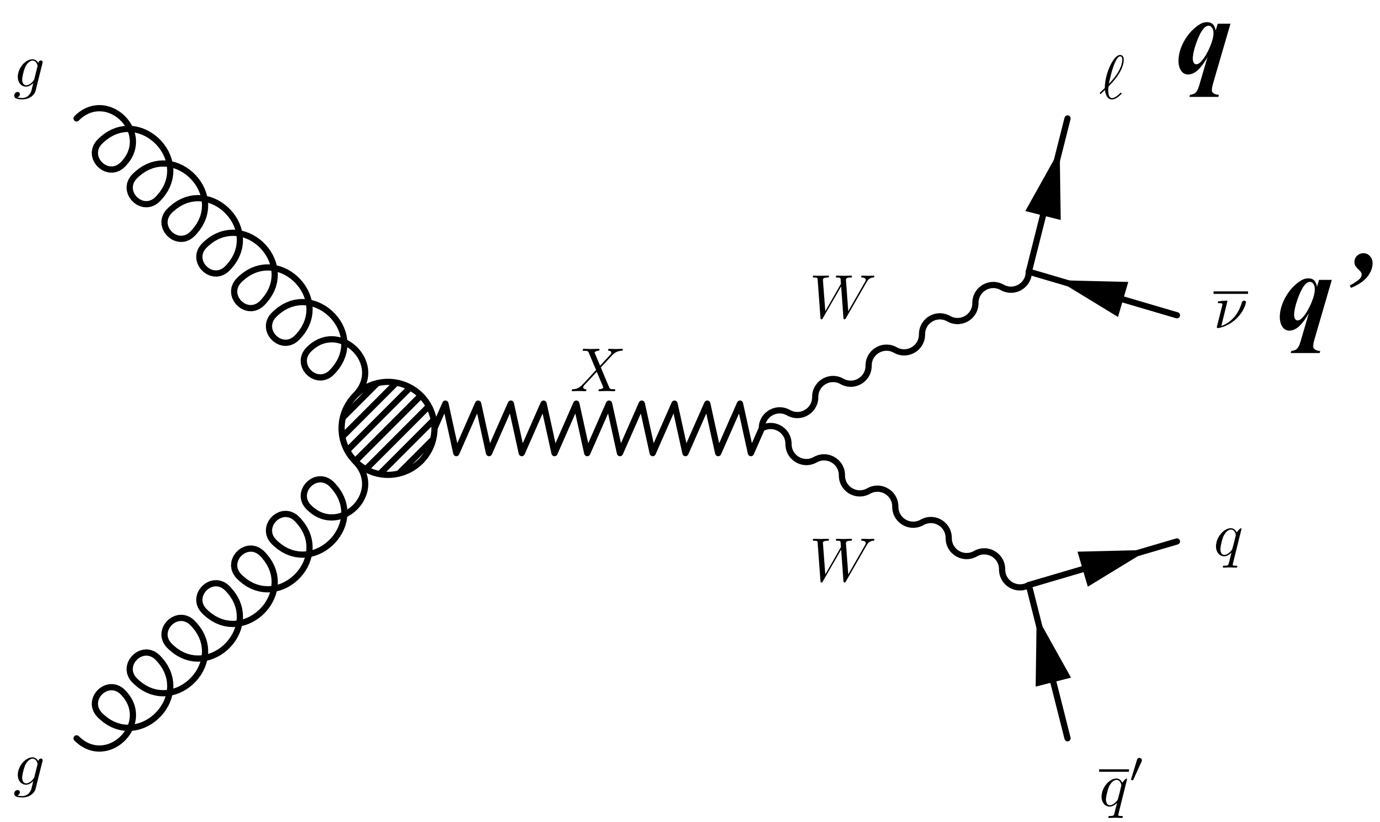
Search For New Physics In Boosted Di-Bosons

Shin-Shan Eiko Yu
Department of Physics, National Central University
On behalf of the CMS Collaboration and the VHEPP Group

IAS Program on High Energy Physics, 18 January 2016
The Hong Kong University of Science and Technology, Hong Kong

Outline

- Searches for new physics in boosted di-boson events with 13 TeV CMS data (CMS PAS EXO-15-002)
    - Benchmark models: Bulk G→WW, ZZ or W'→WZ
- Status of calorimeter studies for future colliders from the VHEPP group



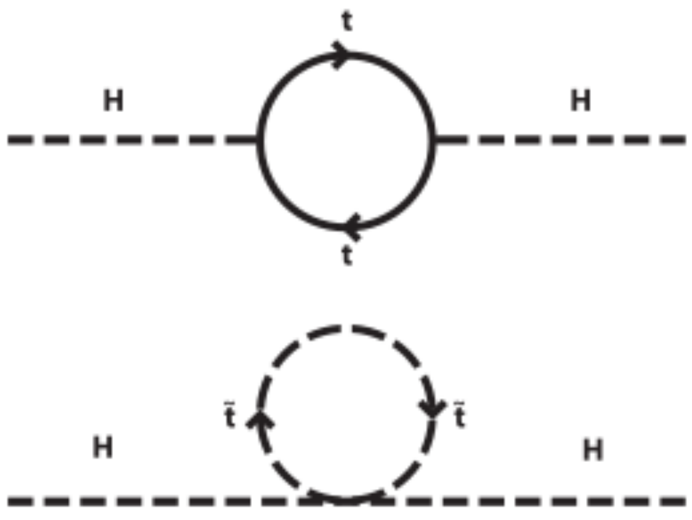
Semileptonic($l^{\pm}\nu j$):
WW,WZ

All hadronic(jj):
WW, ZZ,WZ

Motivation

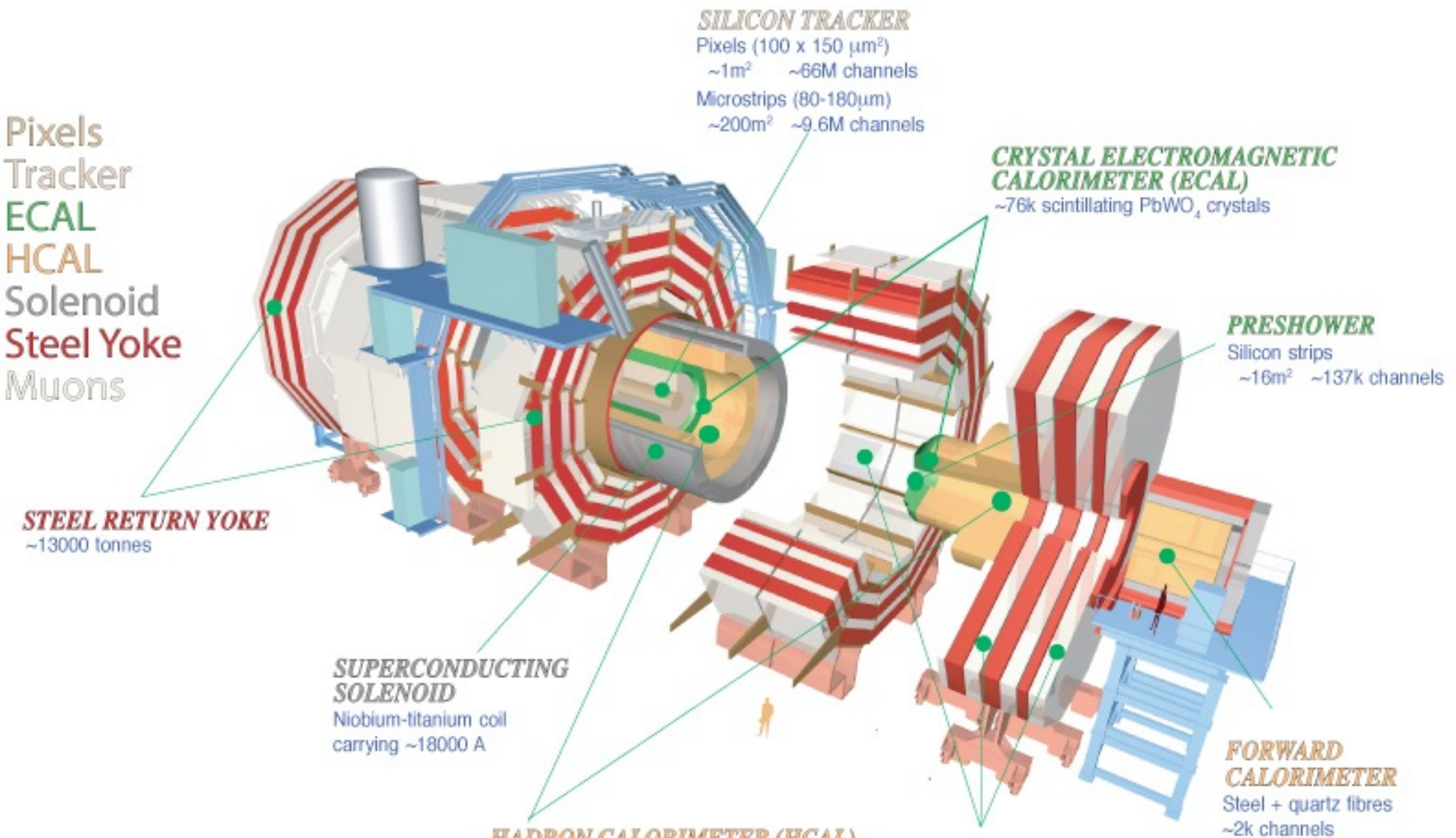
Higgs mass at EWK scale
m_H=125 GeV/c^2

- Hierarchy problem
  - If new physics happens at the Planck scale, radiative corrections to the Higgs mass need to be fine-tuned in new physics theory to cancel at electroweak scale



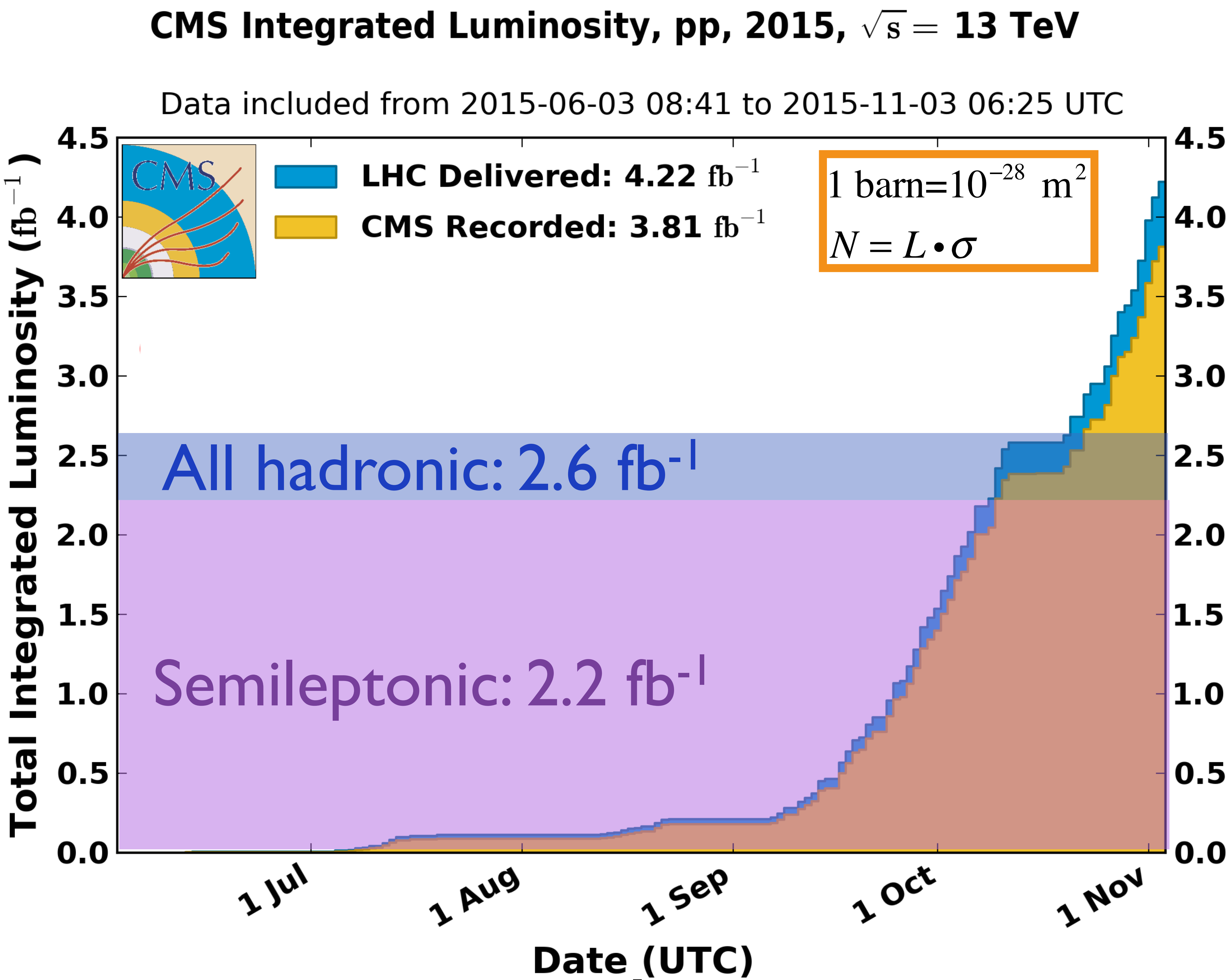
- SUSY introduces new supersymmetric particles that cancel the radiative corrections
- Extra Dimension reduces the effective Planck scale
  - "Bulk Graviton" and "Randall-Sundrum Graviton" scenarios of the Warped extra dimension model
- Higgs is composite object and its mass is generated by a new interaction
  - Heavy Vector Triplet (scenario B), with spin-1 W' and Z' decaying mainly to W, Z, and higgs

The CMS Detector



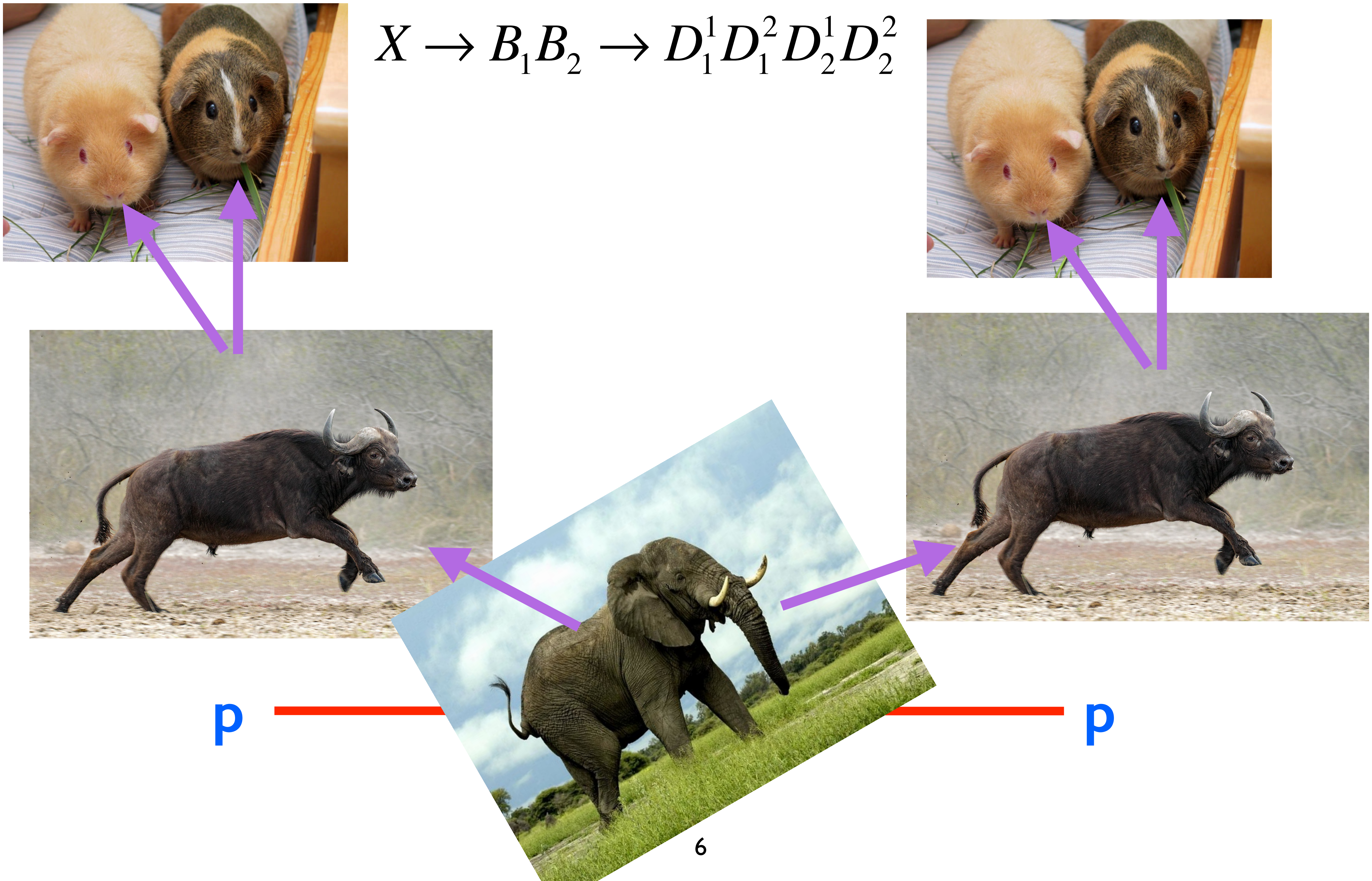
Total weight	**: 14000 tonnes**
Overall diameter	**: 15.0 m**
Overall length	**: 28.7 m**
Magnetic field	**: 3.8 T**

CMS Data Used in This Analysis



Boosted Topology

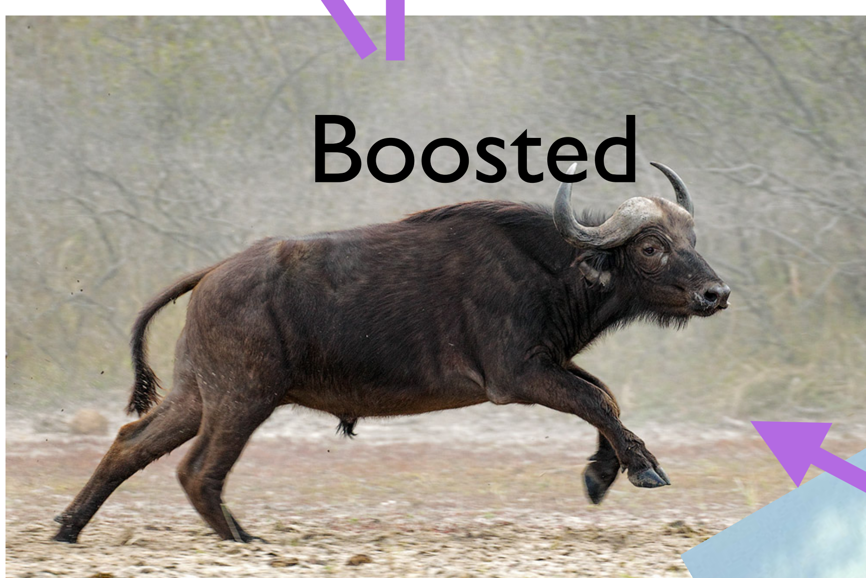
$$X \rightarrow B_1 B_2 \rightarrow D_1^1 D_1^2 D_2^1 D_2^2$$



Boosted Topology

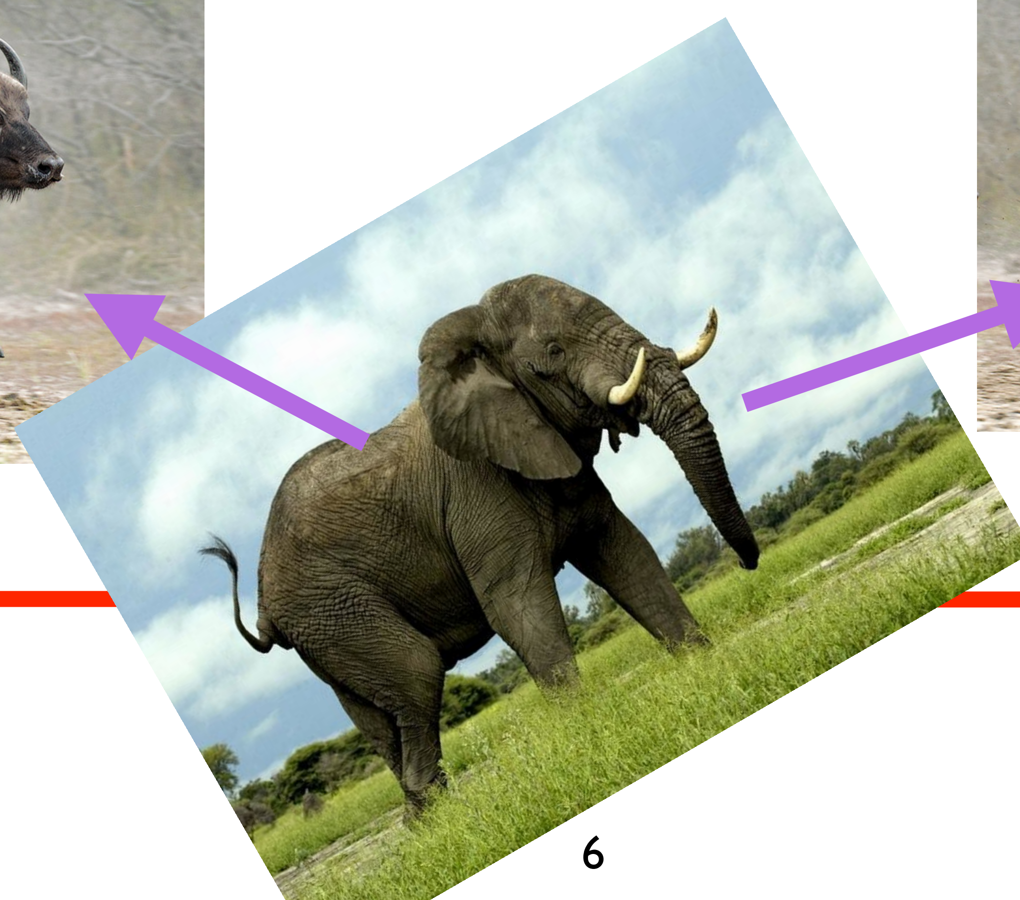
$$X \rightarrow B_1 B_2 \rightarrow D_1^1 D_1^2 D_2^1 D_2^2$$

$$\boxed{\Delta R_{\min} \approx 2\frac{M_B}{p_B}}$$



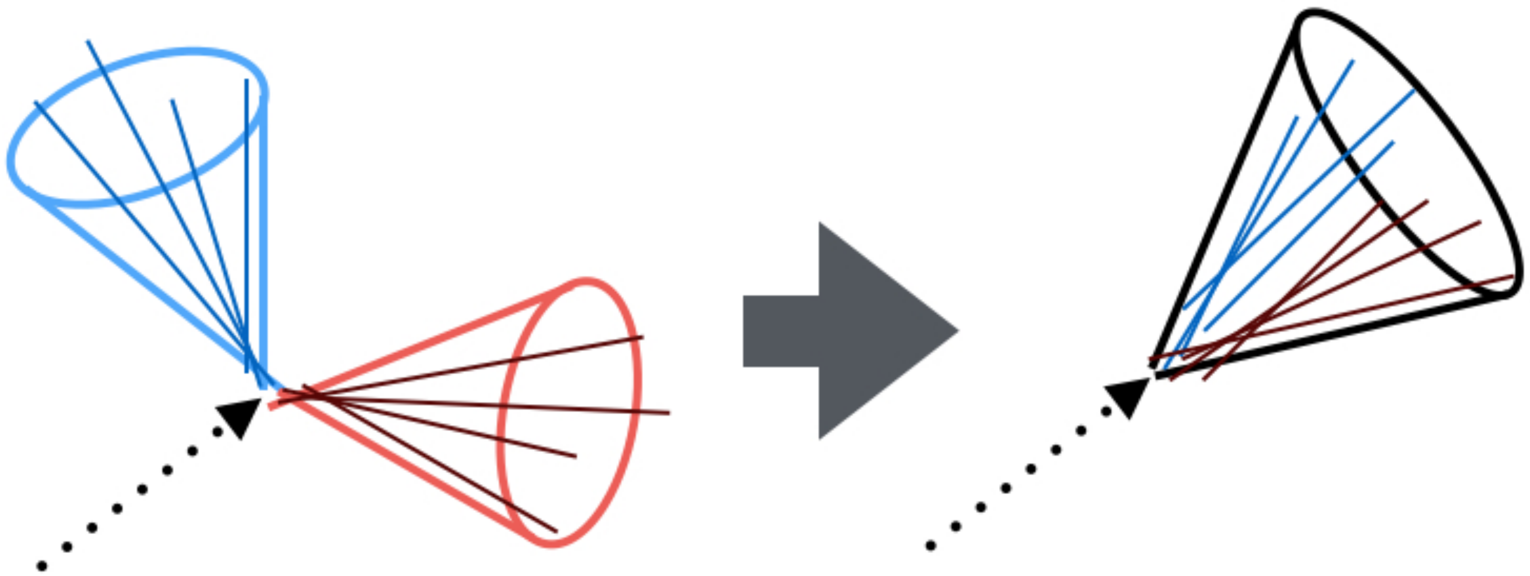
Boosted

Boosted



p p

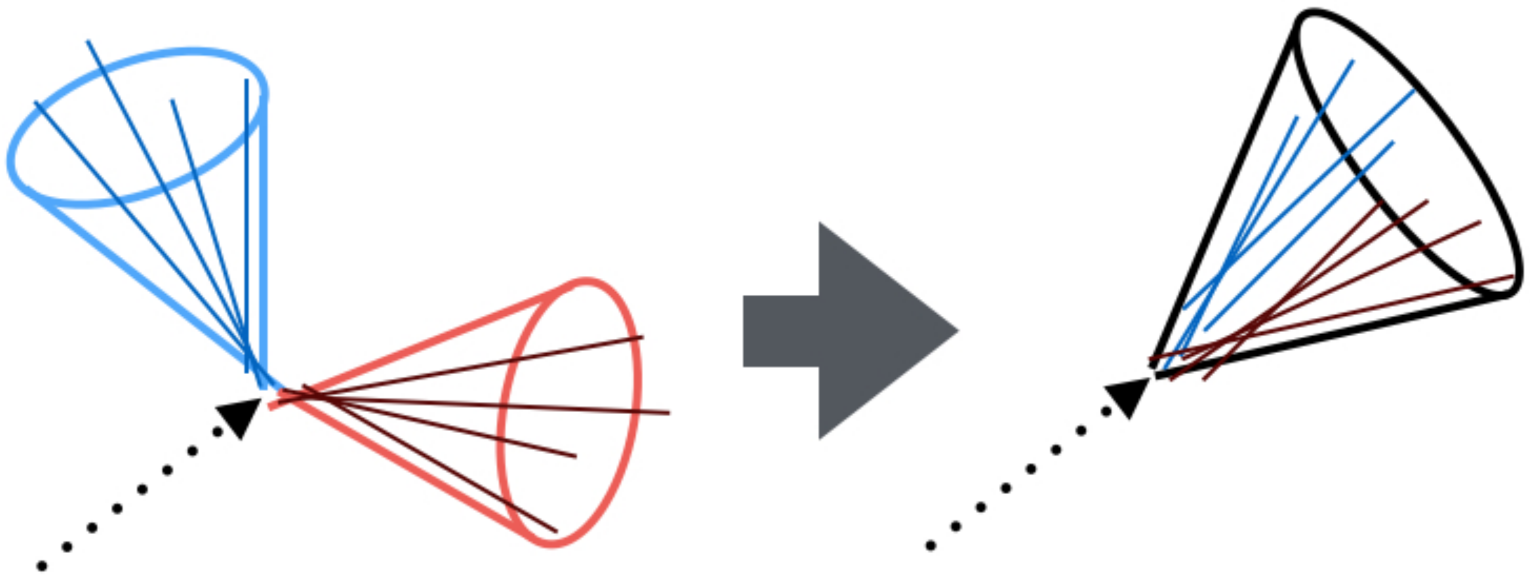
When We Have Boosted W/Z



For W/Z and p > 200 GeV, quarks from W/Z merged to radius=0.8 jets

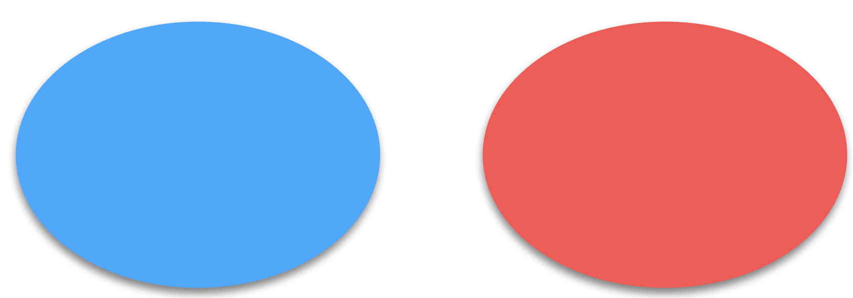
Anti-K_T $\Delta R = 0.4 \rightarrow \Delta R = 0.8$

