The Coming of Age of Jet Substructure at the LHC

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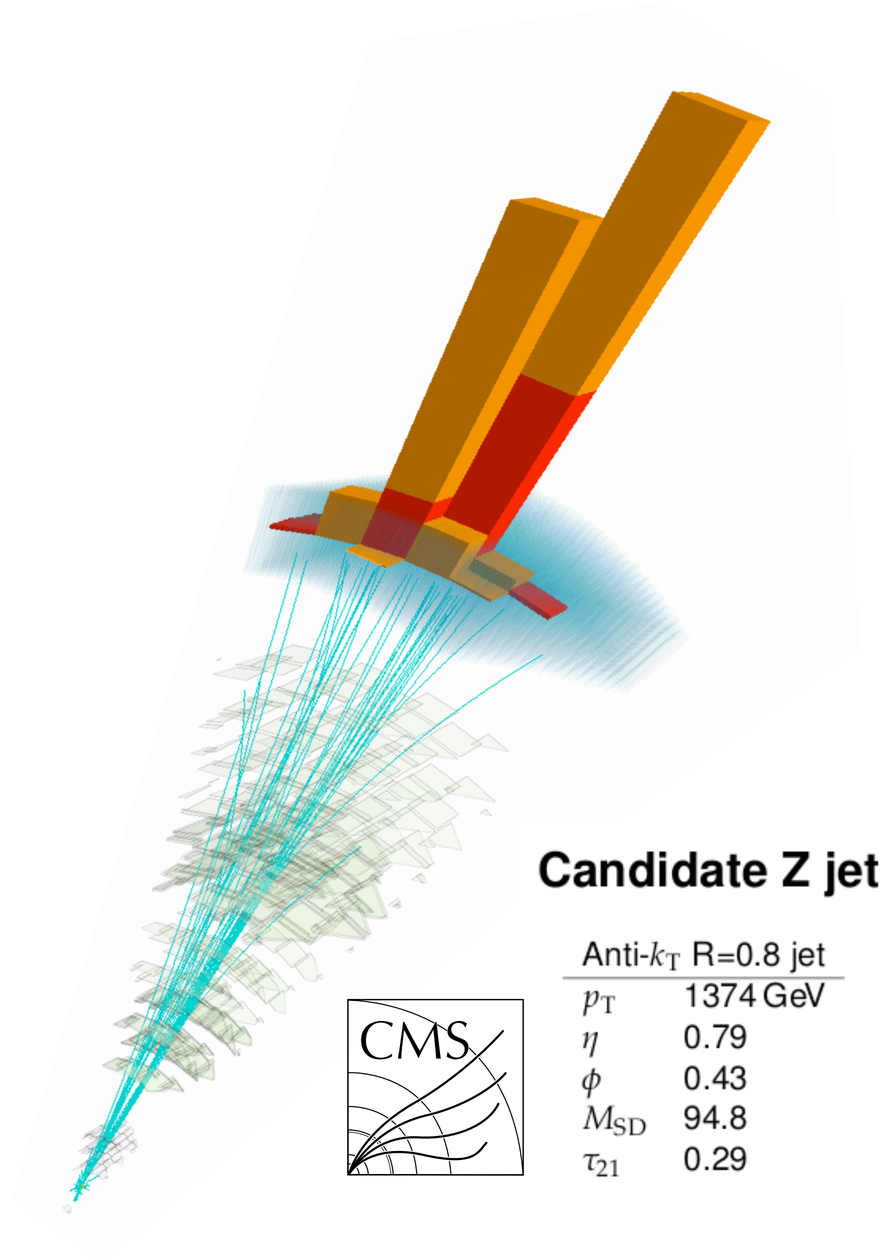
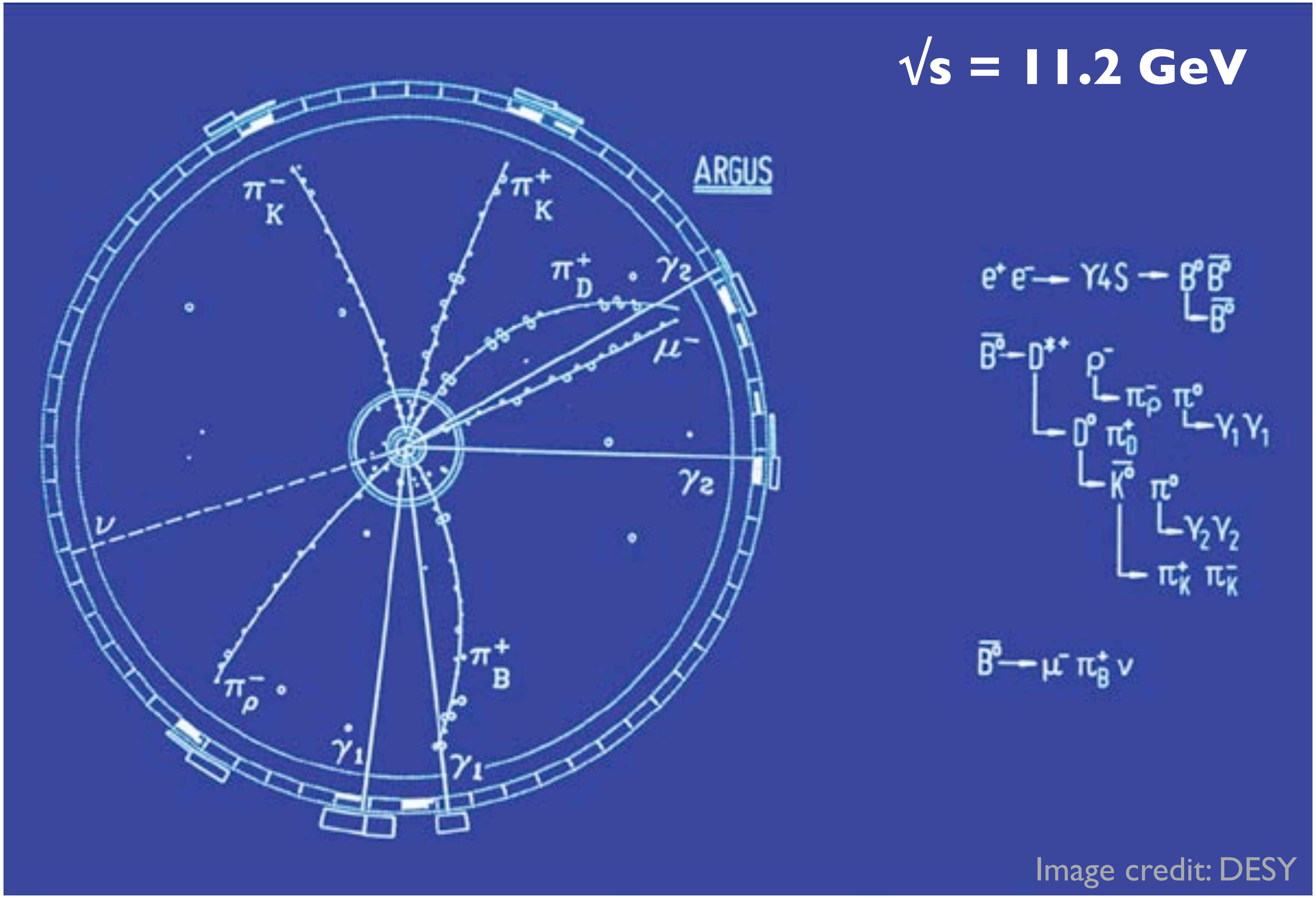
Sep 18, 2023

Overview

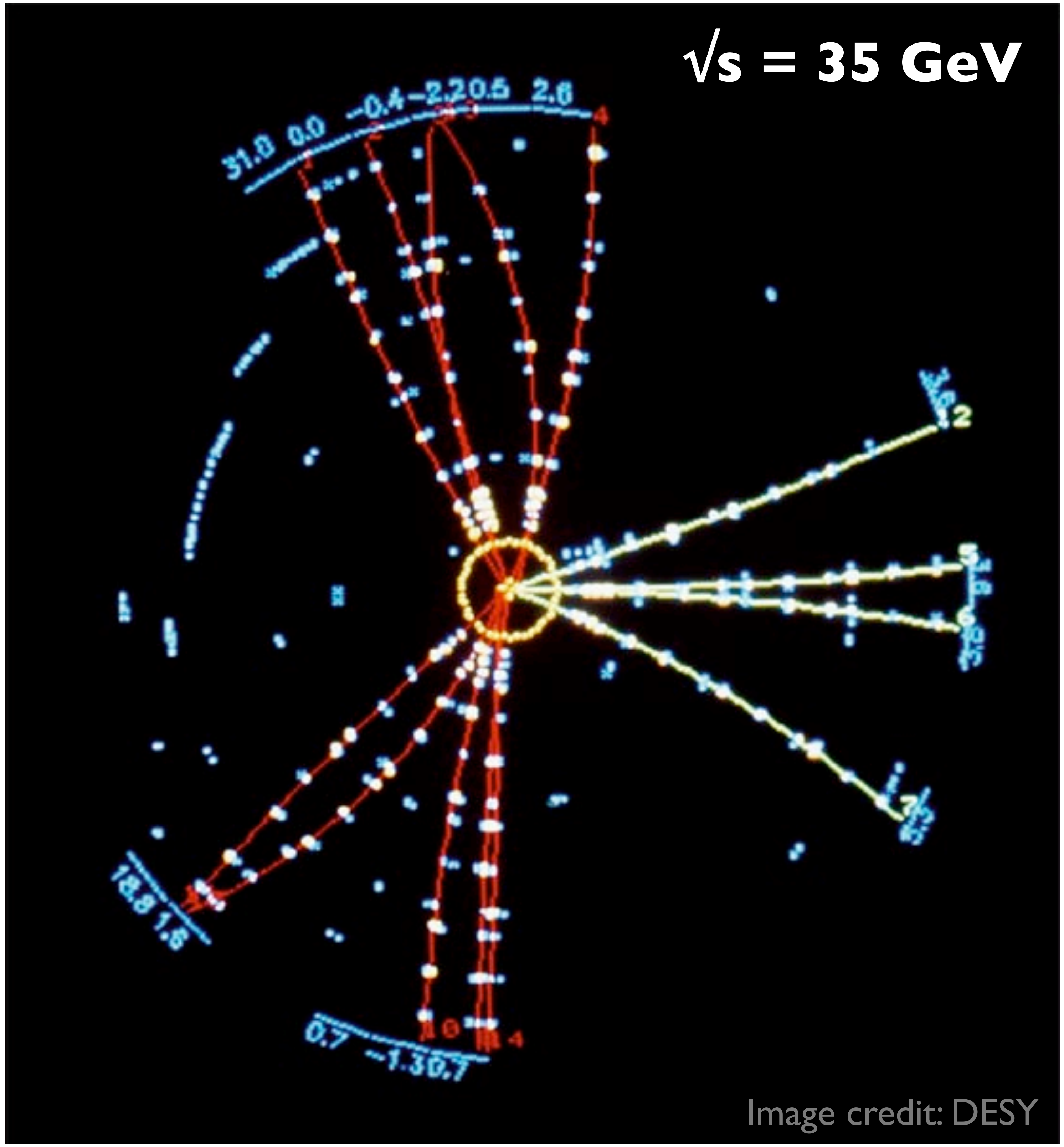
- Introduction
- Jet algorithms and substructure
- Jet tagging with substructure
- Calibration and commissioning
- Standard model measurements
- Searching for new phenomena
- Summary



ARGUS at DORIS, 1987



TASSO at PETRA, 1979



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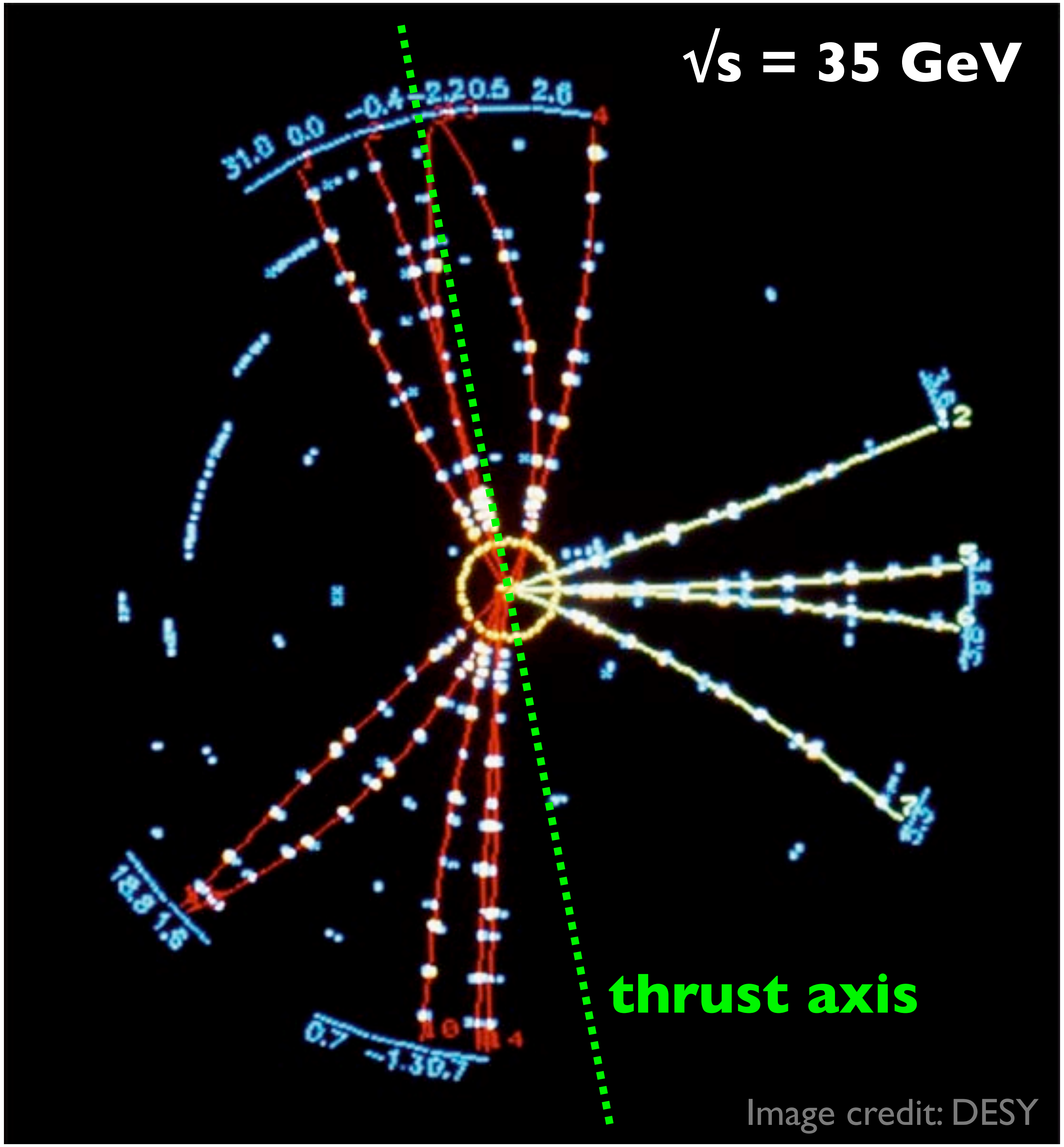
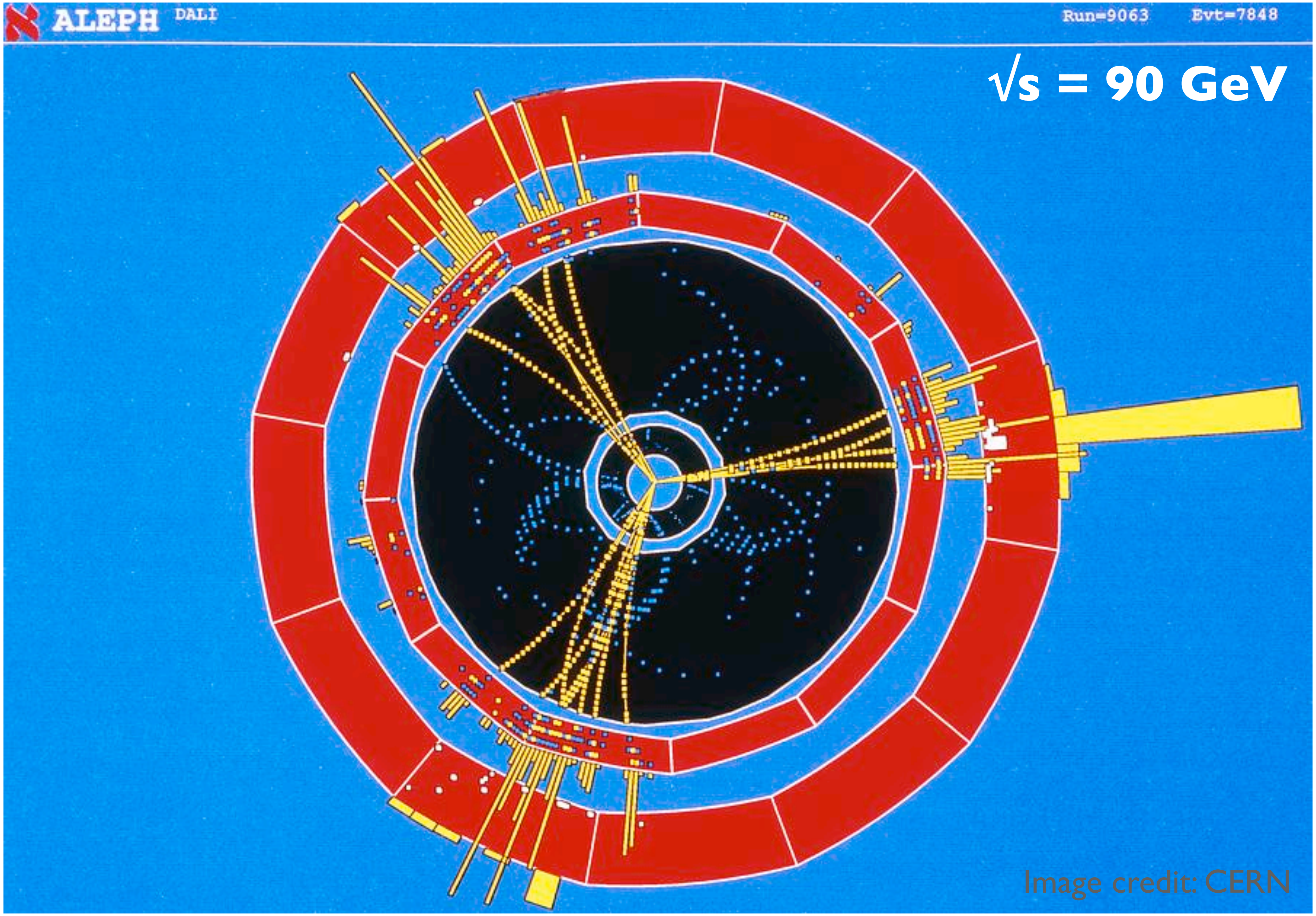
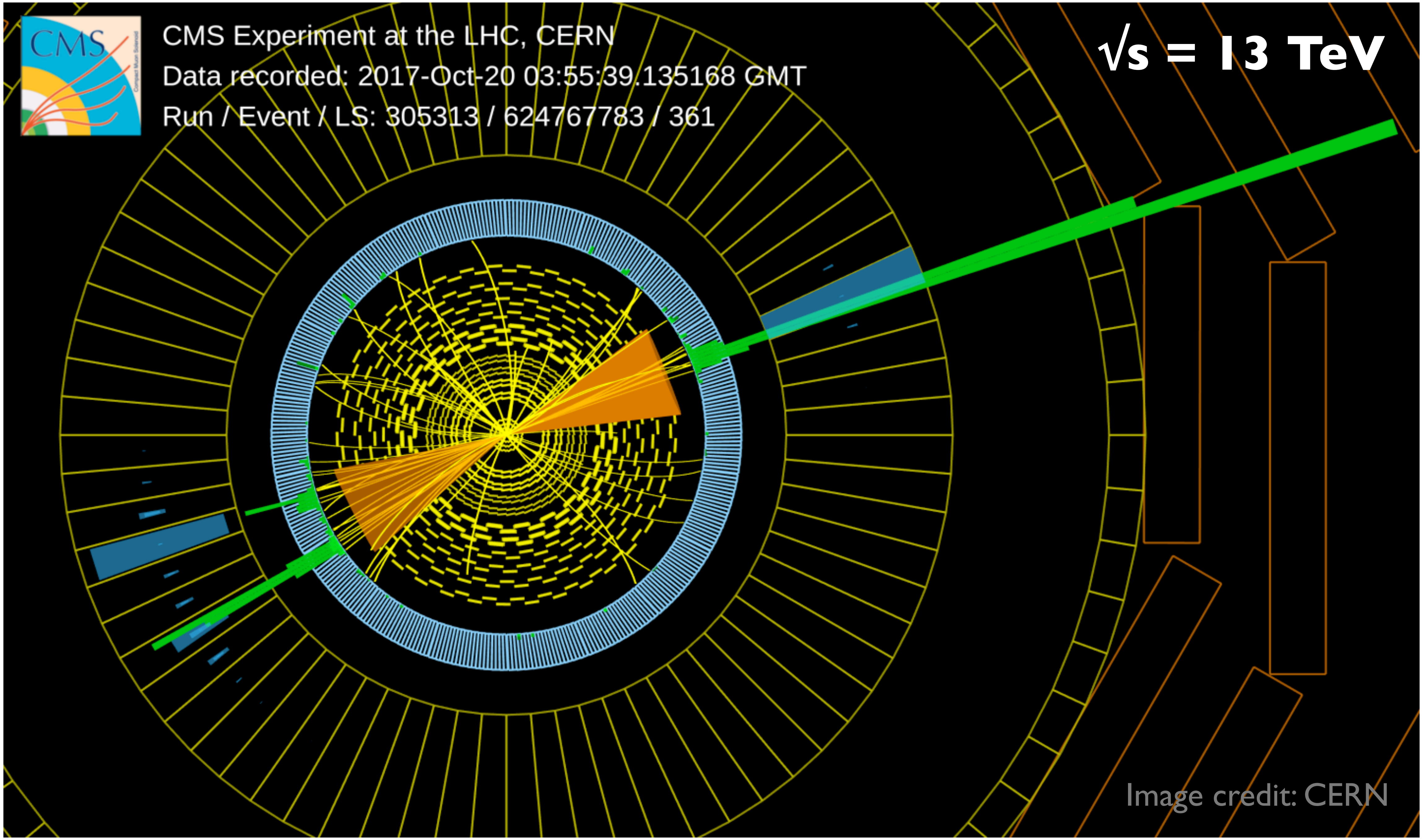


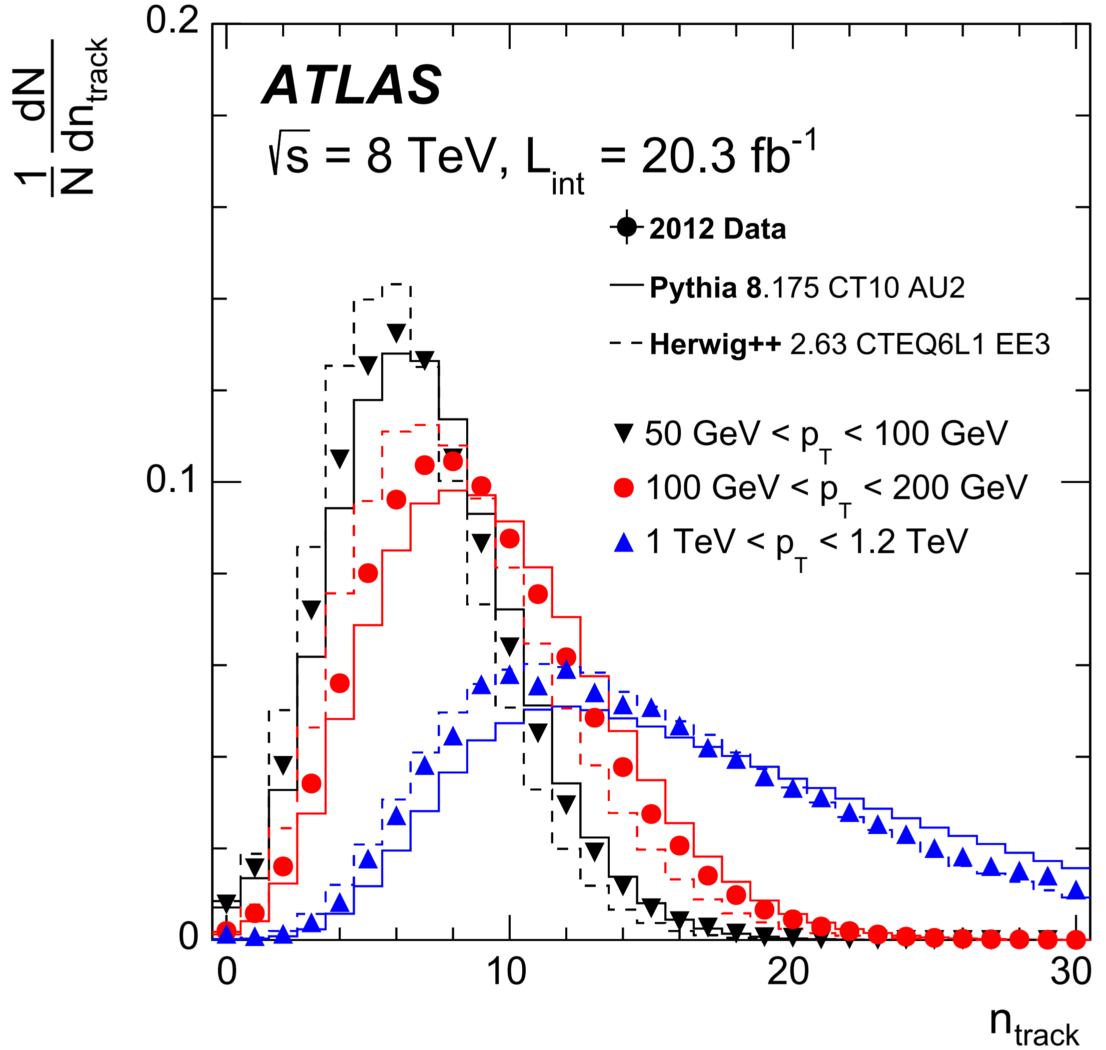
ALEPH at LEP, 1992



CMS at LHC, 2017



Charged particles in jets



- Approximate particle content in a jet: $\pi^+ : \pi^- : \pi^0 = 1 : 1 : 1$ (+10% Kaons, Protons…)

[ATLAS, EPJC 76, 322 (2016)]

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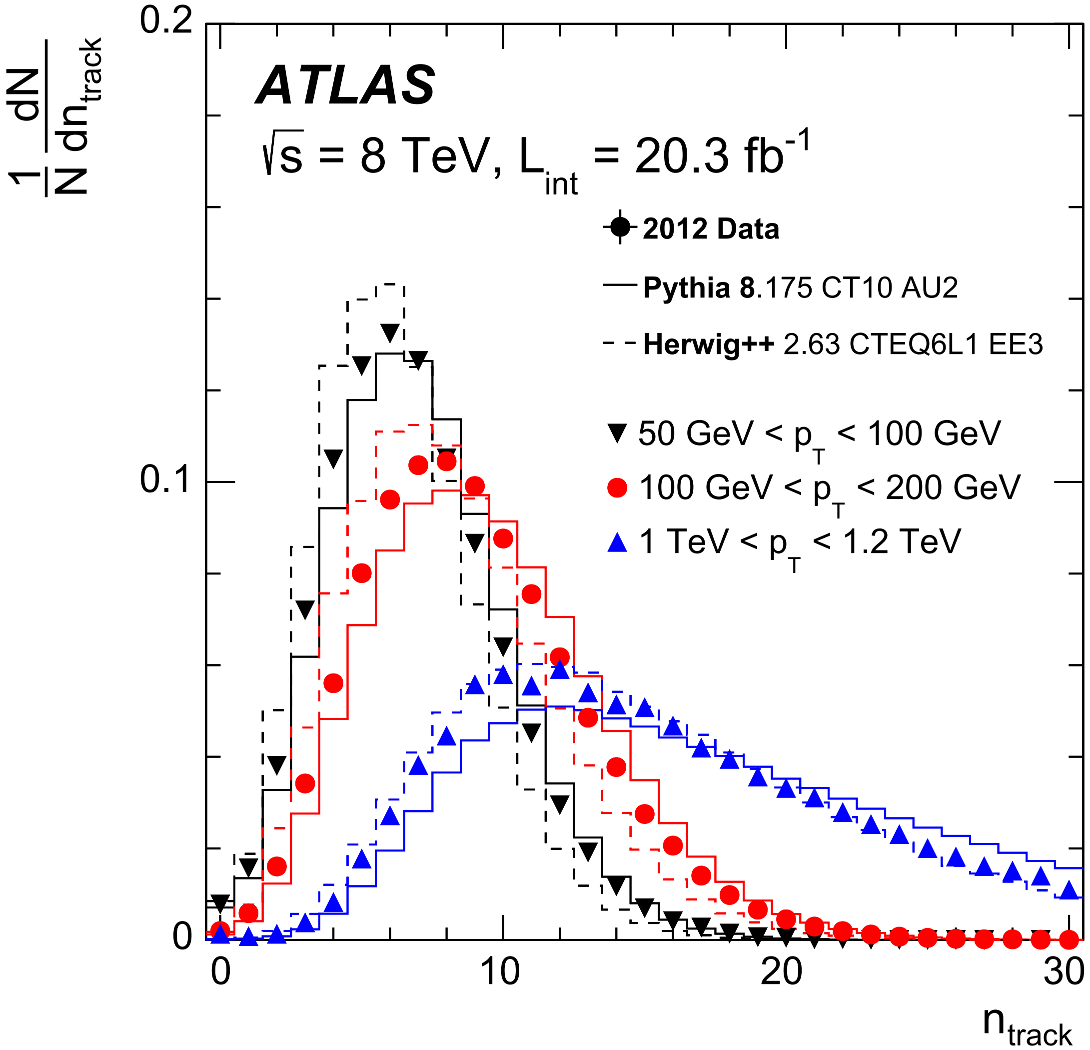
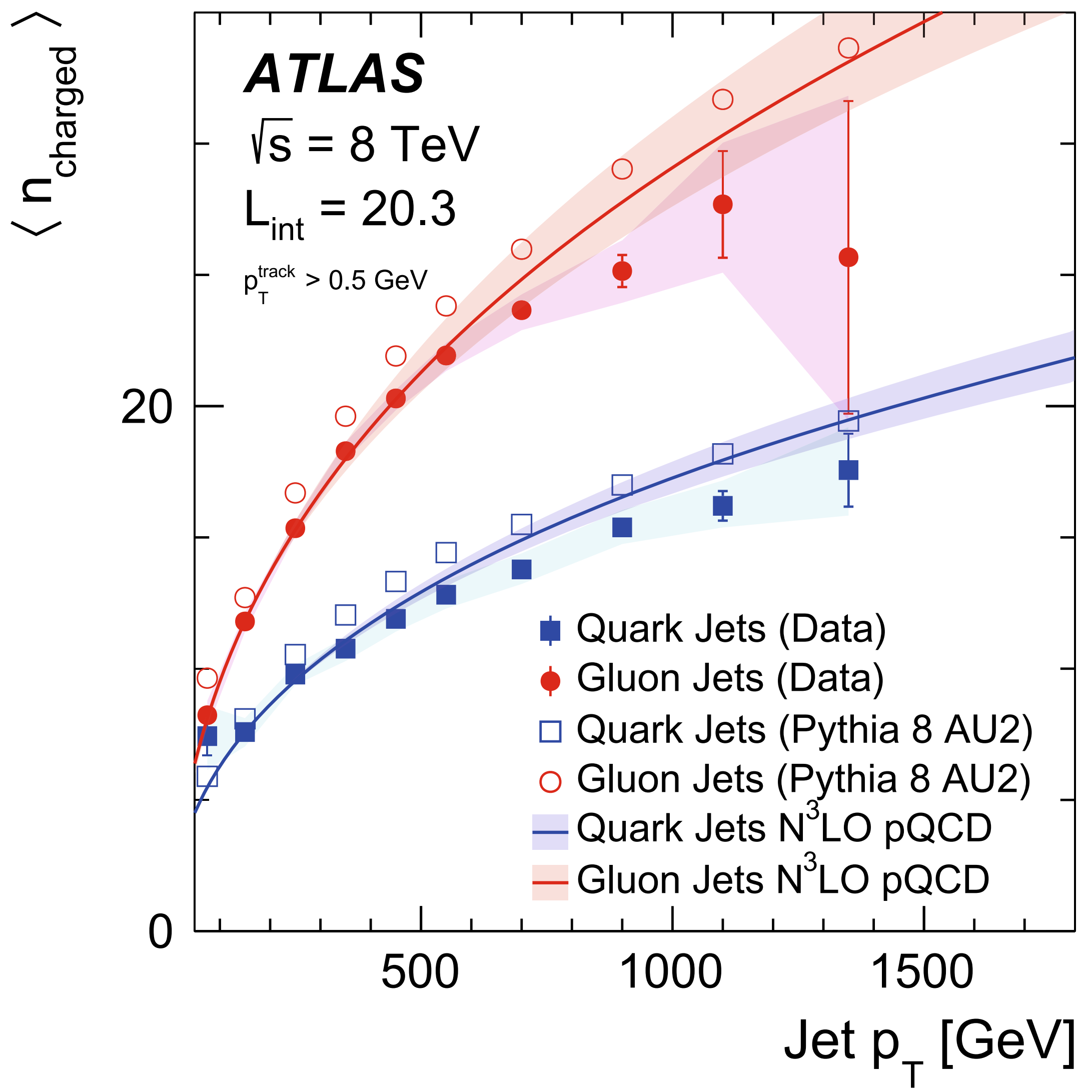
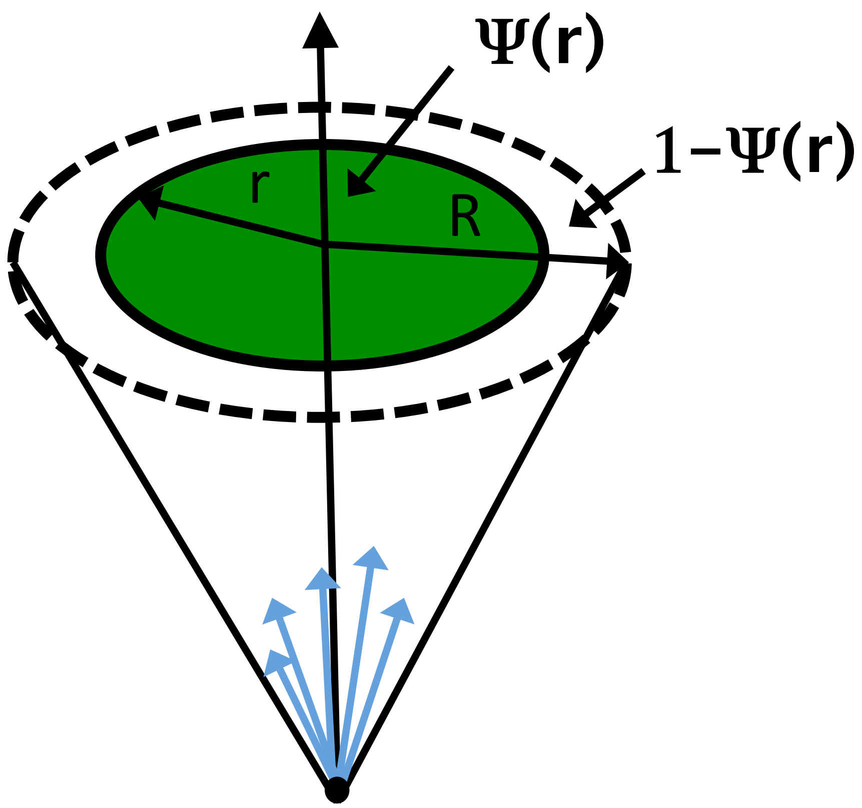




- Approximate particle content in a jet: $\pi^+ : \pi^- : \pi^0 = 1 : 1 : 1$ (+10% Kaons, Protons…)
- Gluon jets have higher multiplicity (colour factor C_A compared to C_F)

[ATLAS, EPJC 76, 322 (2016)]

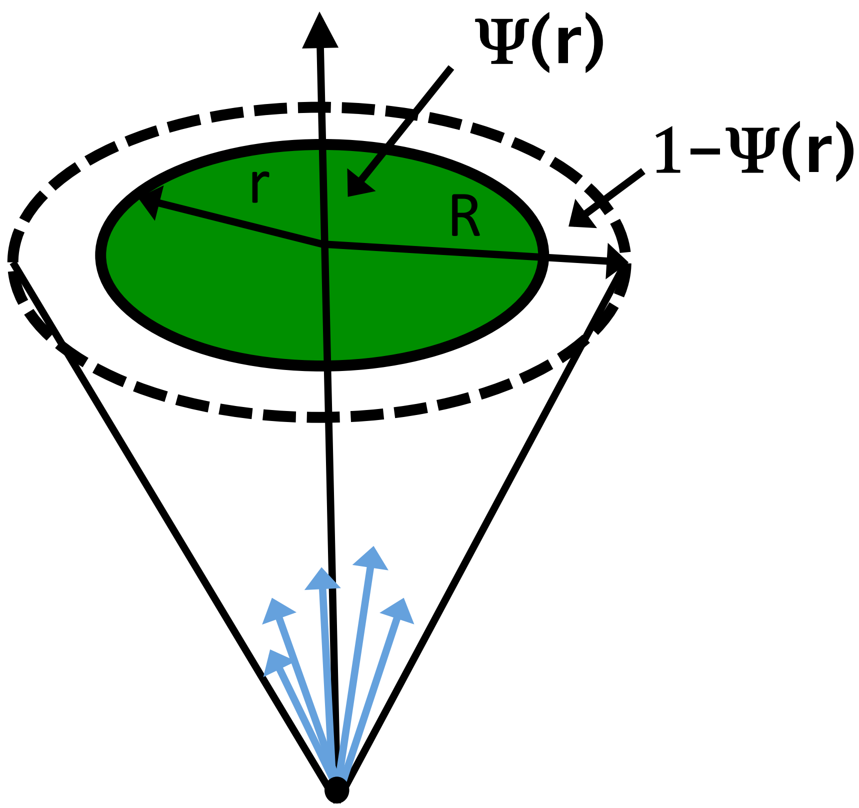
Jet substructure



Jet shape $\Psi(r) = \frac{\sum_{r_i<r} p_{\mathrm{T},i}}{\sum_{r_i<R} p_{\mathrm{T},i}}$

[CMS, JHEP 06, 160 (2012)]

Jet substructure



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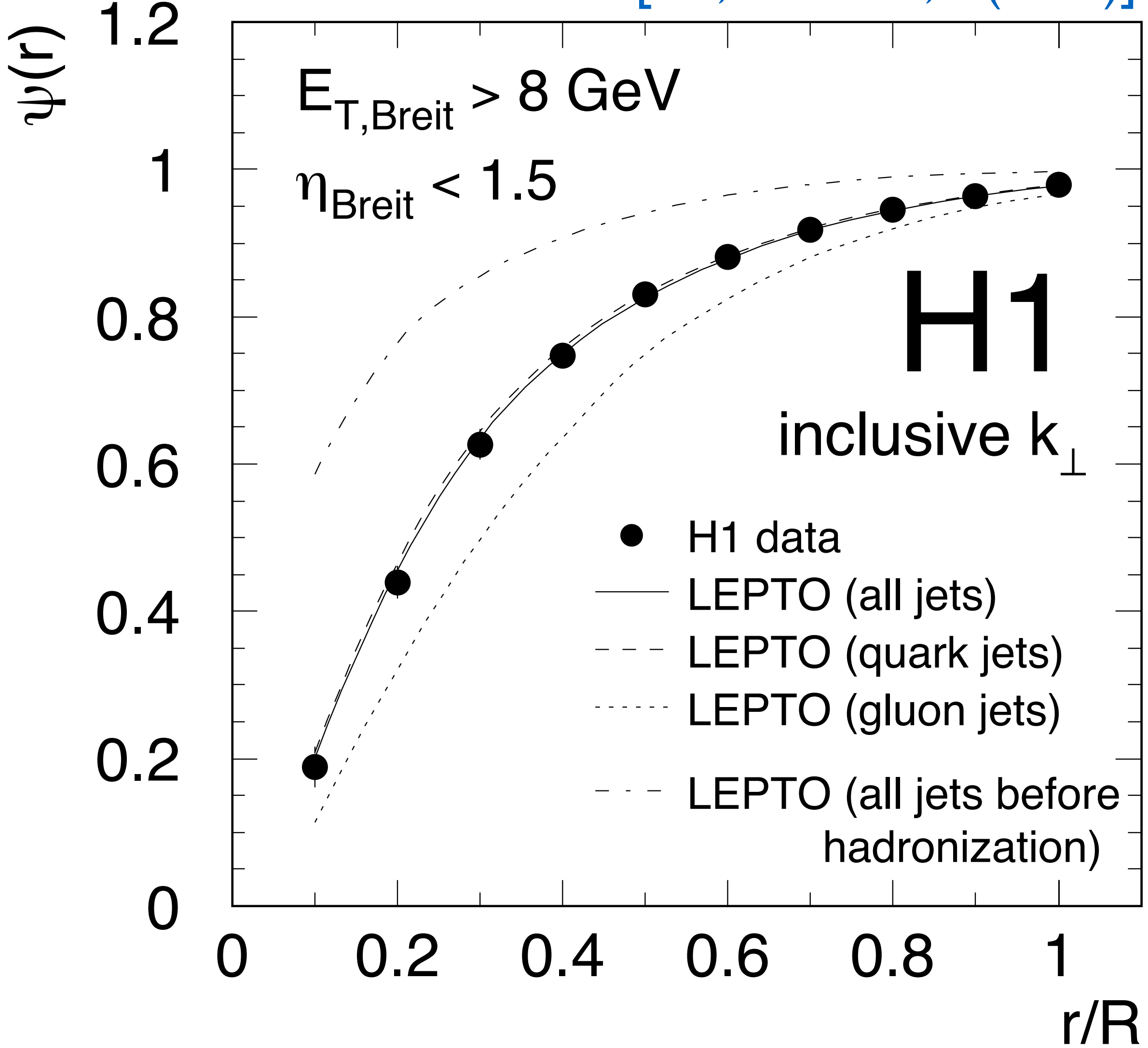
[H1, NPB 545, 3 (1999)]

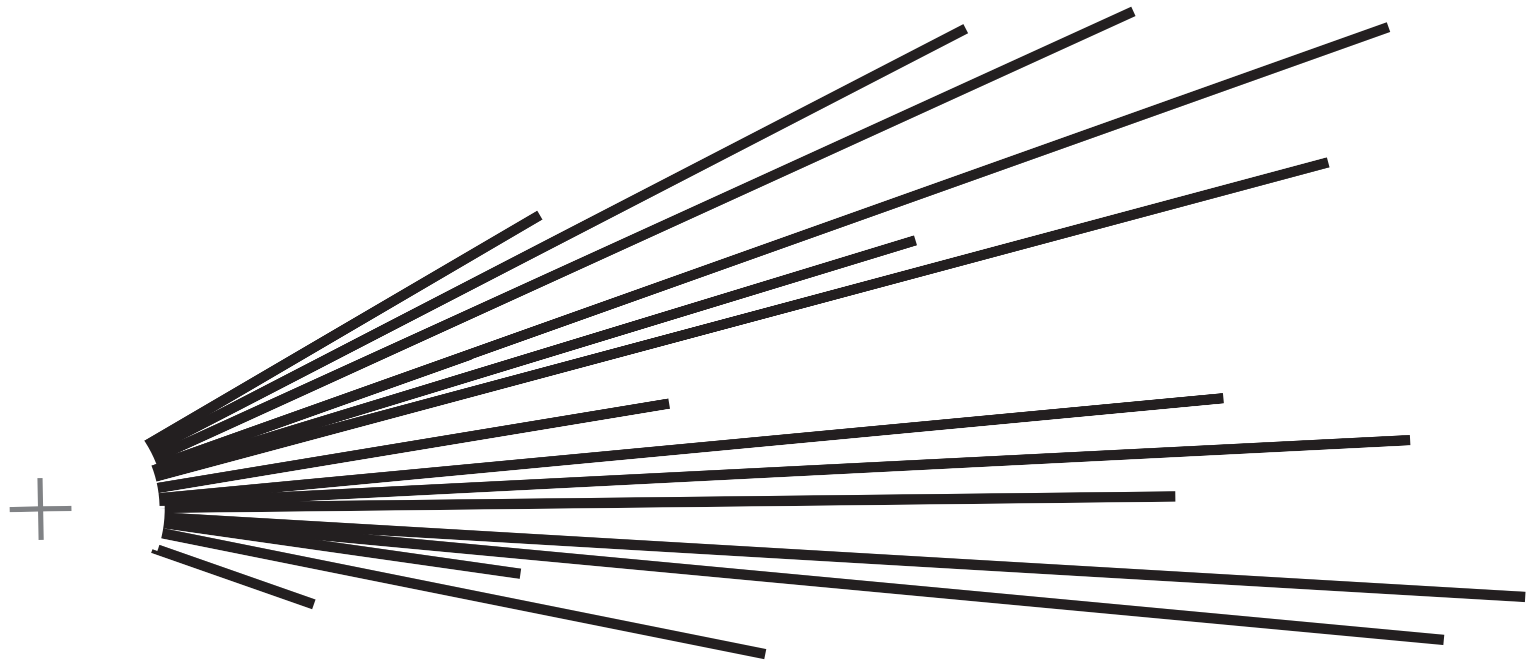


- Quark jets are narrower than gluon jets

[CMS, JHEP 06, 160 (2012)]

Jet substructure today

- Remove unwanted / soft radiation from jets
- Aid the jet reconstruction and calibration
- Distinguish quark/gluon jets
- Tagging of fully merged W, Z, H and top jets



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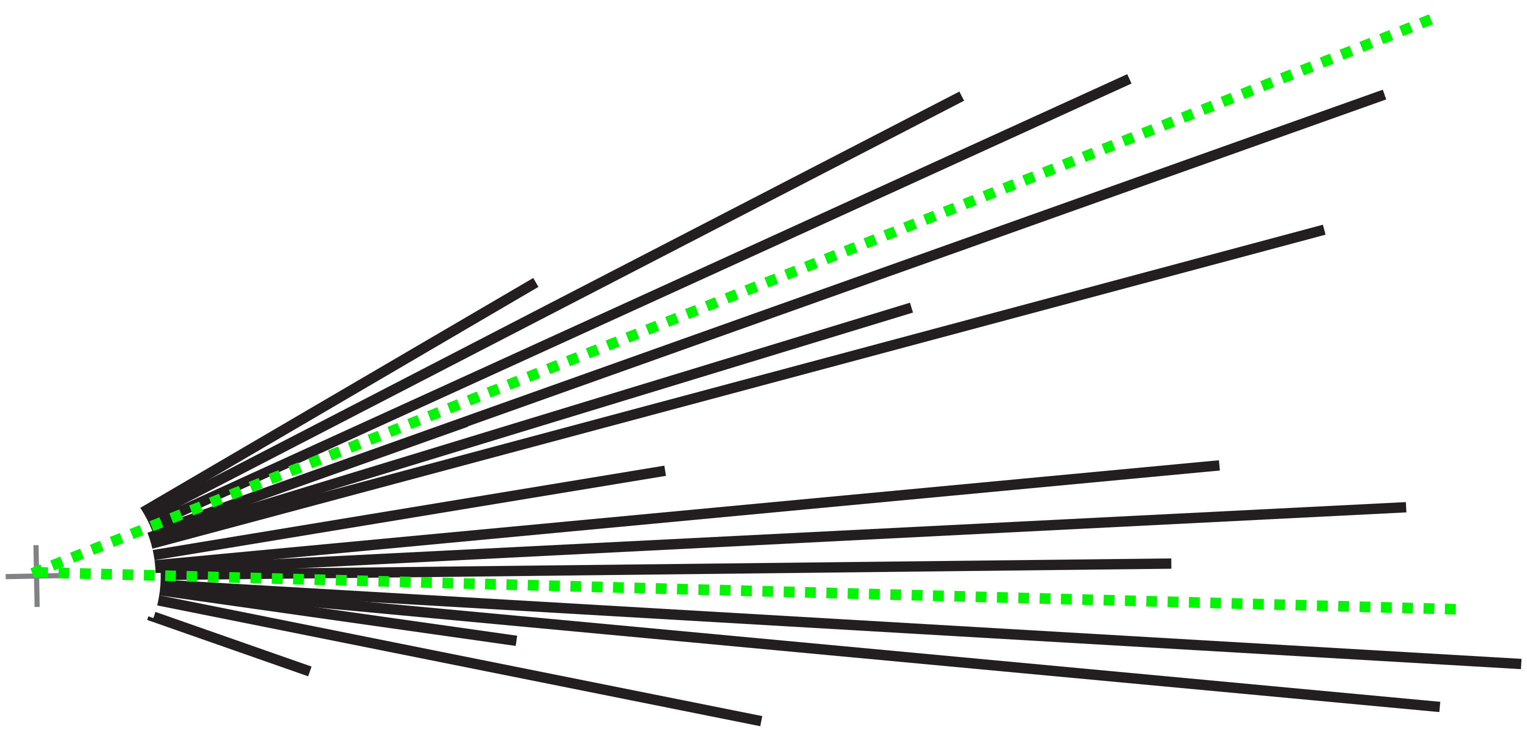
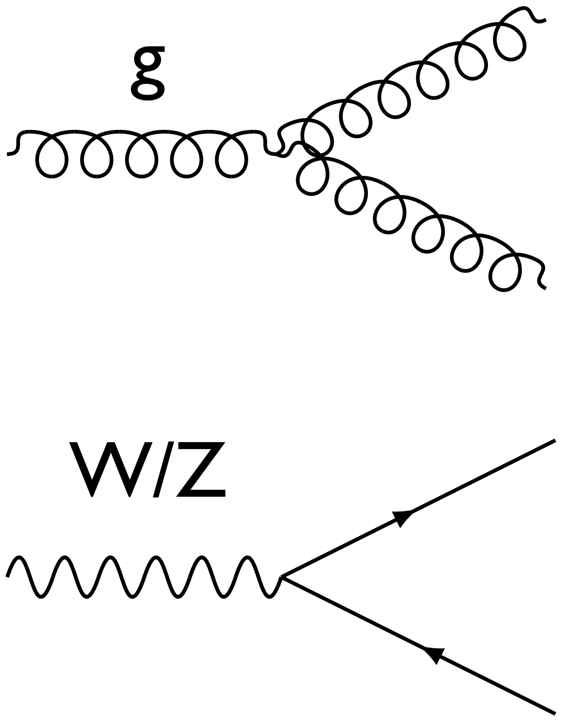


