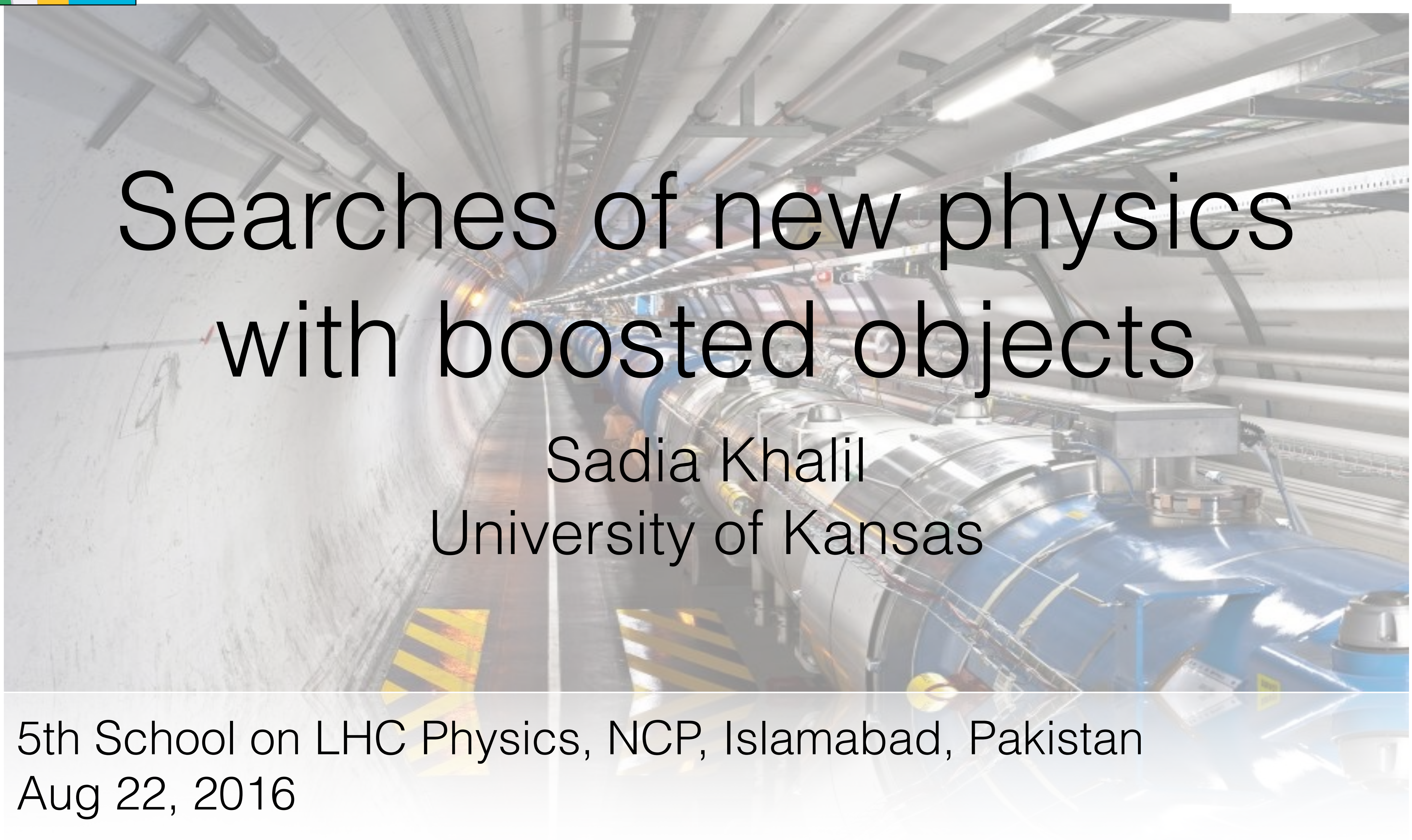


Searches of new physics with boosted objects

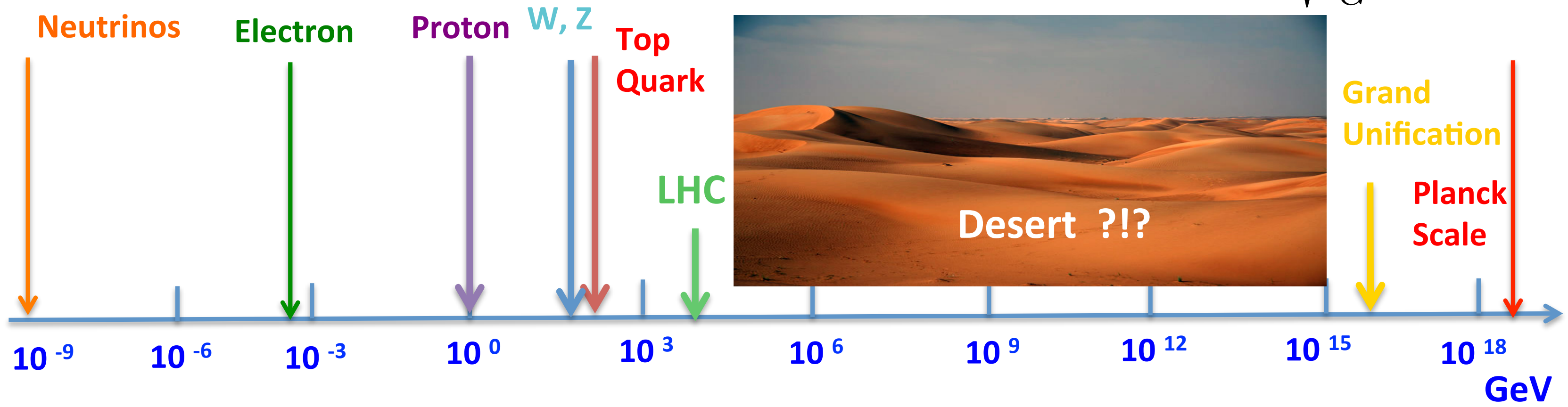
Sadia Khalil
University of Kansas

5th School on LHC Physics, NCP, Islamabad, Pakistan
Aug 22, 2016

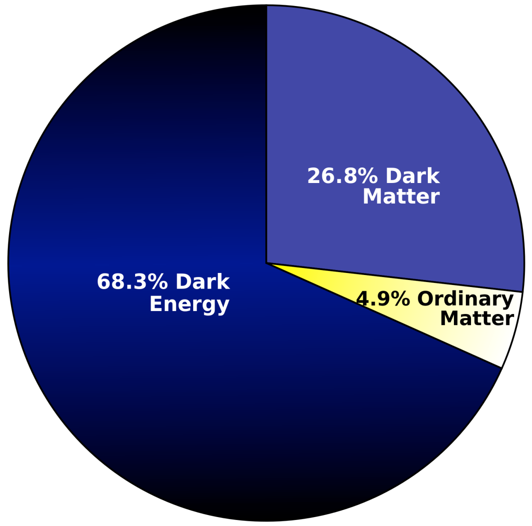
Unsolved problems in Standard Model

- Mass hierarchy
- Dark matter
- Gravity
- Baryogenesis
- Neutrino oscillations
- Strong Charge Parity
- …

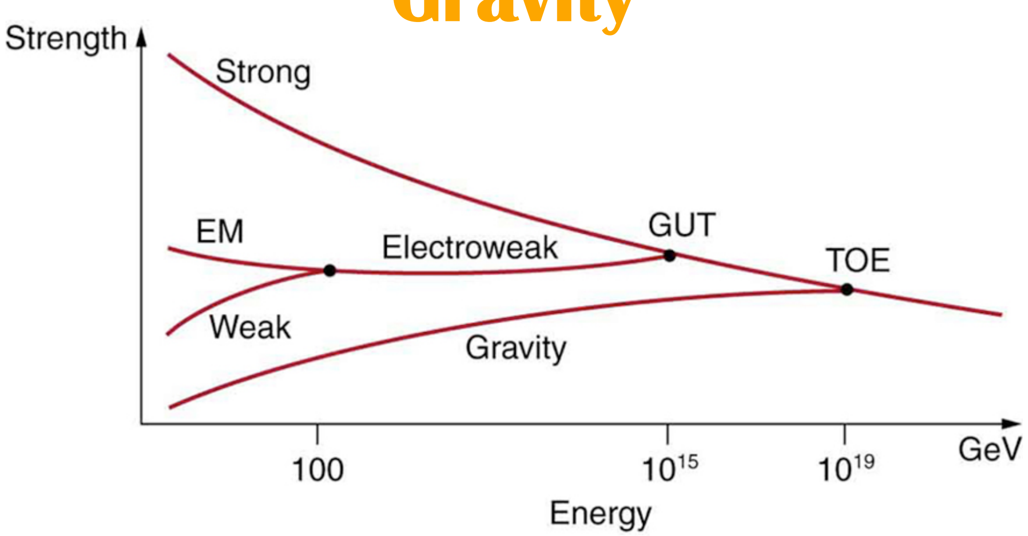
$$(m_h)_0 \approx M_{Pl} = \sqrt{\frac{hc}{G}} \approx 10^{19}\ \text{GeV}$$



Dark Matter

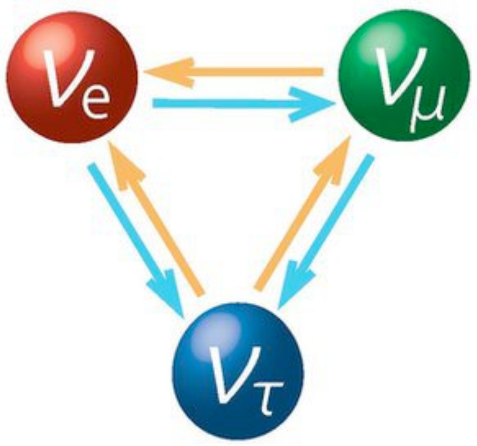


Gravity



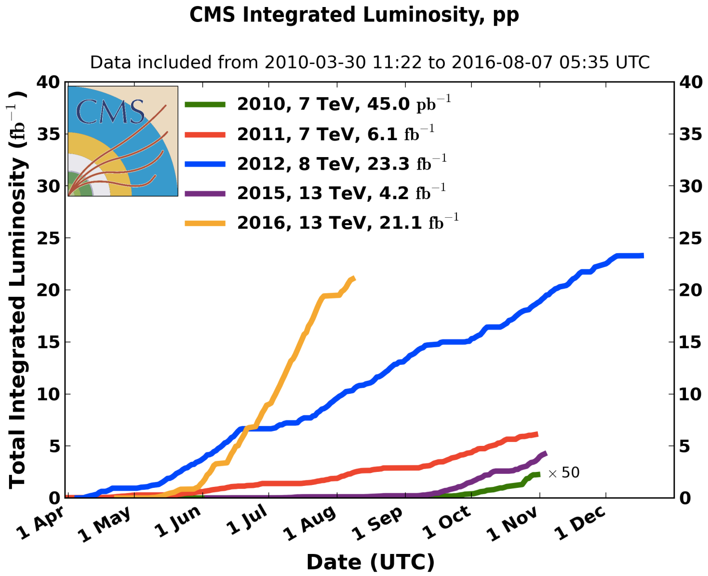
Baryogenesis

Neutrino Oscillations

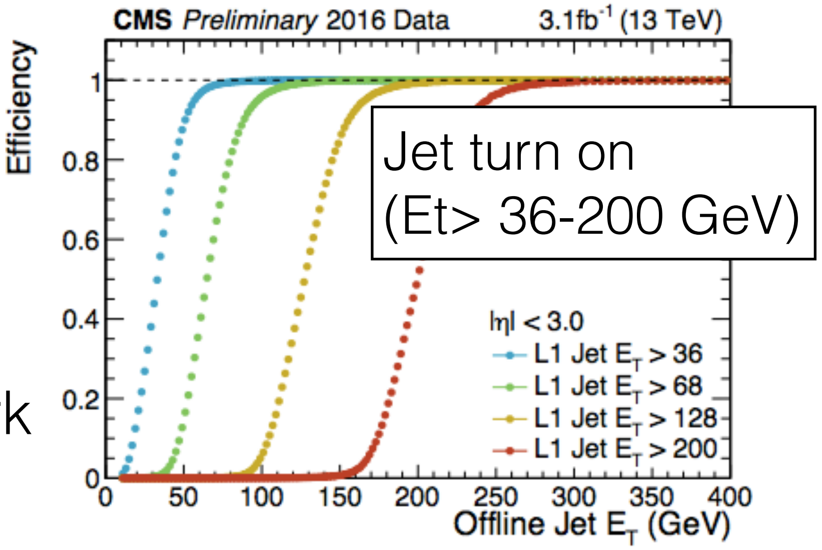


What is required for NP Searches?

- Detector and machine
  - Thanks to the accelerator teams of CERN, the LHC has exceeded even the most optimistic performance estimates



- Triggers
  - See talks by Ferdos Rezaei Hosseinabadi on L1 and HLT performance



- Understanding of SM backgrounds
  - See talks by Ferdos Rezaei Hosseinabadi related to top quark production x-section measurement

- New techniques to probe TeV scale
  - Jet Substructure tools ⇒top, Higgs, W/Z tagging
  - New discriminants (α_T, M_{T2}, S_T, $H_{T...}$), and smart algorithms (BDTs,…)

What is required for NP Searches?

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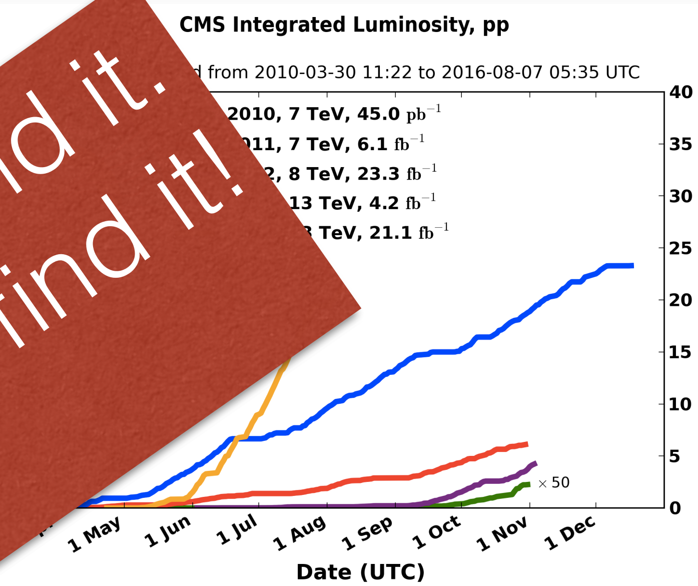
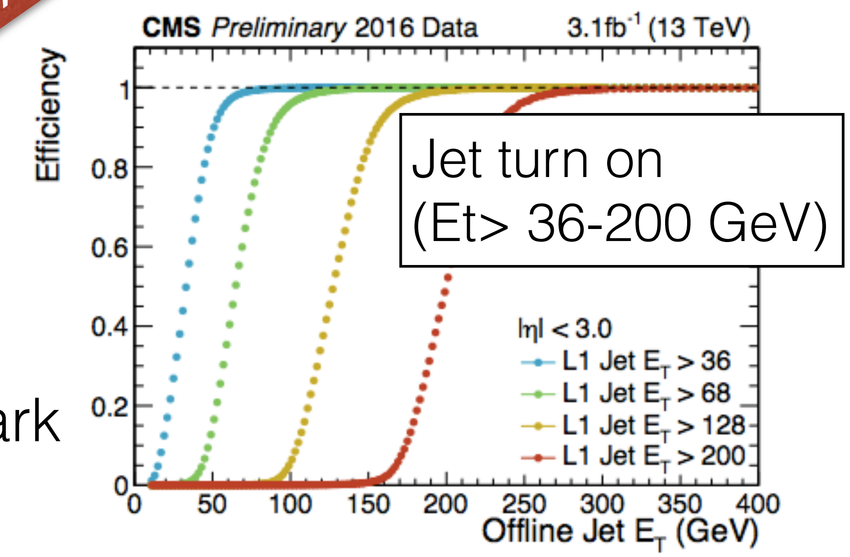
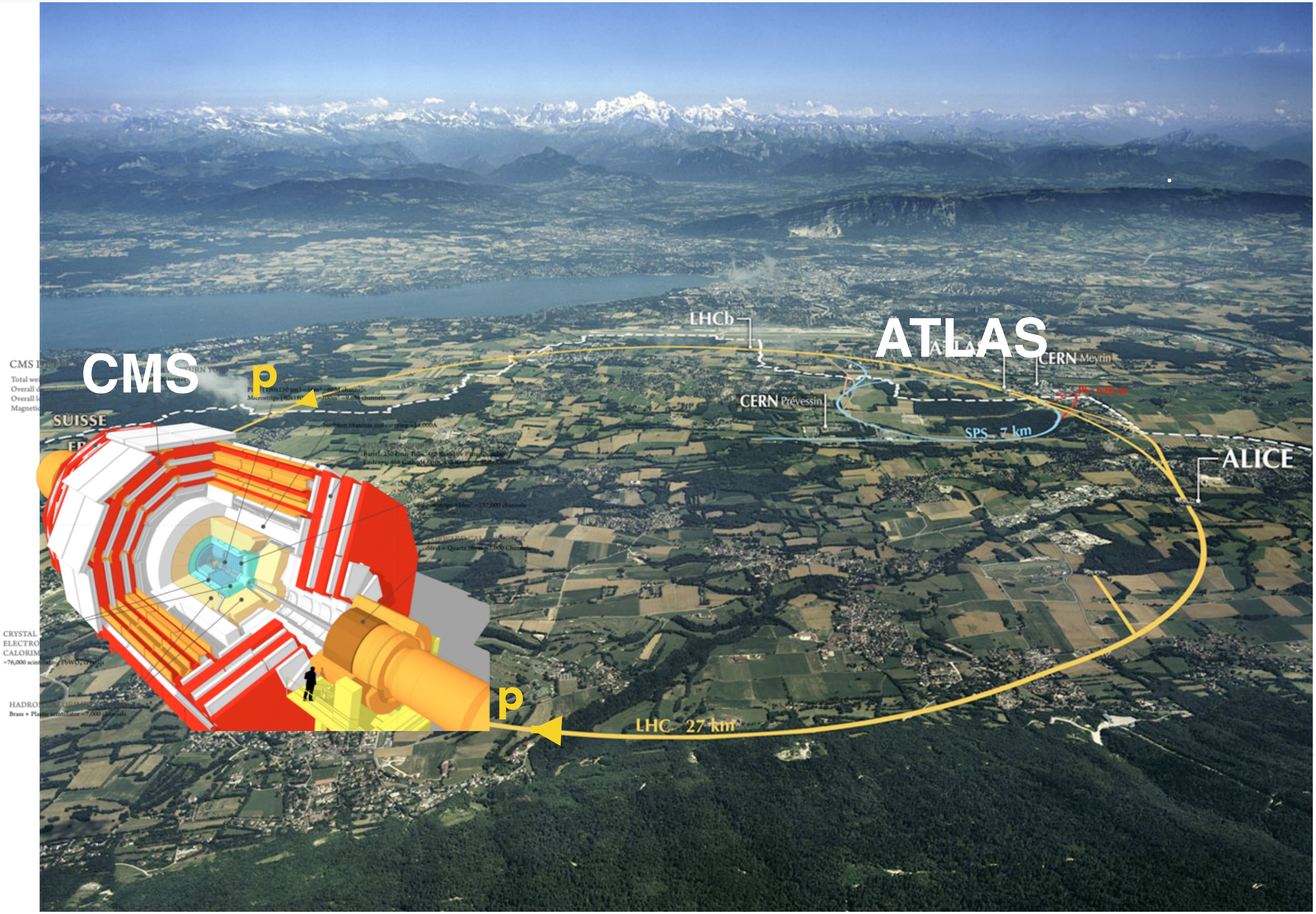
If you look for something, you may find it.
But if you don't look, you will never find it!
(Claudio Campanari)

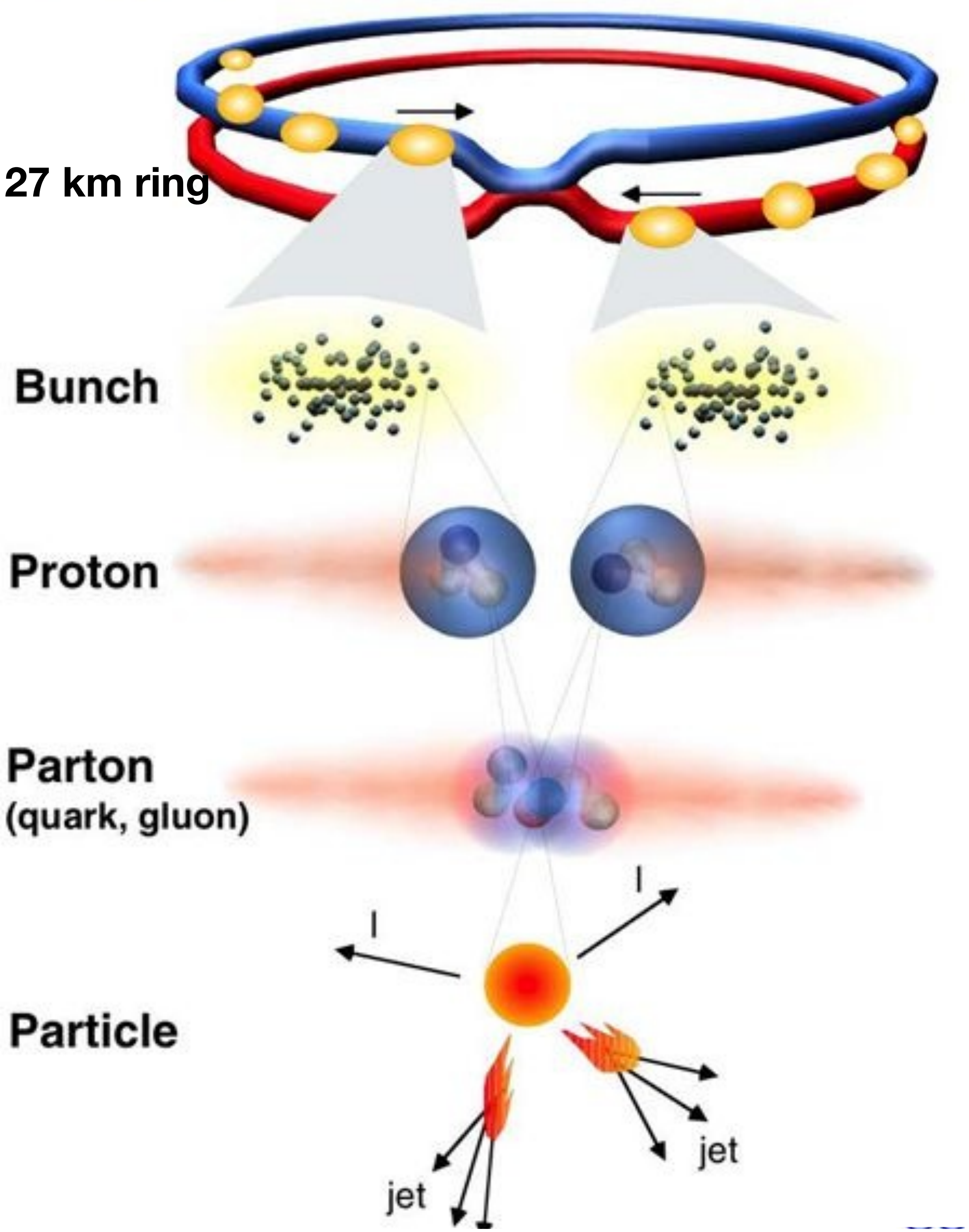




LHC Collider



LHC Collider

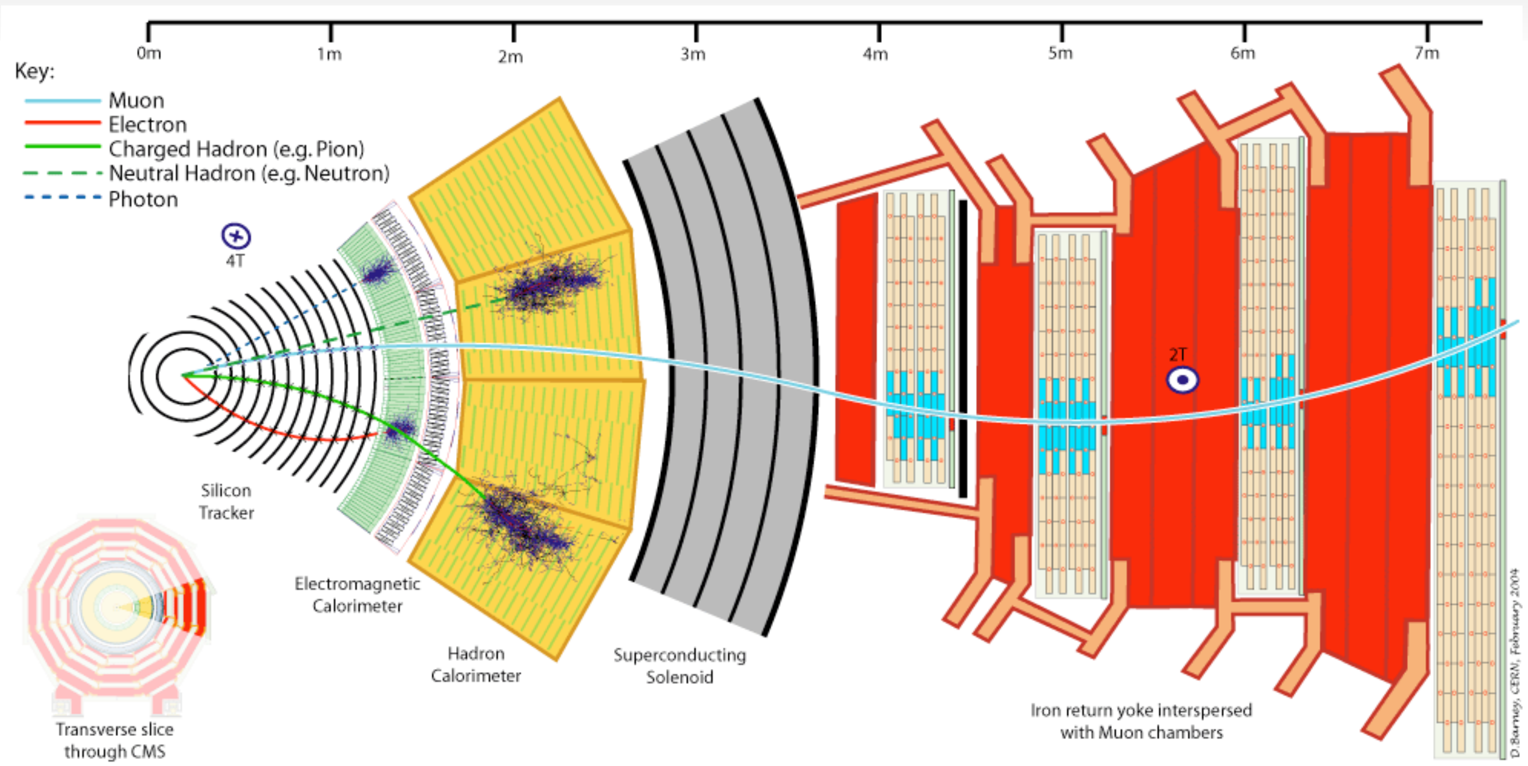


- Largest ever built collider in the world near Geneva, Switzerland
- Proton-Proton 2808 bunch/beam
- Protons/bunch = 1.2×10^{11}
- Beam energy = 13 TeV = 13×10^{12} eV
- Luminosity = 10^{34} cm^{-2} s^{-1}
- Crossing rate = 40 MHz (25 ns)
- Collisions per second = 1 billion