When We Have Boosted W/Z

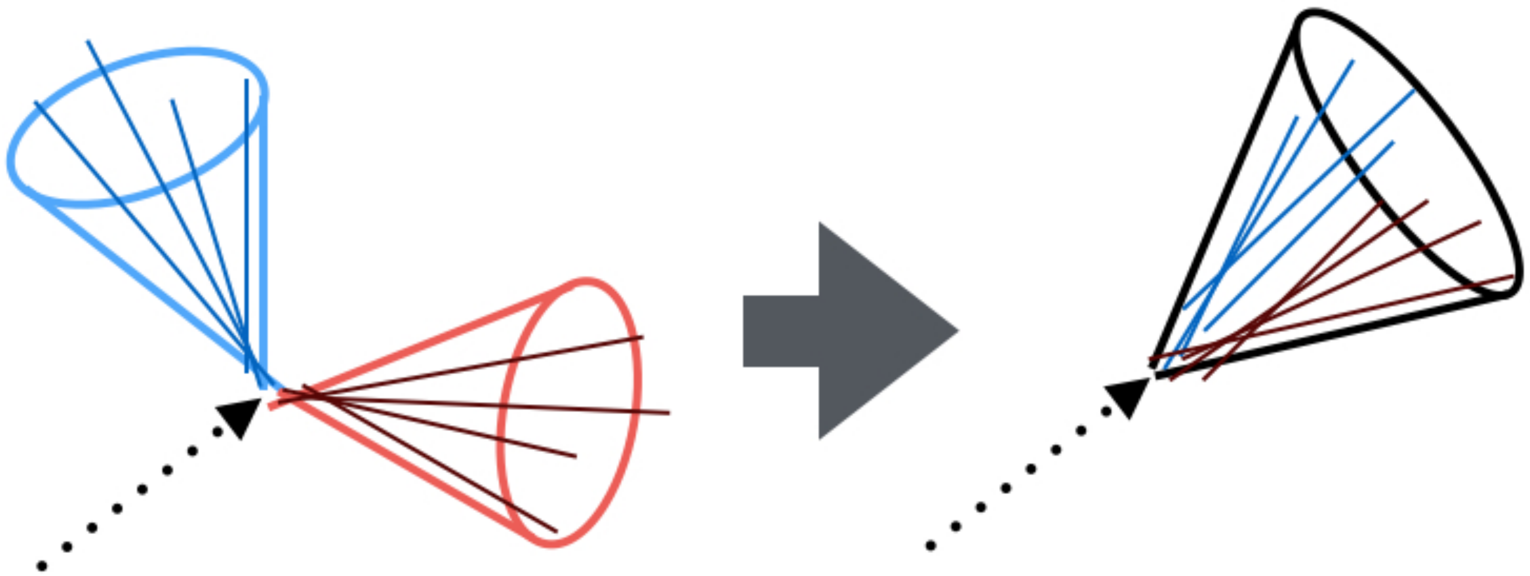


For W/Z and p > 200 GeV, quarks from W/Z merged to radius=0.8 jets

Anti-K_T $\Delta R = 0.4 \rightarrow \Delta R = 0.8$

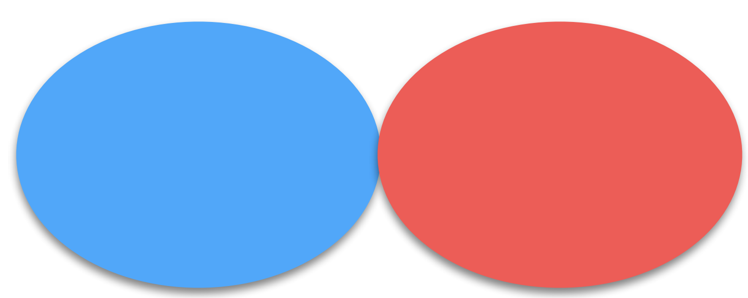


When We Have Boosted W/Z

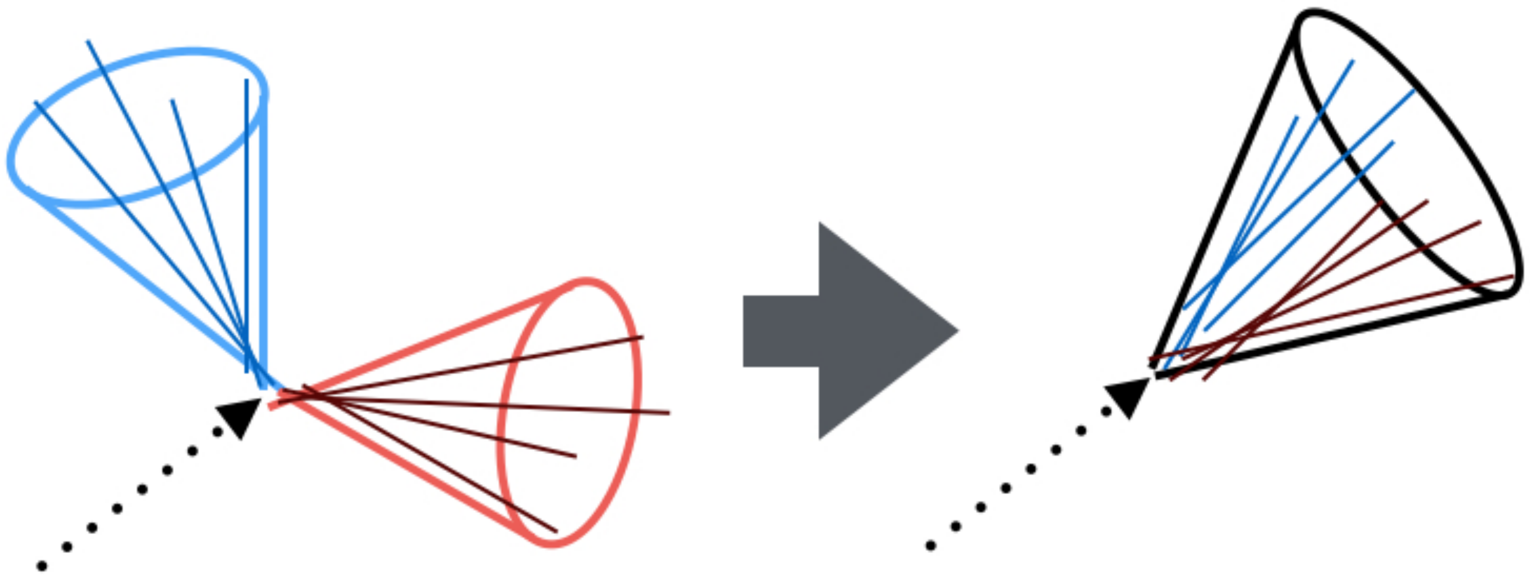


For W/Z and p > 200 GeV, quarks from W/Z merged to radius=0.8 jets

Anti-K_T $\Delta R = 0.4 \rightarrow \Delta R = 0.8$

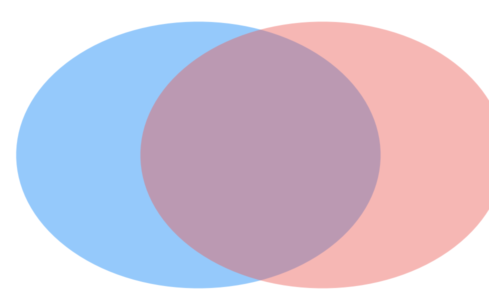


When We Have Boosted W/Z

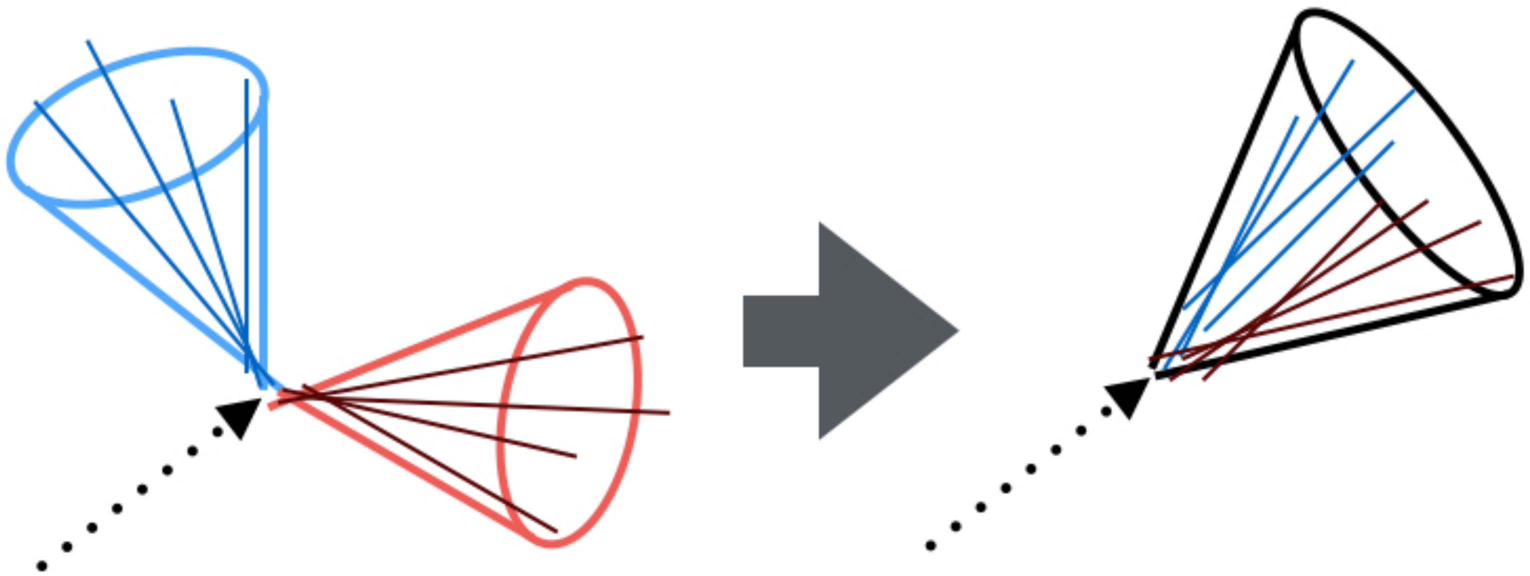


For W/Z and p > 200 GeV, quarks from W/Z merged to radius=0.8 jets

$$\text{Anti-K}_{\text{T}}\ \Delta R = 0.4 \rightarrow \Delta R = 0.8$$

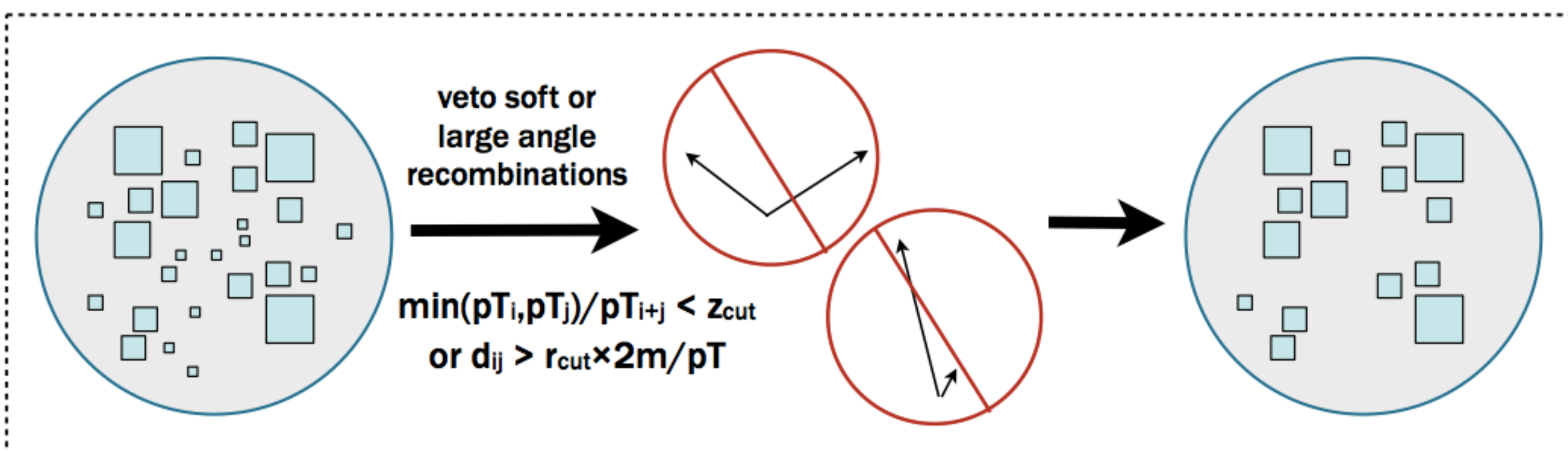


When We Have Boosted W/Z



For W/Z and p > 200 GeV, quarks from W/Z merged to radius=0.8 jets

$$\text{Anti-K}_T\ \Delta R = 0.4 \rightarrow \Delta R = 0.8$$



Jet Pruning

default:

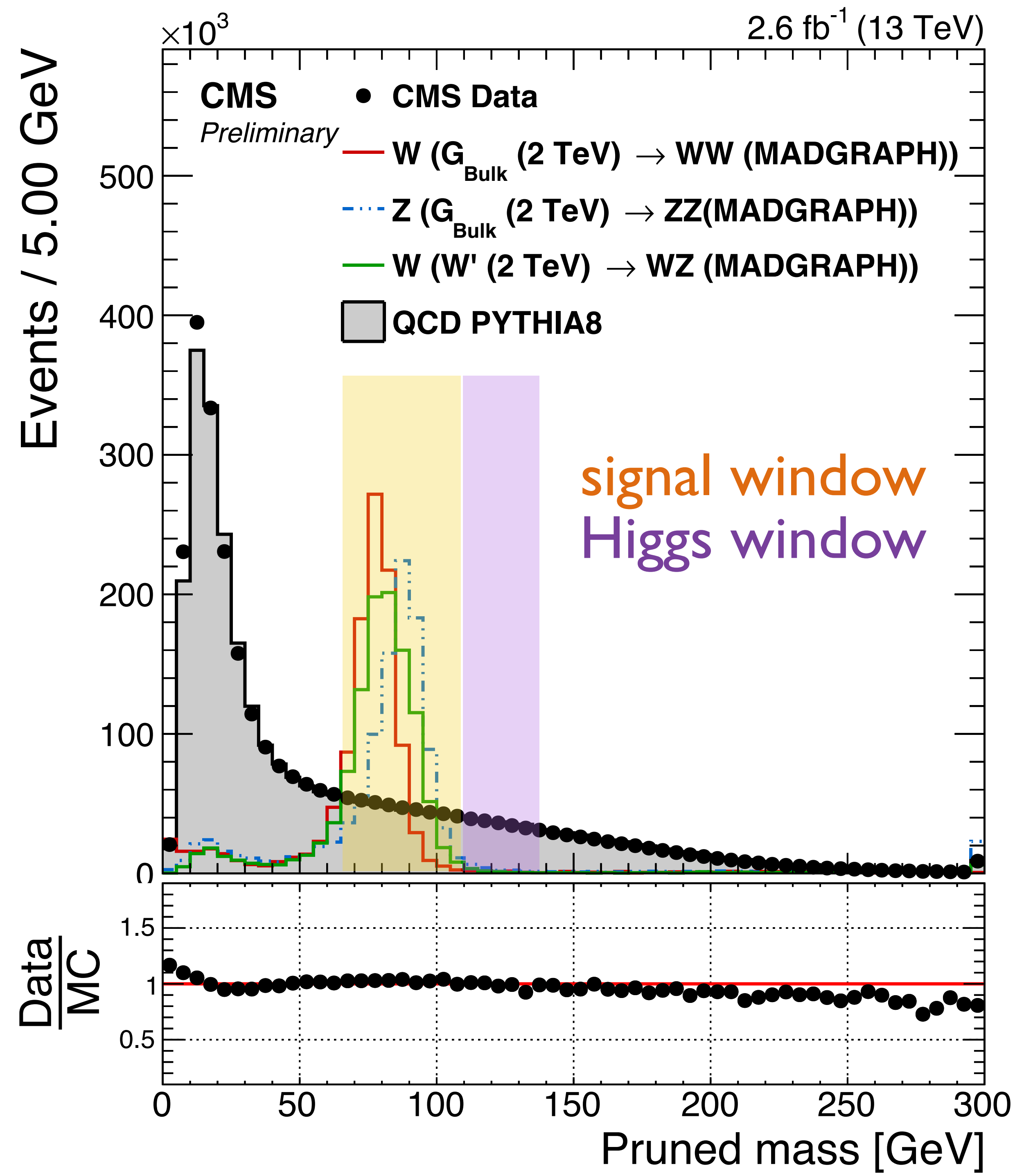
$z_{cut} = 0.1$

$r_{cut} = 0.5$

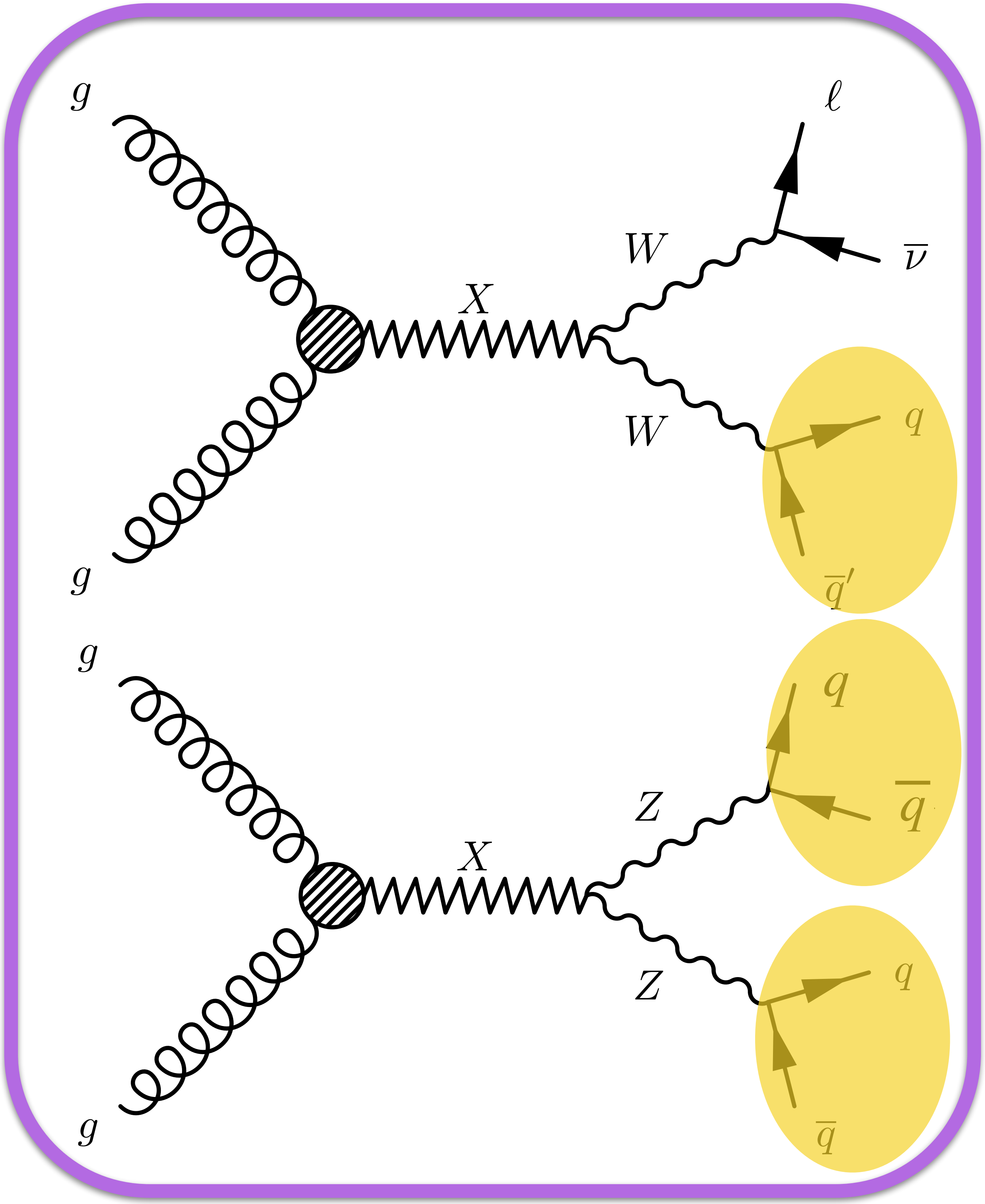
Mass Distribution Of Pruned Jets

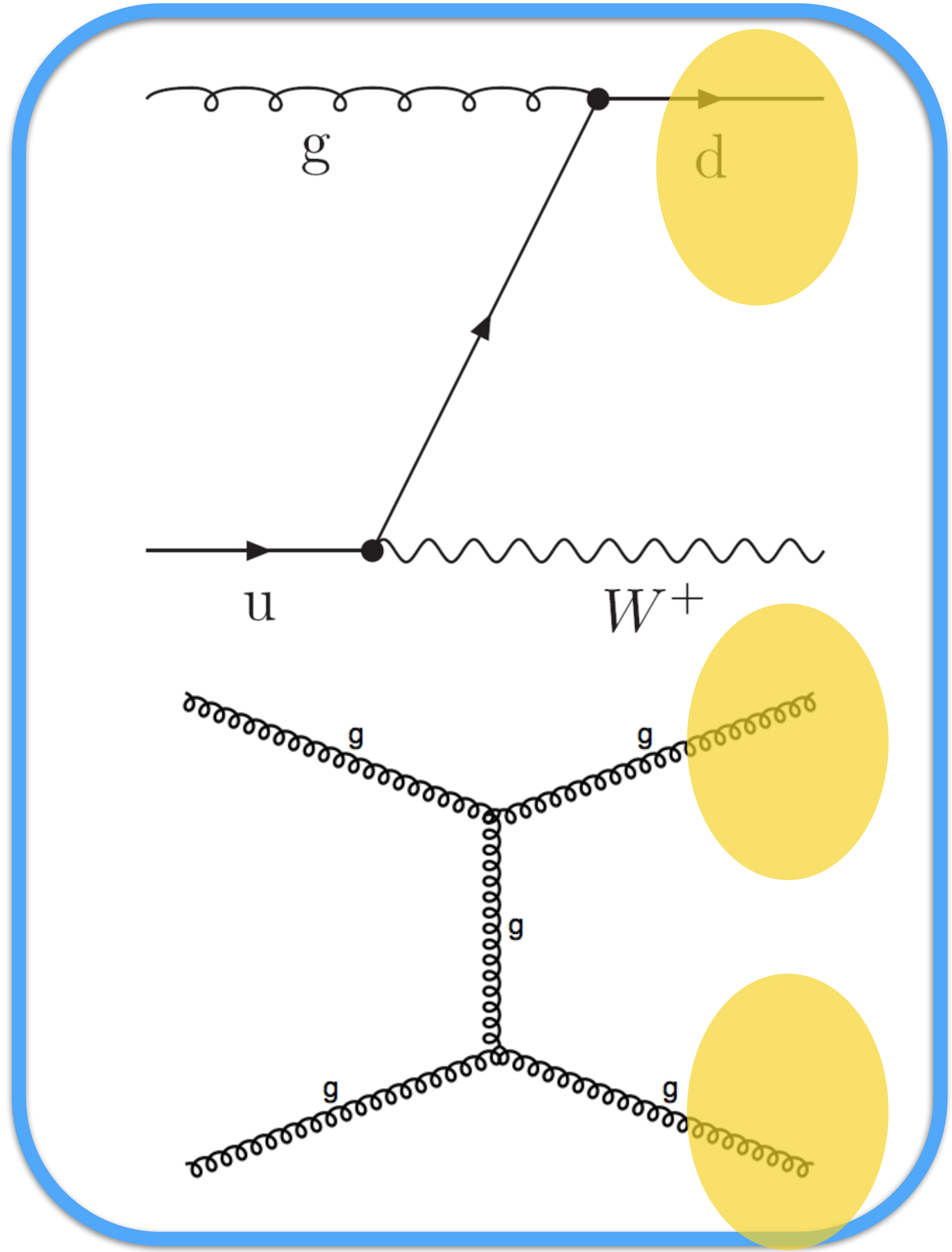
- Based on pruned mass, subdivide events into W and Z categories
  - W: 65-85 GeV
  - Z: 85-105 GeV
  - Higgs window 105-135 GeV stays blinded
- Signal peak position calibrated with W-jets in ttbar events

All hadronic channel

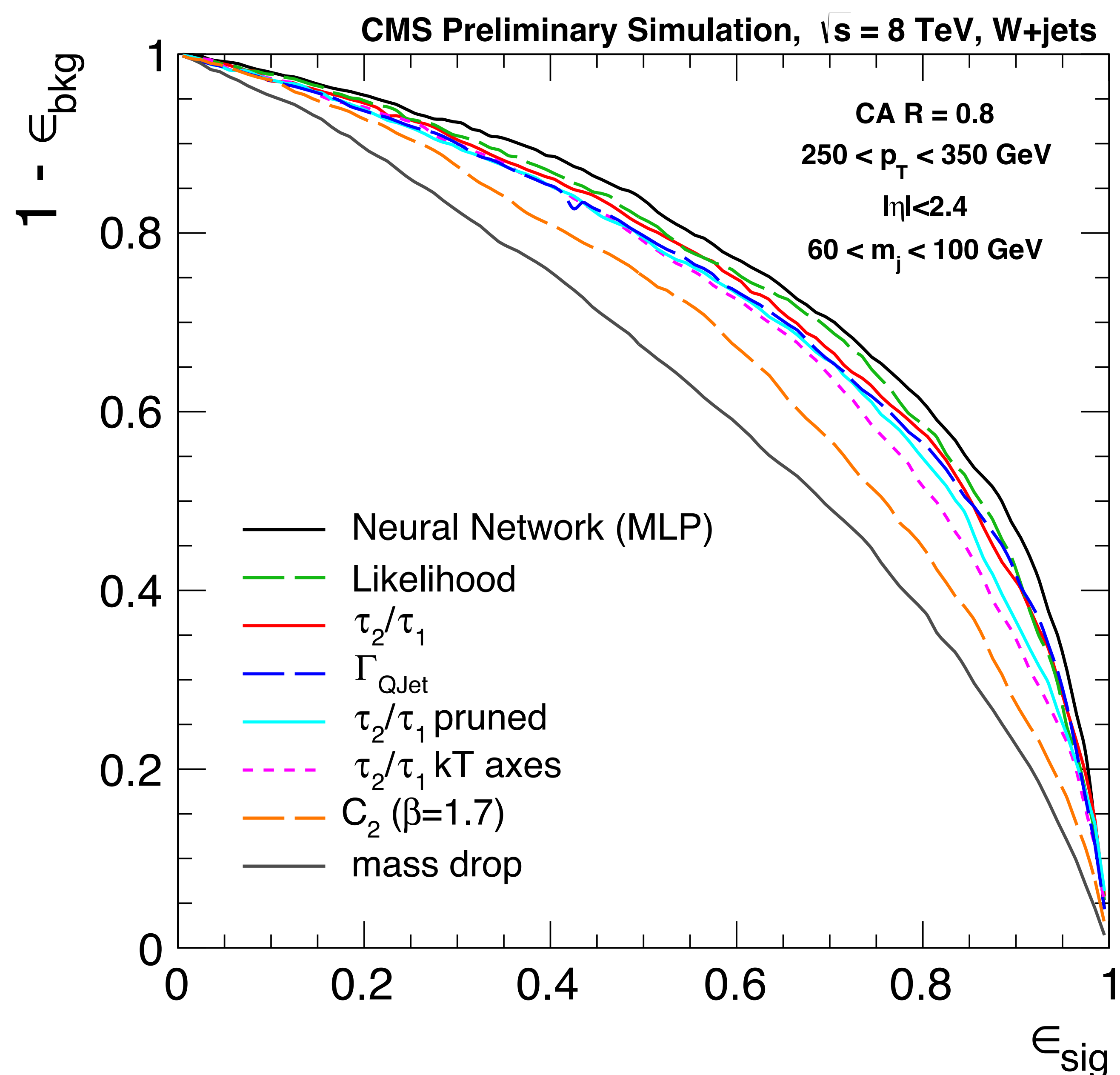


The Signals And Backgrounds





Study The Structure Inside Jets

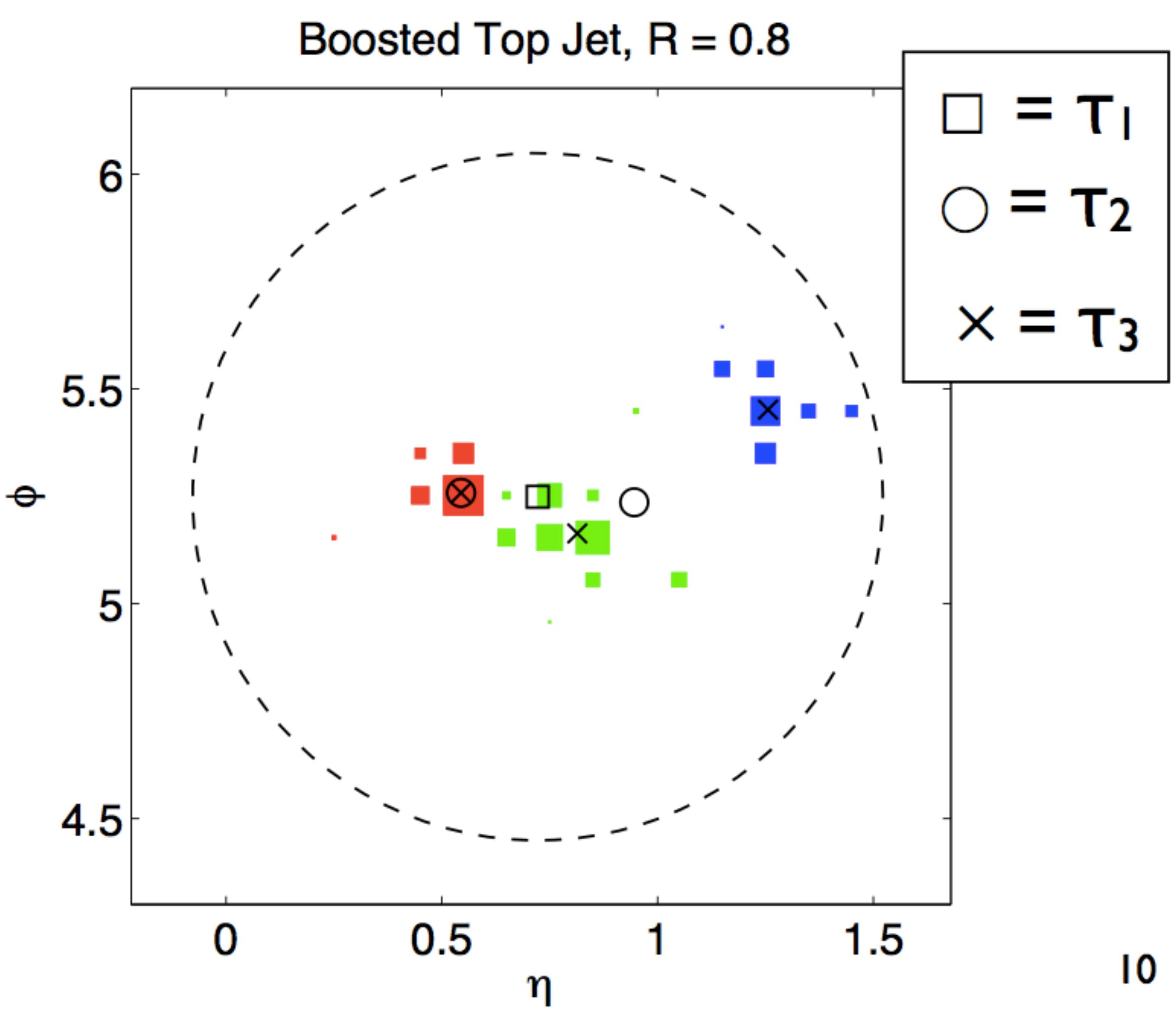


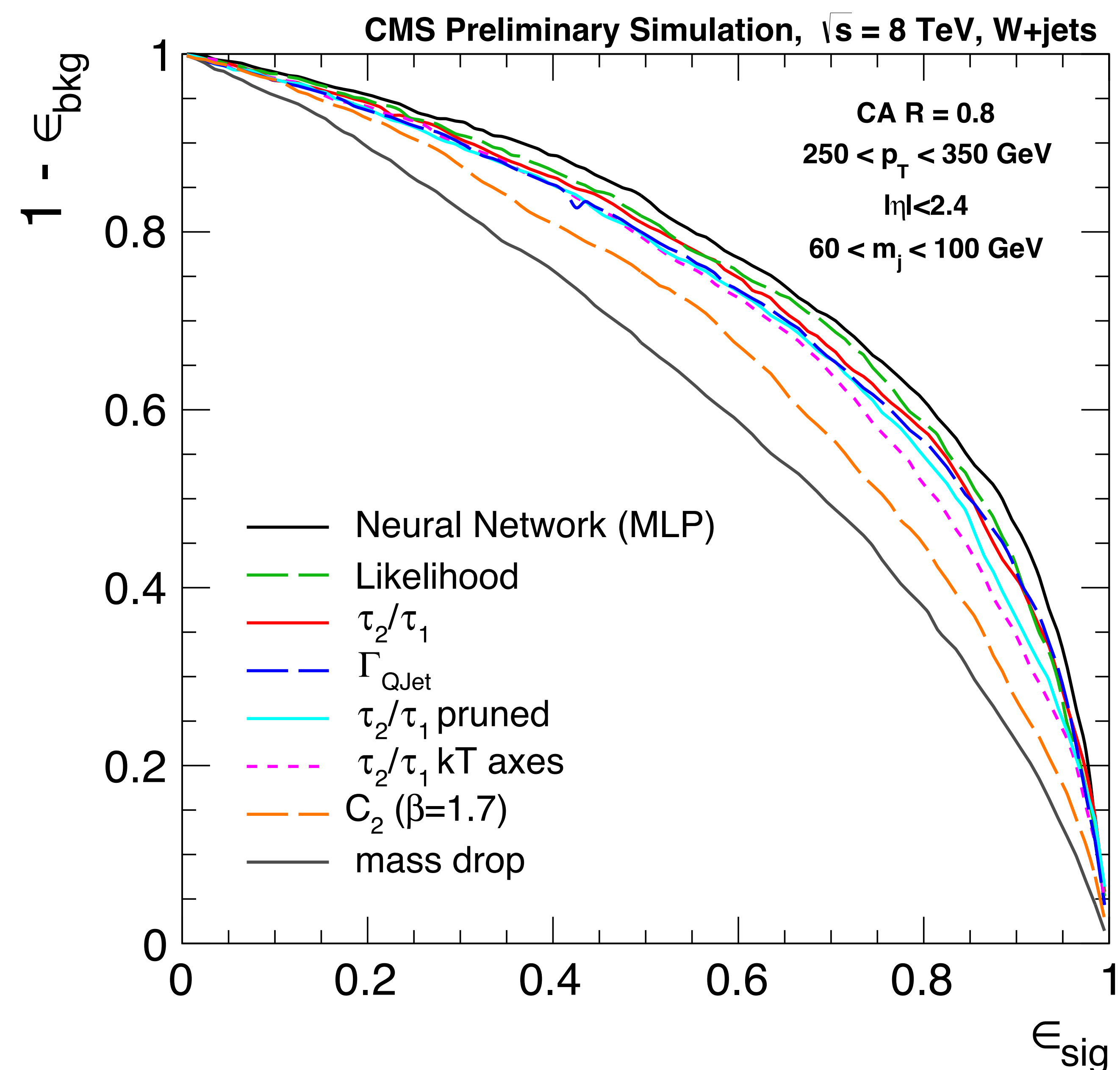
Study The Structure Inside Jets

$$\boxed{\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min\left\{\Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k}\right\}}$$