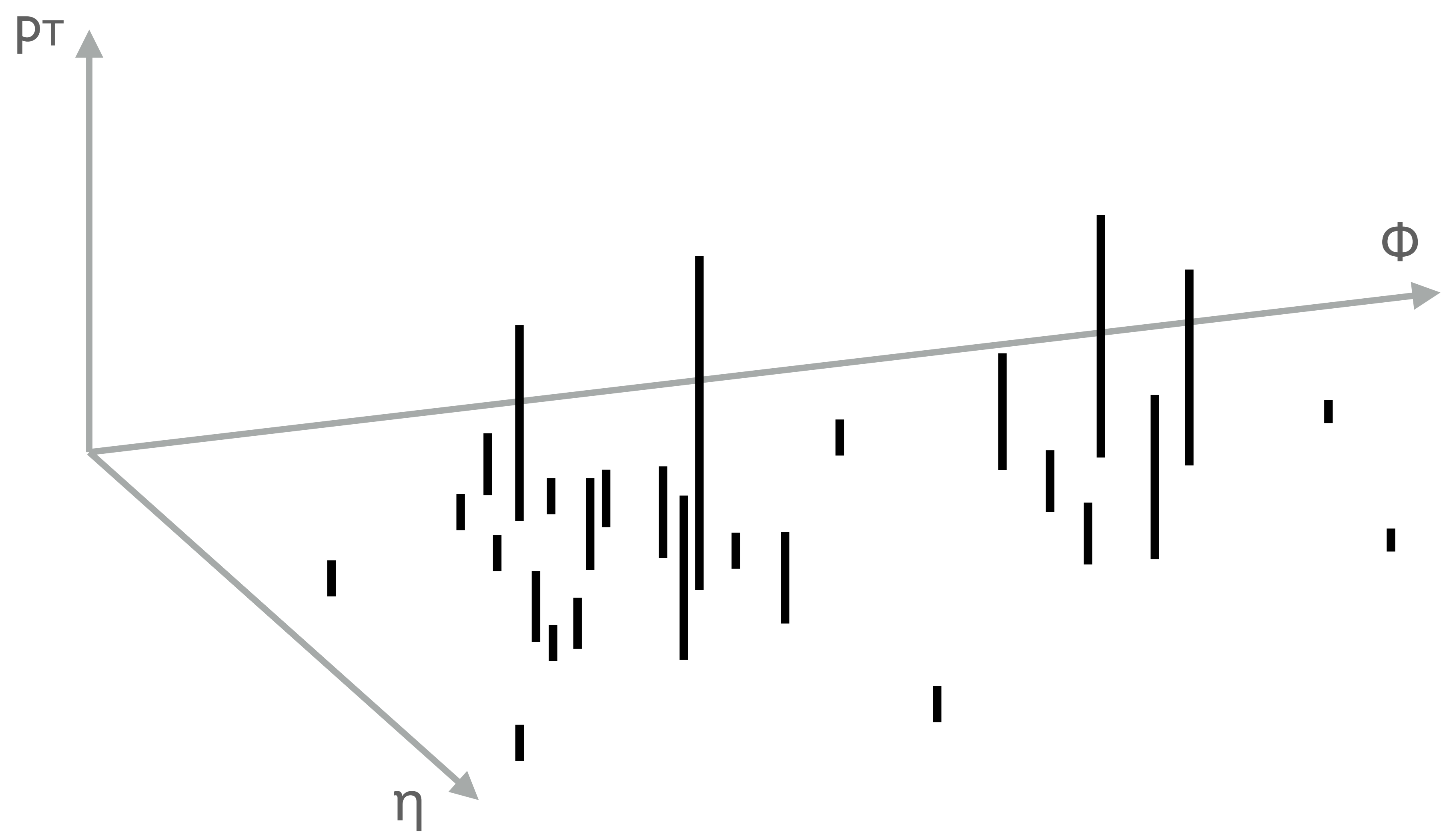


Jet algorithms and substructure

Jet clustering (anti-k_T)

$$d_{ij} = \min(p_{t,i}^{2k}, p_{t,j}^{2k}) \frac{\Delta R^2}{R^2} \quad \text{with } k = -1, \;\; \Delta R^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

$$d_{iB} = p_{t,i}^{2k}$$



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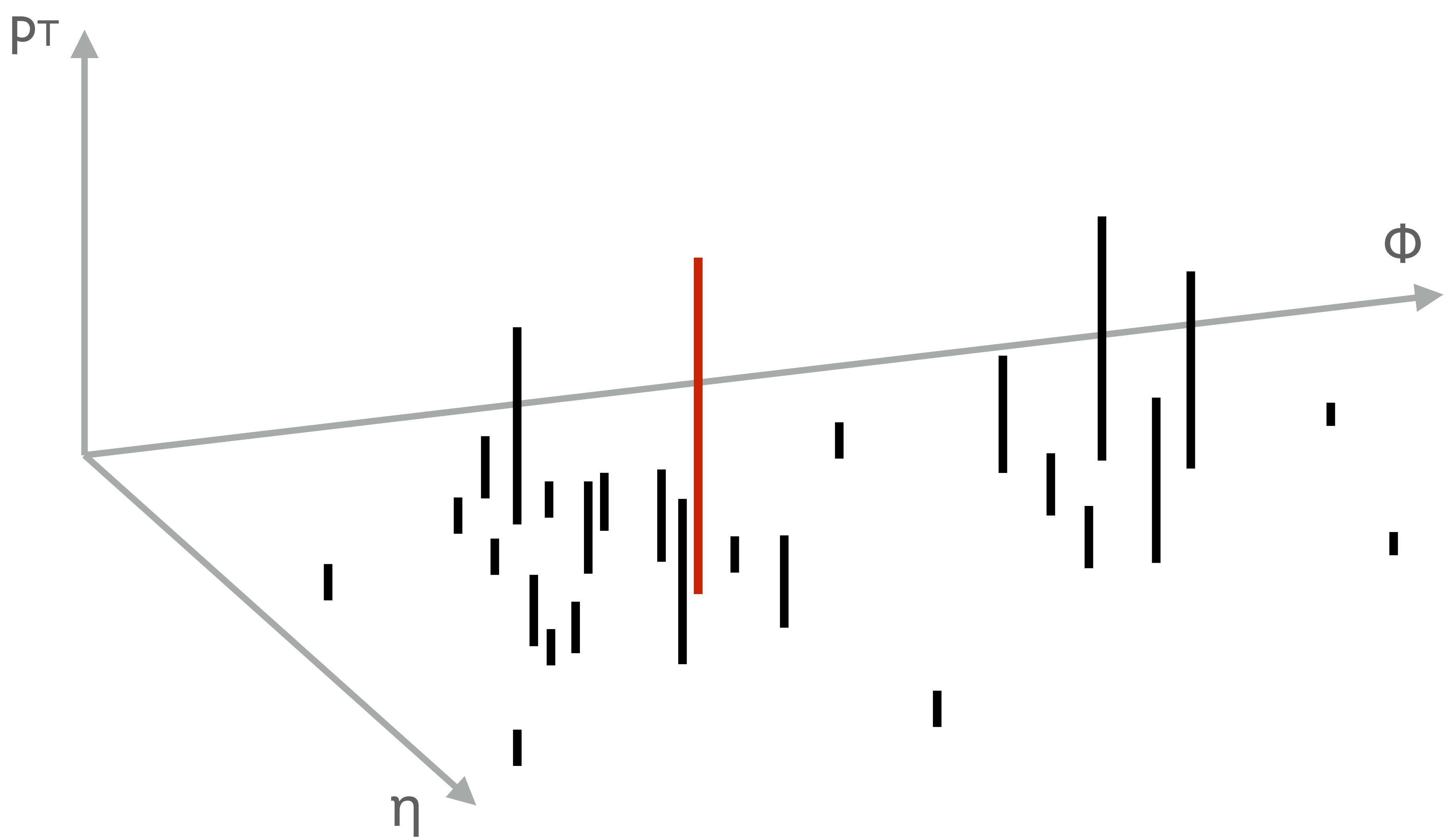

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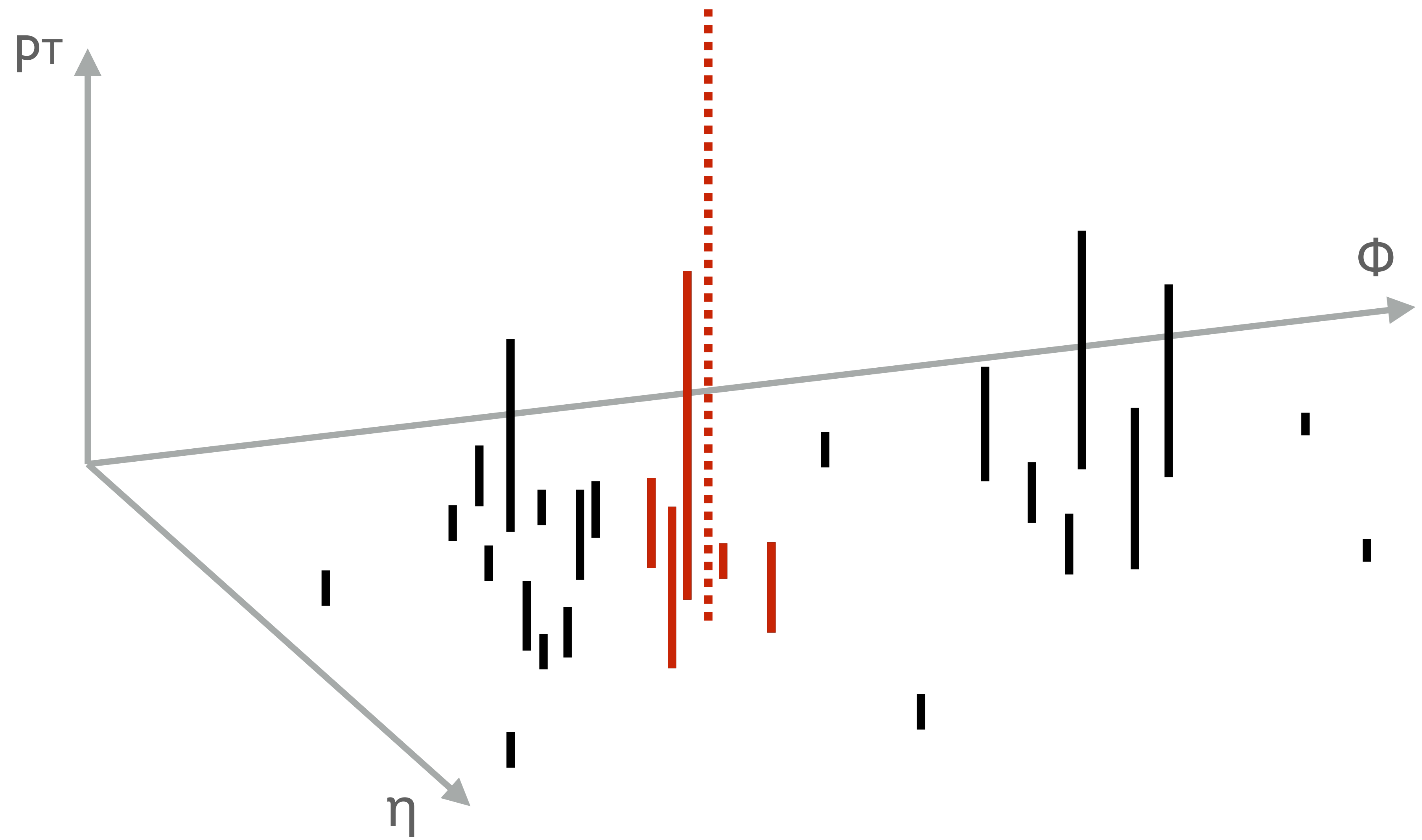

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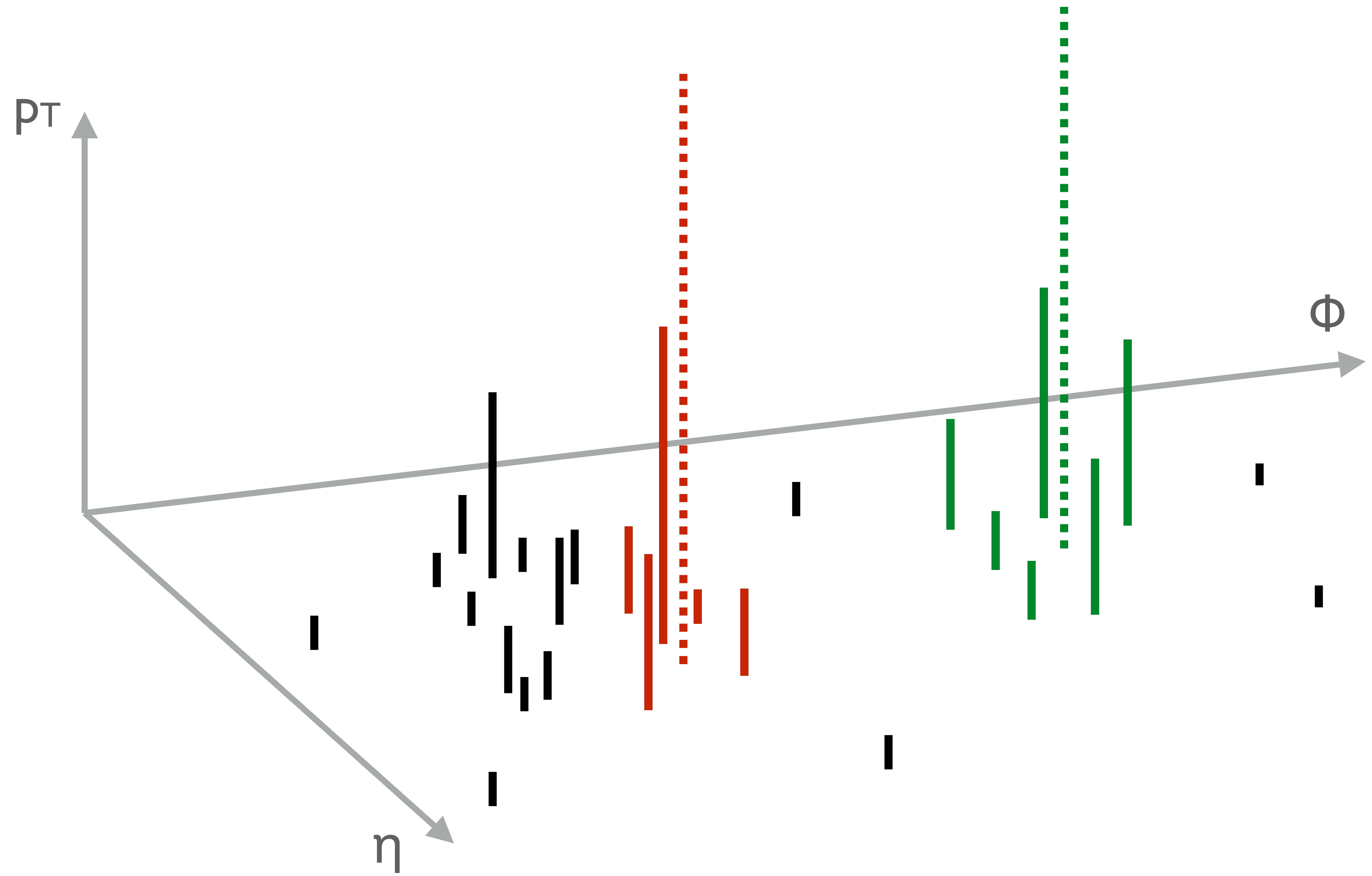

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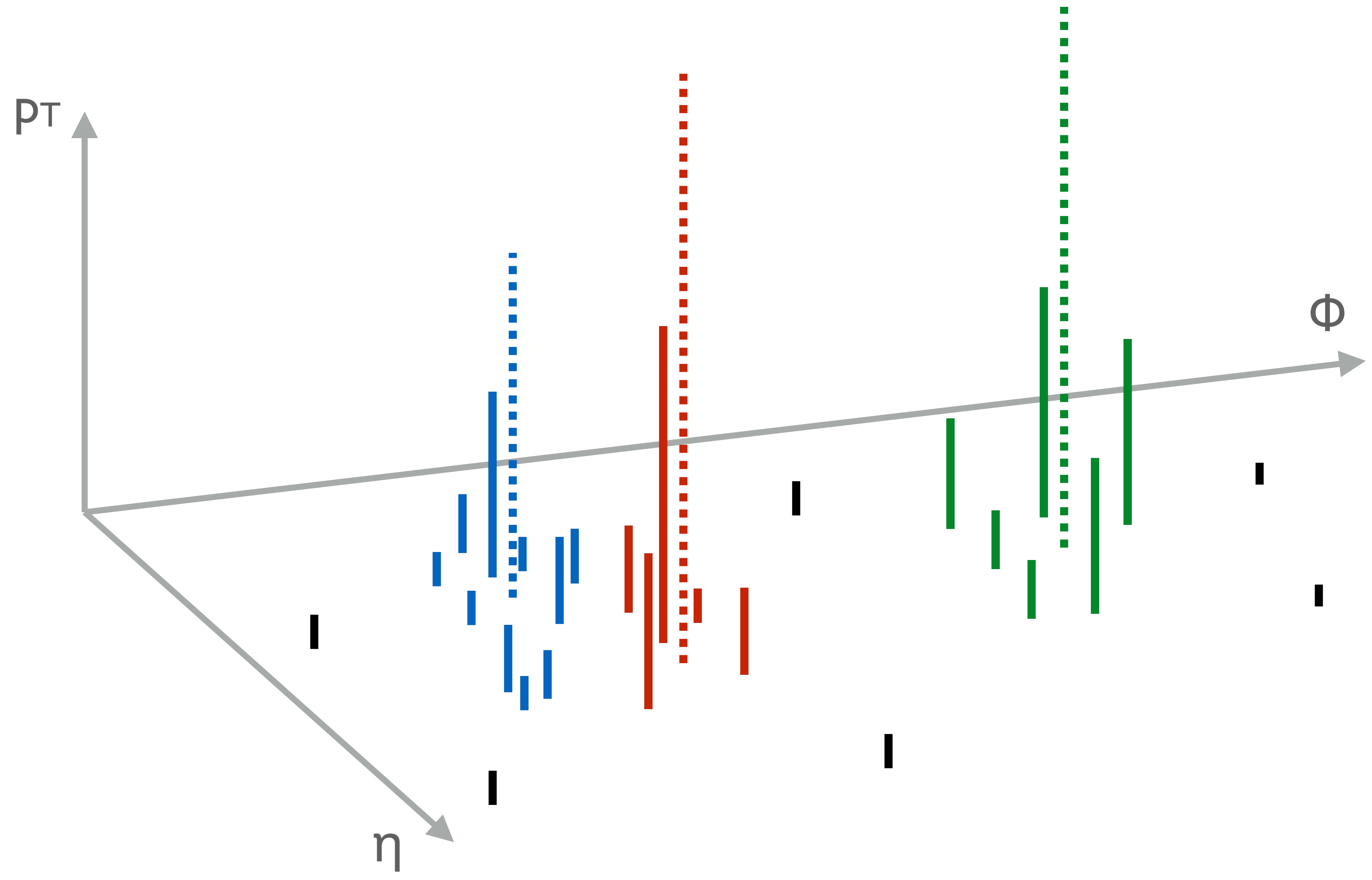

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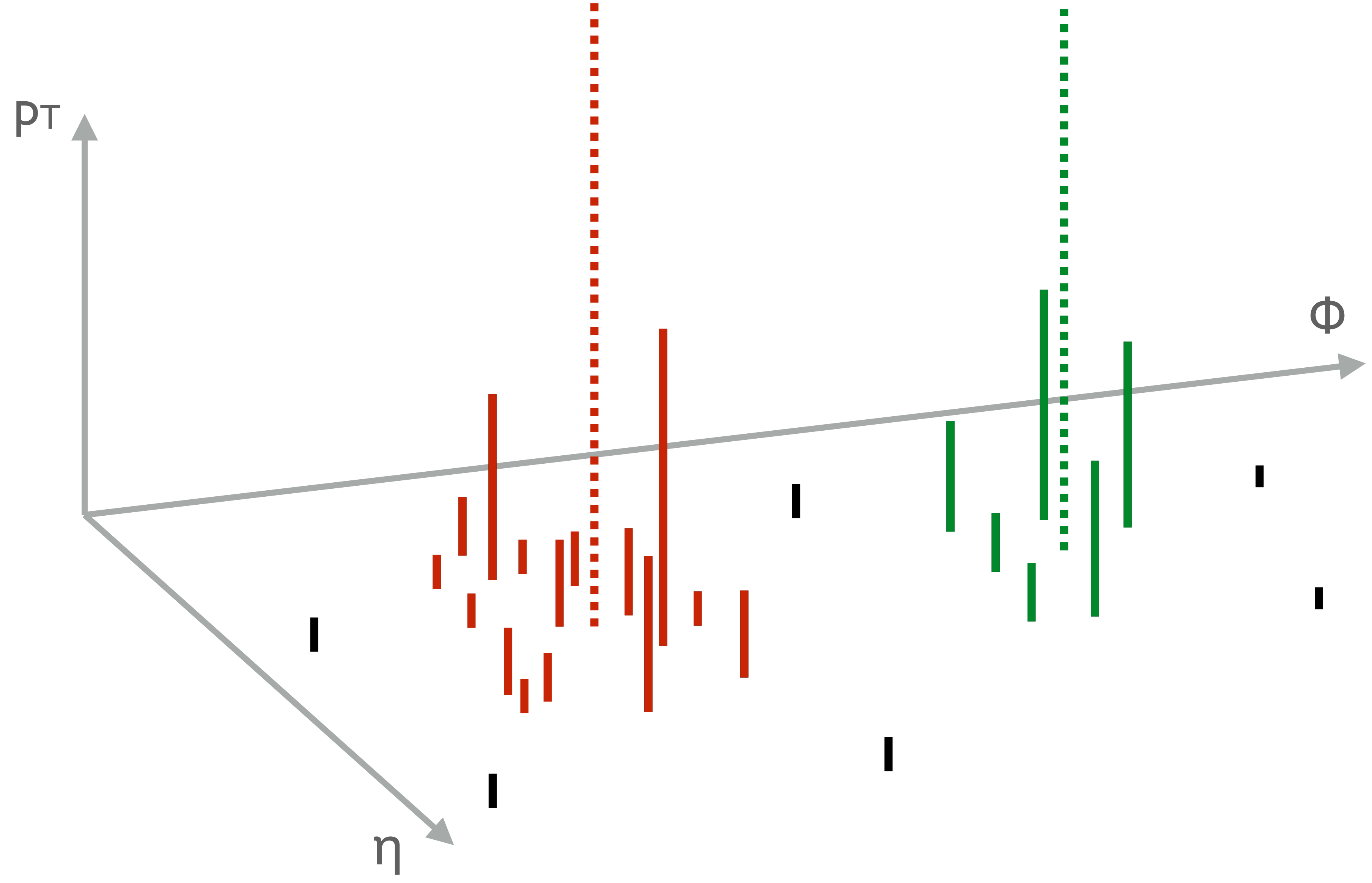

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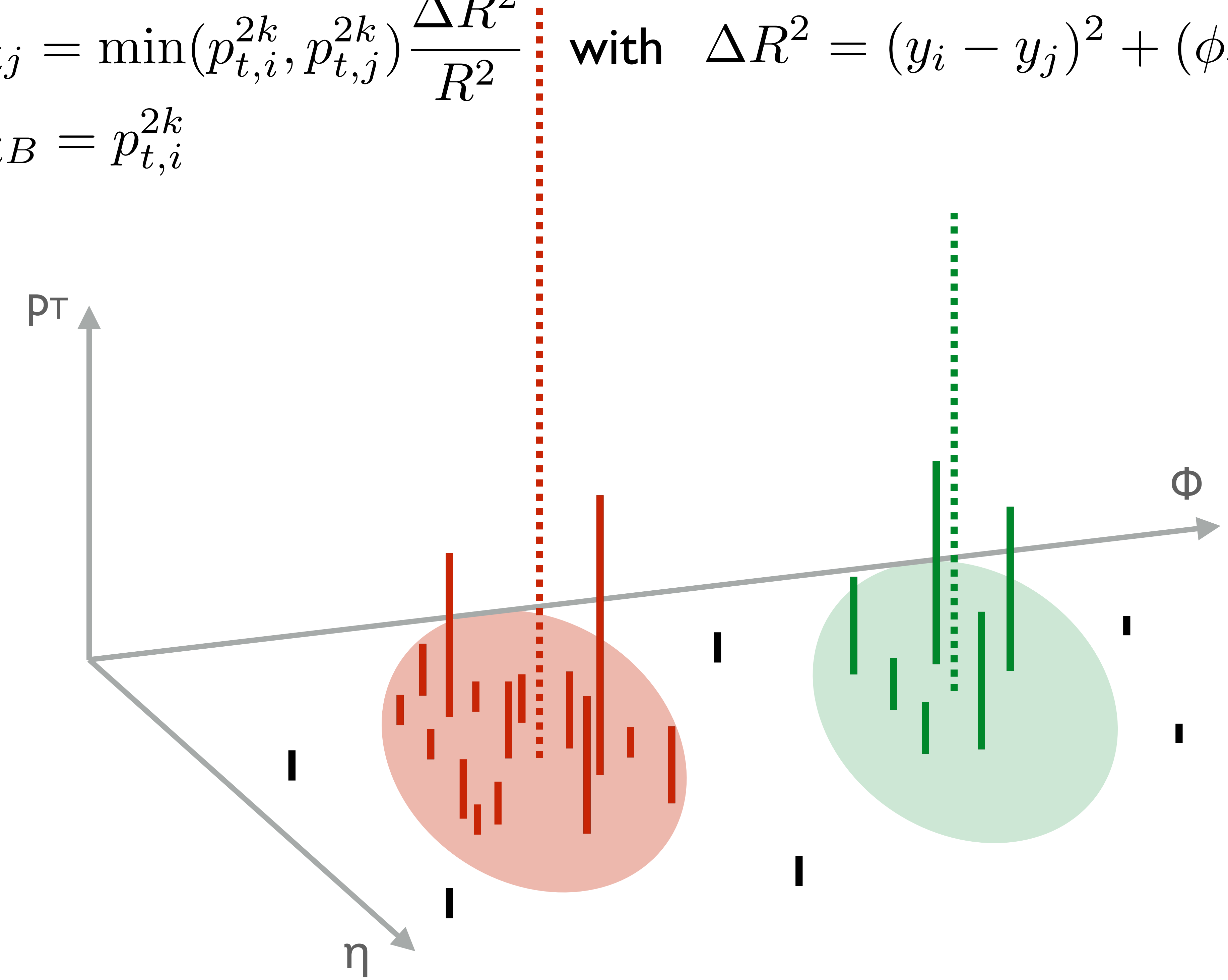

Jet clustering (C/A)

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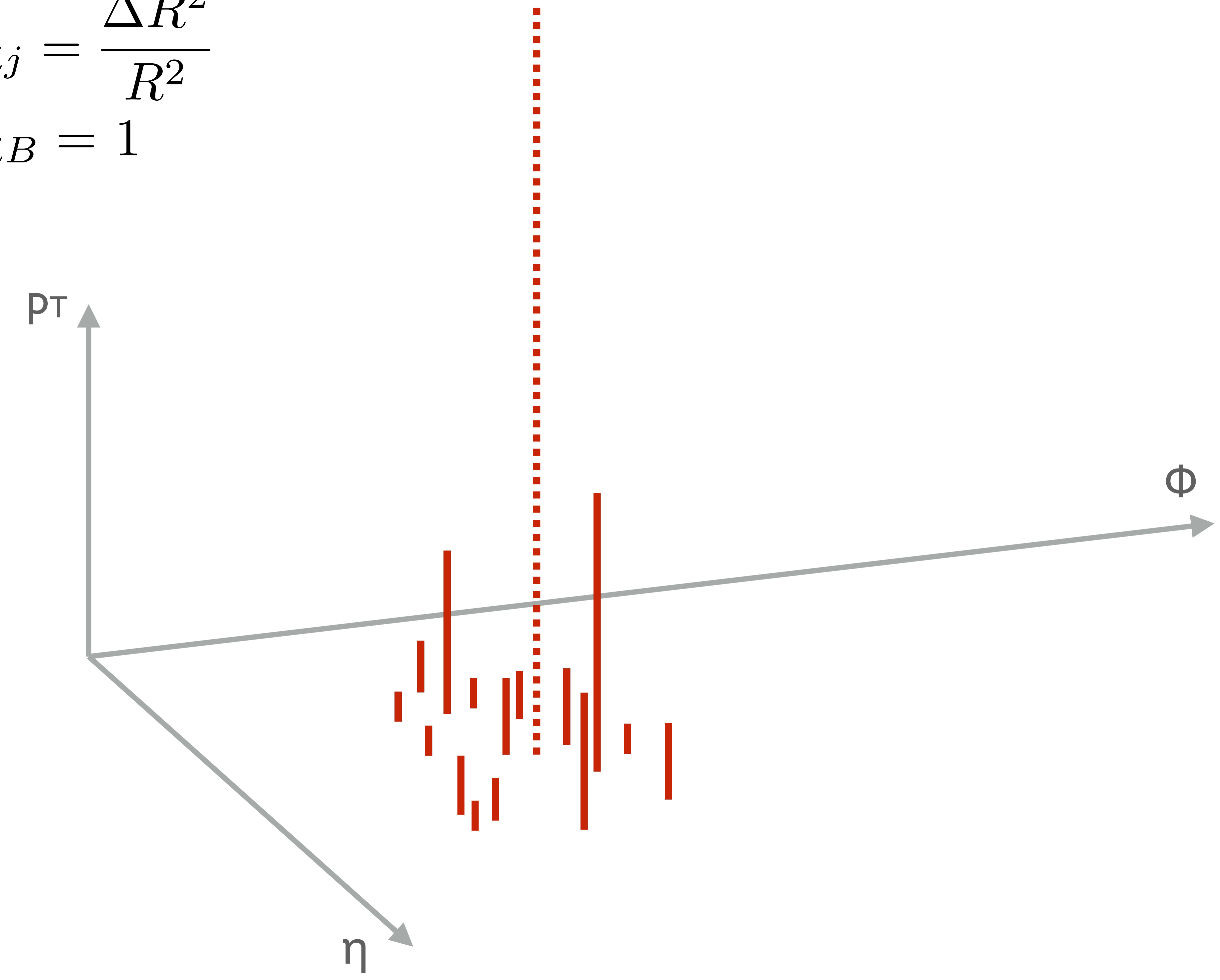

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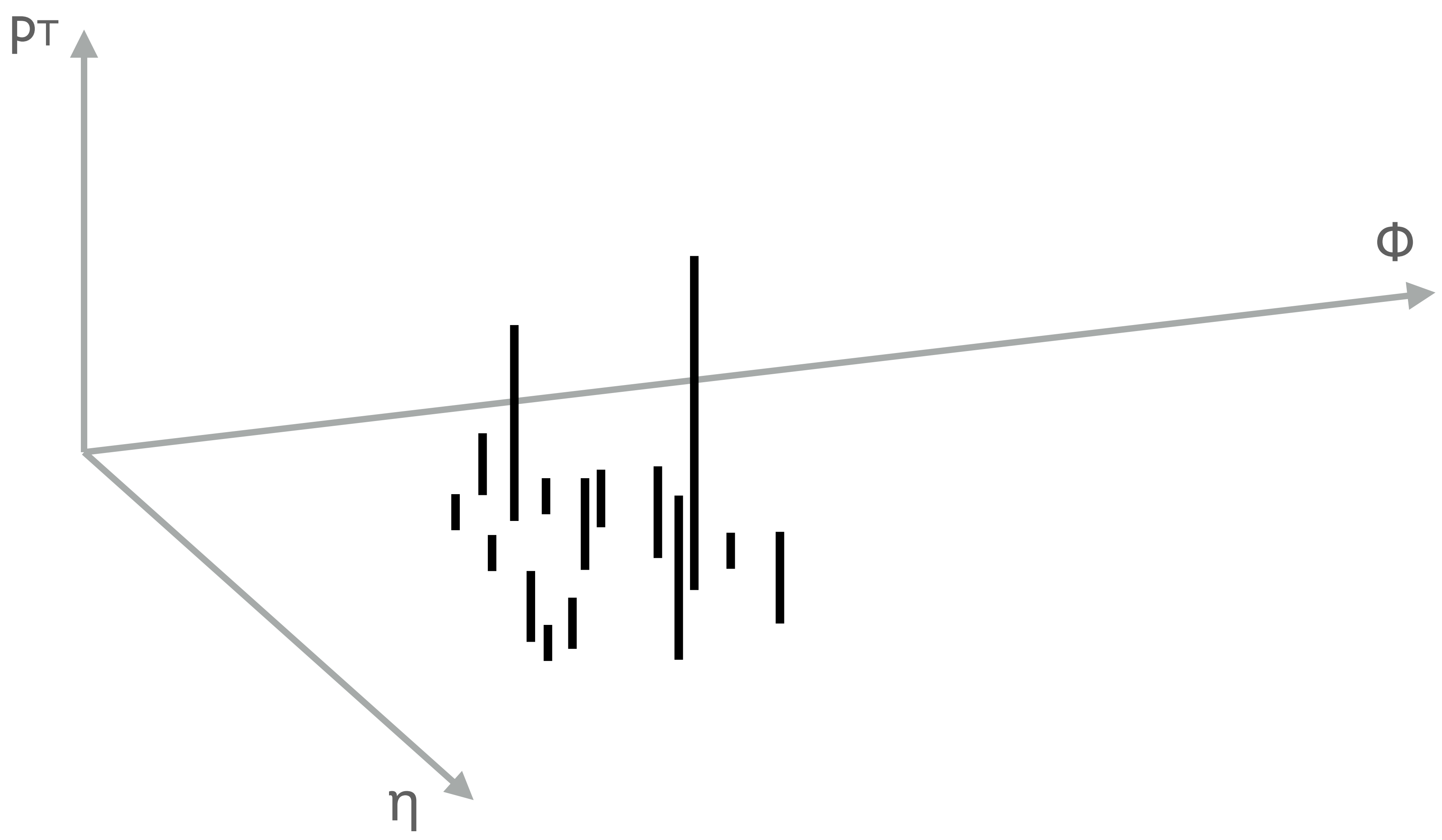

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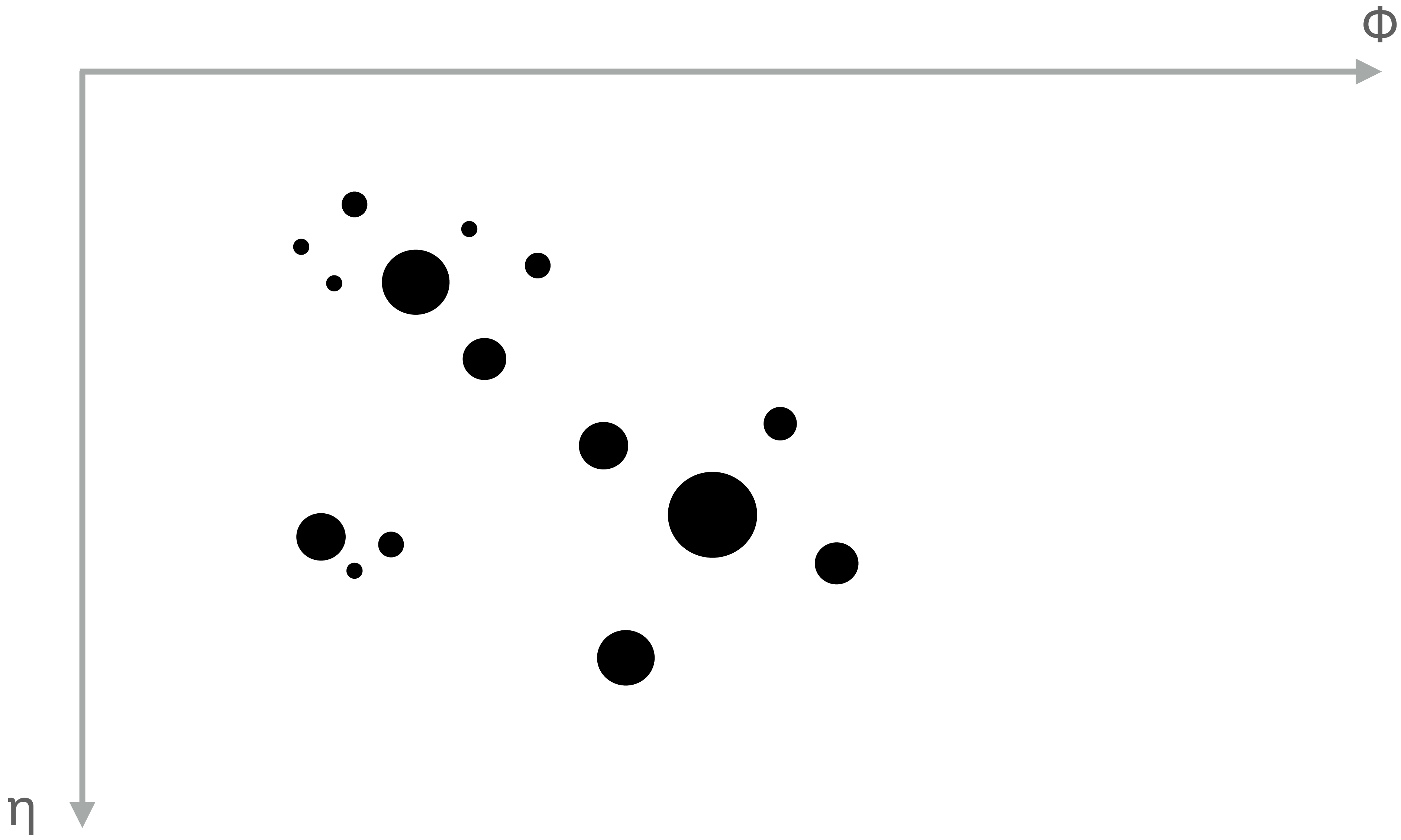

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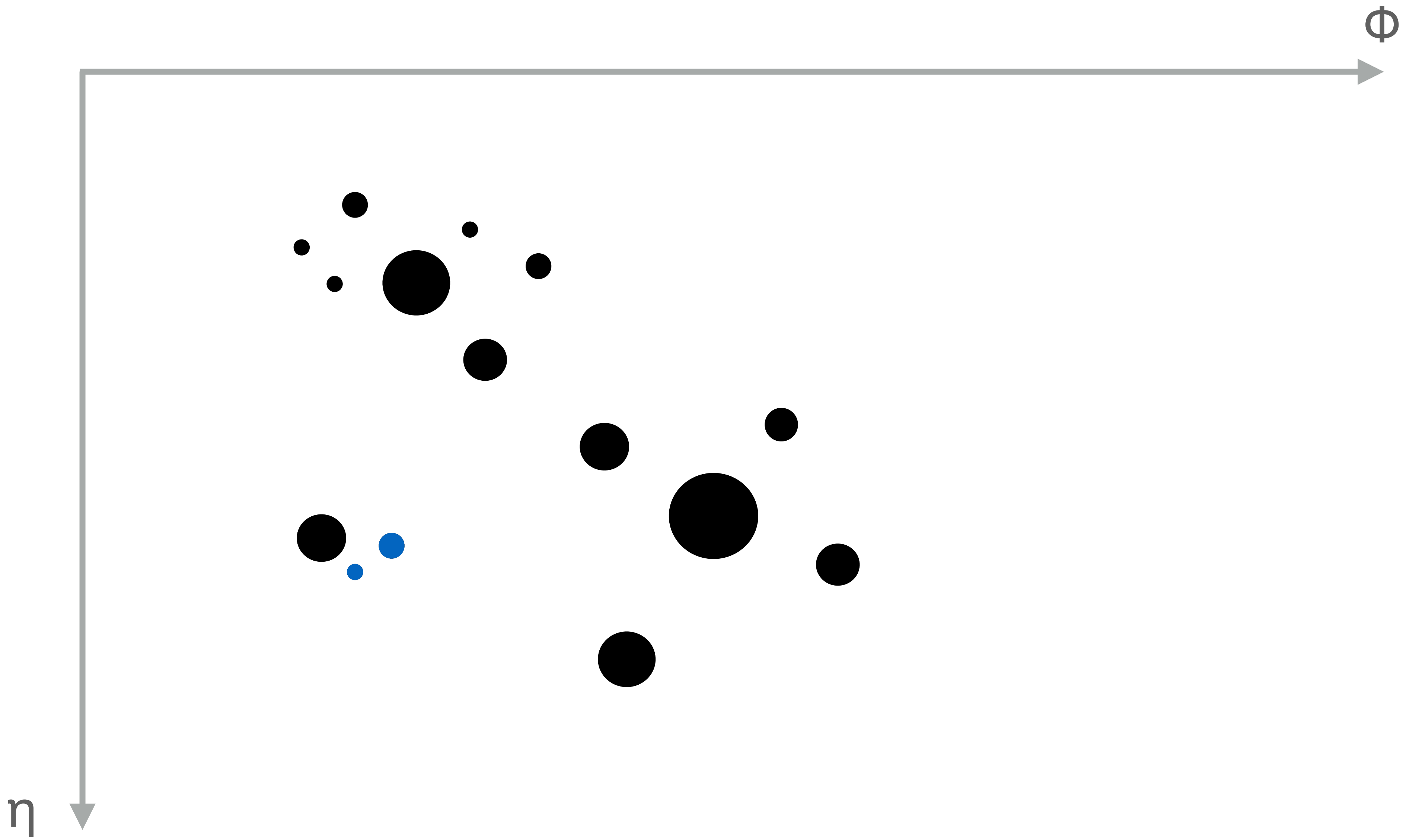

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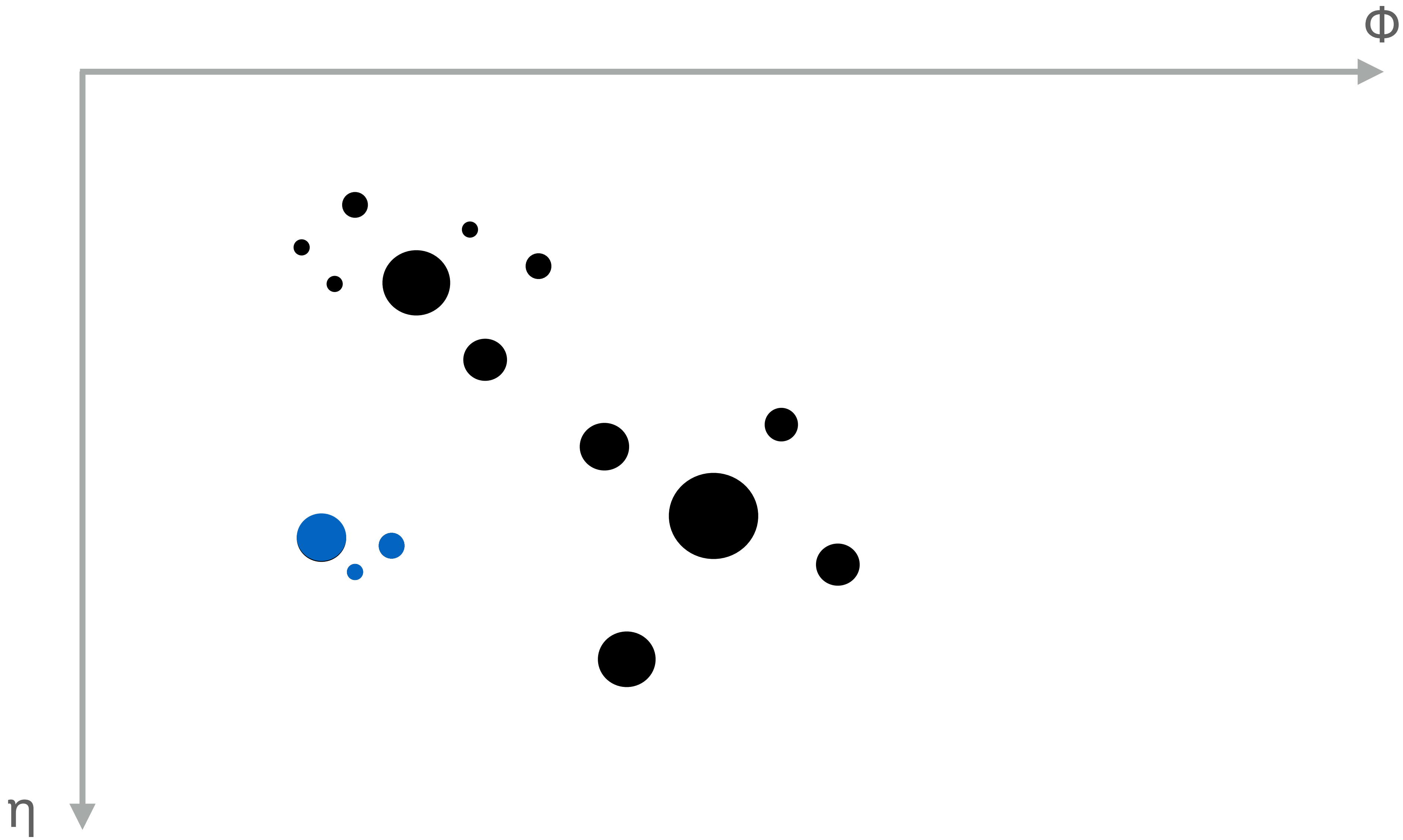

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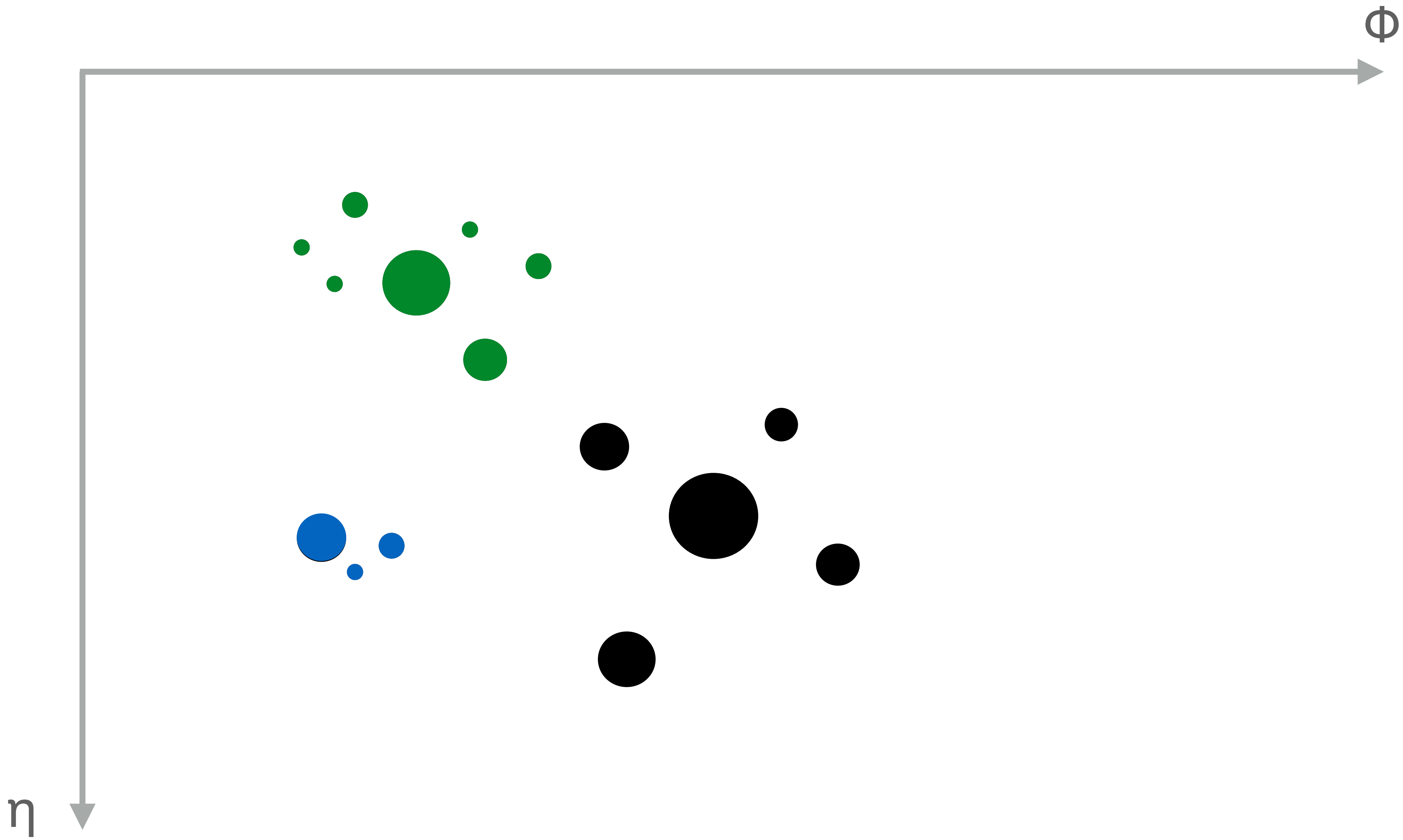

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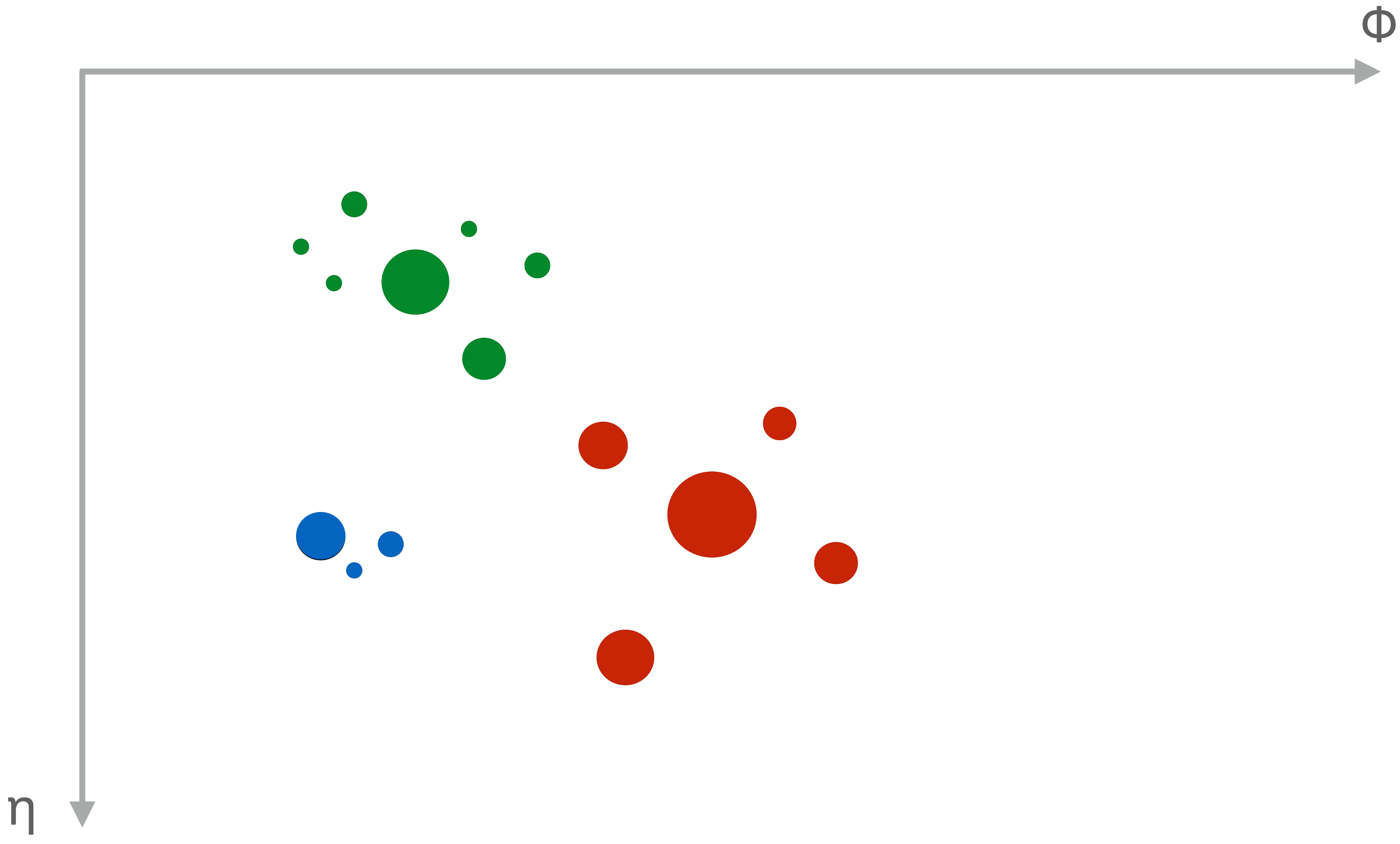

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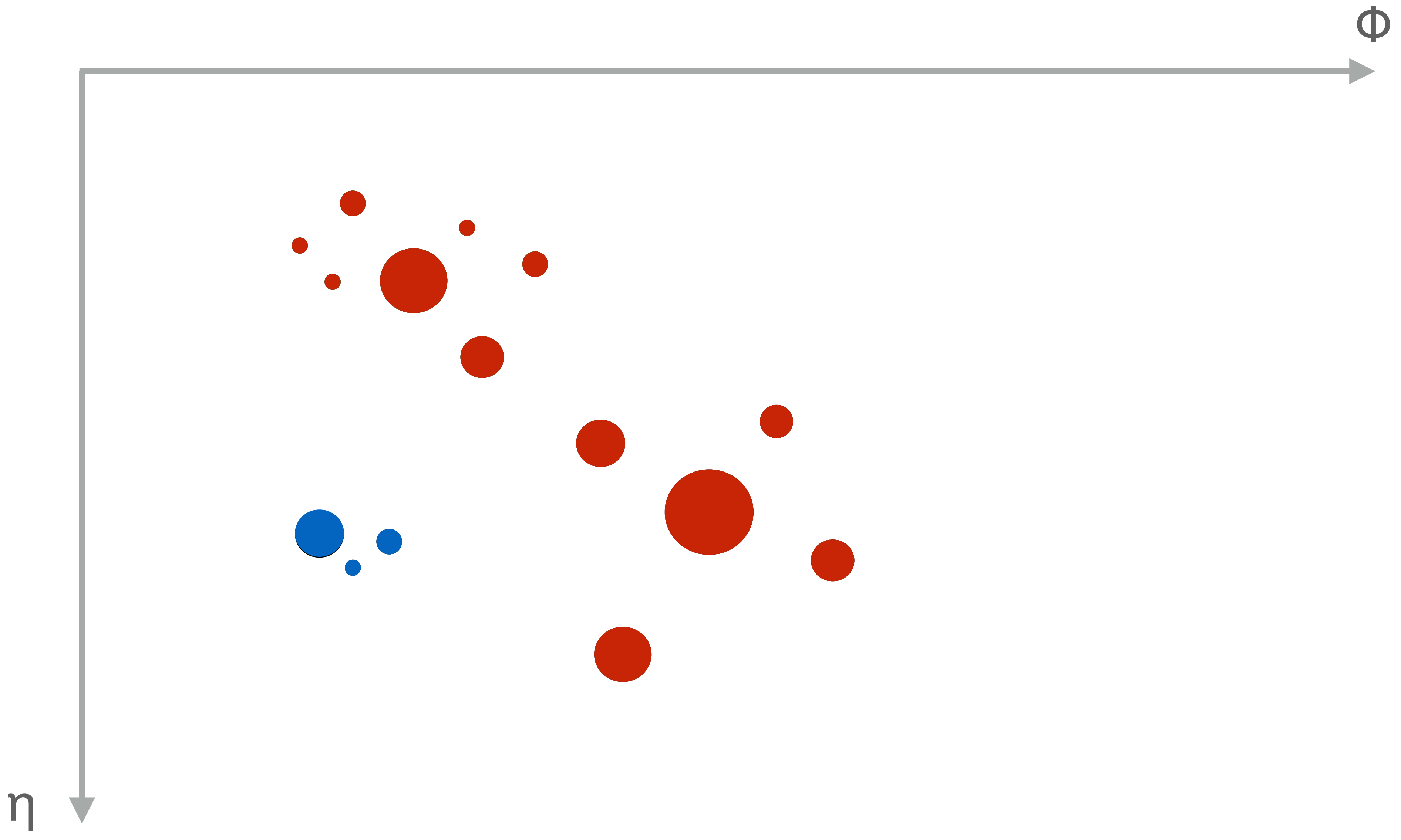

