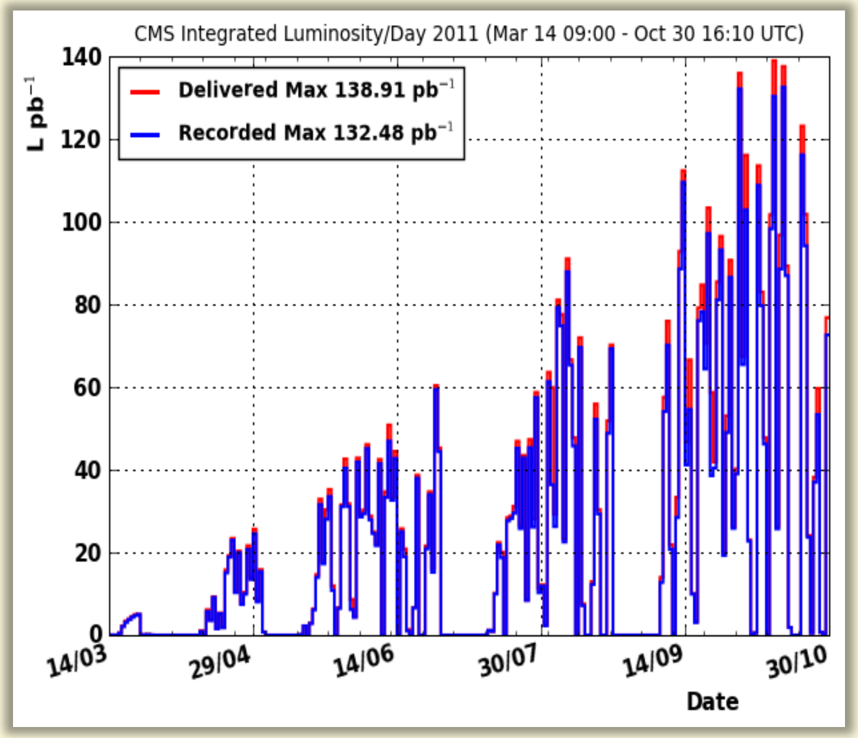
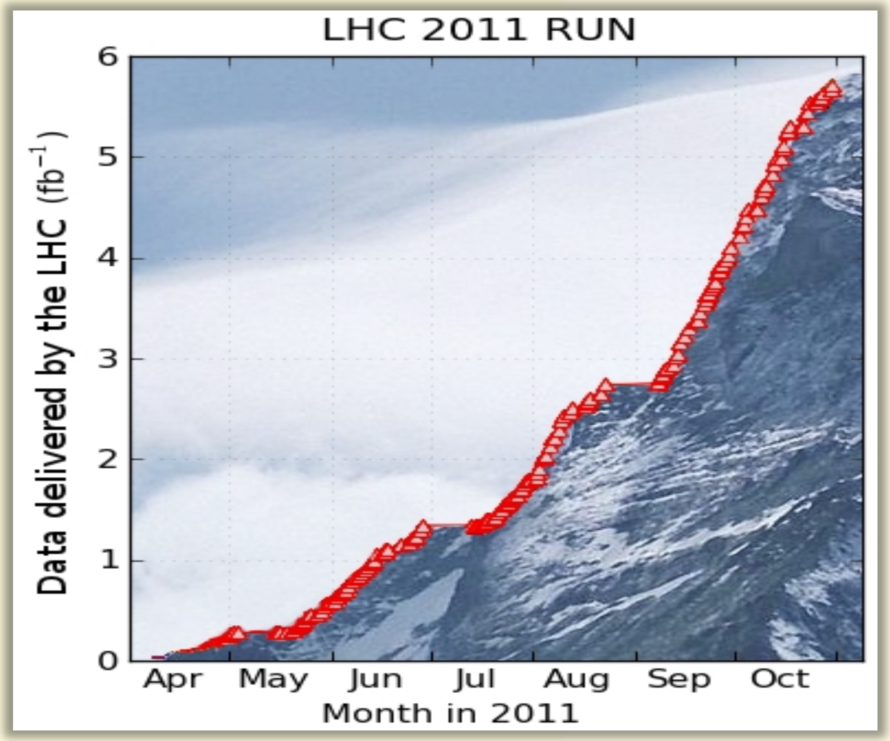
Searches for Physics Beyond SM at CMS

Artur Apresyan
on behalf of the **CMS Collaboration**

LHC *pp* luminosity in 2011





Fantastic performance of the LHC machine

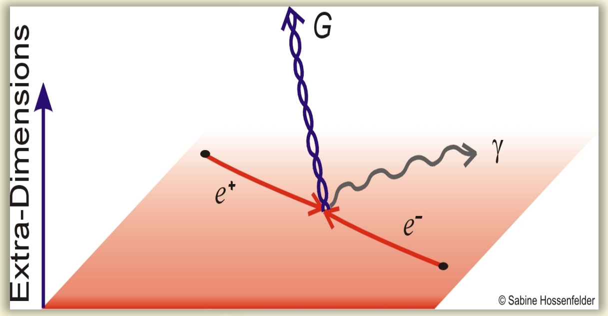
Peak instantaneous luminosity: **3.55 x 10^{33}** Hz/cm^2

Close to **5fb^{-1}** recorded by the CMS experiment

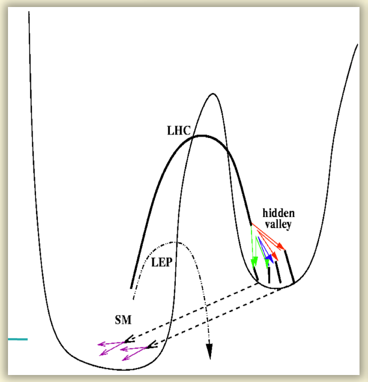
91% data-taking efficiency

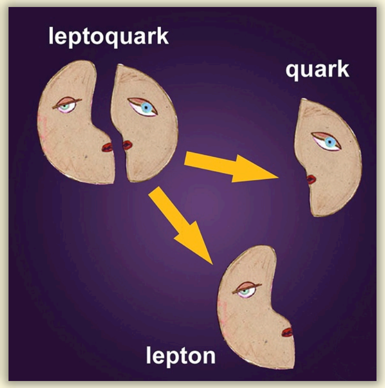
Searches beyond the SM

- The SM will be complete if the Higgs boson with mass < ~1 TeV is discovered
  - Even if the Higgs boson is found, **questions remain…**

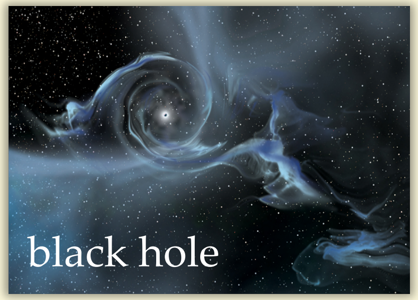


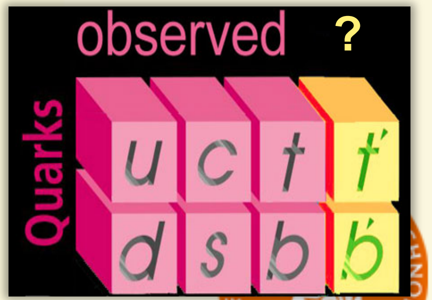
- Non-zero neutrino masses
  - Are there right-handed neutrinos?
- Dark matter
  - No SM particles with "correct" properties
- Mass hierarchy of the SM particles
  - Why 3 generations?
- Baryo- and Leptogenesis
- Gauge hierarchy problem, Gravitation
  - Why is gravity so weak?
- Dark energy





- Many models exist to address these
  - Directly probe them at the LHC





CMS searches

- Signature based searches
  - Cover many theoretical models
  - Practical approach: understand the sample composition → constrain several models

- Resonances of *l*, γ, jets, tops, VV
  - Extra dimensions
  - Sequential SM
  - Technicolor

