PAUL SCHERRER INSTITUT

Jets and Jet Substructure at Future Colliders

Front. Phys. 10:897719

Johan Bonilla, Grigorios Chachamis, Barry M. Dillon, Sergei V. Chekanov, Robin Erbacher, Loukas Gouskos, Andreas Hinzmann, Stefan Höche, B. Todd Huffman, Ashutosh. V. Kotwal, Deepak Kar, Roman Kogler, **Clemens Lange**, Matt LeBlanc, Roy Lemmon, Christine McLean, Benjamin Nachman, Mark S. Neubauer, Tilman Plehn, Salvatore Rappoccio, Debarati Roy, Jennifer Roloff, Giordon Stark, Nhan Tran, Marcel Vos, Chih-Hsiang Yeh and Shin-Shan Yu

BOOST 2022

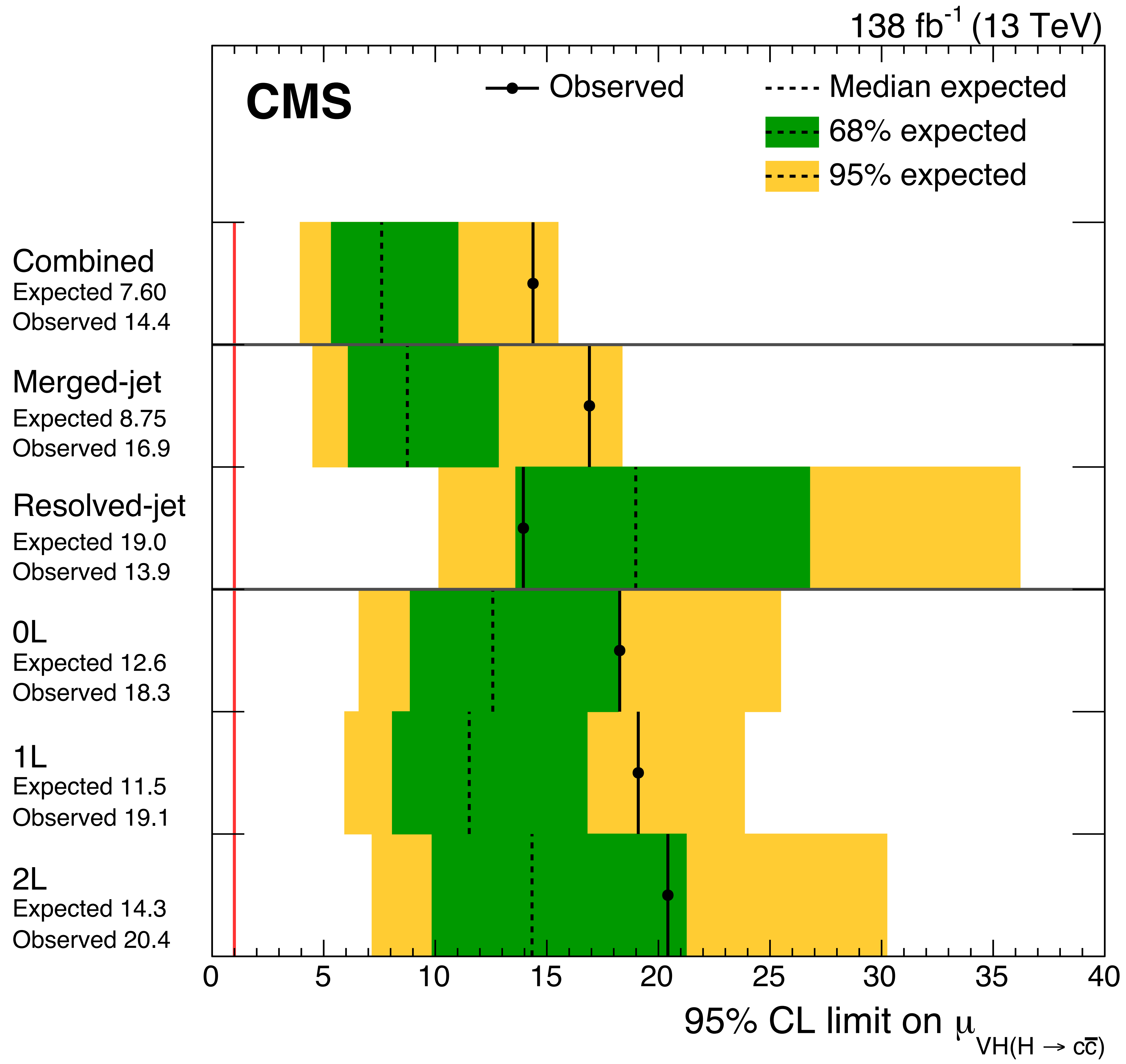
18th August 2022

An underestimated tool set (1)

- CMS TDR (2006): “The [Higgs] decay modes into cc [..] pairs [..] do not play a relevant role at the LHC.”

An underestimated tool set (1)

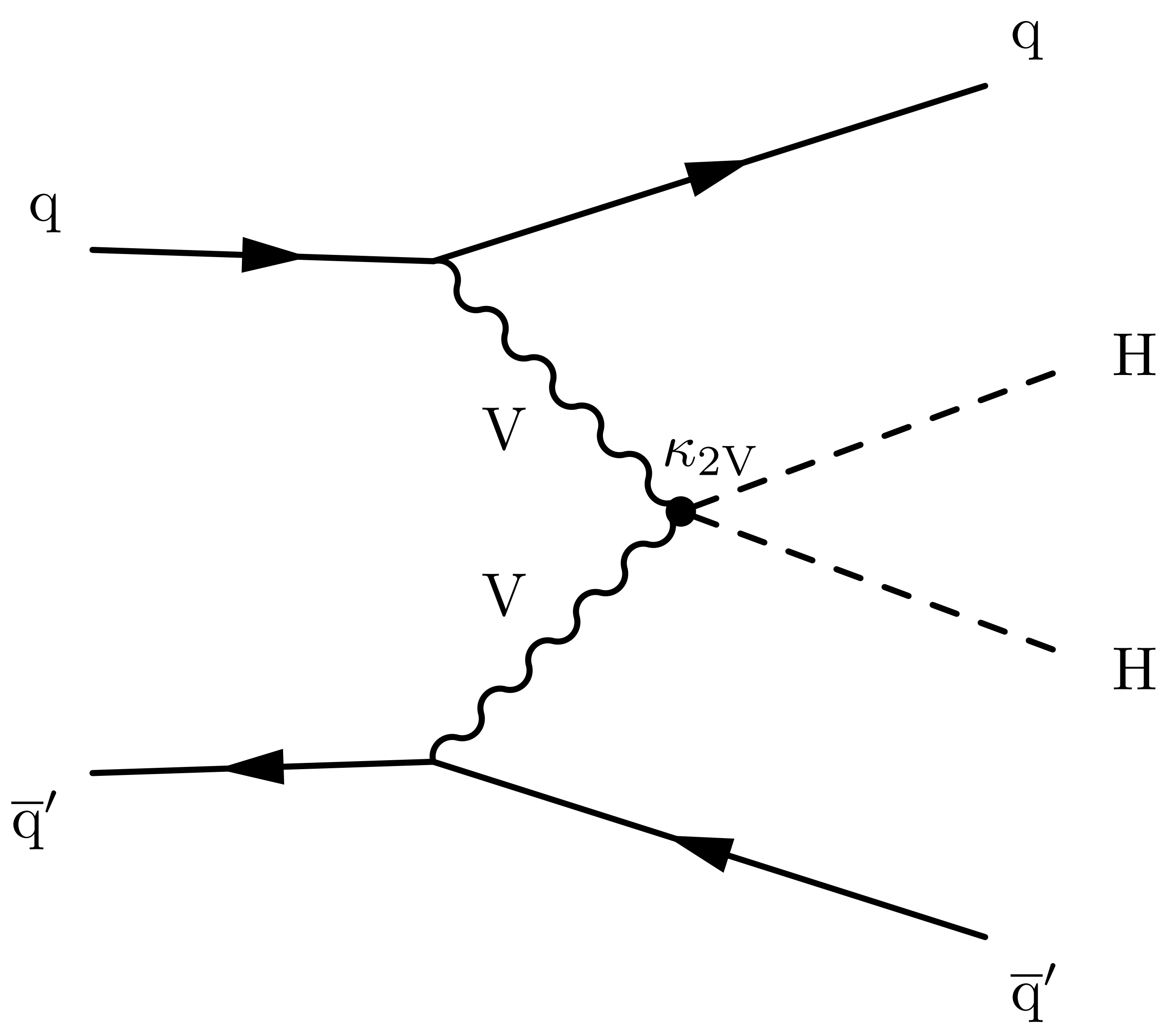
- CMS TDR (2006): “The [Higgs] decay modes into cc [..] pairs [..] do not play a relevant role at the LHC.”



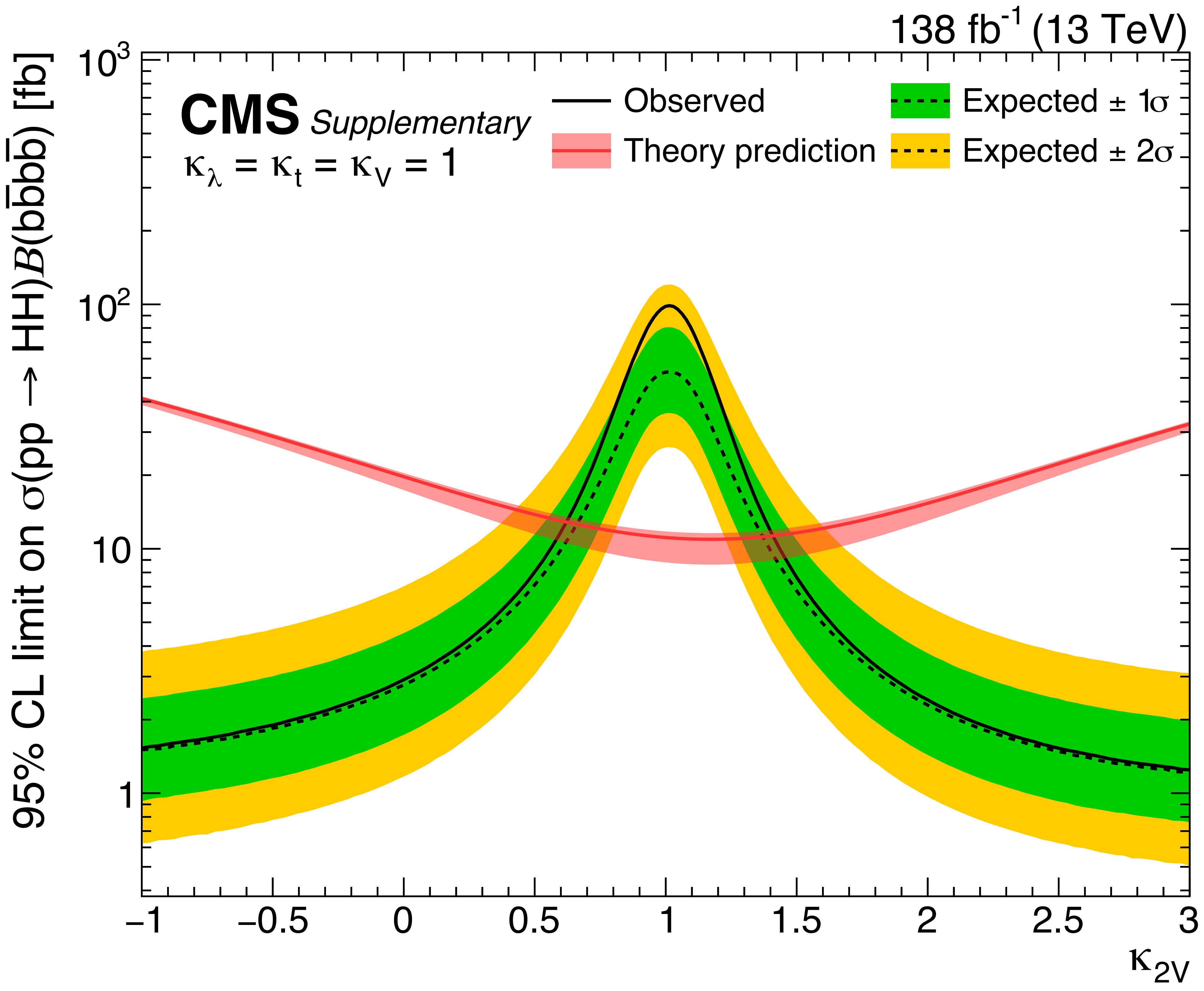
$$Z/W + H(\to c\bar{c})$$

CMS-HIG-21-008 - accepted by PRL

An underestimated tool set (1)



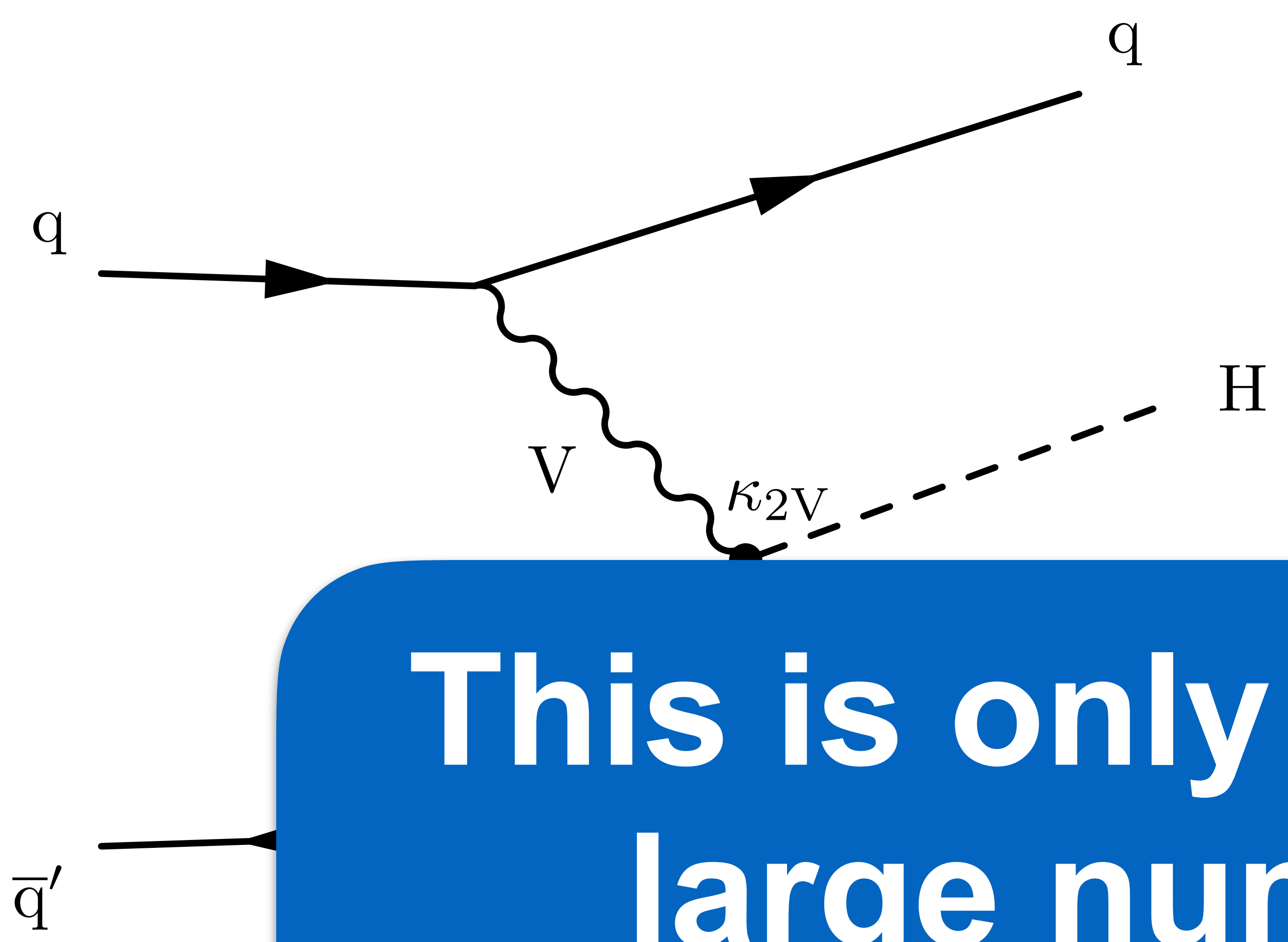
Boosted $HH \rightarrow b\bar{b}b\bar{b}$



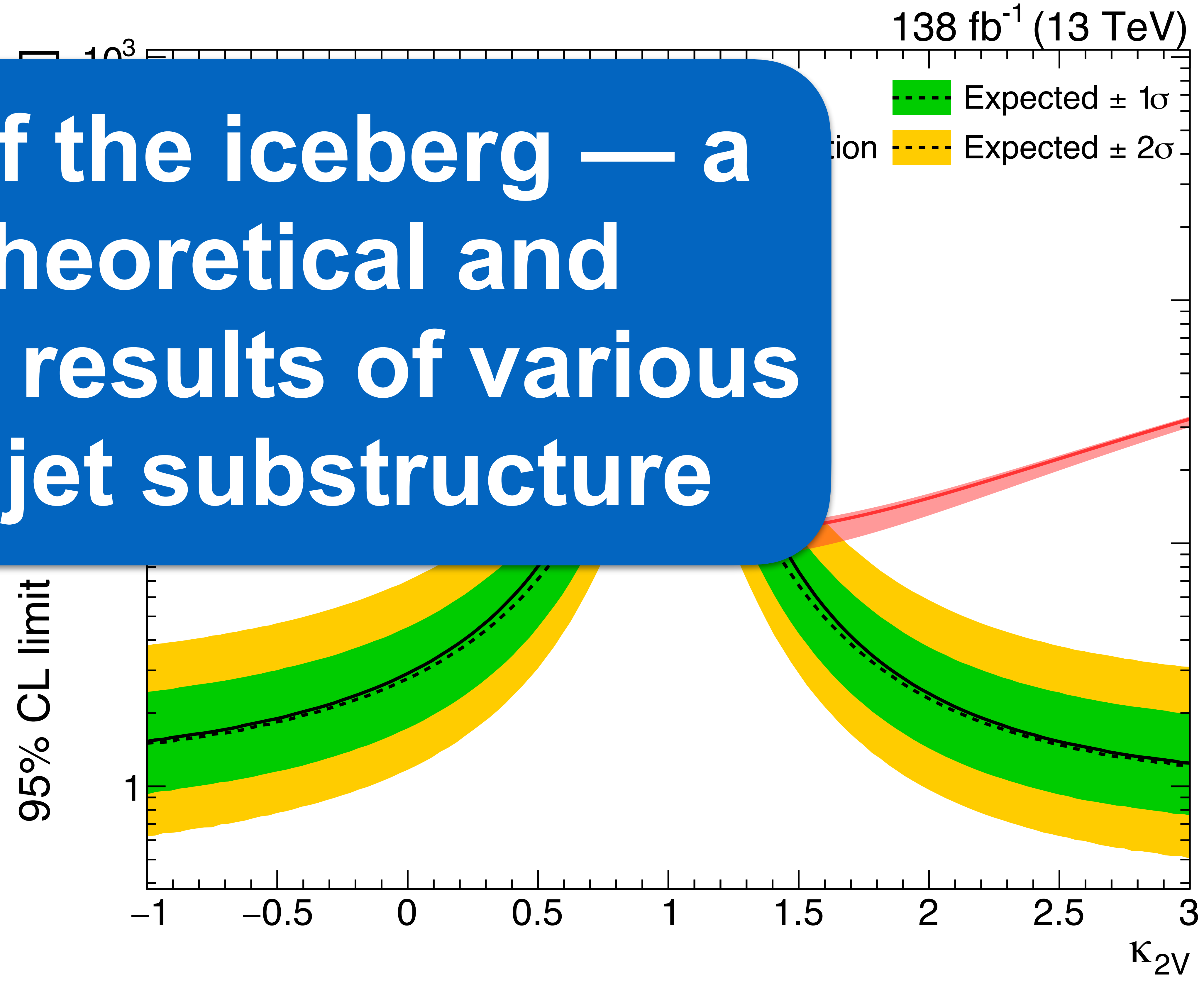
CMS-B2G-22-003 - accepted by PRL

- Exclude $\kappa_{2V} = 0$ when other H couplings are fixed to their standard model values
- Most sensitive HH channel

An underestimated tool set (1)