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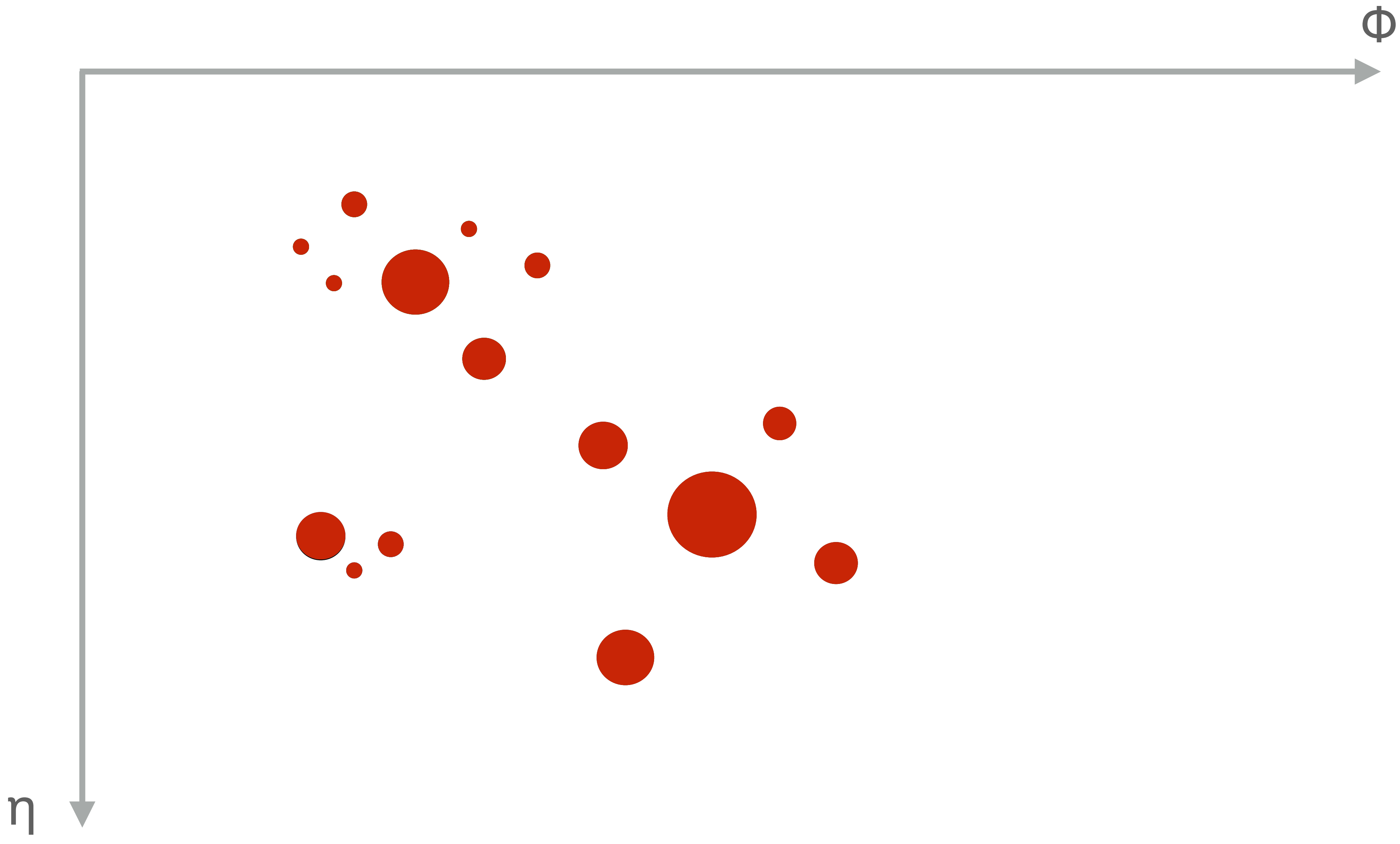

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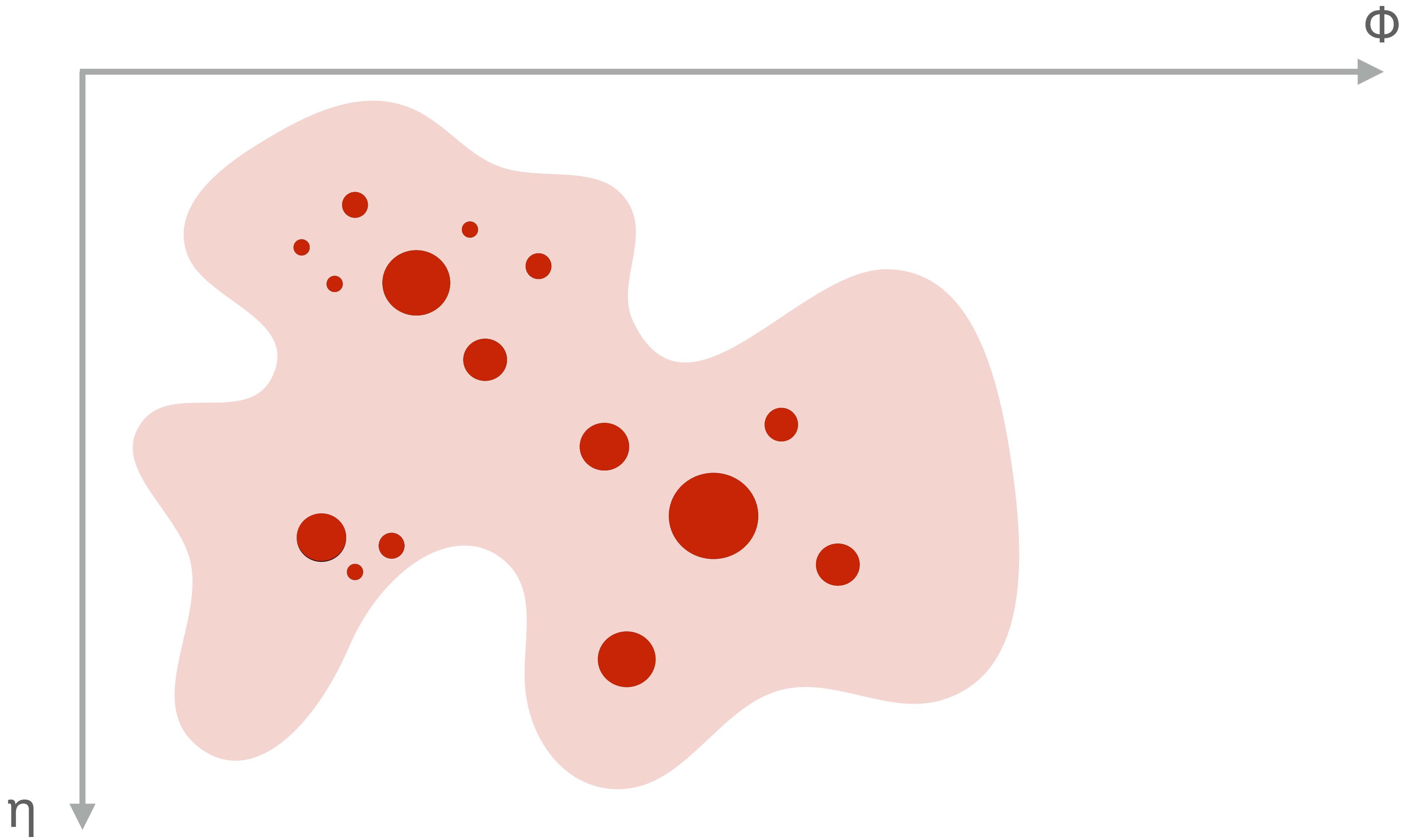

Jet grooming (soft drop)

Invert clustering history with a veto condition:

$$\min(p_{\mathrm{T,i}}, p_{\mathrm{T,j}}) > z_{\mathrm{cut}} \left(p_{\mathrm{T,i}} + p_{\mathrm{T,j}}\right) \left(\frac{\Delta R_{ij}}{R}\right)^{\beta}$$

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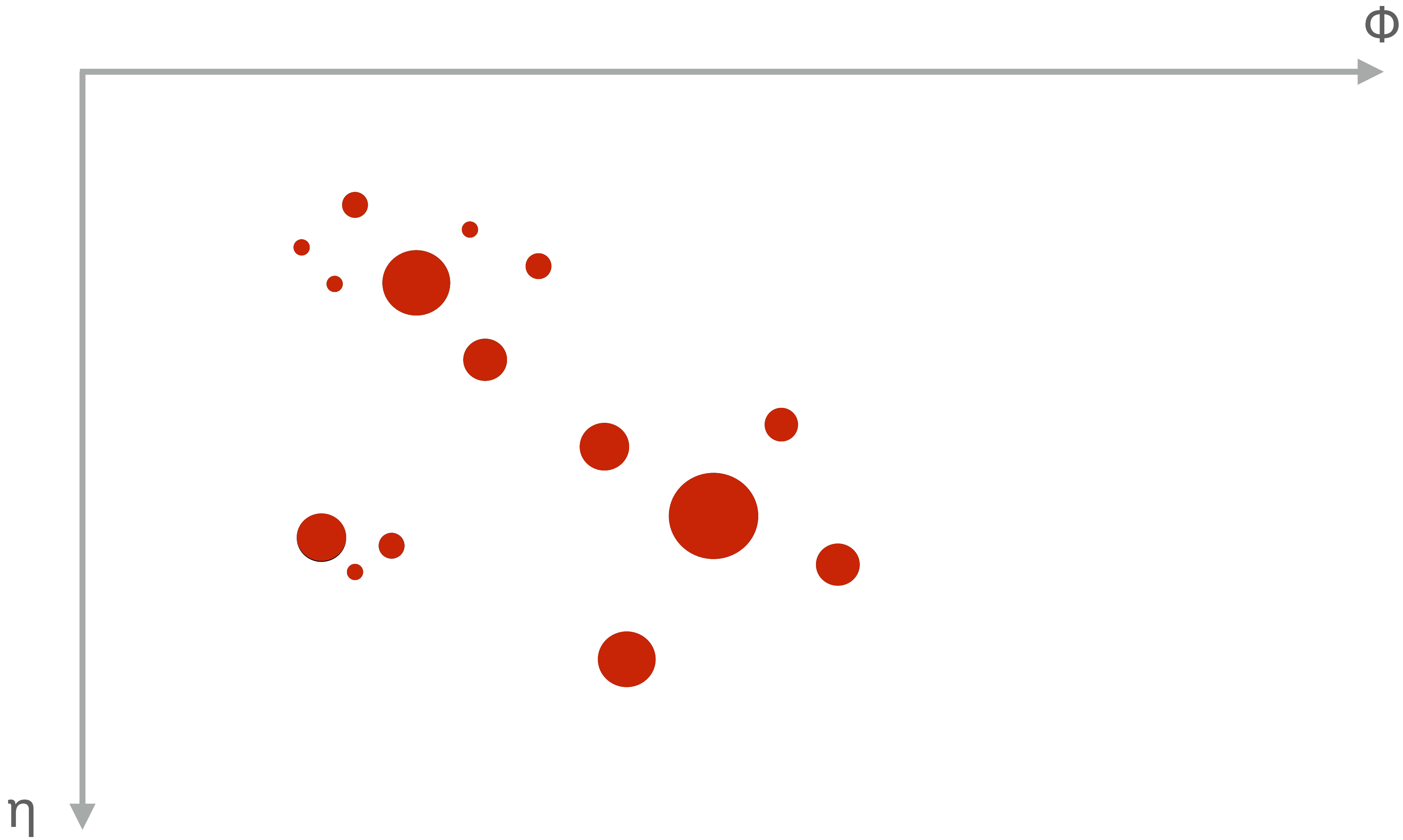

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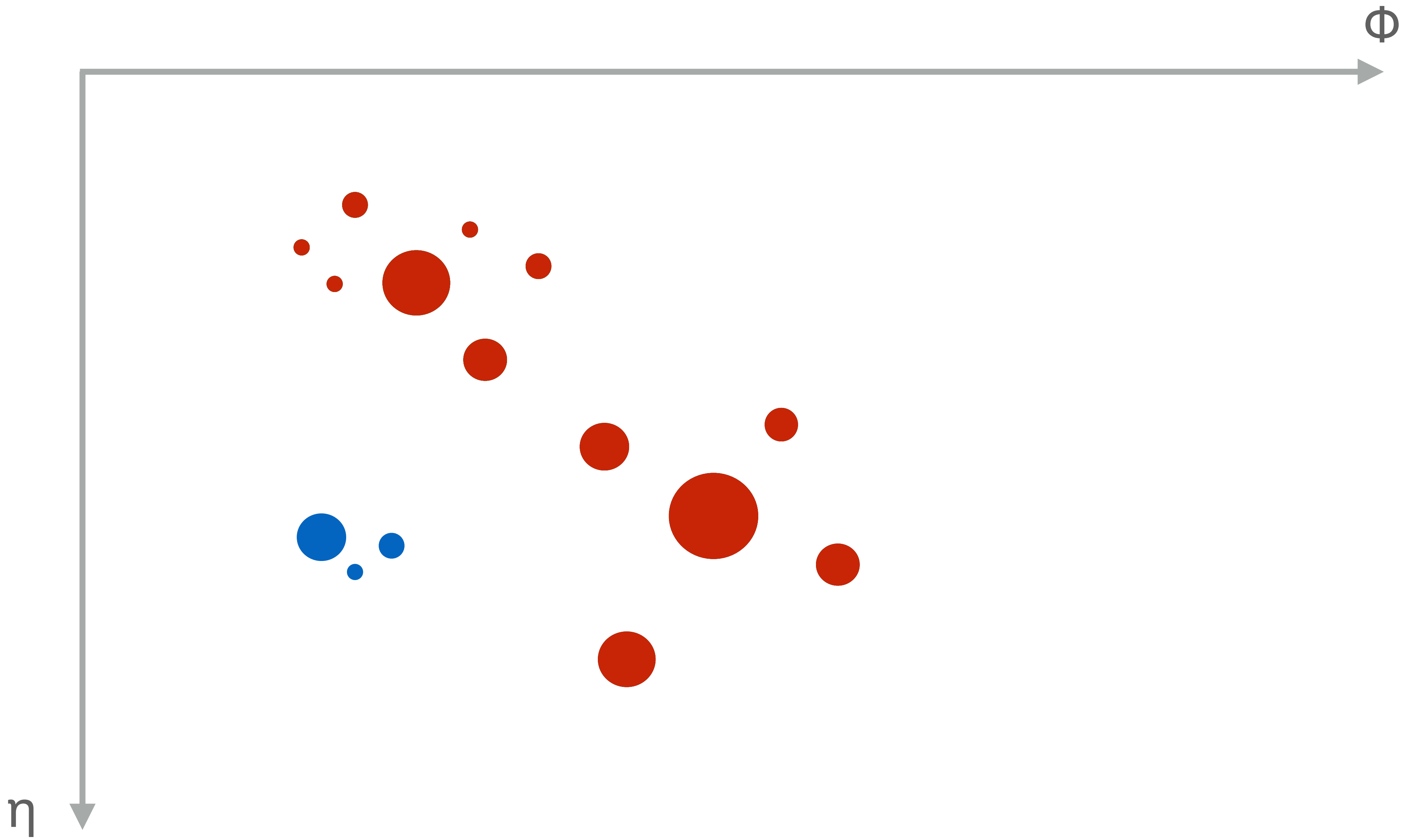

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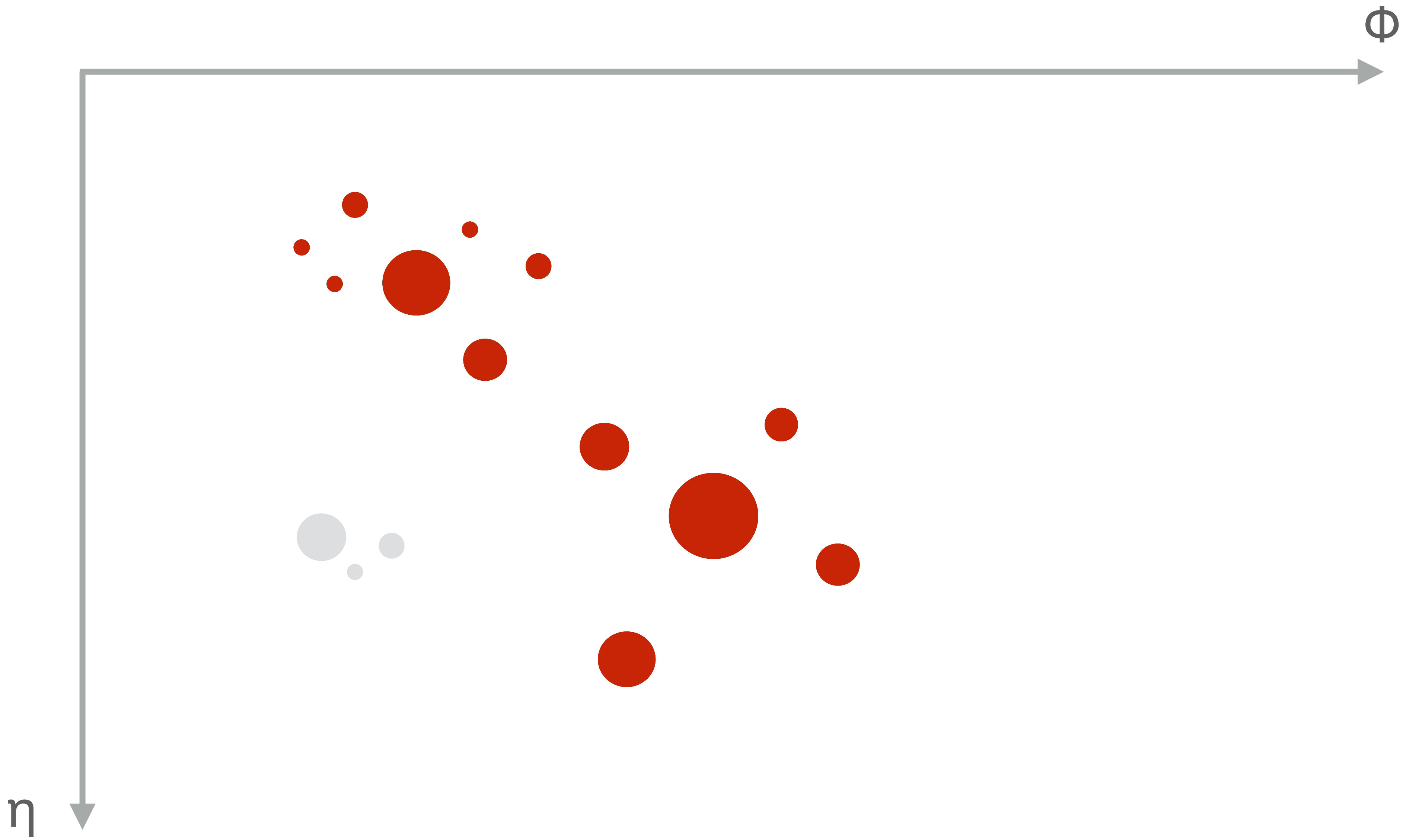

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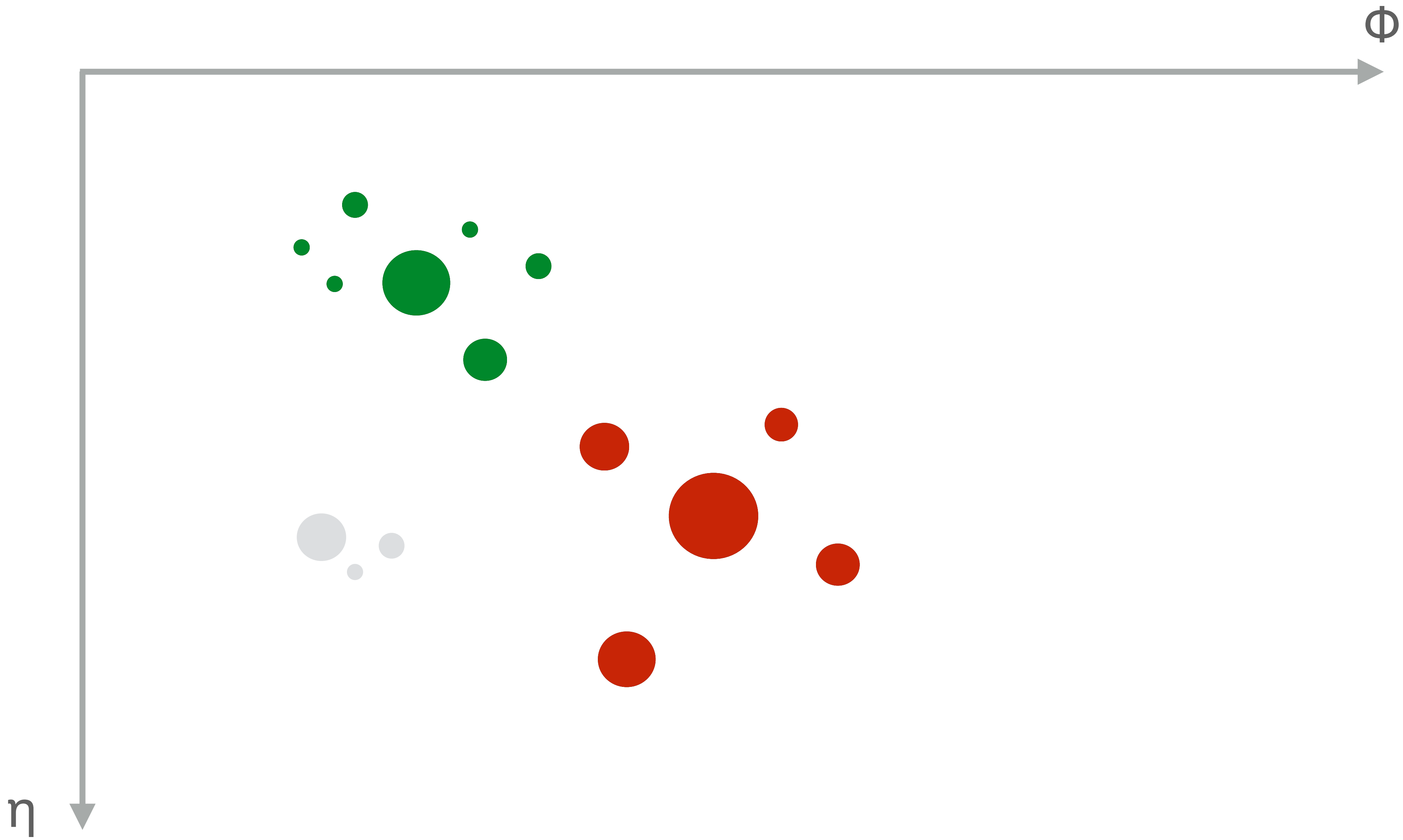

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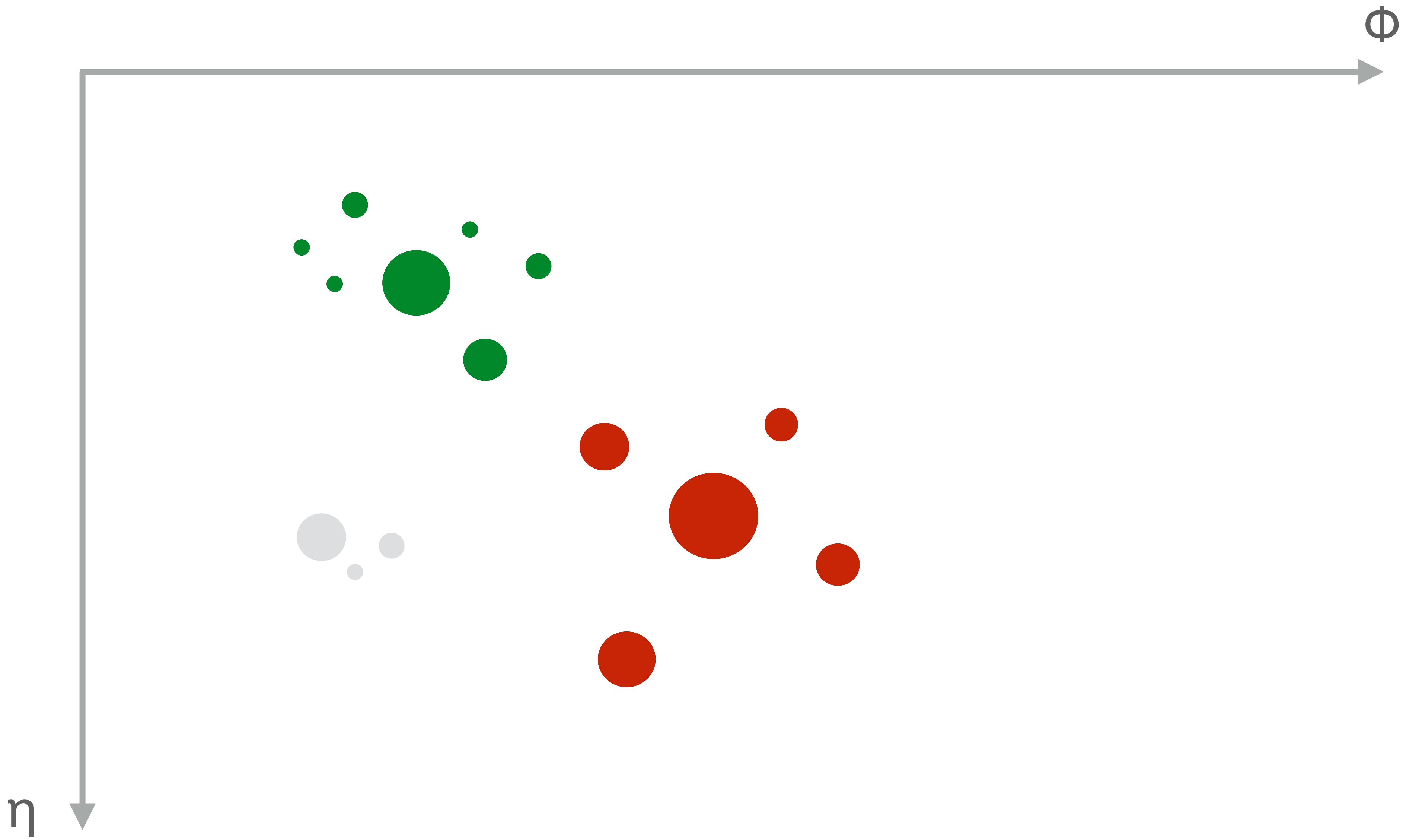

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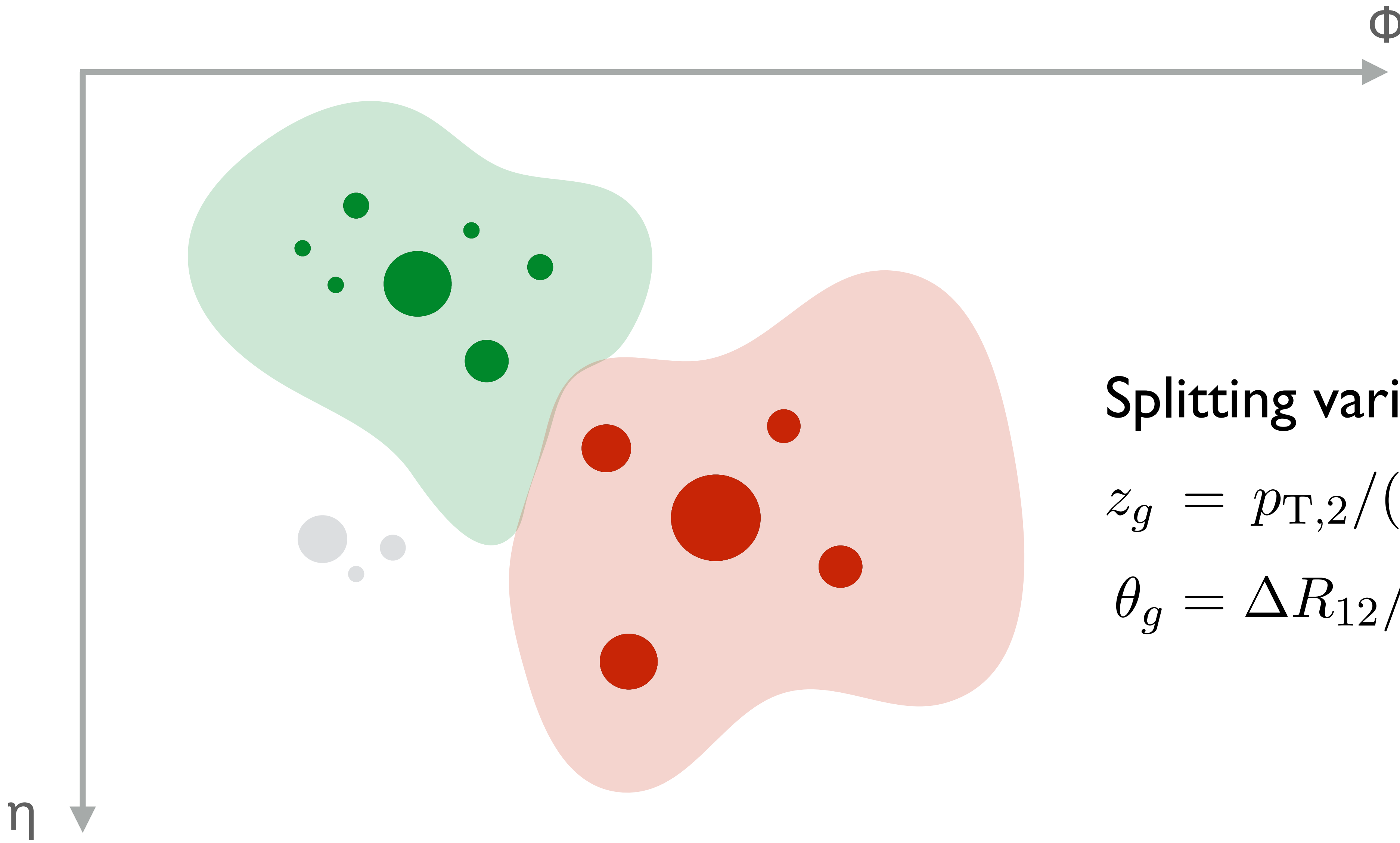


Splitting variables:

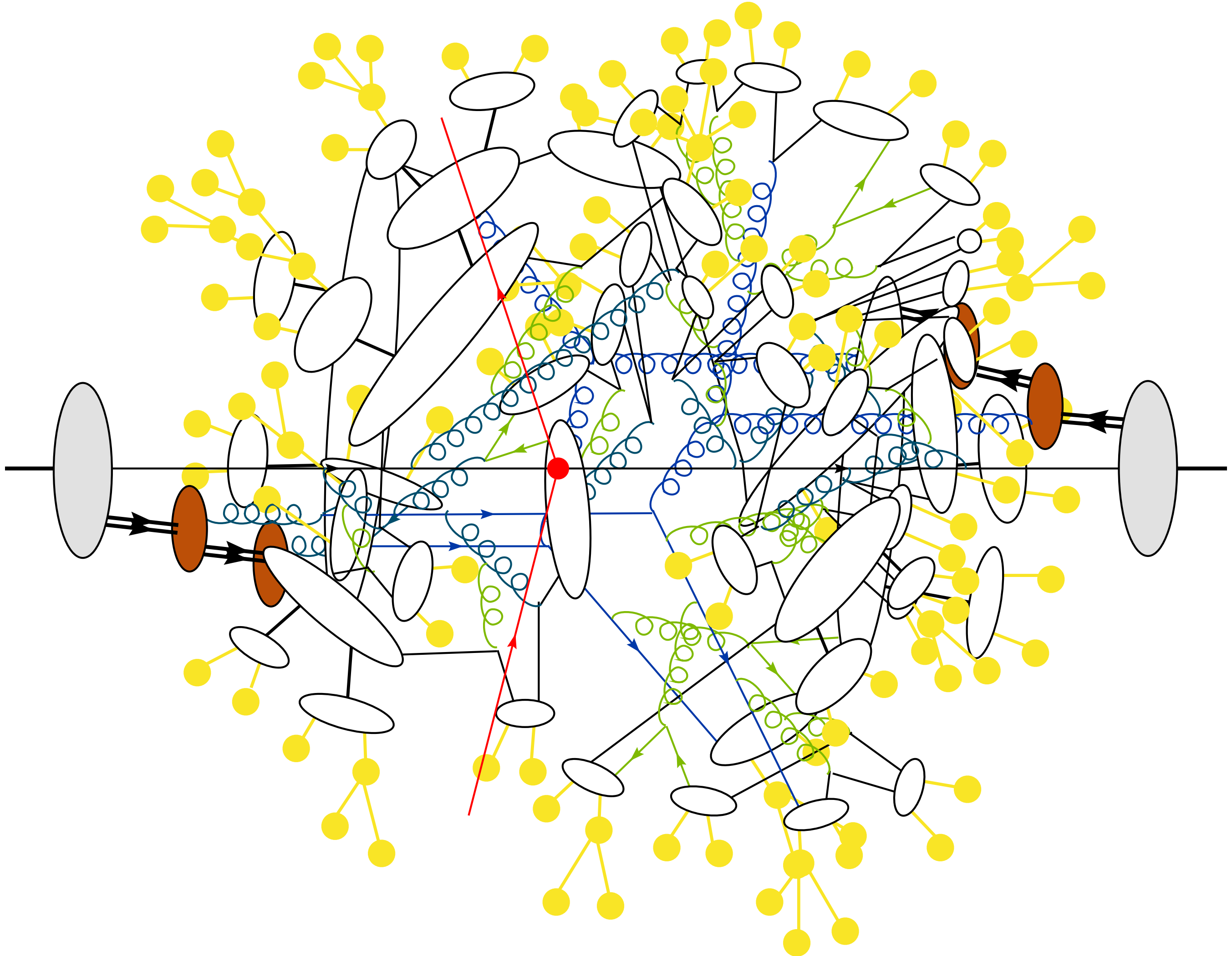
$$z_g = p_{\mathrm{T},2}/(p_{\mathrm{T},1} + p_{\mathrm{T},2})$$

$$\theta_g = \Delta R_{12}/R$$

Importance of grooming

Jet kinematics affected by

- Perturbative radiation
- Hadronisation
- Multiple pp interactions
- Pileup



[S. Gieseke, MCNet 2010]

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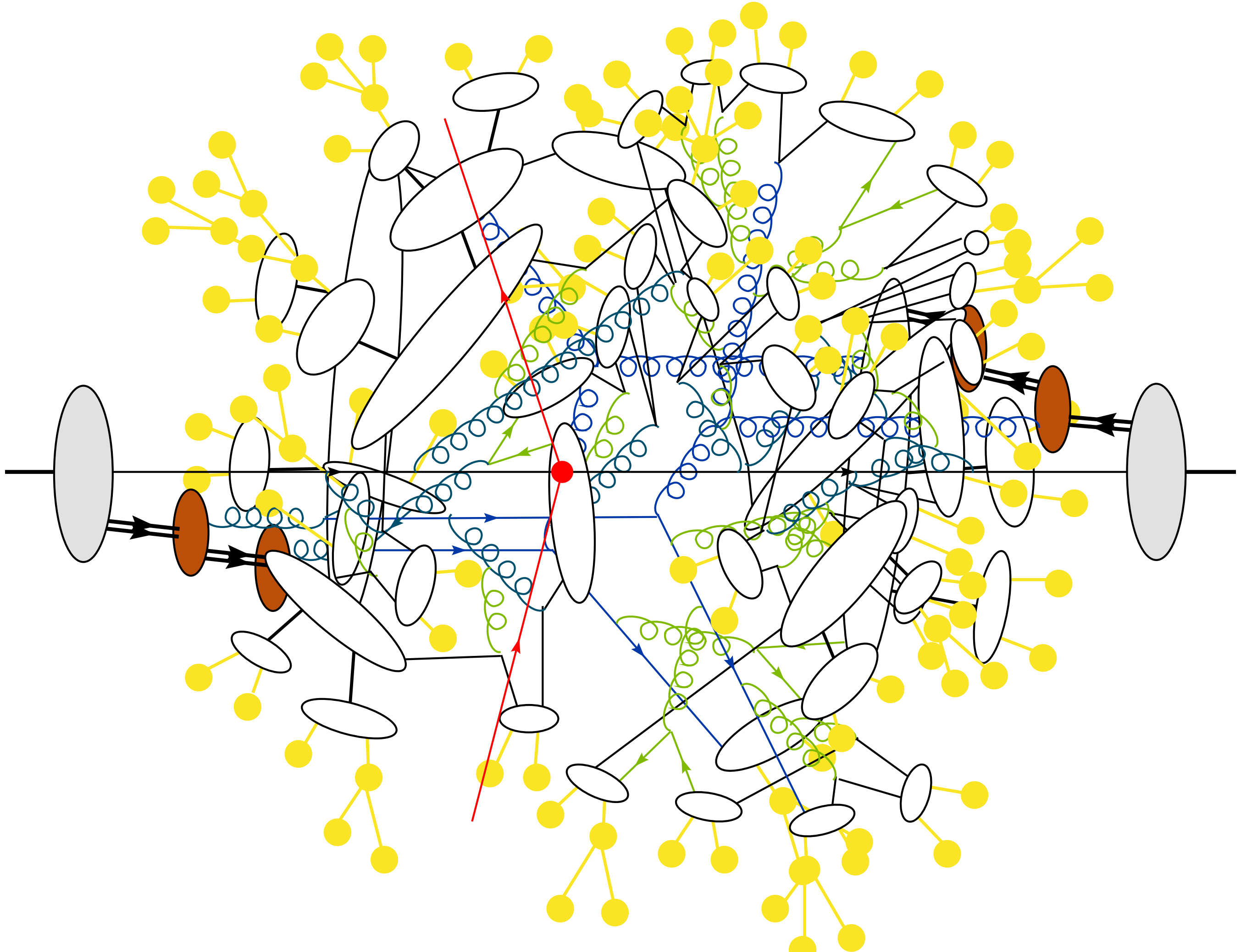
$$\langle \delta p_{\mathrm{T}} \rangle_h = 2 C_R A(\mu_I) M \left(-\frac{1}{R} + \mathcal{O}(R) \right)$$

$$\langle \delta p_{\mathrm{T}} \rangle_{\mathrm{UE}} = \frac{\Lambda_{\mathrm{UE}}}{2} \left(R^2 - R^4/8 + \mathcal{O}(R^6) \right)$$



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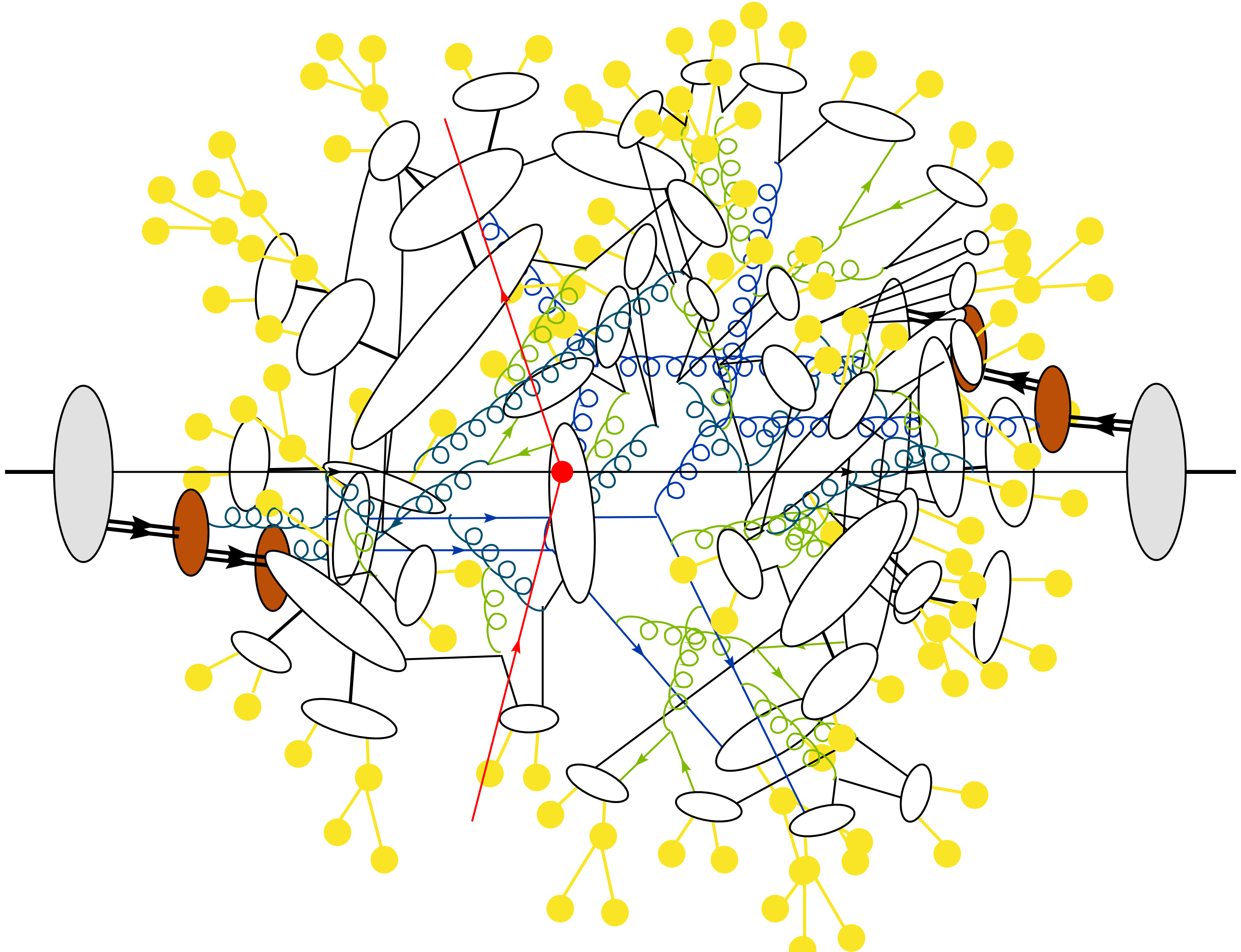


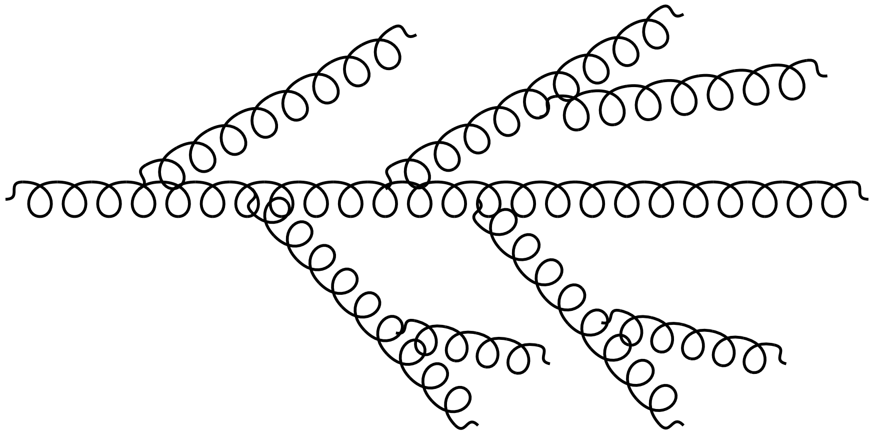
[S. Gieseke, MCNet 2010]

Grooming

- Reduces non-perturbative effects
- Gives access to internal jet structure

Jet mass

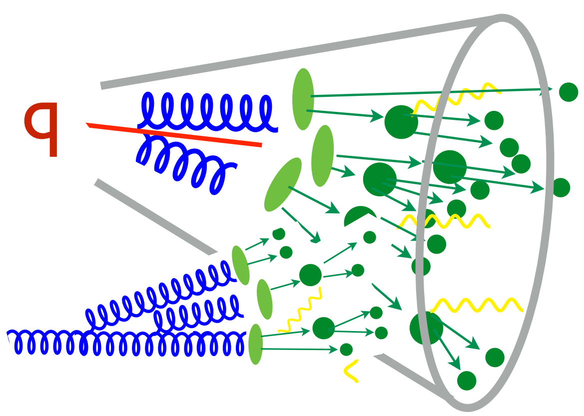
Perturbative effects



Mass generated at each splitting:

$$m^2 = (p_1 + p_2)^2 \approx p_{\mathrm{T},1} p_{\mathrm{T},2} R_{12}^2$$

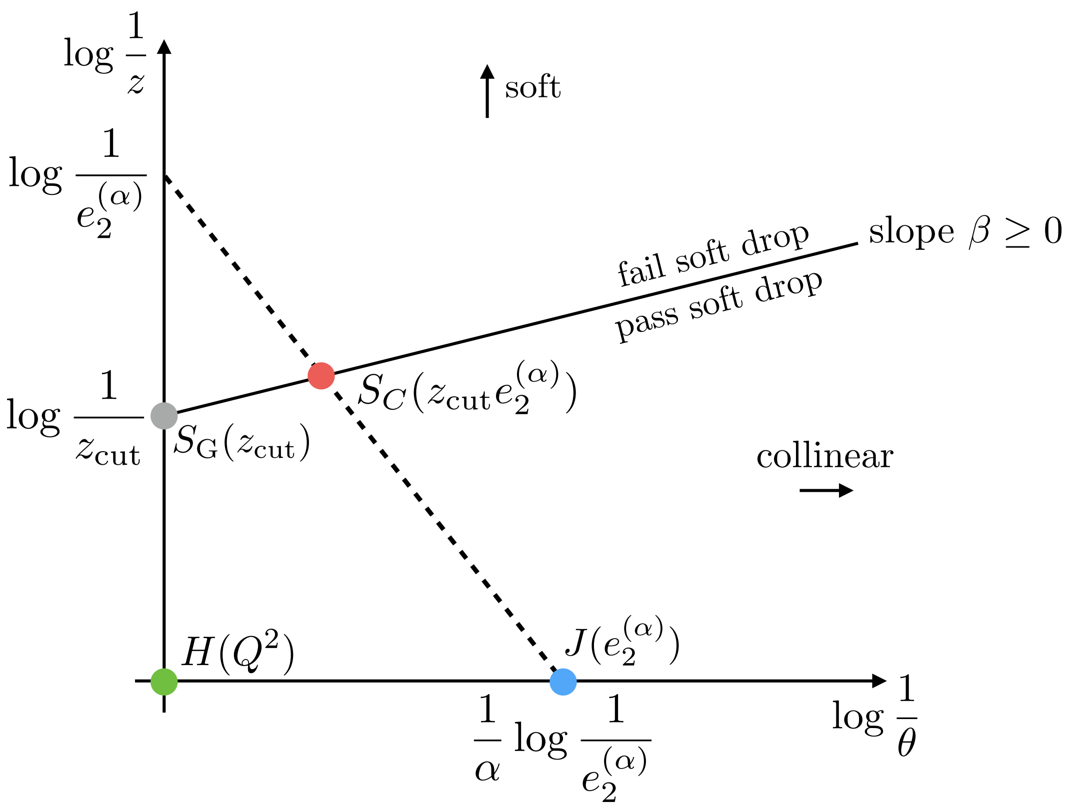
Non-perturbative effects



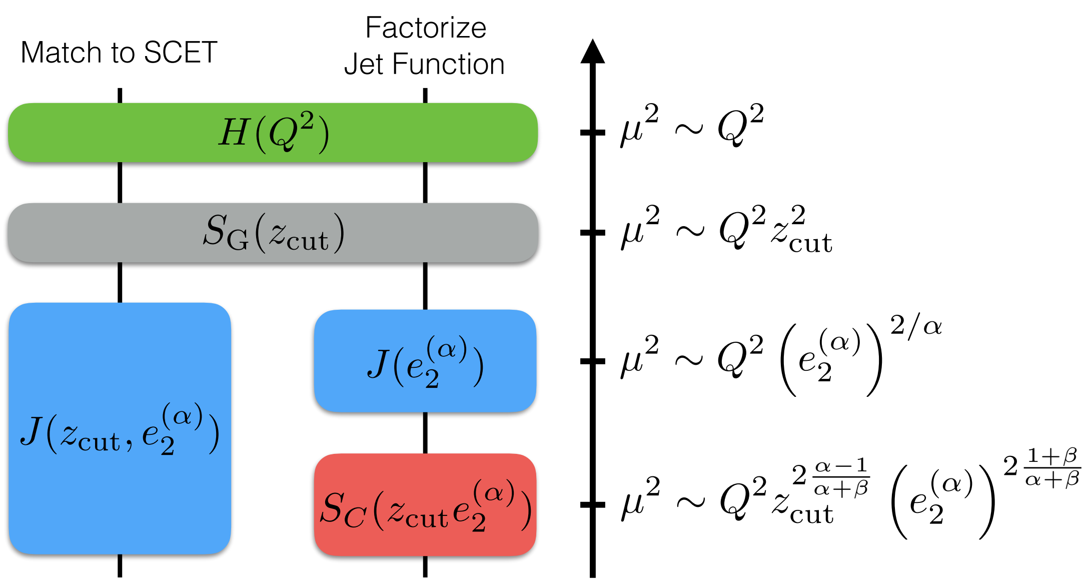
$$\langle \delta m^2 \rangle_h = 2 C_R A(\mu_I) M p_\mathrm{T} \left(R + \mathcal{O}(R^3) \right)$$

$$\langle \delta m^2 \rangle_\mathrm{UE} = C_R \frac{A(\mu_I)}{4} \left(p_\mathrm{T} R^4 + \mathcal{O}(R^6) \right)$$

Jet mass

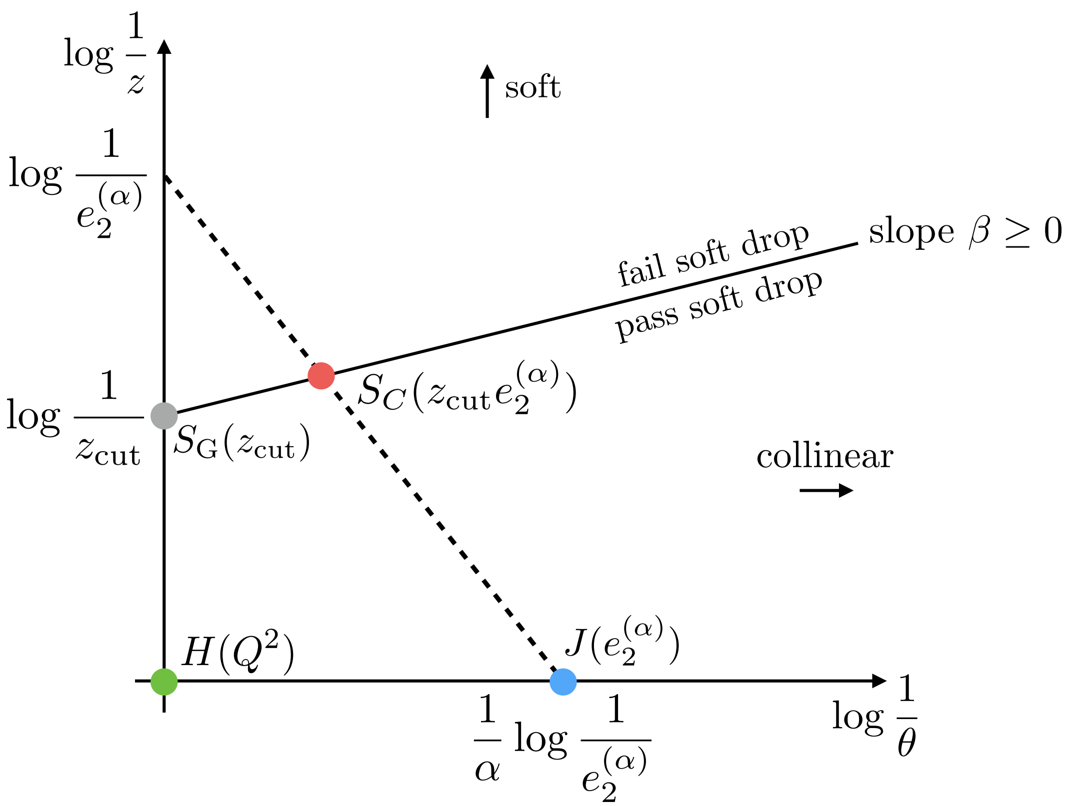


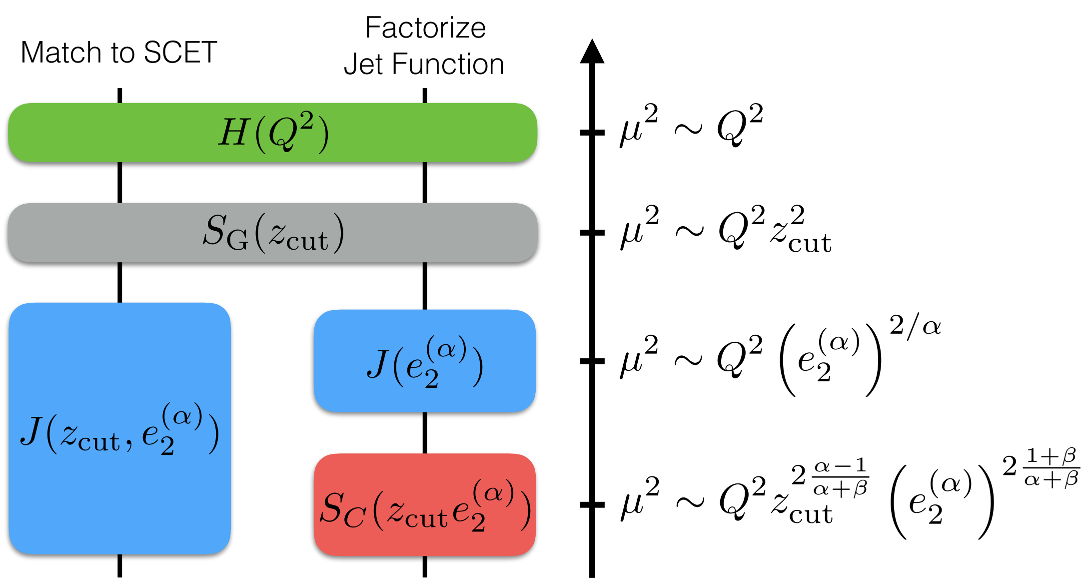
$\log \frac{1}{z}$
soft
$\log \frac{1}{e_2^{(\alpha)}}$
fail soft drop
pass soft drop
slope $\beta \geq 0$
$\log \frac{1}{z_{\text{cut}}}$
$S_C(z_{\text{cut}} e_2^{(\alpha)})$
$S_G(z_{\text{cut}})$
collinear
$H(Q^2)$
$J(e_2^{(\alpha)})$
$\frac{1}{\alpha} \log \frac{1}{e_2^{(\alpha)}}$
$\log \frac{1}{\theta}$



