

Introduction to Jet Substructure at the LHC

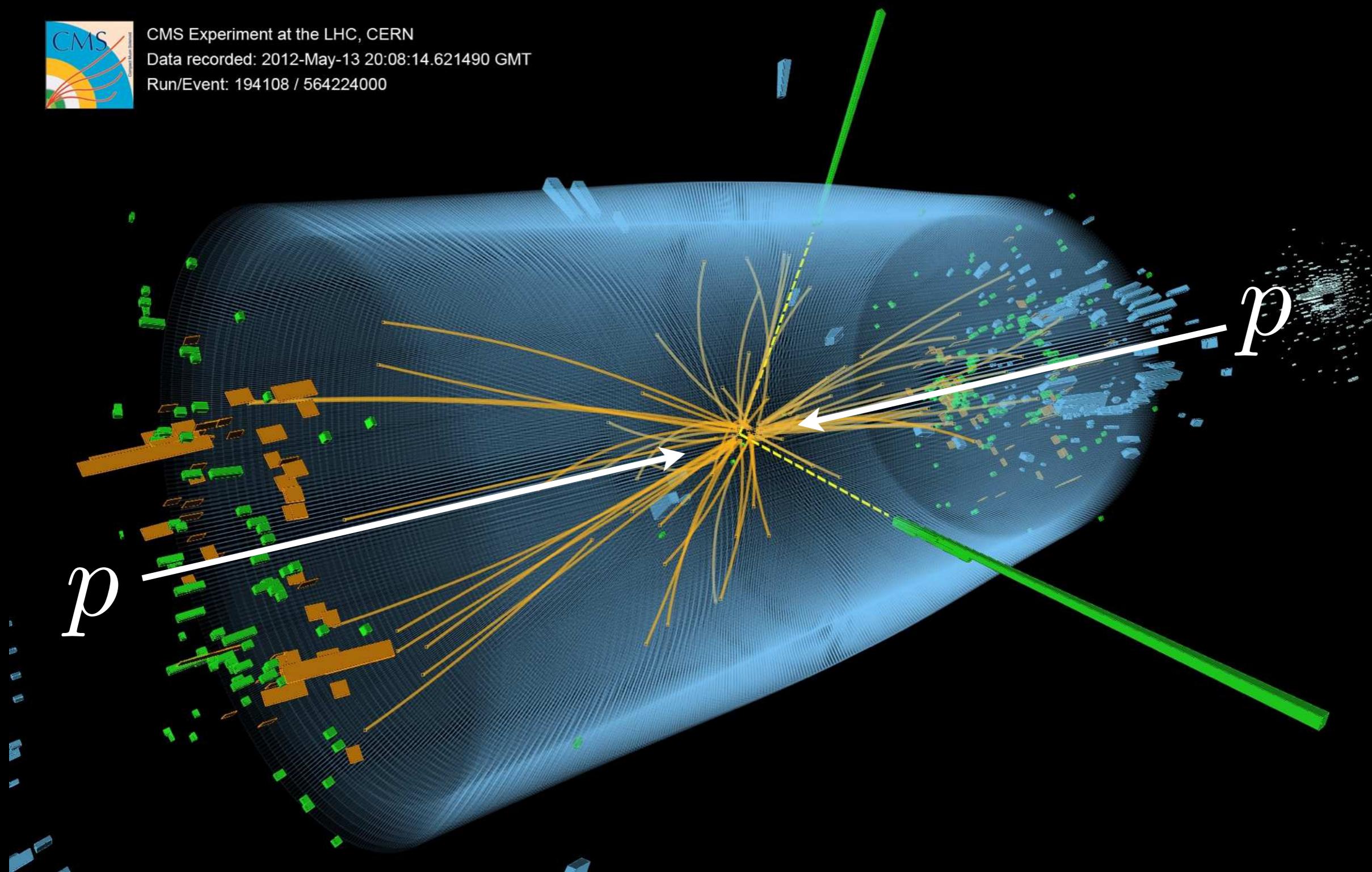
Jesse Thaler



Kavli IPMU — January 12, 2017

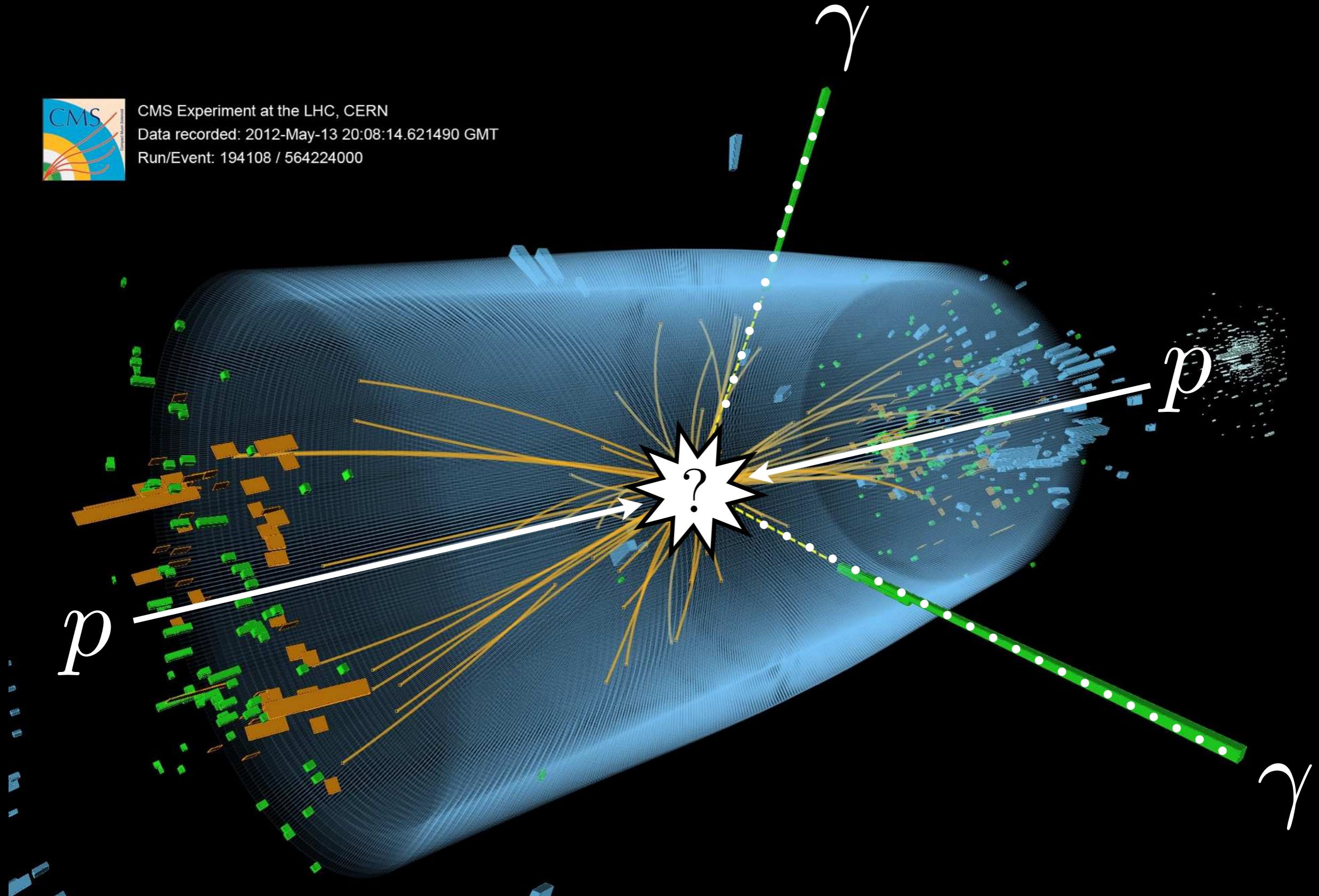


CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000



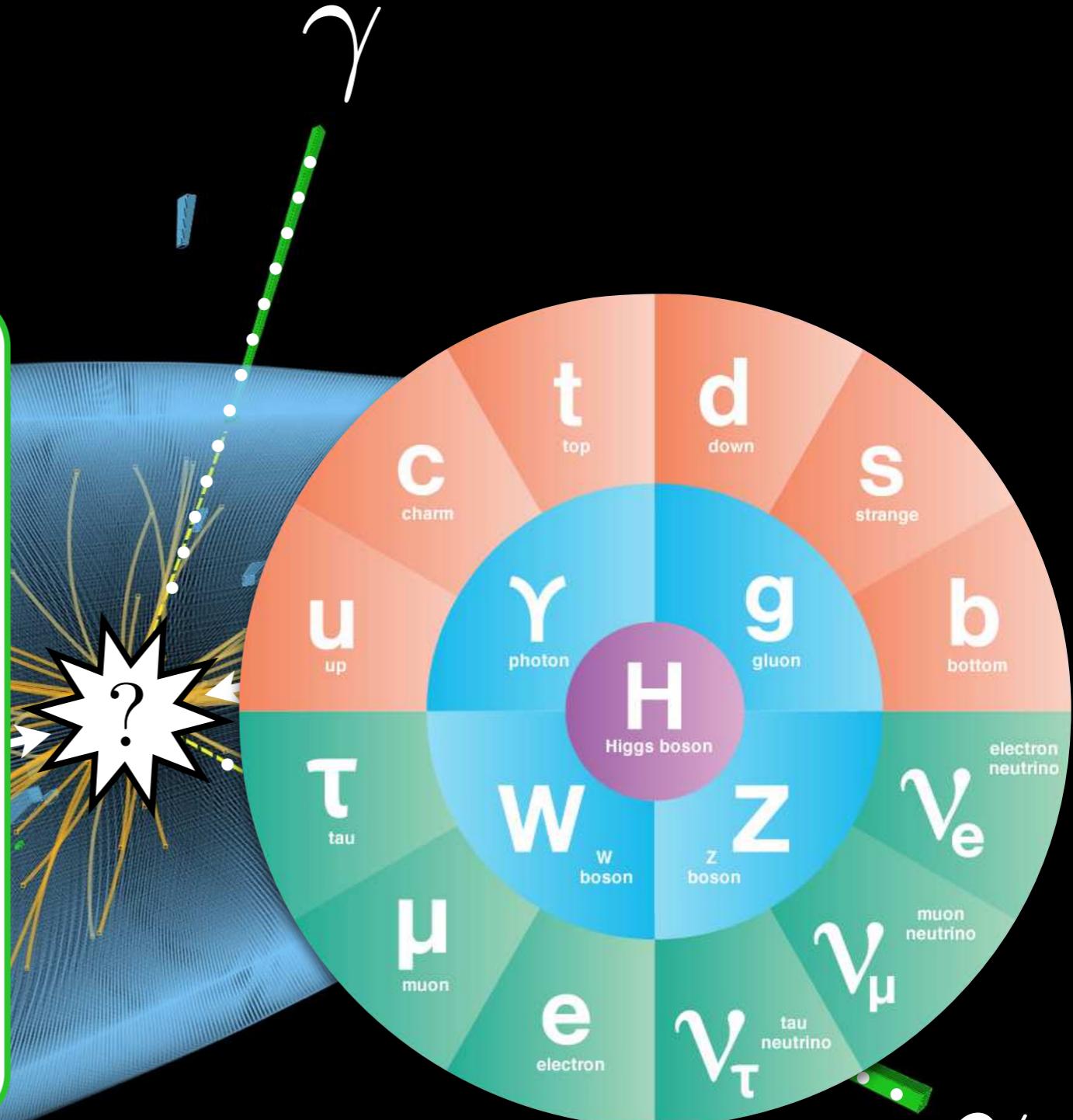
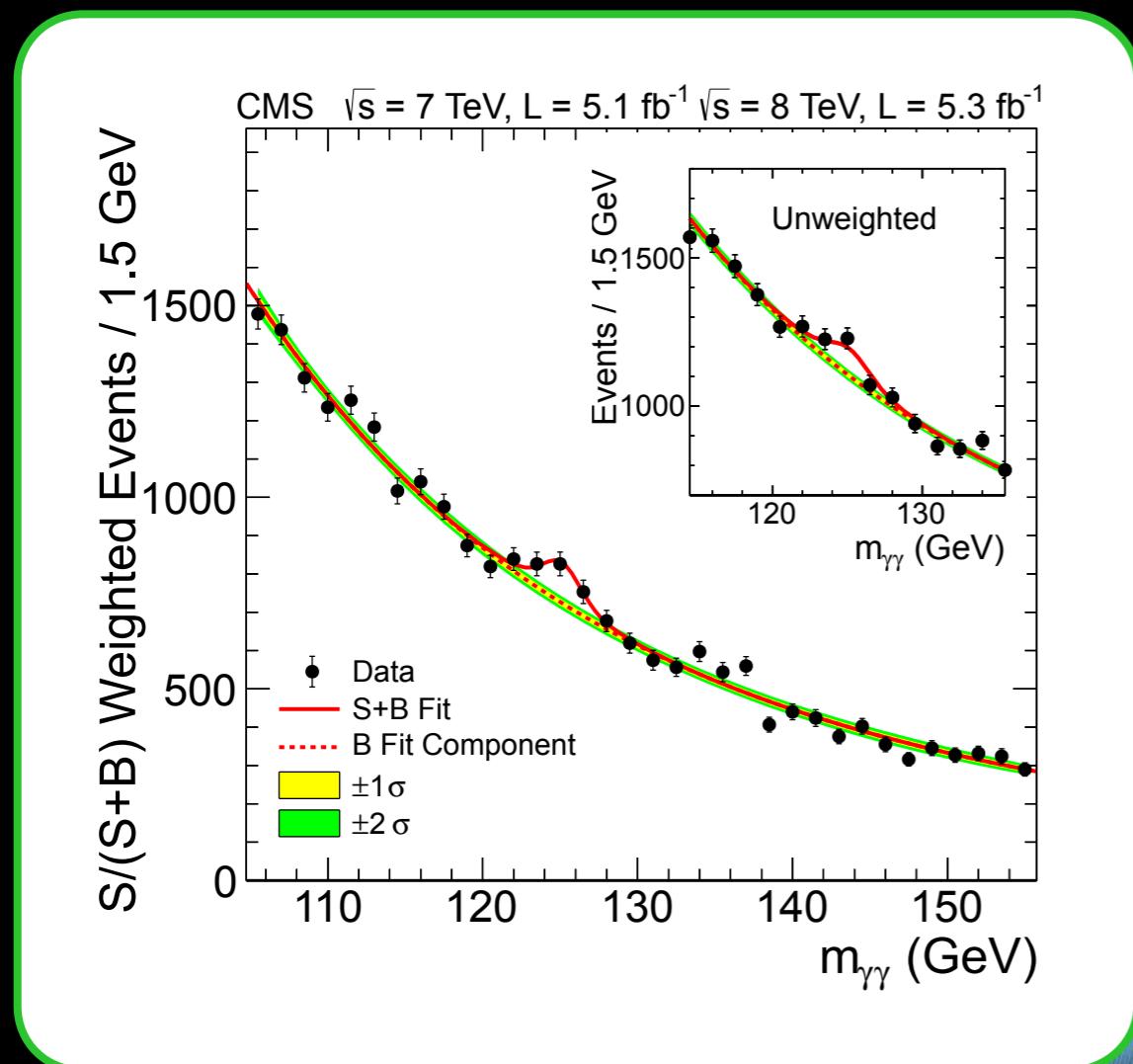


CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
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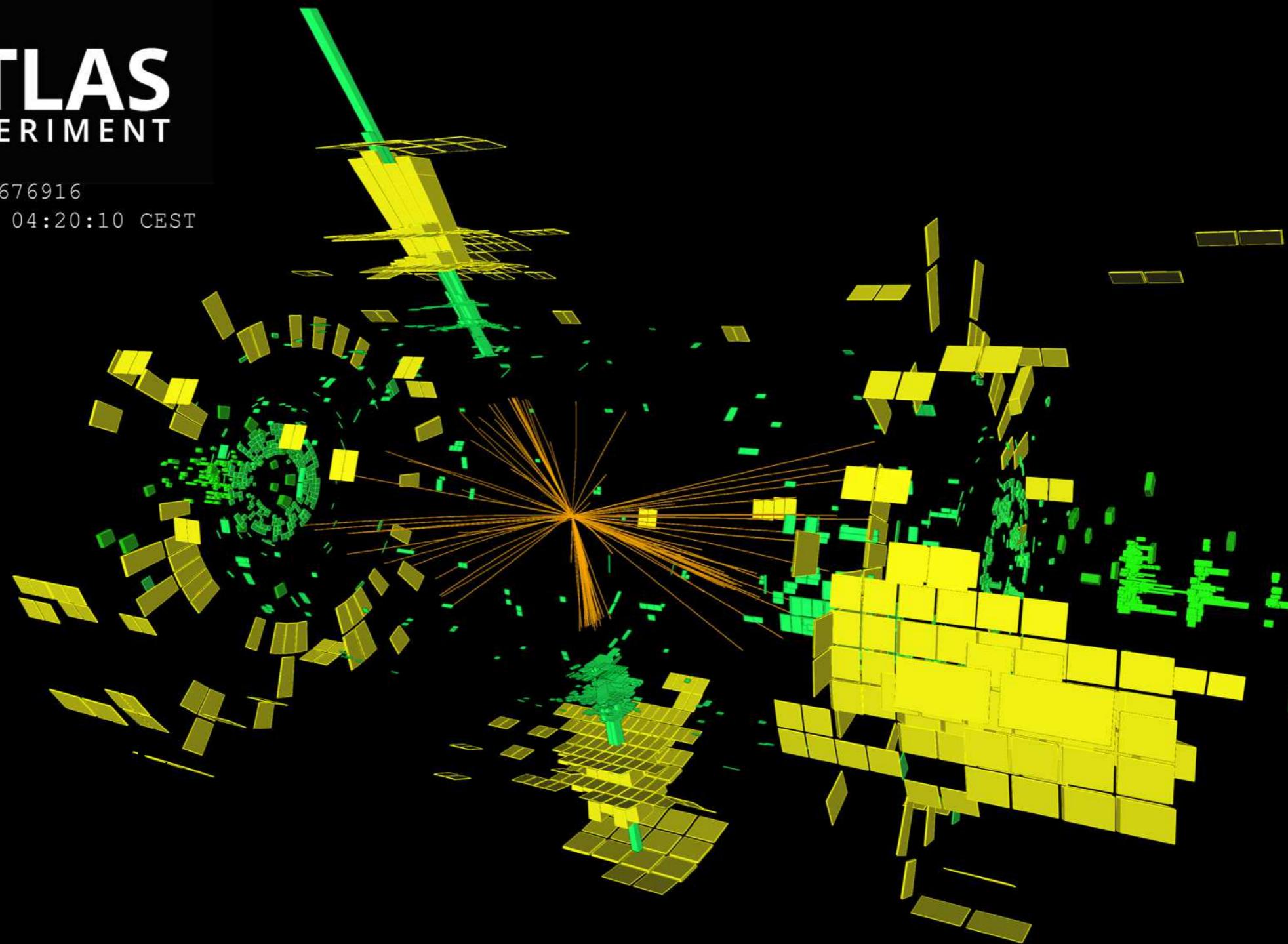


CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000





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

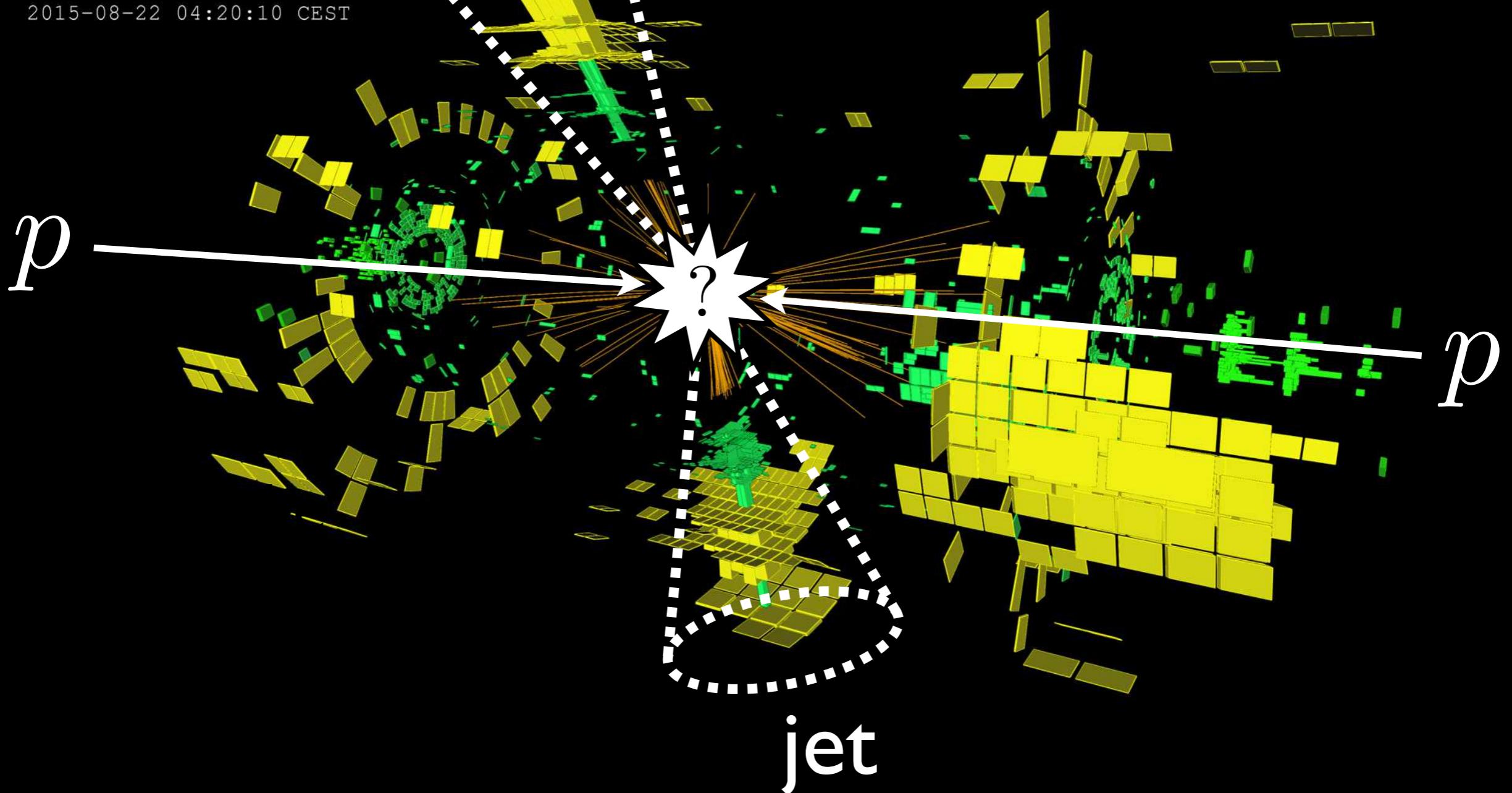




jet

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

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

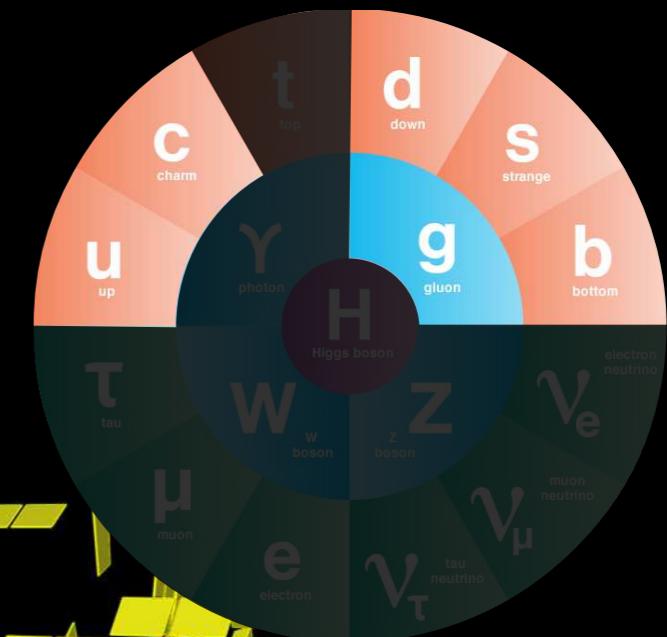




jet

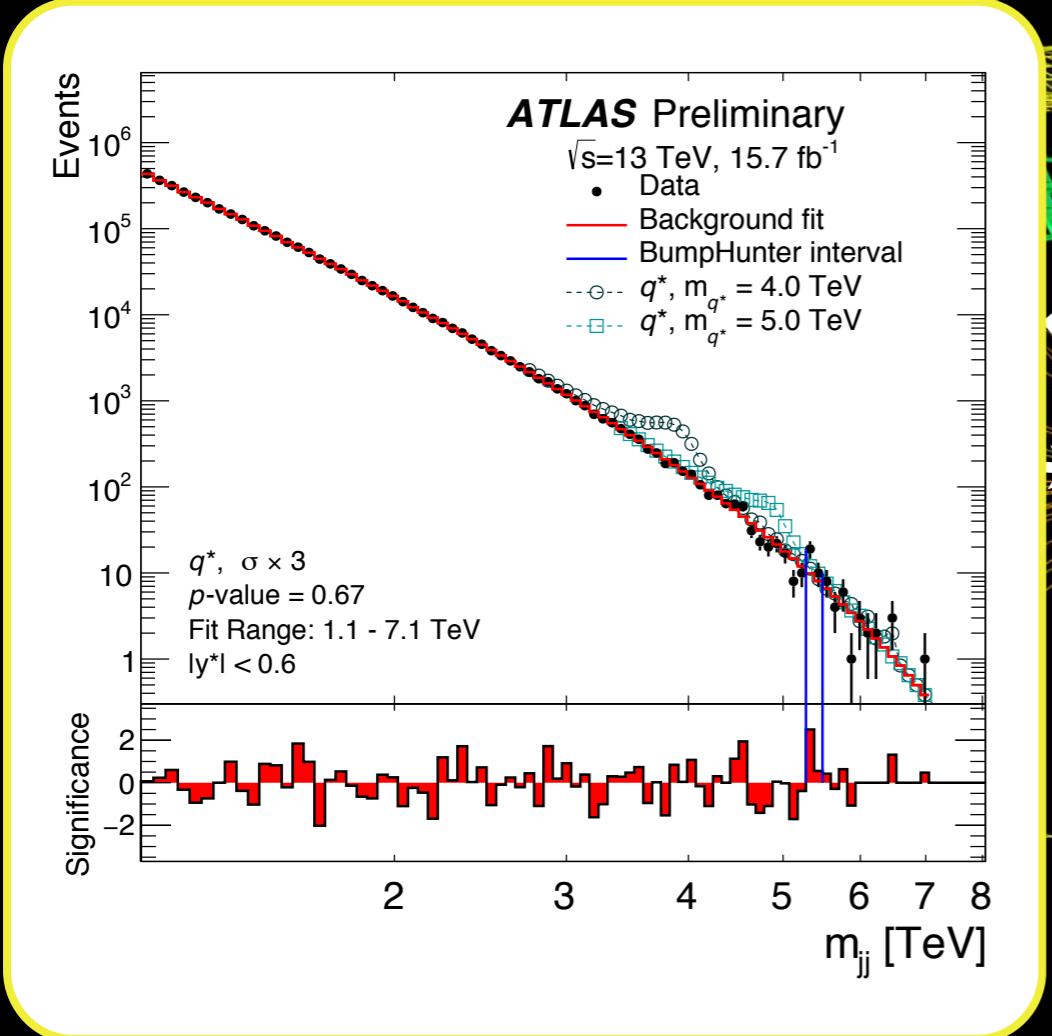
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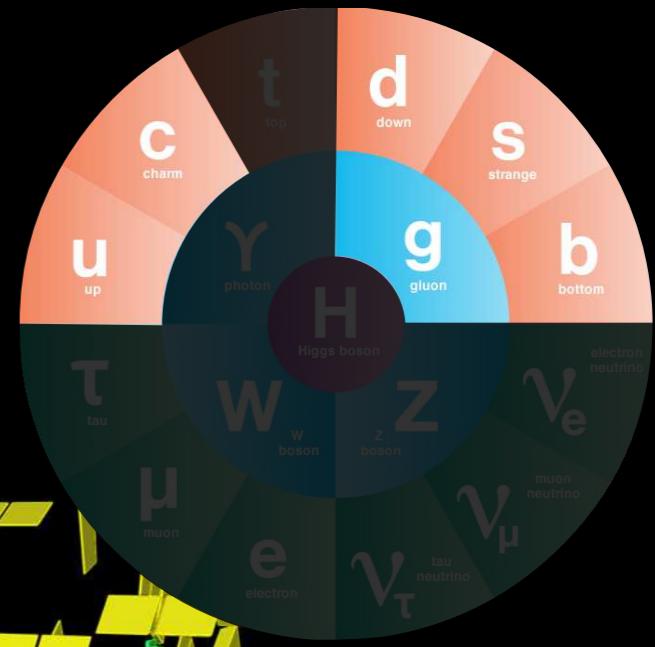




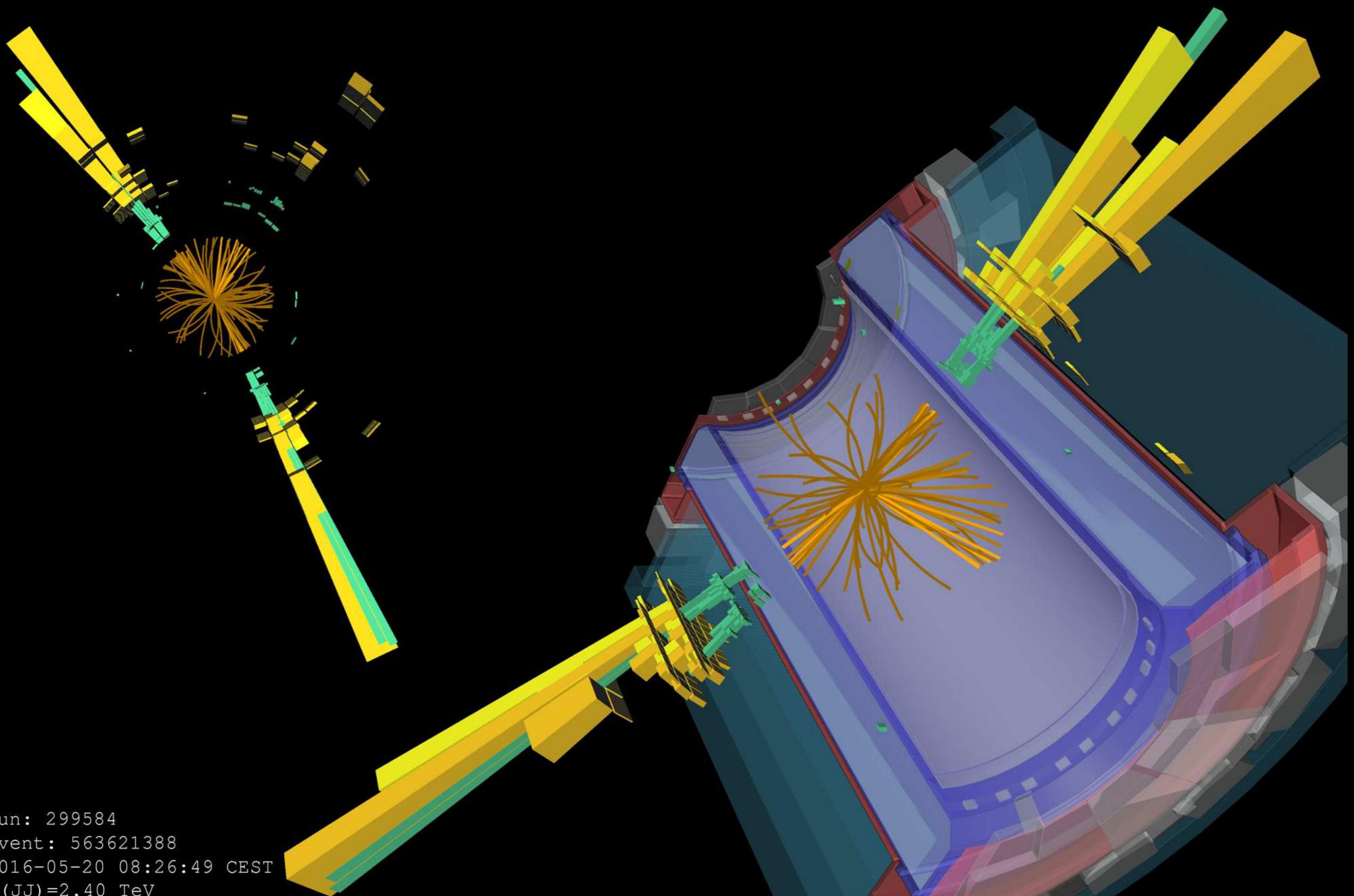
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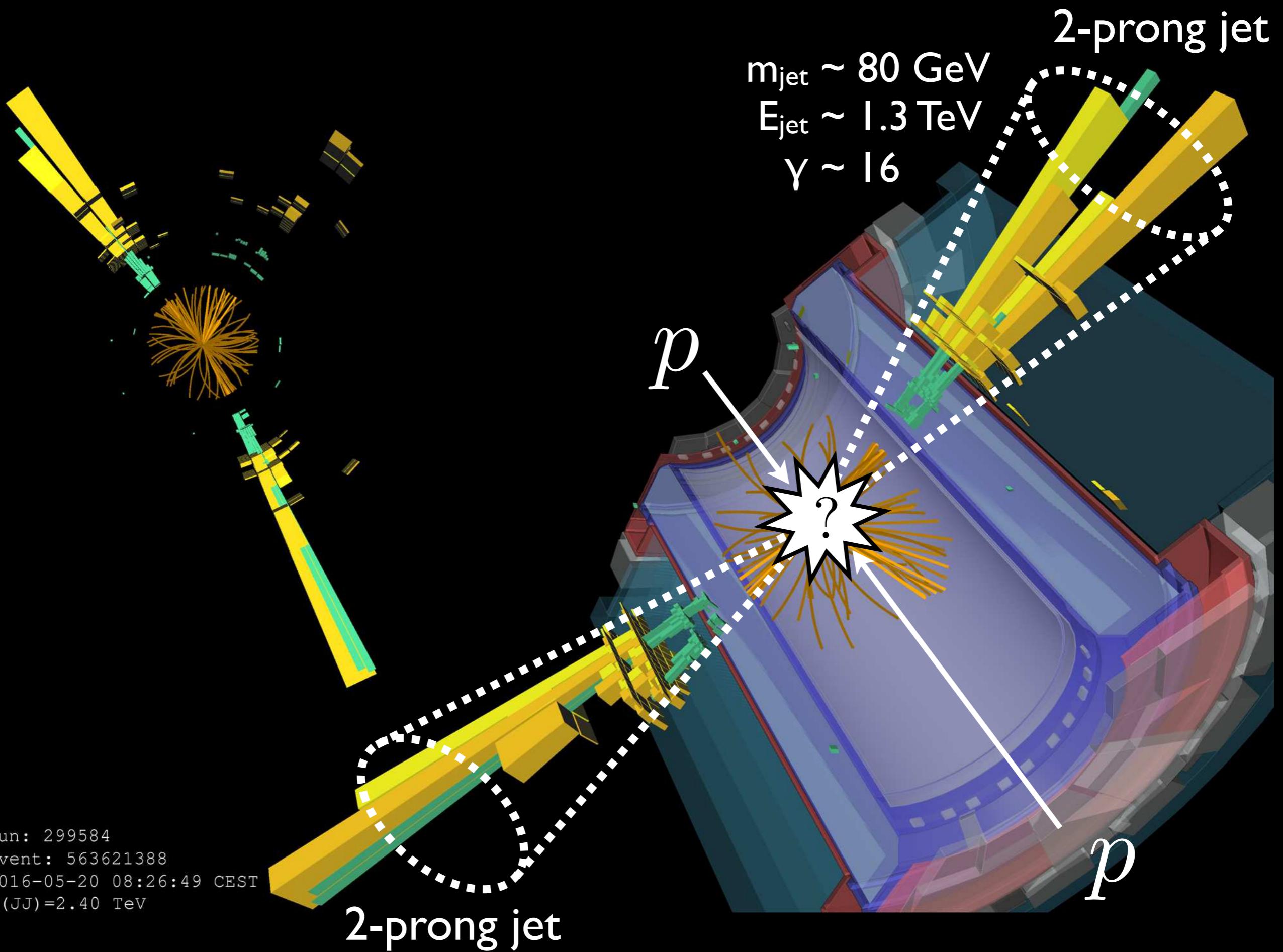