Boosted $HH \rightarrow b\bar{b}b\bar{b}$



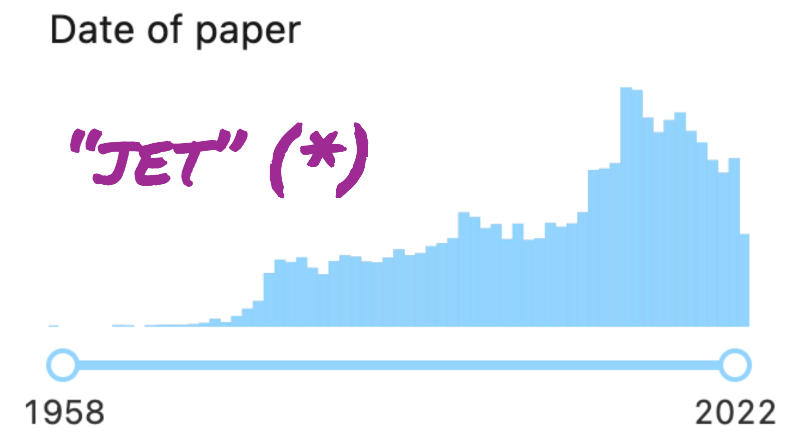
This is only the tip of the iceberg — a large number of theoretical and experimental physics results of various kinds are based on jet substructure

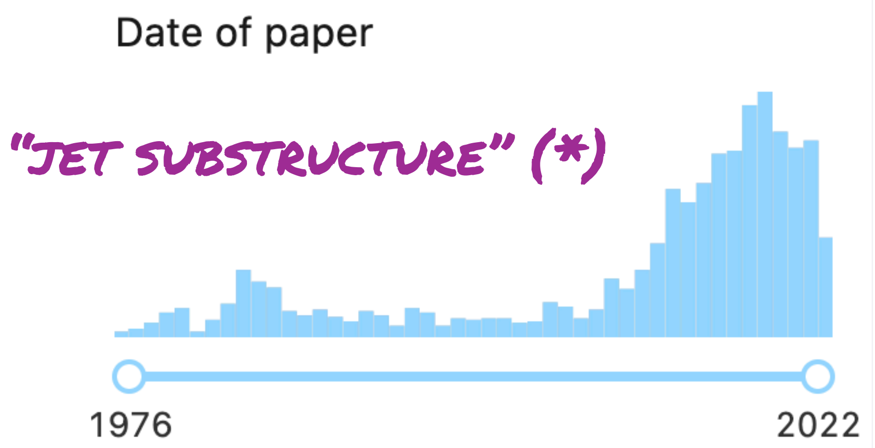
- Exclude $\kappa_{2V} = 0$ when other H couplings are fixed to their standard model values
- Most sensitive HH channel

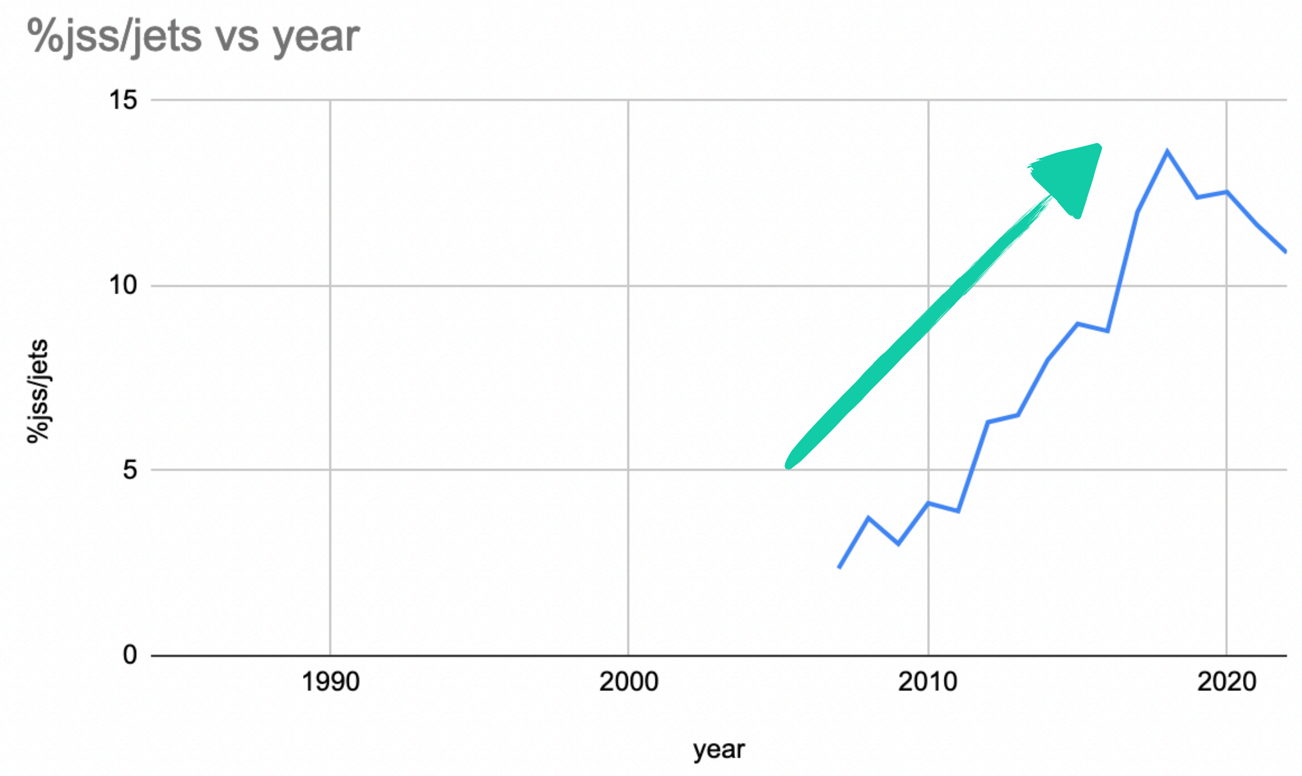
CMS-B2G-22-003 - accepted by PRL

The future is built on jet substructure

Jet substructure is an indispensable tool **today and even more so in the future**







"(Jet) substructure" mentioned?

- ATLAS TDR (1999) ✗
- CMS TDR (2006) ✗
- ALICE Physics TDR (2005) ✗
- EIC CDR (2021) ✓
- ILC TDR (2013) ✓
- ILC Snowmass (2021) (19+ times!) ✓

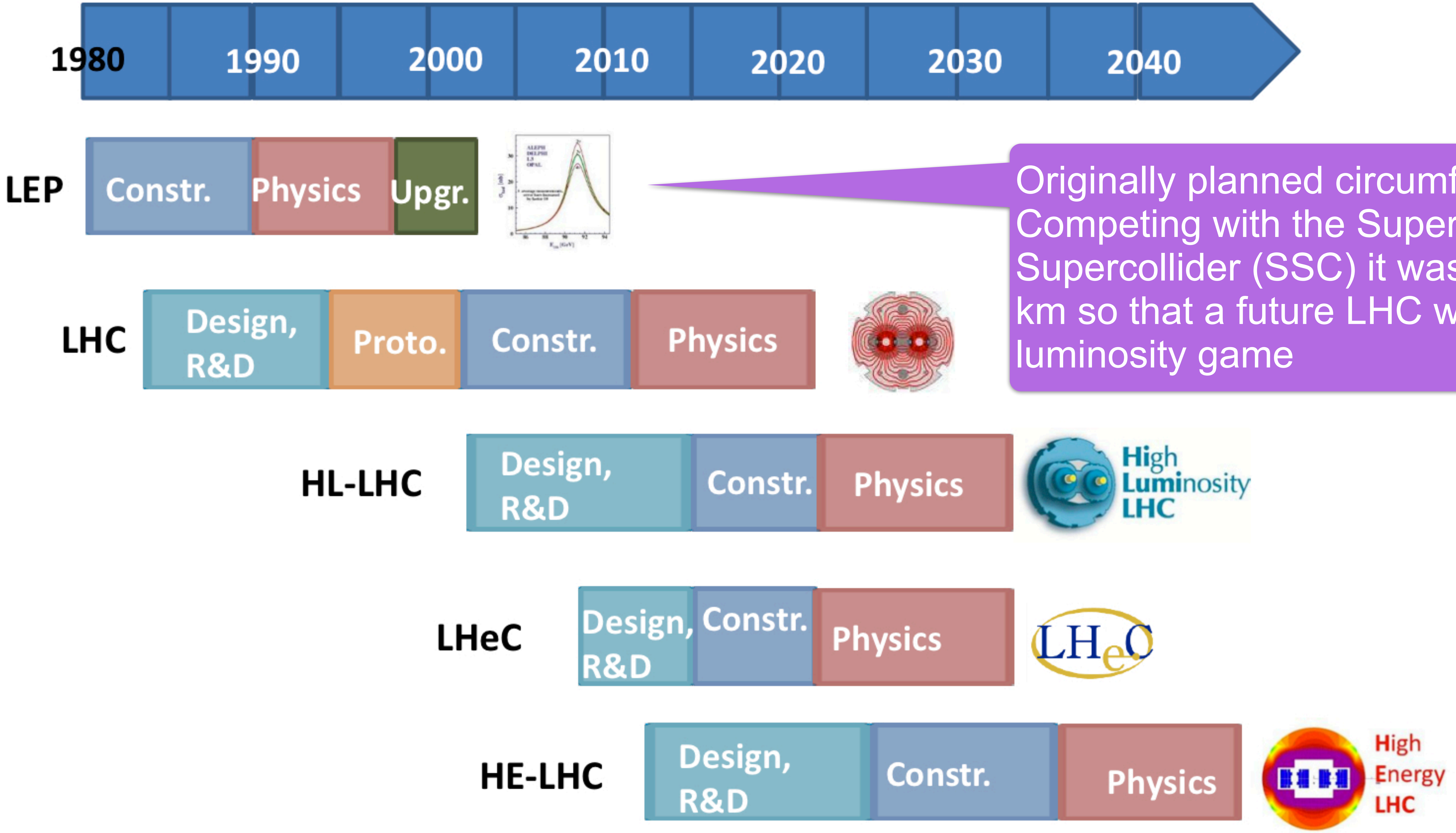
Jet substructure has been established as a versatile + mainstream tool for many areas of collider physics!

Matt LeBlanc (CERN) — Overview (Experimental) — BOOST 2022 — Slide 44

* "jet" not "blazar" not "black hole" not "Kerr" not "Supernovae" not "blazars" not "black holes" not "Radio" not "Galaxy" not "optical" not "accretion" not "GRB" not "gravitational"

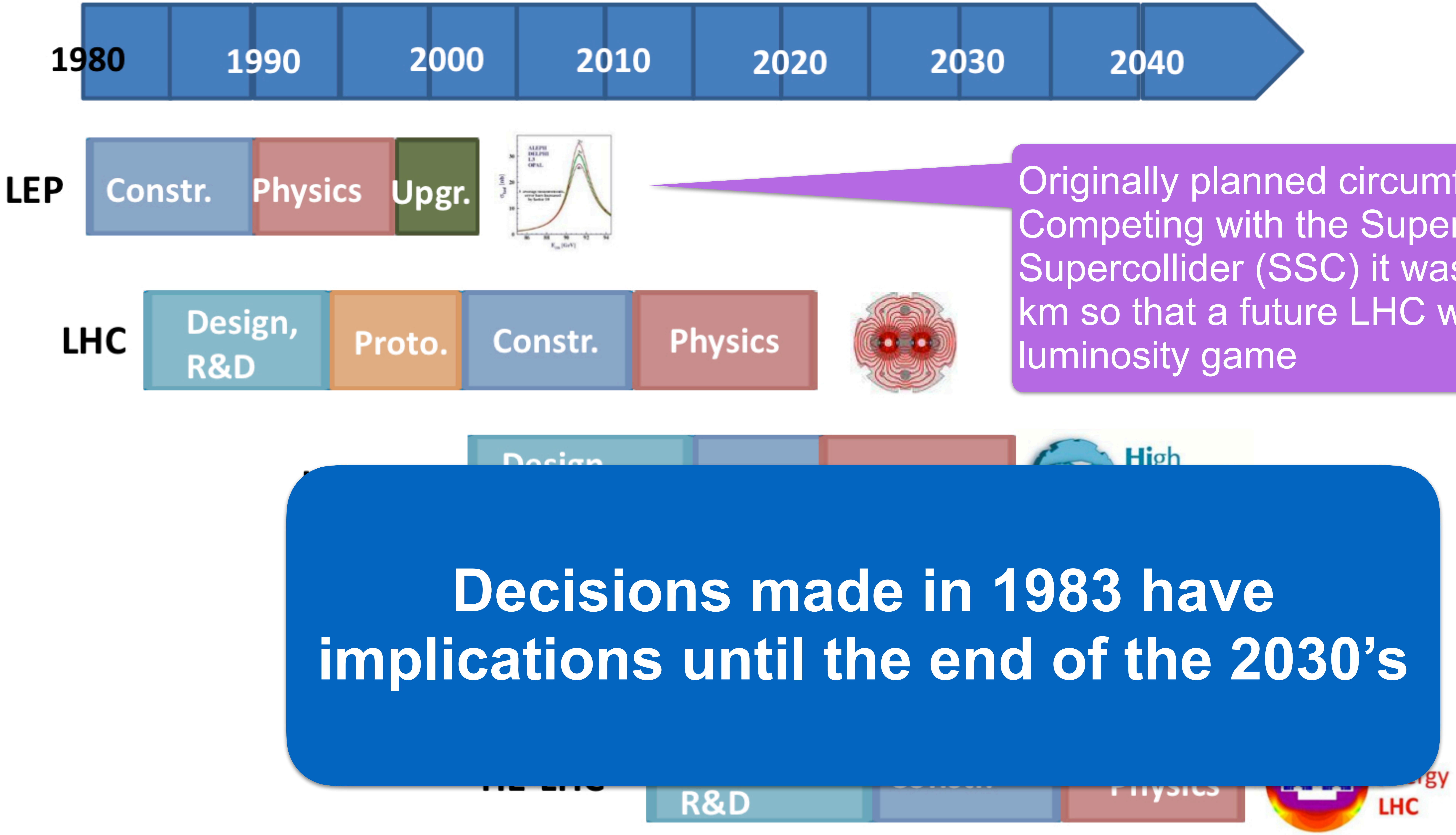
** "jet substructure" or "soft drop" or "soft-drop" or "Lund jet plane" or "jet topics" or "Particle Flow Network" or "boosted top" or "boosted boson" or "jet fragmentation"

CERN Bulletin 2012: LEP tunnel



Originally planned circumference: 22 km
Competing with the Superconducting Supercollider (SSC) it was increased to 27 km so that a future LHC would “win” the luminosity game

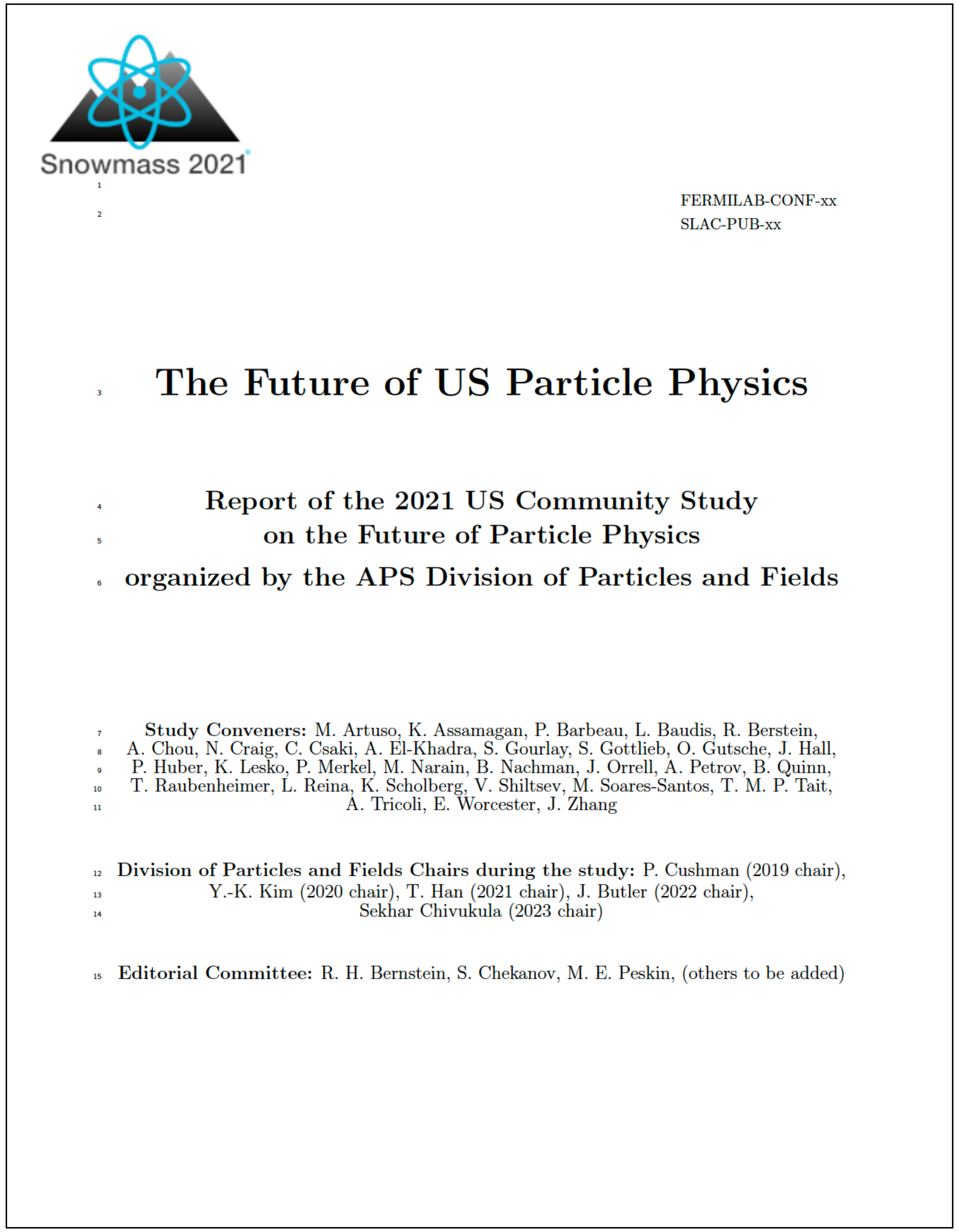
CERN Bulletin 2012: LEP tunnel



Originally planned circumference: 22 km
Competing with the Superconducting Supercollider (SSC) it was increased to 27 km so that a future LHC would "win" the luminosity game

Decisions made in 1983 have implications until the end of the 2030's

Updated strategies



Snowmass 2021

FERMILAB-CONF-xx
SLAC-PUB-xx

The Future of US Particle Physics

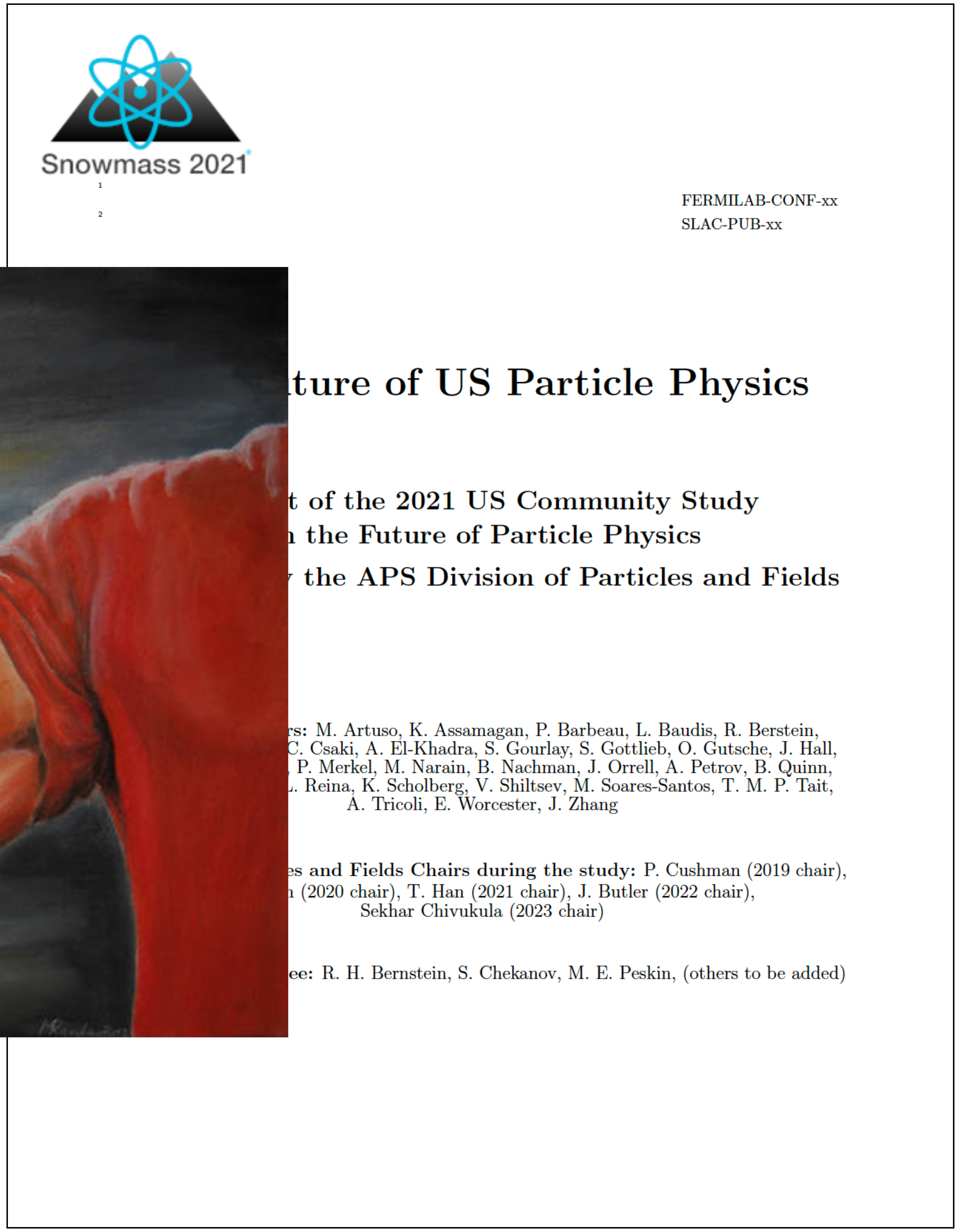
Report of the 2021 US Community Study
on the Future of Particle Physics
organized by the APS Division of Particles and Fields

