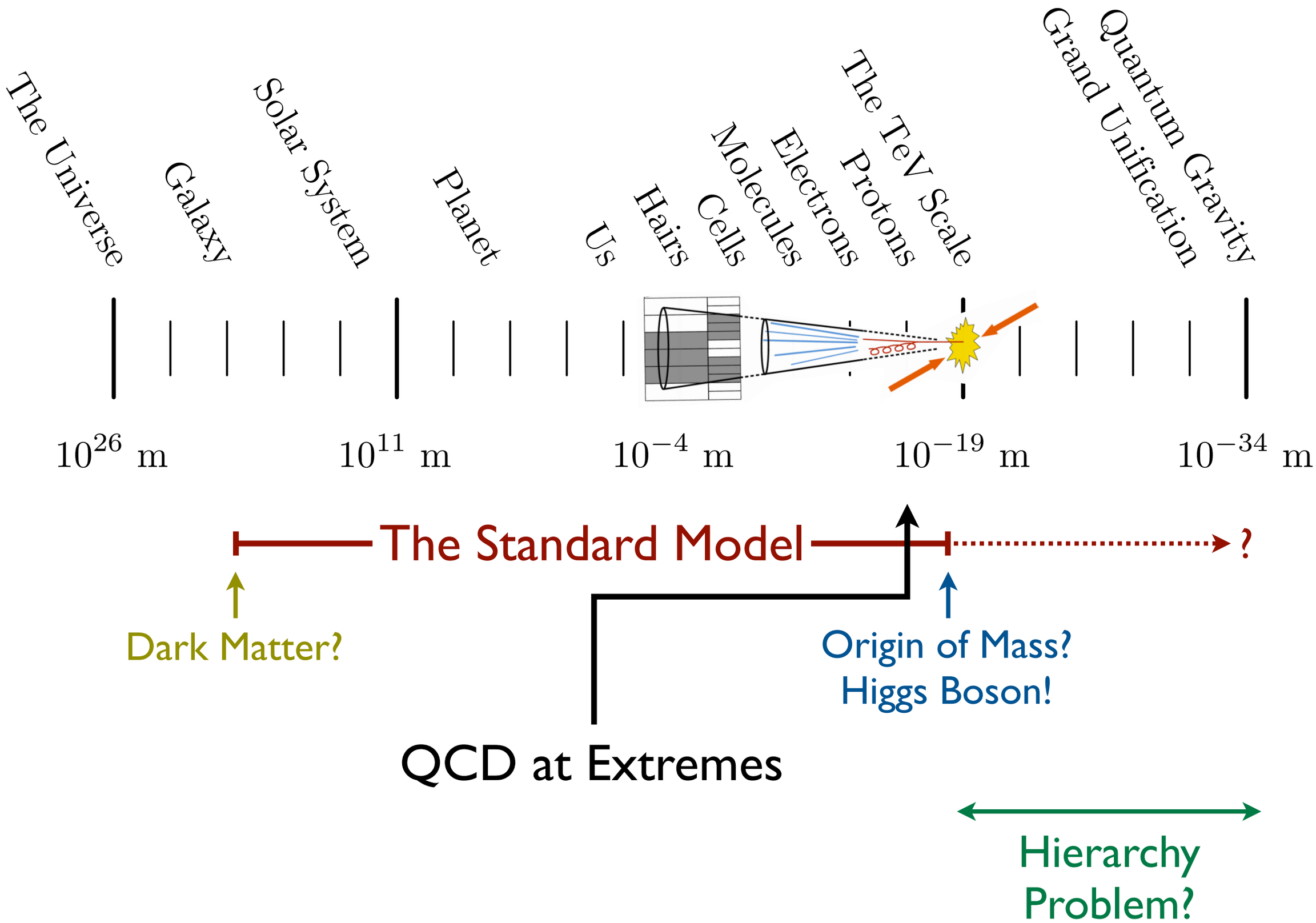
Planar Flow, Trimming, Variable R, N-subjettiness, Energy Correlators, Winner-Take-All Axes, Soft Drop, Jets Without Jets, XCone, Generalized Correlators, …