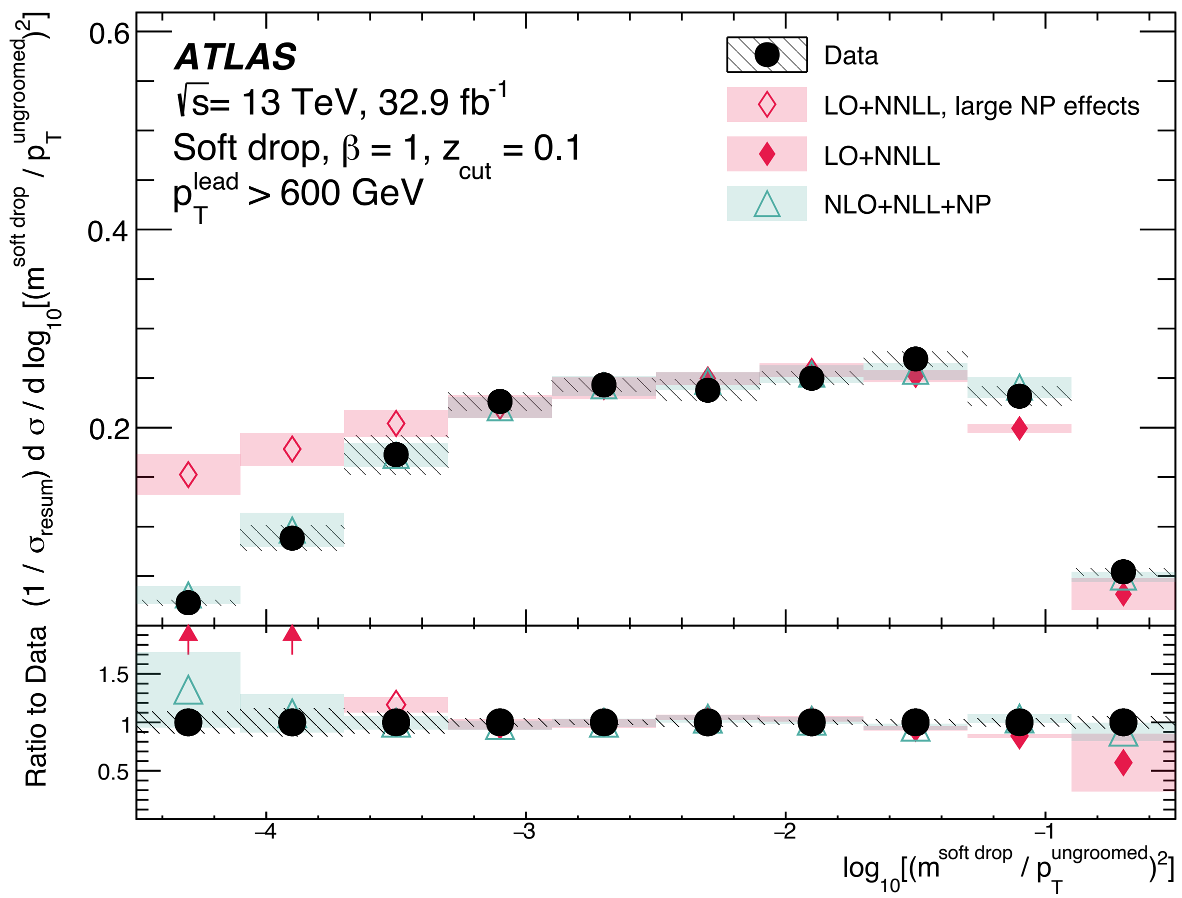
Match to SCET
Factorize Jet Function
$H(Q^2)$
$S_G(z_{\text{cut}})$
$J(z_{\text{cut}}, e_2^{(\alpha)})$
$J(e_2^{(\alpha)})$
$S_C(z_{\text{cut}} e_2^{(\alpha)})$
$\mu^2 \sim Q^2$
$\mu^2 \sim Q^2 z_{\text{cut}}^2$
$\mu^2 \sim Q^2 \left(e_2^{(\alpha)}\right)^{2/\alpha}$
$\mu^2 \sim Q^2 z_{\text{cut}}^{2\frac{\alpha-1}{\alpha+\beta}} \left(e_2^{(\alpha)}\right)^{2\frac{1+\beta}{\alpha+\beta}}$

Jet mass





[ATLAS, PRL 121, 092001 (2018)]



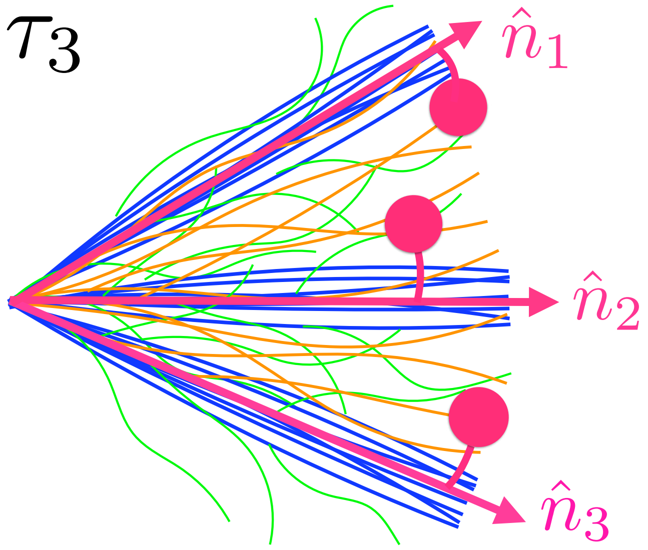
Soft drop

- Enables precise calculations
- Allows tests of QCD in different energy regimes

Jet substructure observables

1. Angularities and energy correlations

N-subjettiness τ_3



[I. Moult et al, JHEP 12, 153 (2016)]

Jet substructure observables

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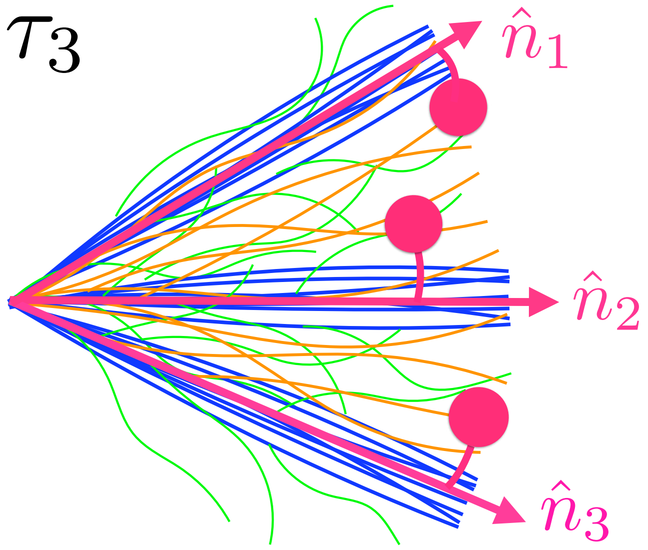
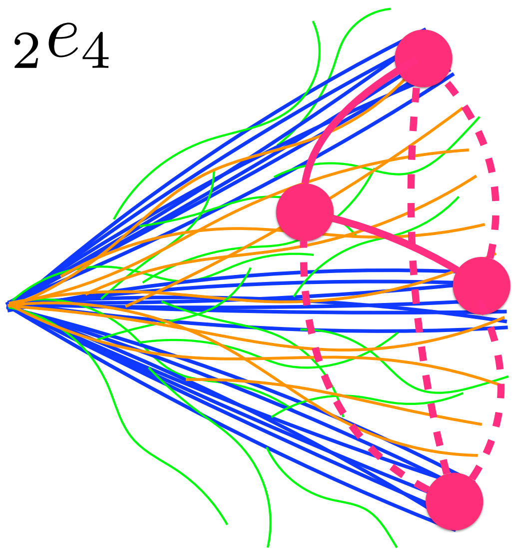
N-subjettiness τ_3



Normalized energy correlation functions $_2e_4$



[I. Moult et al, JHEP 12, 153 (2016)]

Jet substructure observables

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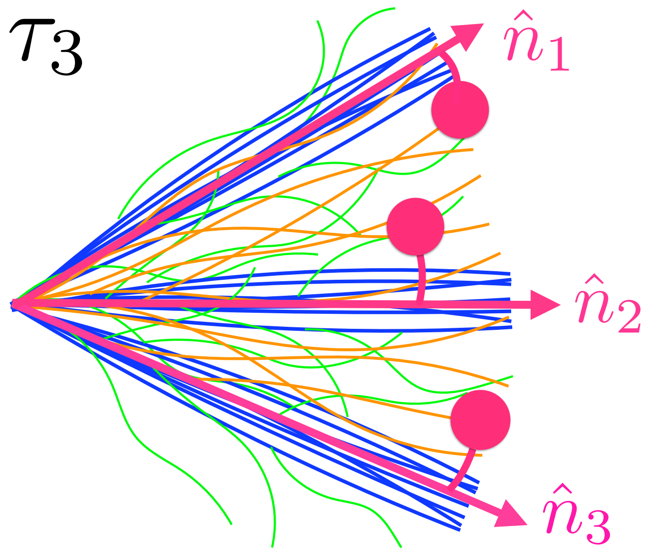
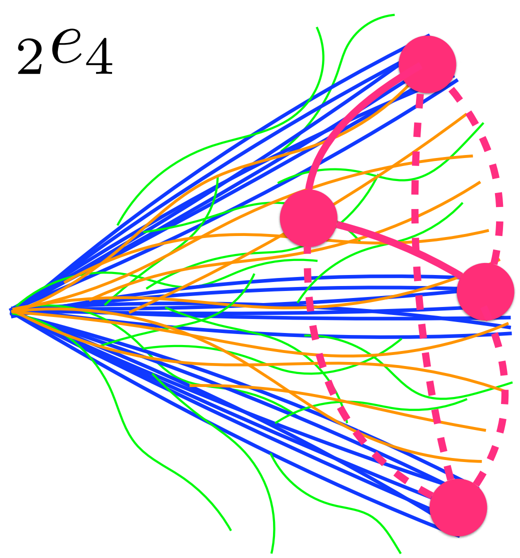
N-subjettiness τ_3



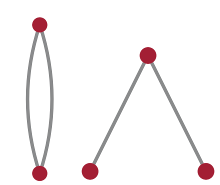
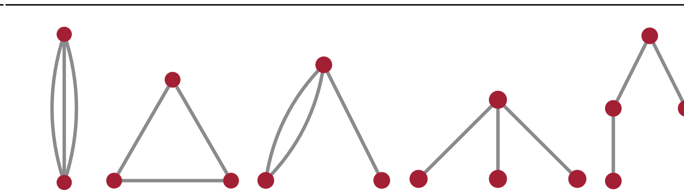
Normalized energy correlation functions $_2e_4$



[I. Moult et al, JHEP 12, 153 (2016)]

Energy Flow Polynomials

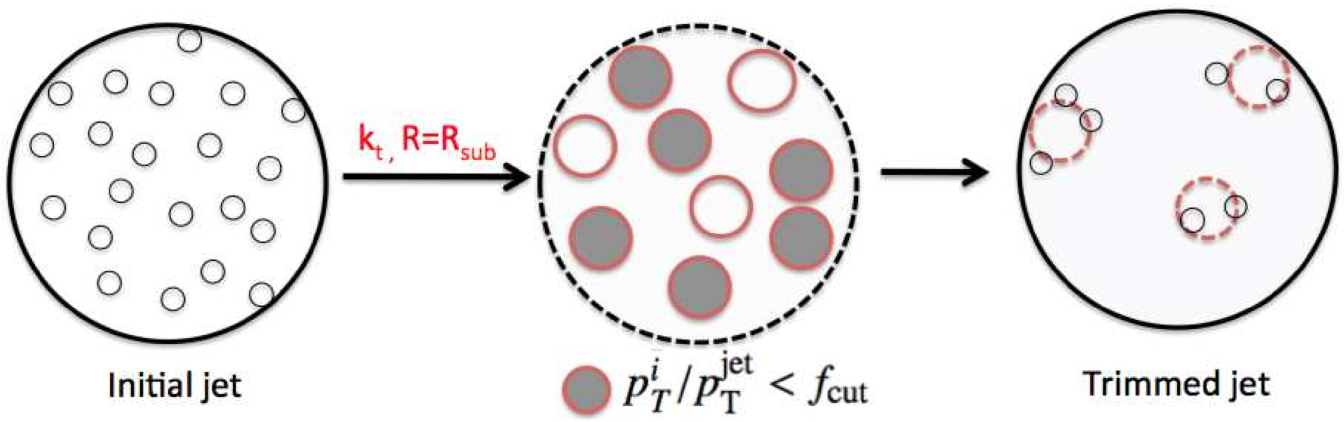
$$\text{EFP}_G = \sum_{i_1=1}^{M} \cdots \sum_{i_N=1}^{M} z_{i_1} \cdots z_{i_N} \prod_{(k,\ell)\in G} \theta_{i_k i_\ell}$$

Degree	Connected Multigraphs
$d=0$	
$d=1$	
$d=2$	
$d=3$	

[P.T. Komiske et al, JHEP 12, 153 (2016)]

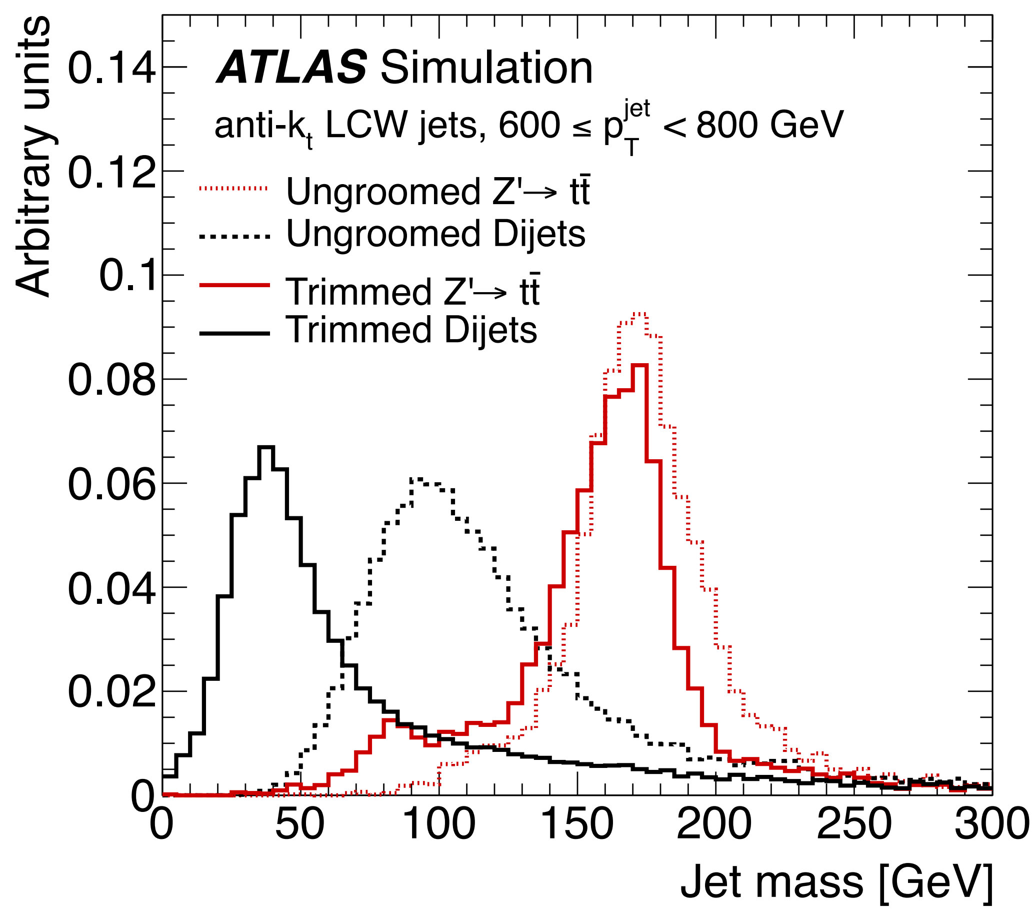
Jet substructure observables

2. Grooming and N-prong taggers



Trimming
(standard in ATLAS)

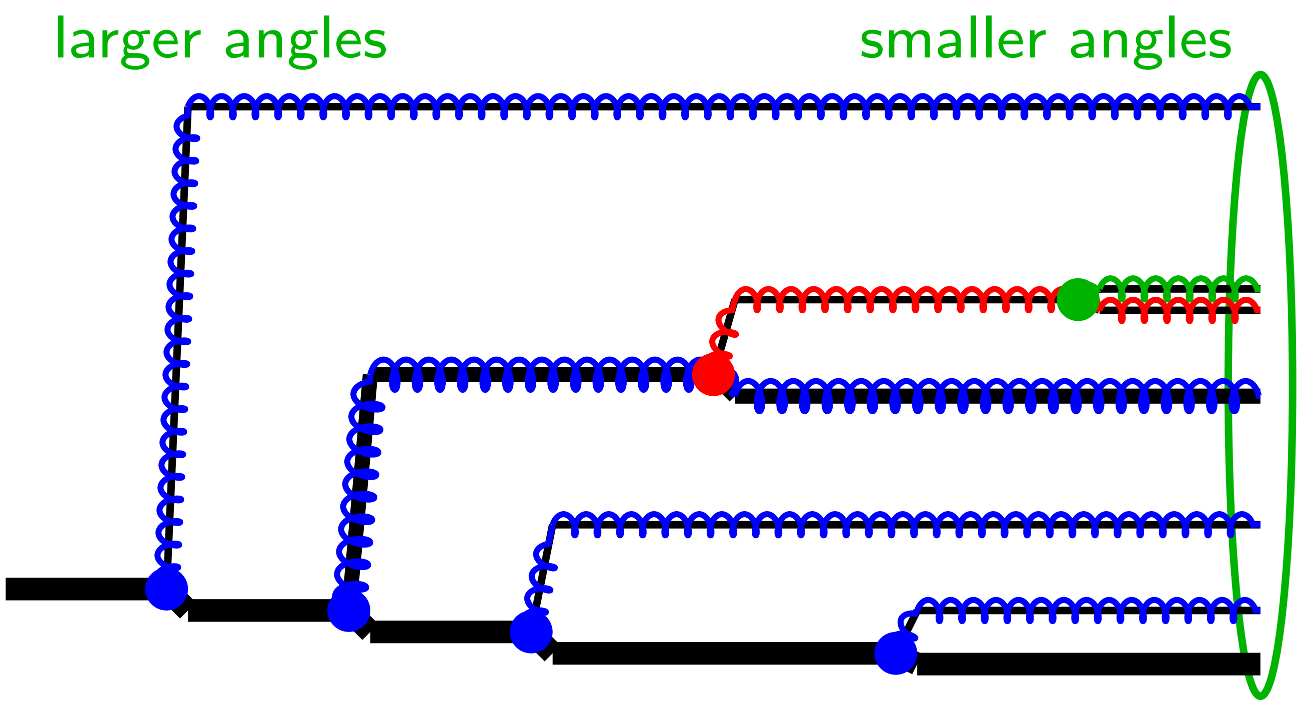
also studied:
Filtering, Pruning, soft drop…



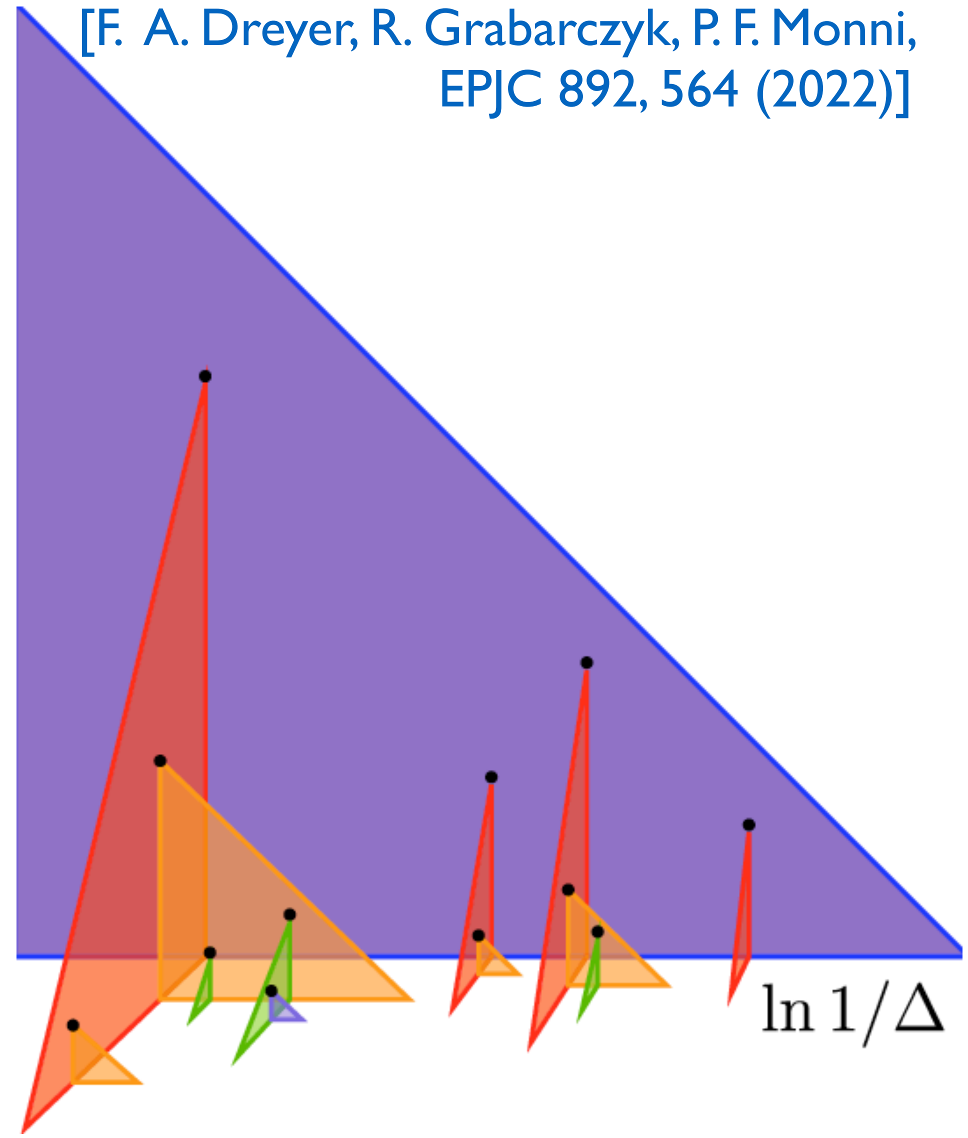
[ATLAS, JHEP 09, 076 (2013)]

Lund jet plane

[G. Soyez, 2022]



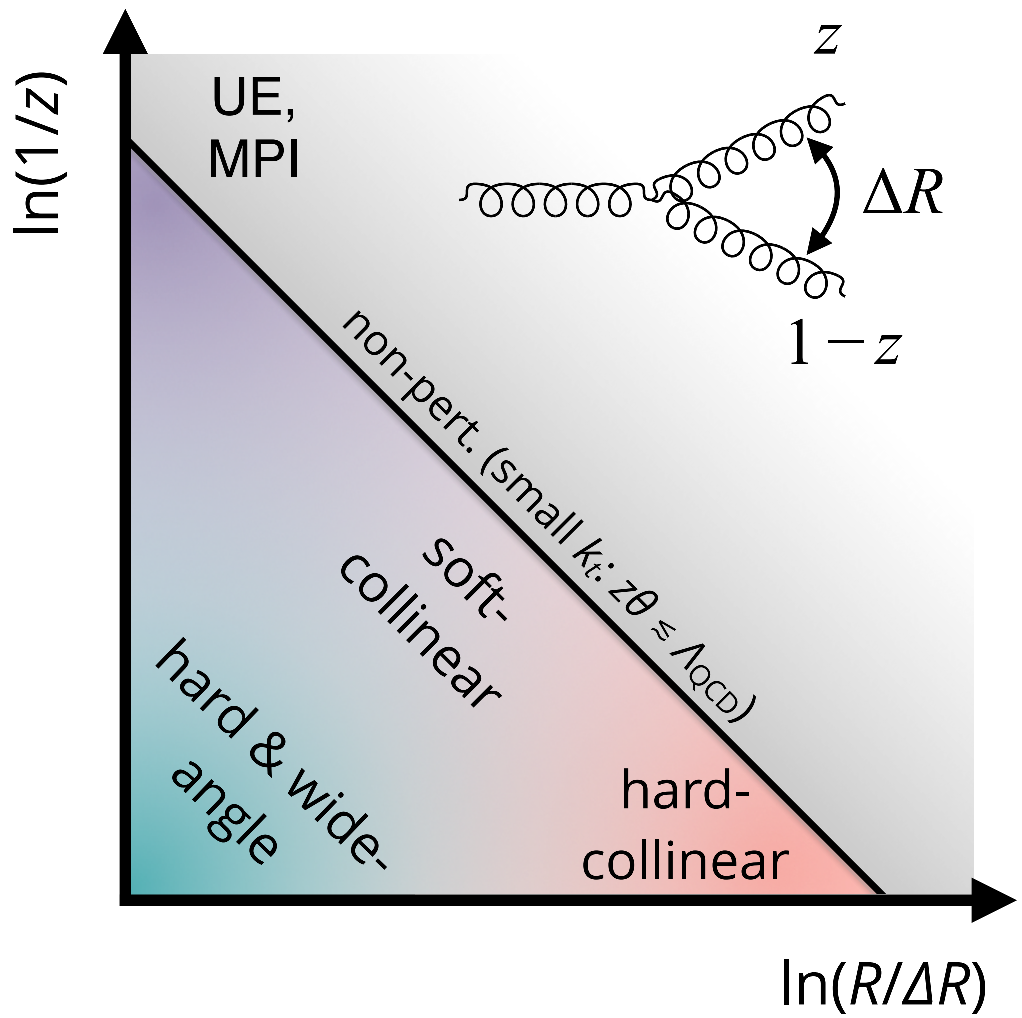
[F. A. Dreyer, R. Grabarczyk, P. F. Monni, EPJC 892, 564 (2022)]



- Decluster a jet to access shower history
- Separate emissions in angular scale and hardness

[F. A. Dreyer, G. P. Salam, G. Soyez, JHEP 12, 064 (2018)]

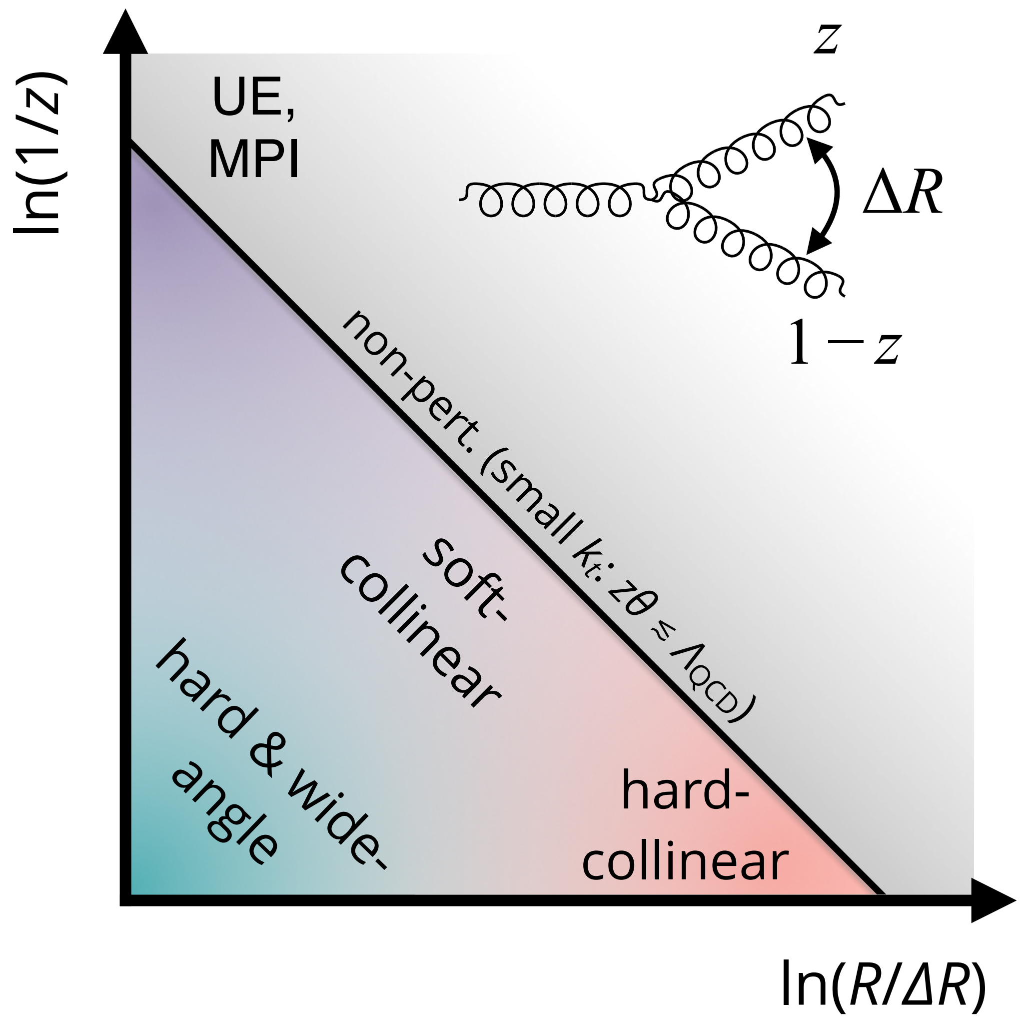
Lund jet plane

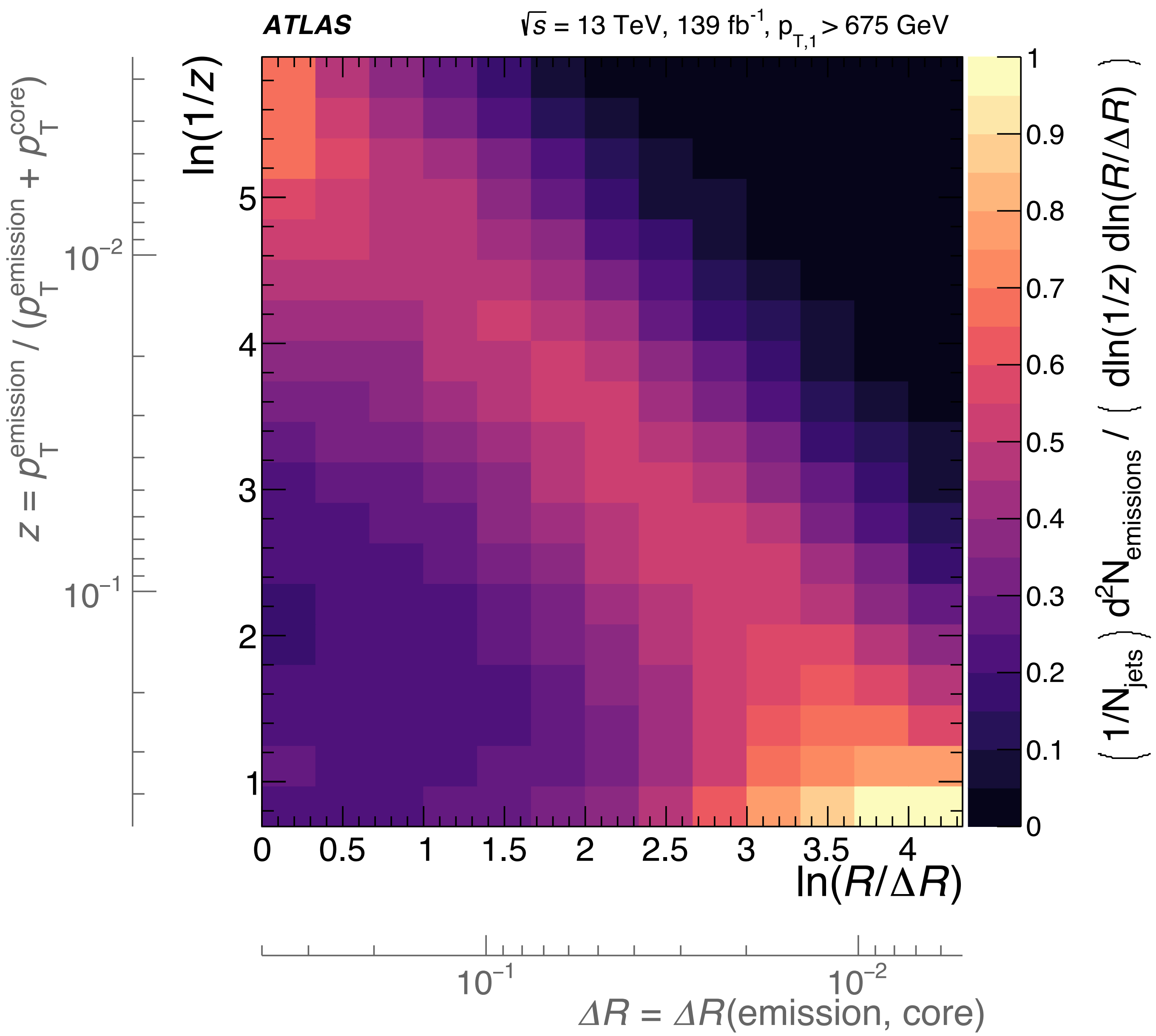


- Access splitting function, jet fragmentation and non-pert. radiation

[ATLAS, PRL 124, 22202 (2020)]

Lund jet plane





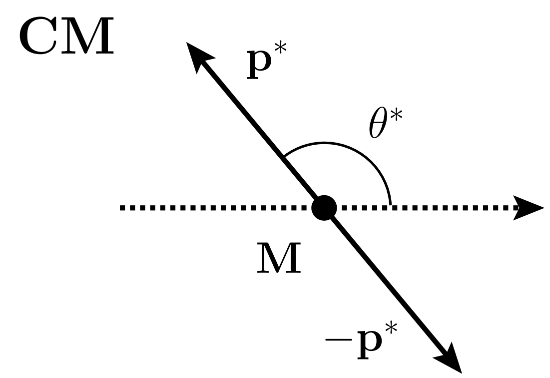
- Access splitting function, jet fragmentation and non-pert. radiation
- Soft-wide angle and hard-collinear radiation dominant

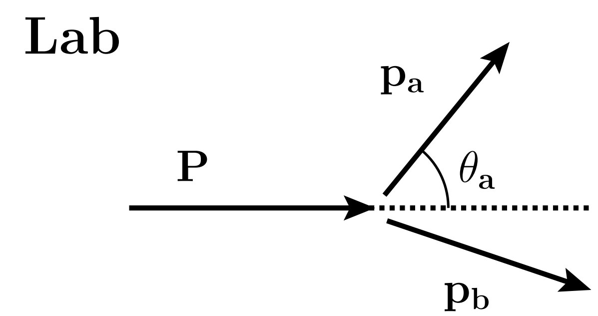
[ATLAS, PRL 124, 22202 (2020)]

Jet tagging with substructure

Particle Decays

W and Z bosons

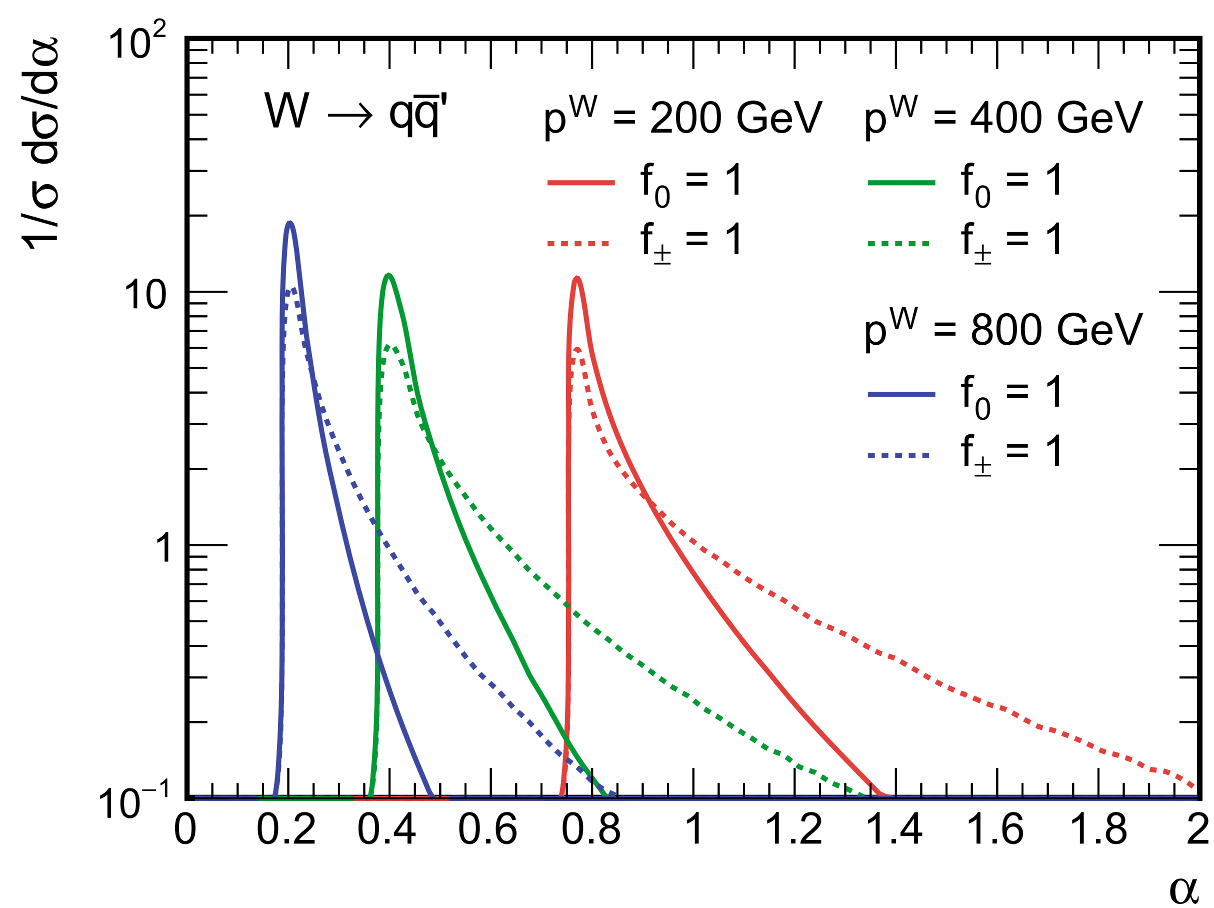




$B_{W\to had} = 67.5\%$

$B_{Z\to had} = 69.2\%$

$$\frac{1}{\sigma}\frac{d\sigma}{d|\cos\theta^*|} = f_\pm \frac{3}{4}\left(1+|\cos\theta^*|^2\right) + f_0 \frac{3}{2}|\sin\theta^*|^2$$



$$\alpha_{\min} \approx \frac{2M}{P}$$

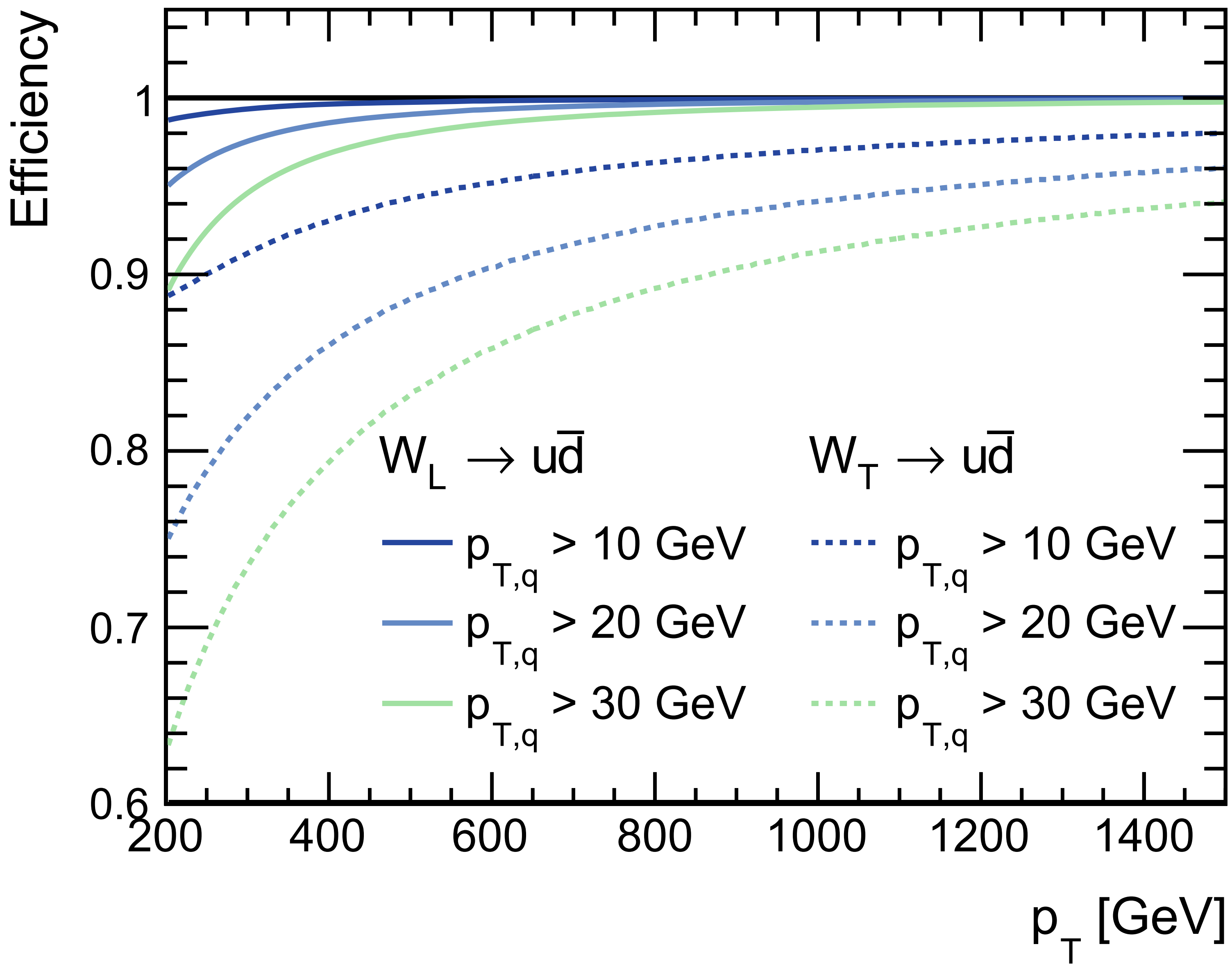
and consequently

$$\Delta R \approx \frac{2M}{P_T}$$

(holds for $P_T \gg M$)

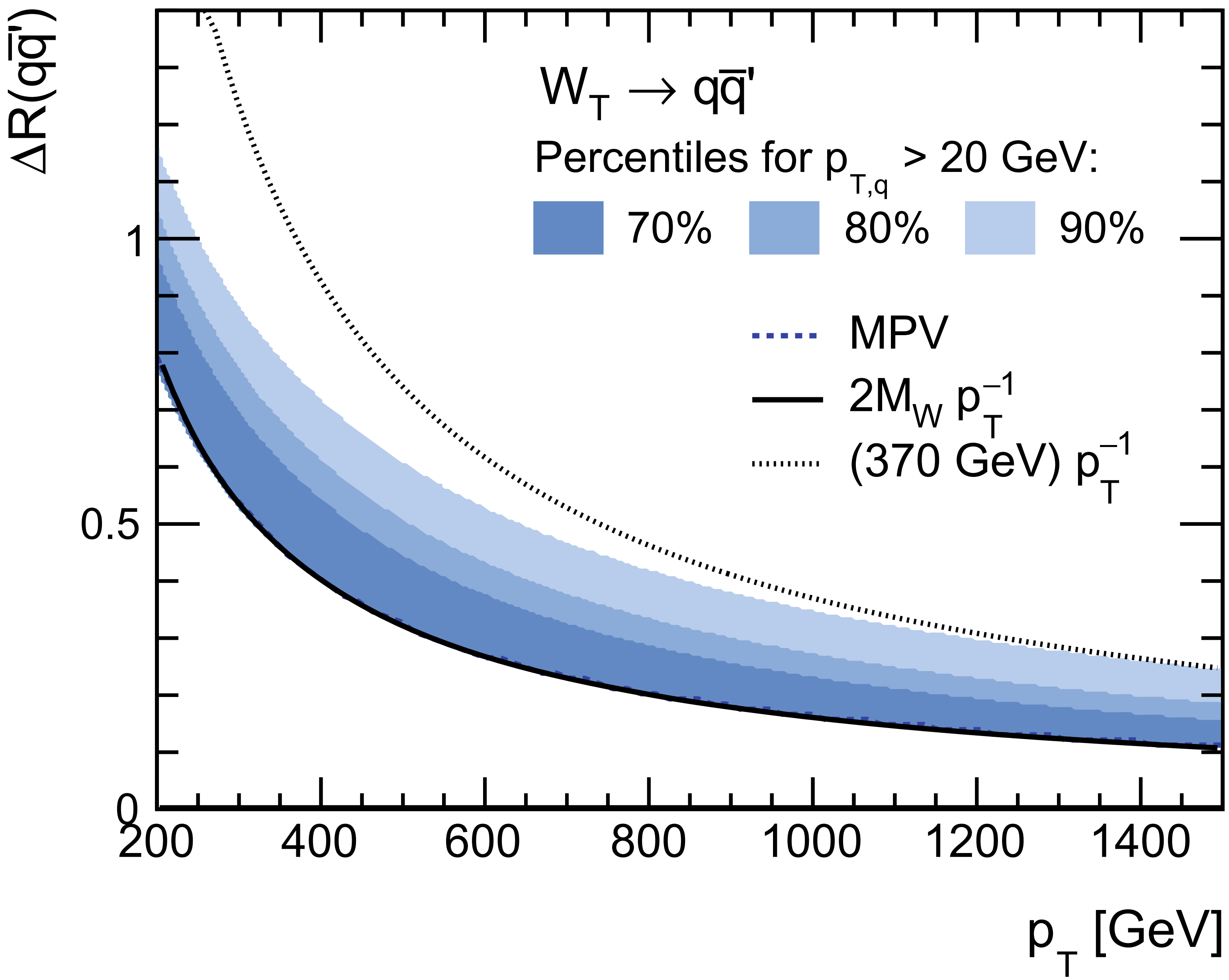
[RK, STMP 284, 2021]

Quark (subjet) p_T thresholds



[RK, STMP 284, 2021]

Decay distance



- Similar picture for top quarks

[RK, STMP 284, 2021]

Heavy Object Tagger with Variable R

One-pass clustering with integrated subjet finding

- jet distance measures (with variable R)

$$d_{ij} = \min[p_{T,i}^{2n}, p_{T,j}^{2n}]\Delta R_{ij}^2$$

$$d_{iB} = p_{T,i}^{2n} R_{\text{eff}}^2 \qquad R_{\text{eff}} = \frac{\rho}{p_T}$$

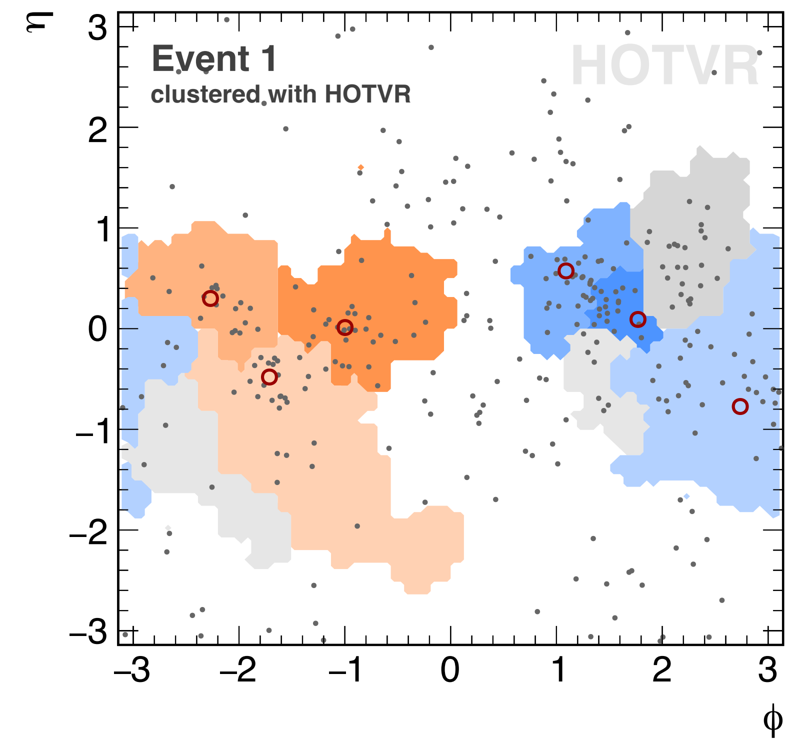
- clustering veto at each step

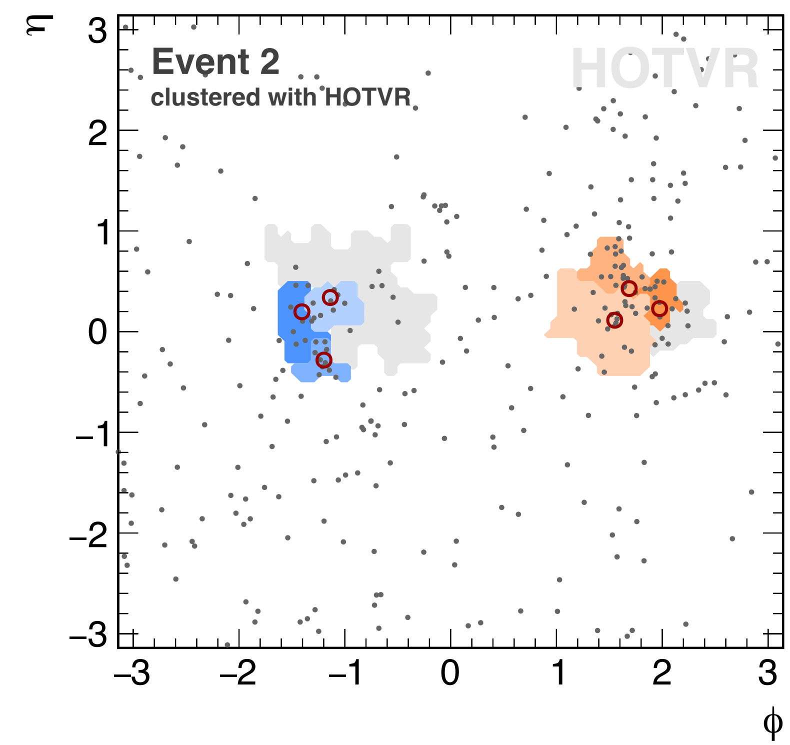
$$m_{ij} < \mu$$

$$\theta \cdot m_{ij} > \max[m_i, m_j]$$

- store objects i and j as subjets if

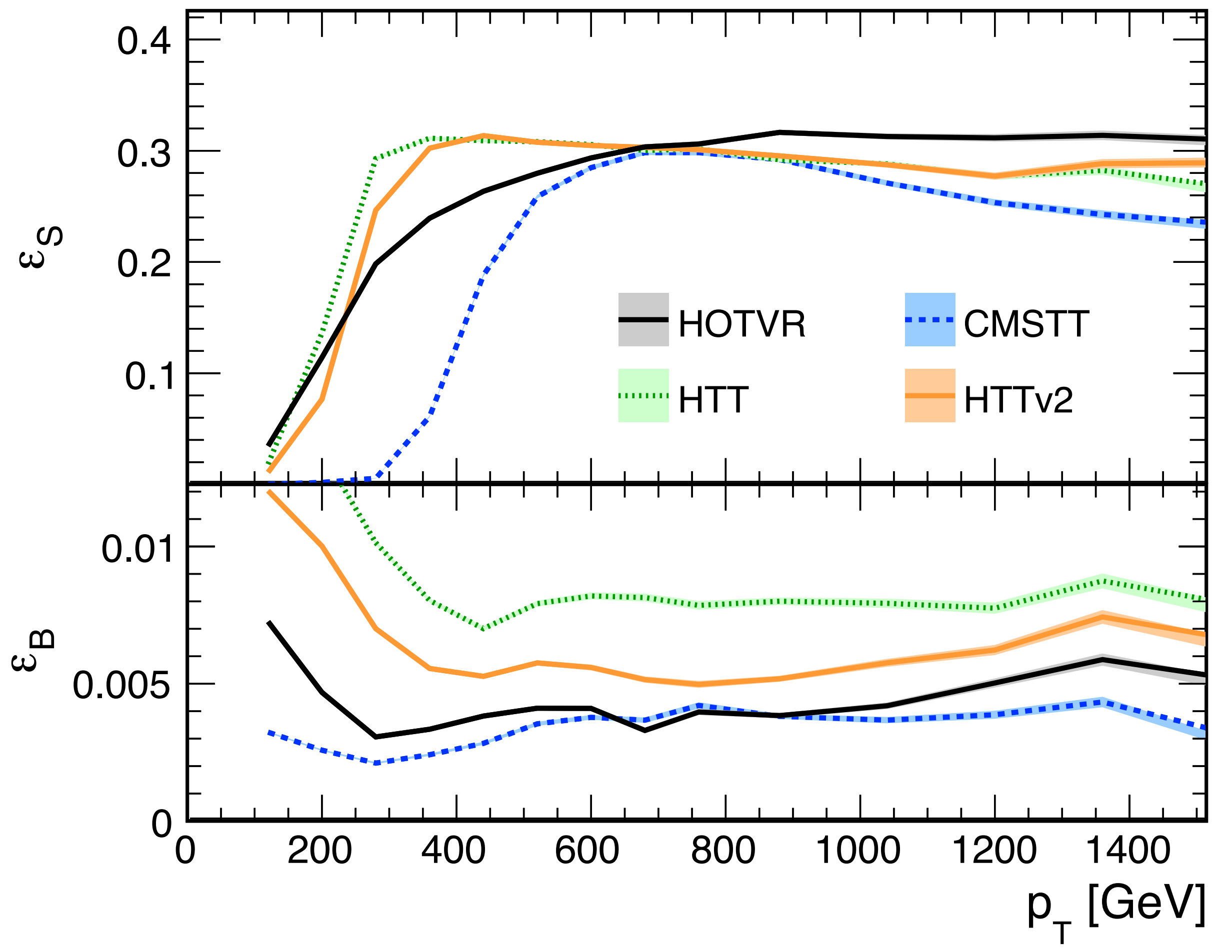
$$p_{T,i}, p_{T,j} > p_{T,\text{sub}}$$





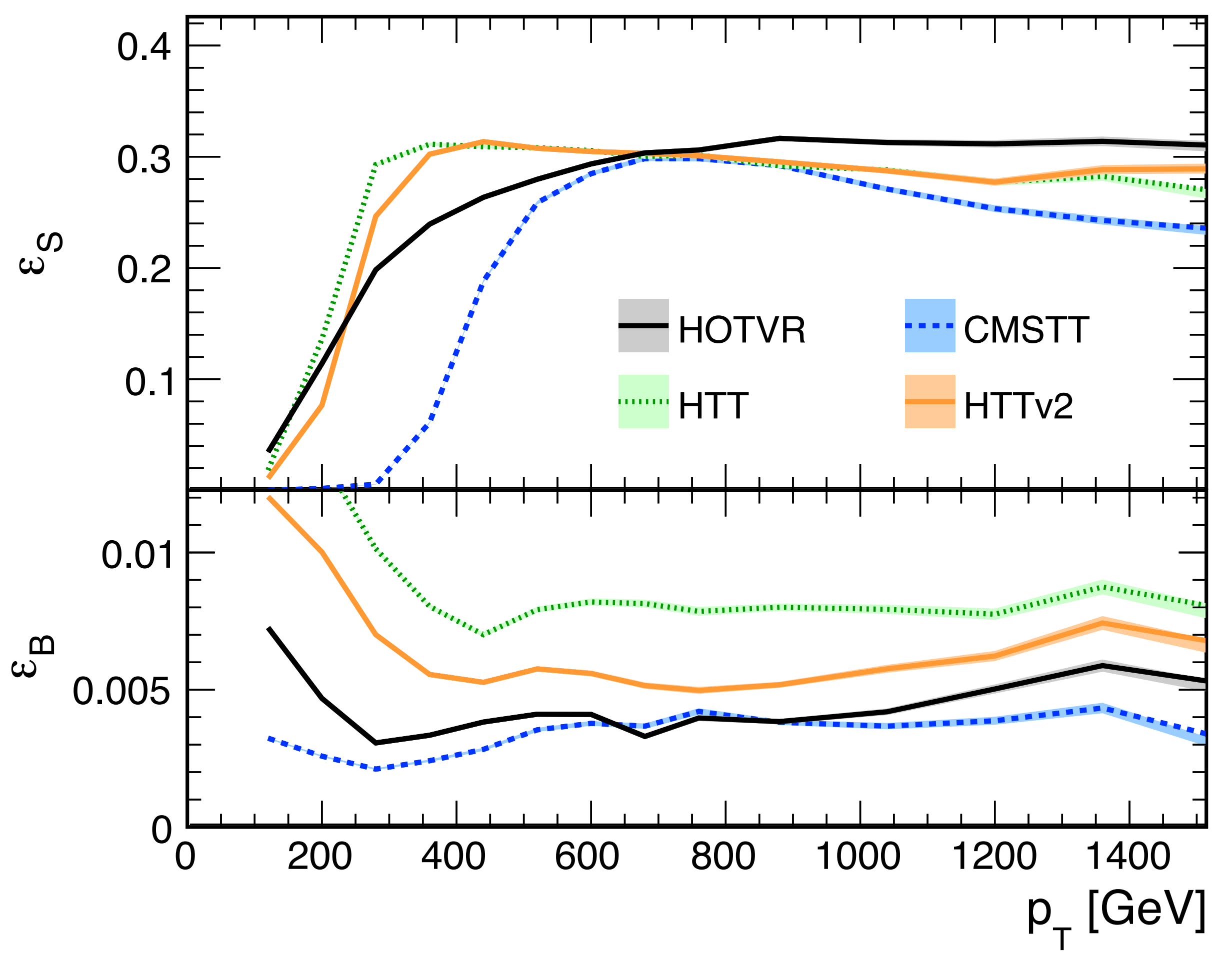
[T. Lapsien et al, EPJC 76, 600 (2016)]

