BSM Searches in Multi-Object Final States with the CMS Detector

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Introduction

The LHC has produced a wealth of physics results in the past few years

We expect physics beyond the Standard Model to appear – must search all possibilities!

Today's talk is focused on multi-object searches , specifically multi-jet based searches for physics Beyond the Standard Model

<u>Multi-jet resonances:</u>

Dijets

Dijets with b-tags

Tri-jet resonances (6-jets)

Paired dijet search (4-jets)

8-jet resonance

<u>Multiplicity Search</u>

Black holes

Why jets??
Because New Physics is likely to appear in strong interactions – high cross sections (but high background!)

CMS detector

Excellent CMS performance for searches for new physics

Silicon Tracking Detector

➡Excellent track momentum resolution
($\Delta p_T / p_T$ ~1% for barrel)

➡Excellent vertex reconstruction and impact parameter resolution for b-tagging jets

Muon System

➡High purity muon identification

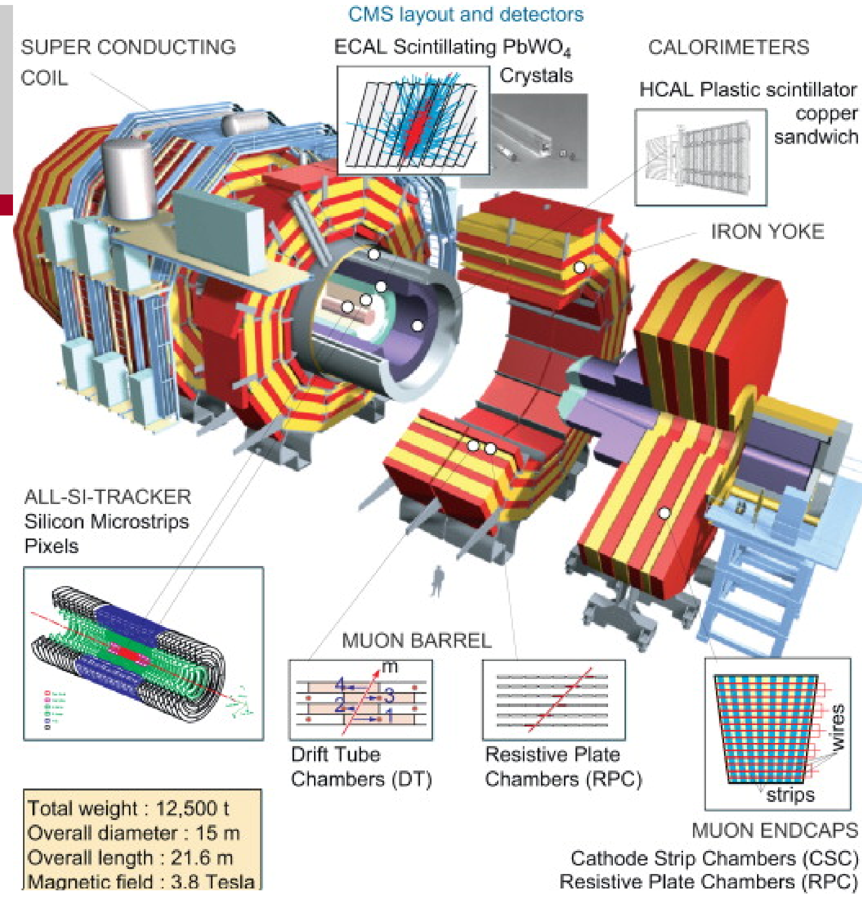
Calorimeter System

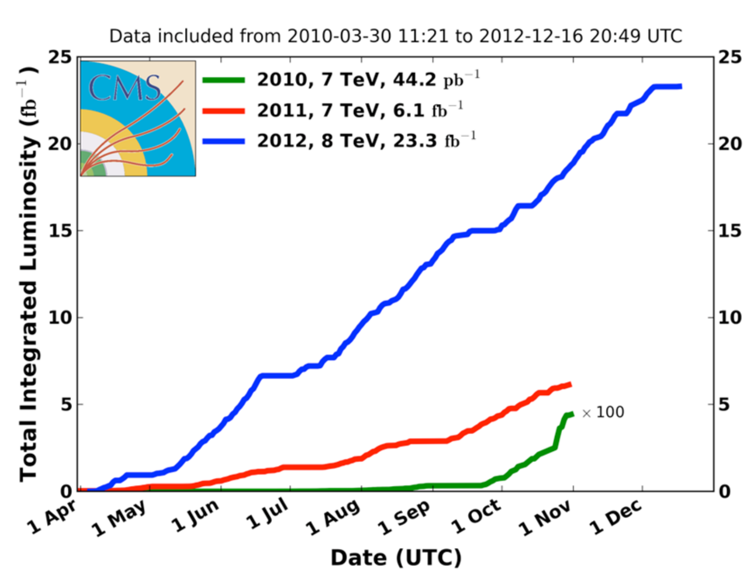
➡Highly granular Electromagnetic calorimeter

➡Hadronic calorimeter combined with ECAL for jet and missing ET reconstruction

LHC Luminosity and CMS Triggers

➡CMS collected ~5 fb^{-1} data during 2011 at $\sqrt{s}$=7 TeV, ~23 fb^{-1} data at increasing instantaneous luminosity during 2012 at $\sqrt{s}$=8 TeV

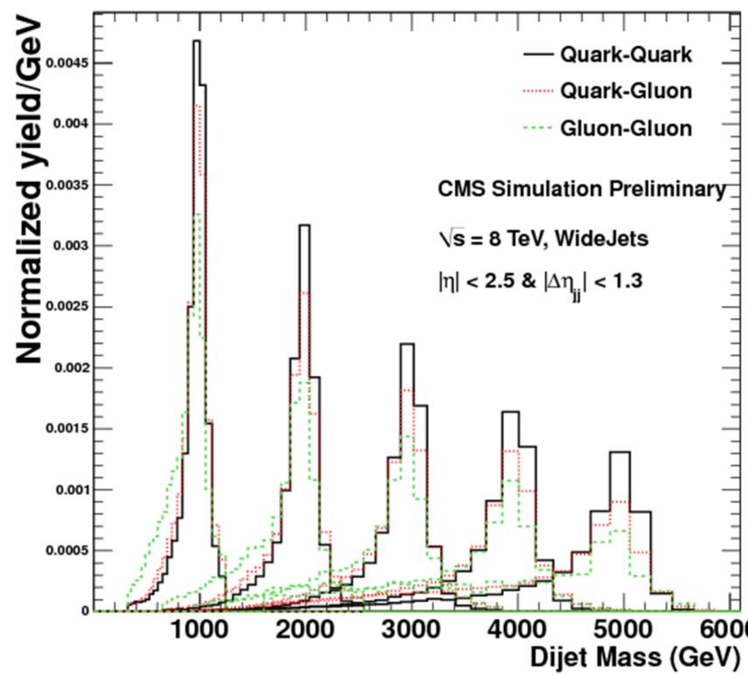




Dijet Resonances Search

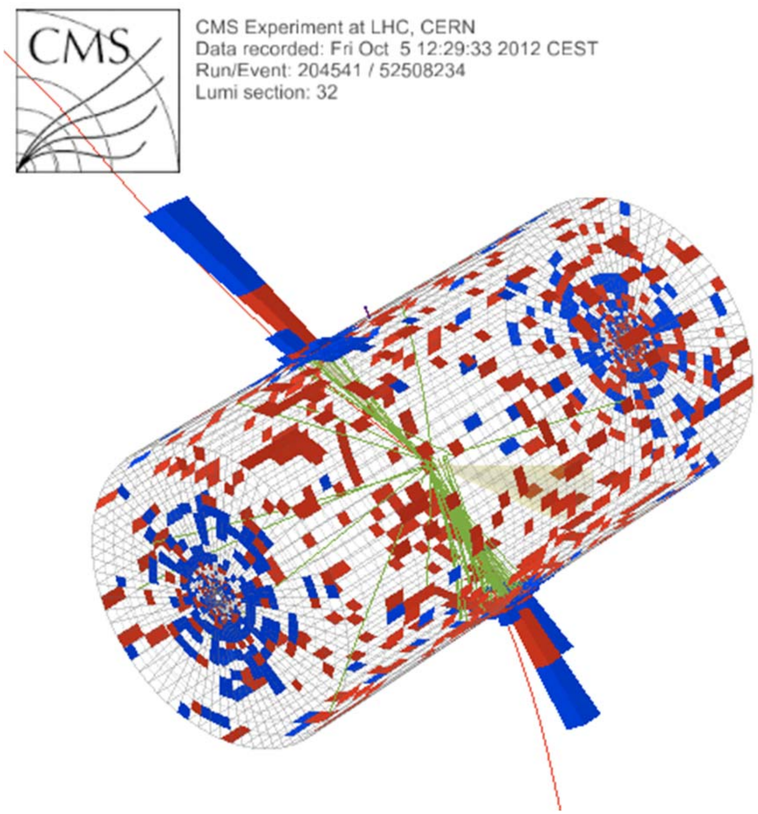
EXO-12-059

- Parton resonances decaying into dijets from various models
- Search for 3 generic types of narrow dijet resonances
  - qq,qg,gg resonances
  - Using Wide Jets
    - Recover FSR by combining nearby jets into leading jets
    - Improves resolution

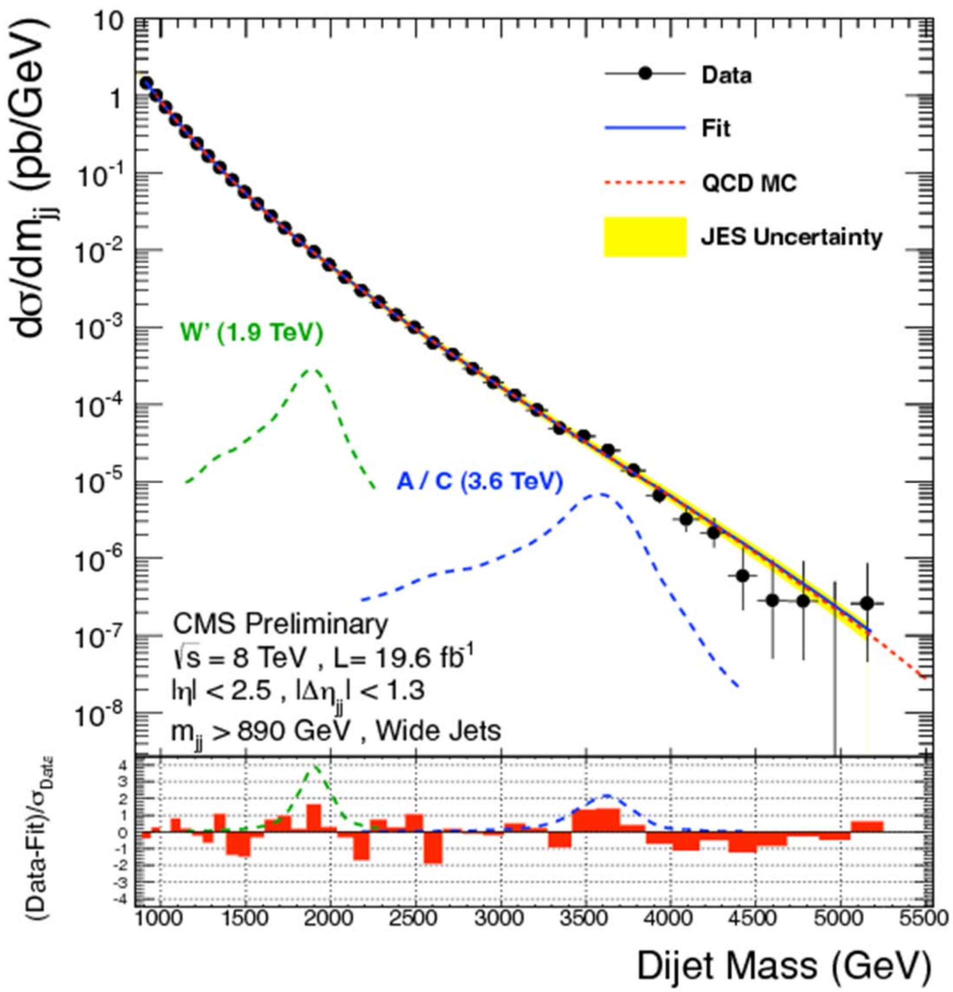


Models	X	Color	J^P	Γ/(2M)	Chan
Excited quark	q*	Triplet	$\frac{1}{2}^+$	0.02	qg
E_6 Diquark	D	Triplet	0^+	0.004	qq
Axigluon	A	Octet	1^+	0.05	$q\bar{q}$
Coloron	C	Octet	1^-	0.05	$q\bar{q}$
RS Graviton	G	Singlet	2^+	0.01	qq, gg
Heavy W	W'	Singlet	1^-	0.01	$q\bar{q}$
Heavy Z	Z'	Singlet	1^-	0.01	$q\bar{q}$
String	S	Mixed	Mixed	0.003-0.037	qg, $q\bar{q}$,gg