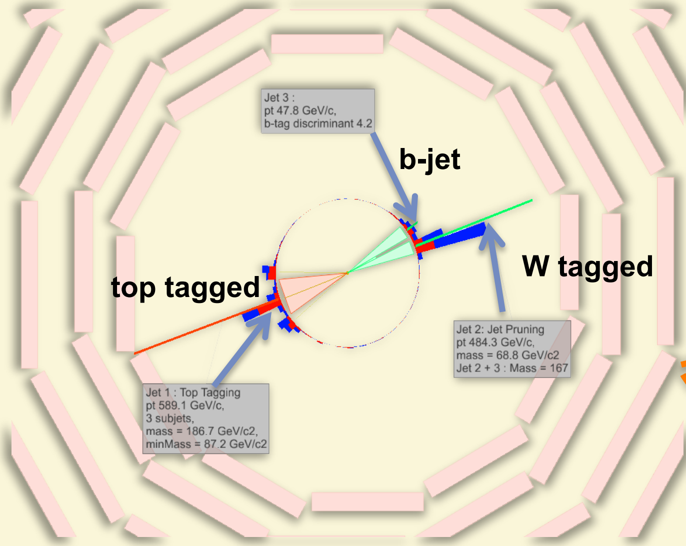
- Non-resonant excesses in *l*+jets
  - 4^{th} generation quarks
  - W'_{KK}
  - Leptoquarks

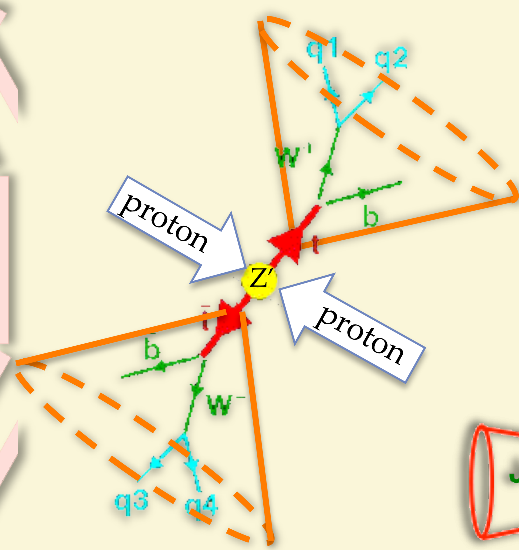
- Displaced decays of stable new particles
  - SUSY
  - hidden valley, UED…

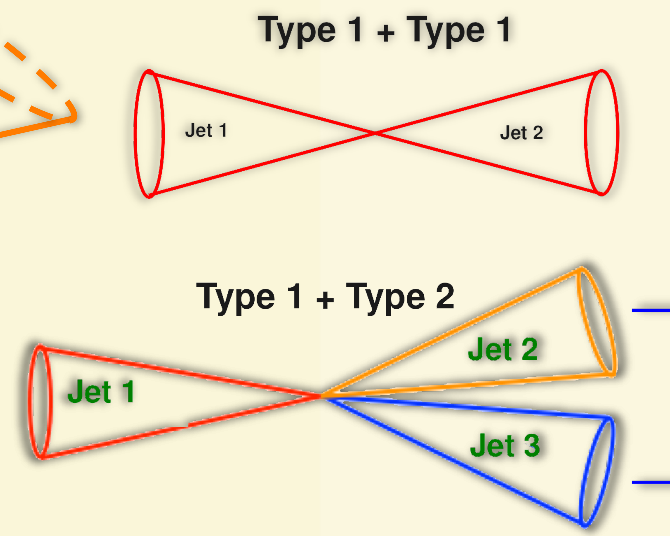
- High/low multiplicity events
  - Mono*jet*, mono*photon*
  - Microscopic black holes
  - Generic multi-muon searches

- Many new results, using full 2011 dataset ($4.7 fb^{-1}$), **four** first releases today
  - Full list: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO

Heavy resonances: $Z' \to t\bar{t}$: *all hadronic*



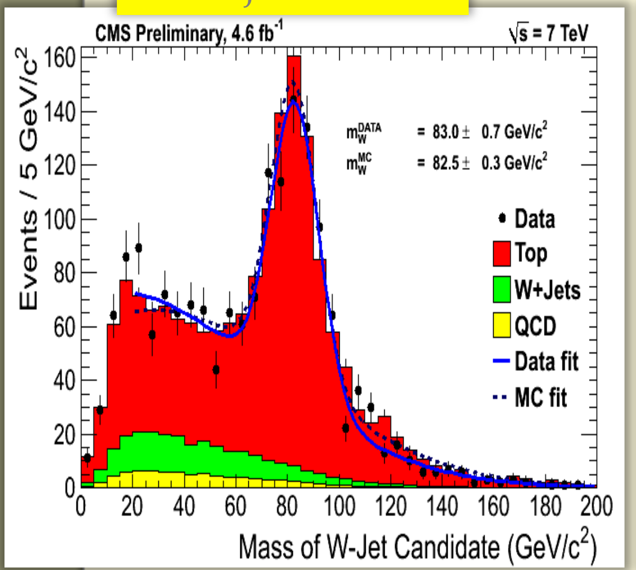




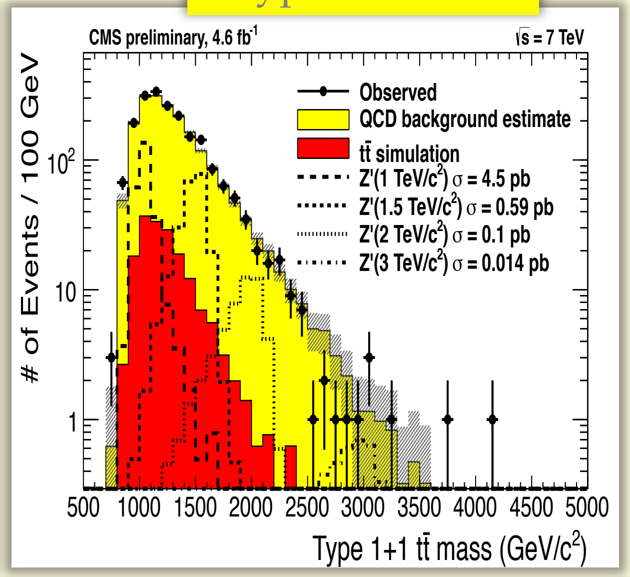
- Large BR($t \to Wb \to qqb$) in all-hadronic final state
  - All 3 jets in one hemisphere are merged into one *top jet*: **Type 1** top candidate
  - Only 2 of the 3 jets are merged, W-tagged: **Type 2** top candidate
- Identify merged jets by looking at jet substructure
  - Type 1 top tagging: at least three subjets in each jet with $\mathbf{M_{jet} \sim M_{top}}$, $\mathbf{M_{jj} \sim M_W}$
  - Jet pruning to identify Type 2 jets in three-jet topologies (W-jet + b-jet)