Study Conveners: M. Artuso, K. Assamagan, P. Barbeau, L. Baudis, R. Berstein, A. Chou, N. Craig, C. Csaki, A. El-Khadra, S. Gourlay, S. Gottlieb, O. Gutsche, J. Hall, P. Huber, K. Lesko, P. Merkel, M. Narain, B. Nachman, J. Orrell, A. Petrov, B. Quinn, T. Raubenheimer, L. Reina, K. Scholberg, V. Shiltsev, M. Soares-Santos, T. M. P. Tait, A. Tricoli, E. Worcester, J. Zhang

Division of Particles and Fields Chairs during the study: P. Cushman (2019 chair), Y.-K. Kim (2020 chair), T. Han (2021 chair), J. Butler (2022 chair), Sekhar Chivukula (2023 chair)

Editorial Committee: R. H. Bernstein, S. Chekanov, M. E. Peskin, (others to be added)

Updated strategies



FERMILAB-CONF-xx
SLAC-PUB-xx

ture of US Particle Physics

t of the 2021 US Community Study
n the Future of Particle Physics
the APS Division of Particles and Fields

rs: M. Artuso, K. Assamagan, P. Barbeau, L. Baudis, R. Berstein,
C. Csaki, A. El-Khadra, S. Gourlay, S. Gottlieb, O. Gutsche, J. Hall,
P. Merkel, M. Narain, B. Nachman, J. Orrell, A. Petrov, B. Quinn,
. Reina, K. Scholberg, V. Shiltsev, M. Soares-Santos, T. M. P. Tait,
A. Tricoli, E. Worcester, J. Zhang

es and Fields Chairs during the study: P. Cushman (2019 chair),
(2020 chair), T. Han (2021 chair), J. Butler (2022 chair),
Sekhar Chivukula (2023 chair)

ee: R. H. Bernstein, S. Chekanov, M. E. Peskin, (others to be added)

Numerous options post HL-LHC

CLIC

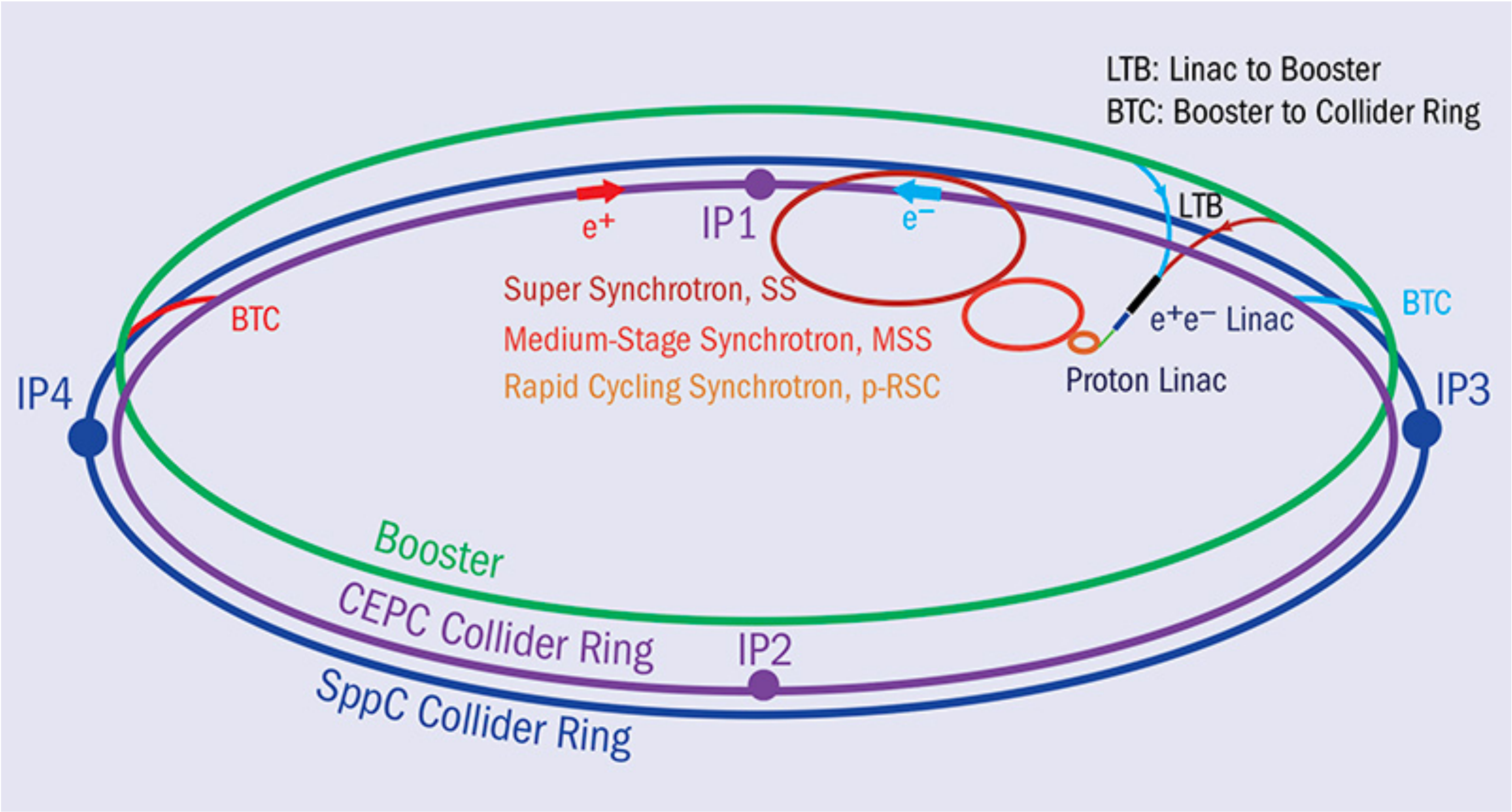
ilc
international linear collider

FCC
hh ee he

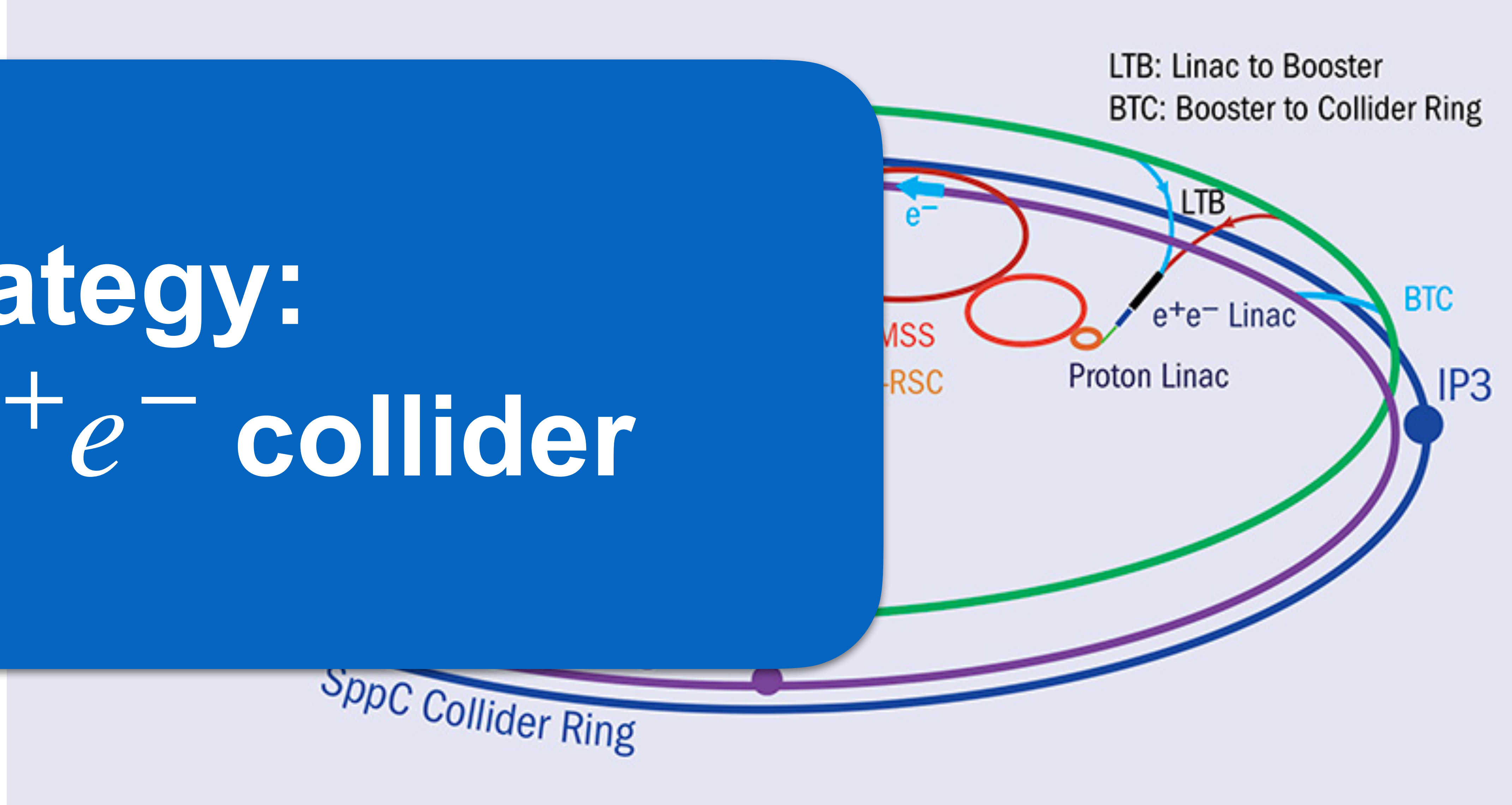
International
MUON Collider
Collaboration

LHeC

High
Energy
LHC



Numerous options post HL-LHC



European Strategy:
highest priority to e^+e^- collider

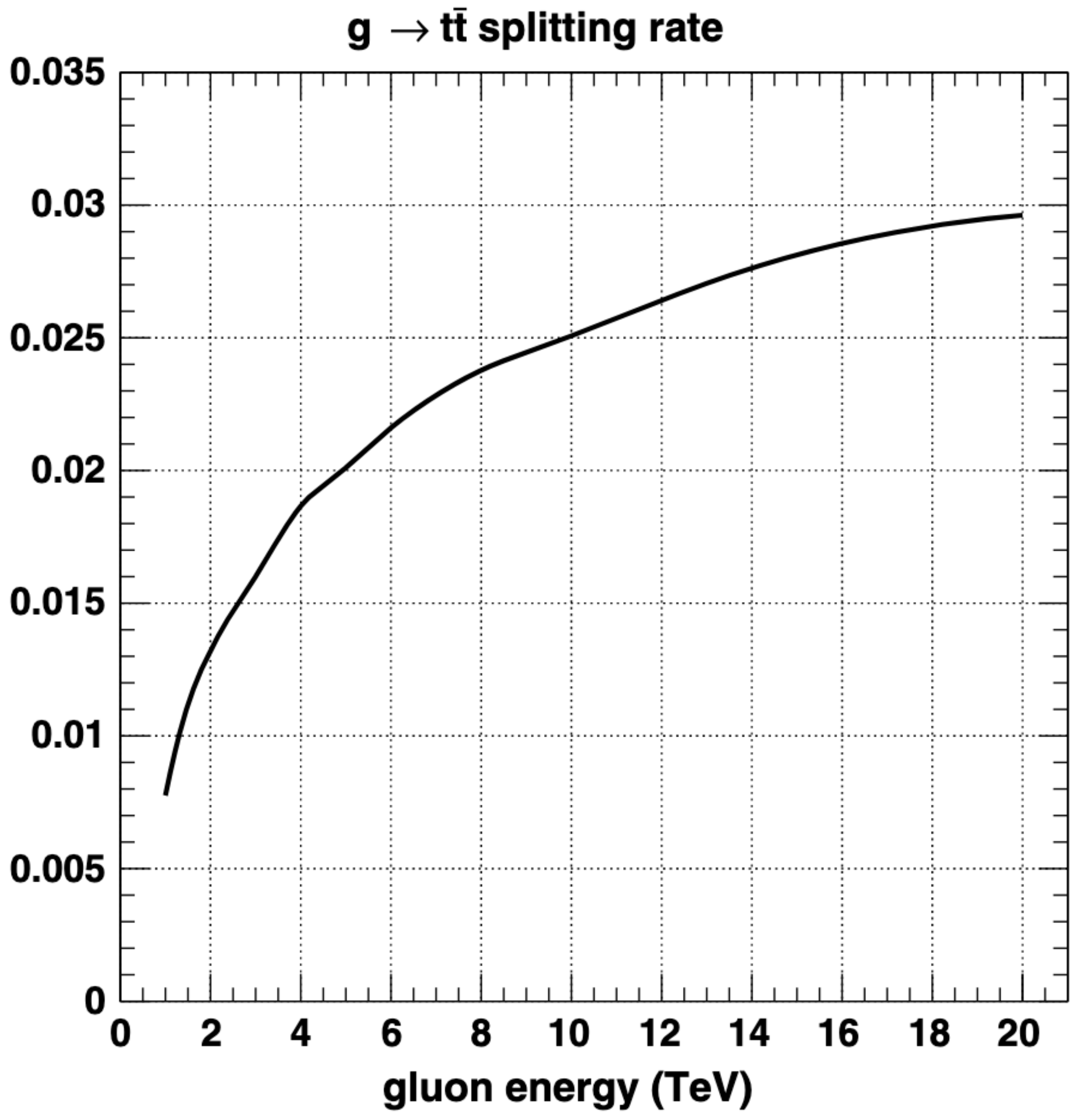
To higher energies

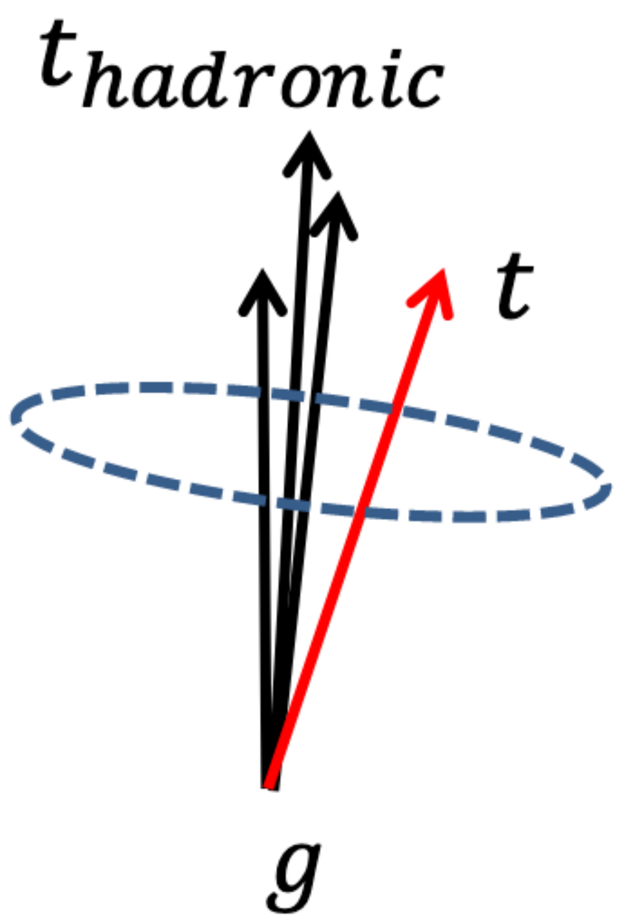
- No matter which collider, on average particles will have higher energies → more boosted objects!
- We will still want to do all the (jet substructure) things we do today:
  - W/Z/H/top/heavy-flavour/q/g tagging
  - Quarks and gluons: test scaling behaviour, α_s, tune MC generators, …
  - Understand high-p_T tails, e.g. vector-boson fusion process, heavy resonance searches, …

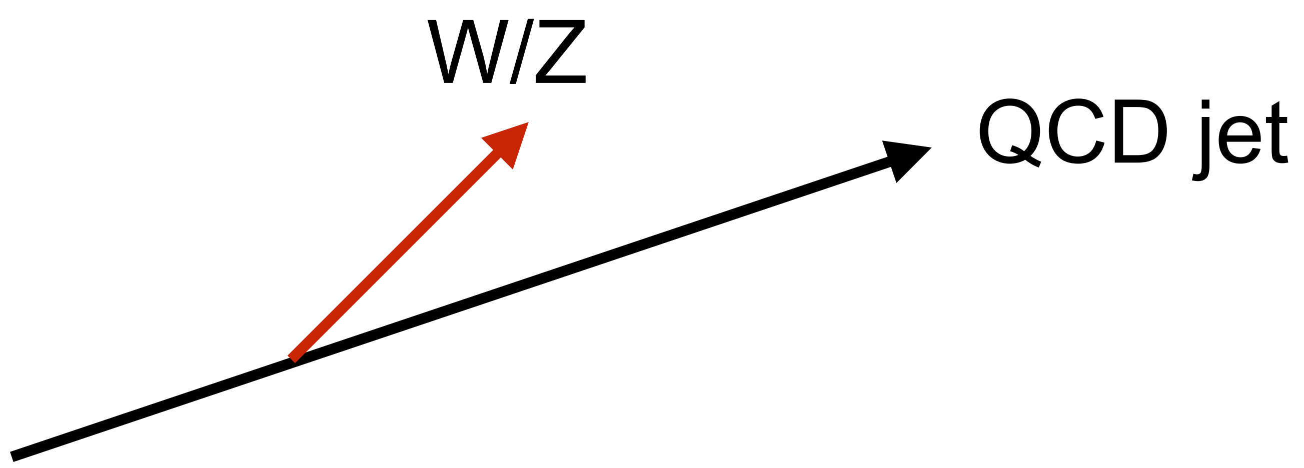
Novel SM effects at tens of TeV

Examples:

- **>** Splitting $g \rightarrow t\bar{t}$:
  - discriminate from prompt ttbar production
- **>** Similarly, particles can radiate H, W, Z bosons (while based on the hard event they are quarks)
- **>** **Our goal is to challenge the standard model** → need to be able to reconstruct such events





