Boosting physics at the LHC

with signatures involving boosted particles

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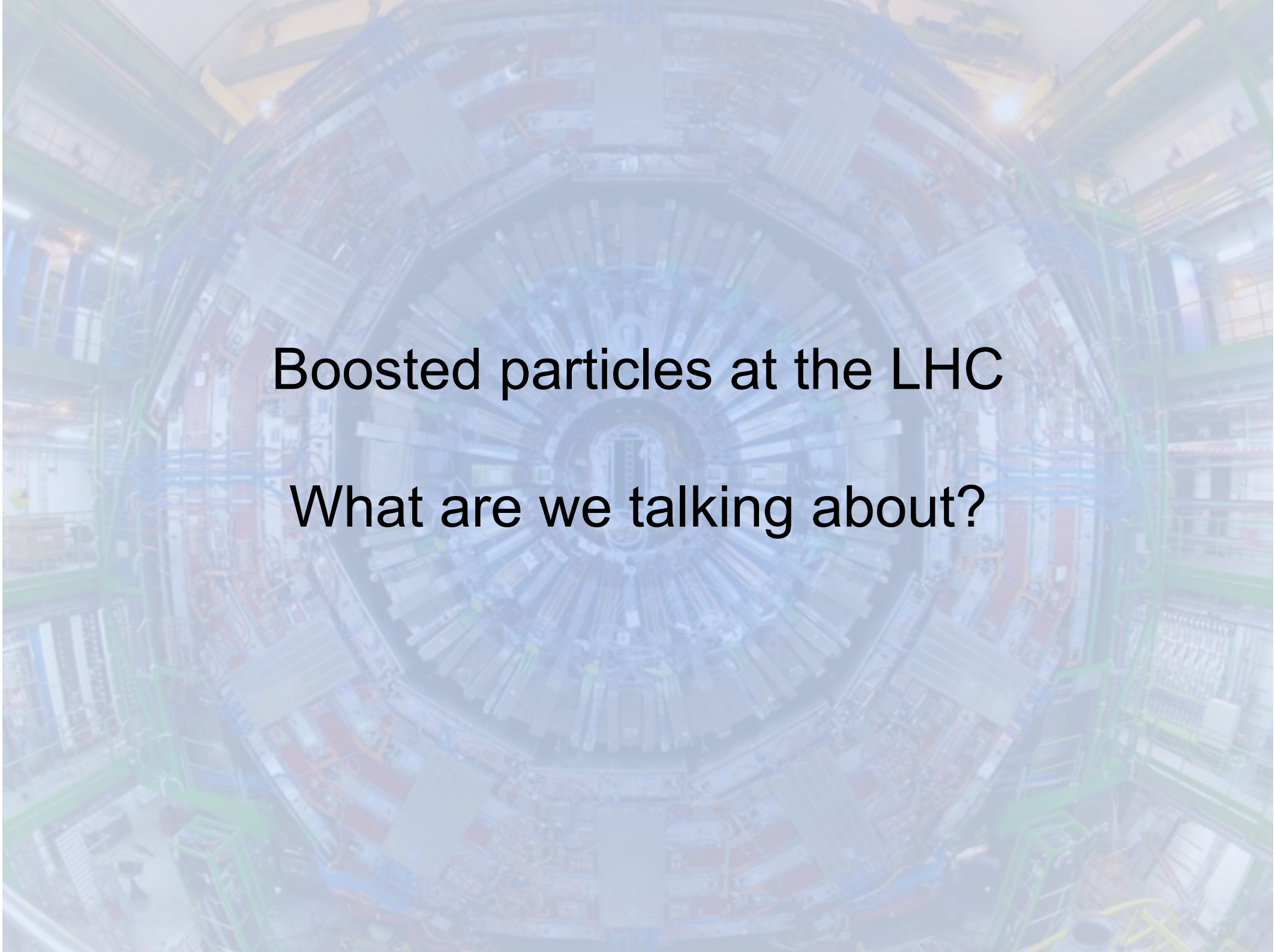
SFB 676 Colloquium

Universität Hamburg

DER FORSCHUNG | DER LEHRE | DER BILDUNG

Boosted particles at the LHC

- What are we talking about?
- How do we measure them?
- What physics can we probe with them?
- What's the future?

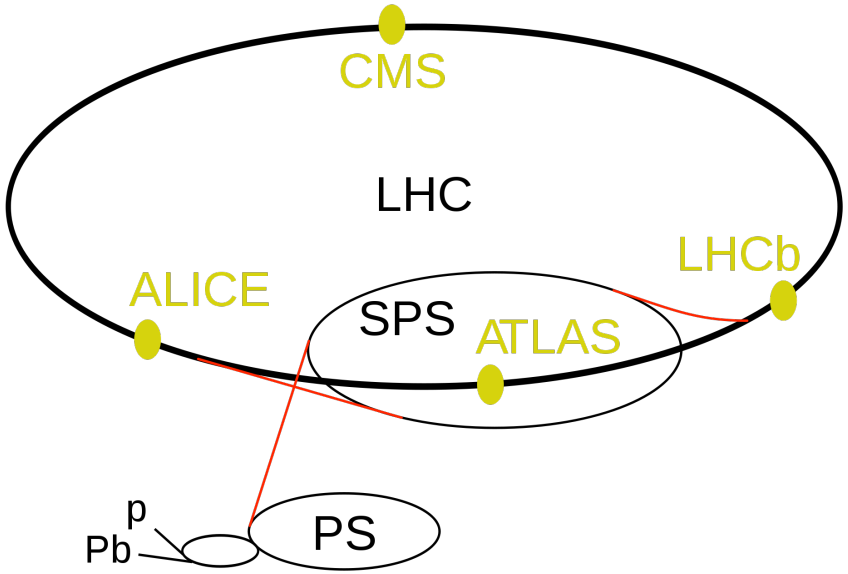


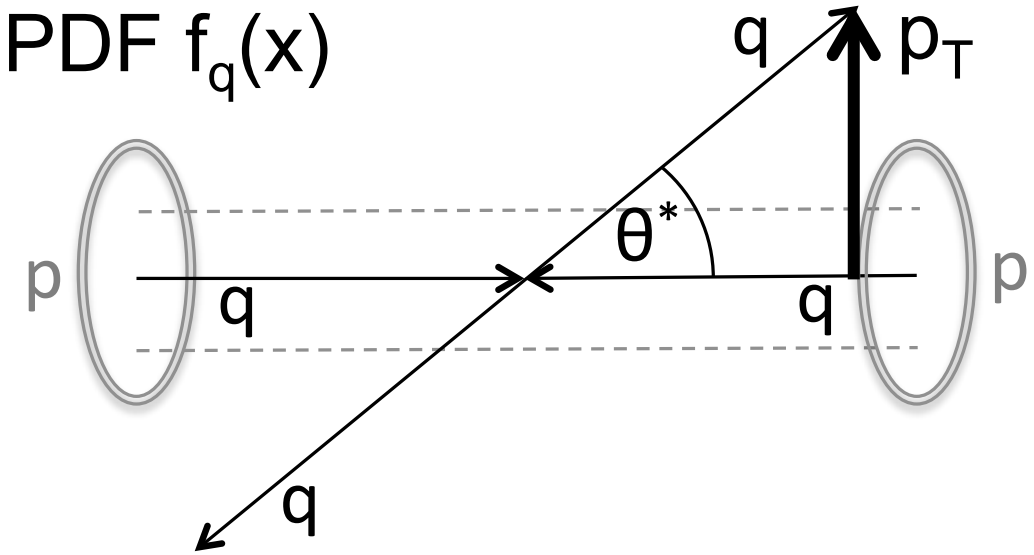
Boosted particles at the LHC

What are we talking about?

Particle production at the LHC

$\sqrt{s} = 13$ TeV (2015-2018)





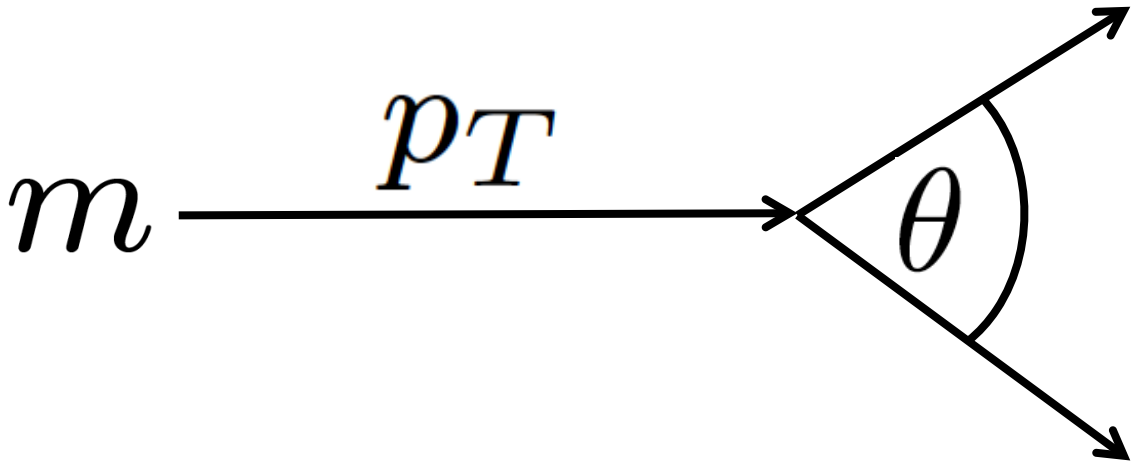
- Maximum (possible) particle transverse momentum p_T at LHC 6.5 TeV

Lorentz boost and decay

- Lorentz boost of particle with mass m

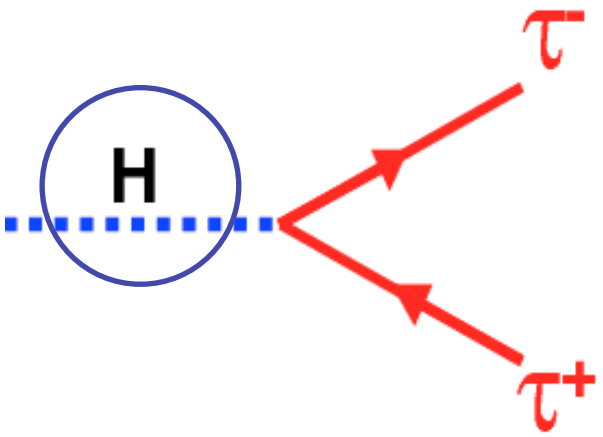
$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} = \frac{E}{mc^2}$$

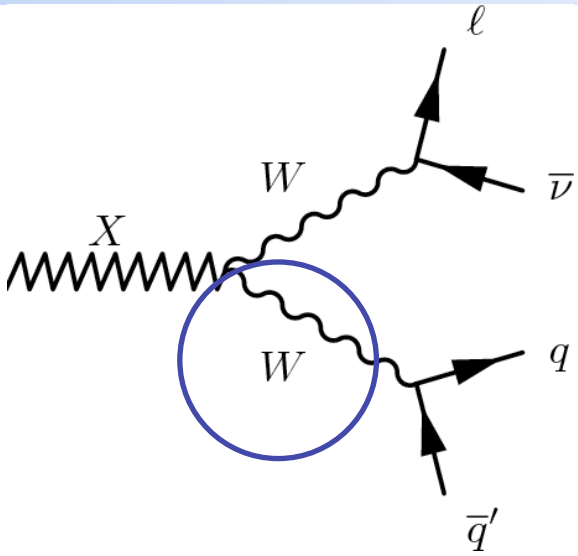
- Decay angle of unstable particles with mass m



$$\theta \lesssim 2\frac{m}{p_T}$$

Examples for boosted particles



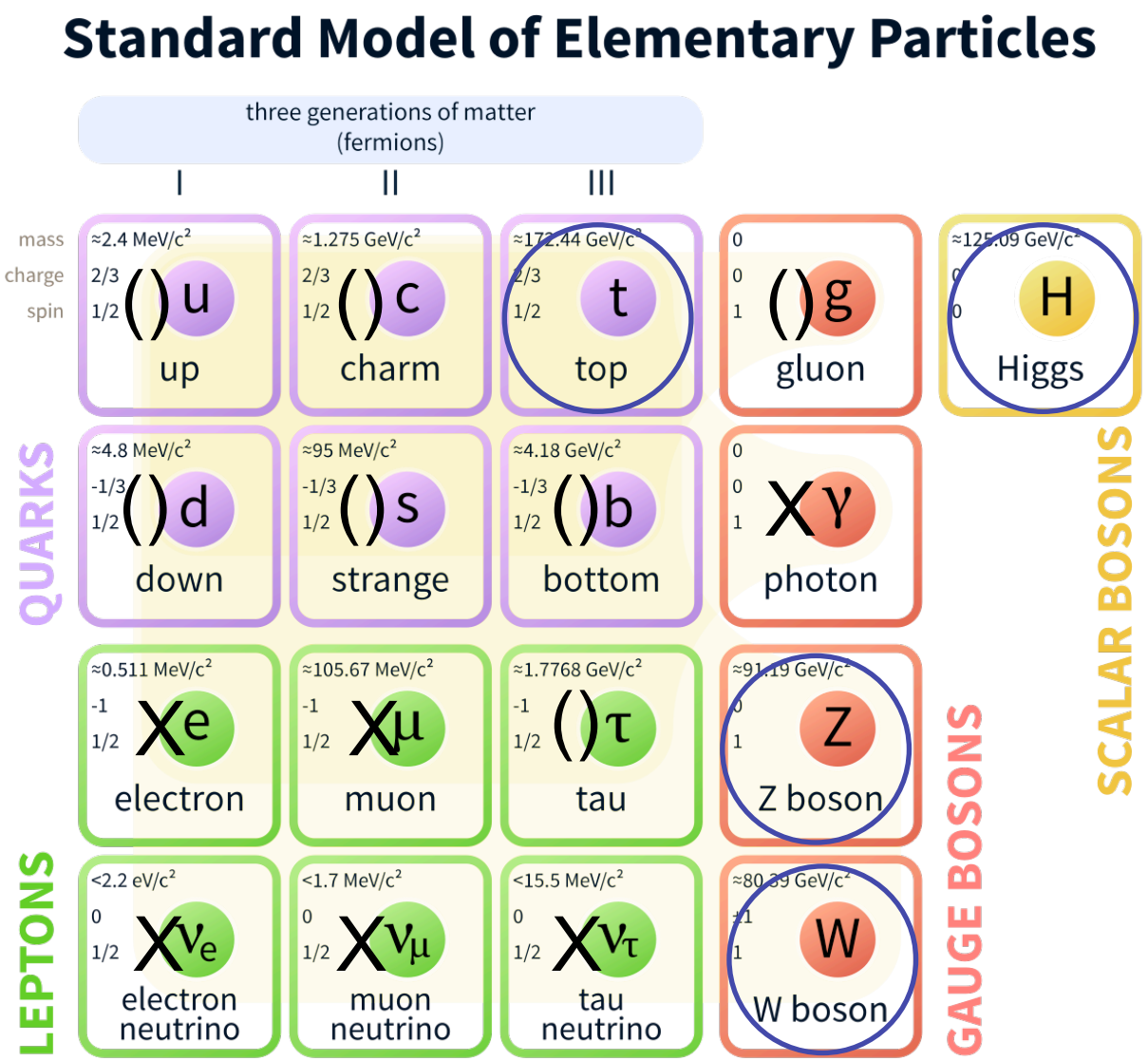


$$\theta \lesssim 2\frac{m}{p_T}$$

p_T = 500 GeV
m^H = 125 GeV
θ ~ 0.5

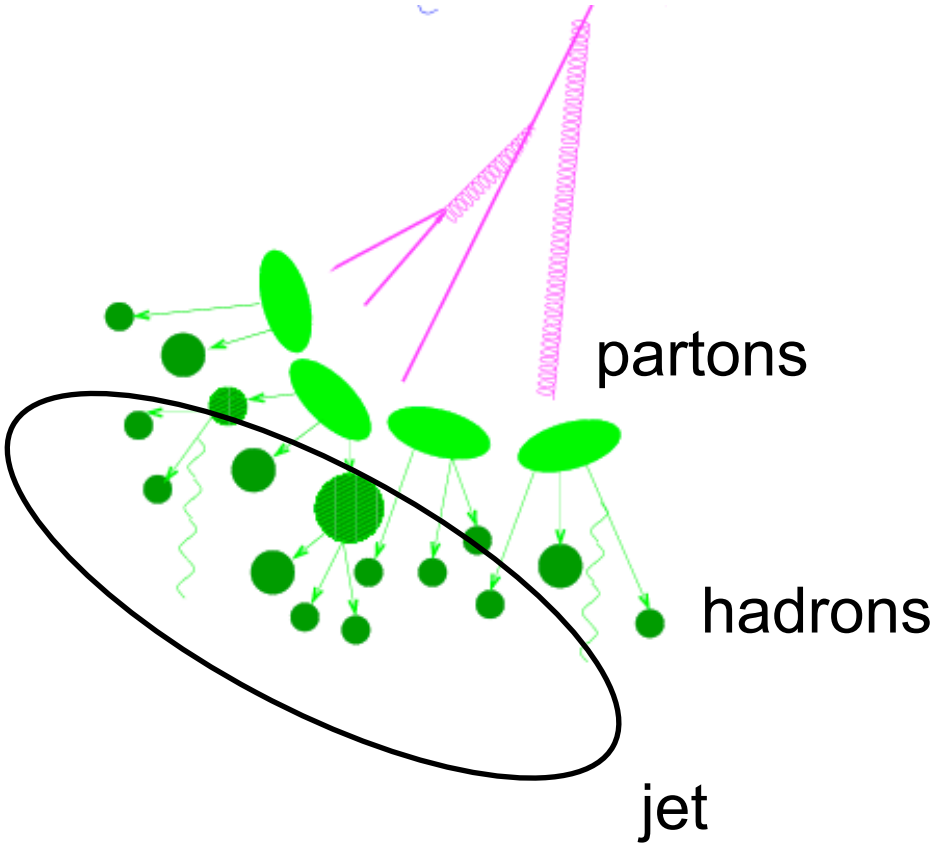
m^X = 4000 GeV
p_T^W ~ 2000 GeV
m^W = 81 GeV
θ ~ 0.08