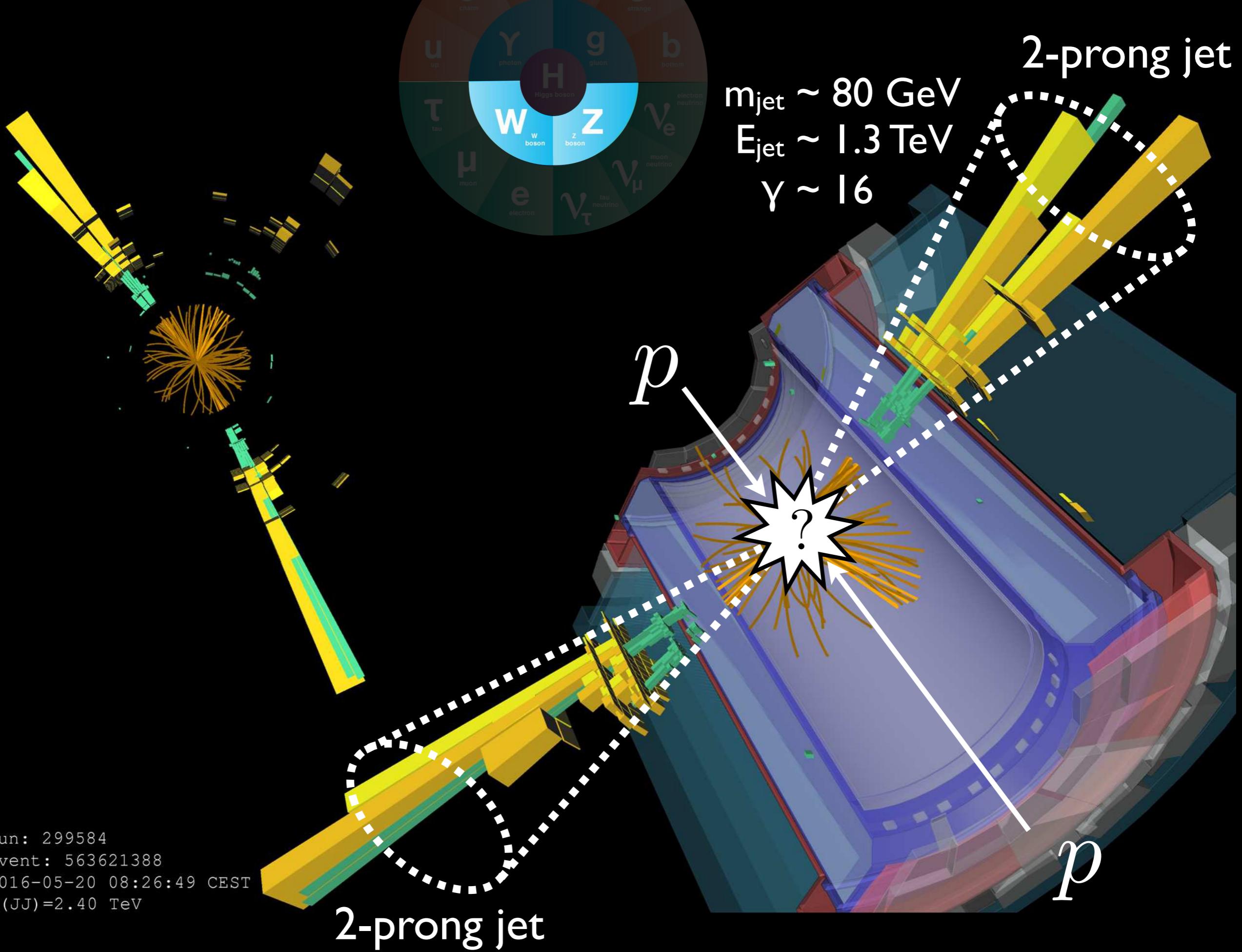
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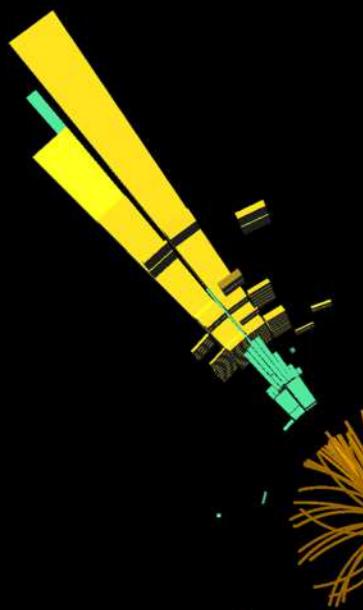


jet



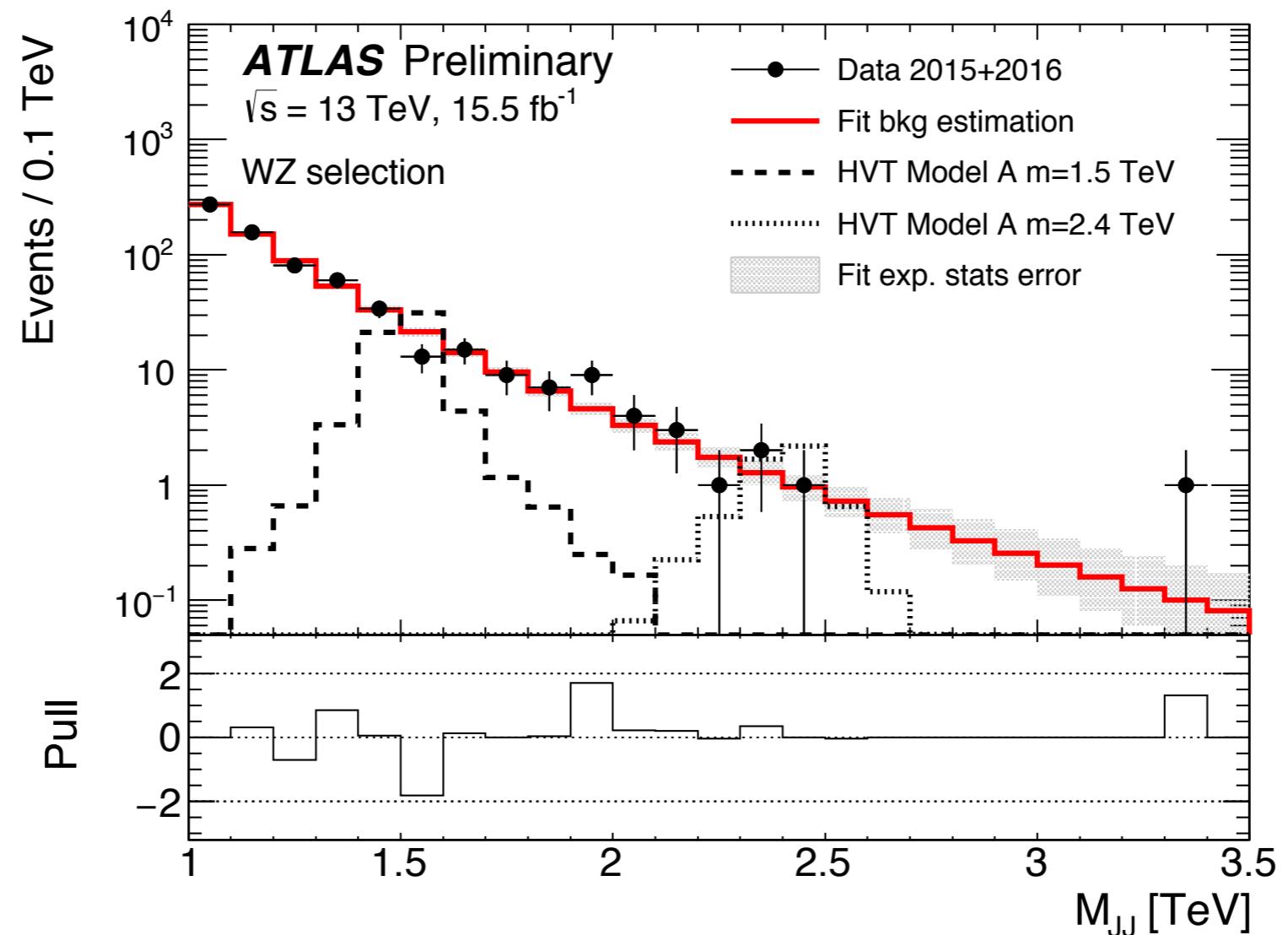






$m_{\text{jet}} \sim 80 \text{ GeV}$
 $E_{\text{jet}} \sim 1.3 \text{ TeV}$

2-prong jet



with *Trimming + Energy Correlators*

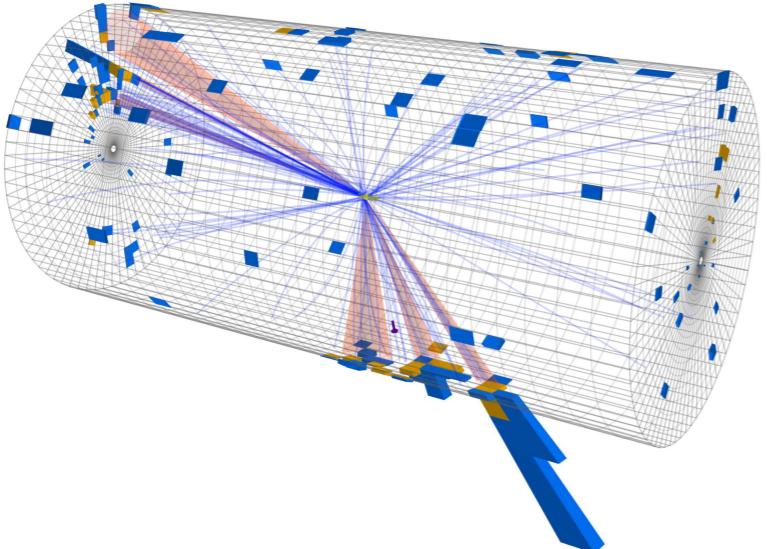
Run: 299584
Event: 563621388
2016-05-20 08:26:4
 $M(JJ) = 2.40 \text{ TeV}$

[Krohn, JDT, Wang, 2009]

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

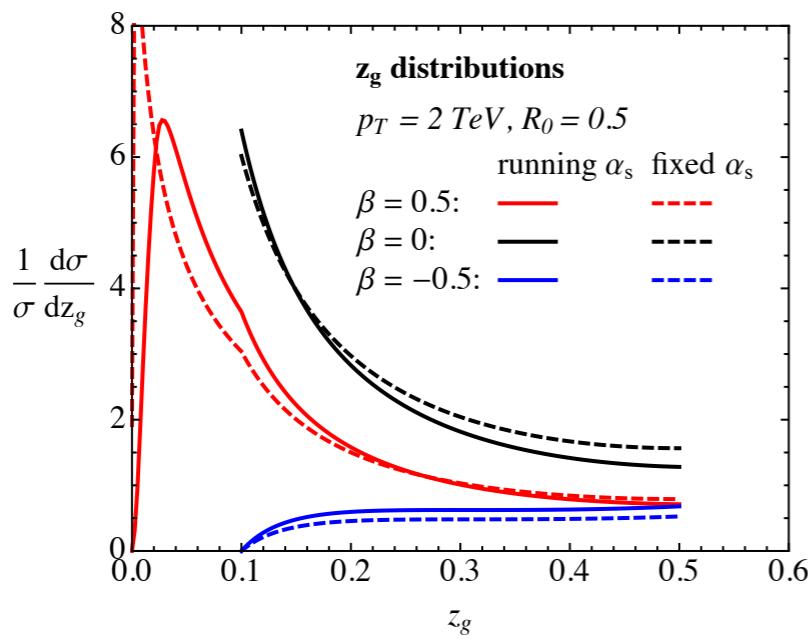
p

Jet Substructure



*Boosting the Search
for New Phenomena*

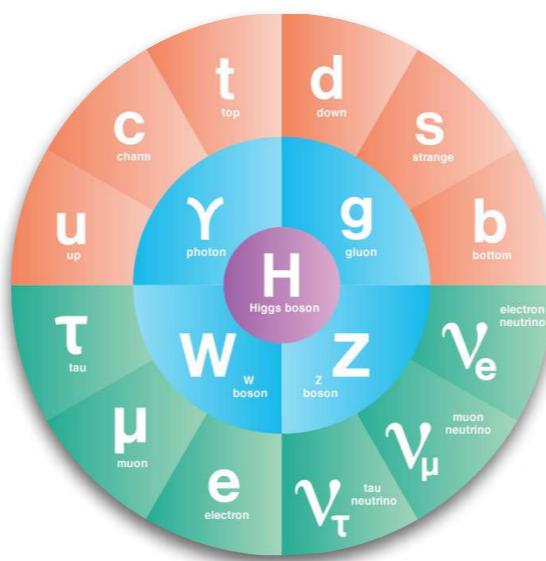
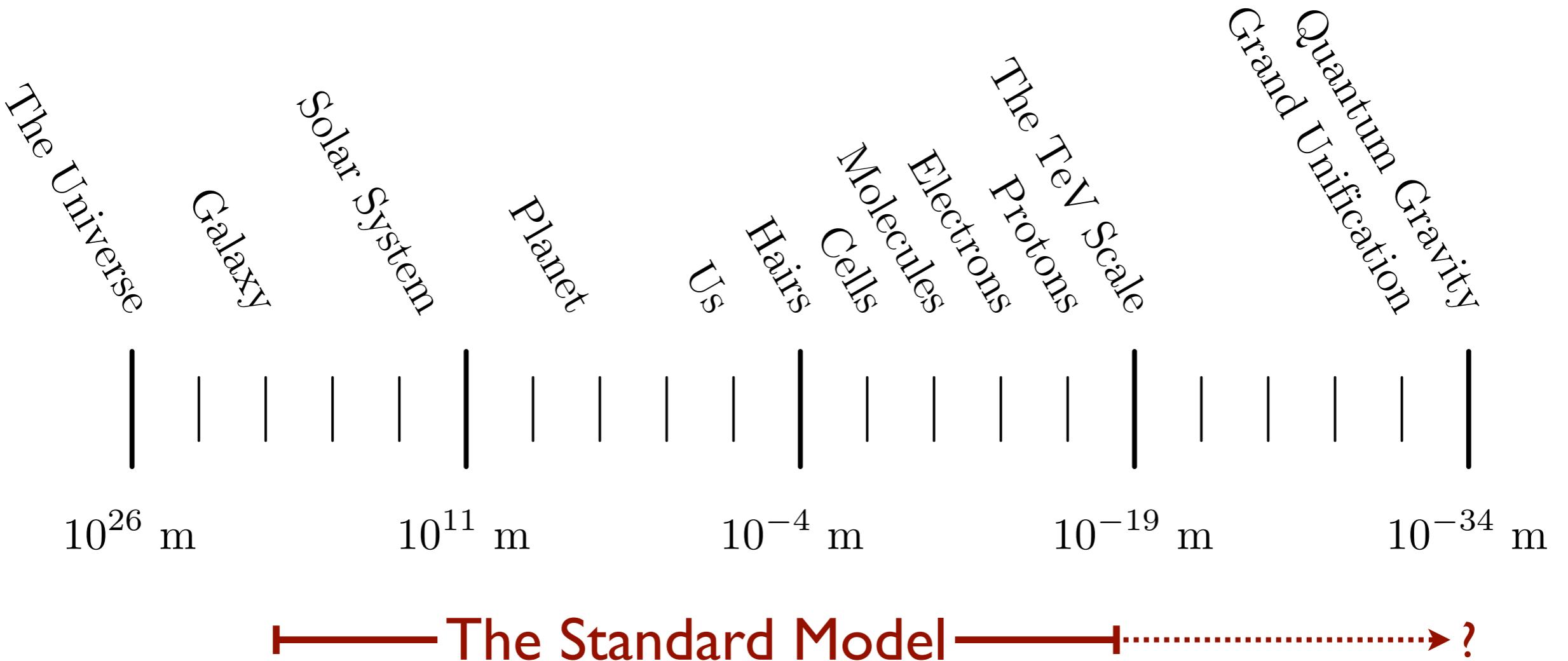
[Today & Friday]

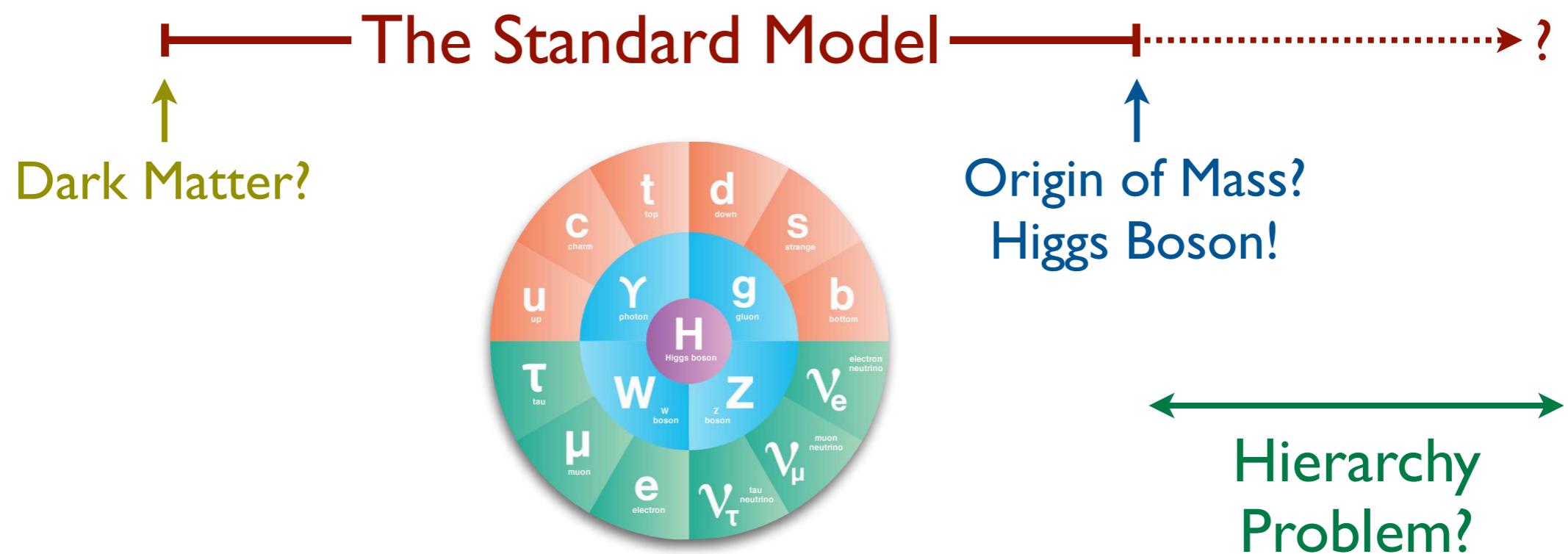
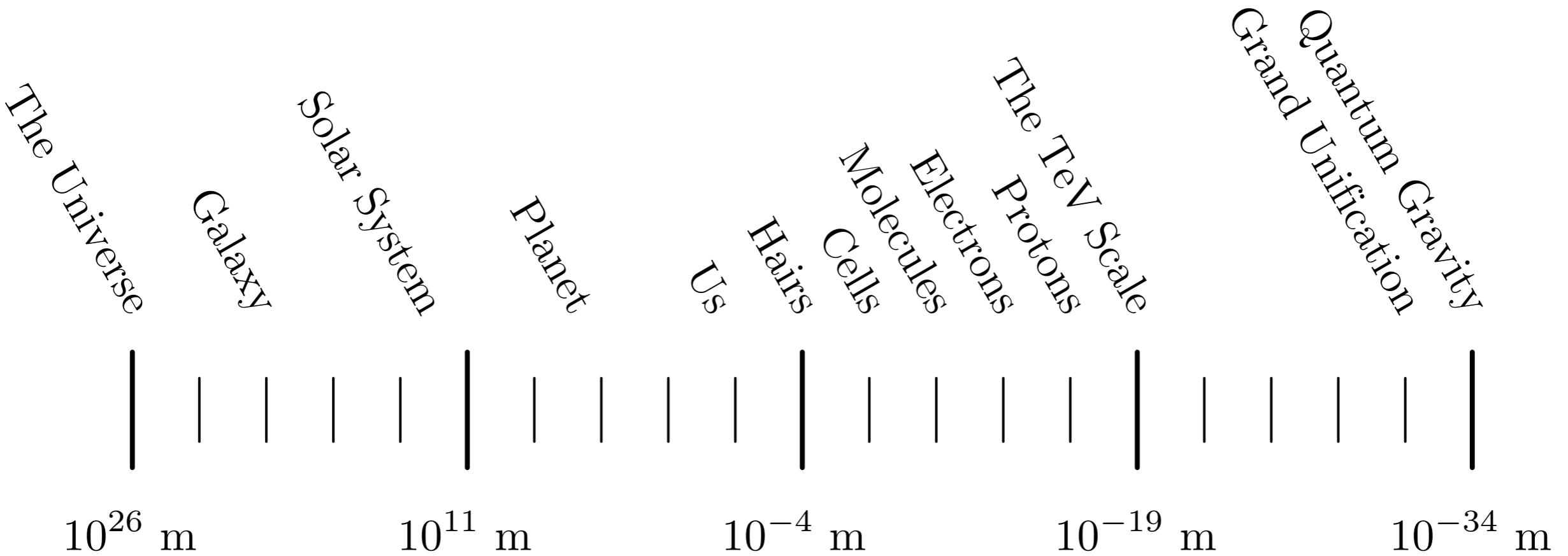


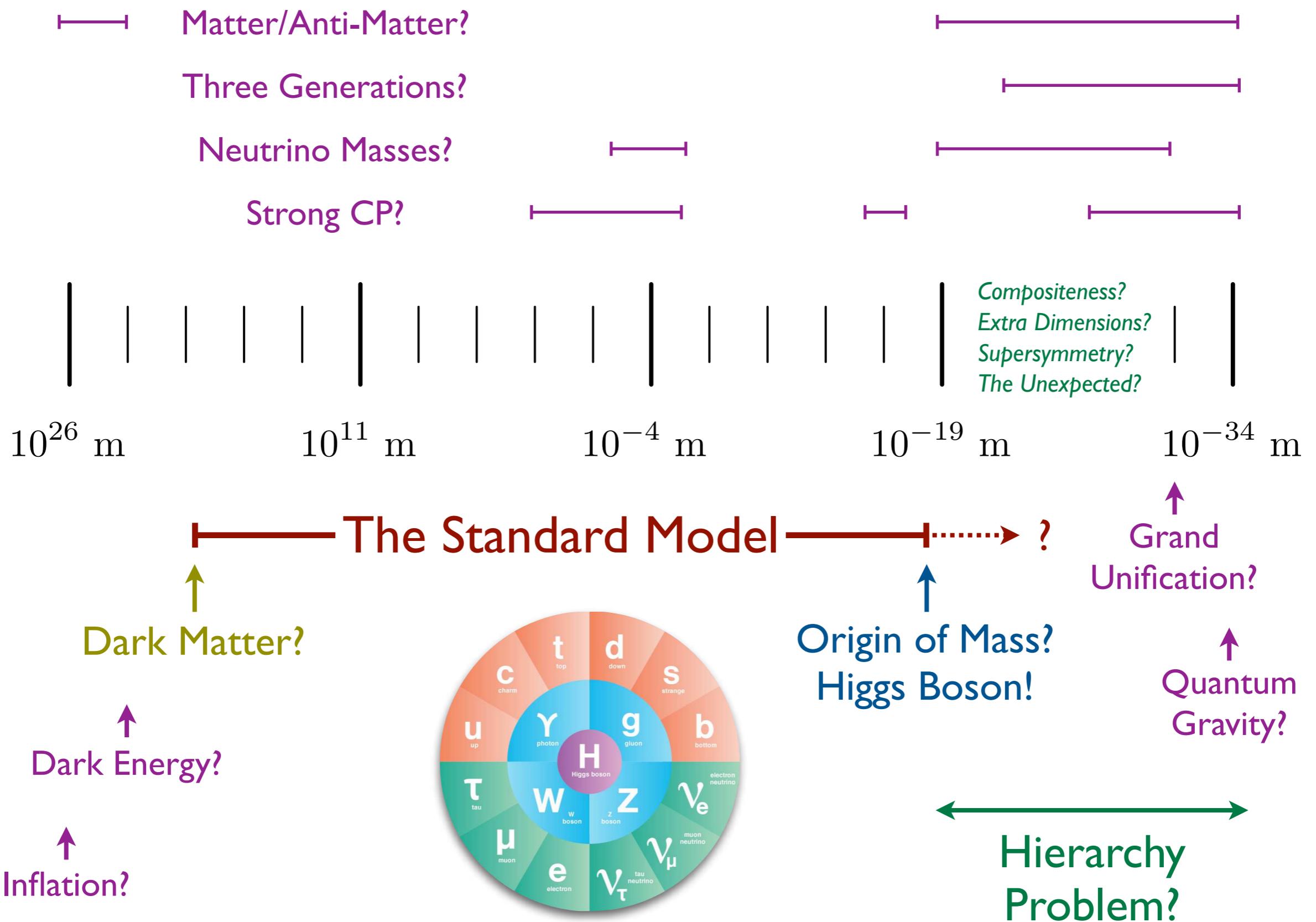
*Pushing the Boundaries
of Quantum Field Theory*

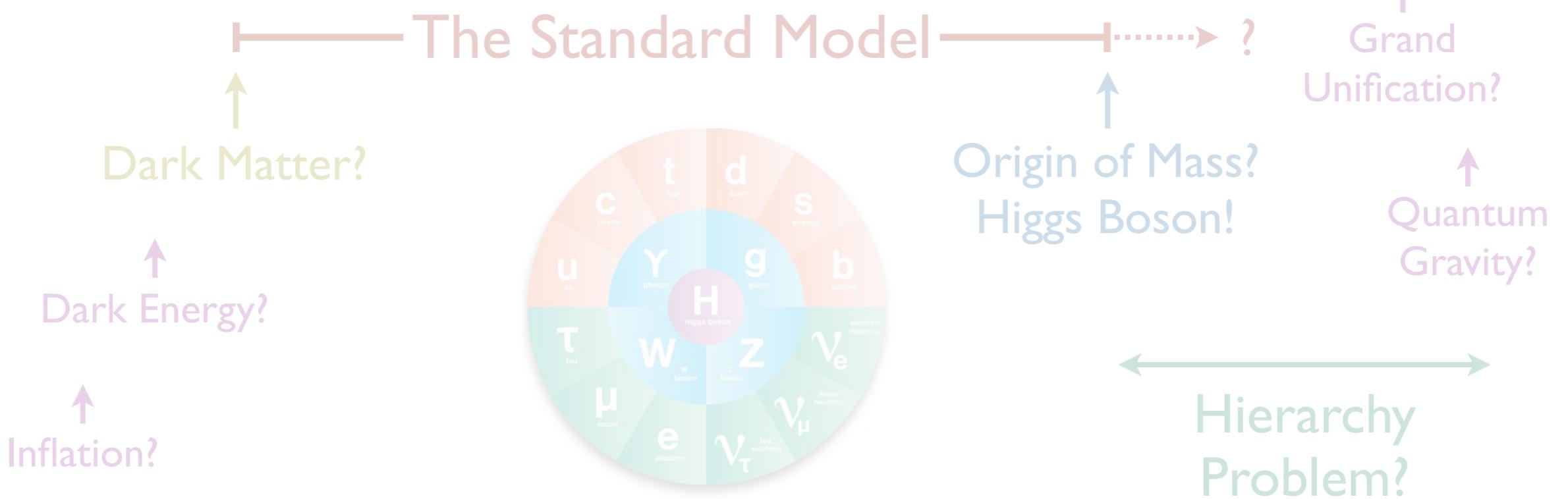
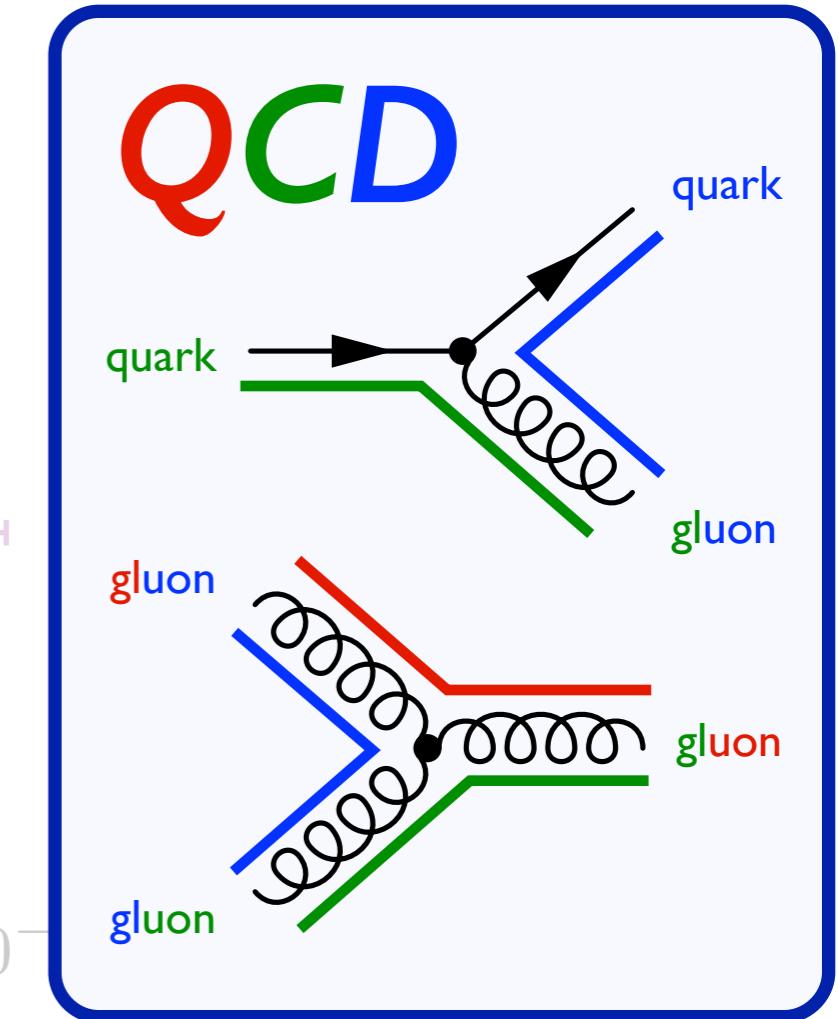
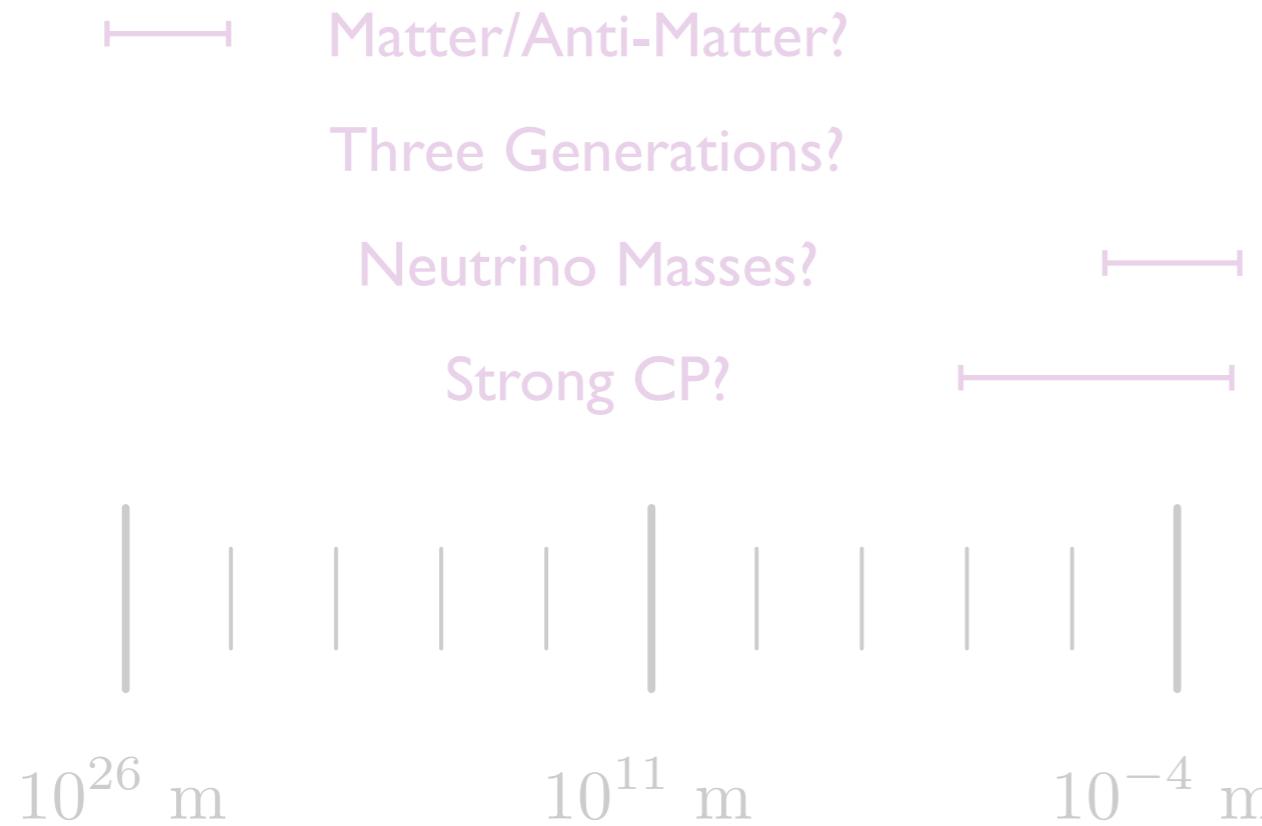
[Next Monday & Tuesday]