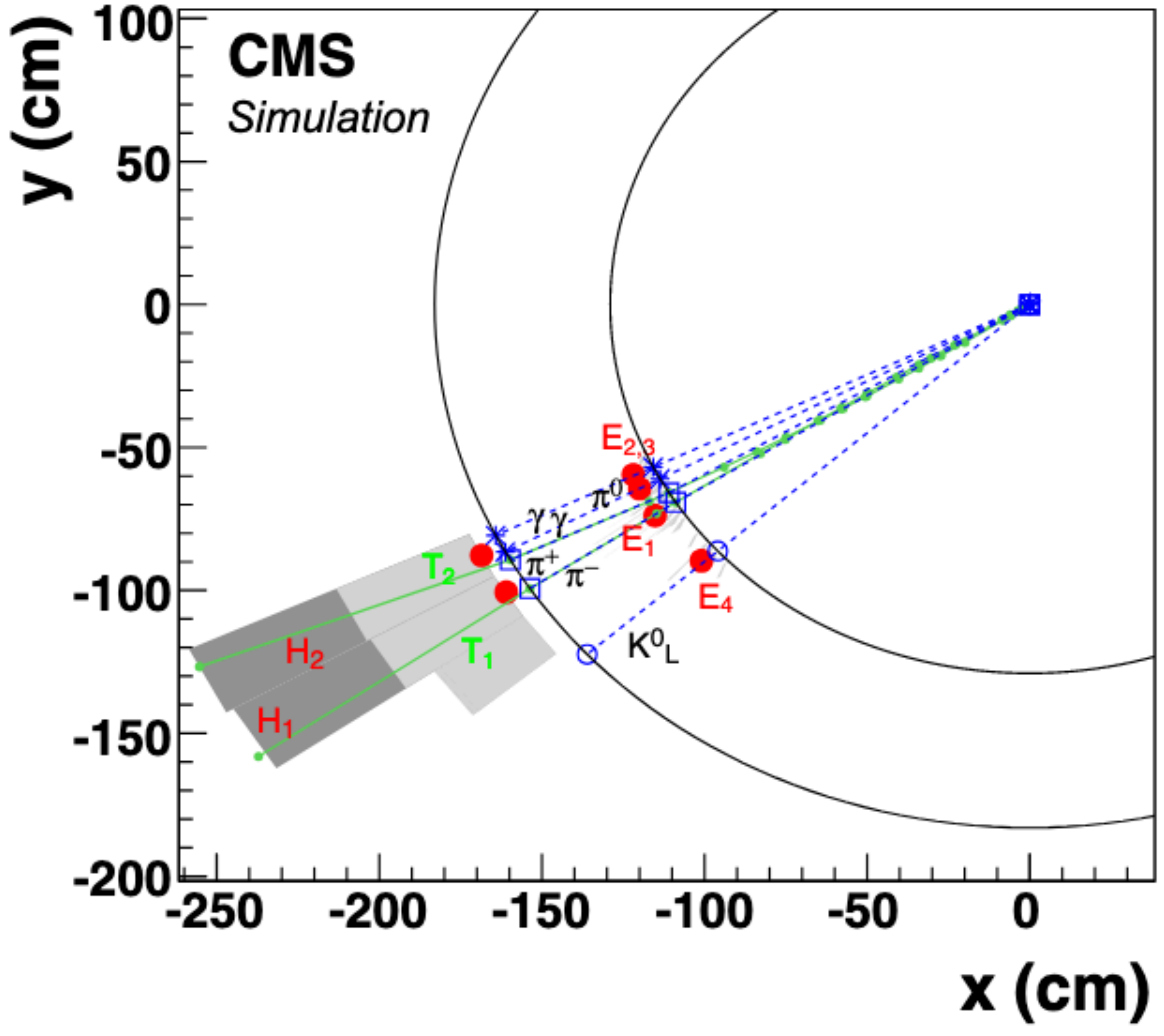


M. Son, TOP2019
PRD 97 036023 (2018)

Investigating jet substructure

Particle flow including pileup removal

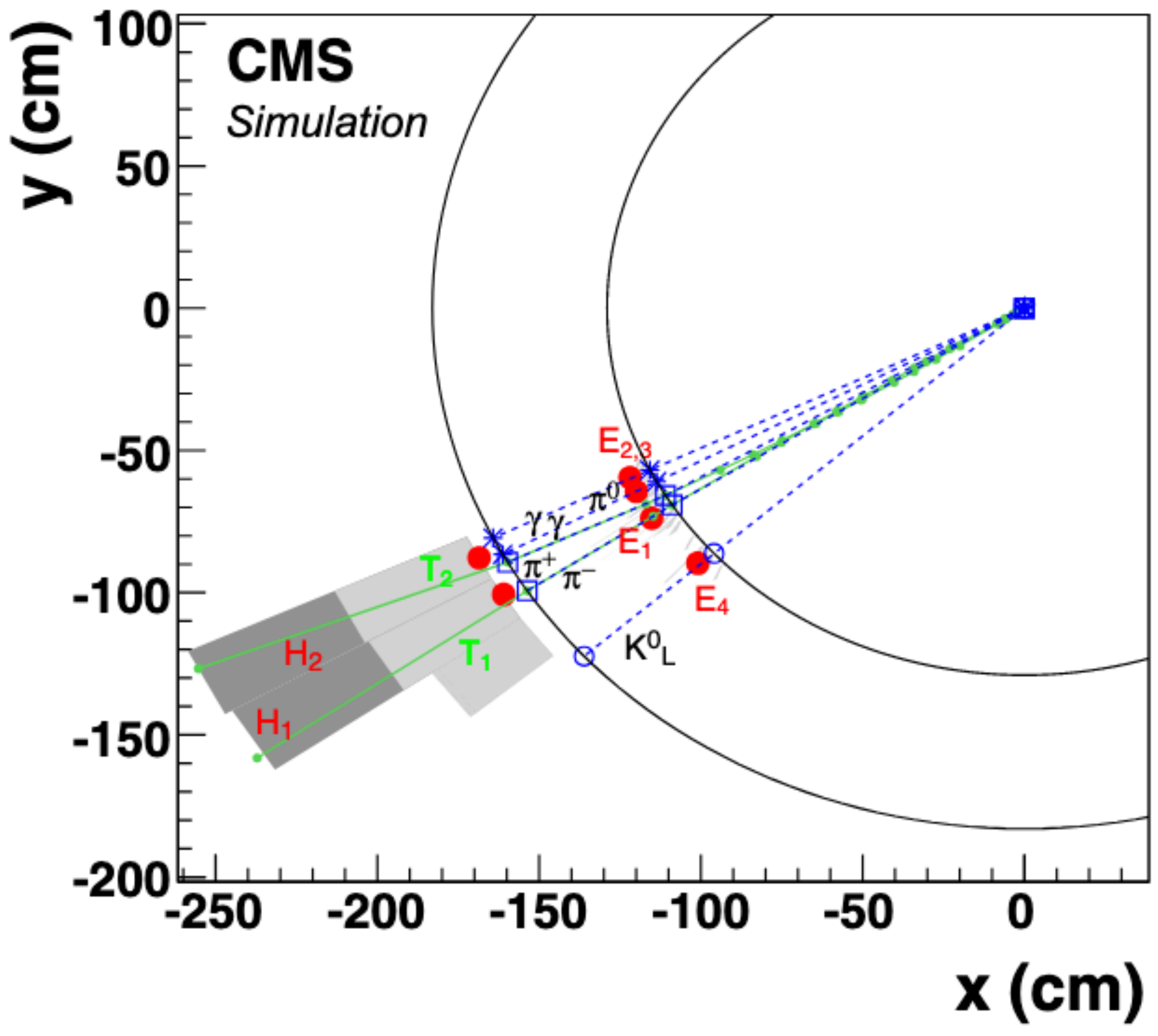
Hits → Tracks, vertices, and calorimeter clusters