$$d_0 = \sum_k p_{T,k} R_0$$

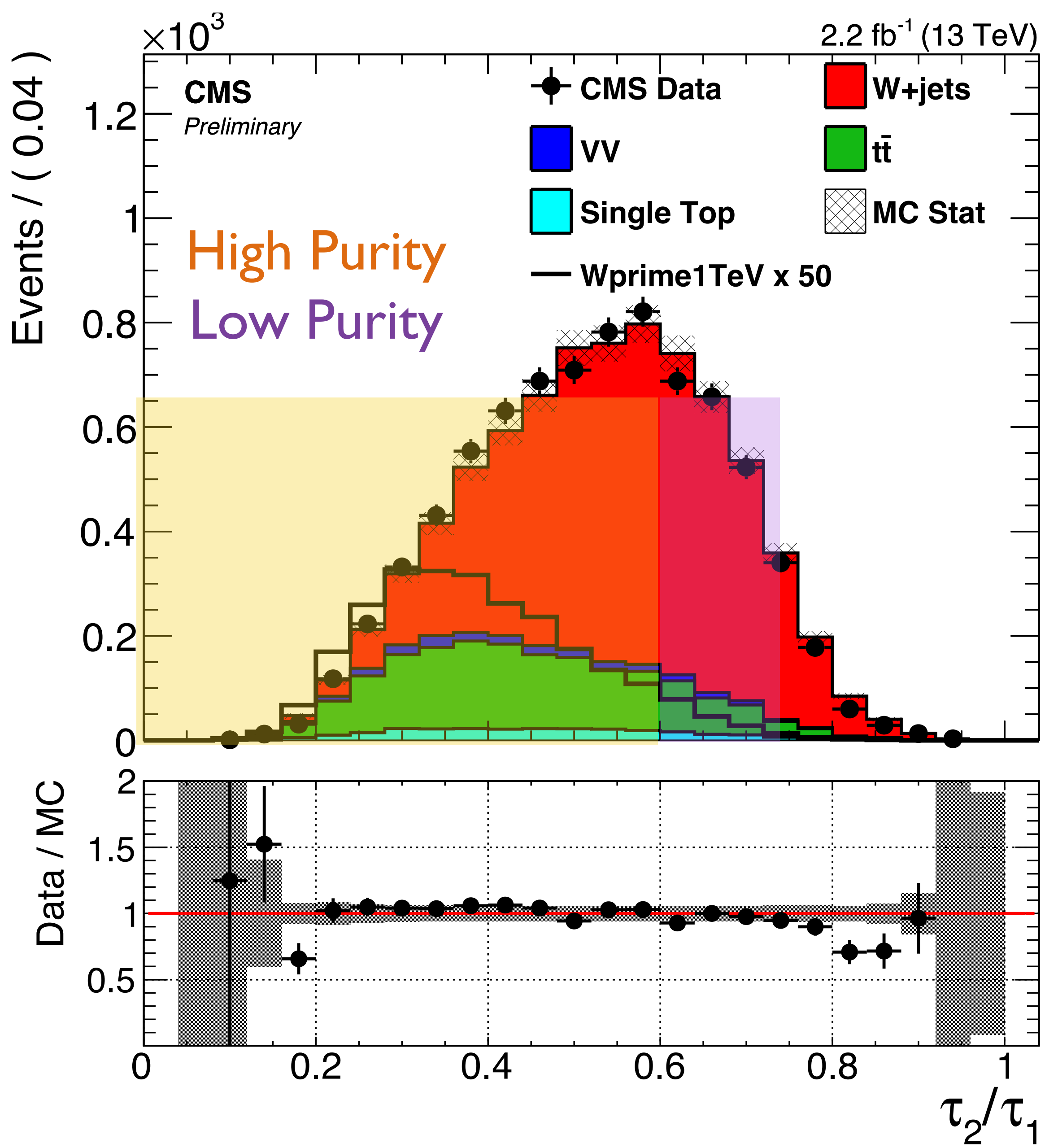
N-subjetness: a measure of how consistent a jet is with having N subjets



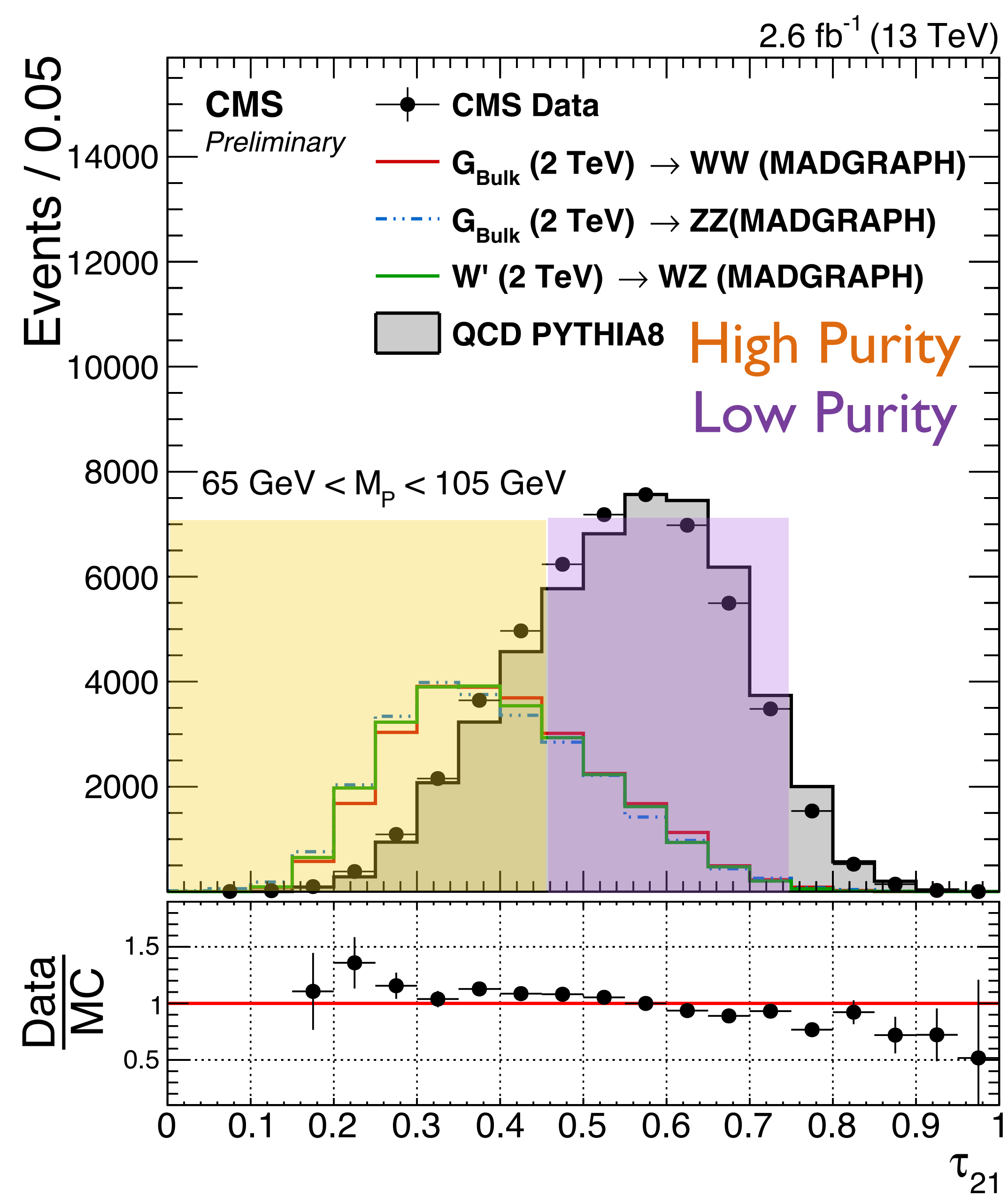


Distribution Of τ_2/τ_1 (τ_{21})

Semileptonic channel
High: τ_{21} < 0.6, Low: 0.6-0.75



All hadronic channel
High: τ_{21} < 0.45, Low: 0.45-0.75



Trigger And Event Selections

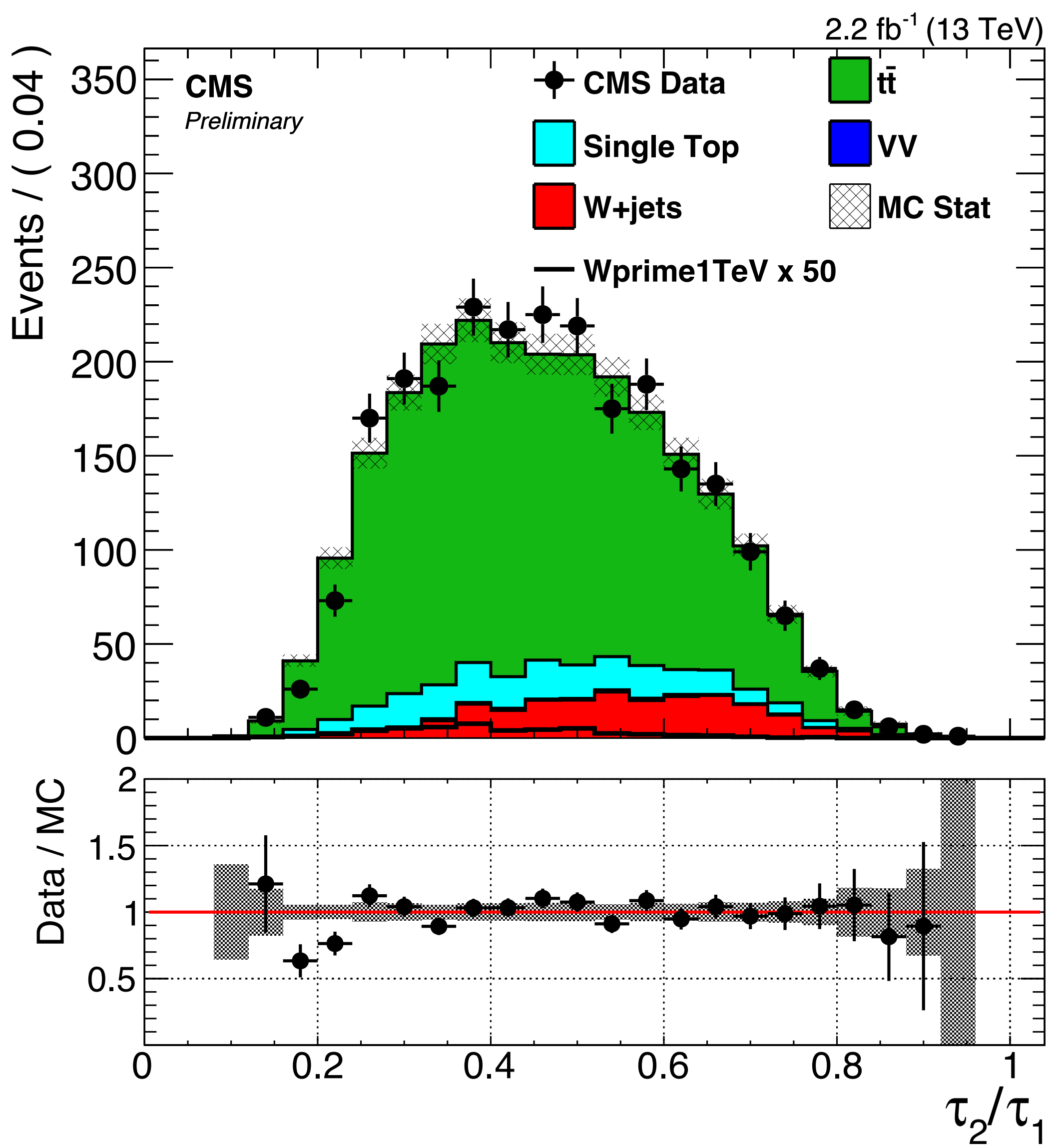
- Semileptonic channel
  - Single electron (muon) trigger with pT>105 (45) GeV and efficiency >98% (82-95%)
  - Offline: isolated electron (muon) with pT>120 (53) GeV and $|\eta|$ < 2.5 (2.1), MET > 80 (40) GeV,
  - pT(W)> 200 GeV
  - Reject events with good b-tags (misID rate 1%, 70% eff)
- All-hadronic channel
  - Simple HT trigger (HT>800 GeV) or combined trigger with HT (HT>650-700 GeV)+ trimmed mass (>30-50 GeV) selections
  - $\Delta\eta_{jj} < 1.3$
- Anti-kT jets with R=0.8 and pT>200 GeV, pruned mass 65-105 GeV, τ_{21}<0.75

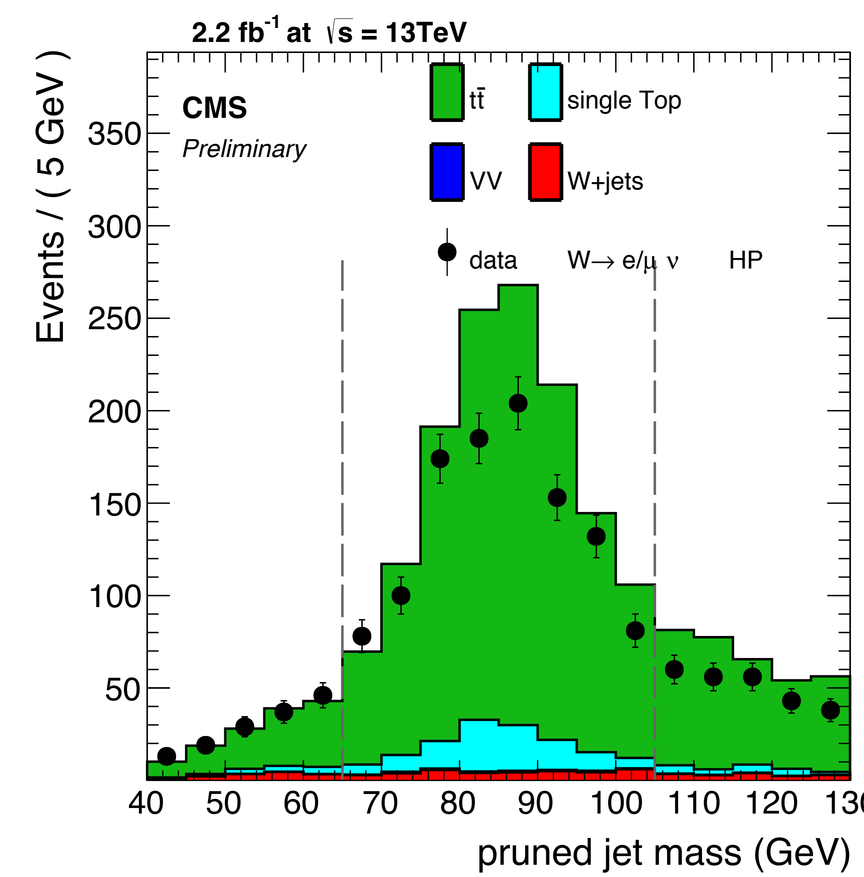
Calibration Of τ_{21} Efficiency

- Reverse the b-tagging requirement to select semileptonic ttbar sample
- Fit the pruned mass distribution to extract the scale factors

Category	Definition	W scale factor
Dijet channel HP	$(\tau_{21} < 0.45)$	0.69 ± 0.14
Dijet channel LP	$(0.45 < \tau_{21} < 0.75)$	1.46 ± 0.38
$\ell\nu$+jet channel HP	$(\tau_{21} < 0.6)$	1.03 ± 0.13
$\ell\nu$+jet channel LP	$(0.6 < \tau_{21} < 0.75)$	0.88 ± 0.49

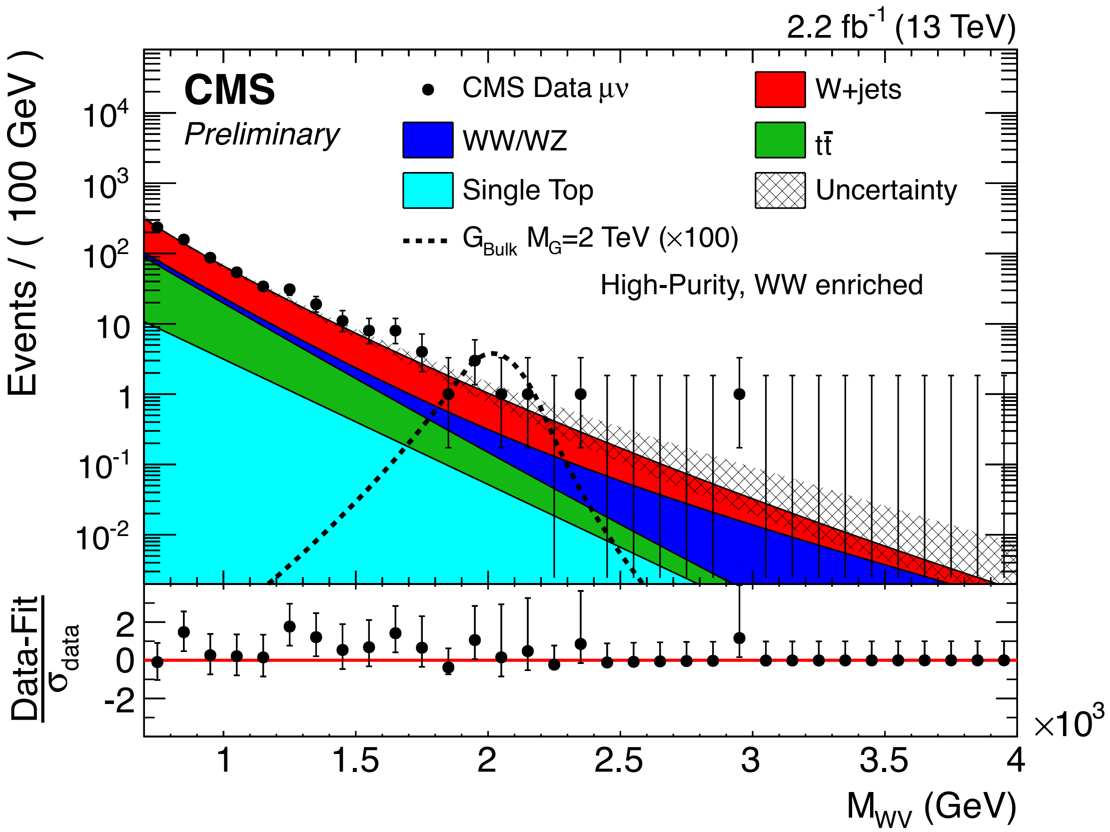
$\tau_{21} < 0.45$	m [GeV]	σ [GeV]
Data	84.7 ± 0.4 GeV	8.2 ± 0.5 GeV
Simulation	85.3 ± 0.4 GeV	7.3 ± 0.4 GeV

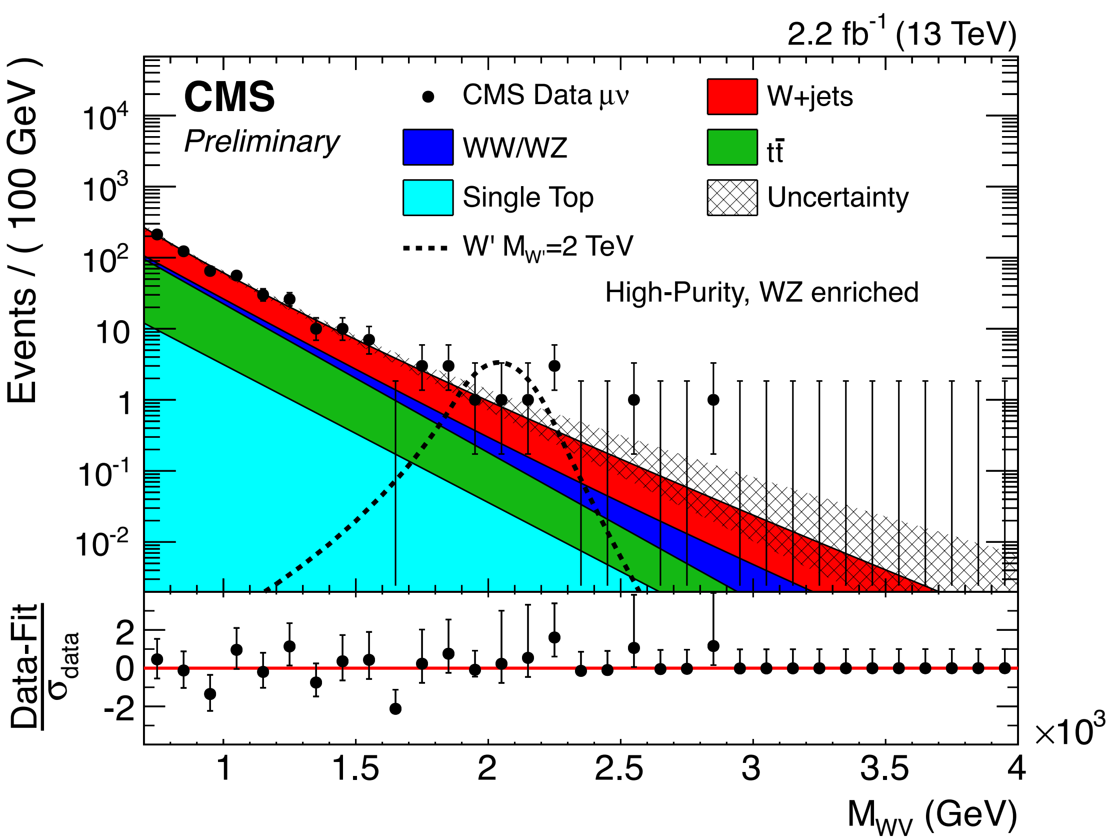




Shin-Shan Eiko Yu

α Ratio For Background Estimate

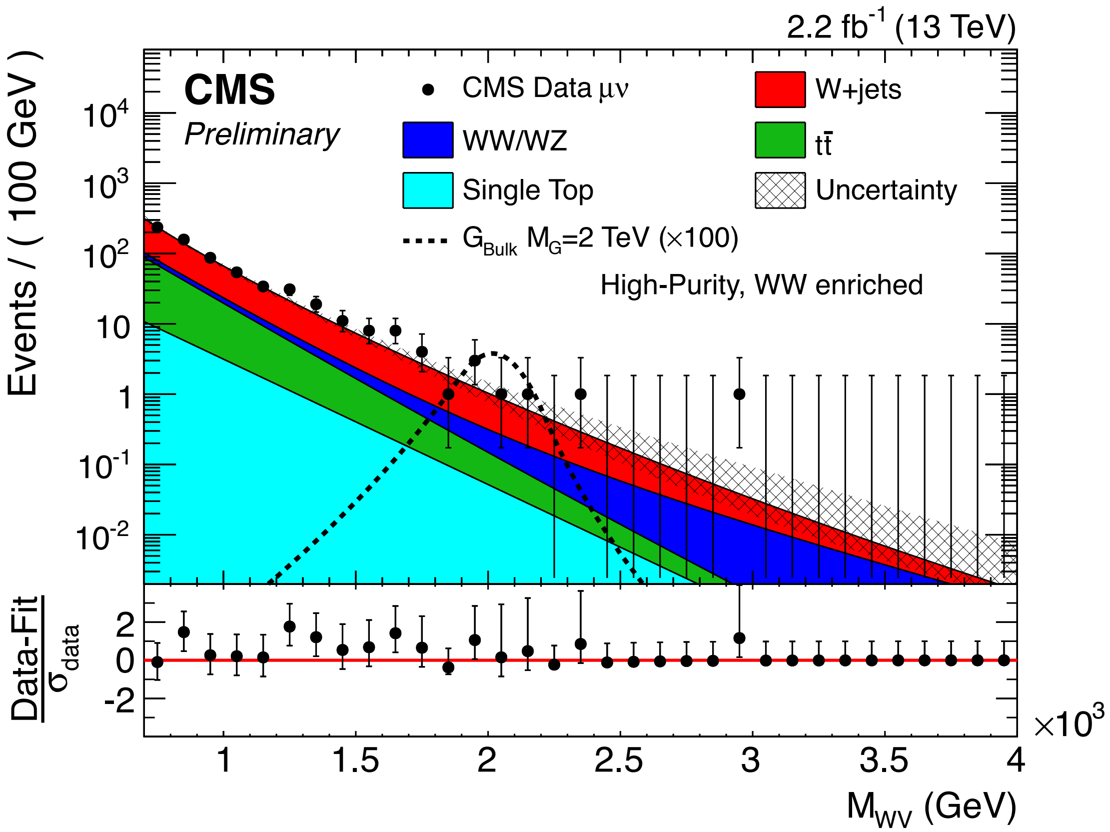


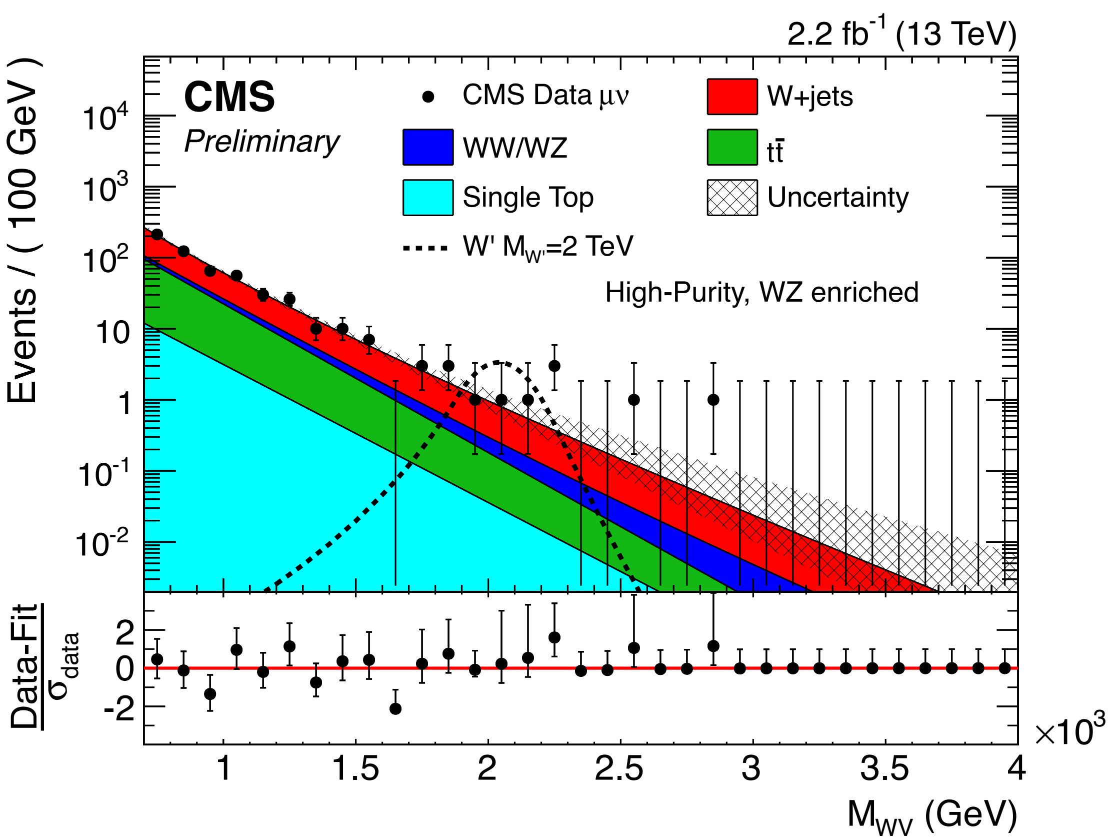


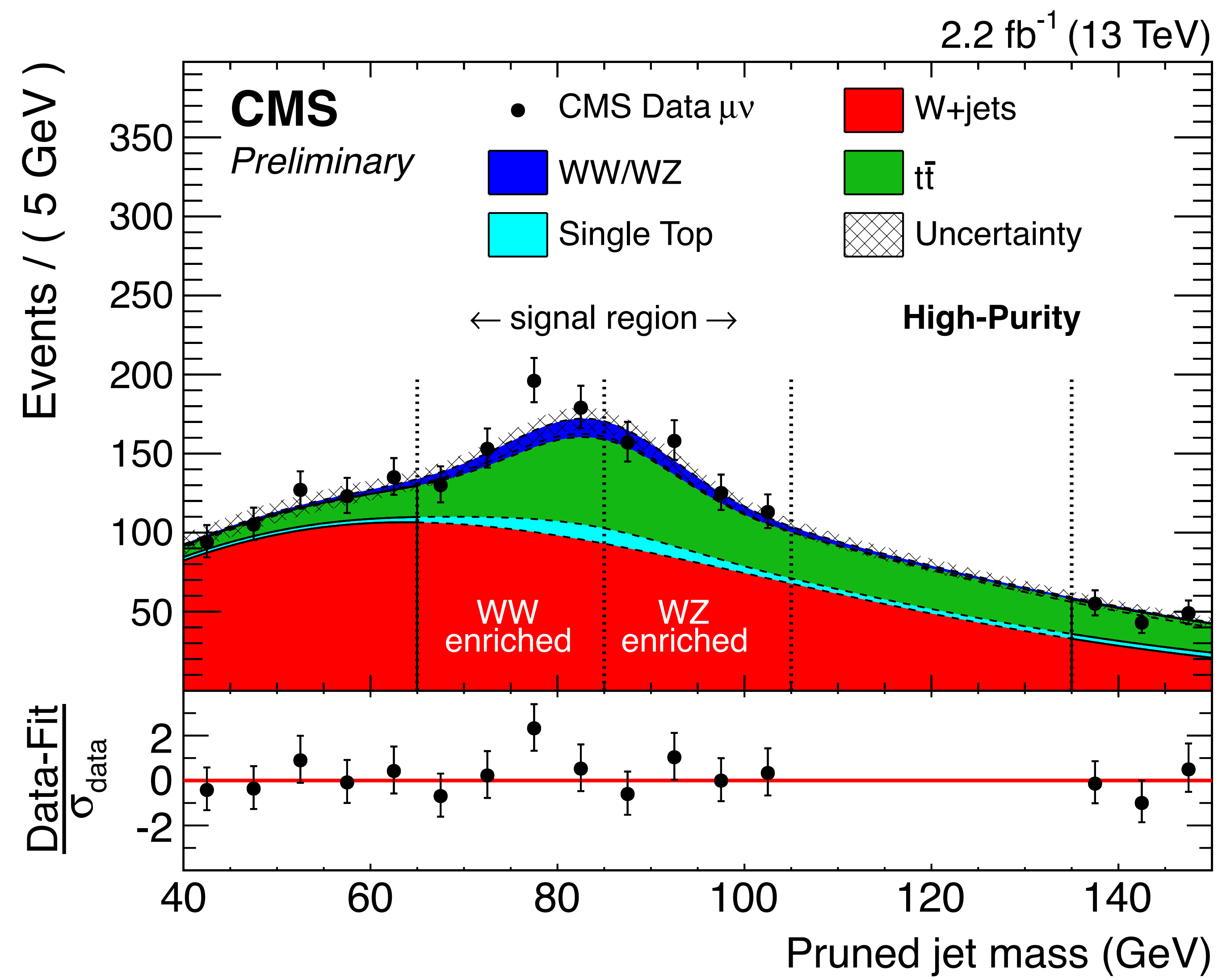
$$N_{\mathrm{bkg}}^{\mathrm{main}}\left(M_{WV}\right)=N_{\mathrm{norm}}P\left(M_{WV}\right)$$