Dijet Resonances

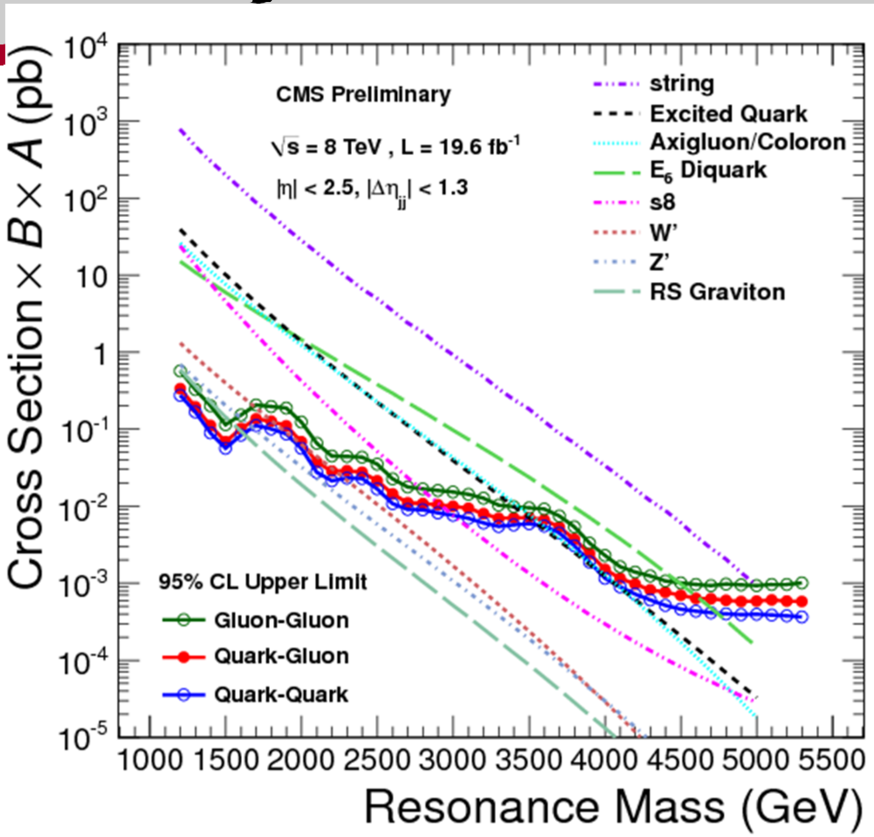


Highest dijet mass
5.15 TeV



Good agreement between data and background parametrization

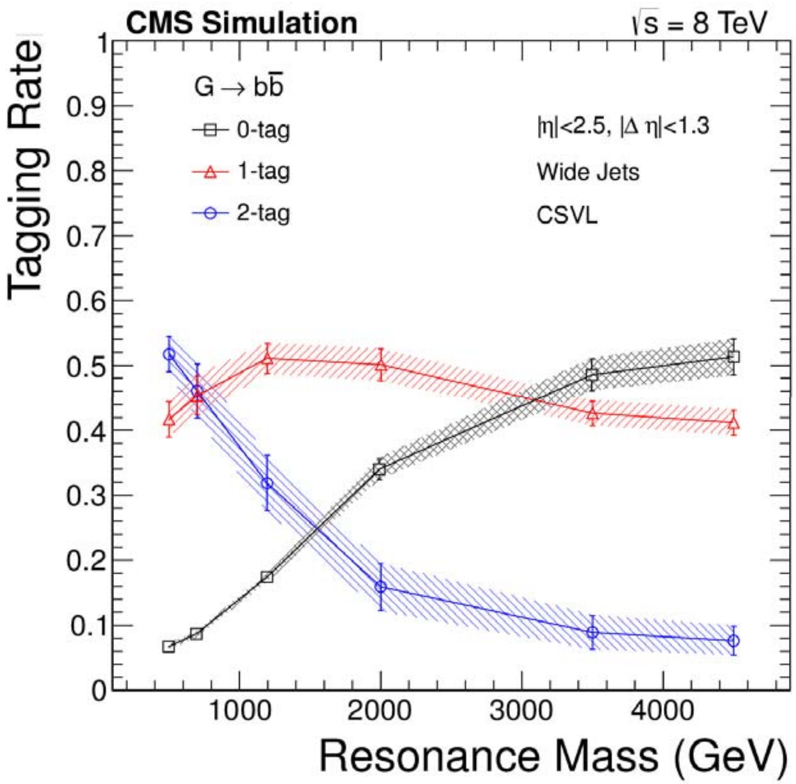
Dijet Resonance Limits



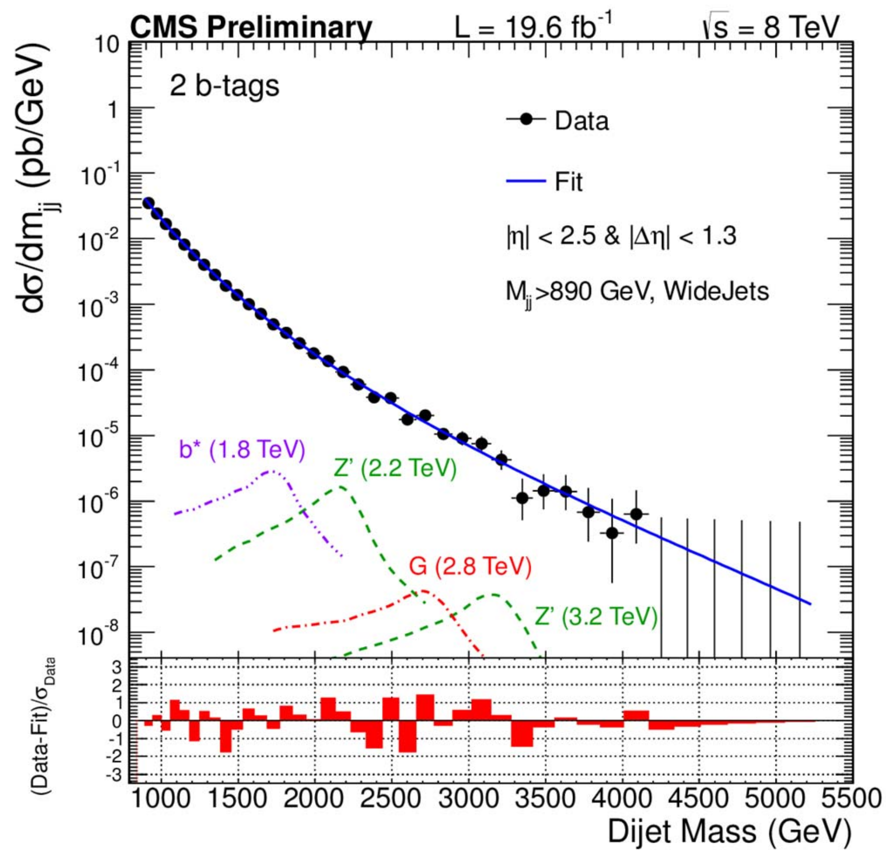
- Resolution: gg > qg > qq. Limits more stringent for: qq > qg > gg.
- Limit on any dijet decaying model may be estimated from those generic limits.

Model	Final State	Obs. Mass Excl. [TeV]	Exp. Mass Excl. [TeV]
String Resonance (S)	qg	[1.20,5.08]	[1.20,5.00]
Excited Quark (q^*)	qg	[1.20,3.50]	[1.20,3.75]
E_6 Diquark (D)	qq	[1.20,4.75]	[1.20,4.50]
Axigluon (A)/Coloron (C)	$q\bar{q}$	[1.20,3.60] + [3.90,4.08]	[1.20,3.87]
Color Octet Scalar (s8)	gg	[1.20,2.79]	[1.20,2.74]
W′ Boson (W′)	$q\bar{q}$	[1.20,2.29]	[1.20,2.28]
Z′ Boson (Z′)	$q\bar{q}$	[1.20,1.68]	[1.20,1.87]
RS Graviton (G)	$q\bar{q}$+gg	[1.20,1.58]	[1.20,1.43]

Dijets with b-tags



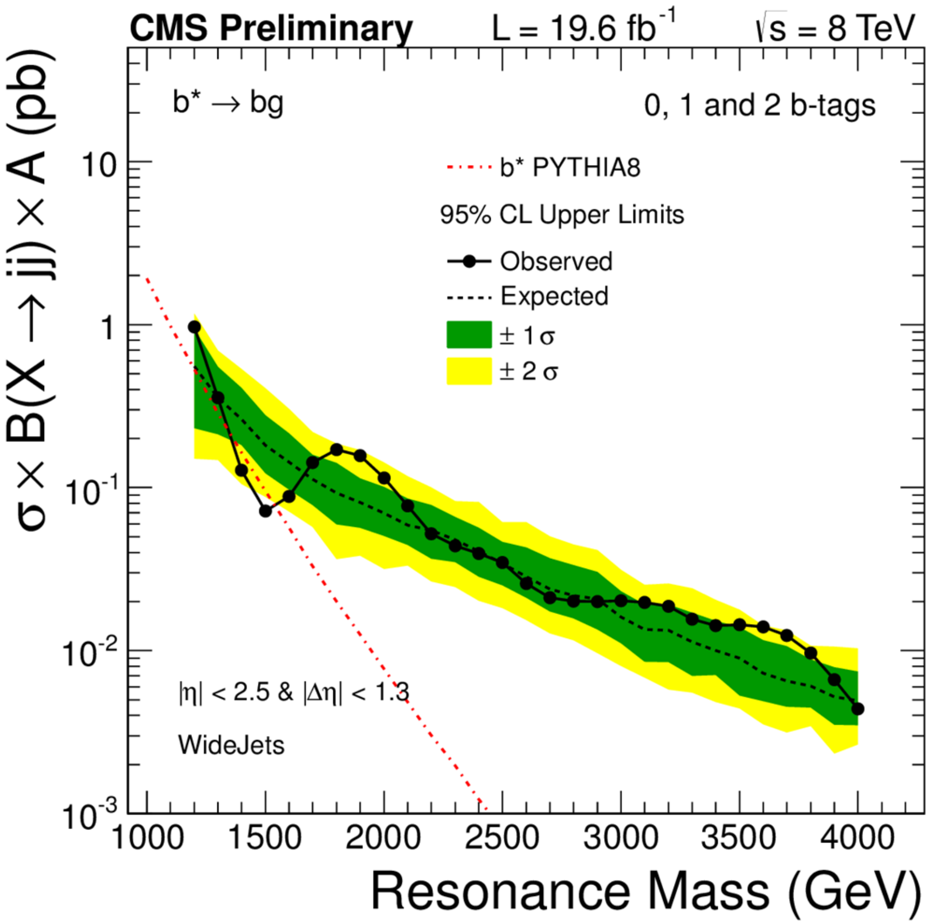
- Extend dijet resonance searches by adding b-tags
- Sensitivity to b*, Z', RS graviton

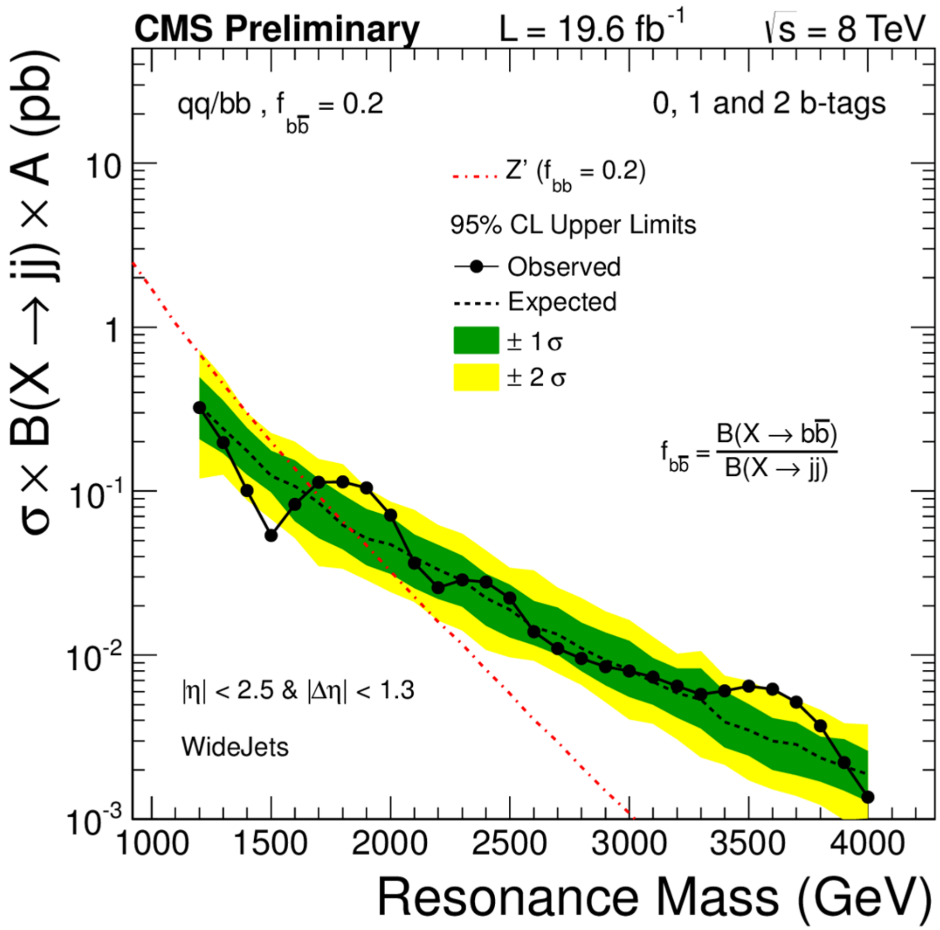


Examine 0, 1, 2 b-tagged jet events, after dijet selection

EXO-12-023

Dijets with b-tags

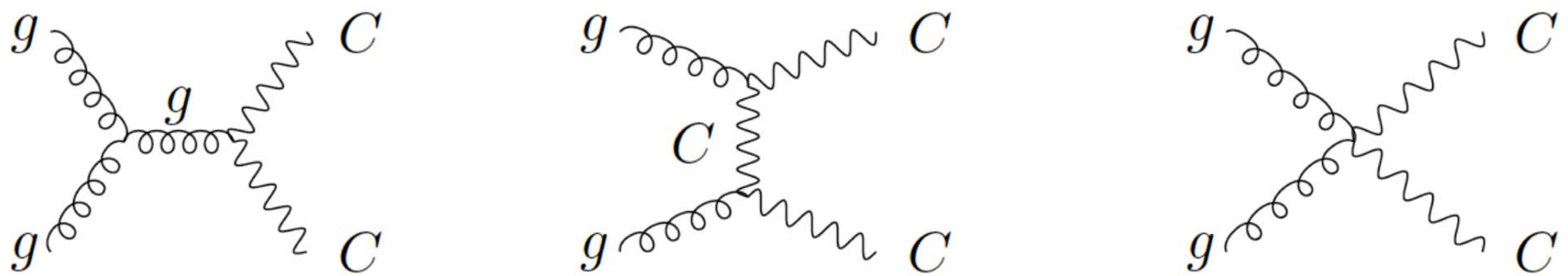




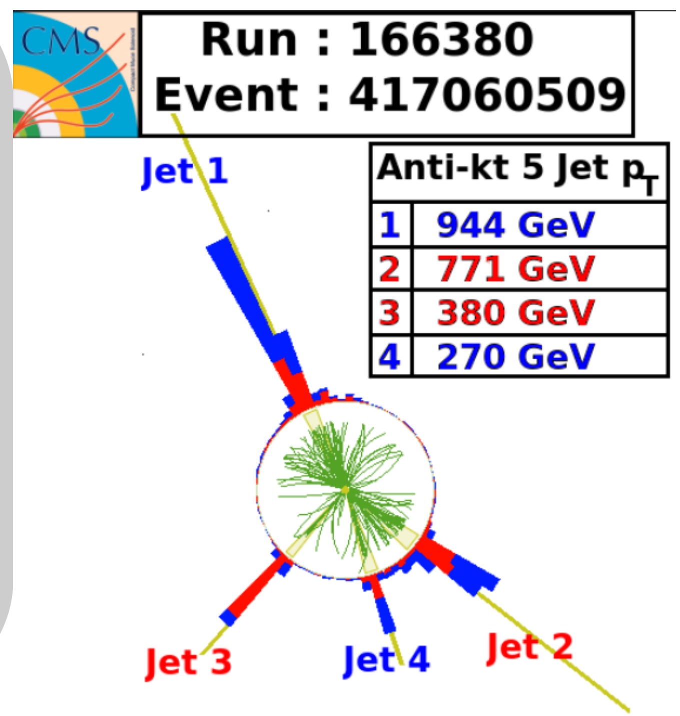
- Exclusion:
  - Z' [1.20, 1.68] TeV ($f_{bbbar} = 0.2$)
  - B* [1.34, 1.54] TeV
  - RS Graviton [1.42, 1.57] TeV

EXO-12-023

Paired Dijet Resonance Search (4-jets)