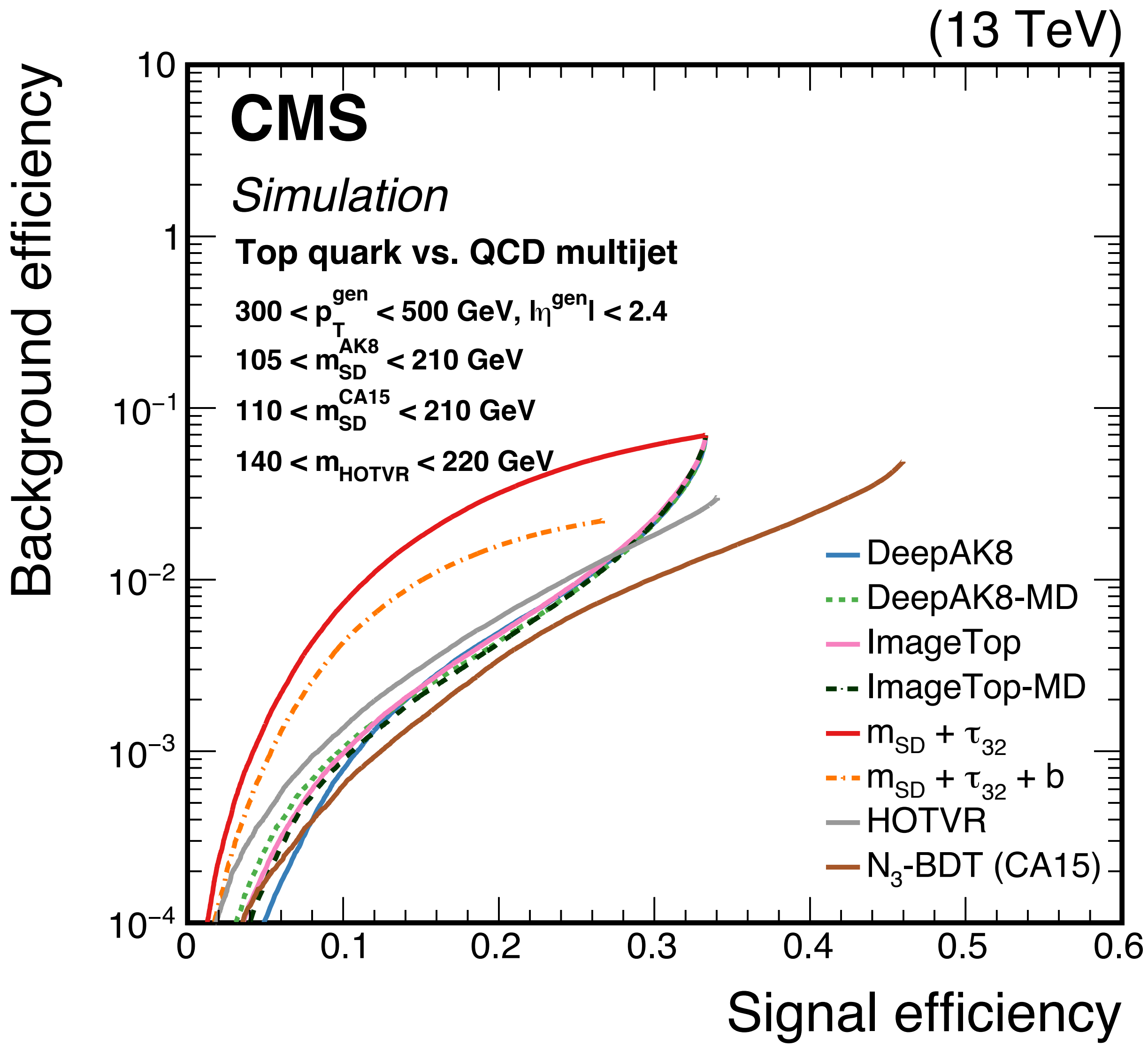
Top Quark Tagging



[RK, STMP 284, 2021]

Top Quark Tagging

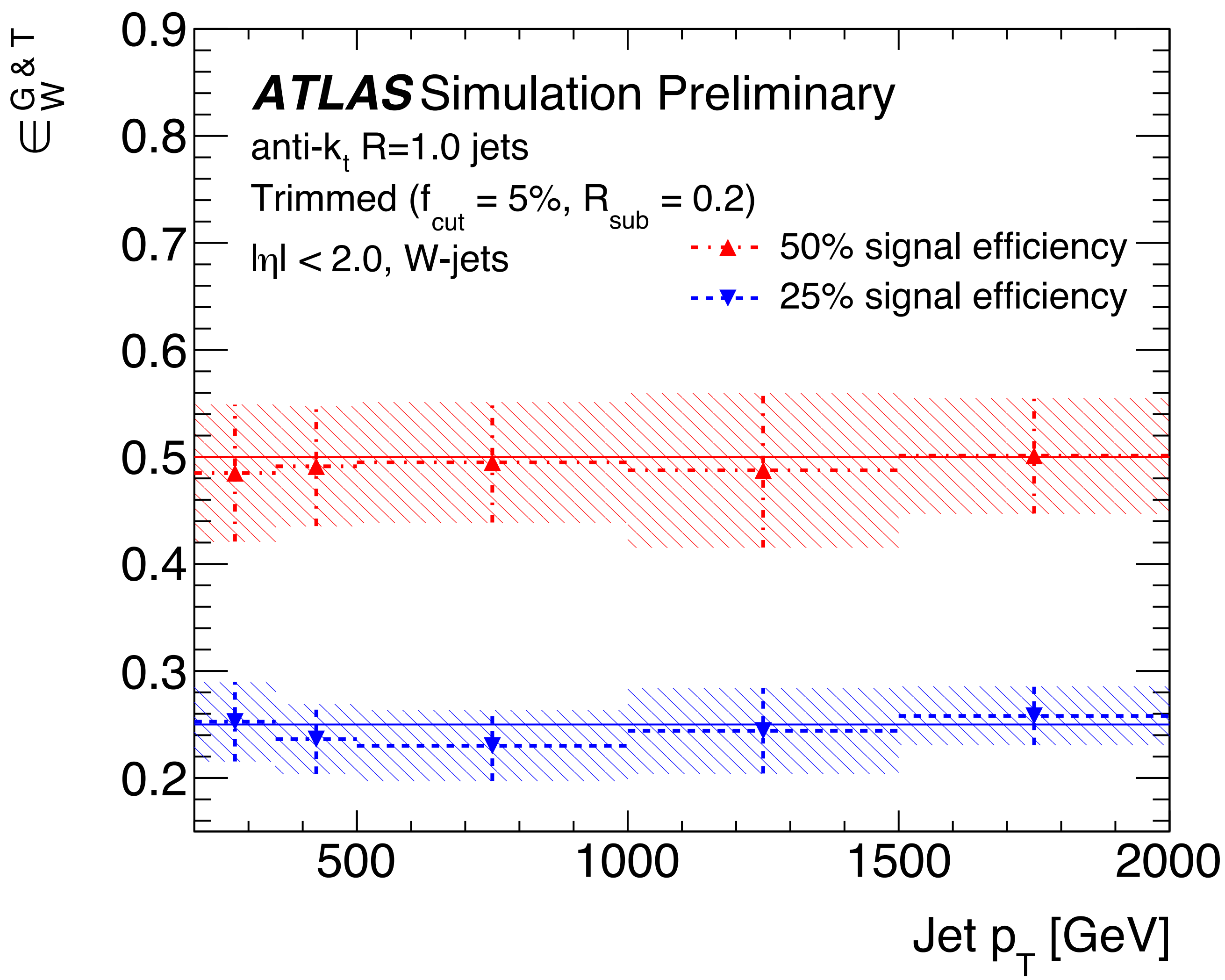


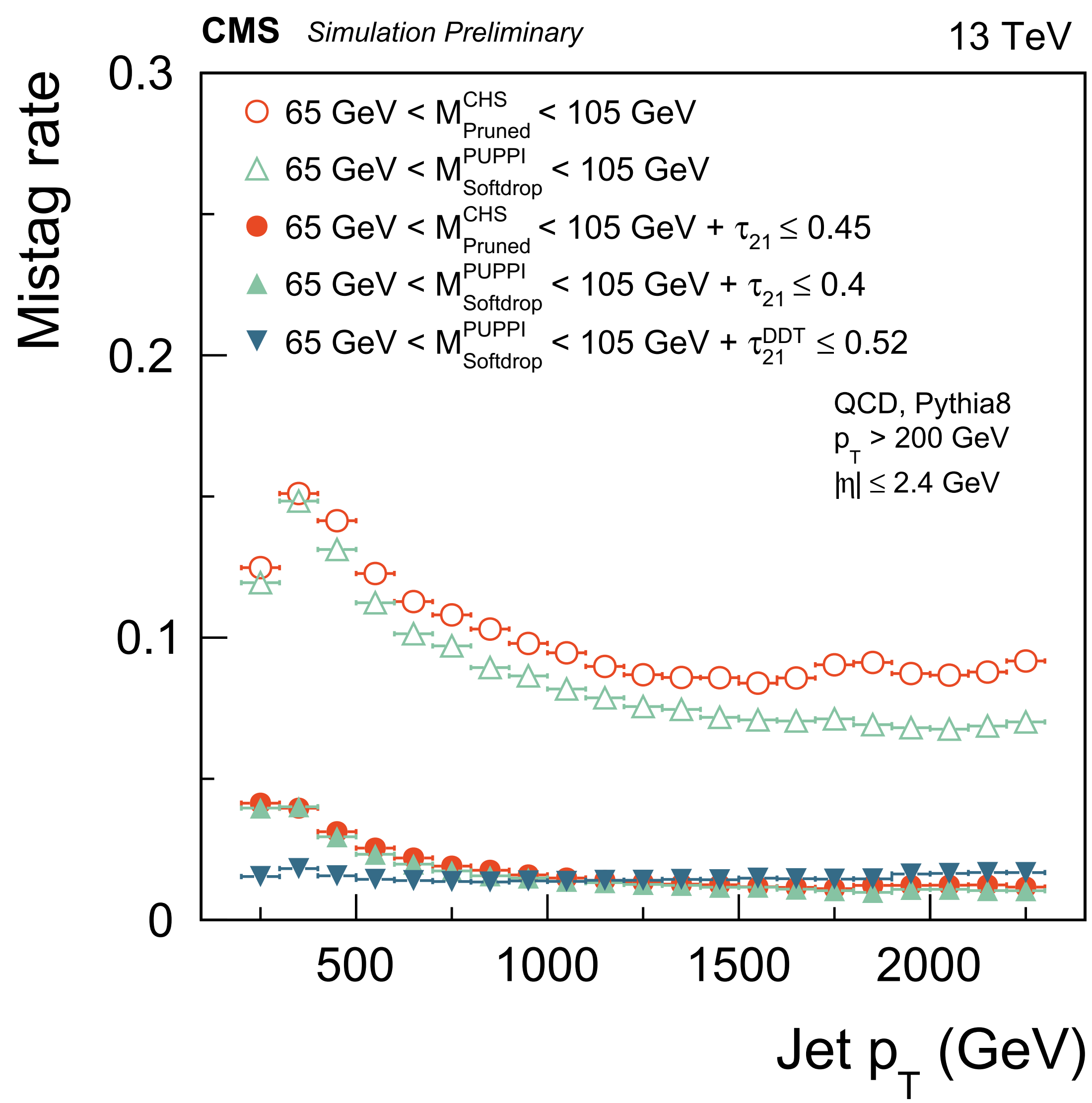


[RK, STMP 284, 2021]

[CMS, JINST 15, P06005 (2020)]

W/Z Tagging





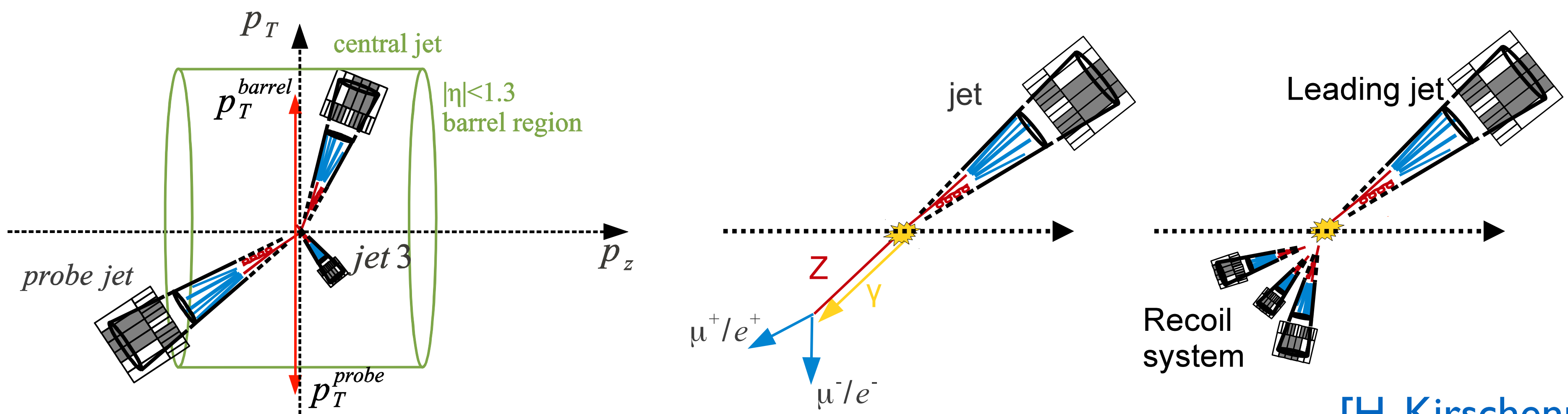
- Constant signal efficiency by p_T-dependent selection
- Constant background efficiency with DDT technique

[ATL-PHYS-PUB-2015-033] [CMS-PAS-JME-16-003]

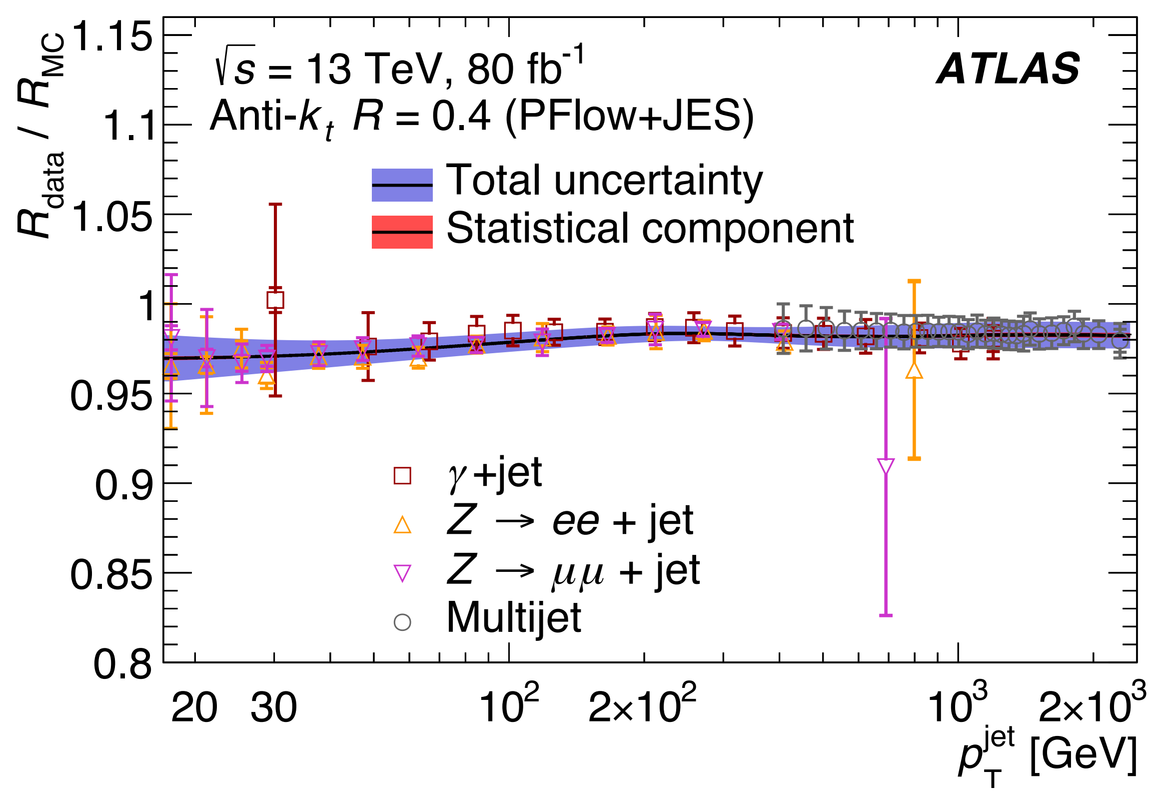
Calibration and Commissioning

Jet calibration

- Local calorimeter calibration based on test beam data and simulation
- Pileup corrections based on jet area and average energy density

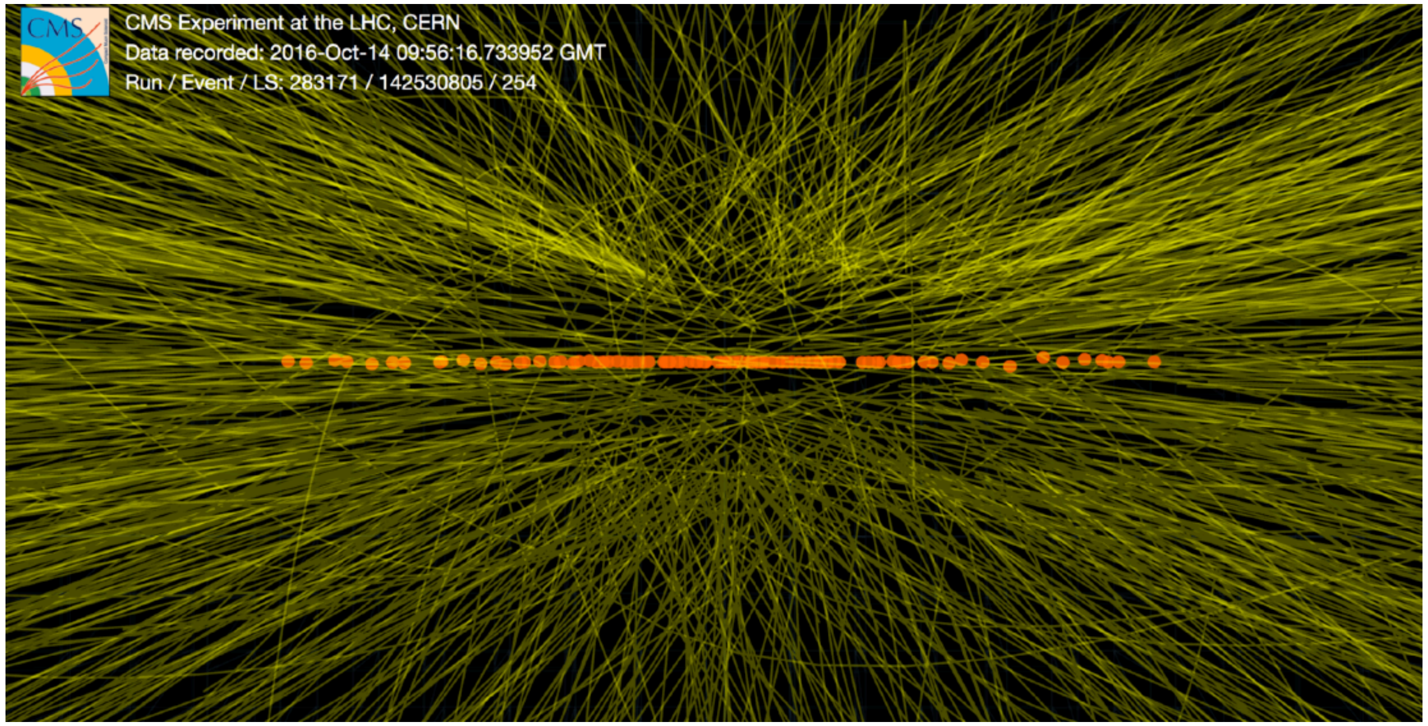


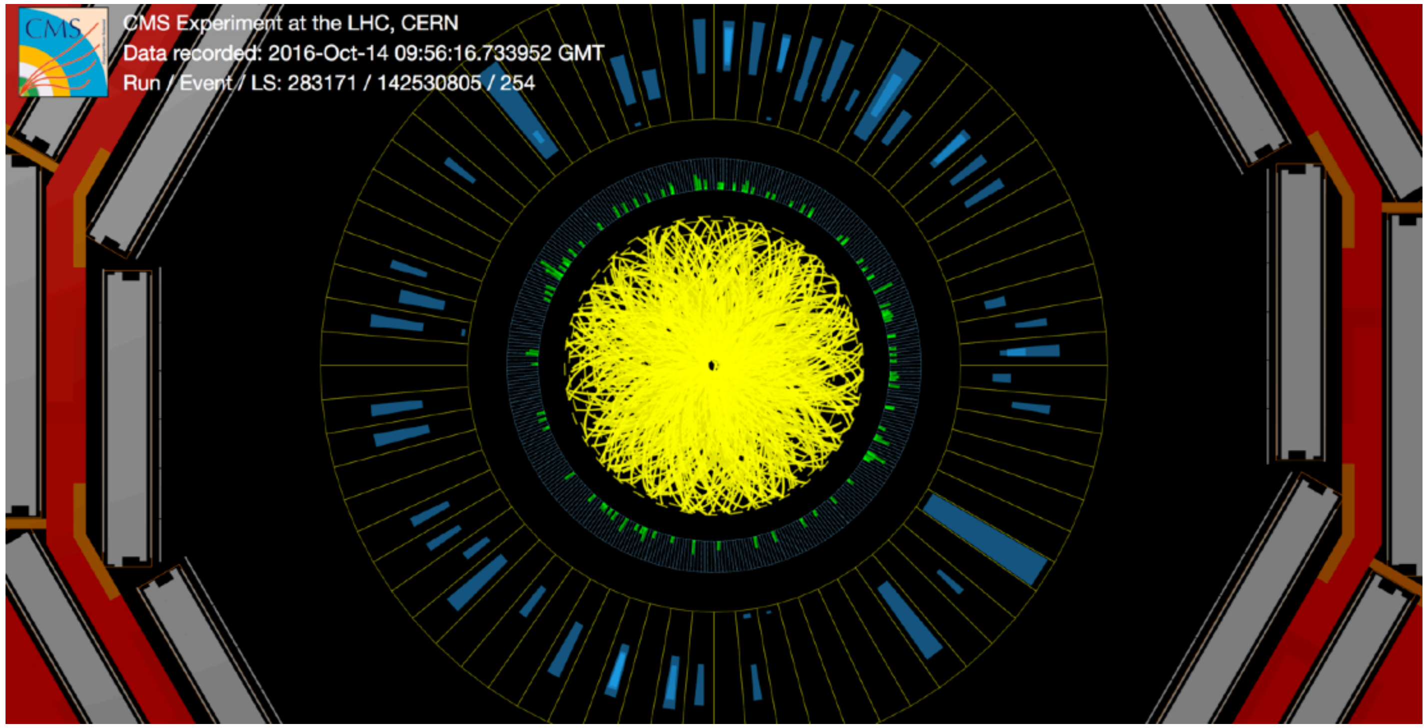
[H. Kirschenmann, M. Schröder]



[ATLAS, EPJC 81, 689 (2021)]

Pileup mitigation

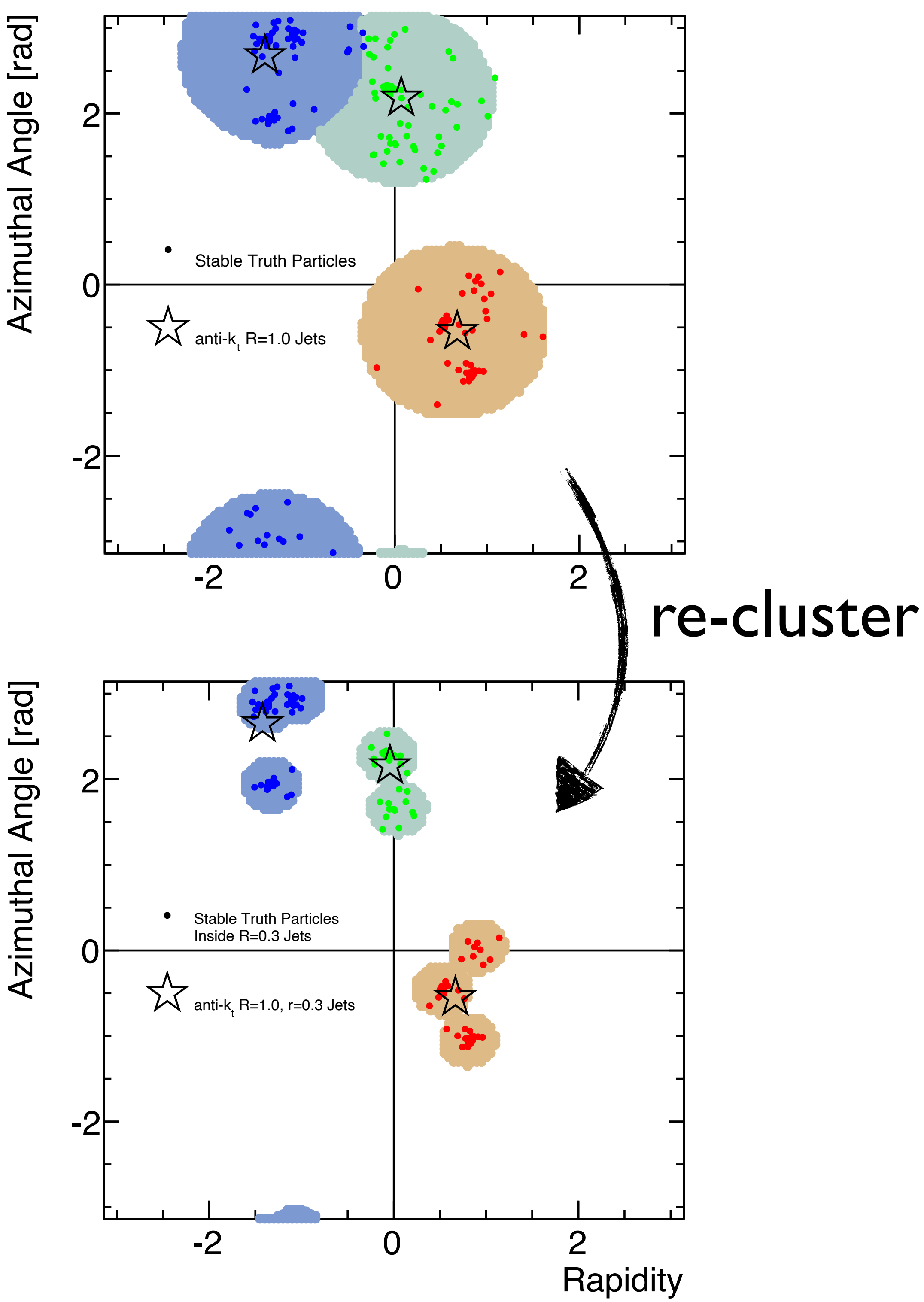




13 TeV, 2016
high-PU fill

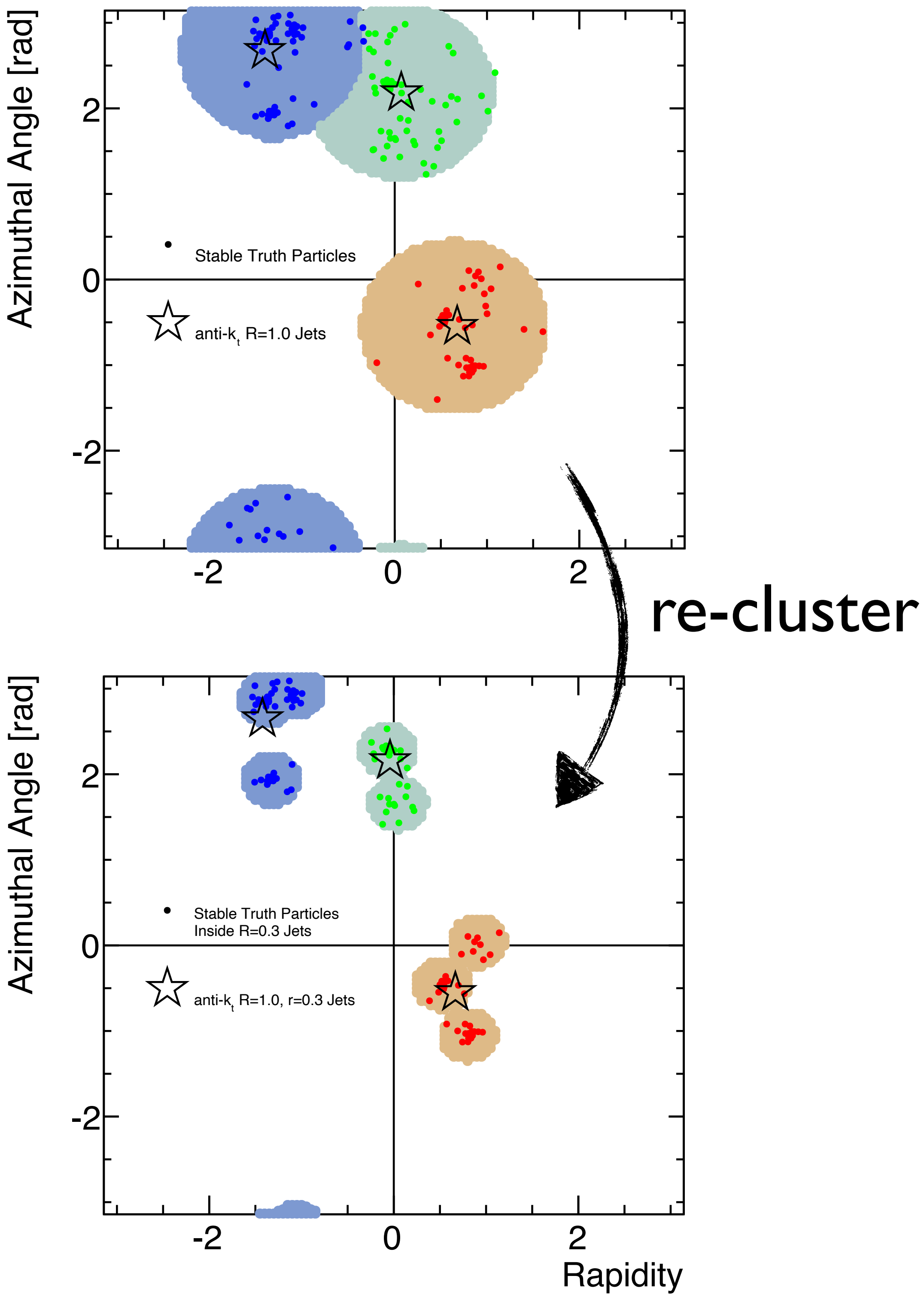
Image credit: CERN

Pileup mitigation

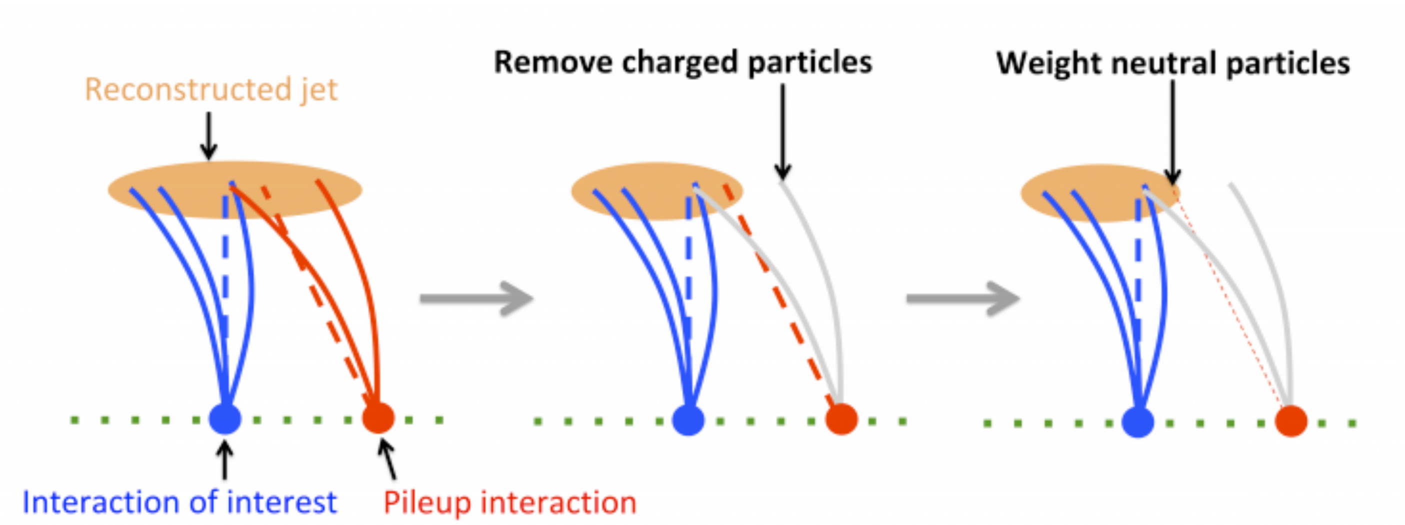


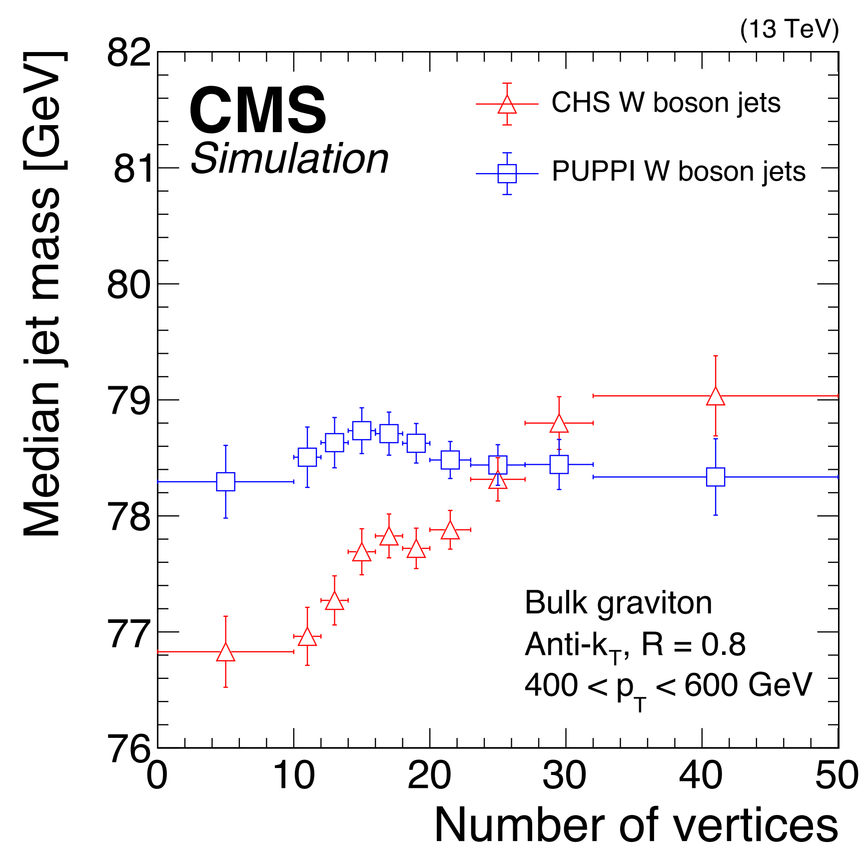
[B. Nachmann, JHEP 02, 075 (2015)]

Pileup mitigation



Pileup-per-particle identification (PUPPI)



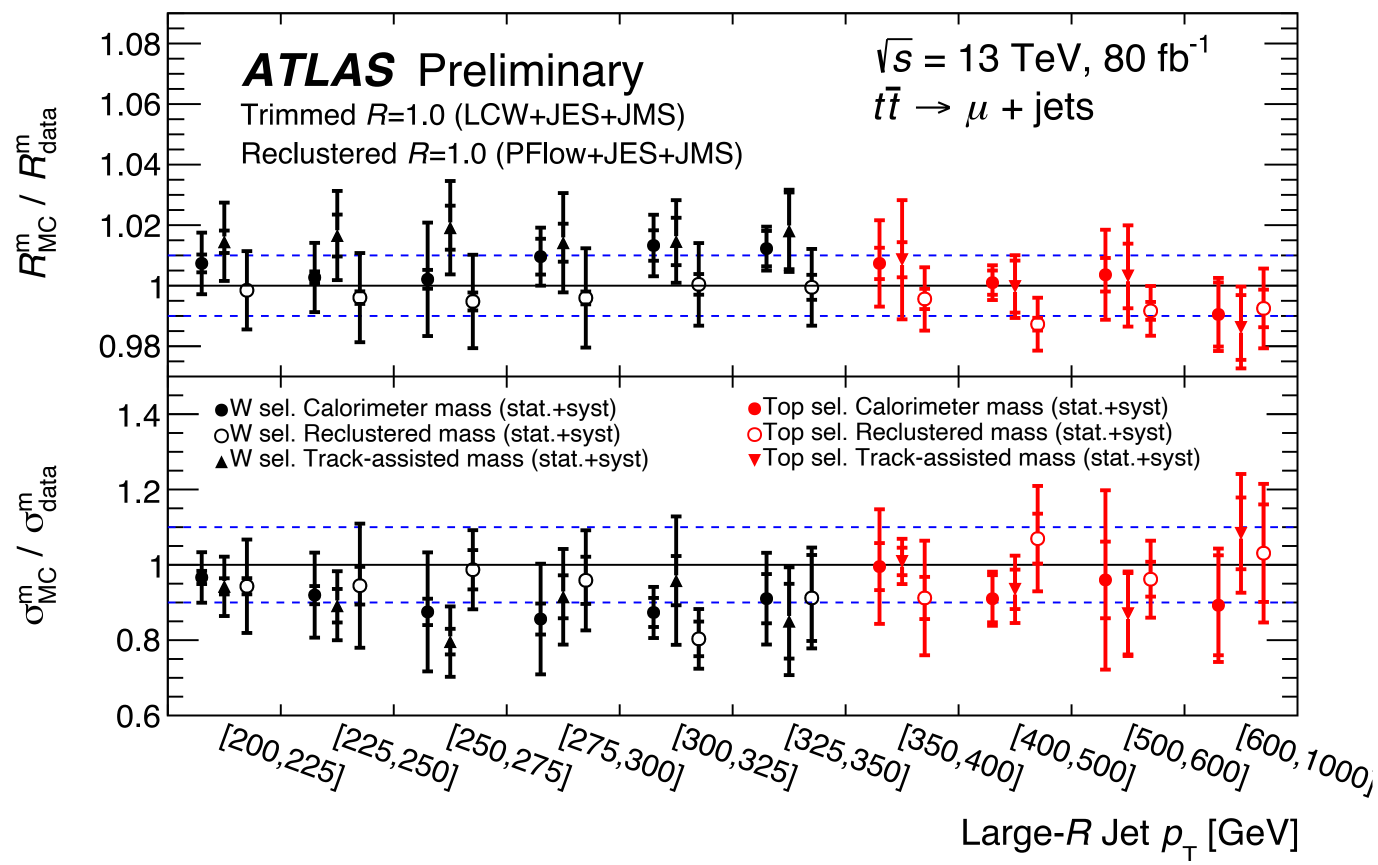


[B. Nachmann, JHEP 02, 075 (2015)]

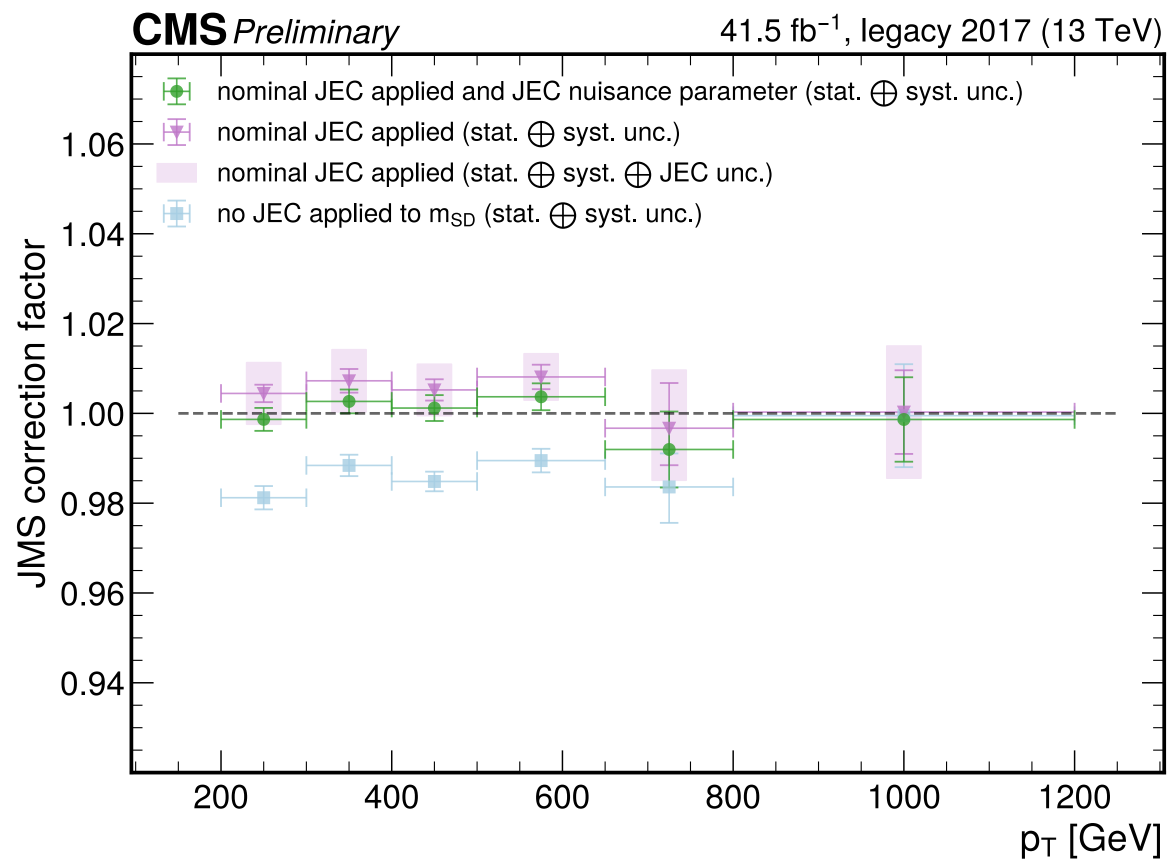
[CMS, JINST 15, P09018 (2020)]

Jet mass calibration

[ATLAS-CONF-2020-022]



[CMS, DP-2023/044]

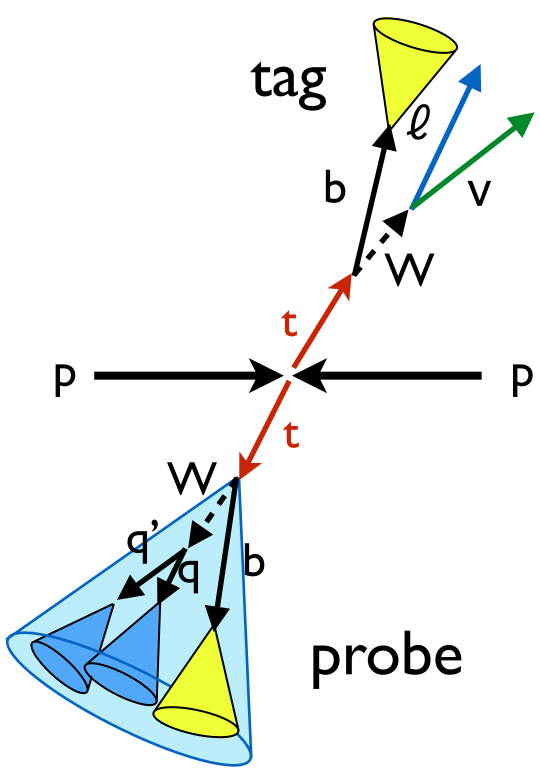


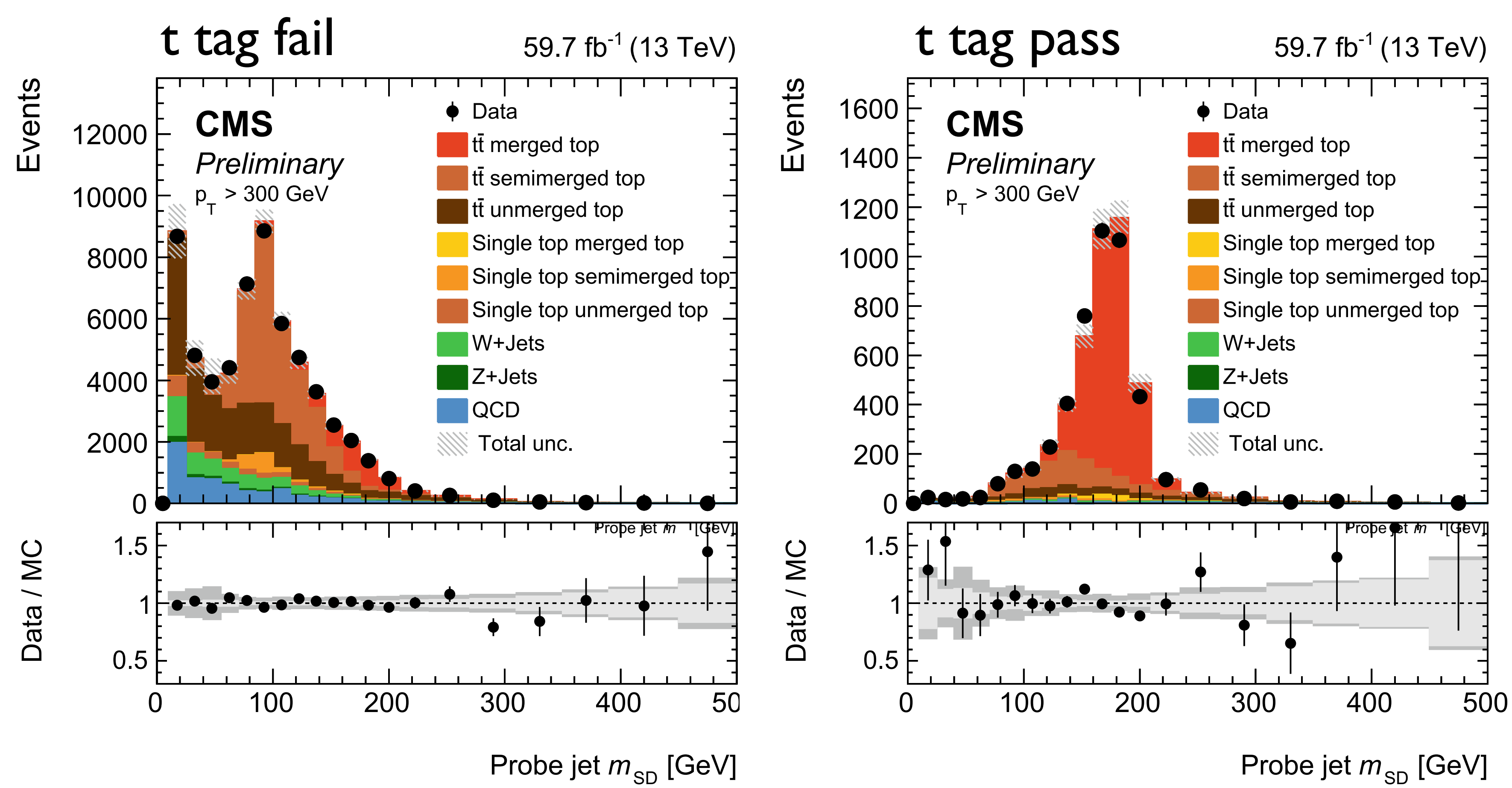
- ATLAS: Forward-folding approach for absolute scale and resolution
- CMS: Template fit to W peak in tt and W+jets
- Uncertainties of 1-2% (scale) and 10-20% (resolution) achieved

Tagging Efficiencies

Tag-and-probe measurements

- $t\bar{t}$ production for W and t tagging



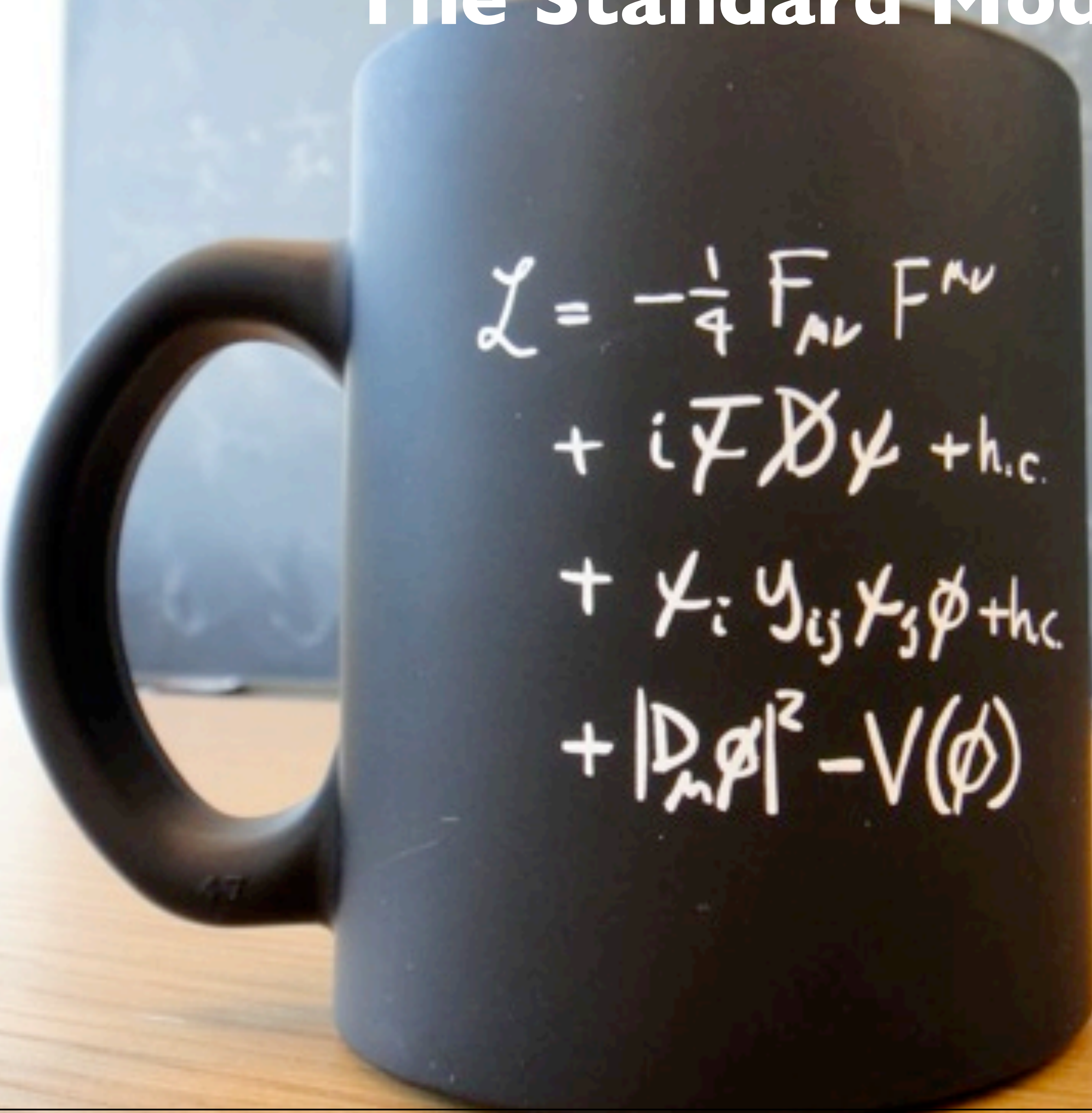


- Extrapolations to Z and H from simulation

[CMS, DP-2020/025]