Boosted particles in SM

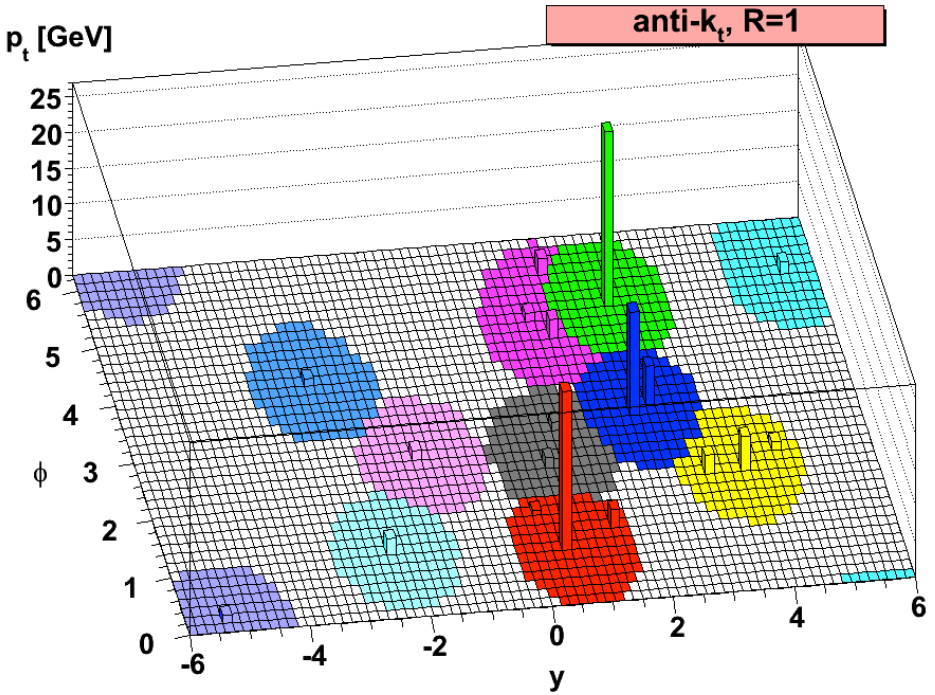


Jets from light partons

- Light partons (quarks, gluons) form jets of particles in detector



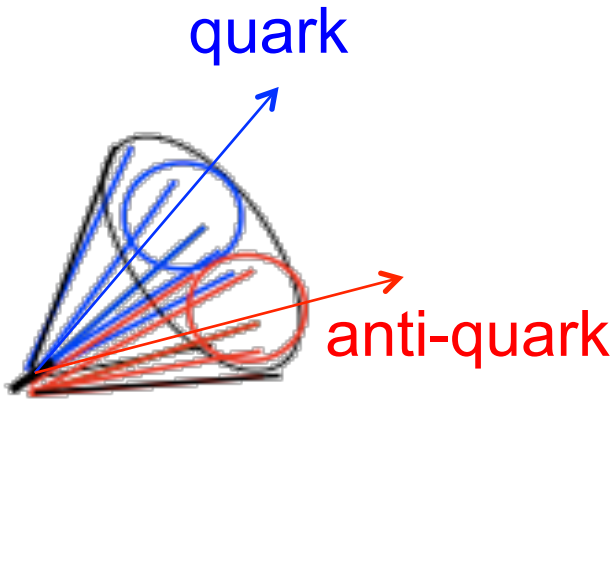
Jet clustering



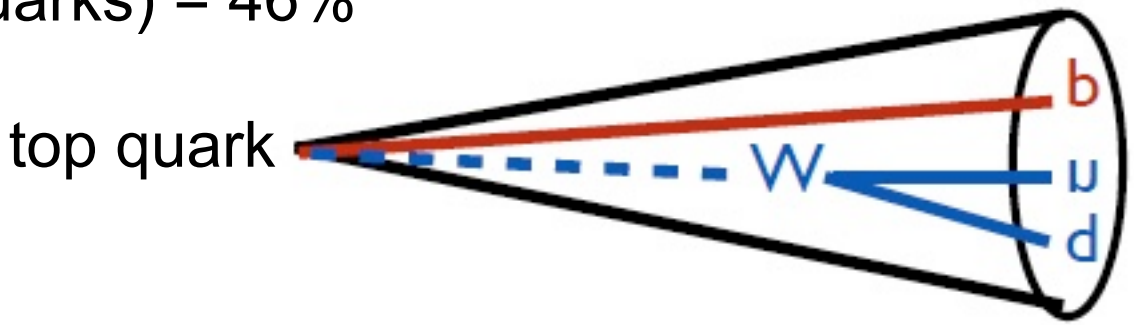
https://arxiv.org/abs/0802.1189

Jets from boosted particles

BR(W/Z/H→quarks) > 60%



BR(top→quarks) = 46%



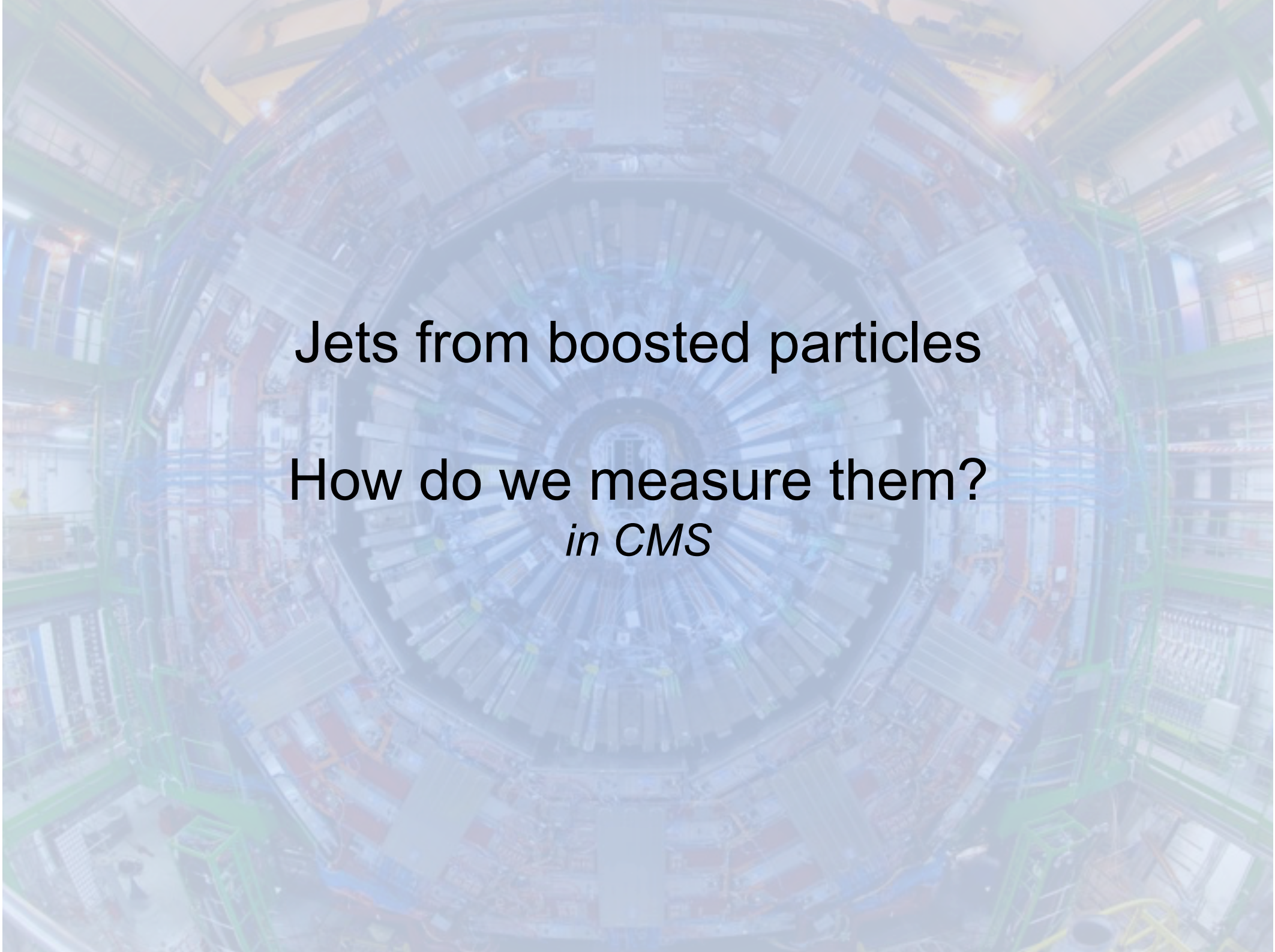
- Identify with jet mass and jet substructure

Boosted particles at the LHC

- What are we talking about?
- How do we measure them?
- What physics can we probe with them?
- What's the future?

„Boosted bosons at CMS“

Particles, Strings,
and the Early Universe
Collaborative Research Center SFB 676

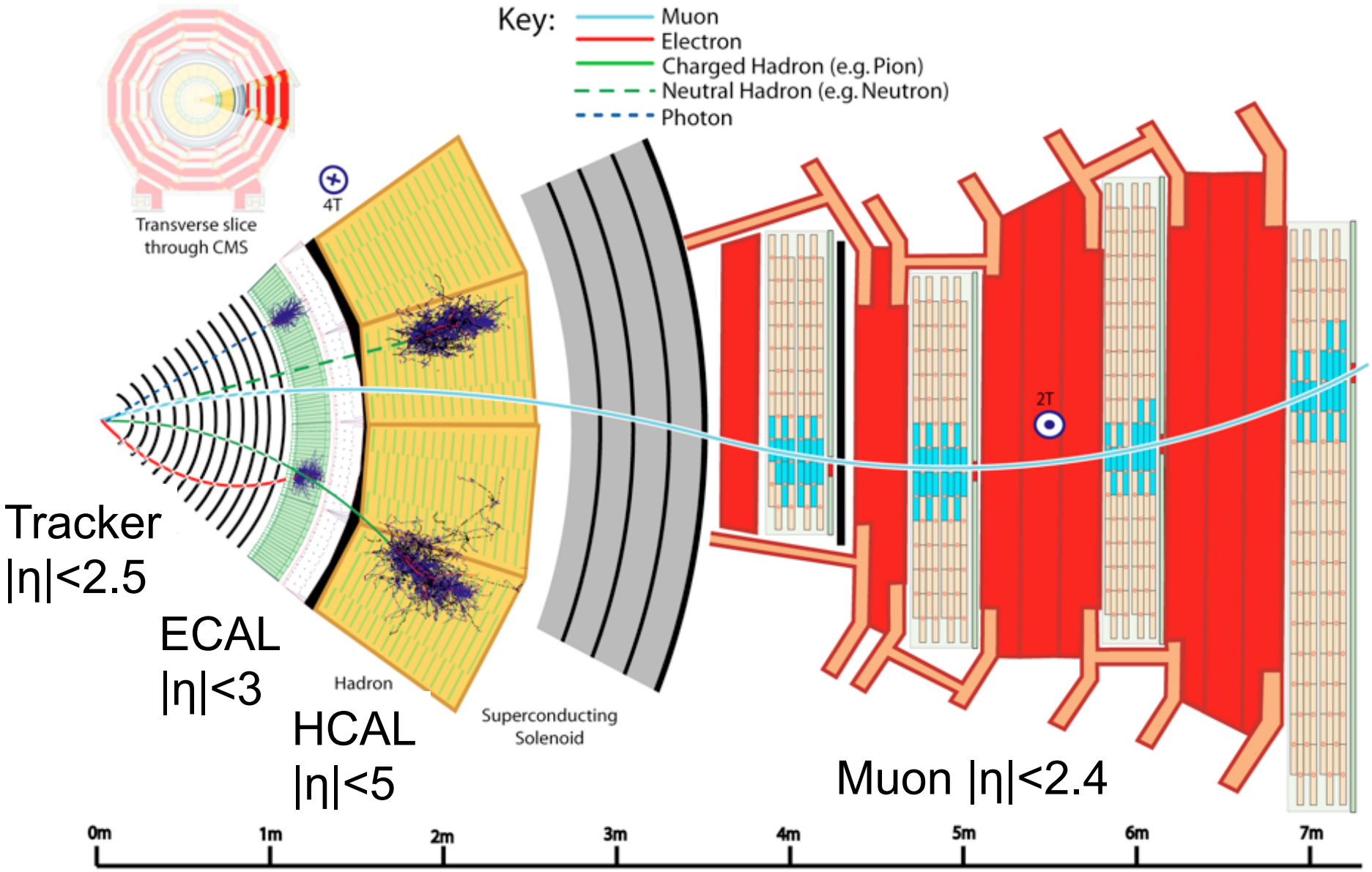


Jets from boosted particles

How do we measure them?

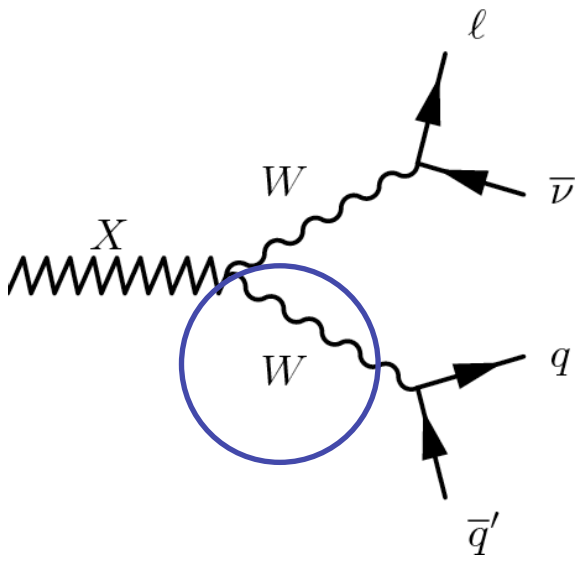
in CMS

The CMS detector



Energy and spatial resolutions

Detector	p_T-resolution	η/Φ-segmentation
Tracker	0.6% (0.2 GeV) – 5% (500 GeV)	0.002 x 0.003 (first layer)
ECAL	1% (20 GeV) – 0.4% (500 GeV)	0.017 x 0.017 (barrel)
HCAL	30% (30 GeV) – 5% (500 GeV)	0.087 x 0.087 (barrel)



m^X = 4000 GeV

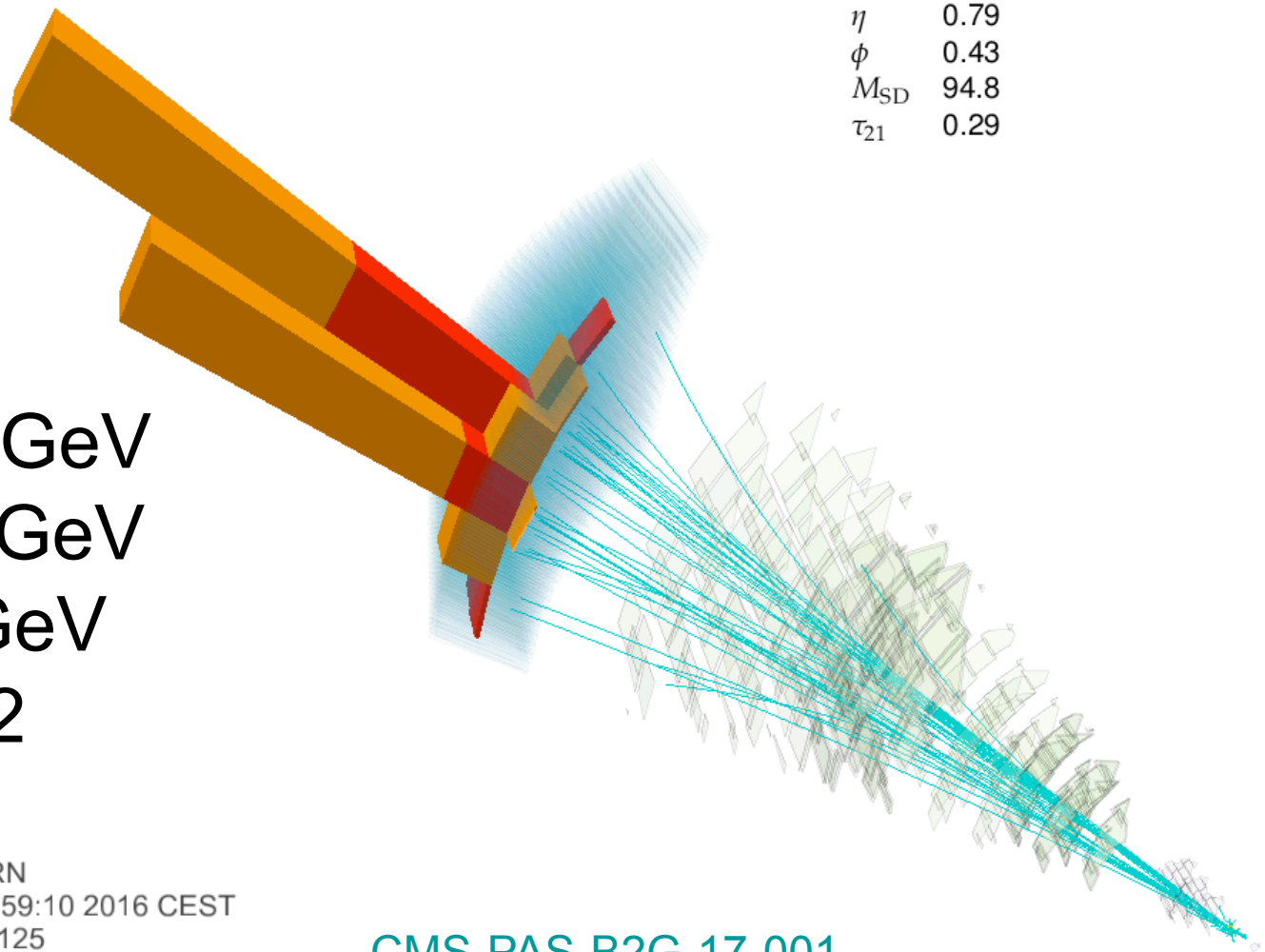
p_T^W ~ 2000 GeV

m^W = 81 GeV

θ ~ 0.08

- Coarse HCAL resolution makes substructure reconstruction challenging

Boosted Z event display



Candidate Z jet

Anti-k_T R=0.8 jet	
p_T	1374 GeV
η	0.79
ϕ	0.43
M_{SD}	94.8
τ_{21}	0.29

m^X = 3200 GeV

p_T^Z =1400 GeV

m^Z = 90 GeV

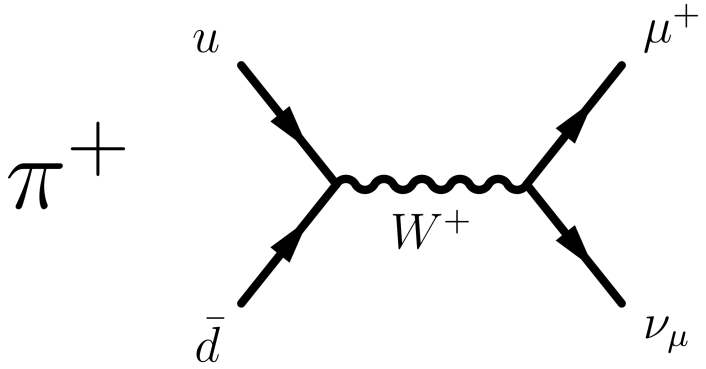
$\theta \sim 0.12$

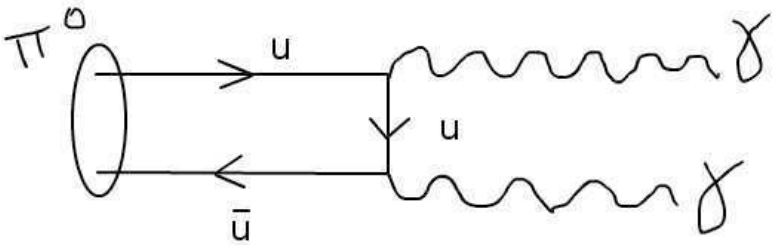
CMS Experiment at LHC, CERN
Data recorded: Mon Jul 18 19:59:10 2016 CEST
Run/Event: 276950 / 1080730125
Lumi section: 573

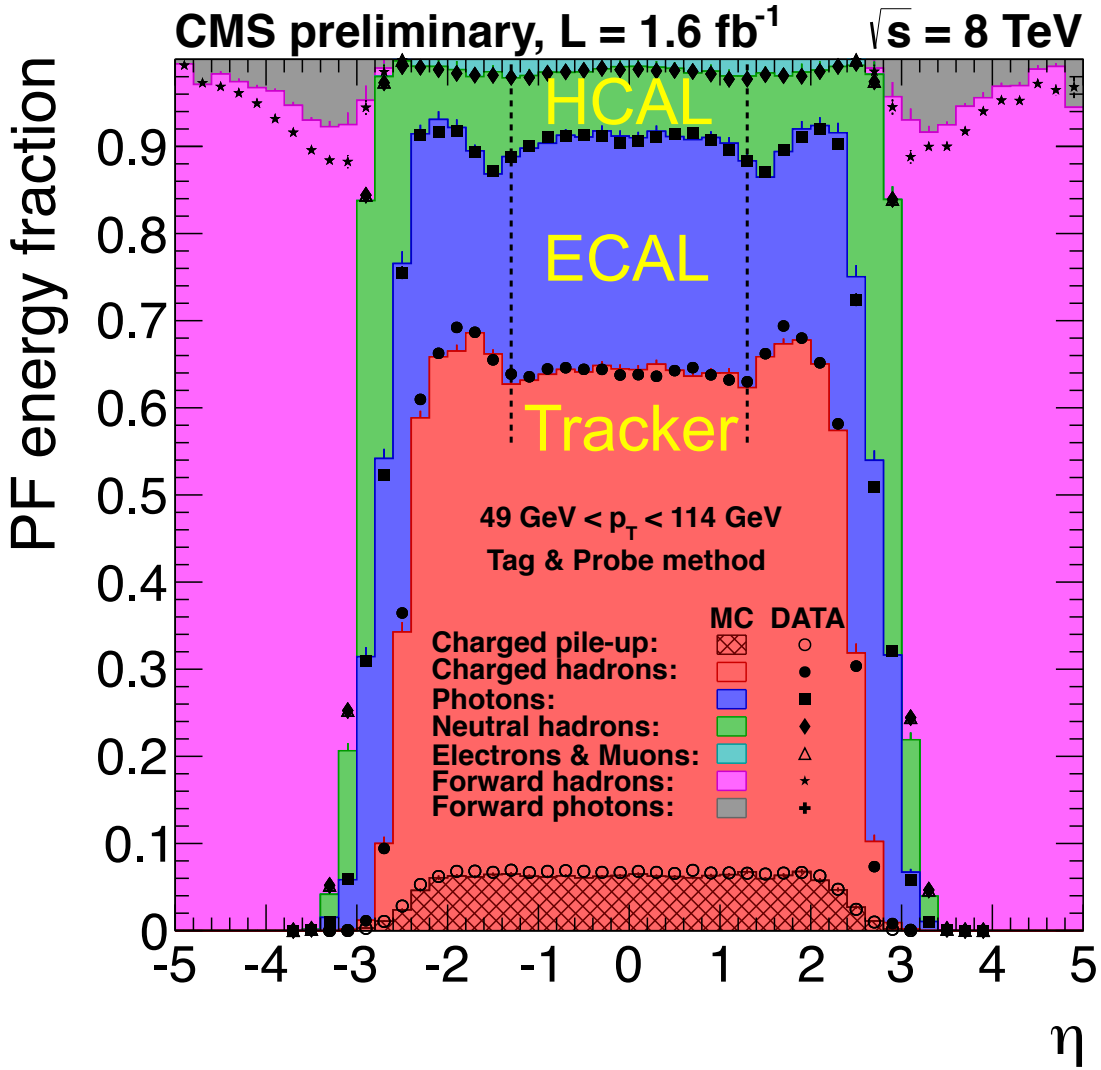
CMS-PAS-B2G-17-001

Jet composition and particle flow

- 30% $|\pi^+\rangle = |u\bar{d}\rangle$
  30% $|\pi^-\rangle = |d\bar{u}\rangle$
  30% $|\pi^0\rangle = \frac{1}{\sqrt{2}}\left[|u\bar{u}\rangle - |d\bar{d}\rangle\right]$
  10% other hadrons







CMS-DP-2012/012

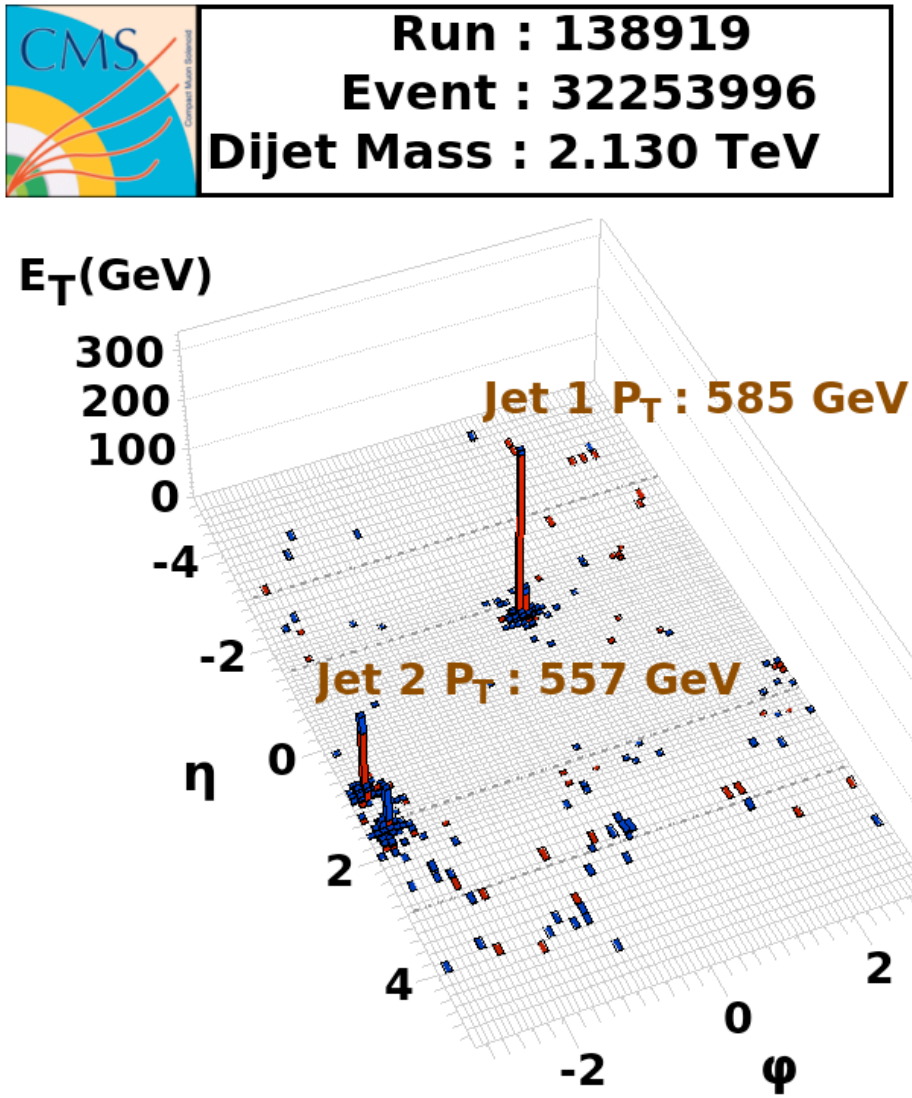
Jet clustering

- Cluster towers with anti-k_T jet algorithm

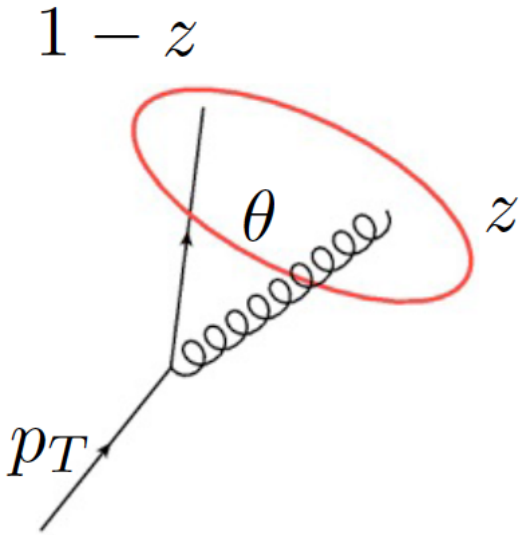
$$d_{ij} = \frac{1}{\max(k_{Ti}^2, k_{Tj}^2)} \frac{\Delta R_{ij}^2}{R^2}$$