With every bunch crossing 23 Minimum Bias events with ~1725 particles produced

selection of 1 in 10^{13}

Particle Detection

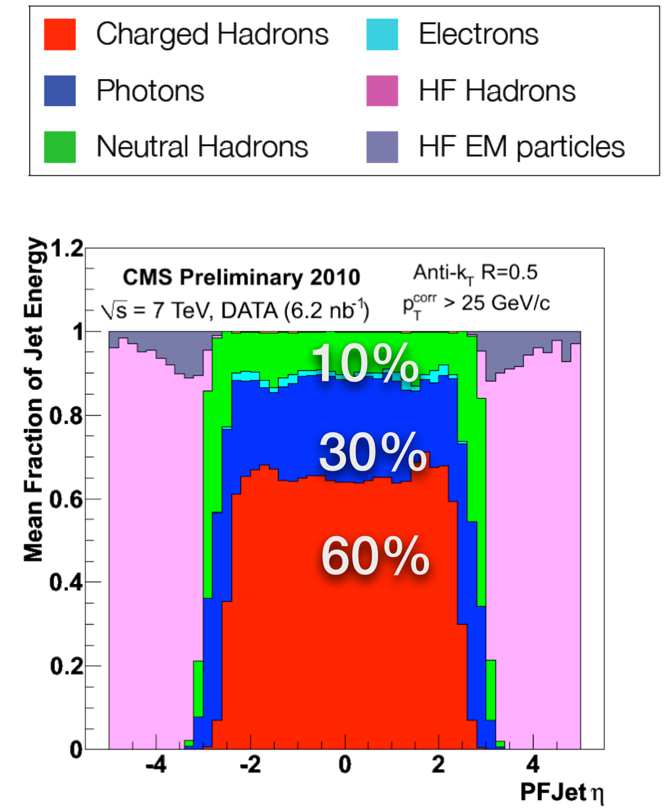


ECAL hits/ clusters, tracks

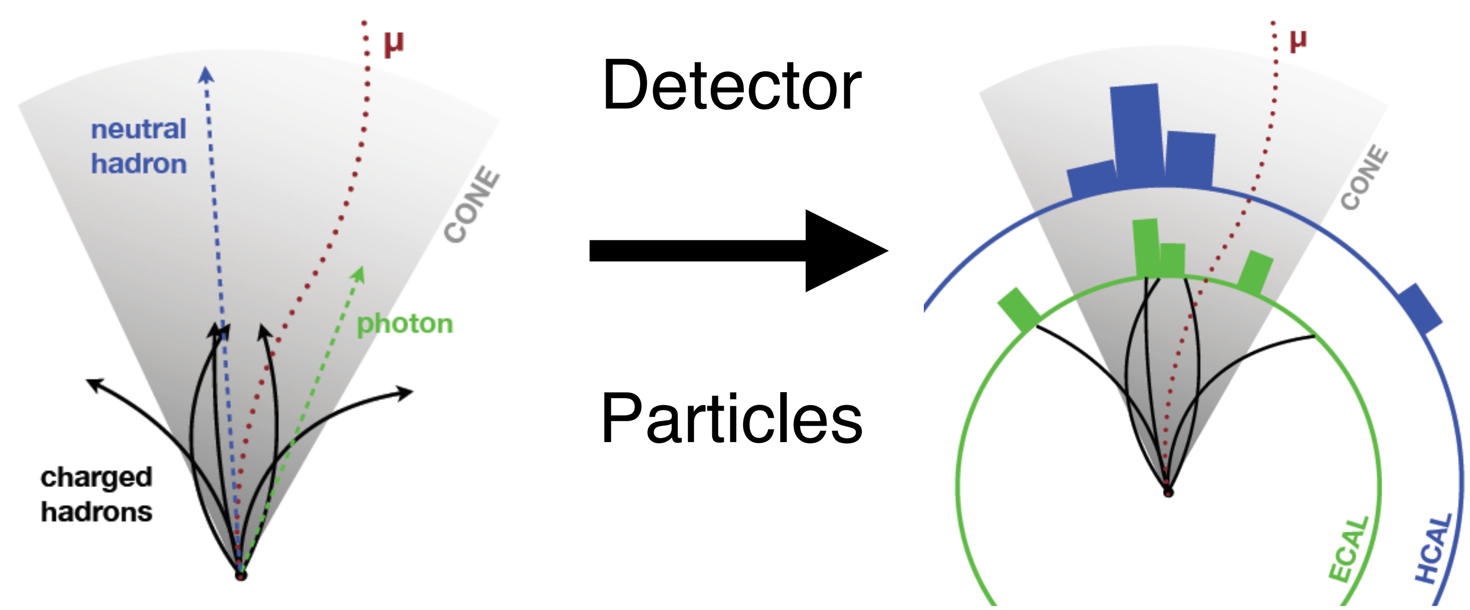
Tracks, ECAL, HCAL hits

reco Muon Tracks

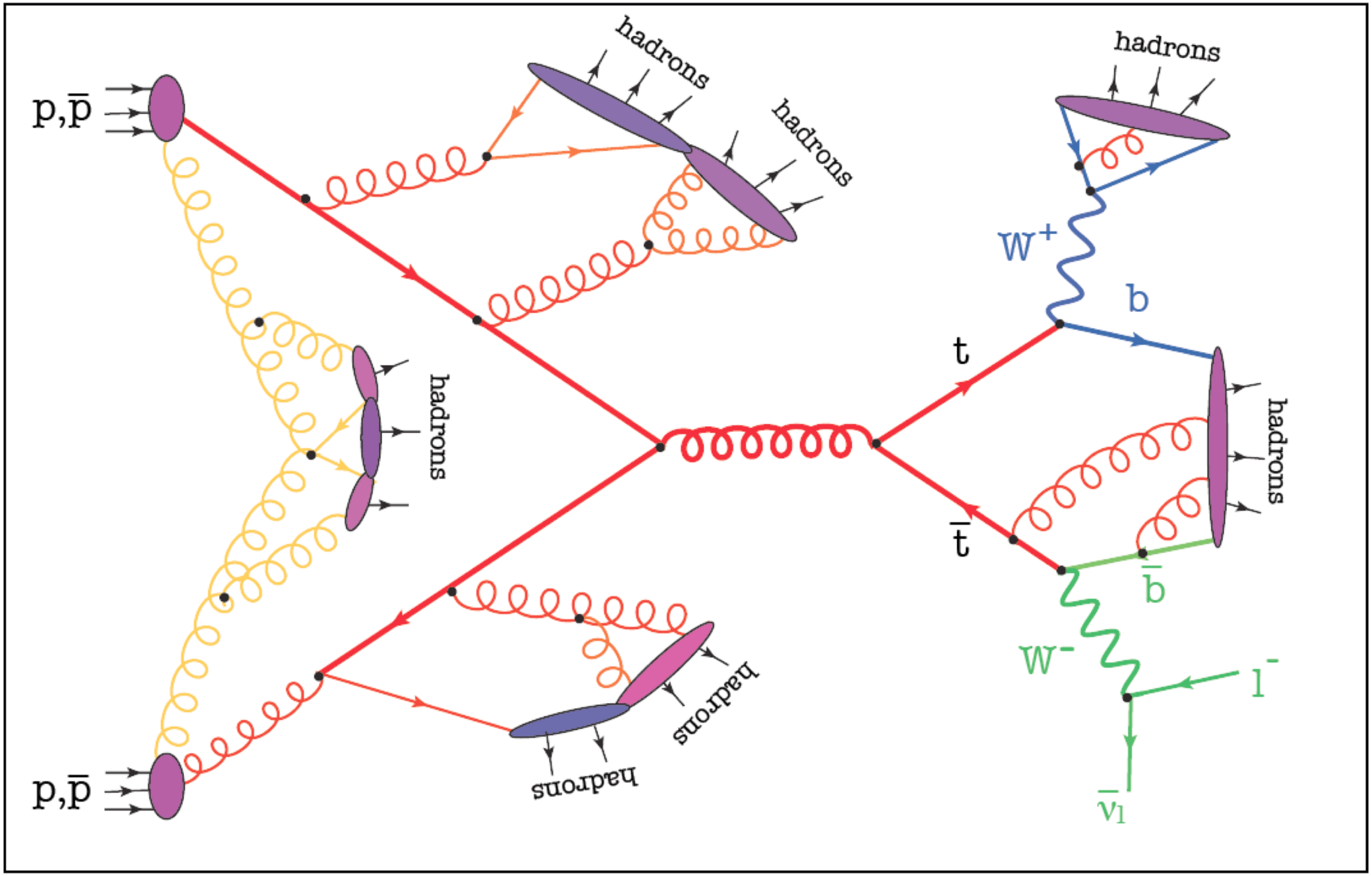
PF Jets composition



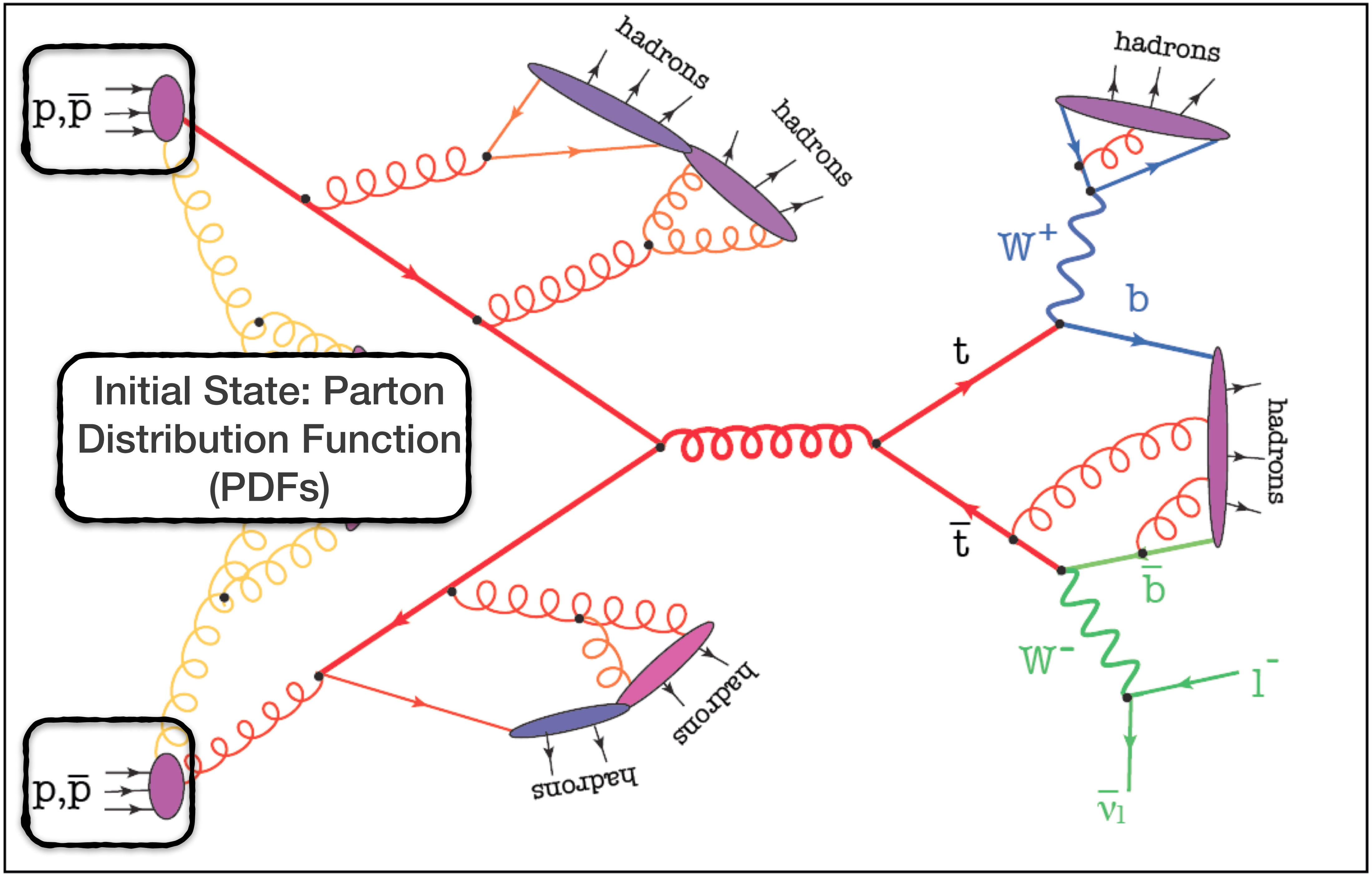
Particle Flow



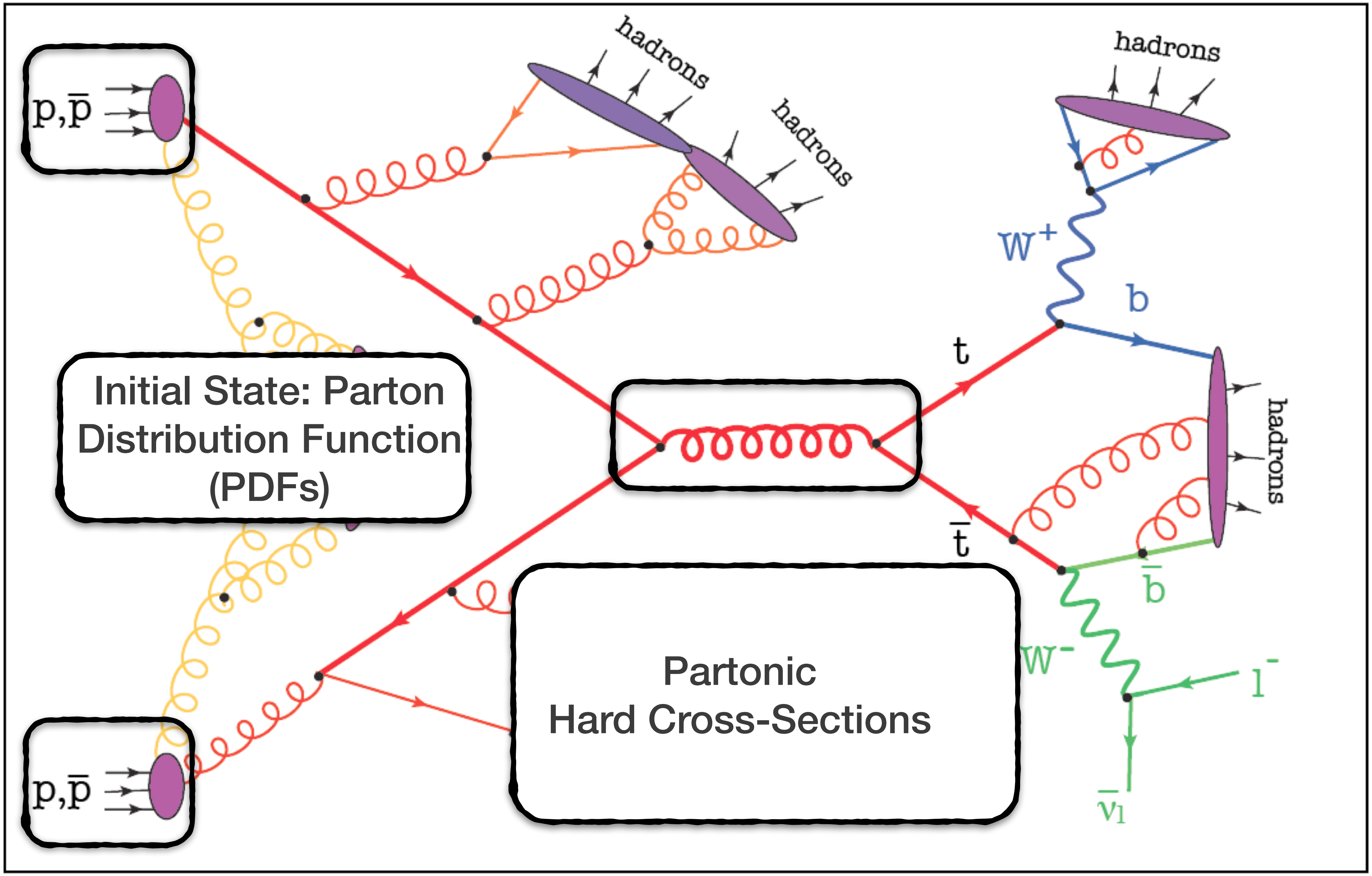
Particle Collision



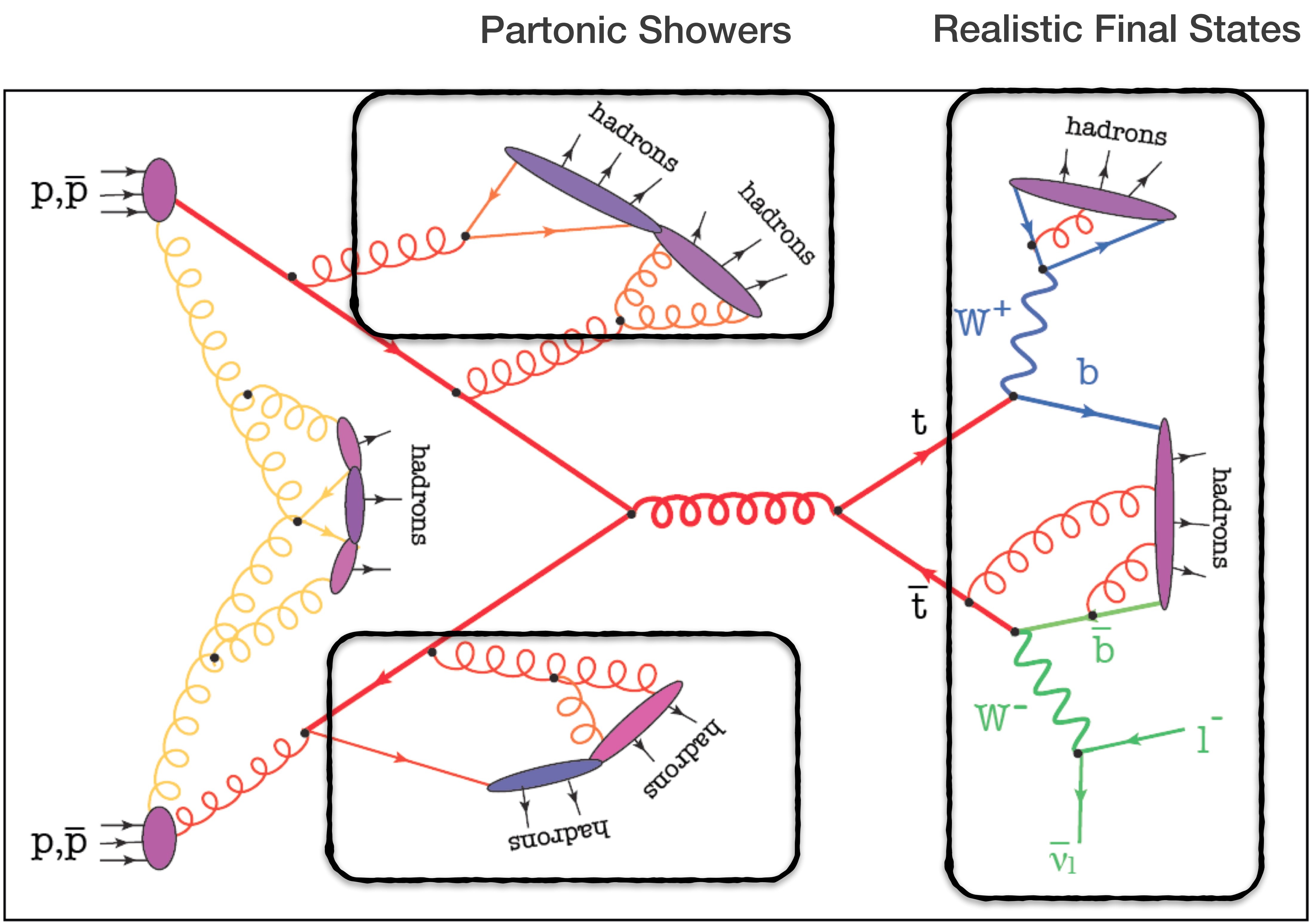
Particle Collision



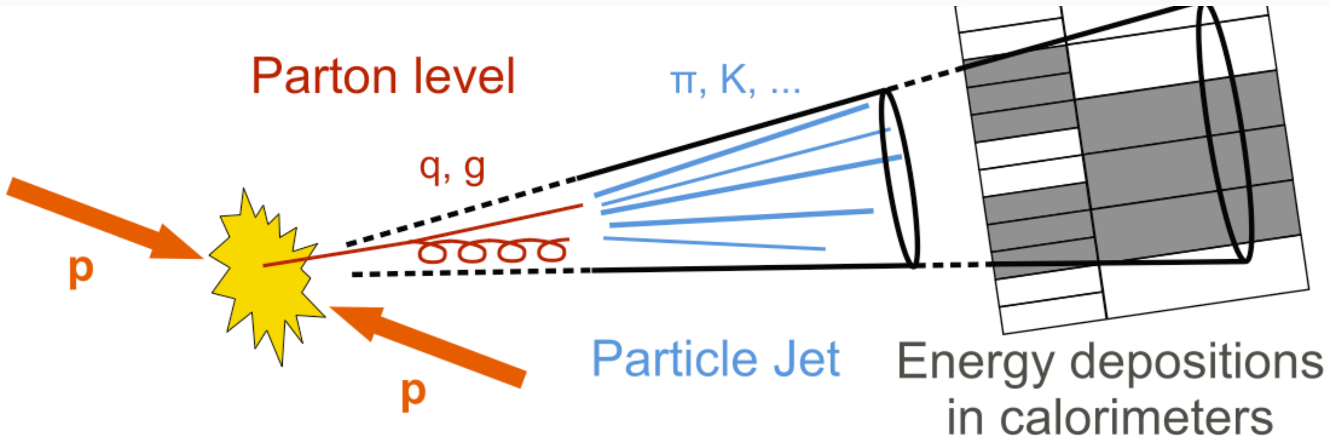
Particle Collision



Particle Collision

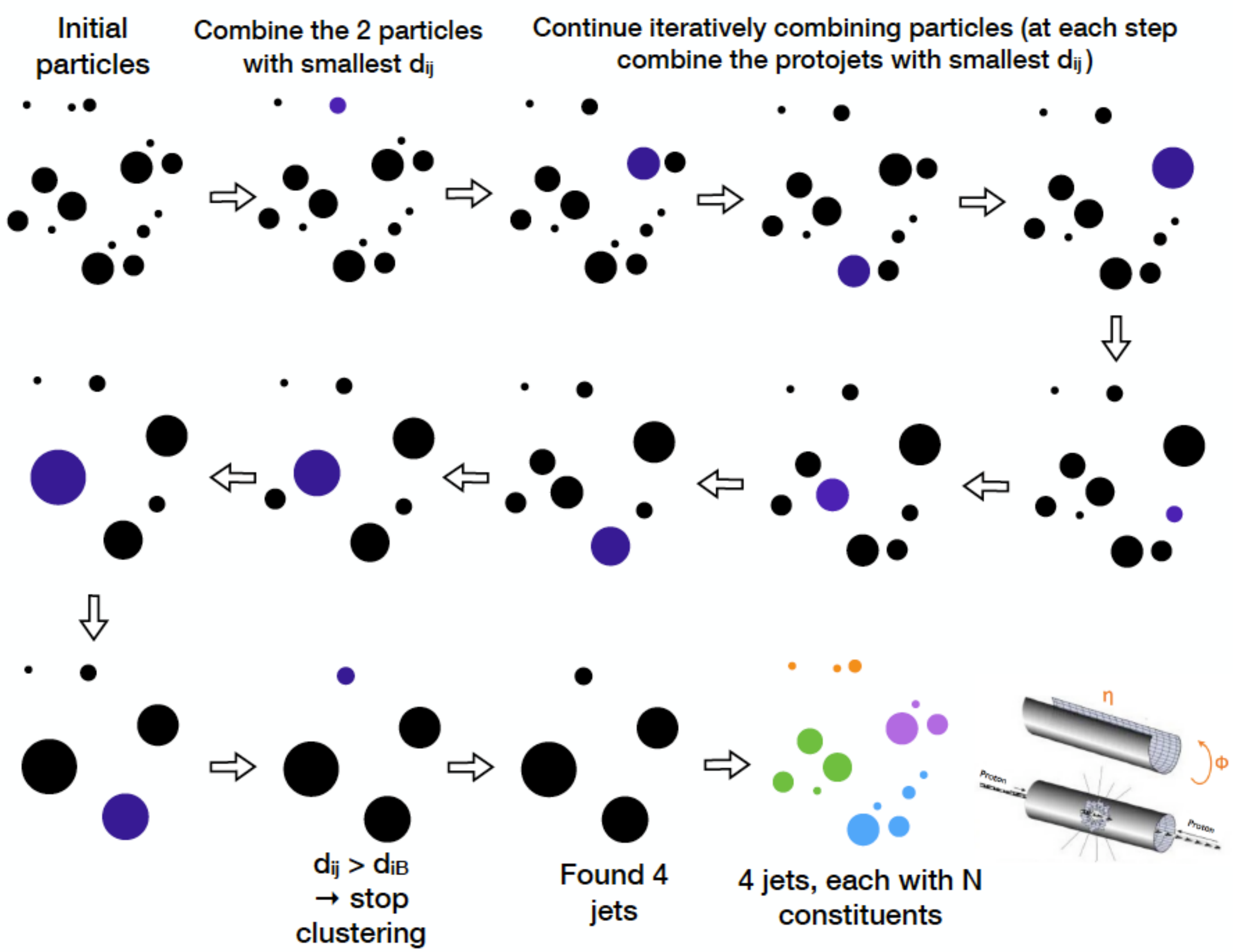


Jets



- Need a "jet algorithm" to associate the charged/neutral hadrons in a spray to initial quarks and gluons

- Sequential recombination algorithm:
  Find min of all d_{ij} and d_{iB},
  - If min is a d_{ij}, merge and iterate
  - If min is a d_{iB}, classify as a final jet
  - Continue until list is exhausted



$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p})\, \Delta R_{ij}^2 / R^2$$

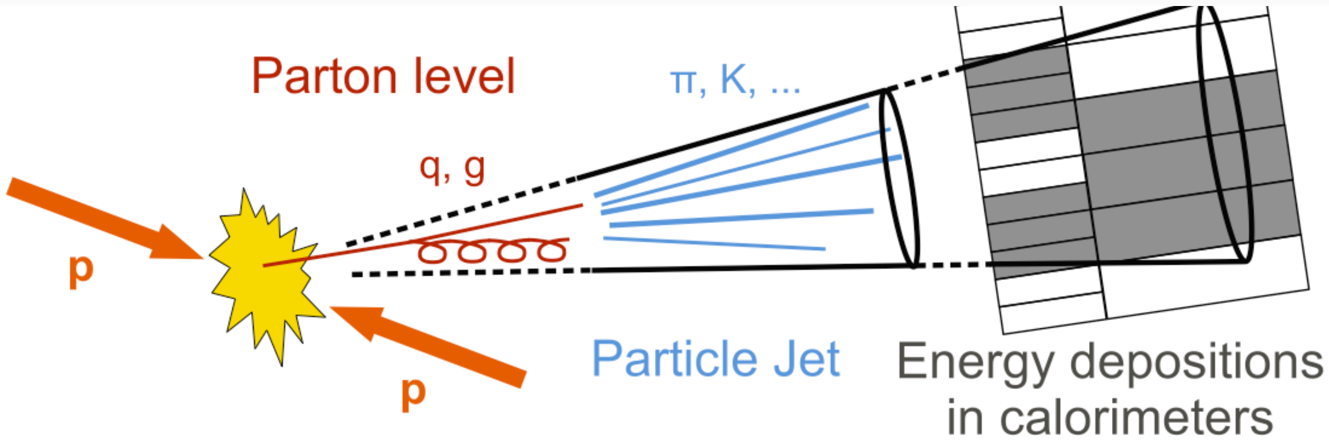
$$d_{iB} = p_{ti}^{2p}$$ (beam distance)

$p = 1$ → kt algorithm (KT)

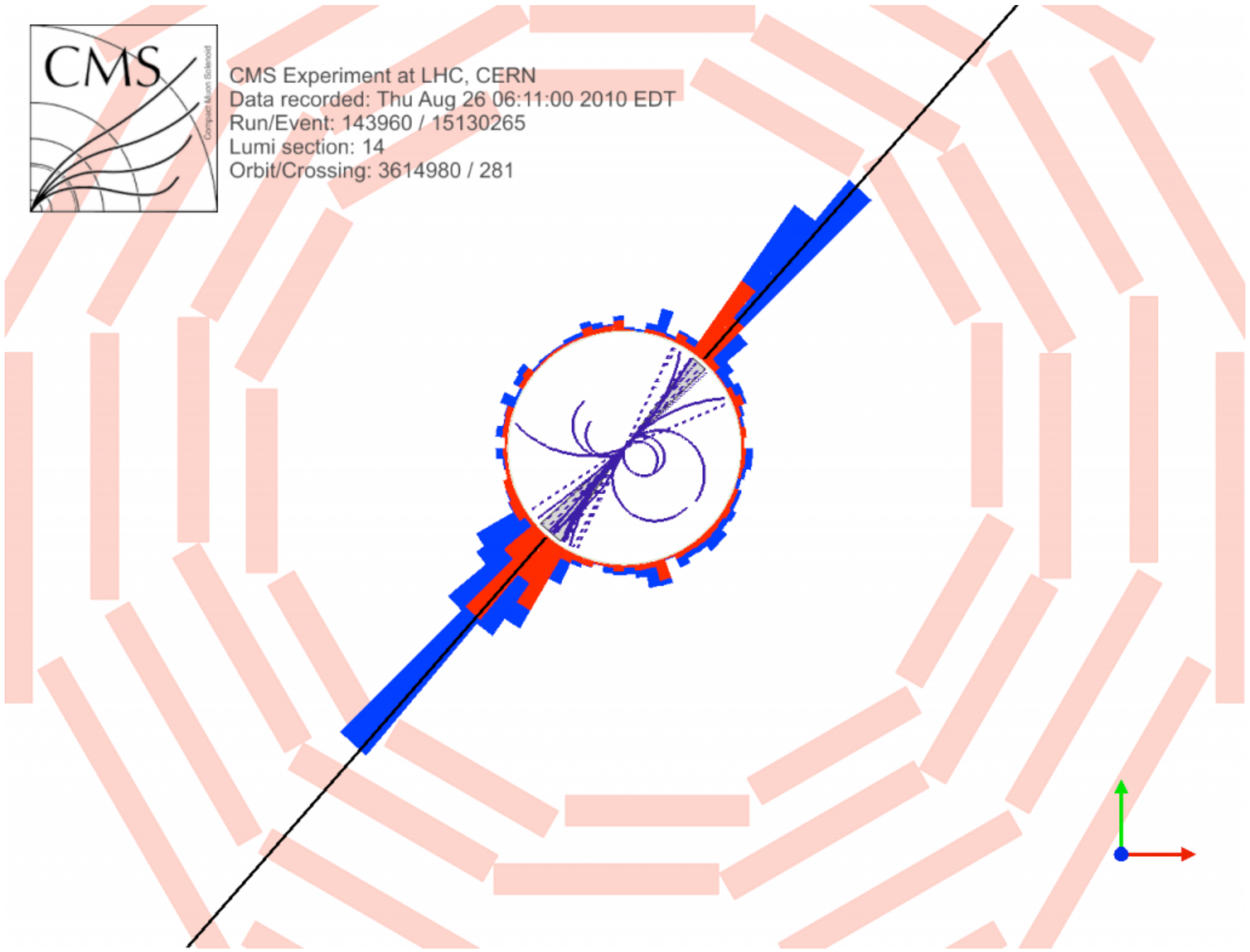
$p = 0$ → Cambridge Aachen algorithm (CA)

$p = -1$ → anti-kt algorithm (AK)

Jets

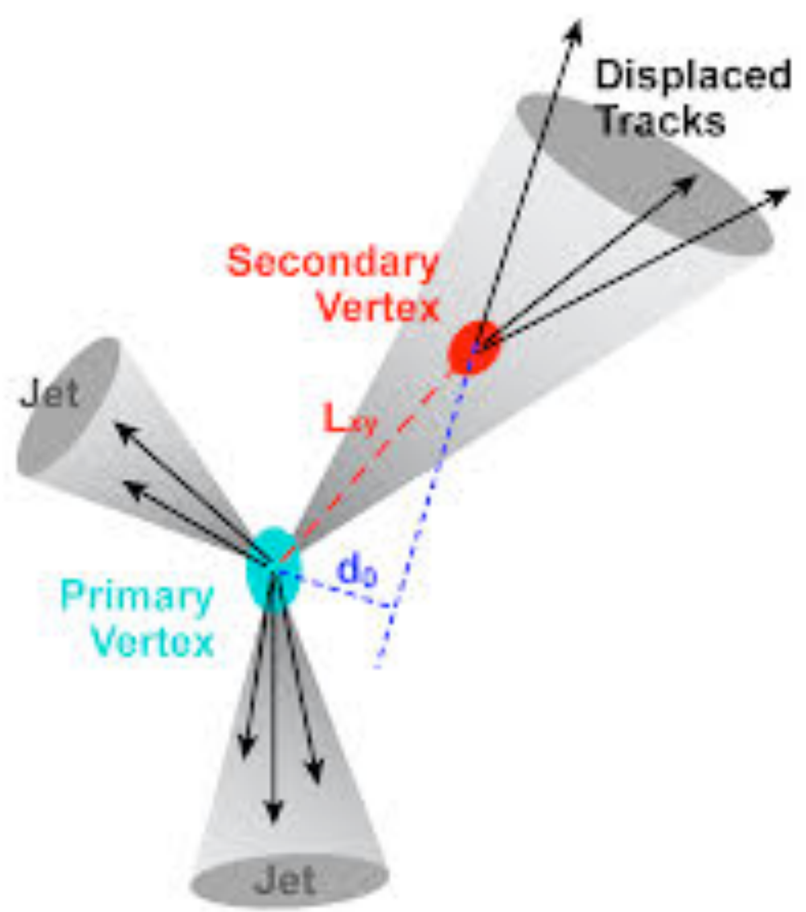


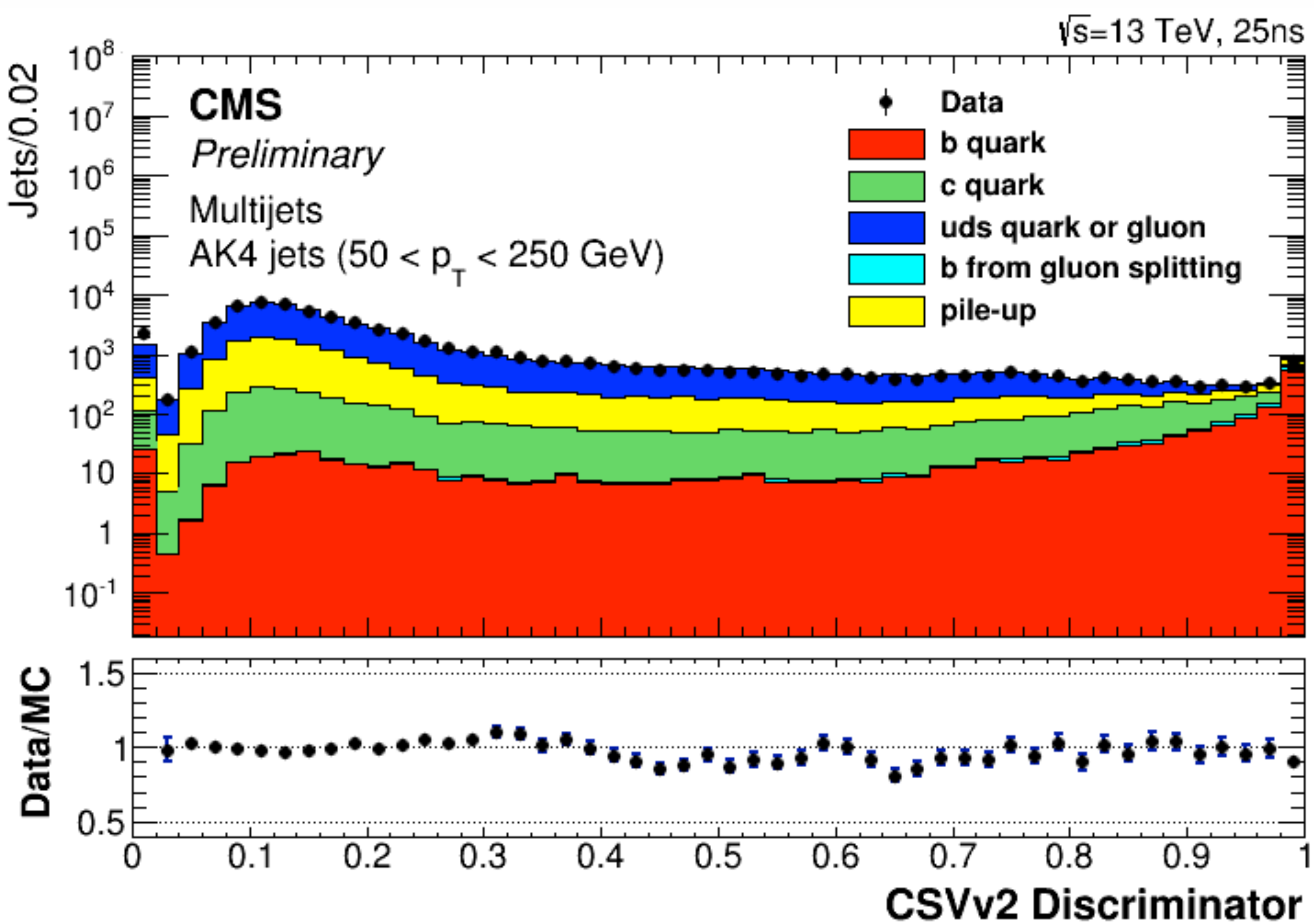
dijet event



b-jets

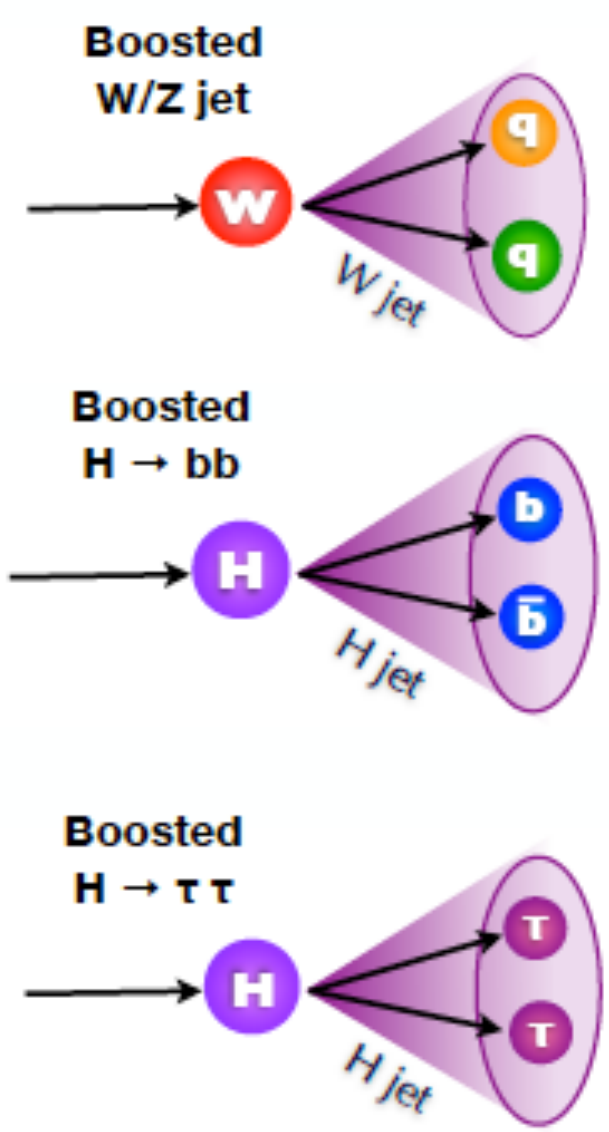
- Combined Secondary Vertex version 2 algorithm, based on secondary vertex and track-based lifetime informations
- Combines the variables with a neural network instead of a likelihood ratio and the secondary vertex information is obtained with the Inclusive Vertex Finder algorithm.

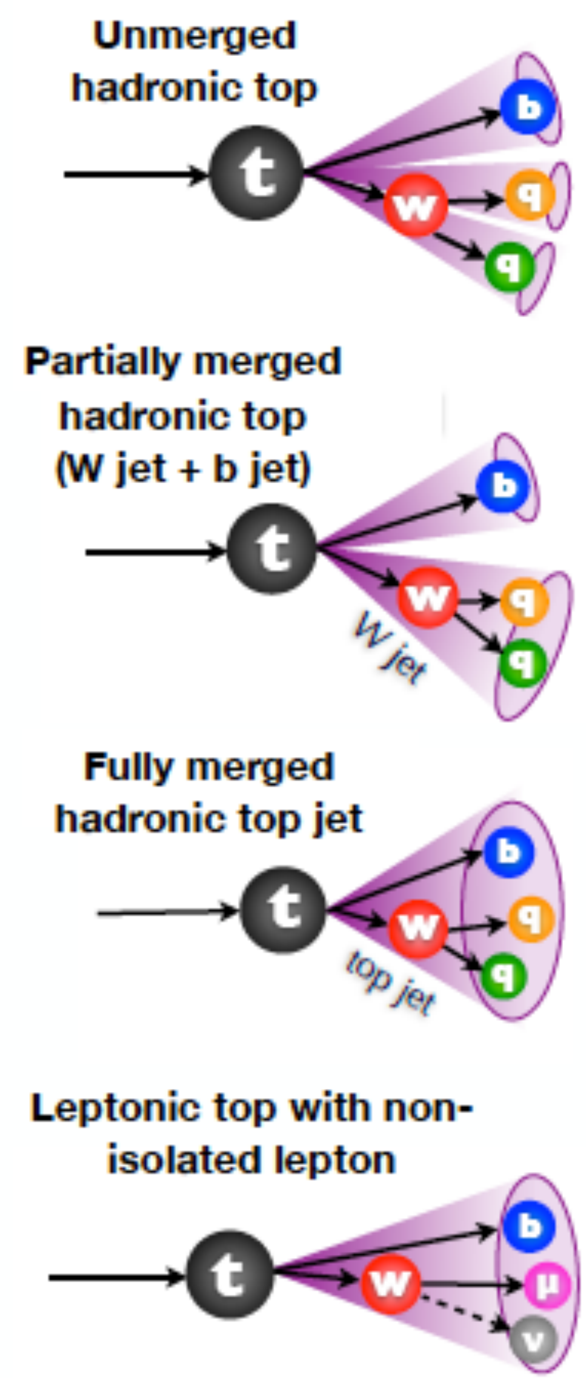




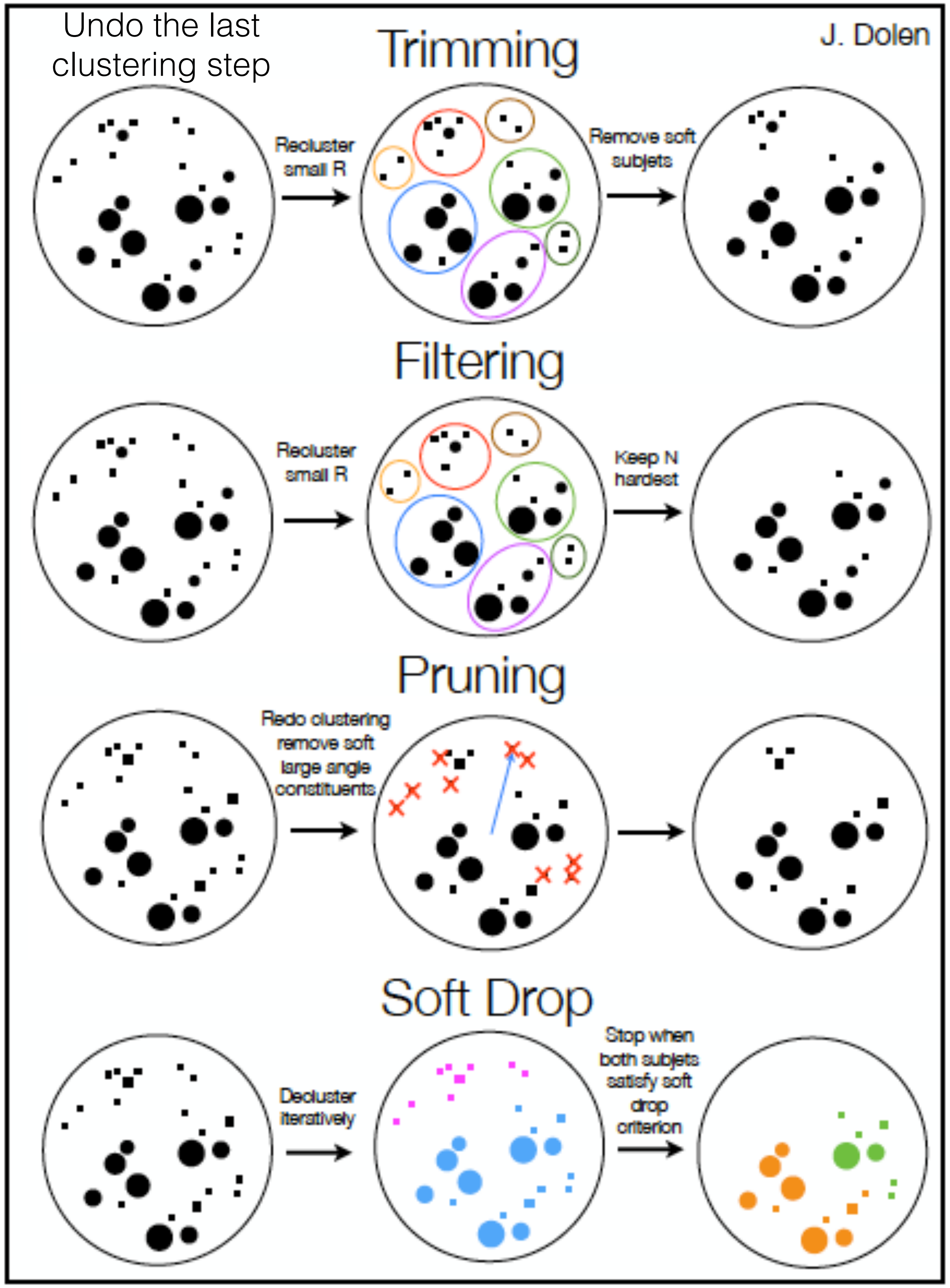
Boosted Jets

- Heavier the mass, more is the boost received by its decay products





Jet Grooming



- **Pruning - recluster. Throw out subjets which are too soft, requiring that each recombination satisfy**

$$\frac{\min(p_{T1}, p_{T2})}{p_{Tp}} > 0.1$$

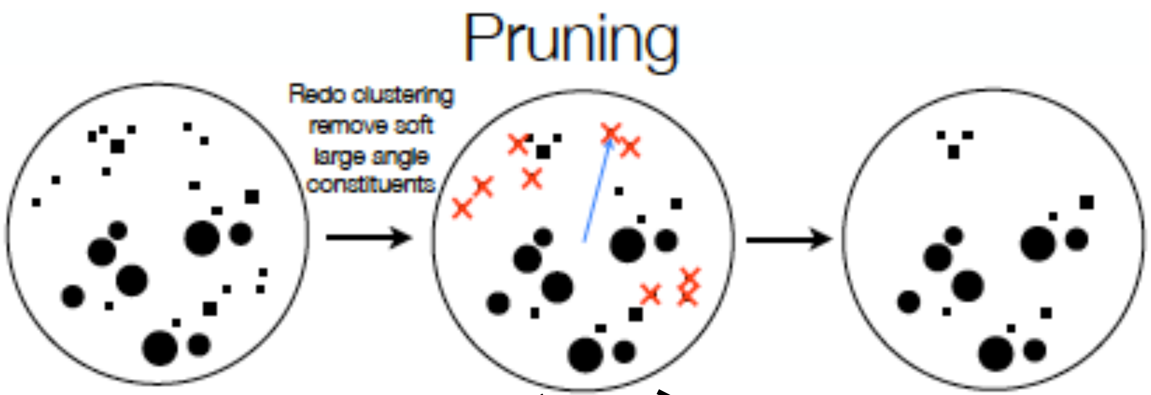
$$\Delta R_{12} < 0.5 \times \frac{m_{\mathrm{jet}}}{p_{\mathrm{T}}}$$

- **Soft drop - decluster. Throw out subjets which do not satisfy the soft drop condition**

$$\text{Soft Drop Condition:} \quad \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\mathrm{cut}} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$