Standard model measurements

The Standard Model



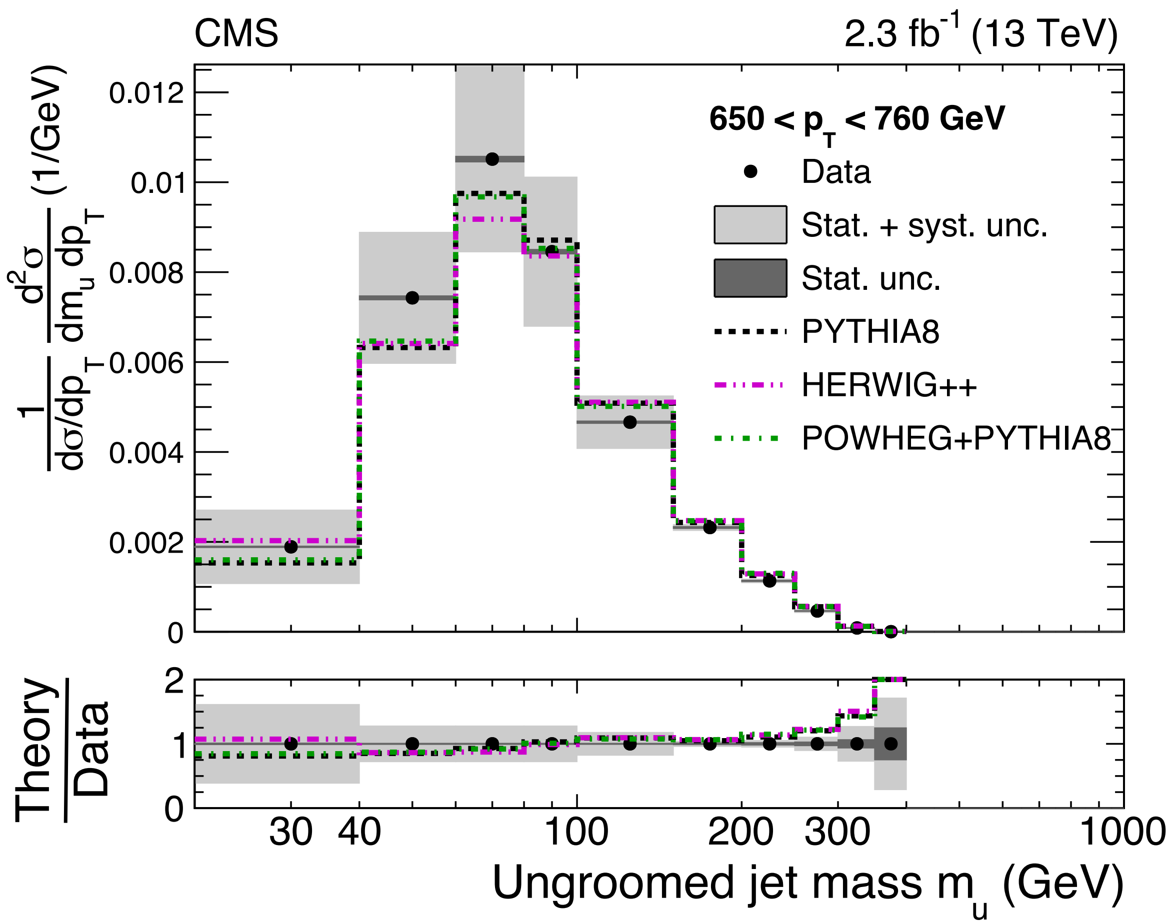
c (SLAC, Brookhaven ’74)
τ (SLAC ’75)
b (Fermilab ’77)
g (DESY, ’78-79)
W/Z (CERN ’83)
t (Fermilab ’95)

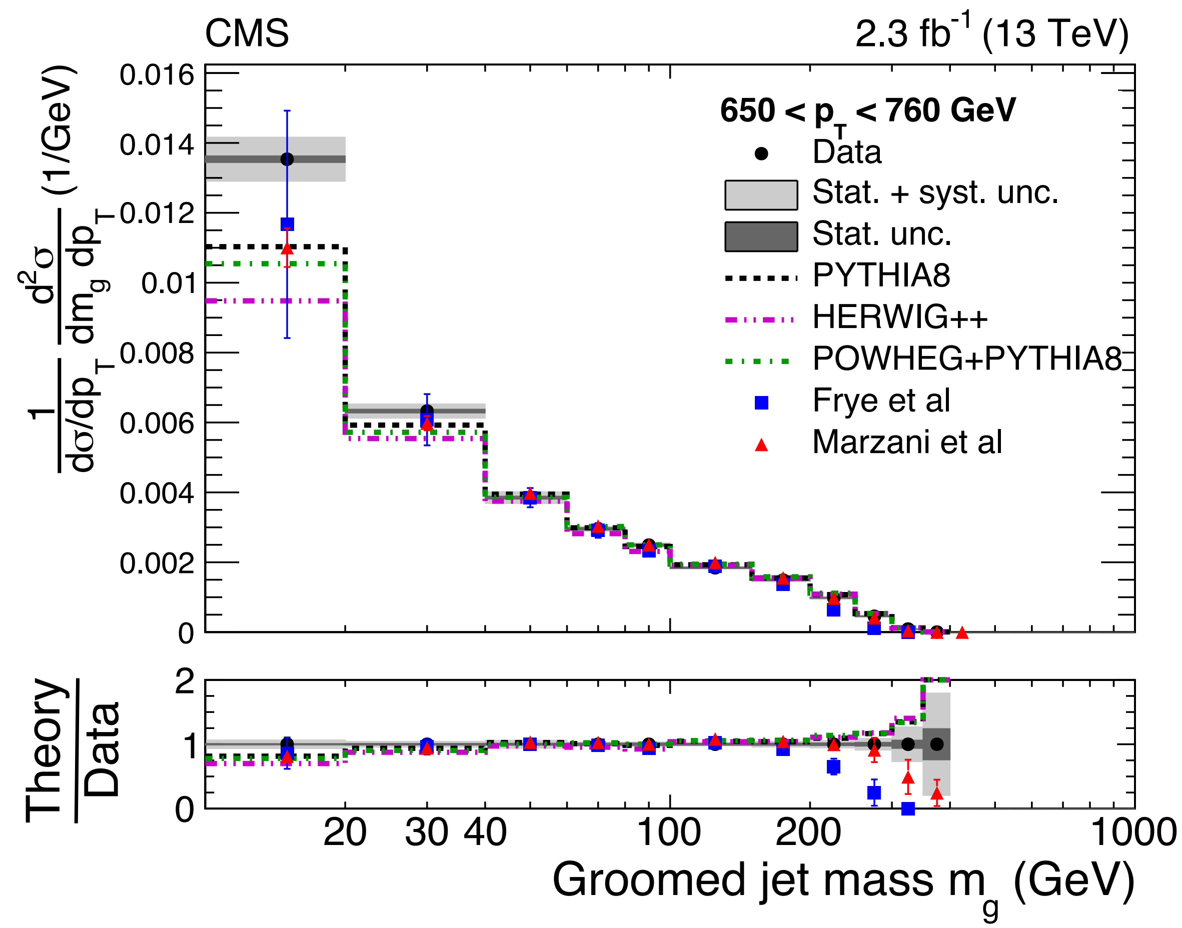
… did not mention the ν sector

Yukawa interactions (CERN ’16-18)

H (CERN ’12) and its gauge interactions

Jet mass of q/g jets

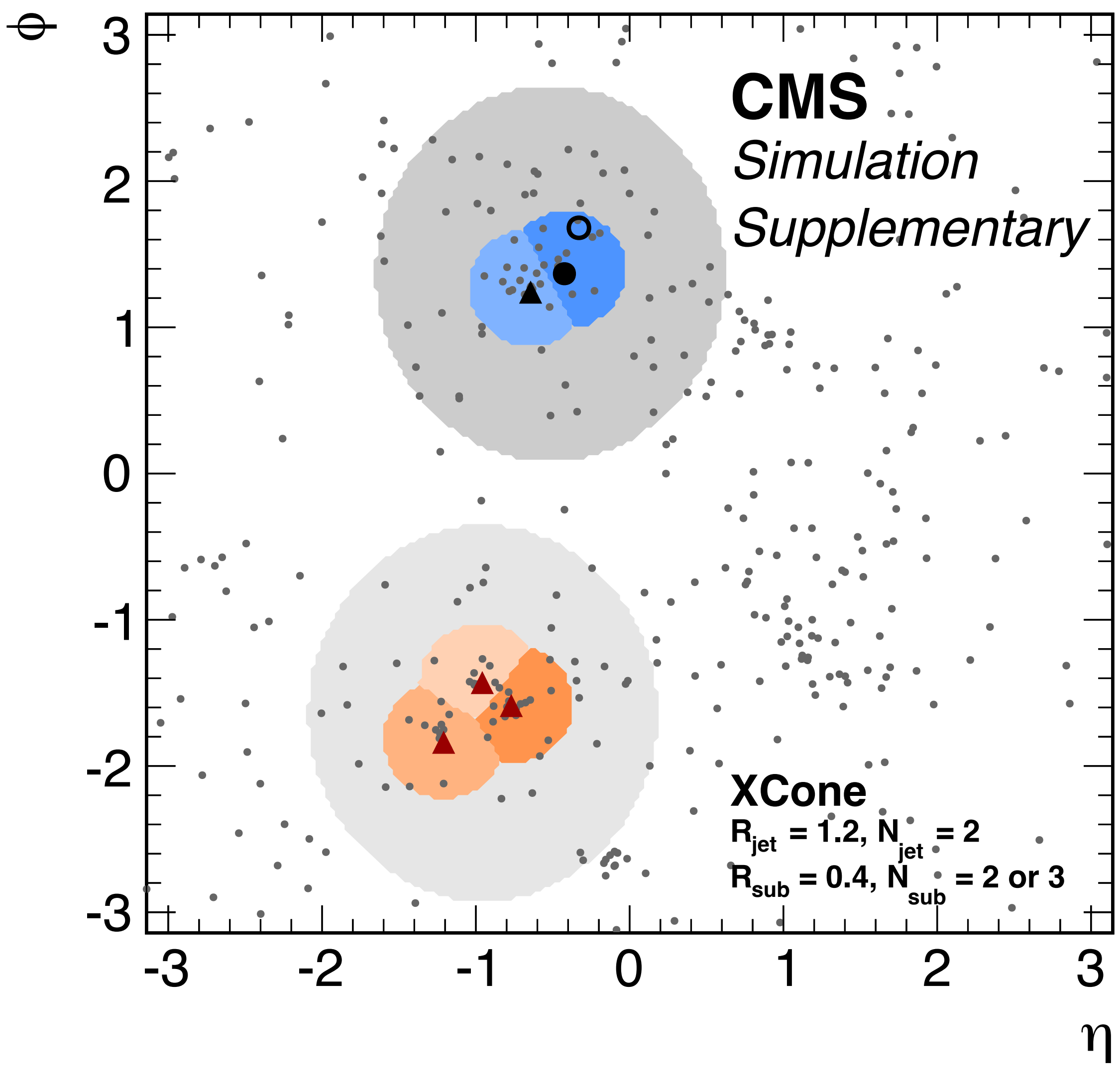


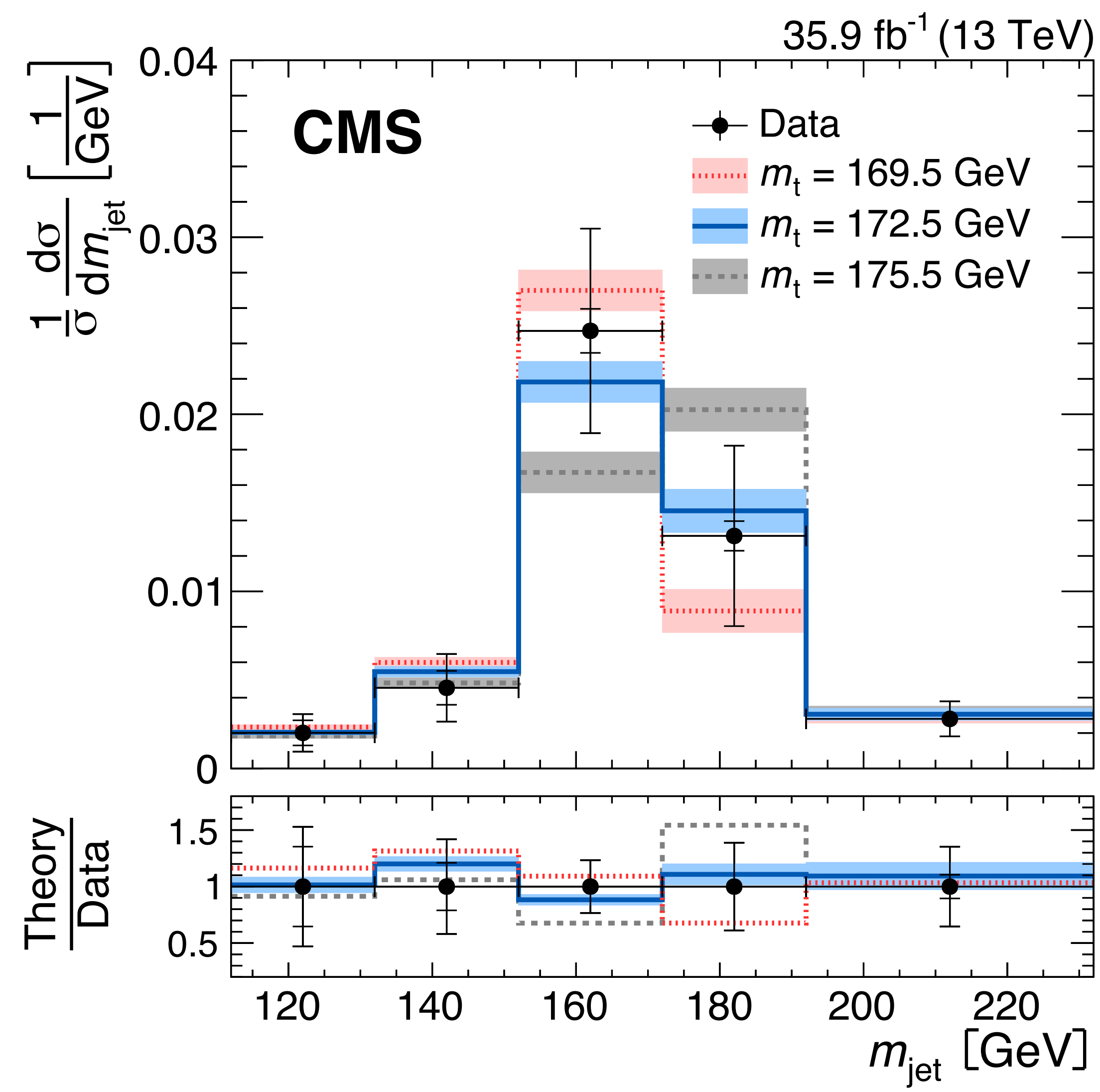


- Sudakov peak shifts to smaller values for soft drop grooming
- Soft drop grooming reduces modelling uncertainties

[CMS, JHEP 11, 113 (2018)]

Jet mass of top quark jets

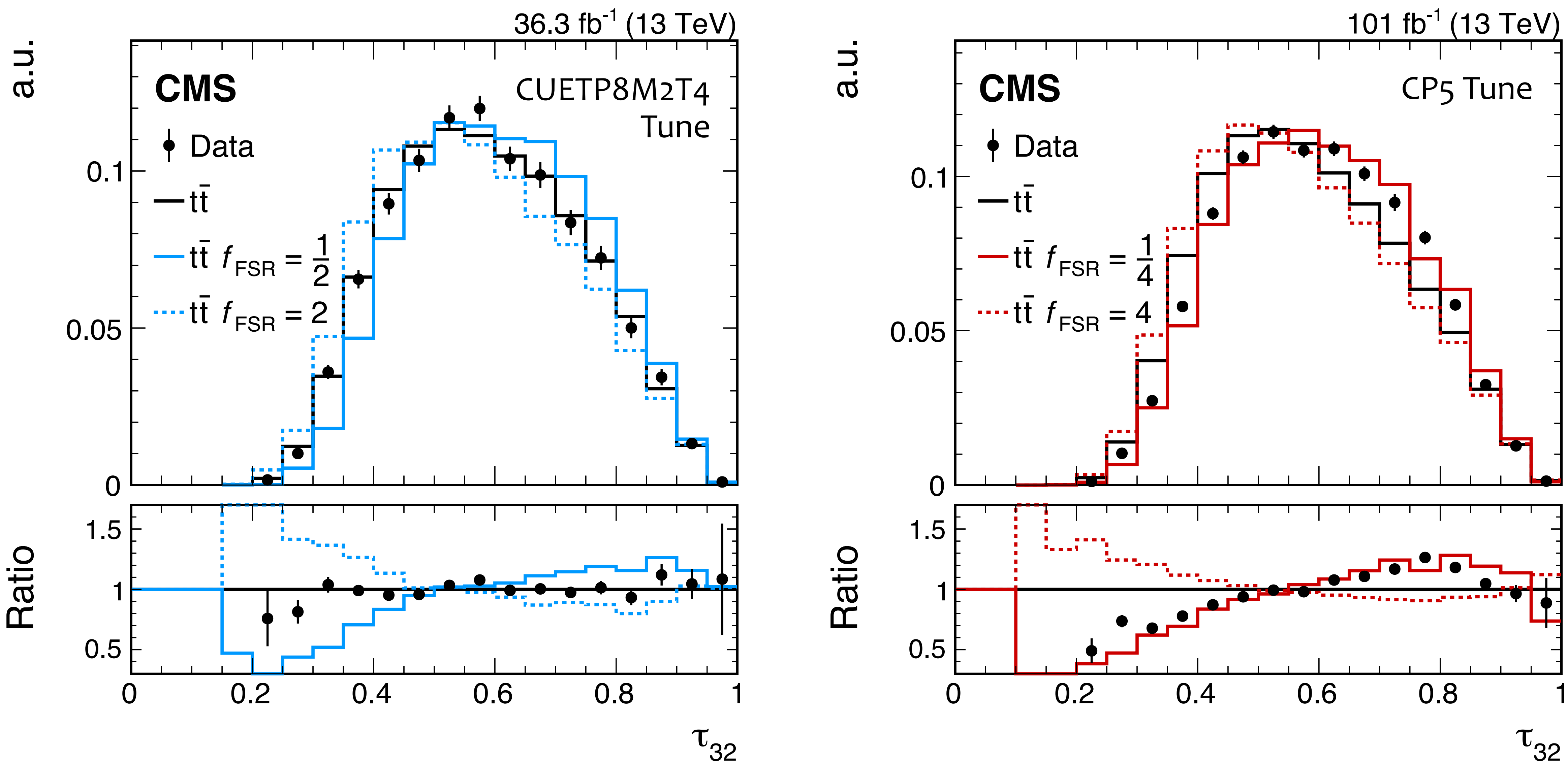




- XCone clustering improves mass resolution by a factor of two
- Measurement of top quark mass: m_t = 172.6 ± 2.5 GeV
  - Equal size of stat, modelling and JES uncertainties

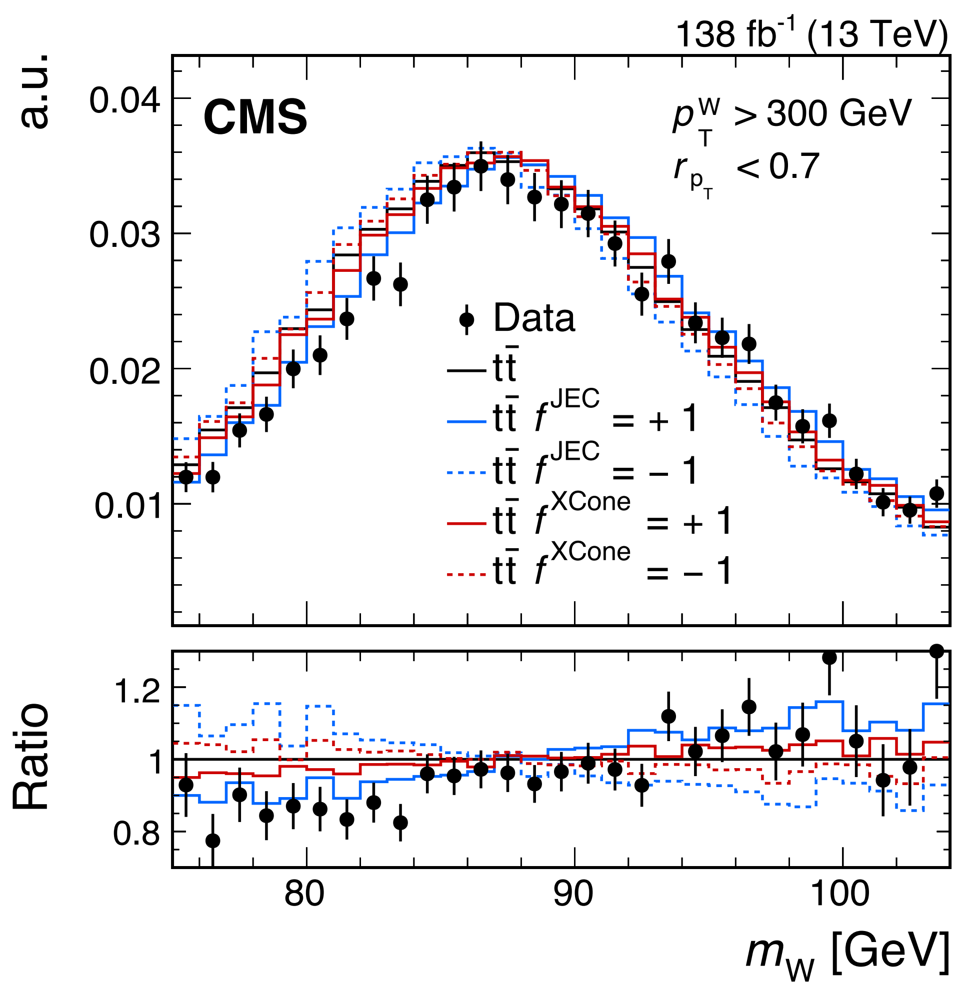
[CMS, PRL 124, 202001 (2020)]

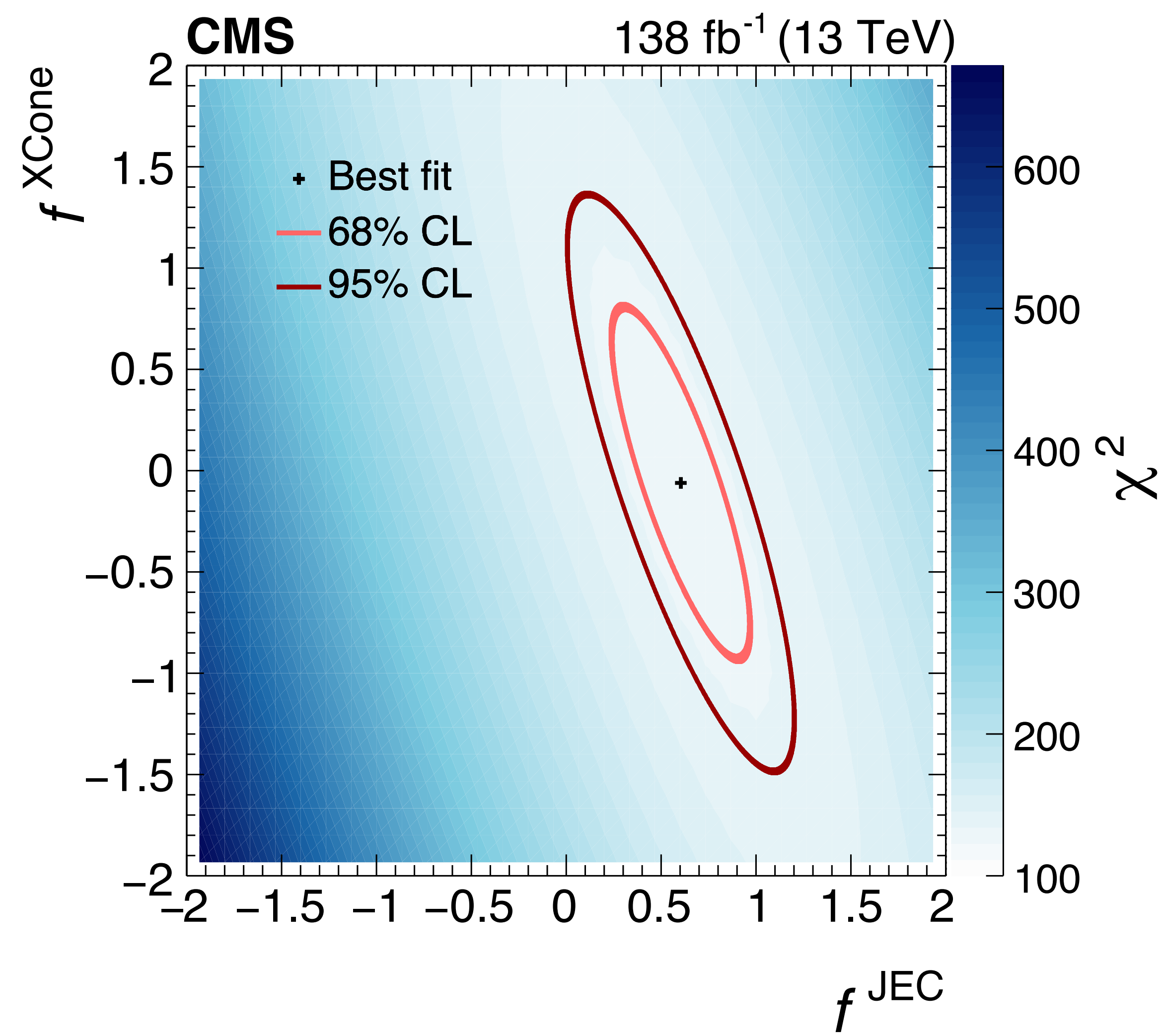
Constraining the Parton Shower



- Adjust f_{FSR} in $\alpha_S^{FSR}(f_{FSR}\,\mu_0)$, equivalent to choosing different $\alpha_S^{FSR}(M_Z)$

Jet mass calibration

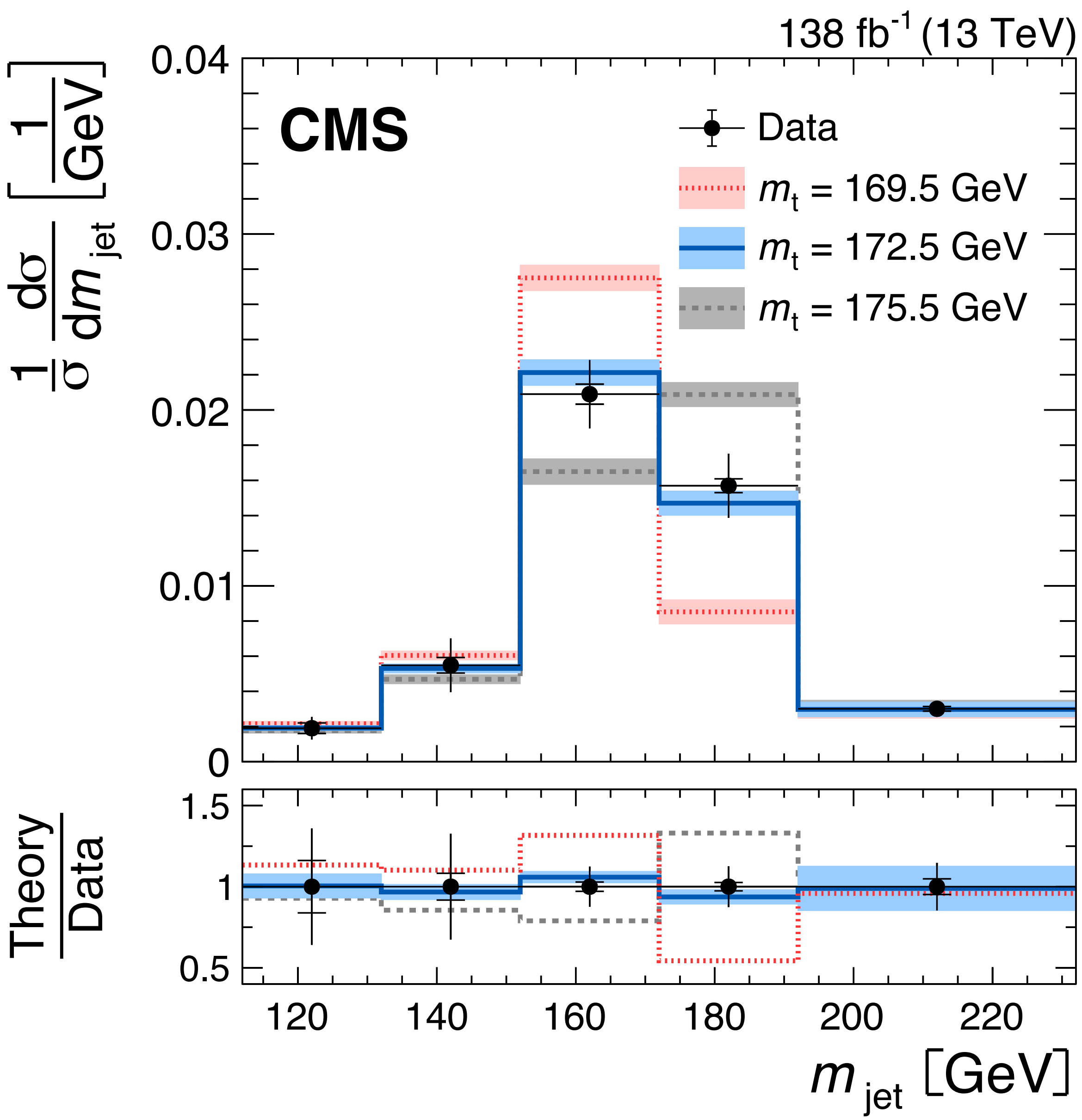




- Reconstruct m_W using the two light-flavoured subjets
- Measure m_W in four regions
- Measure jet mass scale (JMS) by adjusting XCone and JES corrections

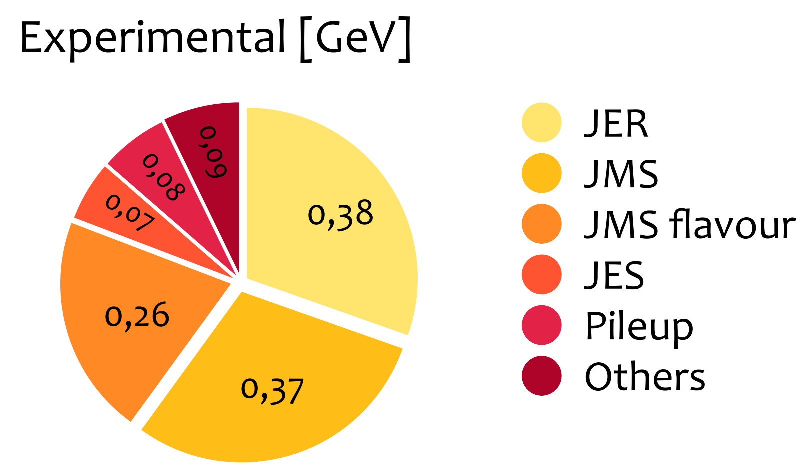
[CMS, EPJC 83, 560 (2023)]

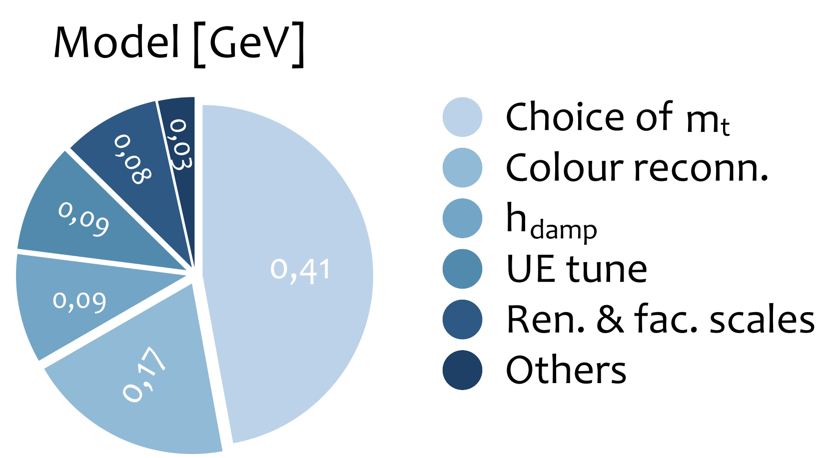
After many improvements…



$$m_t = 173.06 \pm 0.84\,\text{GeV}$$

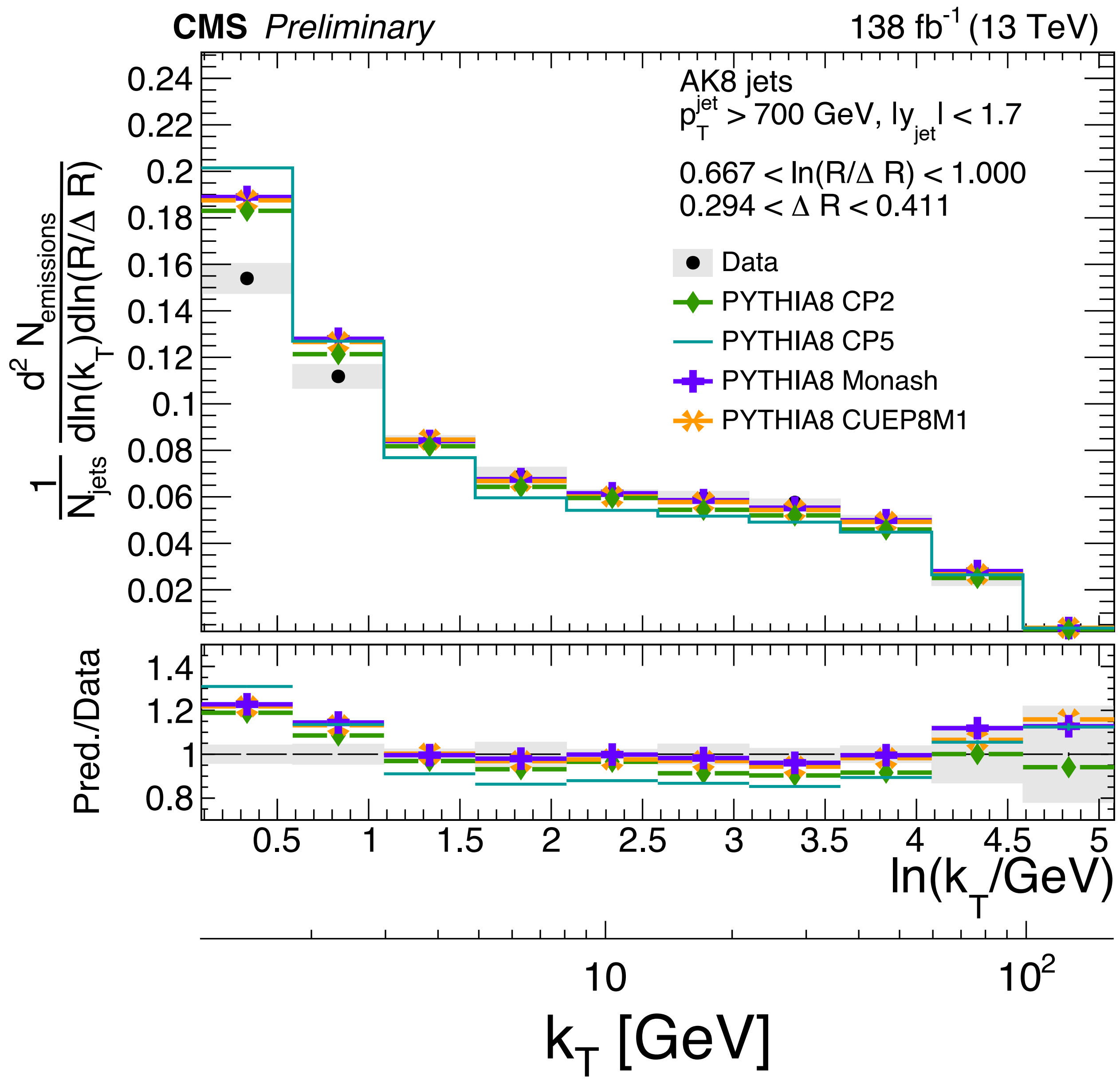
± 0.24 (stat) ± 0.61 (exp) ± 0.47 (model) ± 0.23 (theo) GeV

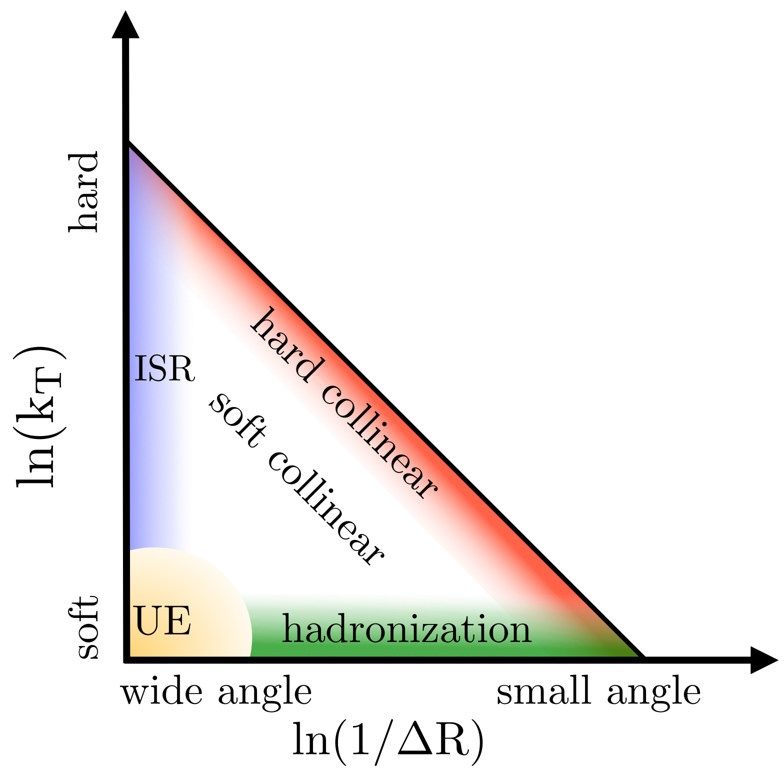




[CMS, EPJC 83, 560 (2023)]

Dedicated Measurements



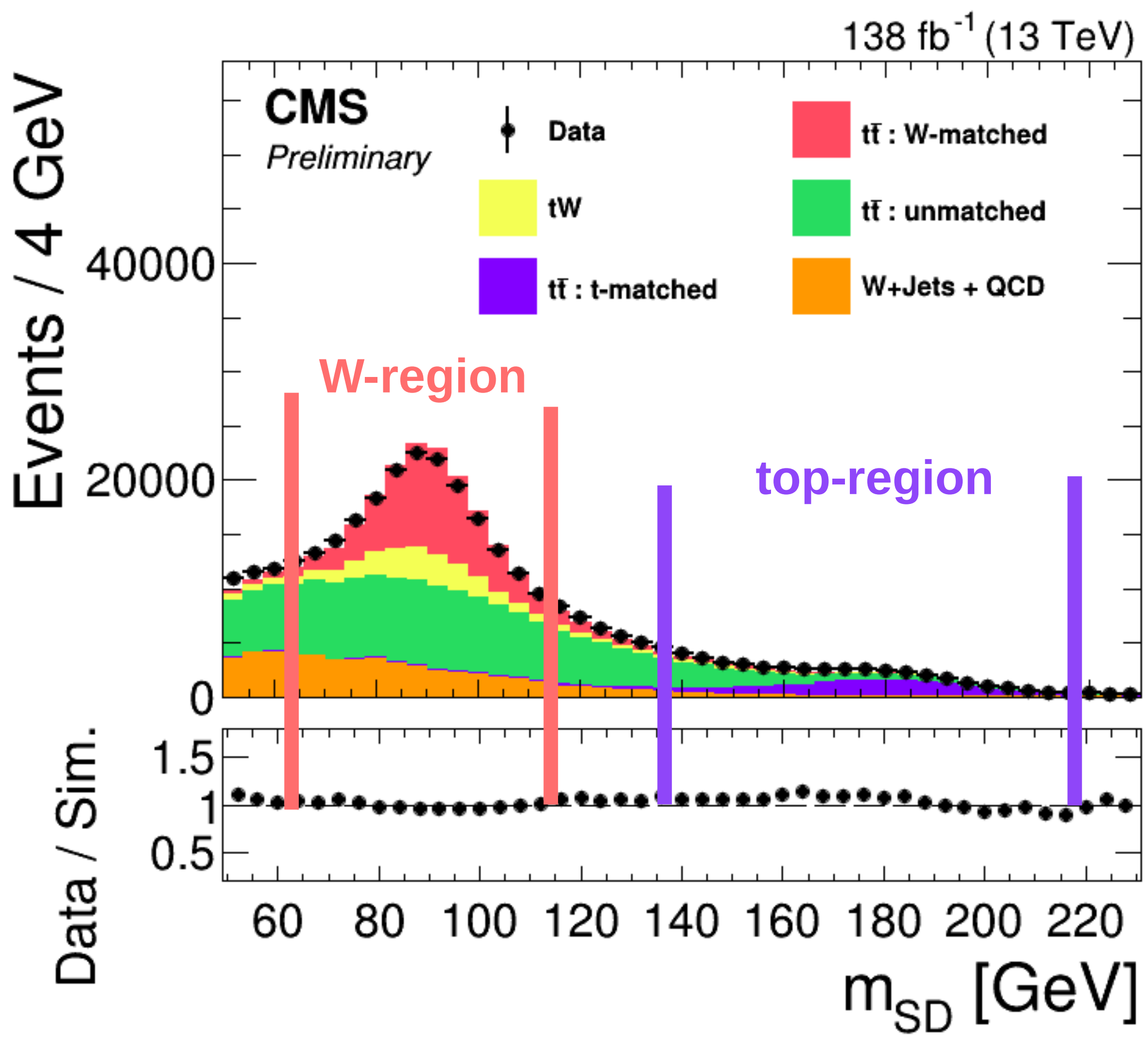


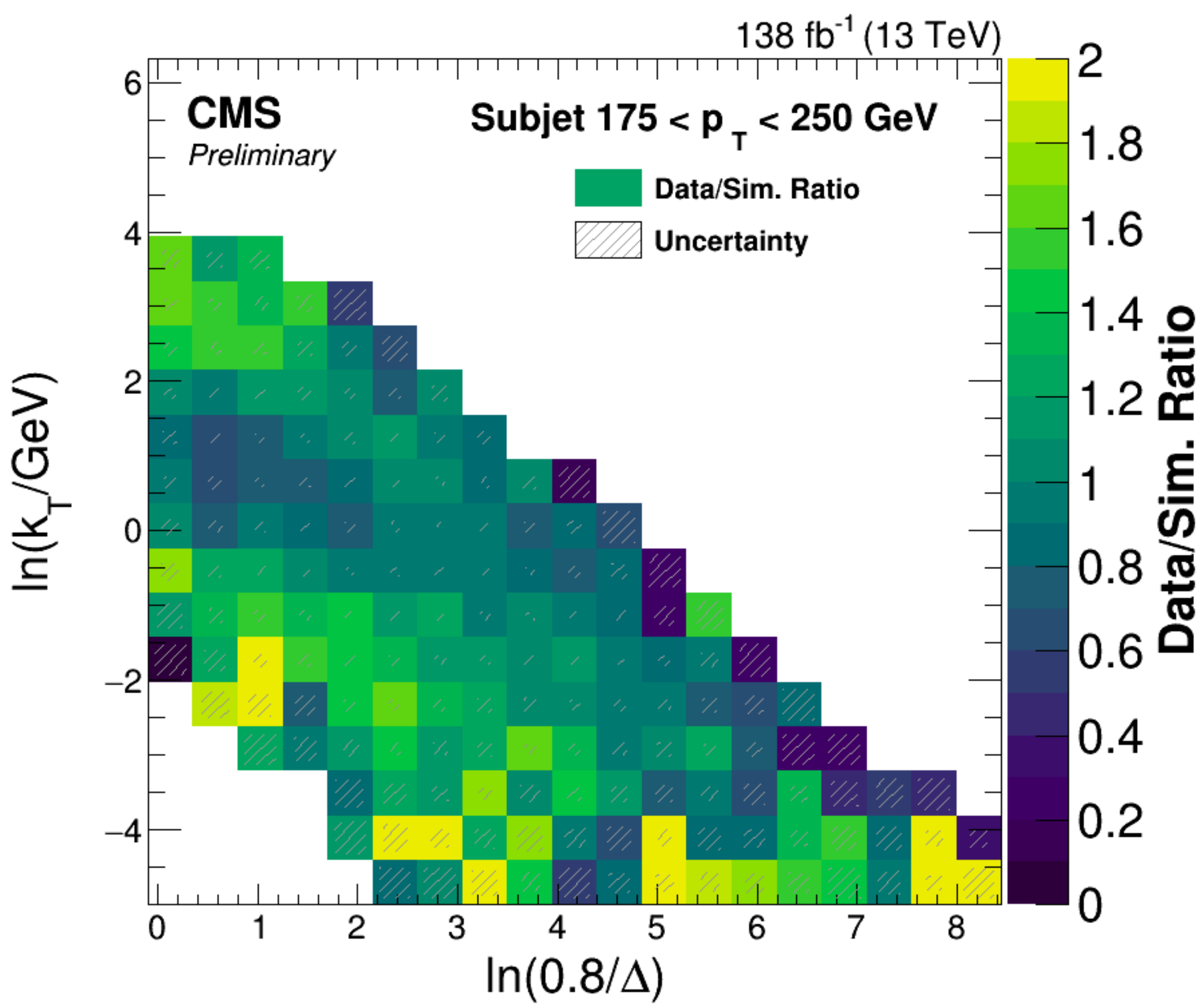
- Unfolded measurement of Lund jet plane
- Can be used to test new PS / hadronization models and tunes

[CMS, PAS-SMP-22-007 (2023)]

Ad-hoc Corrections with LJP

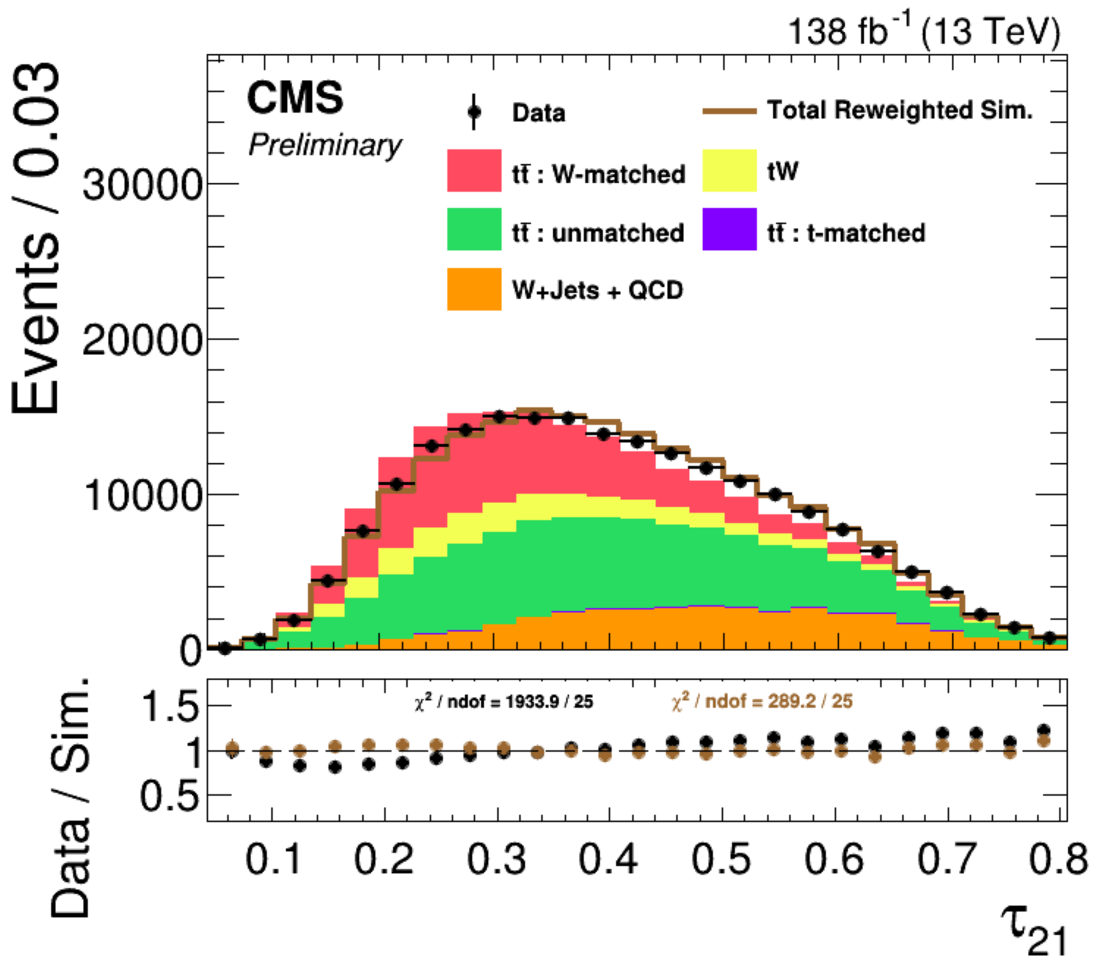
- Derive corrections 'per prong' to calibrate $N > 3$ prong jets
- Use merged W two-prongs to derive corrections, test on top quarks

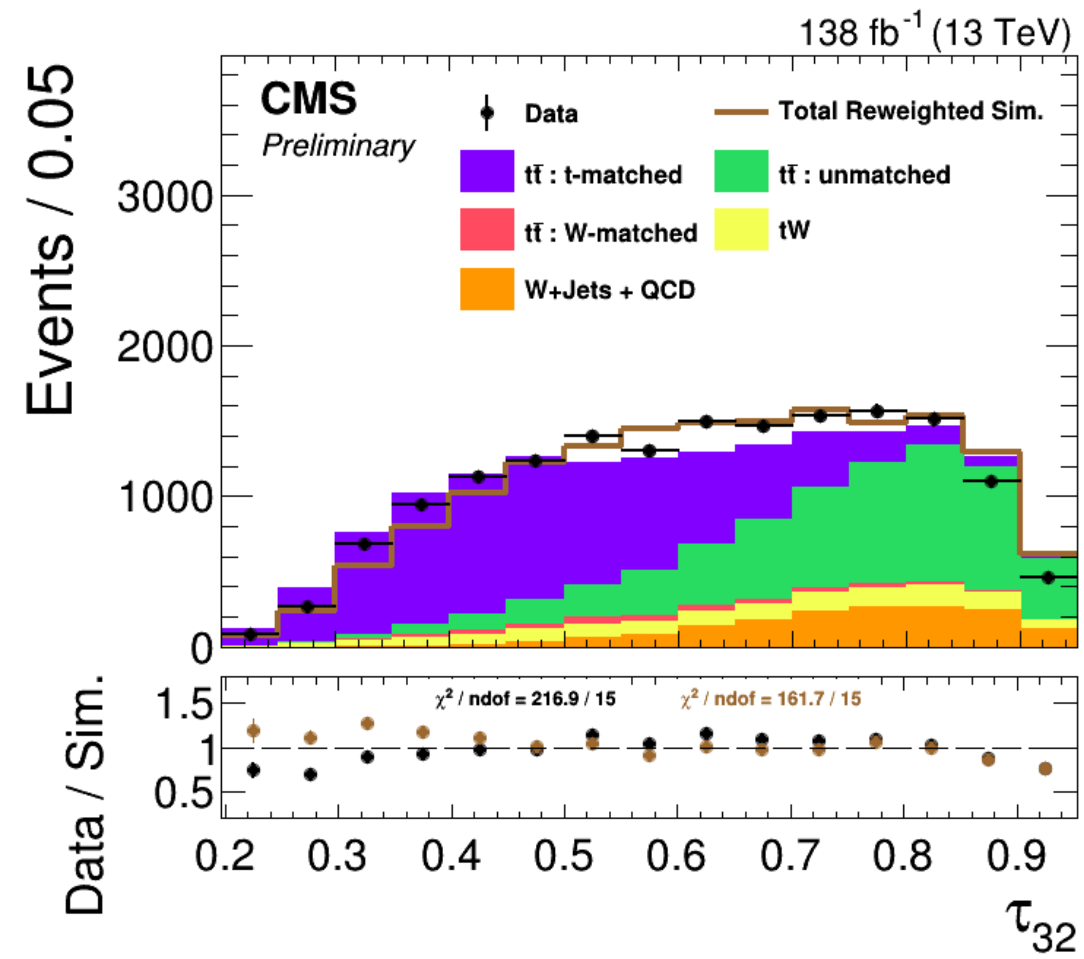




[CMS, DP-2023/046]