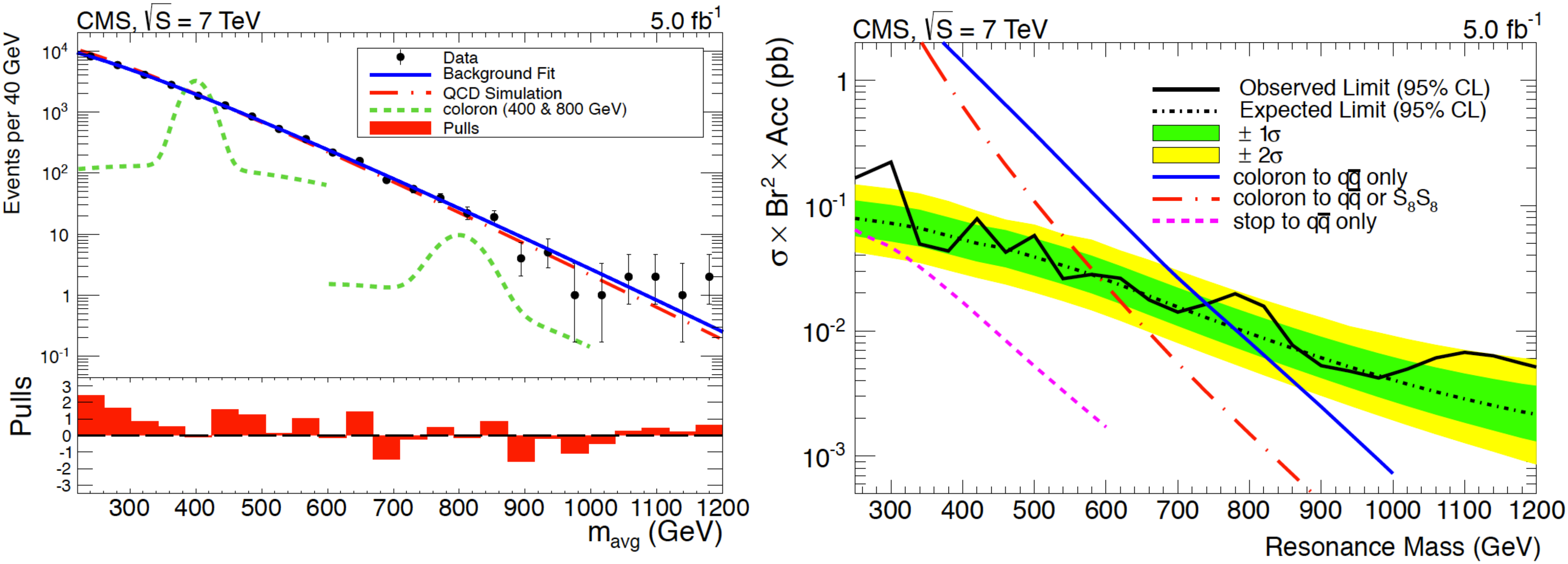


- Benchmark model: pair-produced colorons, decay to qq
- Require four well-separated, central, energetic jets -- optimized for a generic coloron search
- Combinations give 3 pairs -- examine average dijet mass of pairs—(m_{avg}), select the best matched pair—$\Delta m/m_{avg}<15\%$



7TeV EXO-11-016, 10.1103/PhysRevLett.110.141802

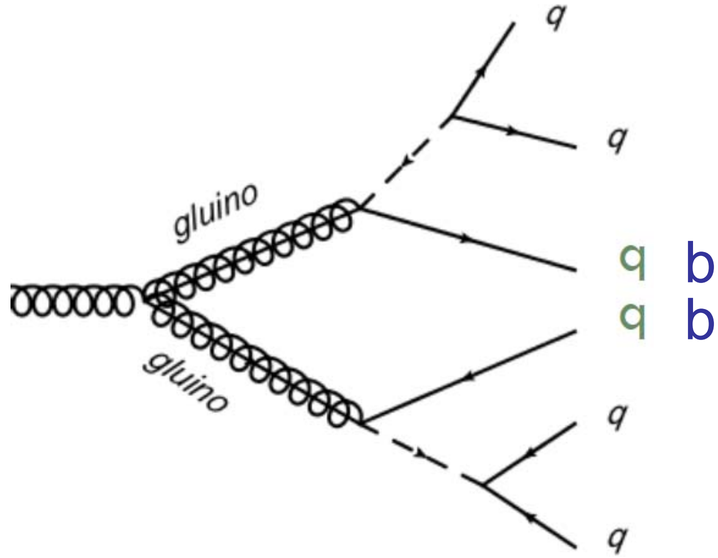
Paired Dijet Resonance Search (4-jets)

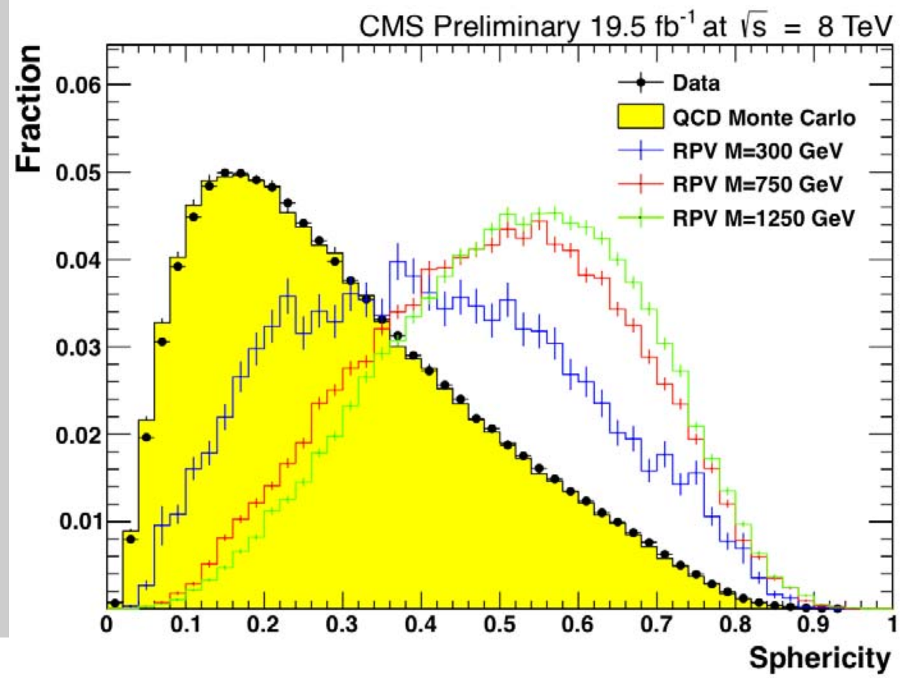


- Well described by QCD MC and parameterization (same as in the dijet search)
- No evidence for new physics
- Exclude pair production of colorons with mass between 250 and 740 GeV assuming decays into qqbar

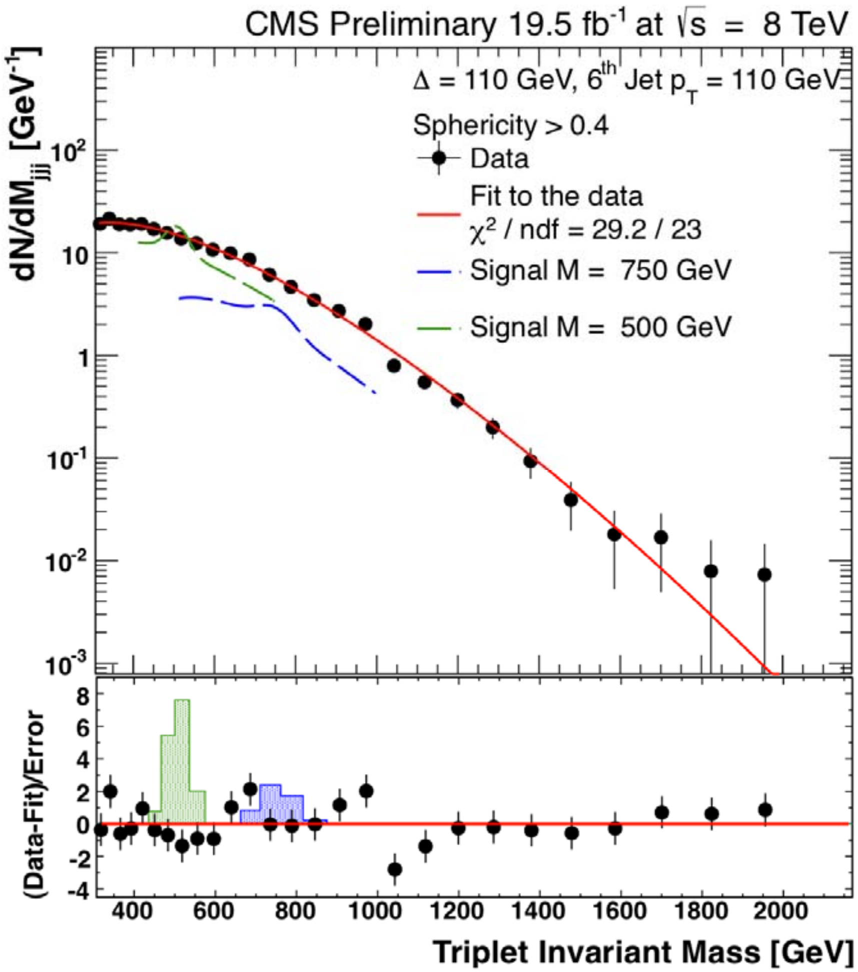
Triple Jet Resonances Search (6-jets)

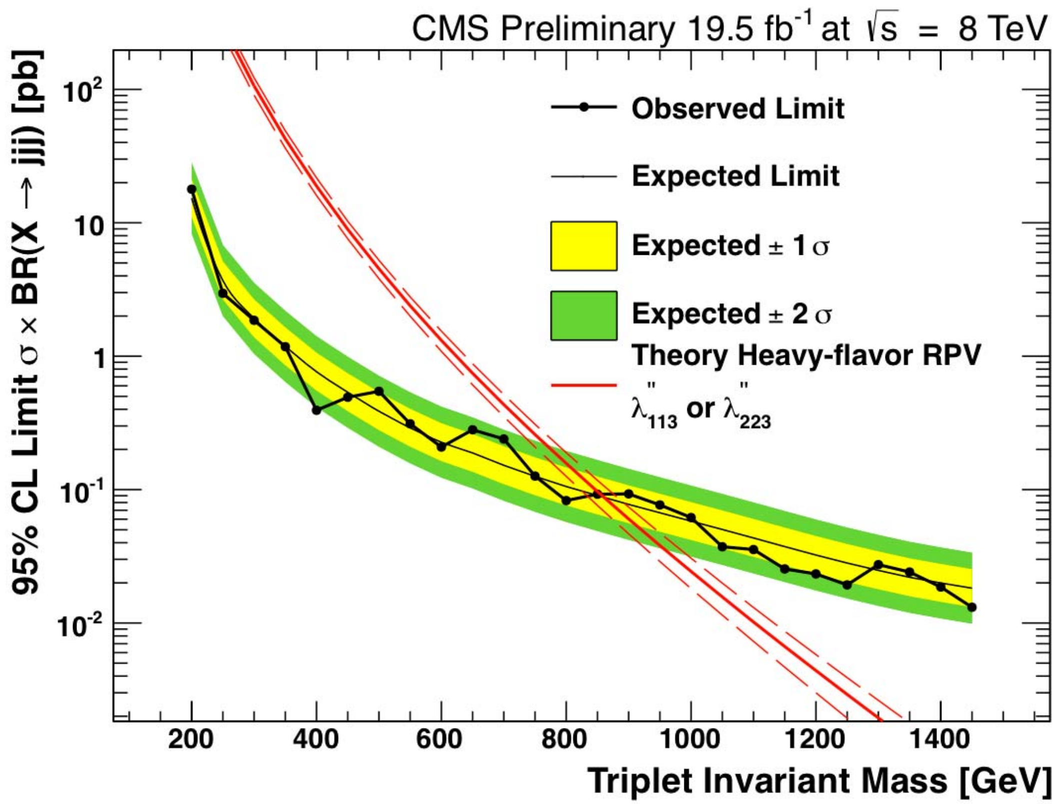
- Search for strongly coupled resonances decaying into three jets
- Benchmark model: SUSY RPV gluino with 3-body decay, BR depends on model parameters
  - Light-flavor decay : gluino →uds
  - Heavy-flavor decay: gluino →udb or csb
  - Sphericity (event-shape variable) reduces background at high mass
  - Apply b-tagging for heavy-flavor decay





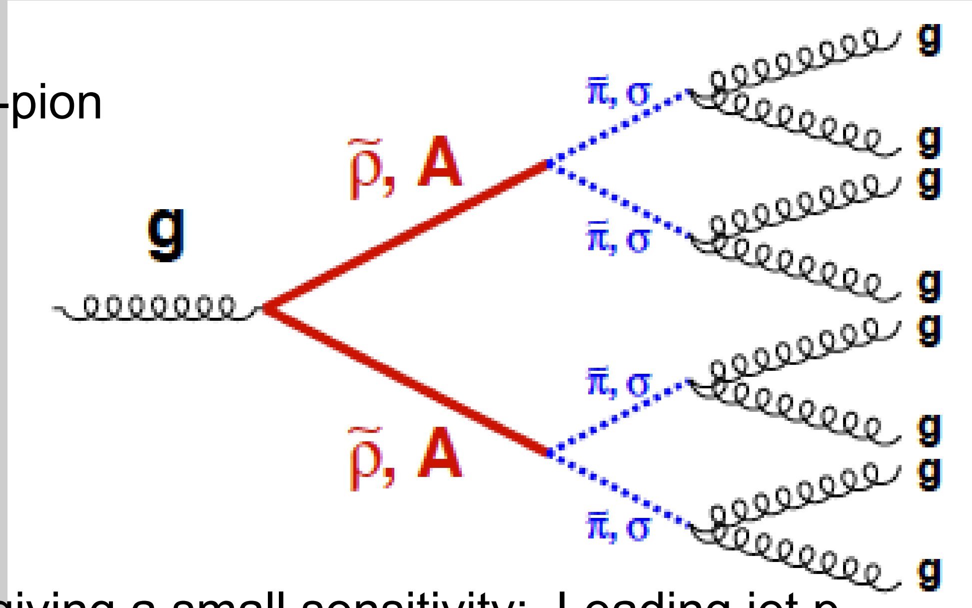
Triple Jet Resonances Search (6-jets)