α Ratio For Background Estimate

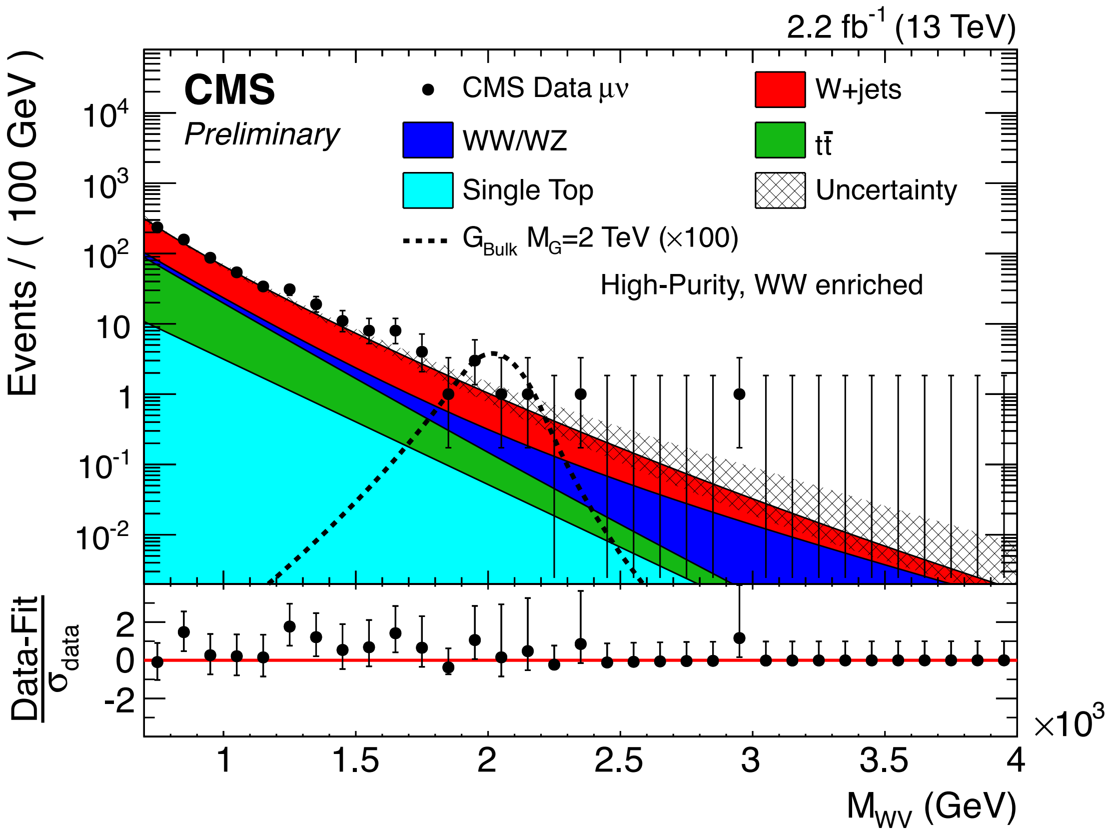
$$N_{\mathrm{bkg}}^{\mathrm{main}}\left(M_{WV}\right)=N_{\mathrm{norm}}P\left(M_{WV}\right)$$



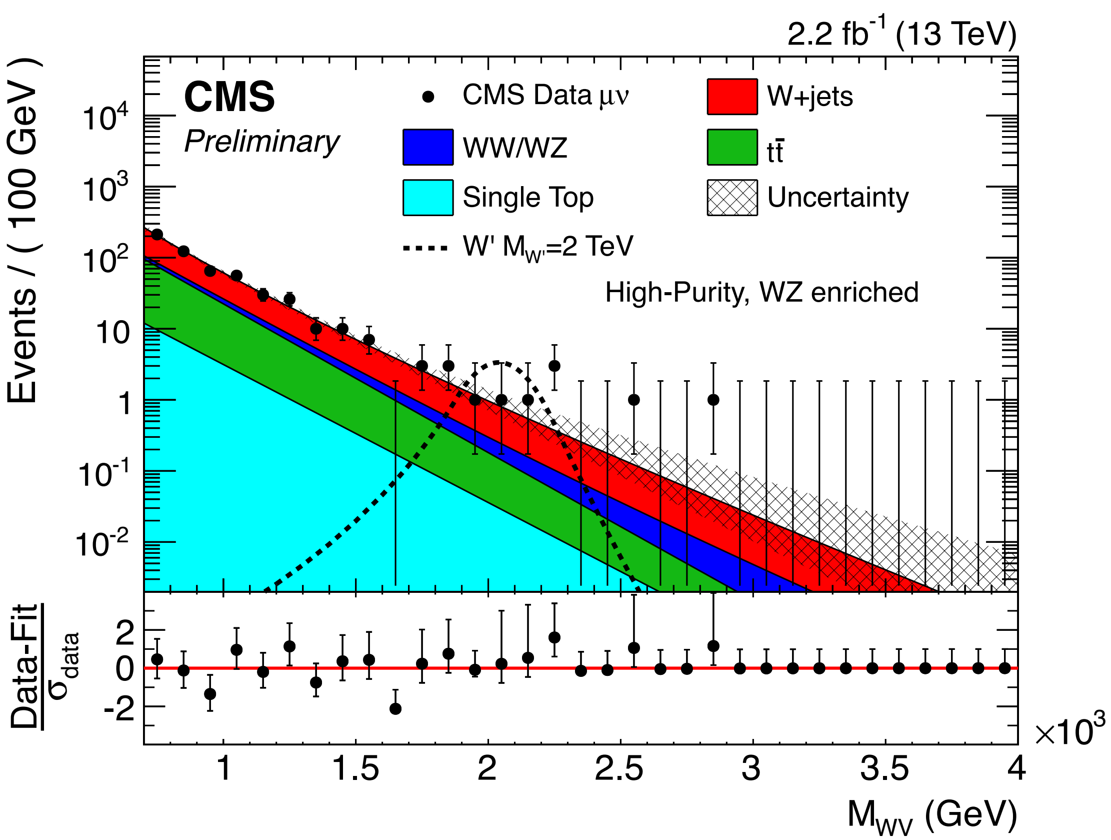


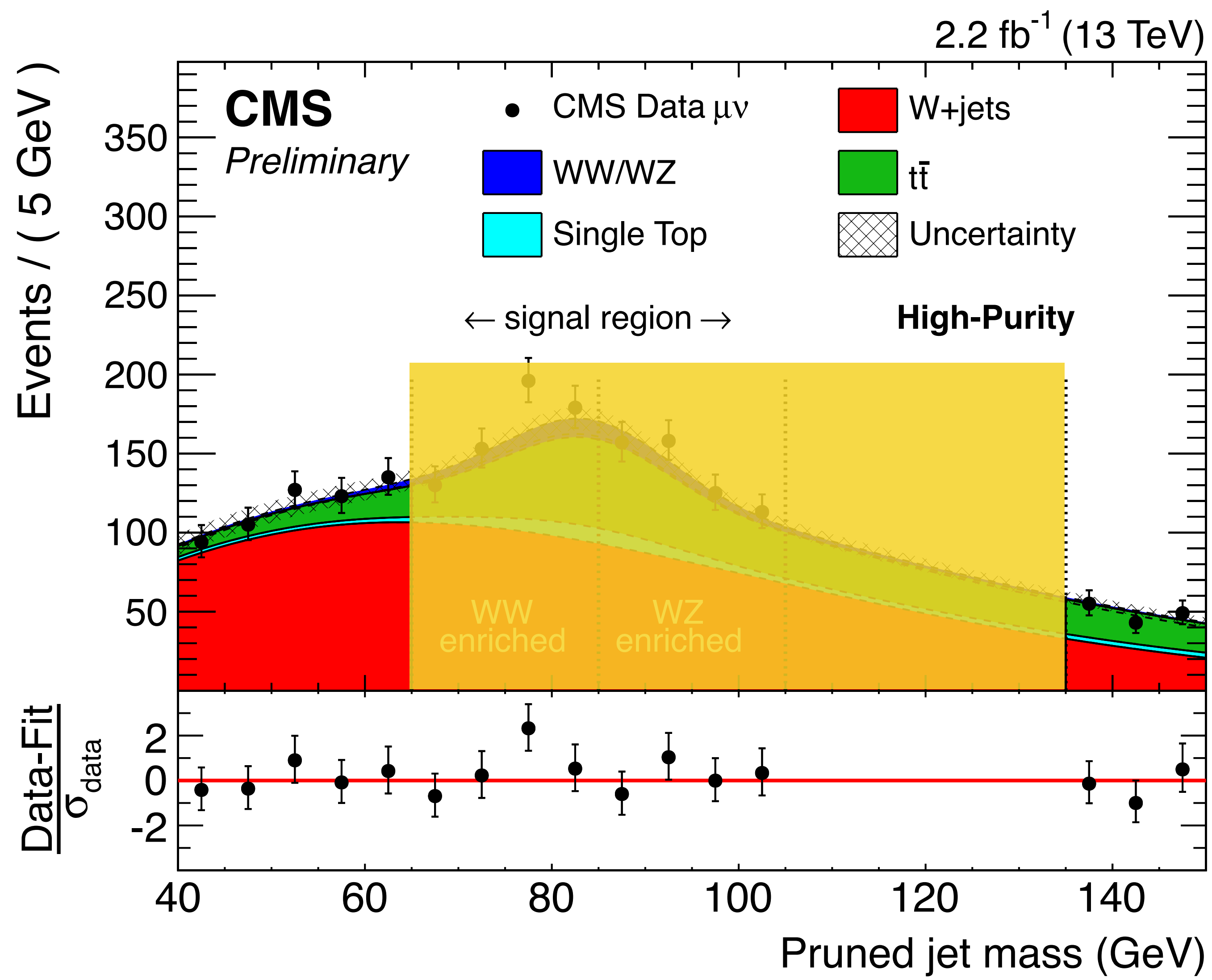


α Ratio For Background Estimate

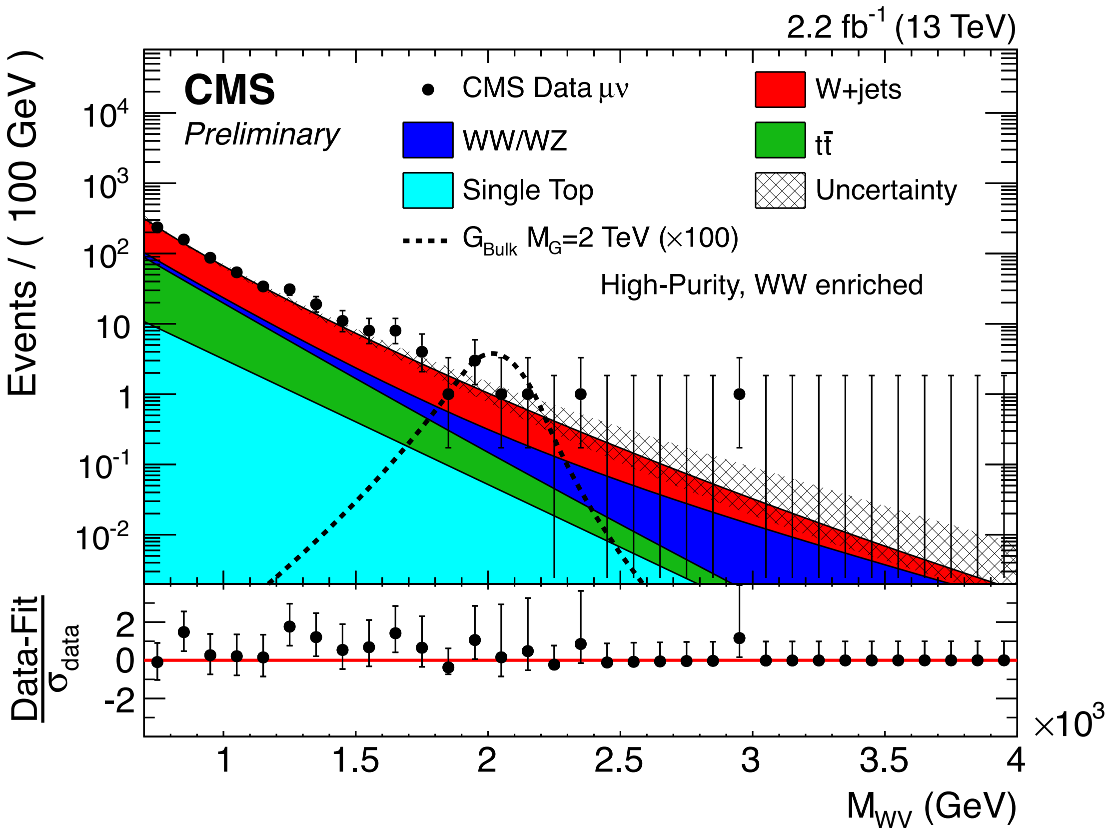


$$N_{\rm bkg}^{\rm main}\left(M_{WV}\right) = N_{\rm norm} P\left(M_{WV}\right)$$



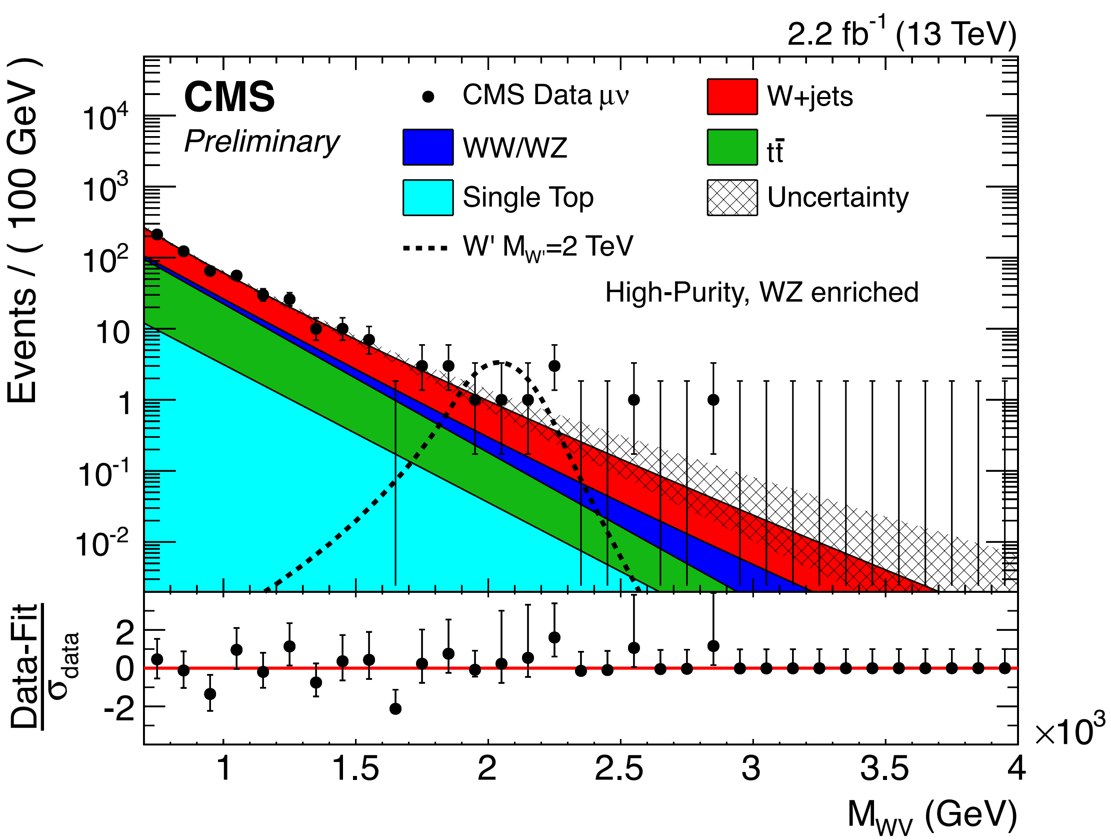


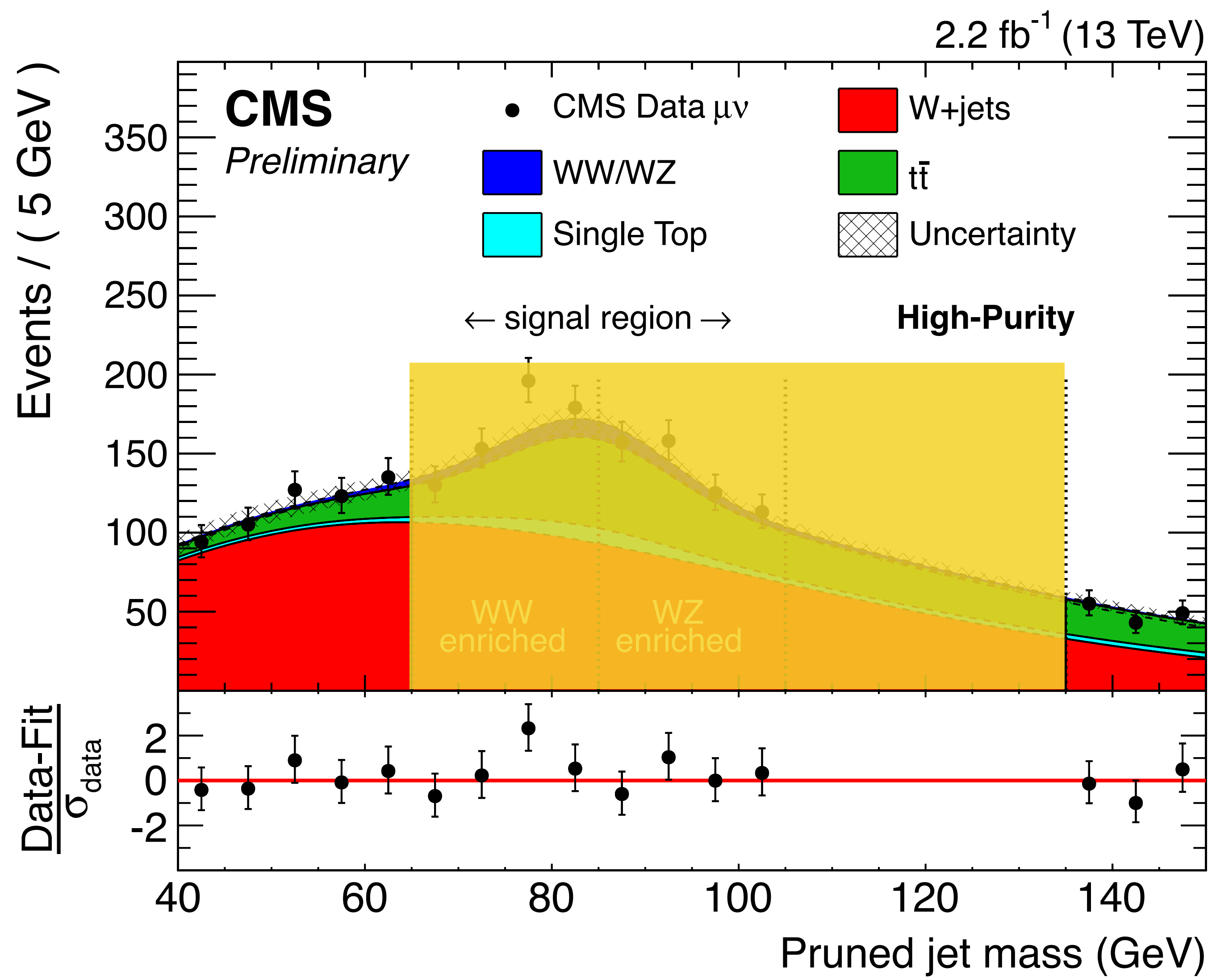
α Ratio For Background Estimate



$$N_{\mathrm{bkg}}^{\mathrm{main}}\left(M_{WV}\right)=N_{\mathrm{norm}}P\left(M_{WV}\right)$$

$$P\left(M_{VV}\right)=\Phi_{\mathrm{sideband}}^{\mathrm{data}}\,\alpha=\Phi_{\mathrm{sideband}}^{\mathrm{data}}\,\frac{M_{VV}^{\mathrm{MC,SIG}}}{M_{VV}^{\mathrm{MC,SB}}}$$

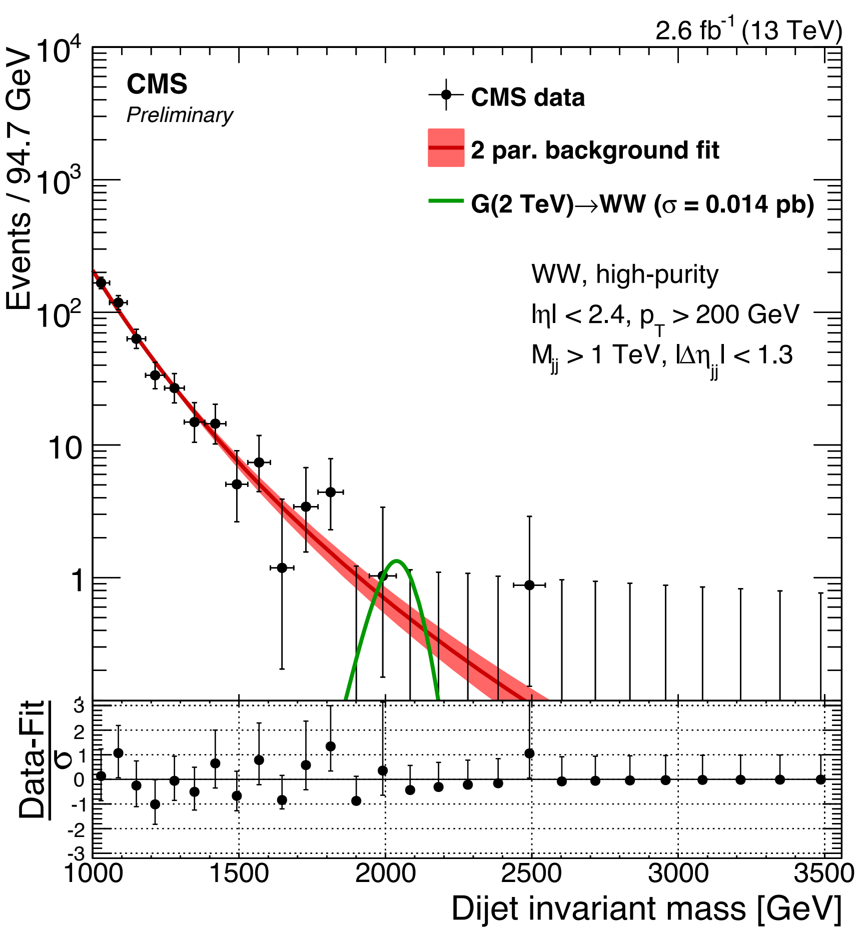


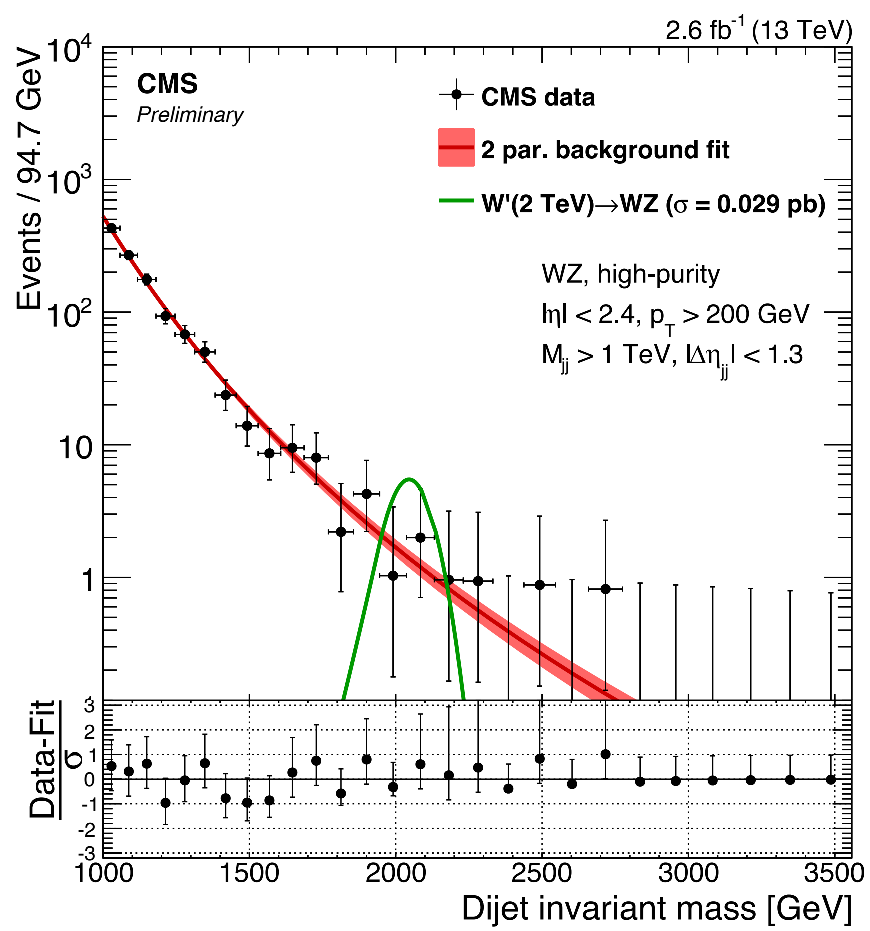


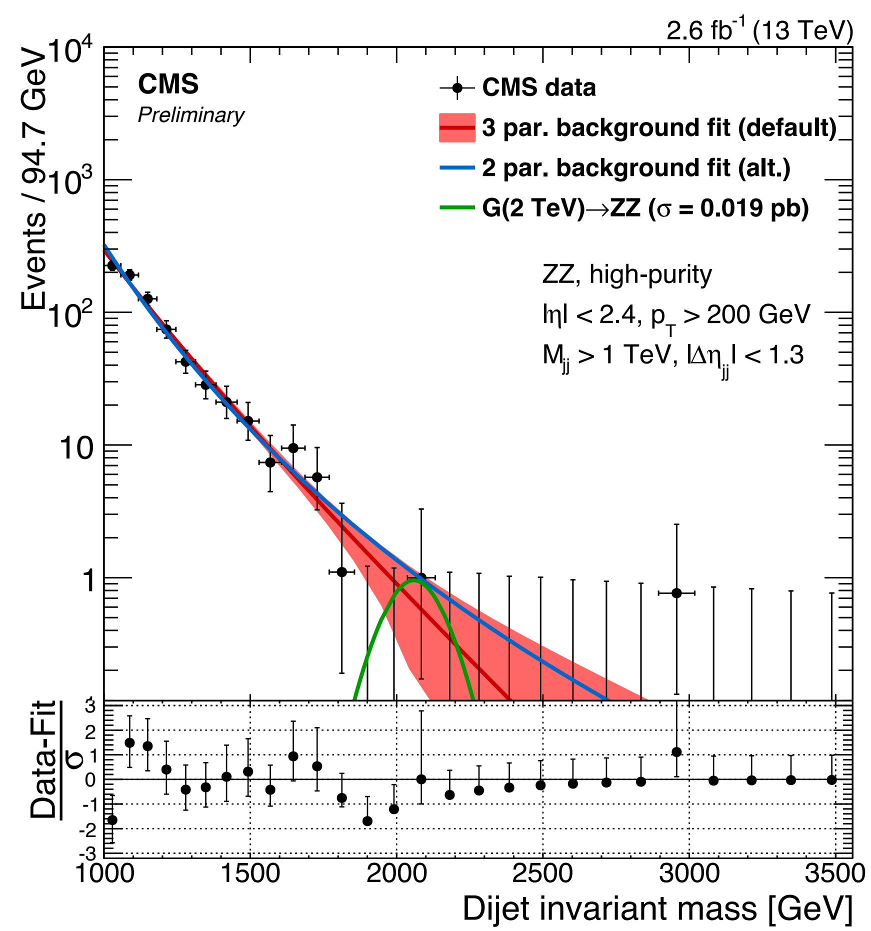
All-Hadronic Background

- Fisher's test with the sideband data to decide the number of parameters for the background function

$$\frac{dN}{dm_{jj}} = \frac{P_0}{(m_{jj}/\sqrt{s})^{P_2}} \text{ (2-par. form)} \qquad \frac{dN}{dm_{jj}} = \frac{P_0(1 - m_{jj}/\sqrt{s})^{P_1}}{(m_{jj}/\sqrt{s})^{P_2}} \text{ (3-par. form)}$$