Heavy resonances: $Z' \rightarrow t\bar{t}$: *all hadronic*

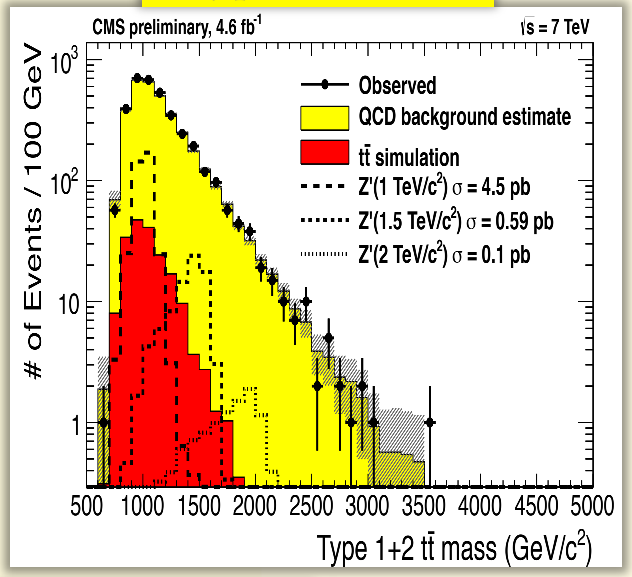
W jet mass



Type1+1 mass



Type1+2 mass

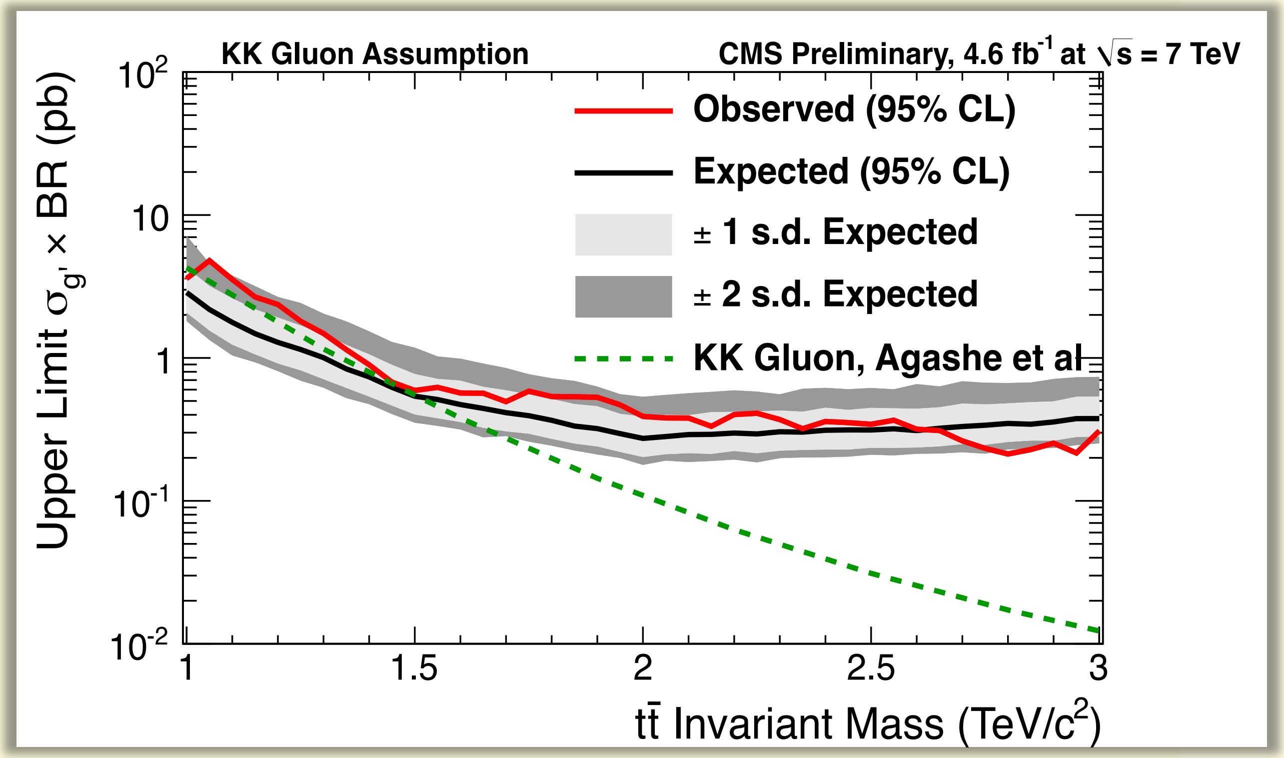


Type1 jet P_T>350GeV; W jet P_T>200 GeV; b jet P_T>30 GeV

- Main background are QCD multijet production and top pairs
  - Top tagging mistag rate for QCD events in signal depleted sample, $R(p_T)$~0.01-0.07
- Fit M_W to derive the JES for subjets from semileptonic ttbar sample
  - Data/MC scale factor for finding jets with substructure from control sample

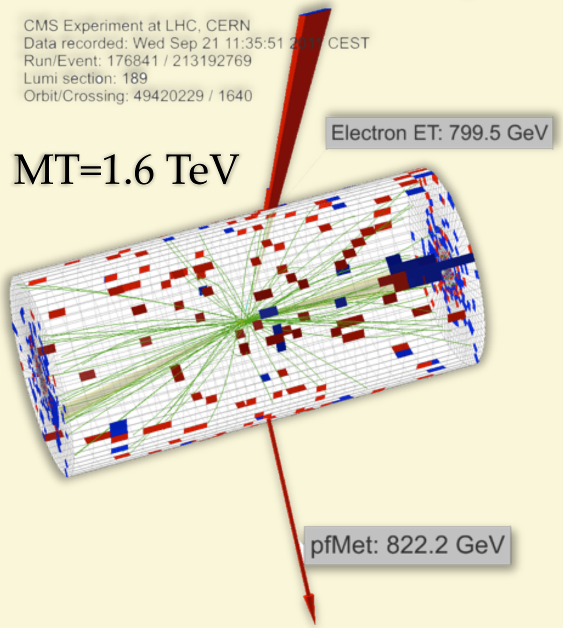
CMS-PAS-EXO-11-006, 4.6 fb^{-1}

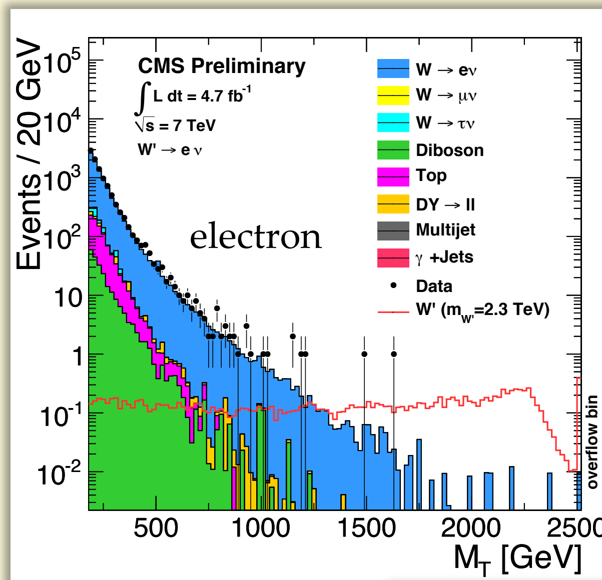
Heavy resonances: *Z′→tt̄: all hadronic*

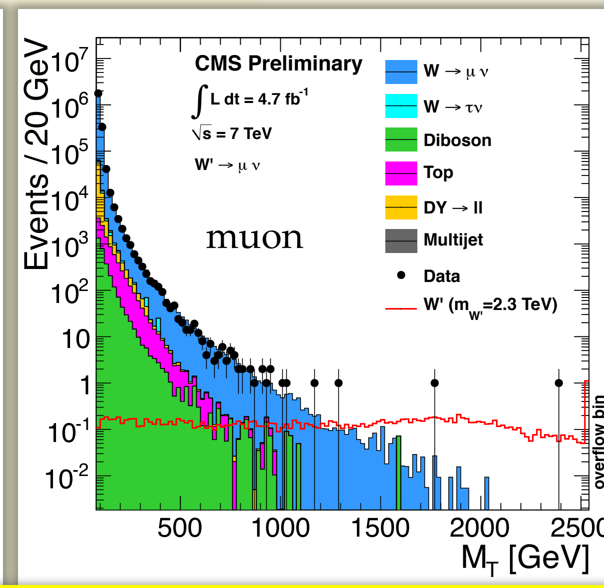


- Type 1+1: expect 1709 ± 99 events, observe: 1738
- Type 1+2: expect 2379 ± 147 events, observe: 2423
- Set limits on generic Z′ with two widths (1% and 10%) and KK gluon
- Any enhancement to the σ_{tt} above 1 TeV is < **2.8** times the σ_{NLO}