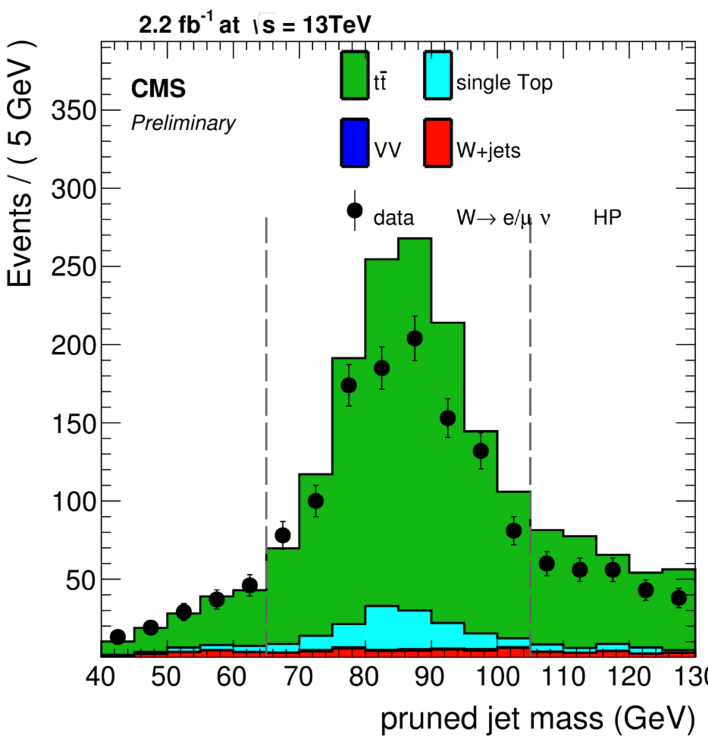
W-tagging

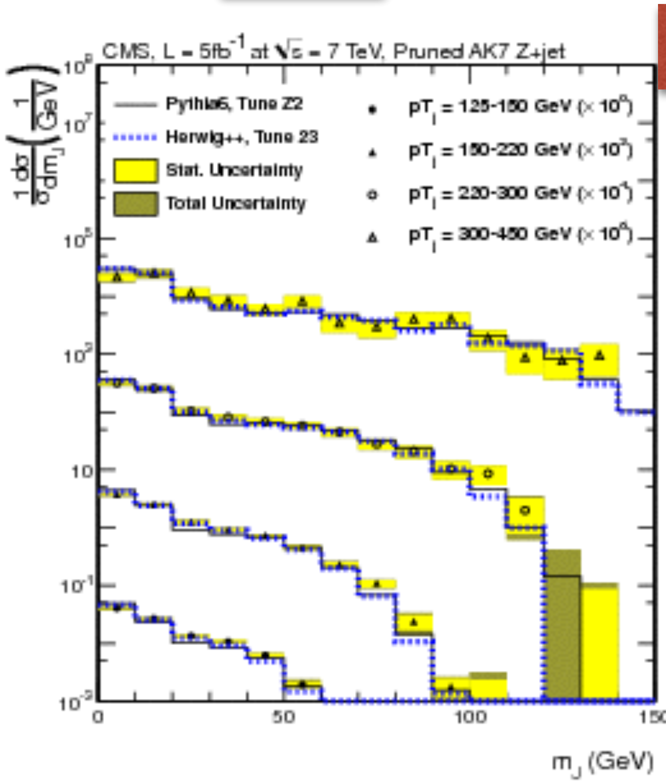
Pruning



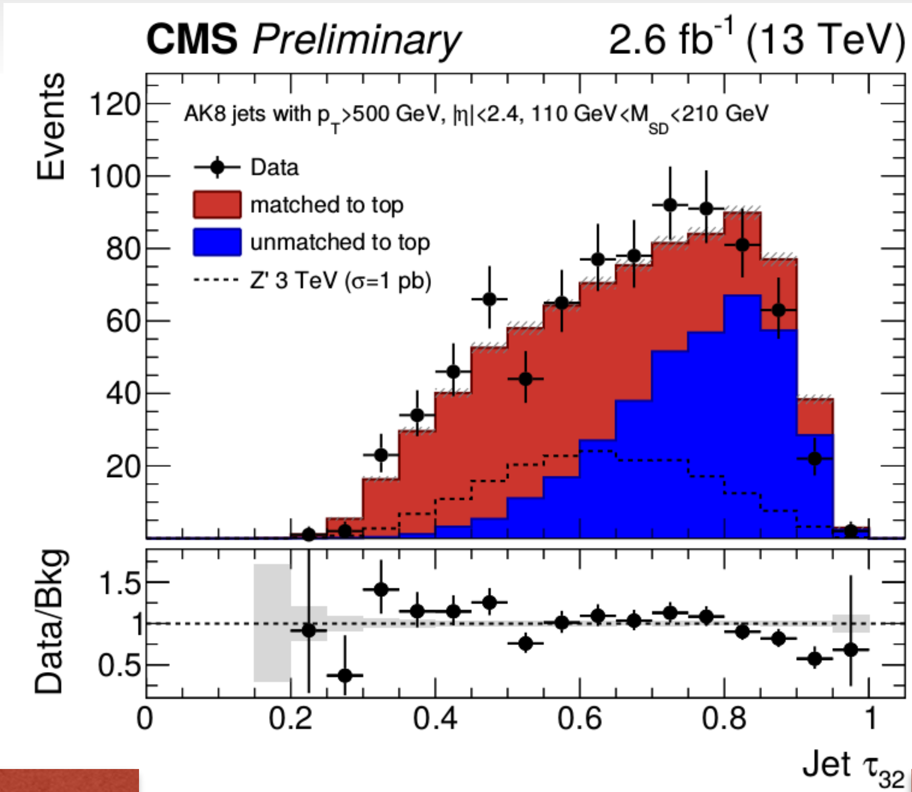
WJets

QCD

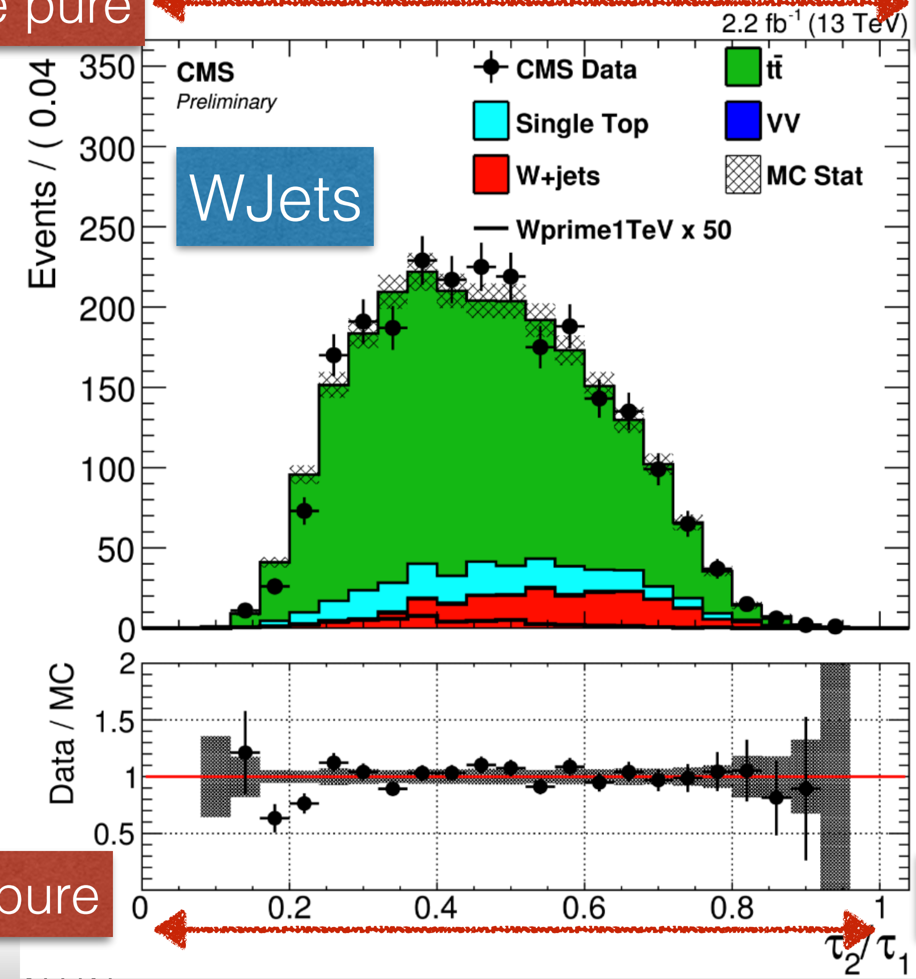




N-Subjettiness



More pure — Less pure



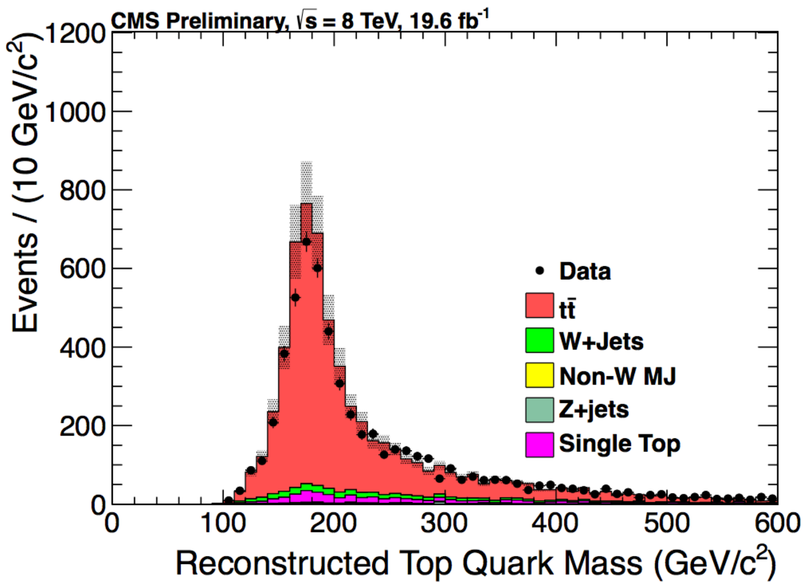
More pure — Less pure

S.Rappoccio, ICHEP 2016

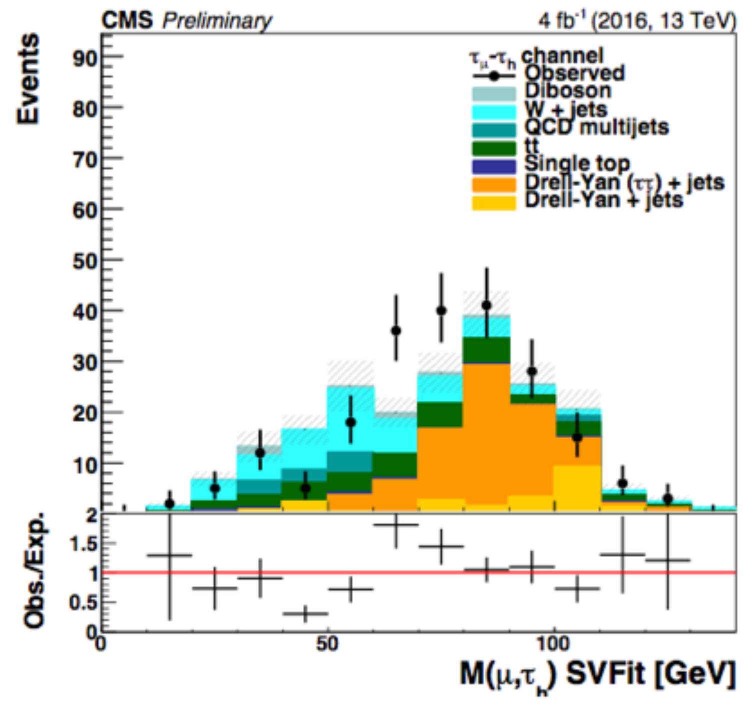
JME-13-006,JME-16-003,SMP-12-019

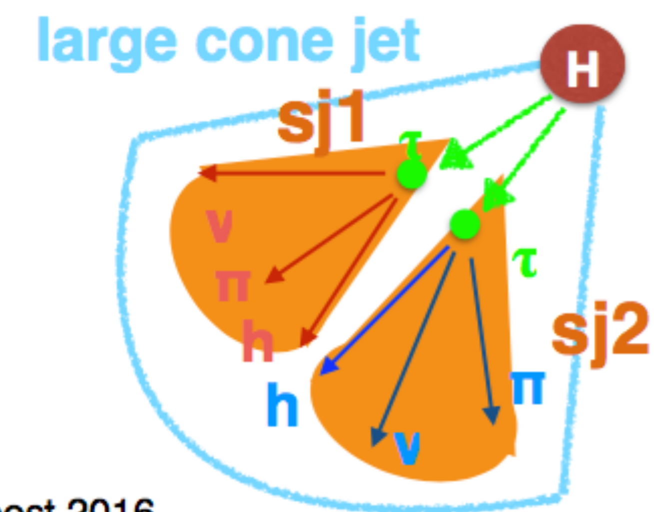
More taggers

top-tagging



Boosted tautau-tagging

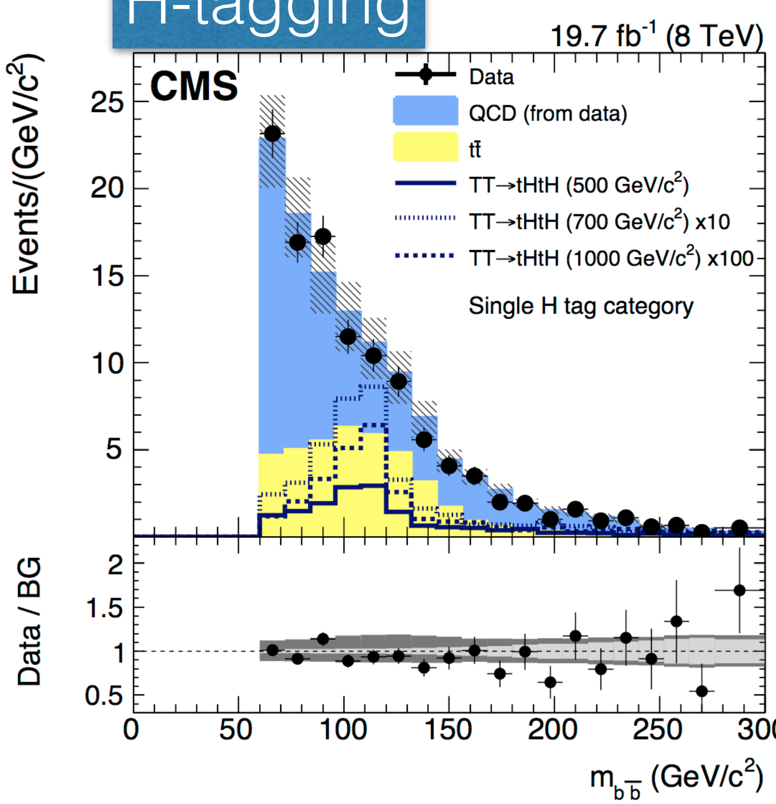




Boost 2016

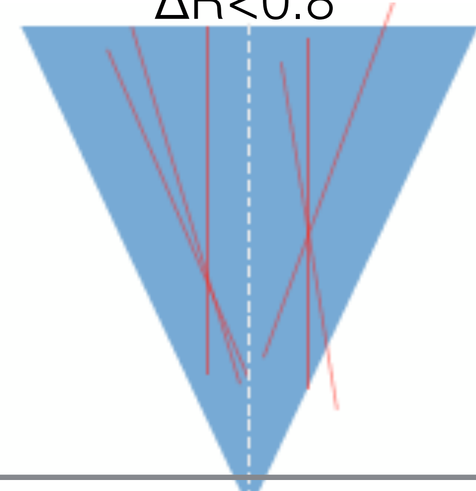
CMS-DP-2016/038

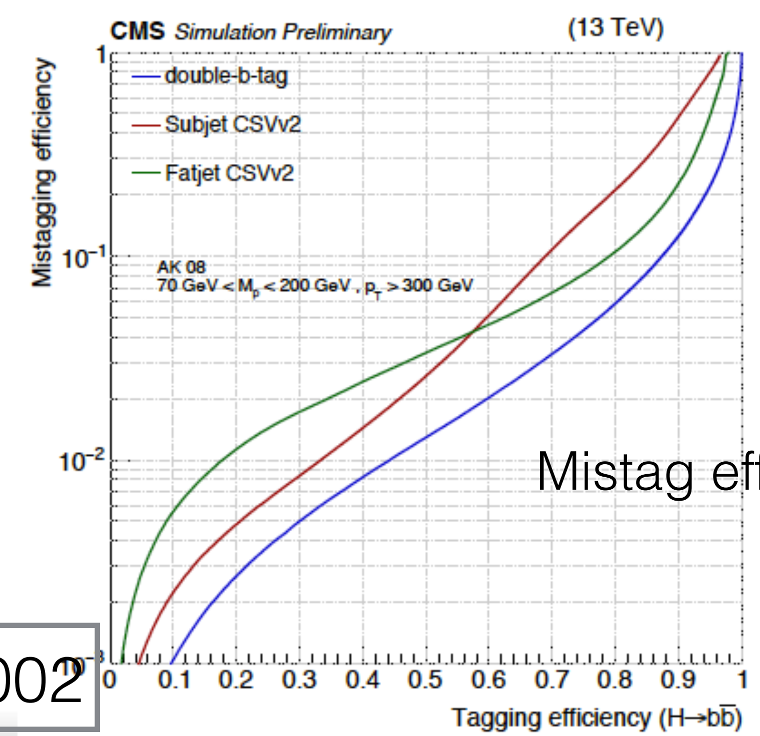
H-tagging



- Reconstruct the two B hadrons from the b and $\bar{b}$ within the same fat jet

Double tagger

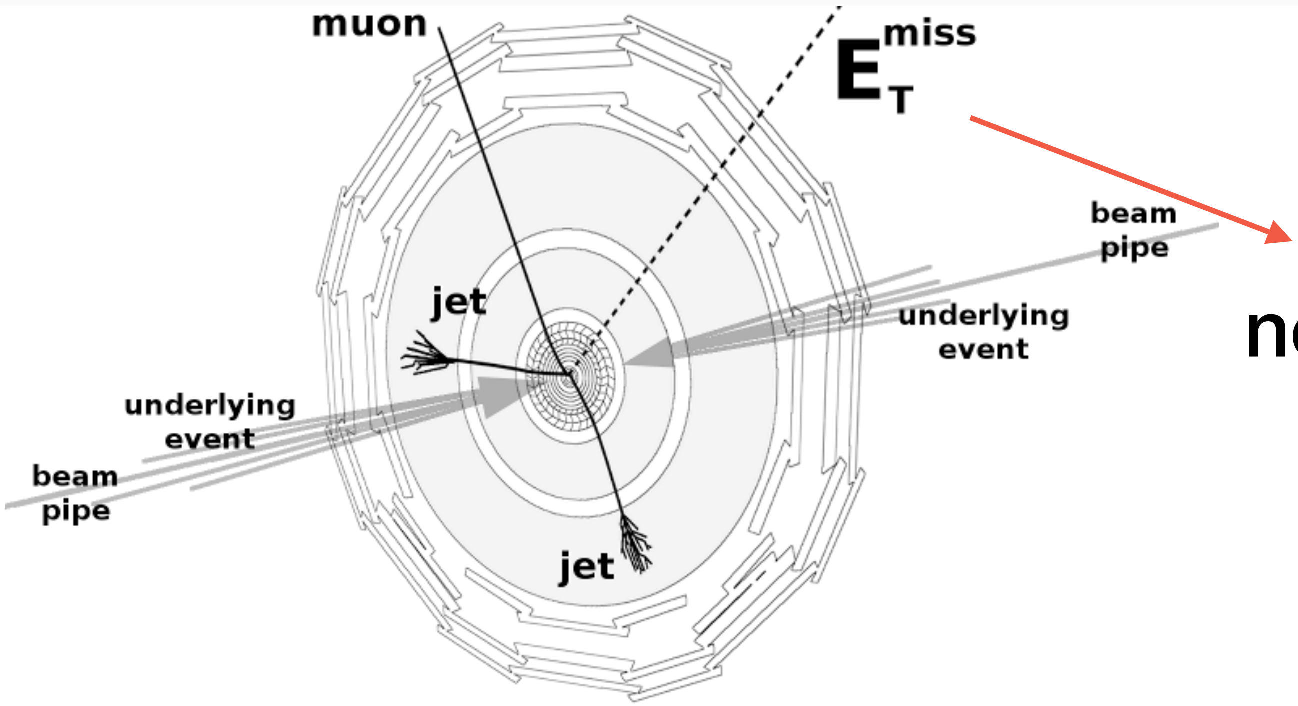




Mistag efficiency

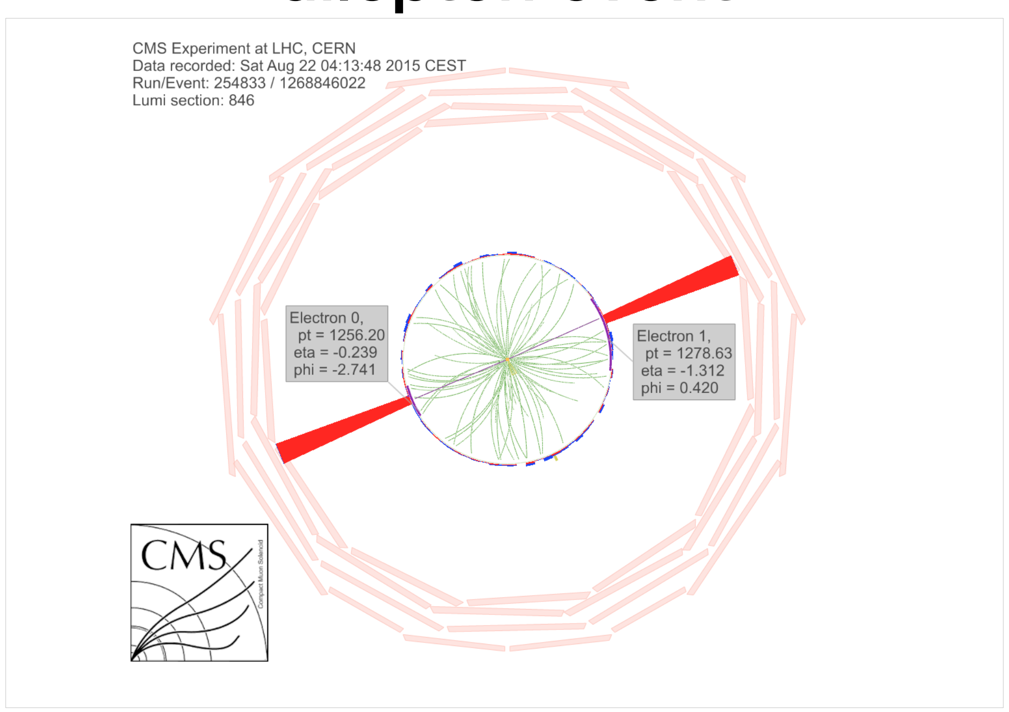
BTV-13-001, BTV-15-002

Missing Transverse Energy

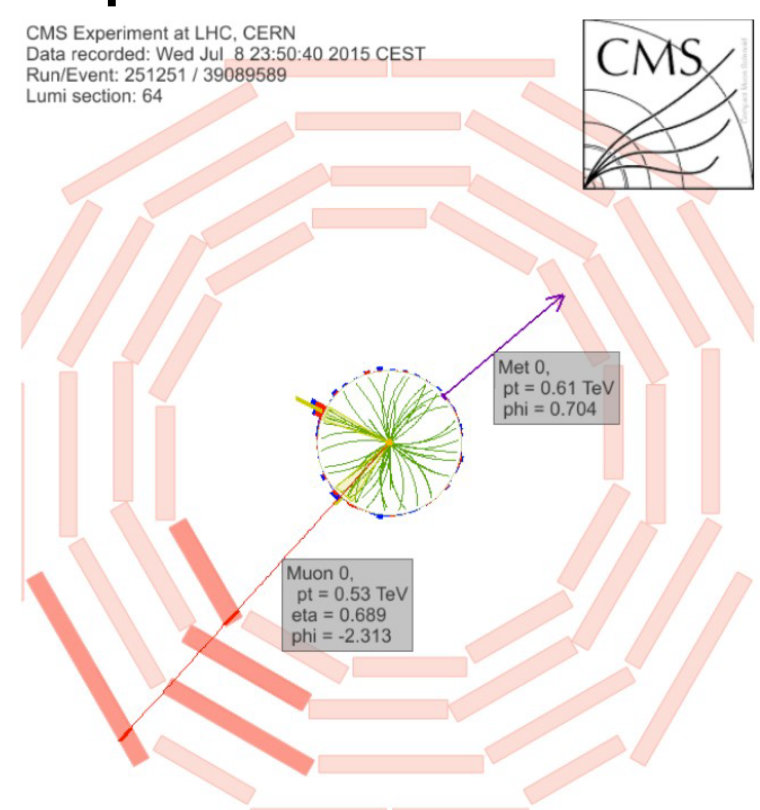


negative vector sum of energies of all final state particles

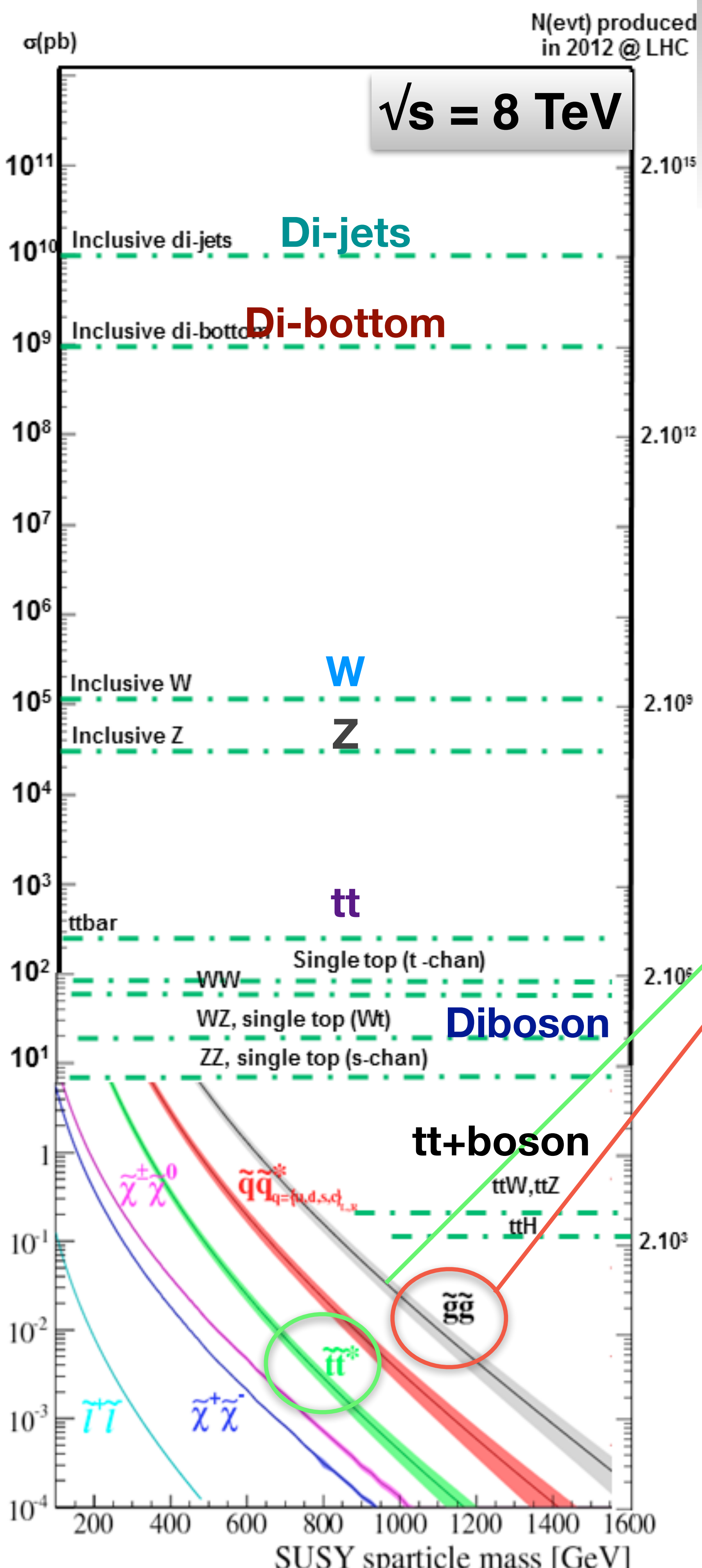
dilepton event



lepton+neutrino event



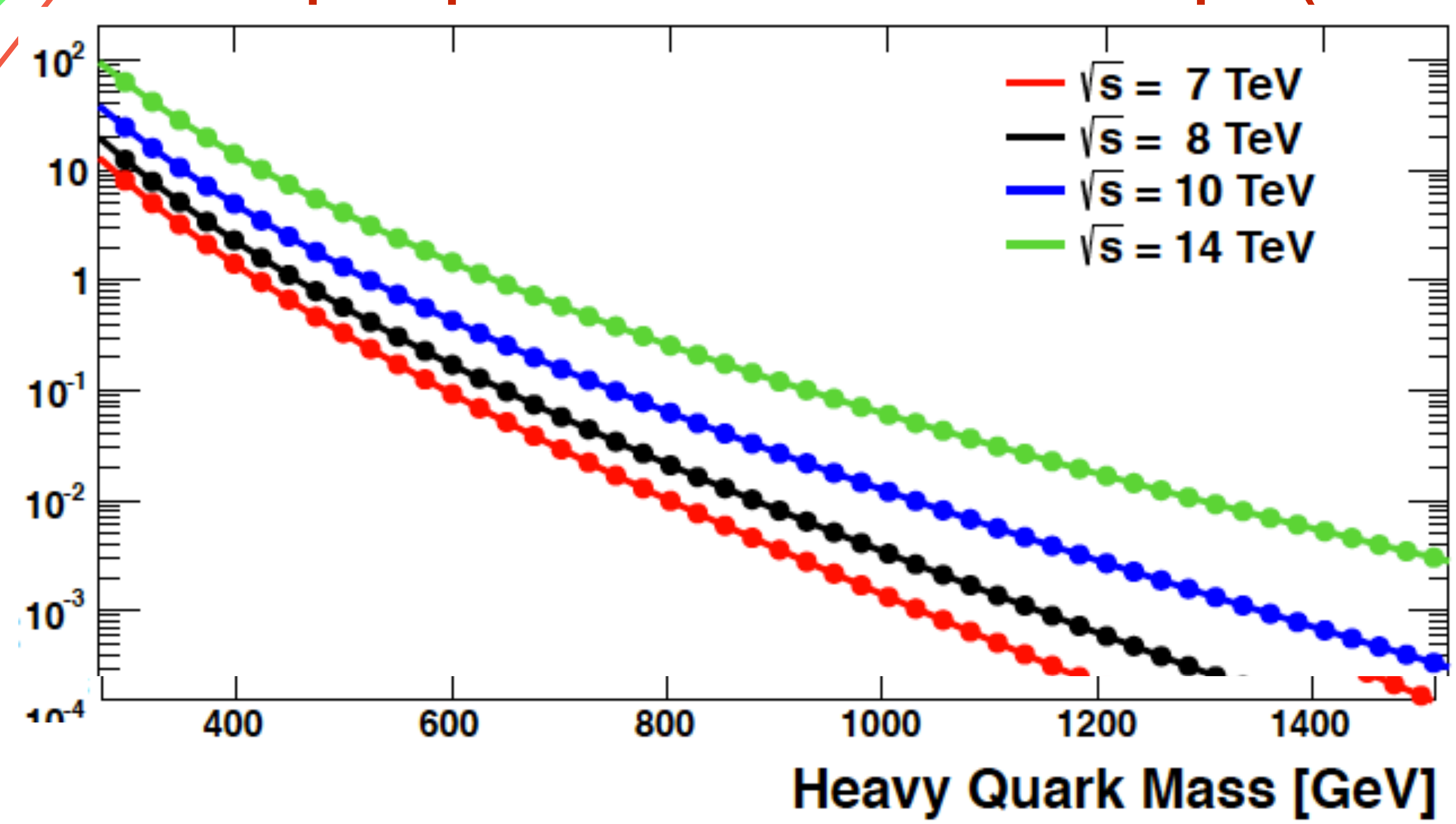
Production x-sections at LHC



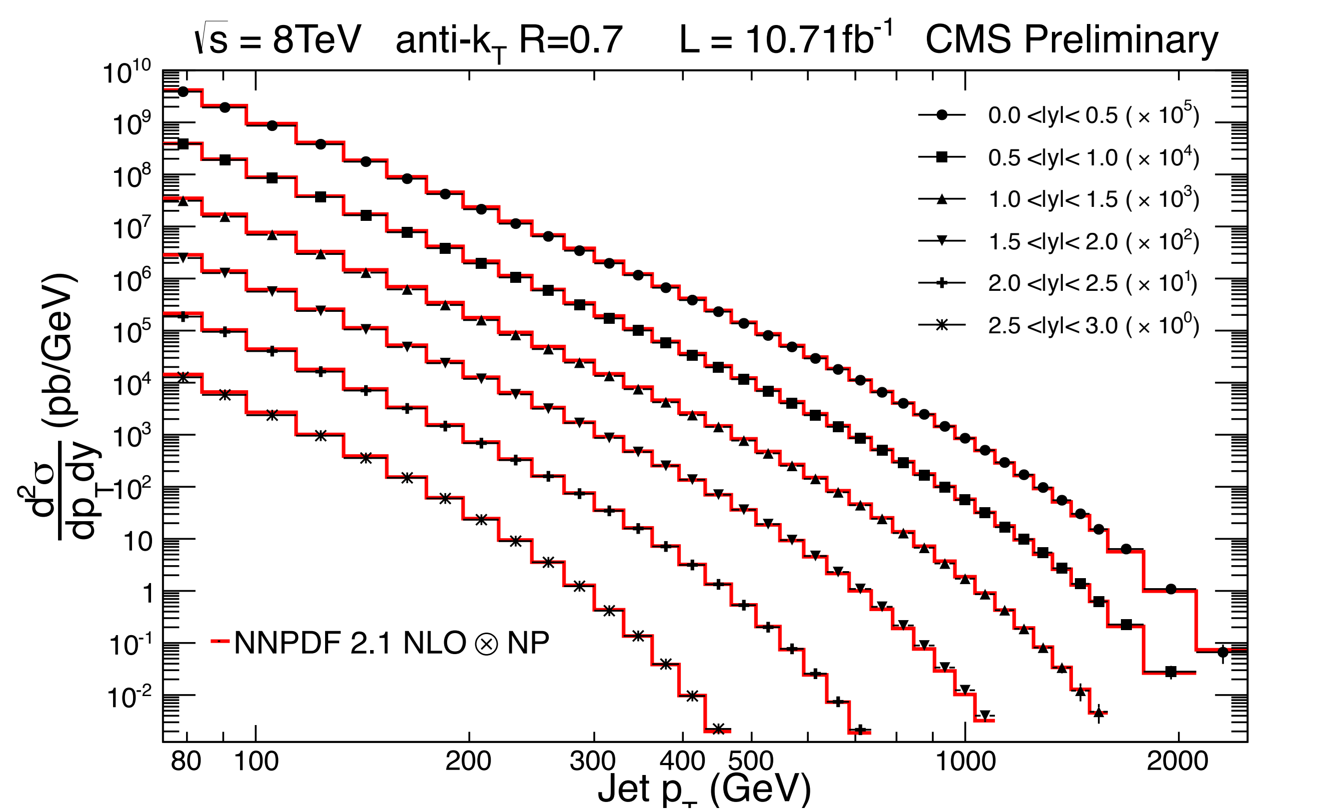
- The production cross sections of new physics are 10 and more orders of magnitude lower than full pp collision rate at the LHC

Relevant for stops search

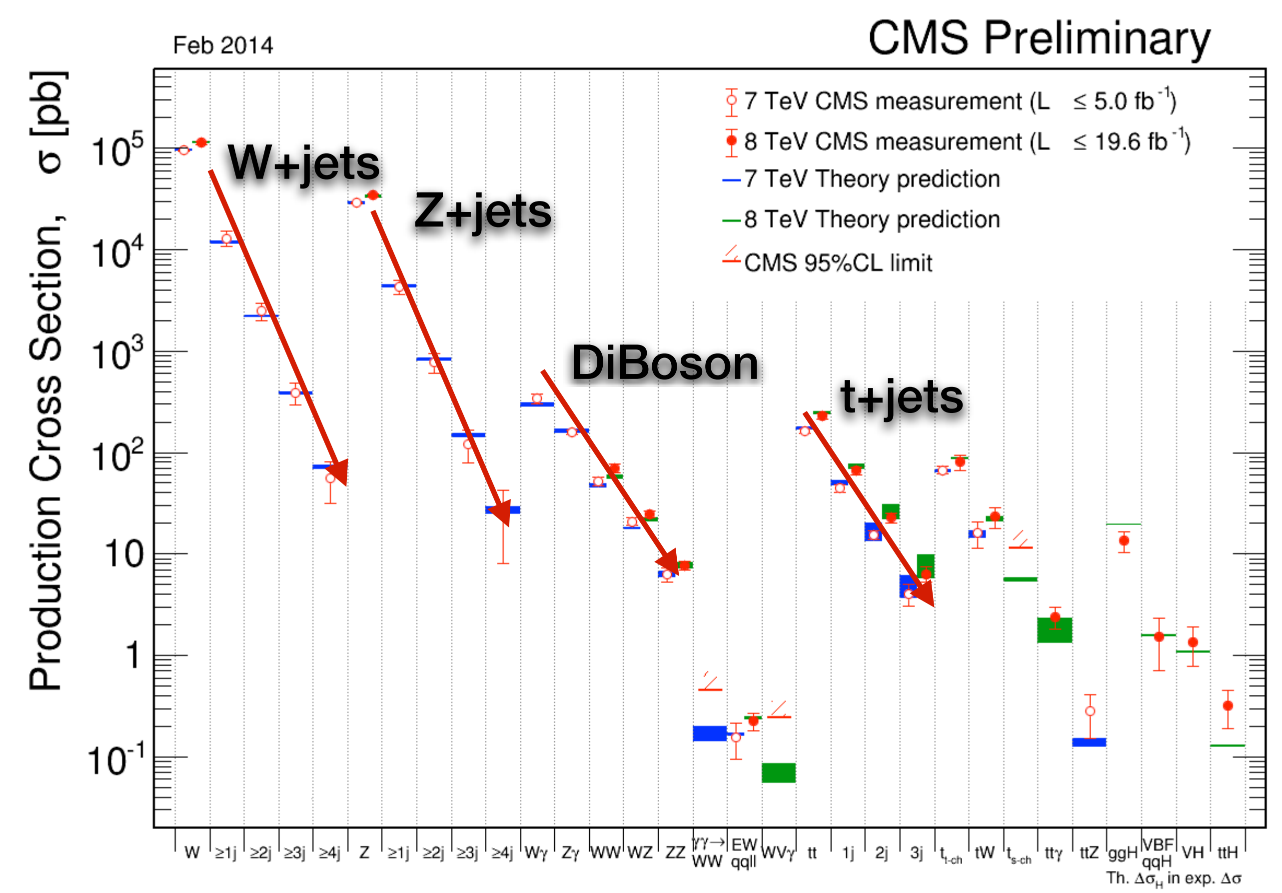
VLQs pair production x-section in pb (NNLO)



Standard Model Backgrounds



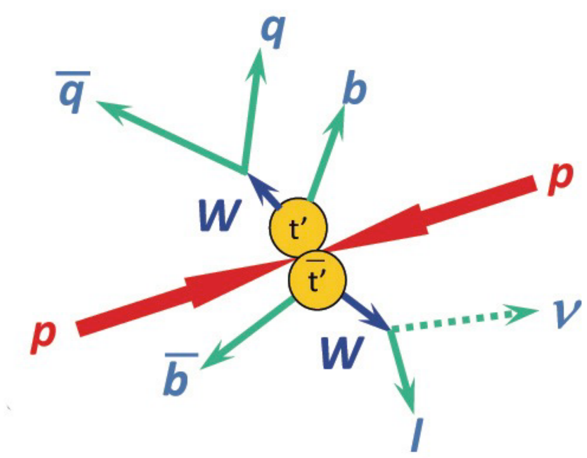
- The x-section decrease exponentially with jet p_T and # of jets

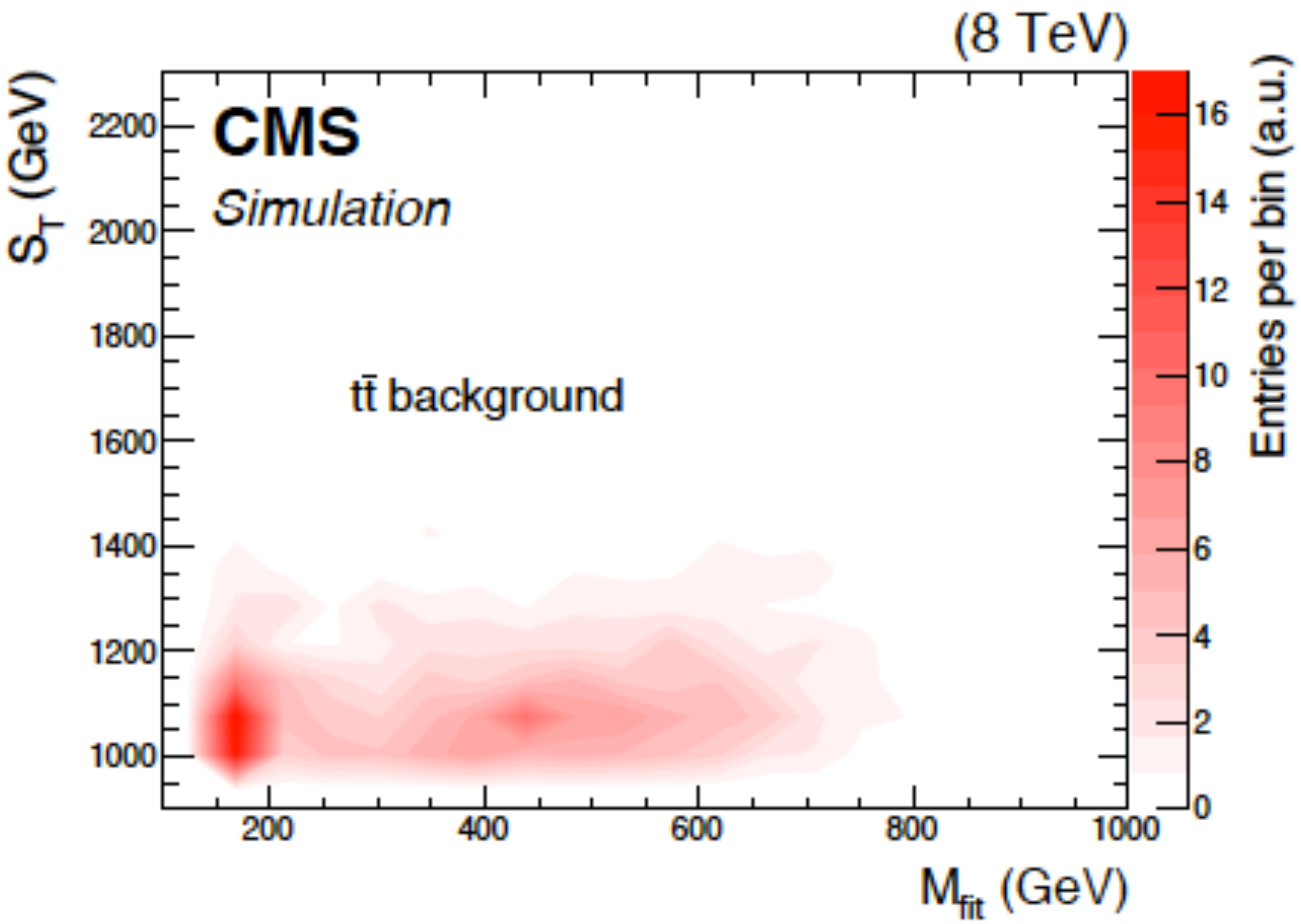


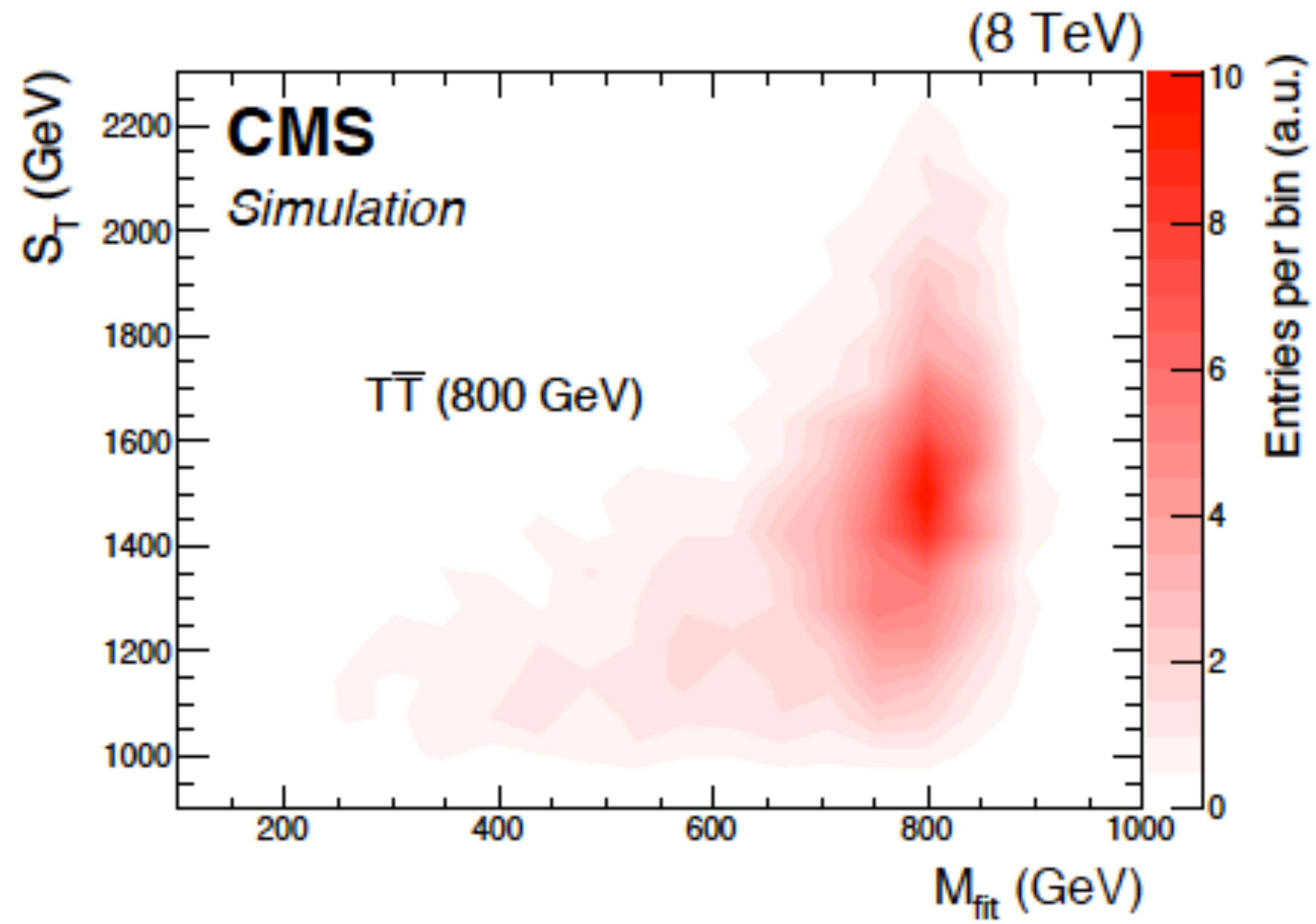
- New physics often appears in an event with multiple jets and very high jet pt

Common Search Procedures

- Look for excesses over known backgrounds in
  - Reconstructed new particle mass tails
  - High S_T tails: $S_T = p_T^l + \Sigma p_T^{jet} + E_T^{miss}$

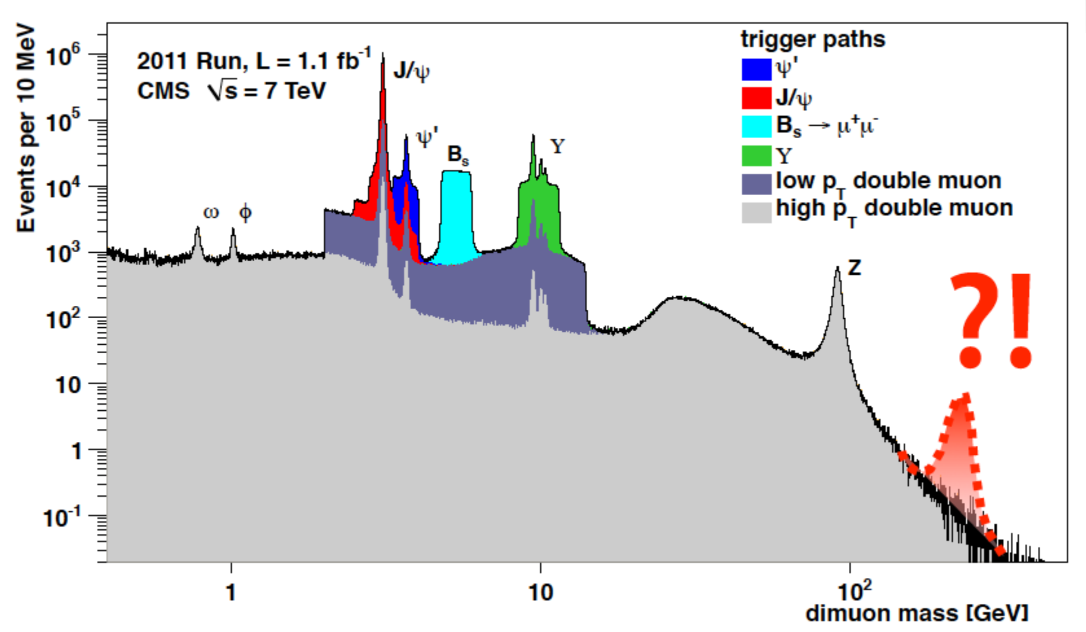




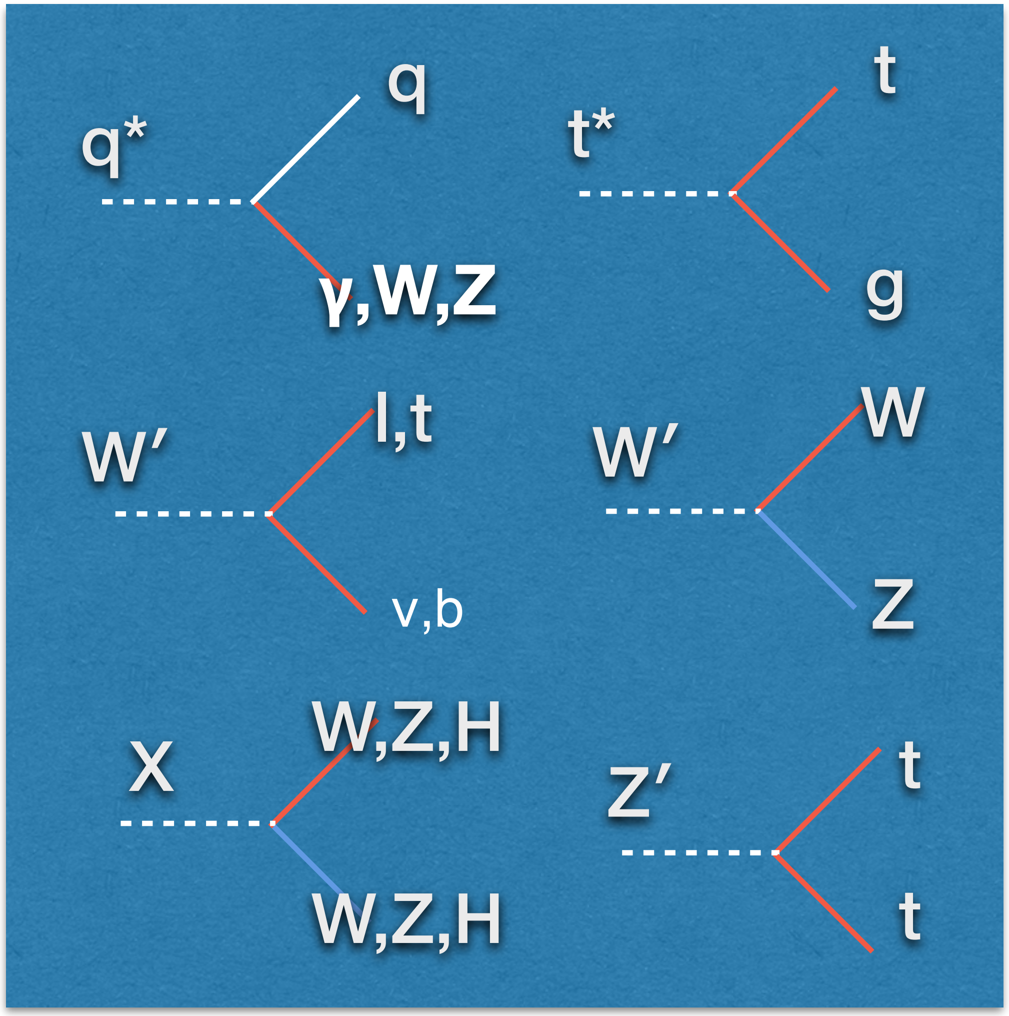


Resonances

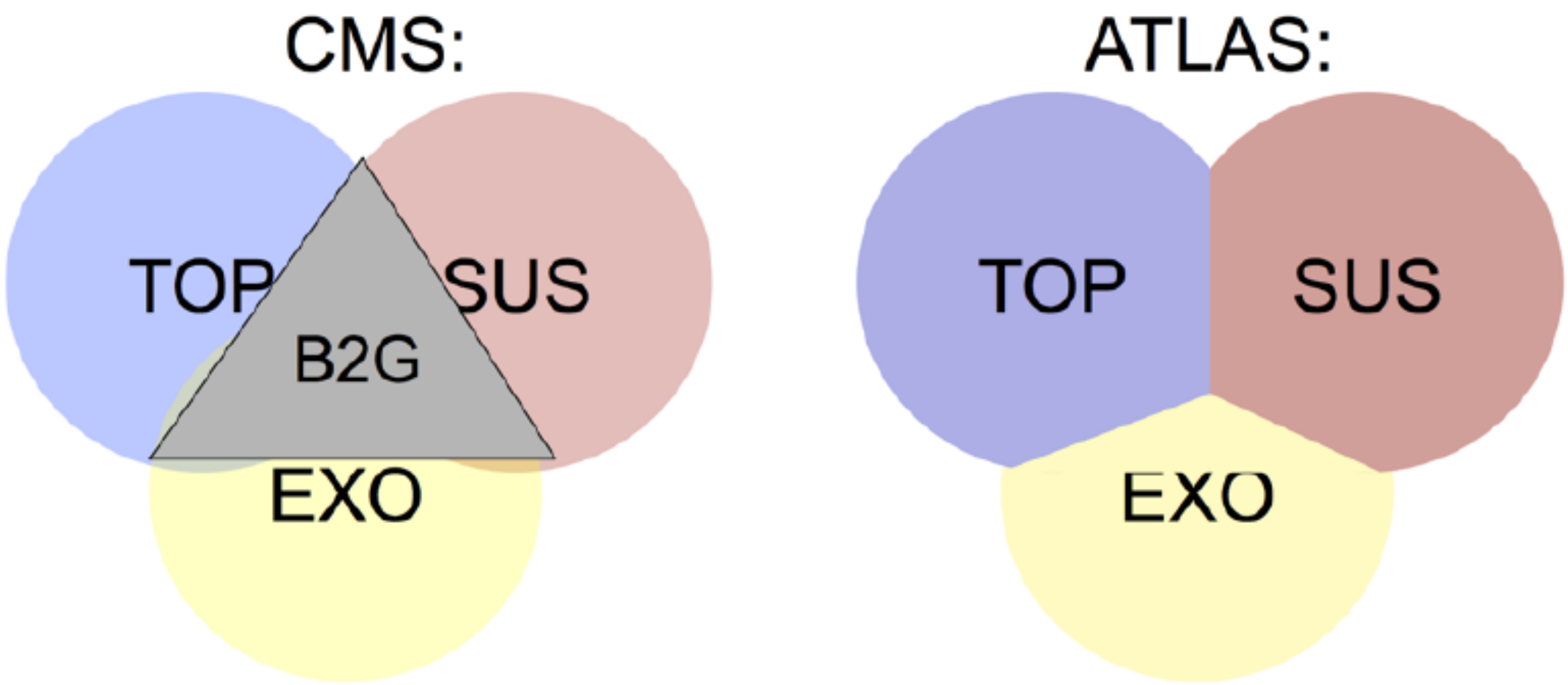
- Powerful, model-independent probe to new physics
  - Simple Strategy: Look for a “bump”
  - Example: If $m_{ff} > m_Z$ or m_H ➡ New Physics!