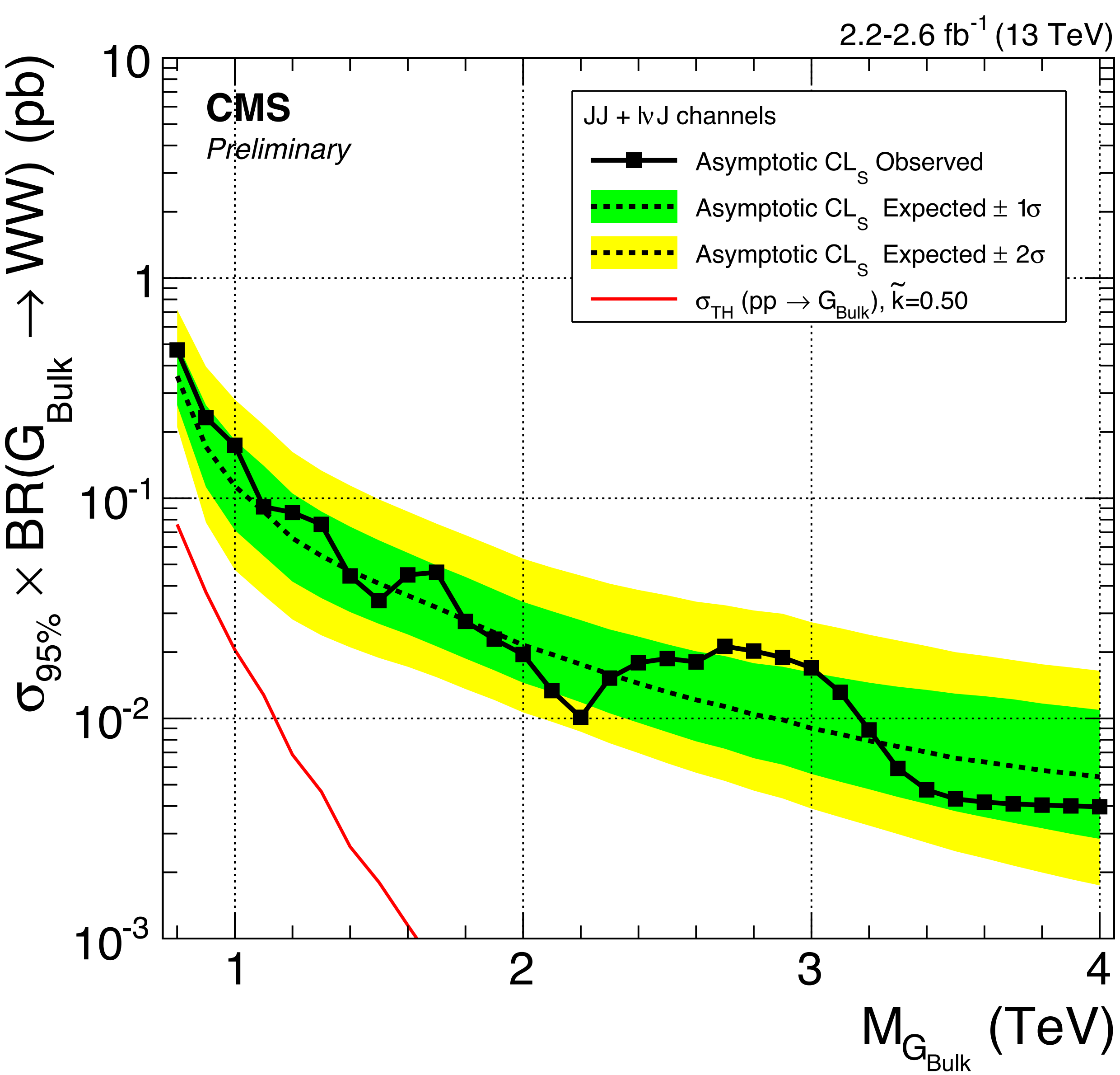


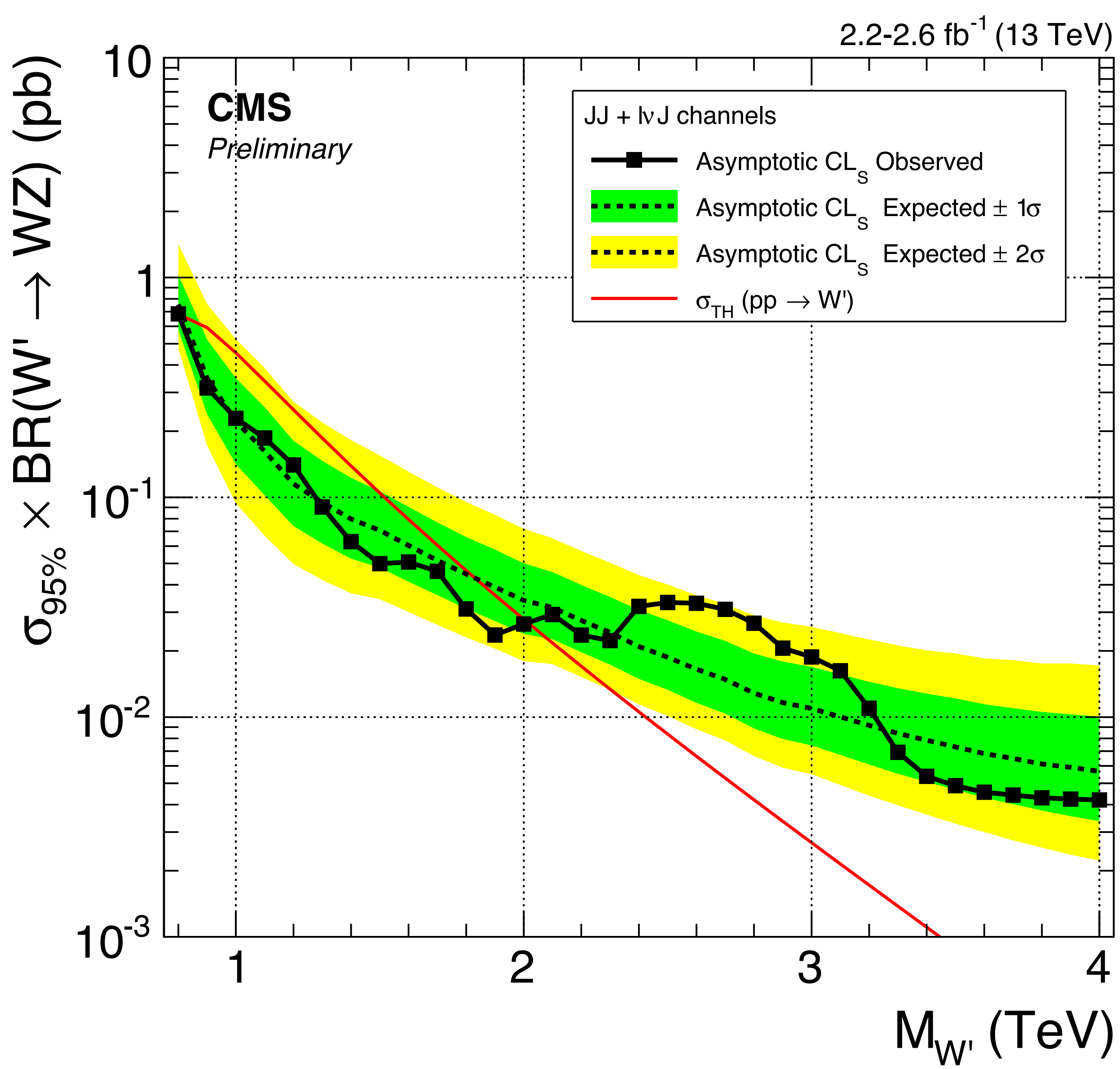
Systematic Uncertainties

- Semileptonic
  - Signal: dominated by τ_{21} efficiency, PDF, and jet energy scale
  - Background: dominated by size of sideband data, τ_{21} efficiency, and shape of α ratio
- All hadronic
  - Signal: dominated by τ_{21} efficiency, PDF, and jet energy scale
  - Background: dominated by uncertainties on the background fitting function

Combined Limits

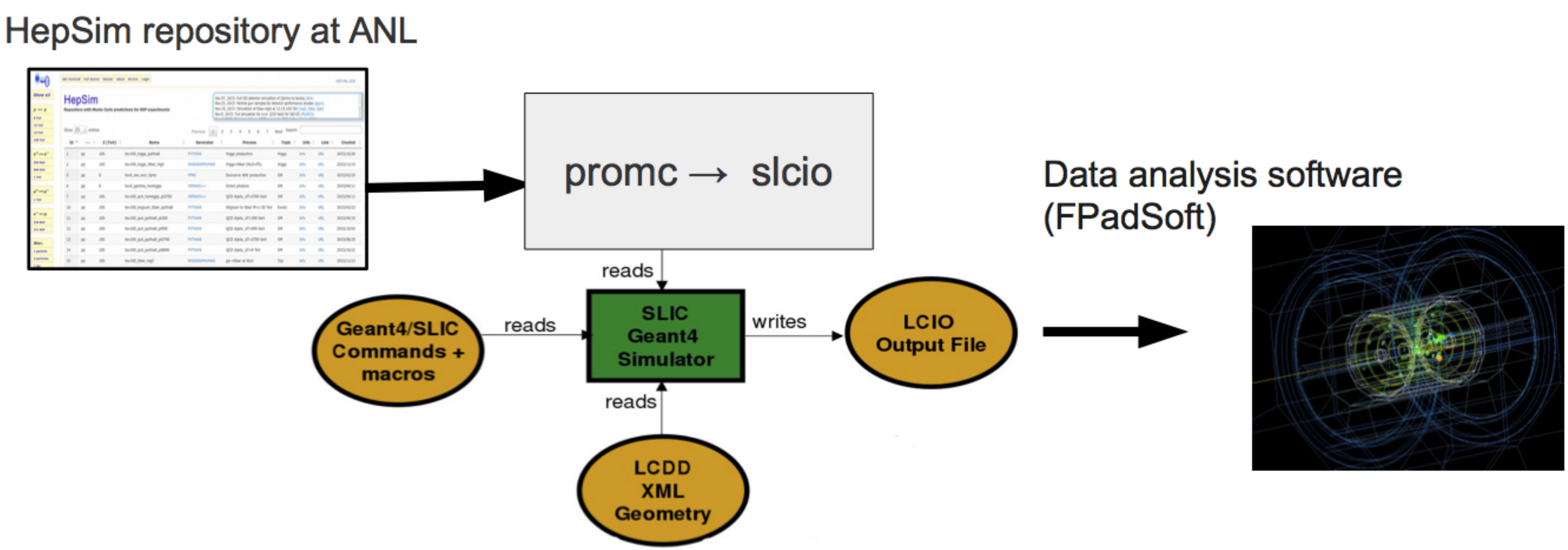
- Limits computed with asymptotic CL_s method
- M(W')<2 TeV excluded





A Framework For Boosted Object Simulation

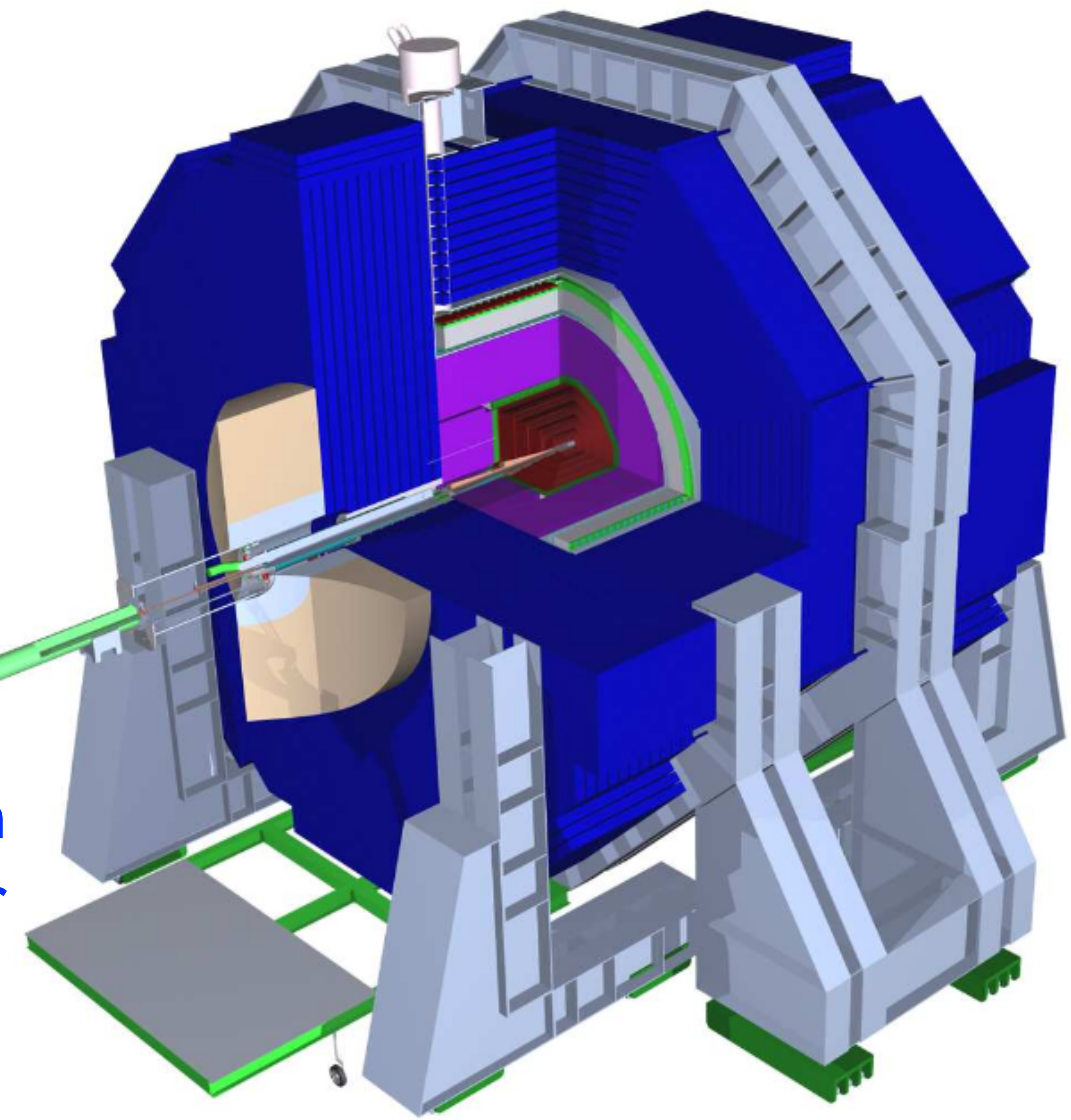
- Using HepSim public repository with EVGEN and full simulations
  - http://atlaswww.hep.anl.gov/hepsim/
- EVGEN files were created with MG5/Pythia6
- Files are being processed with a full GEANT detector simulation which includes high-granularity calorimeter (1x1 cm cell size)



SiD Detector

More details in
SiD Letter of Intent

- A multi-purpose detector for ILC
- The key characteristics
  - 5 Tesla solenoid & silicon tracker
  - 3.5 mm cell size for ECAL with tungsten absorber and silicon sensors for active layer, 30 layers
  - 10 x 10 mm cell size for HCAL with stainless steel absorber and RPC for active layer, 40 layers for barrel
- Optimized for particle-flow algorithms

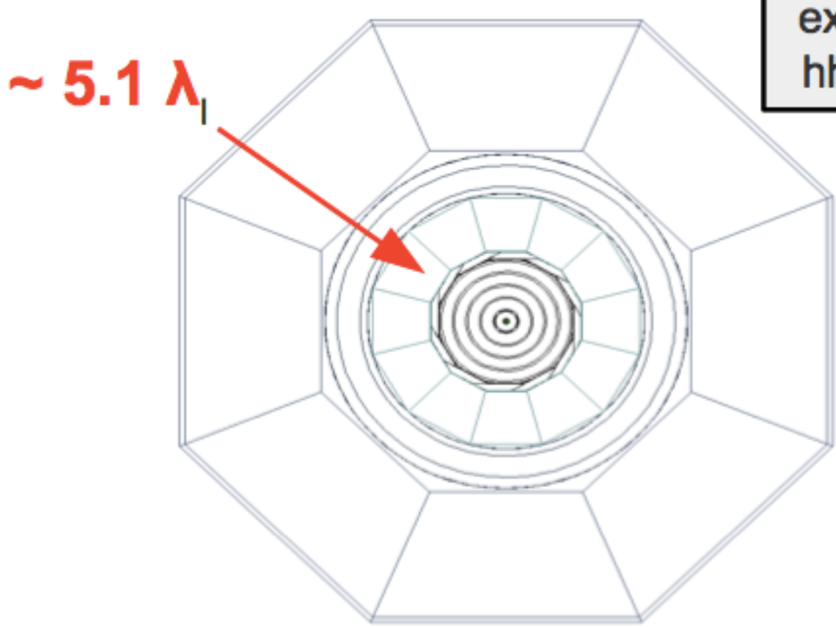


Designing A Detector For TeV-Scale Boosted Objects

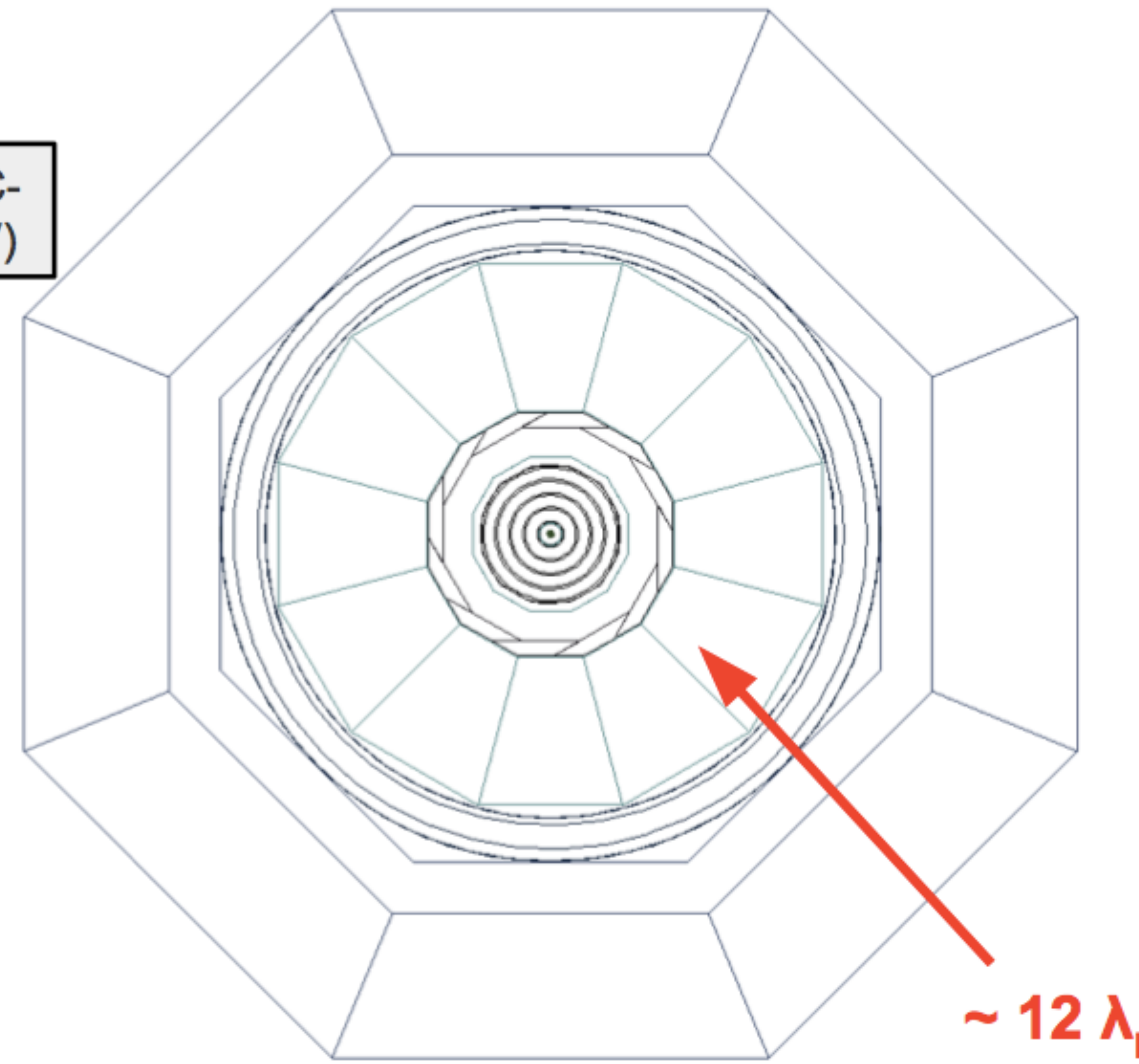
SiD detector was designed for ~500 GeV jets

A FCC-like detector for studies of CAL transverse and longitudinal granularity, depth, material, magnetic fields, pixel sizes etc, responses to particles etc.

SiD



expanding to FCC-hh (pp at 100 TeV)



Designing a Geant4 simulation for high-granularity calorimeter (1 cm x 1 cm) with 12 λ to contain 20-30 TeV jets

S. Chekanov (ANL)
A. Kotwal (Fermilab/Duke)
M. Ruan (IHEP)
J. Strube (PNNL)
N. Tran (Fermilab)
S-S. Yu (NCU Taiwan)

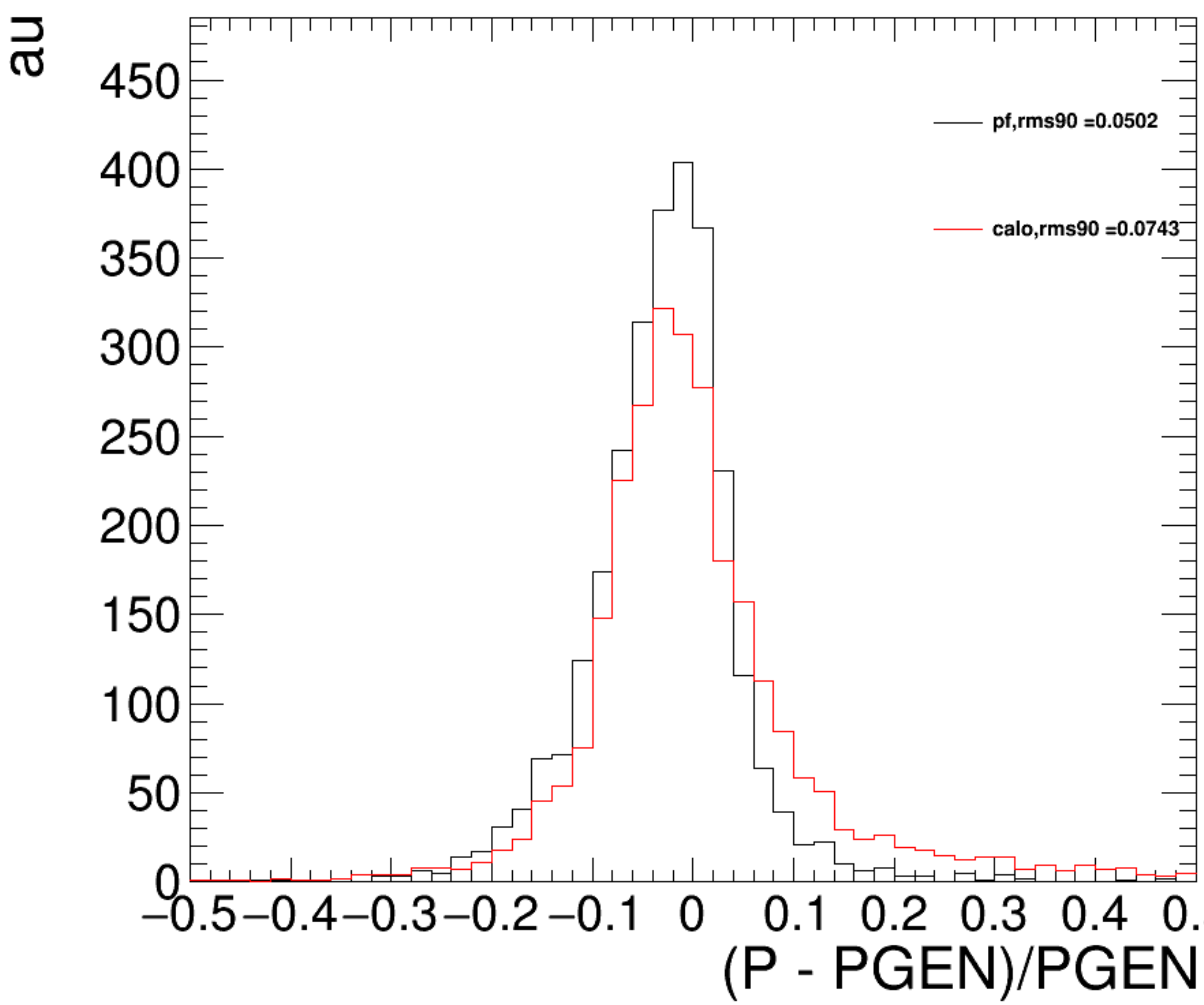
Conclusion And Outlook

- We present a preliminary search for new physics in boosted diboson events using 2.2-2.6 fb^{-1} of 13 TeV data collected with the CMS detector
- Future improvements
  - Signal interpretation with other models or wide width
  - Adding the VZ channel and combination with the 8 TeV results
  - Event categorization based on the number of b-jets
  - Combination with the VH channels
- A detector for TeV-scale boosted-object physics is being designed and studied by the VHEPP group

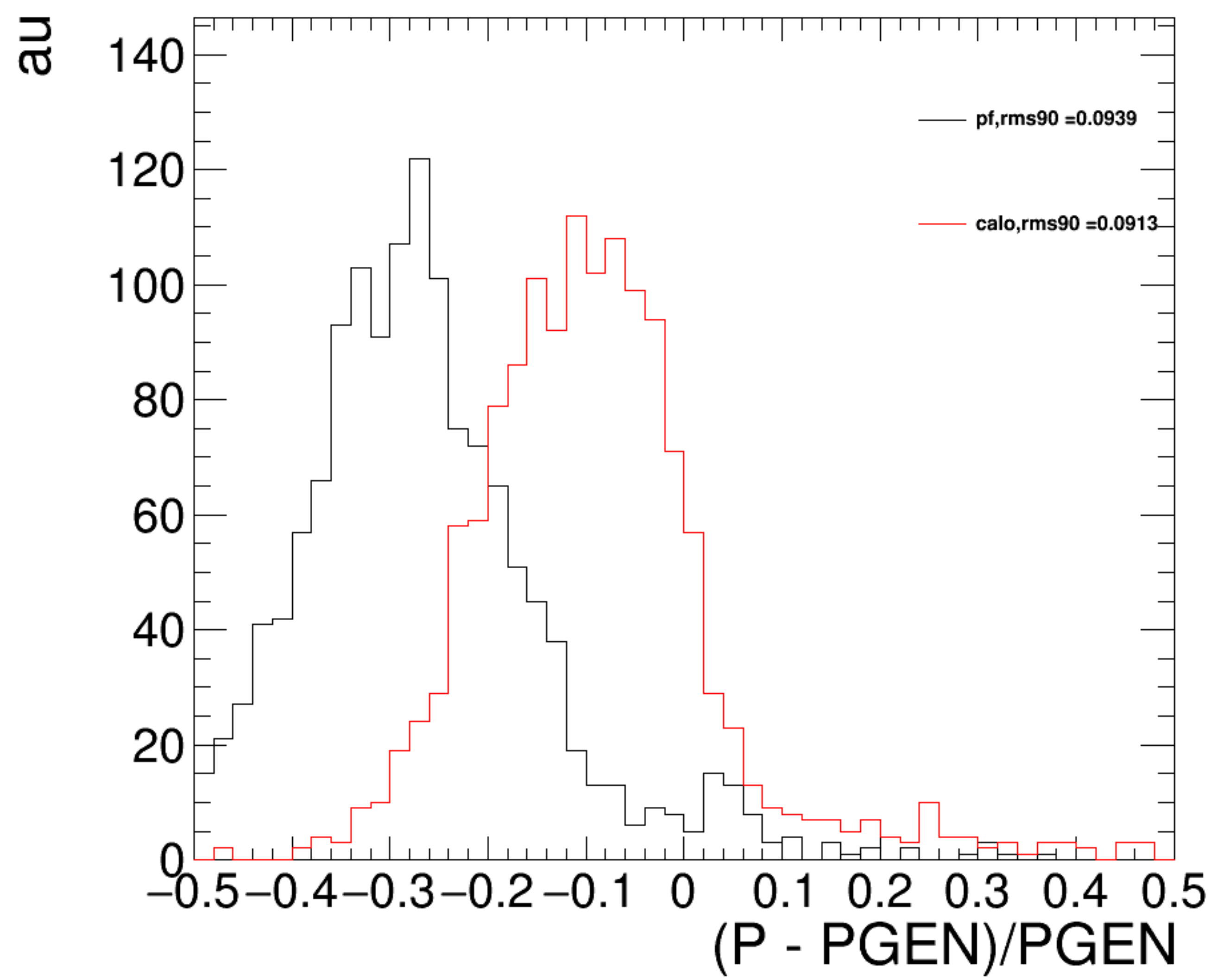
Backup Slides

Jet Energy Resolution With SiD

500-GeV jet from 1 TeV Z'→qq



5 TeV jet from 10 TeV Z'→WW

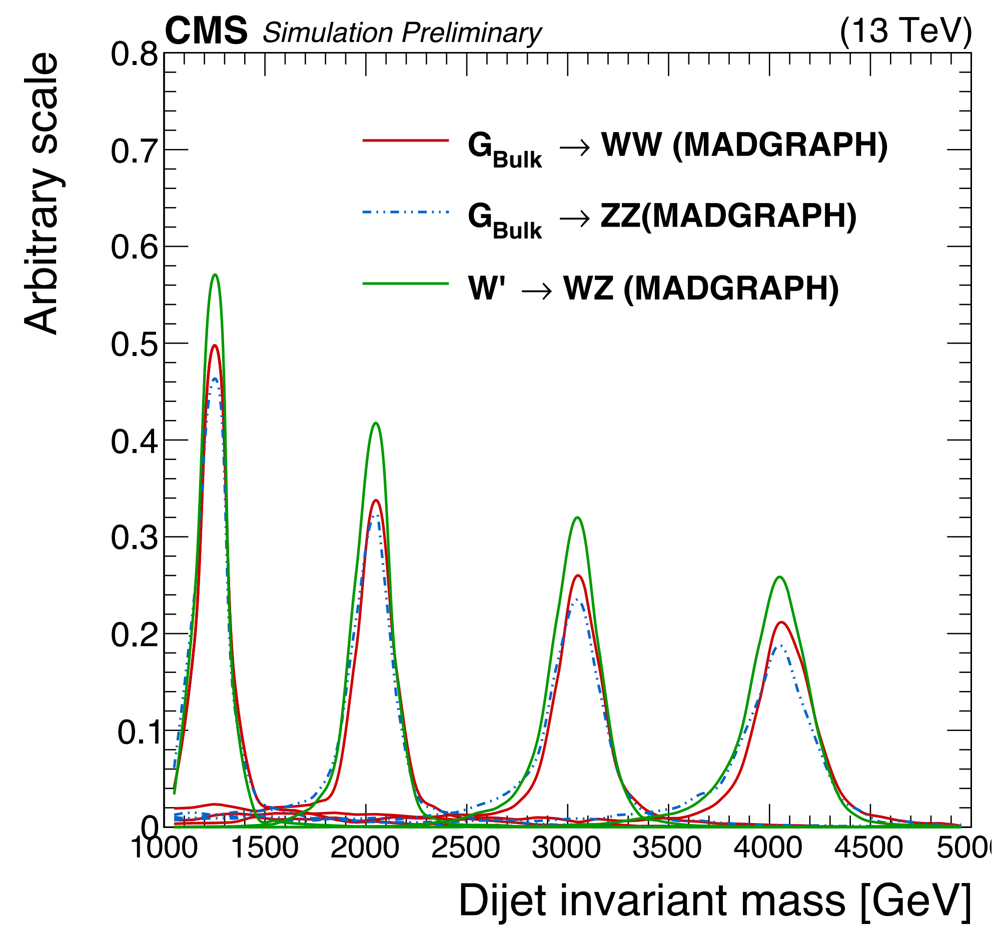


Signal Modeling And Efficiency

- Modeled with double-sided Crystal-Ball function, resolution 10%-3% for the resonance mass of 1-4 TeV