- Typical size parameter
  - R=0.4 for light partons
  - R=0.8 for boosted W/Z/H/top

p_T = 500 GeV
m^H = 125 GeV
θ ~ 0.5

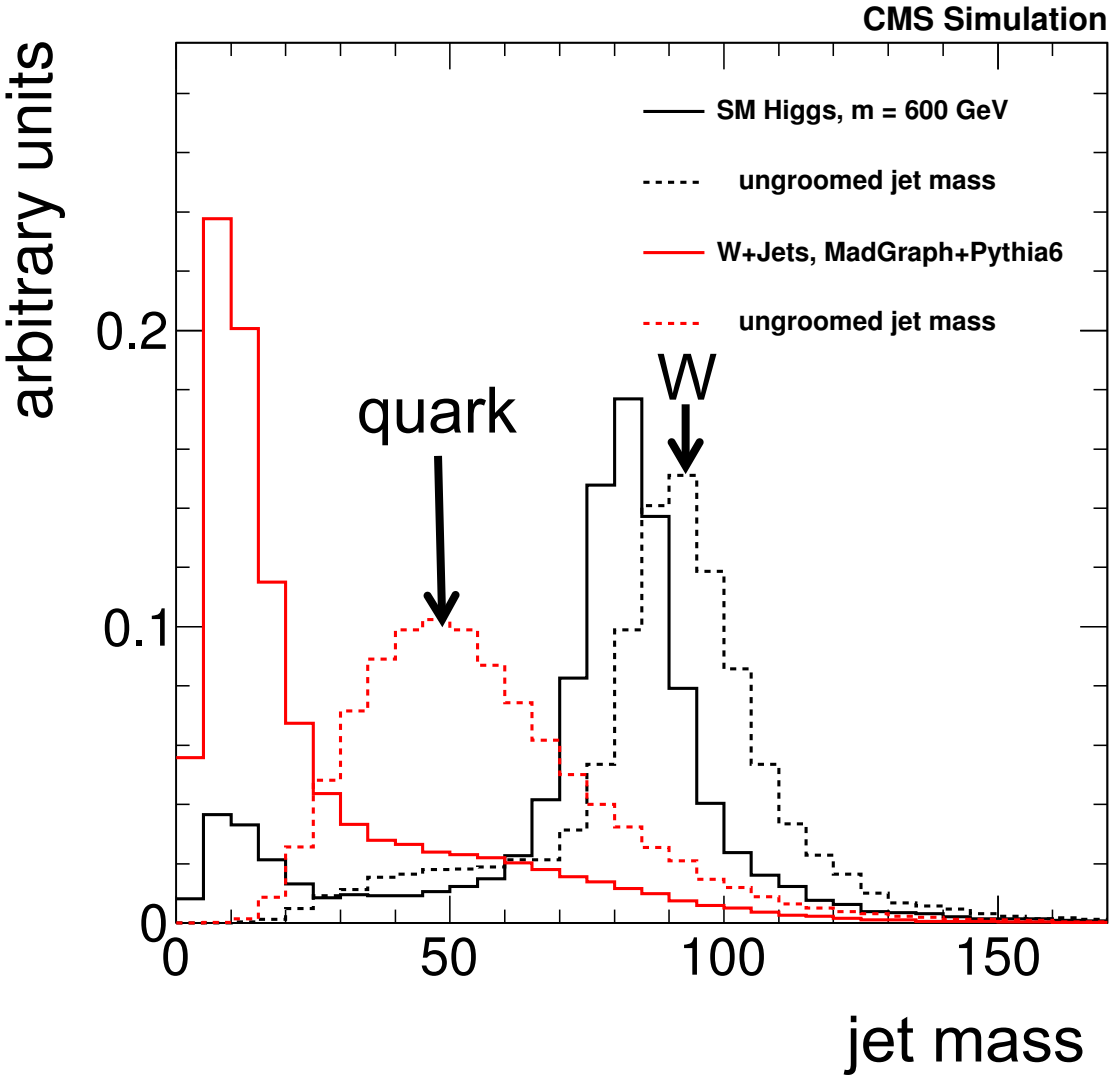


Parton shower



$$P(\theta) \propto \alpha_s \frac{d\theta}{\theta}$$

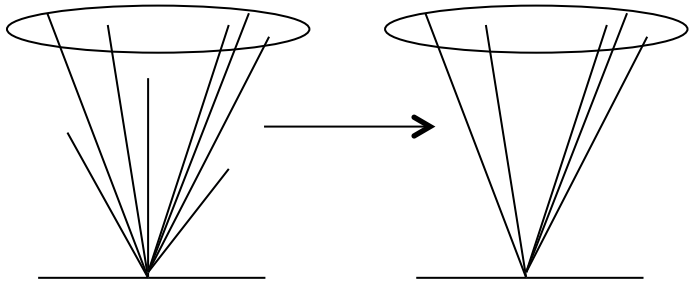
$$P(z, p_T) \propto \alpha_s P(z) \frac{dp_T}{p_T}$$



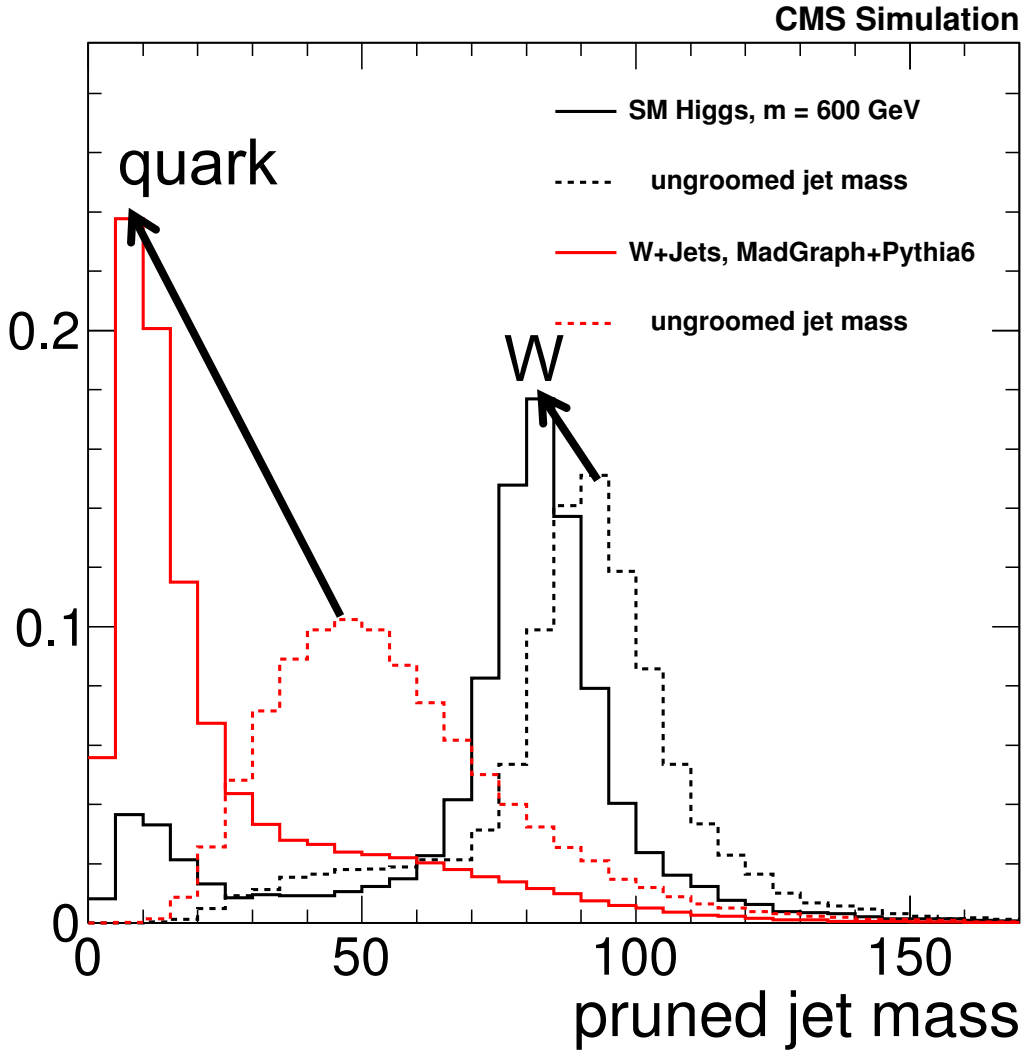
- Parton shower creates mass

Jet grooming

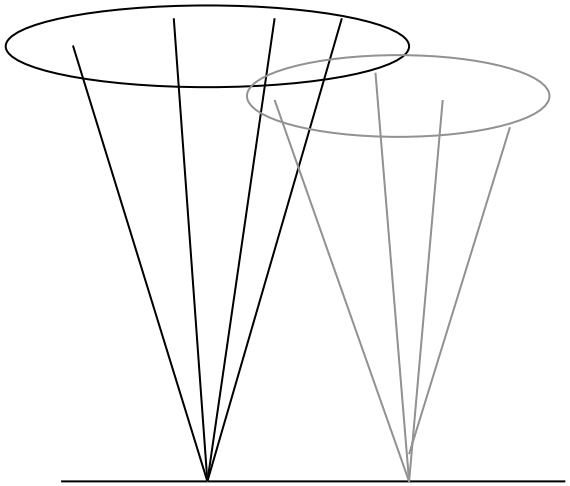
- Remove soft, large angle radiation

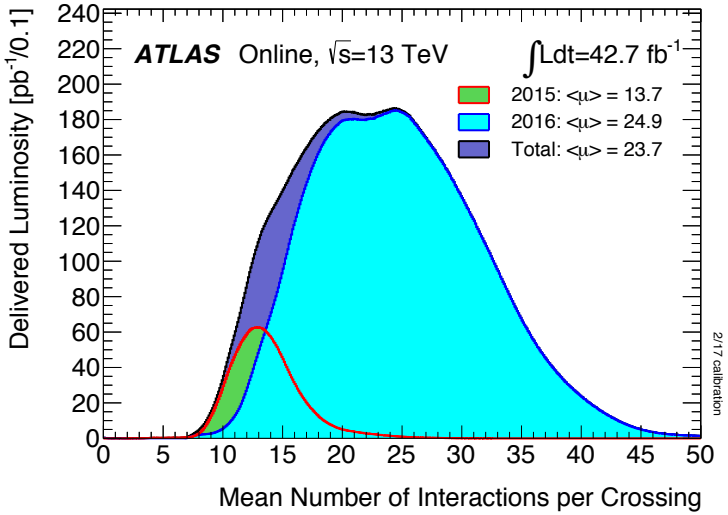


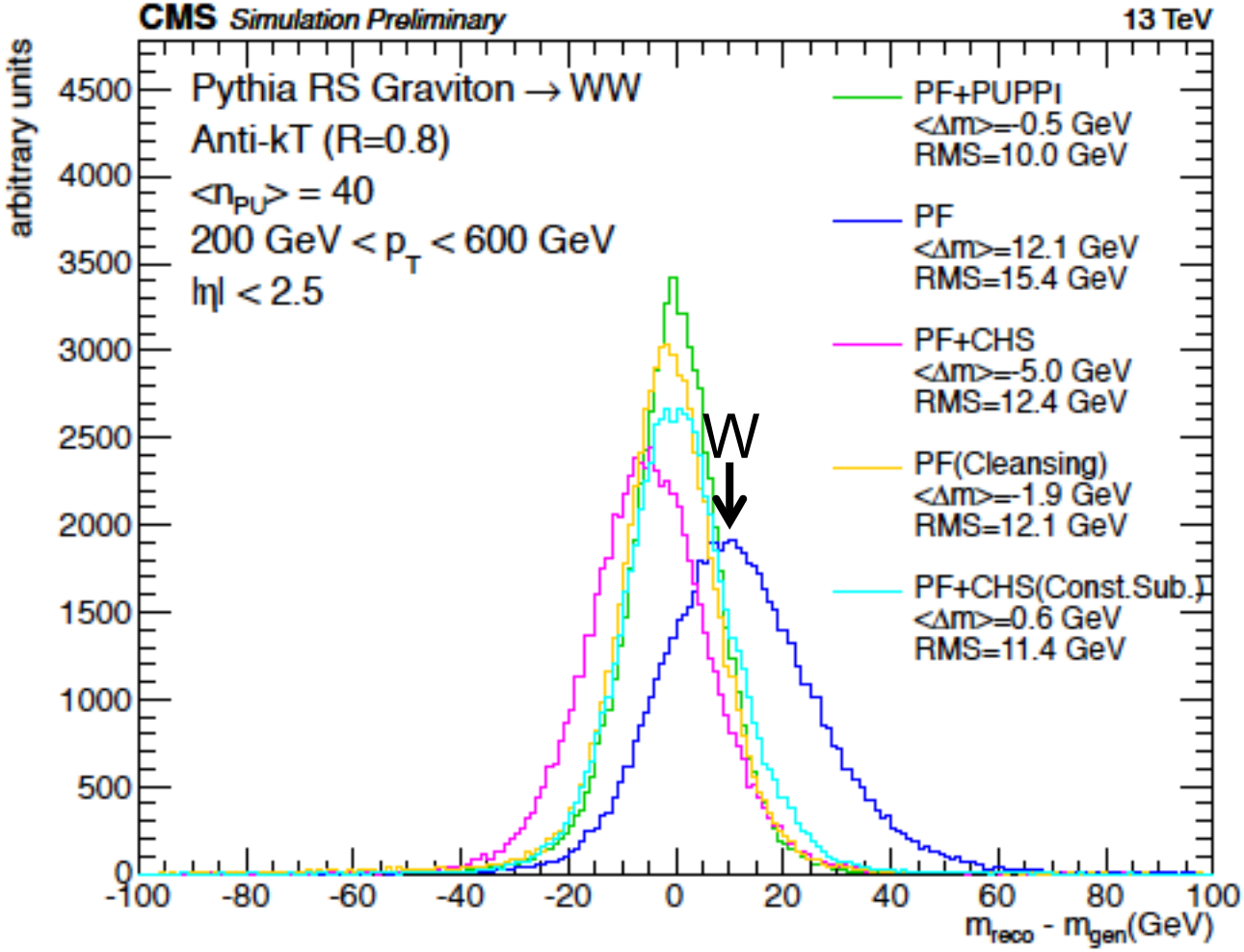
- Many approaches proposed
  - BDRS: Butterworth, Davison, Rubin, Salam arXiv:0802.2470
  - Pruning: Ellis, Vermilion, Walsh arXiv:0912.0033
  - Trimming: Krohn, Thaler, Wang arXiv:0912.1342
  - Softdrop/mMDT: Dasgupta et al. arXiv:1307.0007, Larkoski et al. arXiv:1402.2657
- And studied by experiments
  - CMS: JHEP 12 (2014) 017
  - ATLAS: Eur. Phys. J. C 76(3) (2016) 1-47



Pileup



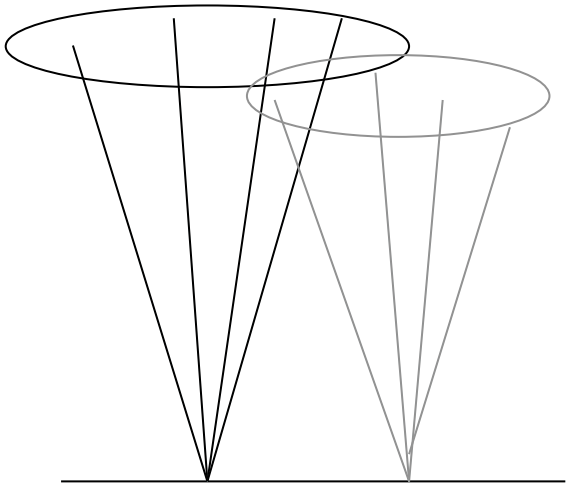


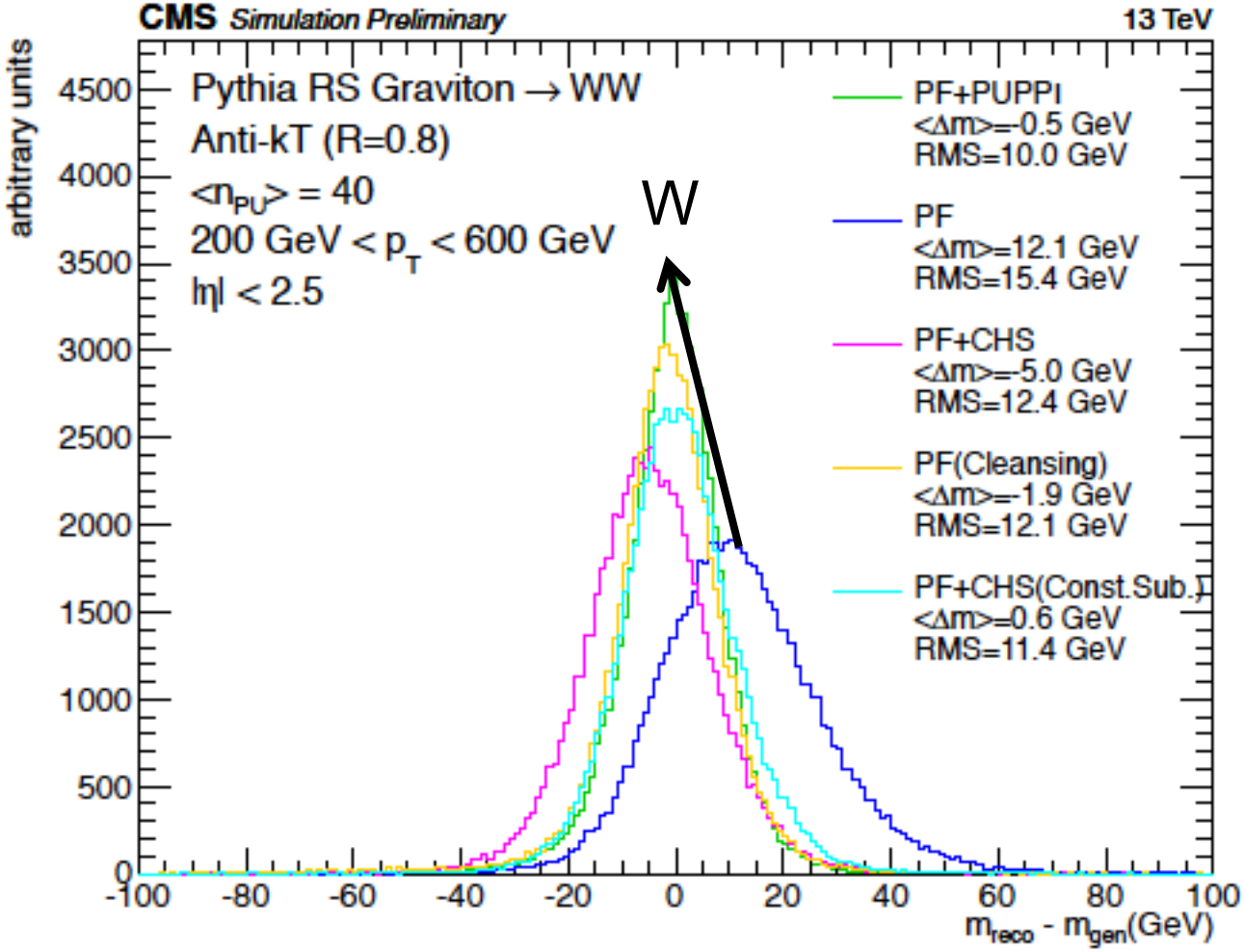


CMS-PAS-JME-14-001

- Pileup creates mass
- Maximum pileup at future HL-LHC is 200 interactions per bunch crossing

Pileup suppression techniques



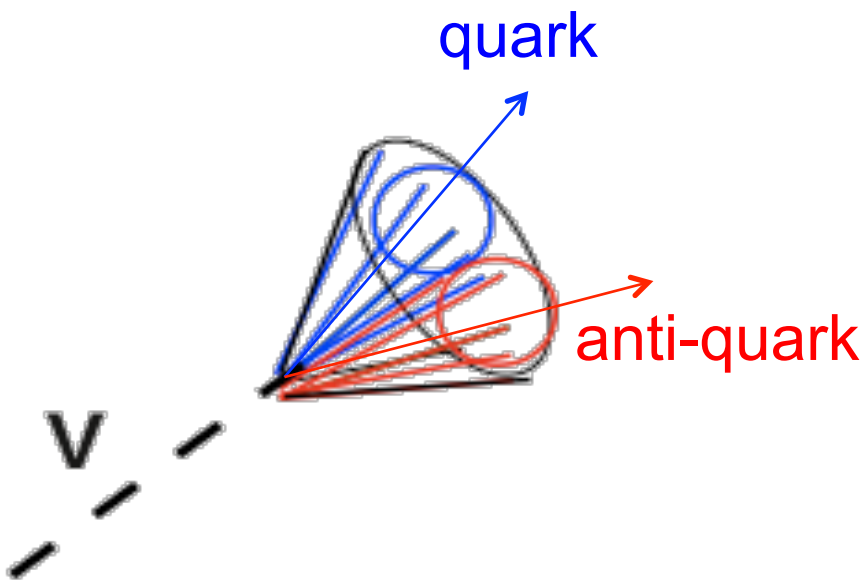


CMS-PAS-JME-14-001

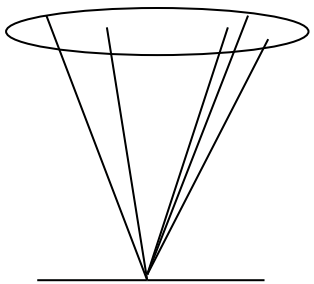
- Charged pileup component (60%) removed reconstructing vertices (CHS)
- Neutral pileup component (40%) weighted with pileup probability (PUPPI)