- Top quark resonances in BSM Models
  - Extended gauge sectors: Z′, W′ and G′ bosons
  - Complex Strategy: Use boosted techniques to identify t, W, Z, H along with b and reconstruct the resonance mass



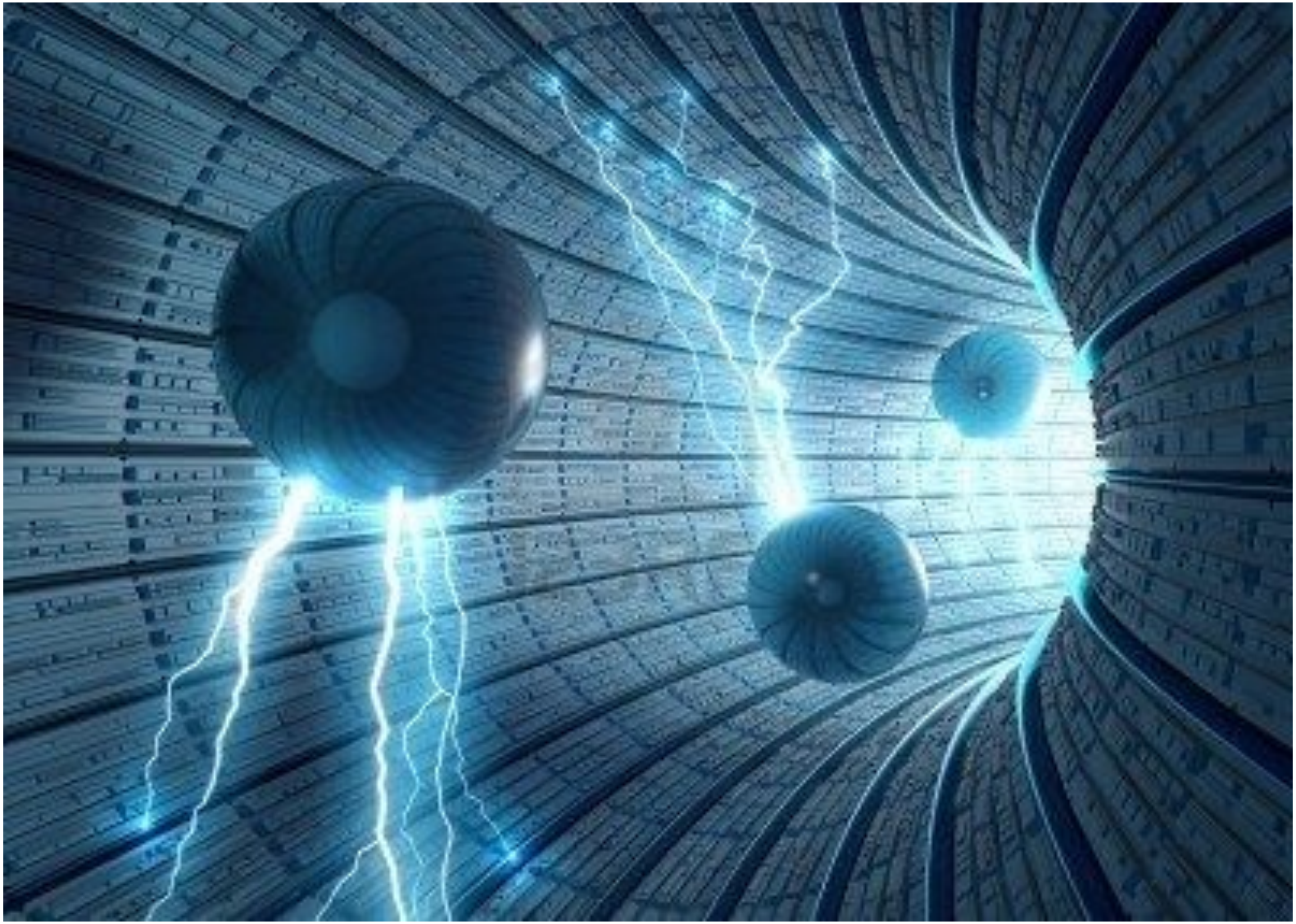
New Physics Searches



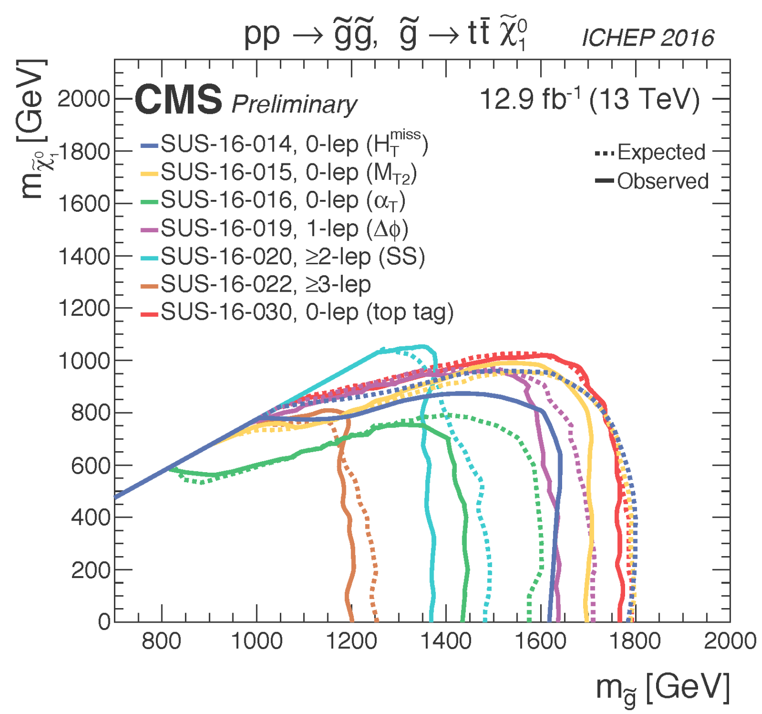
- For physics including boosted SM particles, CMS has the“Beyond Two Generations” Physics Analysis Group (B2G PAG)
- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G
- I will cover mostly the B2G results, see more talks by Albert De Roeck related to EXO and SUSY results

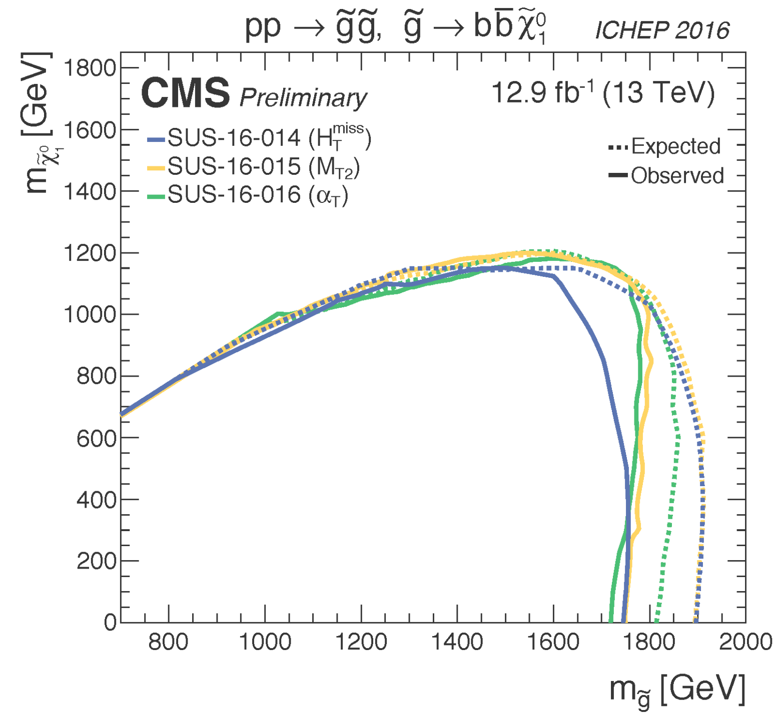
A glimpse of overwhelming results!

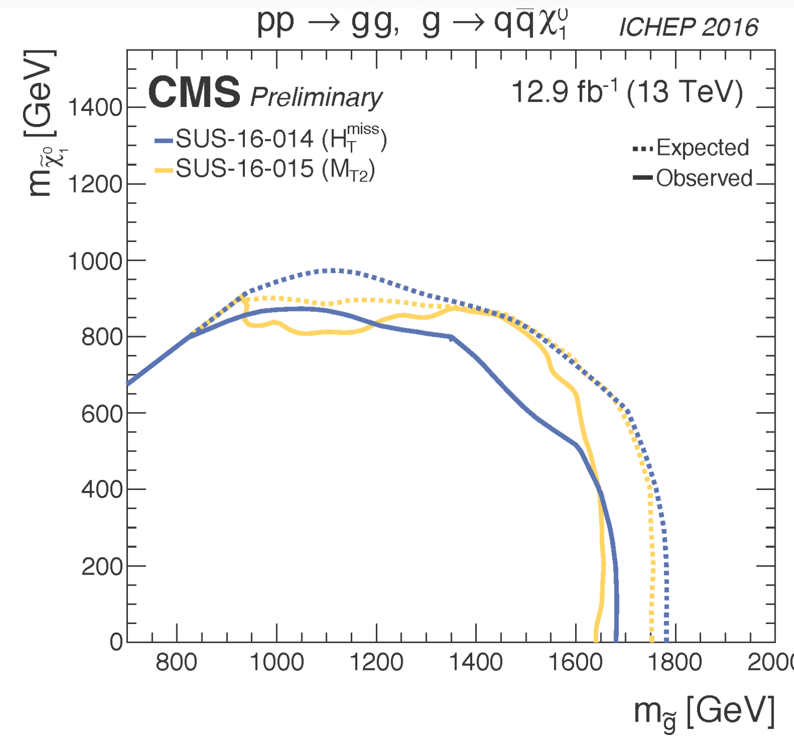
- Just new for ICHEP 2016, more than 70 CMS results !!

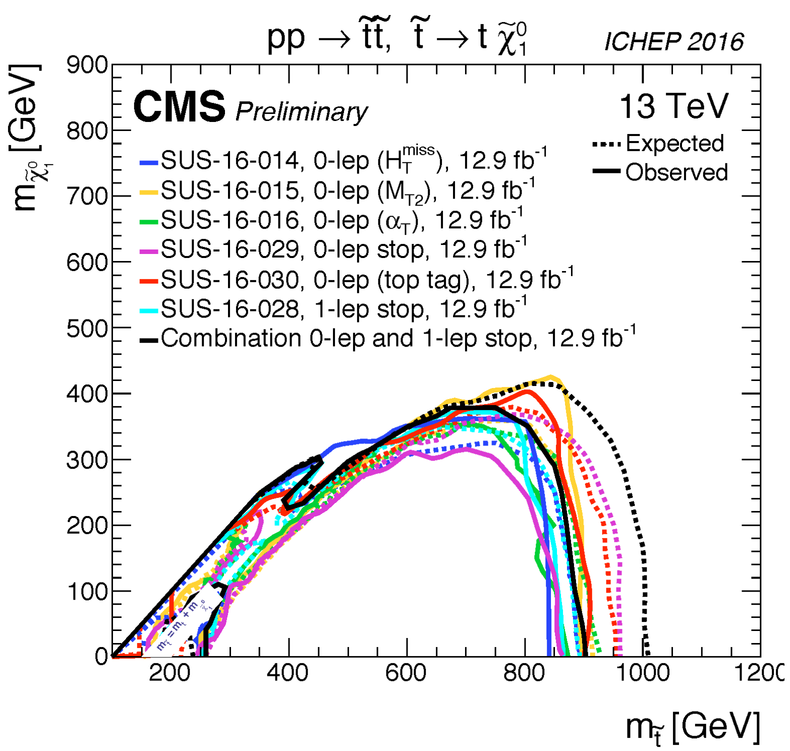


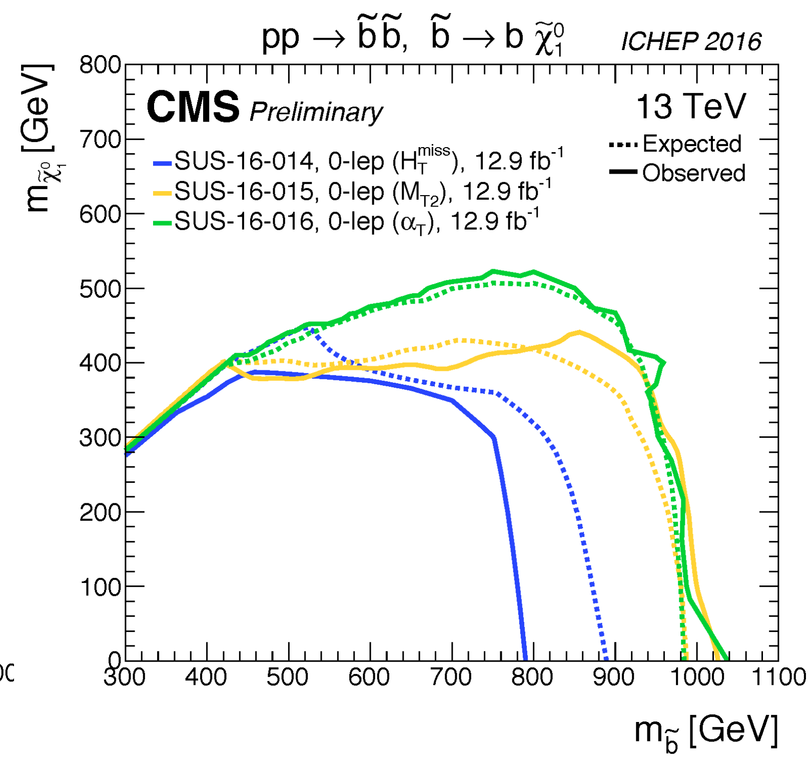
SUSY Results

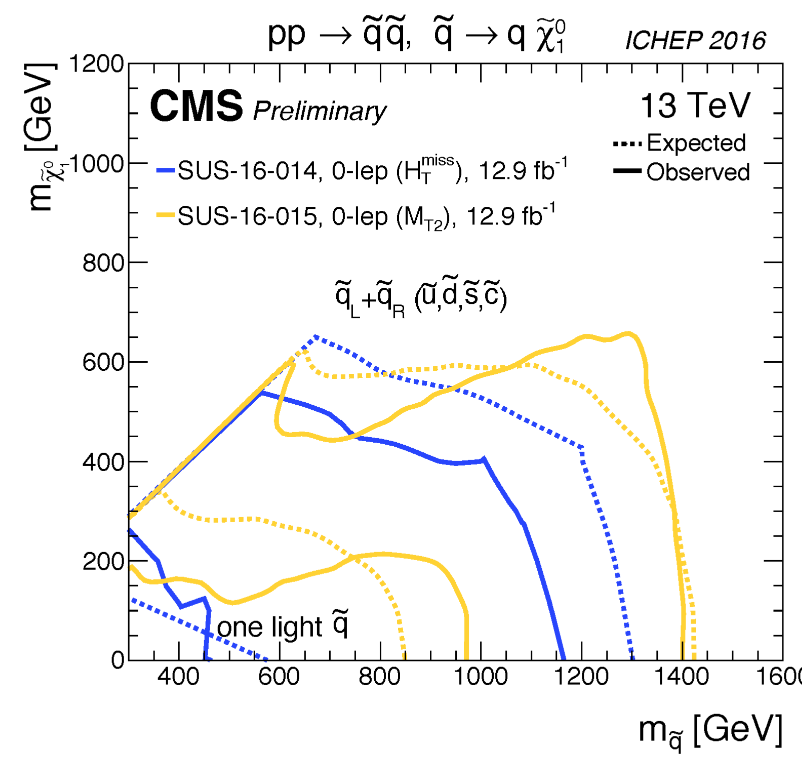






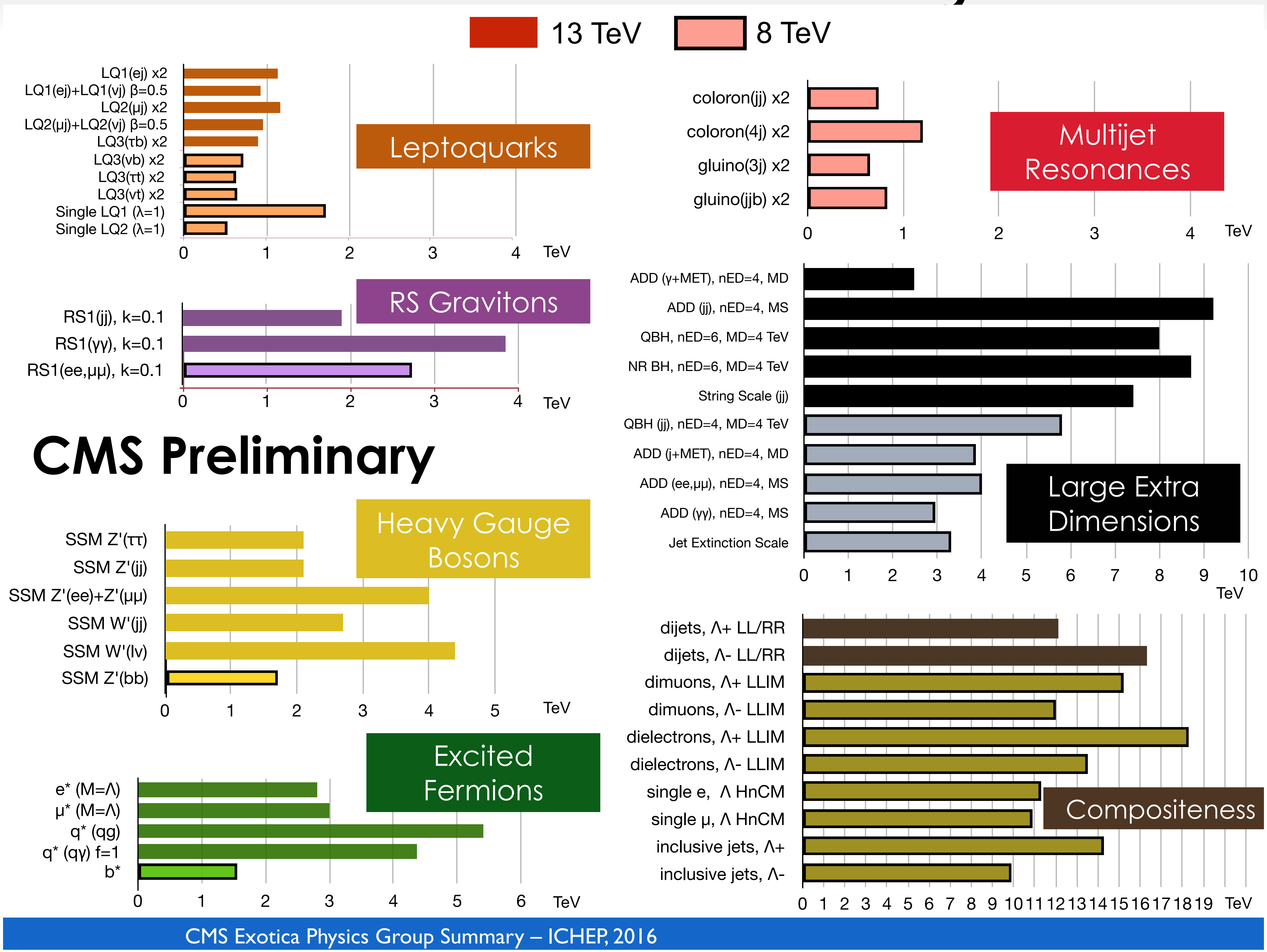






- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS#Run_2_Summary_plots_13_TeV

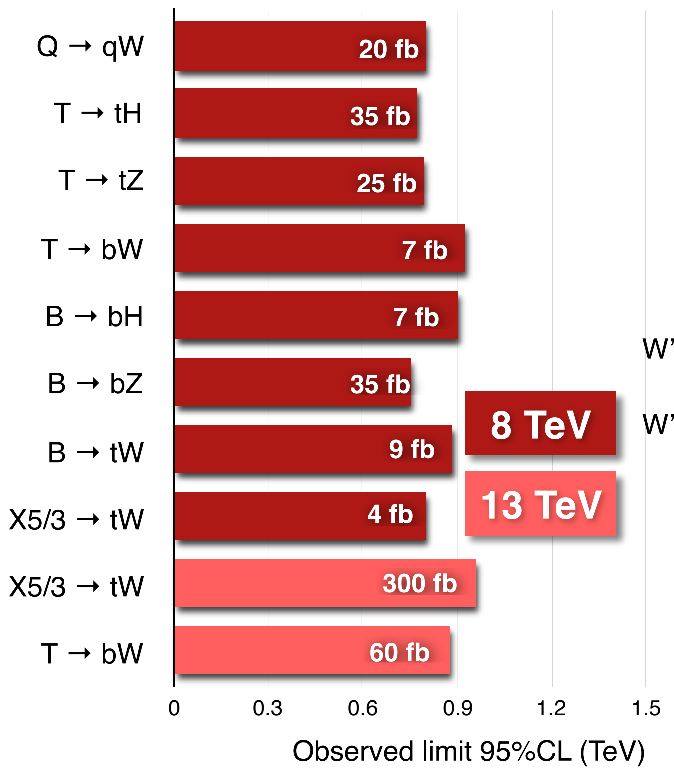
EXO Summary



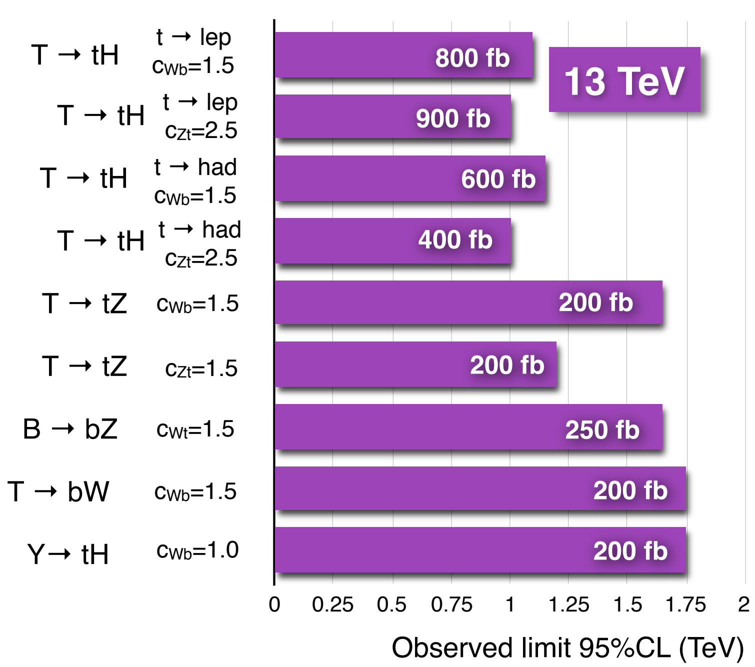
13 TeV
8 TeV
LQ1(ej) x2
LQ1(ej)+LQ1(νj) β=0.5
LQ2(μj) x2
LQ2(μj)+LQ2(νj) β=0.5
LQ3(τb) x2
LQ3(νb) x2
LQ3(ττ) x2
LQ3(νt) x2
Single LQ1 (λ=1)
Single LQ2 (λ=1)
Leptoquarks
0 1 2 3 4 TeV
RS Gravitons
RS1(jj), k=0.1
RS1(γγ), k=0.1
RS1(ee,μμ), k=0.1
0 1 2 3 4 TeV
CMS Preliminary
Heavy Gauge Bosons
SSM Z'(ττ)
SSM Z'(jj)
SSM Z'(ee)+Z'(μμ)
SSM W'(jj)
SSM W'(lν)
SSM Z'(bb)
0 1 2 3 4 5 TeV
Excited Fermions
e* (M=Λ)
μ* (M=Λ)
q* (qg)
q* (qγ) f=1
b*
0 1 2 3 4 5 6 TeV
coloron(jj) x2
coloron(4j) x2
gluino(3j) x2
gluino(jjb) x2
Multijet Resonances
0 1 2 3 4 TeV
ADD (γ+MET), nED=4, MD
ADD (jj), nED=4, MS
QBH, nED=6, MD=4 TeV
NR BH, nED=6, MD=4 TeV
String Scale (jj)
QBH (jj), nED=4, MD=4 TeV
ADD (j+MET), nED=4, MD
ADD (ee,μμ), nED=4, MS
ADD (γγ), nED=4, MS
Jet Extinction Scale
Large Extra Dimensions
0 1 2 3 4 5 6 7 8 9 10 TeV
dijets, Λ+ LL/RR
dijets, Λ- LL/RR
dimuons, Λ+ LLIM
dimuons, Λ- LLIM
dielectrons, Λ+ LLIM
dielectrons, Λ- LLIM
single e, Λ HnCM
single μ, Λ HnCM
inclusive jets, Λ+
inclusive jets, Λ-
Compositeness
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 TeV
CMS Exotica Physics Group Summary – ICHEP, 2016

B2G Summary

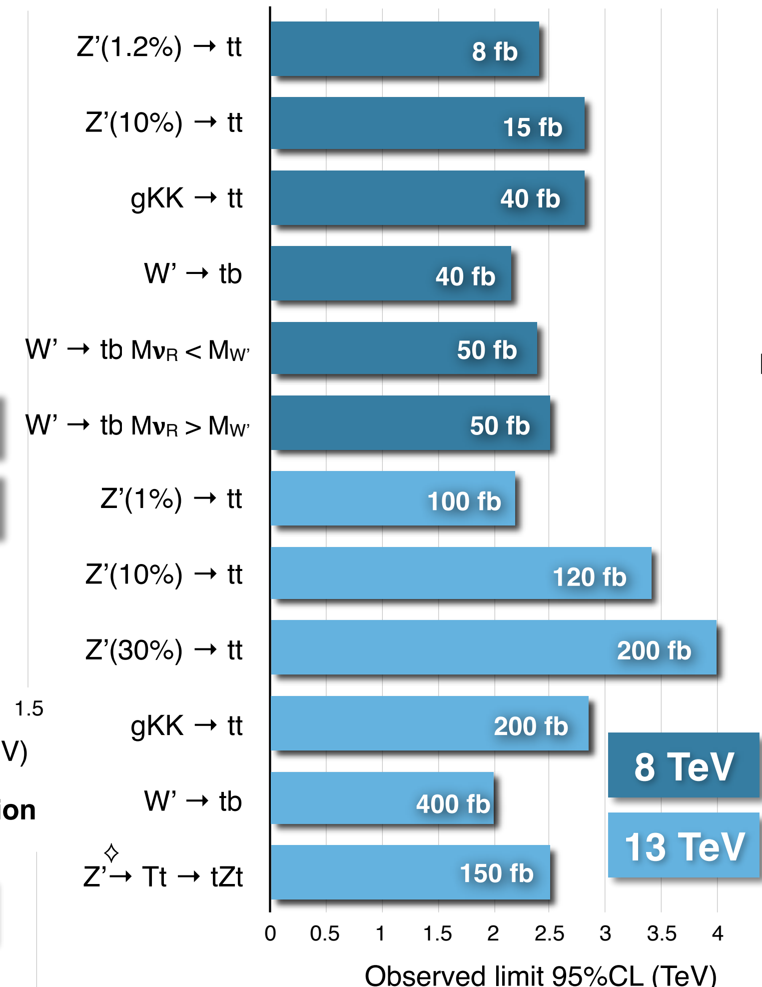
Vector-like quark pair production



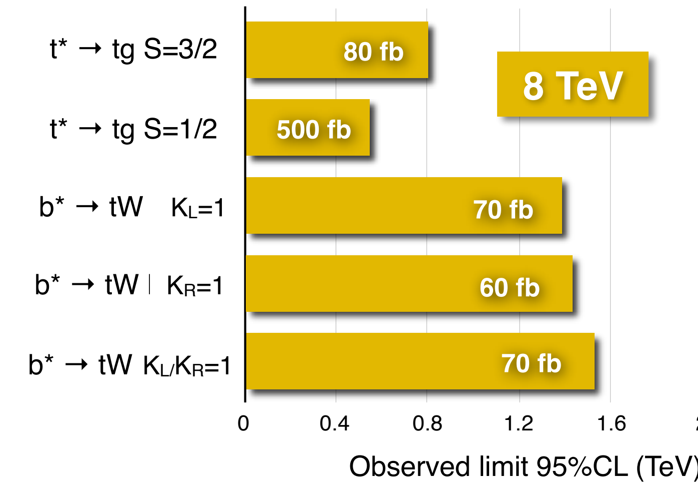
Vector-like quark single production



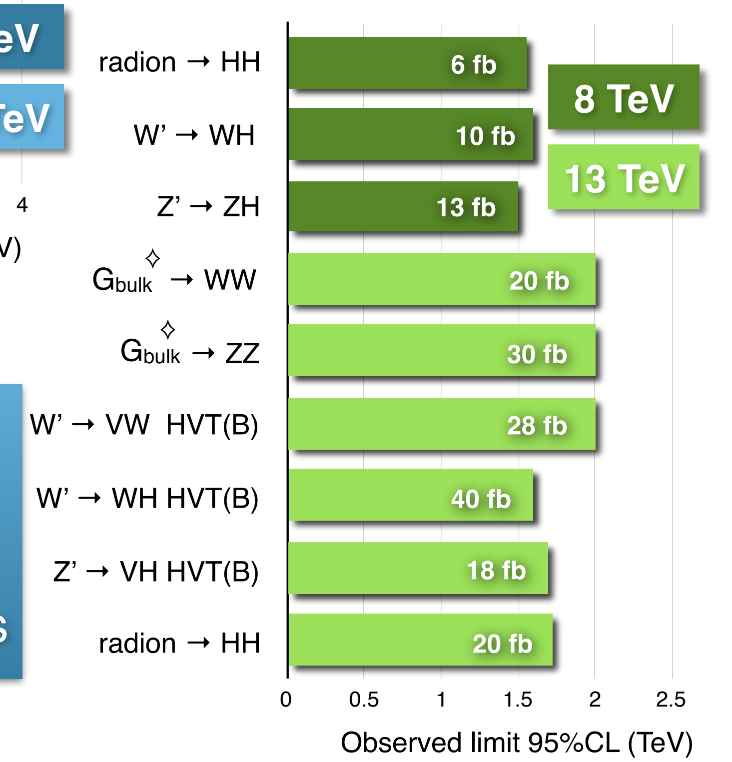
Resonances to heavy quarks



Excited quarks



Resonances to dibosons



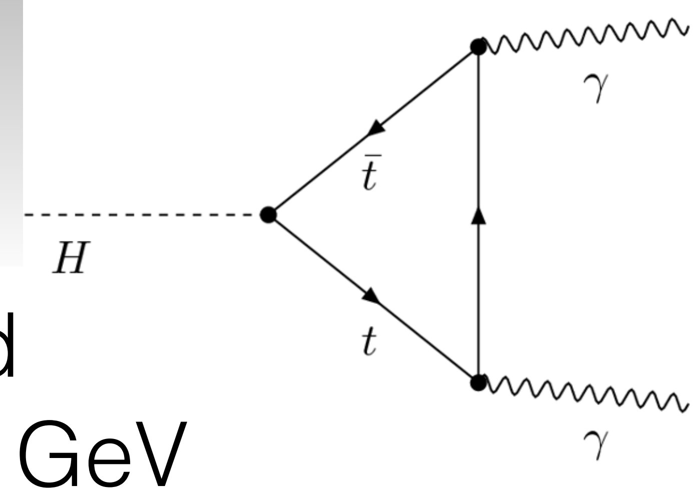
◊model-independent

B2G
new physics searches with heavy SM particles

- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G

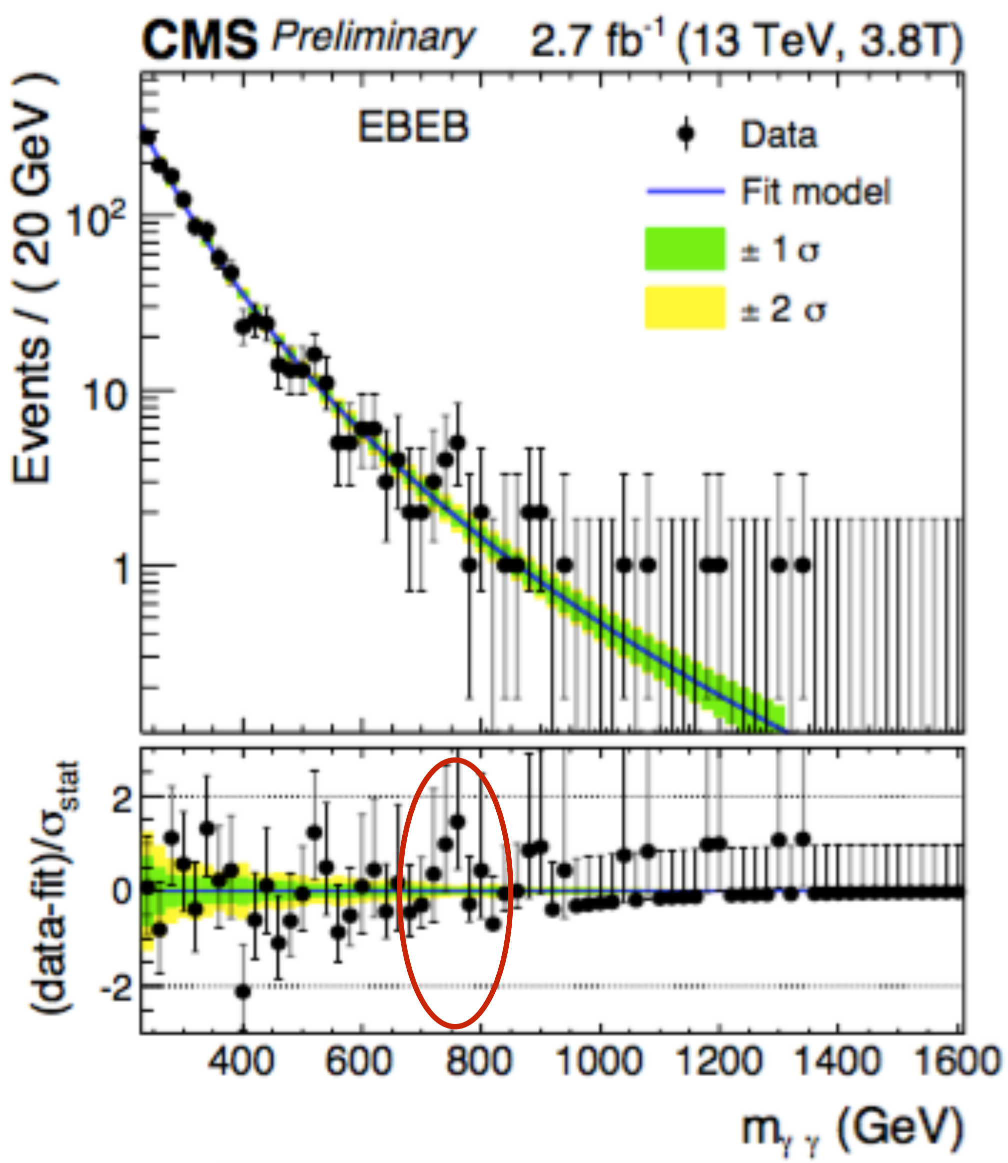
X $\rightarrow$ Dibosons

X(750) → γγ

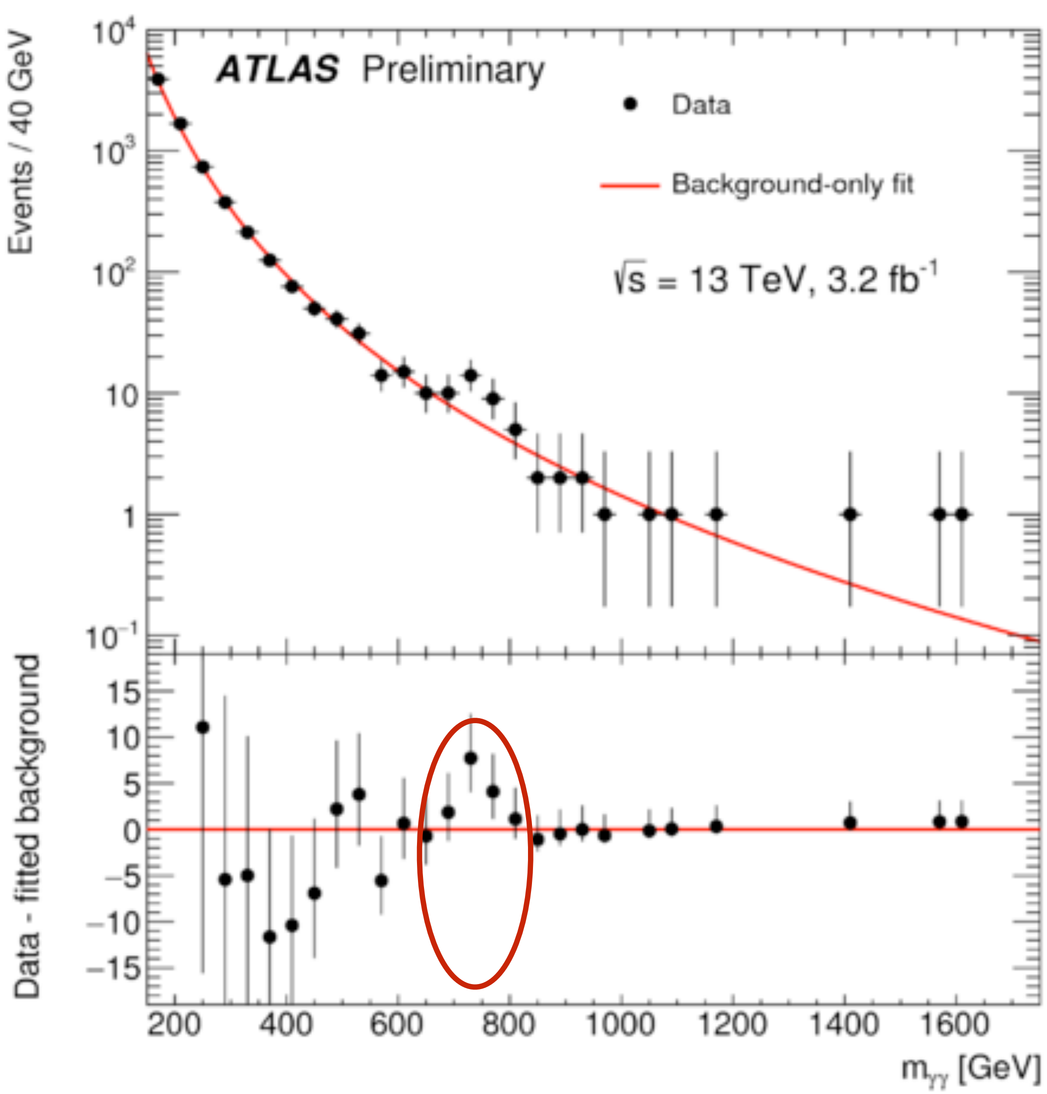


- From Dec 2015 to March 2016, both ATLAS and CMS observe a diphoton excess of around 750 GeV