Heavy resonances: *W'*→*lν*



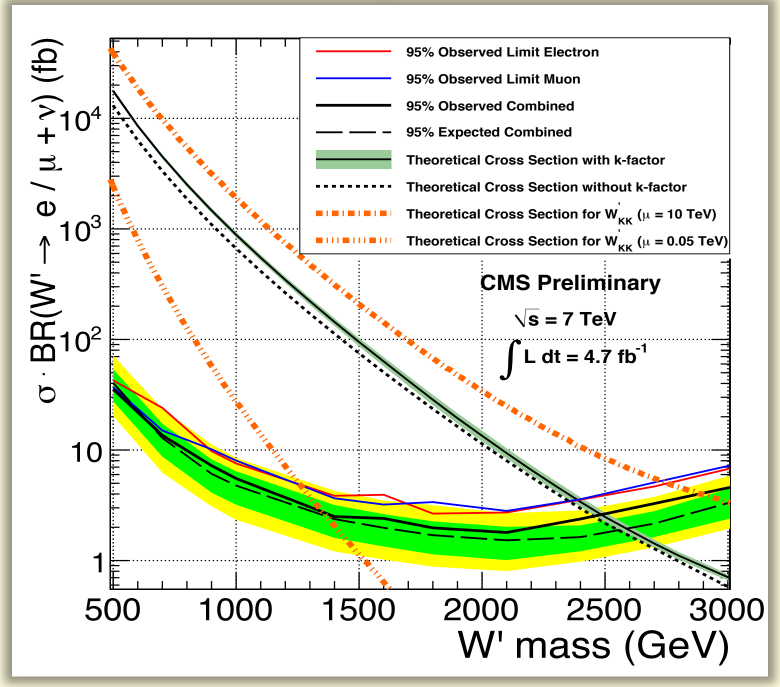


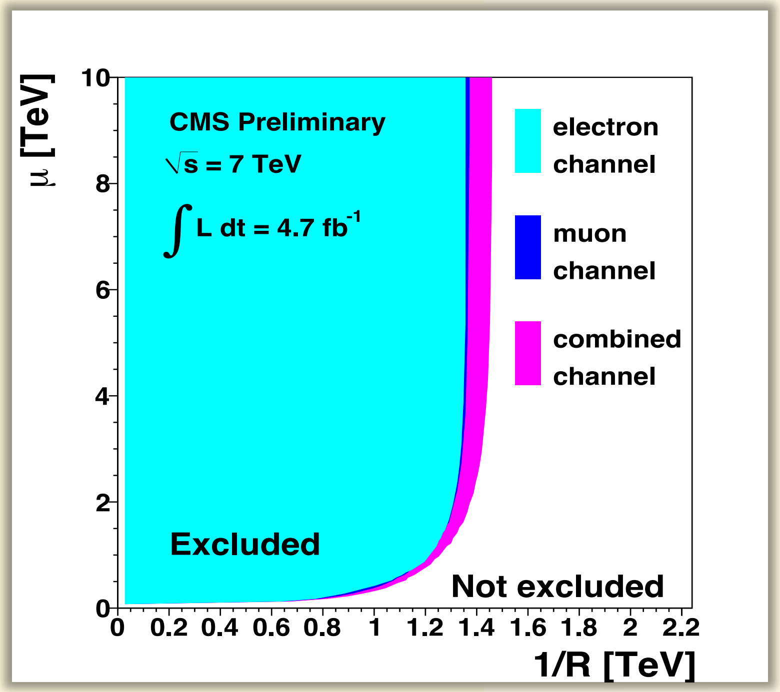


$0.4 < P_T^{l}/MET < 1.5$, $\Delta\phi$(lepton, MET) >2.5

- A heavy analogue of the SM *W* boson
  - Look for a Jacobian peak: $M_T = \sqrt{2E_T^{\ell} E_T^{miss}[1 - \cos\Delta\phi(\ell, E_T^{miss})]}$
  - Assume SM-like branching fractions and decay modes (also *tW* opens up)
- SM backgrounds: *W*→*lν*, DY→*ll*, top, dibosons, QCD multijets
- Fit M_T shape in MC → normalize to data in sideband

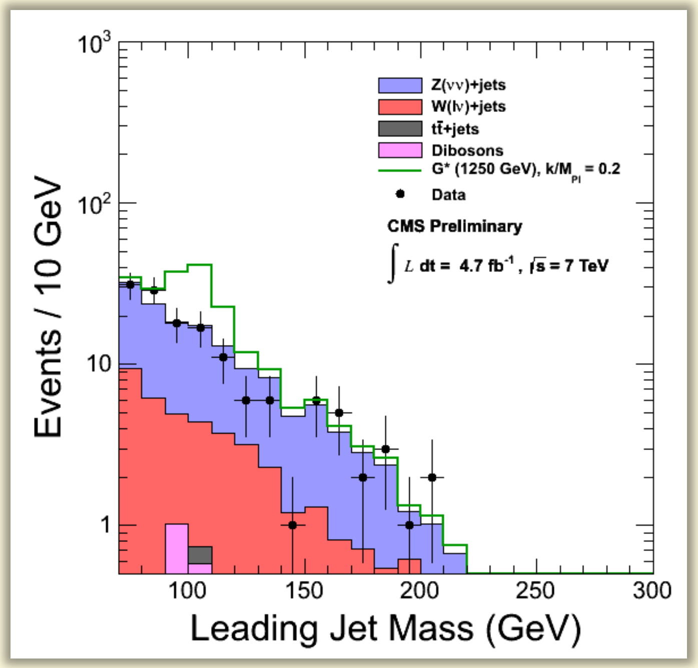
Heavy resonances: $W' \rightarrow l\nu$

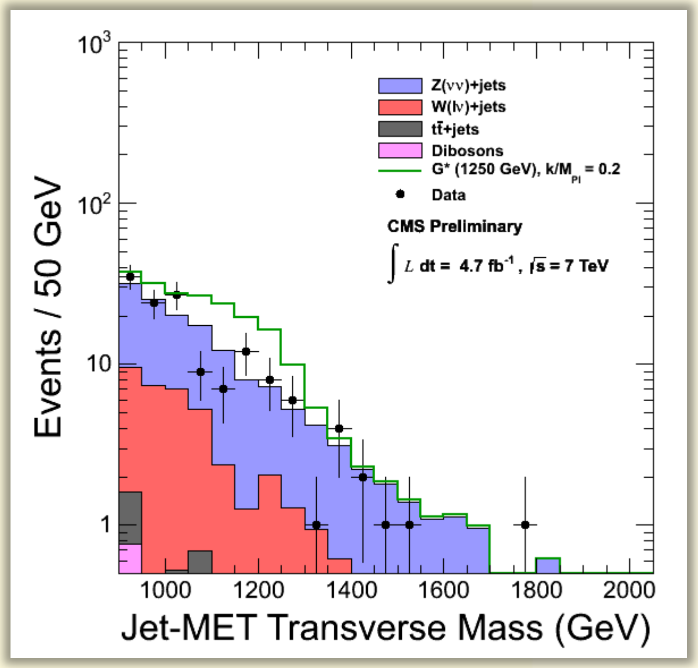




- Exclusion limits for different W' models:
  - RH W' with SM-like couplings, and W'_{KK}-states in the framework of UED
  - LH W' including interference with the SM W
- W' with SM-like couplings is excluded below 2.5 TeV
  - Including interference, exclude: **< 2.63 TeV** (constructive), **< 2.43 TeV** (destructive)