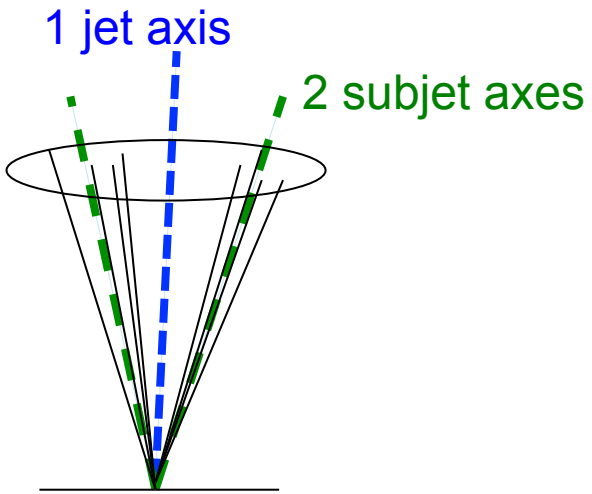
Bertolini, Harris, Low, Tran, arXiv:1407.6013

Boosted W or Z identification

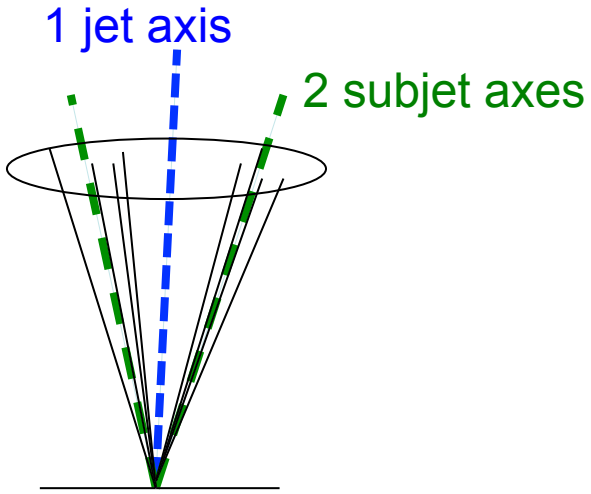


groomed jet mass + jet substructure



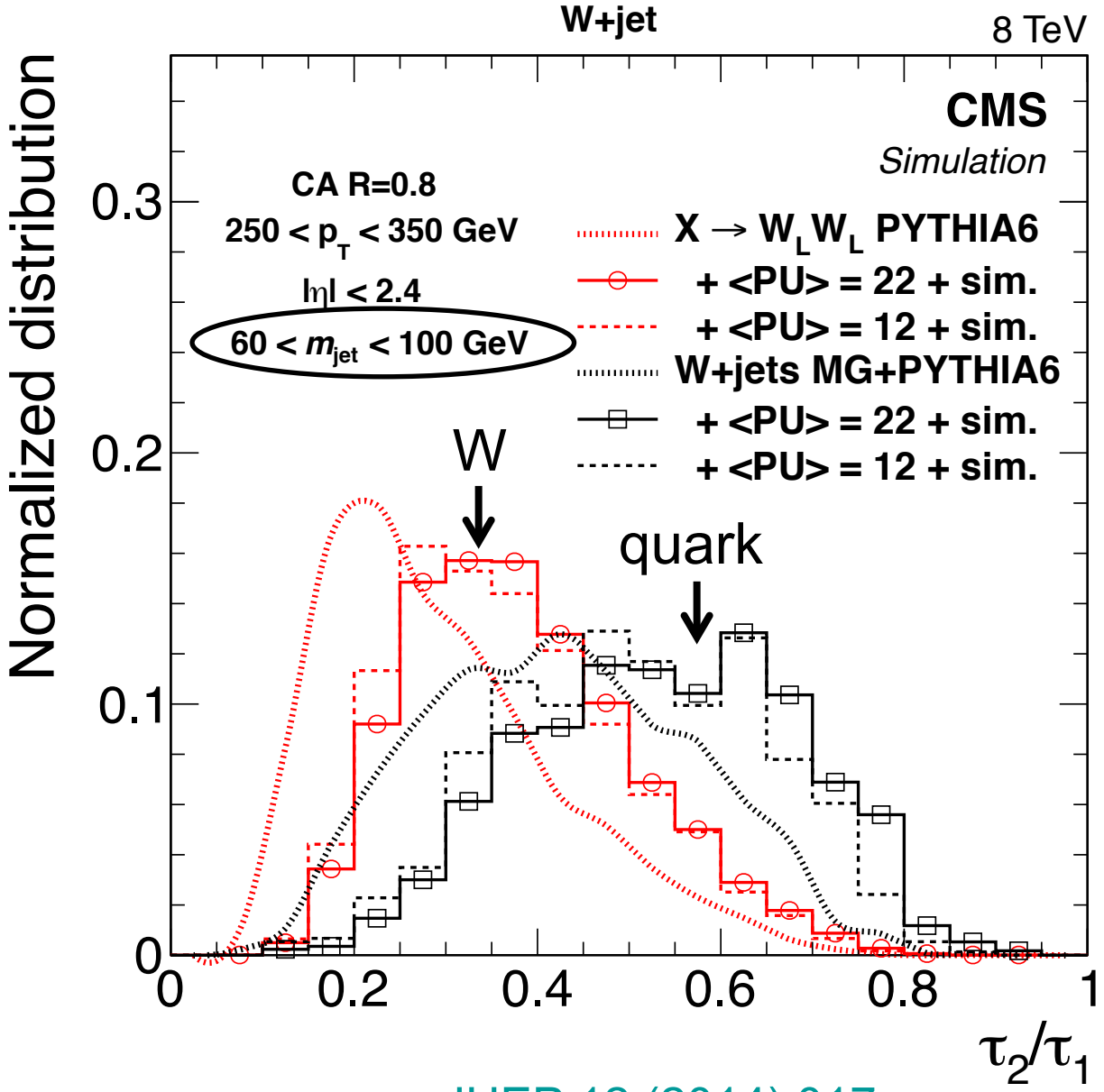


Jet substructure tagging



- Probability to be composed from 2 rather than 1 subjet

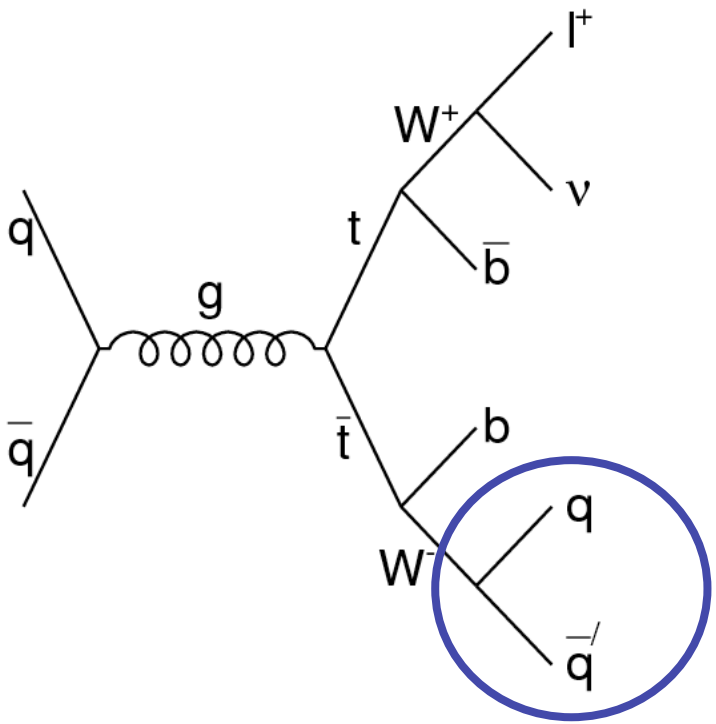
- Many approaches studied
  - N-subjettiness: Thaler, Tilburg arXiv:1011.2268
  - ECF: Larkoski, Salam, Thaler arXiv:1305:0007

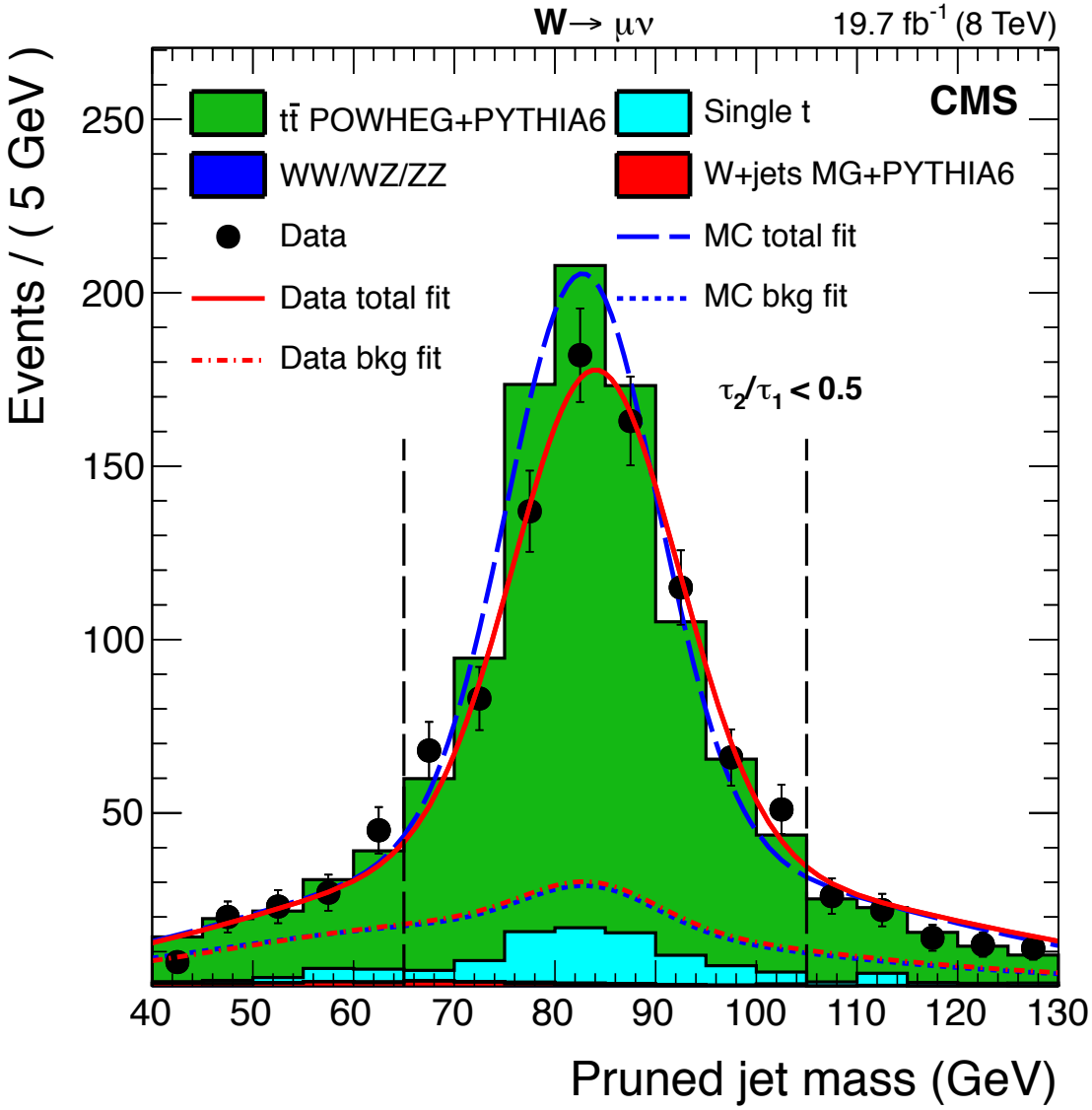


JHEP 12 (2014) 017

Validation in data

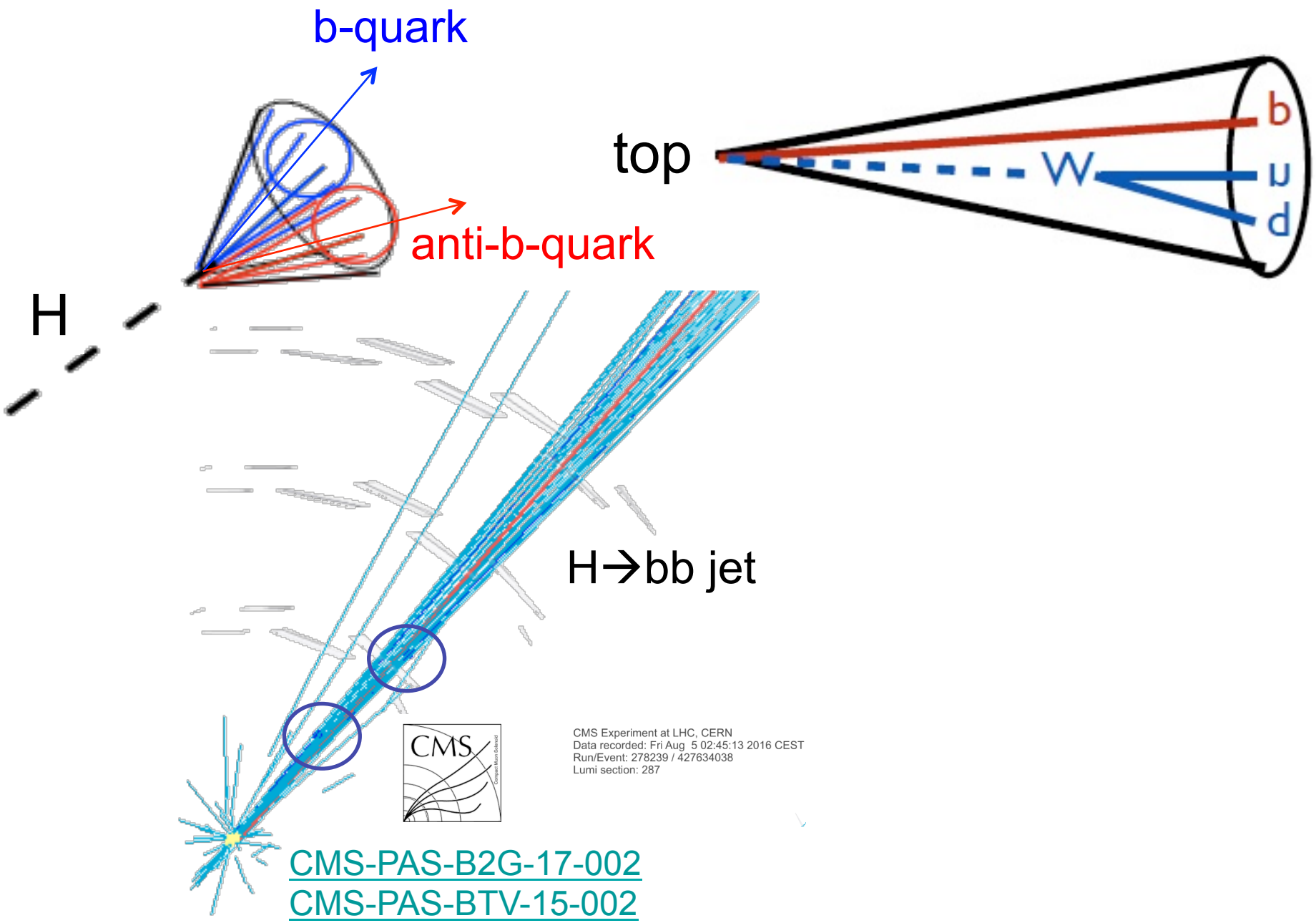
- Semileptonic ttbar data sample with real boosted W and tops



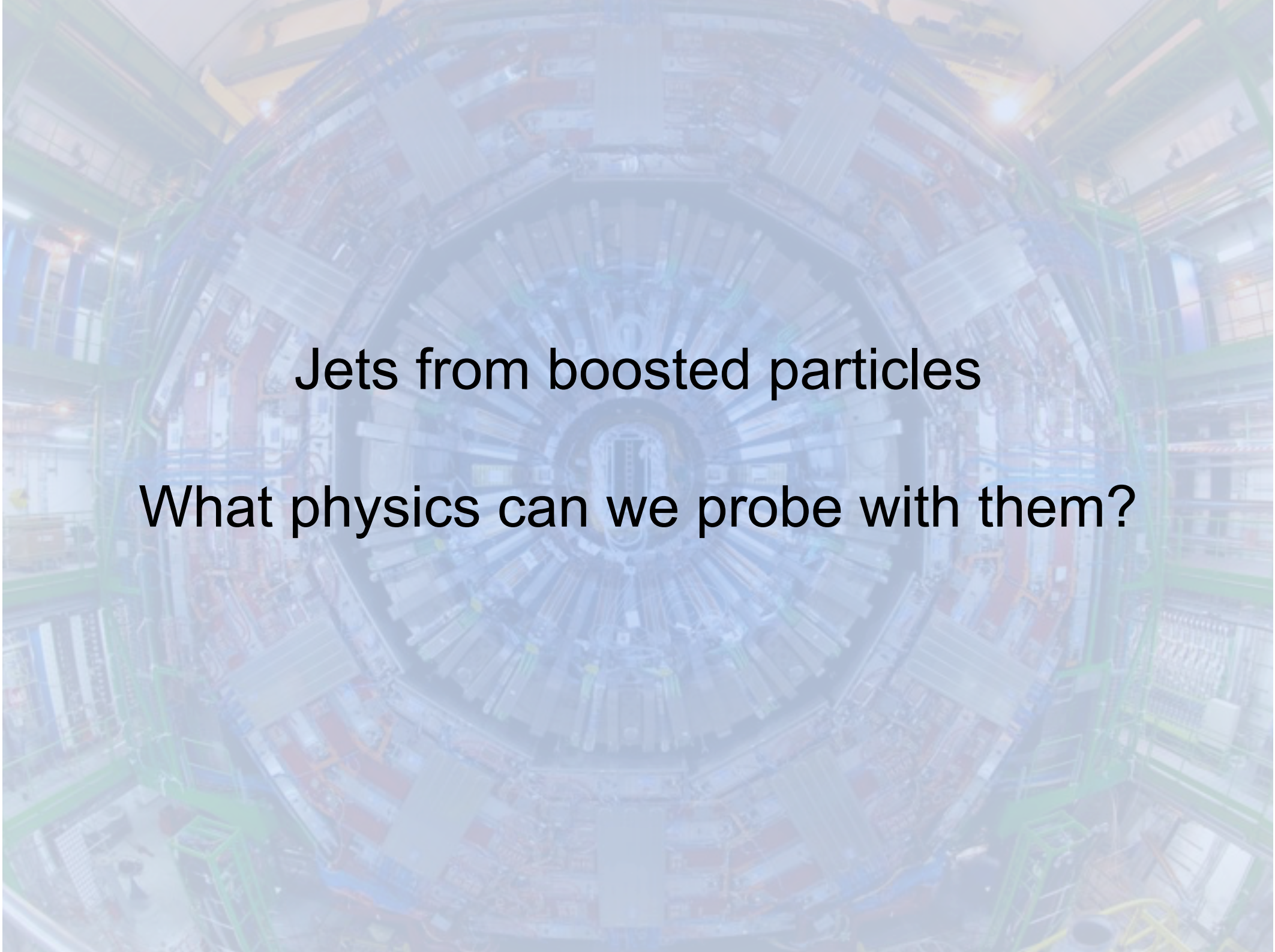


JHEP 12 (2014) 017

Boosted Higgs and top identification



CMS-PAS-B2G-17-002
CMS-PAS-BTV-15-002



Jets from boosted particles

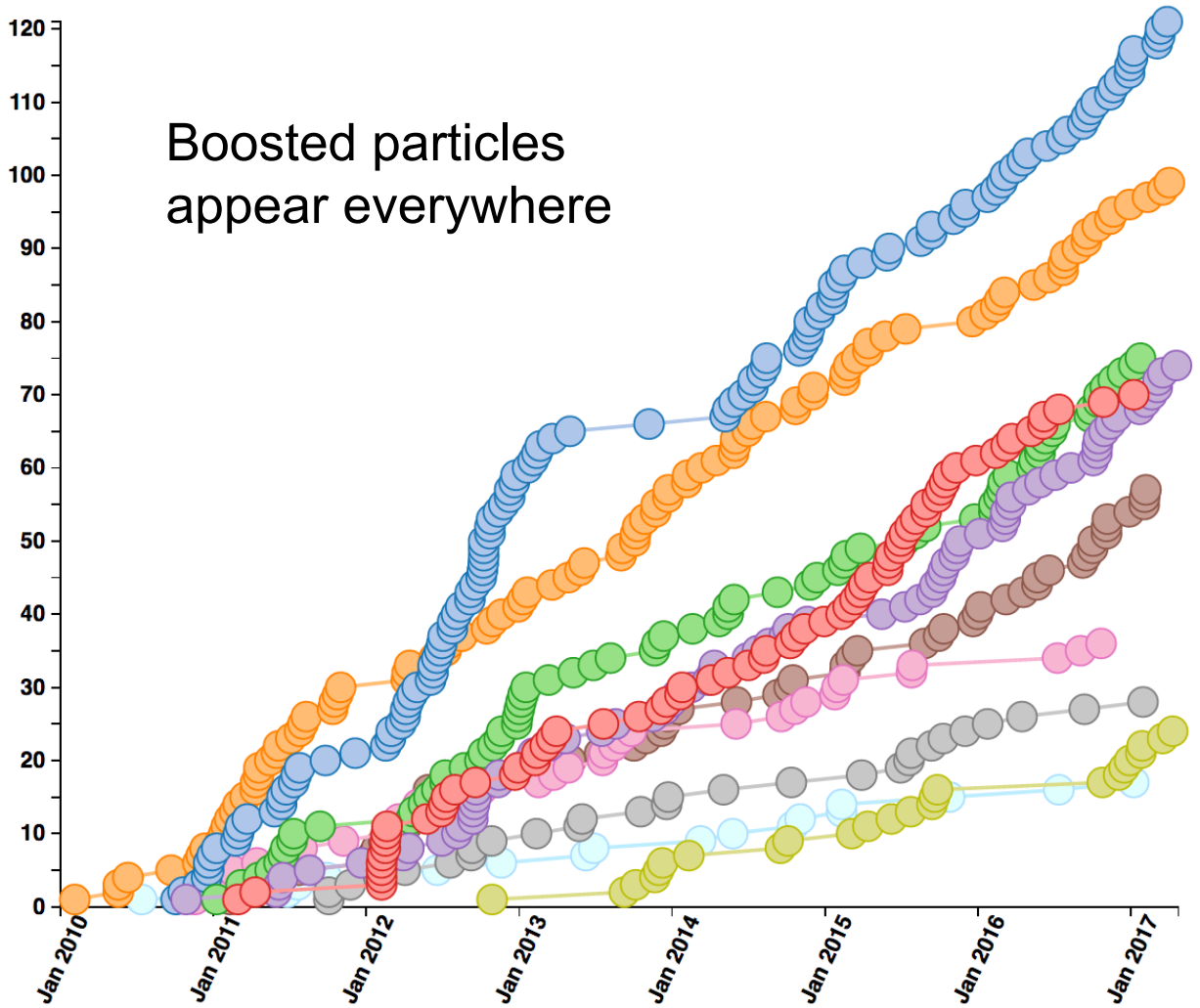
What physics can we probe with them?