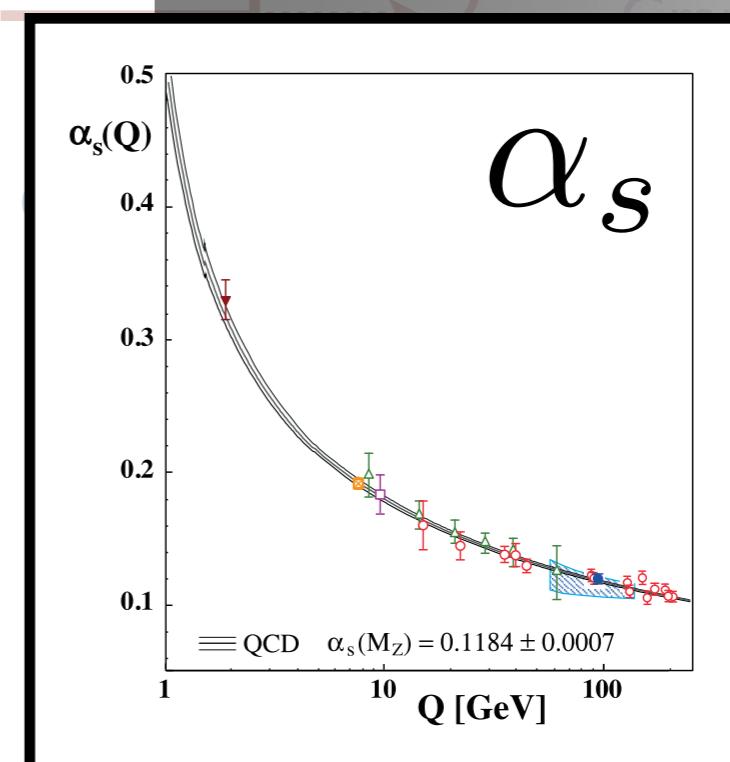
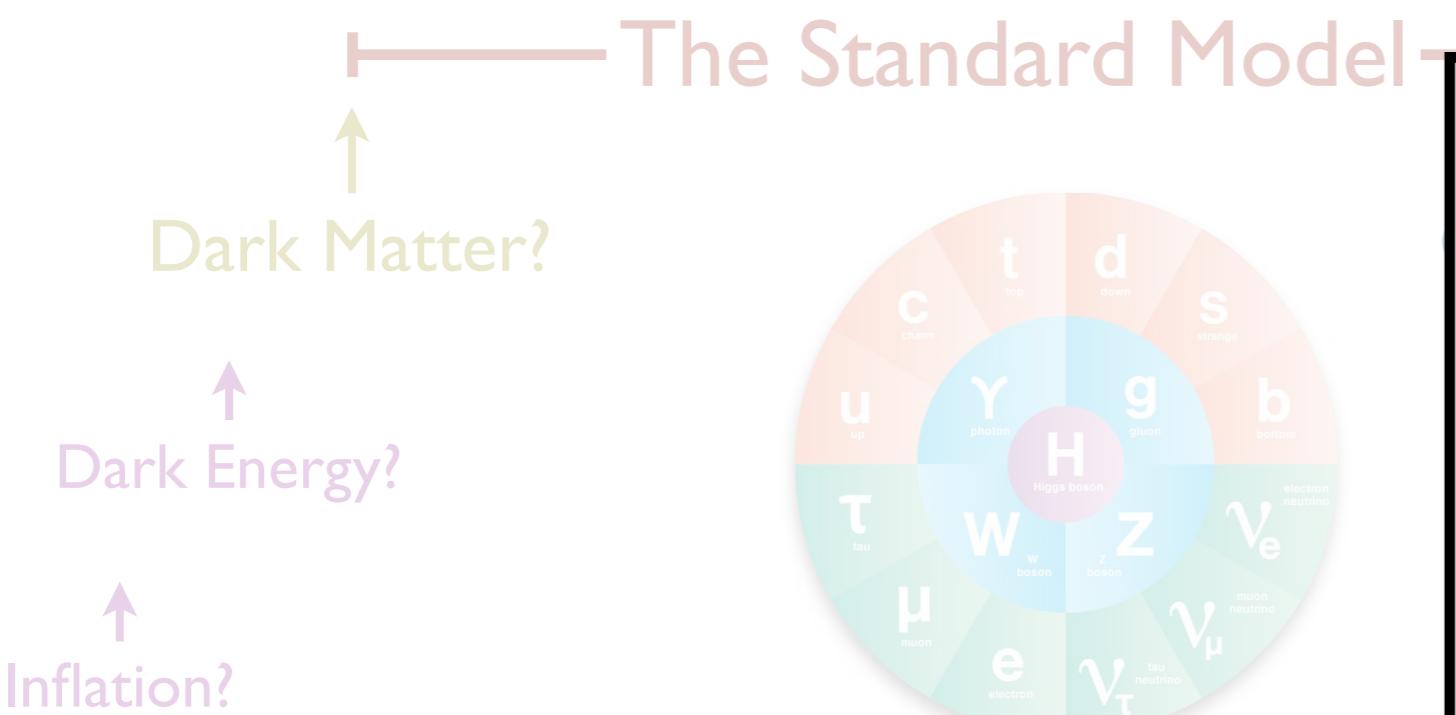
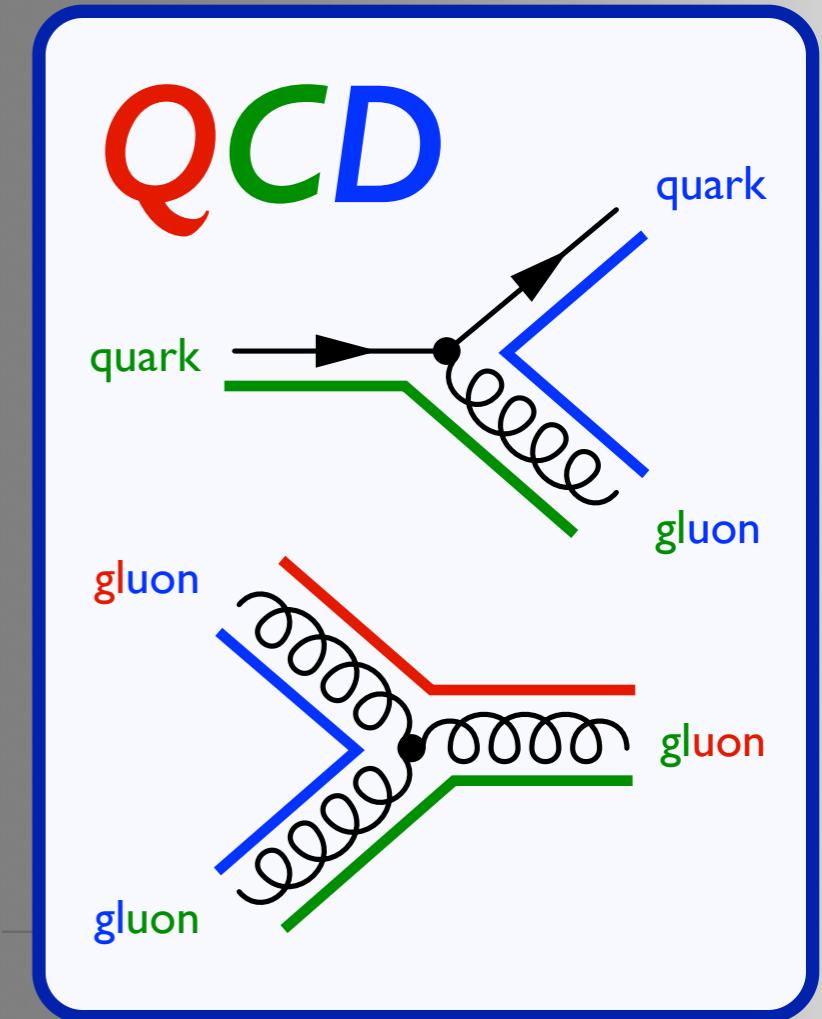
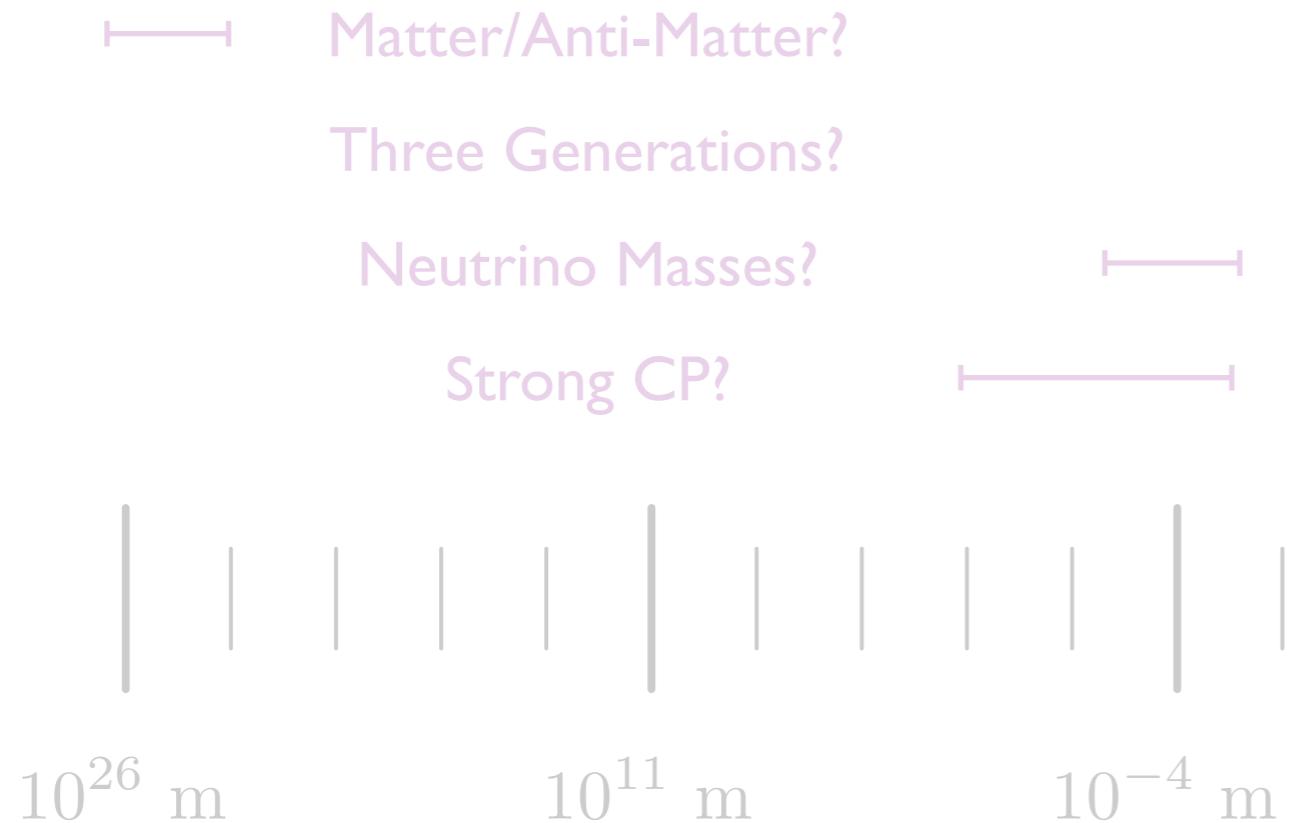
Jets in the Big Picture











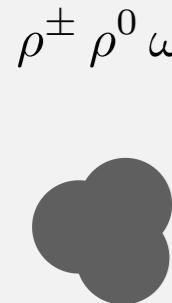
→ Matter/Anti-Matter?

Three Generations?



Mesons

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



Baryons

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

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



Tetraquarks (?)

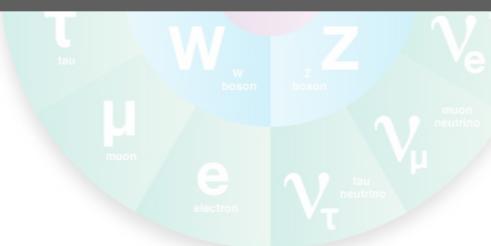
$X(3872) Y(4260) Z(4430) \dots$



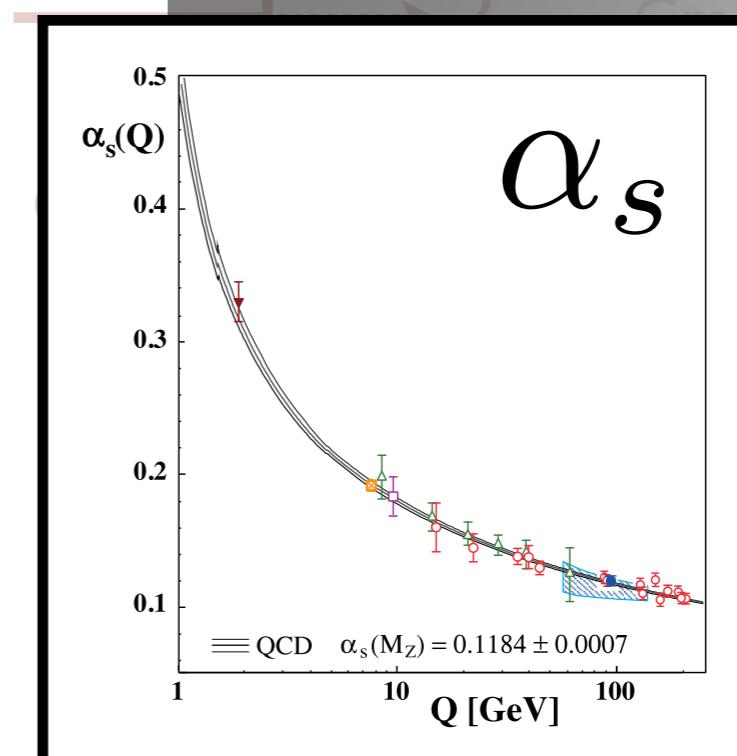
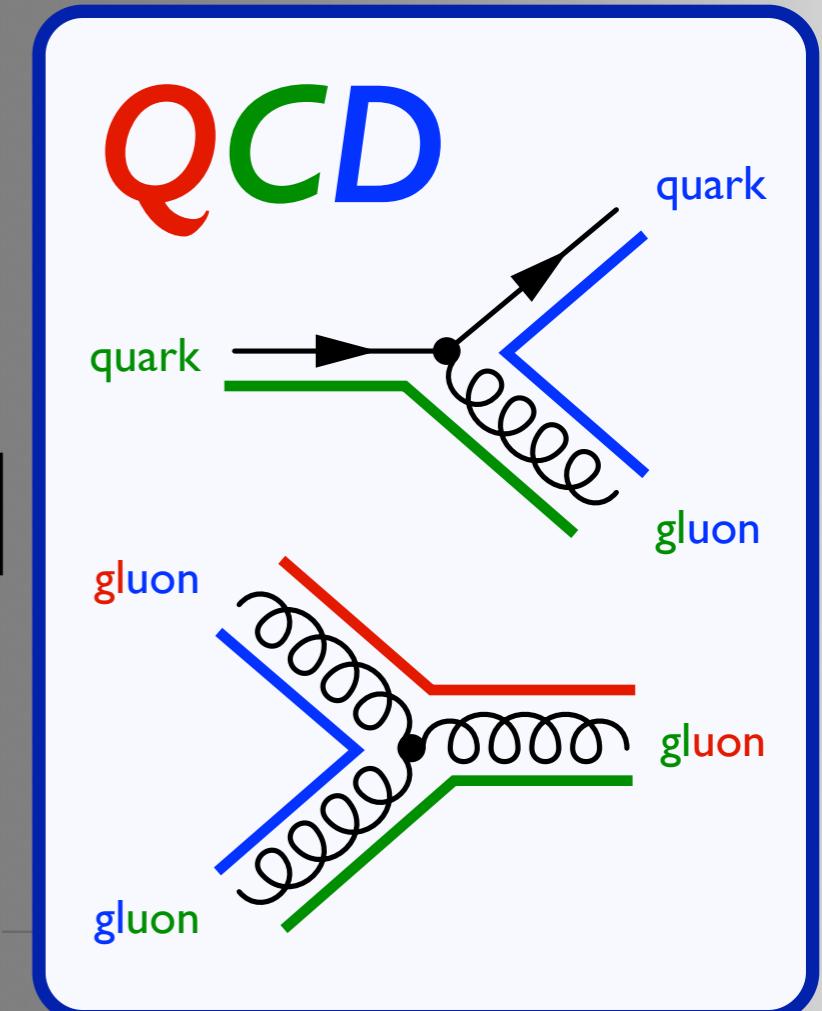
Pentaquarks (?)

$P_c^+(4450) \dots$

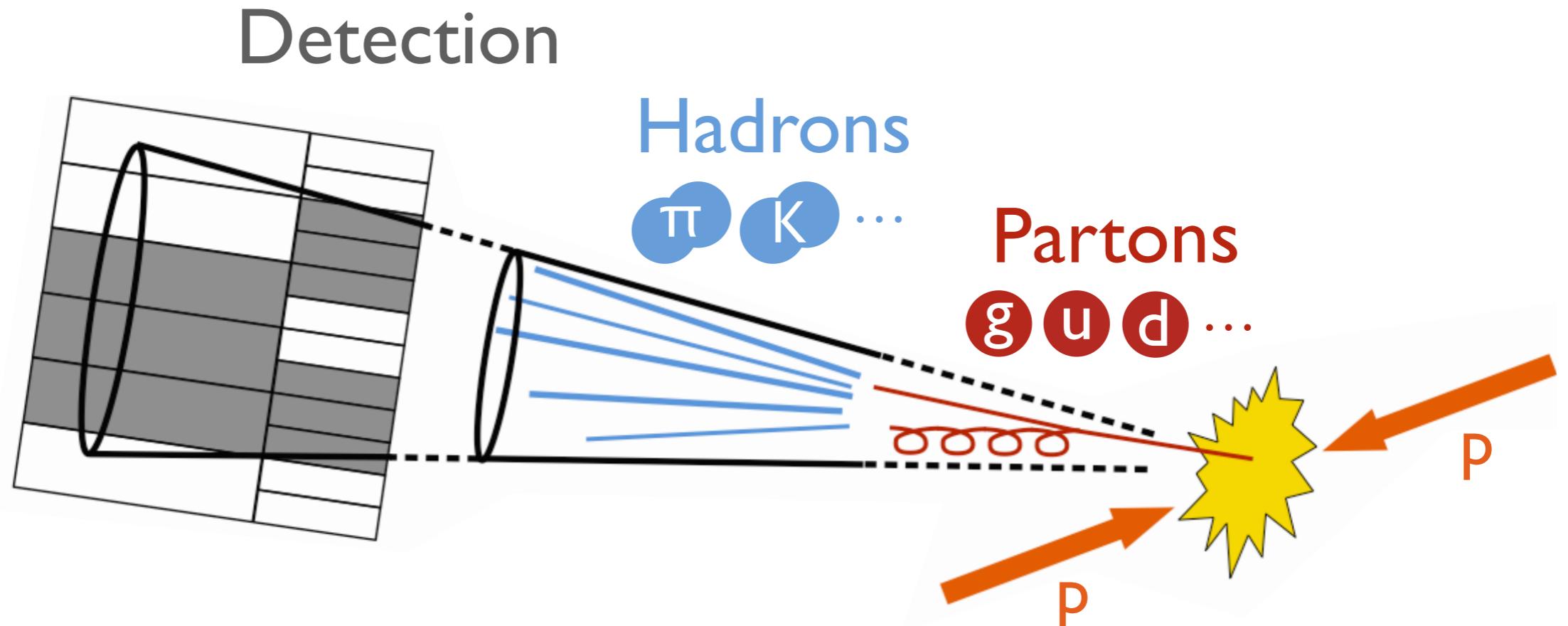
↑
Inflation?



Jets



Back to Basics: What is a Jet?



reconstruction
 $\approx 1\text{-to-}1 @ \text{LHC}$
(e.g. particle flow)

nonperturbative
confinement
(hadronization)

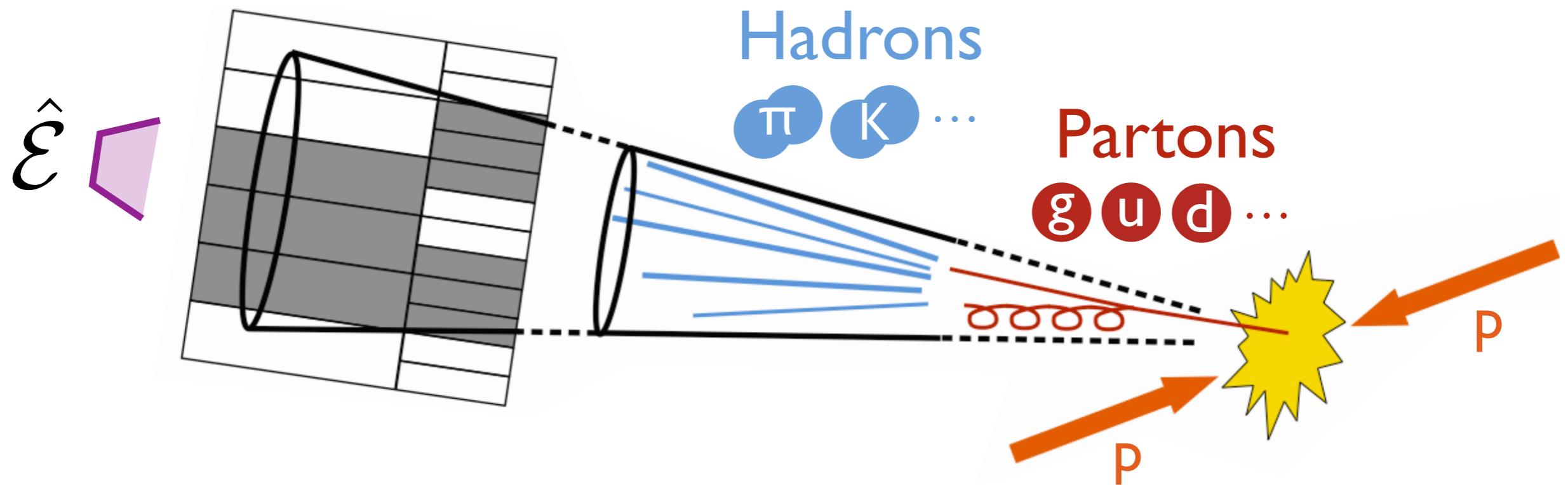
perturbative
gluonic radiation
(parton shower)

short-distance
collision
(hard scattering)

Back to Basics: What is a Jet?

Theory

Detection



theoretical
calculations
(energy flow)

reconstruction
 $\approx 1\text{-to-}1$ @ LHC
(e.g. particle flow)

nonperturbative
confinement
(hadronization)

perturbative
gluonic radiation
(parton shower)

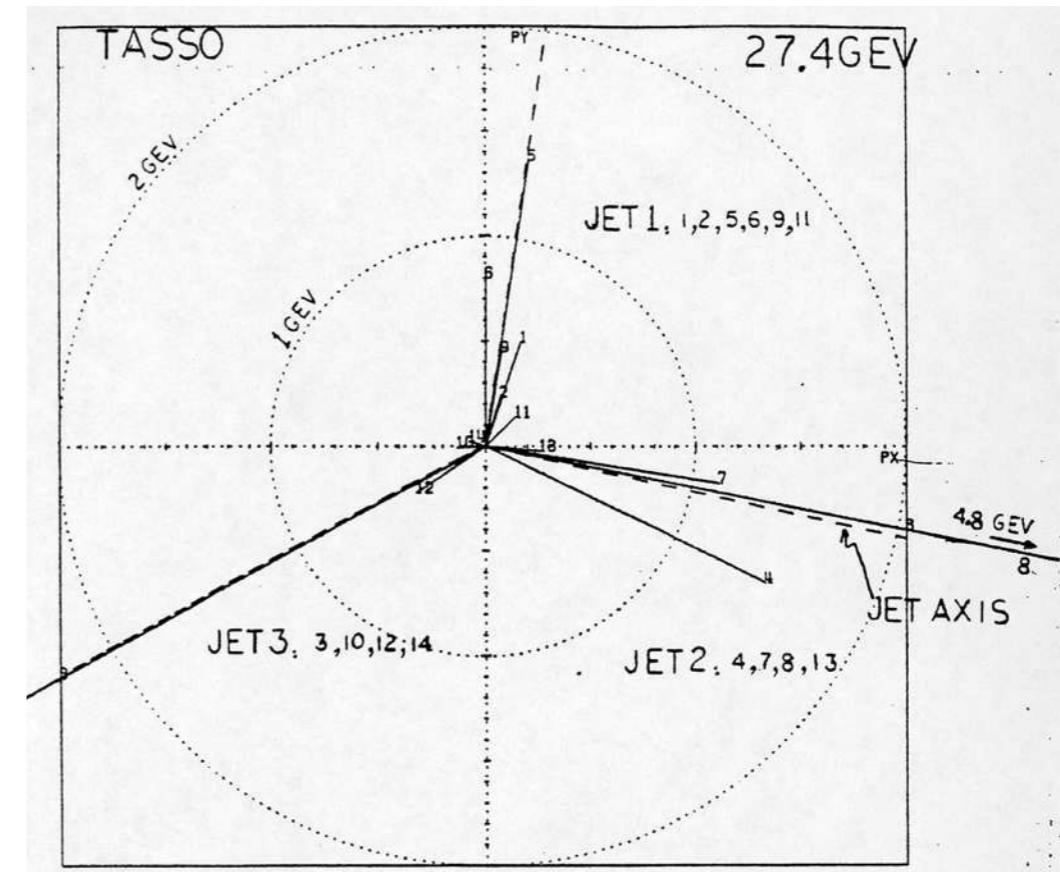
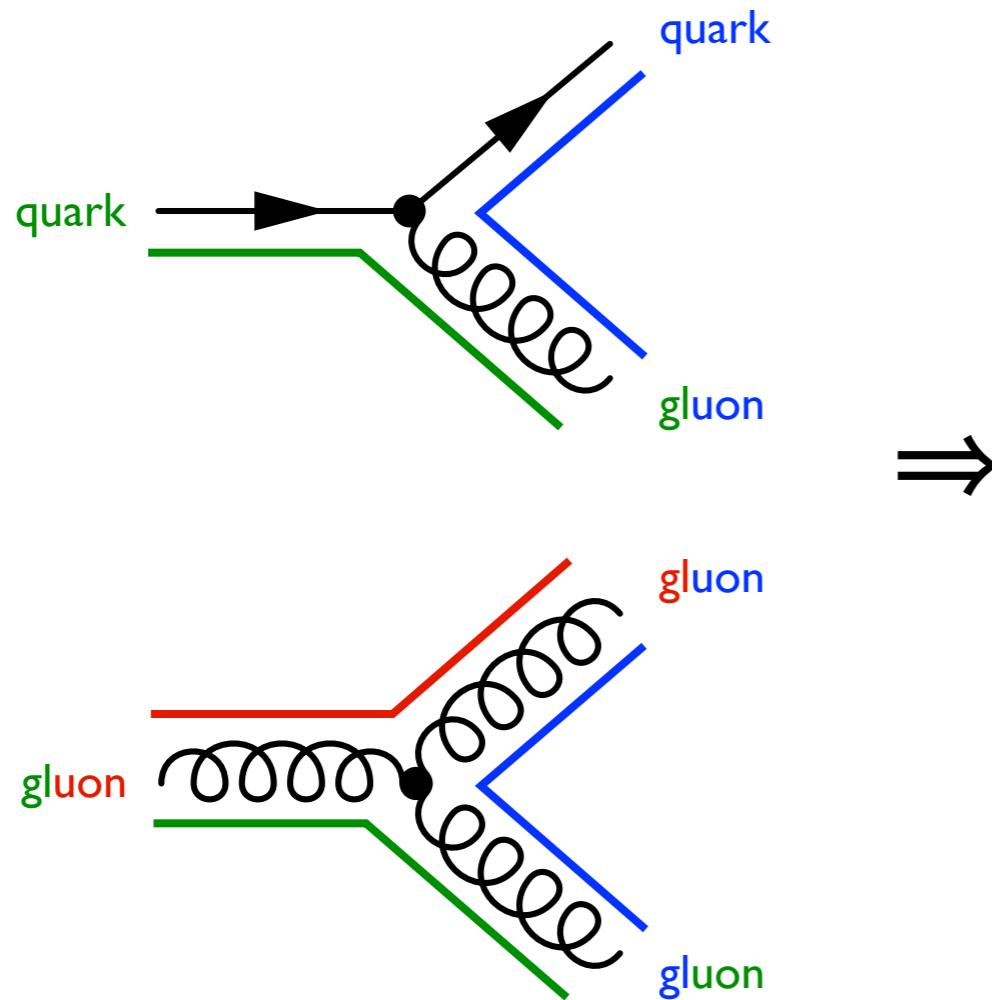
short-distance
collision
(hard scattering)

$$\mathcal{L} = \frac{1}{4g^2} G_{\mu\nu}^\alpha G_{\mu\nu}^\alpha + \sum_j \bar{q}_j (\not{\partial}^\mu D_\mu + m_j) q_j$$

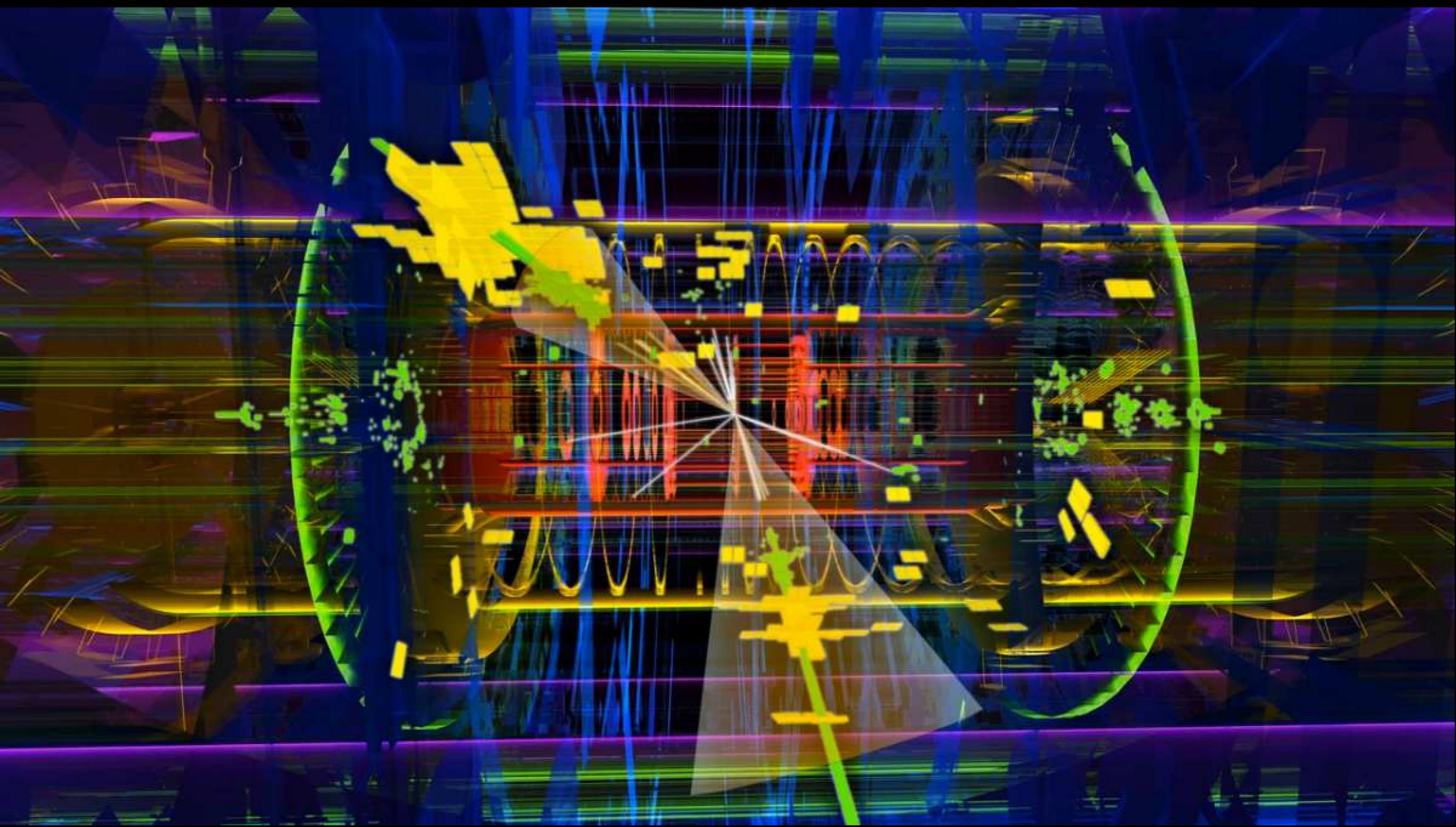
where $G_{\mu\nu}^\alpha = \partial_\mu A_\nu^\alpha - \partial_\nu A_\mu^\alpha + i f_{bc}^{~~a} A_\mu^b A_\nu^c$

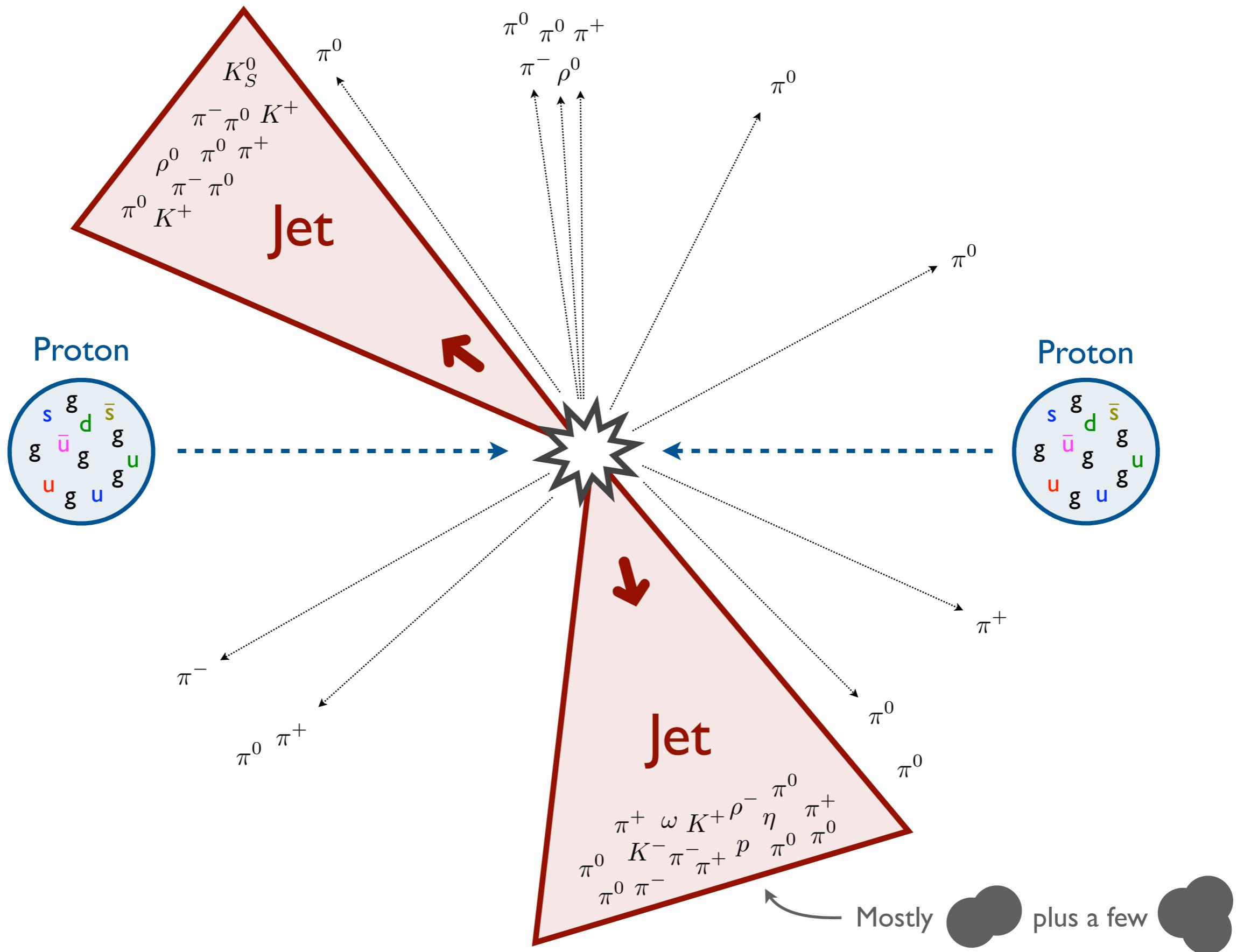
and $D_\mu \equiv \partial_\mu + i t^\alpha A_\mu^\alpha$

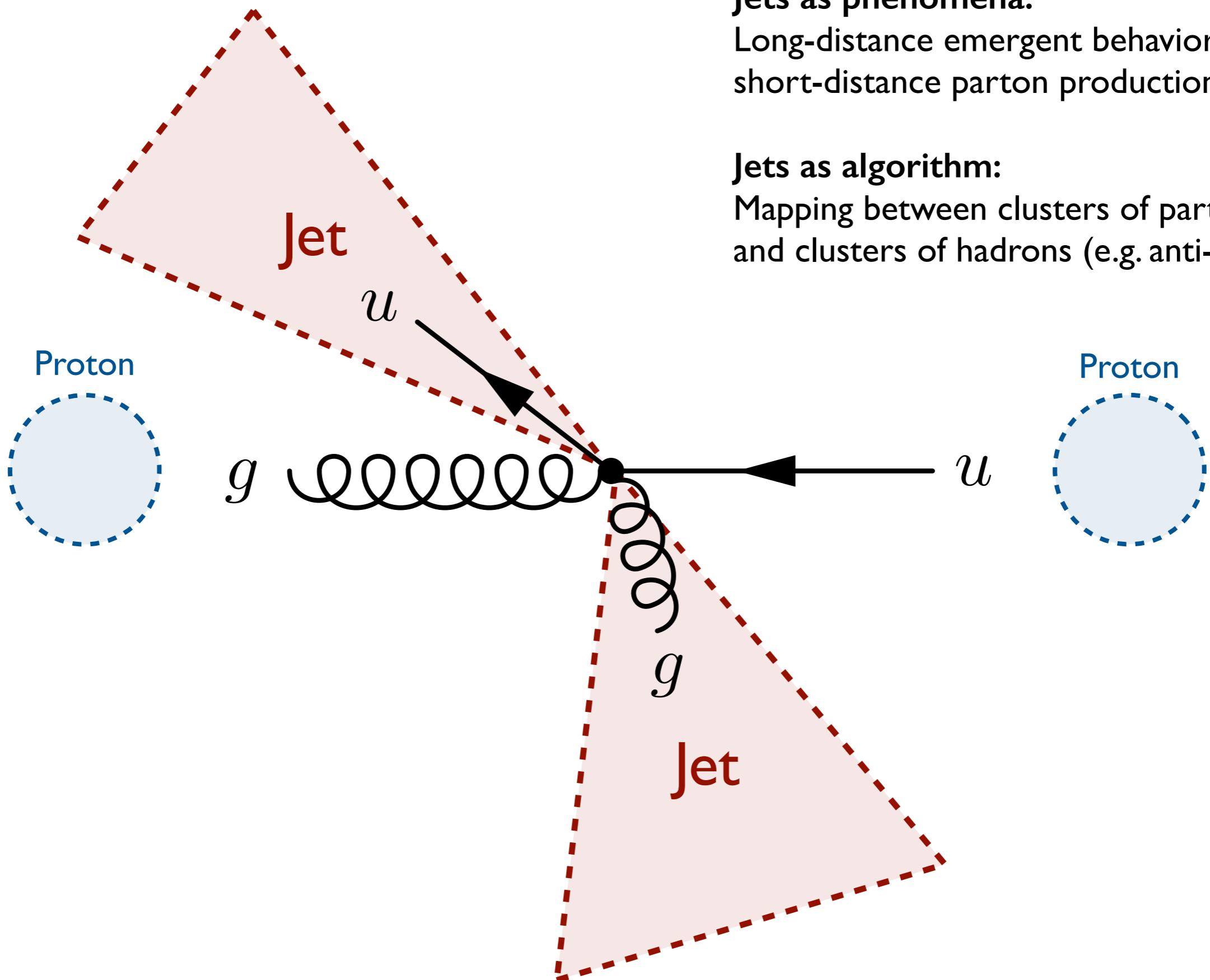
That's it!