Ad-hoc Corrections with LJP



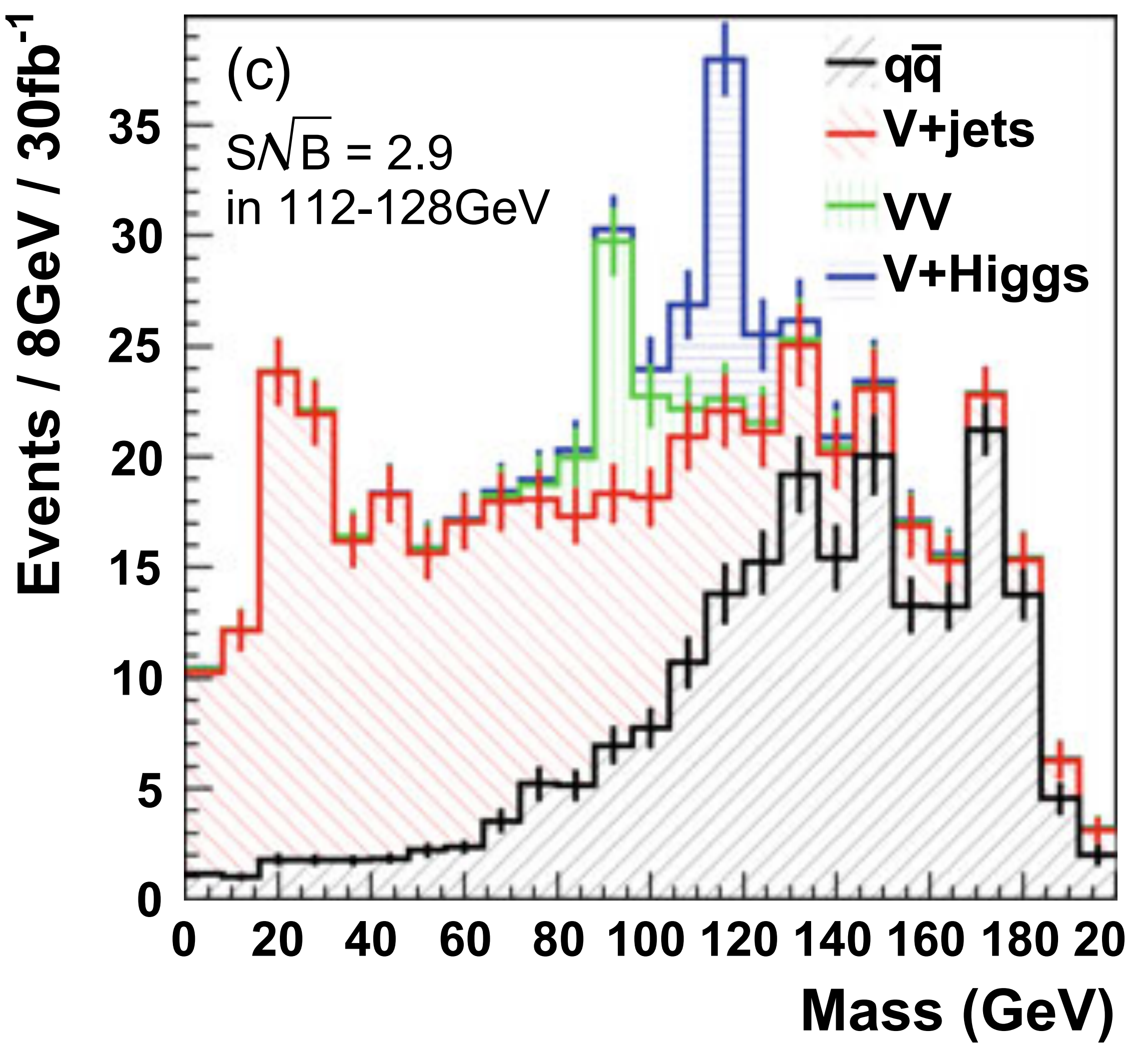


- Correction works perfectly for boosted Ws
- Improvement for boosted top quarks, but uncertainties of 15-20%
- Best way to calibrate high-prong decays (H→4q, BSM)

[CMS, DP-2023/046]

Higgs production in VH($b\bar{b}$)

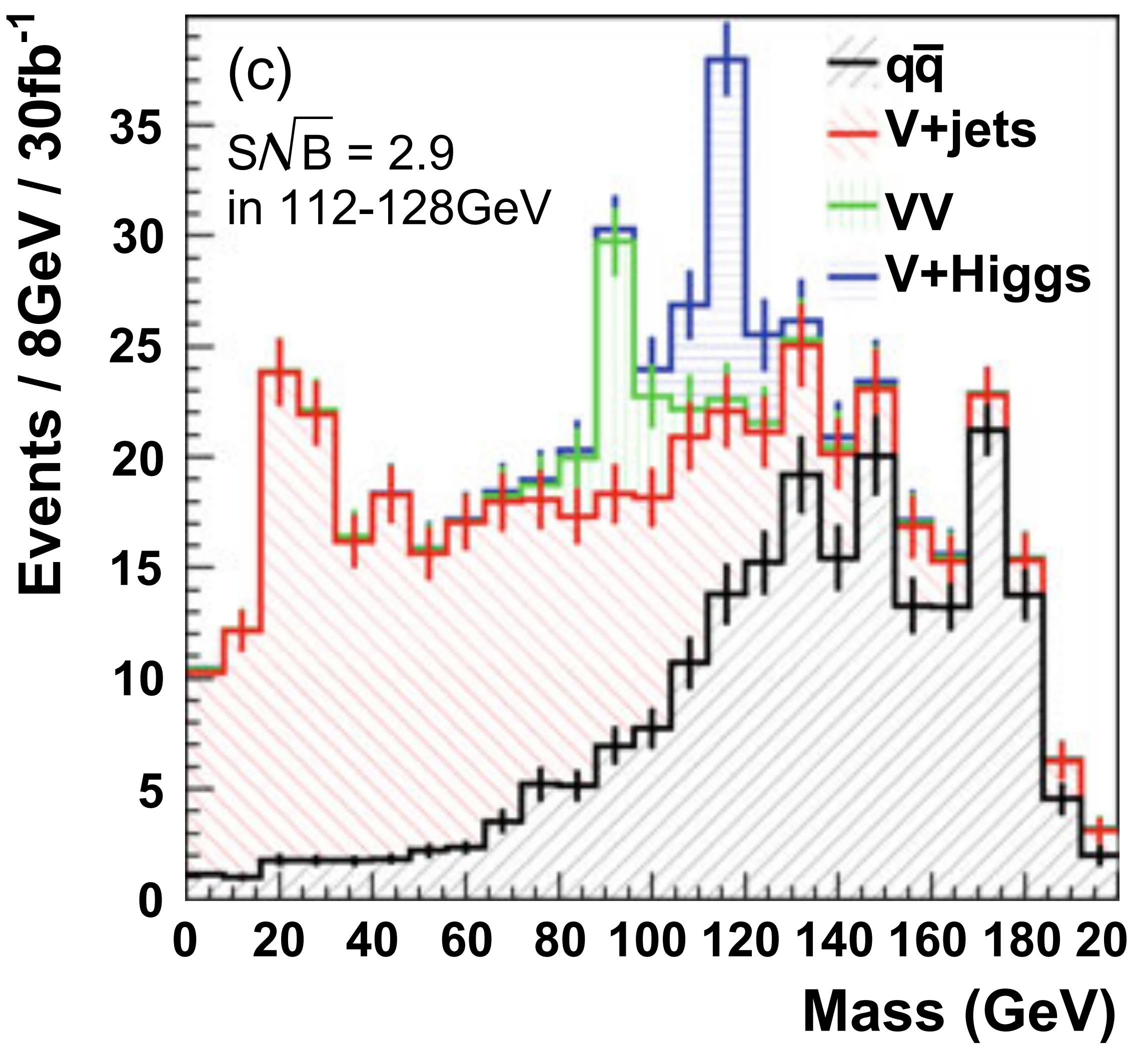
2008



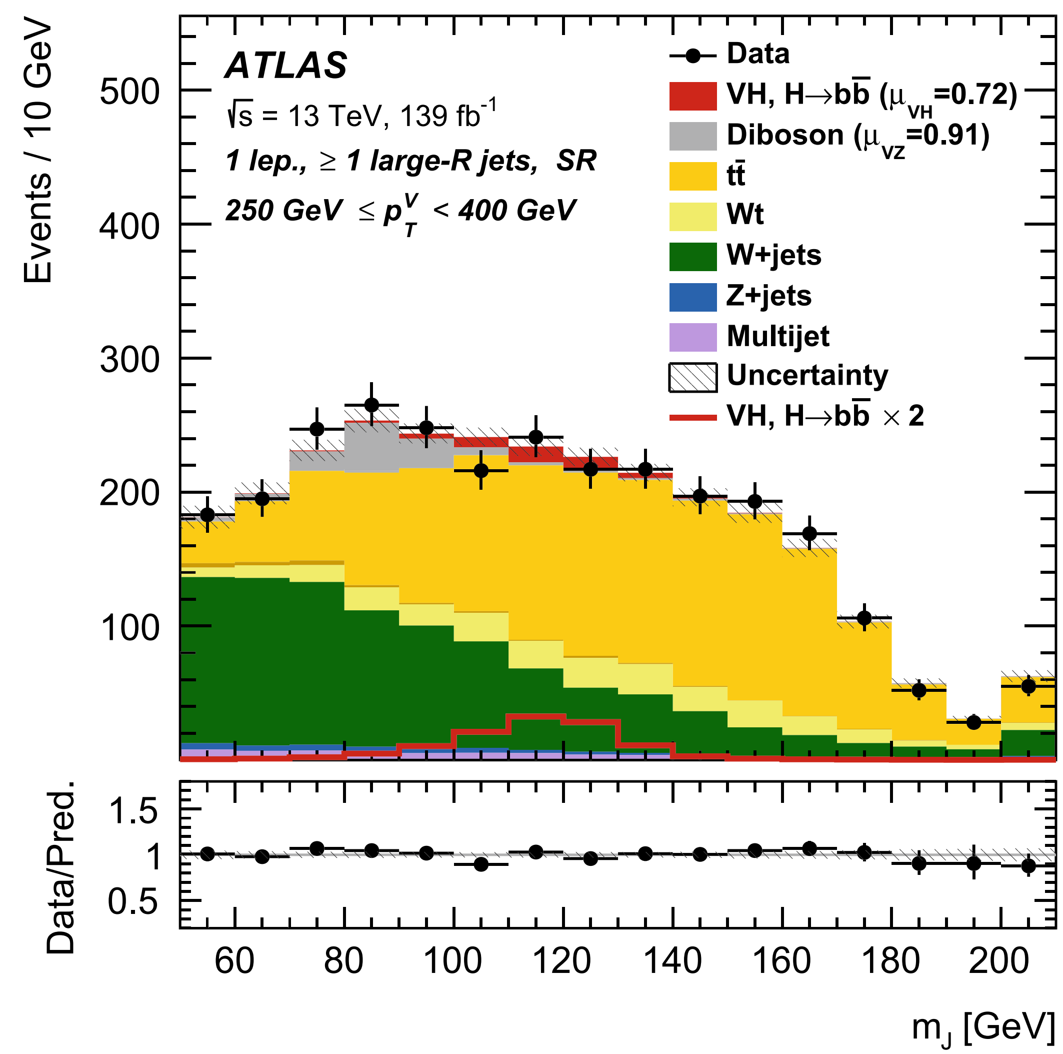
[J. M. Butterworth et al, PRL 100, 242001 (2008)]

Higgs production in VH($b\bar{b}$)

2008



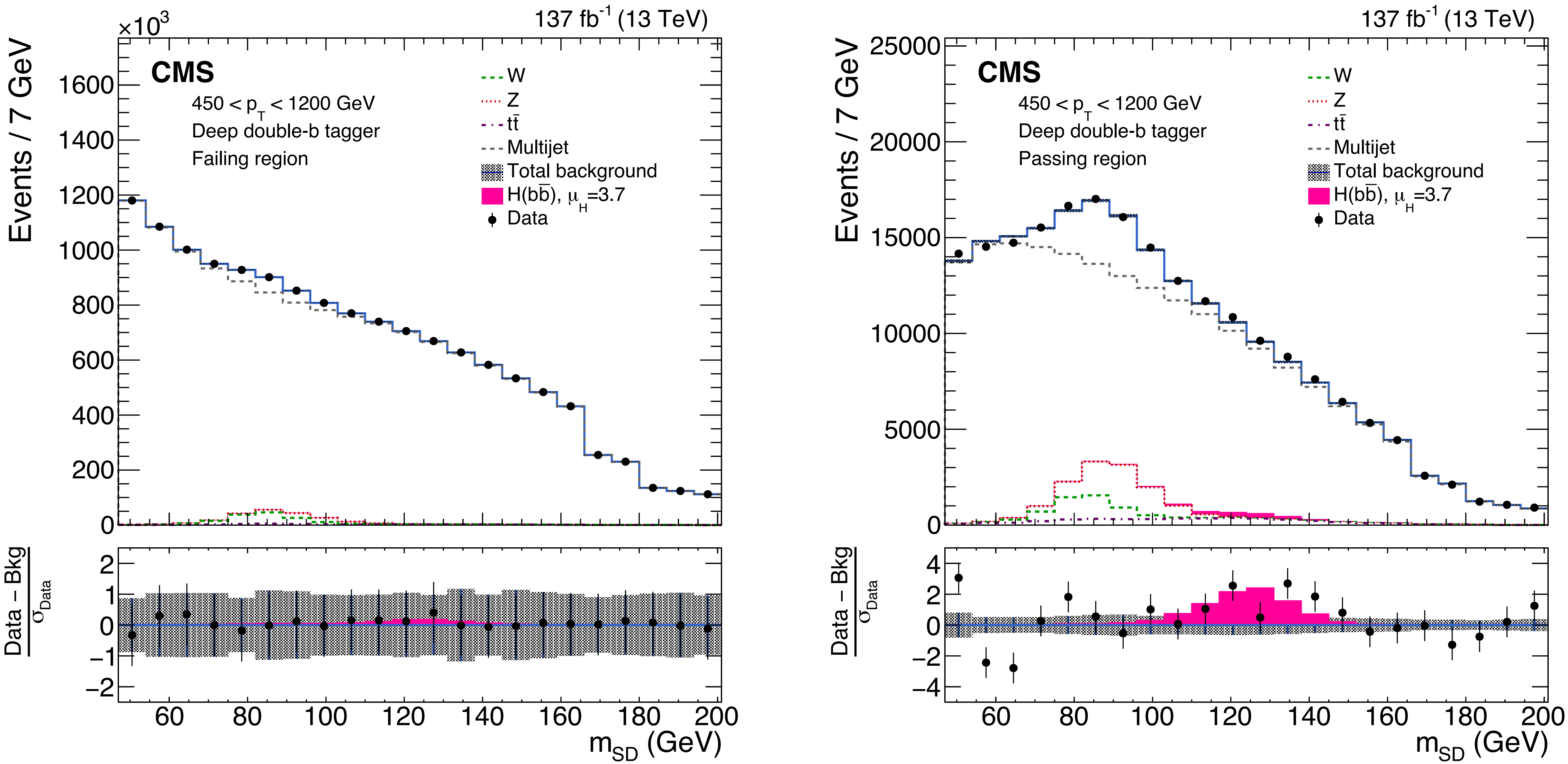
2020



[J. M. Butterworth et al, PRL 100, 242001 (2008)]

[ATLAS, PLB 816, 136204 (2021)]

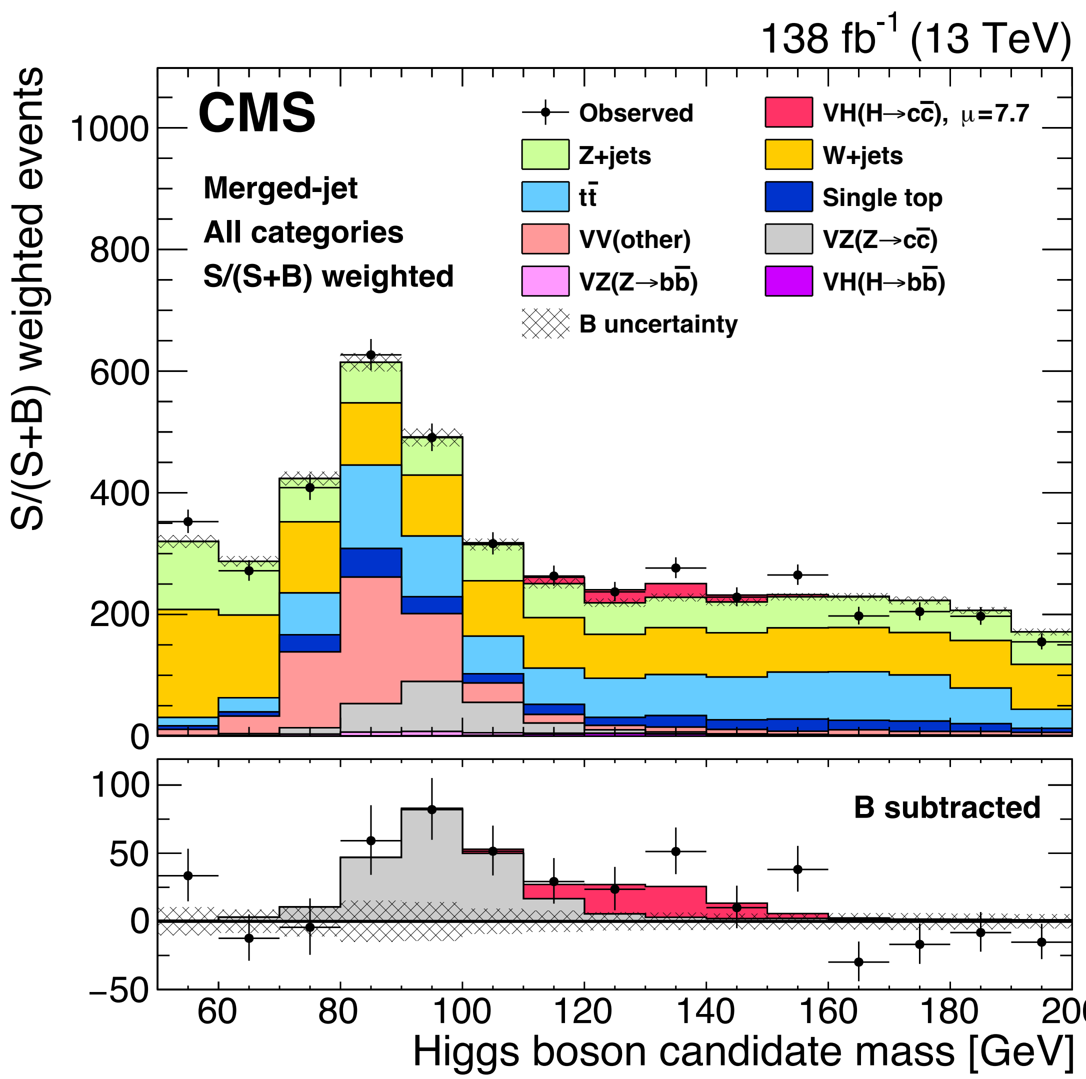
$H(b\bar{b})$ in ggF

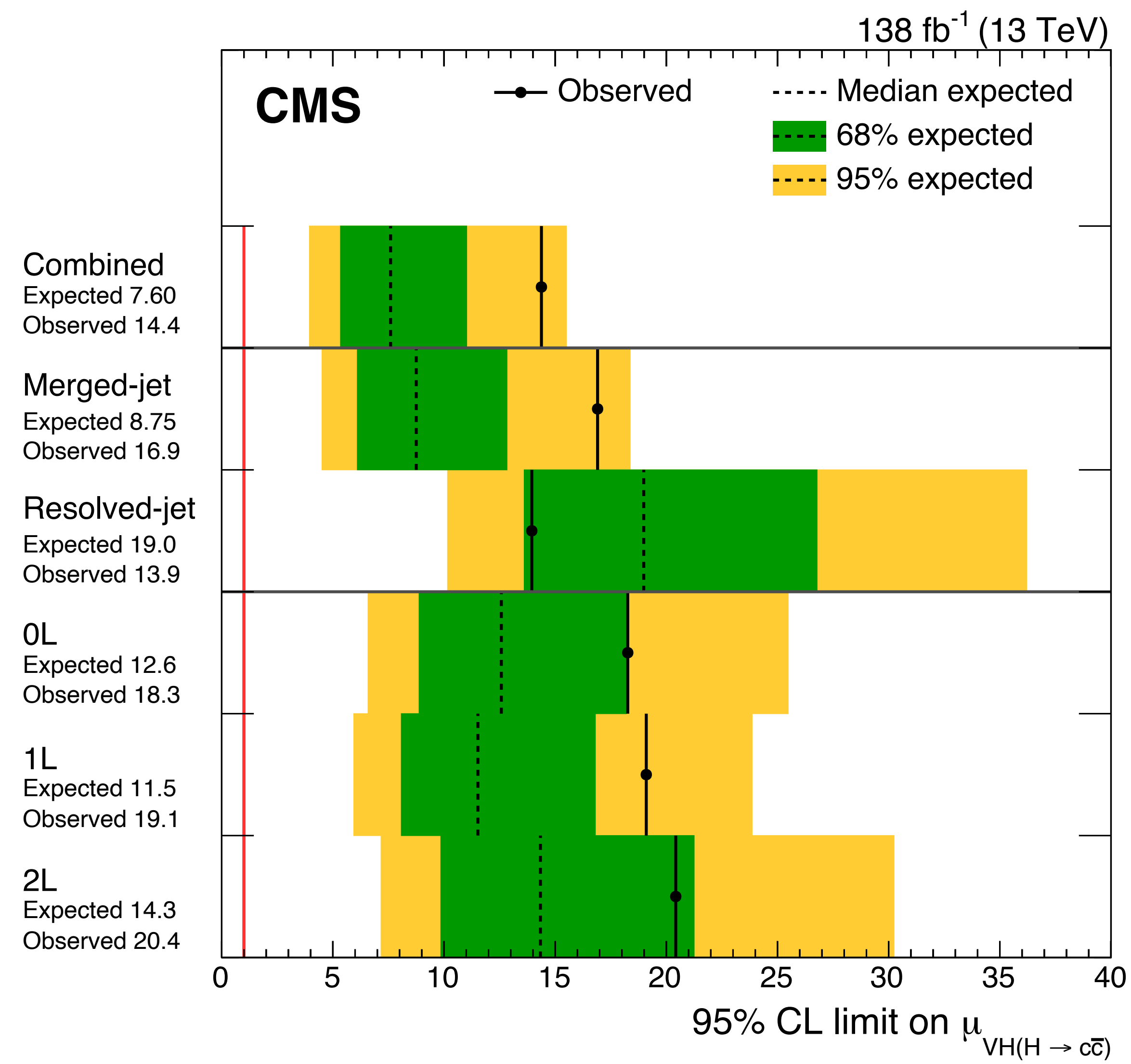


- Multijet background prediction from pass-to-fail ratio
- Observed significance of 2.5σ (0.7 expected)

[CMS, JHEP 12, 085 (2020)]

Doing the impossible: H($c\bar{c}$)





- Made possible by ParticleNet tagger (graph-based NN)
- Observed significance 14 × SM (7.6 × SM expected)

[CMS, PRL 131, 061801 (2023)]

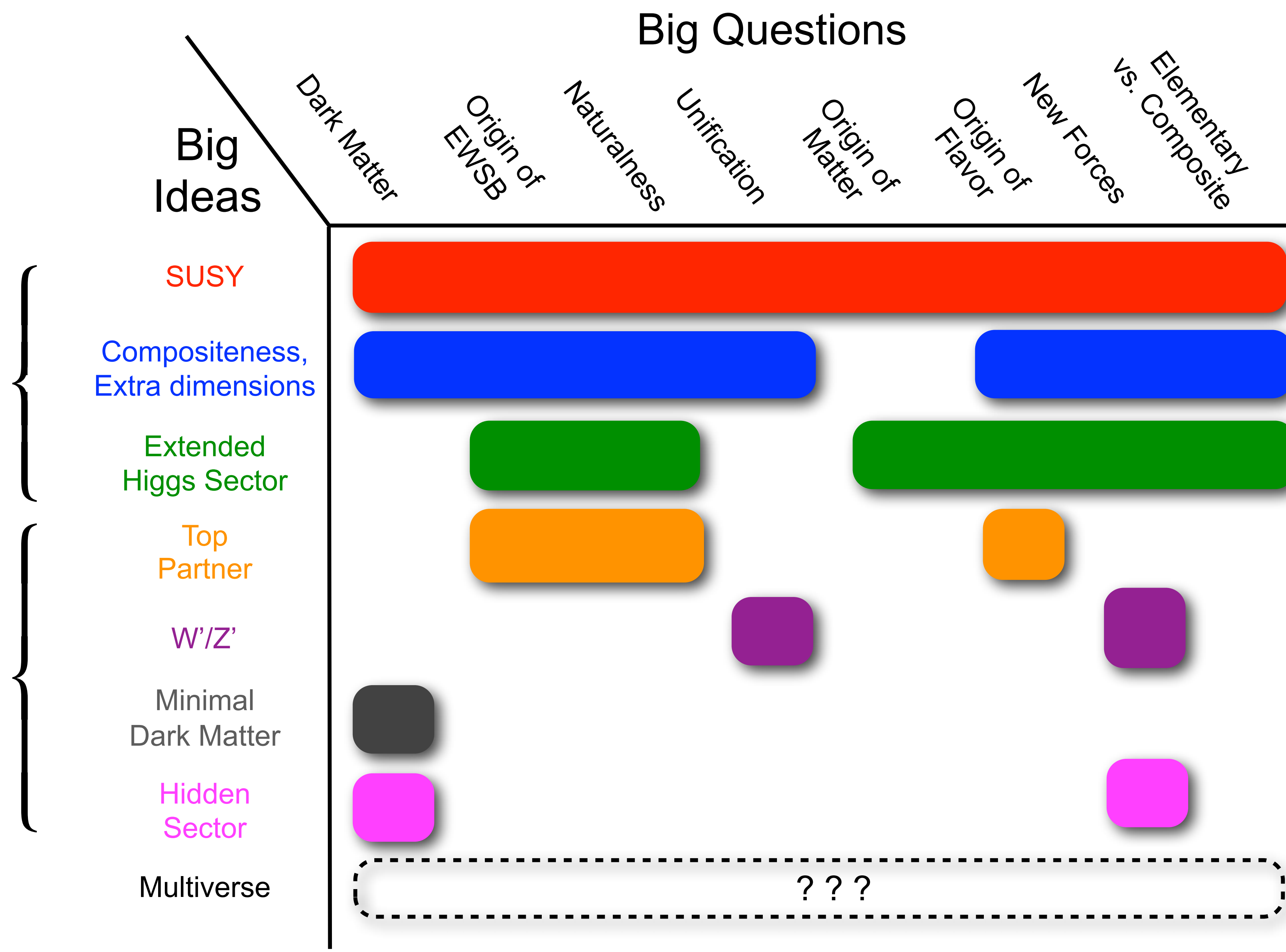
Searches for new phenomena

Beyond the Standard Model

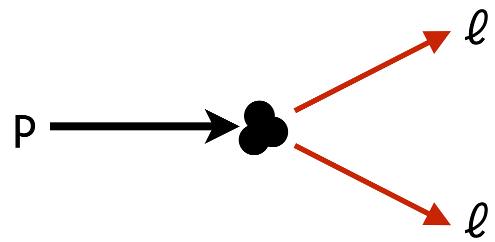
Complete models

New matter fields / interactions

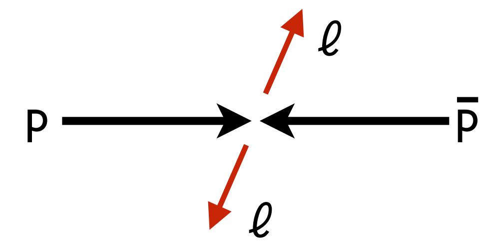
The unknown

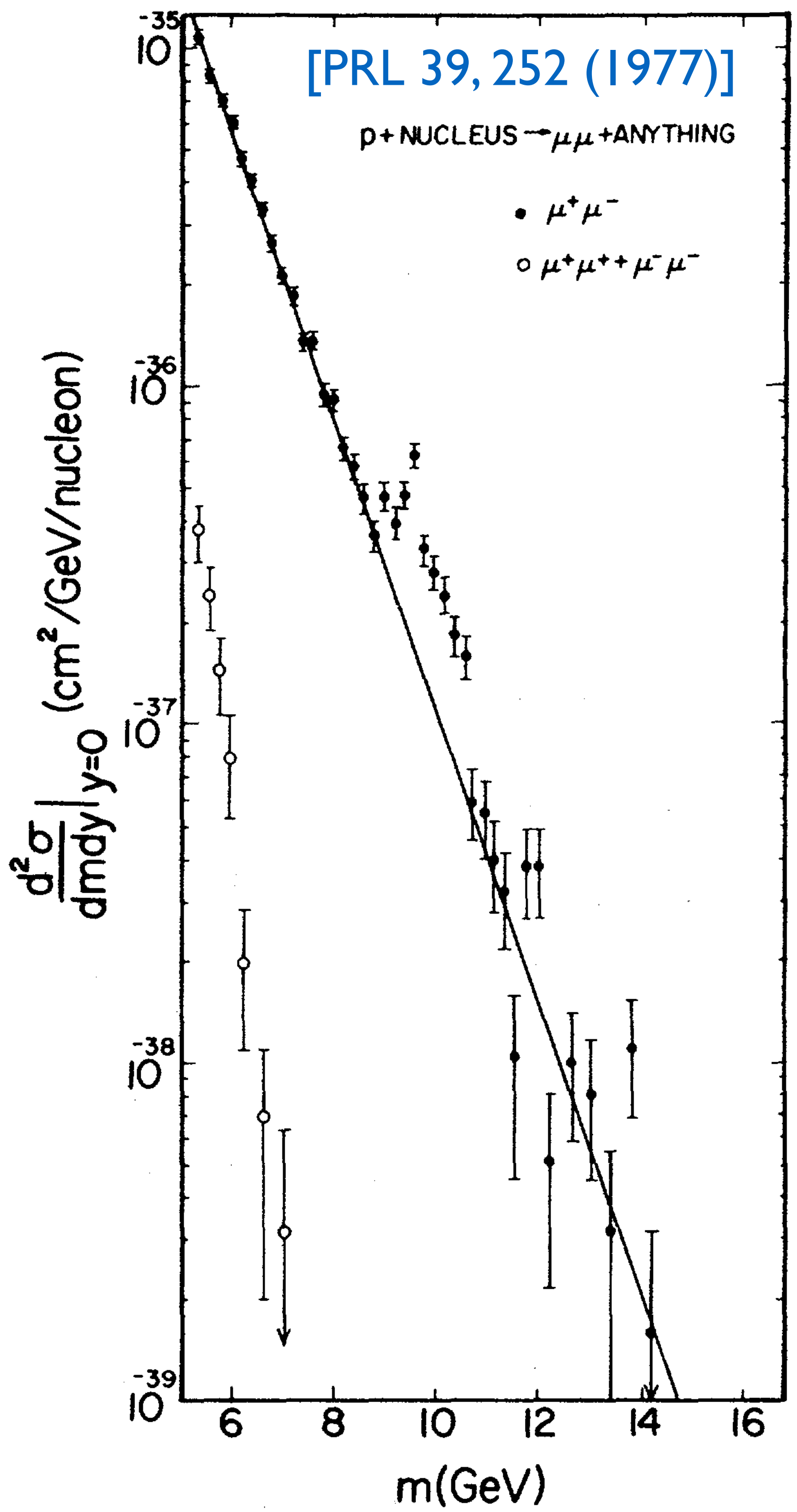


[Snowmass White Paper, arXiv:1311.0299]

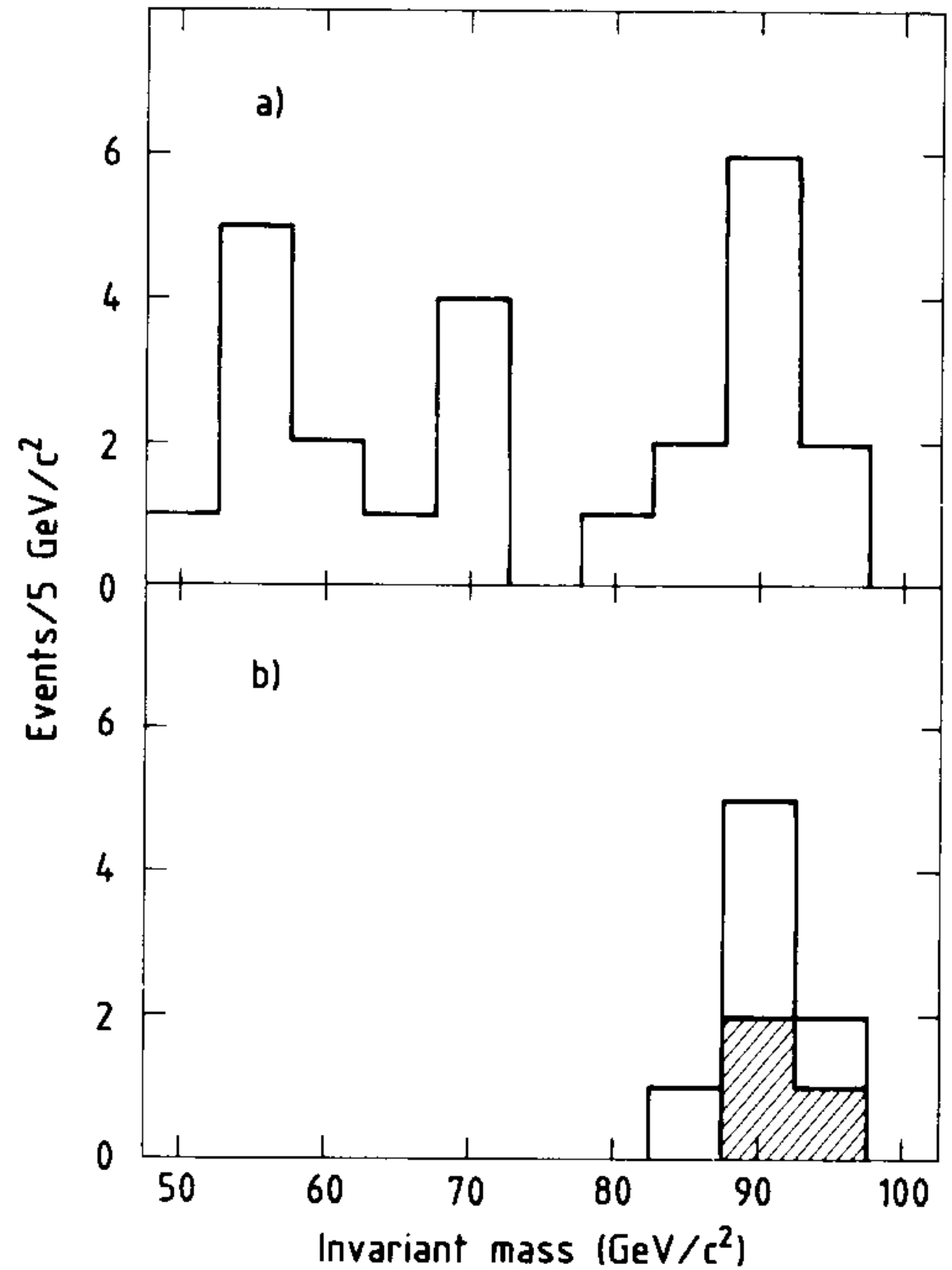


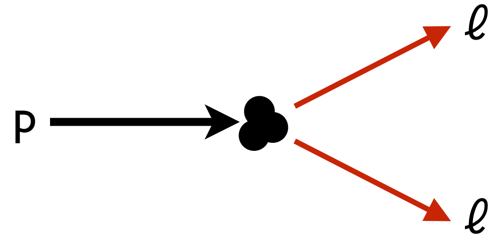
ℓℓ Resonances



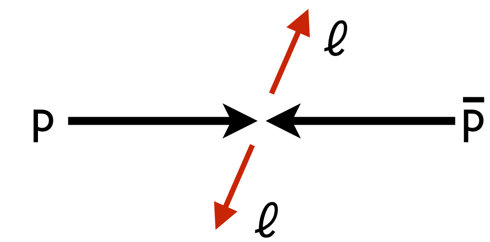


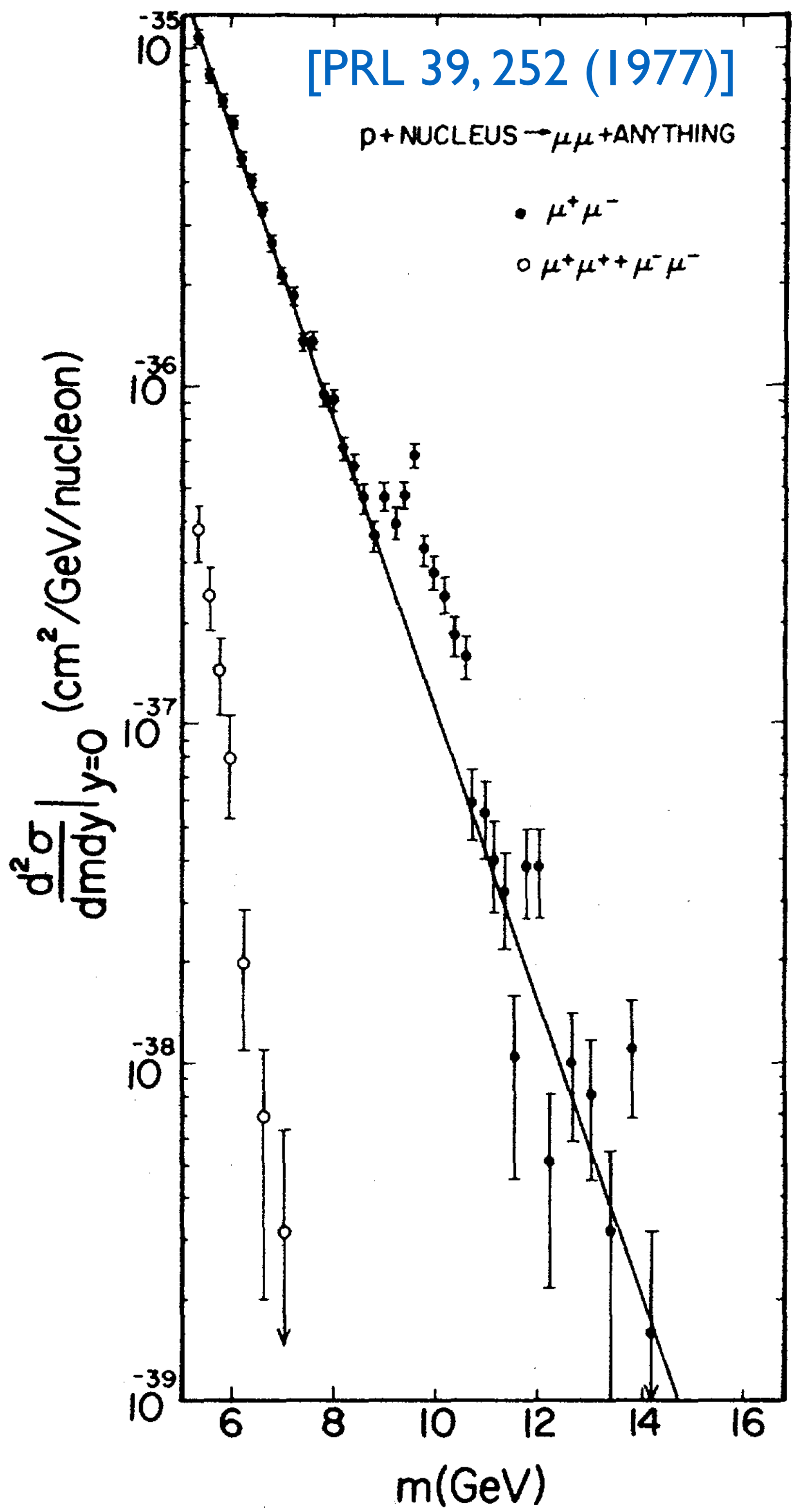
[UA1, PLB126, 398 (1983)
UA2, PLB129, 130 (1983)]



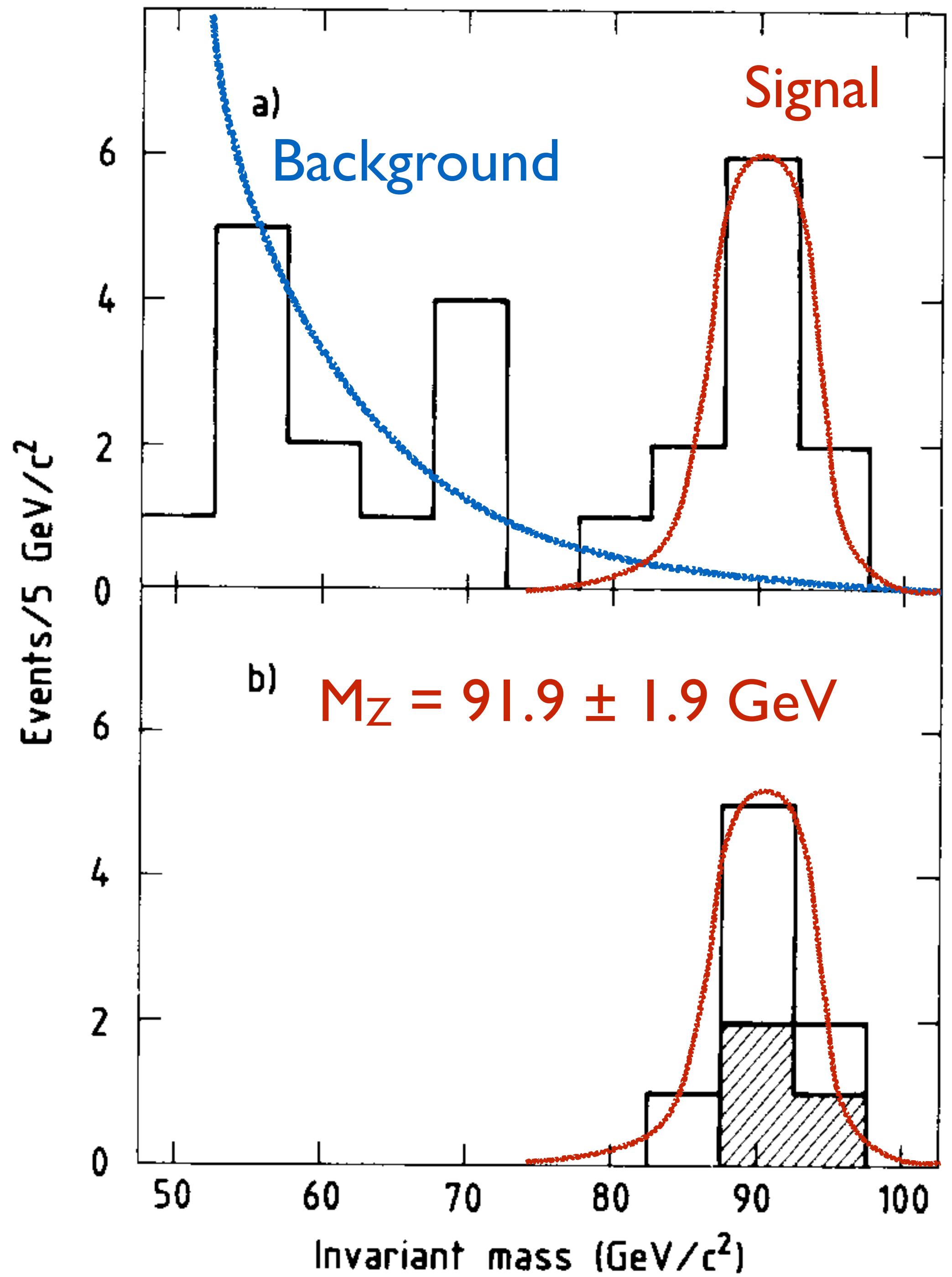


ℓℓ Resonances

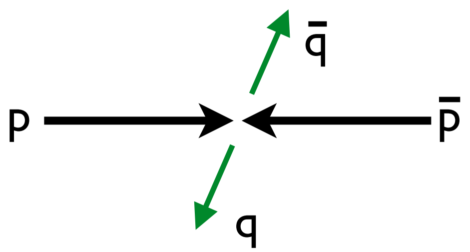




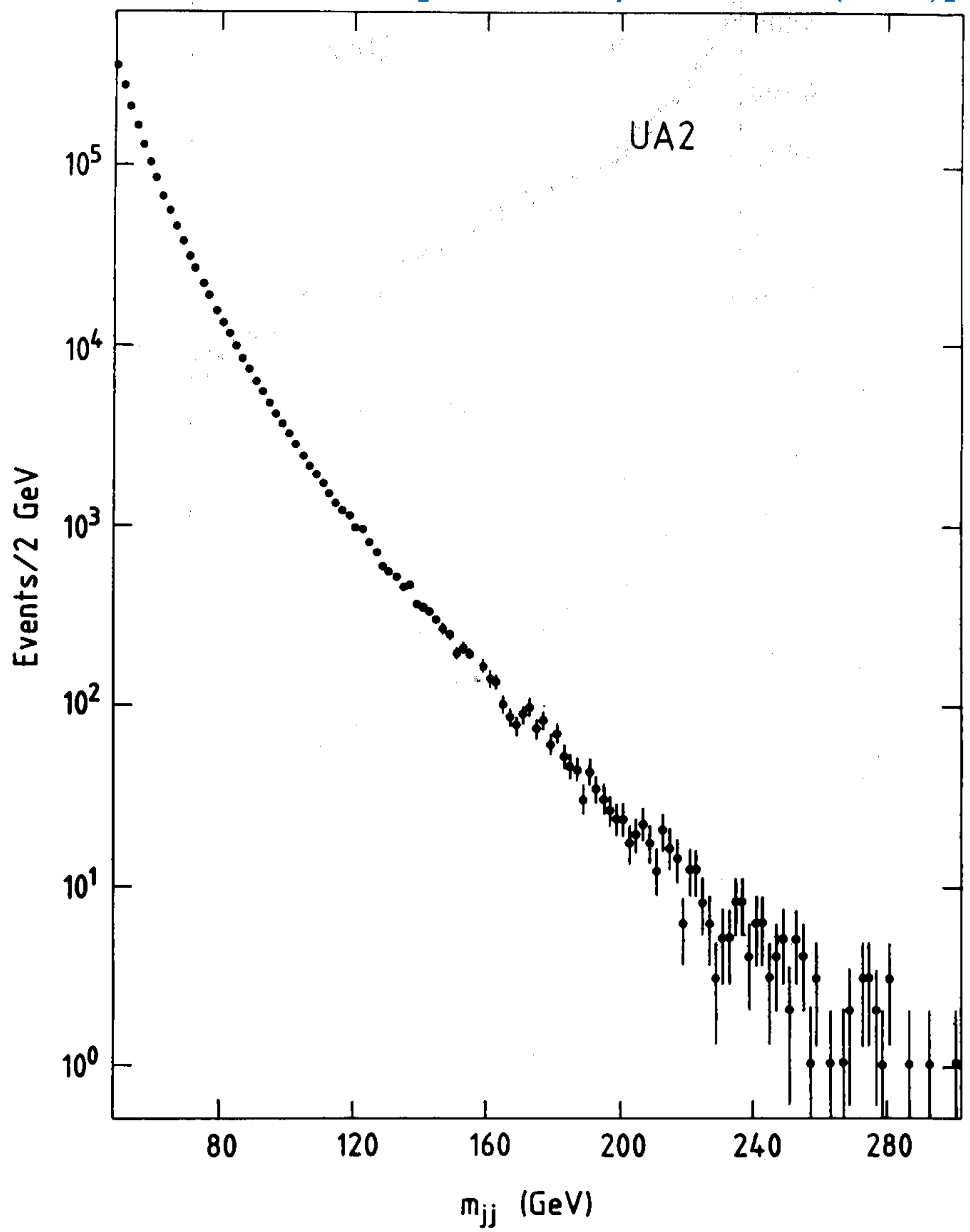
[UA1, PLB126, 398 (1983)
UA2, PLB129, 130 (1983)]



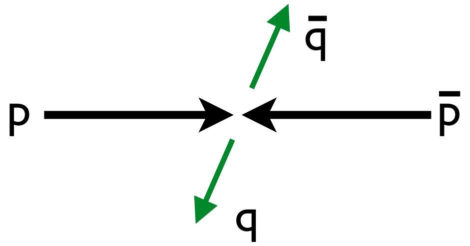
qq/gg Resonances



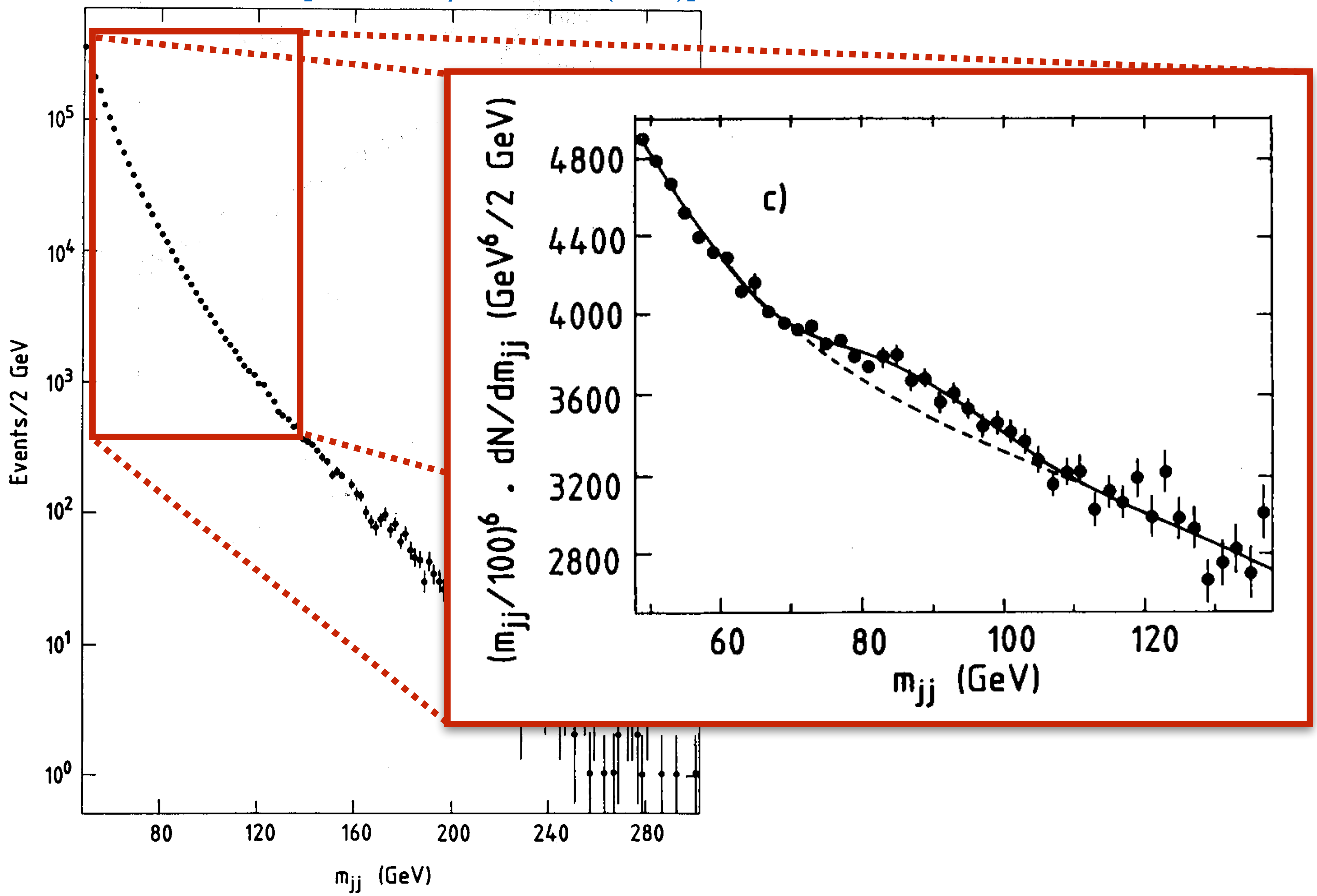
[UA2, Z. Phys. C 49, 17 (1991)]



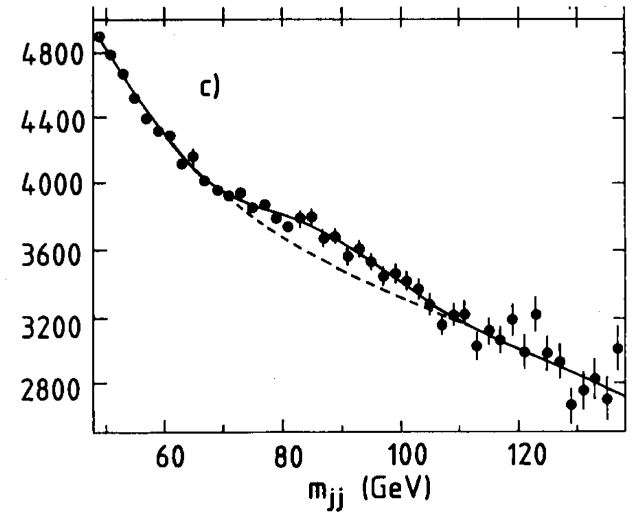
qq/gg Resonances

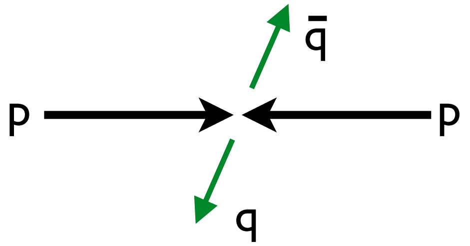


[UA2, Z. Phys. C 49, 17 (1991)]



qq/gg Resonances

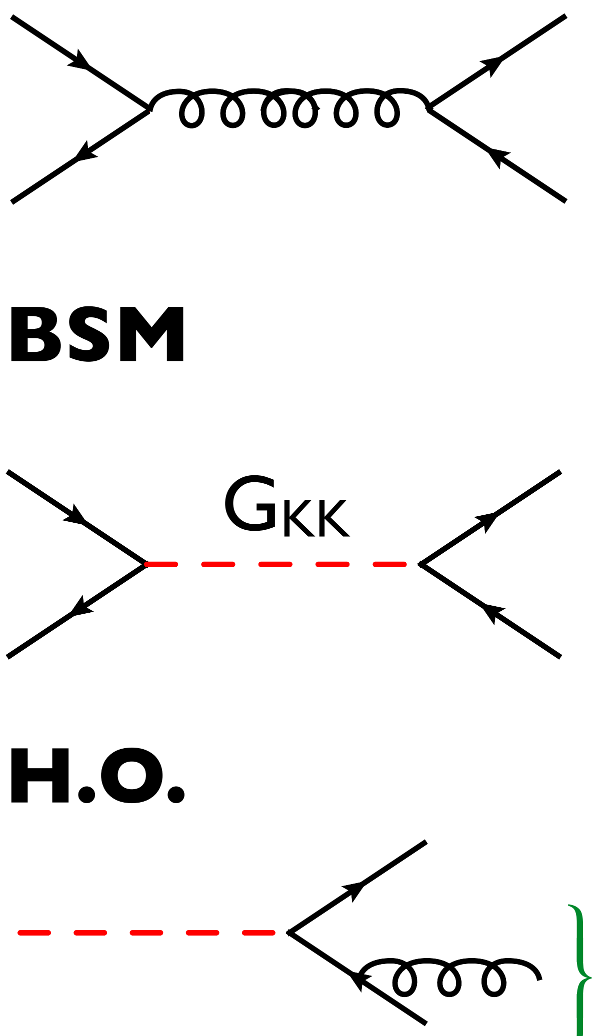




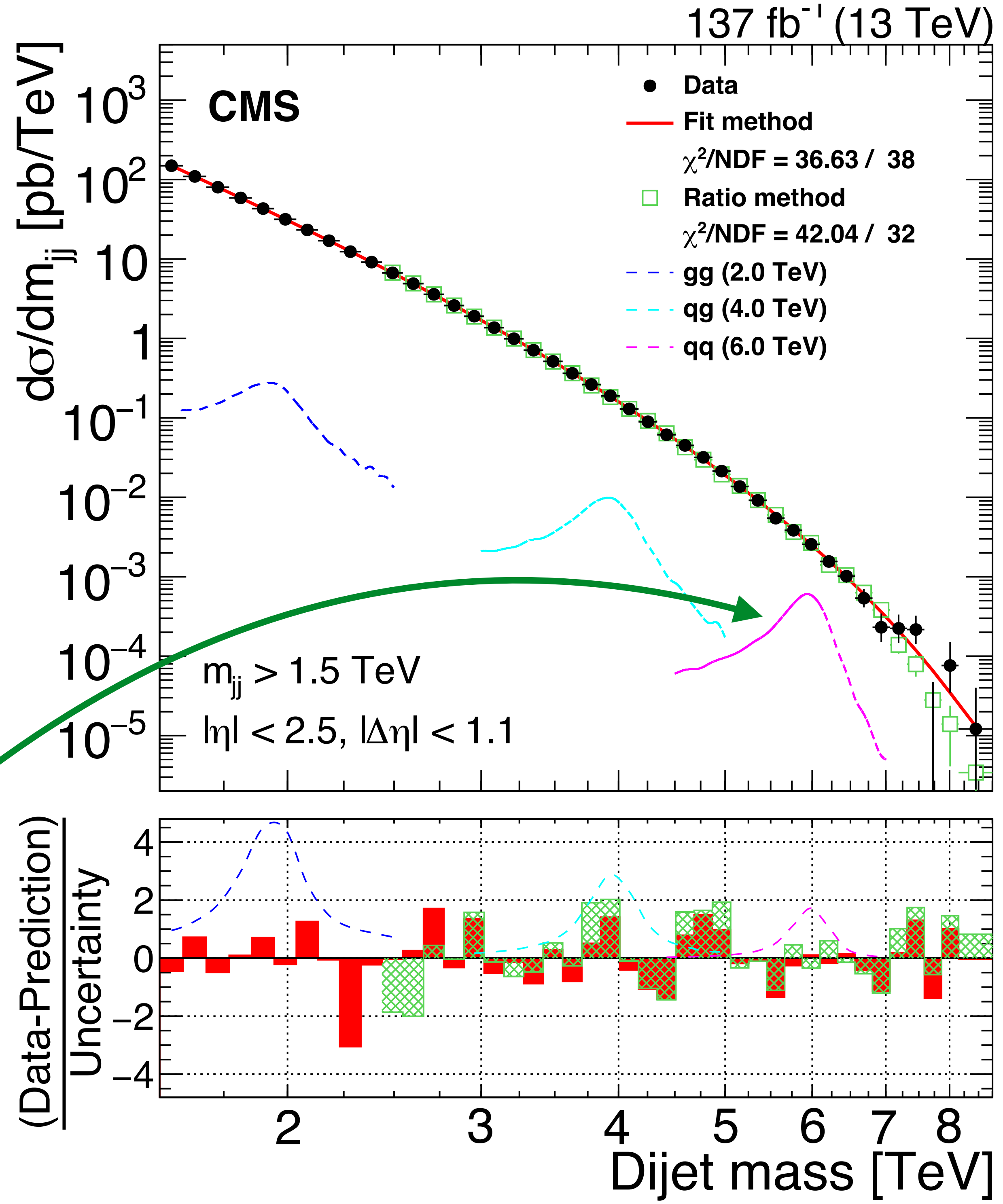
SM

BSM

H.O.