Physics publications of CMS

Show all | Total | Exotica | Standard Model | Supersymmetry | Higgs | Top Physics

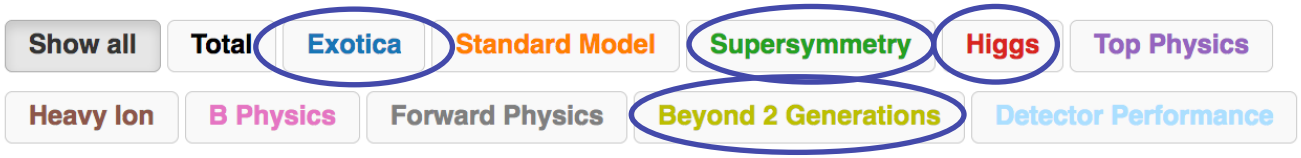
Heavy Ion | B Physics | Forward Physics | Beyond 2 Generations | Detector Performance

600 collider data papers submitted as of 2017-04-21



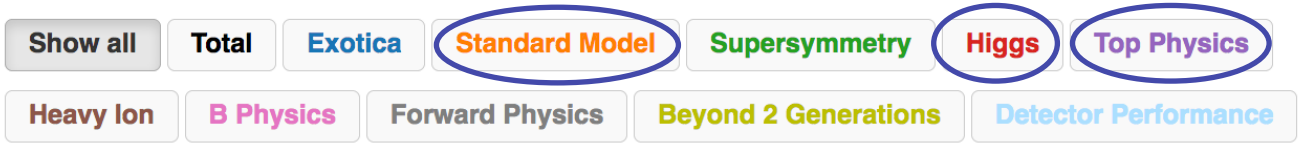
http://cms-results.web.cern.ch/cms-results/public-results/publications-vs-time/

Boosted physics



1. Searches for high energy new physics decaying to boosted tops/W/Z/H

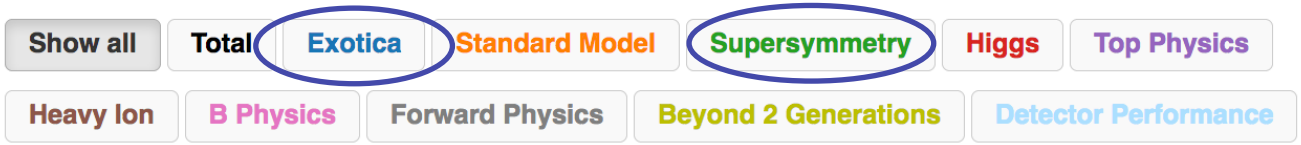
Boosted physics



1. Searches for high energy new physics decaying to boosted tops/W/Z/H

2. Measurements with boosted tops/W/Z/H to test the Standard Model

Boosted physics



1. Searches for high energy new physics decaying to boosted tops/W/Z/H

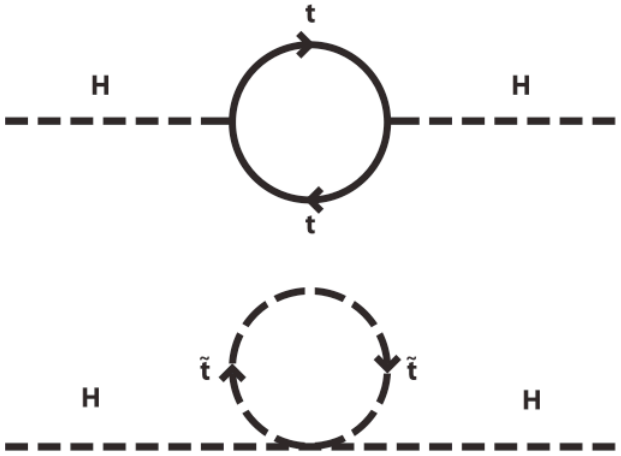
2. Measurements with boosted tops/W/Z/H to test the Standard Model

3. Searches for new boosted particles

1. High energy new physics

- Among other unresolved problems of particles physics:
  the hierarchy problem

Higgs mass at EWK Skala
m_H=125 GeV/c^2



Planck mass
m_{Pl} = 10^{19} GeV/c^2

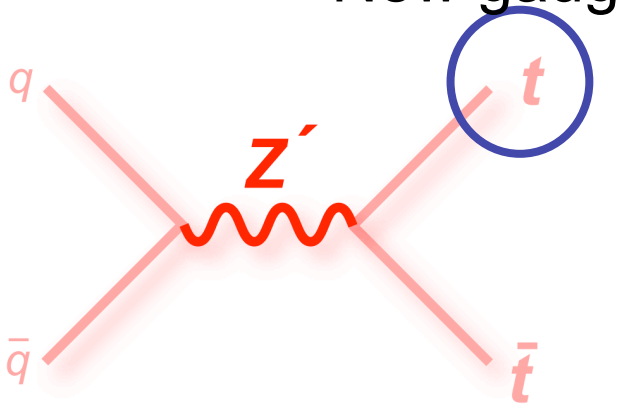
$$m_{Pl} = \sqrt{\frac{\hbar \cdot c}{G}}$$

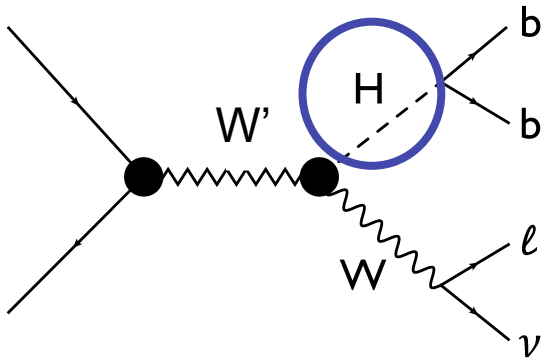
- Popular solutions:
  - New supersymmetric (SUSY) particles cancel the radiative corrections
  - Extra dimensions reduce the effective Planck scale
  - Higgs is composite object and its mass generated by a new interaction

New TeV particles

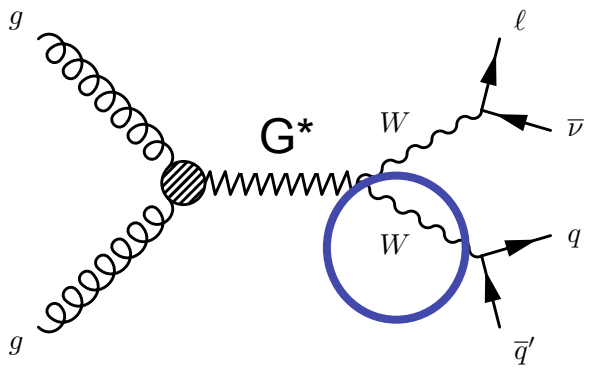
- Solve problems related to particles at the EWK scale
  → Many decay to W, Z, H and top