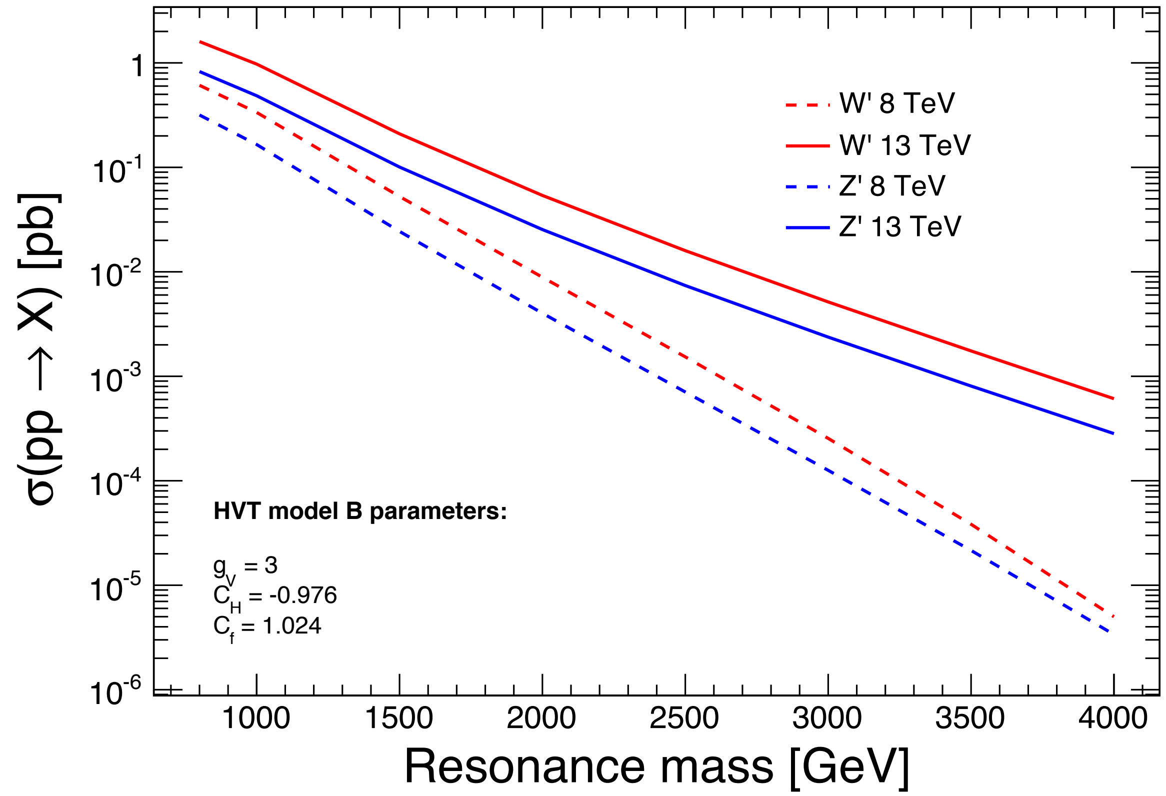
Semileptonic: 50-60% efficiency in HP, 5% in LP

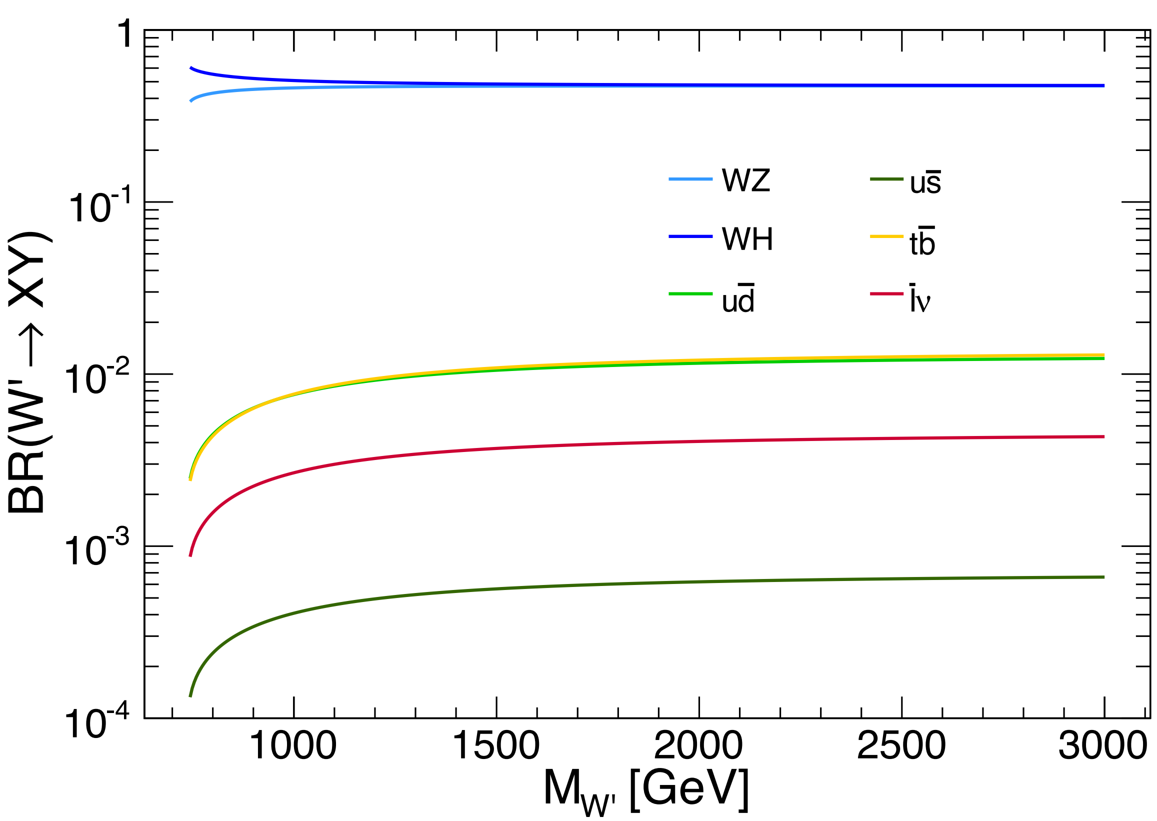
Signal	Mass	Dijet channel						$\ell\nu$+jet channel			
		WW		WZ		ZZ		WW		WZ	
		HP	LP	HP	LP	HP	LP	HP	LP	HP	LP
$G_{bulk} \to WW$	1.2 TeV	3.1	5.7	2.3	4.0	0.4	0.5	13.2	0.5	3.8	0.1
$G_{bulk} \to WW$	2.0 TeV	4.1	9.3	1.3	2.9	0.1	0.3	15.4	0.9	2.9	0.1
$G_{bulk} \to WW$	3.0 TeV	3.1	8.0	1.5	3.4	0.1	0.3	14.7	1.2	3.2	0.2
$G_{bulk} \to WW$	4.0 TeV	2.7	8.2	1.8	4.0	0.2	0.5	14.1	1.2	3.9	0.2
$G_{bulk} \to ZZ$	1.2 TeV	0.3	0.6	1.7	2.5	1.9	2.3	-	-	-	-
$G_{bulk} \to ZZ$	2.0 TeV	0.4	1.1	1.6	3.4	1.5	2.2	-	-	-	-
$G_{bulk} \to ZZ$	3.0 TeV	0.3	1.2	1.4	3.6	1.2	2.3	-	-	-	-
$G_{bulk} \to ZZ$	4.0 TeV	0.3	1.3	1.2	3.7	1.1	2.2	-	-	-	-
HVT $W' \to WZ$	1.2 TeV	1.7	3.0	4.6	6.9	0.9	1.3	2.8	0.1	6.3	0.1
HVT $W' \to WZ$	2.0 TeV	1.9	4.8	3.8	6.8	0.5	0.8	3.9	0.3	6.4	0.2
HVT $W' \to WZ$	3.0 TeV	1.4	4.6	3.2	6.9	0.6	0.8	3.9	0.4	6.4	0.2
HVT $W' \to WZ$	4.0 TeV	1.9	2.8	4.5	4.7	1.1	0.8	3.9	0.4	6.1	0.3

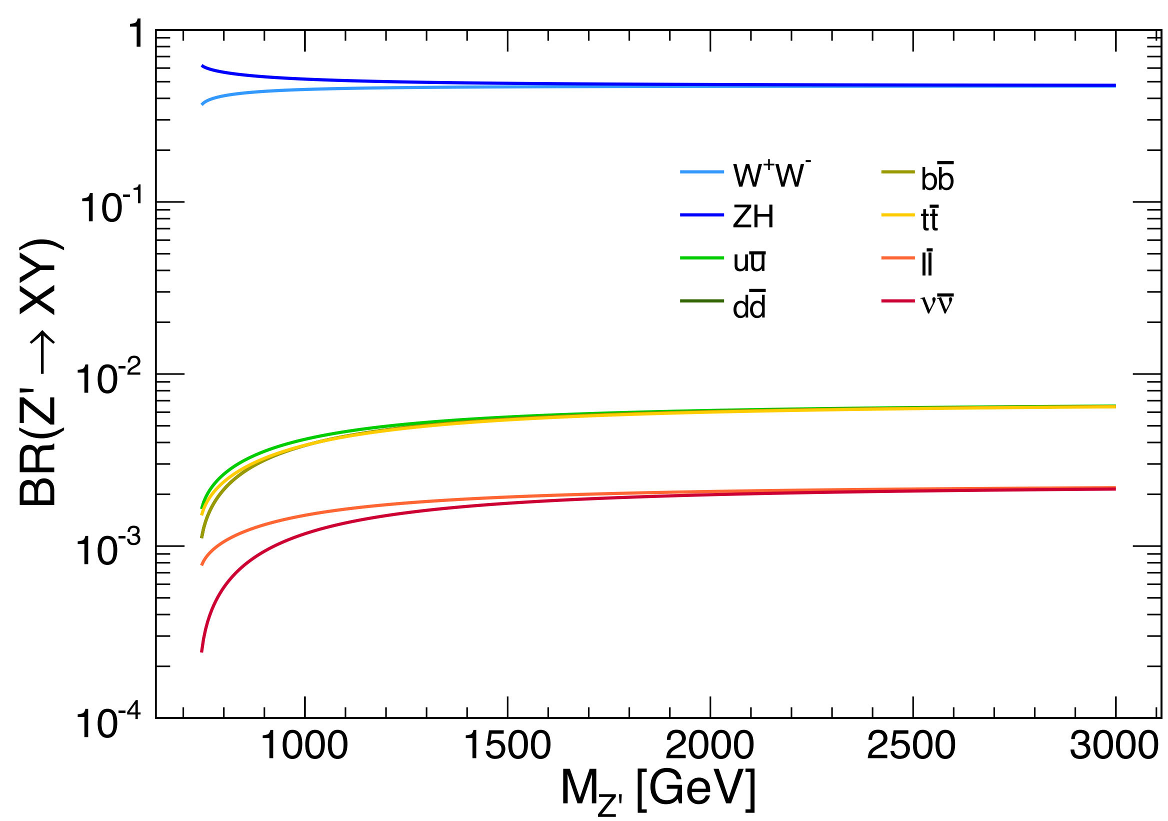


All hadronic: 16-23% efficiency

Heavy Vector Triplet (Model B)

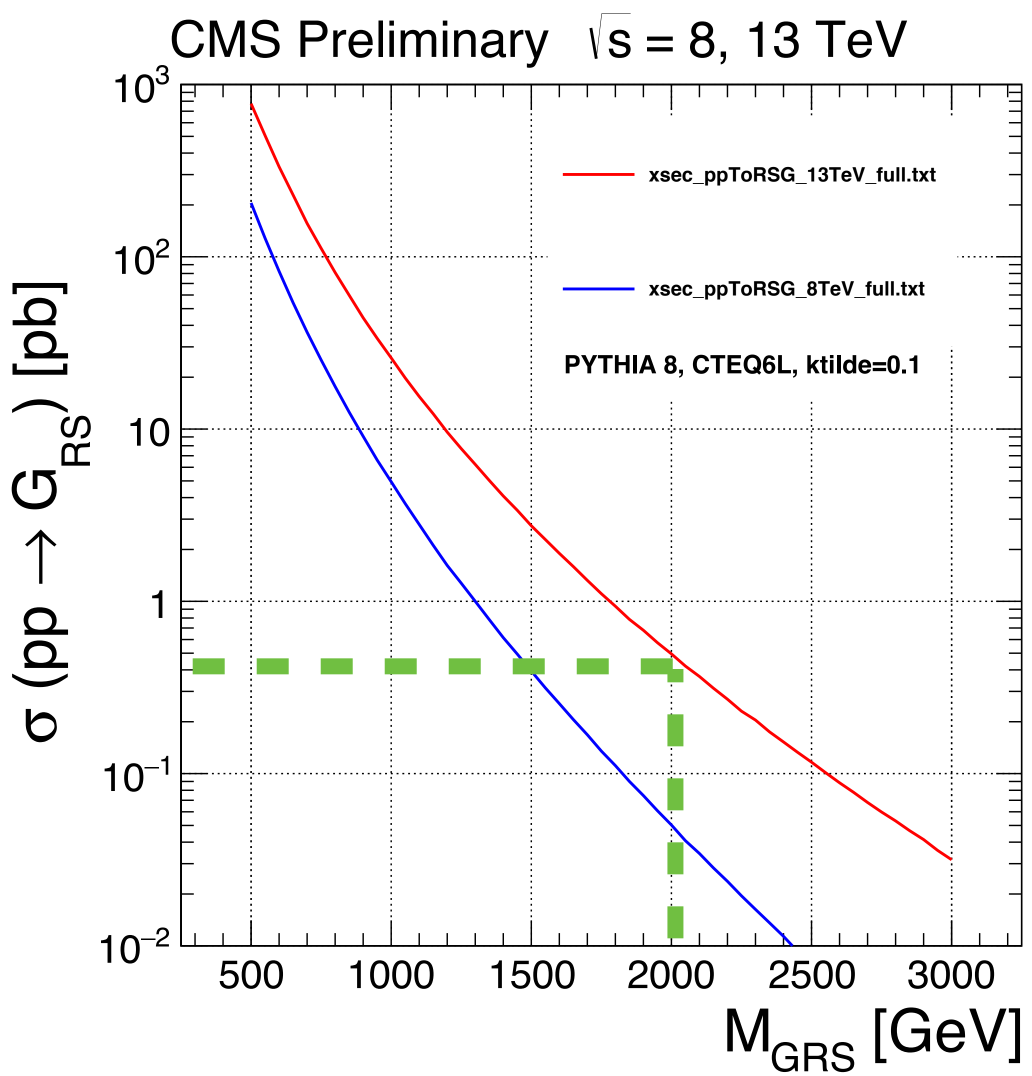


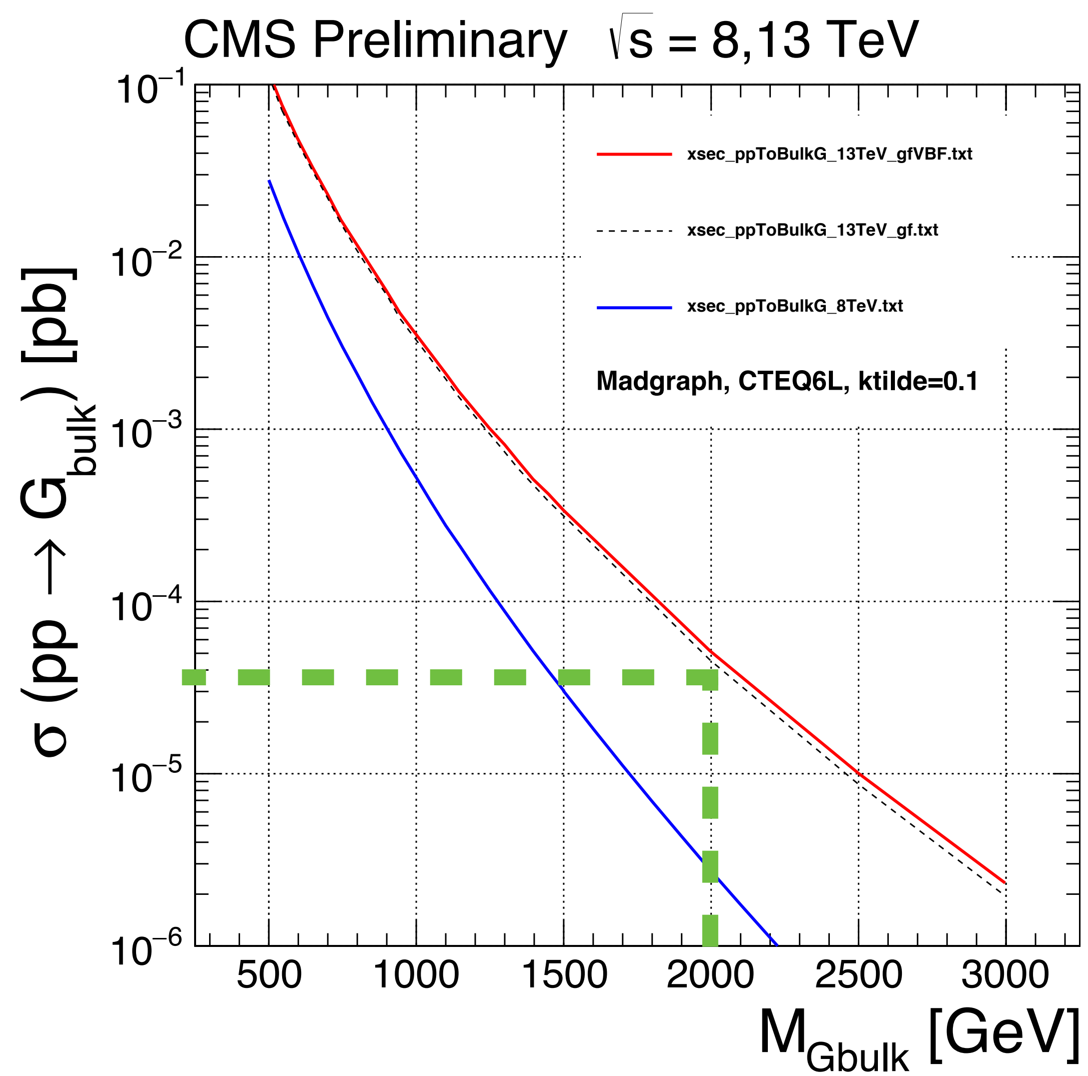




RS Vs Bulk Graviton Scenarios

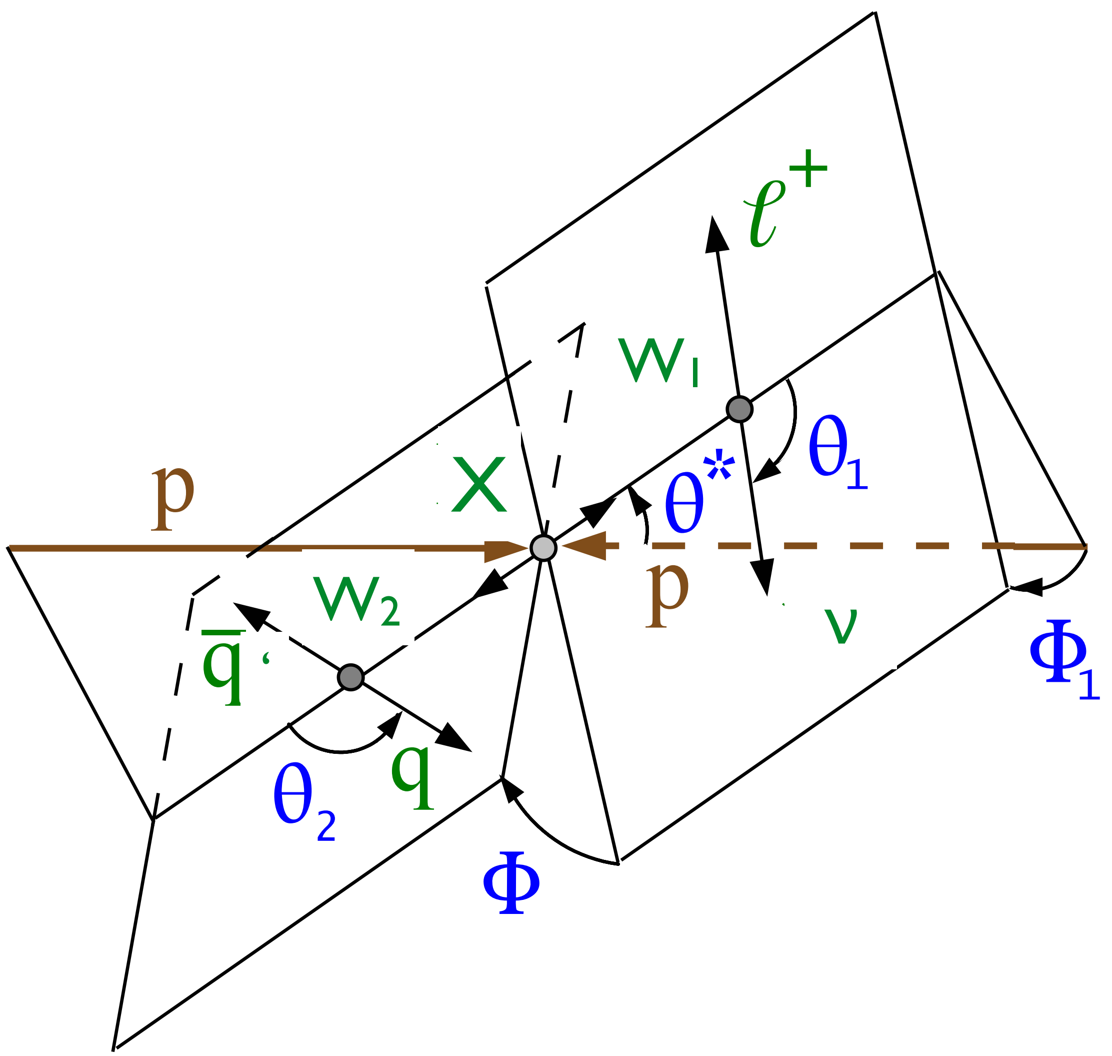
- SM fields are allowed to propagate in the extra dimension (bulk)
- BRs of RS graviton decays to diboson modes are lower (1% for RS→ZZ and 2% for RS→WW, 10% for Bulk→ZZ, 20% for Bulk→WW for M=2 TeV)
- Production cross section of Bulk graviton is 10^4 smaller

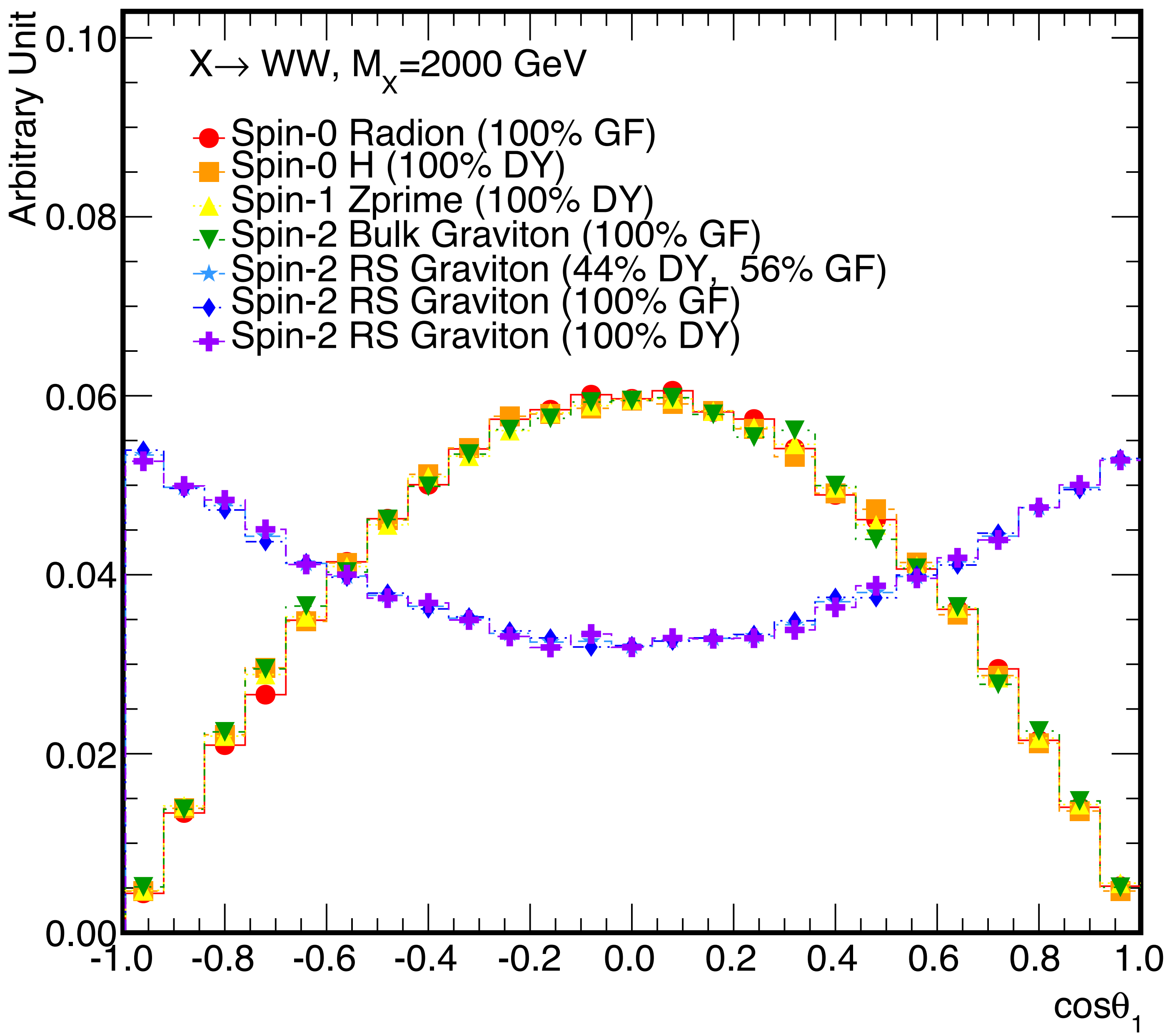




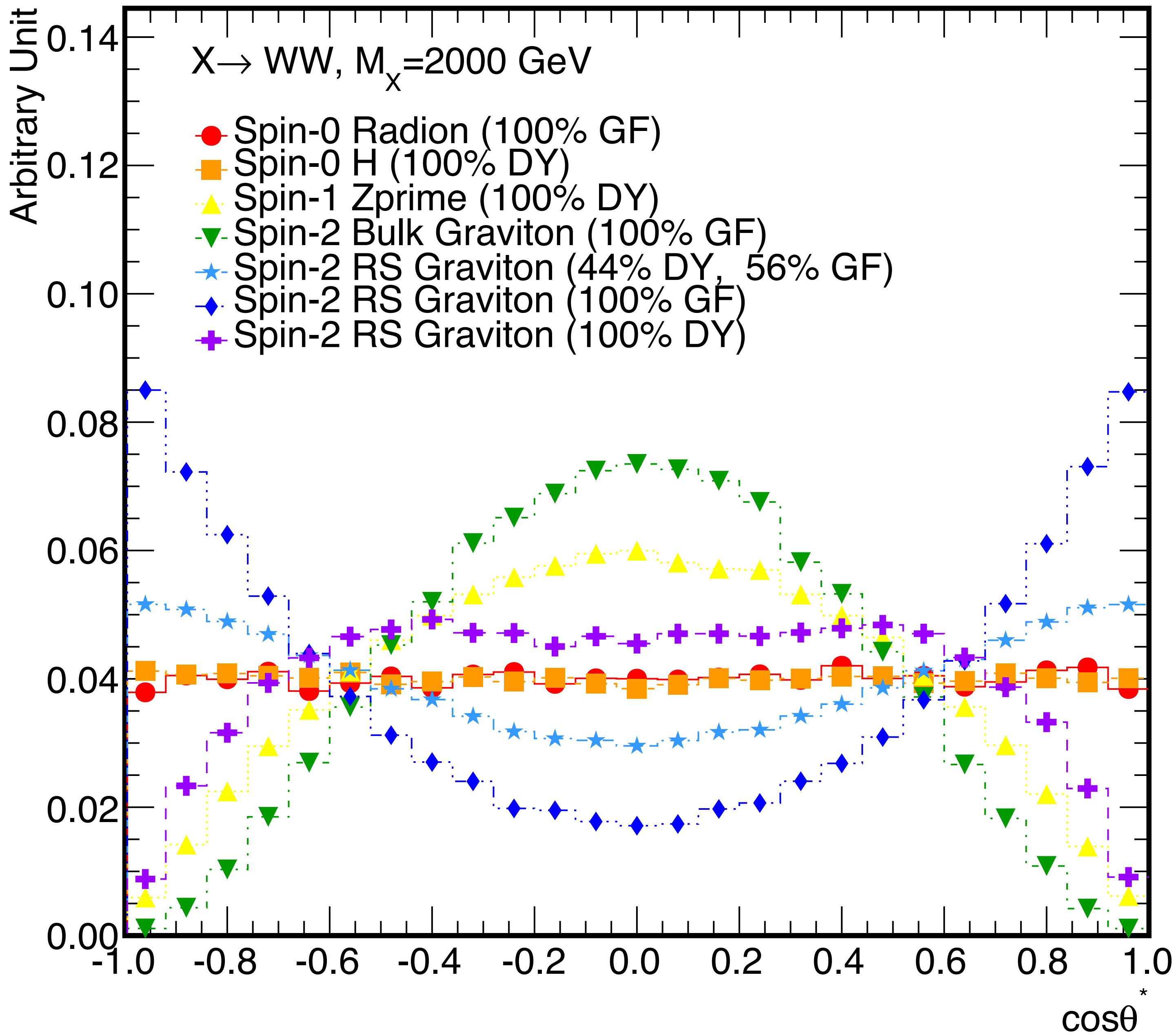
Comparison Of Models

- In the benchmark model we choose, the vector bosons are produced with a longitudinal polarization more than 99% of the time