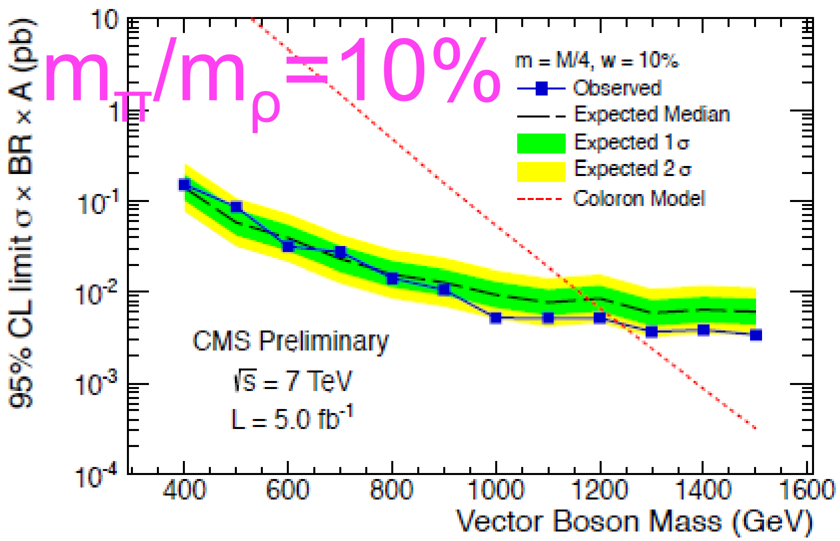


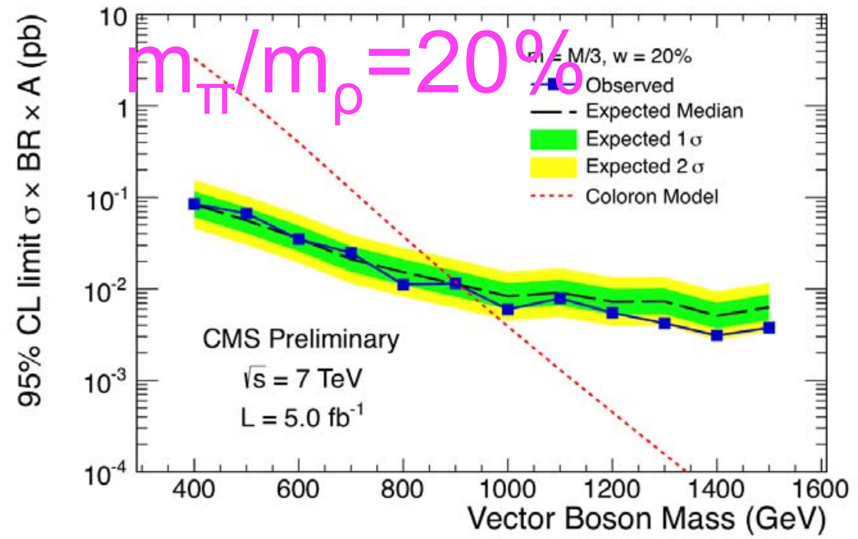
- Exclude gluino masses below 650 GeV (95% C.L.) assuming a branching fraction for RPV gluino decay into three light-flavor jets [Heavy flavor model exclusion between 200 and 835 GeV.]

Pair of Paired Dijet Resonances Search (8-jets)



- Benchmark model: hyper-rho (Vector), hyper-pion (m_{π}/m_{ρ} can have different ratio)
- Two particular challenges:
  - ISR/FSR contamination (4th jet matches to ISR w/ 50% chance 8th jet rarely matches to real Parton)
  - Combinatorial background (many combinations for doublets)
- Use MVA -- 6 kinematic variables each one giving a small sensitivity: Leading jet p_T, 4th jet p_T, 7th jet p_T, 8th jet p_T, H_T (sum of 8 jet p_T), 8-jet mass
- First time search sets limit in 8-jet final state

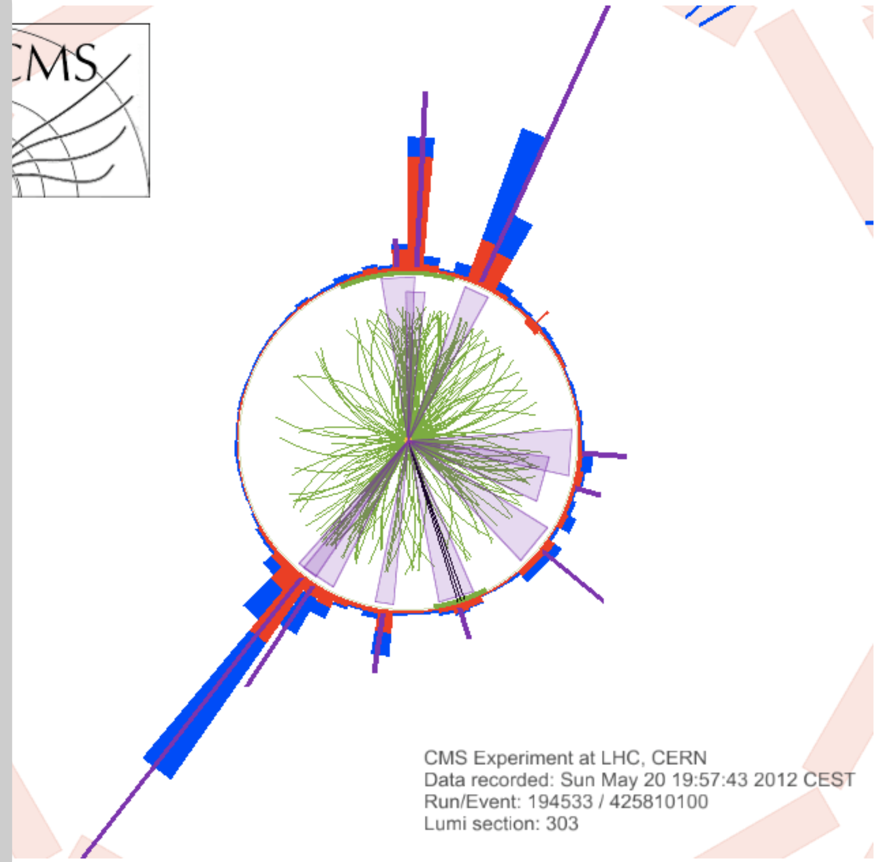




7 TeV EXO-11-075

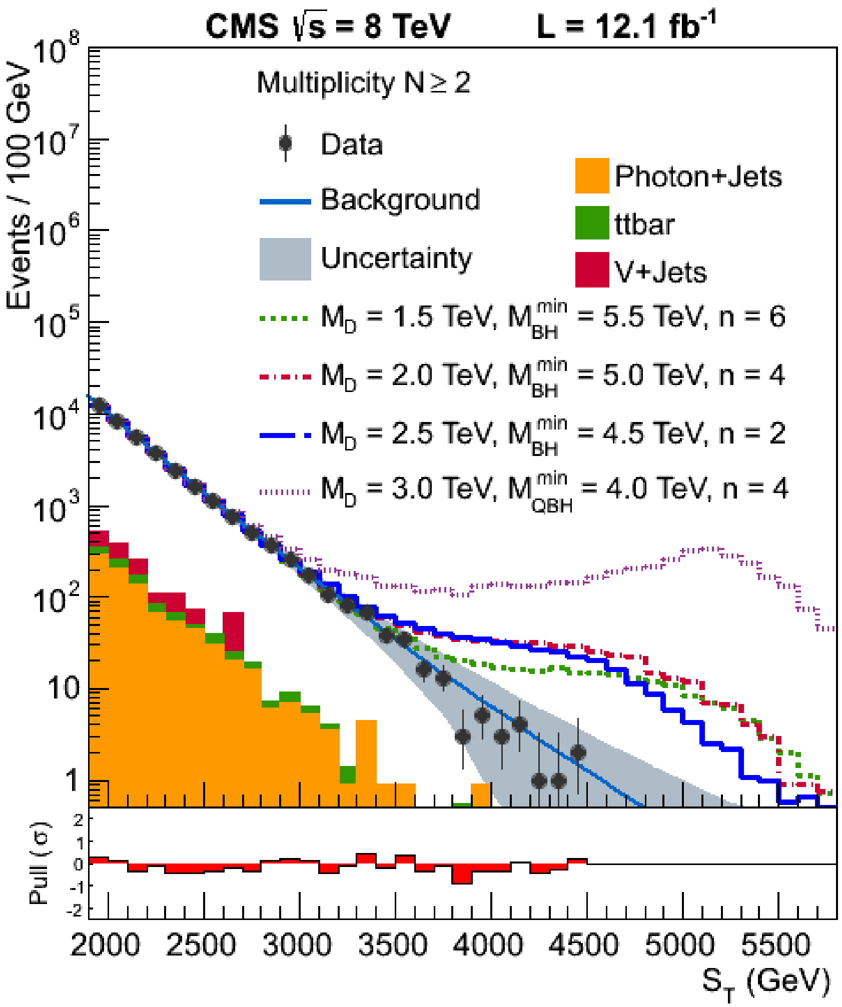
Microscopic Black Hole Search

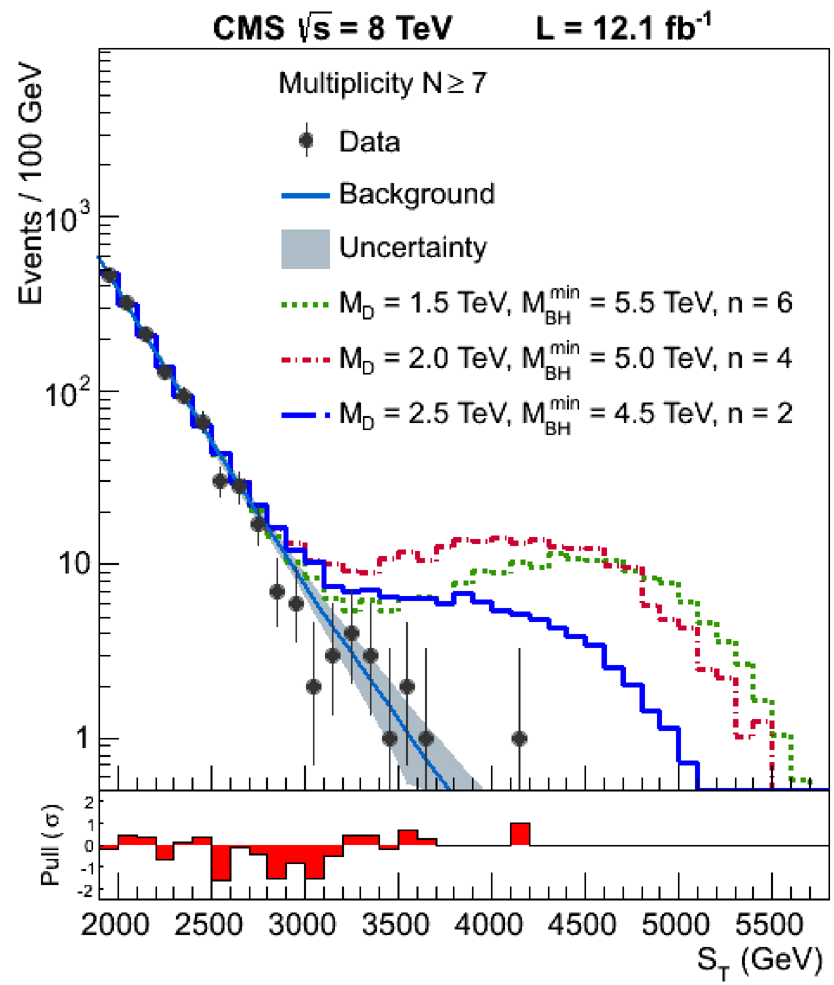
- Semi-classical black holes and string balls are predicted by models such as ADD (Arkani-Hamed, Dimopoulos and Dvali), RS (Randall Sundrum), and Unparticles
- Quantum black holes – decay to few energetic particles
- Semiclassical black holes, string balls : high multiplicity, democratic, and highly isotropic decays with the final-state particles carrying hundreds of GeV of energy.
- CMS search through $\mathbf{S_T=\Sigma E_T}$**(jet, e, μ, γ, MET)** w/ E_T>50 GeV. Multiplicity (N) = number of objects
  - Extract S_T shape from N=2,3 samples.
  - Normalize to events with N ≥ 3,4,5,6,7,8.