[TASSO @ PETRA @ DESY, 1979]

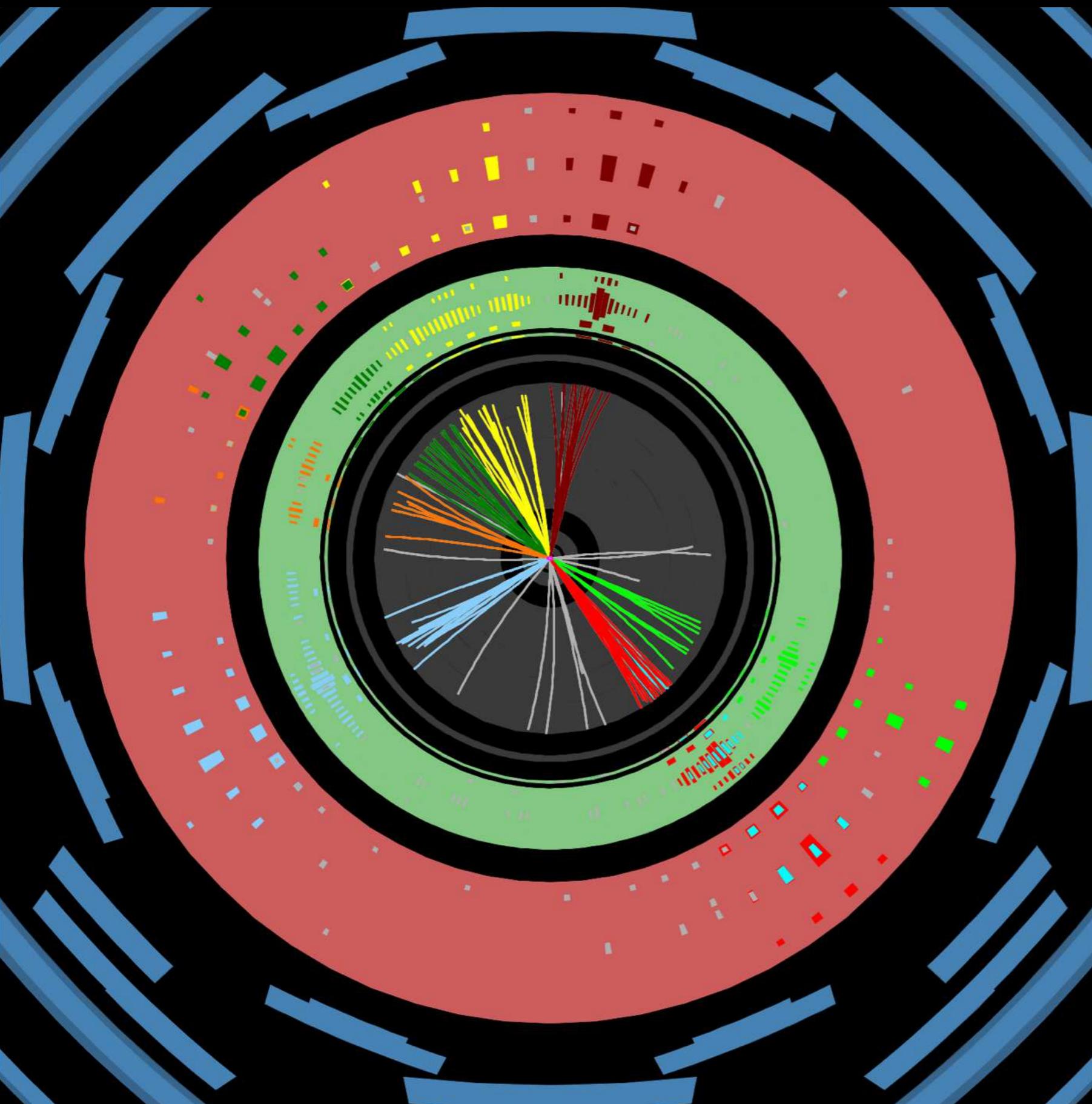






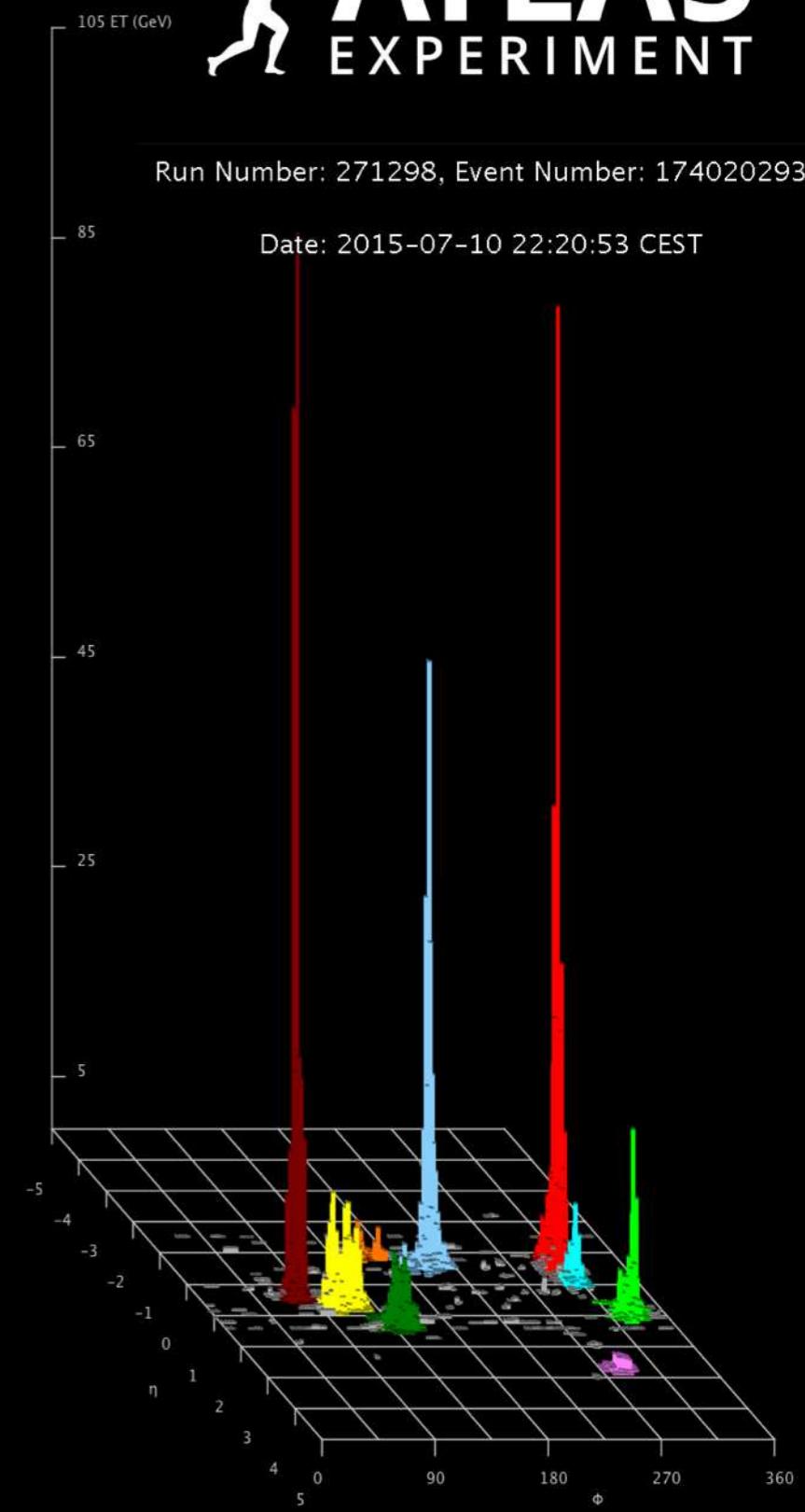
Jets as phenomena:
Long-distance emergent behavior from short-distance parton production

Jets as algorithm:
Mapping between clusters of partons and clusters of hadrons (e.g. anti- k_t)



Run Number: 271298, Event Number: 174020293

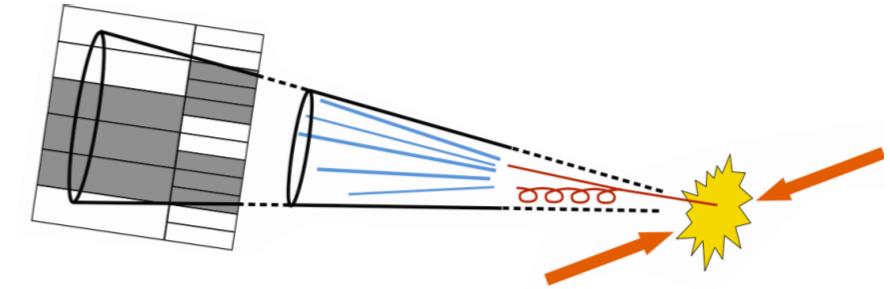
Date: 2015-07-10 22:20:53 CEST



From Jets to Jet Substructure

A Jet/QCD Renaissance

c. 2008–present

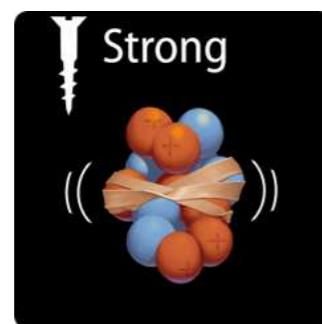


LHC

Higher Energy
Higher Luminosity
Finer Segmentation

vs. Tevatron

$\approx x3.5\text{--}7$
 $\approx x10\text{--}20$
 $\approx x5$



Theoretical Progress

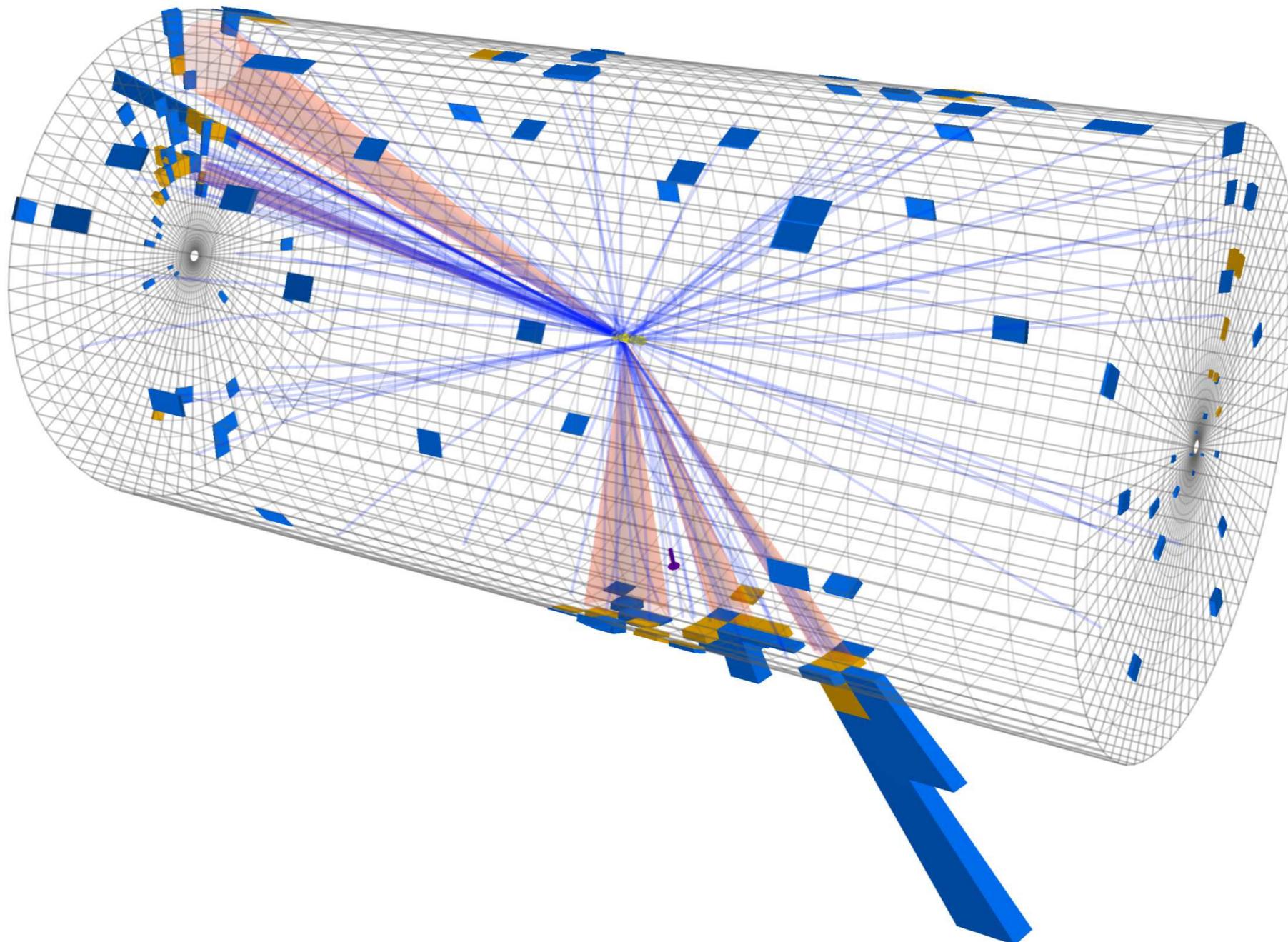
New Jet Algorithms
Loop/Leg/Log Explosion
Jet Substructure

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

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

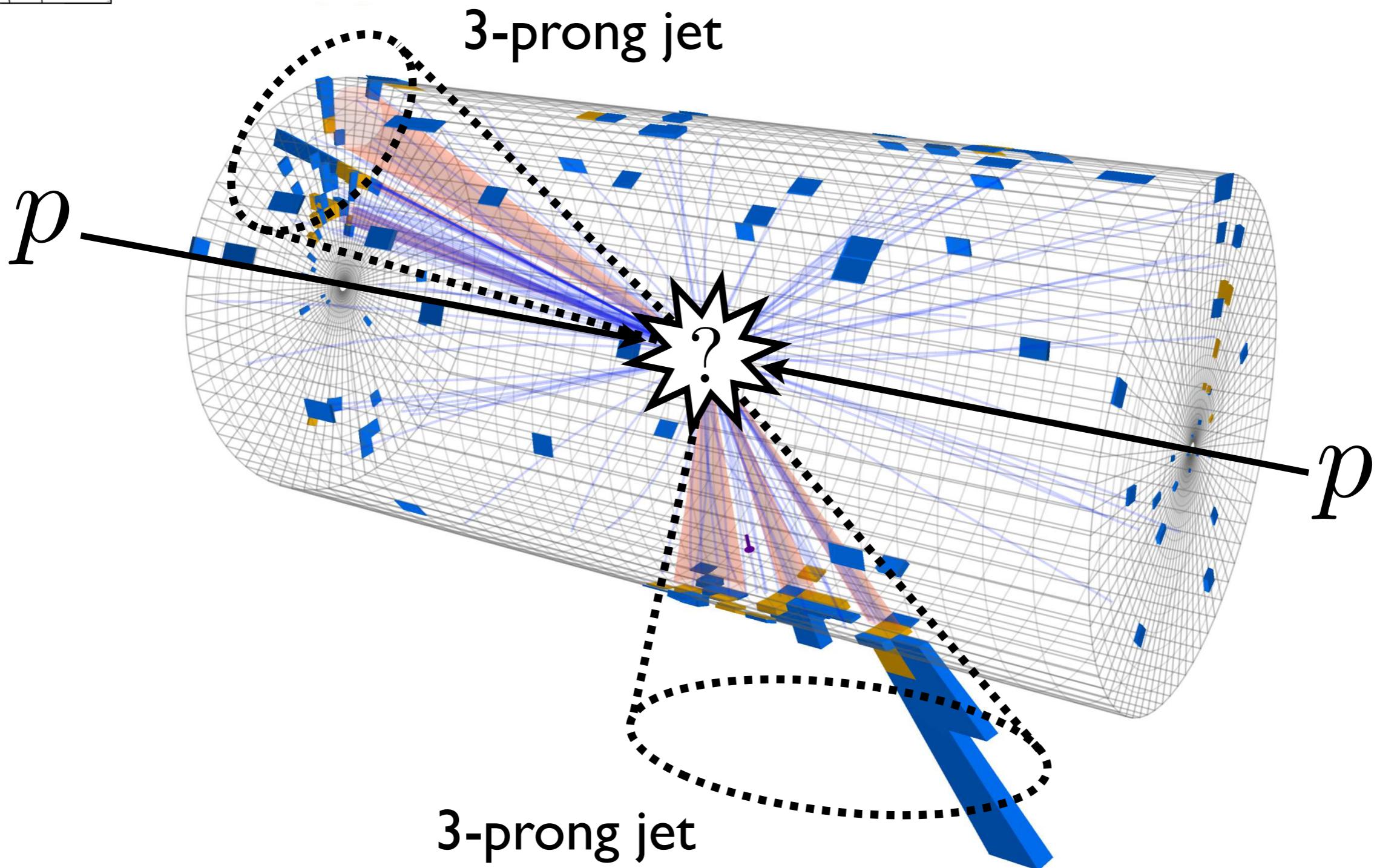


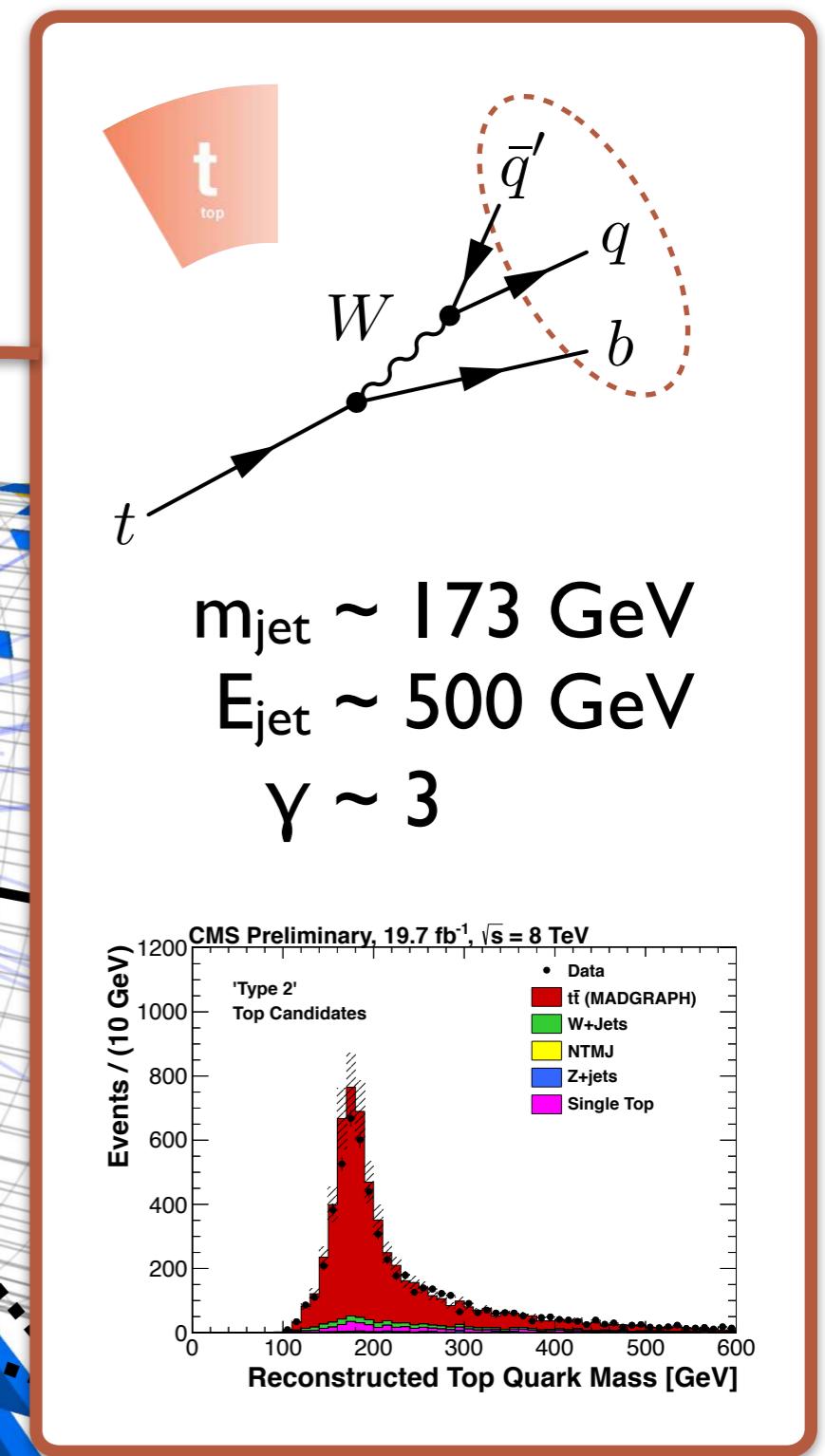
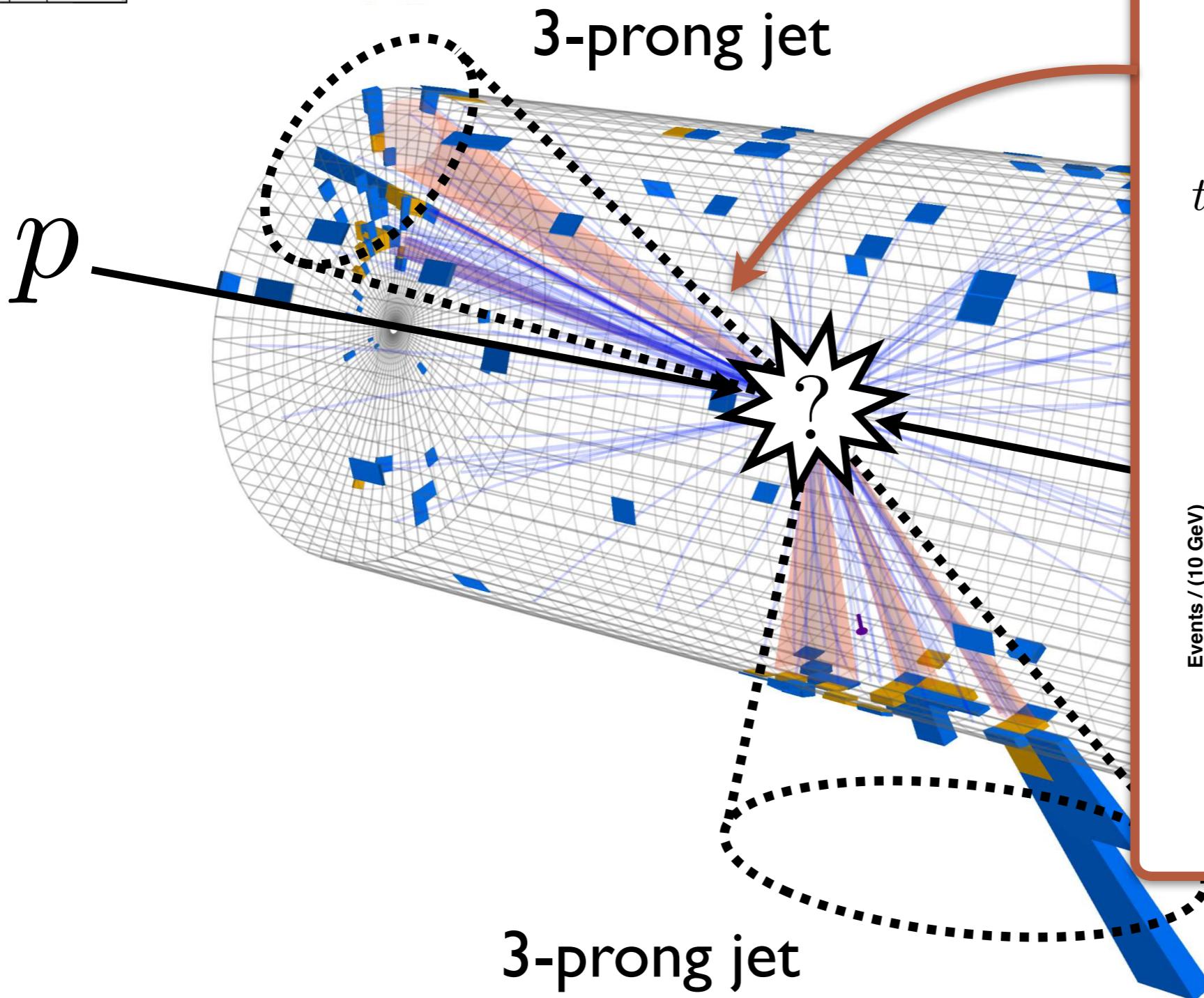
CMS Experiment at LHC, CERN
Data recorded: Sun Jul 12 07:25:11 2015 CEST
Run/Event: 251562 / 111132974
Lumi section: 122
Orbit/Crossing: 31722792 / 2253

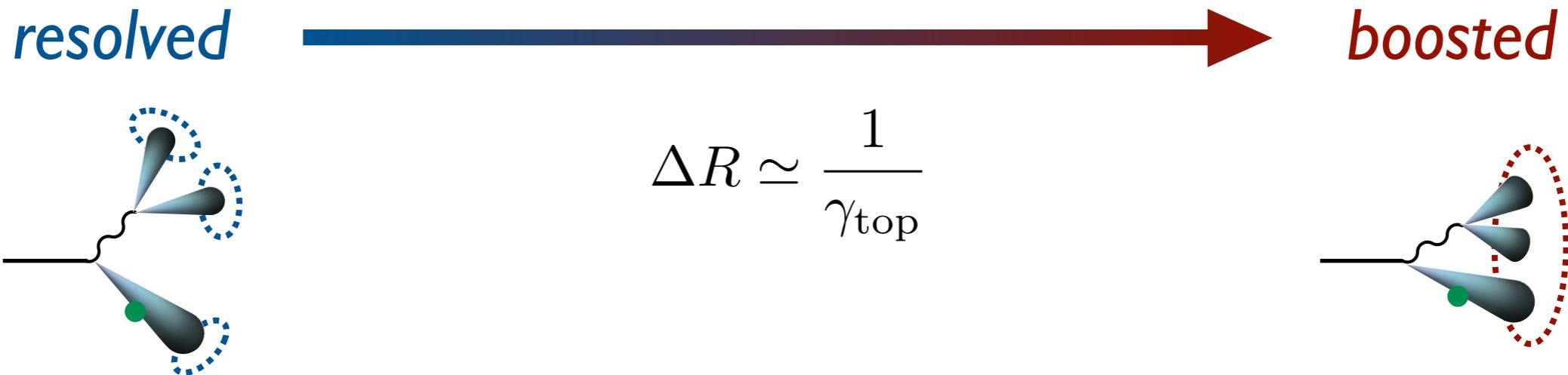
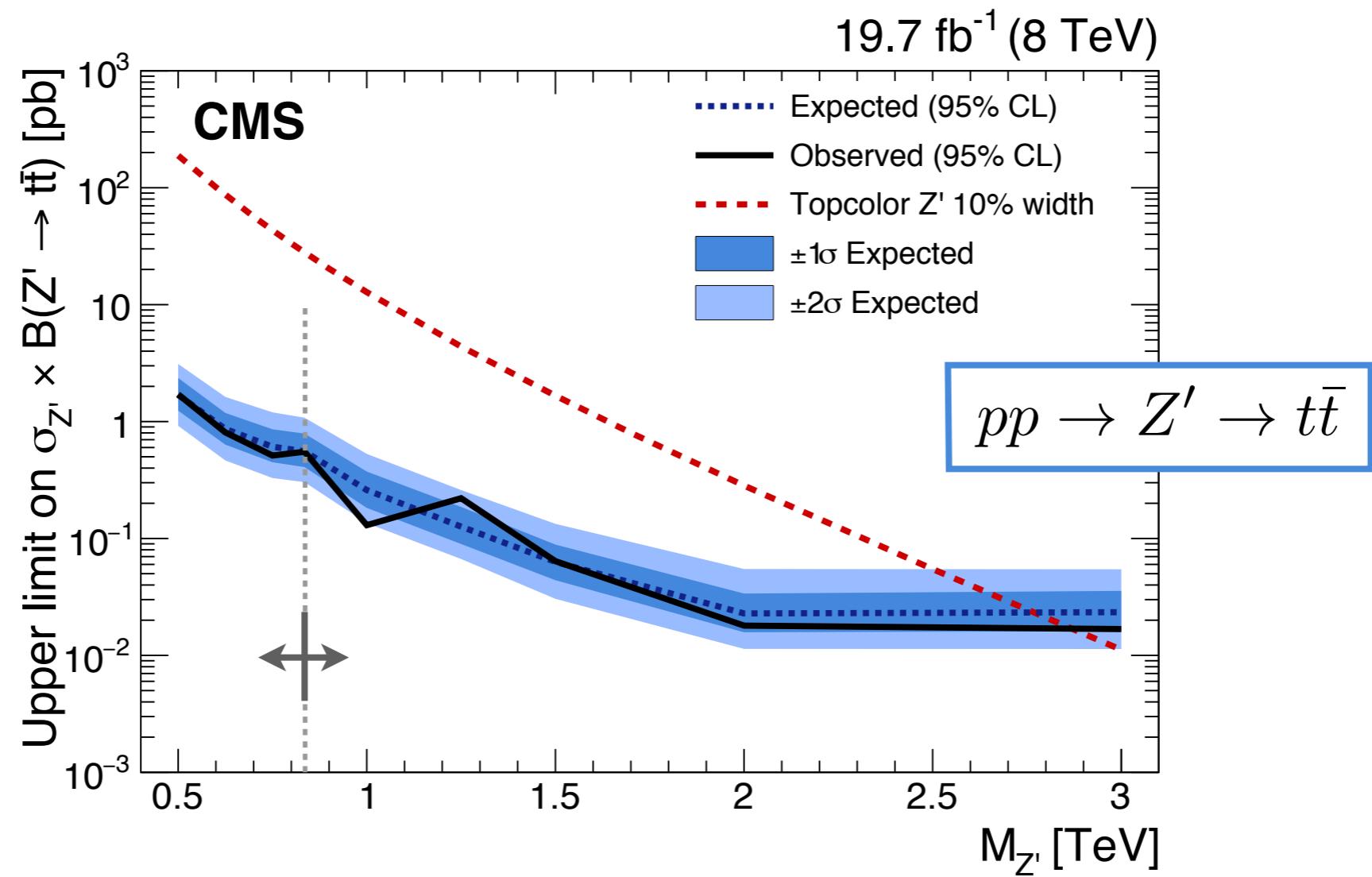




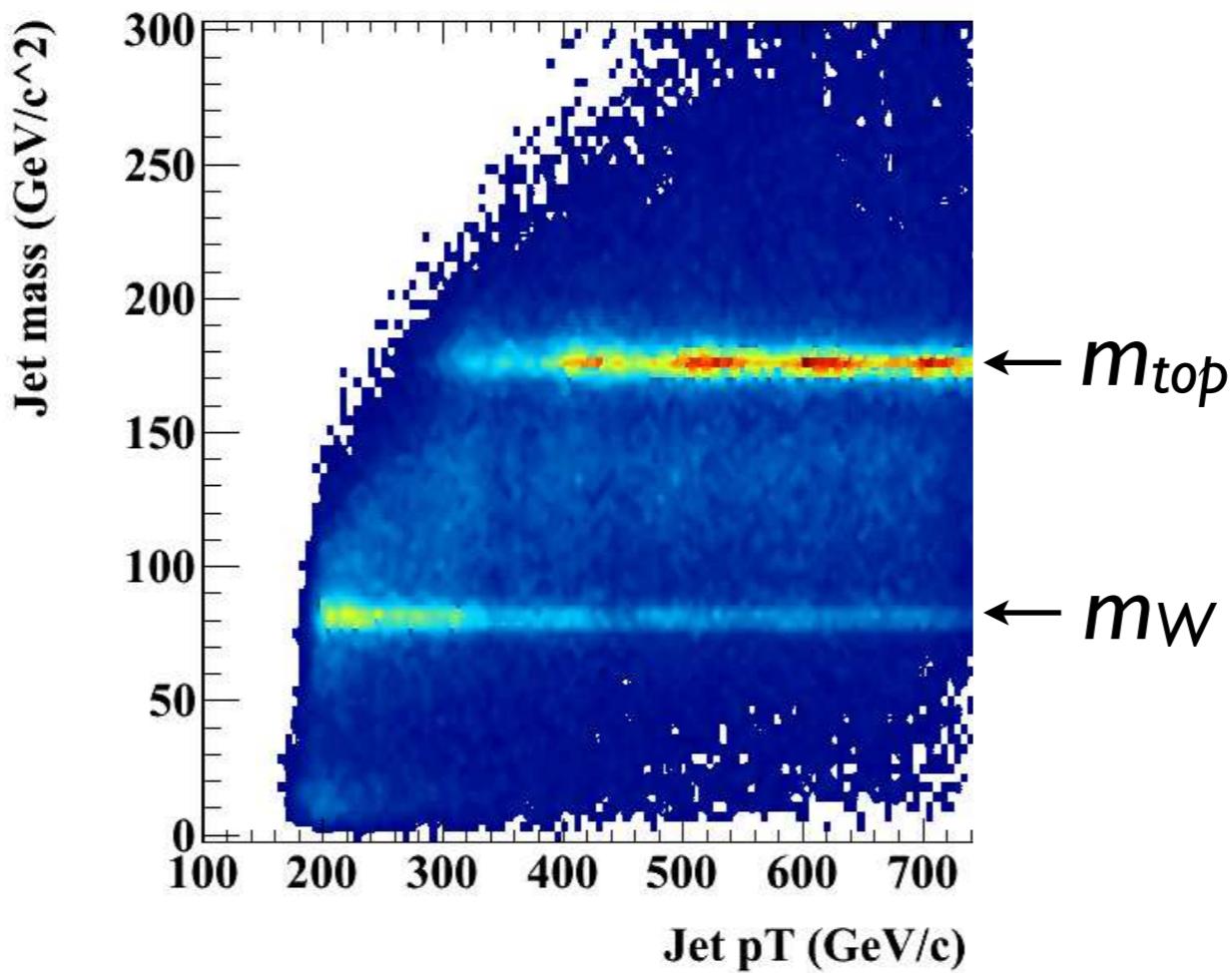
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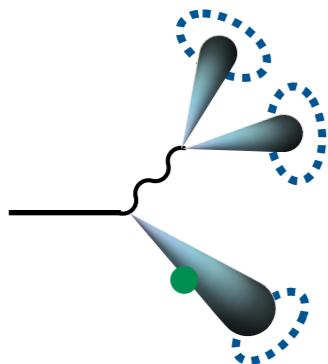




[CMS 2011, 2013, 2015; using Kaplan, Rehermann, Schwartz, Tweedie, 2008; Ellis, Vermilion, Walsh, 2009]