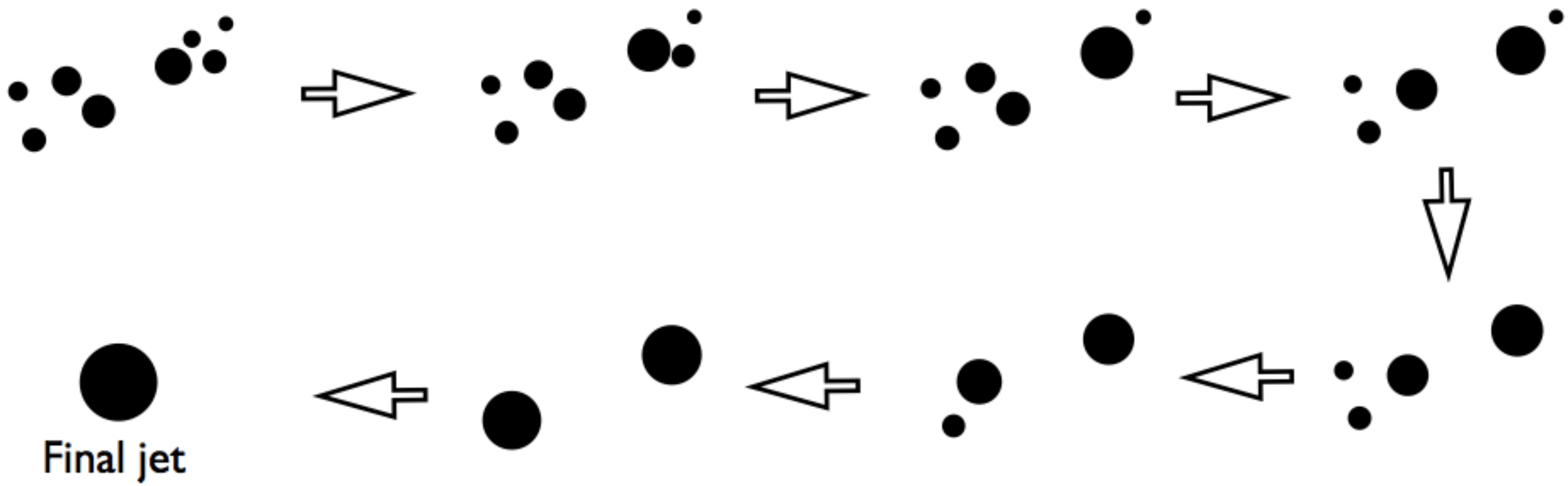


Comparison Of Cosθ*

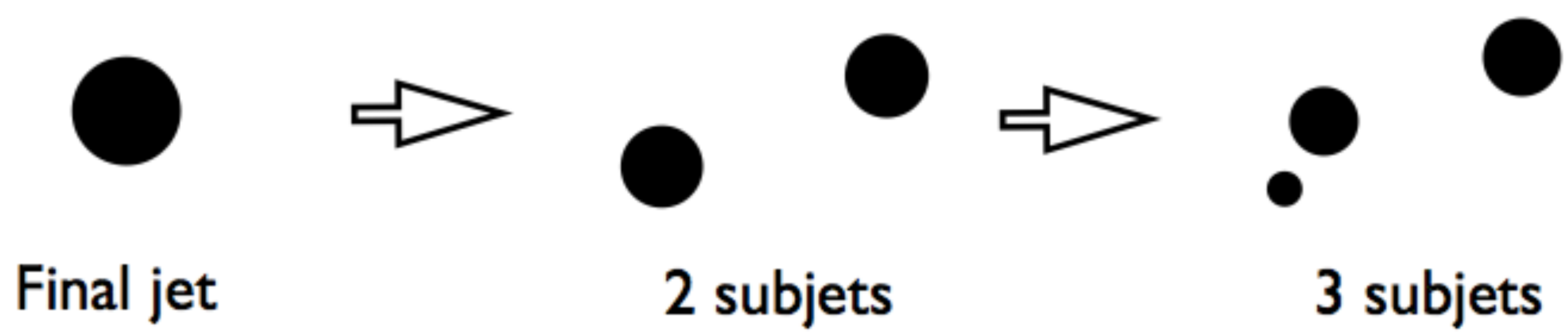


How To Get N-Subjet Axis

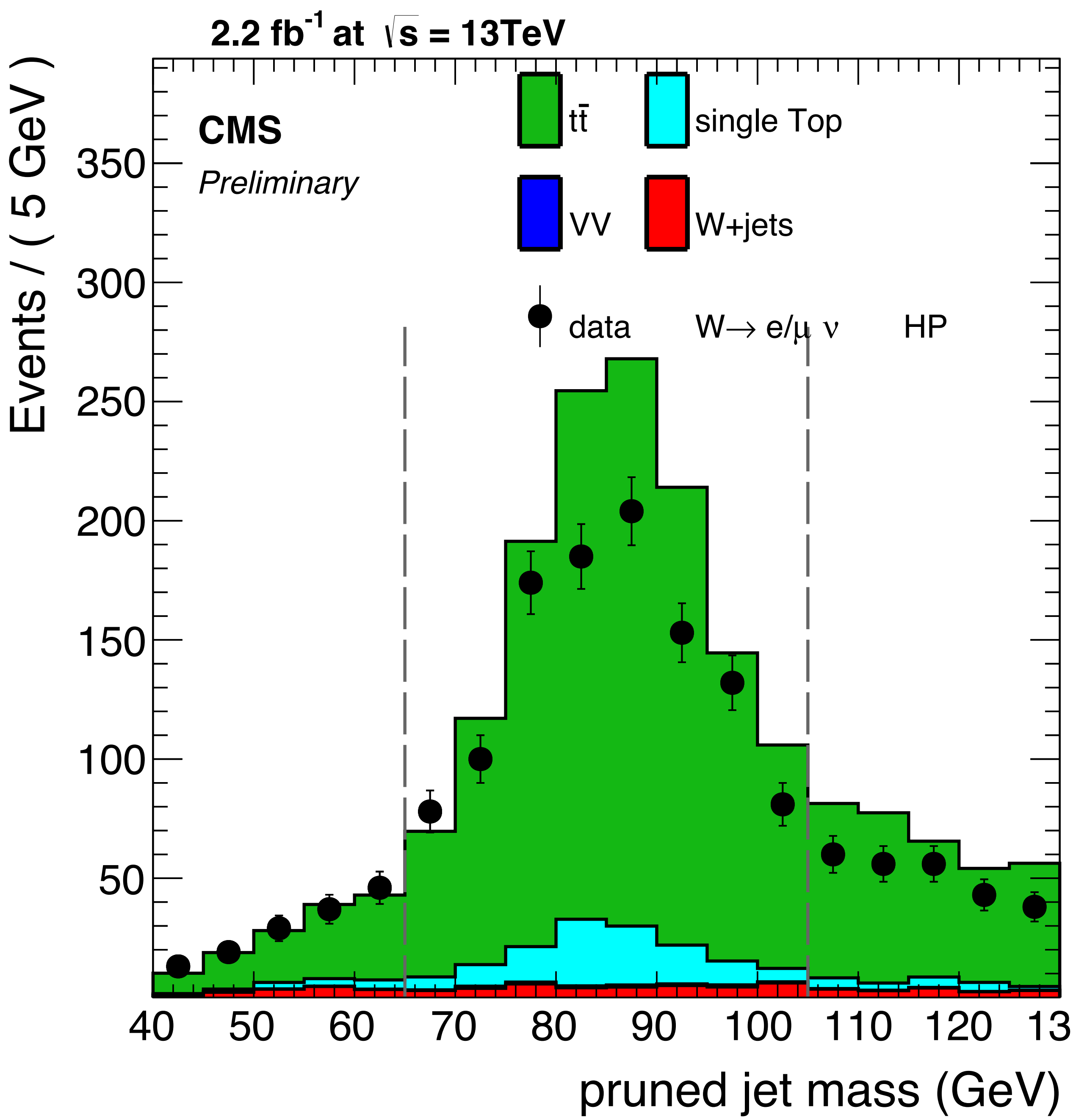
Step 1: Cluster the jet

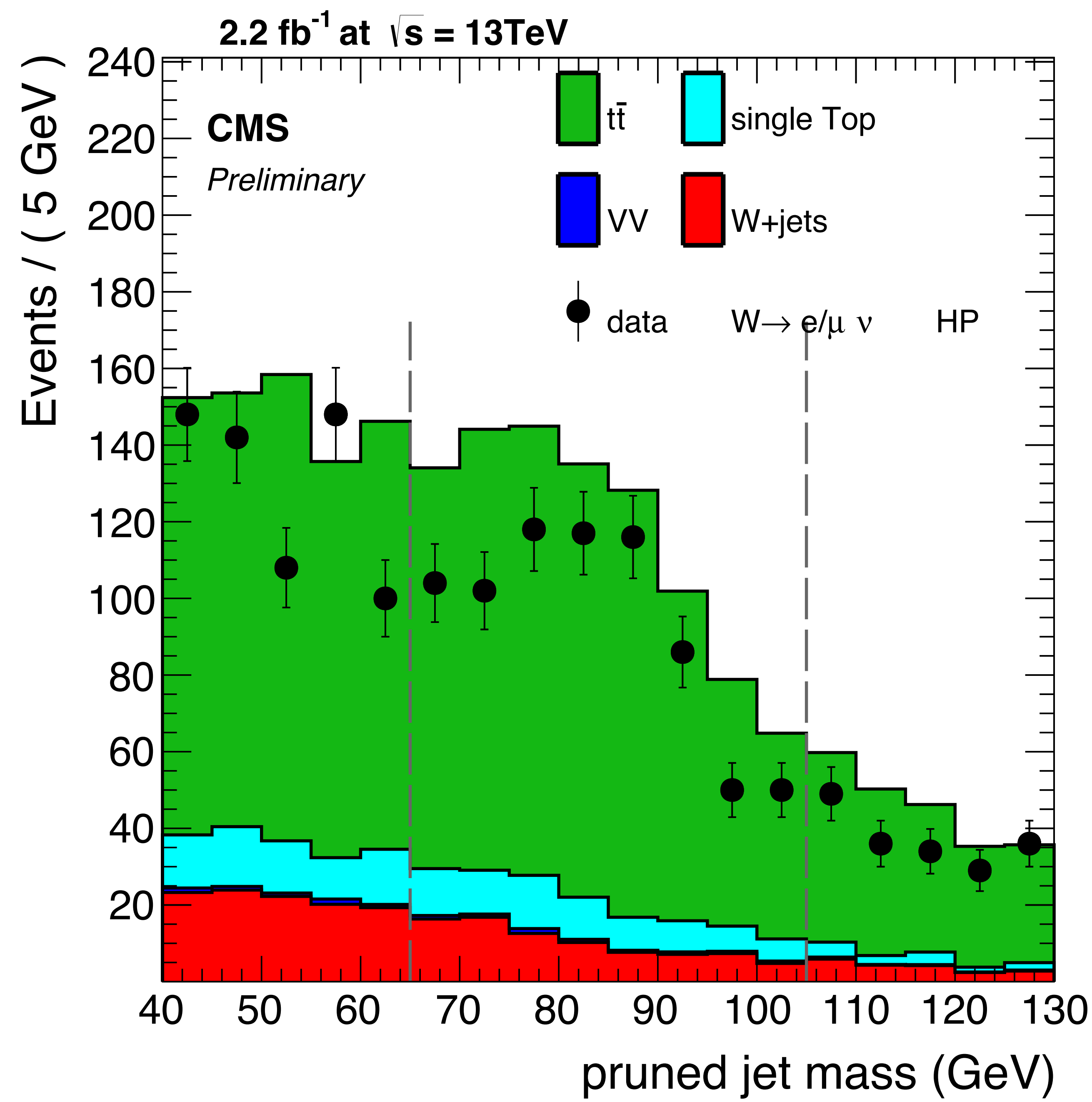


Step 2: Decluster the jet (how far?)



Calibration Of τ_{21} Efficiency





Signal Systematic Uncertainties

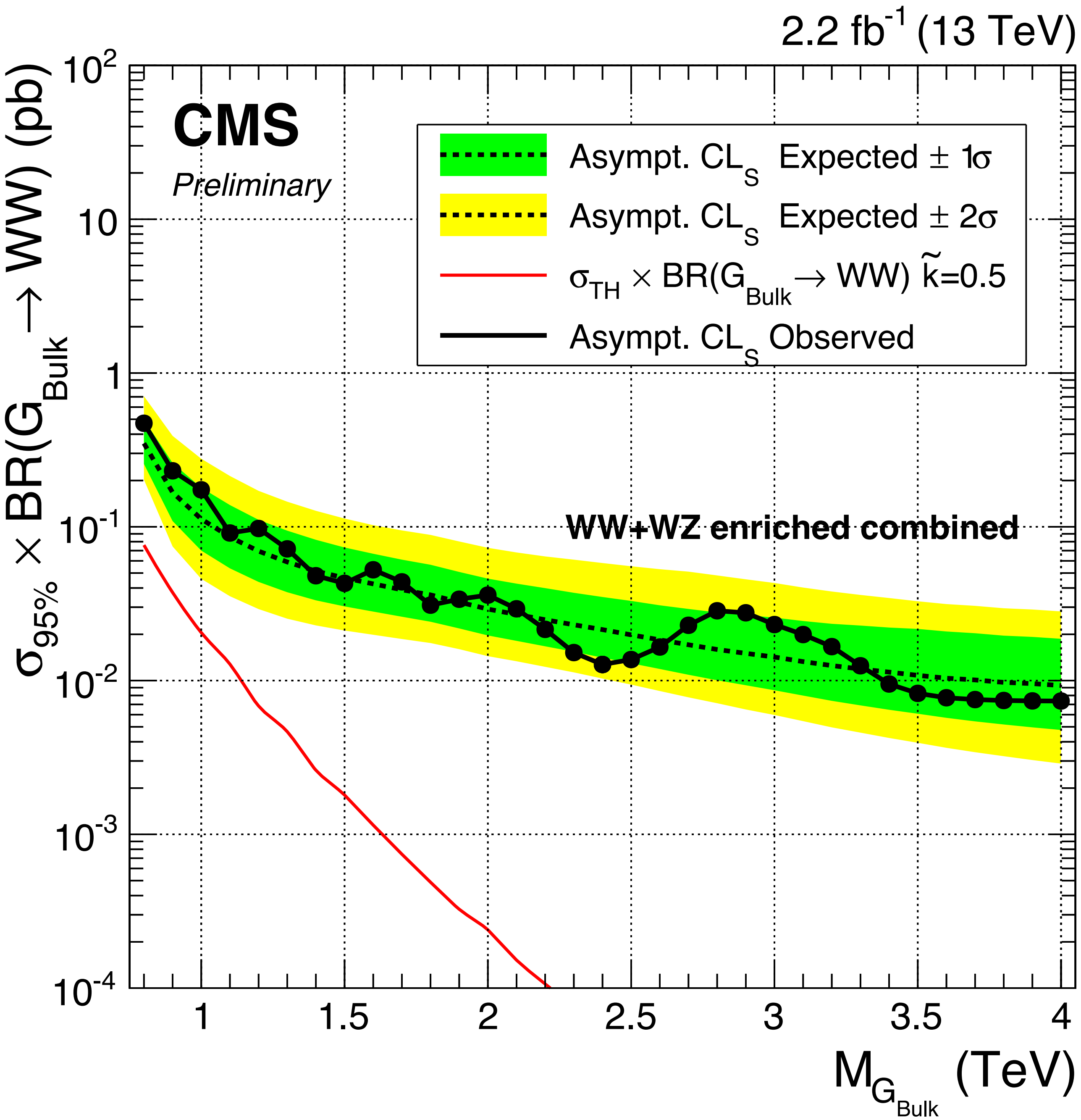
Source	Relevant quantity	$\mu\nu$+jet uncertainty	$e\nu$+jet uncertainty
Lepton trigger	Signal yield	1%	1%
Lepton identification	Signal yield	1%	3%
Jet energy scale	Signal yield	See Tab. 6	
Jet energy scale	Resonance shape (mean)	1.3%	
Jet energy scale	Resonance shape (width)	[2%–3%]	
Jet energy resolution	Signal yield	See Tab. 6	
Jet energy resolution	Resonance shape (mean)	0.1%	
Jet energy resolution	Resonance shape (width)	4%	
Integrated luminosity	Signal yield	4.6%	
PDF uncertainties (W′)	Signal yield	[0.5%–8.5%]	
PDF uncertainties (G_{bulk})	Signal yield	[10%–45%]	
W-tagging τ_{21} (HP/LP)	Migration	13%/49%	

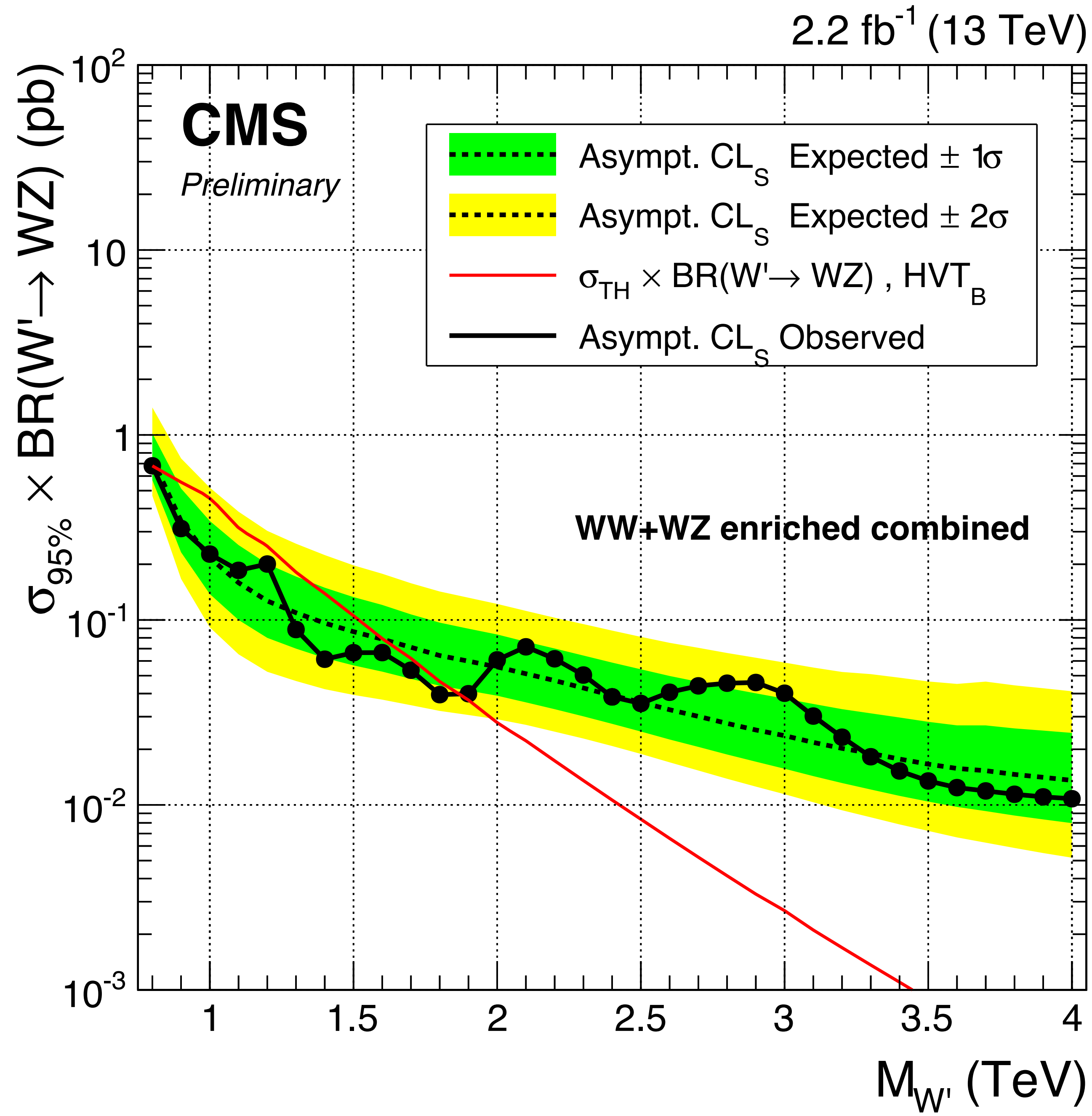
Source	G_{bulk} signal normalisation		W′ signal normalisation	
	WW-enriched	WZ-enriched	WW-enriched	WZ-enriched
Jet Energy Scale	−[4%–7%] +[3%–5%]	+[16%–33%] −[15%–27%]	−[11%–15%] +[14%–17%]	+[3%–9%] −[4%–12%]
Jet Energy Resolution	<0.1%		<0.1%	
Jet Mass Scale	−[4%–10%] +[3%–9%]	+[16%–30%] −[16%–25%]	−[11%–16%] +[12%–20%]	+[1%–8%] −[3%–10%]
Jet Mass Resolution	−[2%–4%] +[2%–4%]	+[1%–12%] −[4%–11%]	−[1%–10%] +[2%–9%]	+[1%–5%] −[2%–4%]

Signal Systematic Uncertainties

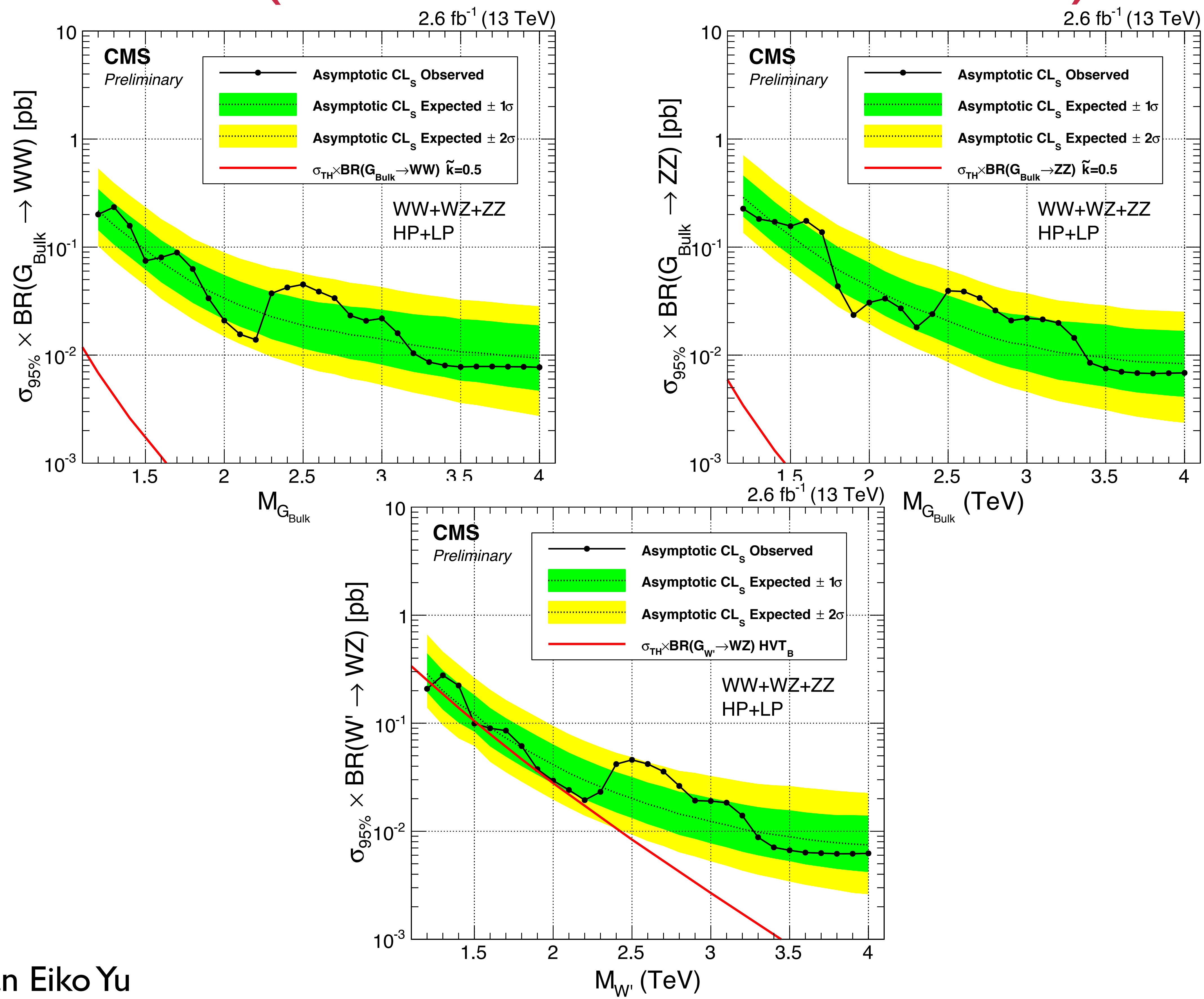
Source	Relevant quantity	HP+HP uncertainty	HP+LP uncertainty
Jet energy scale	Resonance shape	2%	2%
Jet energy resolution	Resonance shape	10%	10%
Jet energy and m_{jet} scale	Signal yield	[0.4%–1.5%]	[0.1%–1.7%]
Jet energy and m_{jet} resolution	Signal yield	[0.1%–1.3%]	[0.1%–1.4%]
Pileup	Signal yield	2%	2%
Integrated luminosity	Signal yield	4.6%	4.6%
Jet energy and m_{jet} scale	Migration	[1%–46%]	[1%–55%]
W-tagging τ_{21}	Migration	44%	14%
W-tagging p_{T}-dependence	Migration	3.6%	6%

Limits (Semileptonic Channel)

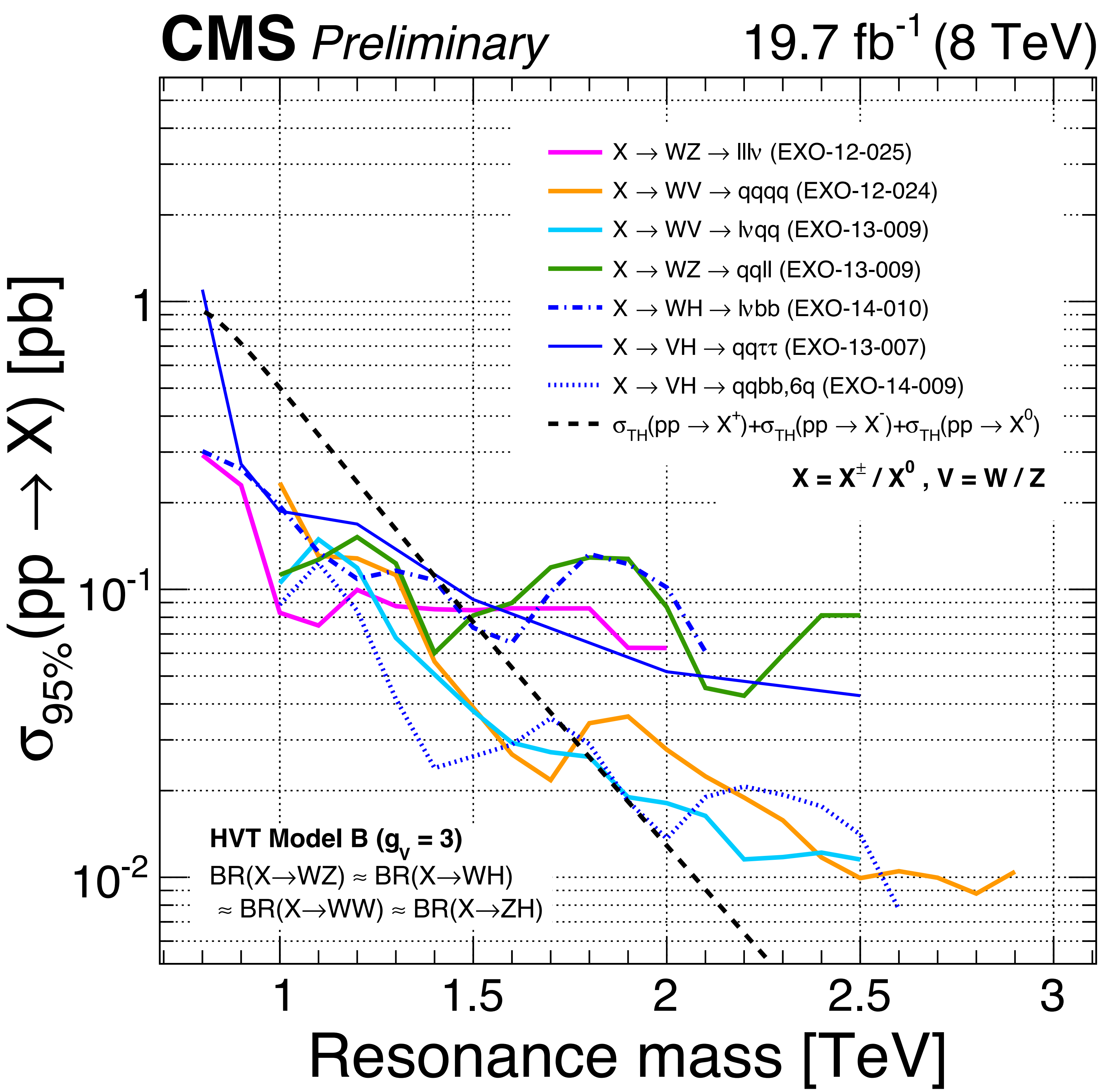




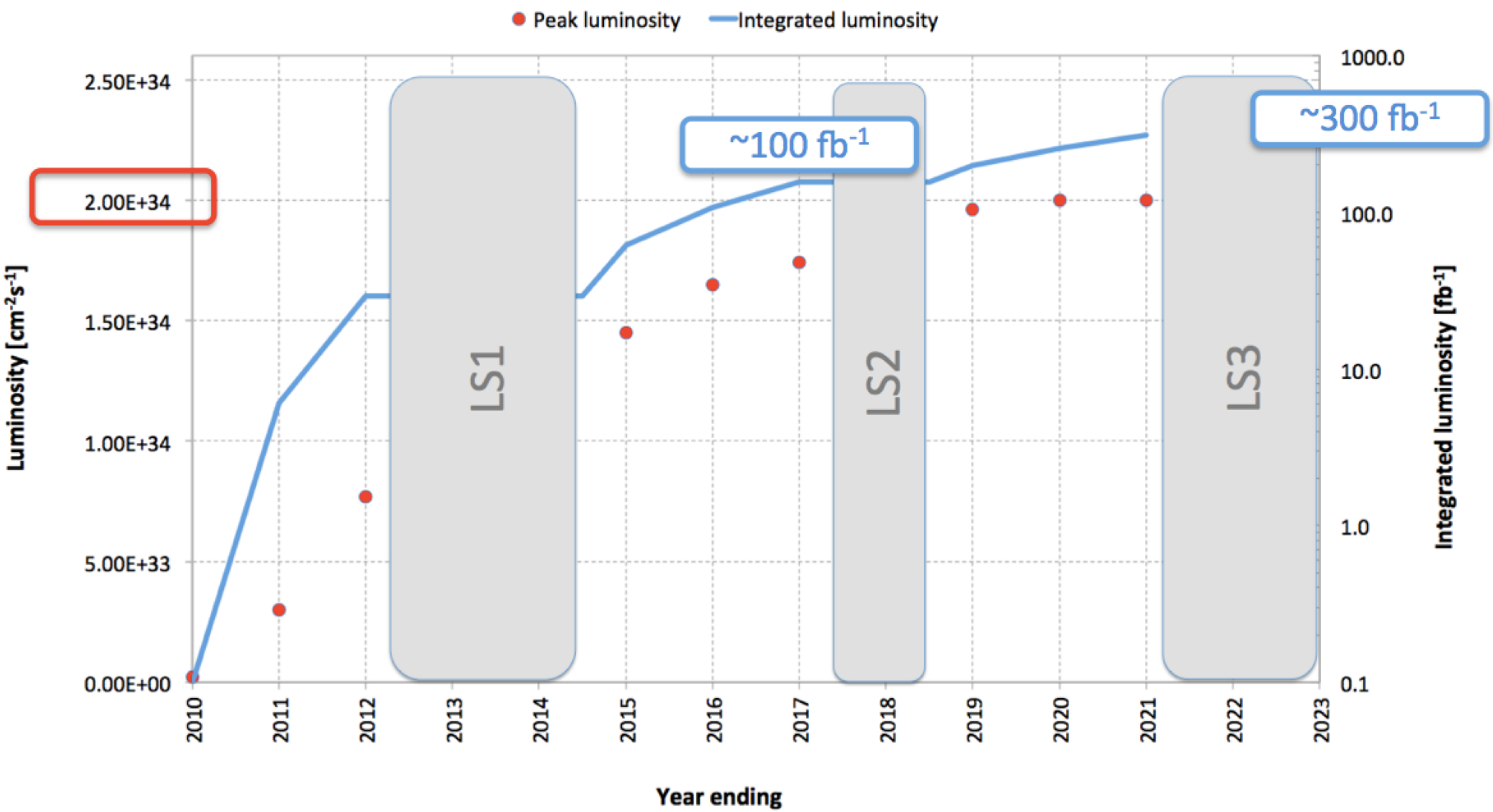
Limits (All Hadronic Channel)