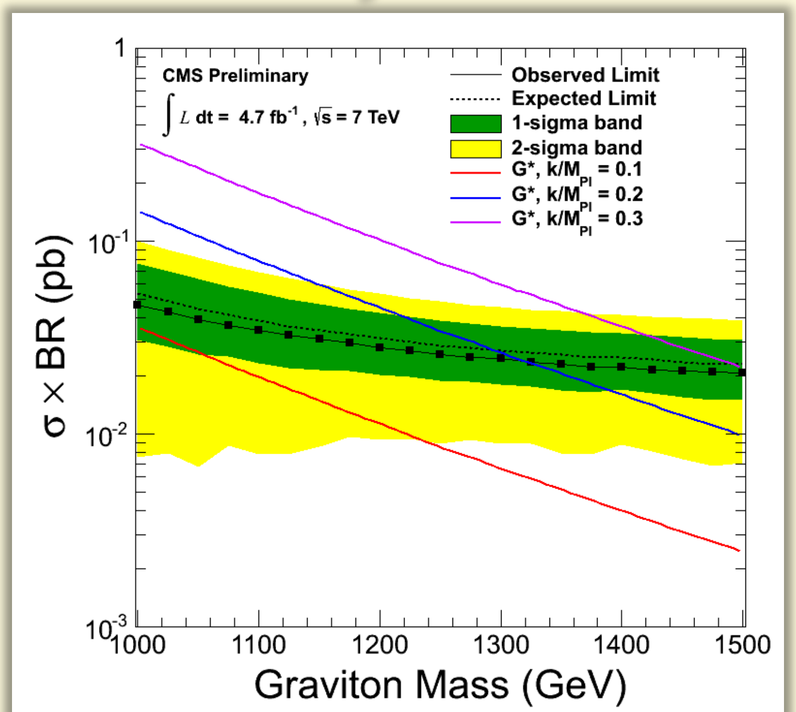
Heavy resonances: G*→ZZ

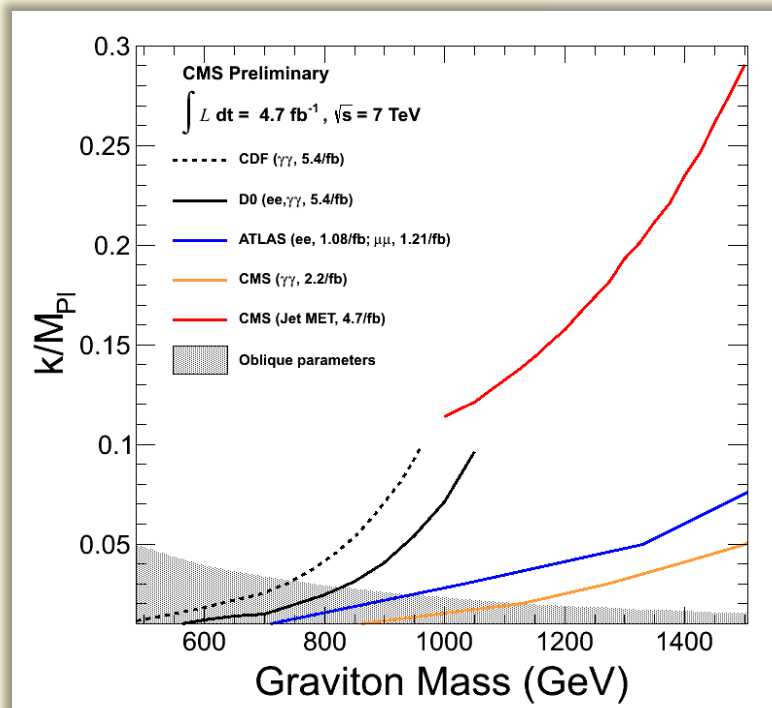




- RS Graviton hadronic decays: G*→ZZ→*qqνν*
  - Focus on high masses (M_G > 1 TeV): boosted Zs merge into single jet
  - Veto events with isolated tracks (EWK bckds) and with back-to-back jets (QCD bckd)
  - M_{j1}>70 GeV, $M_T^G = \sqrt{2\, p_T^{\text{jet}}\, \not{E}_T \left[1 - \cos\Delta\phi(\text{jet}, \not{E}_T)\right]}$ > 900 GeV, MET>300 GeV
- Backgrounds derived from sidebands in data

Heavy resonances: G*→ZZ



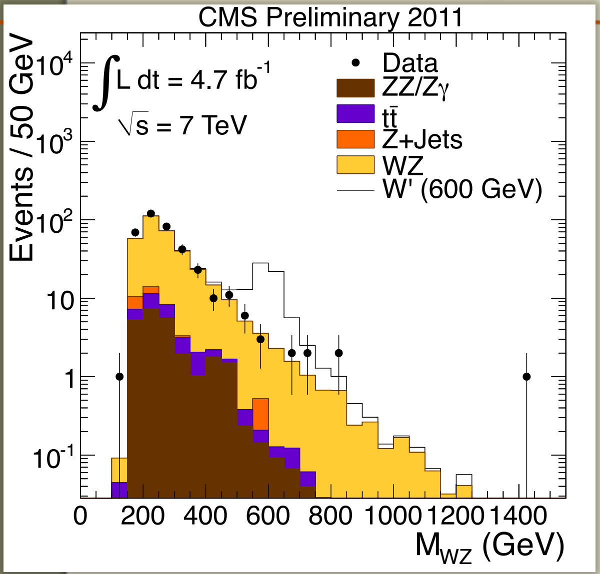


- Agreement between the estimated background and the observed data
- Set limits on the $\sigma x BR$ of a resonance decaying to ZZ
  - The limits interpreted in terms of the coupling parameters of the RS model:
- Exclude RS Graviton for k/M_{Pl} = **[0.11,0.31]** and m_G = **[1000,1500]** GeV

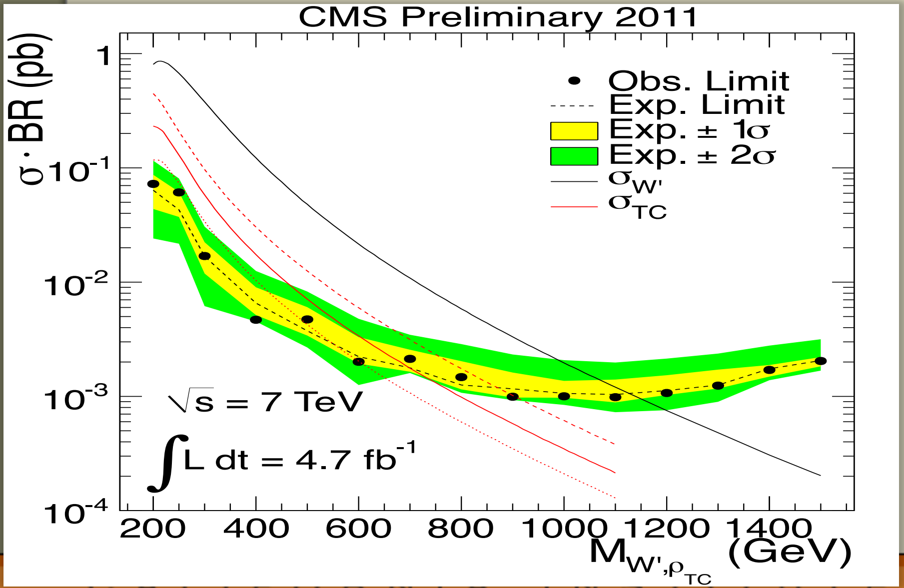
CMS-PAS-EXO-11-041, 4.7 fb^{-1}

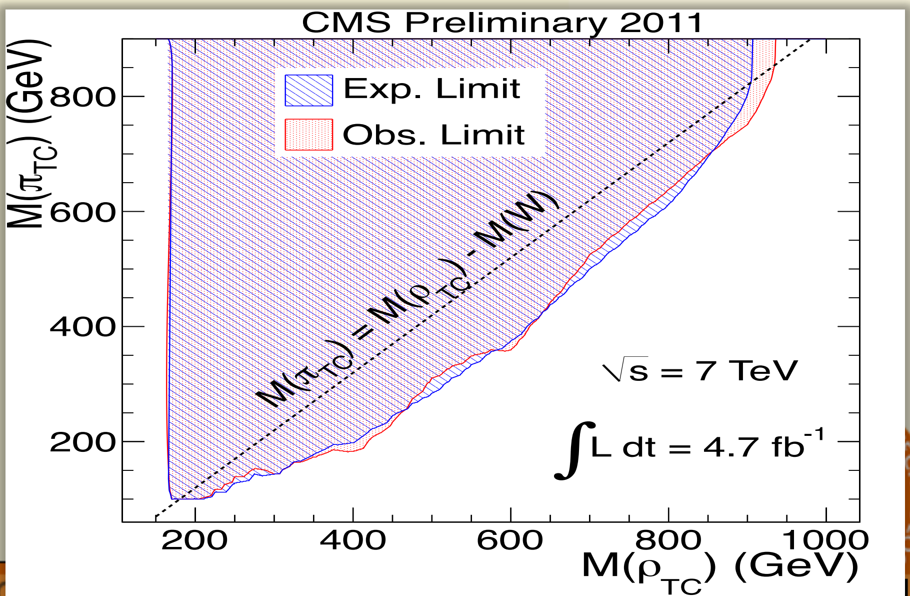
new

Heavy resonances: W'→WZ



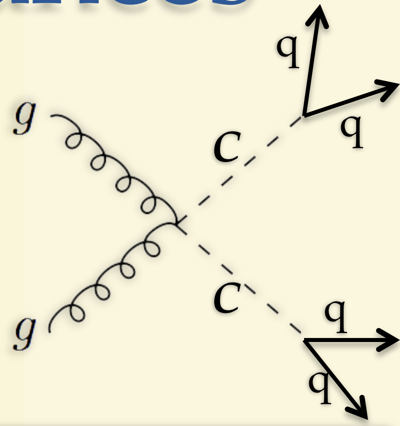
- W' or ρ_{TC} decaying to WZ
    - Couplings to SM leptons may be suppressed
- Select events with three leptons (e, μ) and ν
    - Two SF, OS, isolated leptons consistent with Z
    - Additional high p_T, isolated lepton, high MET
- HT cut optimized for various signal hypothesis