Phys. Rev. Lett. 117 | 2015 data



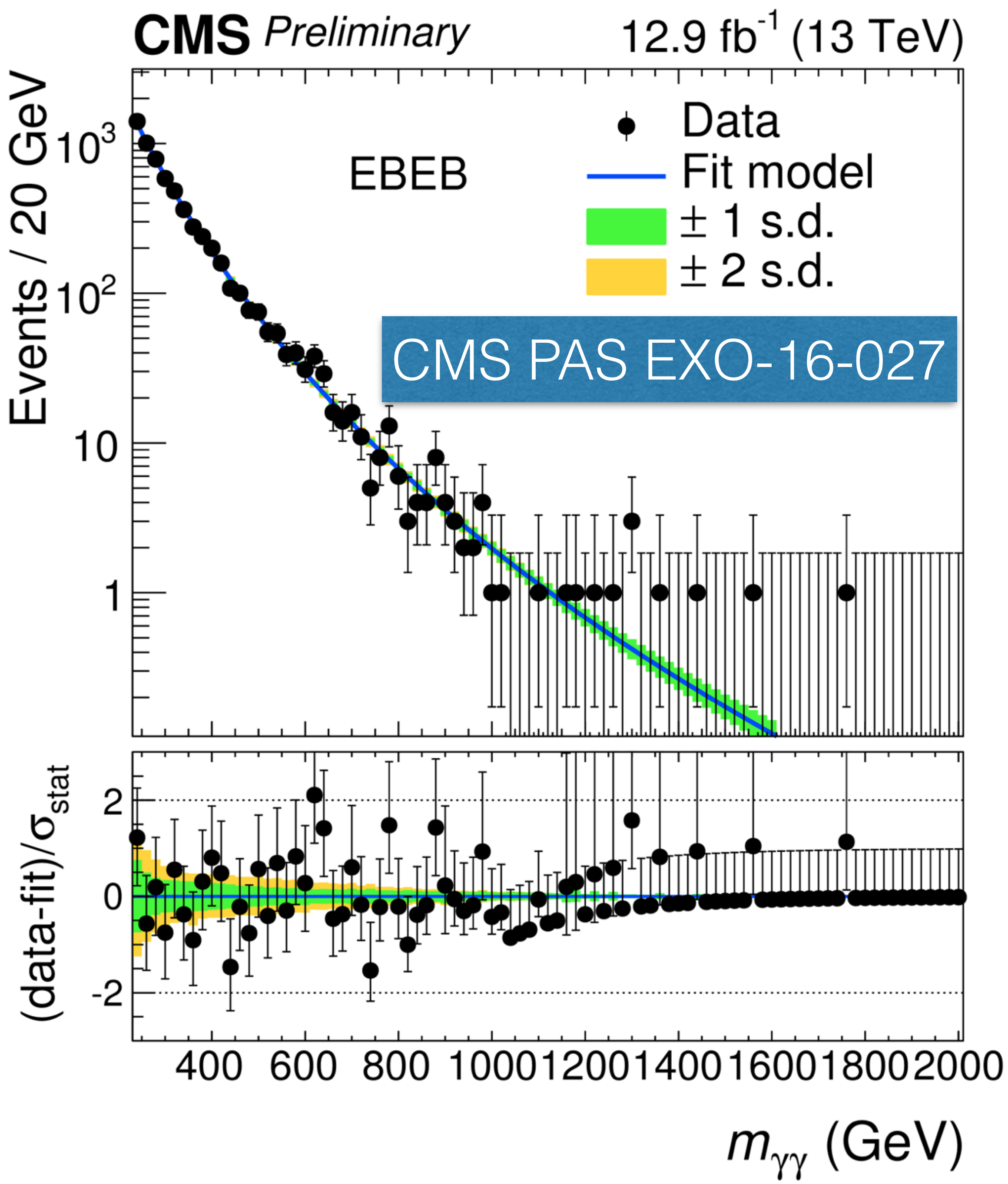
ATLAS-CONF-2015-081 | 2015 data



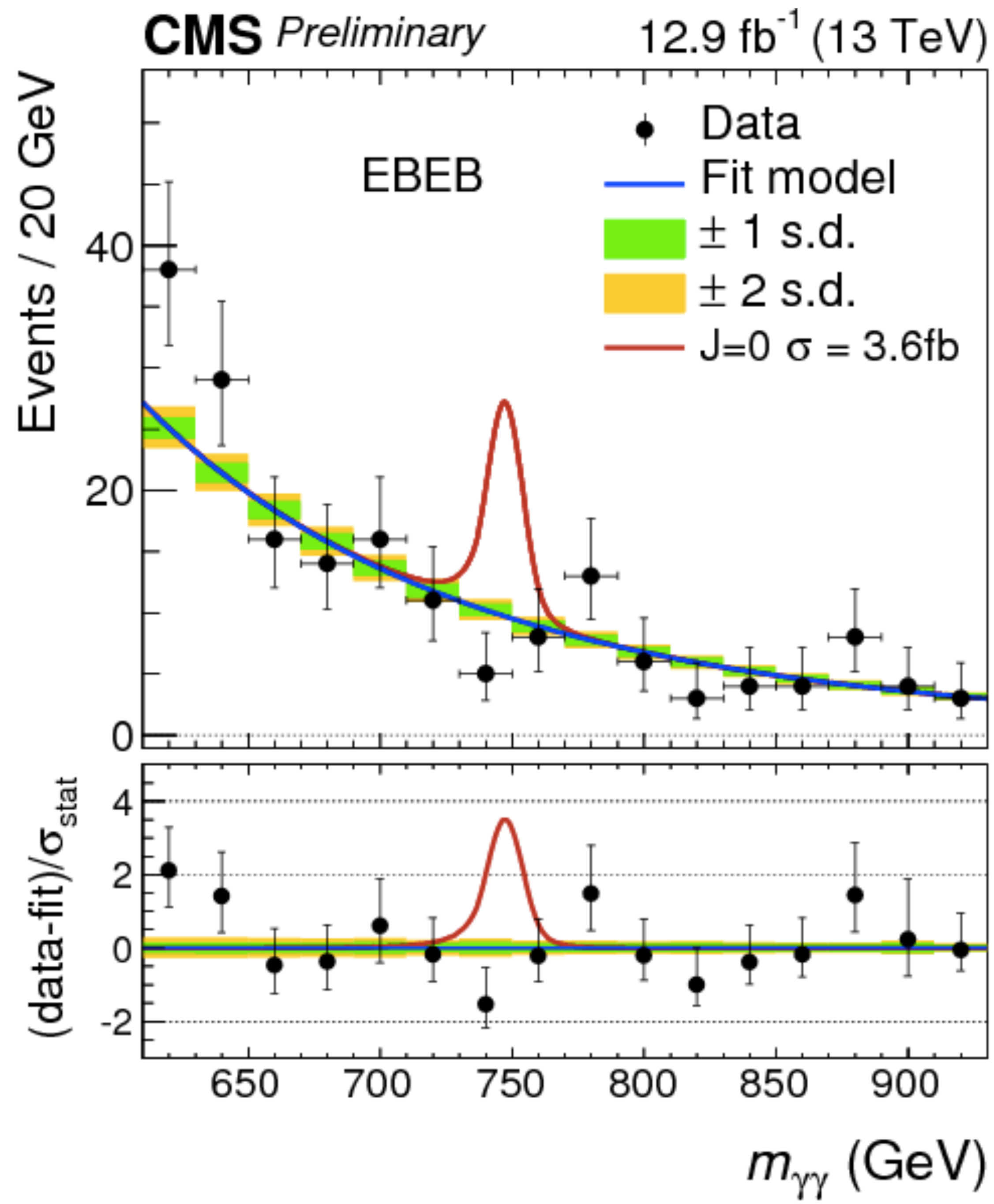
Moriond: CMS (ATLAS) saw 3.4 (3.9) σ global significance

X(750) → γγ

- What is seen now



- What we would have seen



”...just to mess with phenomenologists…”

Papers citing diphoton fluctuation

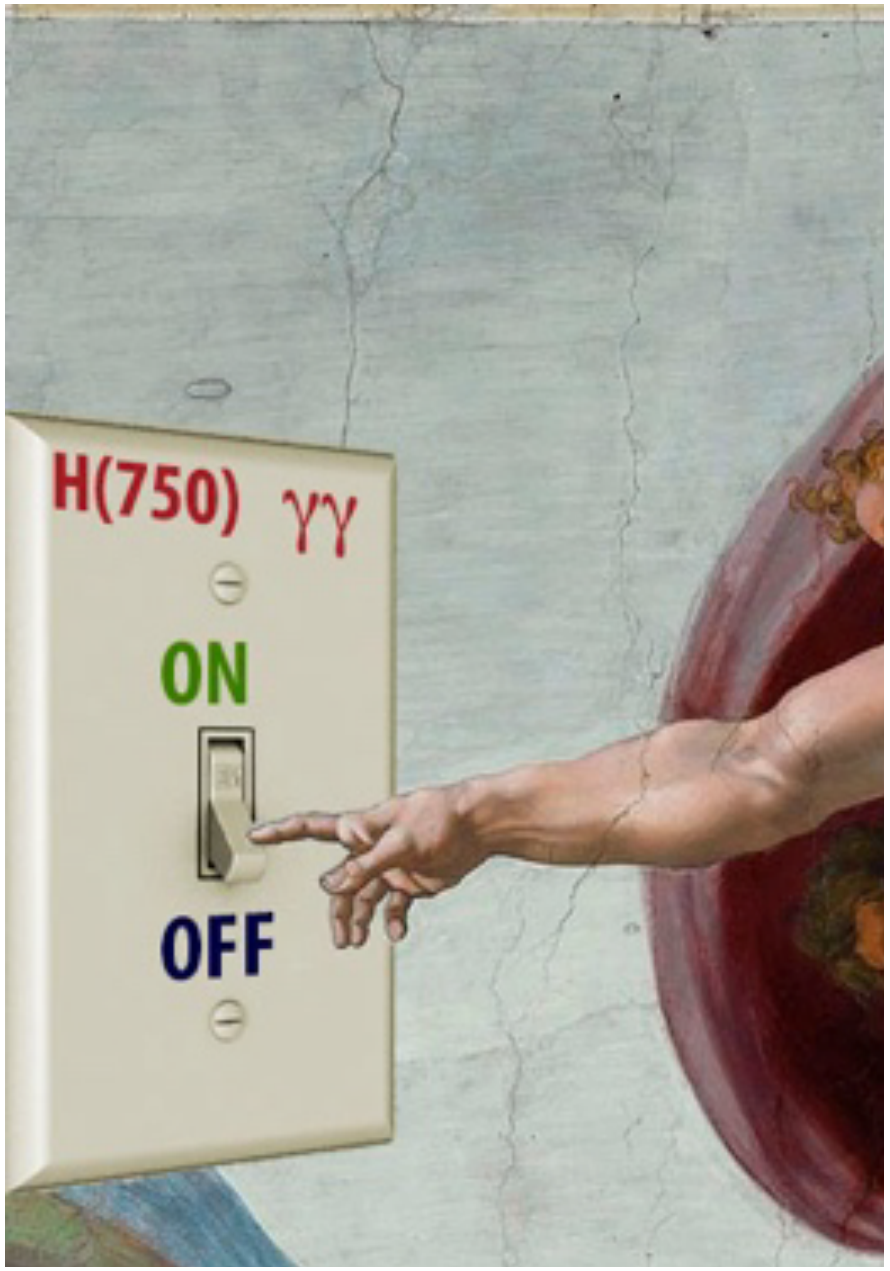
Citations summary

Generated on 2016-07-27

422 papers found, 412 of them citeable (published or arXiv)

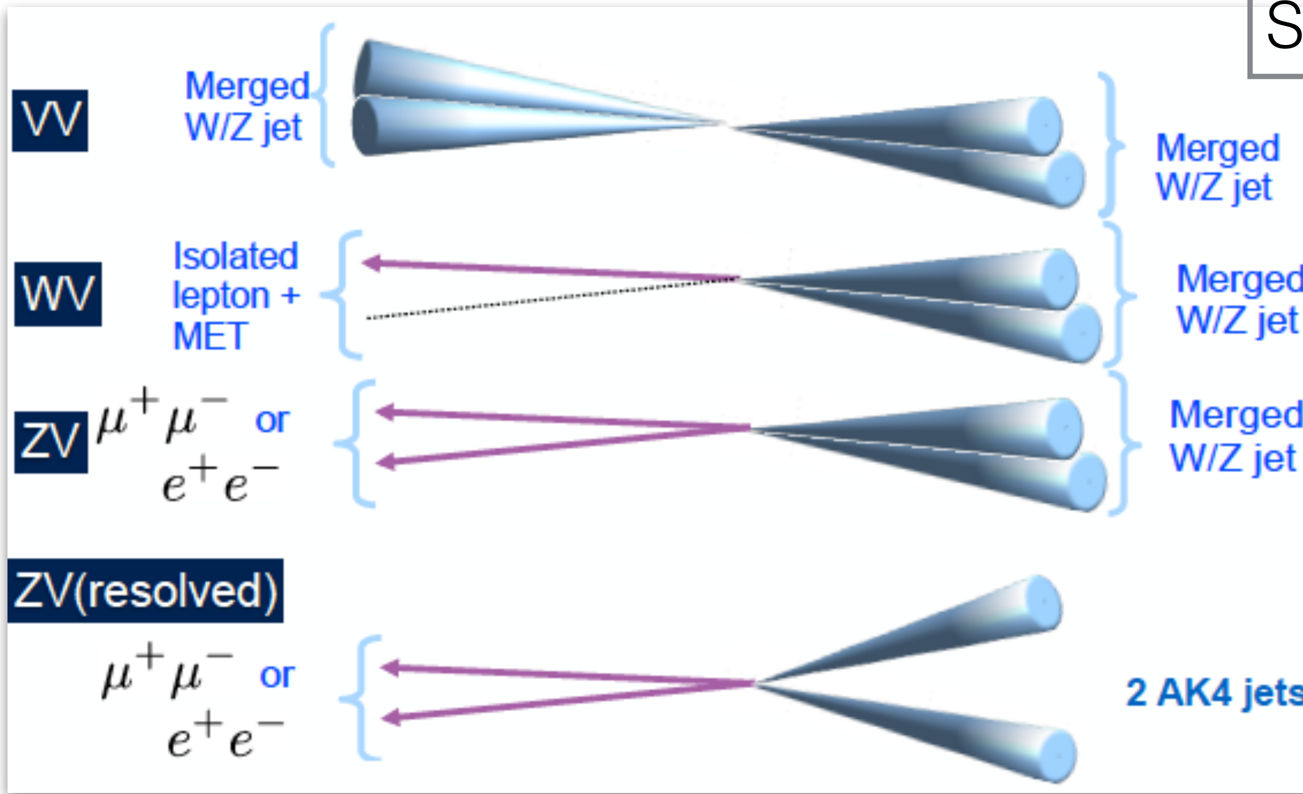
Citation summary results	Citeable papers	Published only
Total number of papers analyzed:	412	206
Total number of citations:	17,418	12,429
Average citations per paper:	42.3	60.3
Breakdown of papers by citations:		
Renowned papers (500+)	0	0
Famous papers (250-499)	0	0
Very well-known papers (100-249)	70	53
Well-known papers (50-99)	61	41
Known papers (10-49)	106	70
Less known papers (1-9)	131	36
Unknown papers (0)	44	6
h_{HEP} index [?]	87	70

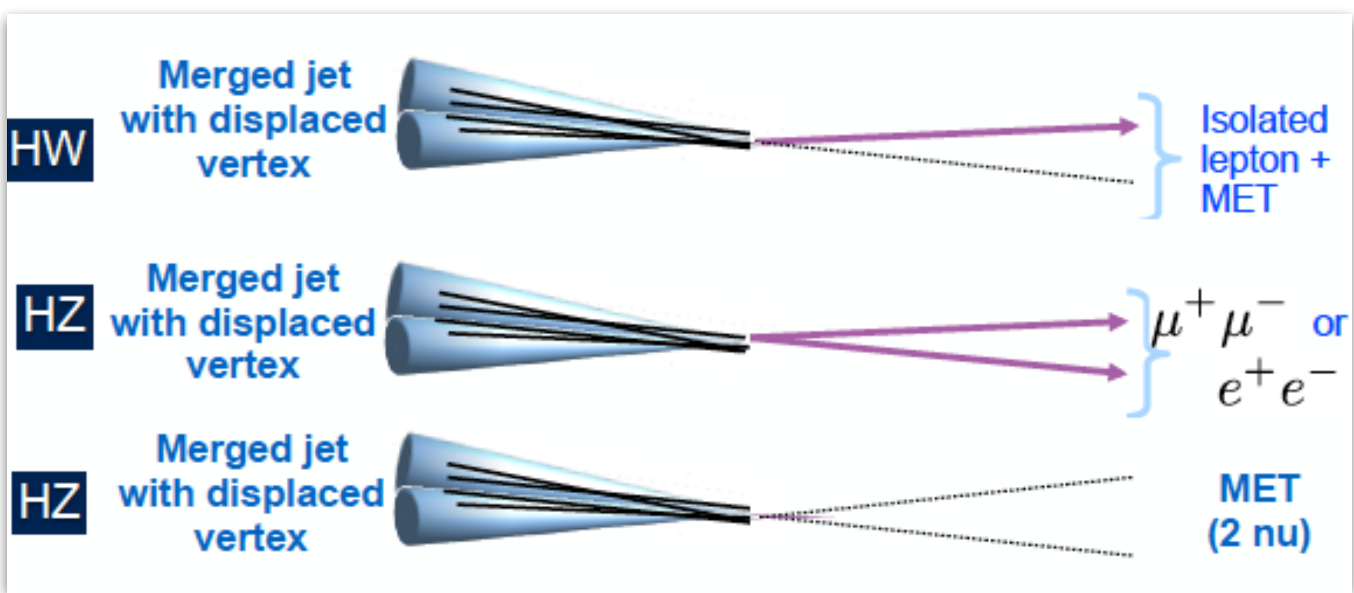
See additional metrics

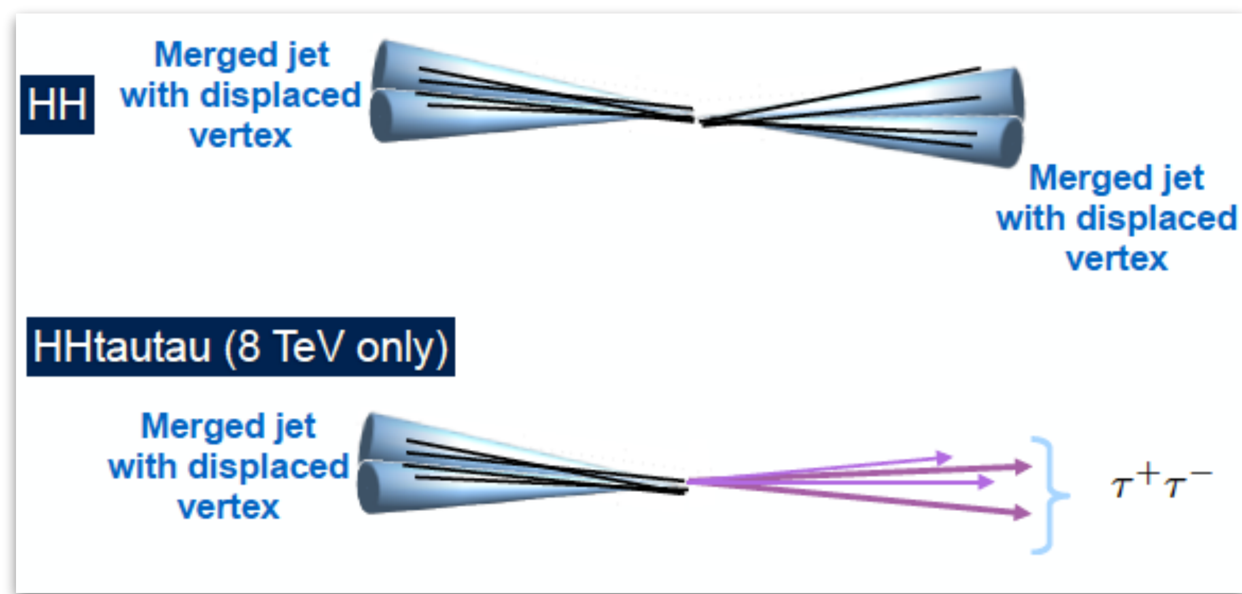


VV / WV / ZV / HW / HV / HH

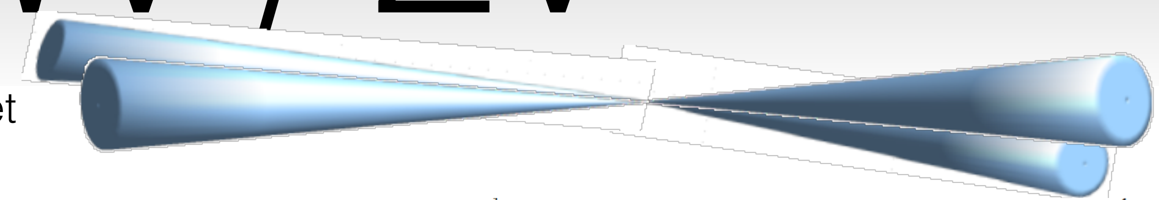
S.Rappoccio, ICHEP 2016



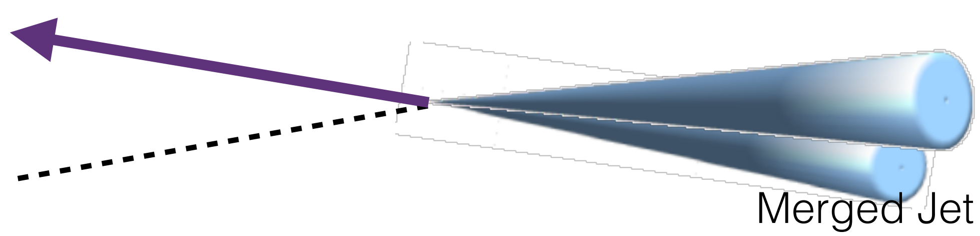


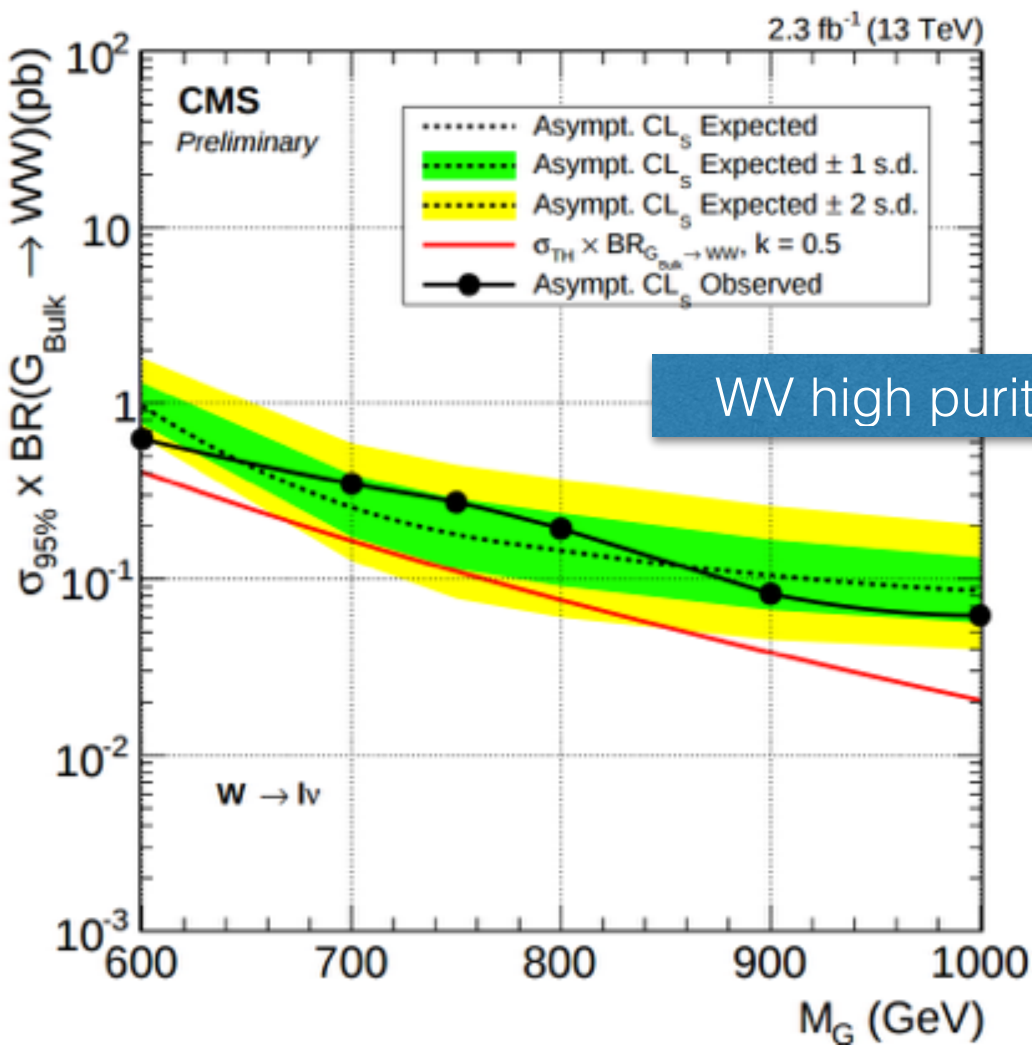


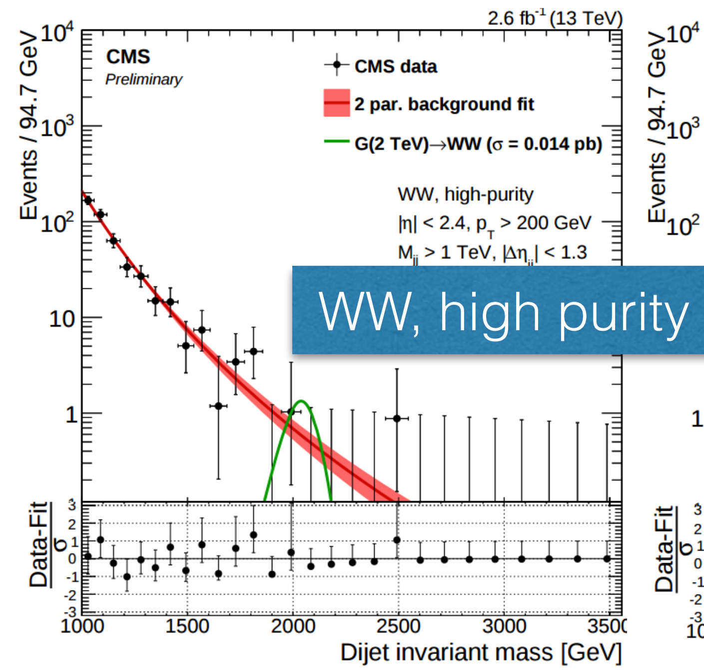
VV / WV / ZV

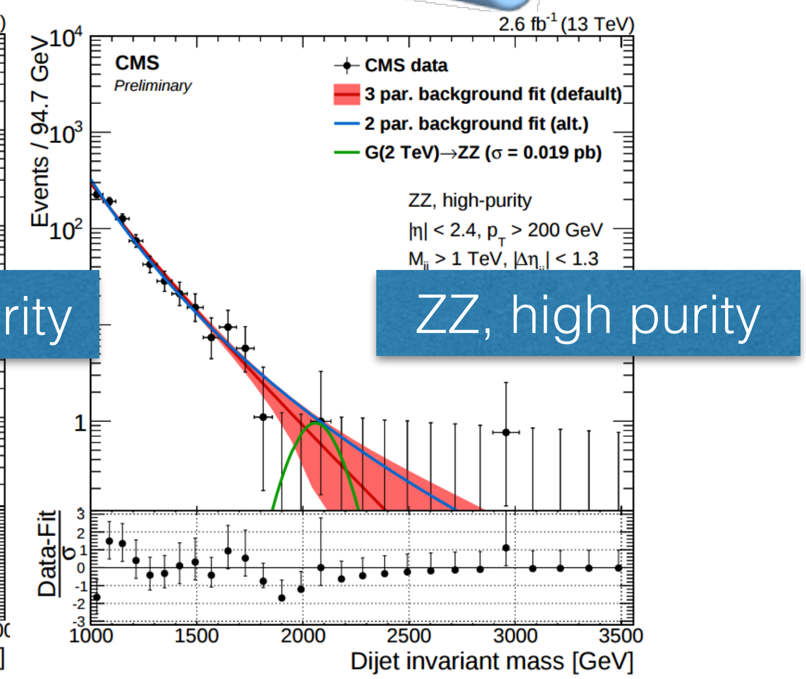


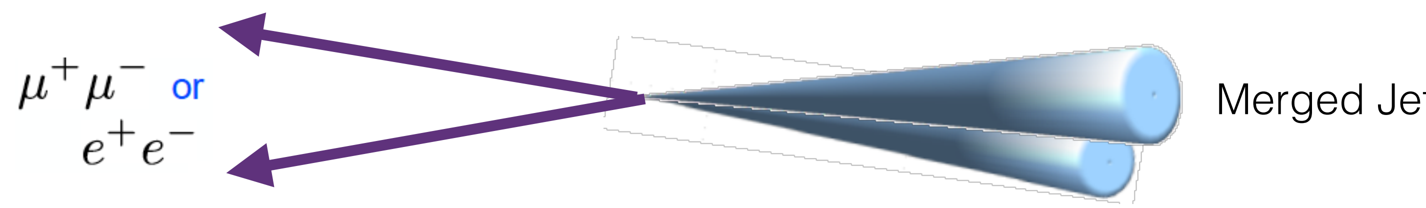
EXO-15-002, B2G-16-004, B2G-16-010

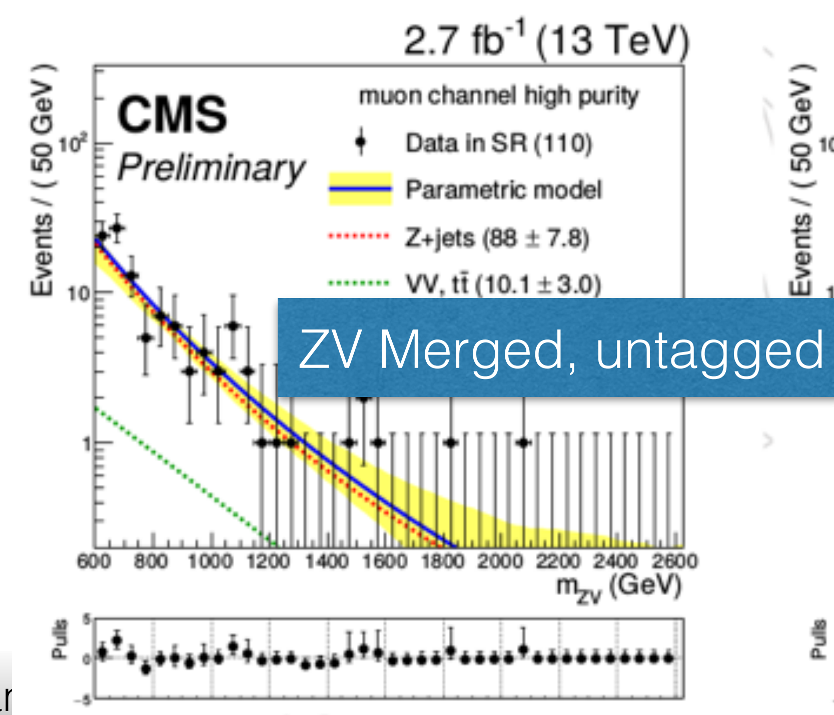


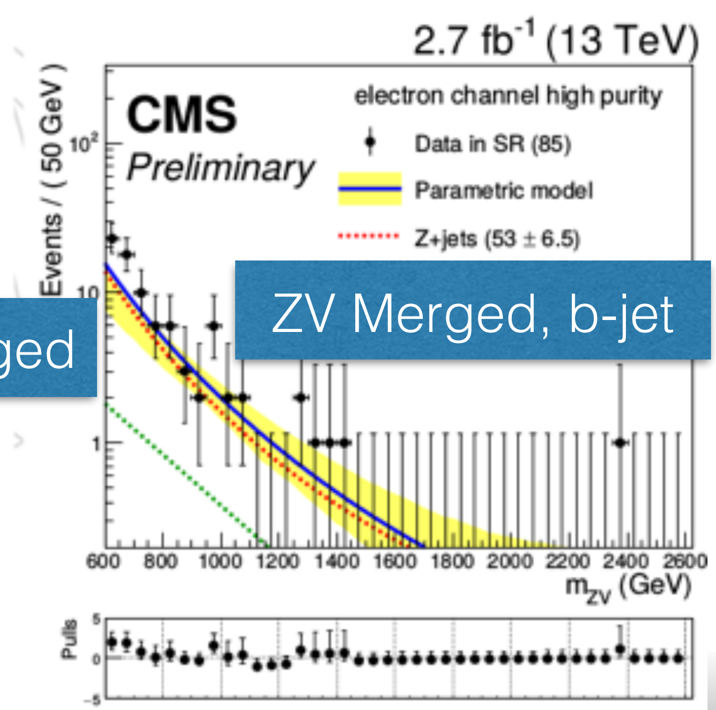








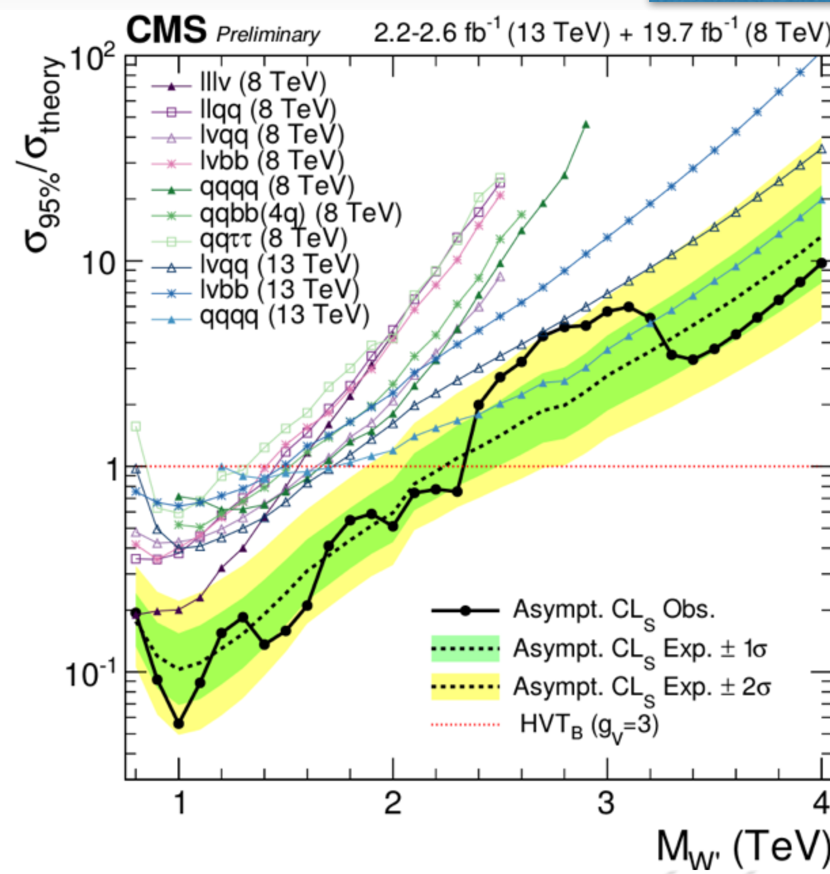




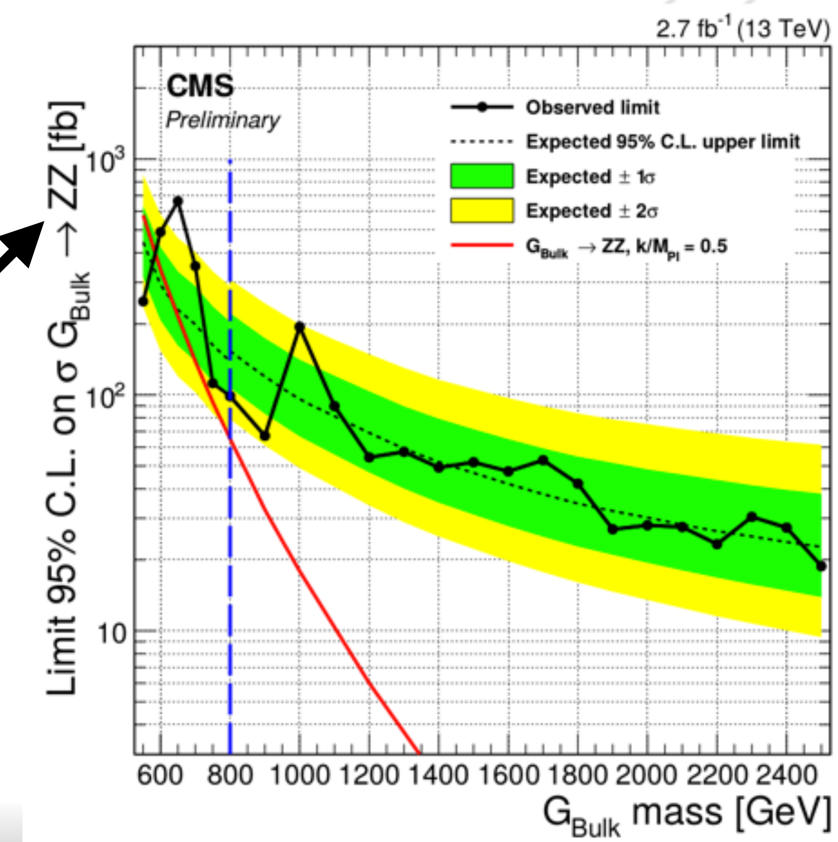
8 + 13 TeV Combination

B2G-16-007

- Combinations prepared for several models of
  - Composite H: W′→WZ/WH, Z′→WW/ZH
  - RS Graviton
  - Bulk Graviton: G_{bulk}→WW/ZZ
  - Heavy Vector Triplet (reference)
- Combined all available channels except ZV, HV, HH 13 TeV