10-jet event

Microscopic Black Holes



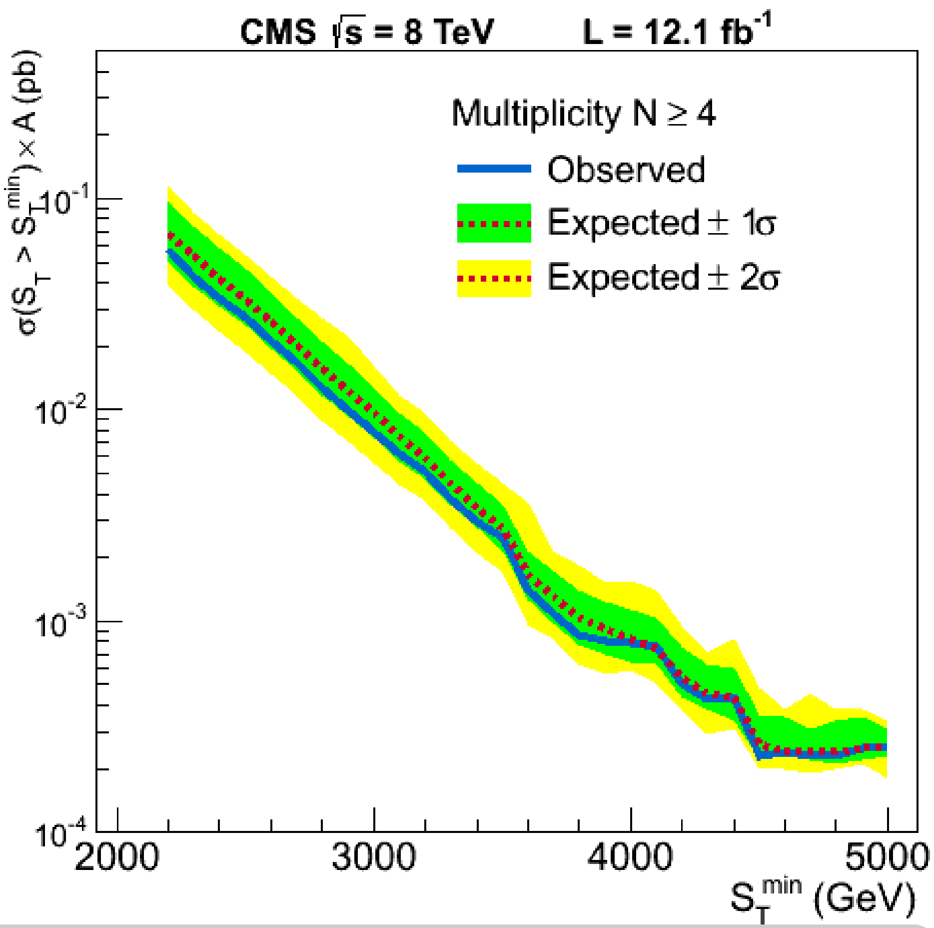


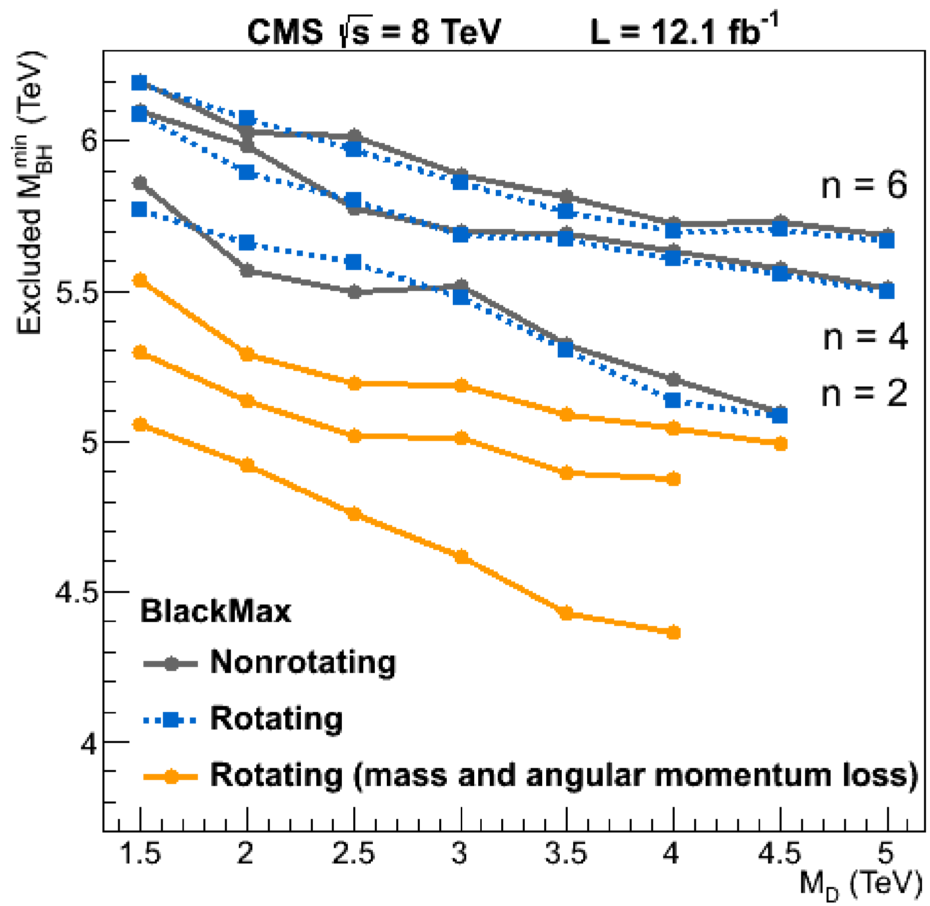
- Non-QCD standard model backgrounds are negligible
- Fit to parameterization

No significant excess is observed

EXO-12-009, 10.1007/JHEP07(2013)178

Limits on Black Holes





Model-independent cross section limit with N≥4 as a function of S_T

Limits on the black hole mass as a function of the multi-dimensional Planck scale M_D for various models with number of extra dimensions = 2,4,6 (area below curve is excluded)

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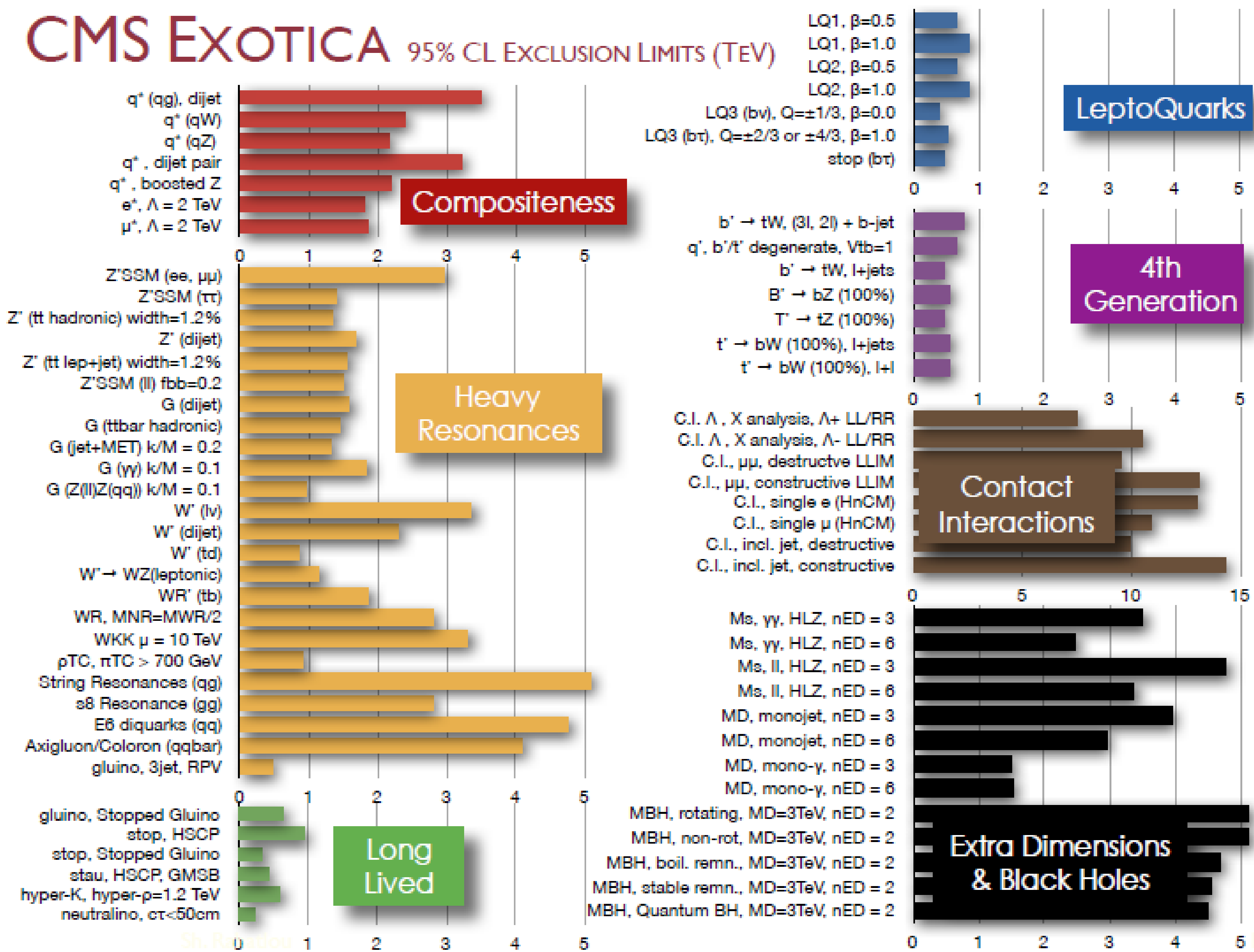
(EXO-12-009, 10.1007/JHEP07(2013)178)

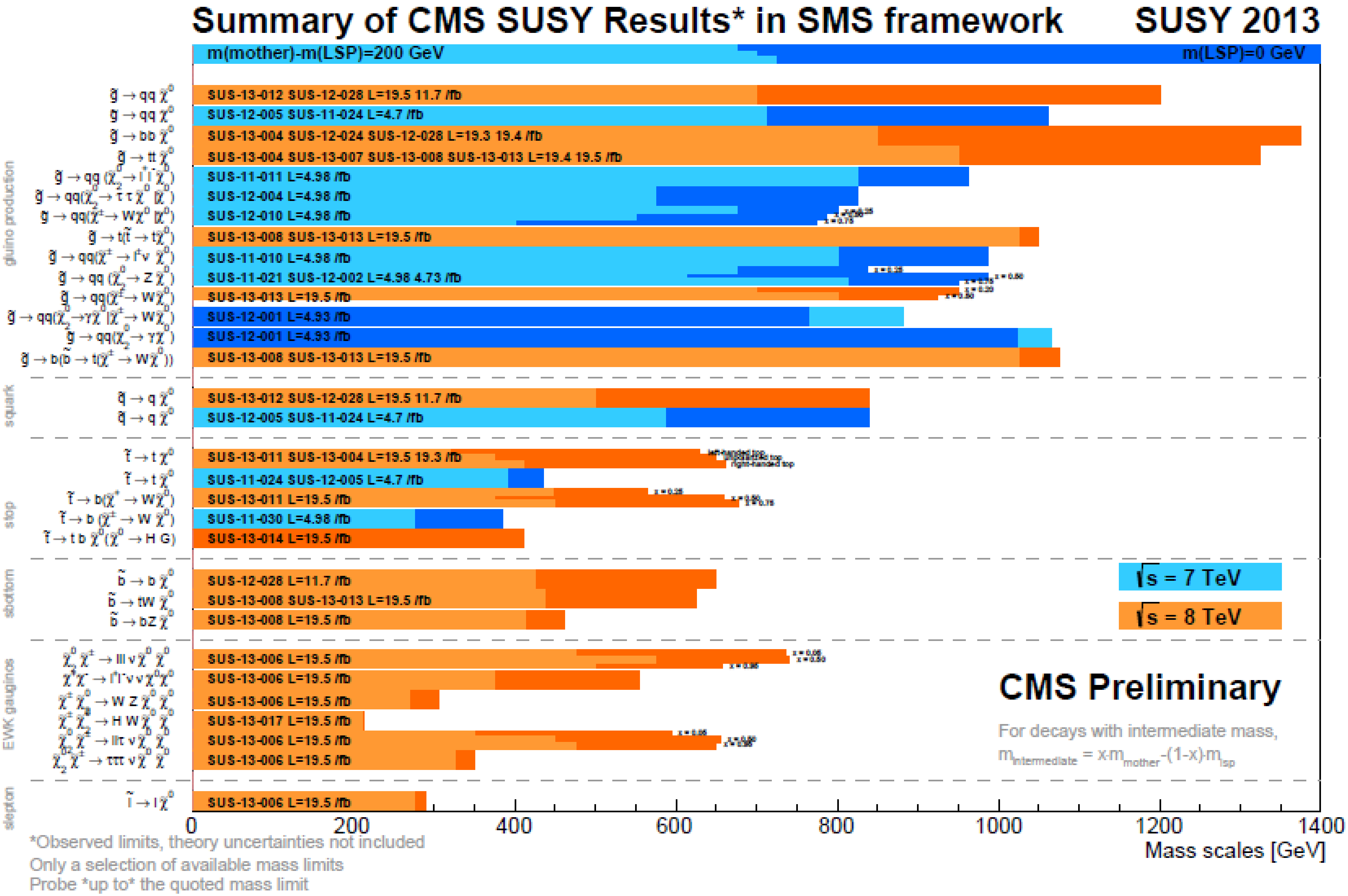
Conclusion

- CMS new physics searches using jets have been presented based on 2011 and 2012 data.
- No evidence for new physics yet.
- Data significantly constrain many models of new physics.
- Ample space for discoveries when the LHC re-starts at higher energy and luminosity!



CMS EXOTICA 95% CL EXCLUSION LIMITS (TEV)
q* (qg), dijet
q* (qW)
q* (qZ)
q* , dijet pair
q* , boosted Z
e*, Λ = 2 TeV
μ*, Λ = 2 TeV
Compositeness
Z'SSM (ee, μμ)
Z'SSM (ττ)
Z' (tt hadronic) width=1.2%
Z' (dijet)
Z' (tt lep+jet) width=1.2%
Z'SSM (ll) fbb=0.2
G (dijet)
G (ttbar hadronic)
G (jet+MET) k/M = 0.2
G (γγ) k/M = 0.1
G (Z(ll)Z(qq)) k/M = 0.1
W' (lv)
W' (dijet)
W' (td)
W'→ WZ(leptonic)
WR' (tb)
WR, MNR=MWR/2
WKK μ = 10 TeV
ρTC, πTC > 700 GeV
String Resonances (qg)
s8 Resonance (gg)
E6 diquarks (qq)
Axigluon/Coloron (qqbar)
gluino, 3jet, RPV
Heavy Resonances
gluino, Stopped Gluino
stop, HSCP
stop, Stopped Gluino
stau, HSCP, GMSB
hyper-K, hyper-ρ=1.2 TeV
neutralino, cτ<50cm
Long Lived
LQ1, β=0.5
LQ1, β=1.0
LQ2, β=0.5
LQ2, β=1.0
LQ3 (bν), Q=±1/3, β=0.0
LQ3 (bτ), Q=±2/3 or ±4/3, β=1.0
stop (bτ)
LeptoQuarks
b' → tW, (3l, 2l) + b-jet
q', b'/t' degenerate, Vtb=1
b' → tW, l+jets
B' → bZ (100%)
T' → tZ (100%)
t' → bW (100%), l+jets
t' → bW (100%), l+l
4th Generation
C.I. Λ , X analysis, Λ+ LL/RR
C.I. Λ , X analysis, Λ- LL/RR
C.I., μμ, destructve LLIM
C.I., μμ, constructive LLIM
C.I., single e (HnCM)
C.I., single μ (HnCM)
C.I., incl. jet, destructive
C.I., incl. jet, constructive
Contact Interactions
Ms, γγ, HLZ, nED = 3
Ms, γγ, HLZ, nED = 6
Ms, ll, HLZ, nED = 3
Ms, ll, HLZ, nED = 6
MD, monojet, nED = 3
MD, monojet, nED = 6
MD, mono-γ, nED = 3
MD, mono-γ, nED = 6
MBH, rotating, MD=3TeV, nED = 2
MBH, non-rot, MD=3TeV, nED = 2
MBH, boil. remn., MD=3TeV, nED = 2
MBH, stable remn., MD=3TeV, nED = 2
MBH, Quantum BH, MD=3TeV, nED = 2
Extra Dimensions & Black Holes
0 1 2 3 4 5
0 5 10 15