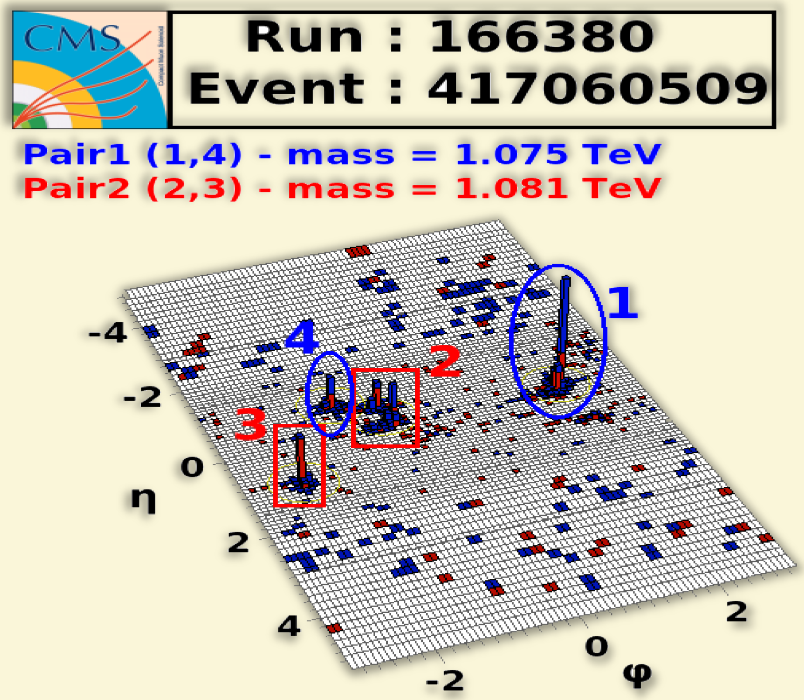


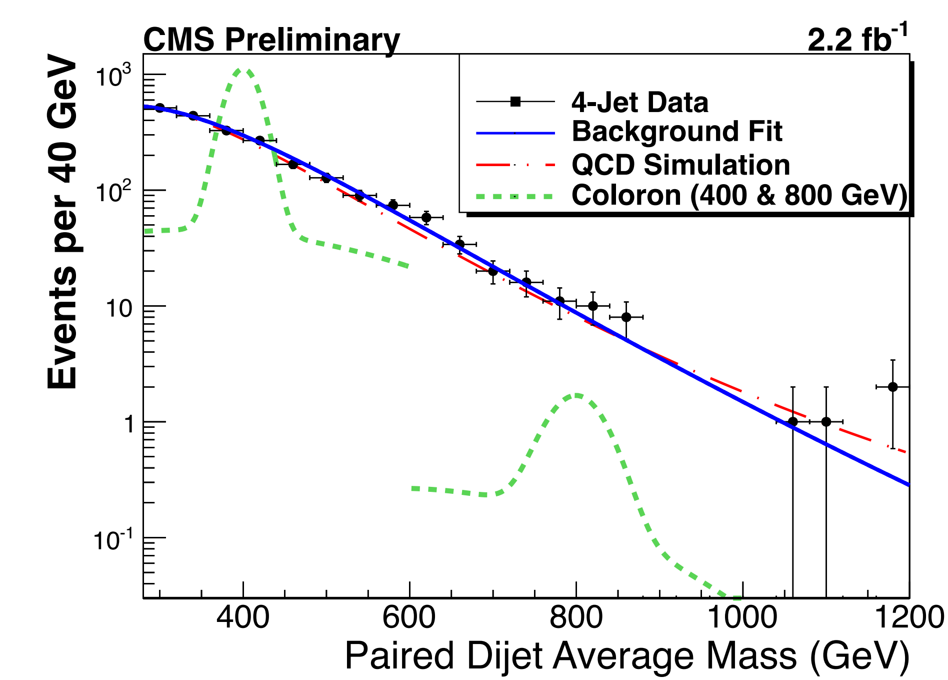


Pair produced di-jet resonances

- Predicted in several models: coloron, axigluon, hyperpions…
- Require two pairs of dijet masses to be close: $|\Delta m|/m_{avg}<15\%$
  - $\geq$4 jets with p_T>150 GeV, optimized for a generic coloron search
- QCD background derived using a 4-parameter fit