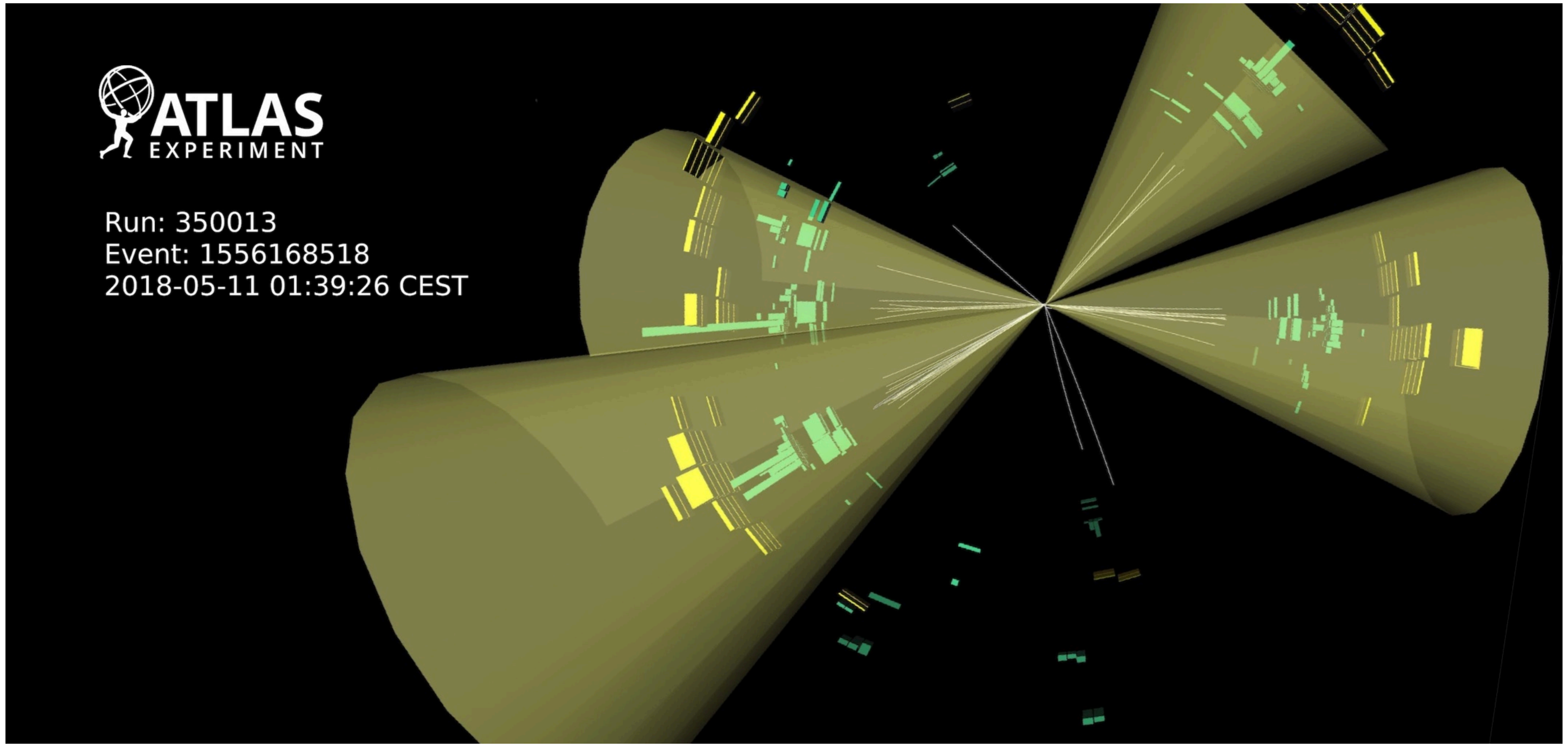


Investigating jet substructure

Particle flow including pileup removal

Hits → Tracks, vertices, and calorimeter clusters → Jets

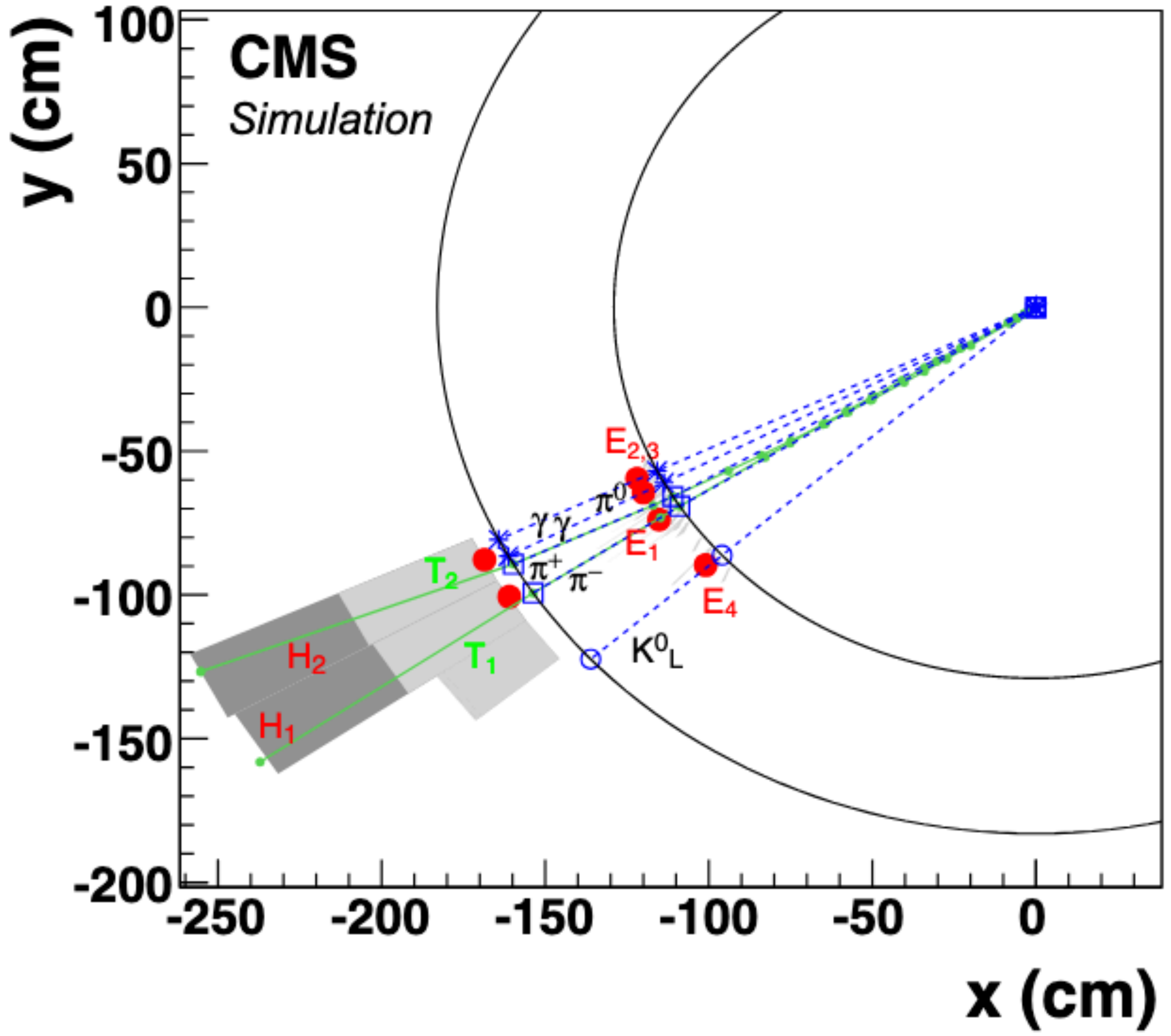


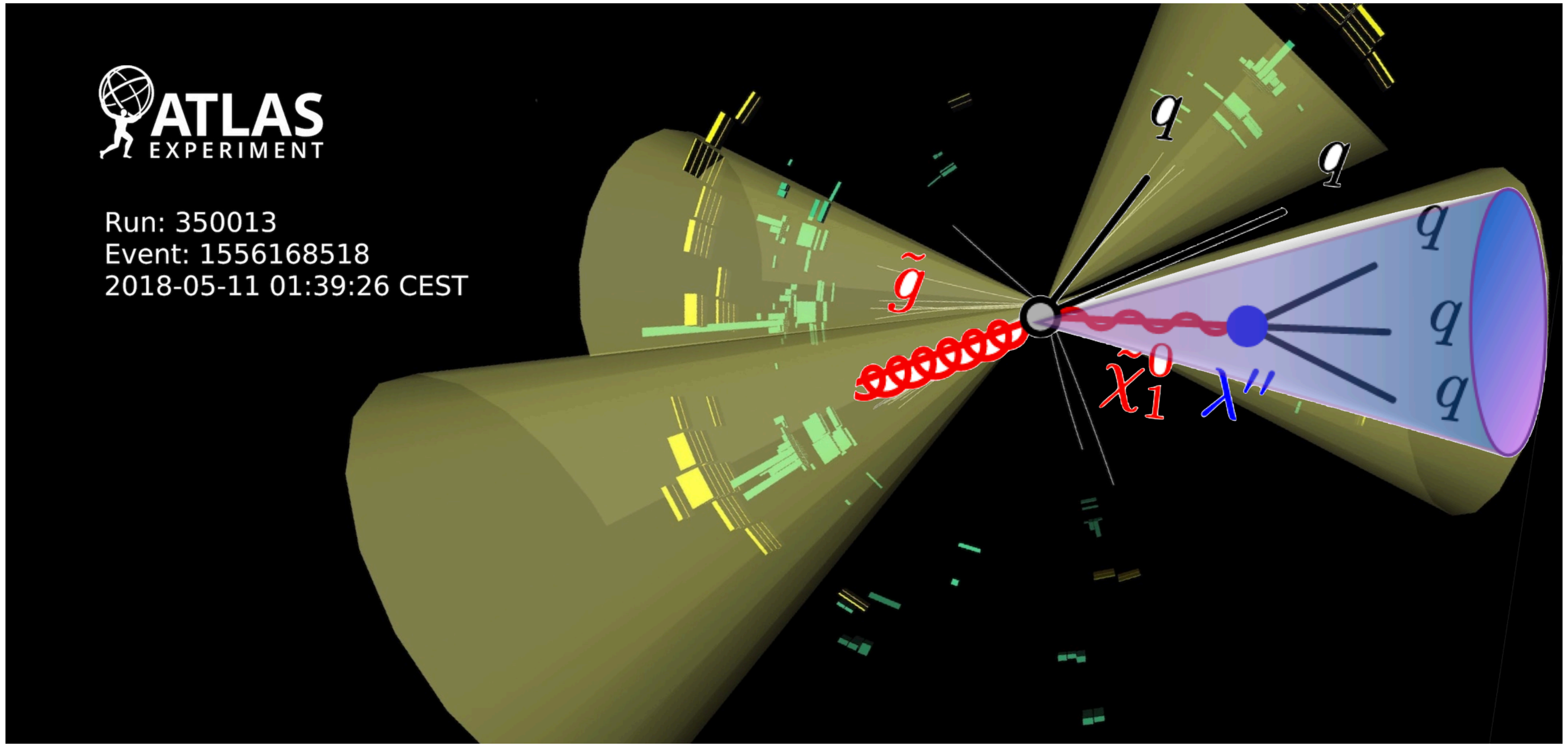


Investigating jet substructure

Particle flow including pileup removal

Hits → Tracks, vertices, and calorimeter clusters → Jets → Jet substructure

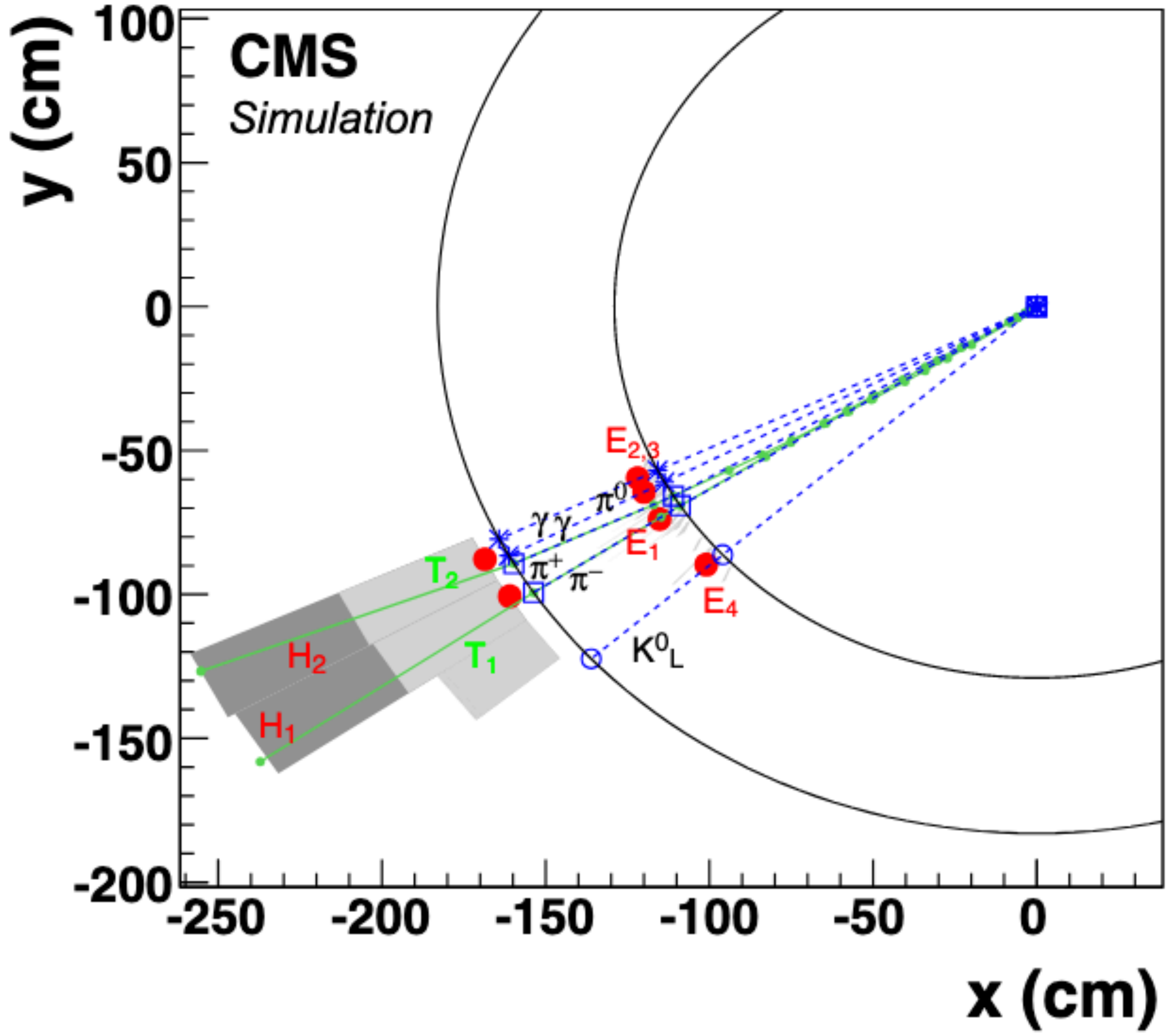


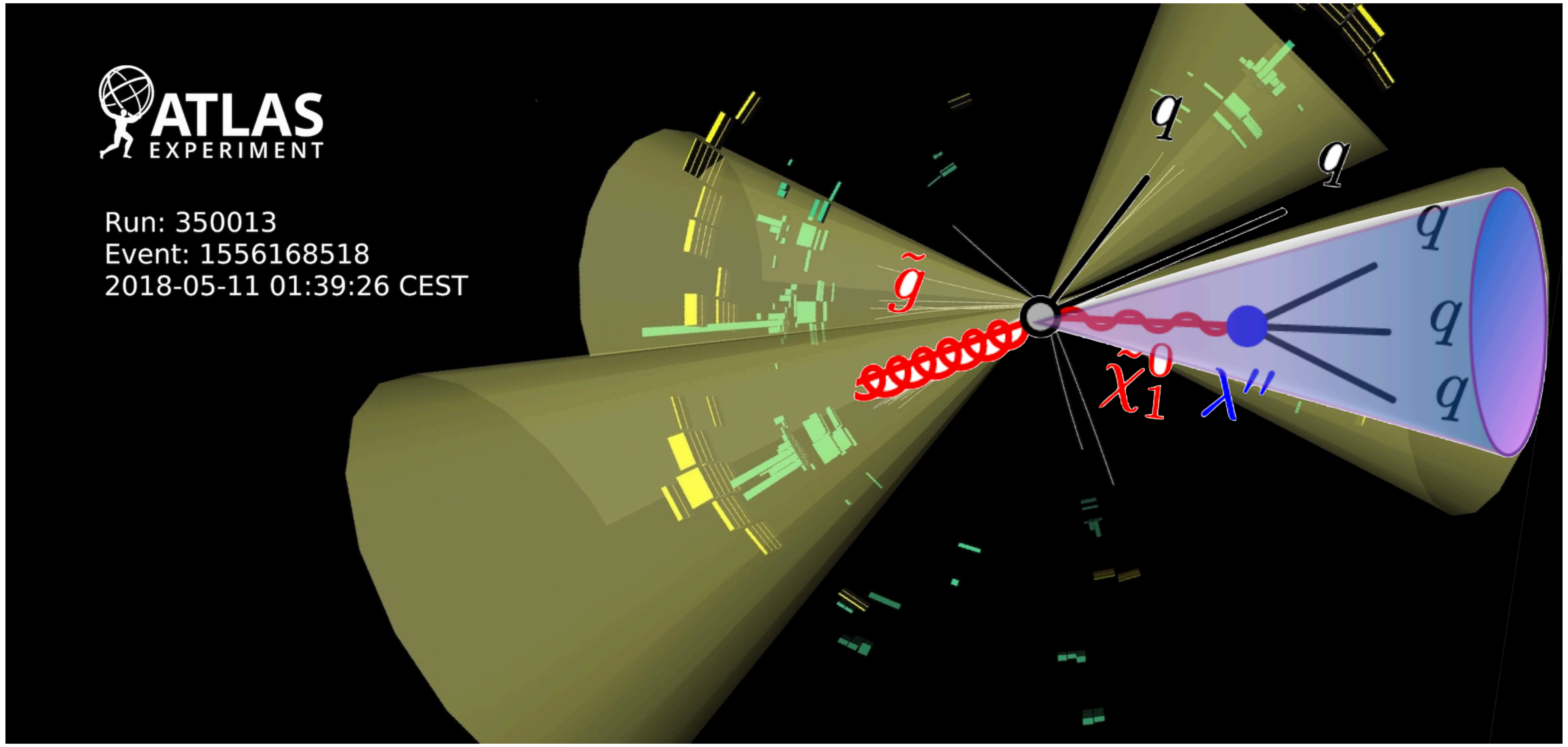


Investigating jet substructure

Particle flow including pileup removal

Hits → Tracks, vertices, and calorimeter clusters → Jets → Jet substructure



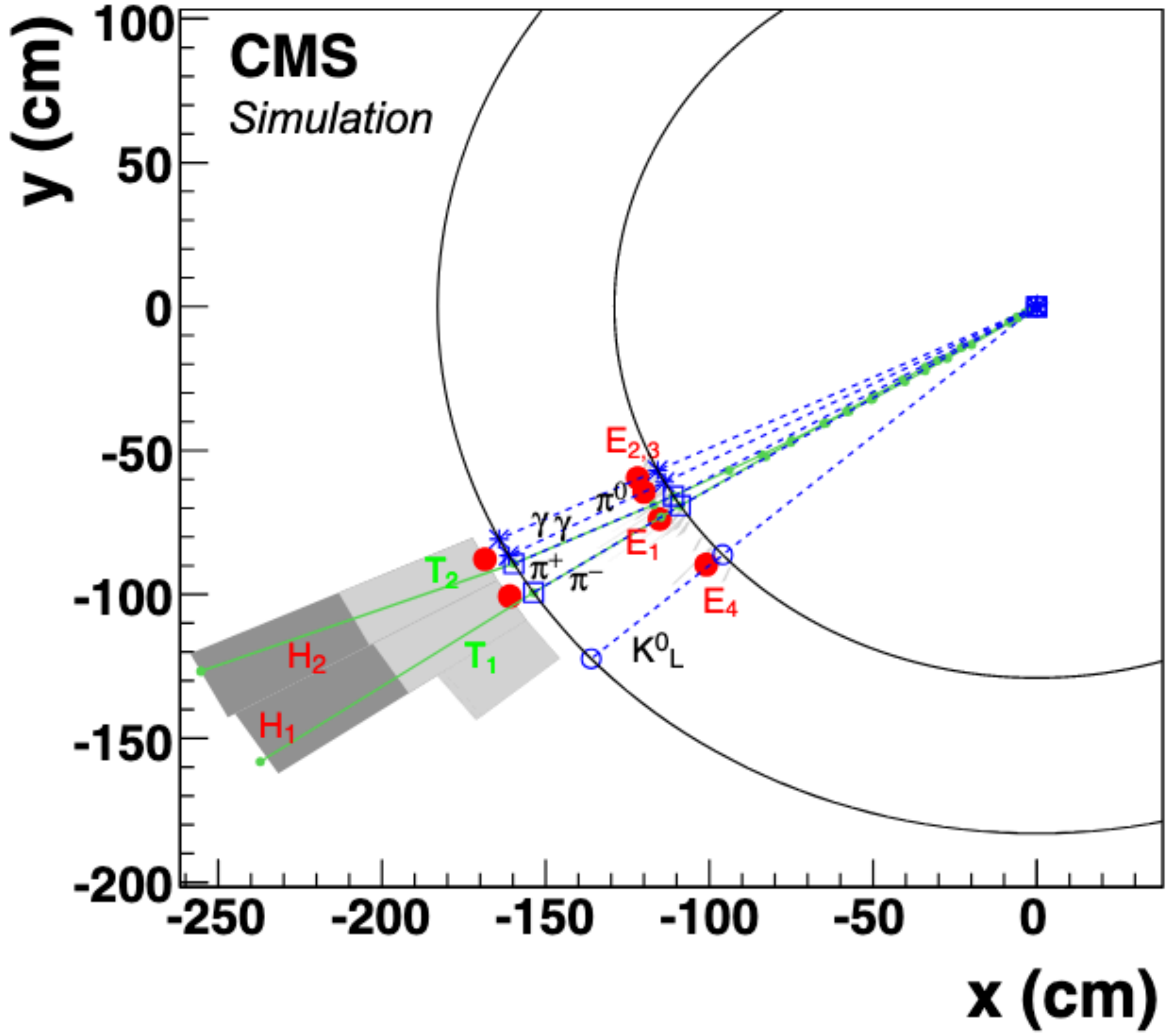


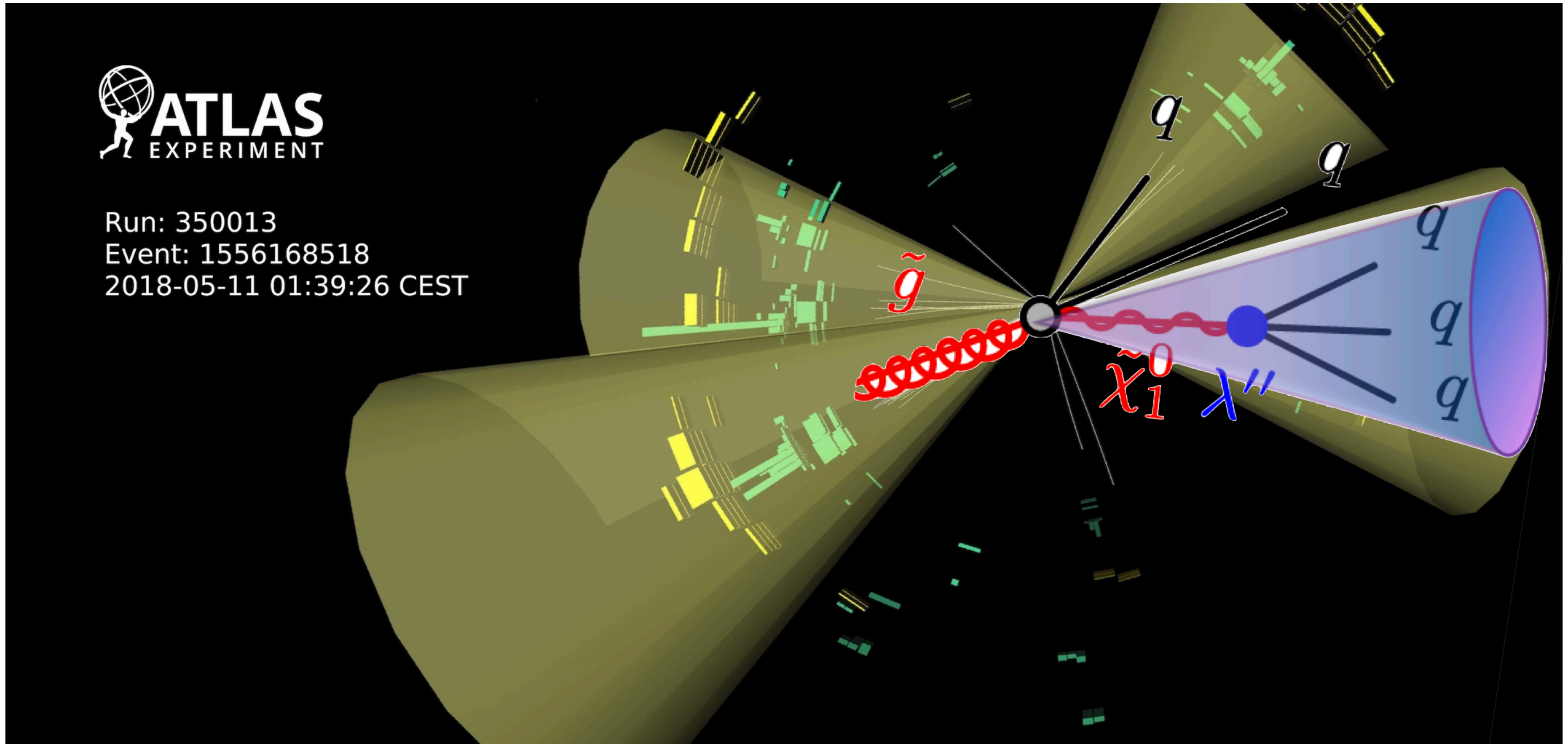
Solve everything with machine learning?

Investigating jet substructure

Particle flow including pileup removal

Hits → Tracks, vertices, and calorimeter clusters → Jets → Jet substructure





see also:

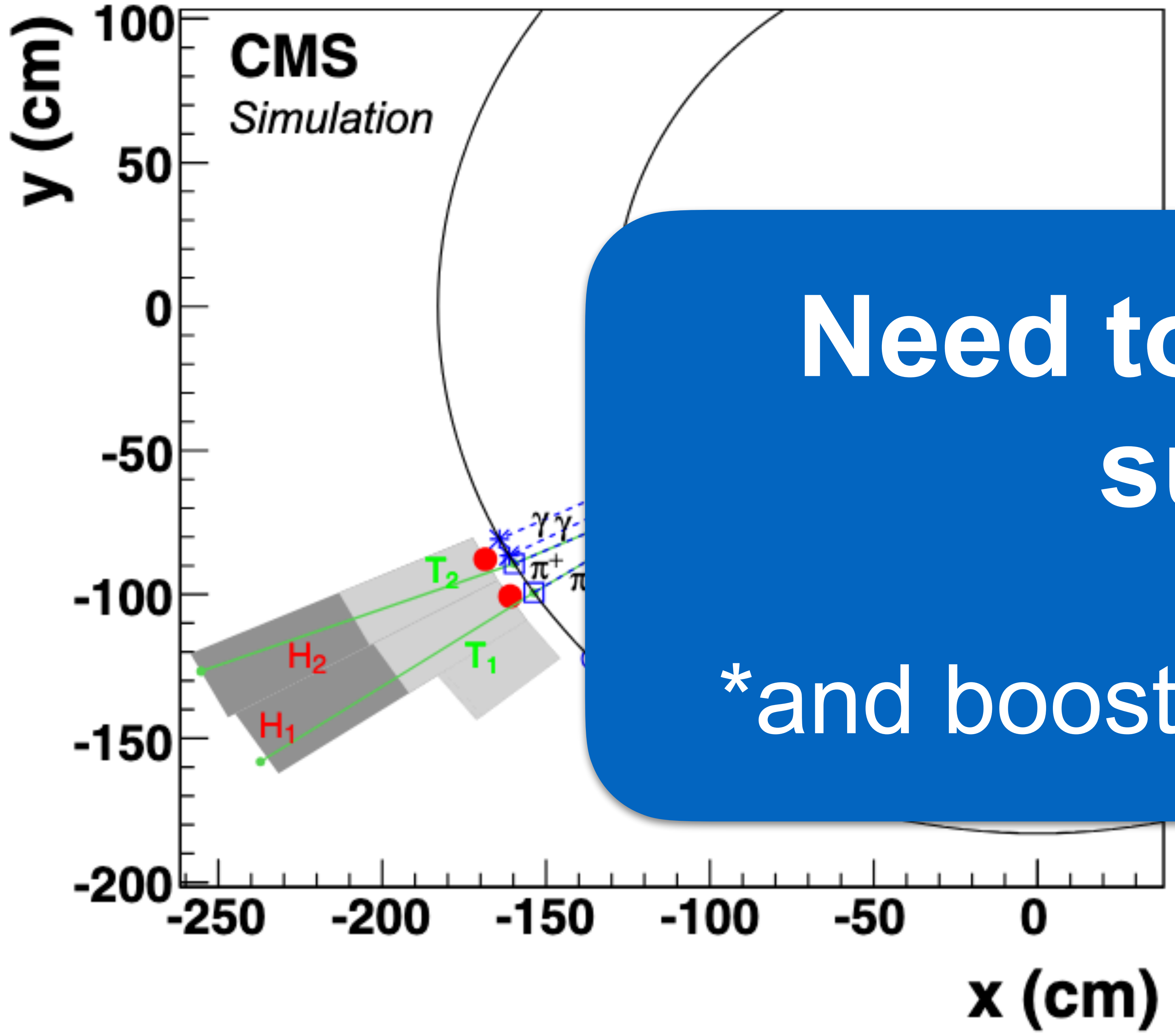
MODE

Solve everything with machine learning?

Investigating jet substructure

Particle flow including pileup removal

Hits → Tracks, vertices, and calorimeter clusters → Jets → Jet substructure



Need to design detectors with jet substructure* in mind

*and boosted object reconstruction in general

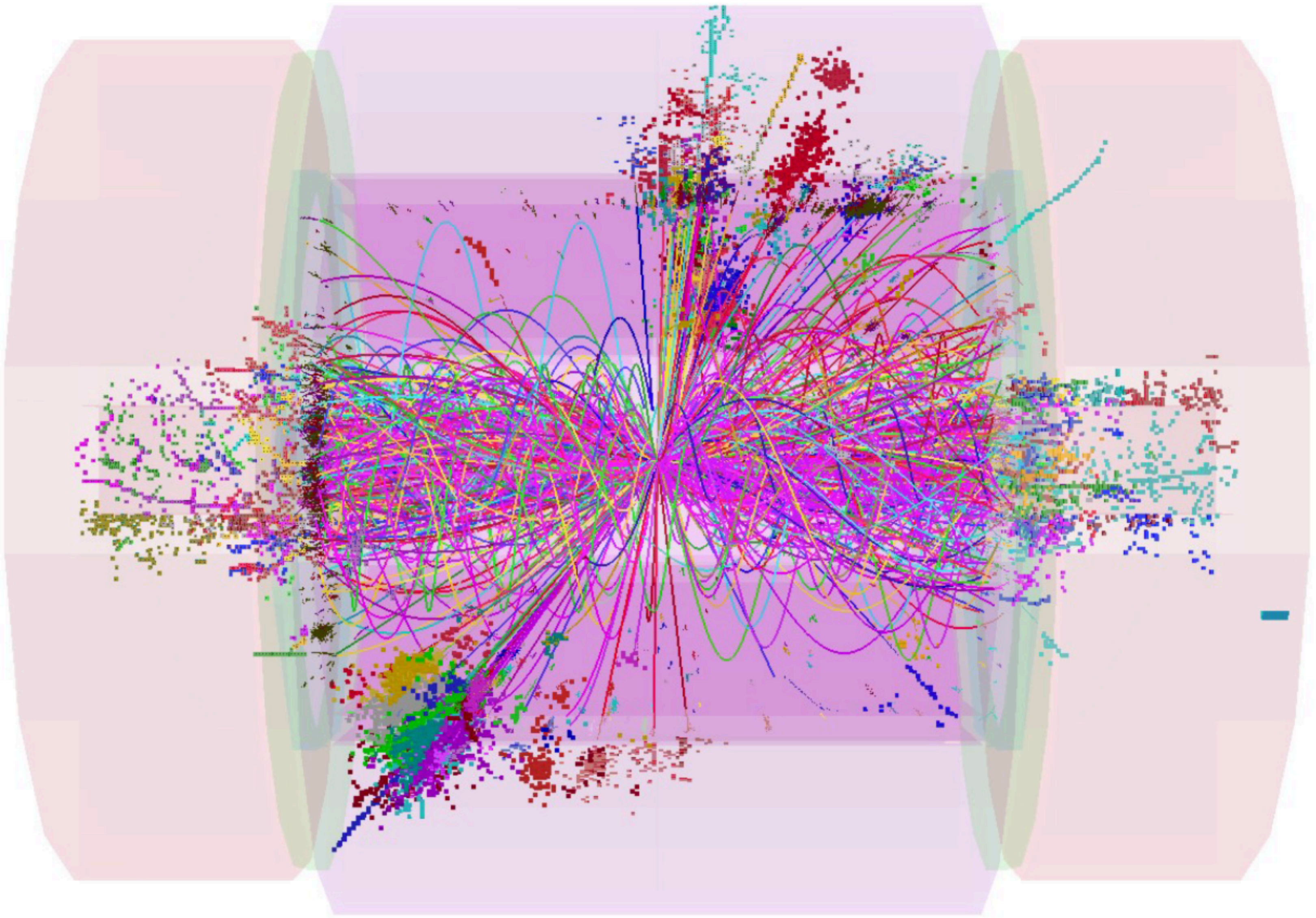
Solve everything with machine learning?

see also: MODE

Beam-induced backgrounds

Different colliders bring along different challenges, e.g.:

- e^+e^-: $\gamma\gamma \rightarrow$ hadrons, incoherent pair production
- $\mu^+\mu^-$: $\mu \rightarrow e\nu\nu$ decays before collision
  - Additional shielding/beam-background detectors required → adds to material budget
- pp: at FCC-hh, expect up to 1000 simultaneous collisions (pileup)
  - LHC Run-3 leveled to ~52 PU
  - HL-LHC 140-200 PU



CLIC: $e^+e^- \rightarrow HH$ with $\gamma\gamma \rightarrow$ hadrons background overlaid (before timing selection)

PAUL SCHERRER INSTITUT

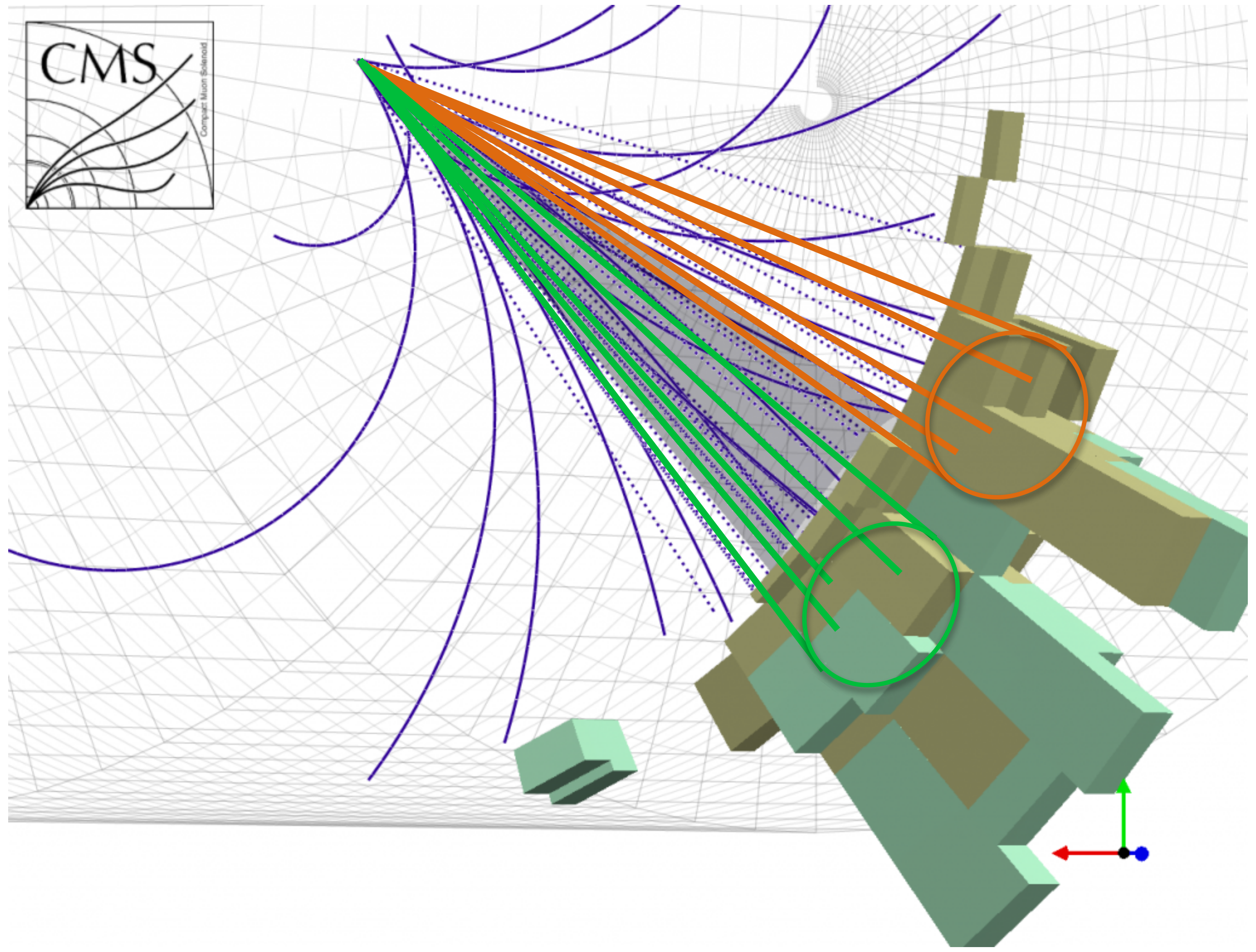
Which kind of collider would you like to have built next?

a) e+e- collider
b) hadron collider
c) μ+μ- collider
d) e-hadron collider

Klicker UZH

https://app.klicker.uzh.ch/join/boost

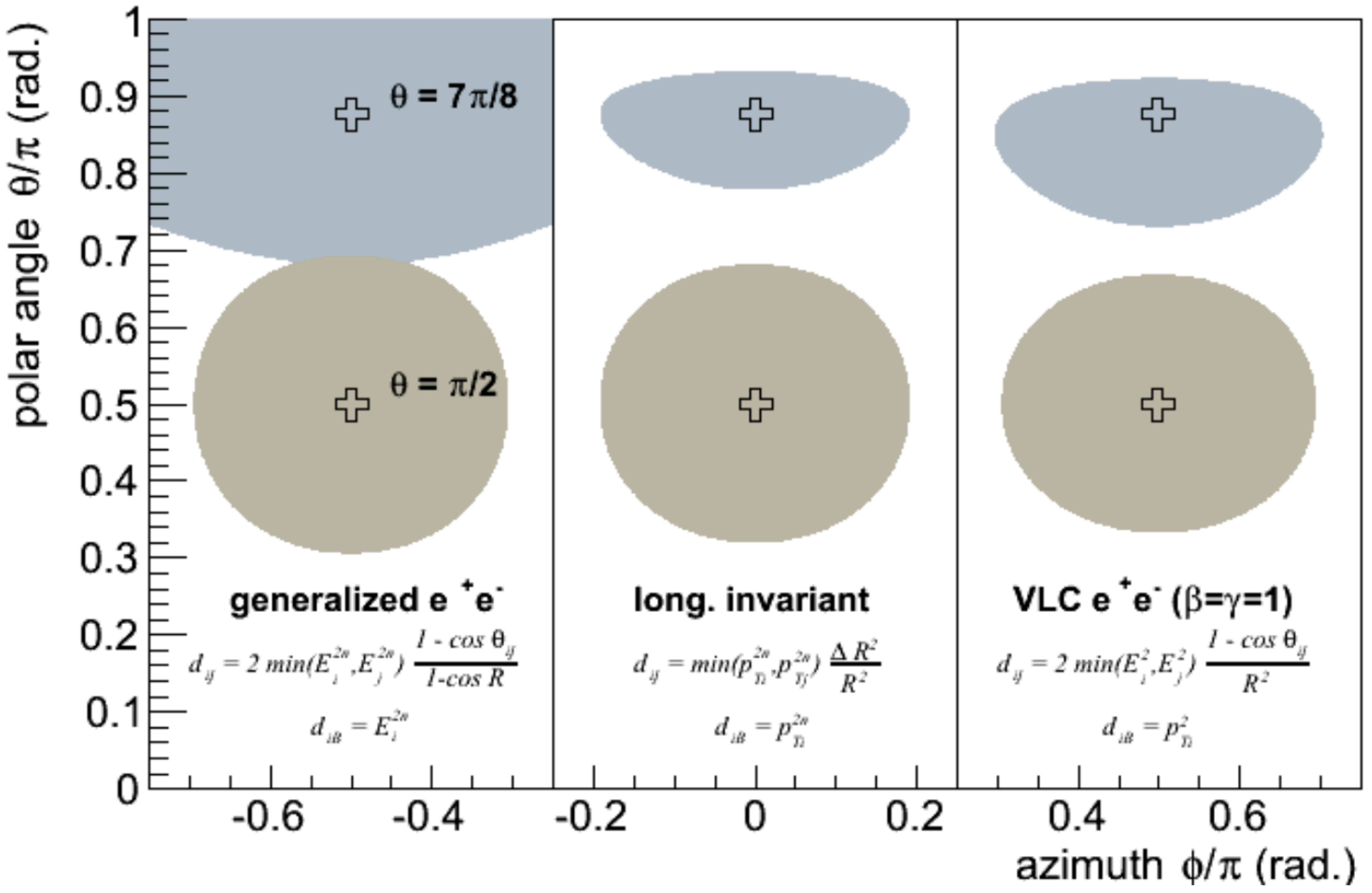
Jet reconstruction



- Traditionally, jet finding + clustering + calibration initial step for jet substructure
- Optimal approach depends on:
  - Varying energy range
  - Centre-of-mass energy fixed or not
  - Respective beam backgrounds
- Crucial: understand shower shapes and (spatial and temporal) shower development in test beams, adjust simulation
- Lots of unknowns in particular for hadron colliders and suitable shower modeling…

Jet reconstruction: lepton collider

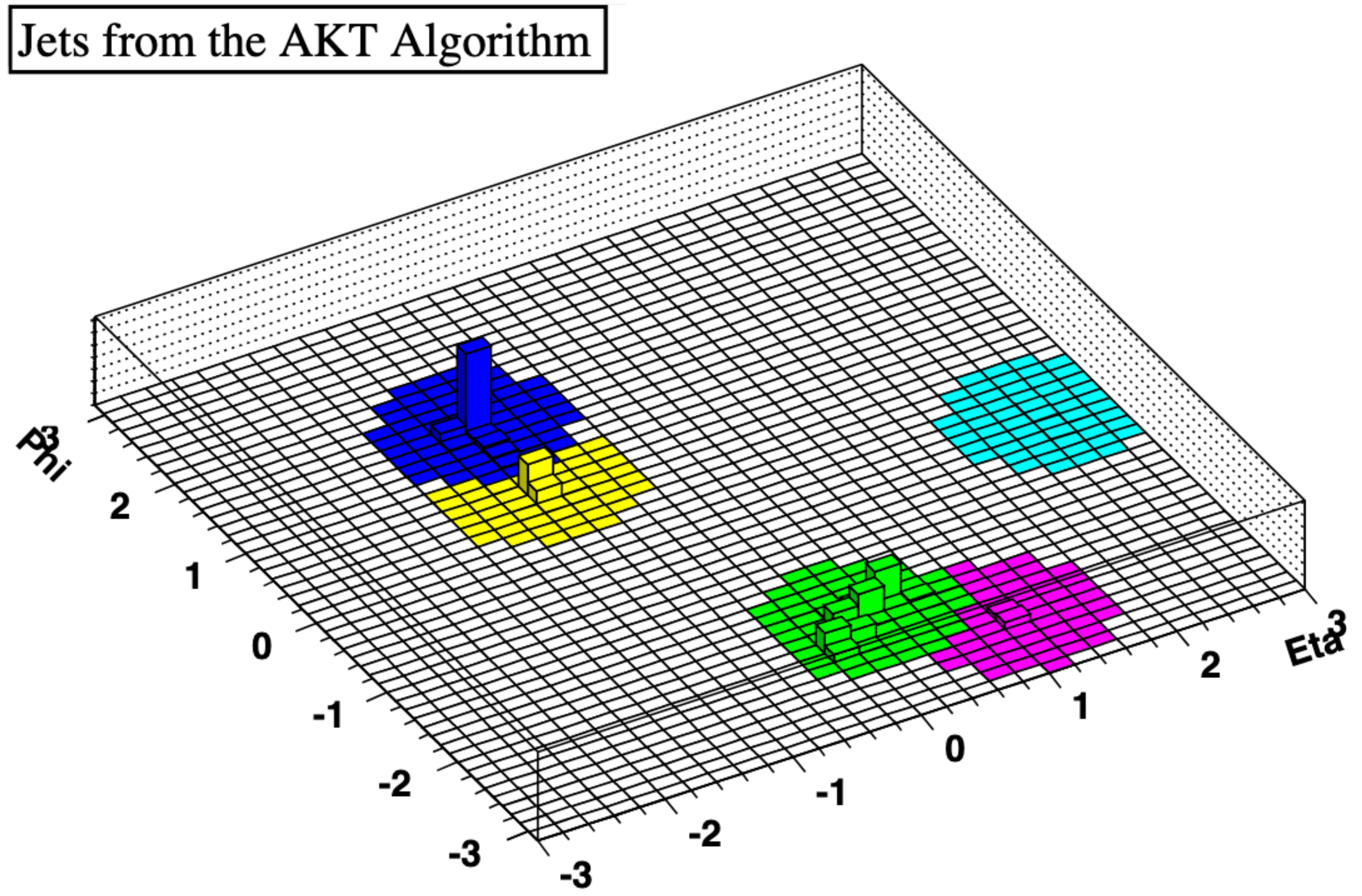
- Consider new/different jet clustering approaches w.r.t. hadron colliders due to different backgrounds
  - In particular important for multi-jet final states, N_j > 6 (HH, ttH etc.)
  - Valencia algorithm promising
  - Also thrust-based clustering an option
  - XCone to accommodate boosted and resolved regimes (close connection to Soft Collinear Effective Theory)

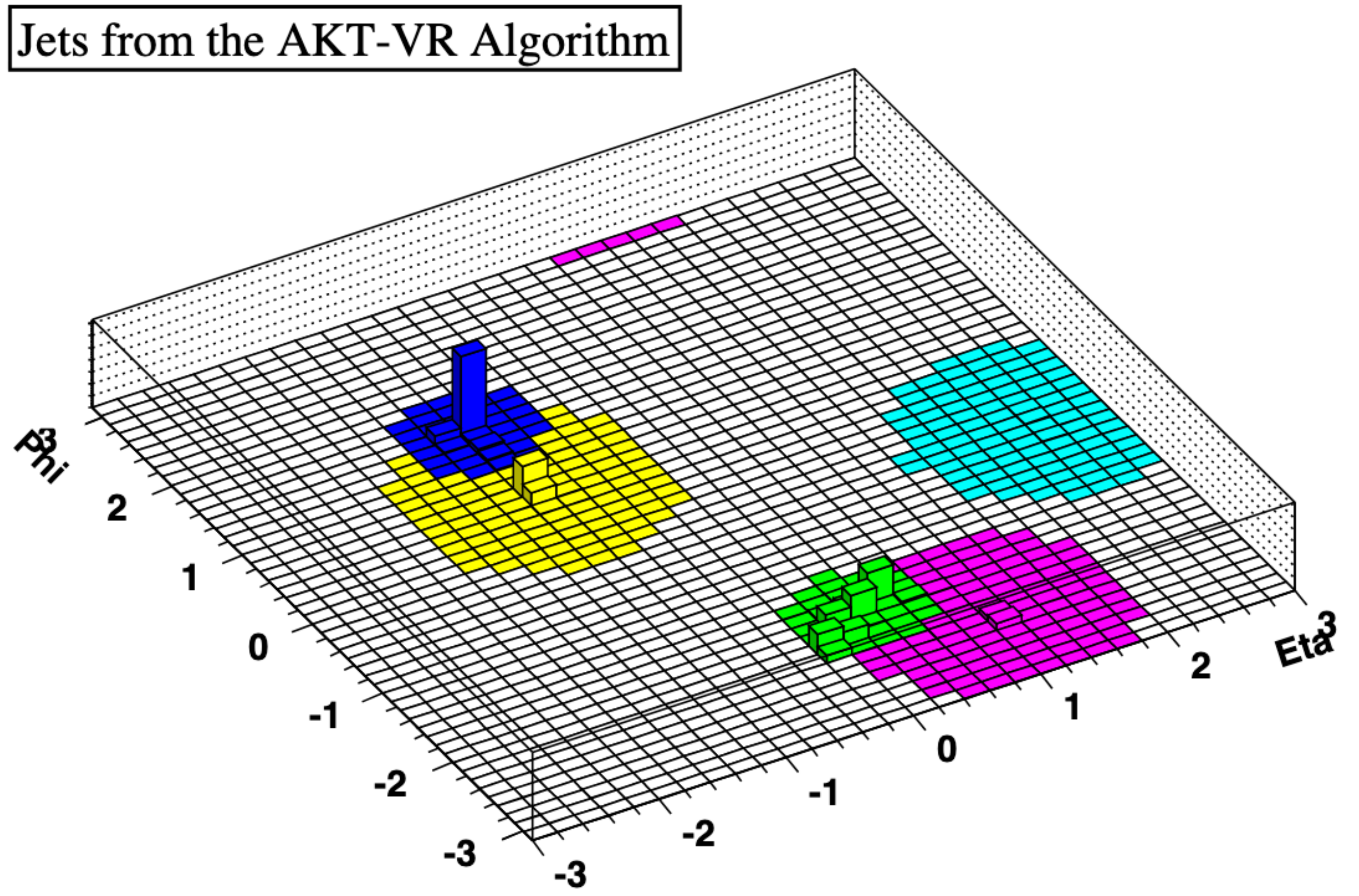


M. Vos

Jet reconstruction: hadron collider

- Well-studied at LHC and Tevatron
  - Mostly fixed-R jet algorithms (help with PU mitigation and calibration)
- Mind: larger R means smaller hadronization corrections in jet p_T (scales with 1/R)
- However, PU and underlying event scale with R^2
- **Need to find a good balance, also consider variable R**