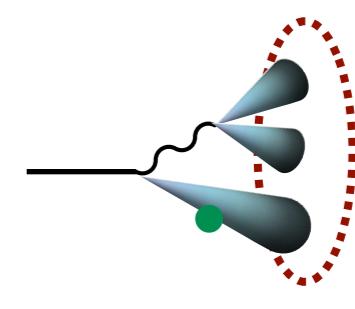
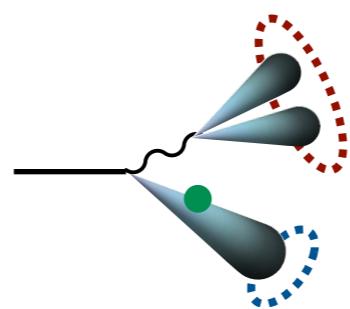


resolved

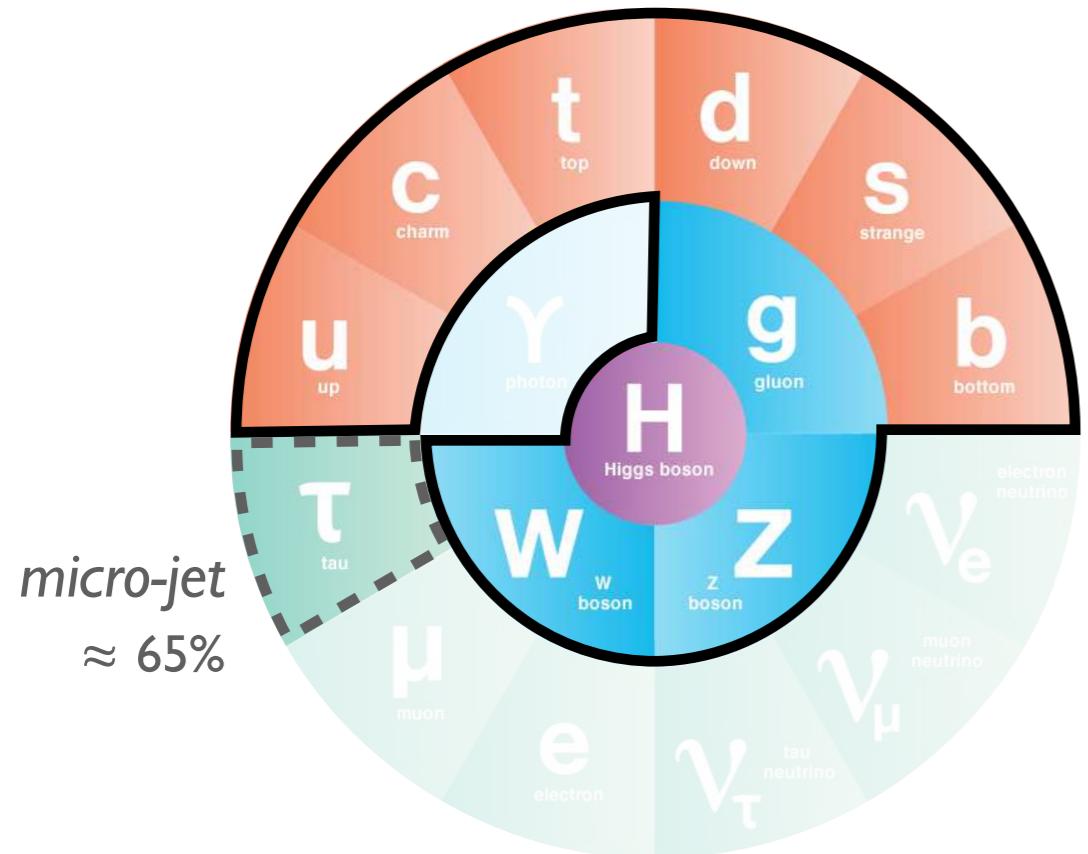


→

boosted

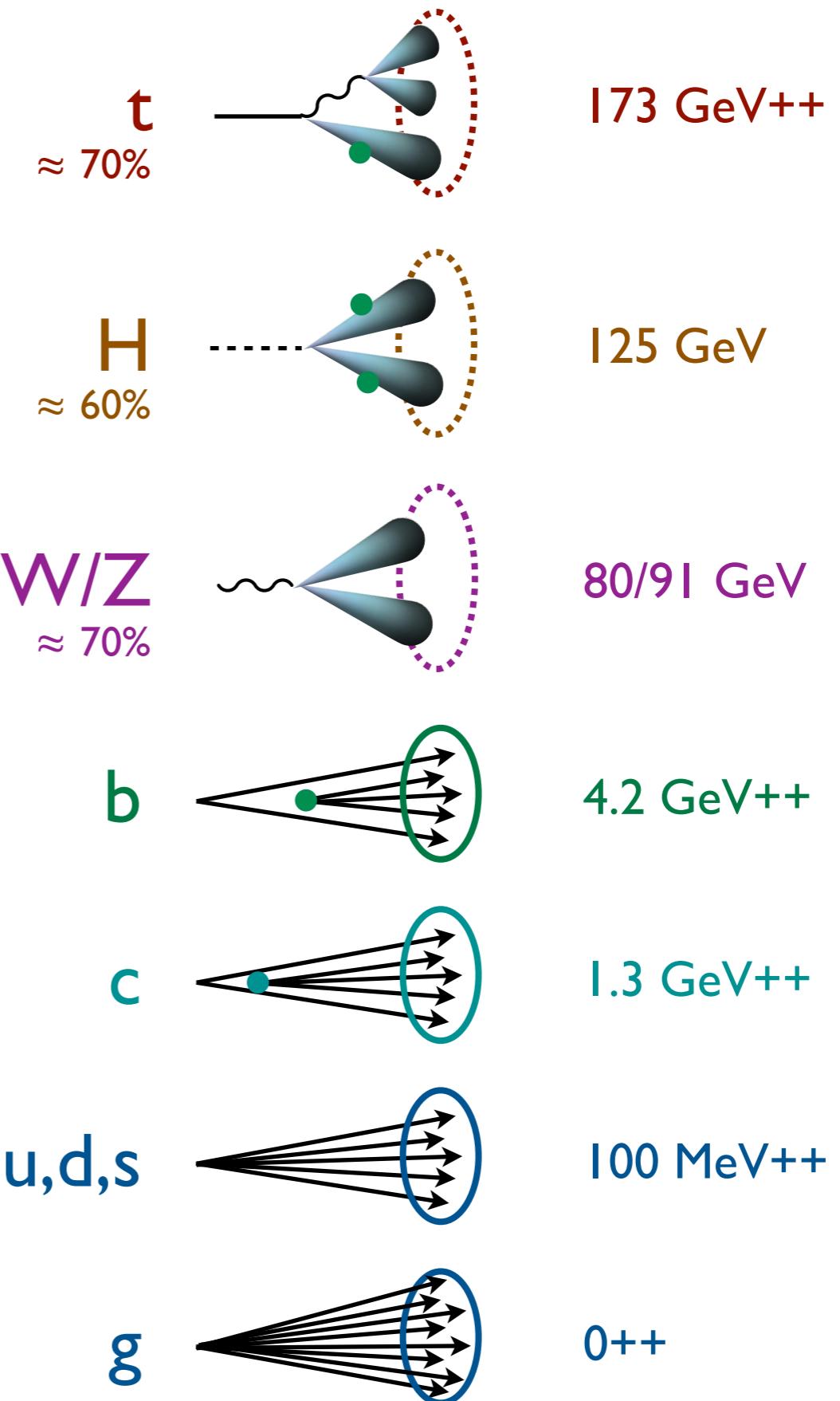


[CMS 2011, 2013, 2015; using Kaplan, Rehermann, Schwartz, Tweedie, 2008; Ellis, Vermilion, Walsh, 2009]



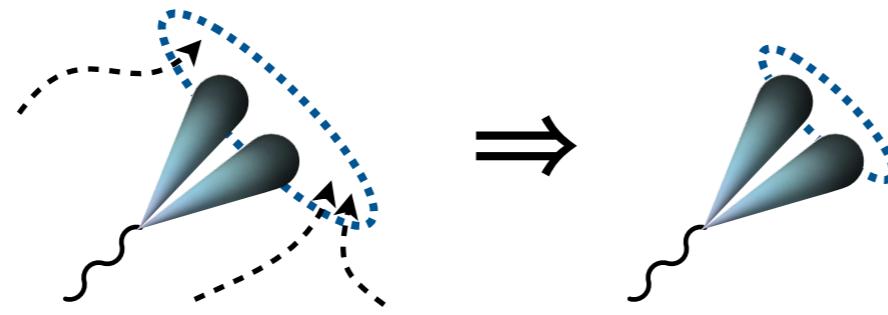
Jets from the Standard Model

++ = plus gluonic radiation



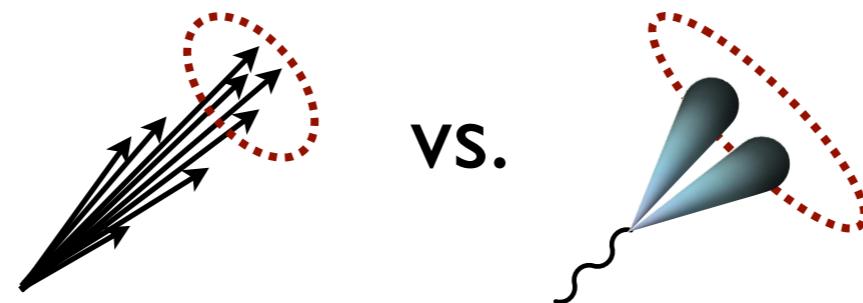
Key Substructure Techniques

Grooming: e.g. ISR/UE/pileup



[Mass Drop/Filtering, Trimming, Pruning, Soft Drop, Jet Reclustering...;
for pileup: Area Subtraction, Jet Cleansing, SoftKiller, PUPPI, Constituent Subtraction...]

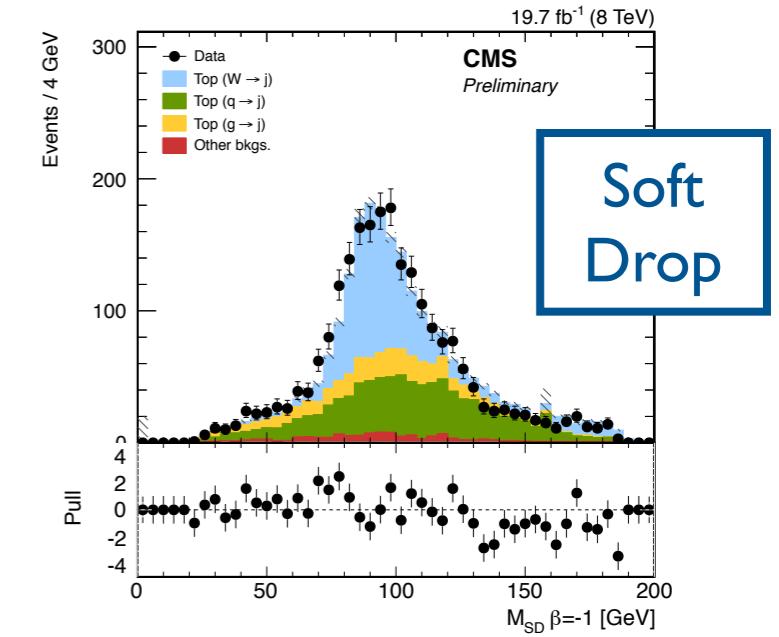
Discrimination: e.g. 1-prong vs. N-prong



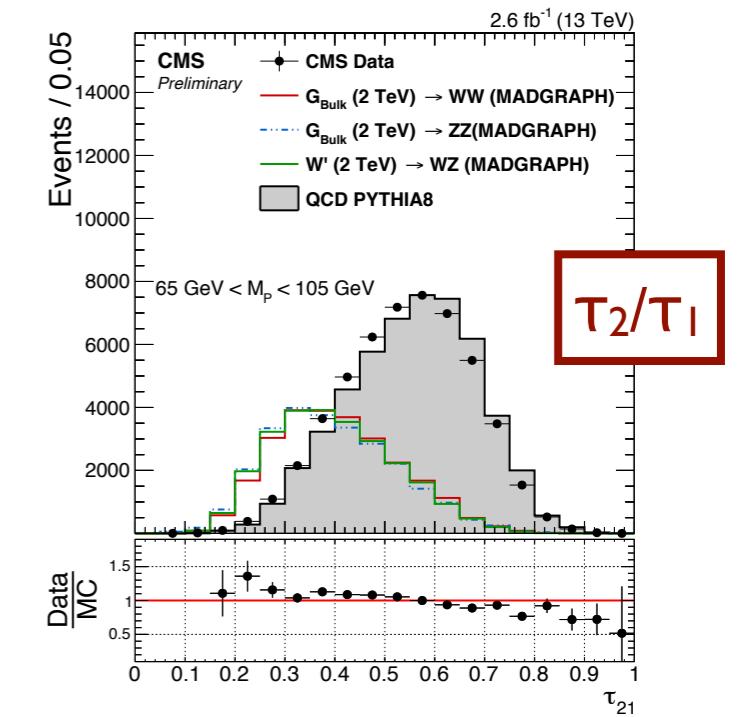
[p_T Balance, Y-splitter, Angularities, Planar Flow, N-subjettiness, Angular Structure Functions, Jet Charge, Jet Pull, Energy Correlation Functions, Dipolarity, p_T^D , Zernike Coefficients, LHA, Fox-Wolfram Moments, JHU/CMS Top Tagger, HEPTopTagger, Template Method, Shower Deconstruction, Subjet Counting, Wavelets, Q-Jets, Telescoping Jets...]

W/Z-Tagging @ CMS

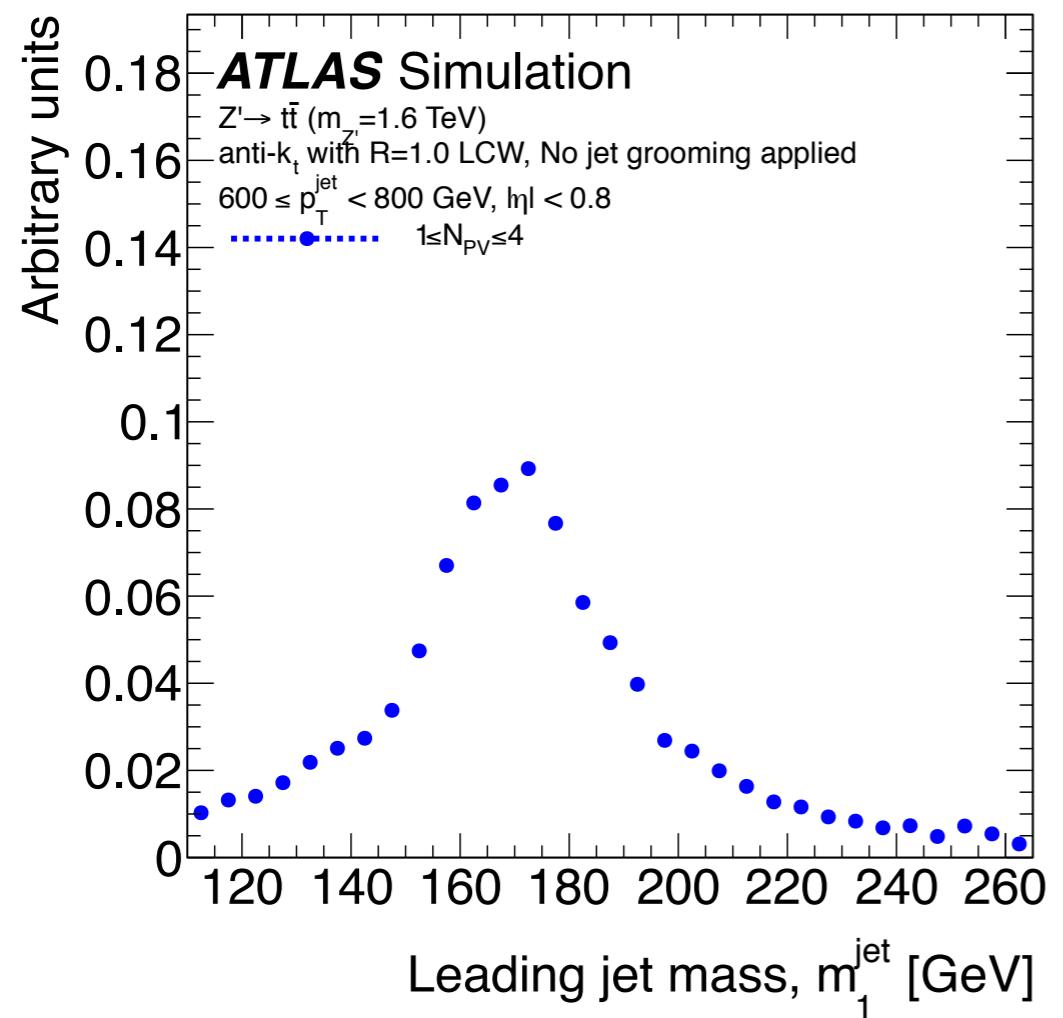
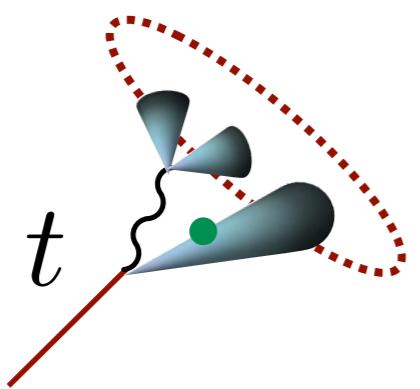
[JME-14-002, CMS-PAS-EXO-15-002]

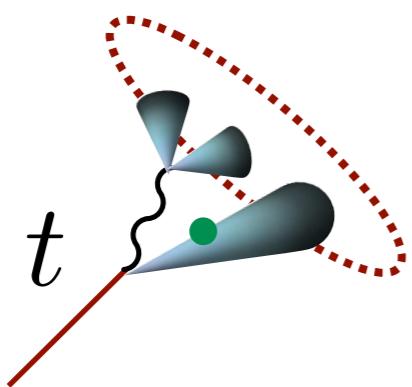


[using Larkoski, Marzani, Soyez, JDT, 1402.2657]

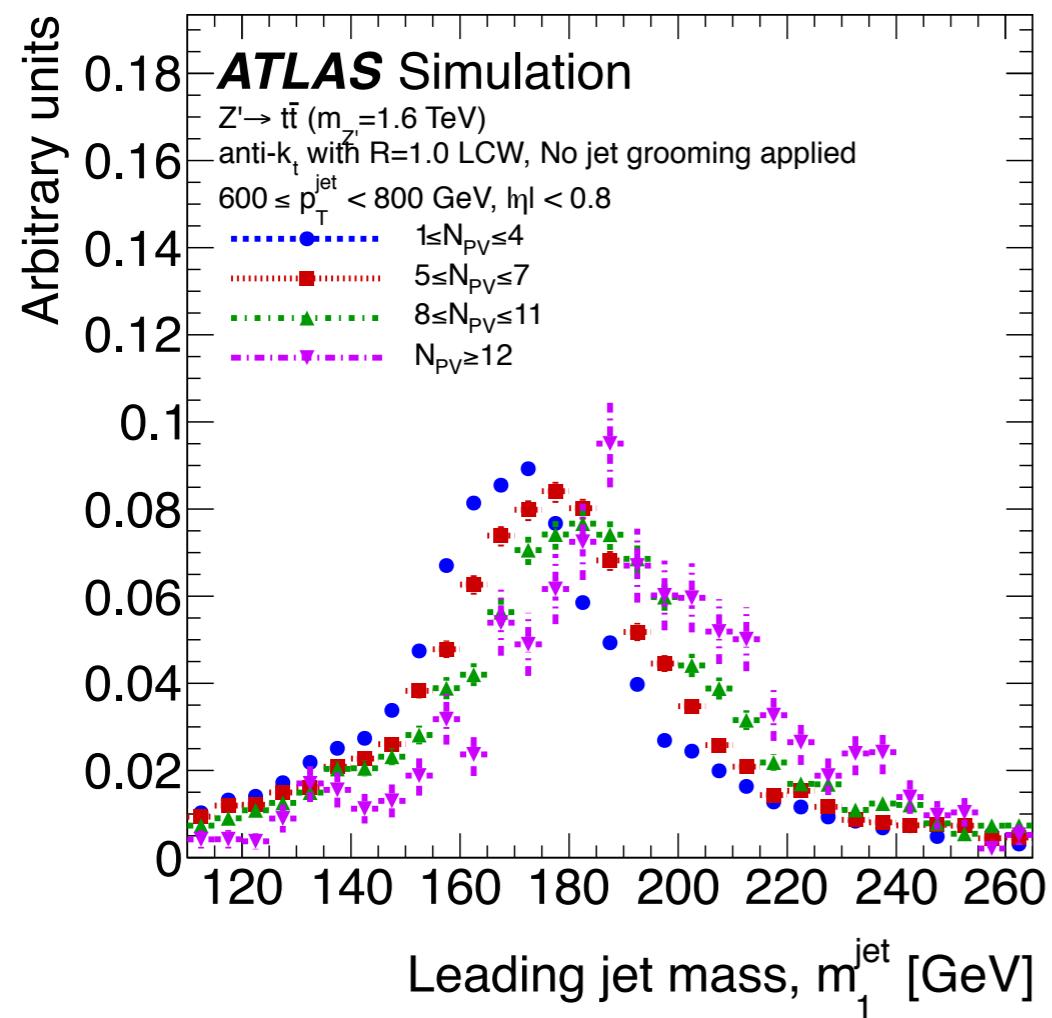
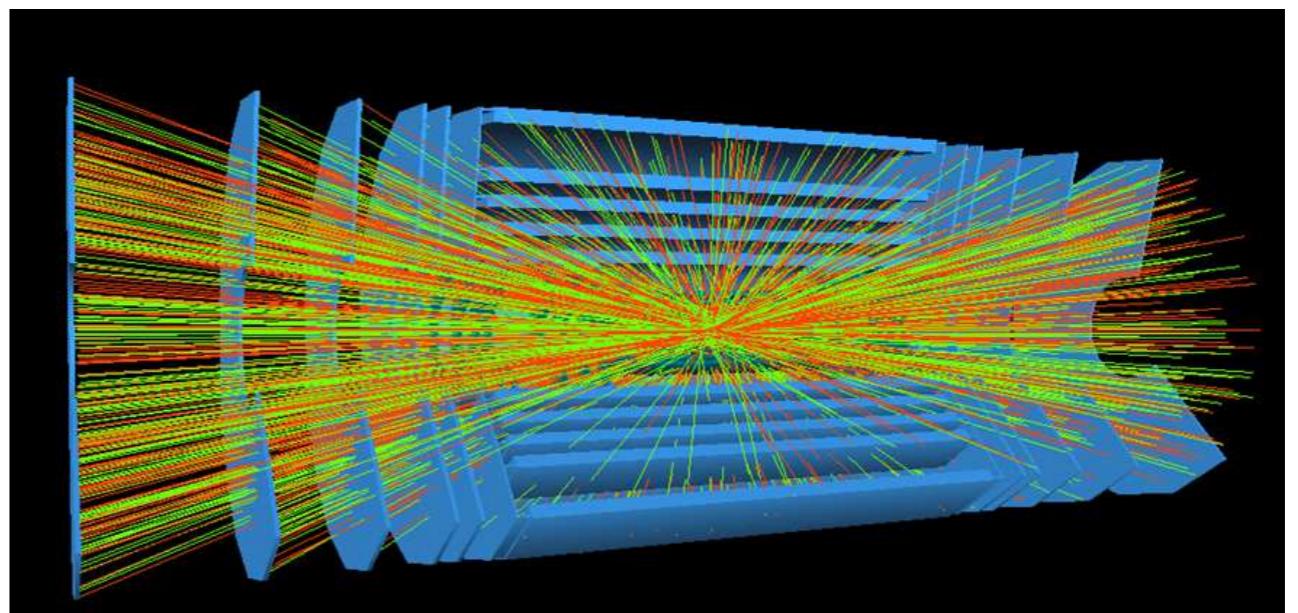


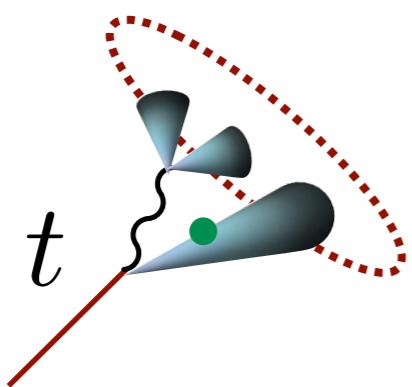
[using JDT, Van Tilburg, 1011.2268, 1108.2701]



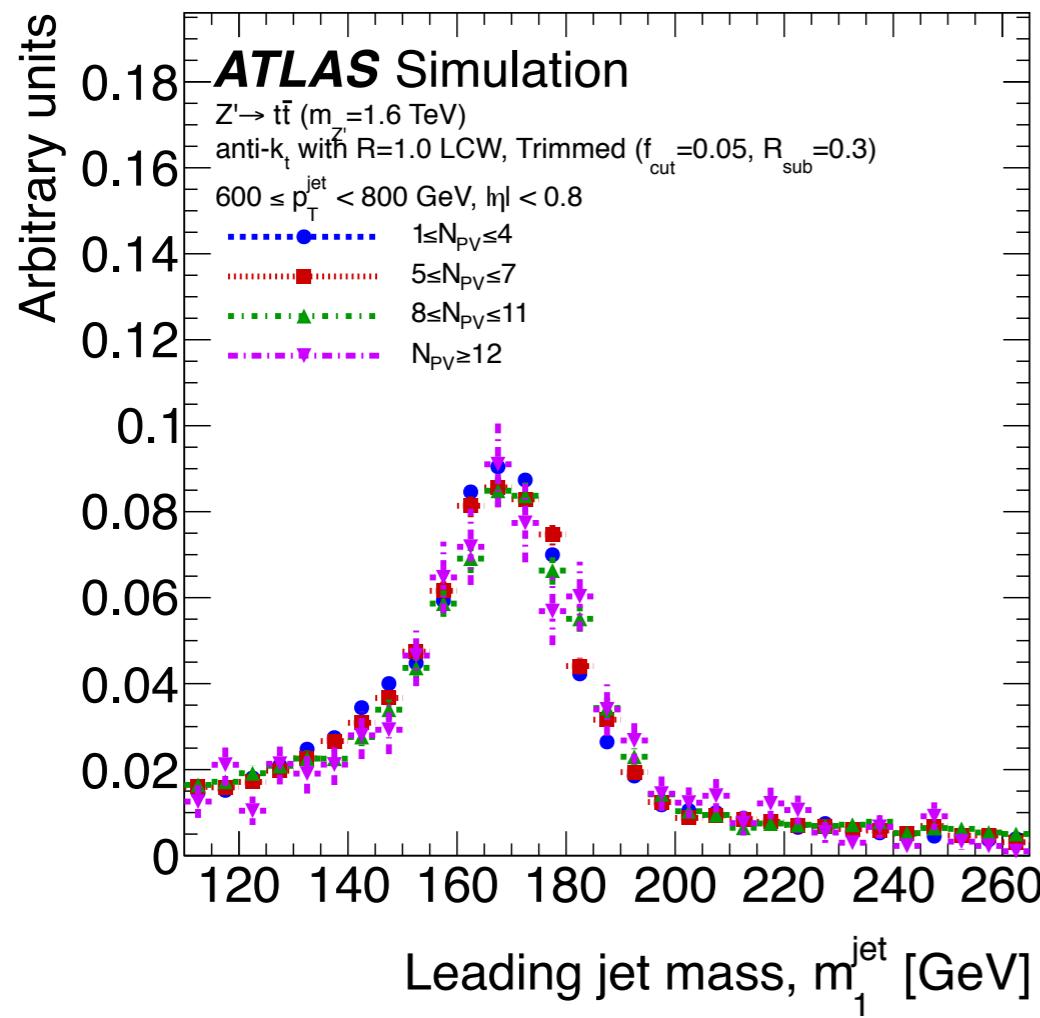
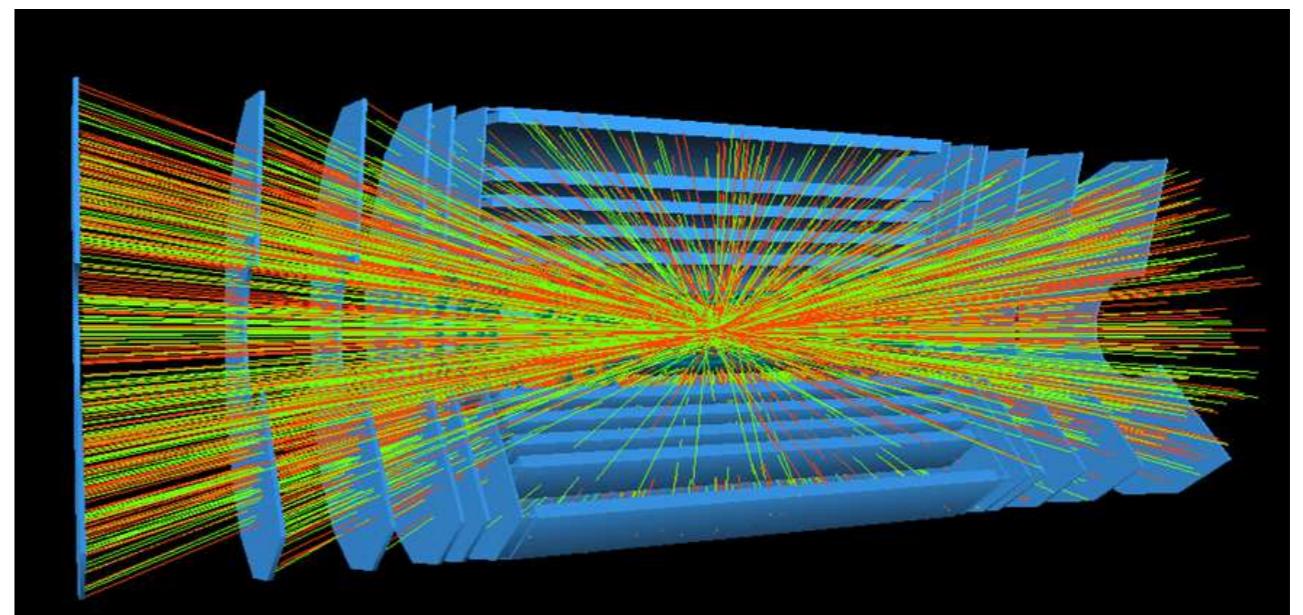


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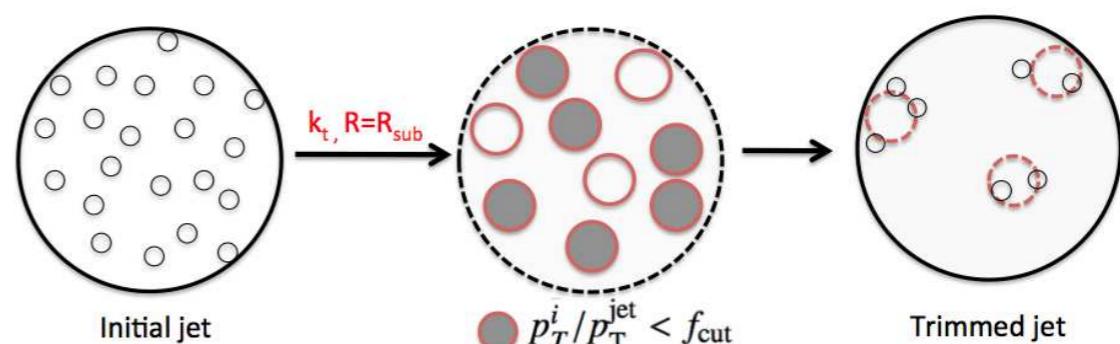


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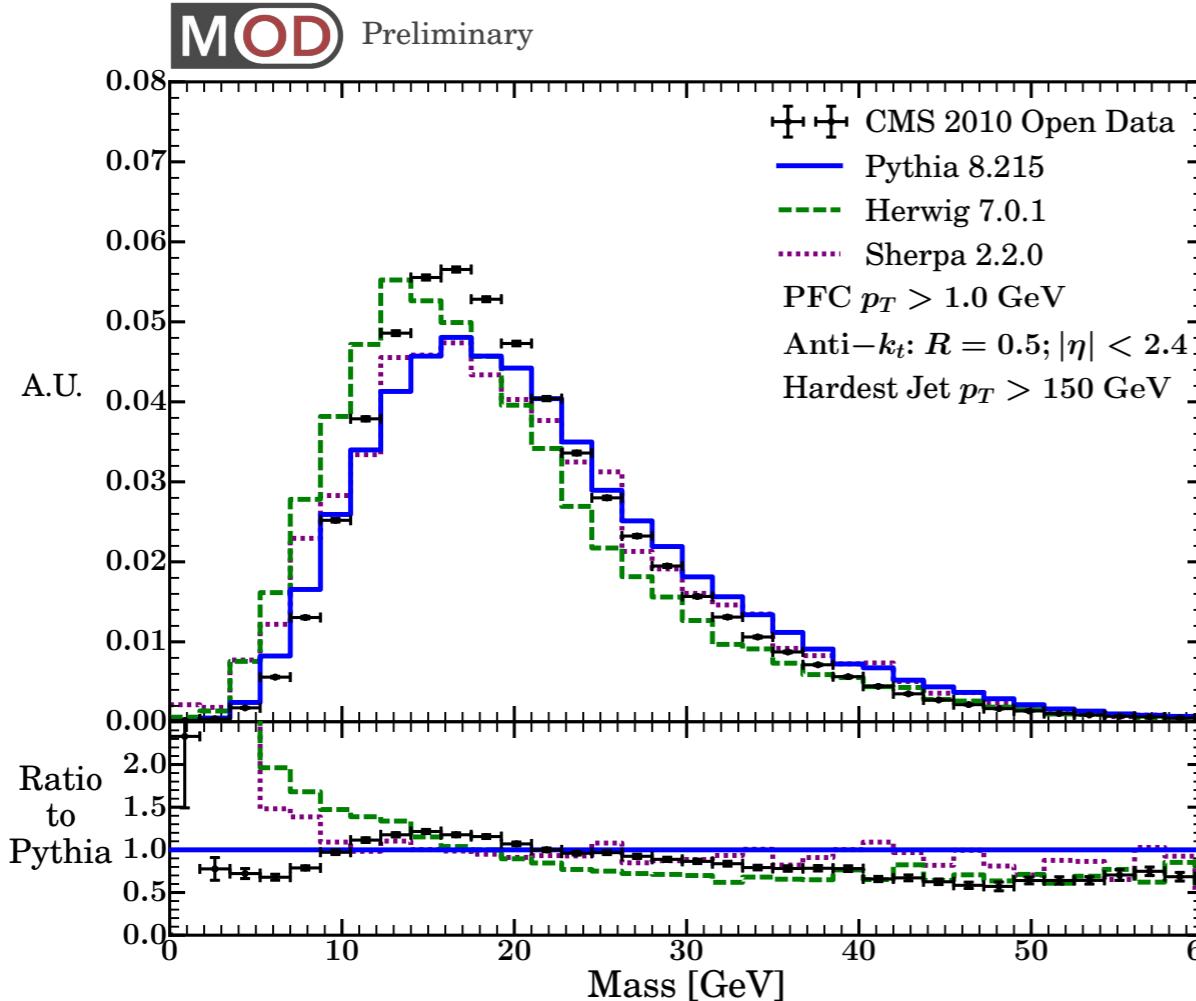
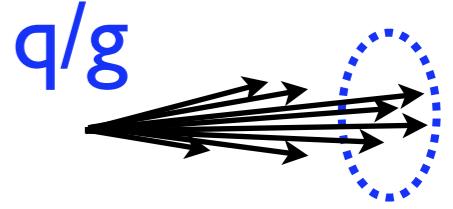
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Jet Trimming



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

Regular Jets Have Mass, Too



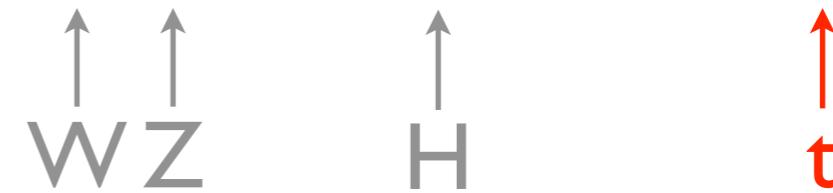
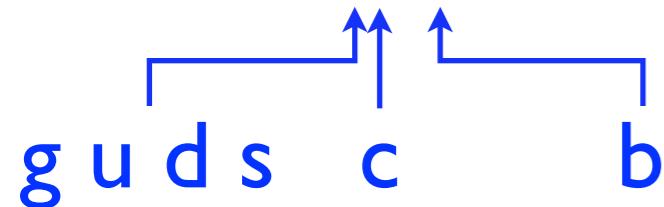
opendata
CERN
“Accelerating science
through public data”

LHC
(2010)