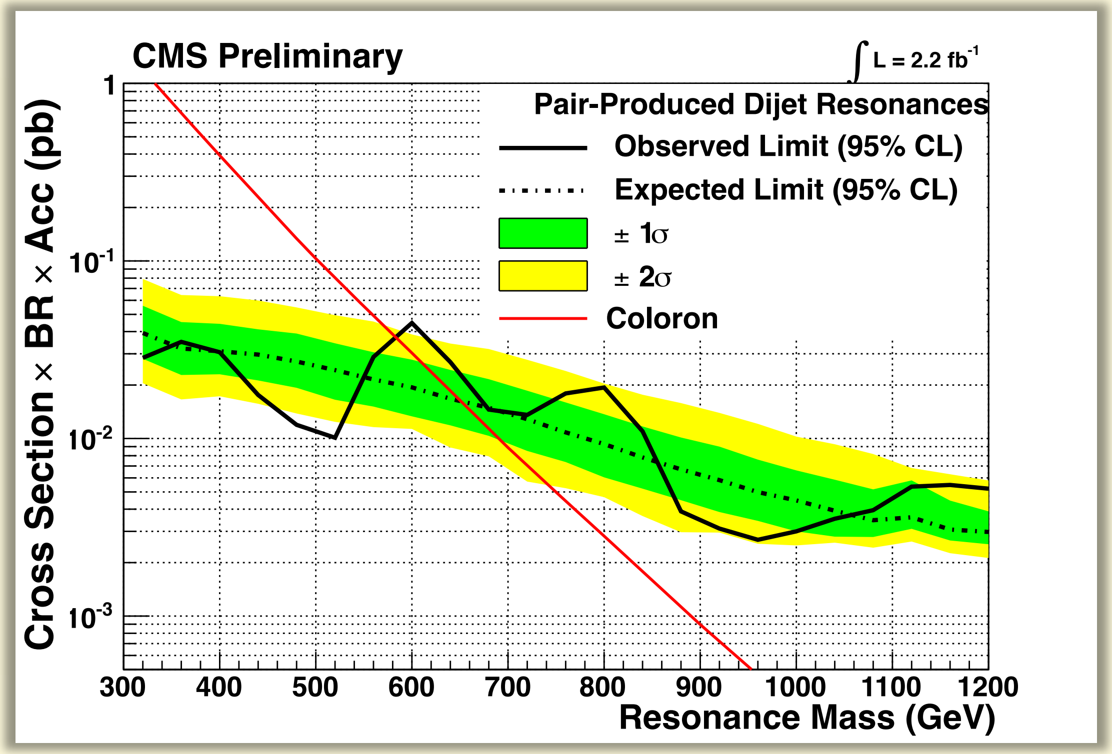






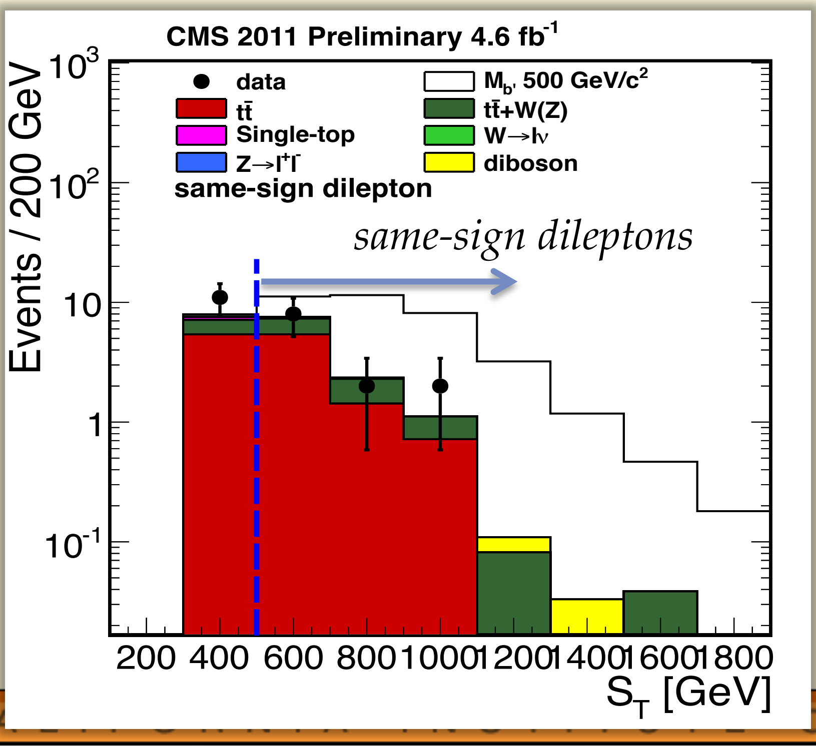
Pair produced di-jet resonances

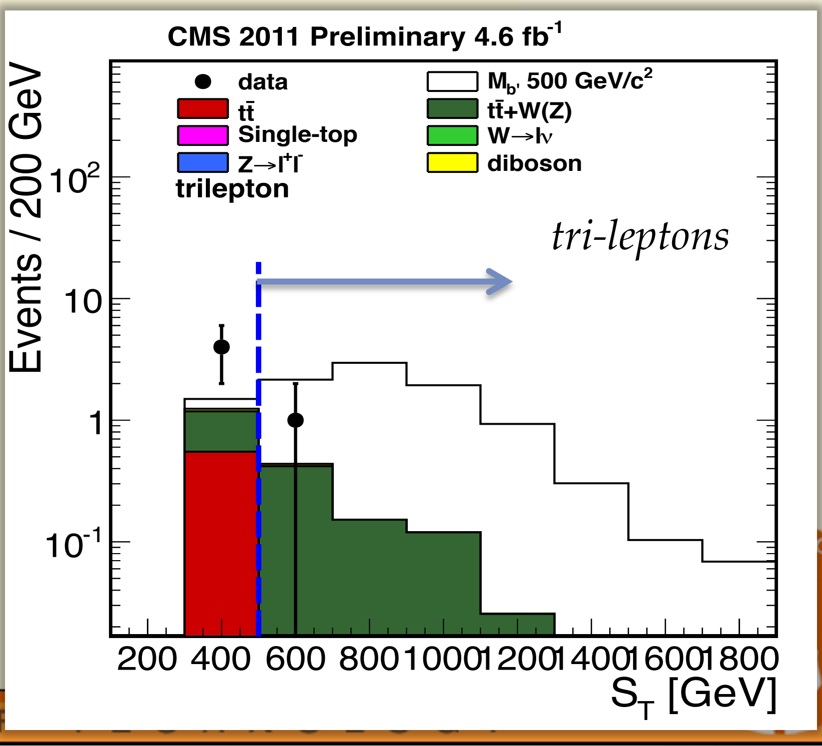
- Overall, good agreement of background model with observed data
  - Largest deviation with respect to the background model is around M=615 GeV
- Exclude pair production of colorons with mass between **320 – 580** GeV



4th generation quarks: *b′*

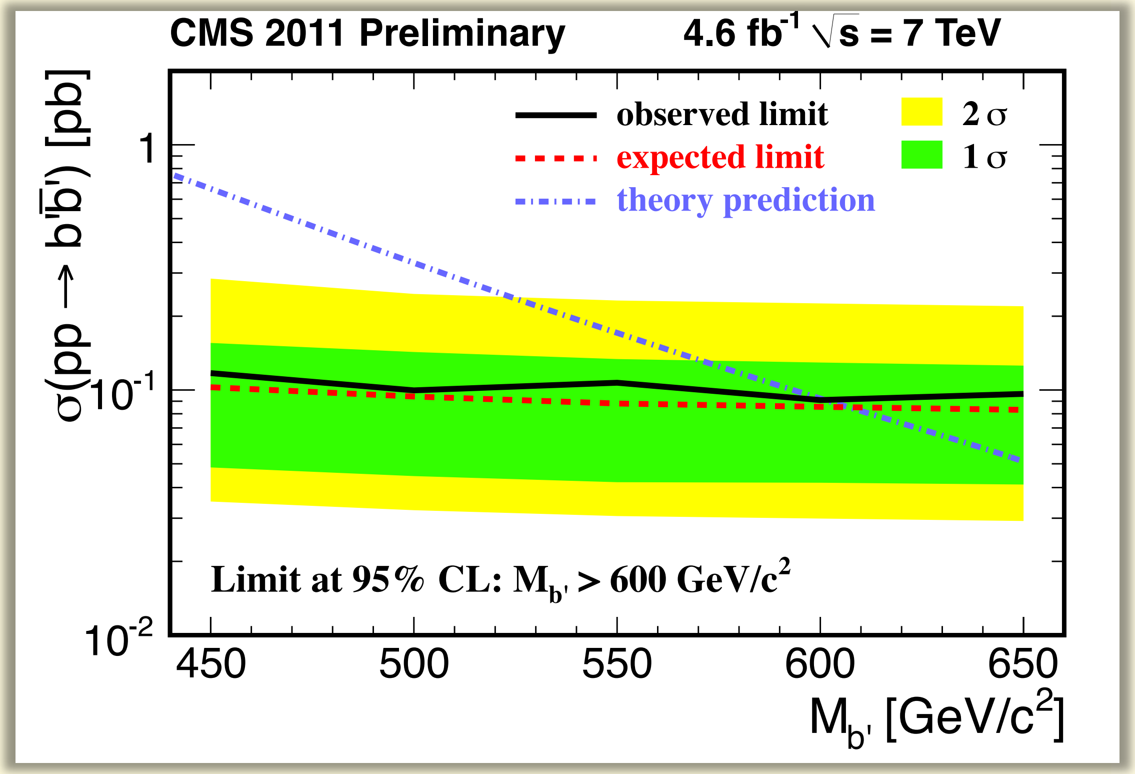
- Could relax indirect bounds on Higgs boson, relevant for baryogenesis
- $b'b' \rightarrow tWtW \rightarrow (bW)W(bW)W$ assuming $M_{b'} > M_{top} + M_W$
- Look at the clean final state of same-sign dilepton or trilepton
  - 7.3% of *b′* decays, but very rare final states for the SM backgrounds
- Fake and mis-ID bckds from data (top,V+jets, WW); MC for *ttV, ZZ, WZ*





4th generation quarks: b'

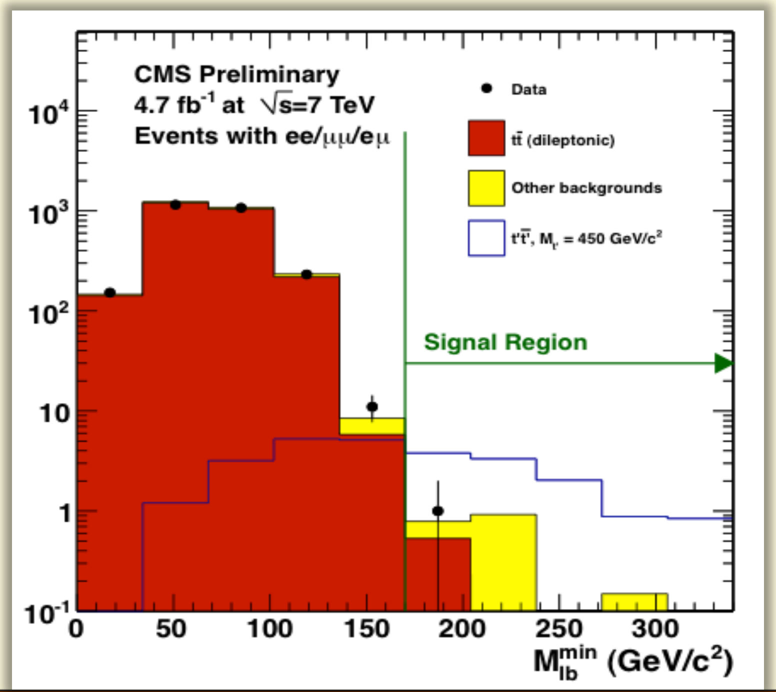
Number of b-tagged jets	same-sign dilepton signal	same-sign dilepton background	same-sign dilepton data	trilepton signal	trilepton background	trilepton data
≥ 0	33	15	14	11	1.3	5
≥ 1 (default)	25	11	12	8	0.73	1
≥ 2	11	4.6	3	3	0.31	0