Backup slides


Summary of CMS SUSY Results* in SMS framework
SUSY 2013
m(mother)-m(LSP)=200 GeV
m(LSP)=0 GeV
gluino production
squark
stop
sbottom
EWK gauginos
slepton
SUS-13-012 SUS-12-028 L=19.5 11.7 /fb
SUS-12-005 SUS-11-024 L=4.7 /fb
SUS-13-004 SUS-12-024 SUS-12-028 L=19.3 19.4 /fb
SUS-13-004 SUS-13-007 SUS-13-008 SUS-13-013 L=19.4 19.5 /fb
SUS-11-011 L=4.98 /fb
SUS-12-004 L=4.98 /fb
SUS-12-010 L=4.98 /fb
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SUS-11-010 L=4.98 /fb
SUS-11-021 SUS-12-002 L=4.98 4.73 /fb
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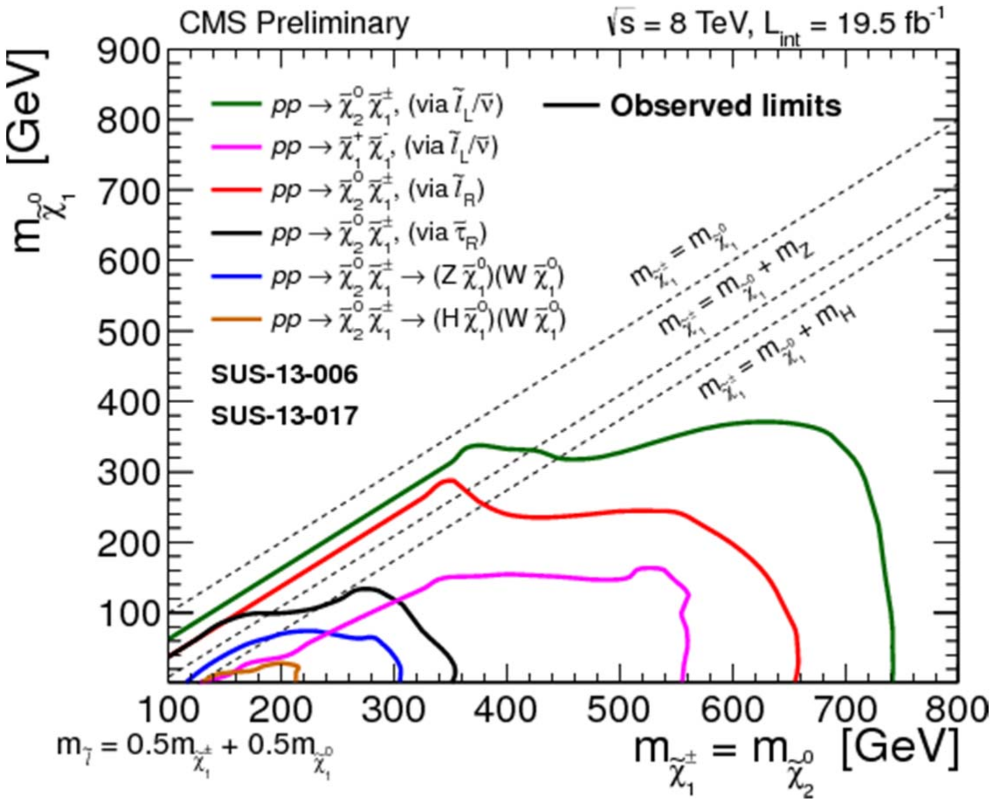
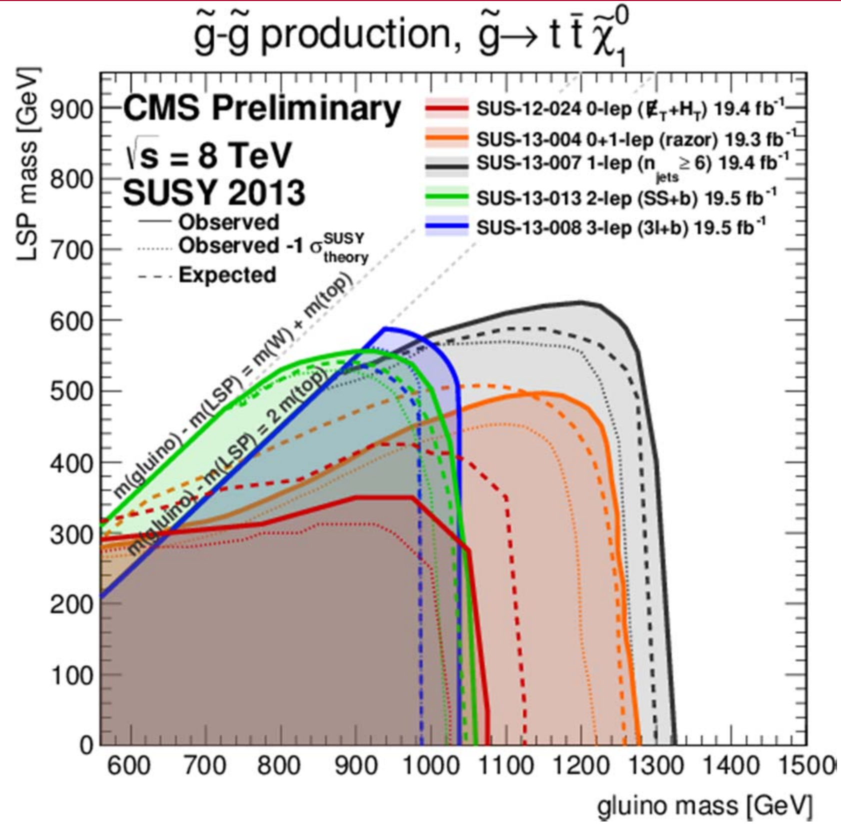
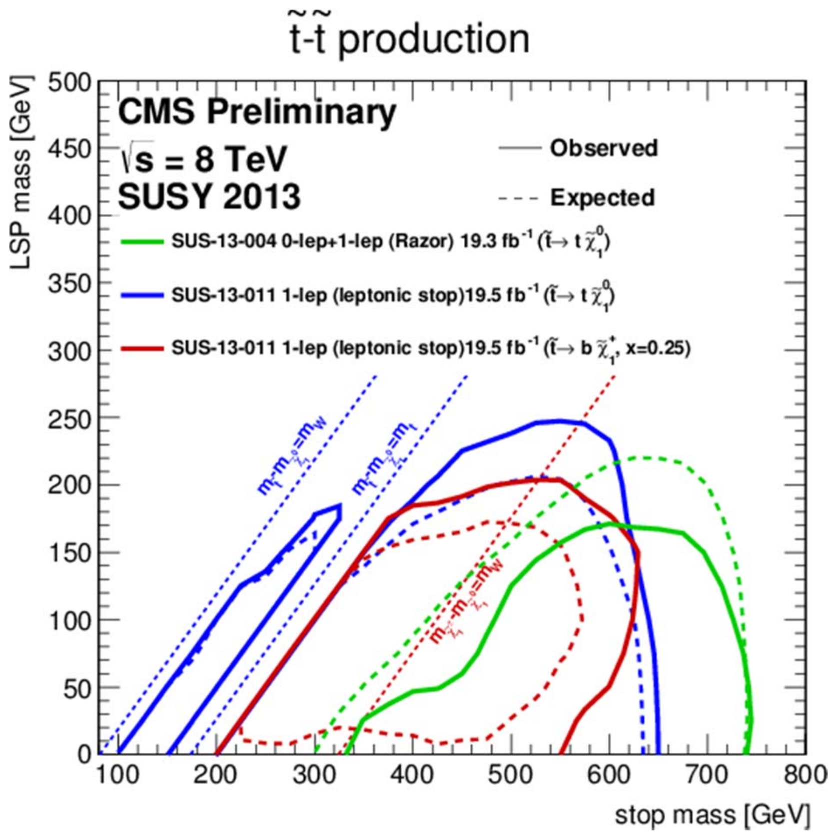
SUS-13-017 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
√s = 7 TeV
√s = 8 TeV
CMS Preliminary
For decays with intermediate mass,
m_intermediate = x·m_mother-(1-x)·m_lsp
0
200
400
600
800
1000
1200
1400
Mass scales [GeV]
*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit


CMS Preliminary
√s = 8 TeV, L_int = 19.5 fb^-1
Observed limits
SUS-13-006
SUS-13-017
m_l̃ = 0.5m_χ̃±1 + 0.5m_χ̃01


g̃-g̃ production, g̃→ t t̄ χ̃01
CMS Preliminary
√s = 8 TeV
SUSY 2013
Observed
Observed -1 σ theory SUSY
Expected
SUS-12-024 0-lep (E̸T+HT) 19.4 fb-1
SUS-13-004 0+1-lep (razor) 19.3 fb-1
SUS-13-007 1-lep (njets ≥ 6) 19.4 fb-1
SUS-13-013 2-lep (SS+b) 19.5 fb-1
SUS-13-008 3-lep (3l+b) 19.5 fb-1
LSP mass [GeV]
gluino mass [GeV]

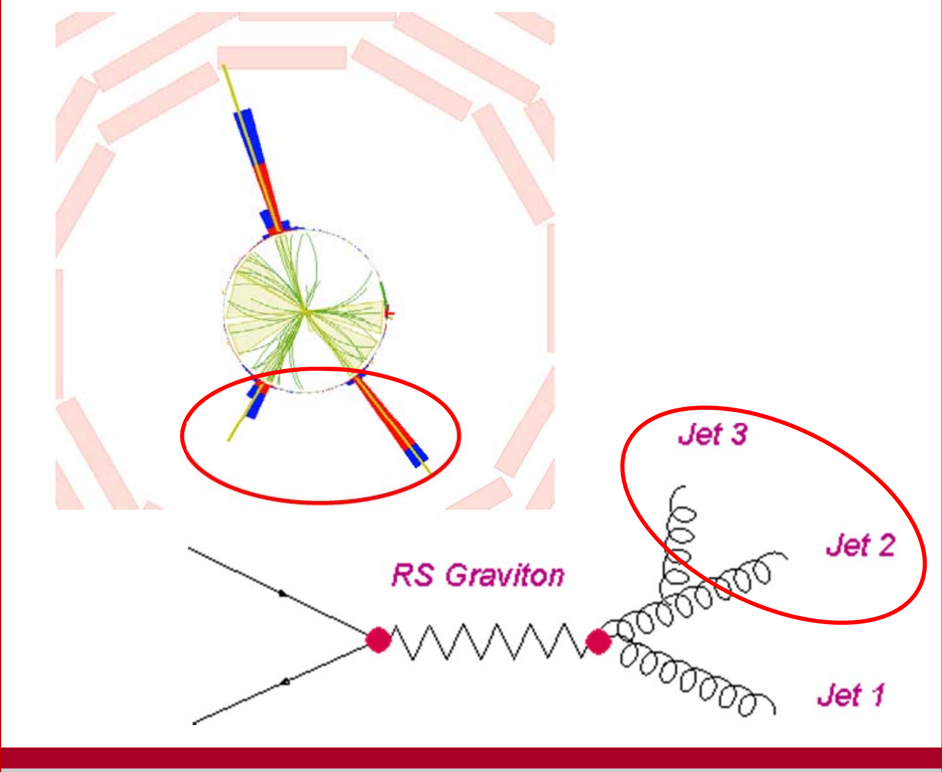


t̃-t̃ production
CMS Preliminary
√s = 8 TeV
SUSY 2013
Observed
Expected
SUS-13-004 0-lep+1-lep (Razor) 19.3 fb⁻¹ (t̃→ t χ̃⁰₁)
SUS-13-011 1-lep (leptonic stop)19.5 fb⁻¹ (t̃→ t χ̃⁰₁)
SUS-13-011 1-lep (leptonic stop)19.5 fb⁻¹ (t̃→ b χ̃⁺₁, x=0.25)
LSP mass [GeV]
stop mass [GeV]

Fat jets definition

Fat jets optimize dijet resonance resolution by recombining FSR into the two leading jets

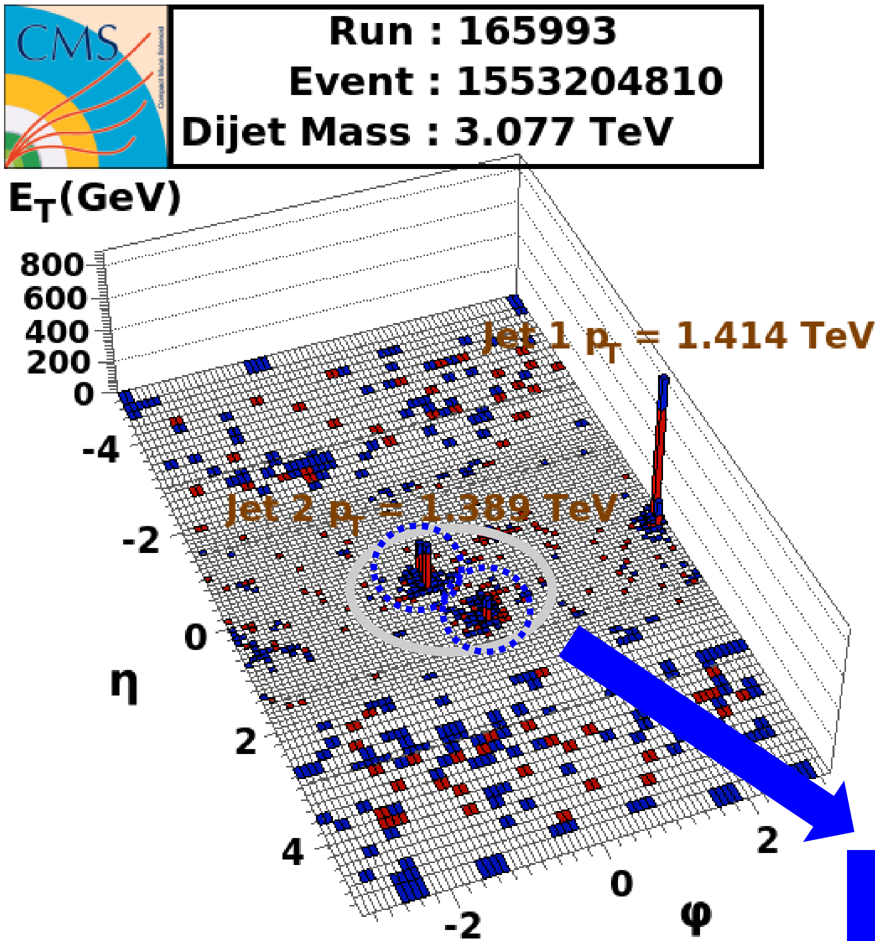
Fat Jets : clusters of AK5 PF Jets
Cluster radius : R=1.1

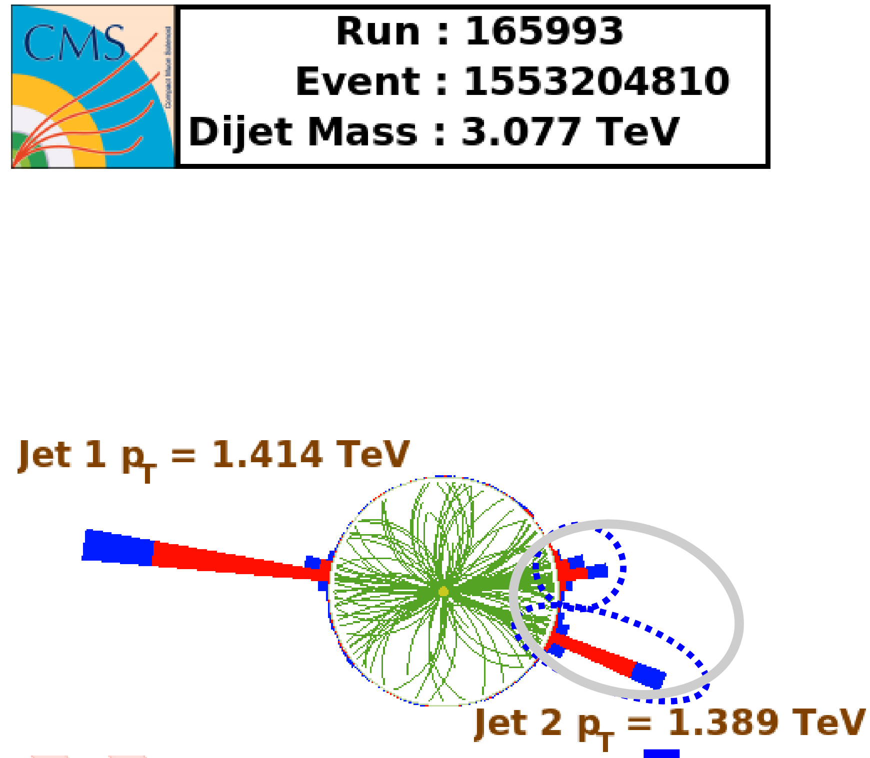


Fat Jets algorithm

- Select 2 leading AK5 PF jets.
- For AK5 PF jets j from 3 to n:
  - Require:
    - $p_{T,j} > 10$ GeV
    - $|\eta| < 2.5$
  - If $\Delta R_{1j} < R_{Fat}$ and ΔR_{2j}.
    - Add j to Fat Jet 1.
  - If $\Delta R_{j2} < R_{Fat}$ and ΔR_{1j}.
    - Add j to Fat Jet 2.
- R = 1.1 is best choice for a single search for qq, qg and gg resonances.