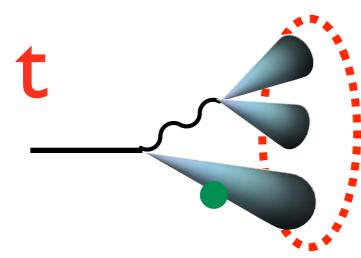
$\approx E_{\text{jet}}$

→

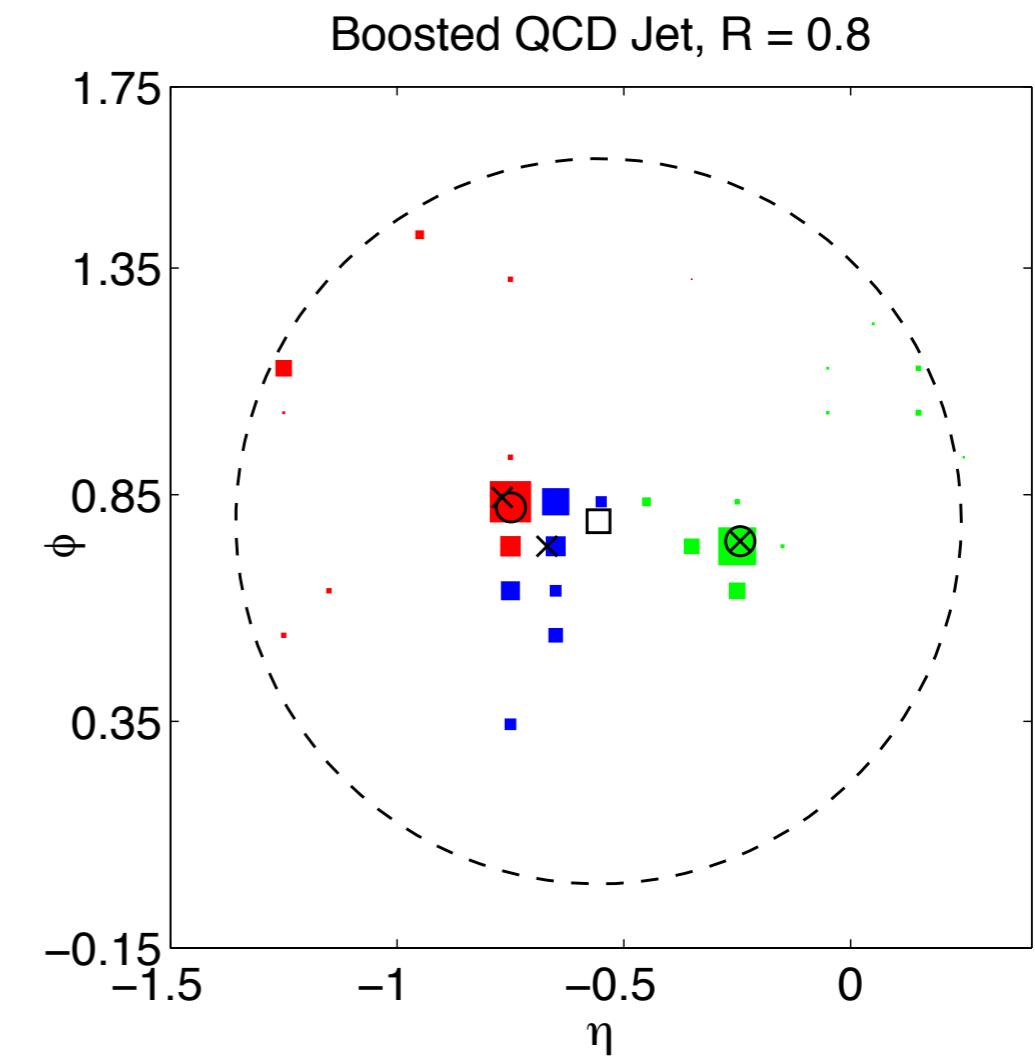
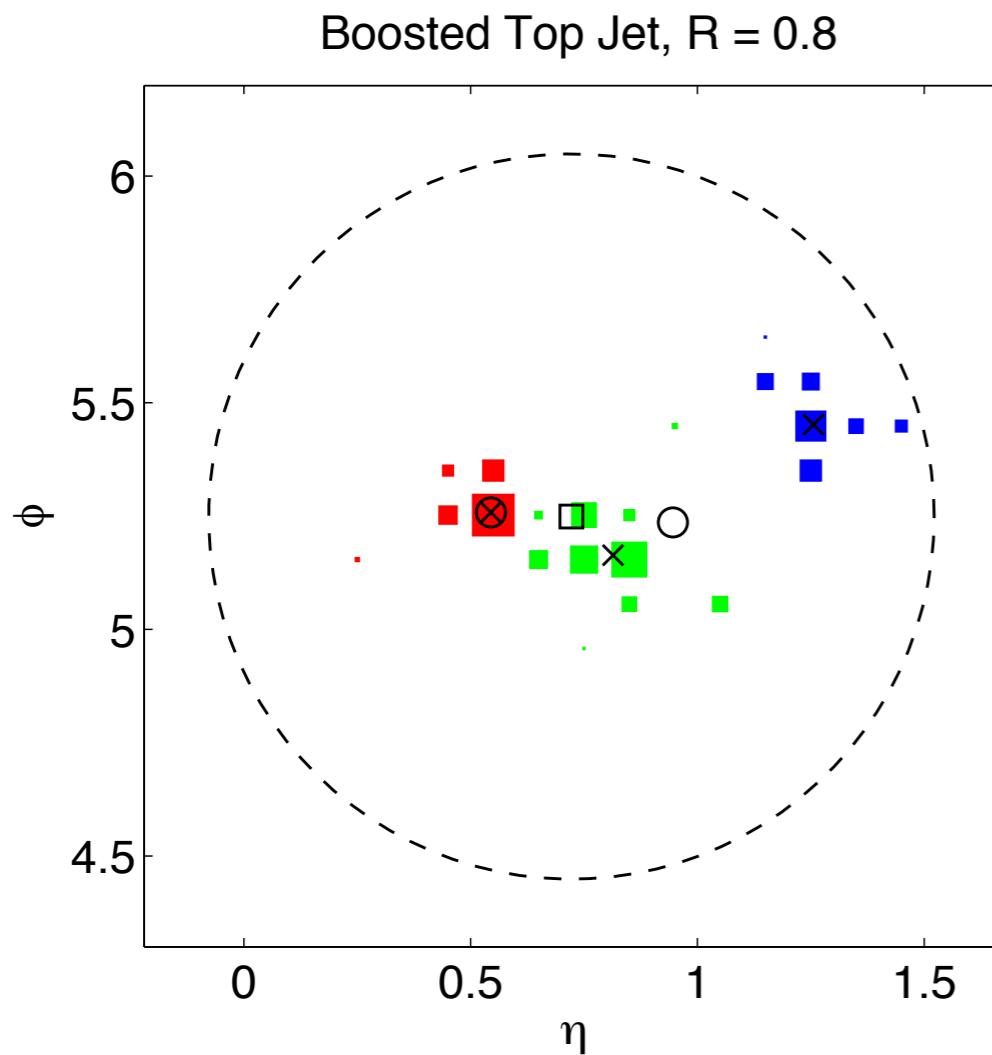
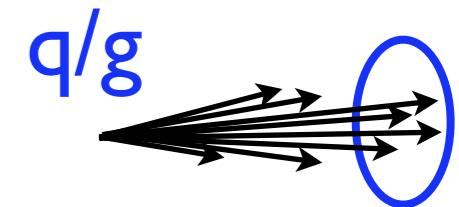
7,000



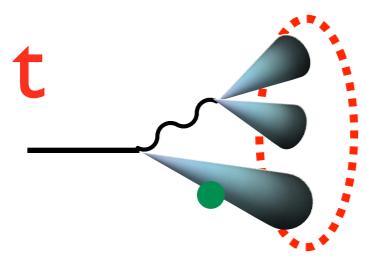
[Larkoski, Marzani, Romero, JDT, Tripathee, Xue, in progress]



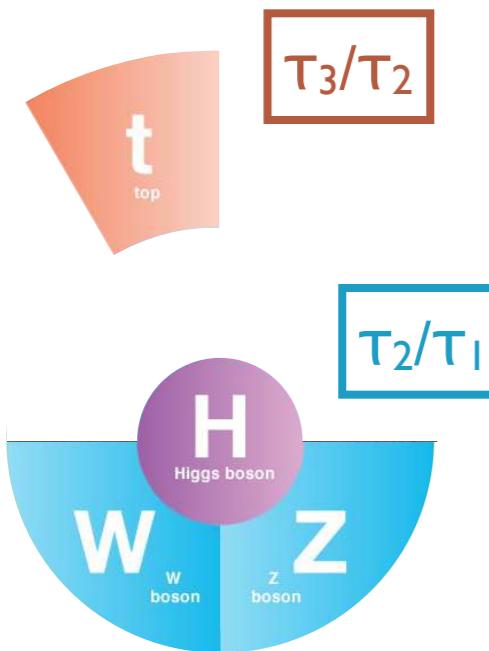
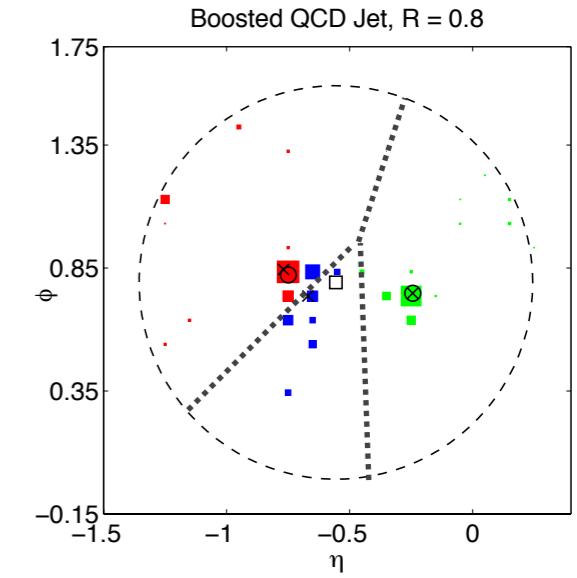
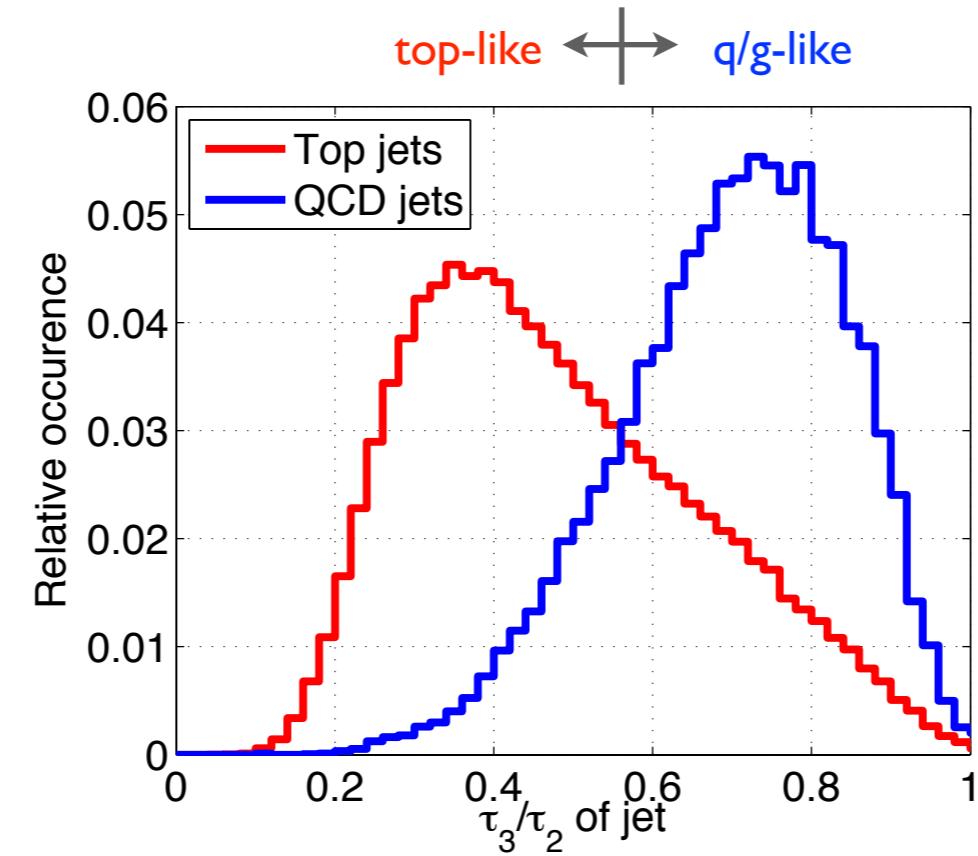
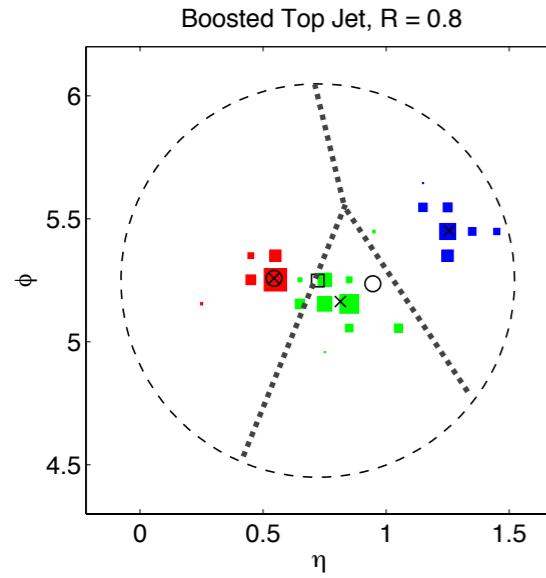
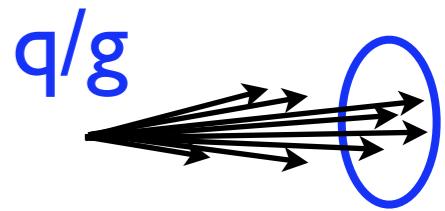
N-Prong vs. I-Prong



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



N-Prong vs. I-Prong

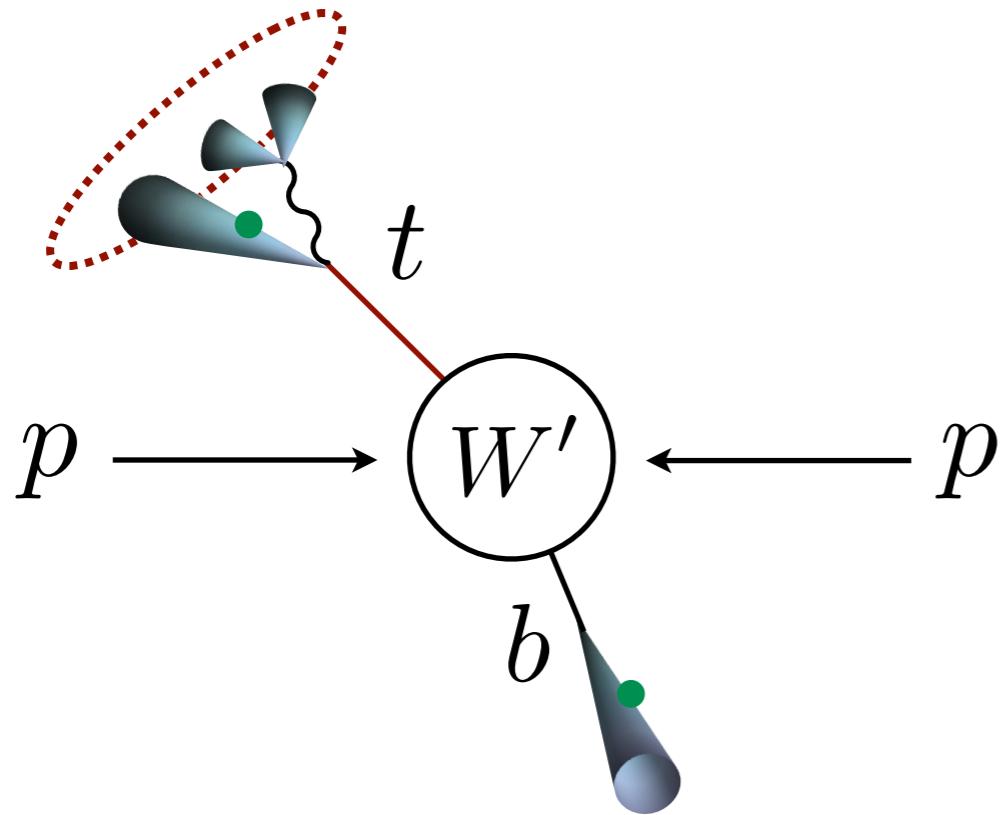


N-subjettiness

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

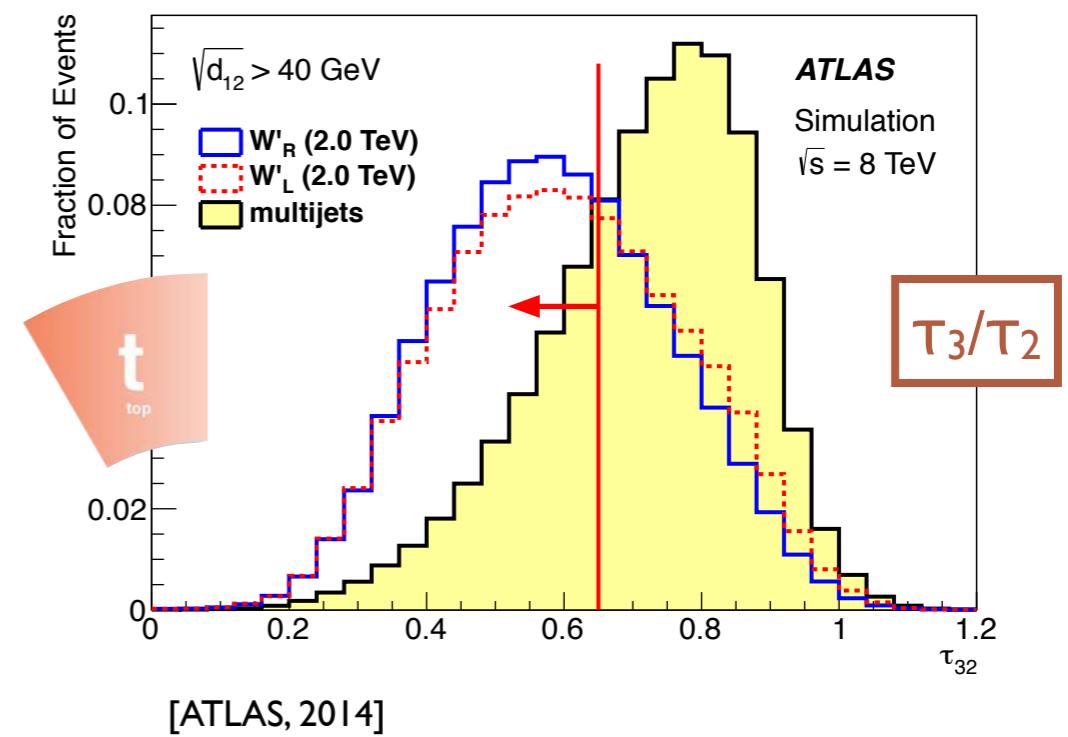
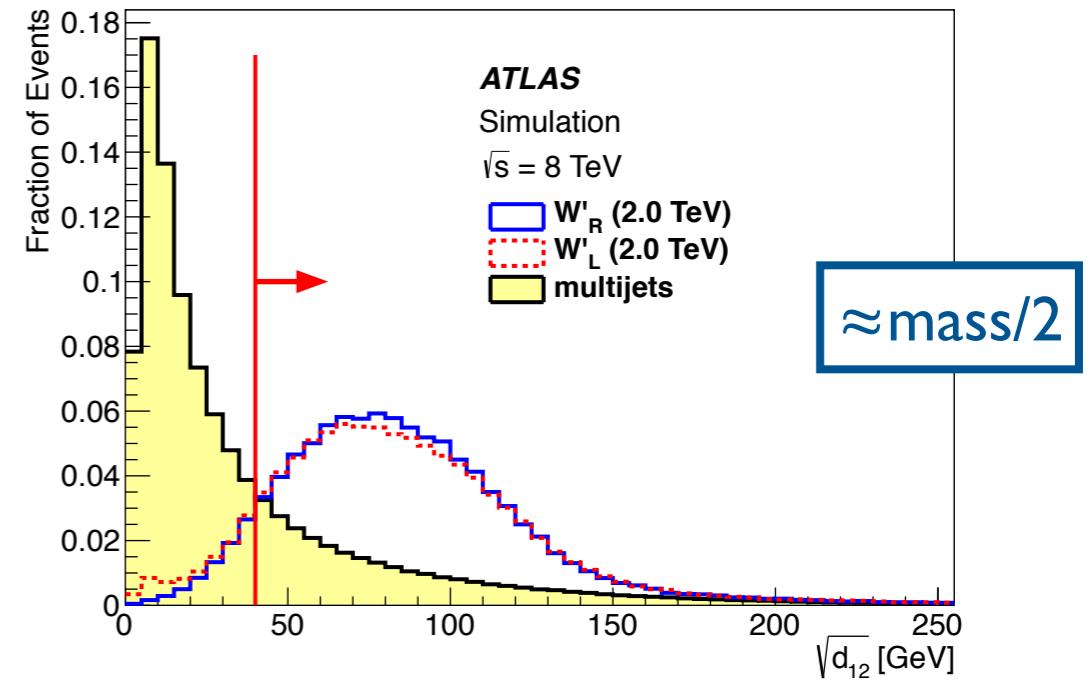
[JDT, Van Tilburg, 2010, 2011; see also Stewart, Tackmann, Waalewijn, 2010; Kim, 2010]

ATLAS: Heavy W Search

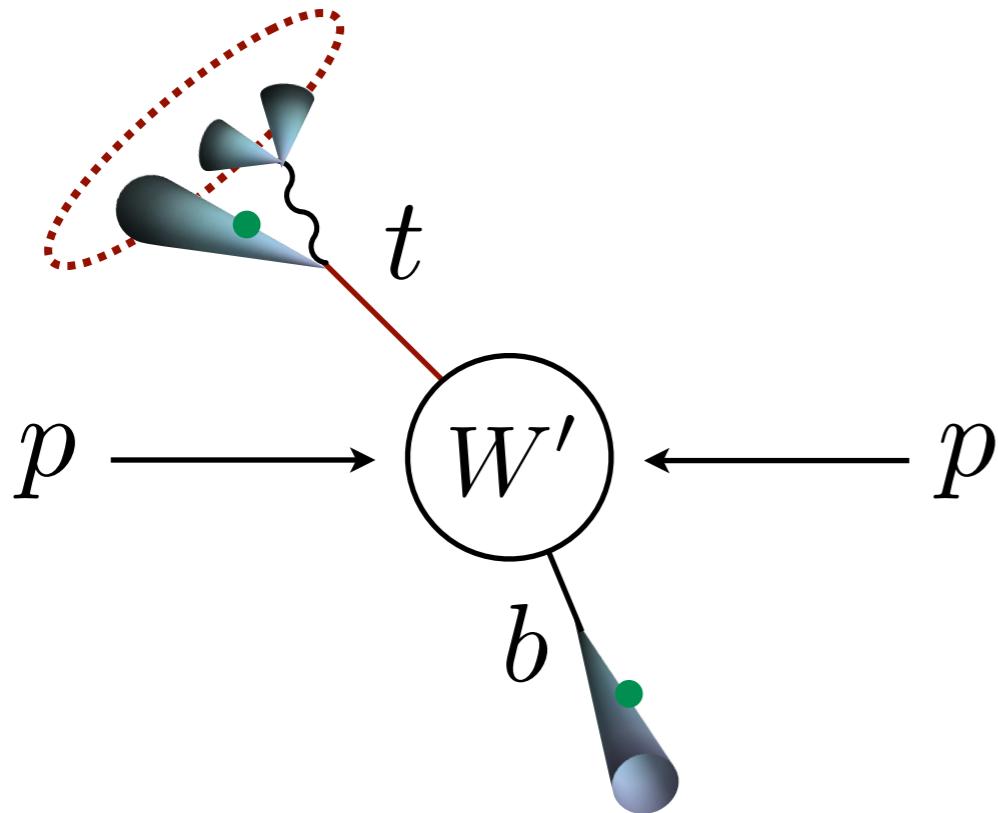


with *B-tagging*
+ *Trimming*
+ *N-subjettiness*

$\approx 100x$ background rejection
@ 50% signal efficiency

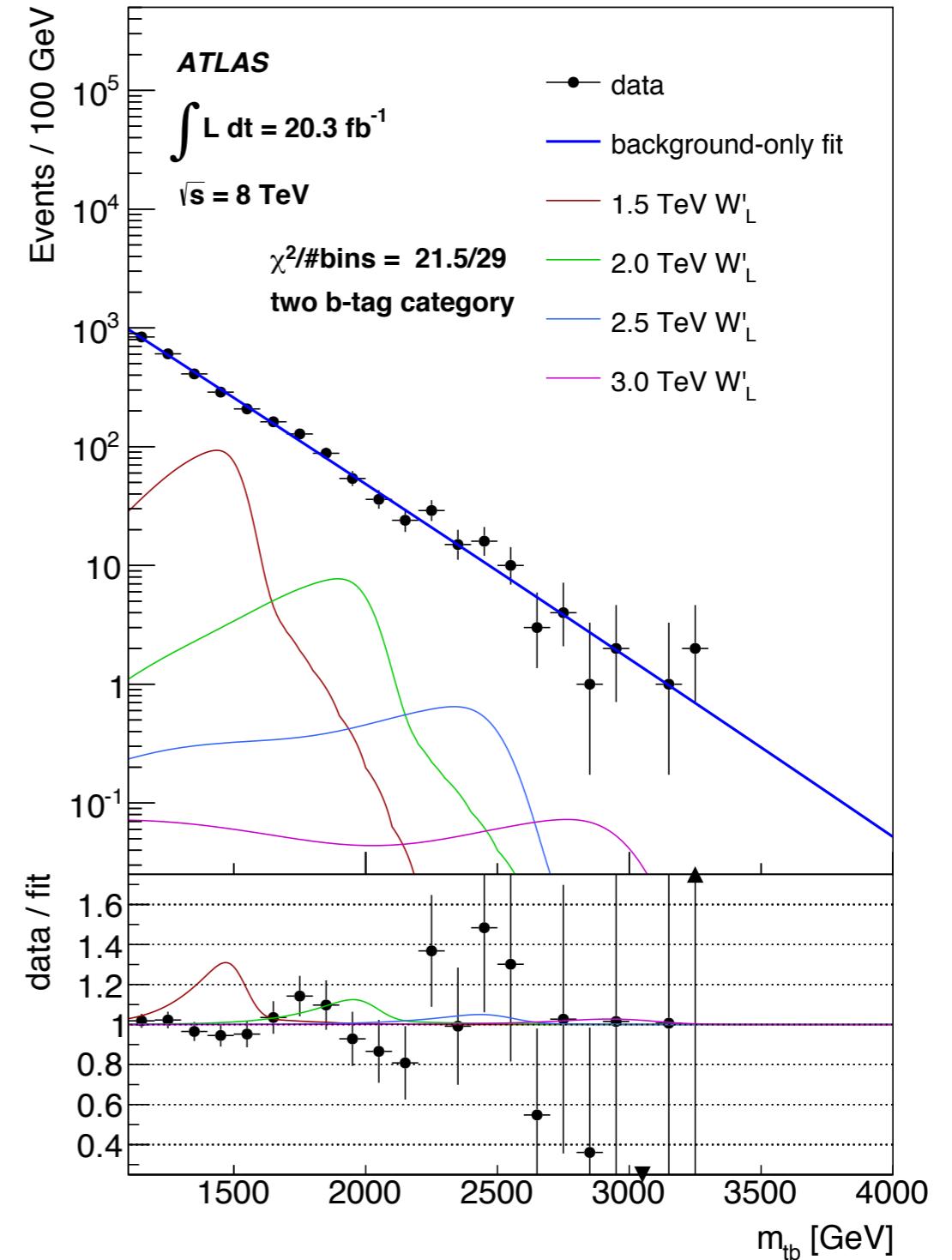


ATLAS: Heavy W Search



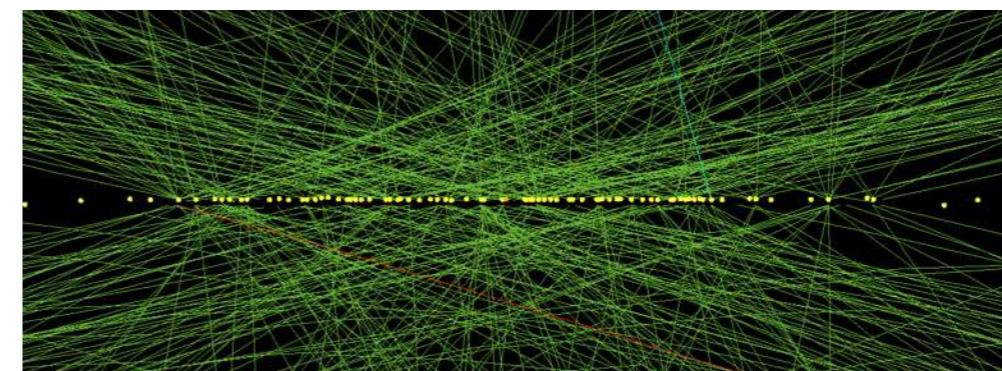
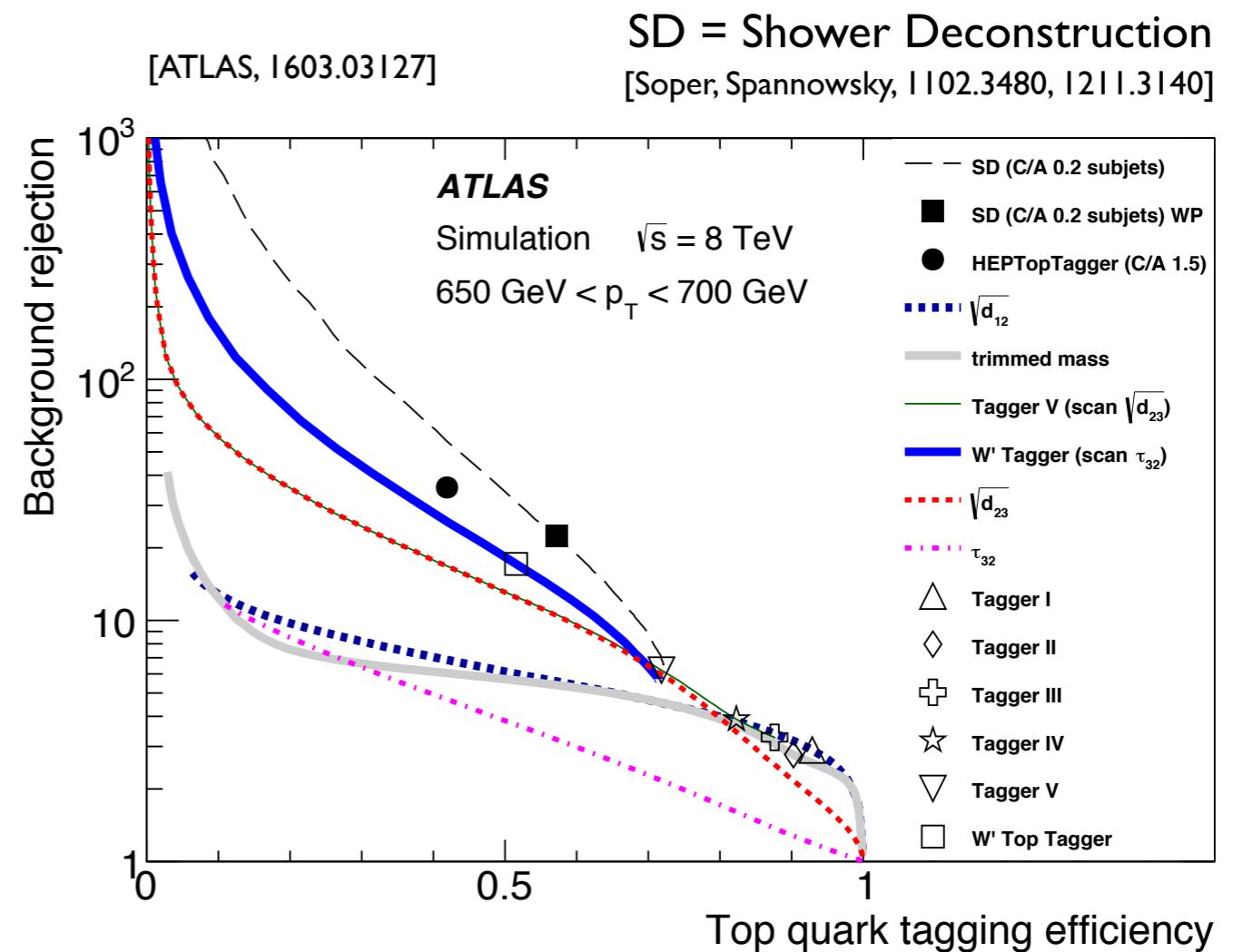
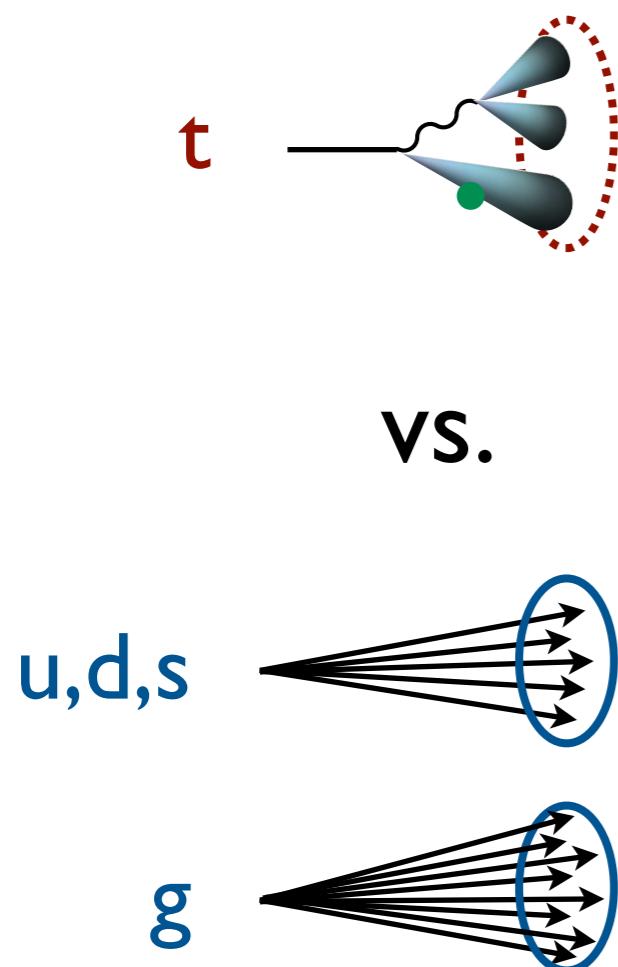
with *B-tagging*
+ *Trimming*
+ *N-subjettiness*

≈ 100x background rejection
@ 50% signal efficiency



ATLAS: Top Tagging Study

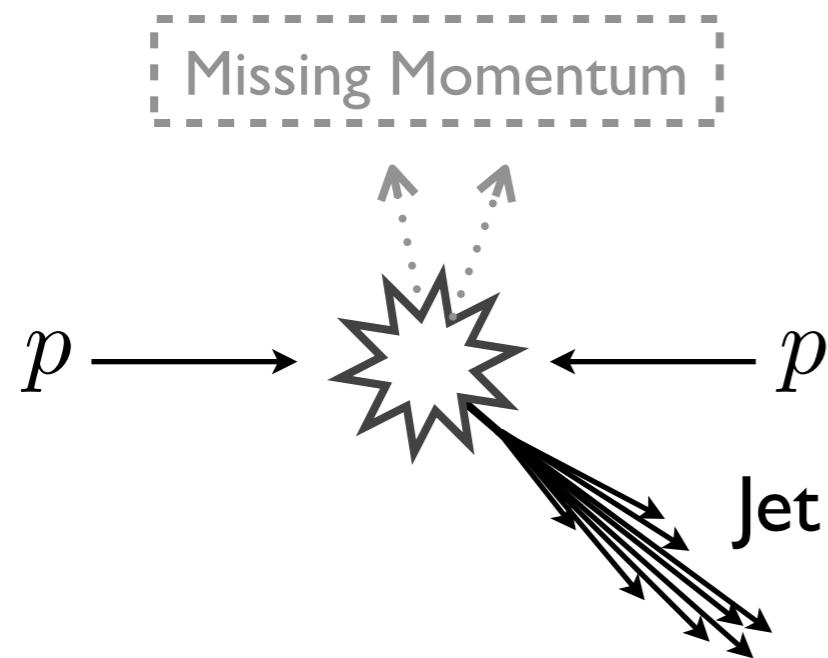
Performance before b -tagging



Good performance even with pileup

CMS: Dark Matter Search

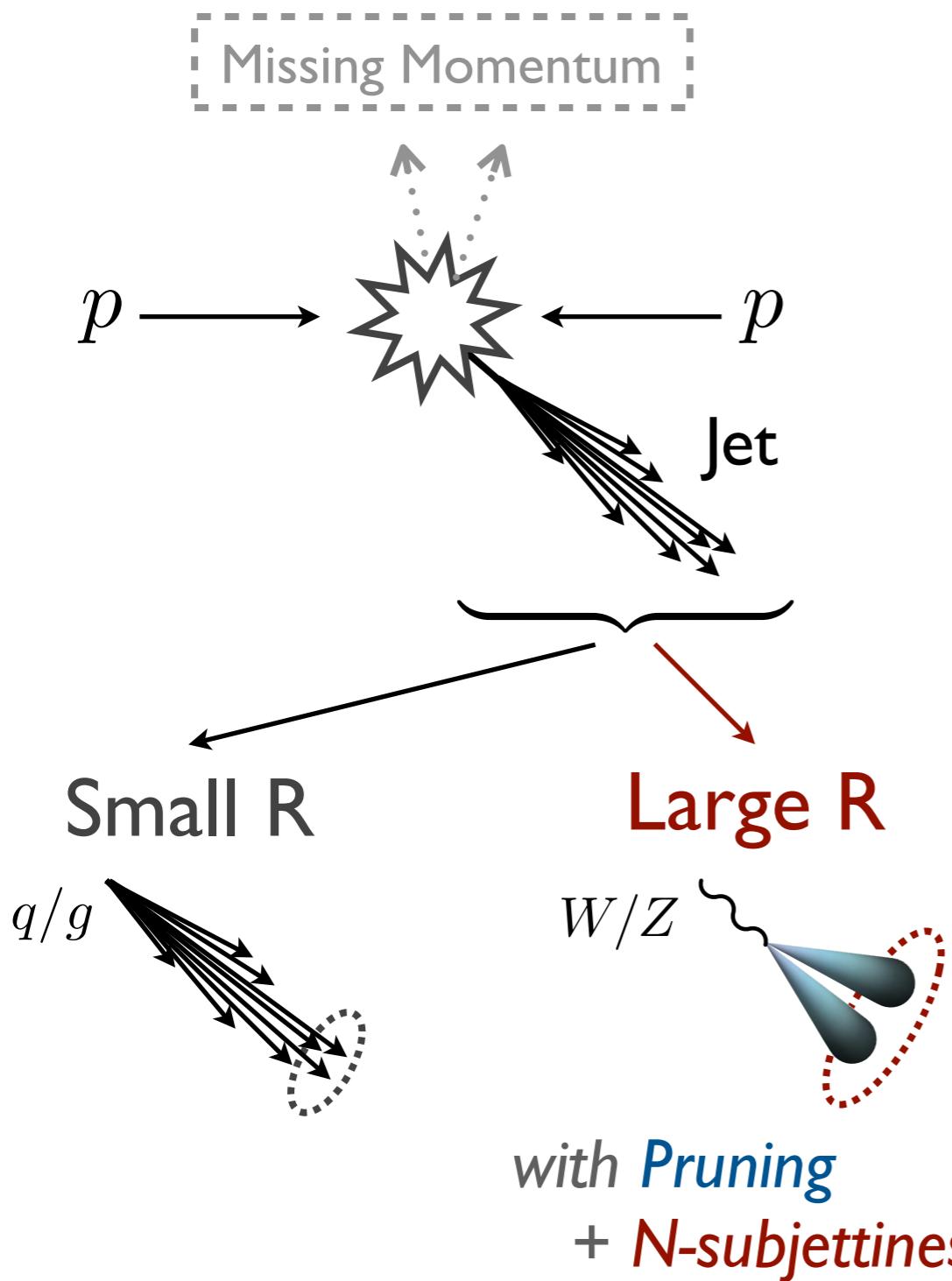
Hot Topic @ **ICHEP2016**



[CMS, 2016; using Ellis, Vermilion, Walsh, 2009; JDT, Van Tilburg, 2010, 2011]