New gauge bosons

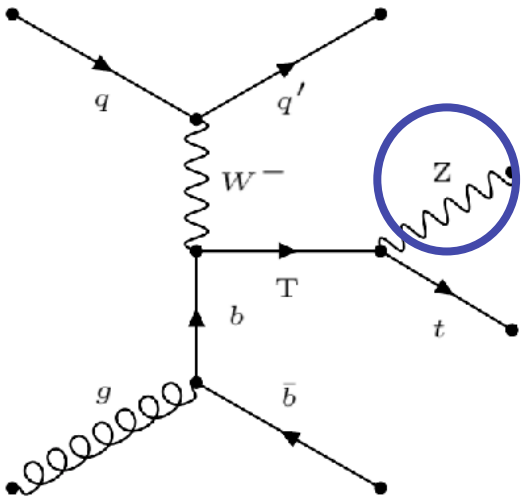




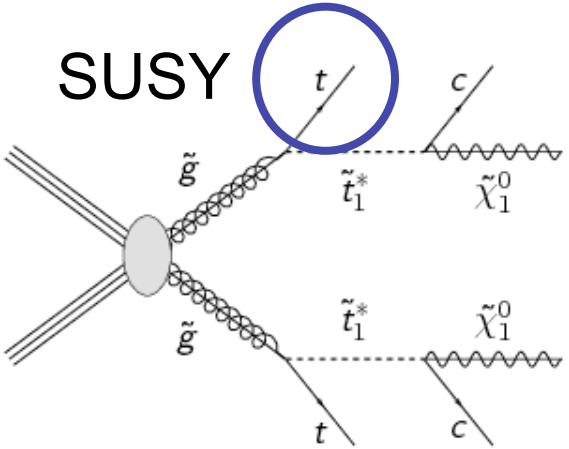
Extra dimensions



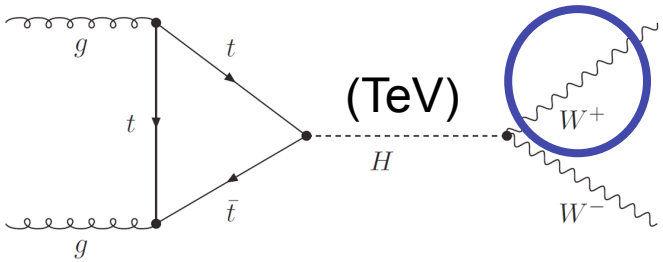
New quarks



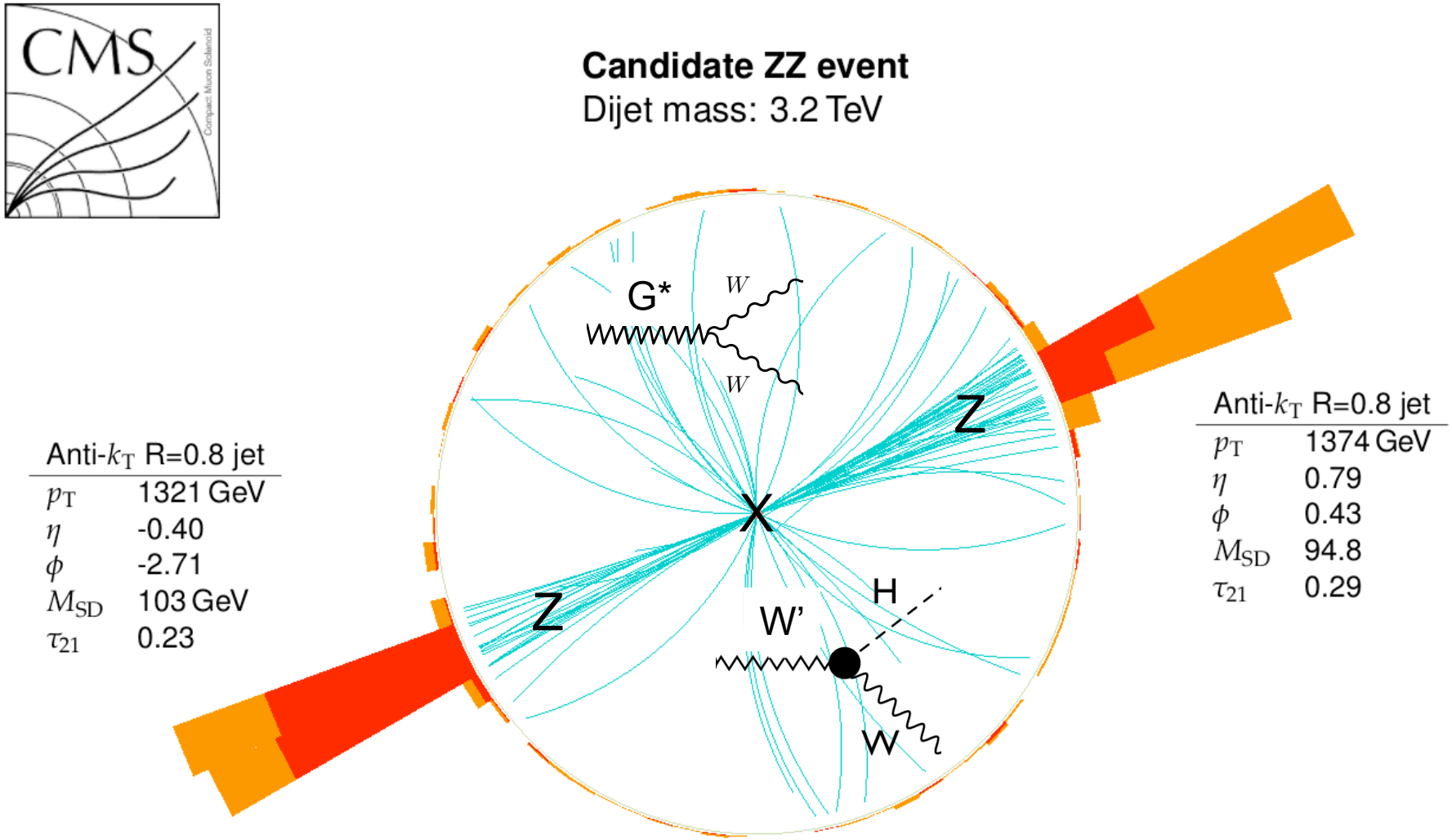
SUSY



New Higgs bosons

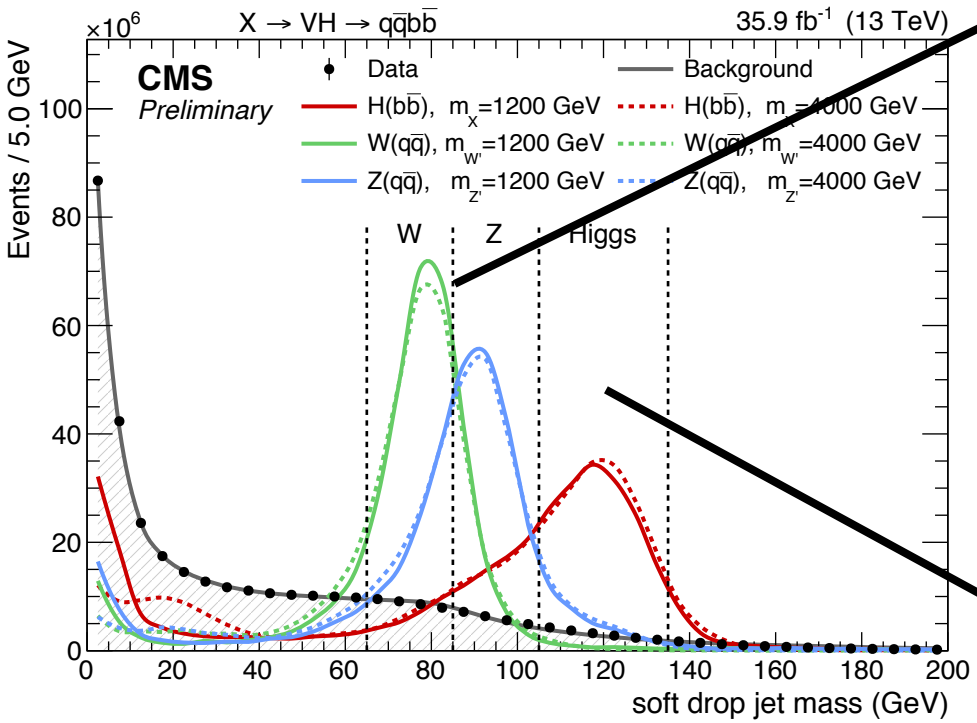


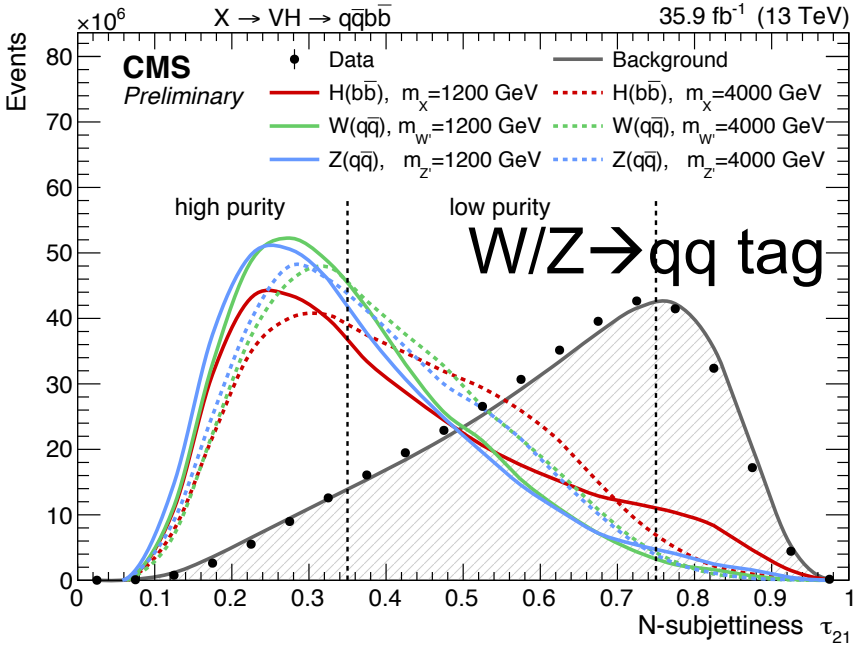
WW/WZ/WH/ZZ/ZH dijet searches

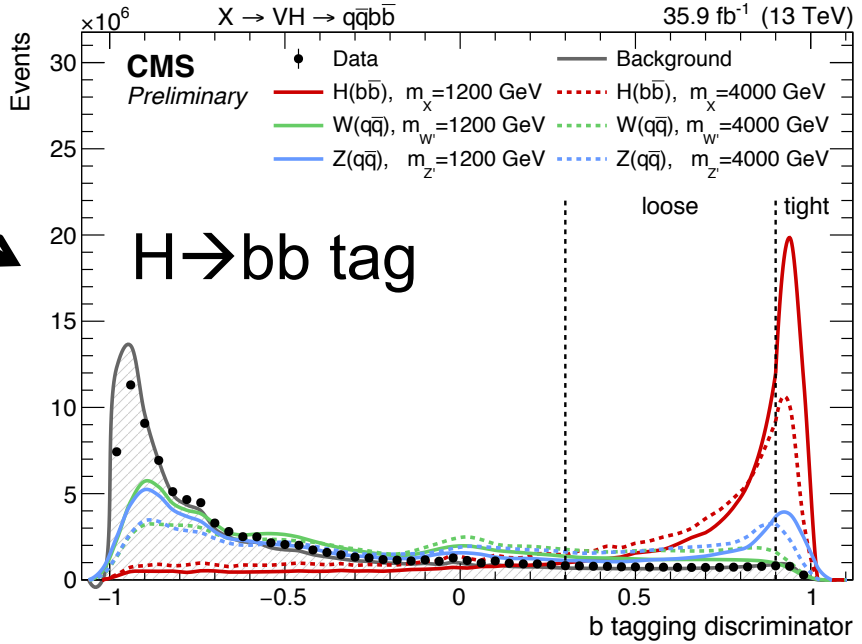


CMS-PAS-B2G-17-001
CMS-PAS-B2G-17-002

Event categorization

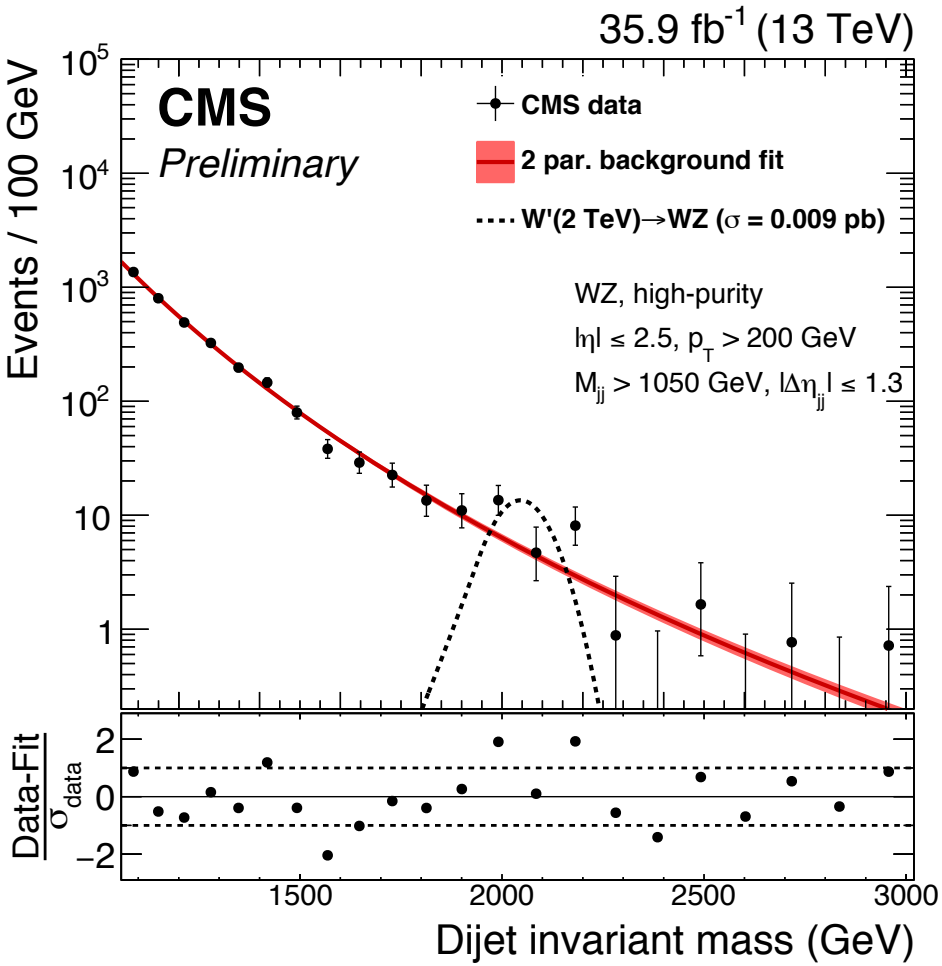


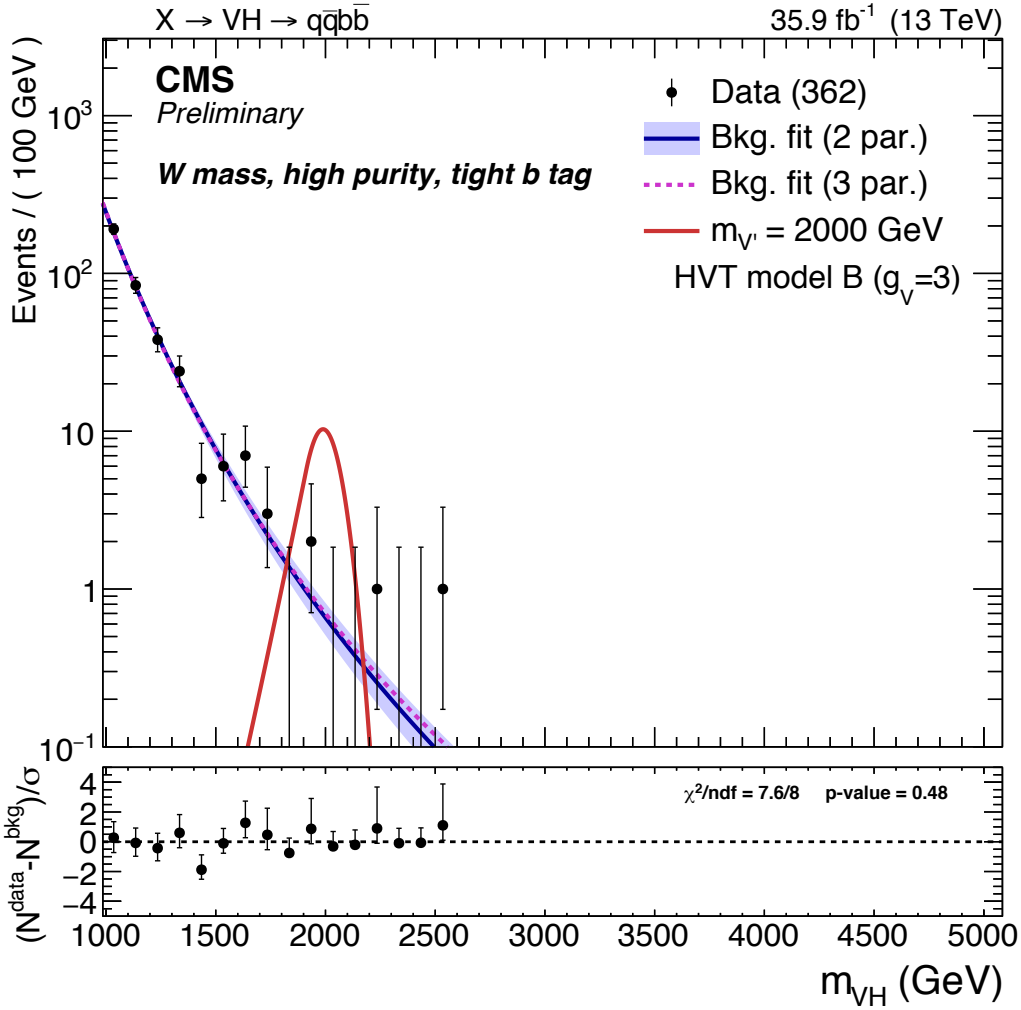




Bump hunt

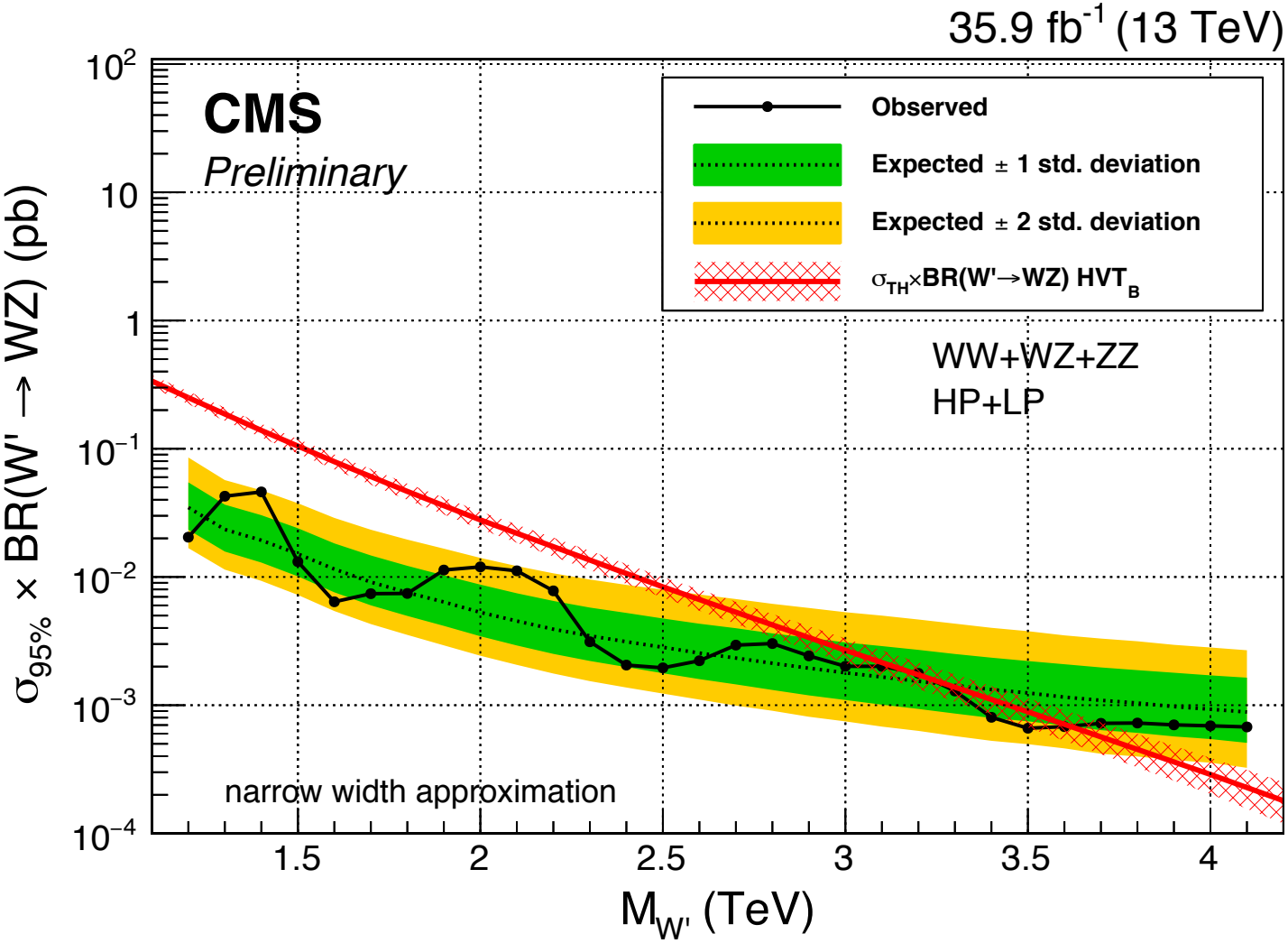
- Search for peaks on falling spectra
- Parameterized background $\frac{dN}{dm_{jj}} = \frac{P_0}{(m_{jj}/\sqrt{s})^{P_2}}$





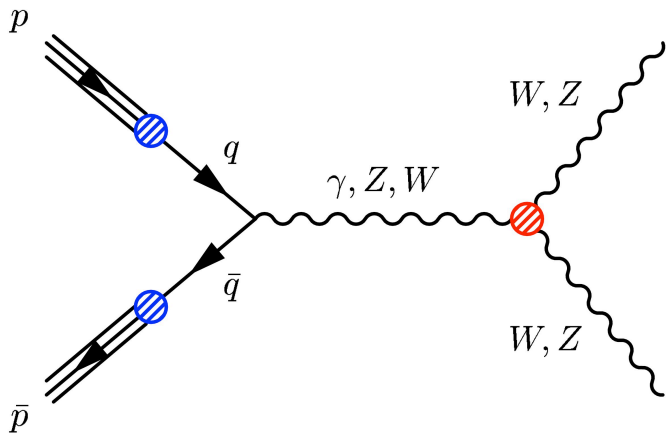
Results

- Set constraints on
  - Cross section of new physics resonances: W', Z', G*, q*
  - Mass of new physics resonances

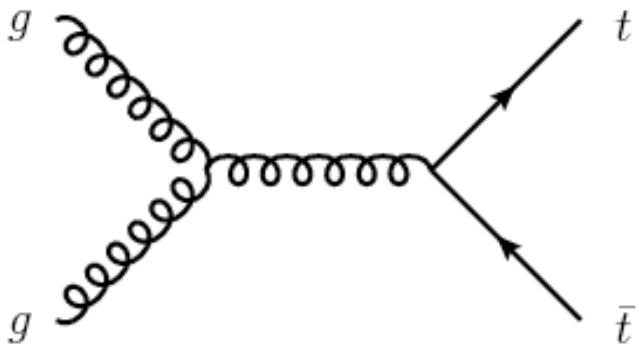


2. SM physics with boosted W, Z, H and top

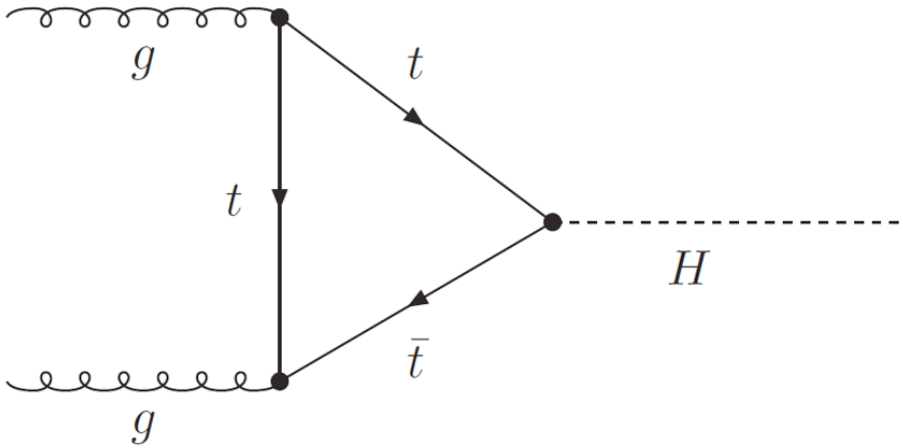
- Diboson differential cross sections, tests of triple gauge couplings



- Top differential cross sections, charge asymmetry

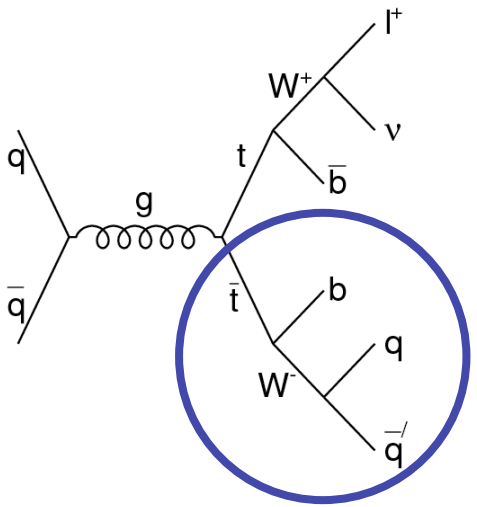


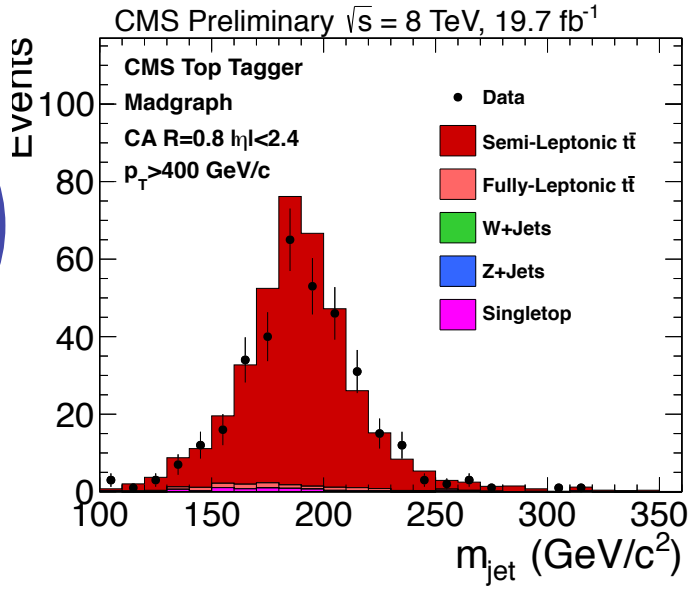
- Higgs differential cross sections
  → near future

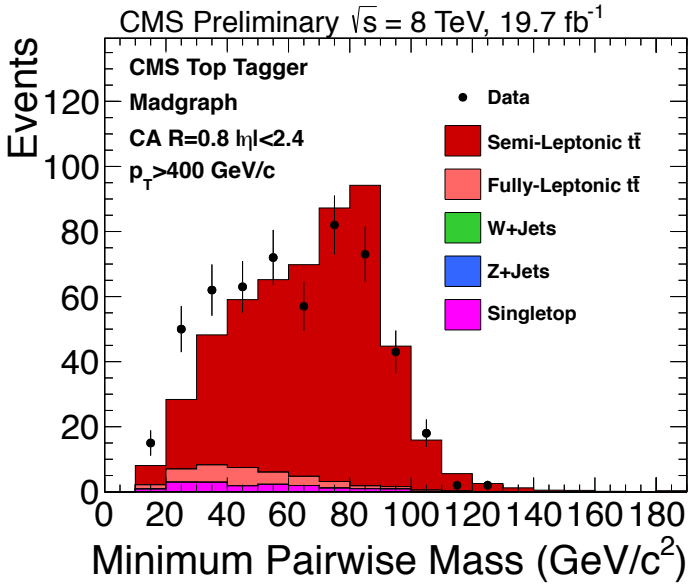


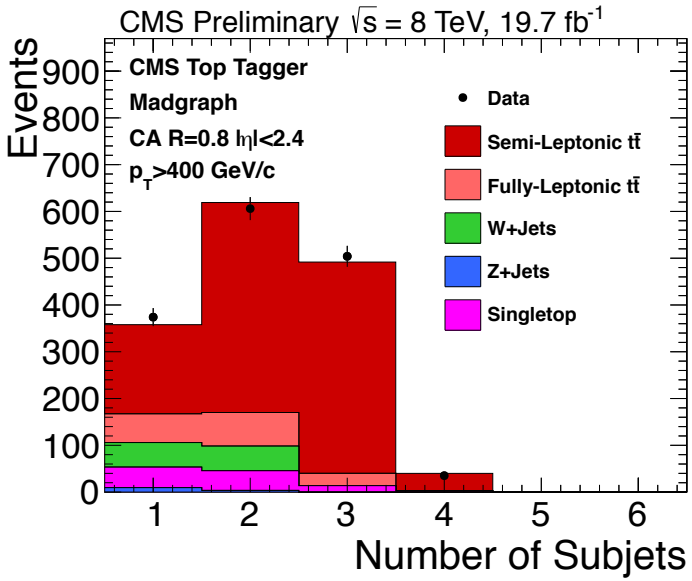
Top p_T differential cross section

- Semileptonic top pair production with top-tag



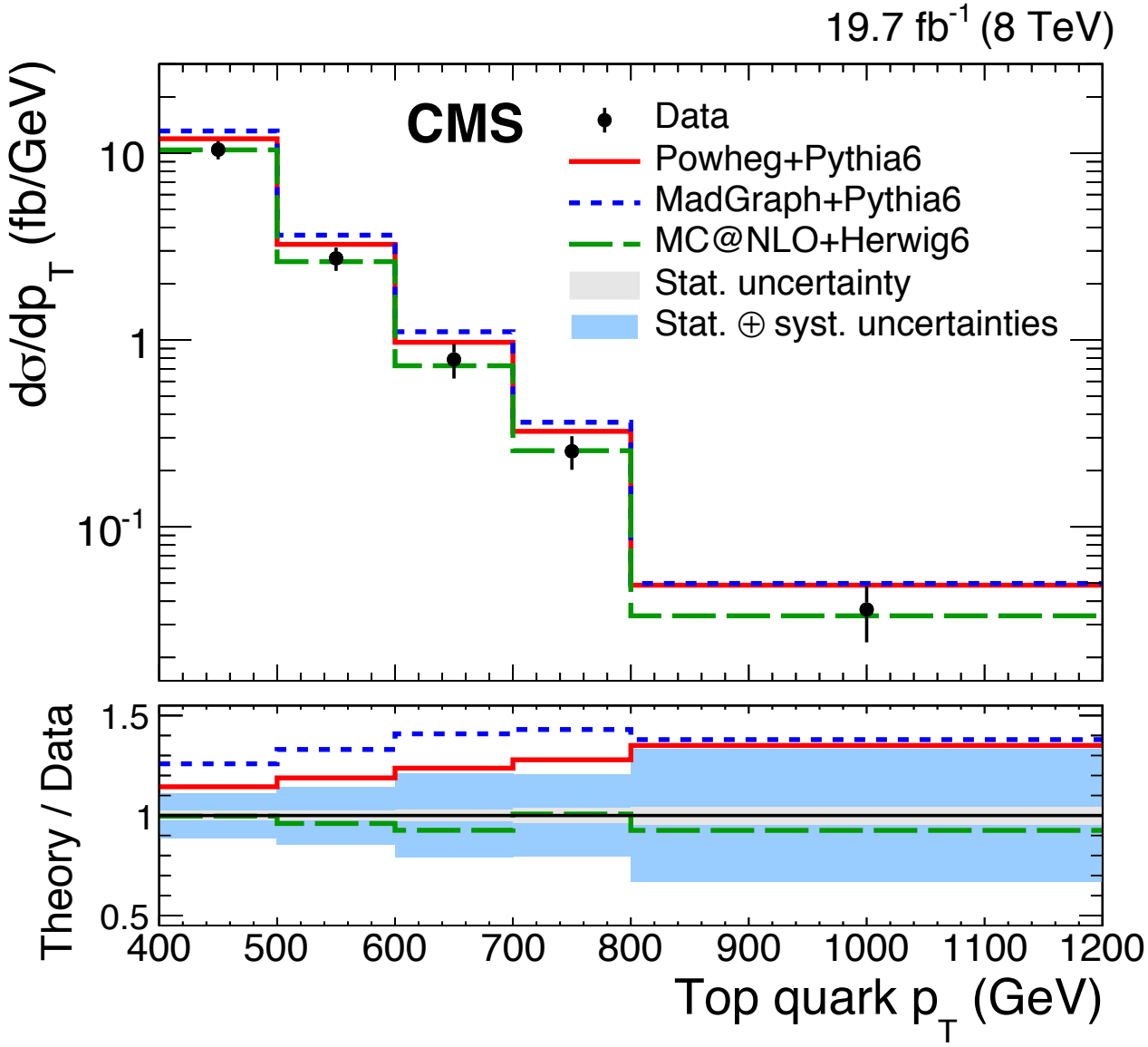






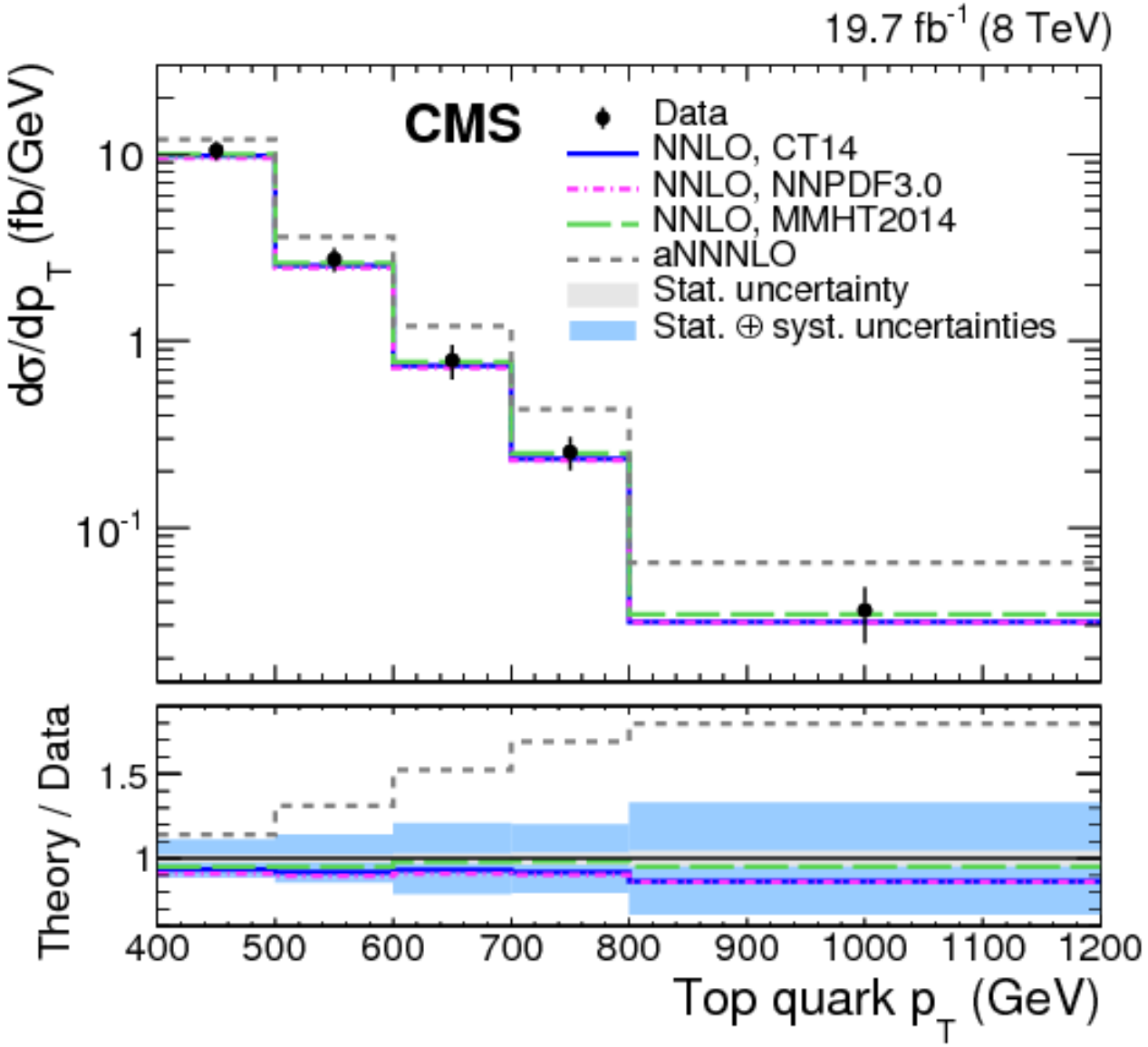
CMS-PAS-JME-13-007
Phys. Rev. D 94, 072002 (2016)