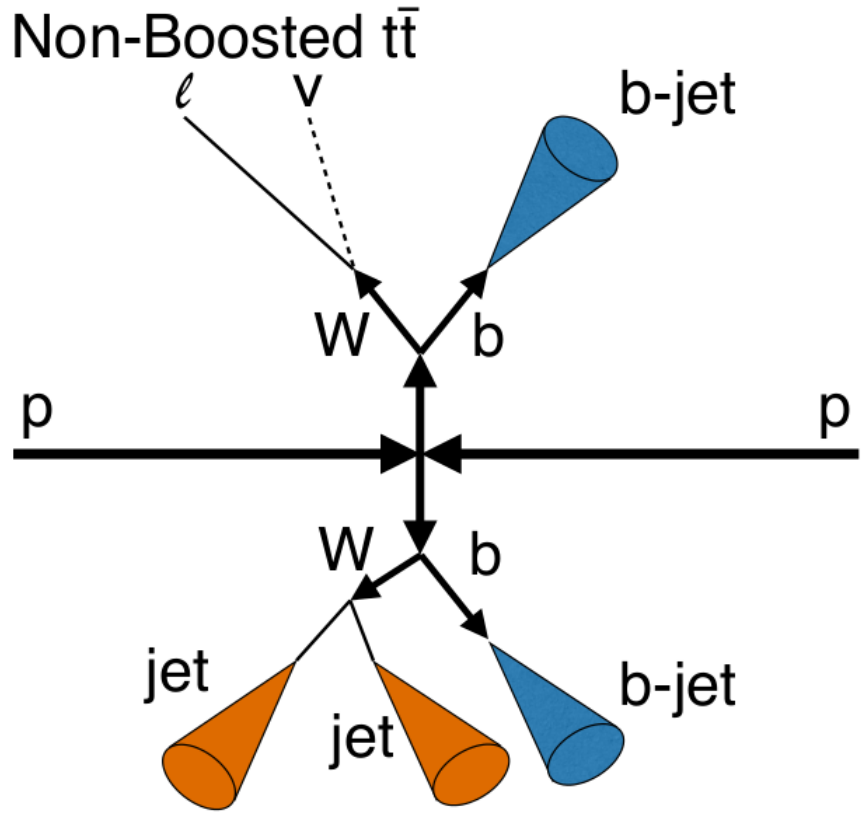


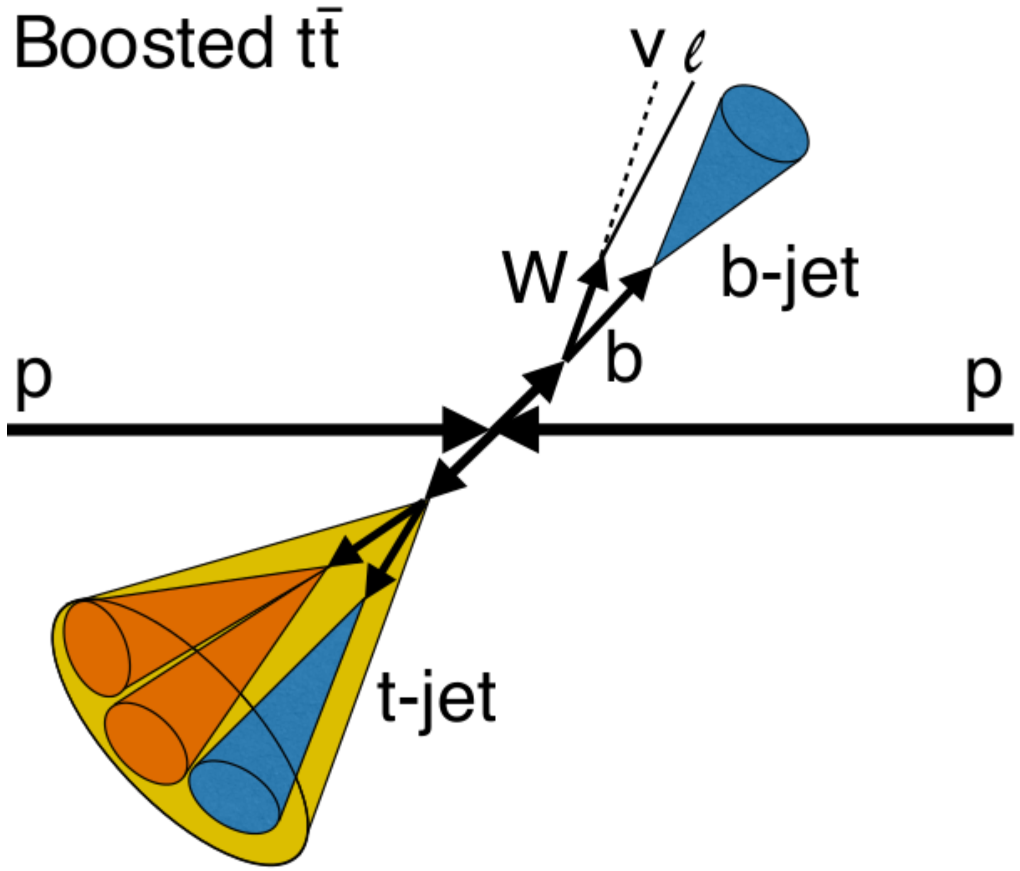
- #650: 3.9 sigma local, 3.5 sigma global
  - However, need to look else where effect for other masses this plot



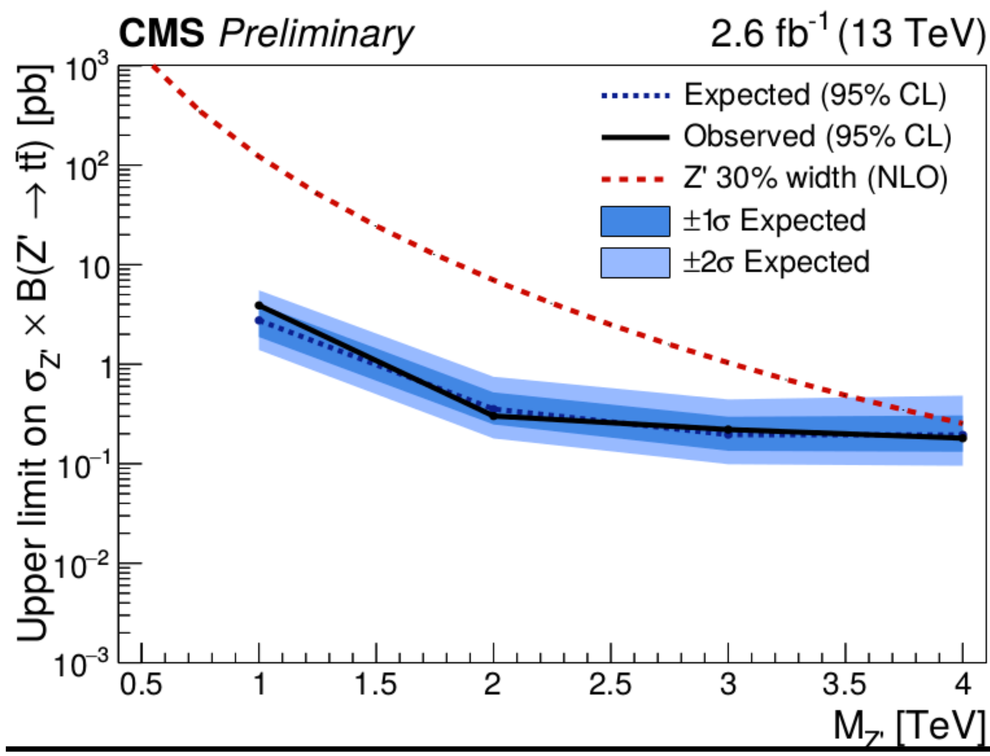
X → third gen quarks

example: Z′→tt



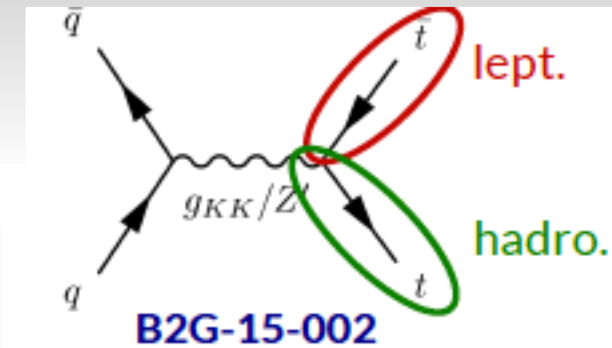


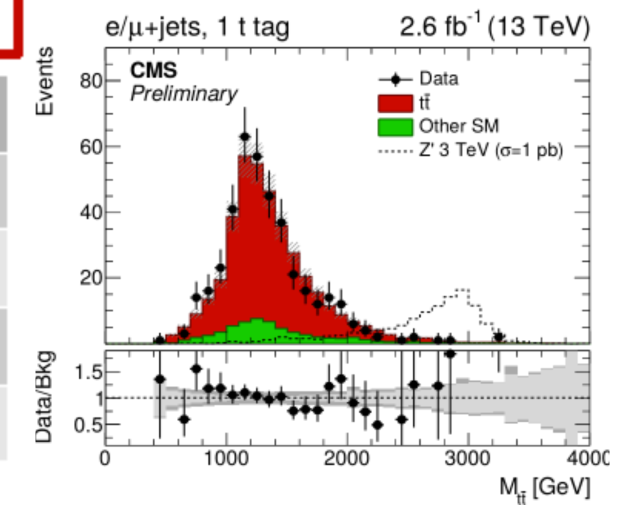
Z′ →tt

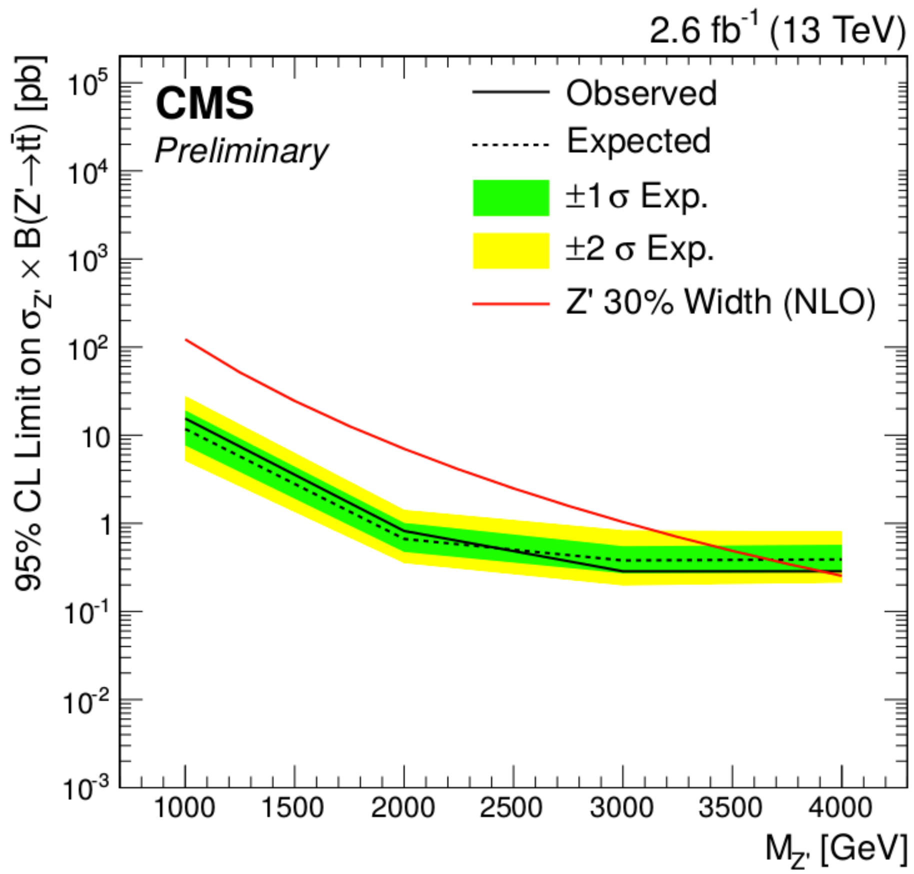


Signal regions : μ/e channel ⊗	1 t-tag 0 t-tag, 1 b-tag 0 t-tag, 0 b-tag

Signal	Observed exclusion
Narrow Z' (1%)	[0.6 – 2.3] TeV
Wide Z' (10%)	[0.5 – 3.4] TeV
Extra wide Z' (30%)	[1.0 – 4.0] TeV
KK gluon	[0.5 – 2.9] TeV

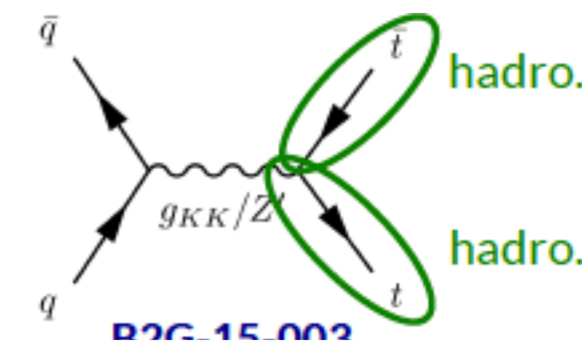




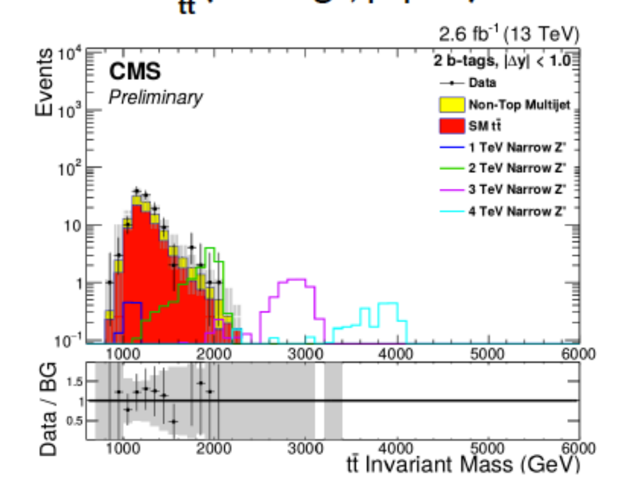


Signal regions :	$\Delta y(j_1,j_2) < 1.0$ $\Delta y(j_1,j_2) > 1.0$	⊗	1 t-tag 0 t-tag, 1 b-tag 0 t-tag, 0 b-tag

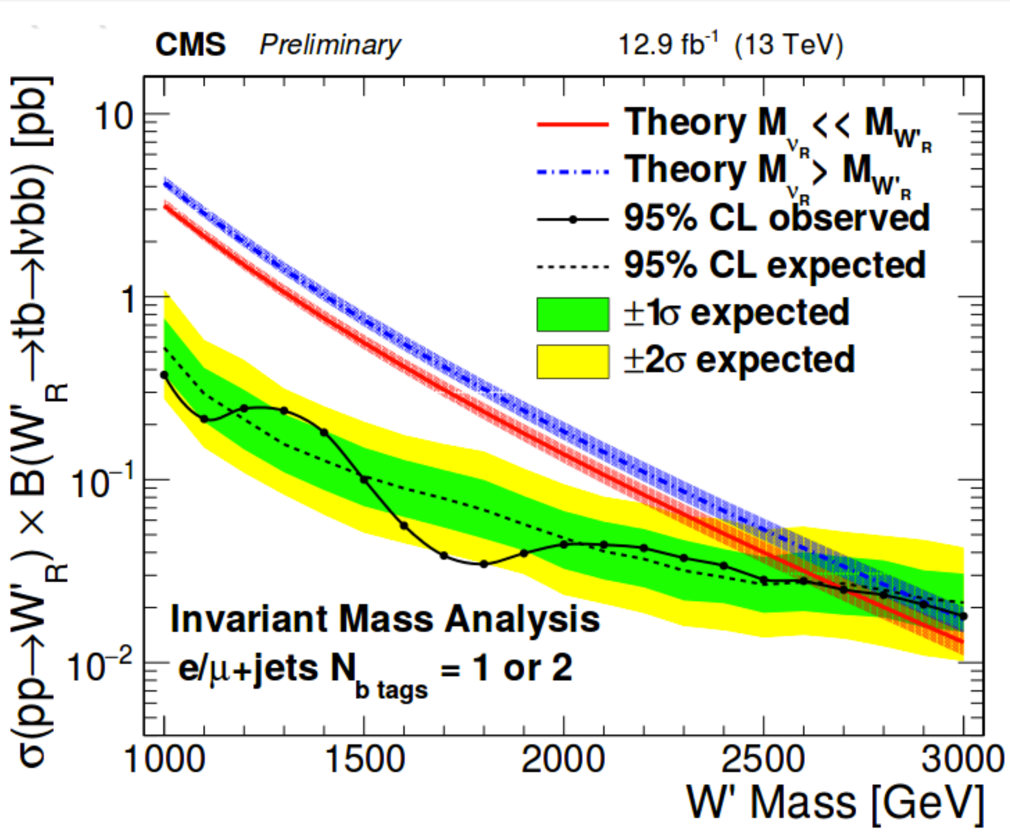
Signal	Observed exclusion
Narrow Z' (1%)	[1.4 – 1.6] TeV
Wide Z' (10%)	[1.0 – 3.3] TeV
Extra wide Z' (30%)	[1.0 – 3.8] TeV
KK gluon	[1.0 – 2.4] TeV

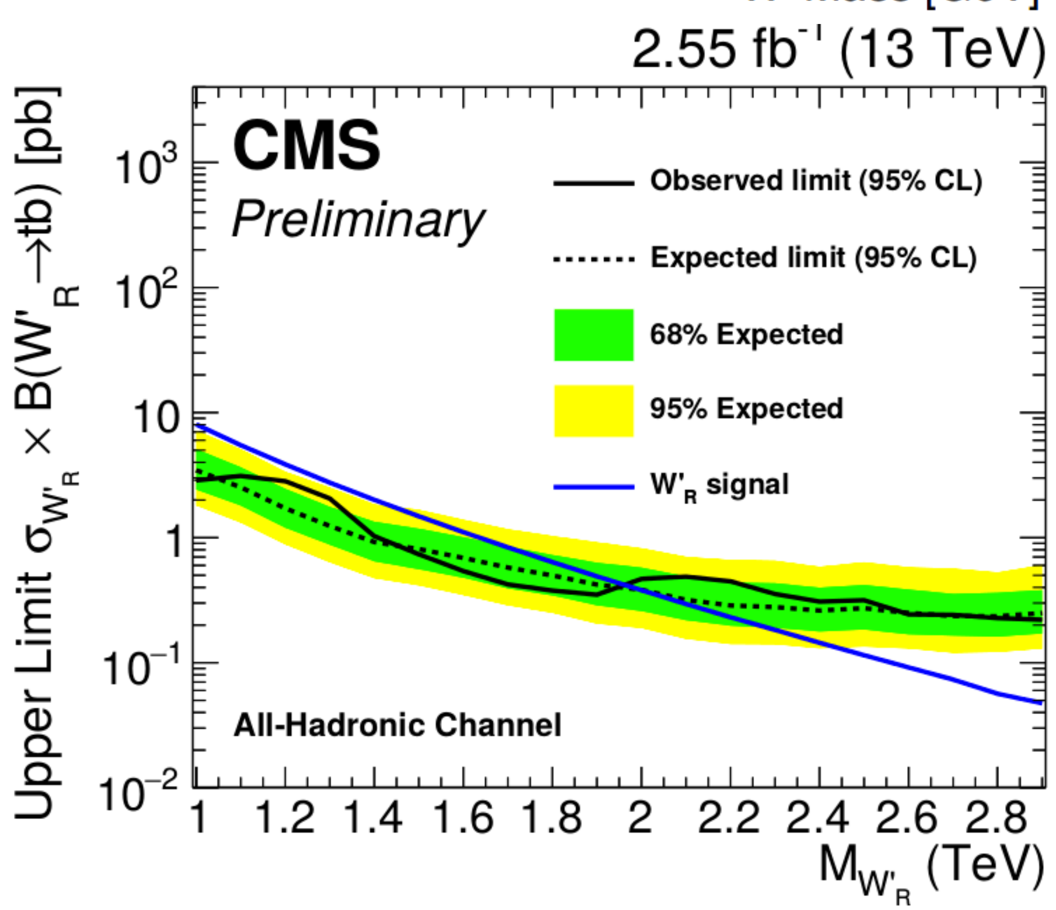


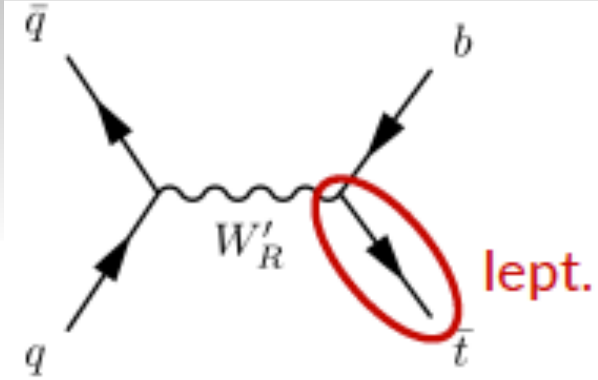
M_{tt} (2 b-tags, |Δ| < 1)



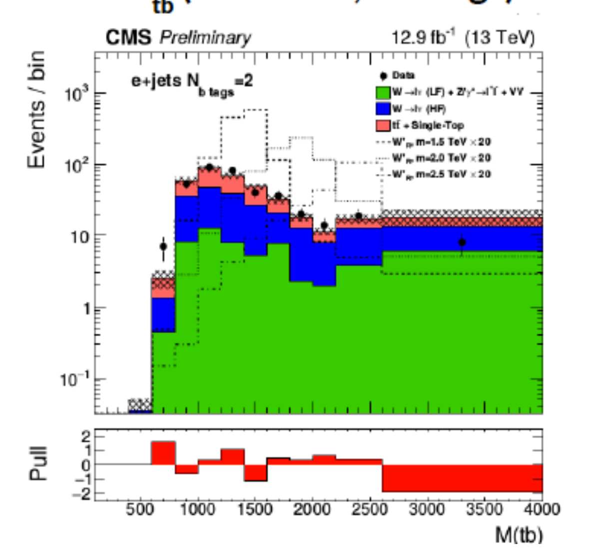
W′→tb







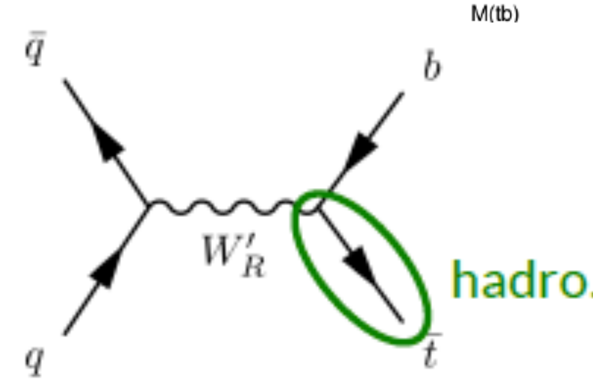
M_{tb} (e channel, 2 b-tags)



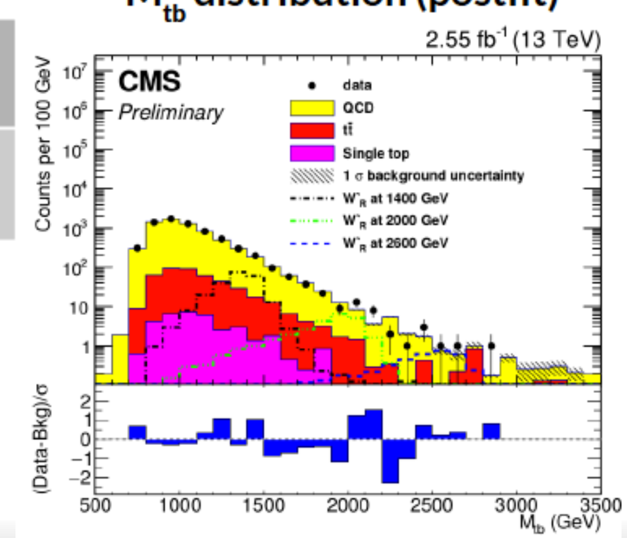
B2G-16-017

Signal	Observed exclusion
Narrow W'	[1.0 – 2.67] TeV

(+ 12 % w.r.t. B2G-15-004)



M_{tb} distribution (postfit)



B2G-16-009

Signal	Observed exclusion
Narrow W'	[1.0 – 2.0] TeV

Vector-like quarks

- Its a non-chiral matter and hence has its own mass:

$$\mathcal{L}_M = -M\bar{\psi}\psi$$ Gauge invariant mass term without the Higgs

- Transforms under the same representation of the SM *SU(3)$_C$×SU(2)$_W$×U(1)$_Y$* gauge symmetry

$$\mathcal{L}_W = \frac{g}{\sqrt{2}}\left(J^{\mu+}W^+_\mu + J^{\mu-}W^-_\mu\right)$$ Charged current Lagrangian

- SM chiral quarks: ONLY left-handed charged currents

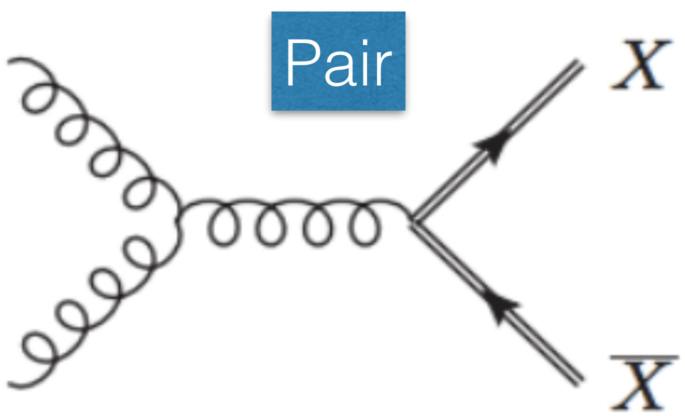
$$J^{\mu+} = J^{\mu+}_L + J^{\mu+}_R \quad \text{with} \quad \begin{cases} J^{\mu+}_L = \bar{u}_L\gamma^\mu d_L = \bar{u}\gamma^\mu(1-\gamma^5)d = V - A \\ J^{\mu+}_R = 0 \end{cases}$$

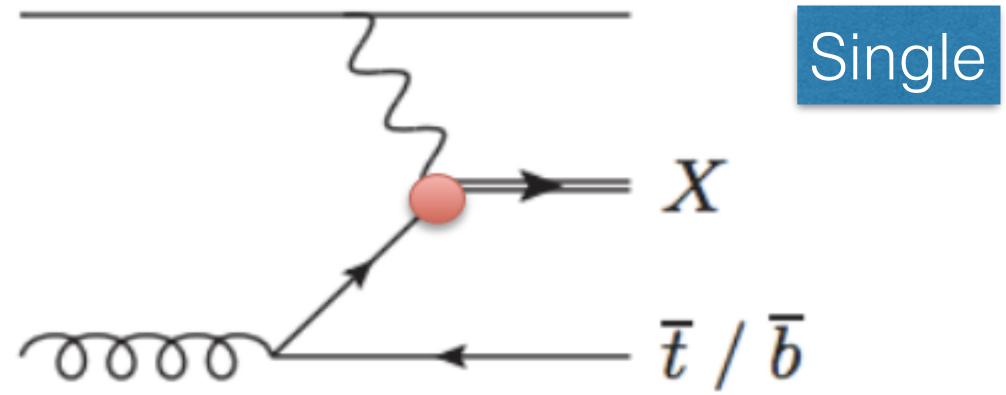
- vector-like quarks: BOTH left-handed and right-handed charged currents

$$J^{\mu+} = J^{\mu+}_L + J^{\mu+}_R = \bar{u}_L\gamma^\mu d_L + \bar{u}_R\gamma^\mu d_R = \bar{u}\gamma^\mu d = V$$

Vector-like quarks

- Production:



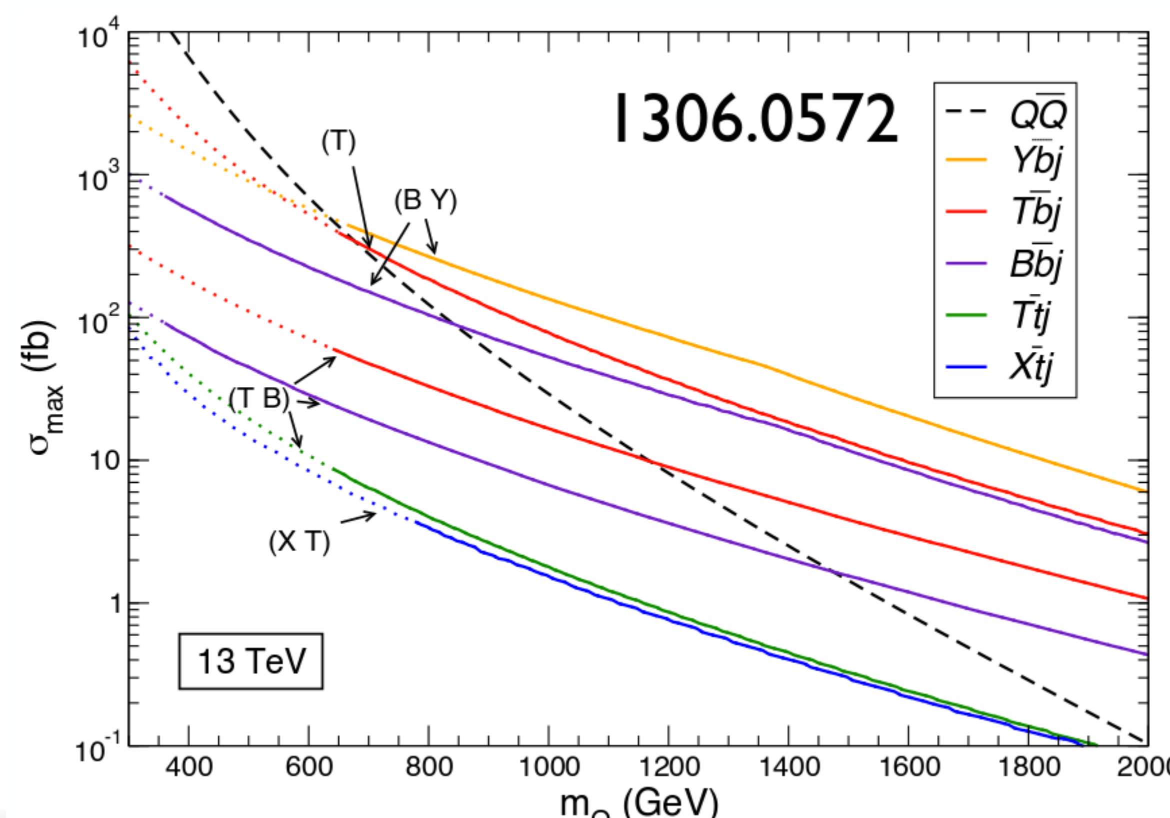


- Decays:

Pair: T → Wb, Zt, Ht; B → Wt, Zb, Hb

Table 1: Branching ratios, following the equivalence theorem

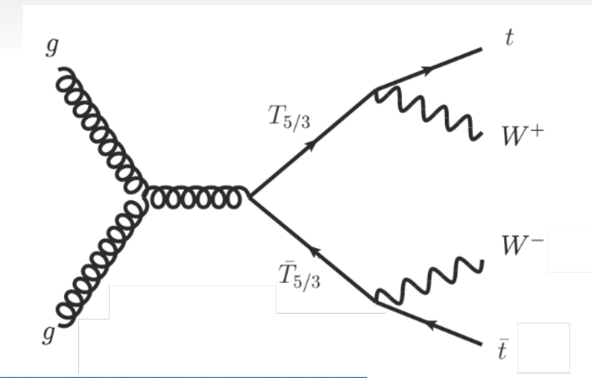
BR	Wt	Wb	Zt	Zb	ht	hb	Chirality
T23 singlet	0	1/2	1/4	0	1/4	0	L
T23 doublet	0	0	1/2	0	1/2	0	R
X53 doublet	1	0	0	0	0	0	L/R
B13 singlet	1/2	0	0	1/4	0	1/4	L
B13 doublet	1	0	0	0	0	0	R
Y43 triplet	0	1	0	0	0	0	L/R



VLQ: Pair production

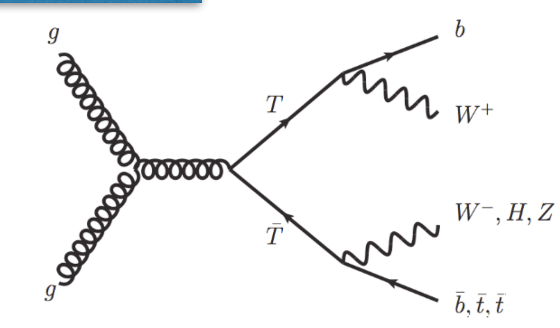
B2G-15-006

- Search for $X_{5/3} \to tW$ in same-sign 2ℓ and ℓ+jets final states

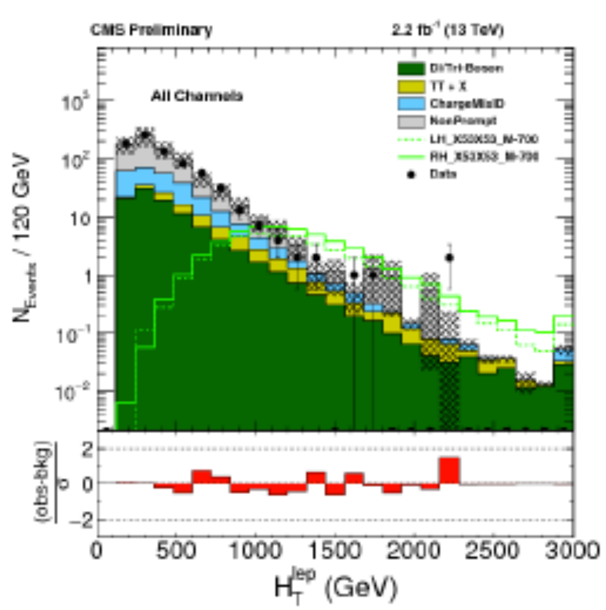


- Search for $T_{2/3} \to bW(50\%)$, $tZ(25\%)$, $tH(25\%)$ in ℓ+jets
  - Inclusive analysis targeting singlet VLQ decay combination
  - Single lepton final state will be joined by boosted Higgs, 2ℓ, and 3ℓ states

B2G-16-002

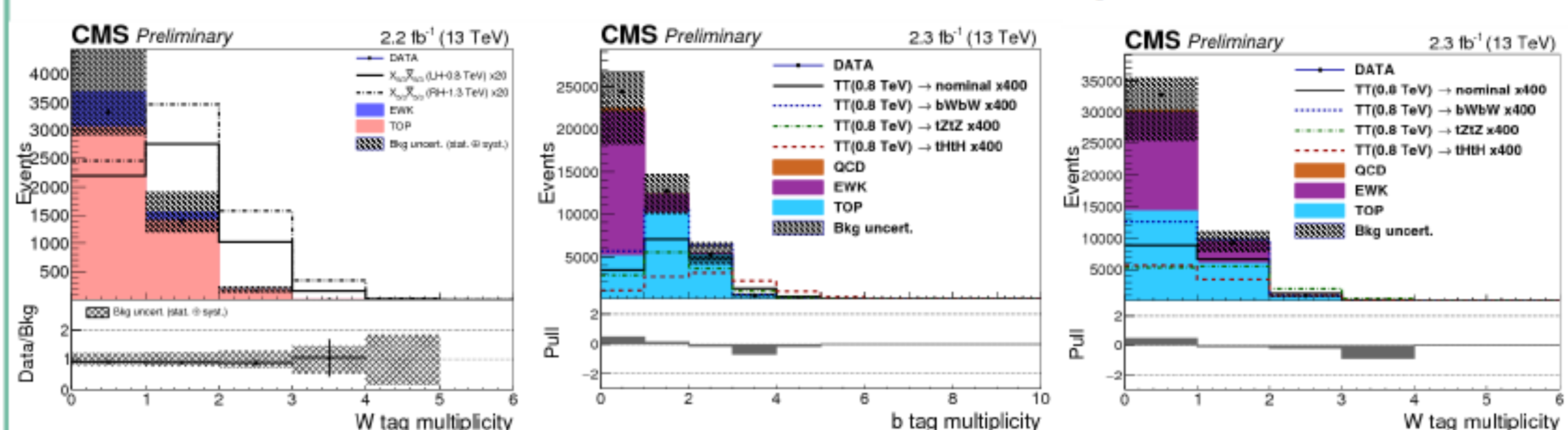


SS 2ℓ: cut & count in lepton categories, data-driven non-prompt/charge mis-ID bkgd



ℓ+jets: XX → 4W + 2b, TT → 6 final states! Reconstructing M(VLQ) with 1ℓ + jets becomes unfeasible. Maximize sensitivity by categorizing according to jet tags: (e, μ) x (0, 1, 2, 3+ b jets) x (0, 1+ W jets).

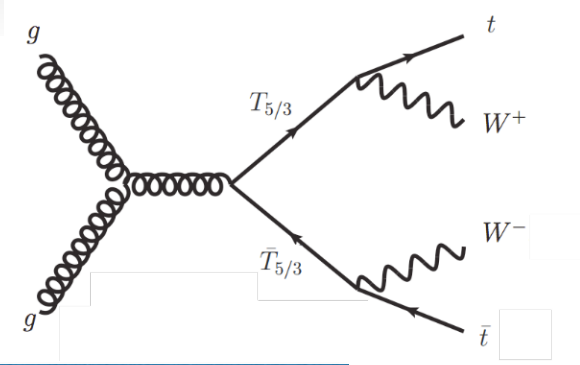
W jet: $M_P + \tau_2/\tau_1 < 0.55$ (X), 0.6 (T)



VLQ: Pair production

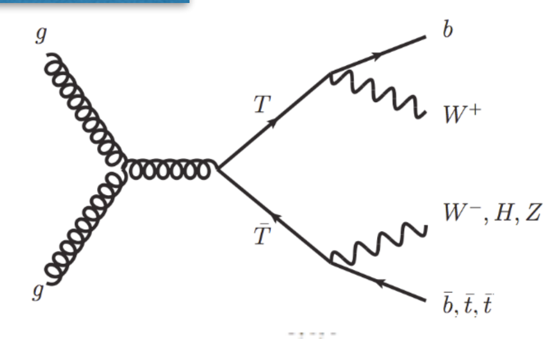
B2G-15-006

- Search for $X_{5/3} \to tW$ in same-sign 2ℓ and ℓ+jets final states

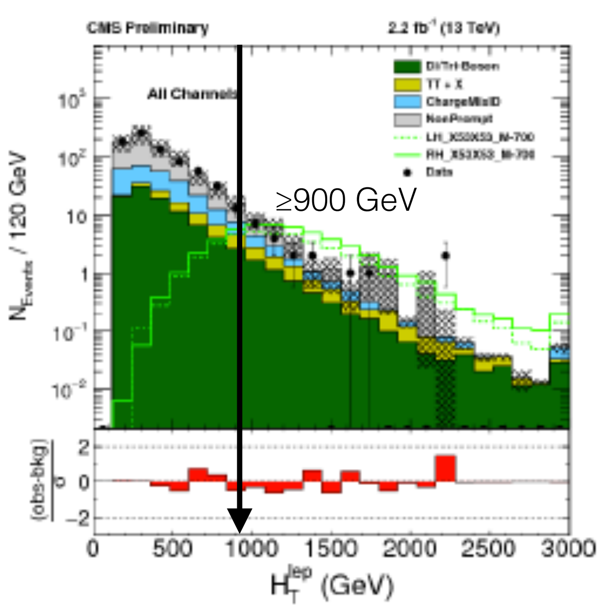


- Search for $T_{2/3} \to bW(50\%)$, $tZ(25\%)$, $tH(25\%)$ in ℓ+jets
  - Inclusive analysis targeting singlet VLQ decay combination
  - Single lepton final state will be joined by boosted Higgs, 2ℓ, and 3ℓ states

B2G-16-002

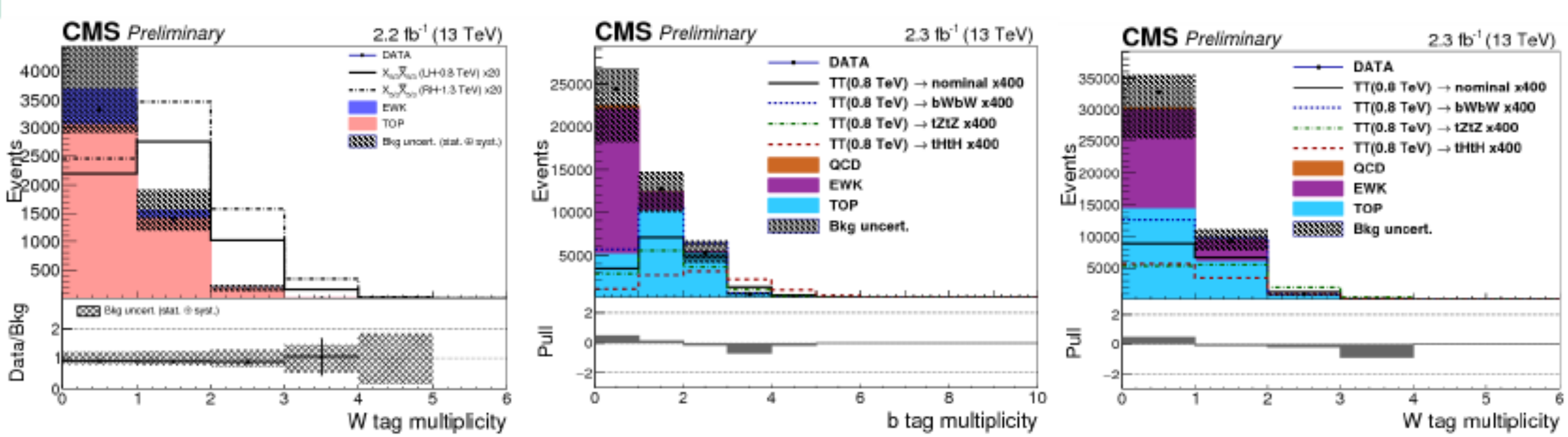


SS 2ℓ: cut & count in lepton categories, data-driven non-prompt/charge mis-ID bkgd



ℓ+jets: XX → 4W + 2b, TT → 6 final states! Reconstructing M(VLQ) with 1ℓ + jets becomes unfeasible. Maximize sensitivity by categorizing according to jet tags: (e, μ) x (0, 1, 2, 3+ b jets) x (0, 1+ W jets).