CMS: Dark Matter Search

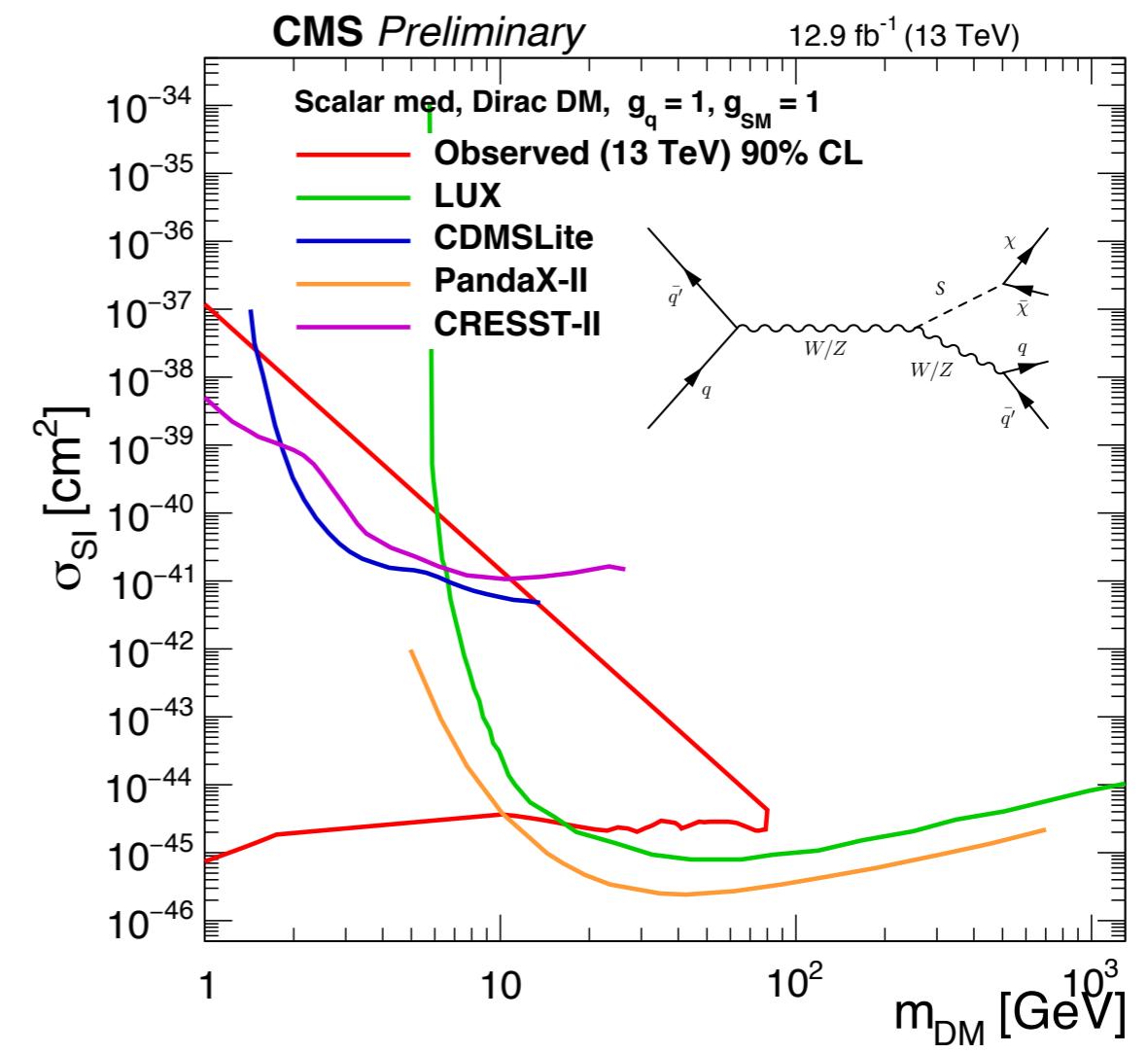
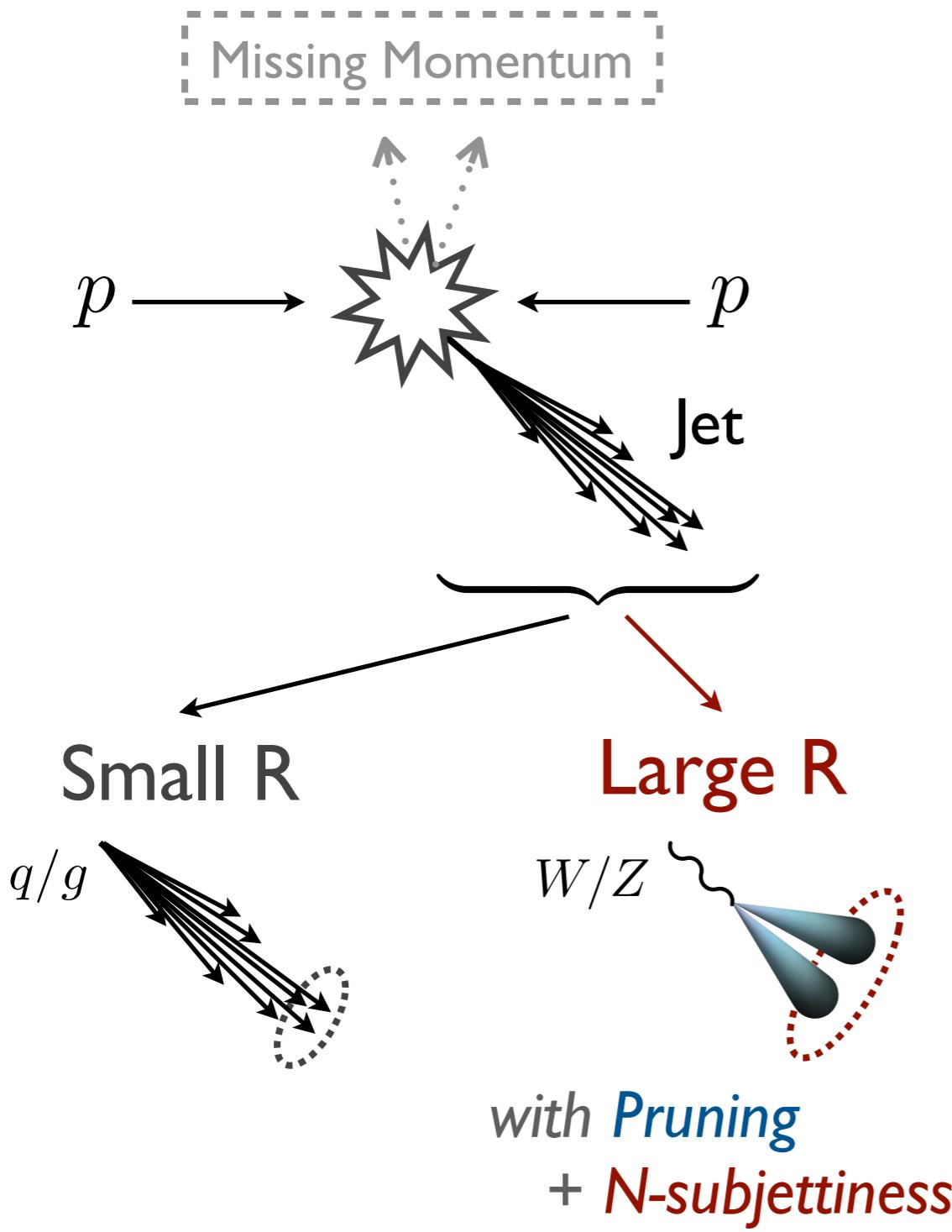
Hot Topic @ **ICHEP2016**



[CMS, 2016; using Ellis, Vermilion, Walsh, 2009; JDT, Van Tilburg, 2010, 2011]

CMS: Dark Matter Search

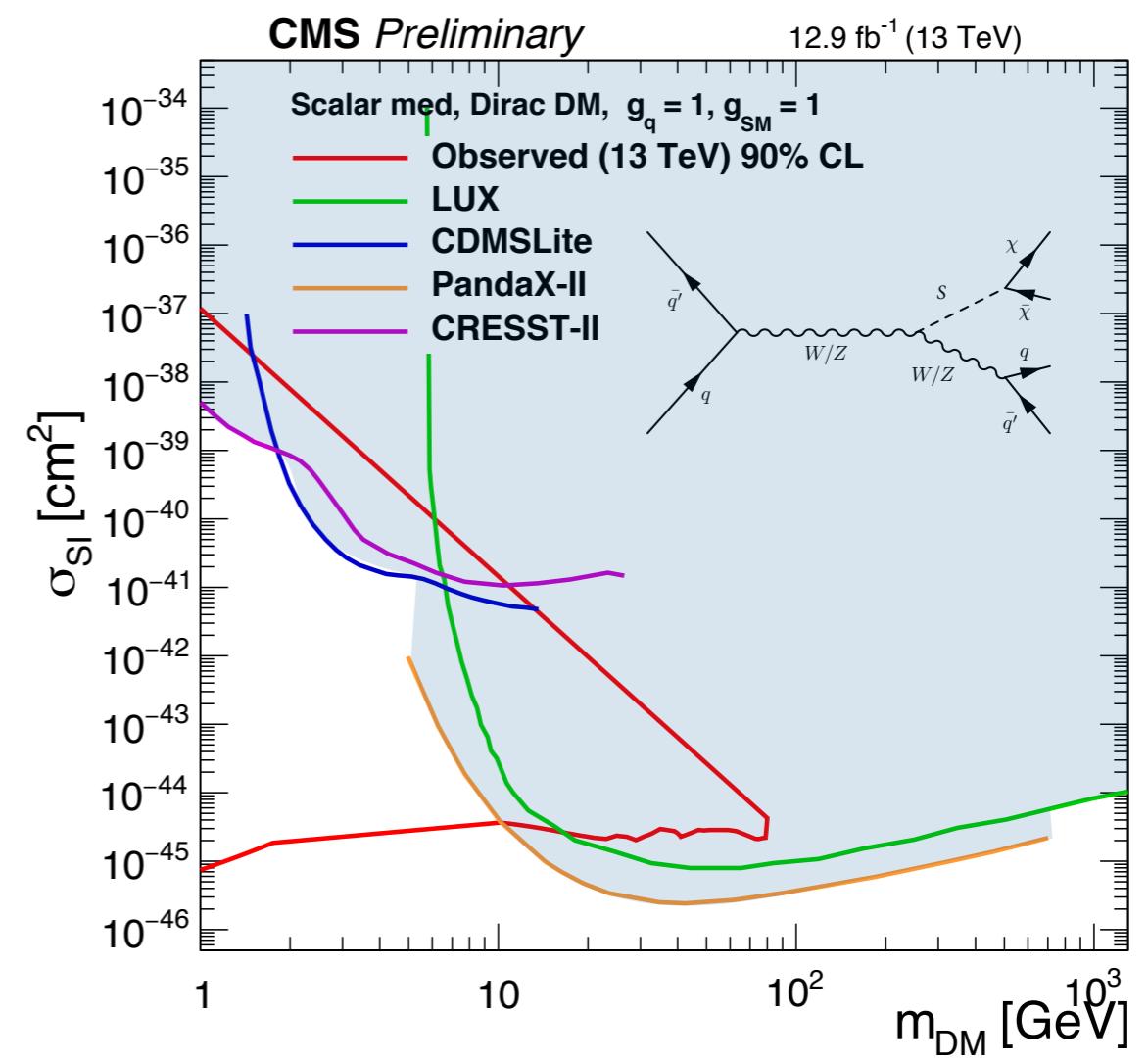
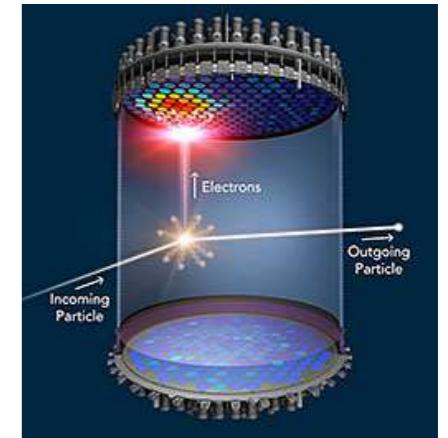
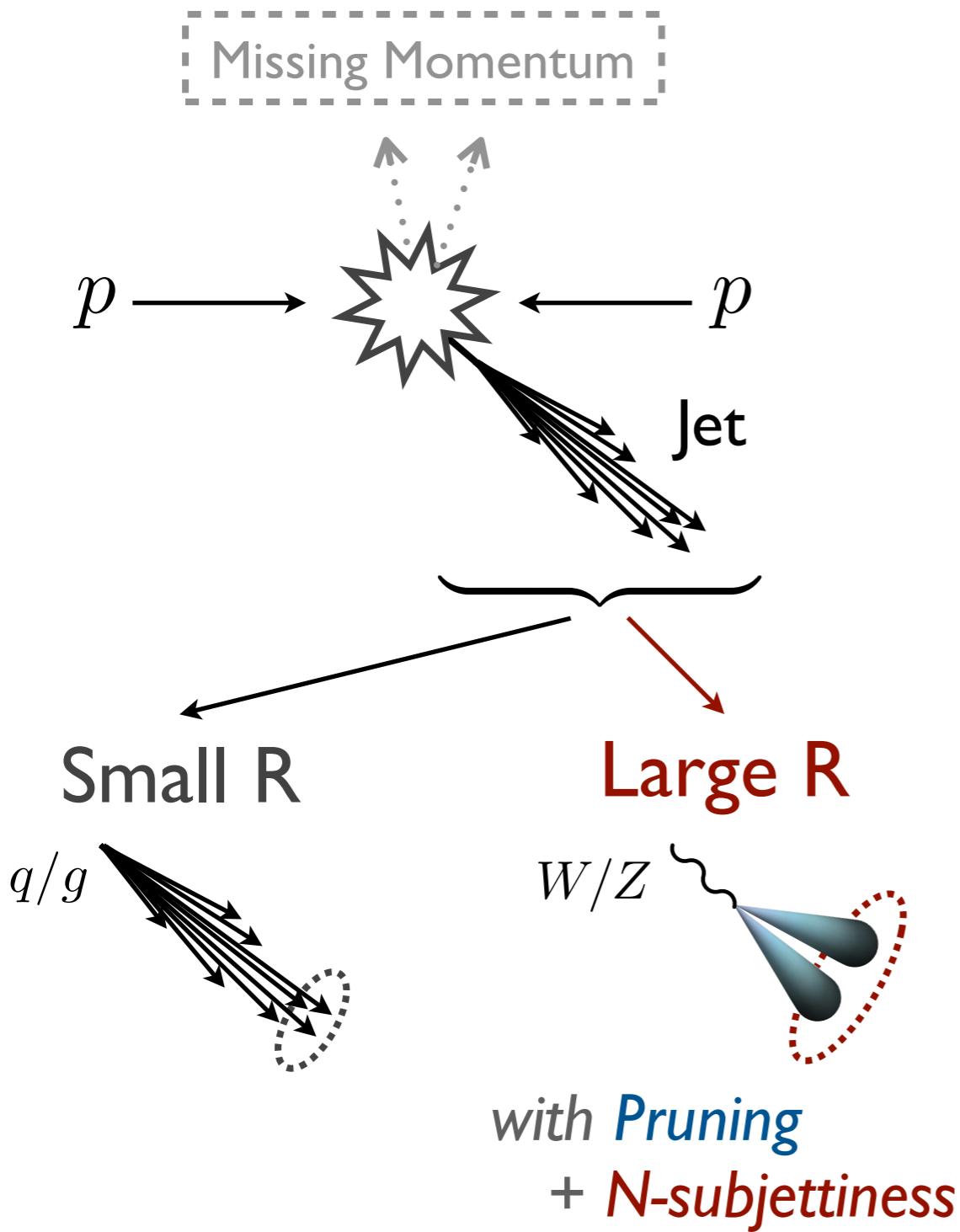
Hot Topic @ **ICHEP2016**



[CMS, 2016; using Ellis, Vermilion, Walsh, 2009; JDT, Van Tilburg, 2010, 2011]

CMS: Dark Matter Search

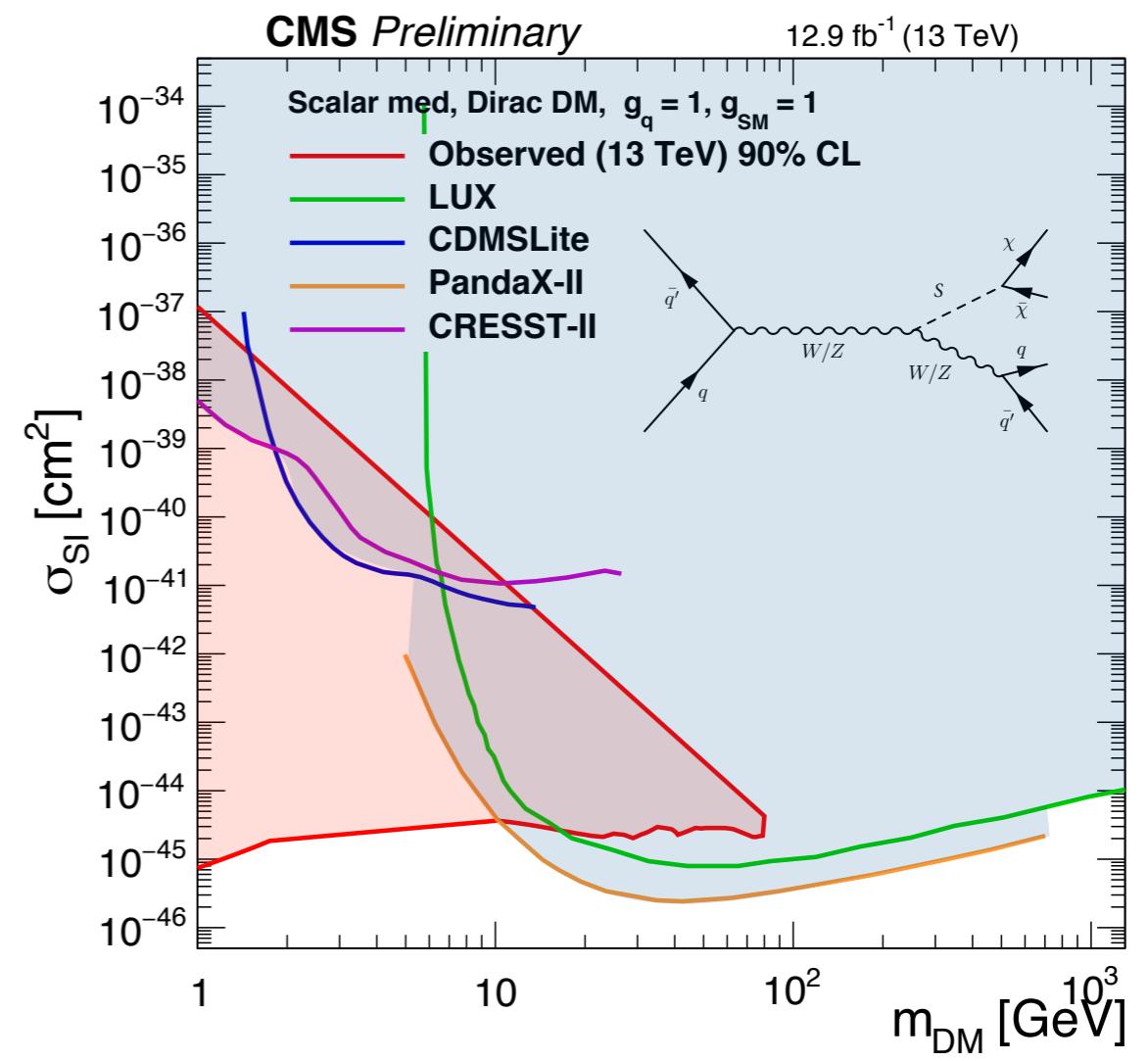
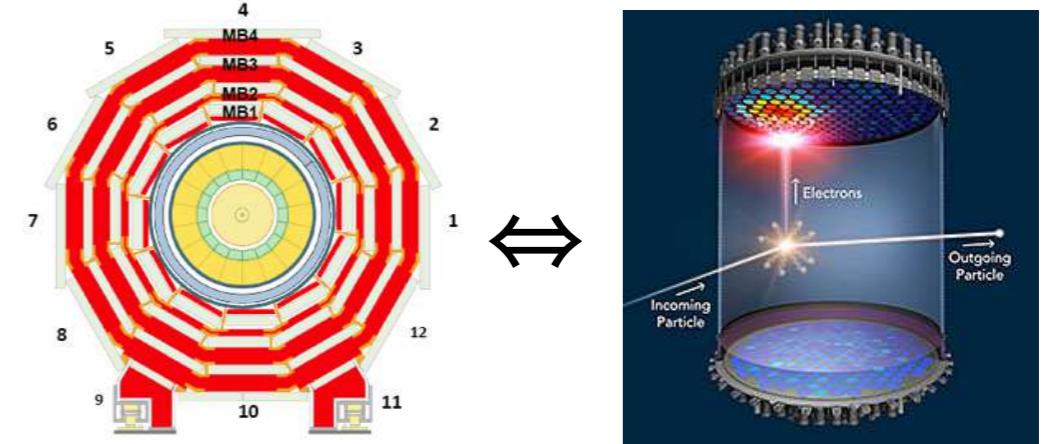
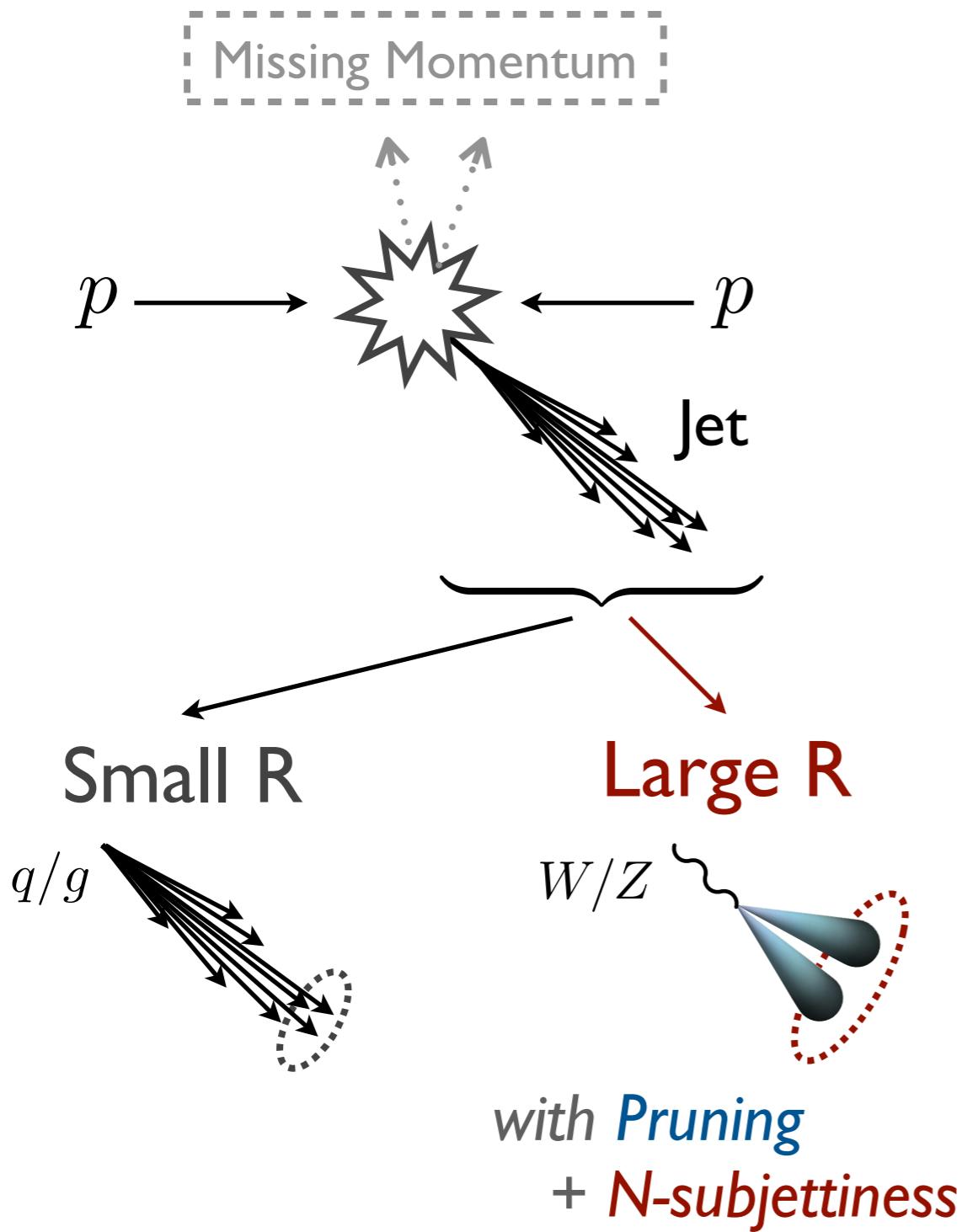
Hot Topic @ **ICHEP2016**



[CMS, 2016; using Ellis, Vermilion, Walsh, 2009; JDT, Van Tilburg, 2010, 2011]

CMS: Dark Matter Search

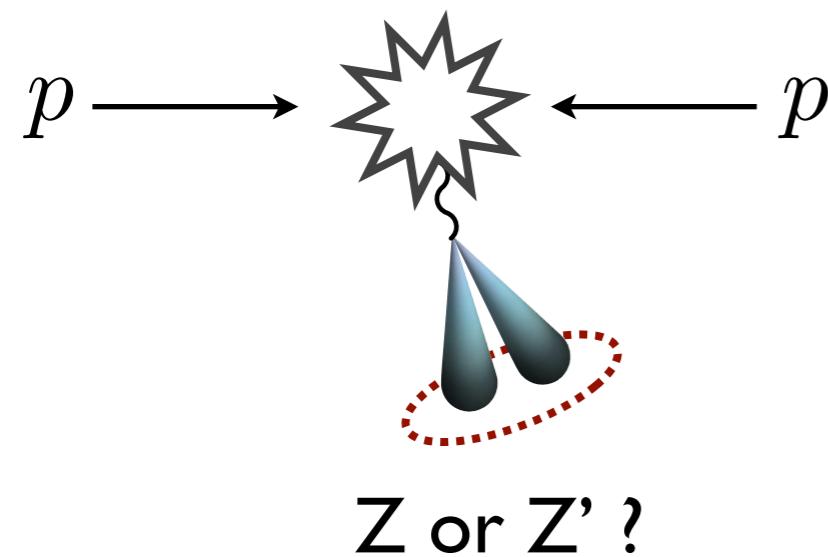
Hot Topic @ **ICHEP2016**



[CMS, 2016; using Ellis, Vermilion, Walsh, 2009; JDT, Van Tilburg, 2010, 2011]

CMS: Boosted Z' Search

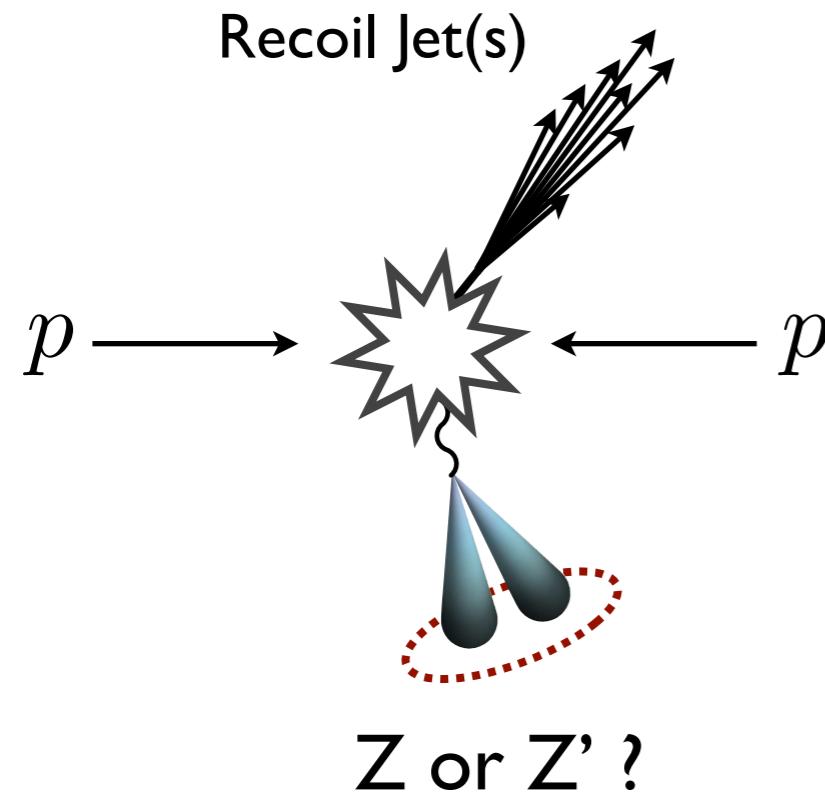
Hot Topic @ **ICHEP2016**



[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 @ **ICHEP2016**

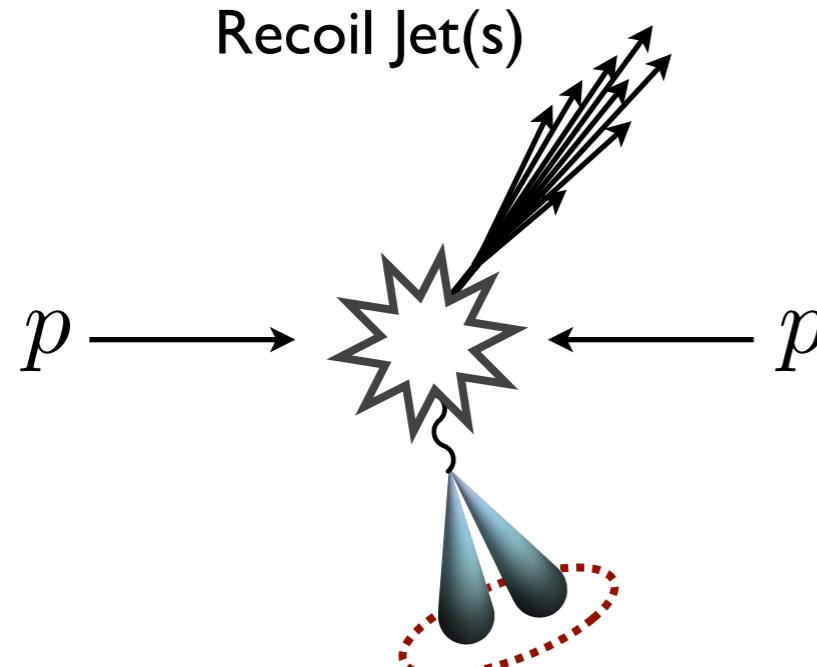


with *Soft Drop*
+ *N-subjettiness*
+ *Decorrelation*

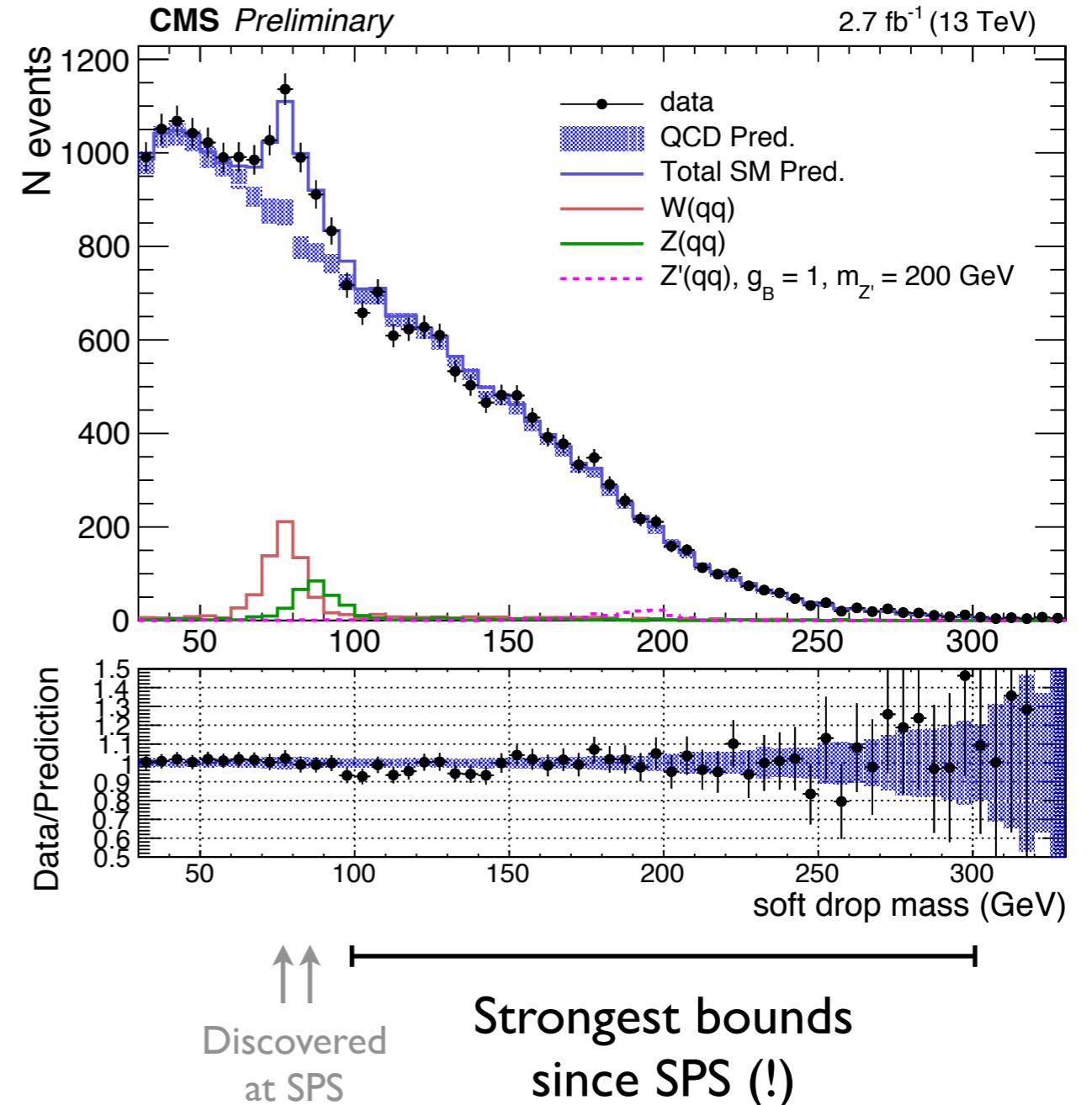
[CMS, 2016; using Larkoski, Marzani, Soyez, JDT, 2014;
JDT, Van Tilburg, 2010, 2011; Dolen, Harris, Marzani, Rappoccio, Tran, 2016]