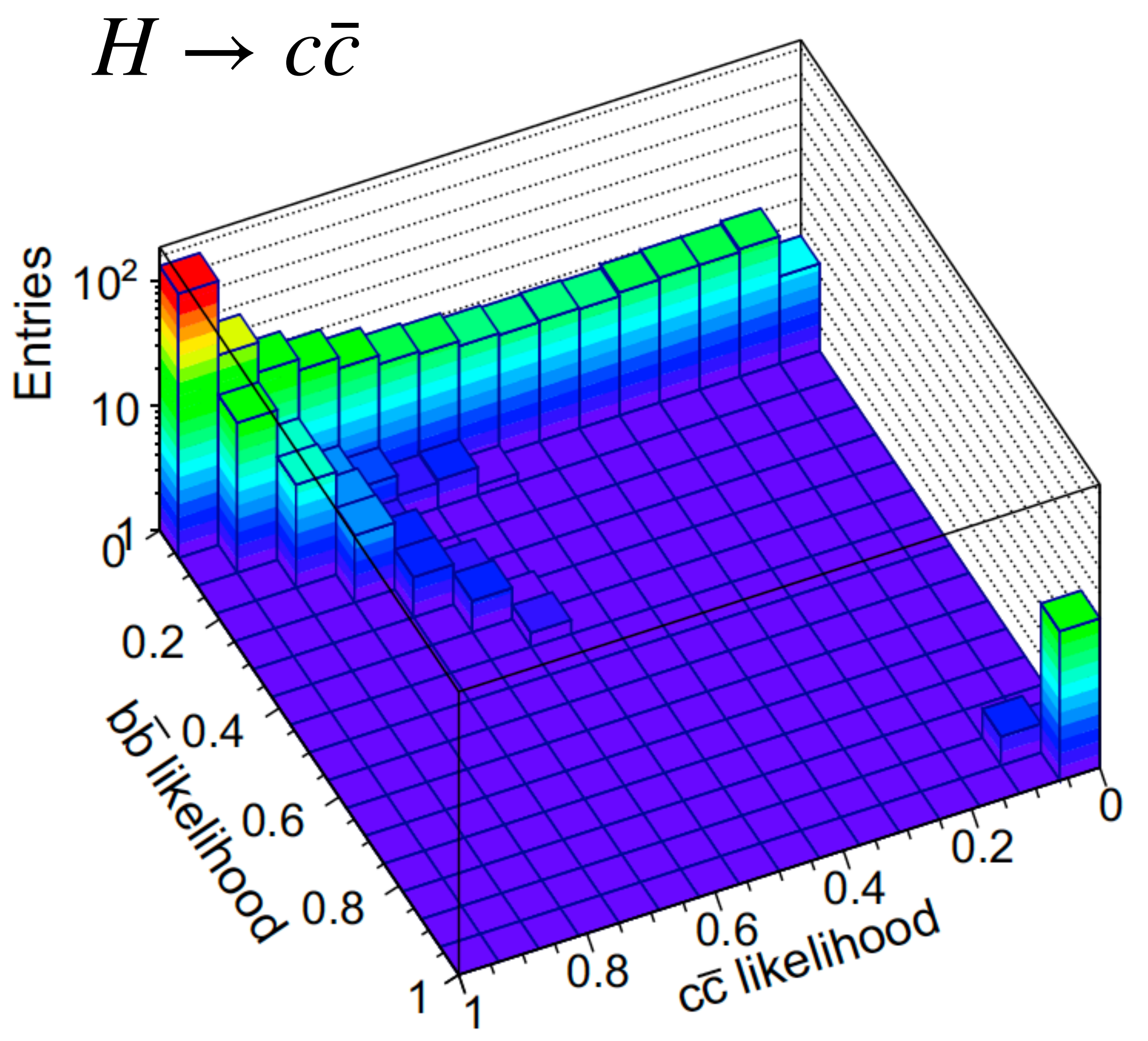


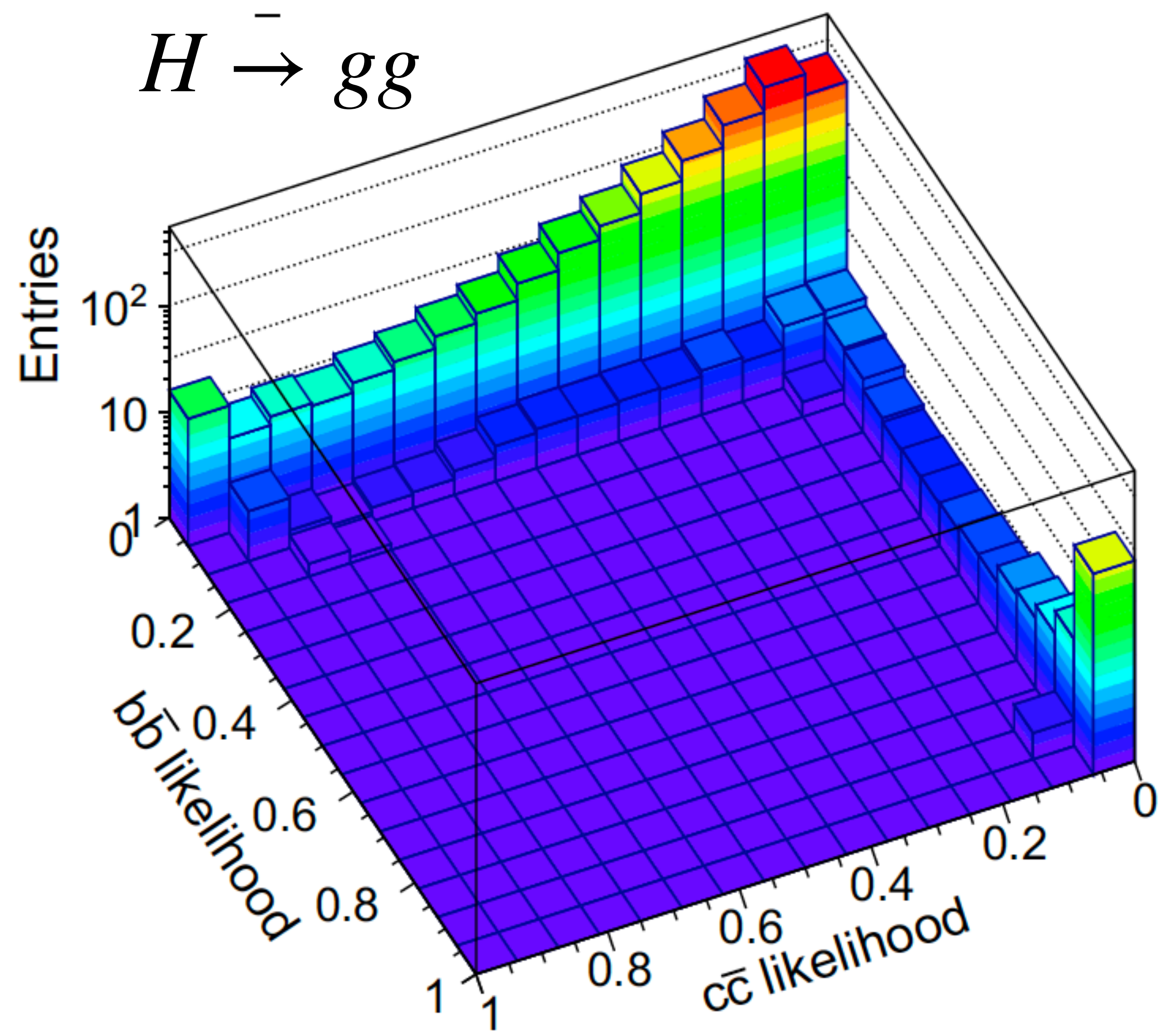


JHEP06(2009)059

Jet substructure: e^+e^- selected opportunities

- Actively studied for CLIC for boosted top tagging $\rightarrow$ works well
- For lower $\sqrt{s}$, e.g. 250 GeV, particularly interesting for $H \rightarrow gg$ vs. $H \rightarrow b\bar{b}$ and $H \rightarrow c\bar{c}$
- Determine α_s: requires both experimental and phenomenological developments
  - See also ILC study questions
- **Use also for better understanding of fragmentation and hadronization**
  - Then apply this knowledge to hadron colliders

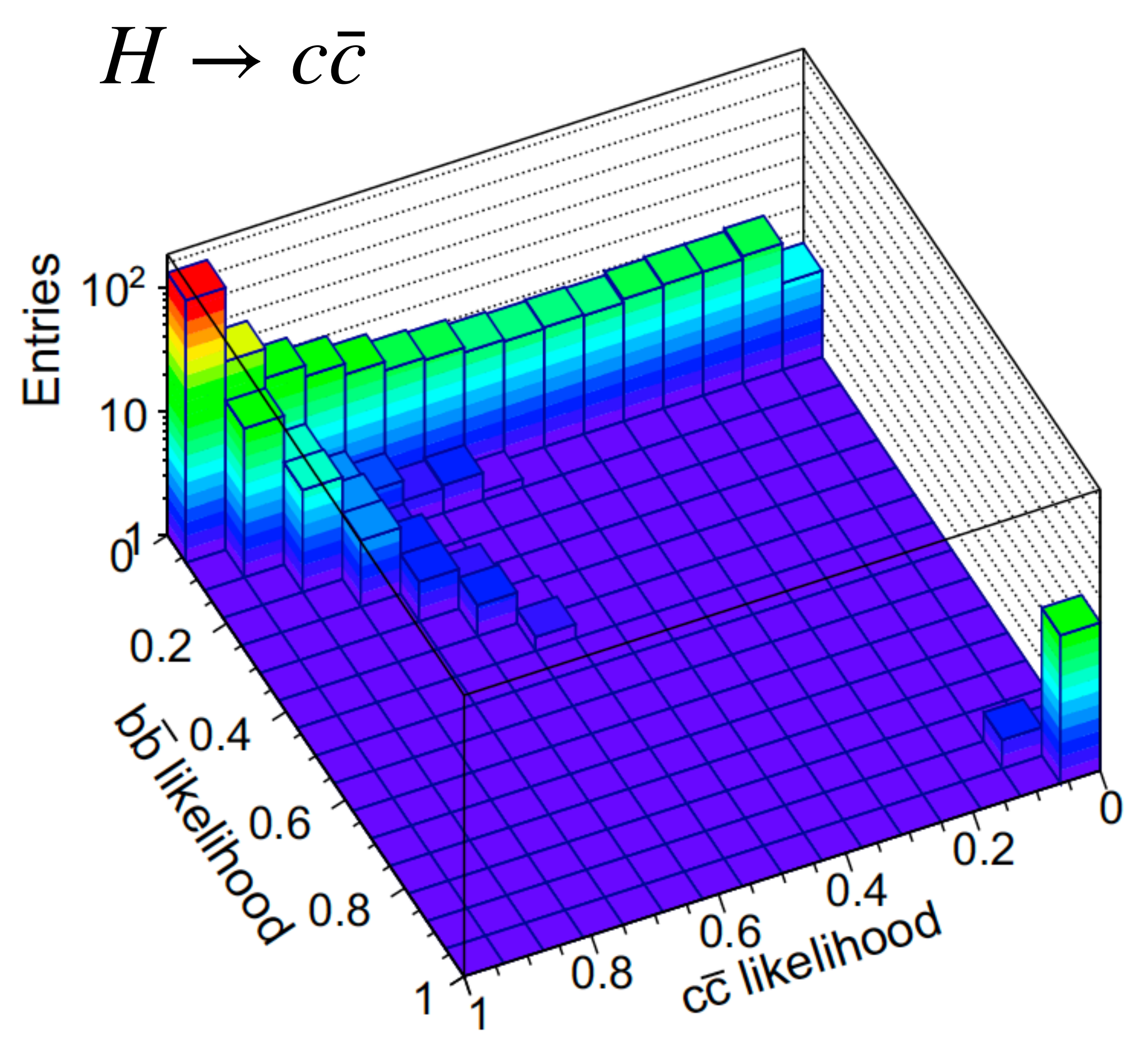


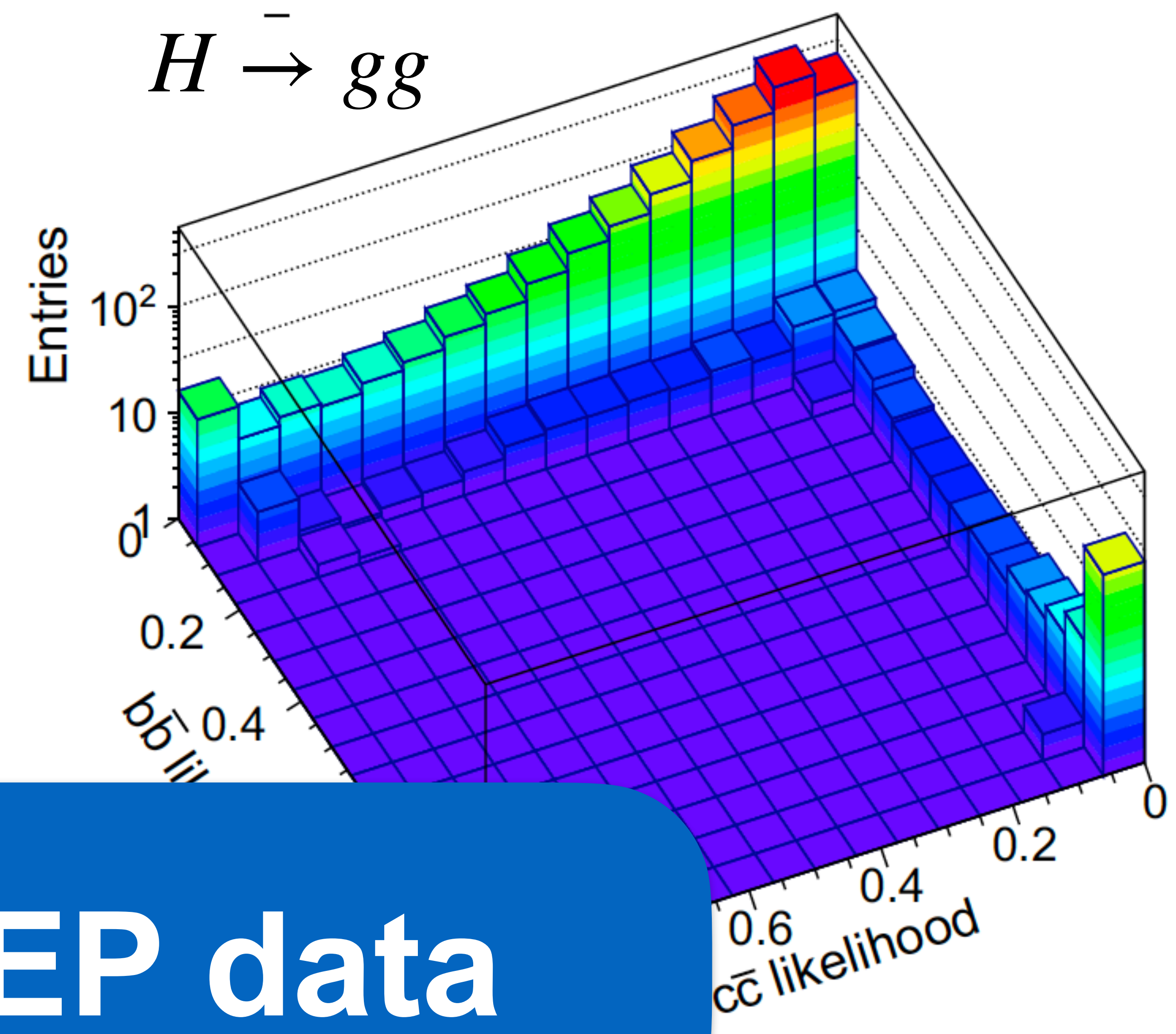


Eur. Phys. J. C (2017) 77:475

Jet substructure: e^+e^- selected opportunities

- Actively studied for CLIC for boosted top tagging $\rightarrow$ works well
- For lower $\sqrt{s}$, e.g. 250 GeV, particularly interesting for $H \rightarrow gg$ vs. $H \rightarrow b\bar{b}$ and $H \rightarrow c\bar{c}$
- Determine α_s: requires both experimental and phenomenological developments
  - See also ILC study questions
- **Use also for better understanding of fragmentation and hadronization**
  - Ther



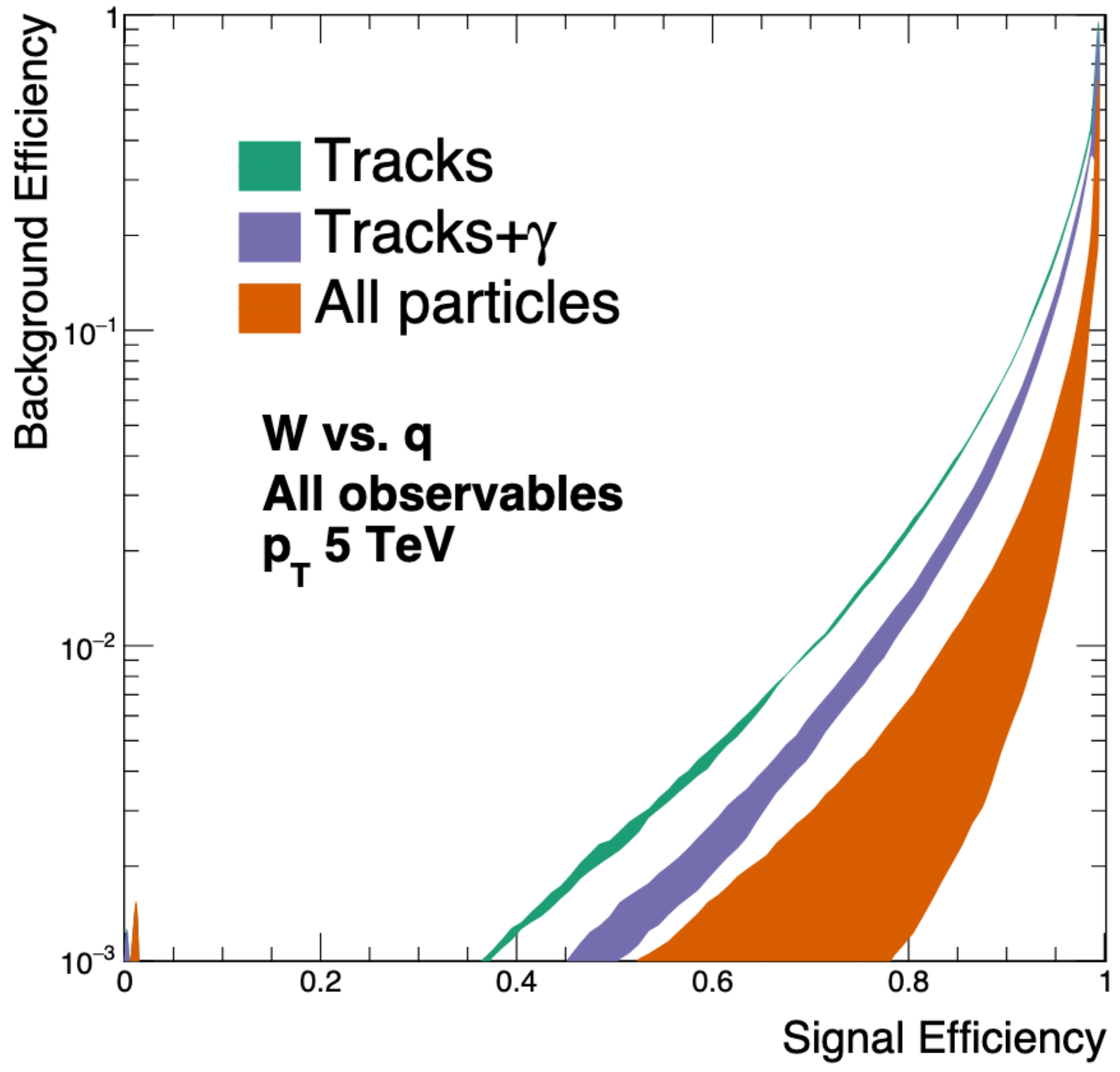


Opportunity today: low-PU LHC + LEP data

Eur. Phys. J. C (2017) 77:475

Jet substructure: hadron colliders sel. opport.

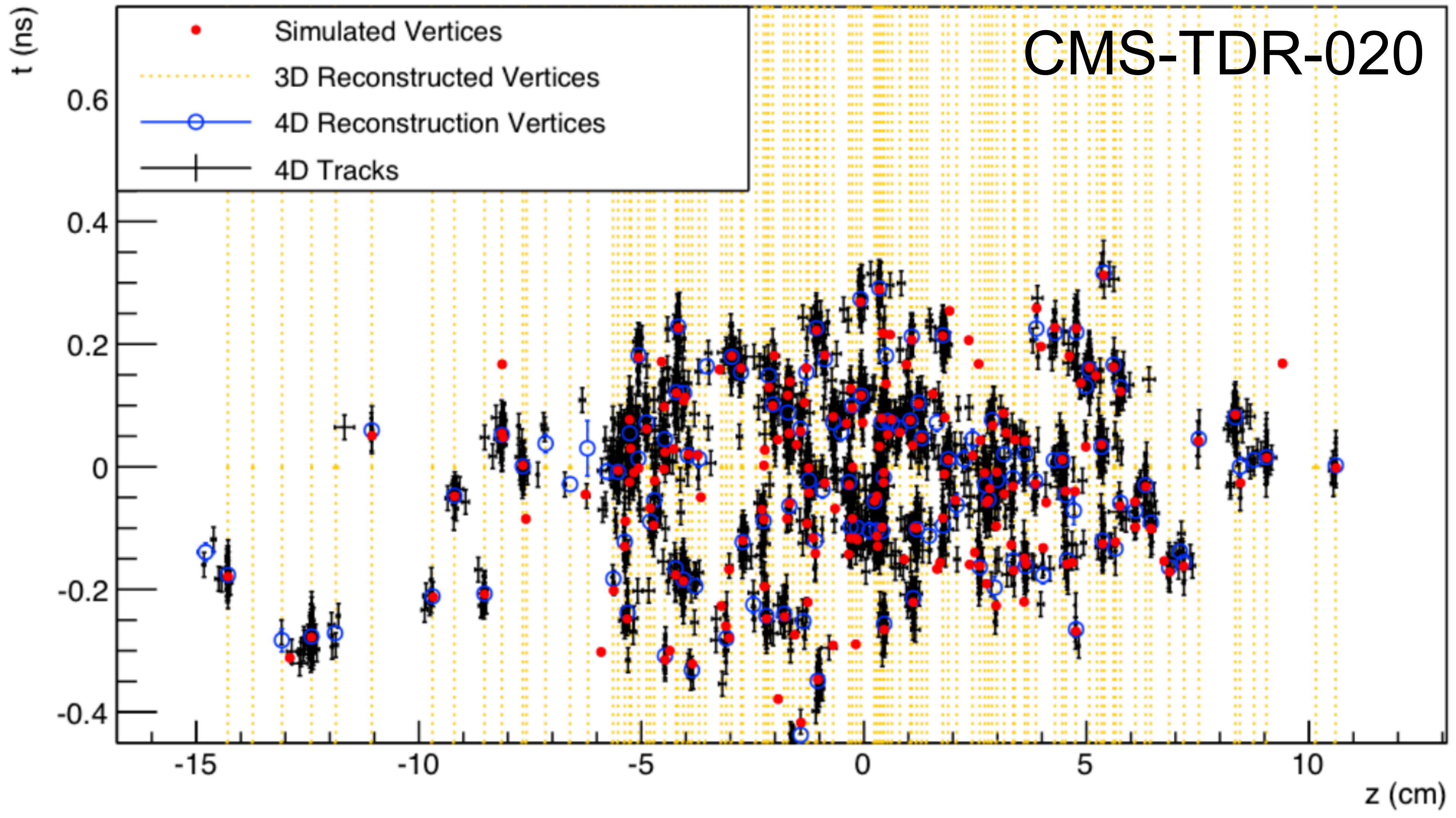
- >Most standard model precision measurements will require jet substructure techniques
- >SM processes at very high rapidity
- >Explore ultra-relativistic particles with p_T 10-15 TeV
  - Contrast with multi-TeV ZZ pair, but p_T < 100 GeV, opening angle 0.1 radians
- >Might need to use largely track-based variables
  - Carefully design calorimeters so that they can provide complimentary information
  - Ideally, need 10 times finer granularity than LHC calorimeters
- >Cope with pileup:
  - Requires jet-vertex reconstruction → 4D tracking
  - Must not forget about neutral particles → timing detectors (for HL-LHC ~30 ps, need < 10 ps for 100 TeV)