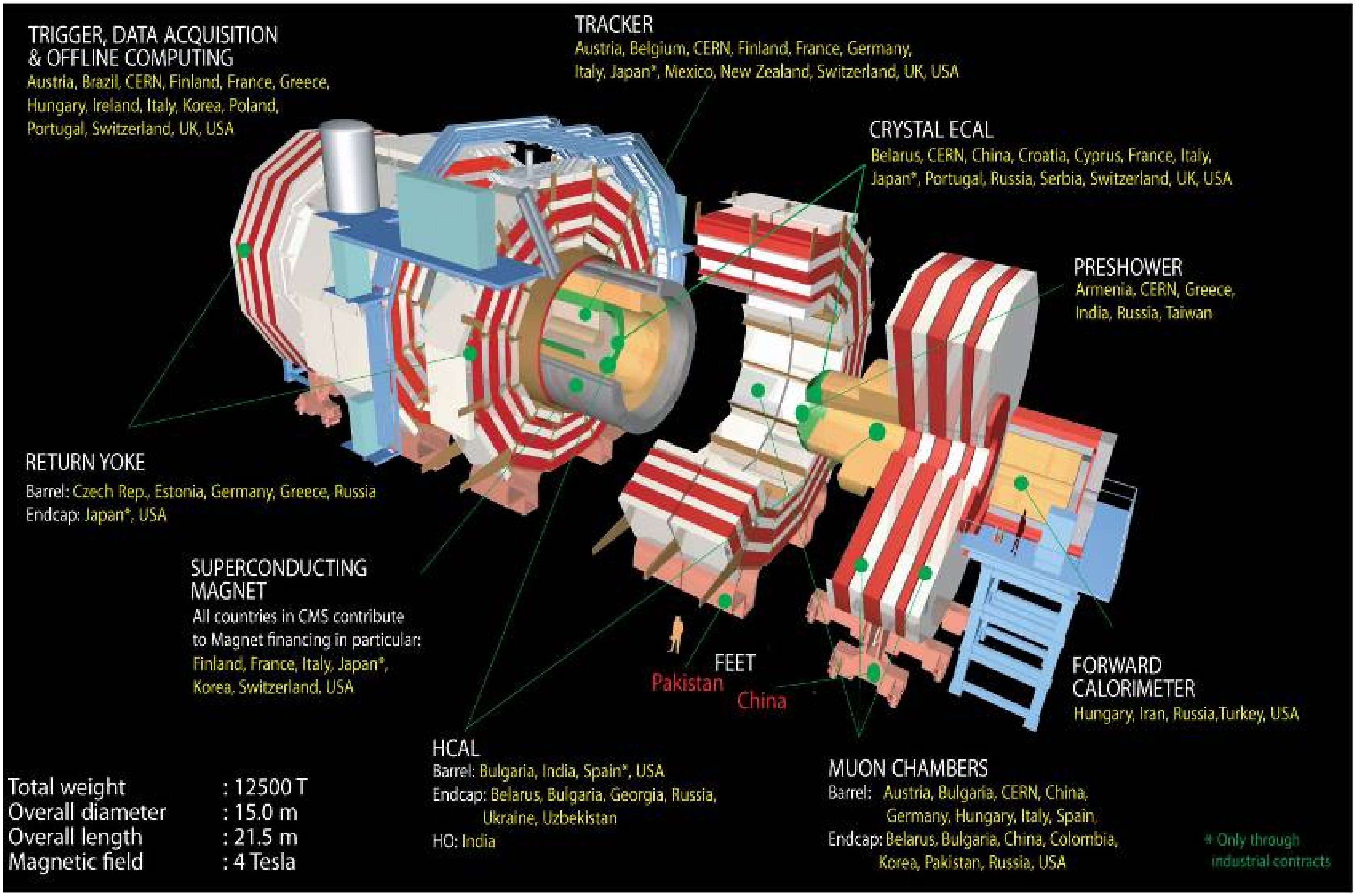
Recombination of Radiation



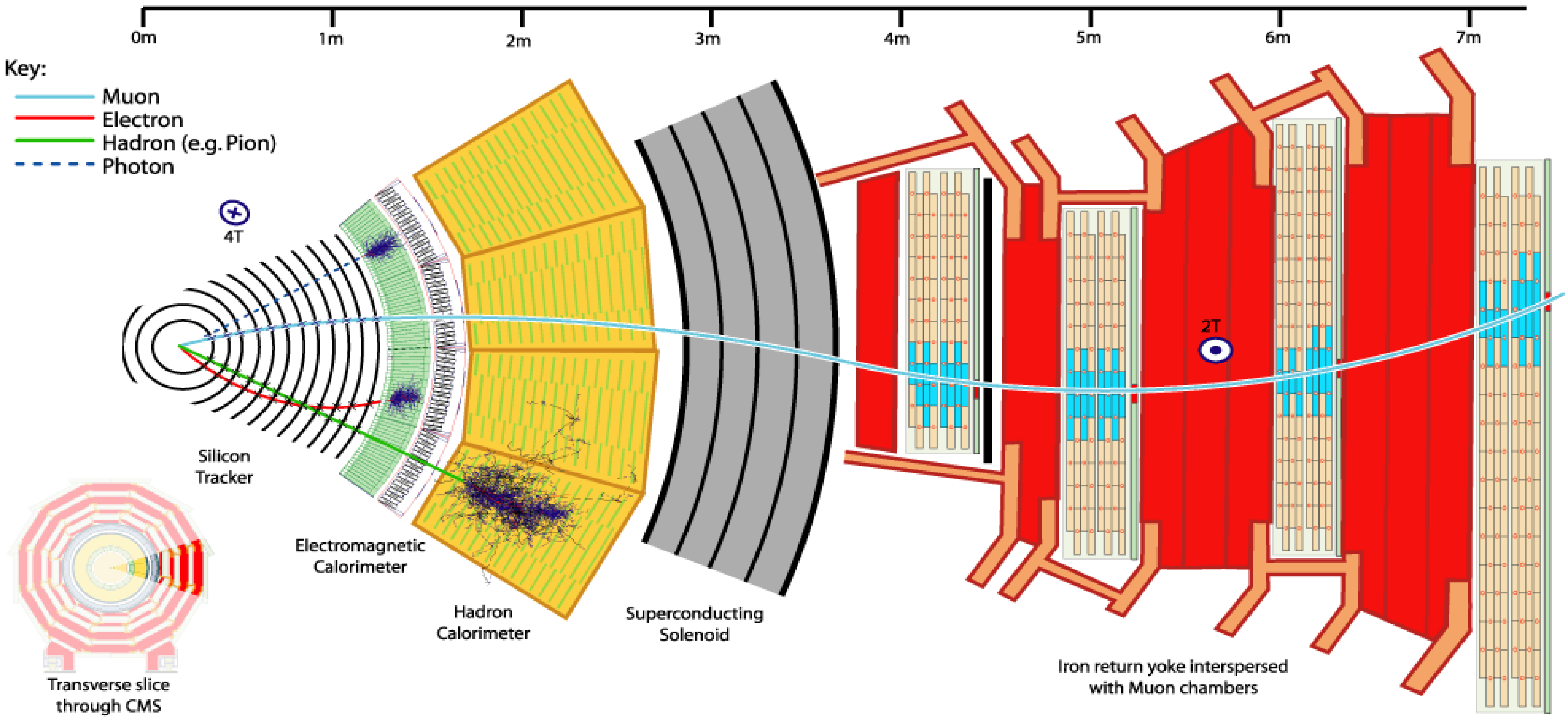


Combined into 1 Fat jet

The Compact Muon Solenoid (CMS) detector



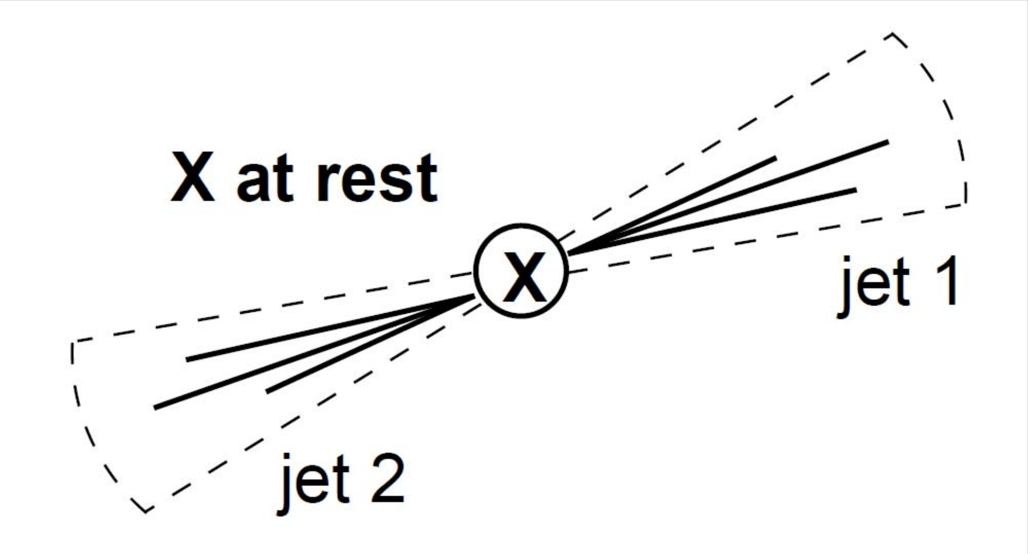
CMS Detector Slice



7 meter lever arm for tracking muons

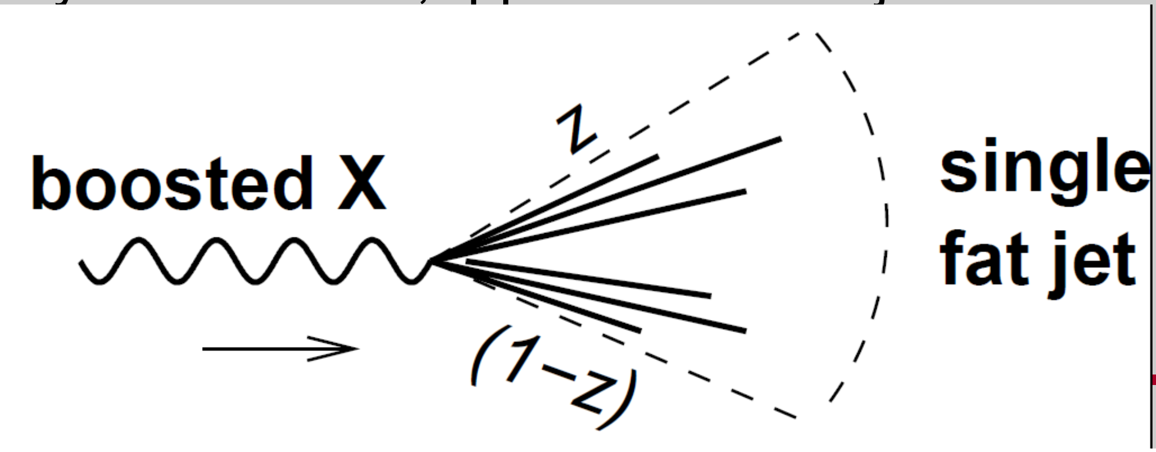
Fat Jets

➡“normal analysis” two quarks from X→qq reconstructed as two jets



➡At high pt, X is boosted, decay is collimated, qq both in same jet

Happens for $p_t \gtrsim 2m/R$
$p_t \gtrsim 320$ GeV for $m = m_W$, $R = 0.5$



Jet Reconstruction

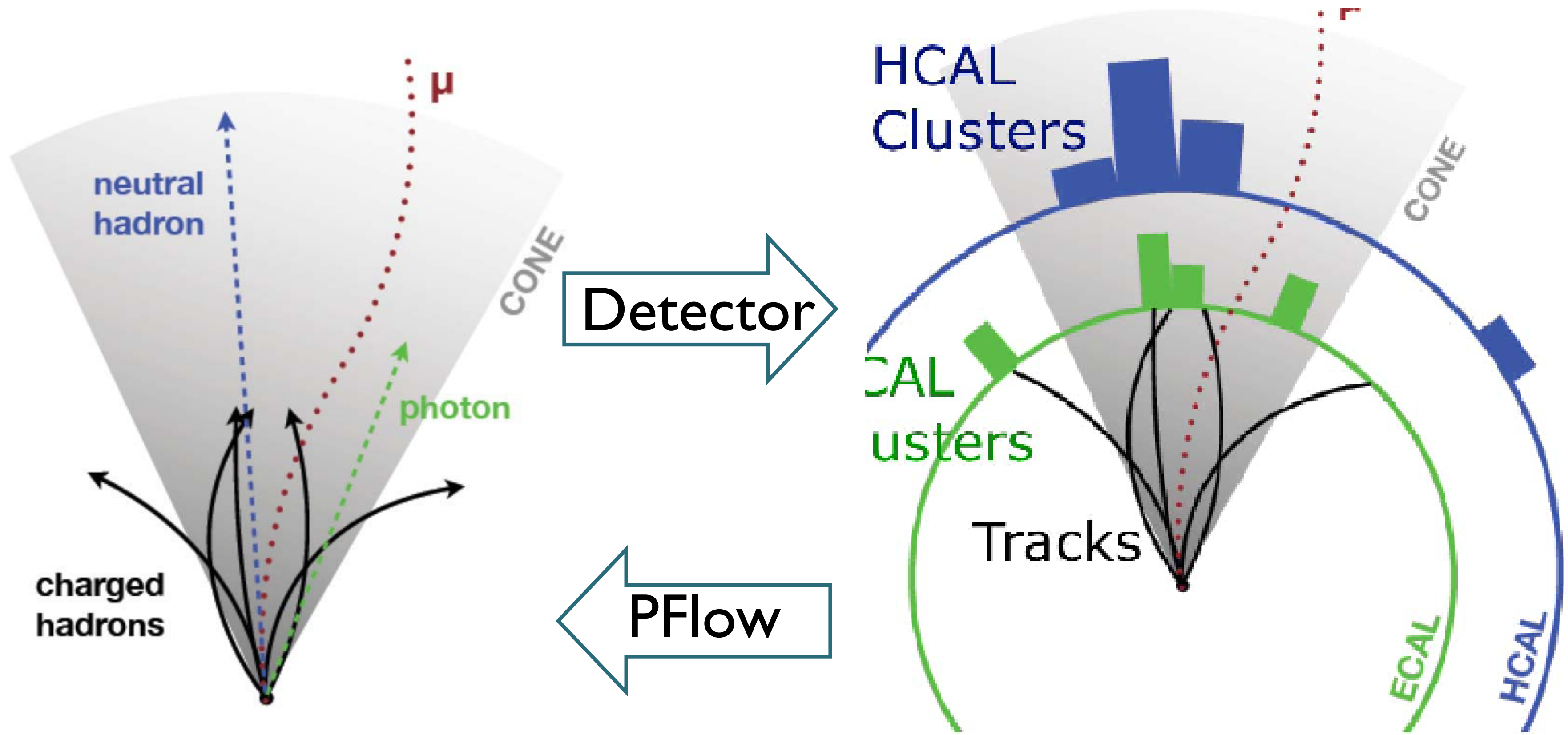
- Anti-kt (AK) clustering algorithm with cone size of 0.5 (AK5) and 0.7 (AK7)
  - Infrared and collinear safe
- Jet types:
  - Calorimeter Jets:

    Reconstructed from energy deposits in the EM and HAD calorimeter, grouped in projective calo towers
  - Particle Flow (PF) Jets (Details in next slide):

    Use all detector elements to reconstruct particles and cluster to jets.
  - Fat Jets:

    Clusters of AK5 PF Jets within radius of 1.1, optimize dijet resonance resolution by recombining FSR into the two leading jets
- Jet energy corrections: using MC truth information and real data (i.e. γ+jet) for residual correction
  - Uncertainty on jet energy scale ~2%
  - Uncertainty on Jet energy resolution ~10%
- MET: negative vector sum of transverse momenta of all particle

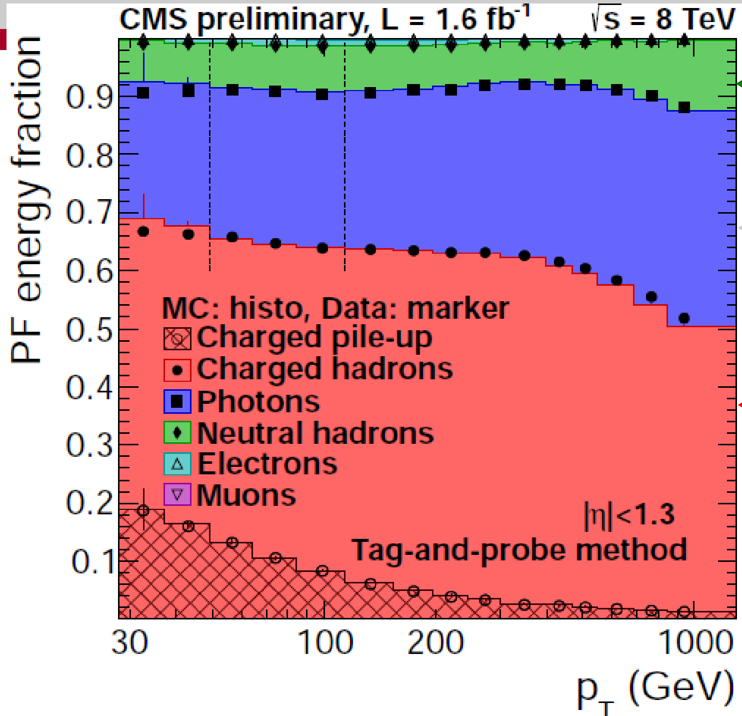
Particle Flow Jet



Particles

Clusters and tracks

Particle Flow Jet



HCAL: $120\%/\sqrt{E}$ +

ECAL: ~$1\%/\sqrt{E}$

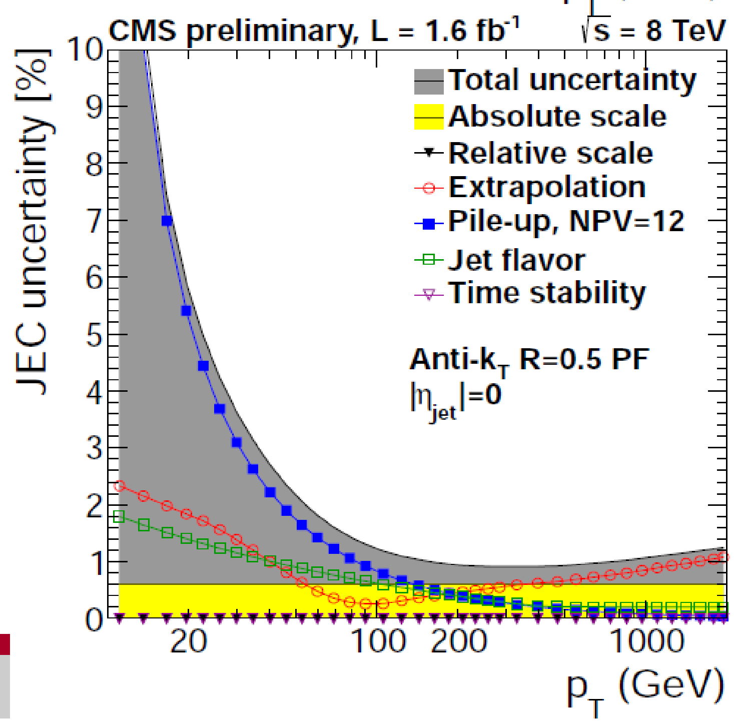
Precise

Tracker $\sigma(p_T)/p$: 1-2% for 10 GeV track

Precise

DP-2012/012

<10% for 100 GeV track



- 60% of pileup mitigation using charged hadrons attached to secondary tracks
- Remaining mitigation using jet area

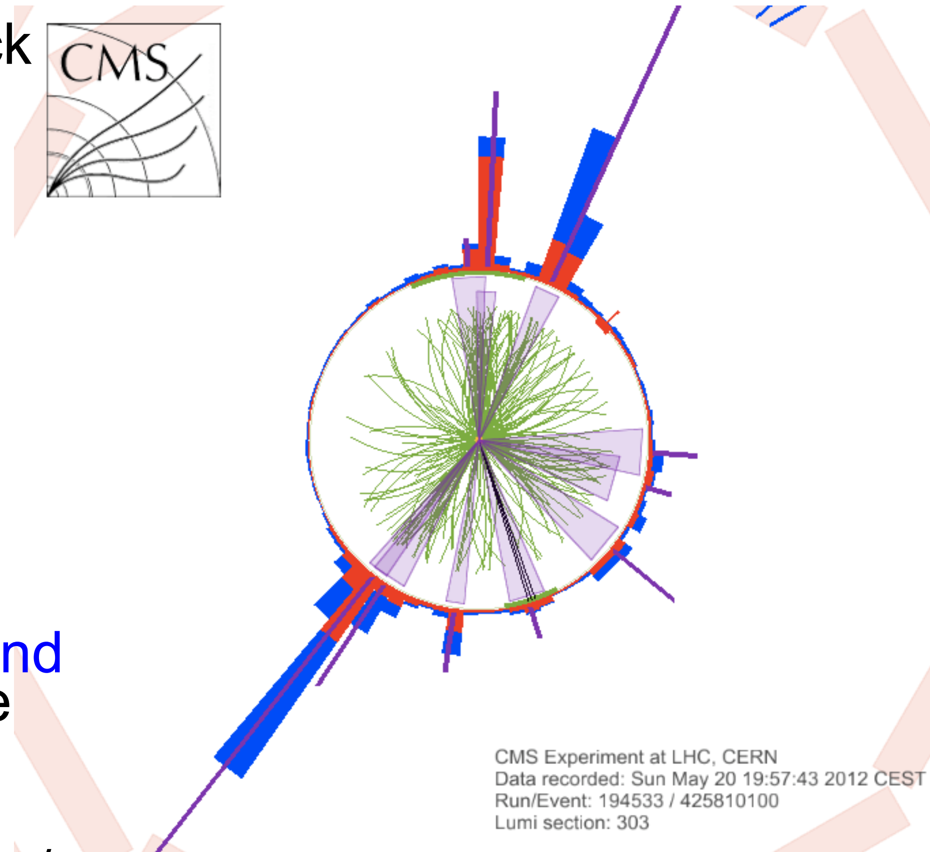
DP-2012/012

Microscopic Black Hole Search

- ADD (Arkani-Hamed, Dimopoulos and Dvali) model's solution to the hierarchy problem:
  - $M_{Pl}^2 = 8\pi M_D^{n+2} r^n$,where M_{Pl} is the Planck scale (~10^{16} TeV), M_D is the "true" Planck Scale in 4+n dimension at the electroweak scale
  - The parton-level cross section $\sigma = \pi r_s^2$, where r_s (Schwarzschild radius) is defined as:

$$r_S = \frac{1}{\sqrt{\pi} M_D} \left[\frac{M_{BH}}{M_D} \frac{8\Gamma(\frac{n+3}{2})}{n+2} \right]^{\frac{1}{n+1}}$$

- Signature: high multiplicity, democratic, and highly isotropic decays with the final-state particles carrying hundreds of GeV of energy.
- CMS search through $S_T = \Sigma E_T$(jet, e, μ, γ) w/ $E_T > 50$ GeV, MET is included.
  - Extract S_T shape from N=2,3 samples.
  - Normalize to events with N ≥ 3,4,5,6,7,8.



10-jet event

Background shape for black hole

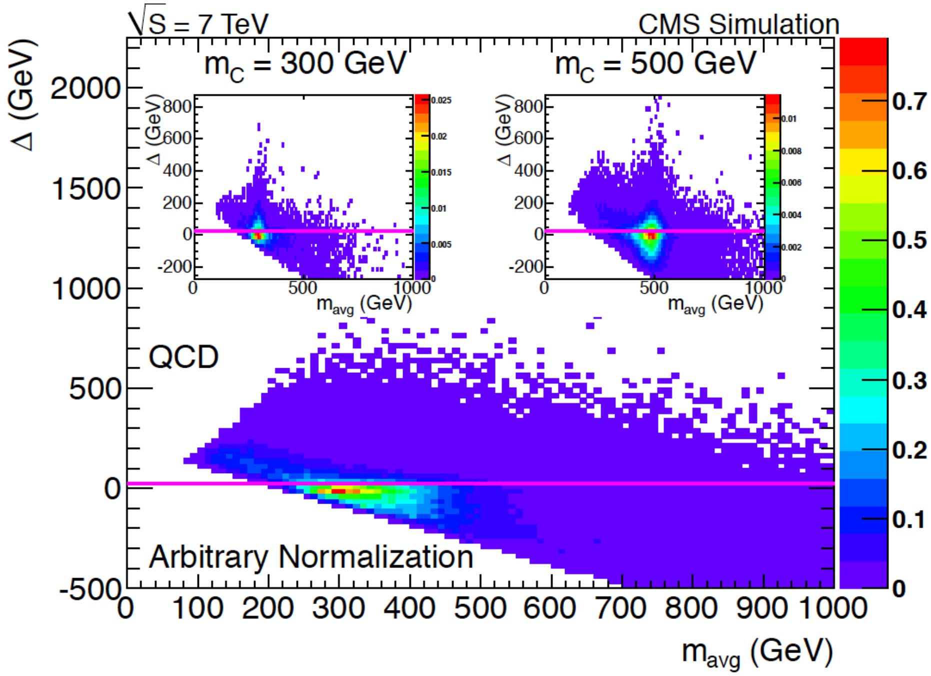
- Assume the shape (tail) of QCD ST spectrum is invariant for difference multiplicity bins, we can model background from lower multiplicity, and rescale to higher multiplicity.

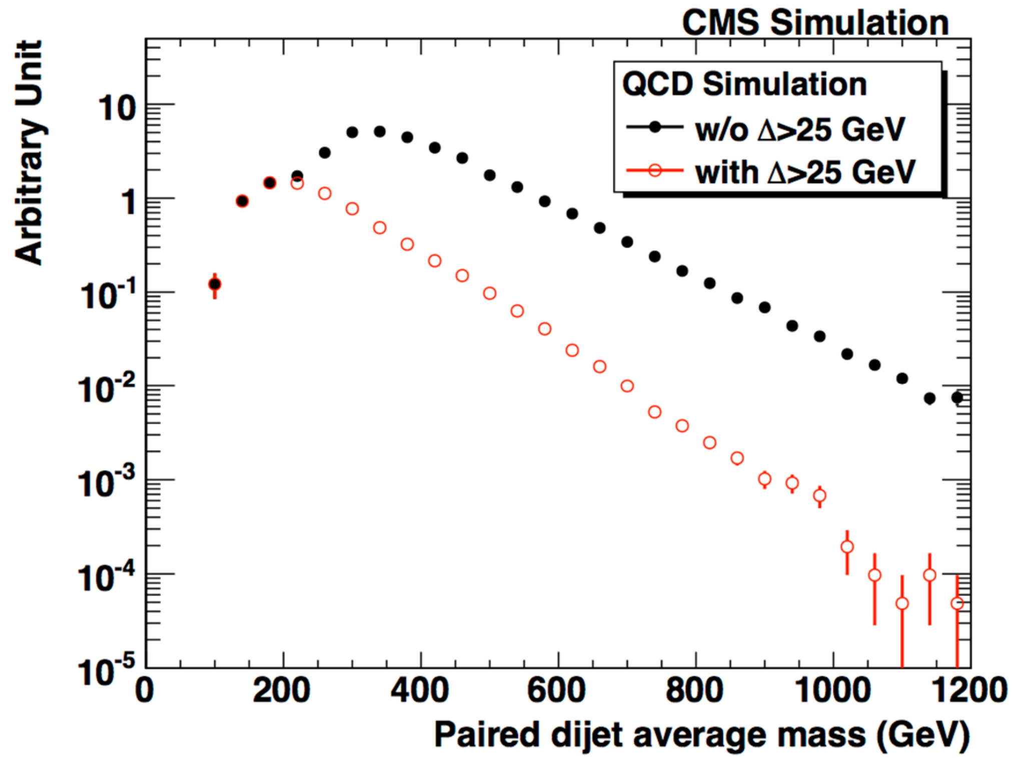
- Fit exclusive multiplicity = 2/3 with the following functions, in ST [800, 2500] GeV.

- **Parameterizations**
  - 0) P0 (1+x)^P1 / x^(P2 + P3 * log(x))
  - 1) P0 / (P1 + P2 * x + x^2)^P3
  - 2) P0 / (P1 + x)^P2
  - 3) P0 * exp((P3+(P1*log(x)))+(P2*(log(x)^2)))*((P3+P4*log(x)))/x)
  - 4) P0 *exp(P1*log(x) + P2*x)

- **Normalization**
- Rescale the fit to inclusive multiplicity ≥3,4,5,6,7,8 in ST [1800, 2000] GeV.

Paired Dijet Resonance Search (4-jets)





- Δ > 25 GeV cut removes the second broad structure and the dijet mass smoothly falling