CMS: Boosted Z' Search

Hot Topic @ **ICHEP2016**

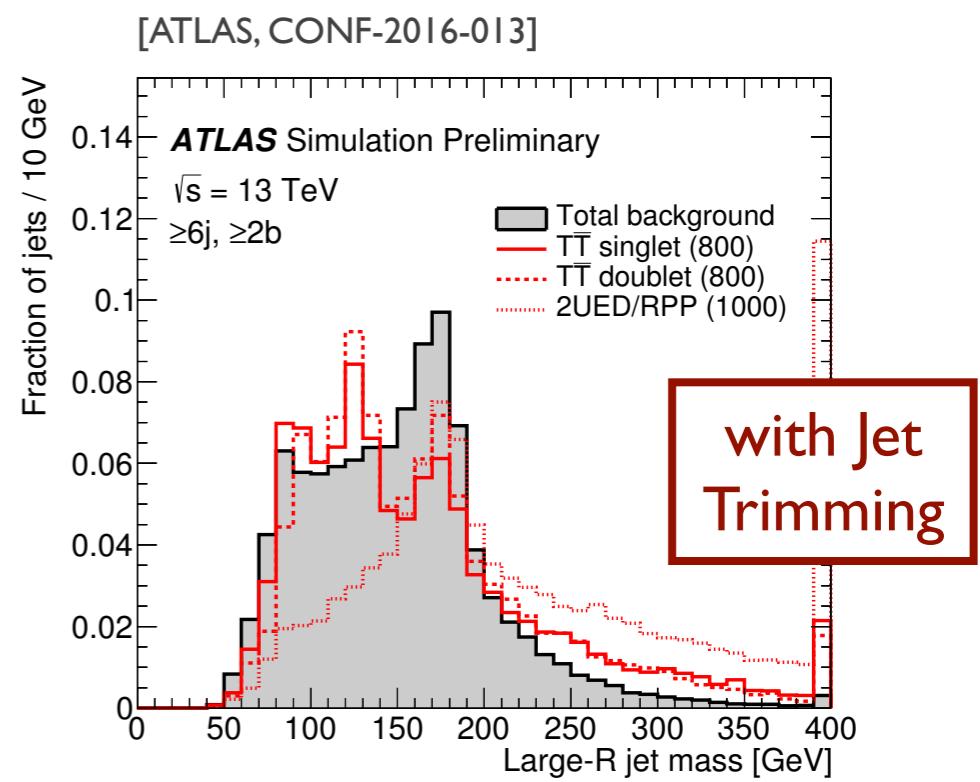
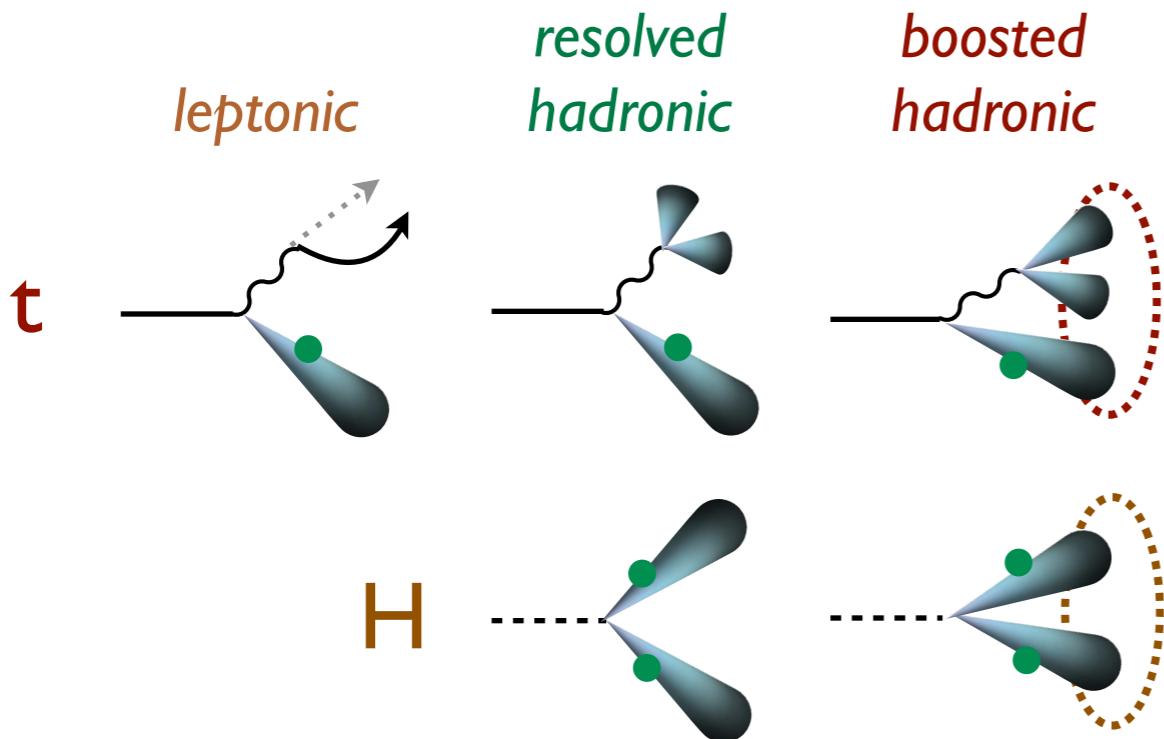
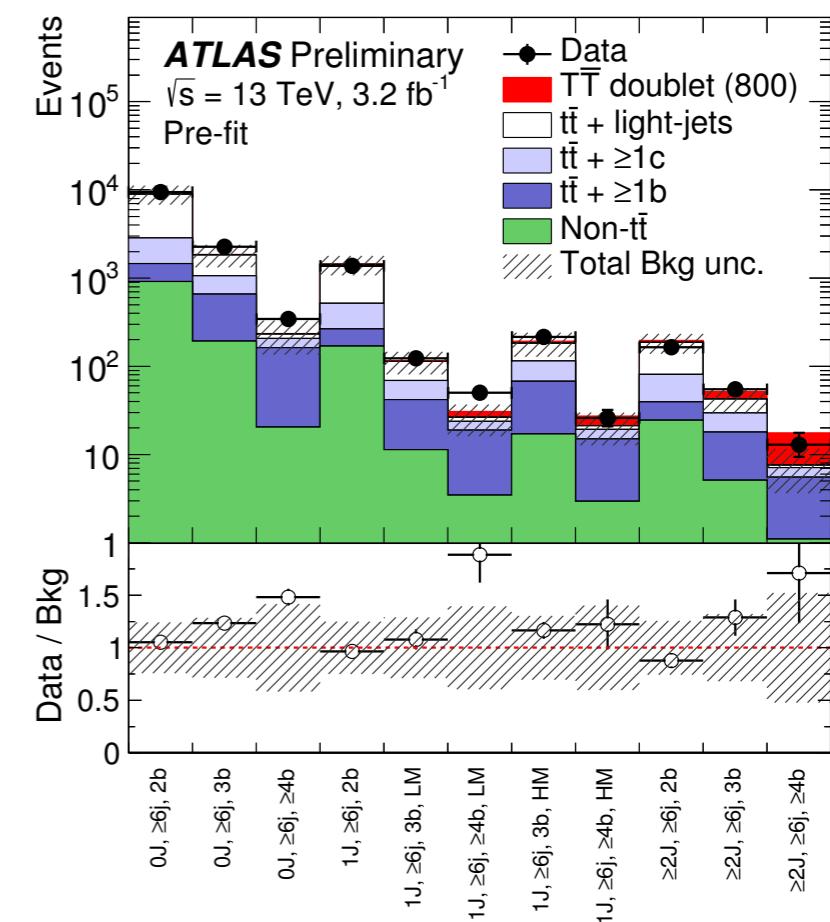
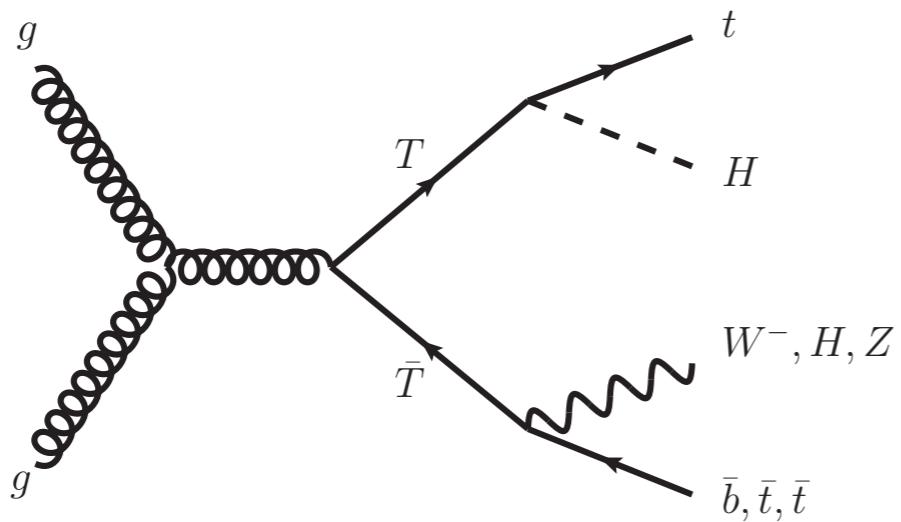


with *Soft Drop*
+ *N-subjettiness*
+ *Decorrelation*



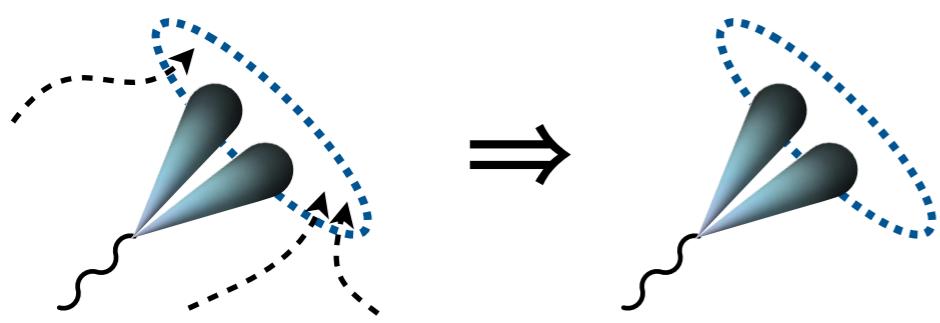
[CMS, 2016; using Larkoski, Marzani, Soyez, JDT, 2014;
JDT, Van Tilburg, 2010, 2011; Dolen, Harris, Marzani, Rappoccio, Tran, 2016]

ATLAS: Vector-like Quarks



Preview of Tomorrow

W/Z Tagging in 2016

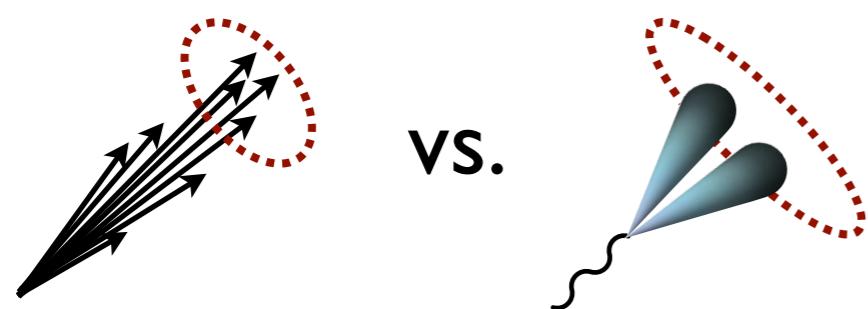


Soft Drop

[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 in 2016



*Can we understand
these choices from
first principles QCD?*

*Can we construct
improved algorithms
for 2017?*

Soft Drop

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

N-subjettiness

before grooming, after decorrelation

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

D₂

after grooming

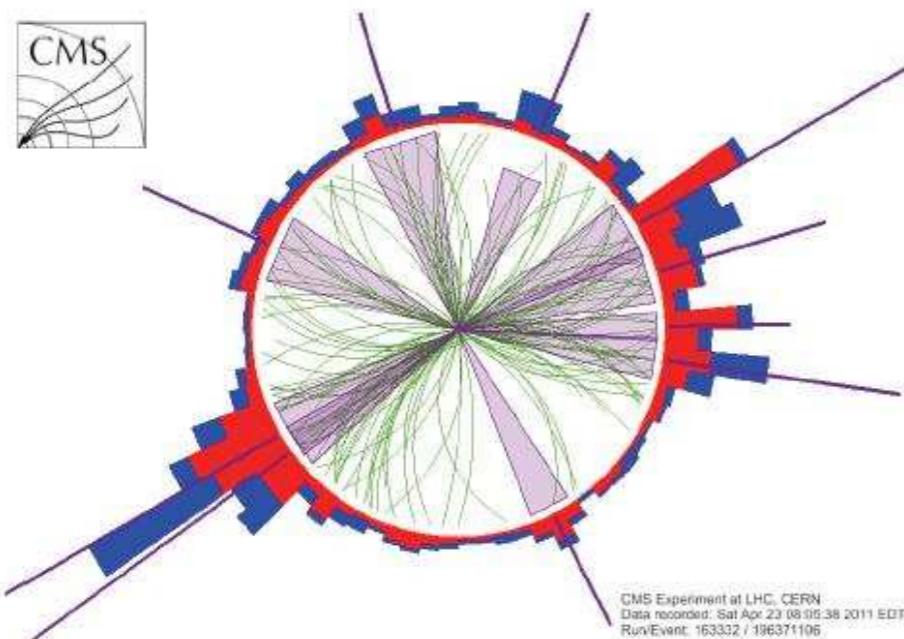
[Larkoski, Moult, Neill, 2014;
based on Larkoski, Salam, JDT, 2013]

Creative Approaches for Hadronic Final States

What is a Jet?

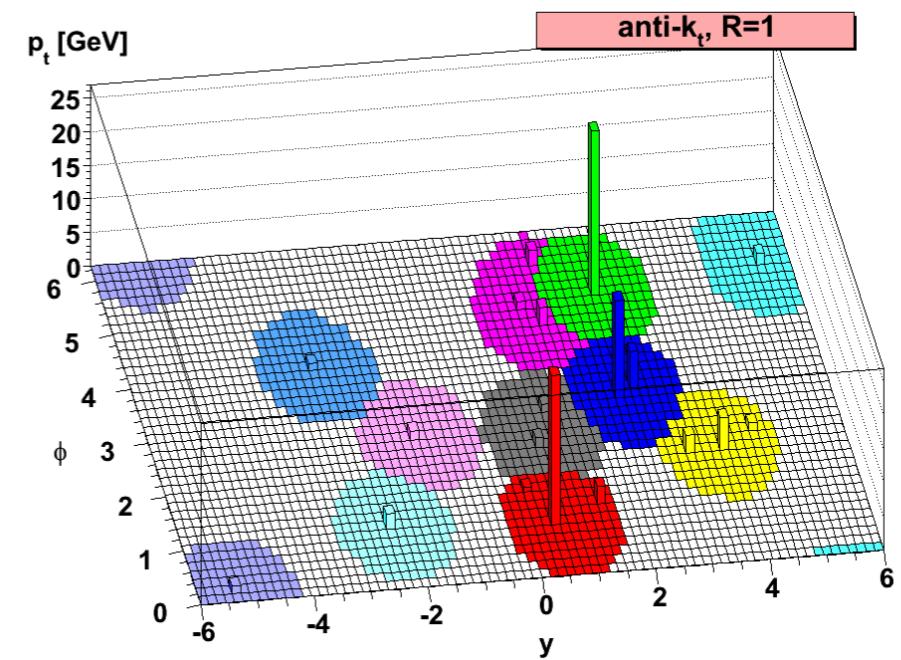
A physical phenomena:

*Emergent feature of
confining gauge theories*



An analysis technique:

*Method to interpret
hadronic final states*

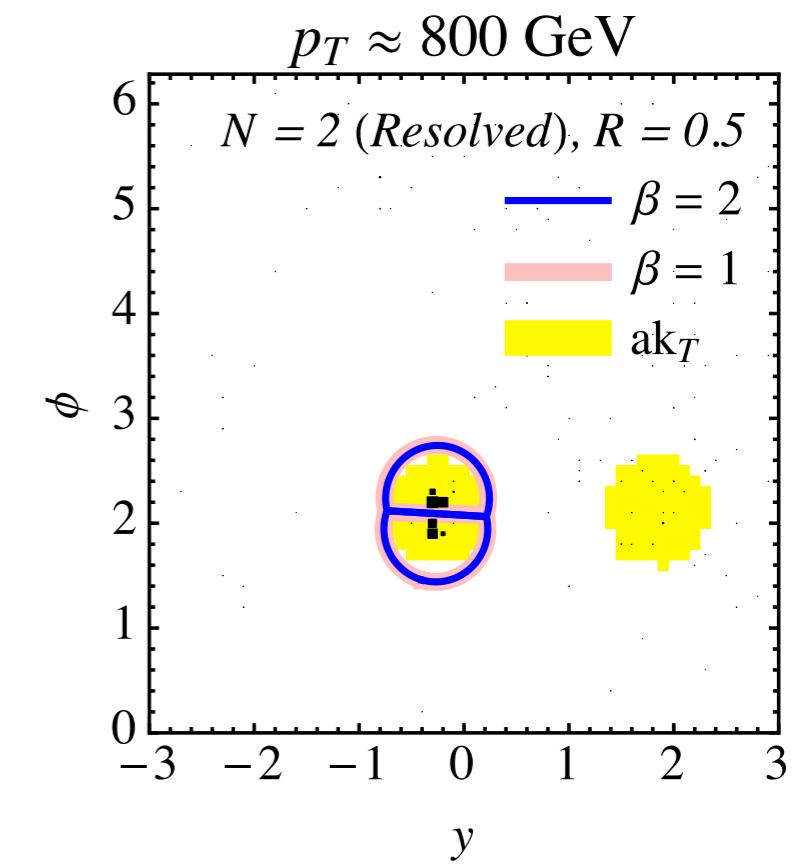
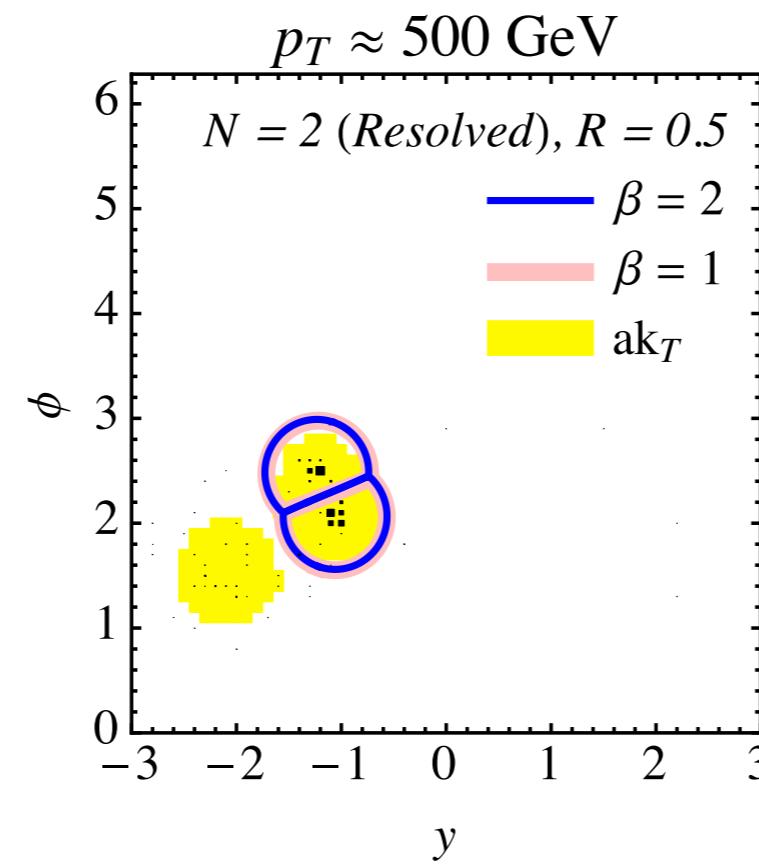
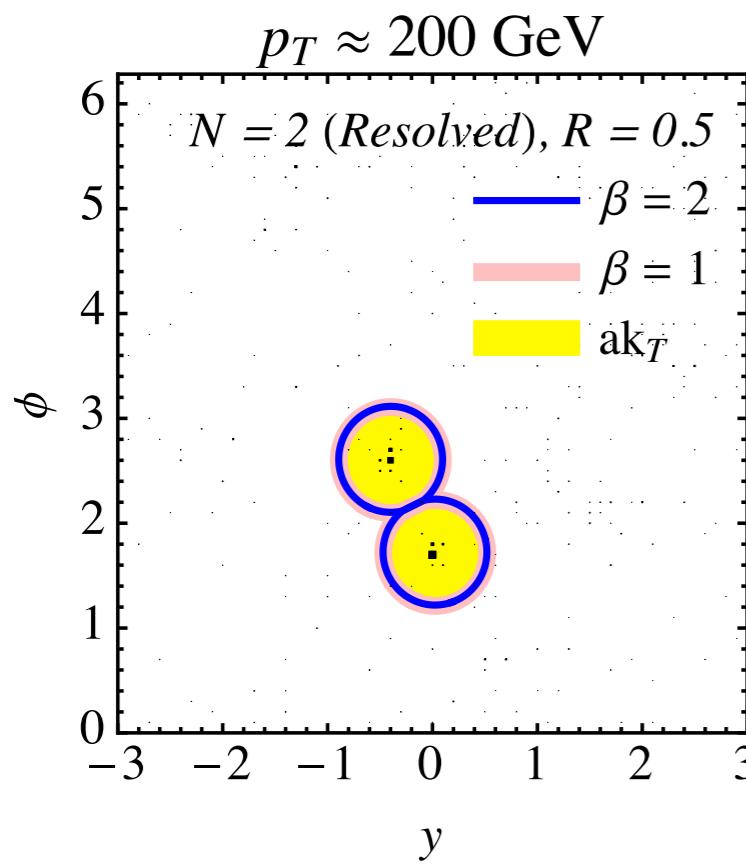
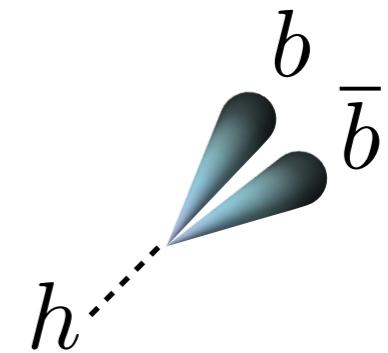
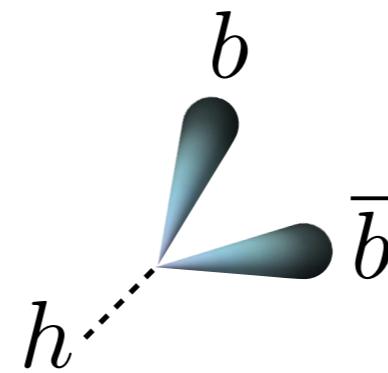
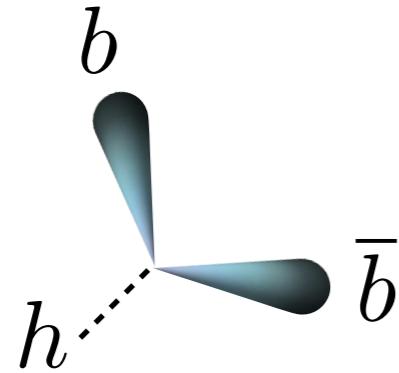


*Freedom to use
different analysis strategies for
different physical questions*

Merging Resolved & Boosted?

XCone for Higgs bosons

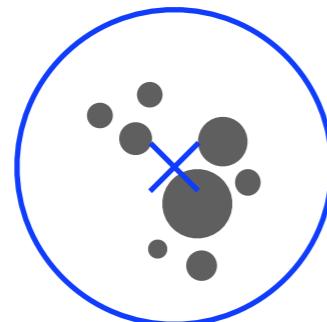
$$\Delta R \simeq \frac{2m_H}{p_T}$$



[inspired by Stewart,Tackmann,Waalewijn, 1004.2489;
Stewart,Tackmann,JDT,Vermilion,Wilkason, 1508.01516; JDT,Wilkason, 1508.01518]

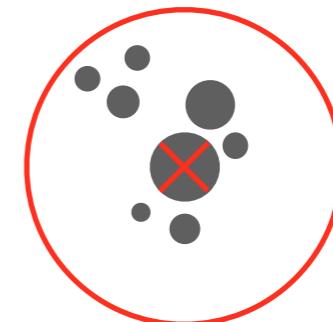
Change Jet Axis?

Jet Momentum Axis



“Mean” \approx minimizes sum of $|distance|^2$
(sensitive to outliers)

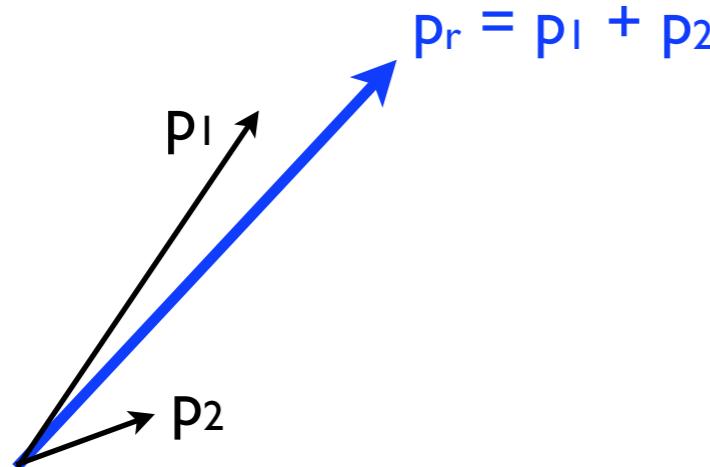
Winner-Take-All Axis



“Median” \approx Minimizes sum of $|distance|$
(insensitive to outliers)

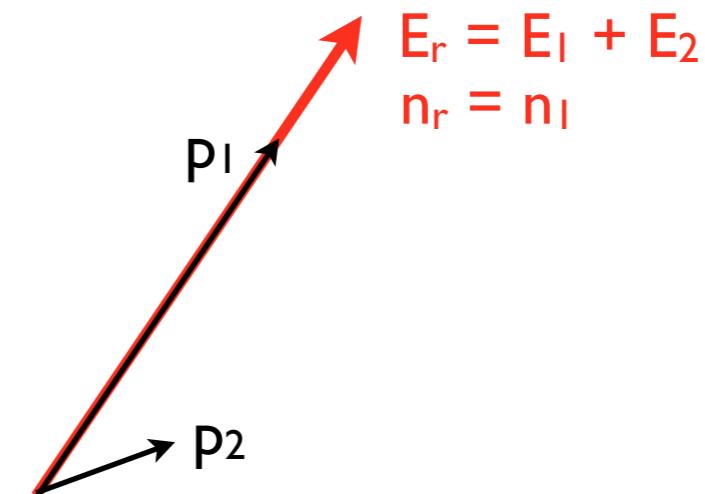
VS.

E-scheme Recombination



One line of code
in FastJet

WTA Recombination

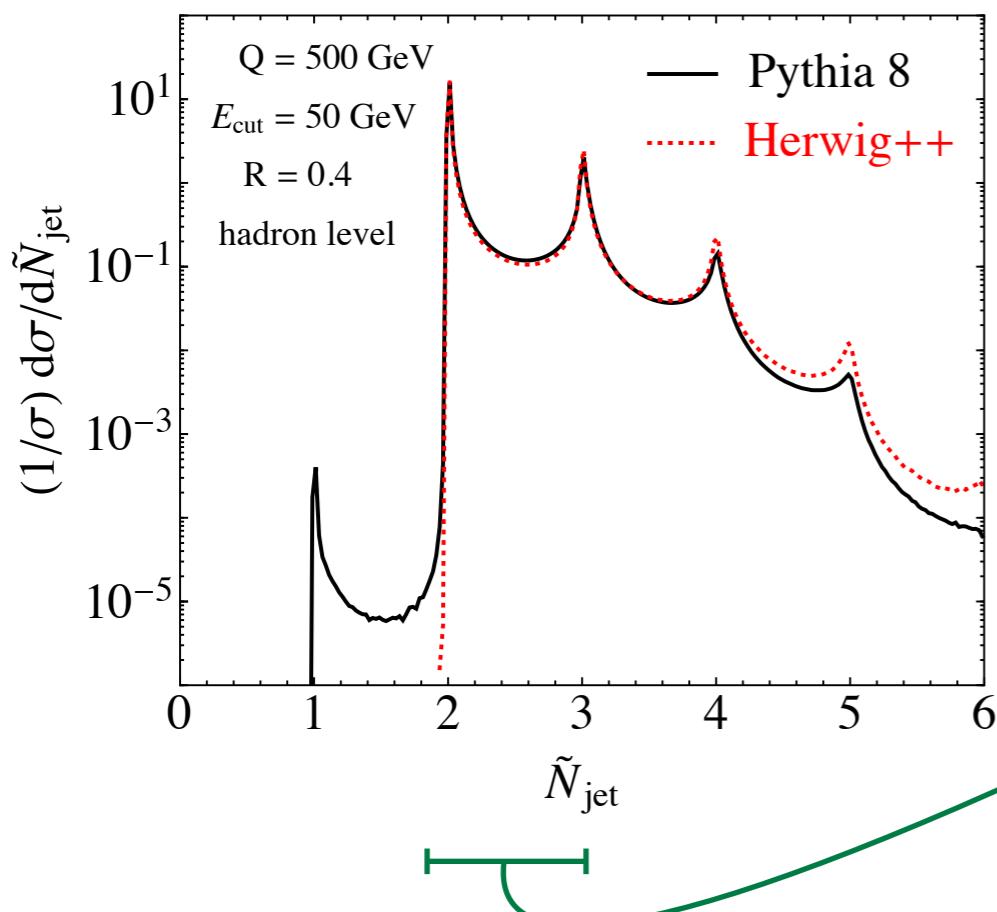


[Bertolini, Chan, JDT, 1310.7584; Larkoski, Neill, JDT, 1401.2158; Salam, unpublished; see also JDT, Van Tilburg, 1108.2701]

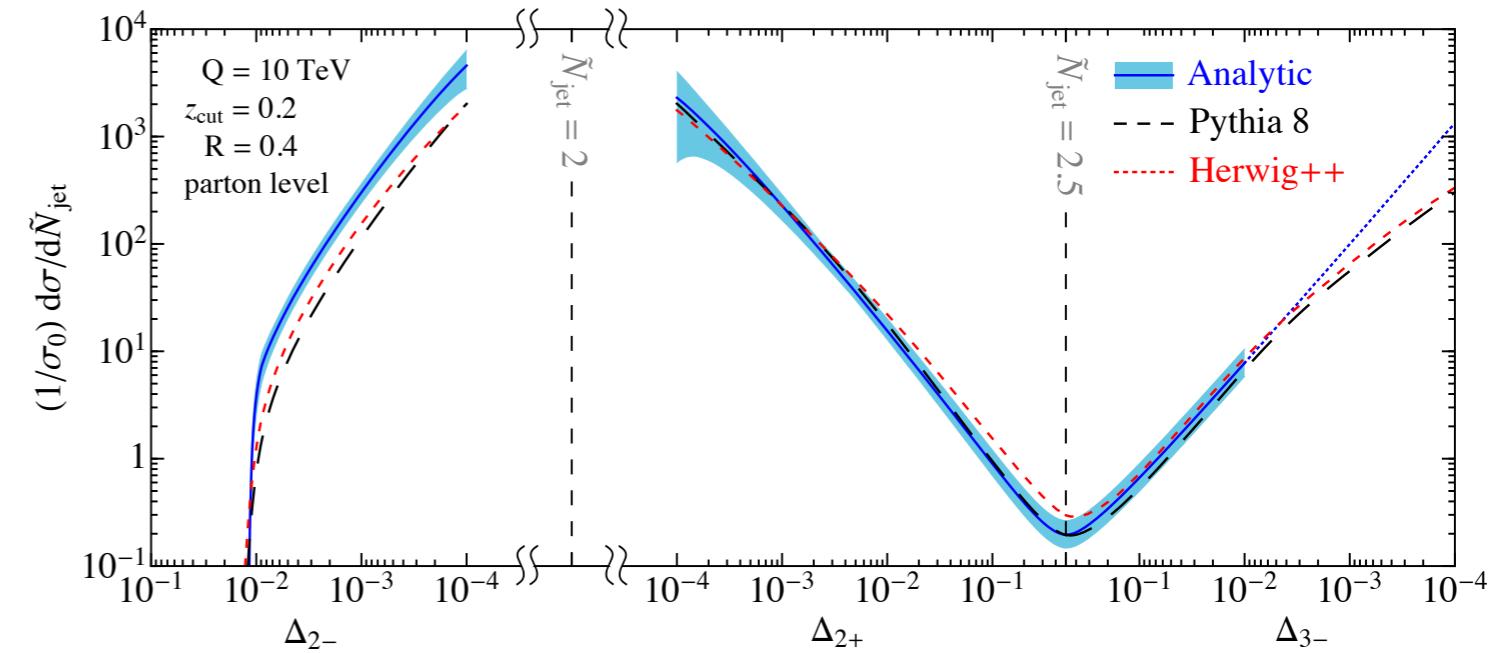
Counting “Fractional” Jets?

$$\tilde{N}_{\text{jet}} = \sum_{i \in \text{event}} \frac{p_{Ti}}{p_{Ti,R}} \Theta(p_{Ti,R} > p_{T\text{cut}})$$

In e^+e^- Monte Carlo...



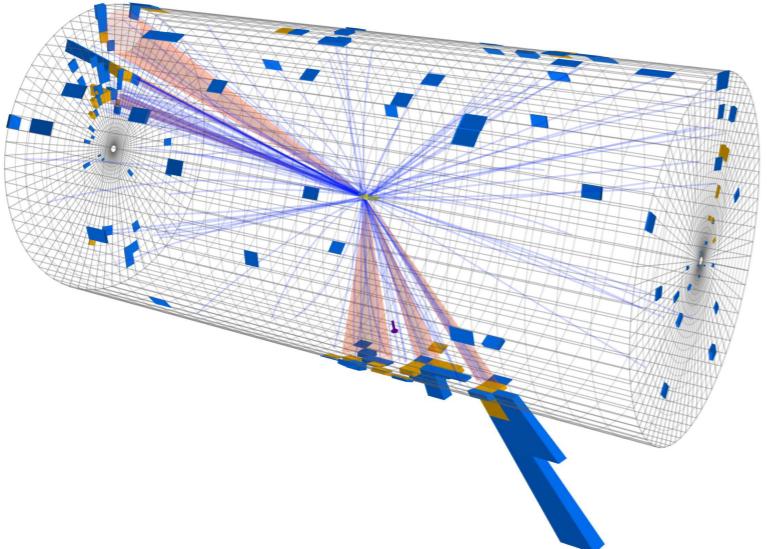
...in QCD at $\mathcal{O}(\alpha_s^2)$...



...at the LHC?

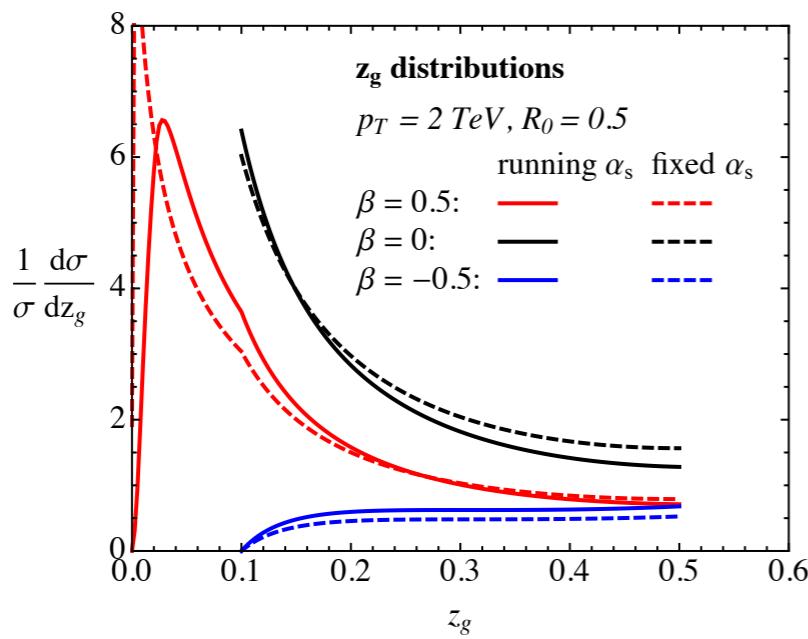
[Bertolini, Chan, JDT, 1301.7584; Bertolini, JDT, Walsh, 1501.01965]

Jet Substructure



*Boosting the Search
for New Phenomena*

[Today & Friday]



*Pushing the Boundaries
of Quantum Field Theory*

[Next Monday & Tuesday]

$m_{jj} = 7.5 \text{ TeV}$
(out of 13 TeV)



Run: 302347
Event: 753275626
2016-06-18 18:41:48 CEST