2018 JINST 13 T01003

Tackling new physics scenarios

- New detectors will enable new analysis techniques
- Example scenarios to consider: jets containing hard leptons, displaced vertices, hard photons, semi-visible jets, significant missing p_T…
- Make use of new detector capabilities, e.g. timing
  - Use e.g. for identification of delayed jets
  - Also generally useful/crucial (see PU)
- Carefully evaluate definition of “time profile”
  - Preserve link to parton-level information
  - Minimize spread in particle arrival time (promising: p_T-weighted sum of times)
  - Depends also on η, but for delayed jets, need to take into account global event kinematics…



PAUL SCHERRER INSTITUT

Klicker UZH

I'm excited about…

a) Available data
b) LHC Run-3
c) HL-LHC
d) A future collider

https://app.klicker.uzh.ch/join/boost

PAUL SCHERRER INSTITUT

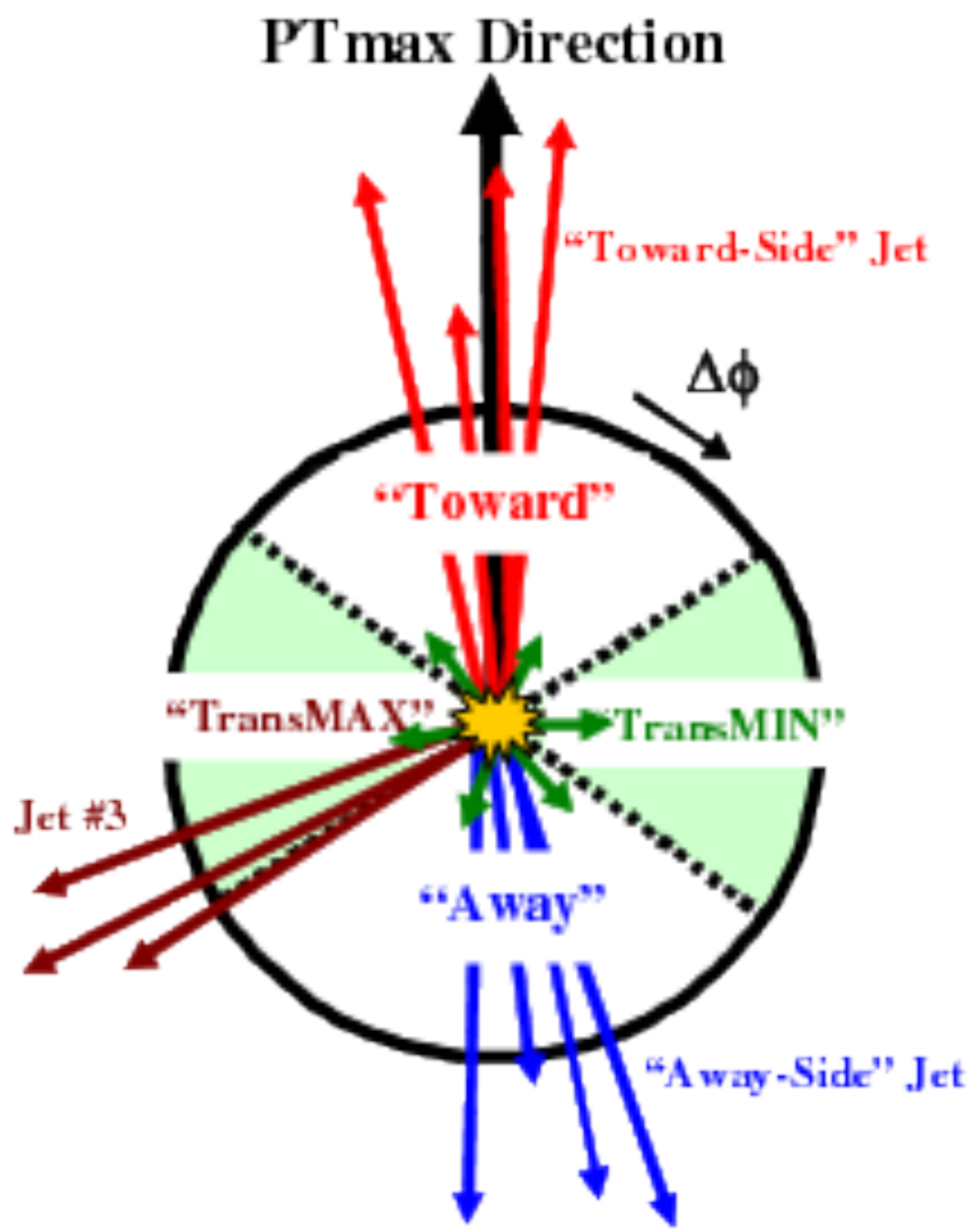
PAUL SCHERRER INSTITUT

PSI

PAUL SCHERRER INSTITUT

Theoretical innovation - parton shower

- MC generators: Pythia, Herwig, Sherpa etc. differ significantly and exhibit strong dependence on underlying event tunes
  - Can we improve the tools themselves?
  - Would provide better input for machine learning techniques and to model backgrounds
- Improved and continuous (iterative) MC generator tuning with latest collider data
- “Less magic”: make programs respect theoretical boundary conditions while preserving data-simulation agreement
- Further progress towards improved treatment of hadronization uncertainties
  - Generator-intrinsic uncertainties vs. replacing generator including parton shower



CMS-GEN-14-001

PAUL SCHERRER INSTITUT

Which parton shower?

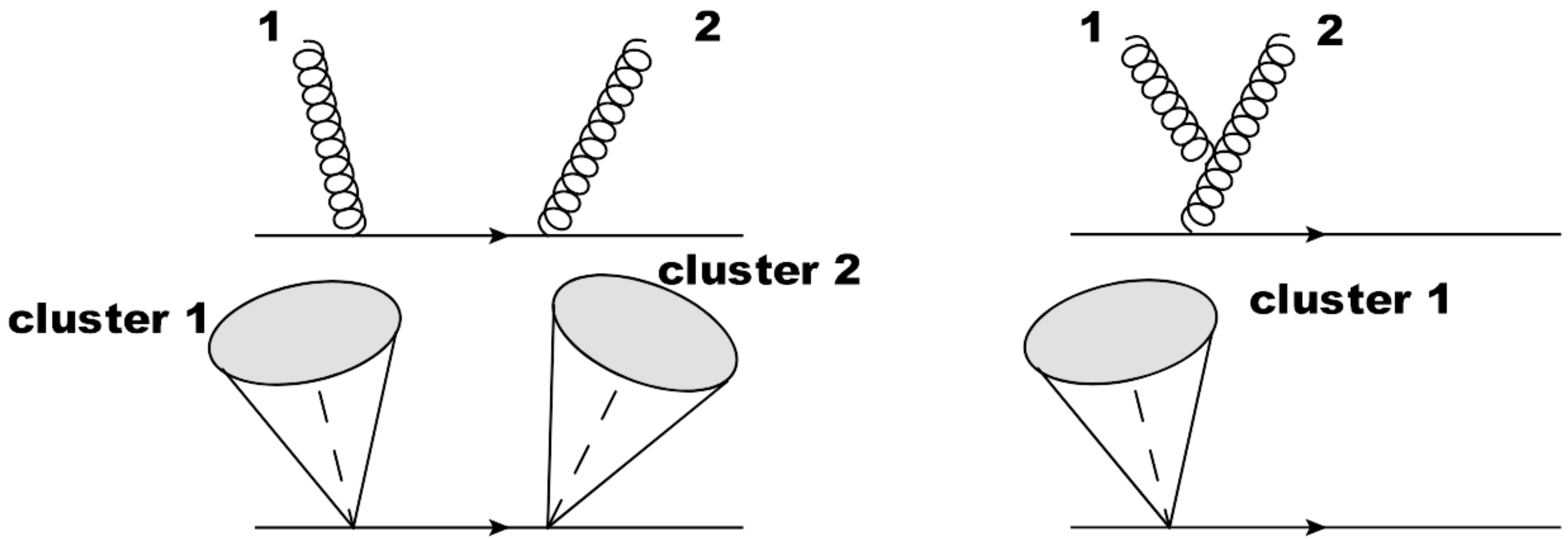
a) Herwig
b) Pythia
c) Sherpa
d) Whizard
e) Need something else

Klicker UZH

https://app.klicker.uzh.ch/join/boost

Theoretical innovation - further examples

- Include sub-leading colour and spin (correlation) effects
- Link analytical predictions for resummed jet observables to event generator predictions
- Matching of higher order calculations (real-radiative corrections), can become leading uncertainty (jet veto vs. jet p_T modification)
- Handling higher orders: At NNLO, consistent treatment of unitarity, resumming at low p_T
- …



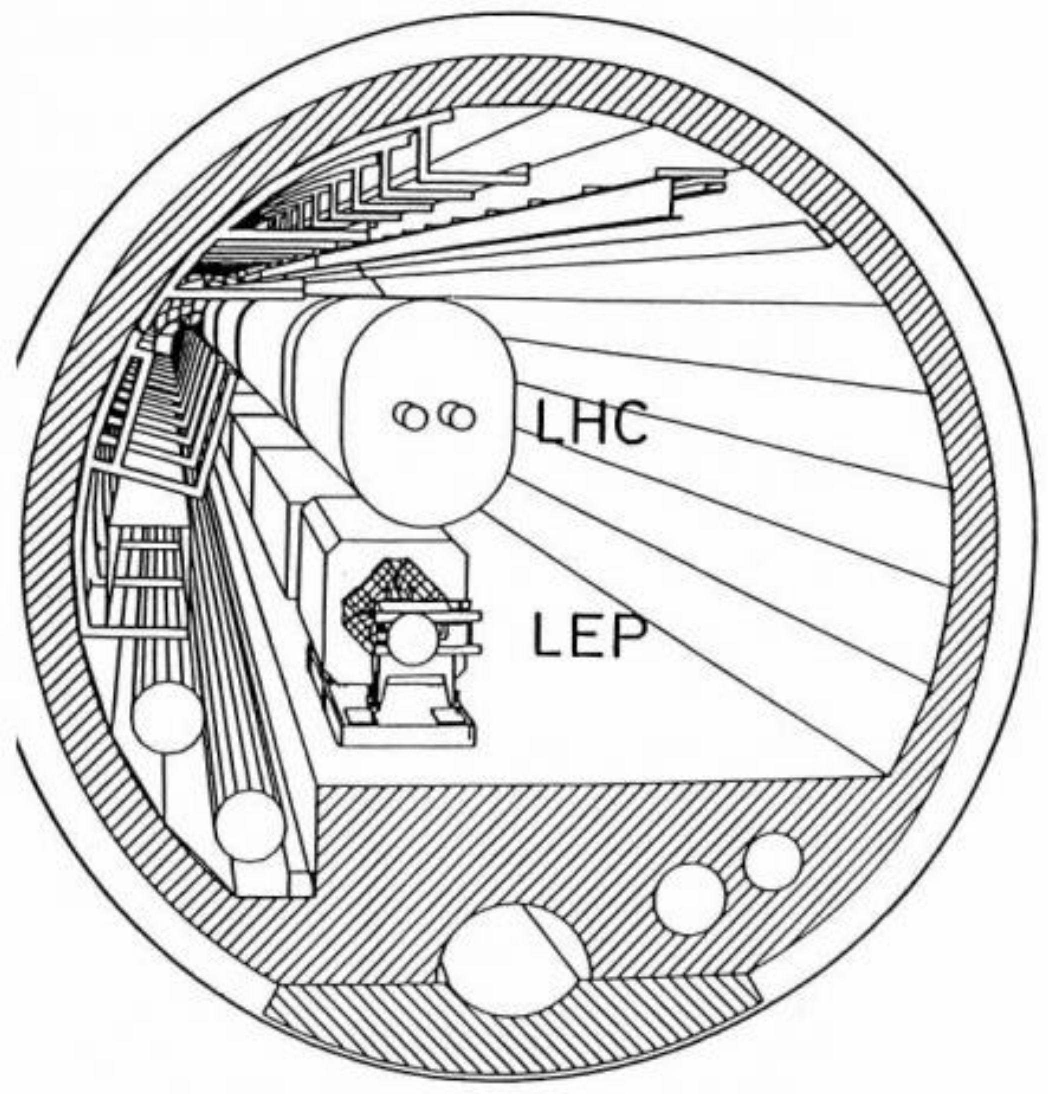
JHEP 05 (2020) 143

Direct searches vs. anomaly detection

- ML for model-agnostic anomaly searches
  - Direct searches (hypothesis testing) will always be limited
- Instead, search for outliers (low probability density) or over-/under-densities in phase space w.r.t. SM
  - Apply to individual objects or entire events
  - Can also do this at trigger level
- Challenge: balance between performance on given scenario and model dependence
- See also machine learning intro this week

Conclusions and outlook

- We have **large and unique data sets available** that allow us to make progress today on both the experimental and theoretical frontiers
  - We should not wait until the next collider to do so
- More work is needed to **optimally exploit upgraded detectors** at the HL-LHC for boosted objects
  - Timing information particularly useful
- For a future collider: weigh concepts against each other, then build an optimal detector
  - Will shape particle physics for the next ~50 years
  - (Almost) **everything will be boosted then!**



HiLumi
HL-LHC PROJECT

BOOSTAMOS!

PAUL SCHERRER INSTITUT

PSI

Collider scenarios

>From Snowmass 2021 Energy Frontier

Snowmass 2021 Higgs Factory Study Scenarios

Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1}
HL-LHC	pp	14 TeV		6
ILC and C^3 c.o.m almost similar	ee	250 GeV 350 GeV 500 GeV 1 TeV	$\pm 80/\pm 30$ $\pm 80/\pm 30$ $\pm 80/\pm 30$ $\pm 80/\pm 20$	2 0.2 4 8
CLIC	ee	380 GeV 1.5 TeV 3.0 TeV	$\pm 80/0$ $\pm 80/0$ $\pm 80/0$	1 2.5 5
CEPC	ee	M_Z $2M_W$ 240 GeV		16 2.6 5.6
FCC-ee	ee	M_Z $2M_W$ 240 GeV $2\ M_{top}$		150 10 5 1.5
muon-collider (higgs)	$\mu\mu$	125 GeV		0.02

Snowmass 2021 EF Discovery Collider Scenarios

Collider	Type	$\sqrt{s}$	$\mathcal{L}_{\text{int}}$ ab^{-1}
HE-LHC	pp	27 TeV	15
FCC-hh	pp	100 TeV	30
LHeC FCC-eh	ep ep	1.3 TeV 3.5 TeV	1 2
High energy muon-collider	$\mu\mu$	3 TeV 10 TeV 30 TeV	1 10 10

Questions about QCD and jets

12 Questions about QCD and jets

1. Jet shapes and jet substructure. There is now an extensive literature on the shapes and substructure of QCD jets motivated by studies of jets at the LHC [105, 106]. This theory can be tested much more stringently at ILC, using the known CM energy, the absence of underlying events and pile-up, and the higher precision calorimetry. What level of precision is possible here? What level of precision can be achieved in the measurement of α_s? Can we study effects of the b and c masses? Are there interesting BSM models that can become visible through these measurements? [GEN]

2. Hadronization. The large sample of 2-jet events that the ILC will make available offers the opportunity to test and improve models of hadronization. What can be learned beyond the knowledge that we gained from LEP? Specific physics topics that need new data are: flavor production in jets, and characterization of s- and g-initiated jets; baryon production; polarization of vector mesons (especially, D^*) and baryons in jets. To what extent can this improved information feed back into improvements in LHC event analysis? [TH]

3. Tests of parton showers. Simulations of parton showers now aim for NLO and even NNLO accuracy (*e.g.*, [107, 108, 109]). How well can we test the accuracy of parton shower generators at e^+e^- colliders, both for their general accuracy in reproducing event shapes and for specific modelling of features of QCD that appear at high order? [GEN]

4. Structure of gluon jets. The Higgs production processes in e^+e^- with the decay $h \to gg$ gives a clean, low-background sample of gluon-initiated jets. A study of the QCD structure of this final state can be found in [110]. How can we use this sample to improve our knowledge of gluon jet substructure and nonperturbative gluon fragmentation? [GEN]

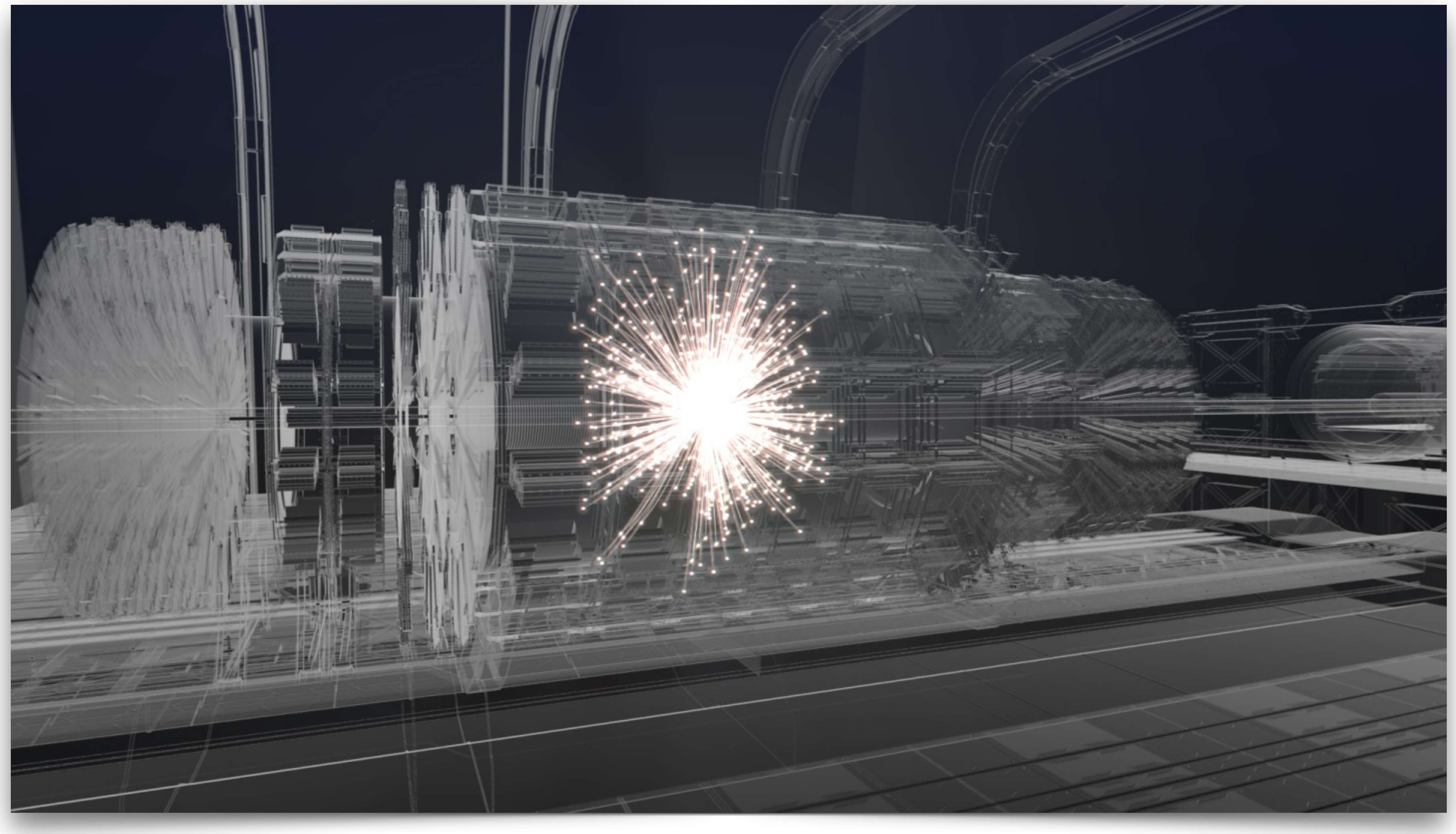
5. Structure of top quark final states. The reaction $e^+e^- \to t\bar{t}$ gives a well-characterized and almost background-free sample of top quark events. How can this be used to improve our knowledge of QCD jet structure? [GEN]

Required detector capabilities

Example of FCC-hh

Need to reconstruct multi-TeV objects + very high-rapidity standard model processes

- e.g. produce multi-TeV ZZ pair, but p_T < 100 GeV, opening angle 0.1 radians → require high detector granularity, 4-10 times finer than today
- Radiation hardness
- Cope with pileup:
  - Requires jet-vertex reconstruction → 4D tracking
  - Must not forget about neutral particles → timing detectors (for HL-LHC ~30 ps, need < 10 ps for 100 TeV)
- For calorimeters, small stochastic term, aim for good jet energy resolution



http://cds.cern.ch/record/2653532