Results



- Some NLO predictions disagree

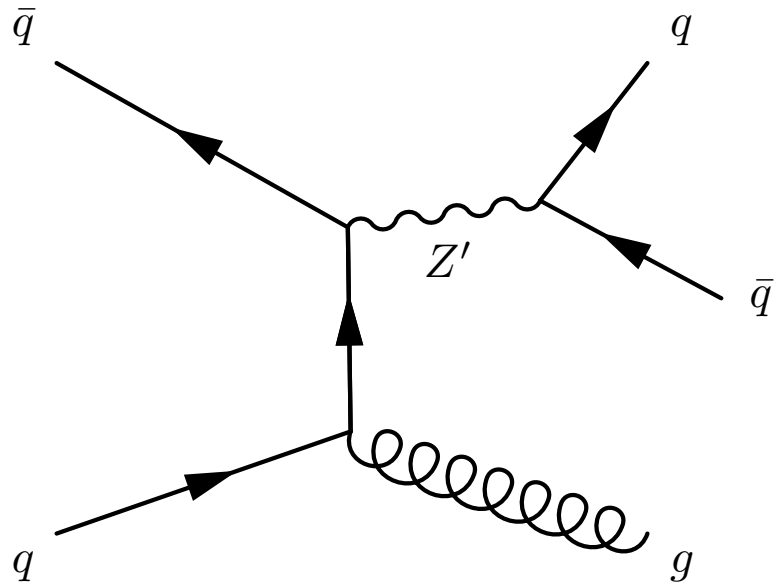
Results



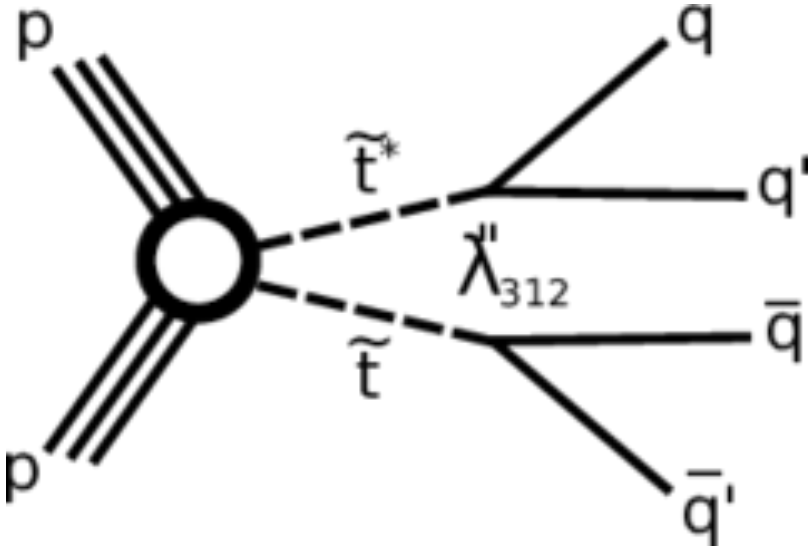
- NNLO predictions give better description

3. New boosted particles

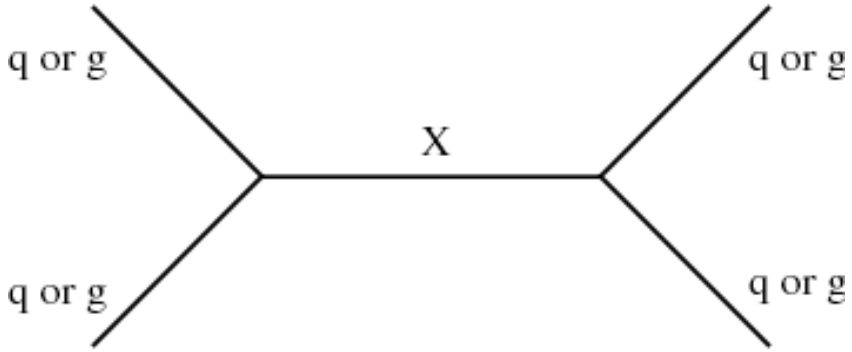
- New physics resonances with ISR

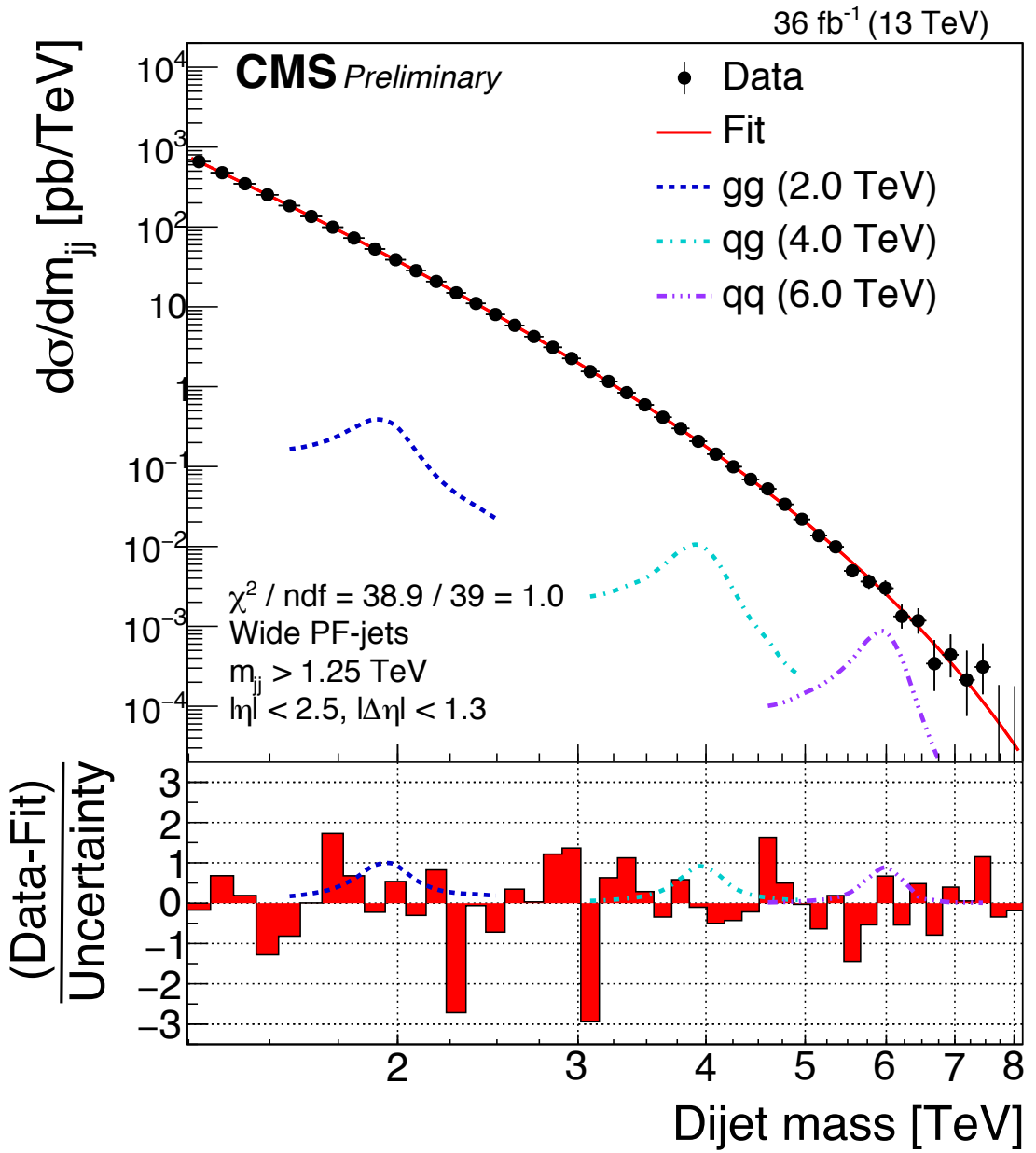


- Pair produced new physics resonances



Classical dijet resonance search

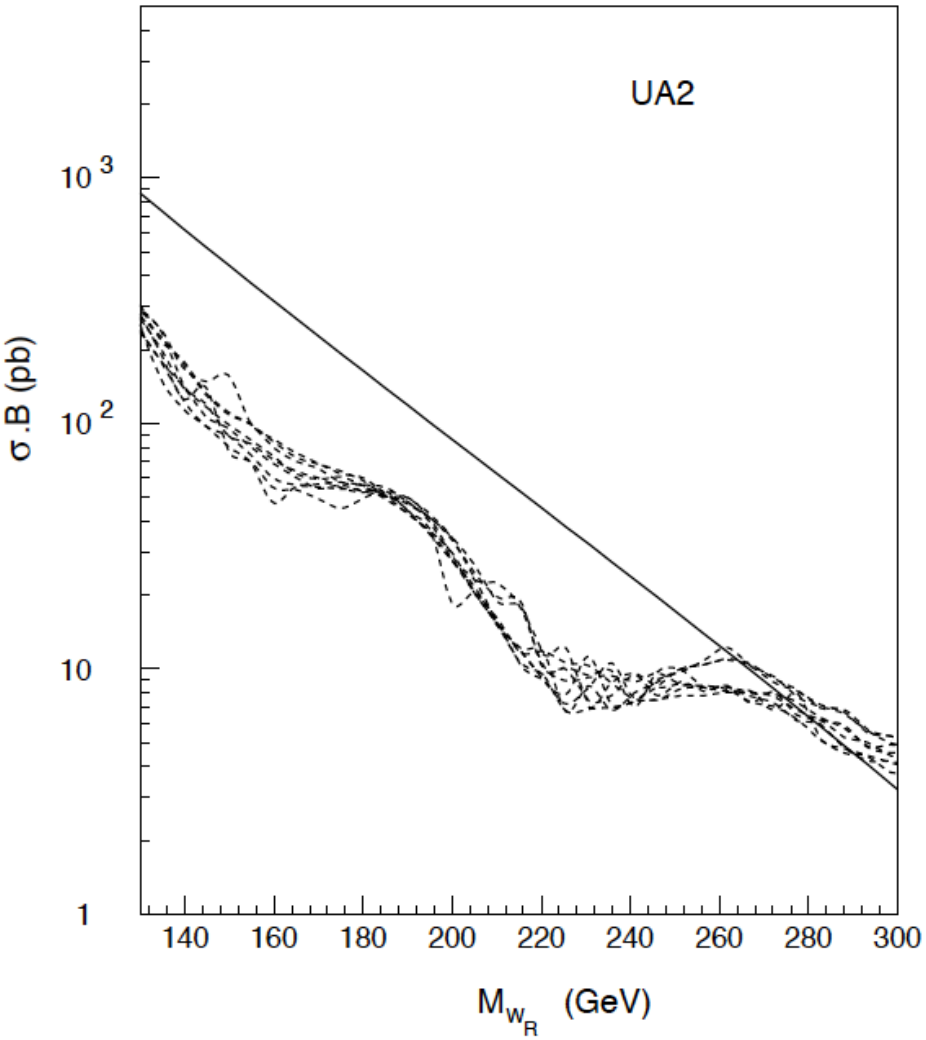


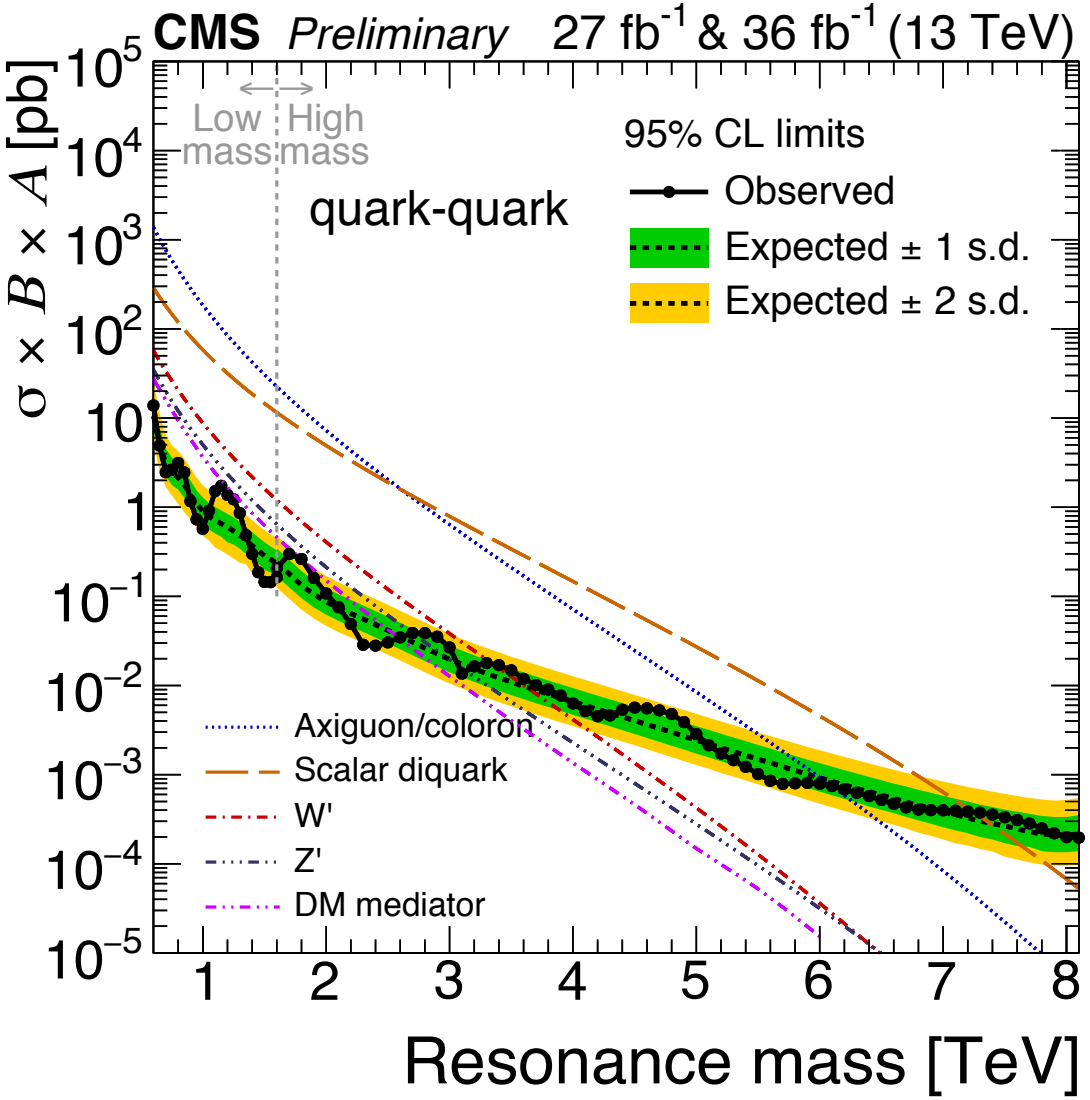


CMS-PAS-EXO-16-056

Results

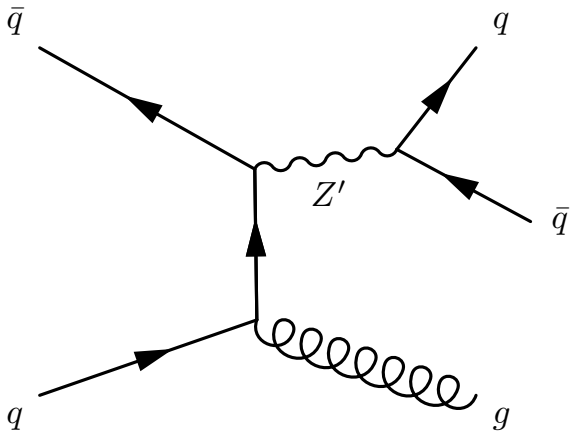
- Limits on dijet resonance production cross section
- Threshold limited by ability to record large amount of multijet data