Comparison Of Diboson

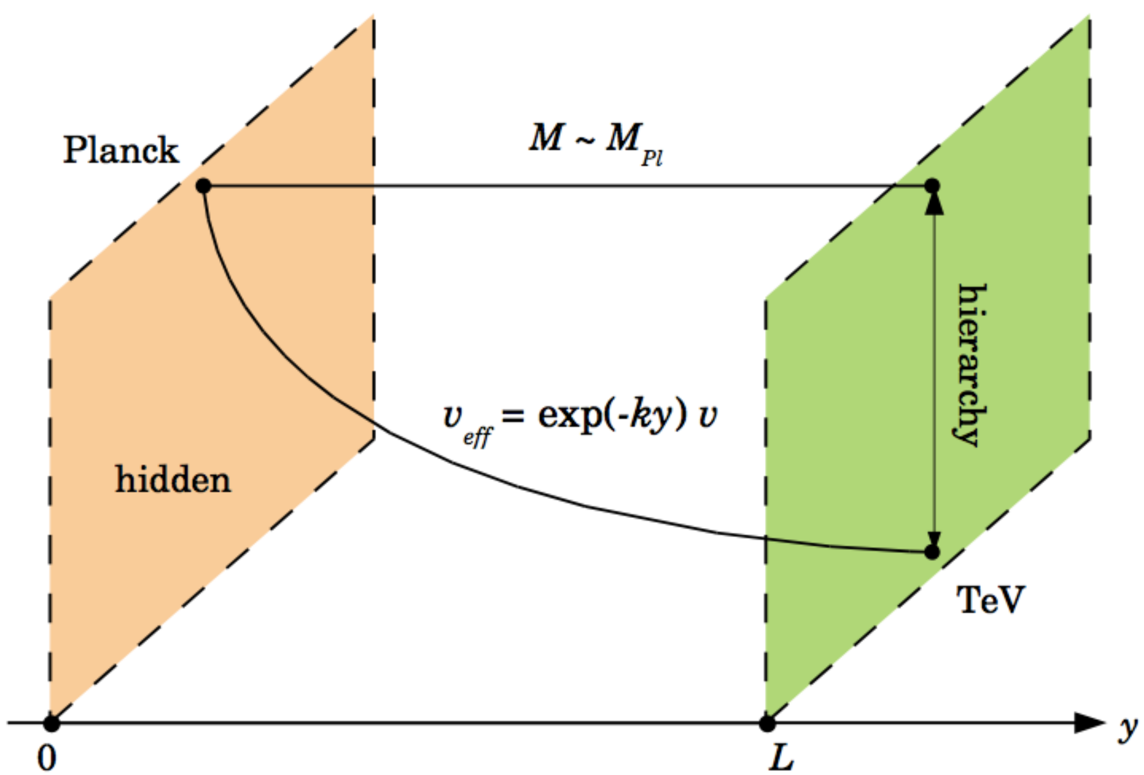


Evolution Of LHC Data



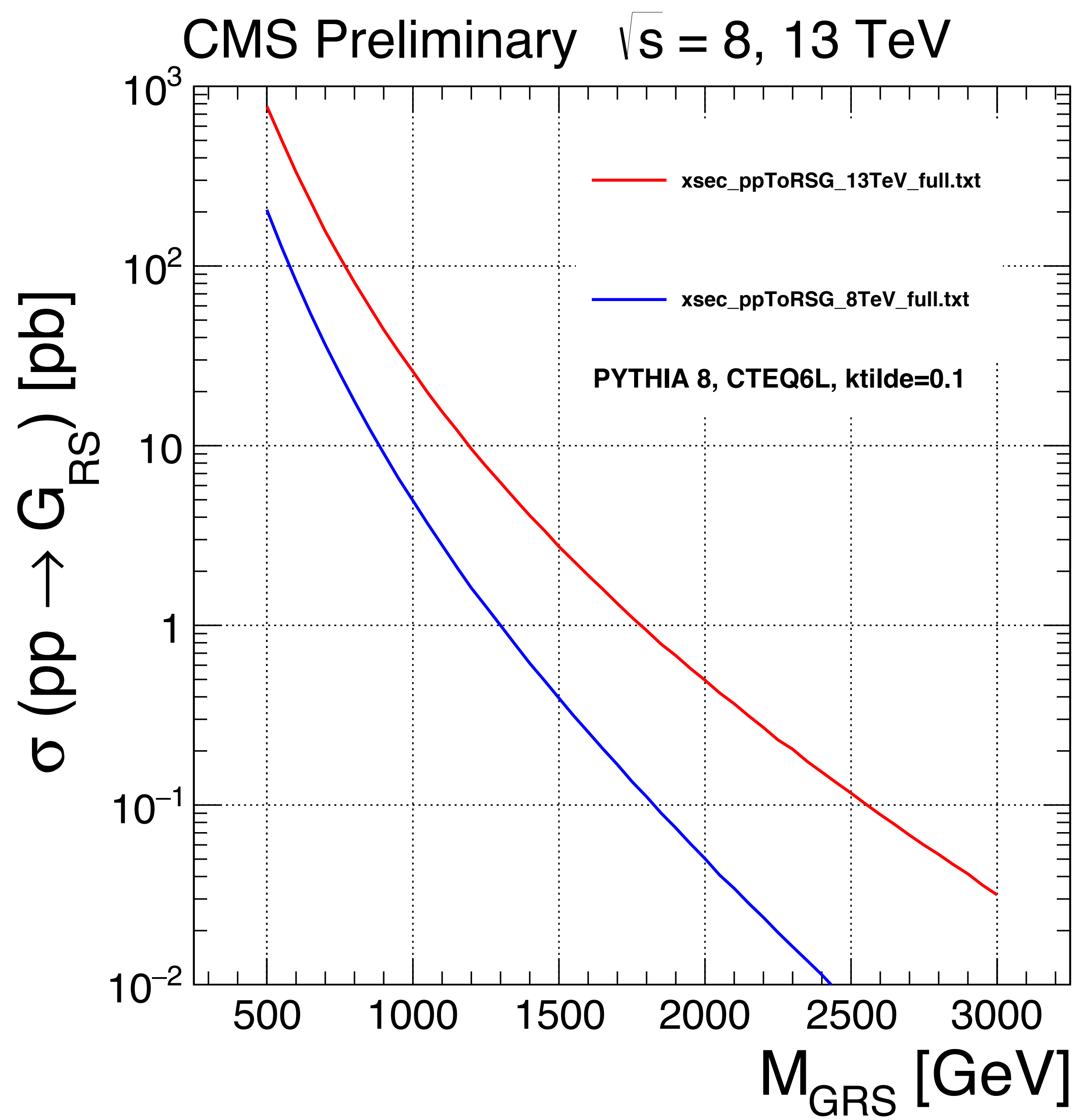
RS Graviton Model

$$k/\overline{M}_{Pl} = \sqrt{8\pi}k/(M_{Pl})$$

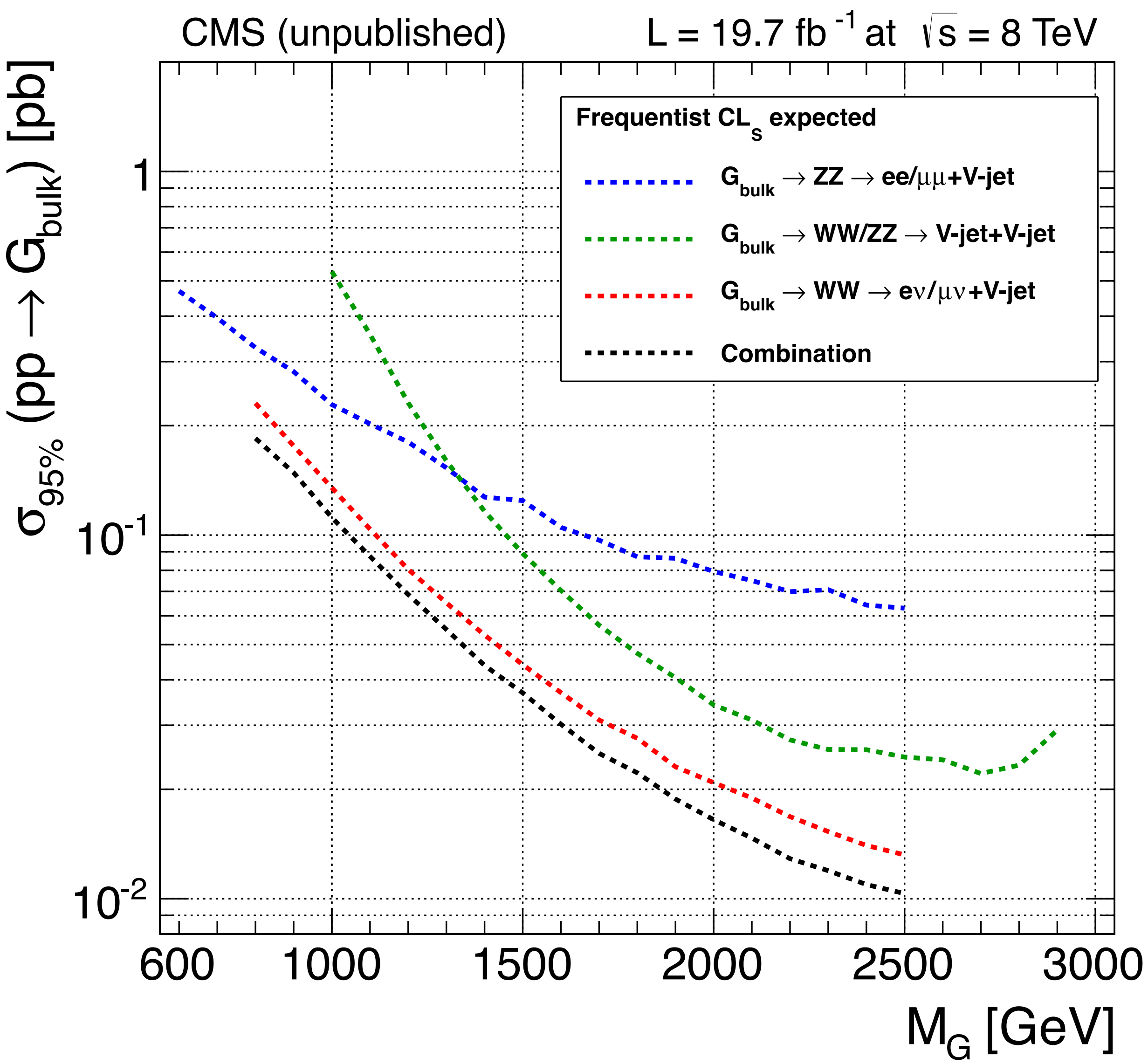


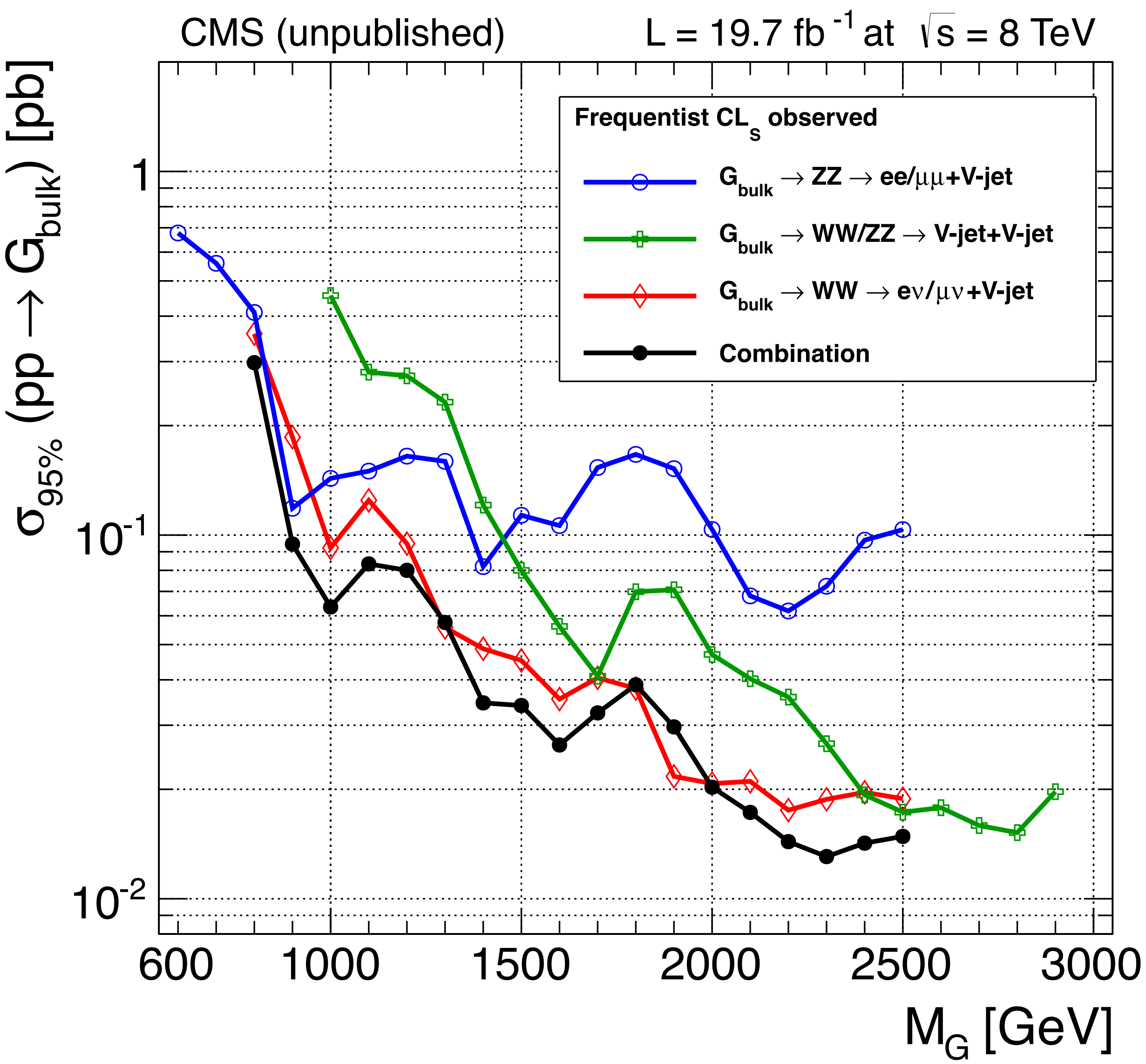
$BR(G \to WW) = 15\%$

$BR(G \to ZZ) = 7\%$



Combined With All-Hadronic Mode





Signal Width From Models

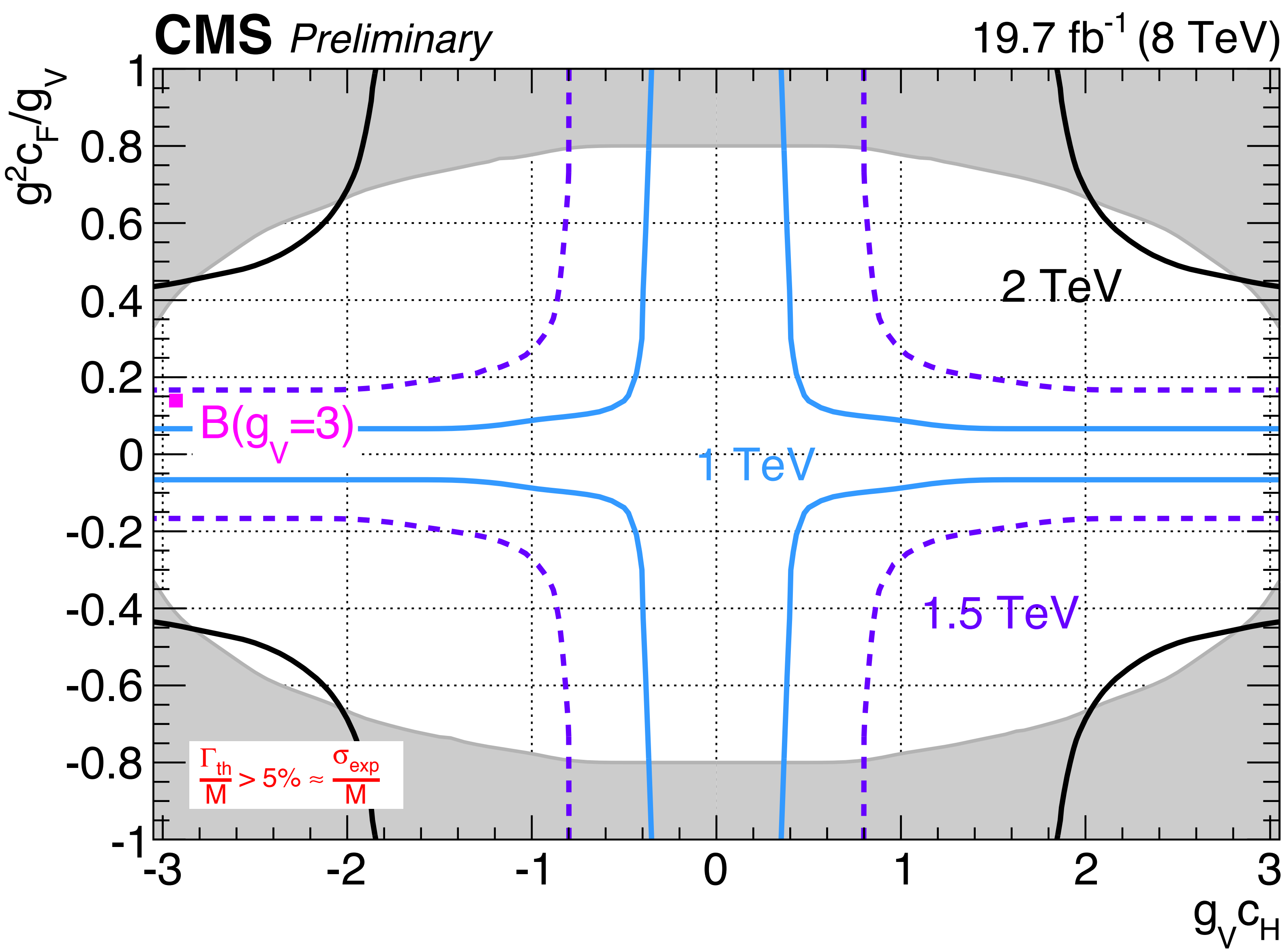
Resonance mass [GeV]	Little Higgs		HVT_B	
	Γ [GeV]	σ [pb]	Γ [GeV]	σ [pb]
800	7.22	5.09×10^{-1}	24.08	3.37×10^{-1}
900	8.12	3.03×10^{-1}	27.10	2.48×10^{-1}
1000	9.02	1.87×10^{-1}	30.11	1.71×10^{-1}
1100	9.92	1.18×10^{-1}	33.12	1.16×10^{-1}
1200	10.83	7.65×10^{-2}	36.13	8.05×10^{-2}
1300	11.73	5.06×10^{-2}	39.14	5.59×10^{-2}
1400	12.63	3.39×10^{-2}	42.15	3.88×10^{-2}
1500	13.53	2.29×10^{-2}	45.16	2.51×10^{-2}
1600	14.44	1.56×10^{-2}	48.17	1.87×10^{-2}
1700	15.34	1.08×10^{-2}	51.18	1.30×10^{-2}
1800	16.24	7.43×10^{-3}	54.19	9.03×10^{-3}
1900	17.14	5.17×10^{-3}	57.20	6.27×10^{-3}
2000	18.05	3.61×10^{-3}	60.21	4.25×10^{-3}
2100	18.95	2.53×10^{-3}	63.22	3.02×10^{-3}
2200	19.85	1.76×10^{-3}	66.23	2.10×10^{-3}
2300	20.75	1.24×10^{-3}	69.24	1.46×10^{-3}
2400	21.65	8.67×10^{-4}	72.25	1.01×10^{-3}
2500	22.56	6.07×10^{-4}	75.27	7.31×10^{-4}

Exclusion Of HVT Parameters

g_V : typical strength

C_H : interaction with Higgs

C_q : interaction with fermions



Jet Definition

These are hierarchical clustering algorithms

Typically they work by calculating a **'distance'** between particles, and then recombine them pairwise according to a given order, until some condition is met (e.g. no particles are left, or the distance crosses a given threshold)

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta y^2 + \Delta \phi^2}{R^2} \qquad d_{iB} = k_{ti}^{2p}$$

If $d_{ij} < d_{iB}$ then merge them together

p = 1 k_t algorithm — S. Catani, Y. Dokshitzer, M. Seymour and B. Webber, Nucl. Phys. B406 (1993) 187; S.D. Ellis and D.E. Soper, Phys. Rev. D48 (1993) 3160

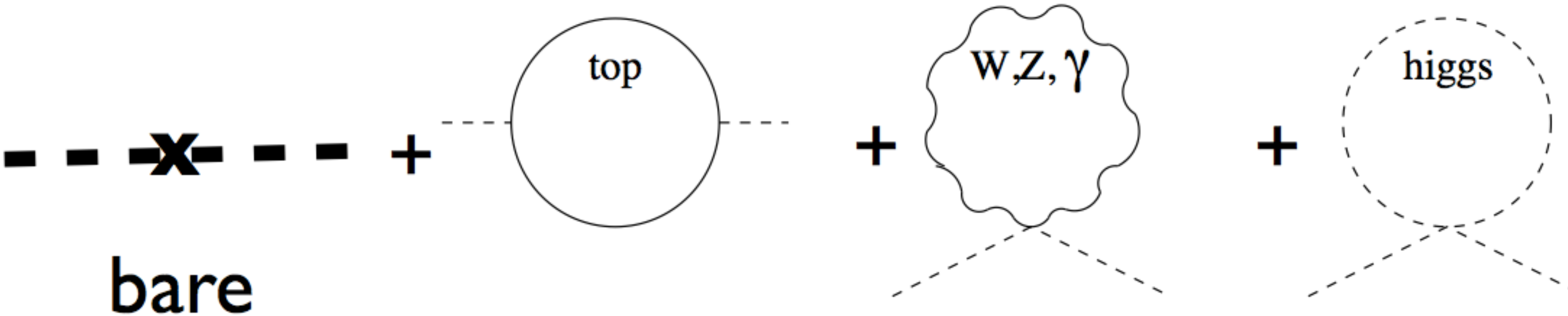
p = 0 Cambridge/Aachen algorithm — Y. Dokshitzer, G. Leder, S.Moretti and B. Webber, JHEP 08 (1997) 001; M.Wobisch and T.Wengler, hep-ph/9907280

p = -1 **anti-k_t algorithm** — MC, G. Salam and G. Soyez, arXiv:0802.1189

NB: in anti-kt pairs with a **hard** particle will cluster first: if no other hard particles are close by, the algorithm will give **perfect cones**

In this tutorial, we explore AK5 and CA8

Quantum Correction To Higgs



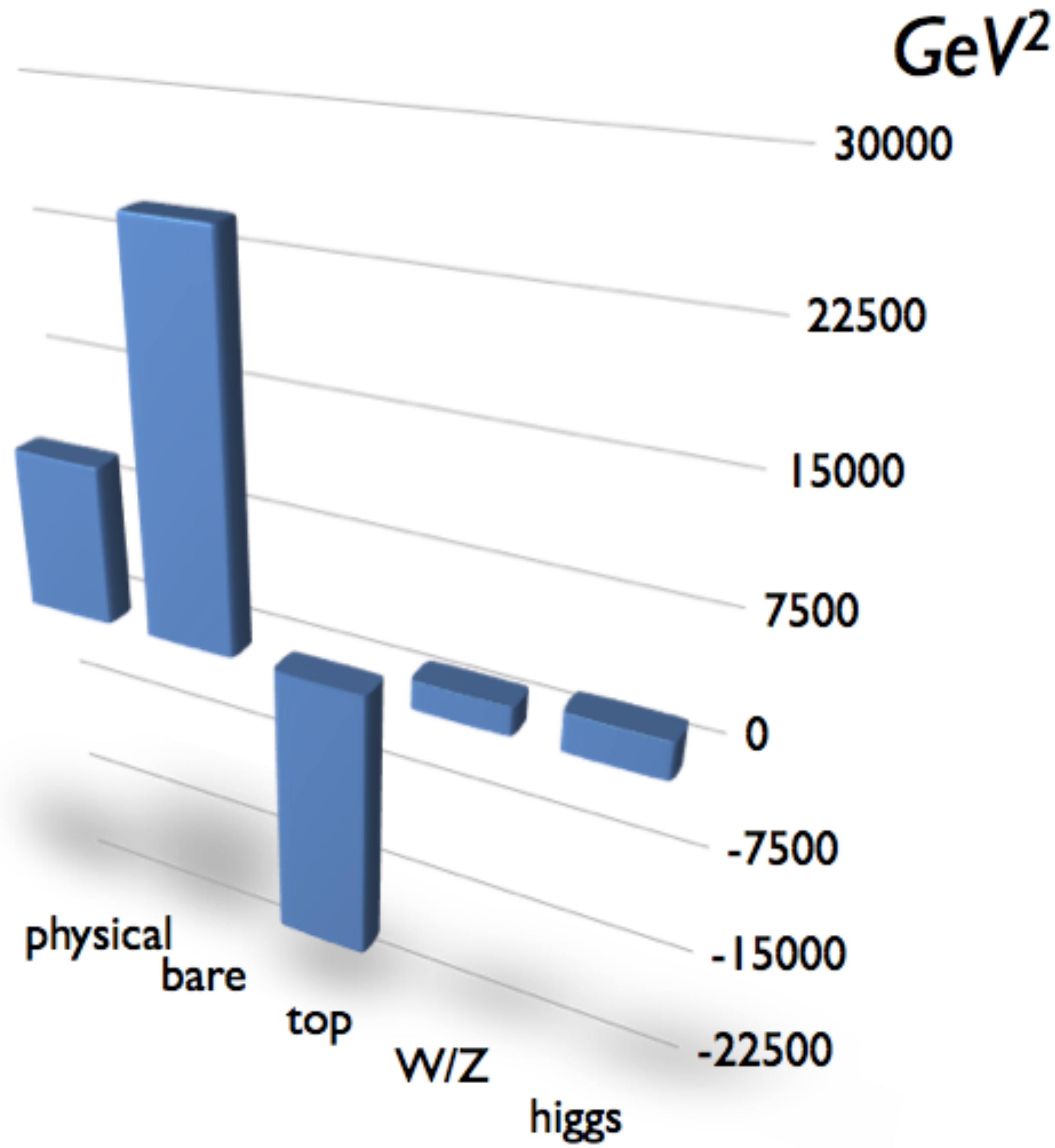
$-\frac{3}{8\pi^2}\lambda_t^2\Lambda^2$ $\quad \frac{9}{64\pi^2}g^2\Lambda^2$ $\quad \frac{1}{16\pi^2}\lambda^2\Lambda^2$

$$m_h^2(\text{physical}) = m_h^2(\text{bare}) + \sum_i a_i\Lambda^2$$

Andreas Weiler

Quantum Correction To Higgs Mass

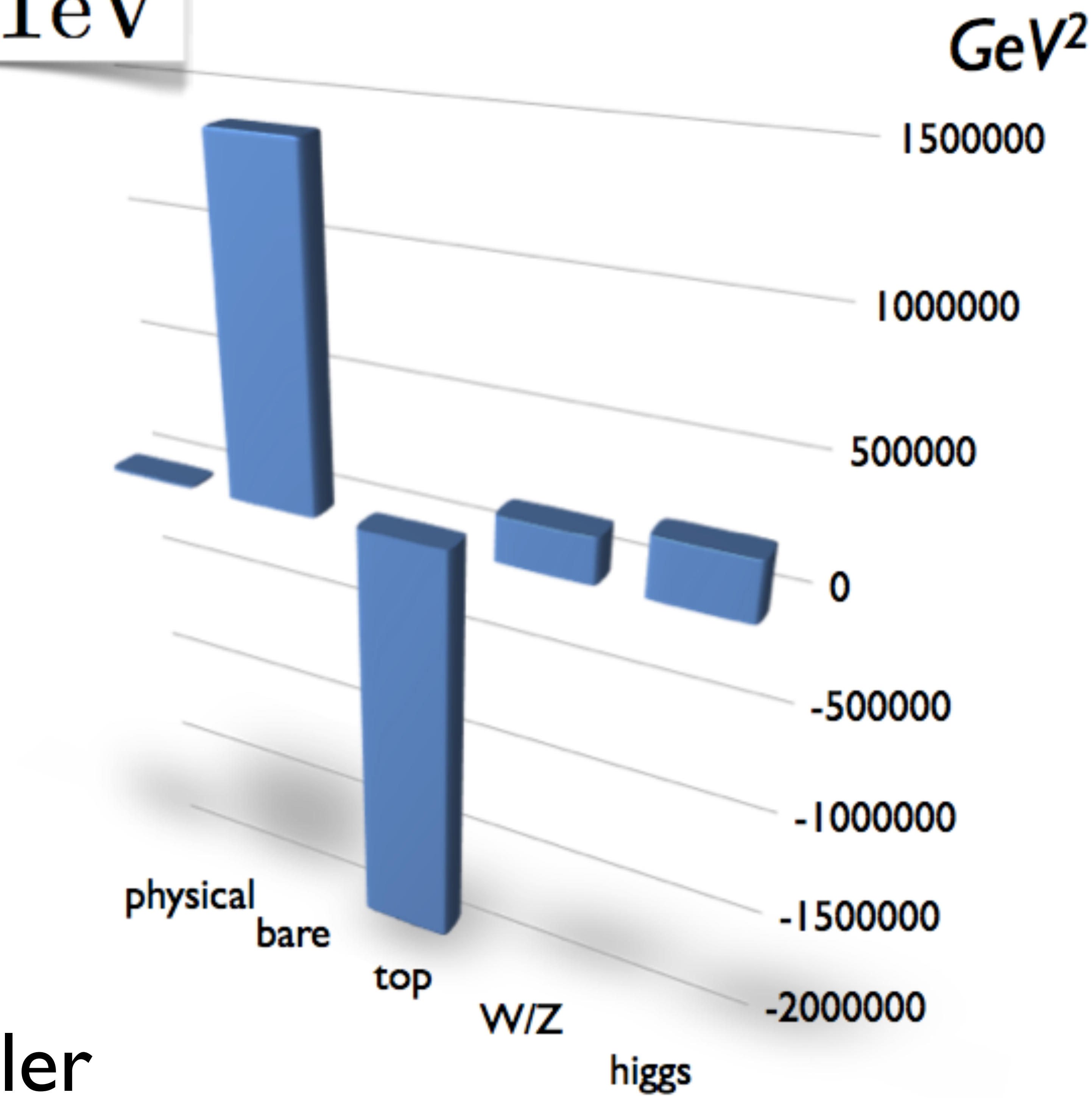
$\Lambda = 1\,\mathrm{TeV}$



Andreas Weiler

Quantum Correction To Higgs Mass

$\Lambda = 10\,\mathrm{TeV}$



Andreas Weiler