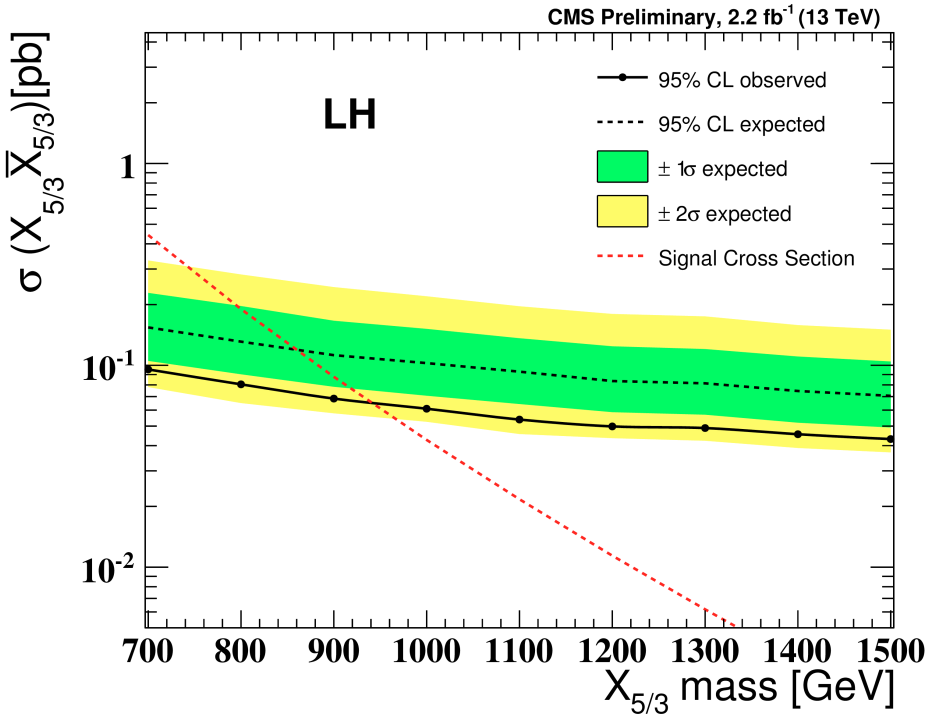
W jet: $M_P + \tau_2/\tau_1 < 0.55$ (X), 0.6 (T)

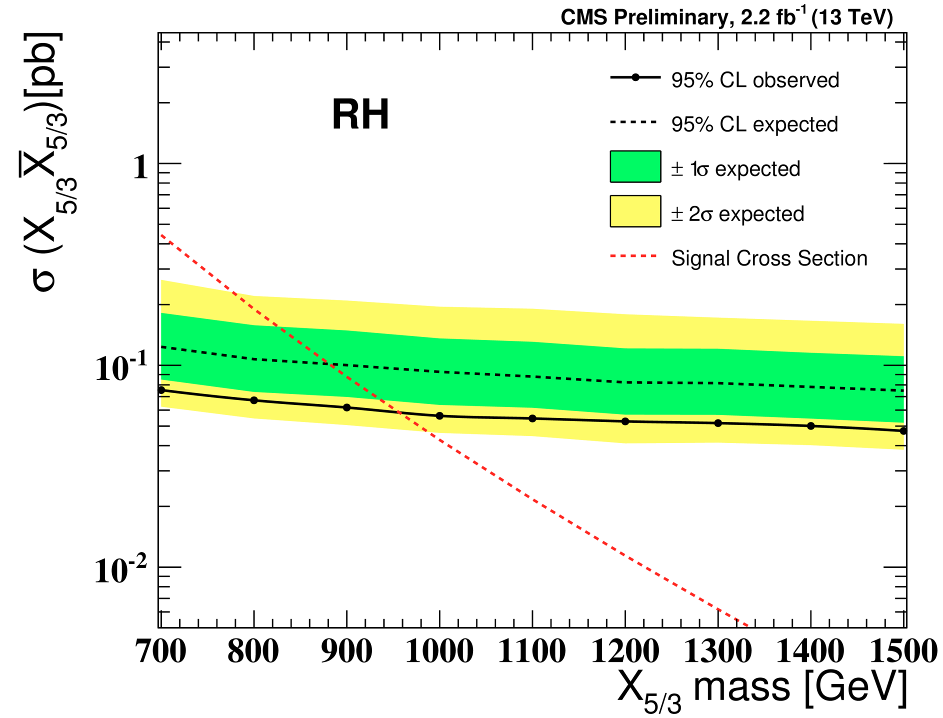


VLQ: Pair production

- $X_{5/3} \to tW$

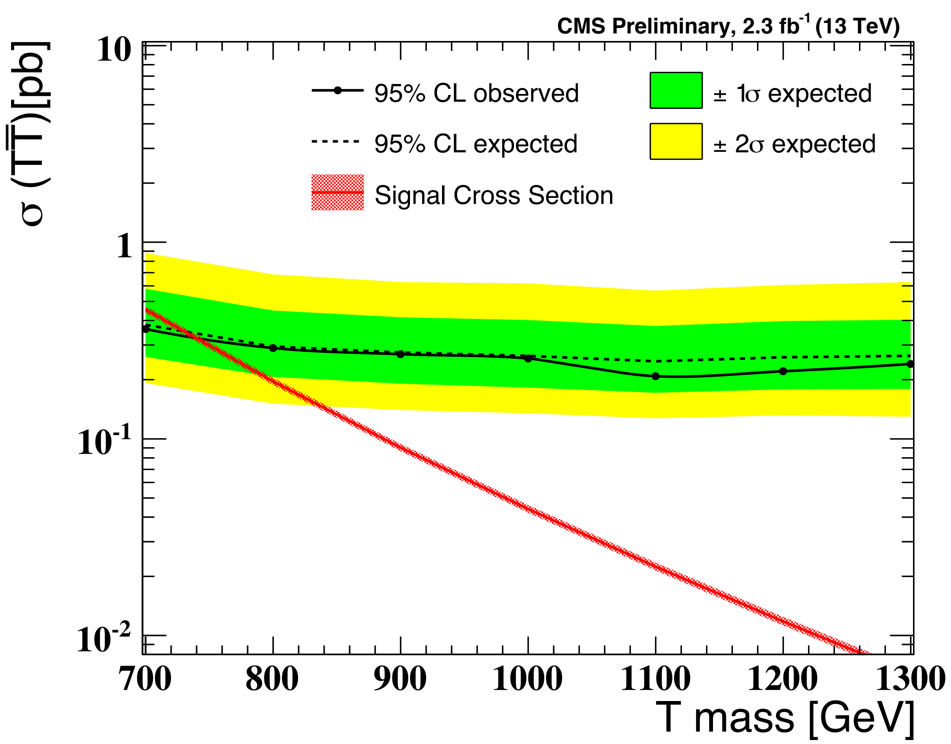
B2G-15-006

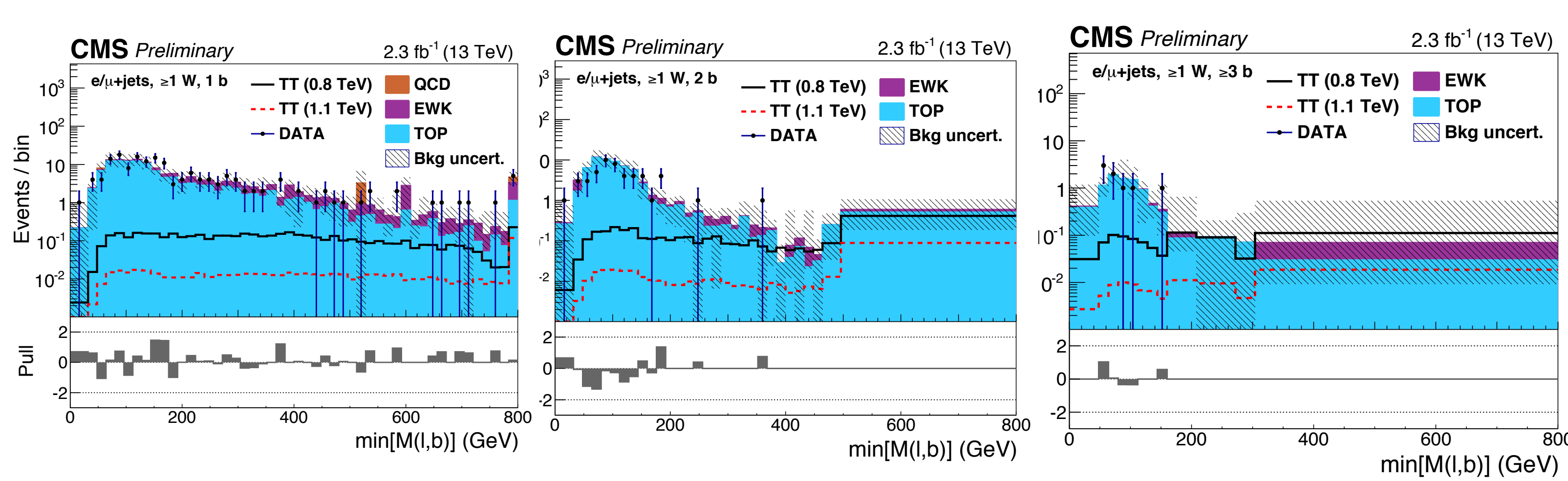




- $T_{2/3} \to bW$: From combination of all exclusive regions, the search has sensitivity of 750 GeV, considering T as isospin singlet

B2G-16-002

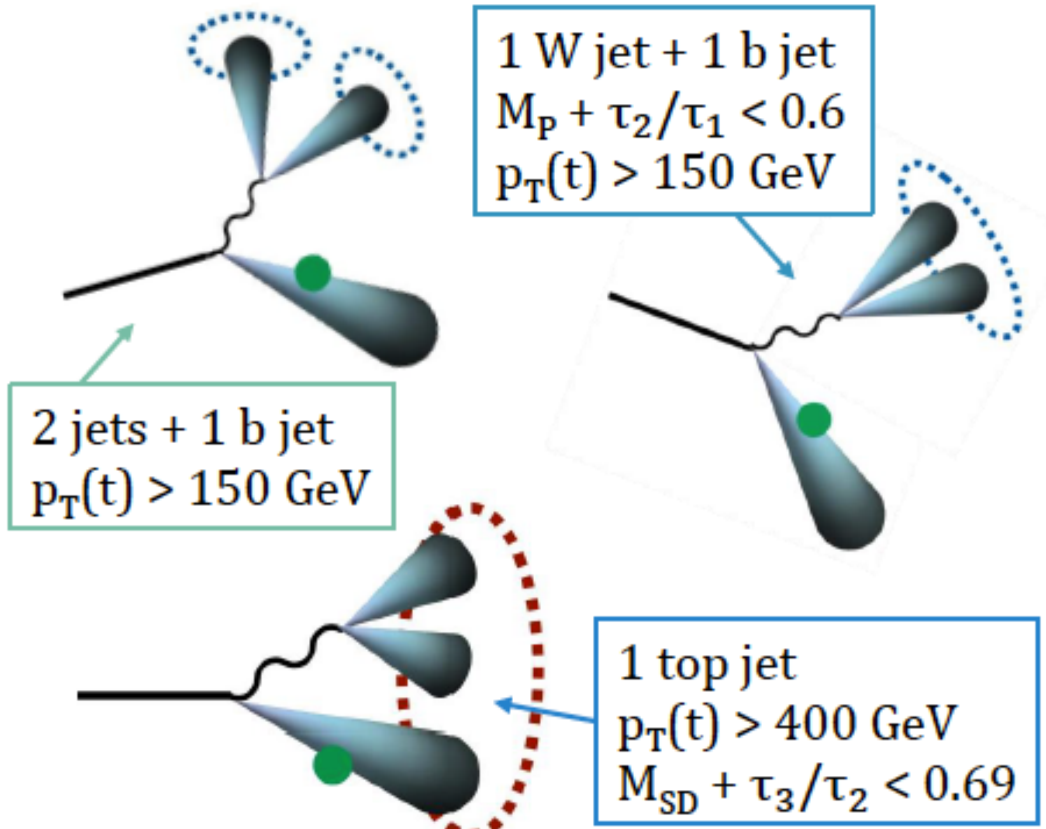




Single $T_{2/3} \to tZ$, dilepton

- Search for $T \to tZ \to t + 2\ell$ and $B \to bZ$, reconstructing $M_{T/B}$ using leptons and boosted jets
  - $T \to tZ$ with 3 top quark decays
  - At least one b tagged jet per event

B2G-16-001

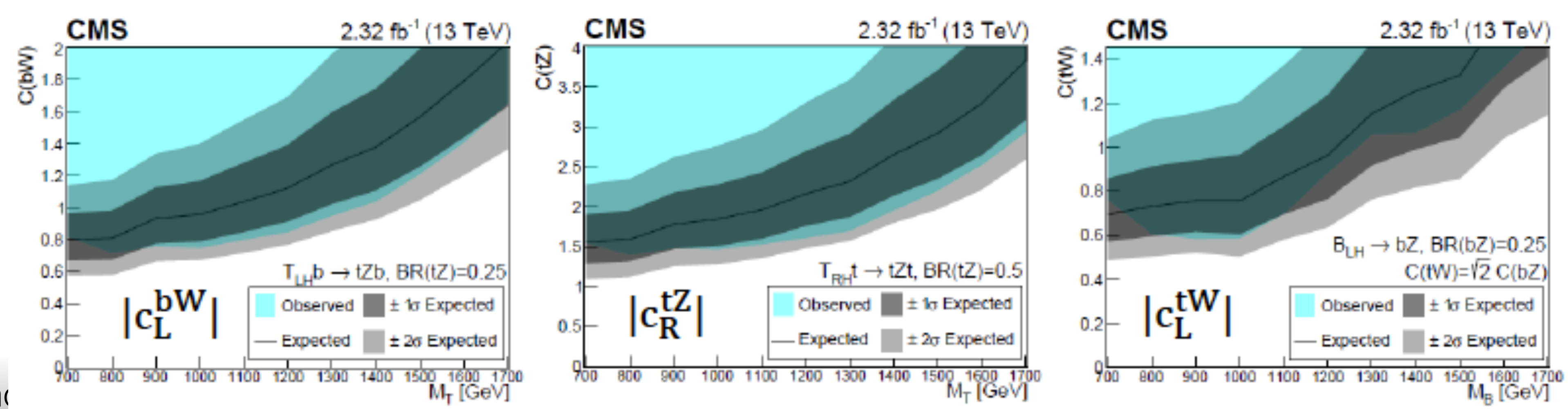


Diagrams J. Thaler

For unit b-associated couplings:

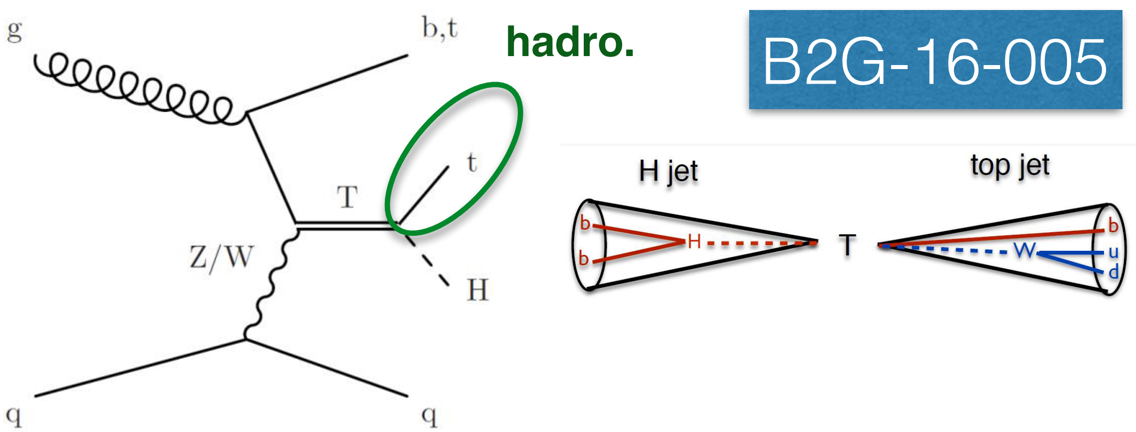
- Exclude T singlet below 1350 GeV
- Exclude B singlet below 1120 GeV
- First Z' → VLQ result from CMS
  - Exotic production mode: Z' → tT → ttZ
  - Probing M(Z') 1.5 – 2.5 TeV

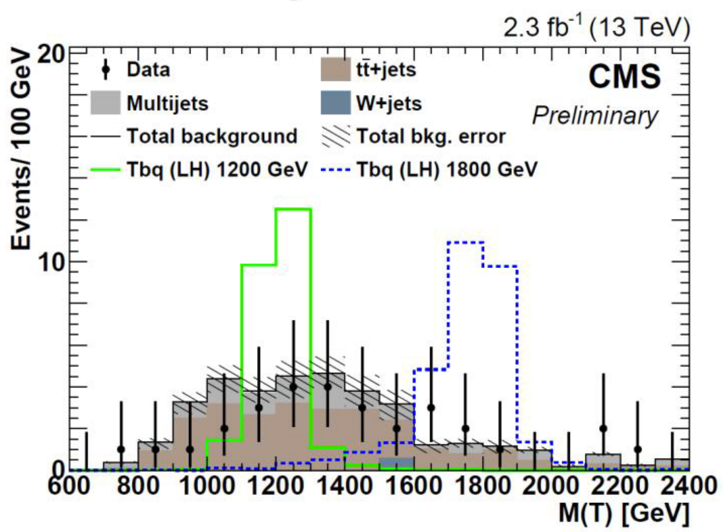
Coupling limits for c(bW), c(tZ), and c(tW) based on T/B singlet or doublet models



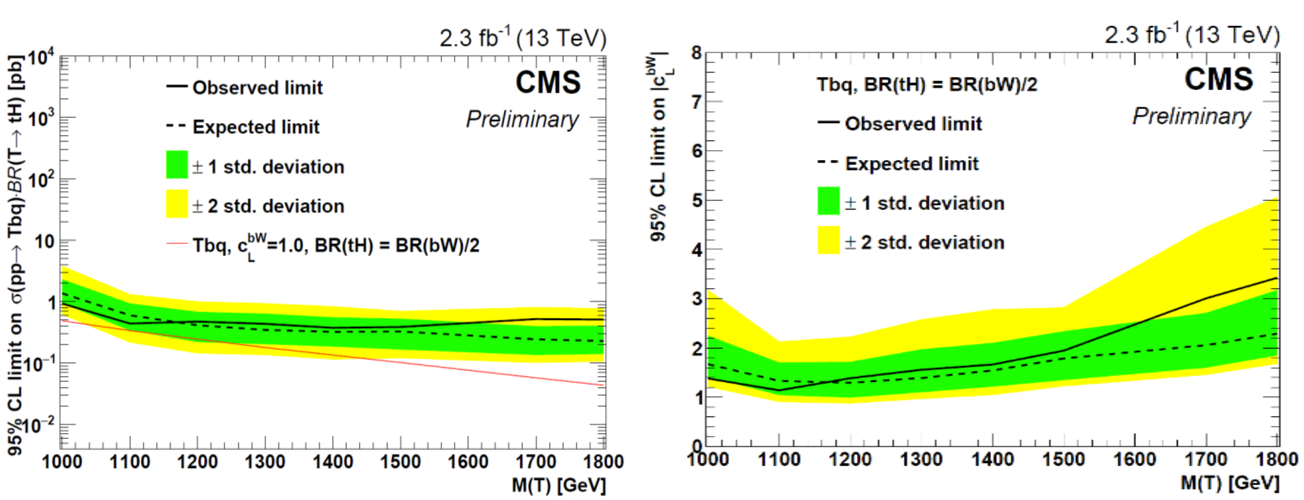
Single $T_{2/3} \rightarrow tH$, Had+ℓjets

B2G-16-005





Limits on T singlet/doublet cross section with 25%/ 50% BR to tH, and couplings c(bW) and c(tZ)



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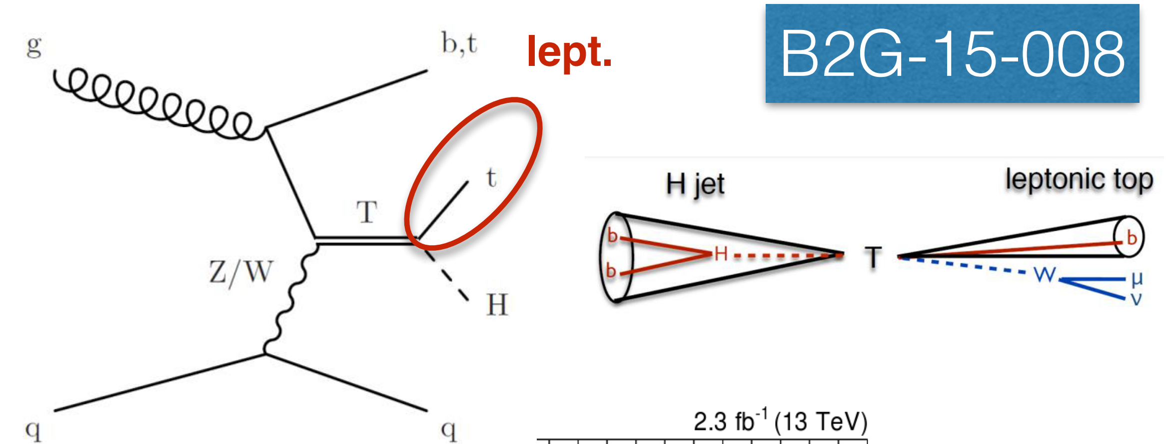
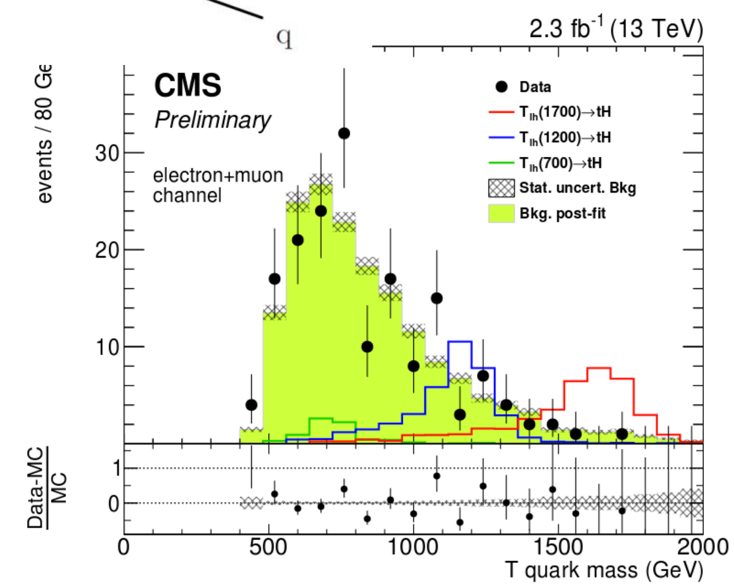
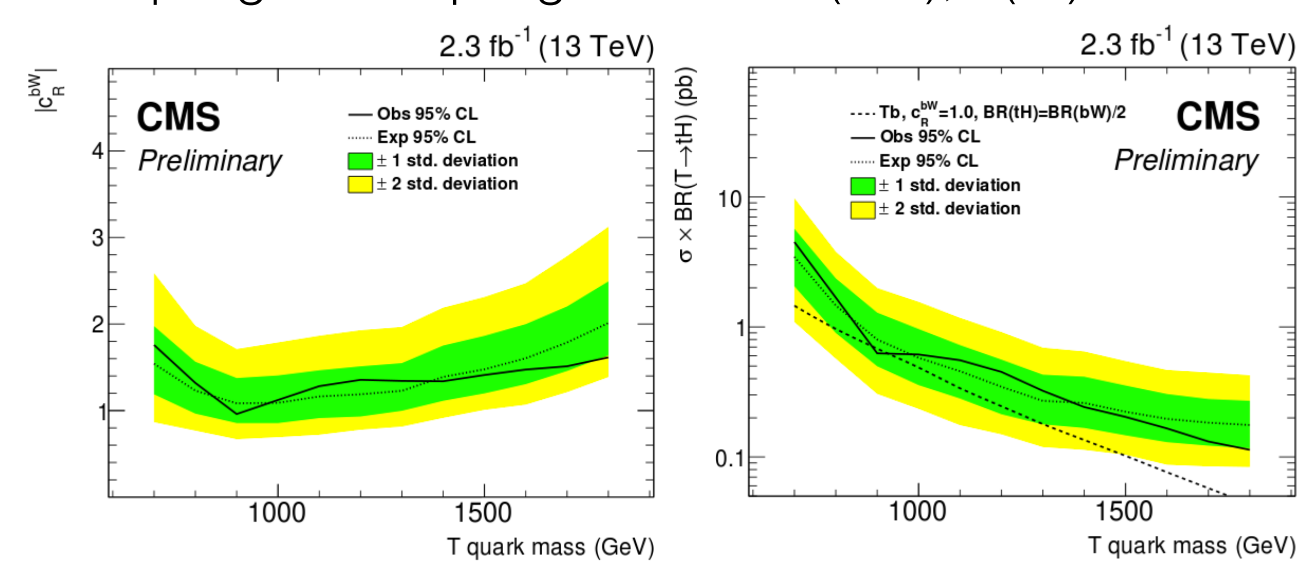




Set cross section limits for LH or RH signal with unit couplings & coupling limits for c(Wb), c(Zt)



Summary

- Described common objects, tools and methods to probe new physics at TeV scale at the LHC

- Due to high advancement in jet sub-structure tools, it is now possible to explore a plethora of models that would otherwise have been inaccessible to LHC

  - The resonance decays: X′ → VV, tt, bb, TT, tT,… that provides a clear signature of new physics

  - VLQs TT, BB, Tjb, Tjt, Bjb, Bjt, have a very rich phenomenology

    - can be a possible solution to mass hierarchy problem

    - can be portal to Dark matter! (See the backup slide)

Summary

- Described common objects, tools and methods to probe new physics at TeV scale at the LHC

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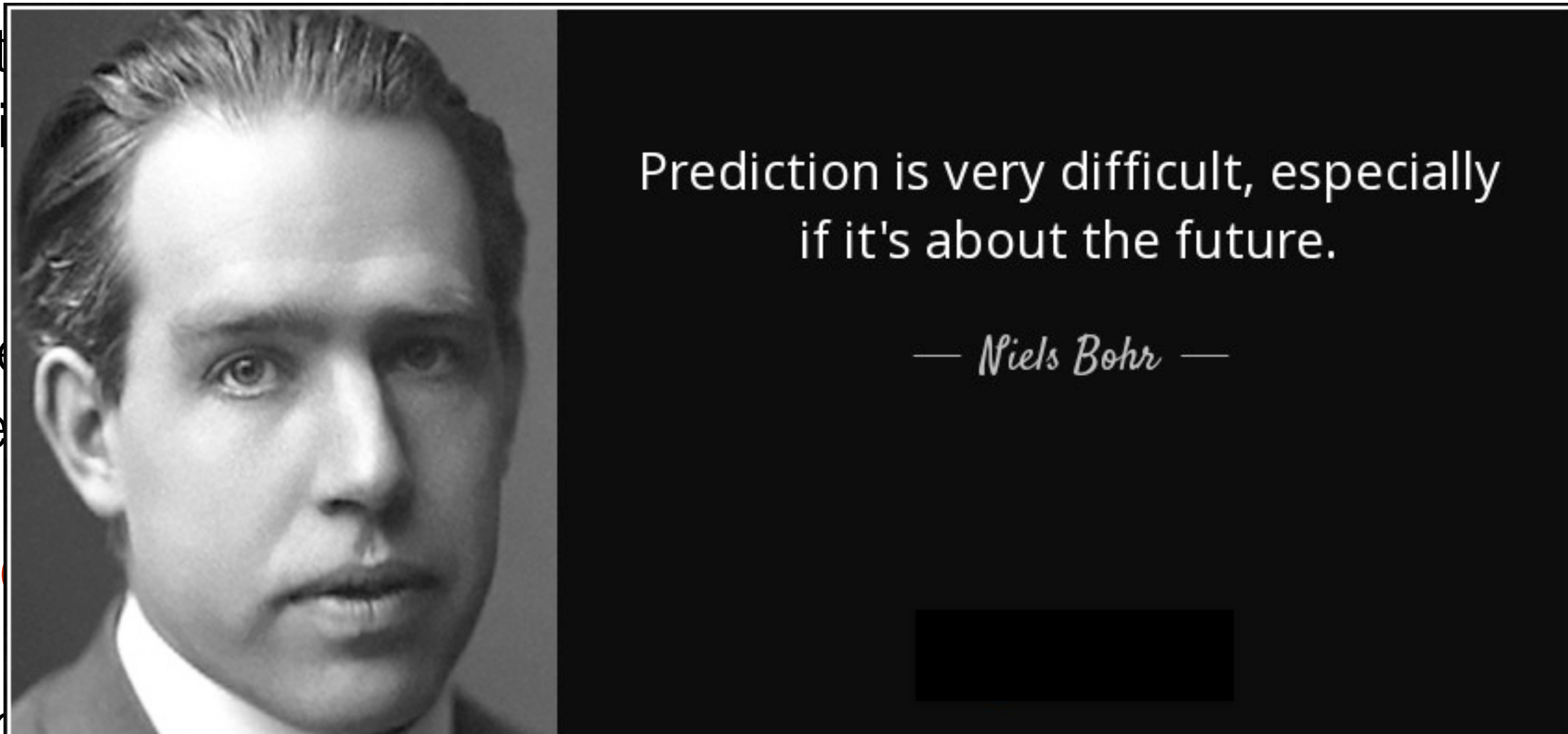
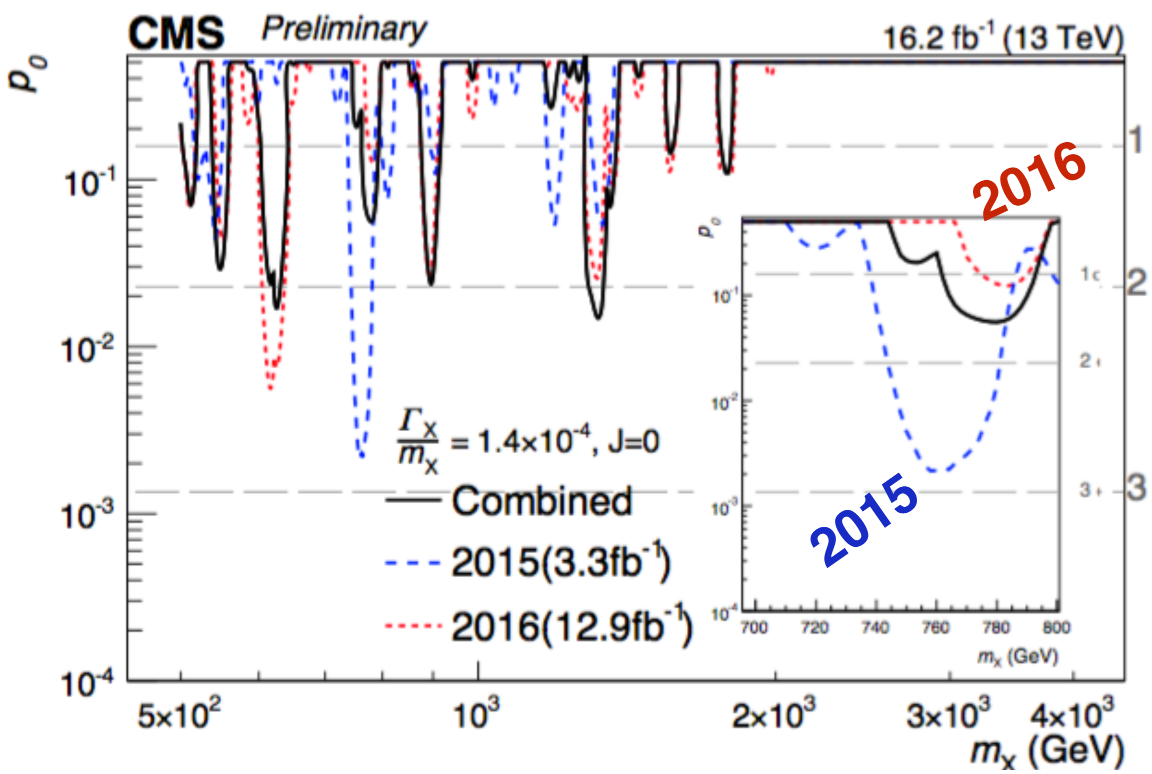


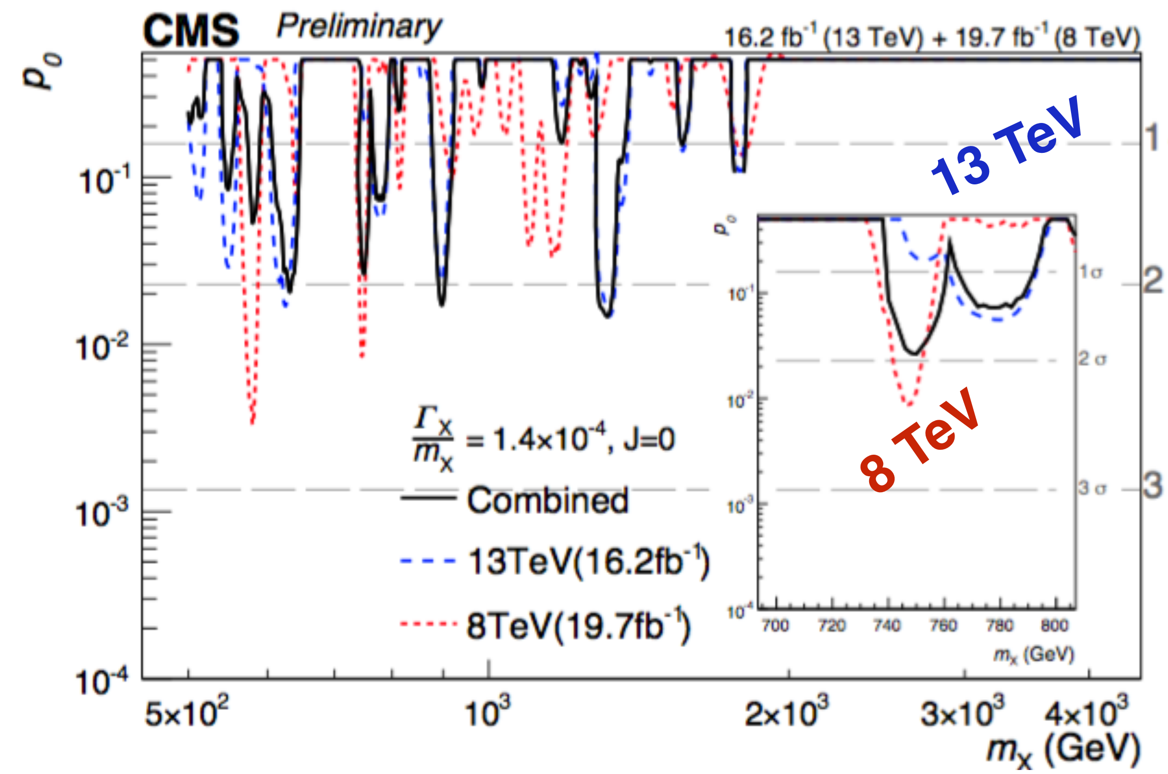
    - can be portal to Dark matter! (See the backup slide)

Backup

P-values and limits

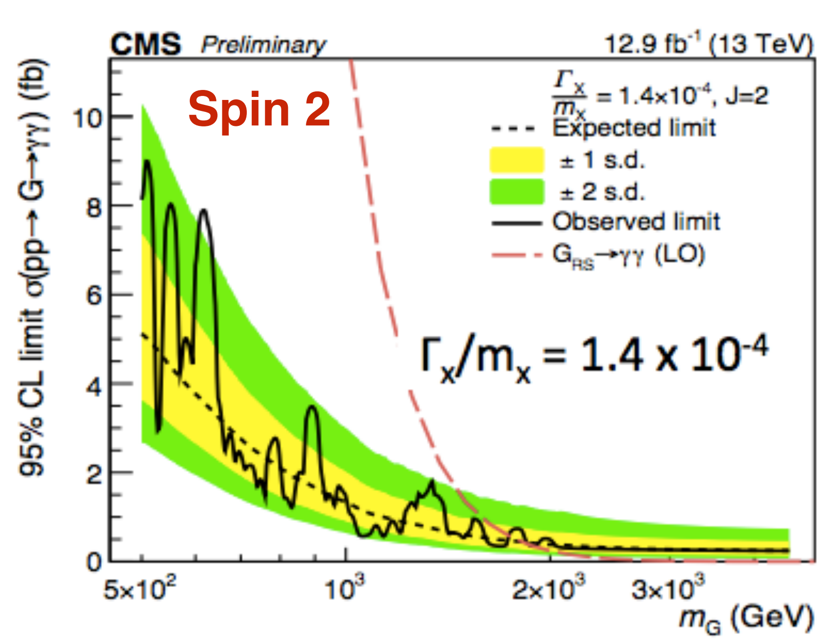
- The 2016 data (based on 12.9 fb^{-1} of integrated luminosity) do not confirm the fluctuations observed earlier in the $m_{\gamma\gamma}$ spectrum in 2015 and Run1 at 8 TeV

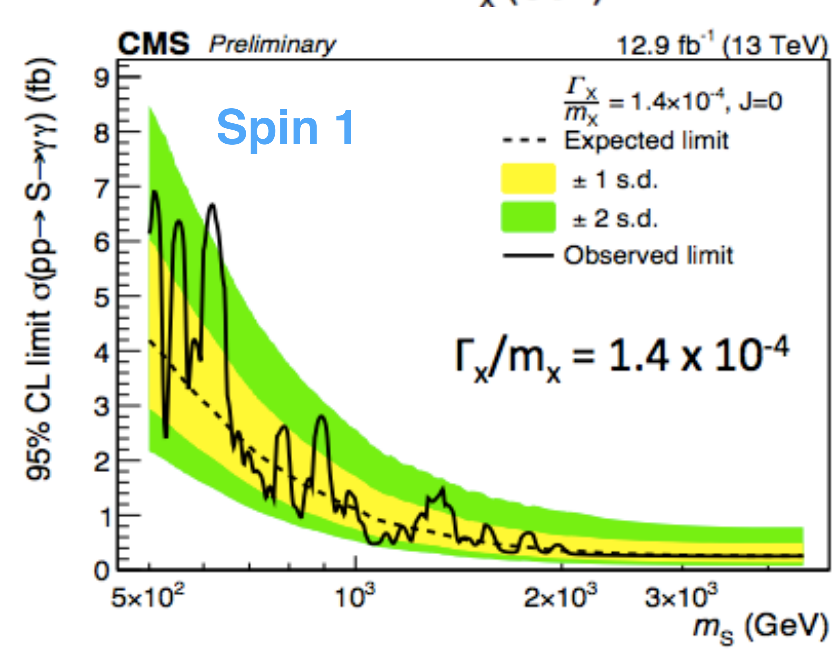




Limits on a RS graviton mass

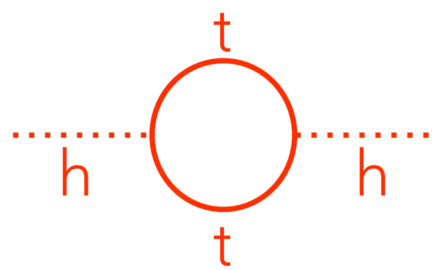
Coupling	Exclusion
0.01	$m_G < 1.75$ TeV
0.1	$m_G < 3.75$ TeV
0.2	$m_G < 4.35$ TeV



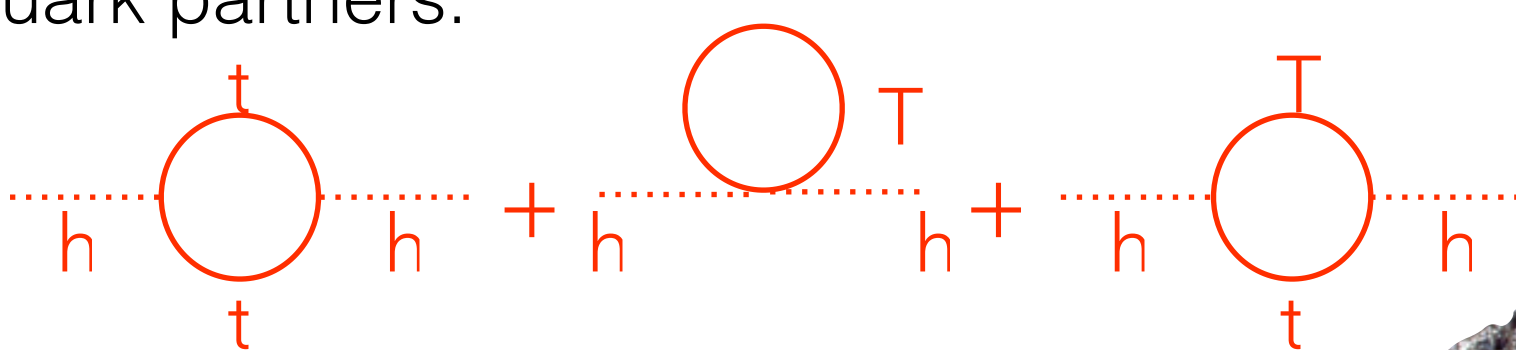


Top Partners

- Quantum loop corrections due to top quark pushes up the Higgs mass, unless severe fine-tuning is introduced
- Higgs mass:
  - $m_h^2 = m_{bare}^2 + \delta m_h^2$
  - $\delta m_h^2 =$



- Solution to this problem invokes the existence of top quark partners:



  - fermionic (vector-like quarks)
  - bosonic (stops in SUSY)