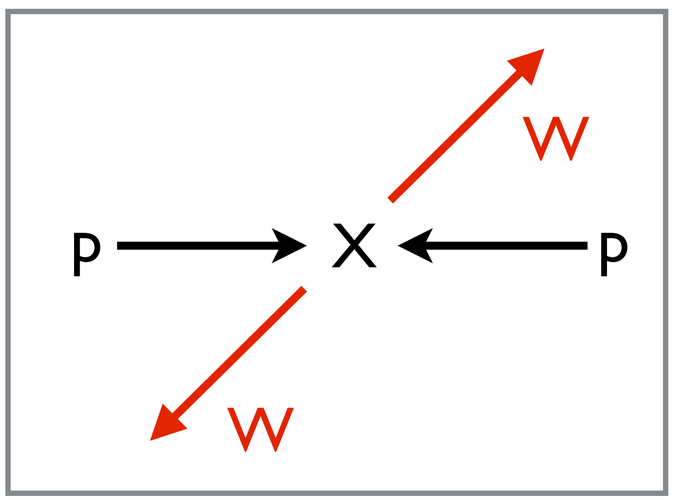
combine



[CMS, JHEP 05, 033 (2020)]

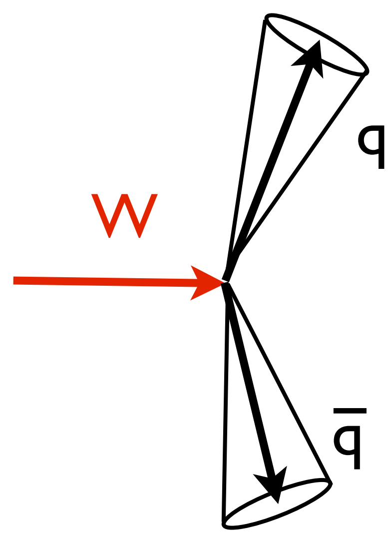
Boost!

pp→X→WW→Jets

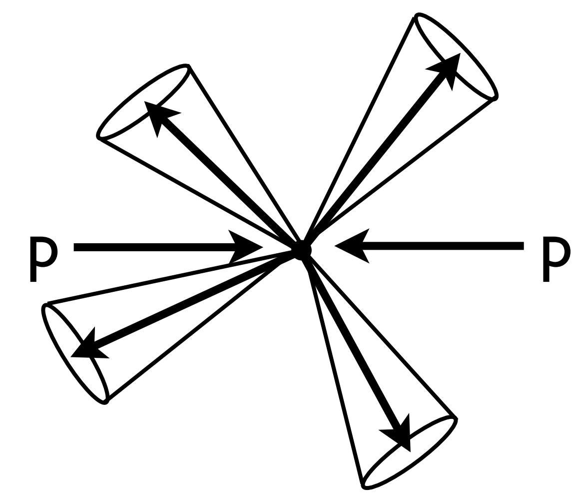


$M_X \sim 2\,M_W$

p_T^W small, $\gamma \lesssim 5$



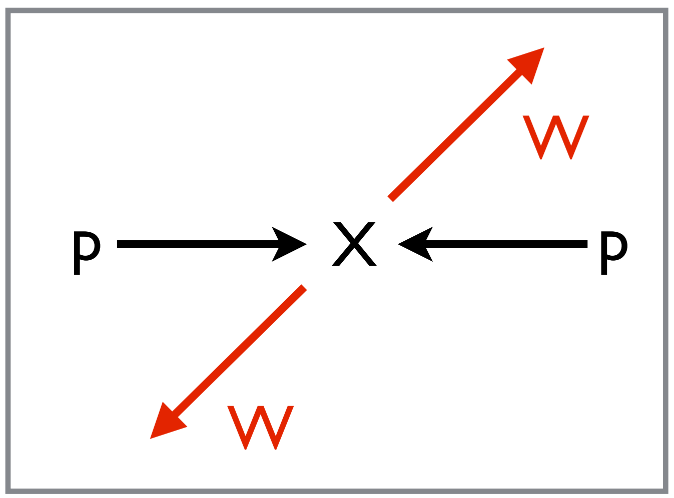
4 jet final state



combinatorics, background!

Boost!

pp→X→WW→Jets



$M_X \sim 2\ M_W$

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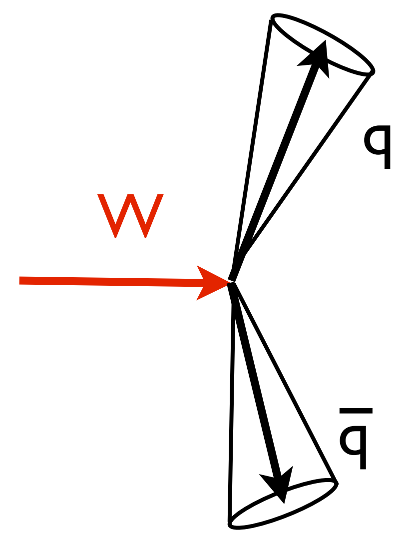
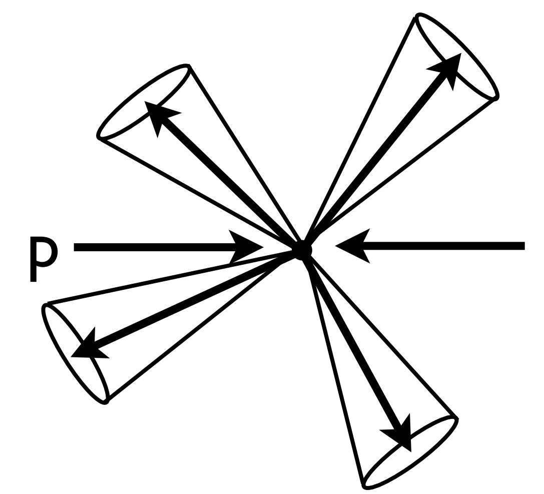


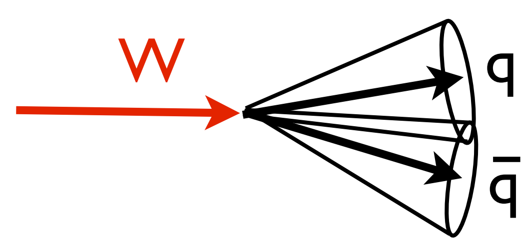
4 jet final state



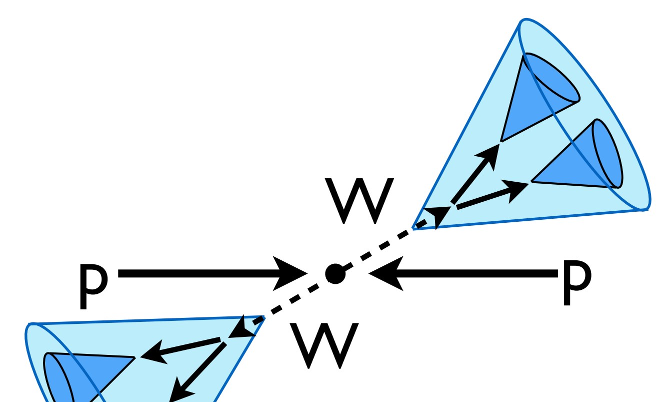
combinatorics, background!

$M_X \gg 2\ M_W$

p_T^W large, $\gamma \gg 5$



Dijet final state



Jet substructure

Diboson-tagged dijet event, M_{JJ} = 5.0 TeV

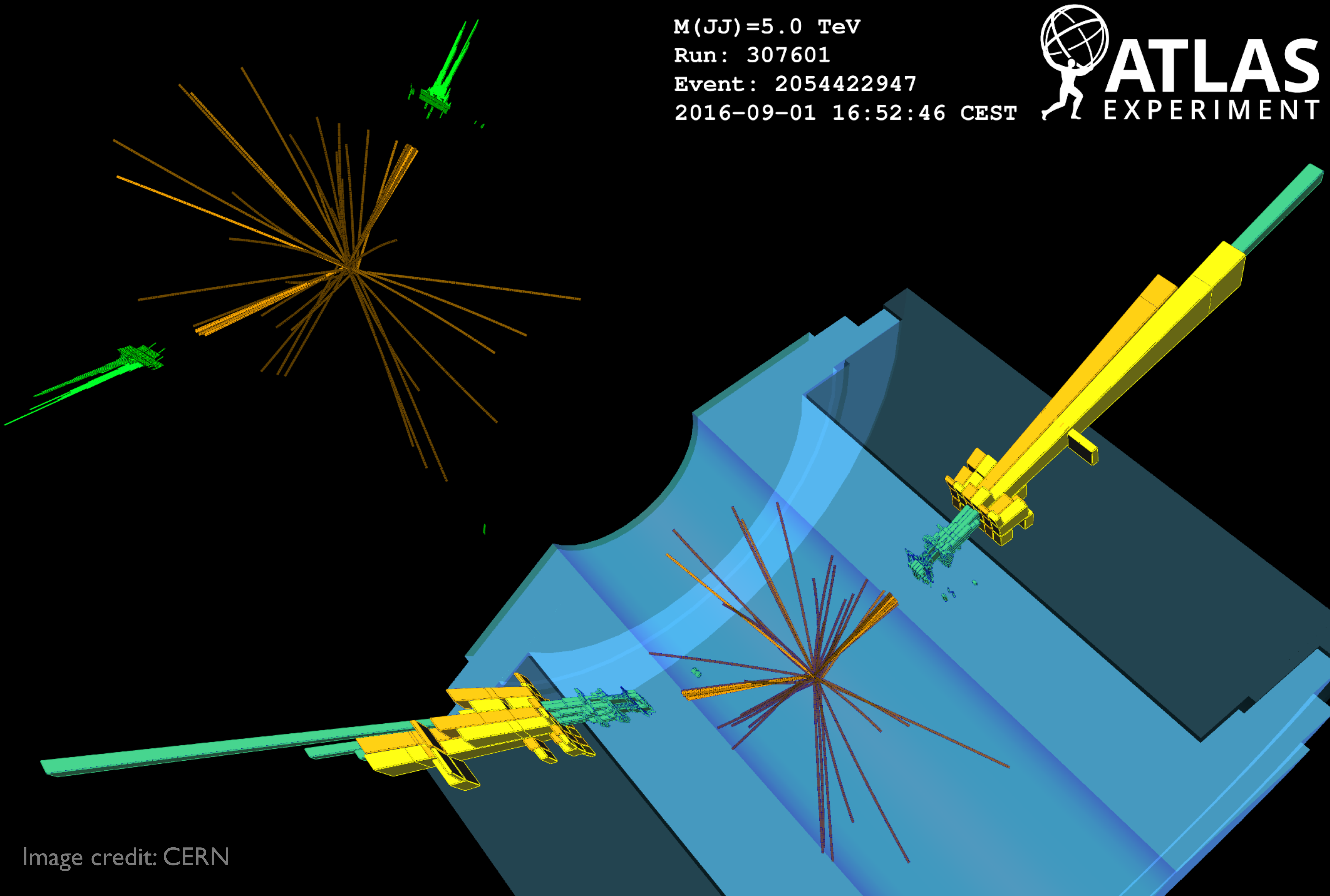
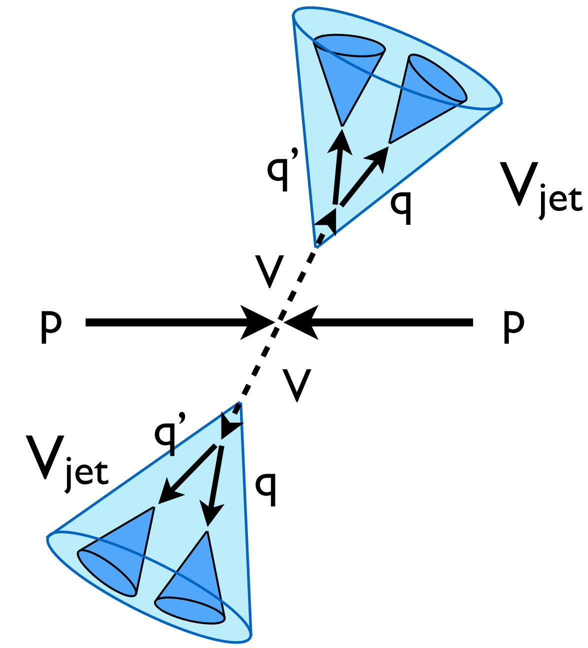


Image credit: CERN

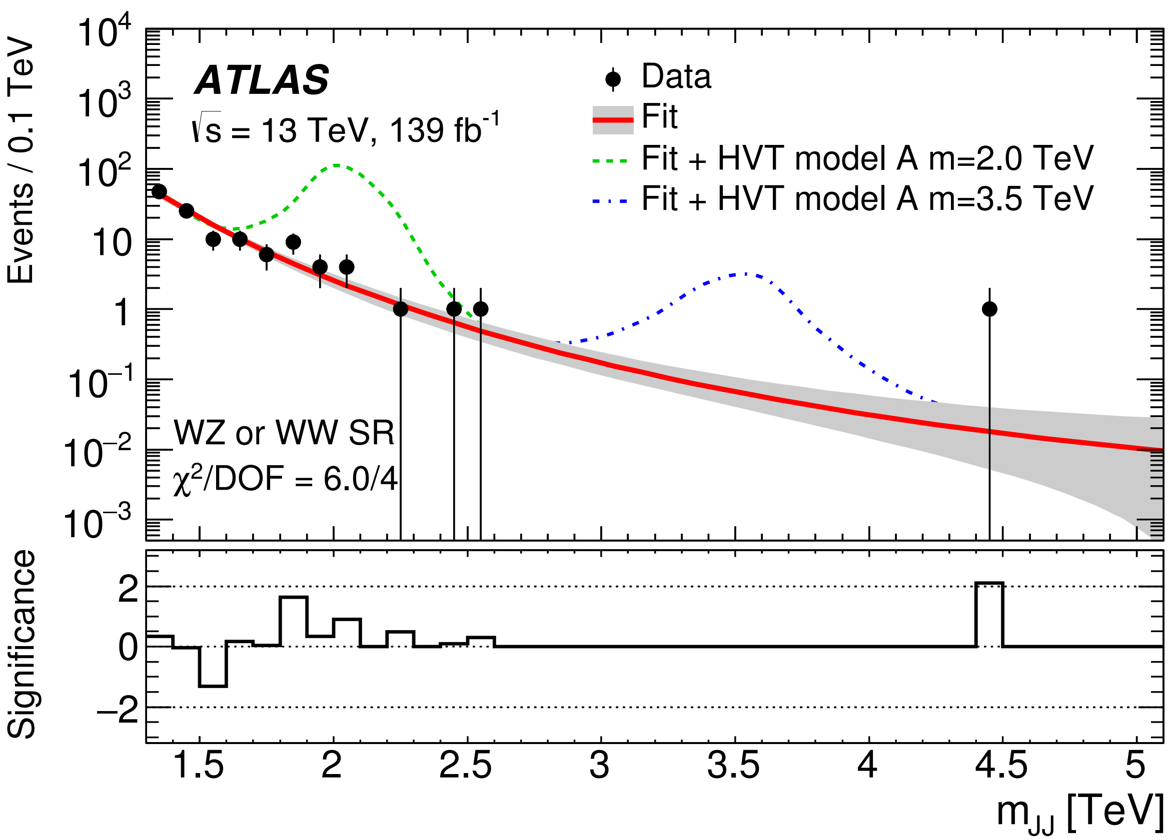
VV Resonances

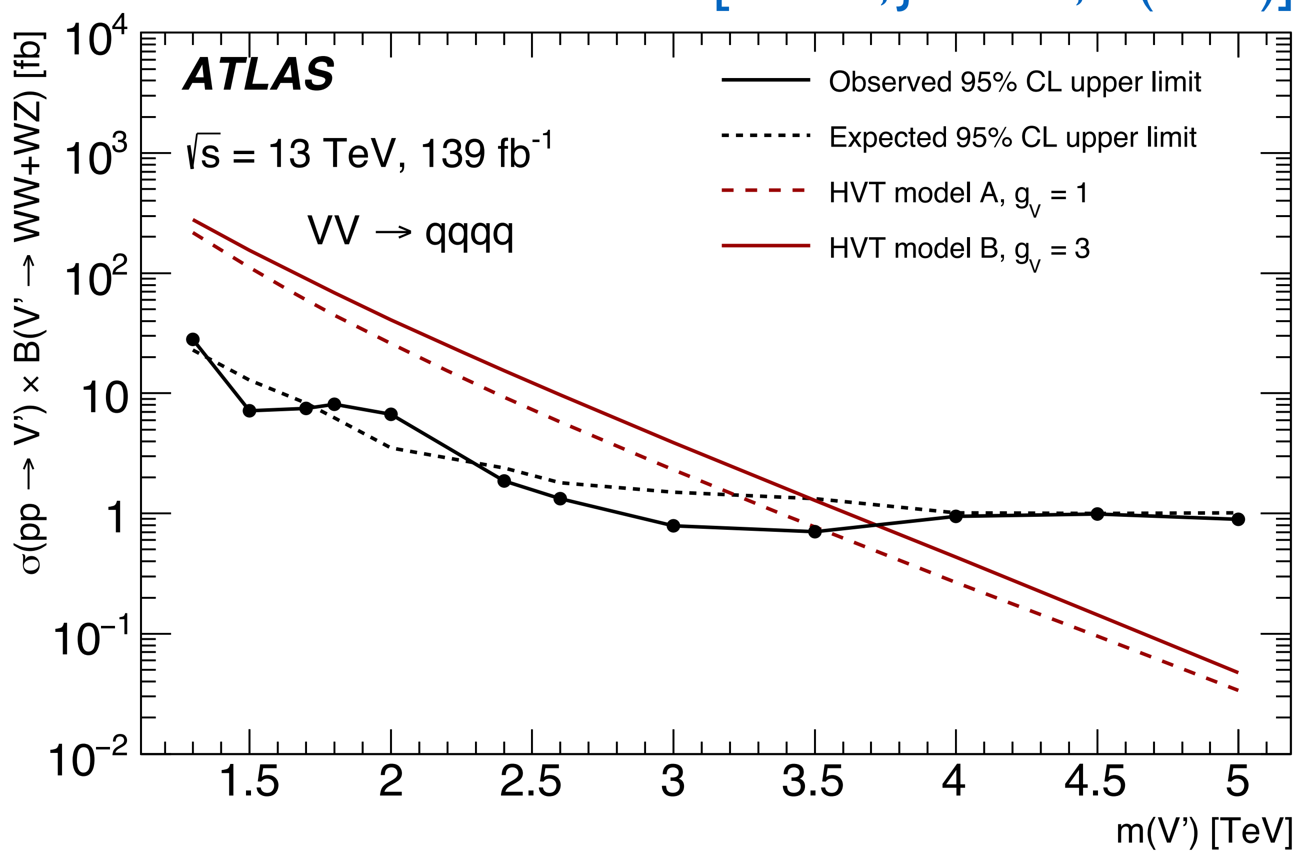


Improved jet substructure resolution with tracking information (TCCs): 50% improvement at high p_T

Optimal S/B with p_T dependent mass and D_2 selections

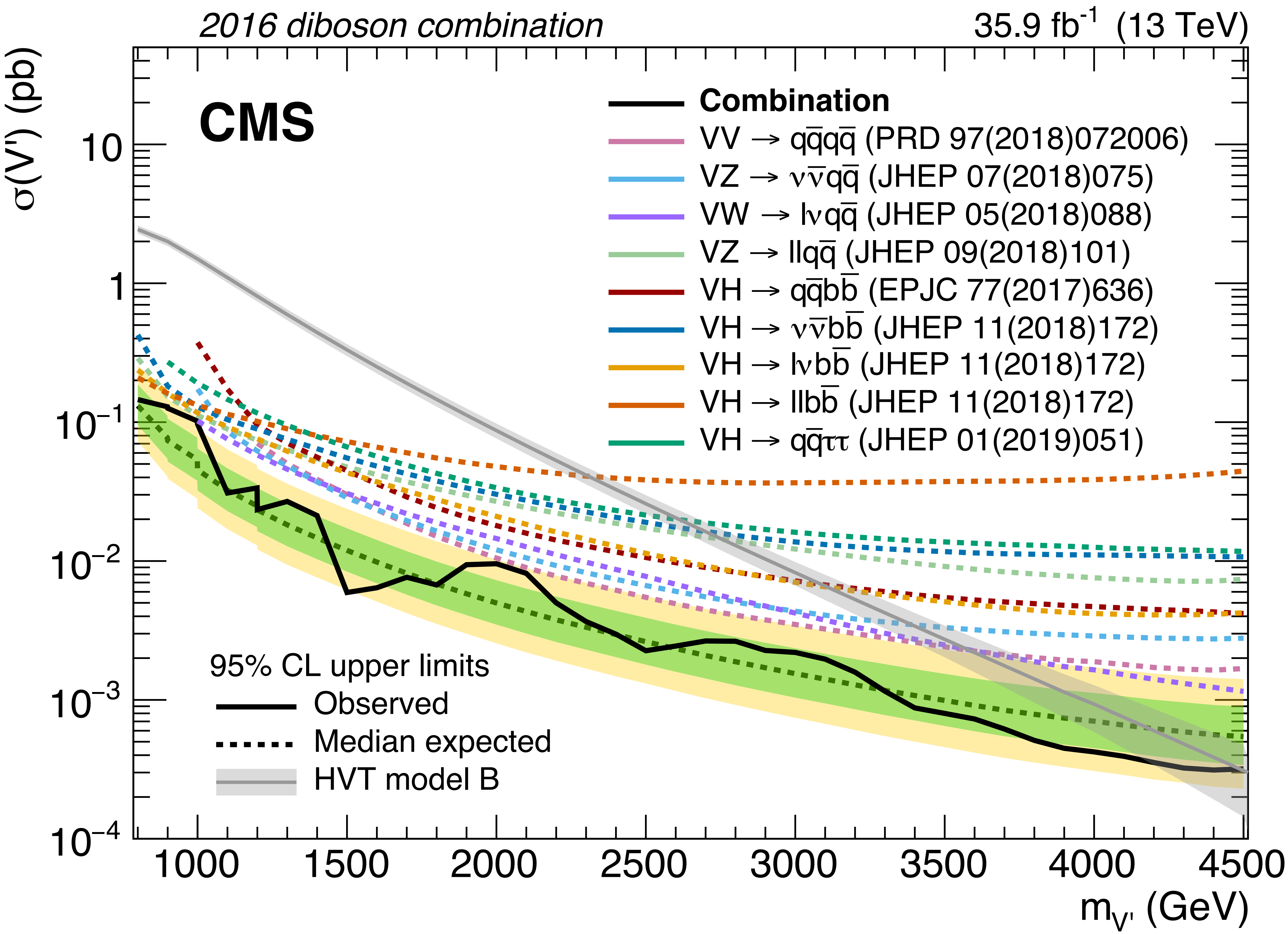
[ATLAS, JHEP 09, 1 (2019)]





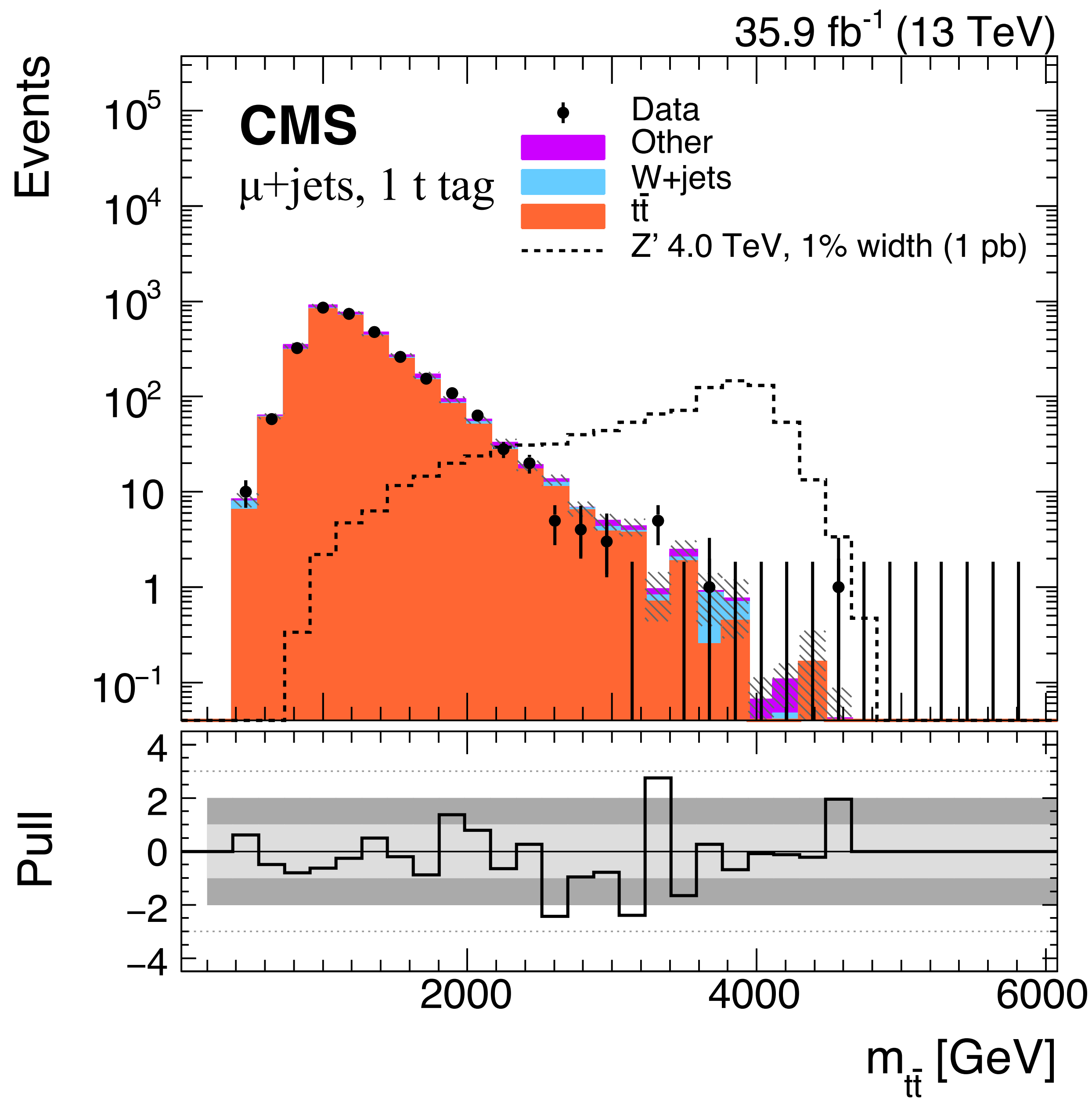
Extension to 4- and 5-prongs: [CMS, PRL 121, 141802 (2018)]

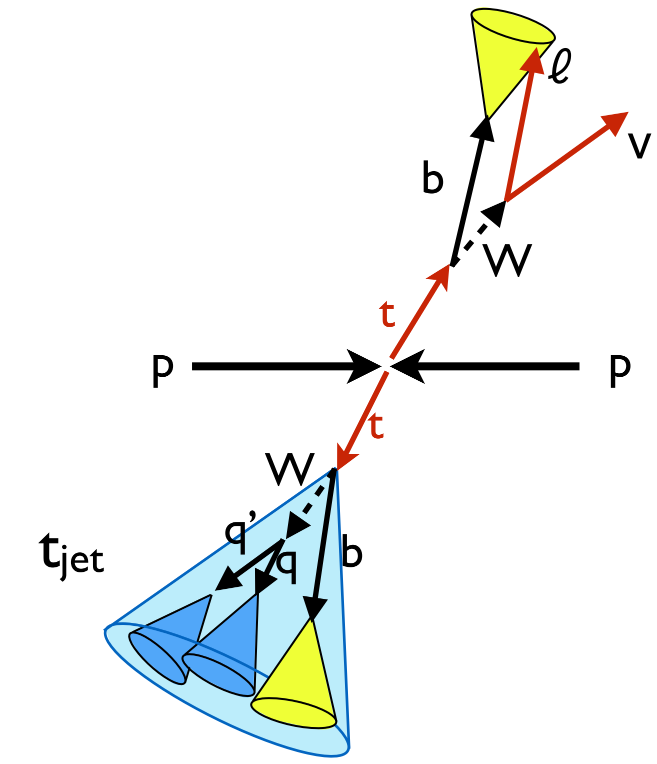
Combination



[CMS, PLB 798, 134952 (2019)]

$t\bar{t}$ Resonances





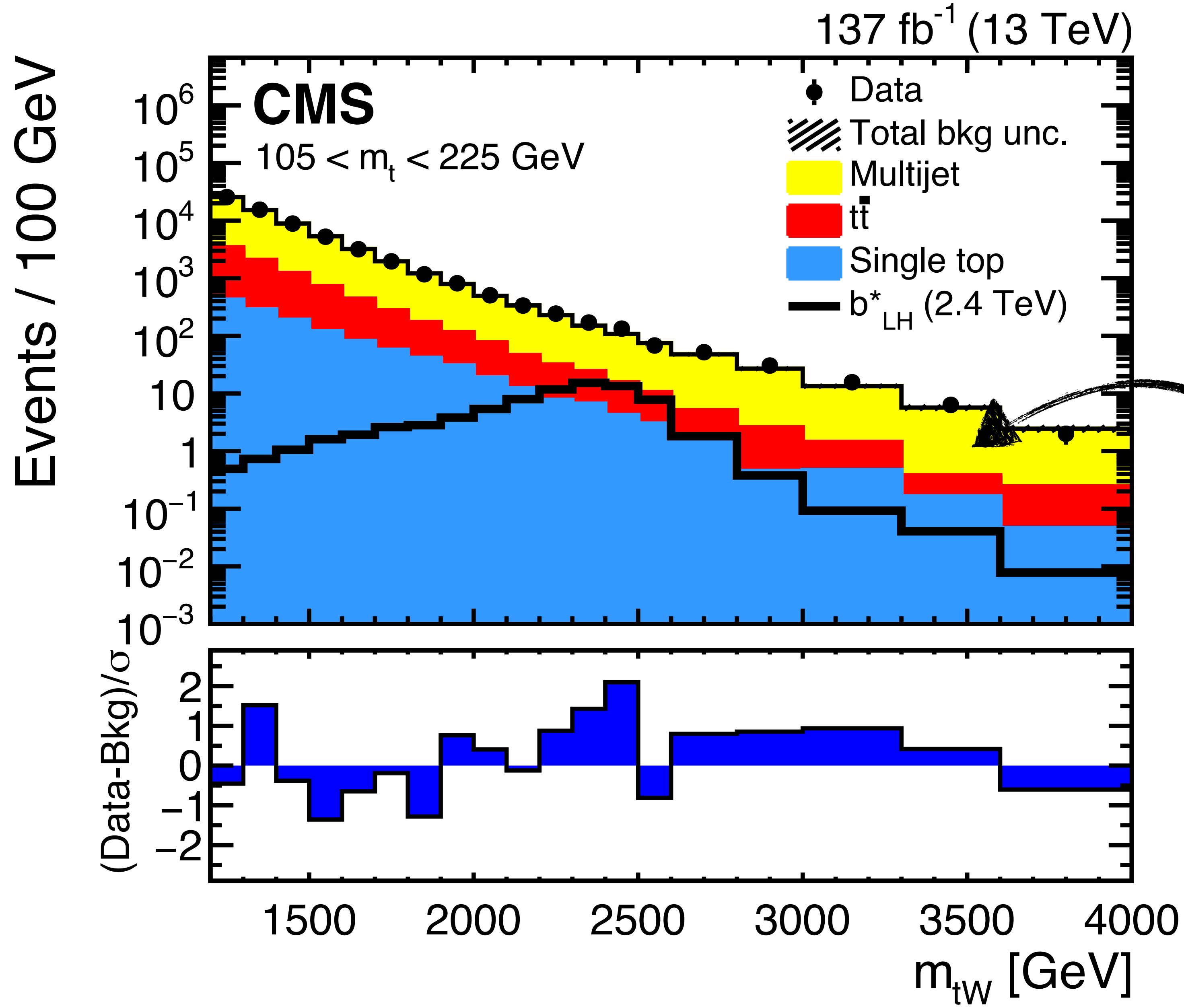
Combination of ℓℓ, ℓ+jets and all-hadronic channels:

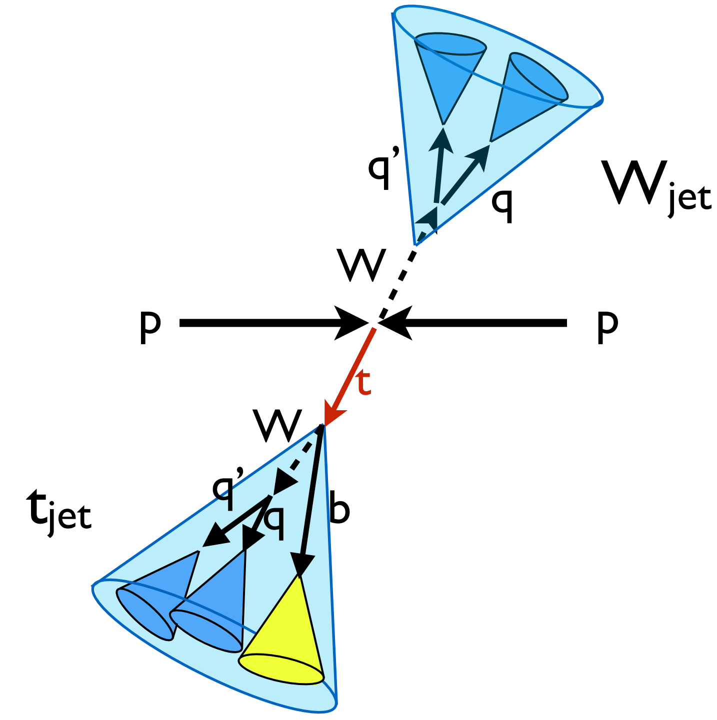
Kaluza-Klein gluons excluded below **4.6 TeV**

- BDT for W+jet suppression
- Sidebands to constrain backgrounds

[CMS, JHEP 04, 031 (2019)]

tW resonances



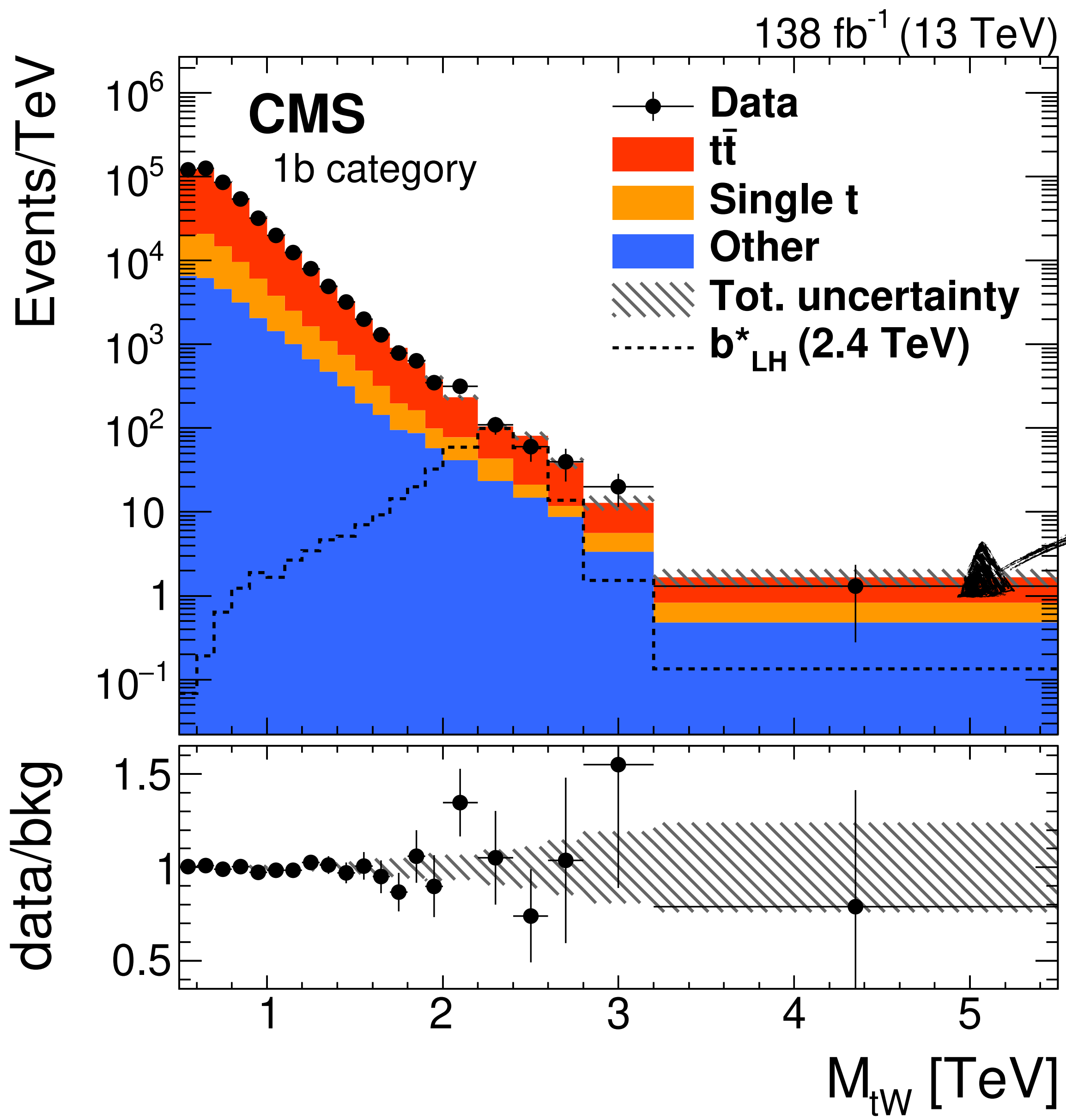


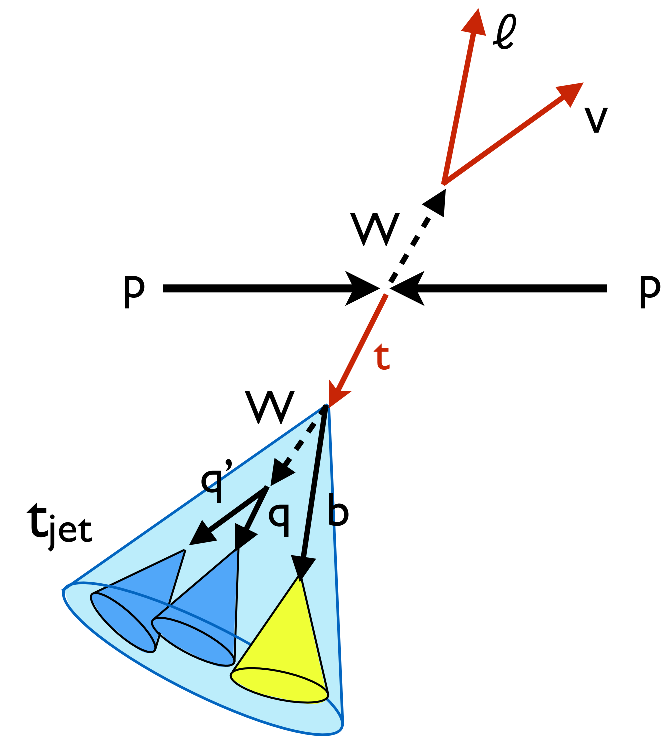
Multijet background estimated from a 2D pass-fail ration in (m_t, m_{tW}) plane

- Sensitivity to excited b* quarks and vector-like quarks

[CMS, JHEP 12, 106 (2021)]

tW resonances



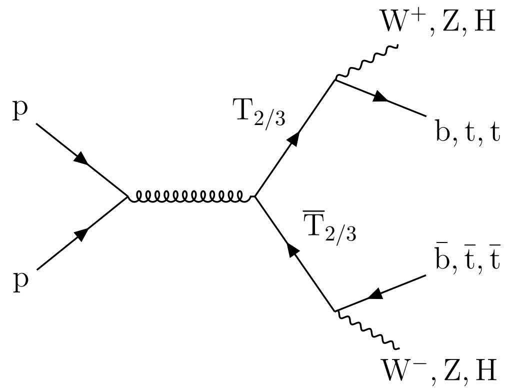


Genuine top quark background dominates (tt, tW)

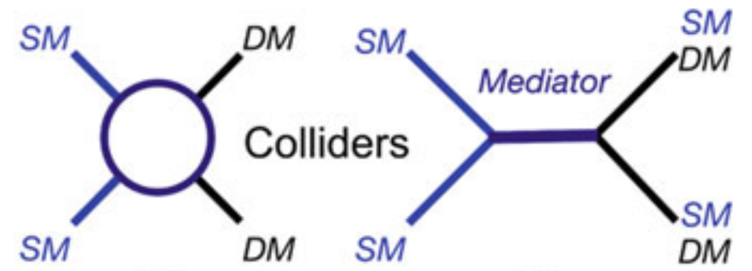
- Extend sensitivity down to 700 GeV using lepton triggers and HOTVR
- Background from misidentified t jets extrapolated from sideband

[CMS, JHEP 04, 048 (2022)]

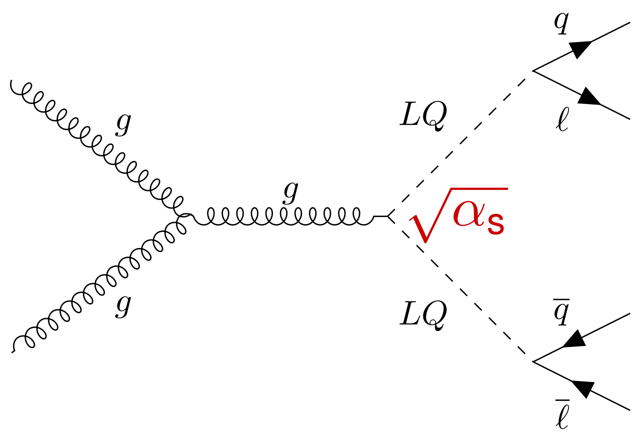
Searches, Searches, Searches



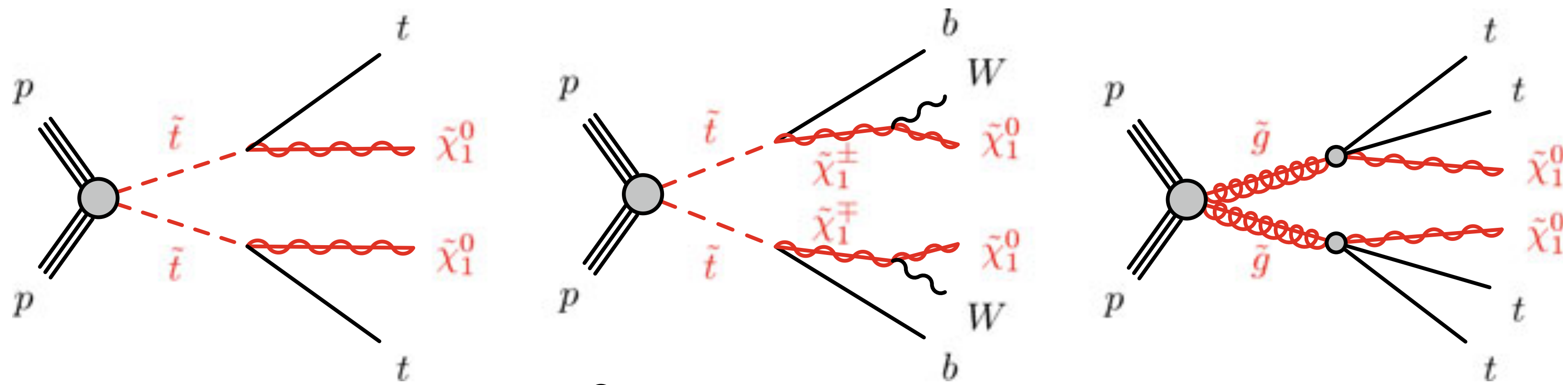
Vector-like quarks



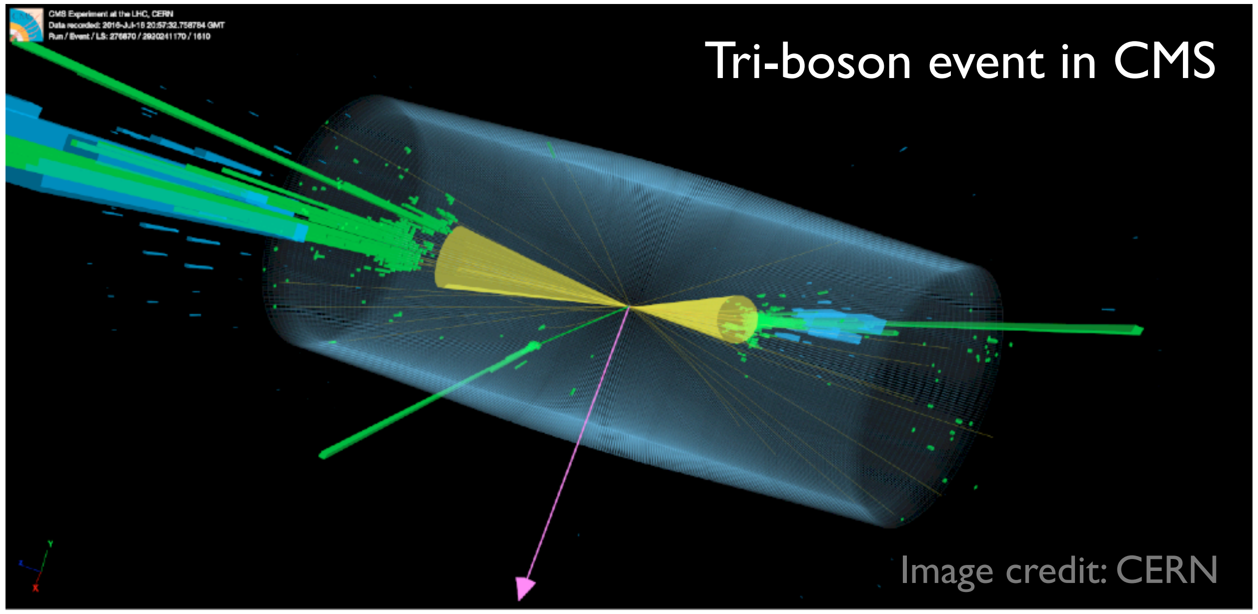
Dark matter



Leptoquarks



Supersymmetry



[CMS, JHEP 08, 177 (2018)]

[https://atlas.cern/updates/atlas-feature/dark-matter]

[ATLAS, JHEP 06, 108 (2018)]

[ATLAS, JHEP 10, 062 (2020)]

Summary

Jet substructure ubiquitous at the LHC

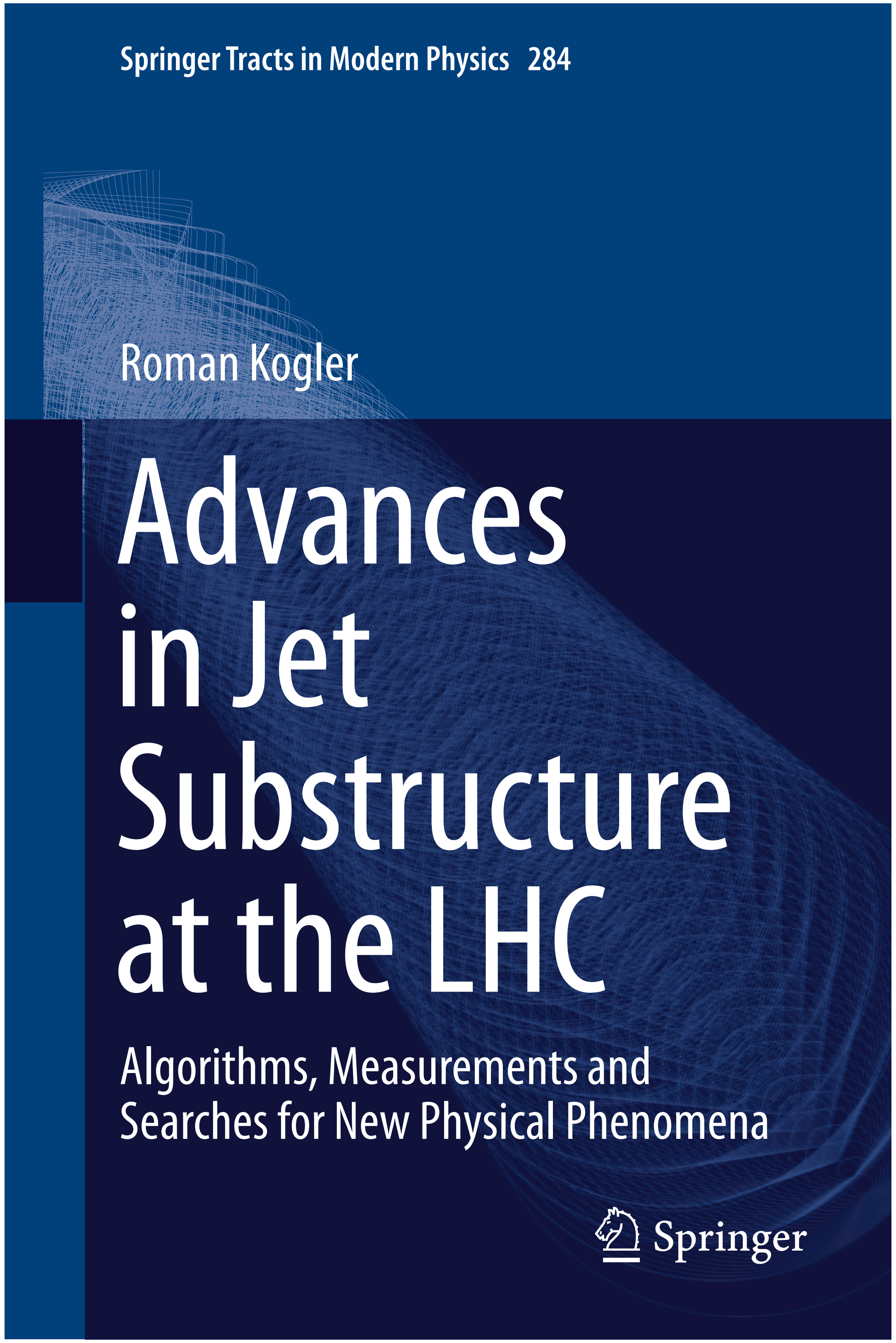
- Remarkable progress in the last 15 years
- Exciting interplay between:
  - theory
  - model building
  - tools development
  - commissioning
  - application

[M. Schwartz at BOOST 2012]

- Jet substructure is past its adolescence: Precision QCD!
- Coming years will bring many novel measurements, searches and algorithms with jet substructure


Image credit: Acton Memorial Library

[RK, STMP 284, 2021]



Thanks

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CMS Physics Group “Beyond 2 Generations”

CMS Physics Group “Top quarks”

CMS Object Group “Jets and Missing Energy”

All colleagues from ATLAS, CMS and Theory

My family and friends