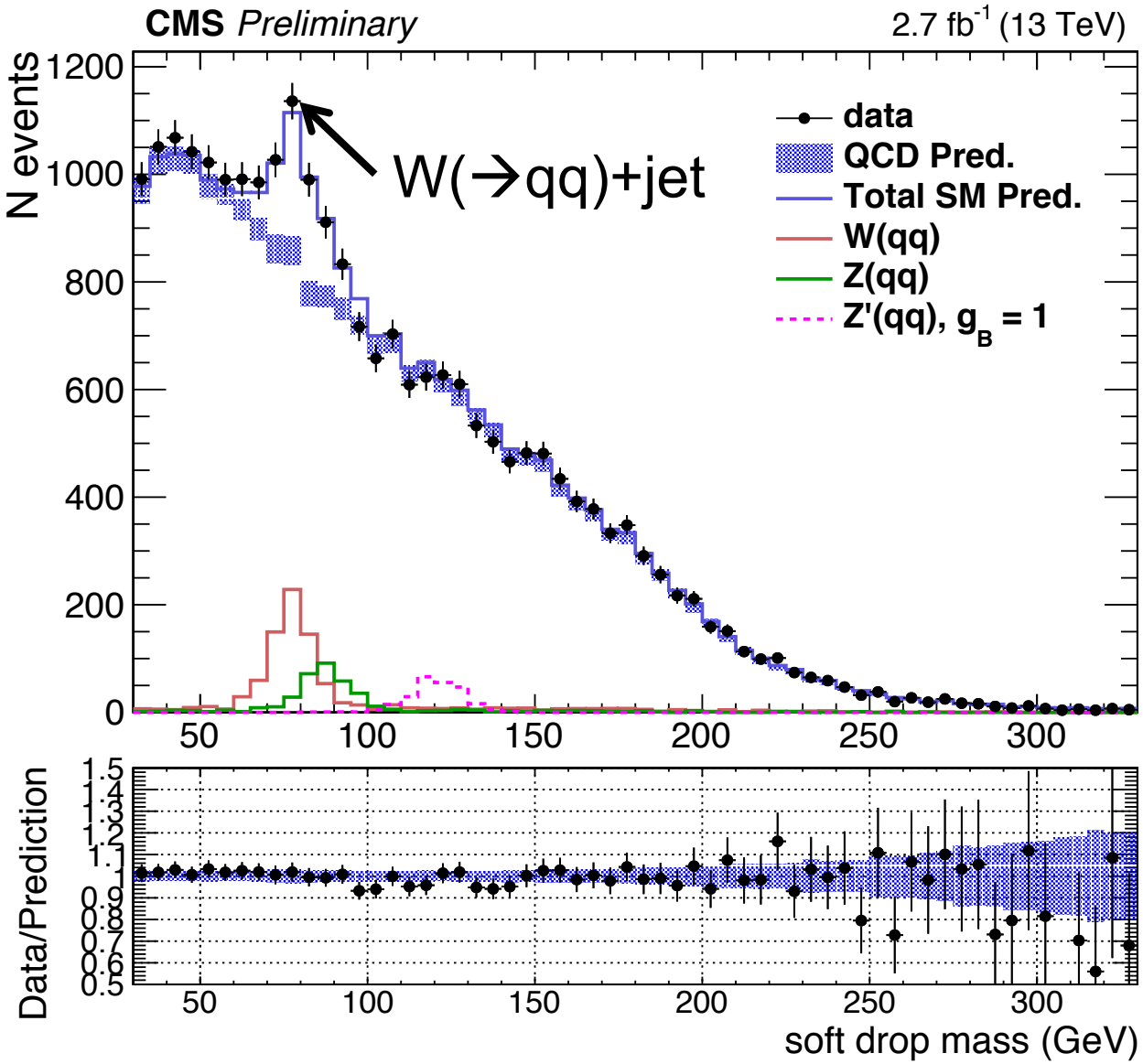




https://doi.org/10.1016/0550-3213(93)90395-6

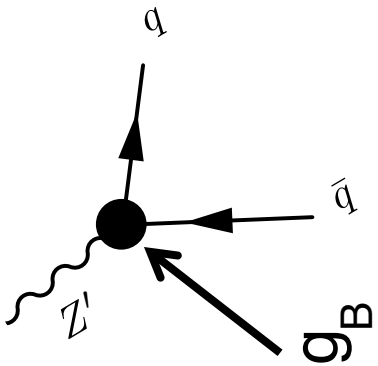
Boosted X → qq search

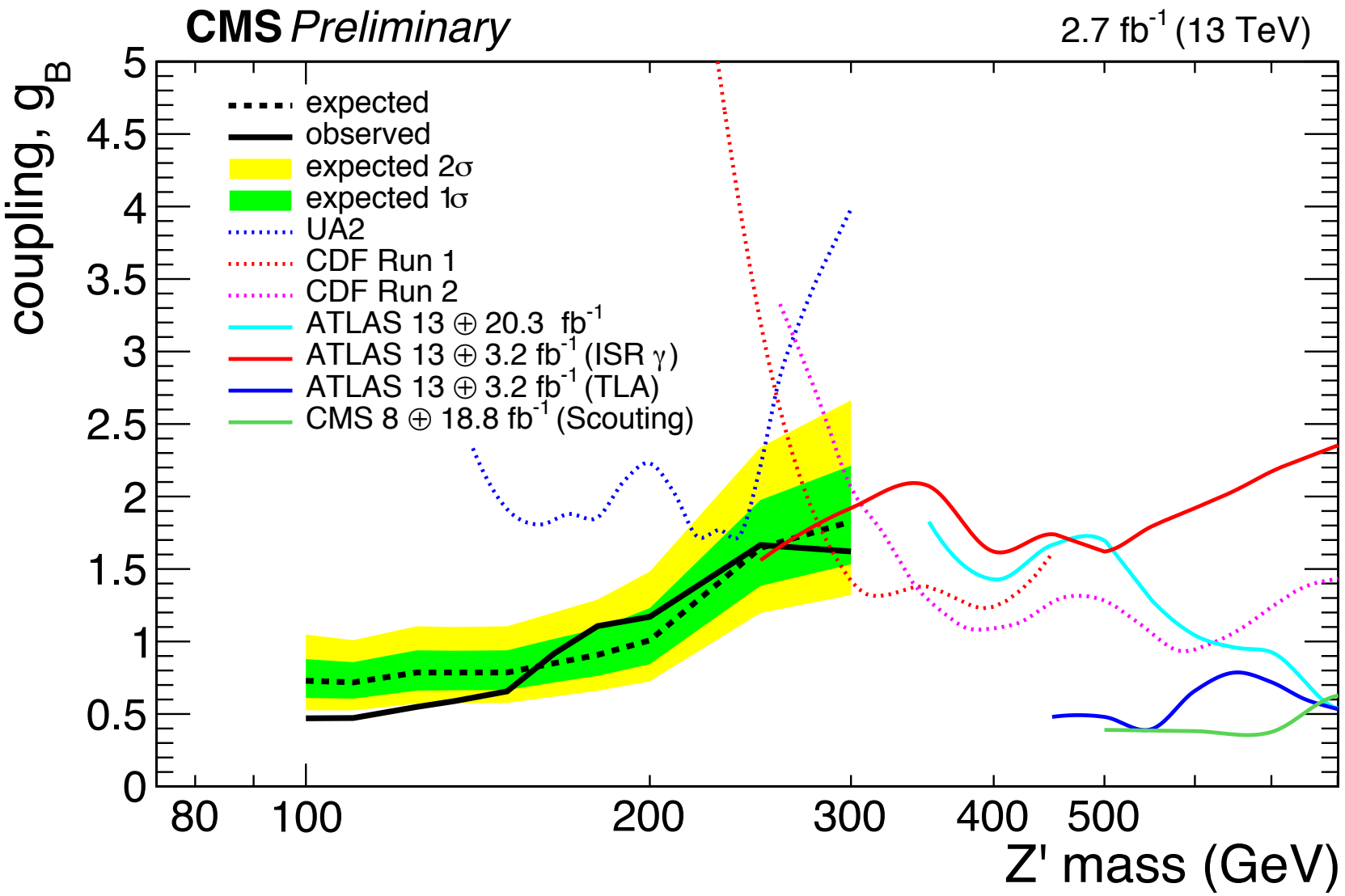


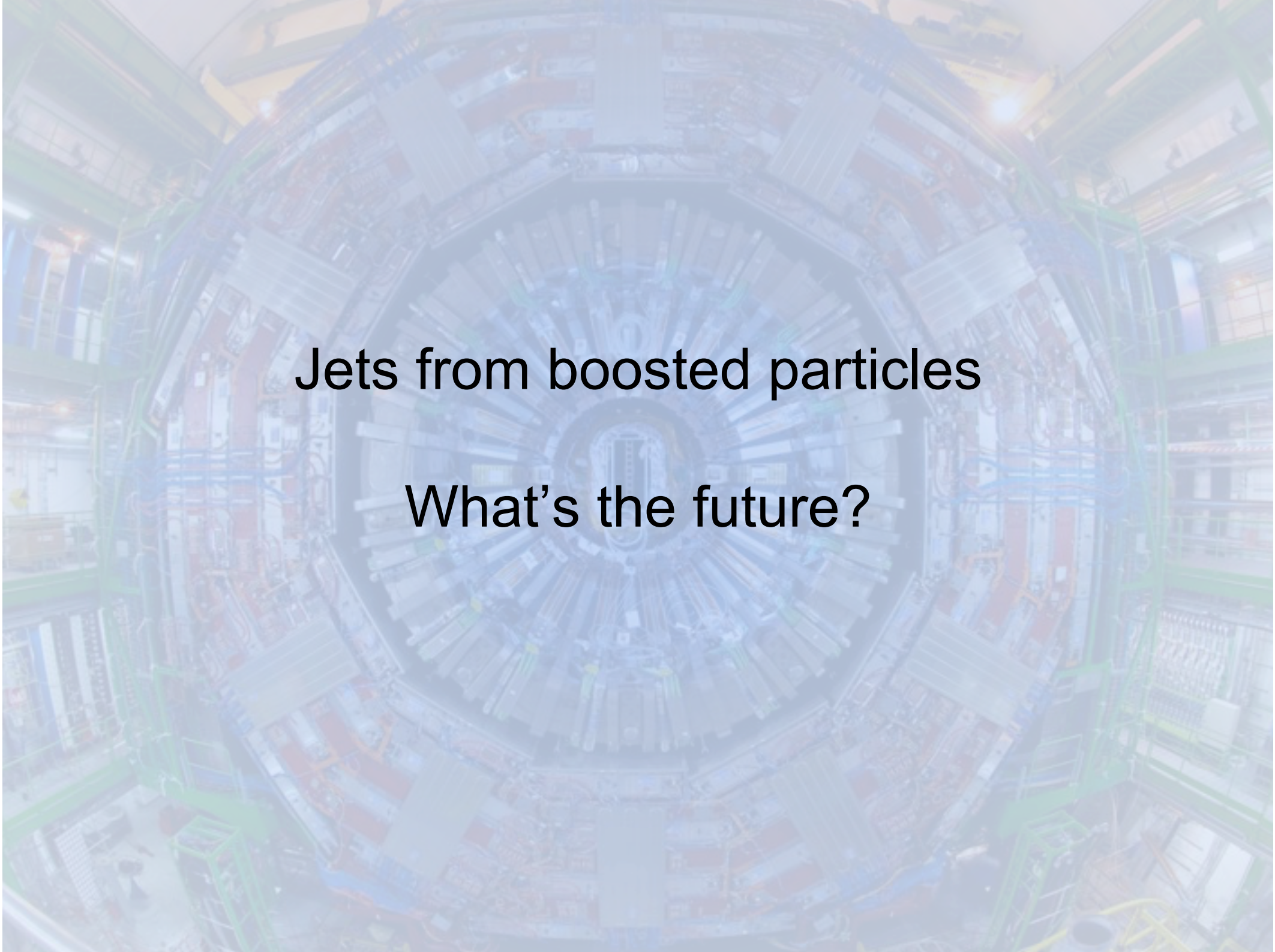


https://cds.cern.ch/record/2202715

Results


q
q̄
Z'


CMS Preliminary
2.7 fb-1 (13 TeV)
coupling, gB
Z' mass (GeV)
expected
observed
expected 2σ
expected 1σ
UA2
CDF Run 1
CDF Run 2
ATLAS 13 ⊕ 20.3 fb-1
ATLAS 13 ⊕ 3.2 fb-1 (ISR γ)
ATLAS 13 ⊕ 3.2 fb-1 (TLA)
CMS 8 ⊕ 18.8 fb-1 (Scouting)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
80
100
200
300
400
500

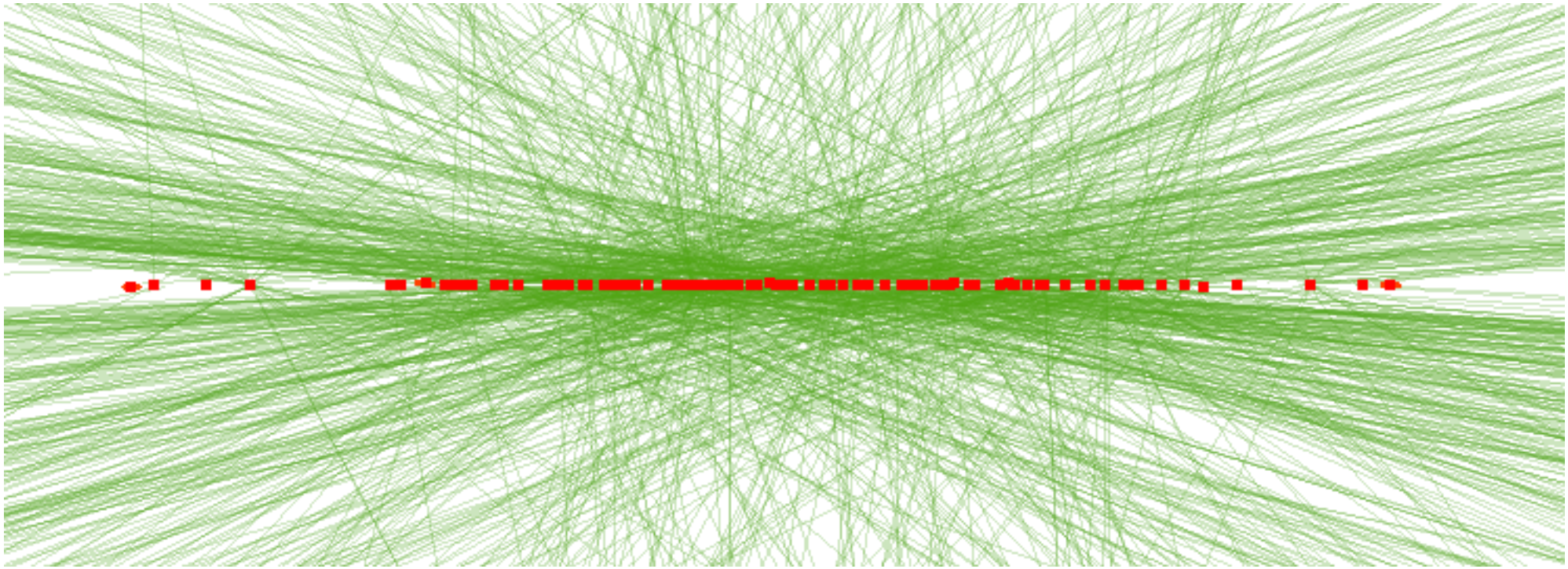


Jets from boosted particles

What’s the future?

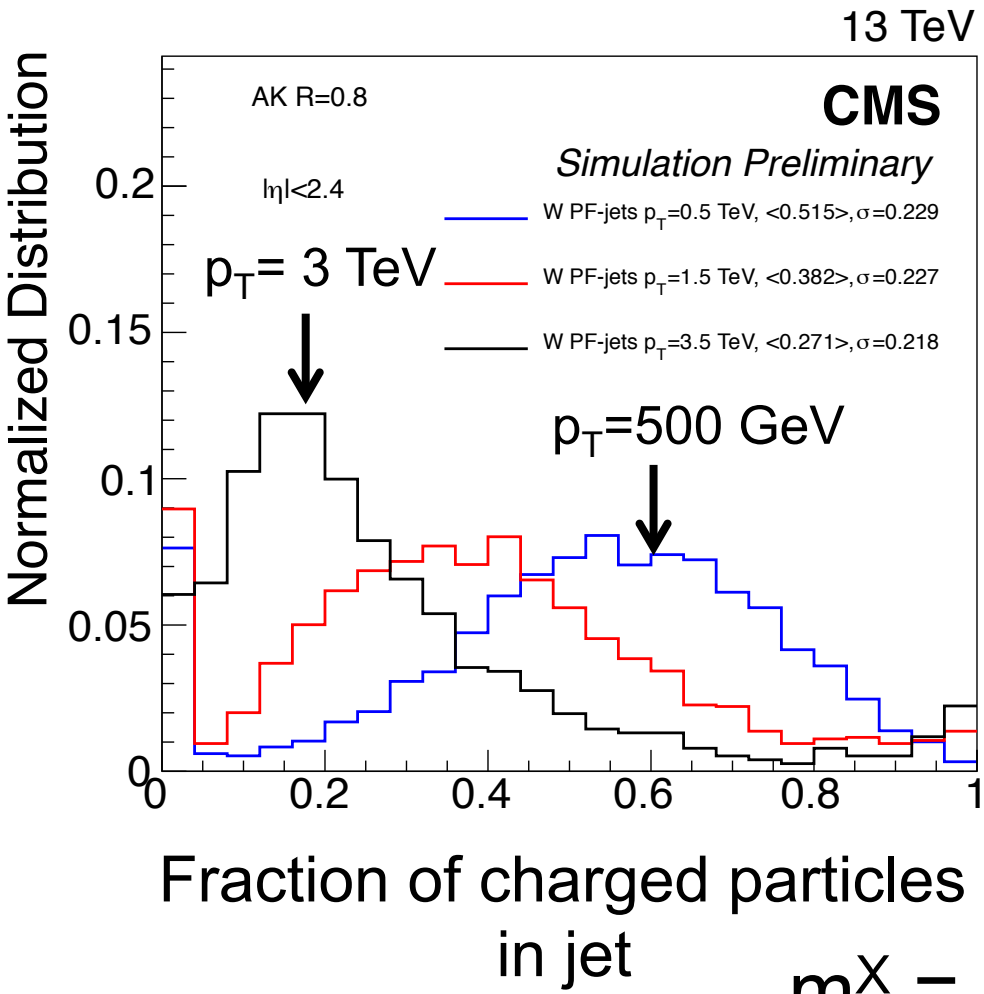
HL-LHC and upgrades

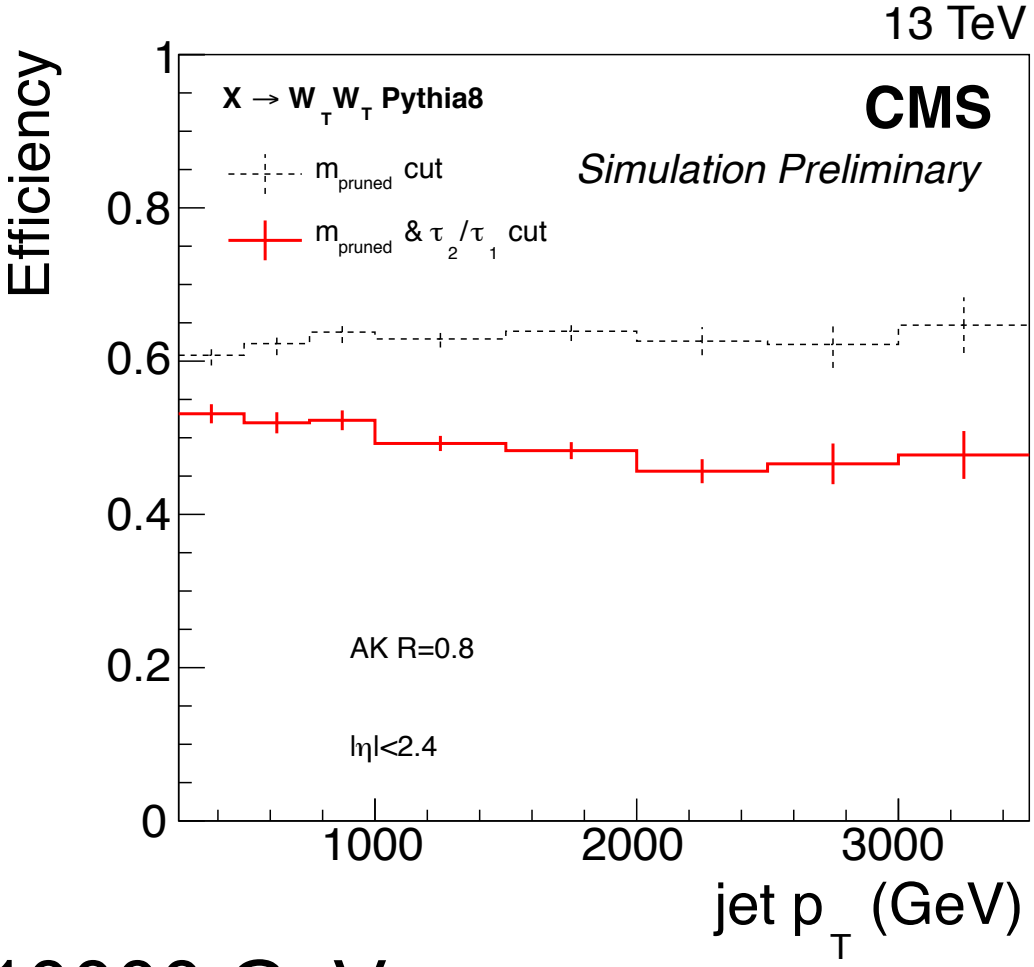
- By the end of running of HL-LHC 2037
  - At √s=14 TeV (√s=13 in 2016)
  - Collect 3000/fb of data (36/fb in 2016) → reach higher particle momenta
  - Have 200 pileup interactions (25 in 2016)



Technical Proposal for the Phase-II Upgrade of the CMS Detector

High p_T boosted object tagging





m^X = 10000 GeV

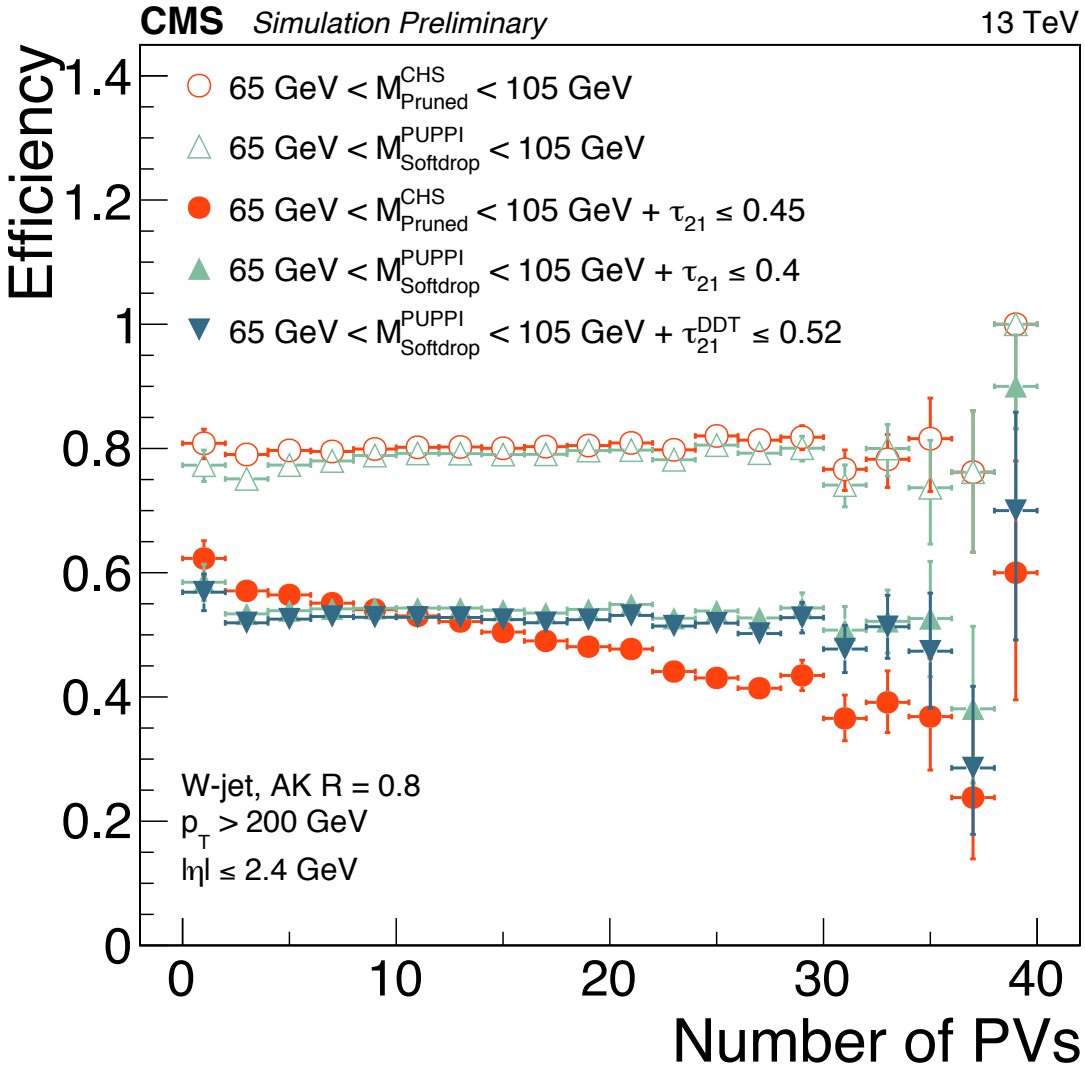
p_T^W ~ 5000 GeV

m^W = 81 GeV

θ ~ 0.03 (CMS ECAL 0.017)

CMS-PAS-JME-14-002

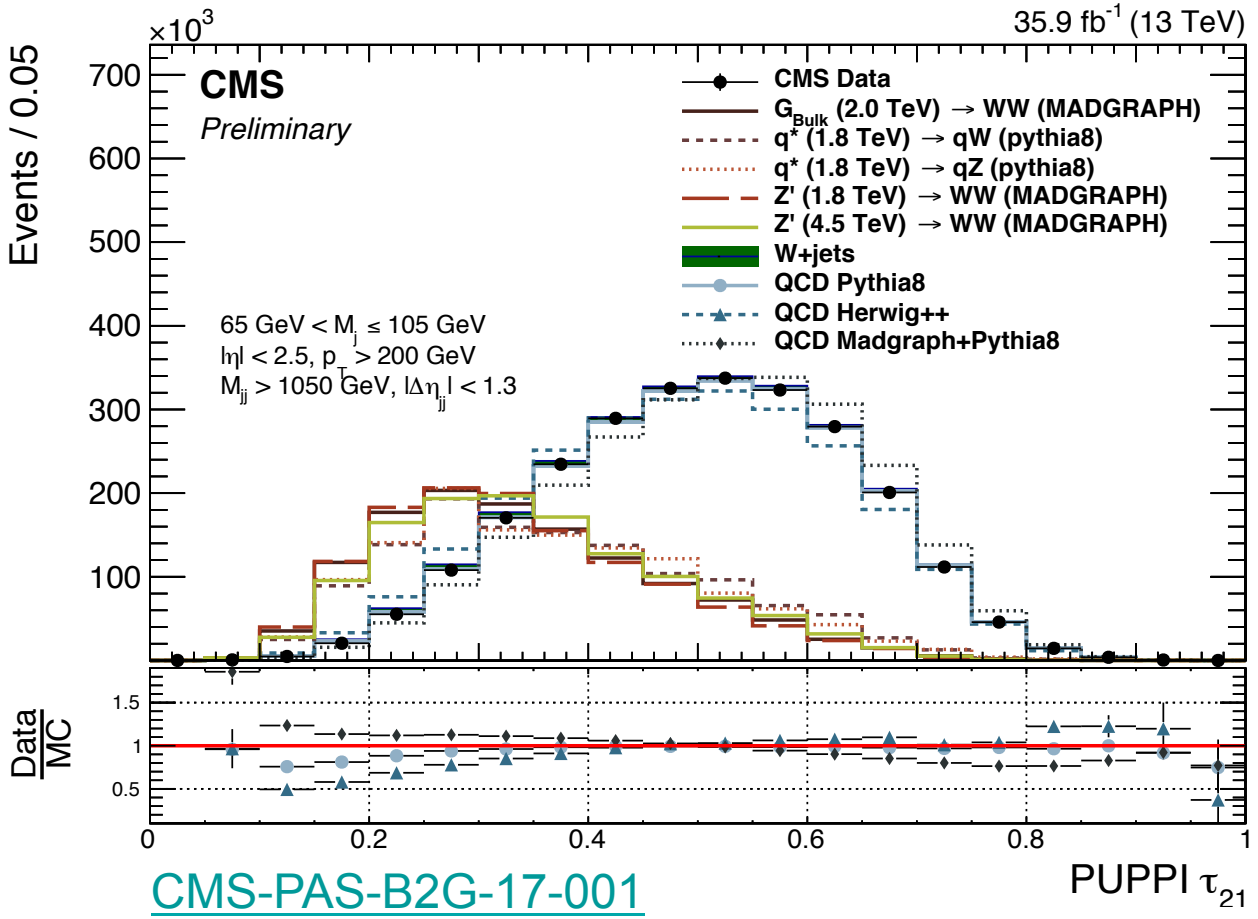
High pileup boosted object tagging



- Boosted object tagging techniques designed to deal with pileup
  - Yet, tracking detector upgrades needed to maintain current performance

CMS-PAS-JME-16-003

Understanding jet substructure



CMS-PAS-B2G-17-001

- Theoretical understanding of jet substructure is a field with lots of progress in the past ~9 years
- Understanding of quark and gluon jet substructure current active field
  - Convolution of perturbative and non-perturbative effects, that need more experimental input
  - See e.g. P. Gras et al. arXiv:1704.03878

Conclusions

- Boost is everywhere at the LHC
- A growing fraction of the LHC physics program deals with boosted particles
- HL-LHC will boost even more
- Boosted W, Z, H bosons and top quarks needed special reconstruction techniques
  - A success story – well established after first few years of LHC running
  - Optimized to cope with the momenta and number of simultaneous interactions expected at the LHC in the future