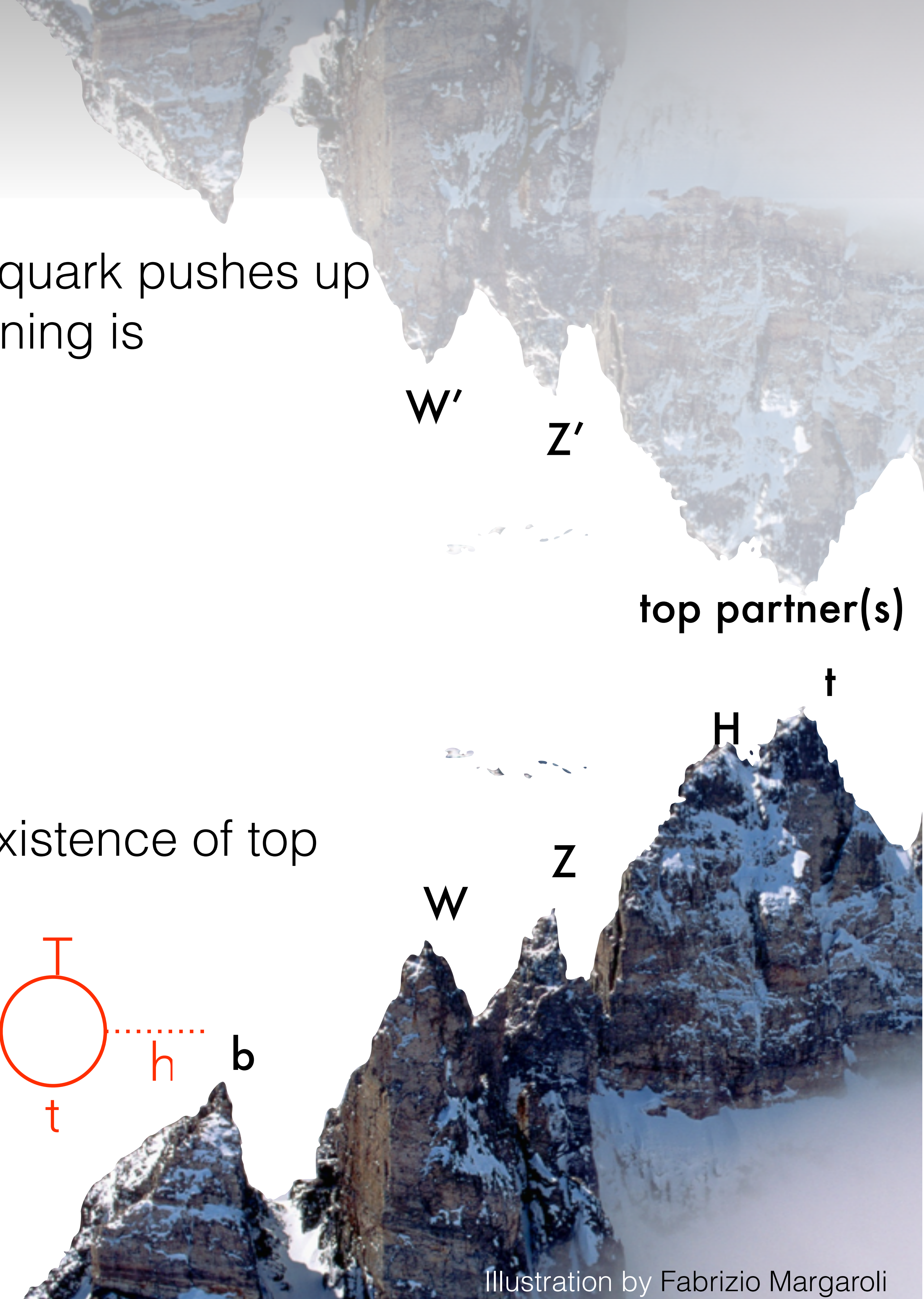
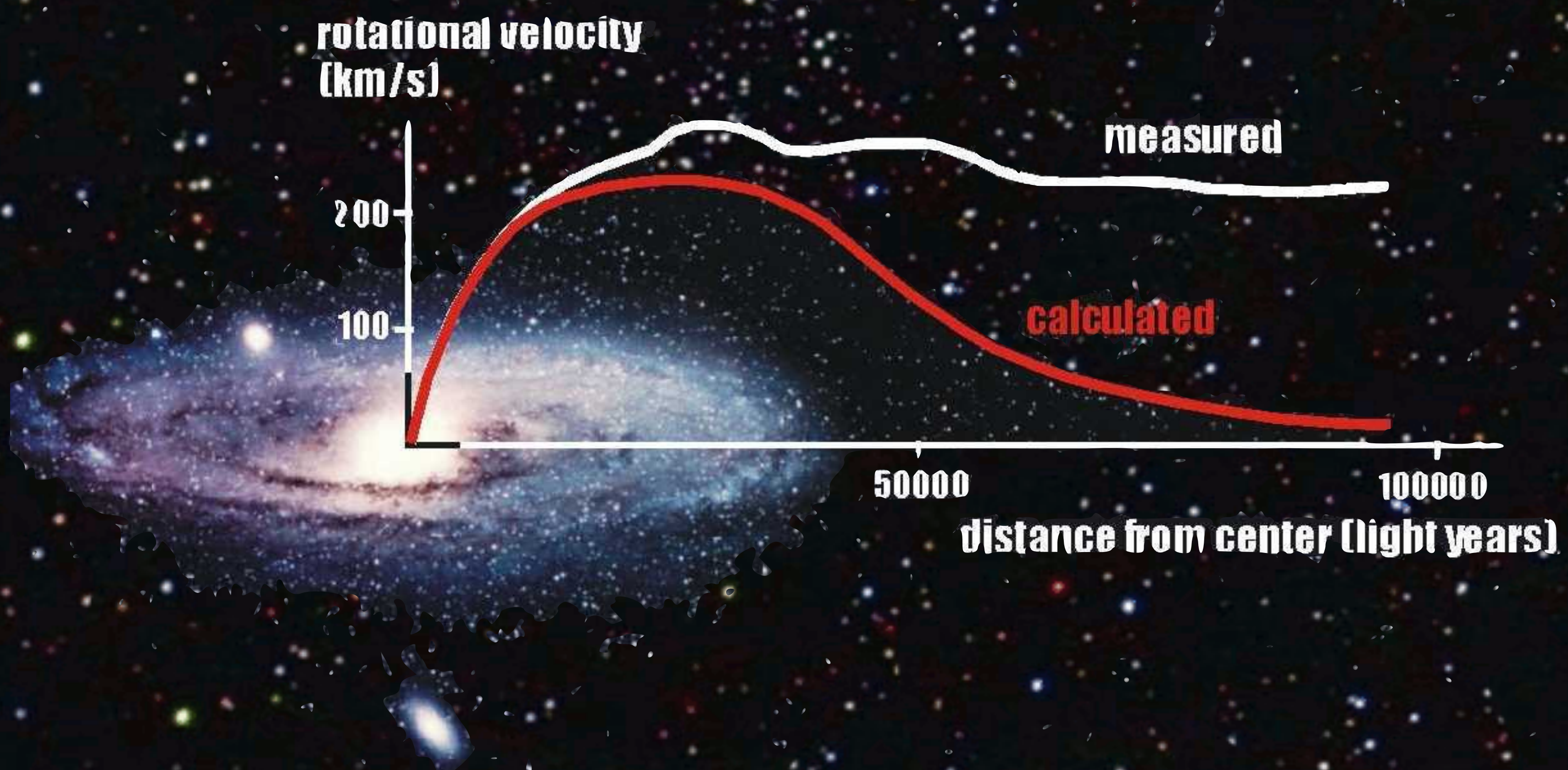


Illustration by Fabrizio Margaroli

Top Partners: Connection to the dark matter



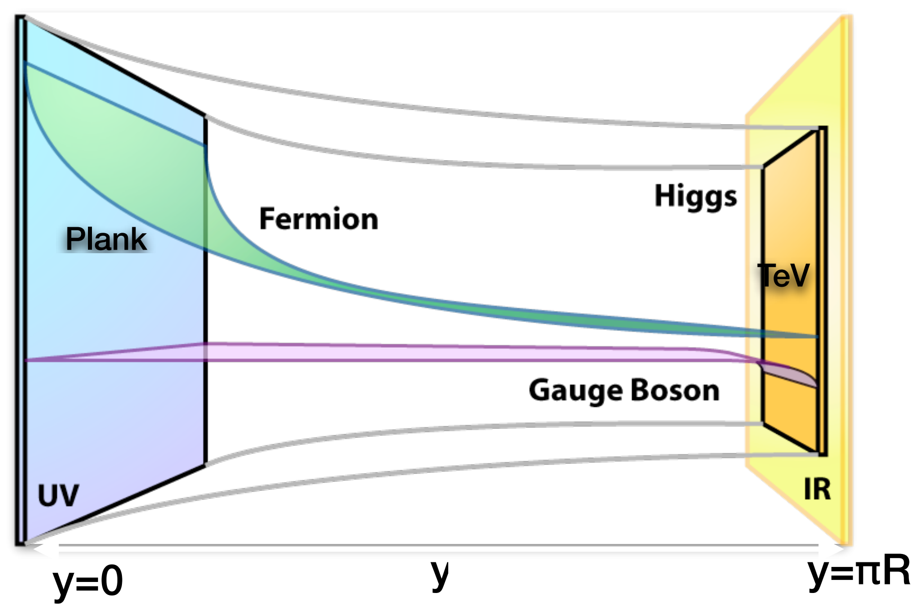
- Little Higgs, Extra Dimensions theories provide dark matter candidates
- VLQs can decay into SM quarks+DM (hep-ph/1604.07941)

Illustration by Fabrizio Margaroli

Where do the VLQs appear?

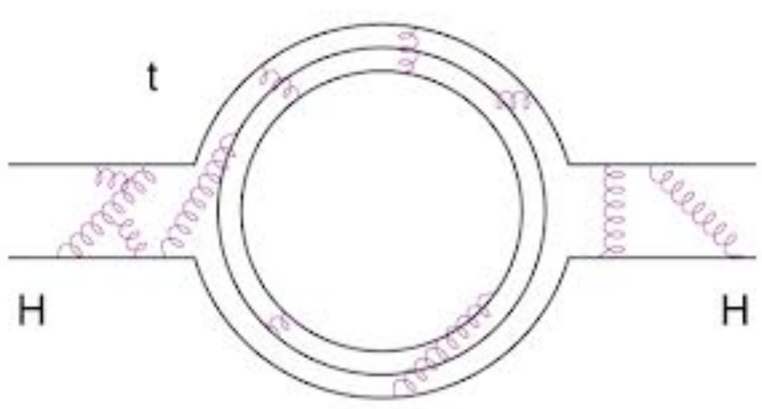
- Wrapped or universal extra dimensions

$\Lambda_{TeV} \sim \Lambda_{Plank}\, e^{-ky}$



lightest states of the fermion KK excitations

- Composite Higgs models:



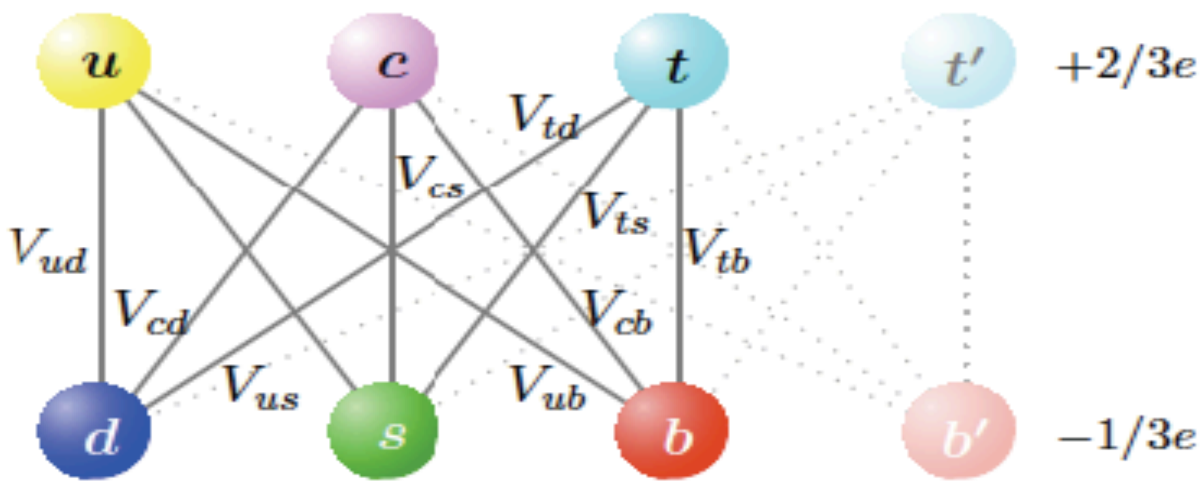
resonance of the bounded states of Higgs

- Little Higgs models:

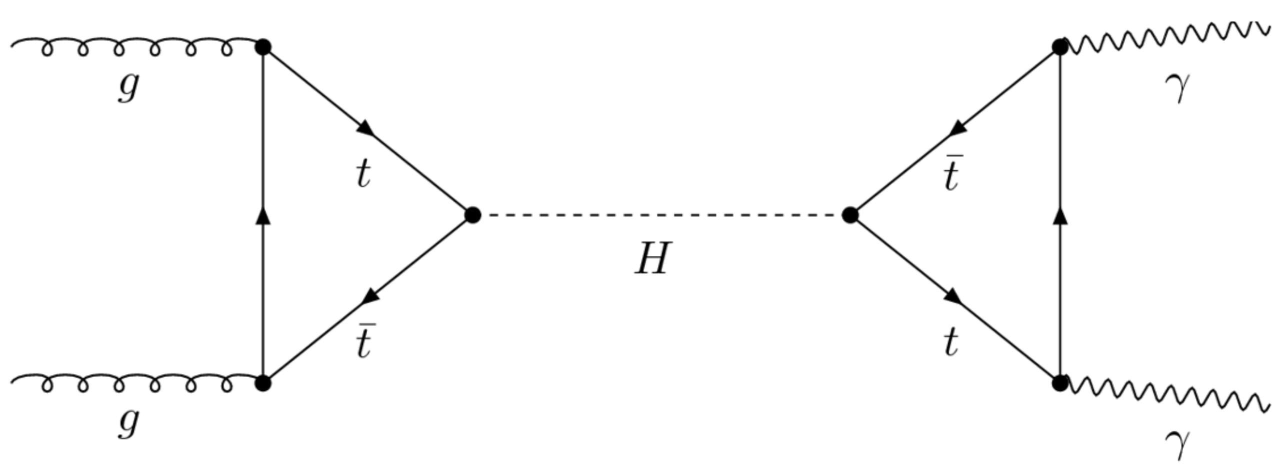
Isospin multiplets in a larger group representations ensuring cancellation of loop divergence

History! The 4th generation

- Remain popular for quite few years!

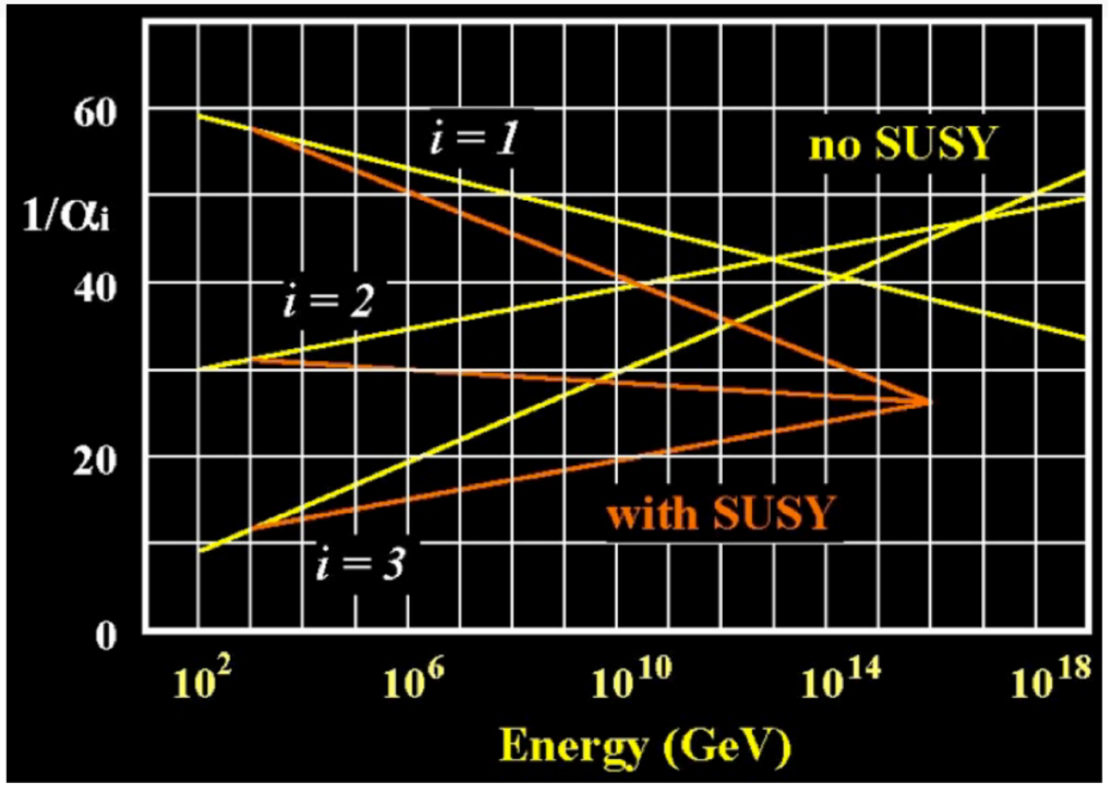


- Higgs discovery ruled out them!
  - coupling to Higgs ∝ fermion mass ⇒ drastic effect on loop induced H-g and H-γ vertices
  - cross section increased by a factor ~9

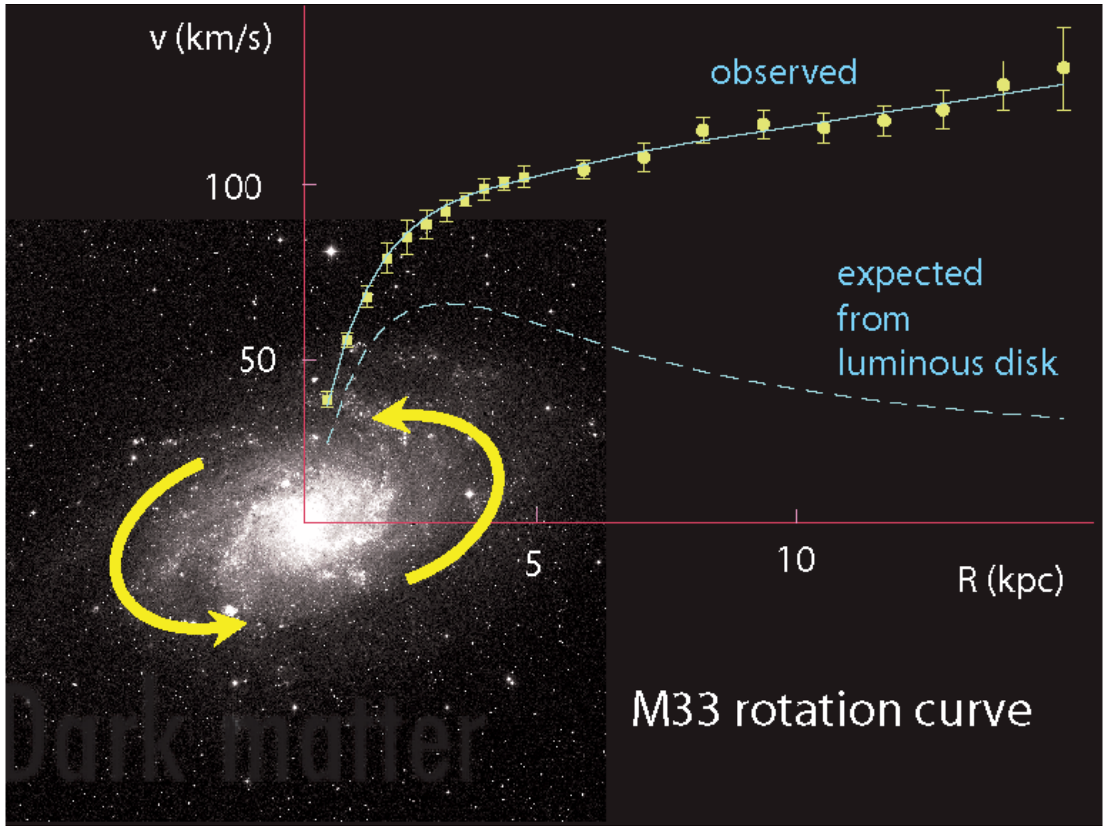


SUSY: Implications

- SUSY unifies the strengths of three forces of nature at 10^{16} GeV

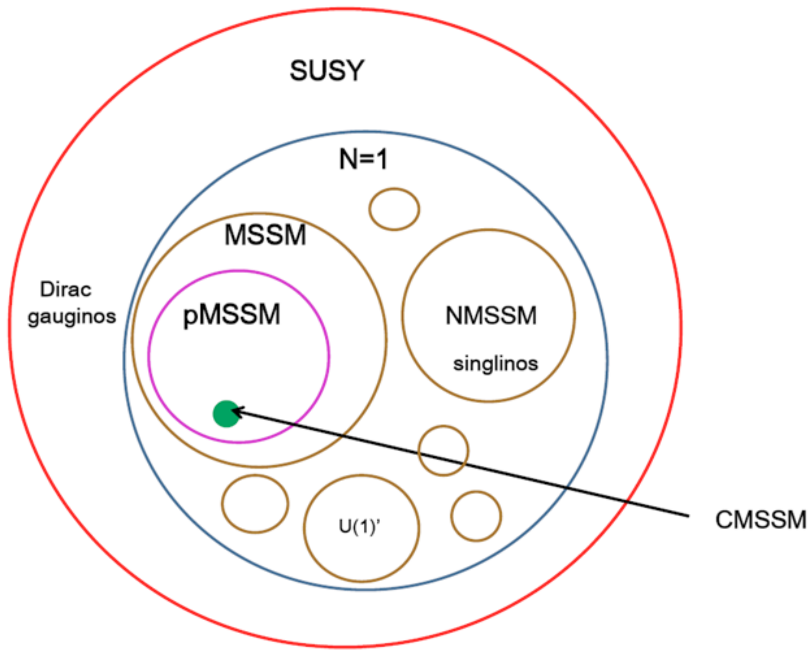


- Explains 25% of the energy in the universe: the dark matter

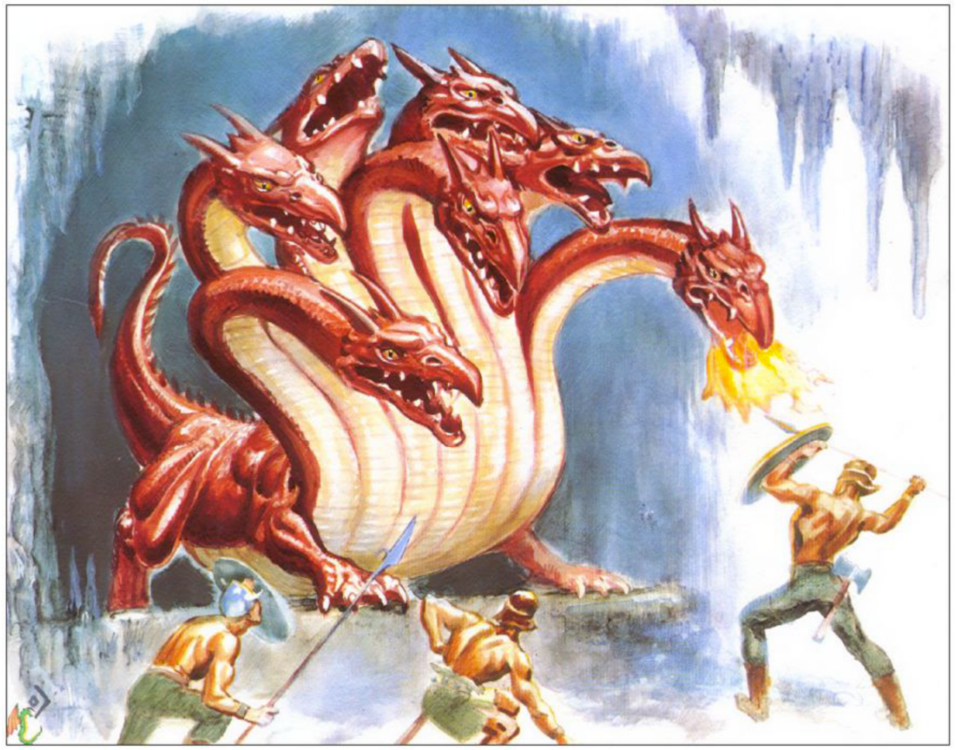


Beautiful but not a minimal theory

- SUSY is a broken symmetry: masses of superpartners are not fixed by theory
- A parameter space which is impossible to fully exclude but to only constrain



- Within the MSSM only:
  - MSSM: 109 parameters
  - pMSSM: 19 parameters
  - CMSSW: 5 parameters



- Complementary strategies are requires to maximally constrain the parameters
  - direct and indirect dark matter detection experiments
  - rare processes production rate
  - precision SM production cross section measurement (tt production)

Leptoquarks

- New bosons that carry both lepton and baryon number are predicted by many BSM theories: GUTs, Composite models
- Dominant processes for LQ pair production at LHC
  - gluon-gluon fusion & quark-antiquark annihilation

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- Exact properties (spin, weak isospin, electric charge) depend on specific model: direct searches at the LHC →Buchmuller-Ruckl-Wyler model (BRW)
    - interact with SM fermions through coupling λ
    - preserves baryon and lepton number
    - couple to a single chirality and generation of SM fermions at a time

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  - interact with SM fermions through coupling λ
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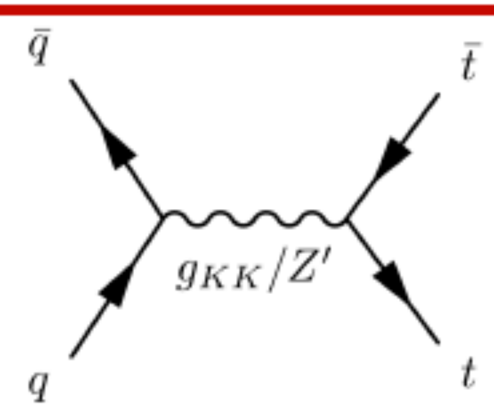
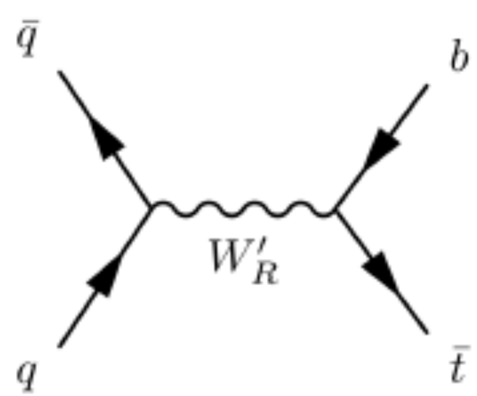
- BR, β is generally unknown, but {ll,lν,νν} + qq maximally produced for β = 1, 0.5, and 0

BR(LQ→lq) = β
BR(LQ→νq) = 1-β

$LQ\overline{LQ}$	β^2	$\beta(1-\beta)$	$(1-\beta)^2$
1st gen	$ee + jj$	$e\nu + jj$	n/a
2nd gen	$\mu\mu + jj$	$\mu\nu + jj$	n/a
3rd gen	$\tau\tau$+bb,tt	n/a	$\nu\nu$+bb,tt

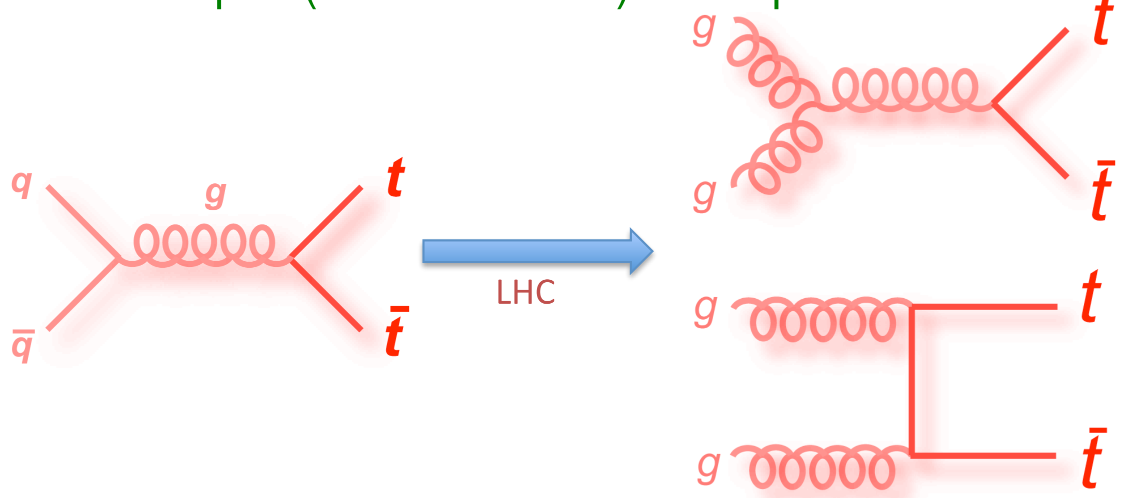
Z′/W′ resonances

- Numerous final states to explore → already several results at 13 TeV !!

resonance	diagram type	final state	luminosity	CMS-PAS
ttbar		lvbbjj	2.6 fb^{-1}	B2G-15-002
		bbjjjj	2.6 fb^{-1}	B2G-15-003
W'		bbjj	2.6 fb^{-1}	B2G-16-009
		lvbb	2.2 fb^{-1}	B2G-15-004
		lvbb	12.9 fb^{-1} 2016 data	B2G-16-017

Top quark production and decya

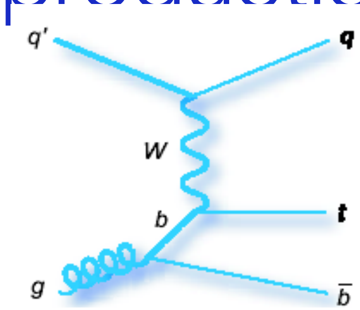
- Pair production
  - σ~7.5 pb (Tevatron 1.96 TeV ppbar)
  - σ~165 pb (LHC 7 TeV) Pair production



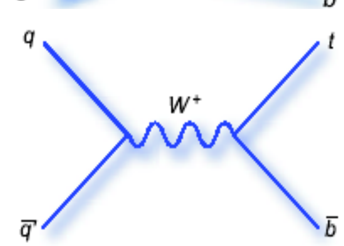
85% (Tevatron)
13% (LHC)

15% (Tevatron)
85% (LHC)

- Single Top quark production
  - t channel
    - σ~2 pb



  - s channel
    - σ~1pb



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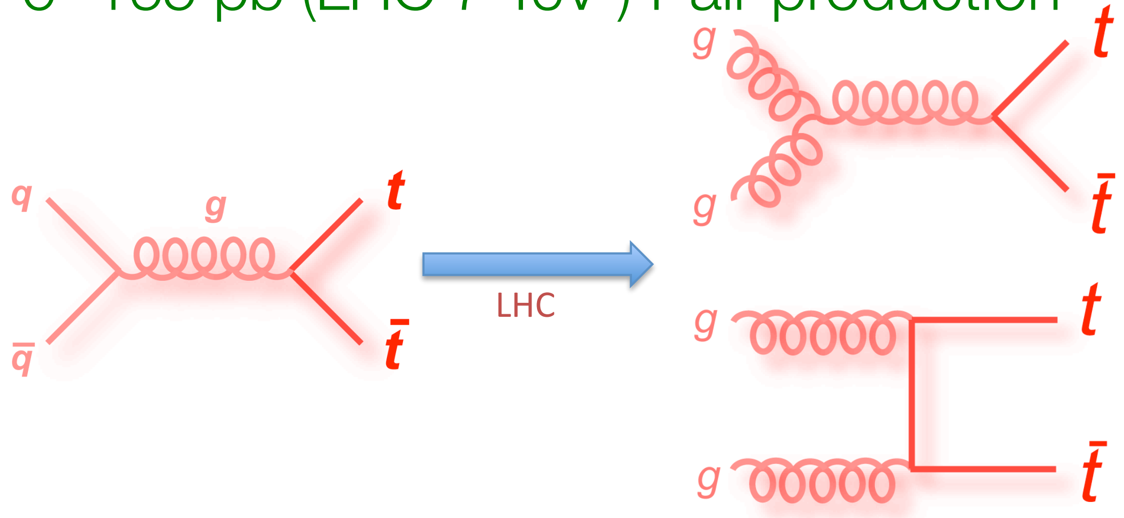

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    - σ~2 pb
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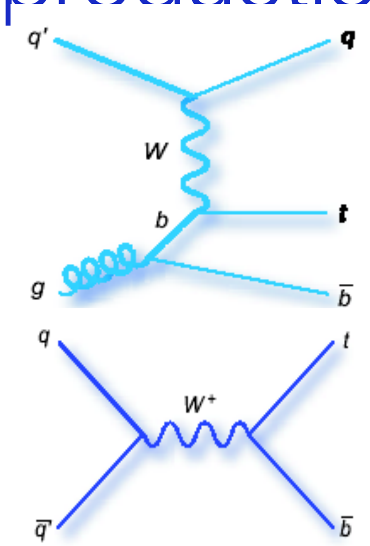
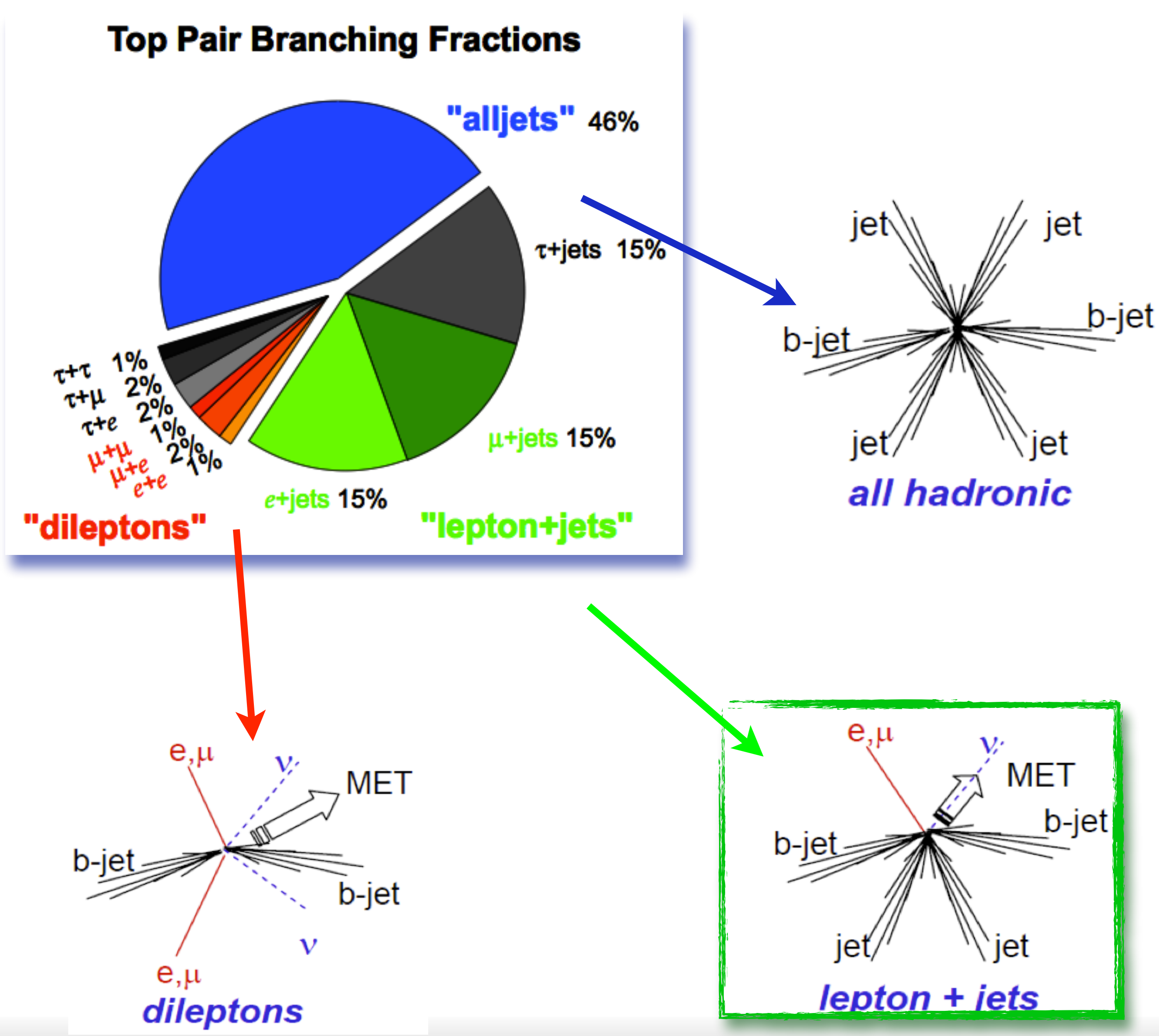
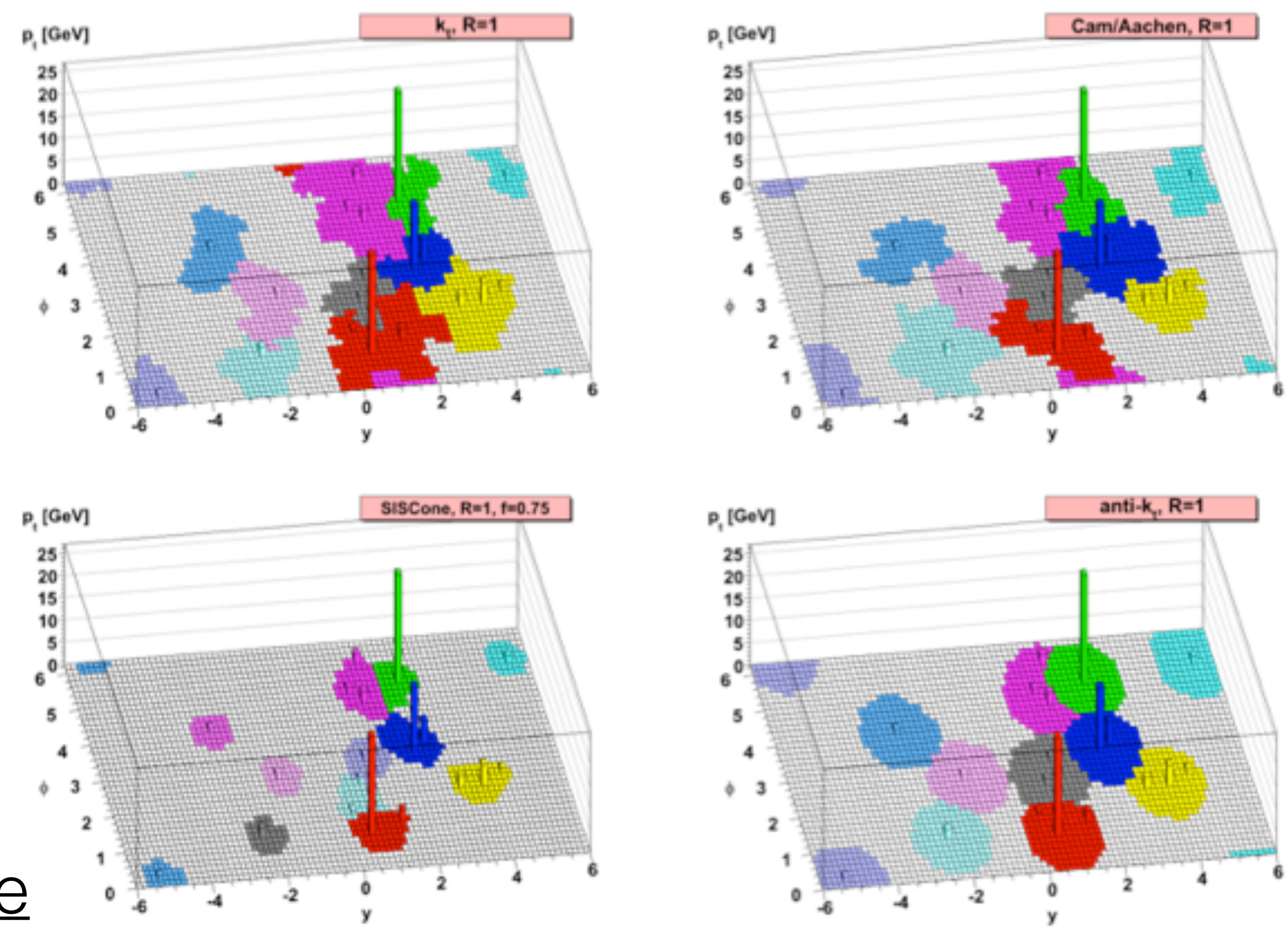


- Top Pair cross section final state categorized by the decay of the W boson
  - Golden channels: lepton + jets and dilepton
  - Challenging channels: full hadronic, tau + mu



Jet Clustering Algorithms

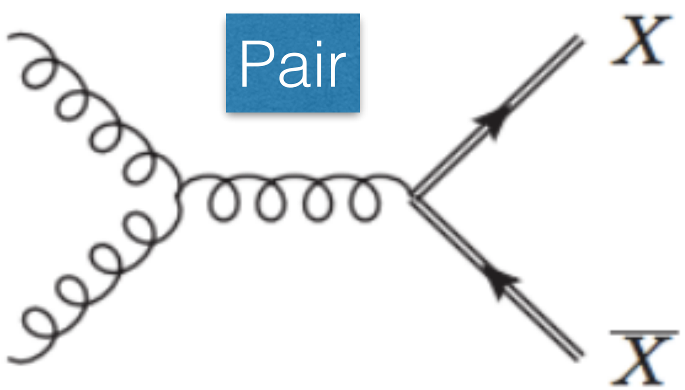
- Different types
  - N = 2: “kT”
    - “Irregular” jets, but good for low pt
  - N = 0 : “Cambridge-Aachen” (CA)
    - Also irregular, very useful for substructure!
  - N = -2: “anti-kT”
    - “Idealized” cone algorithm

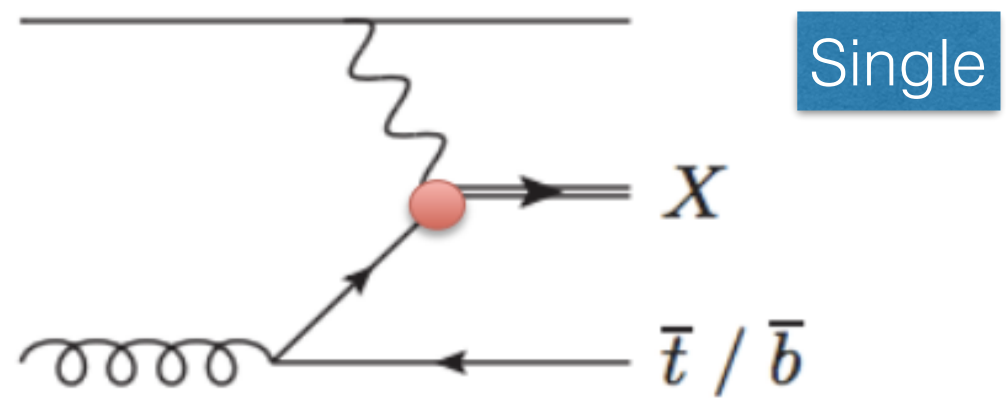


[Tasi Lecture on Jet Substructure]

Vector-like quarks

- Production:





- Decays:

Pair: T → Wb, Zt, Ht; B → Wt, Zb, Hb

Table 1: Branching ratios, following the equivalence theorem

BR	Wt	Wb	Zt	Zb	ht	hb	Chirality
T23 singlet	0	1/2	1/4	0	1/4	0	L
T23 doublet	0	0	1/2	0	1/2	0	R
X53 doublet	1	0	0	0	0	0	L/R
B13 singlet	1/2	0	0	1/4	0	1/4	L
B13 doublet	1	0	0	0	0	0	R
Y43 triplet	0	1	0	0	0	0	L/R