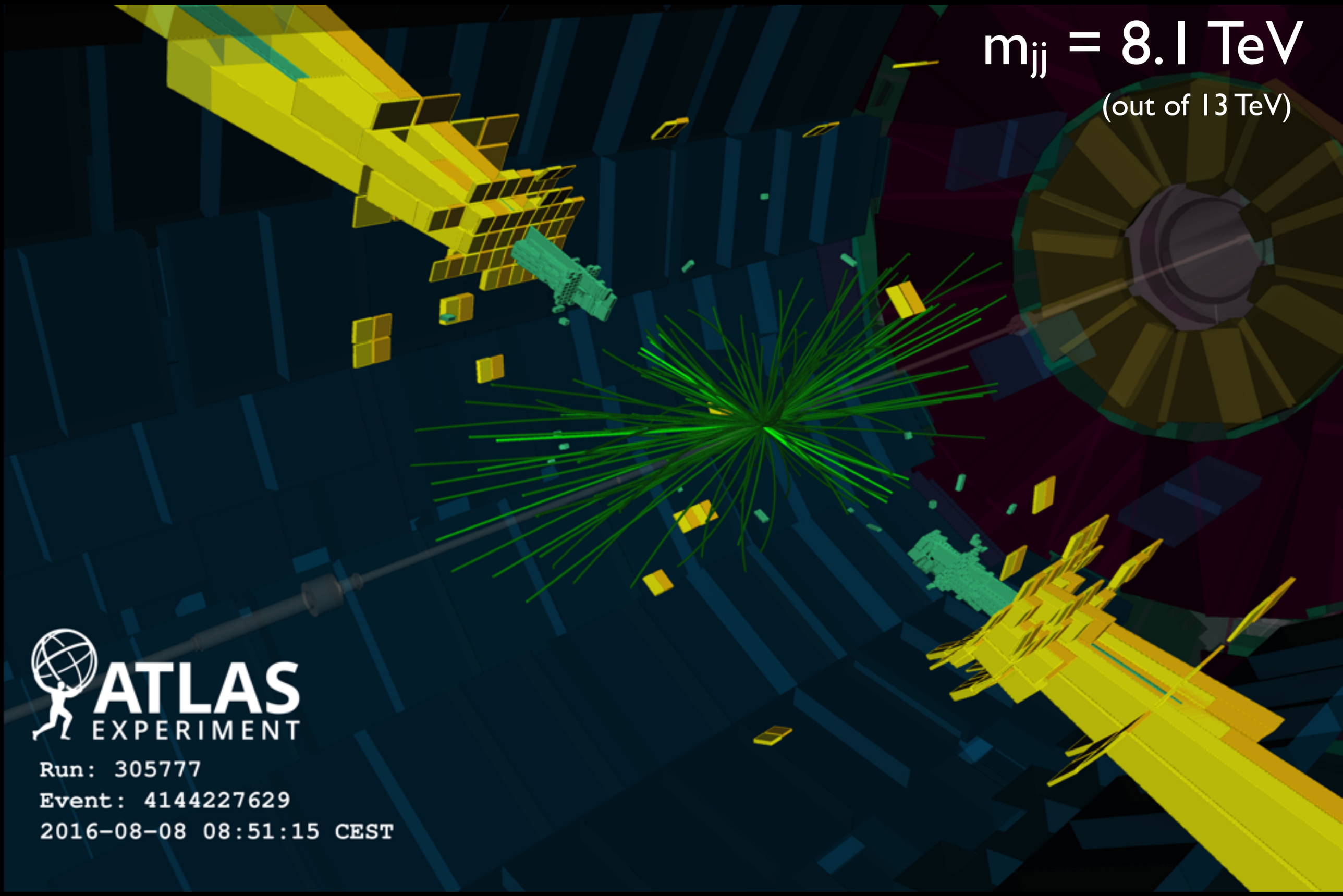


Pushing the Boundaries of Quantum Field Theory

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


The Universe
Galaxy
Solar System
Planet
Us
Hairs
Cells
Molecules
Electrons
Protons
The TeV Scale
Grand Unification
Quantum Gravity
10^{26} m
10^{11} m
10^{-4} m
10^{-19} m
10^{-34} m
The Standard Model
?
Dark Matter?
Origin of Mass?
Higgs Boson!
Hierarchy
Problem?


The Universe
Galaxy
Solar System
Planet
Us
Hairs
Cells
Molecules
Electrons
Protons
The TeV Scale
Grand Unification
Quantum Gravity
10^{26} m
10^{11} m
10^{-4} m
10^{-19} m
10^{-34} m
The Standard Model
?
Dark Matter?
Origin of Mass?
Higgs Boson!
QCD at Extremes
Hierarchy
Problem?


m_{jj} = 8.1 TeV
(out of 13 TeV)
ATLAS
EXPERIMENT
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Event: 4144227629
2016-08-08 08:51:15 CEST