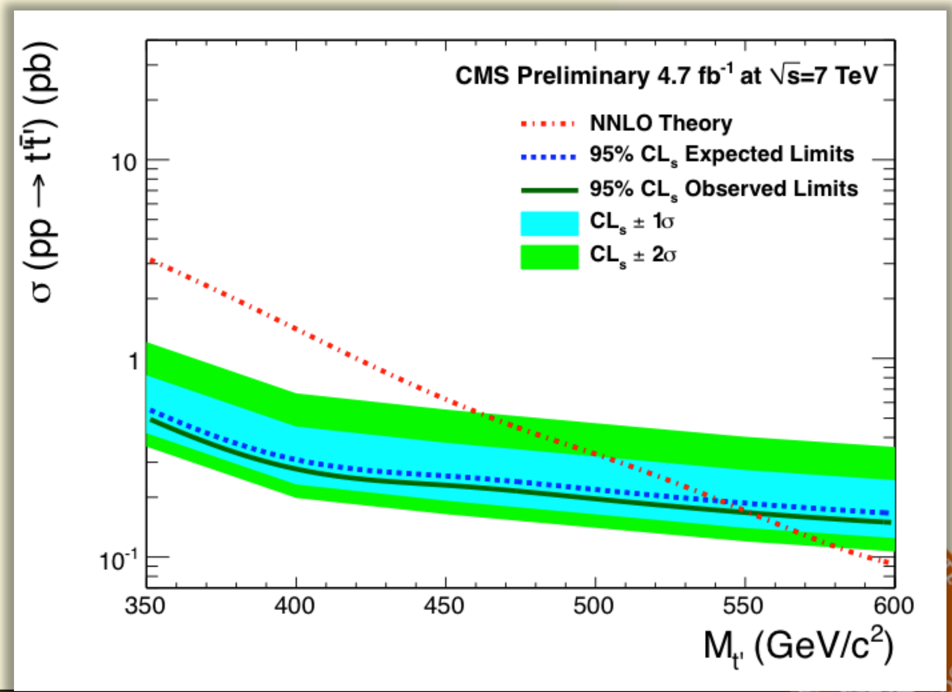


- Exclude $M_{b'} < 600$ GeV assuiming 100% BR for b'→tW

4^{th} generation quarks: *t′*

- Search in the dilepton channel (*ee*, *eμ*, *μμ*): *t′* → *Wb*
- Use M_{lb}^{min}: minimum value of four possible *lb* combinations
  - Reduce top background selecting events with $M_{lb}^{min} > 170$ GeV
  - Main backgrounds (mis-ID leptons, *b*-jets) derived from data in an orthogonal sample
- Exclude t′ with masses below **552 GeV**



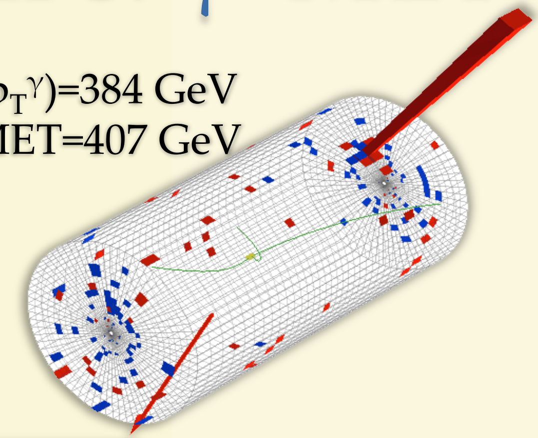


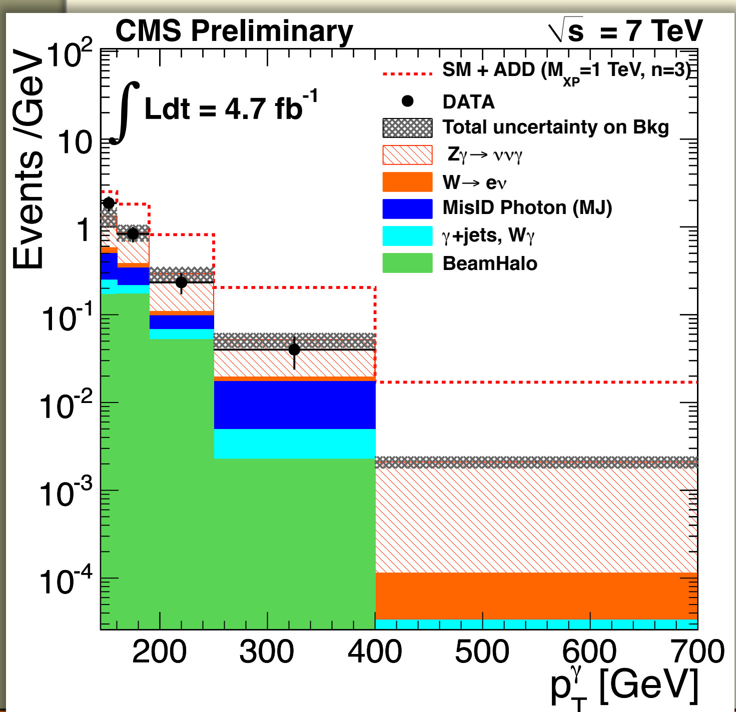
new

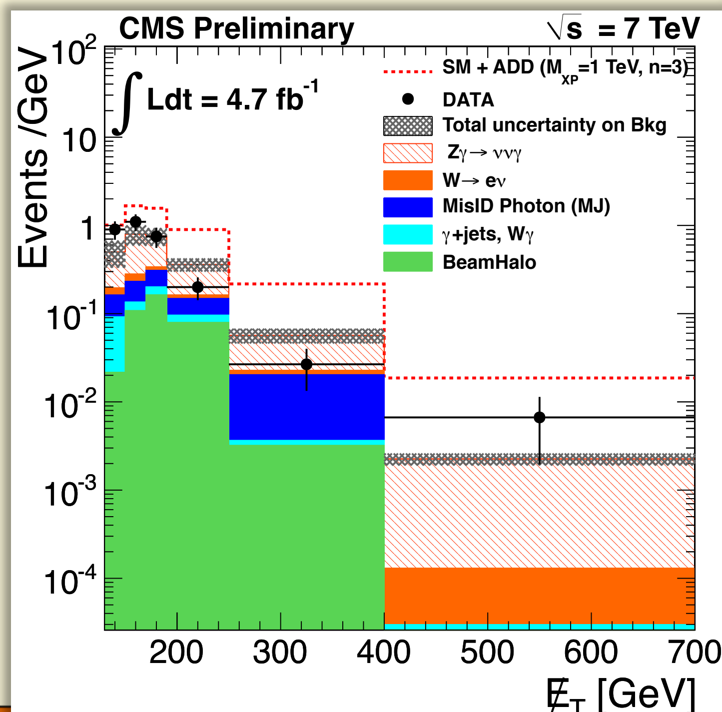
Extra Dimensions and WIMPs: γ+MET

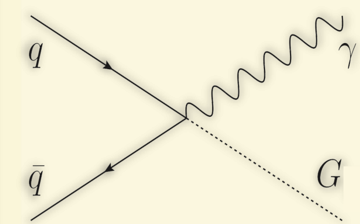
- "Compactified" EDs are hidden from view
  - Gravity only *appears* weaker
  - Probe direct production of Gravitons at LHC
- Similar signature from WIMP + γ from ISR
  - Assume a DM-hadron coupling to quarks exists
- Data-driven estimate of the instrumental bkgds

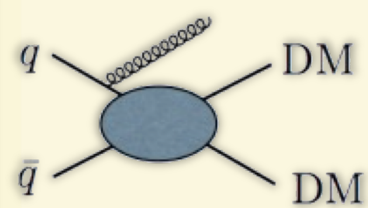
(p_T^{γ})=384 GeV
MET=407 GeV







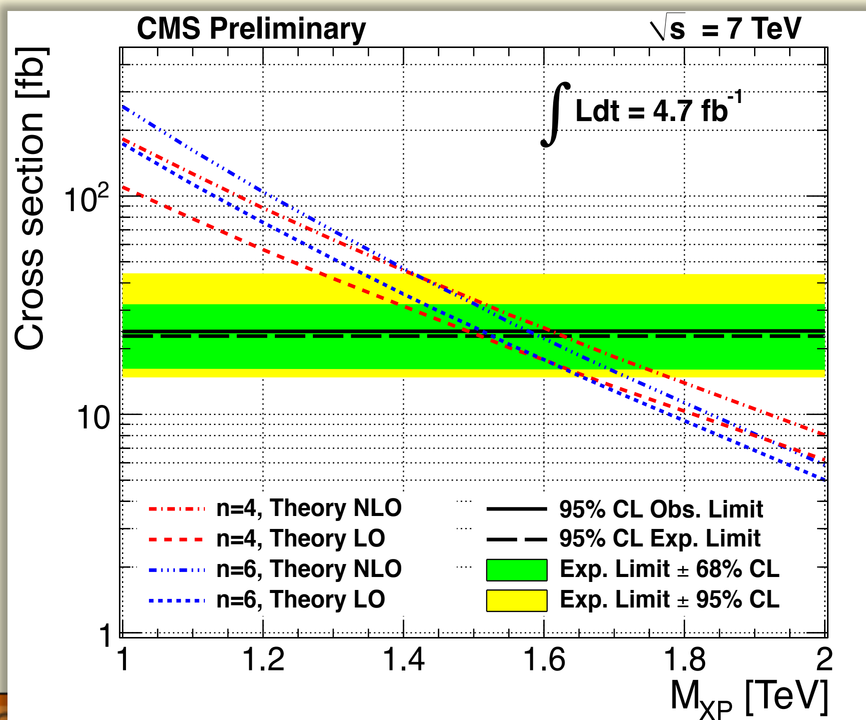


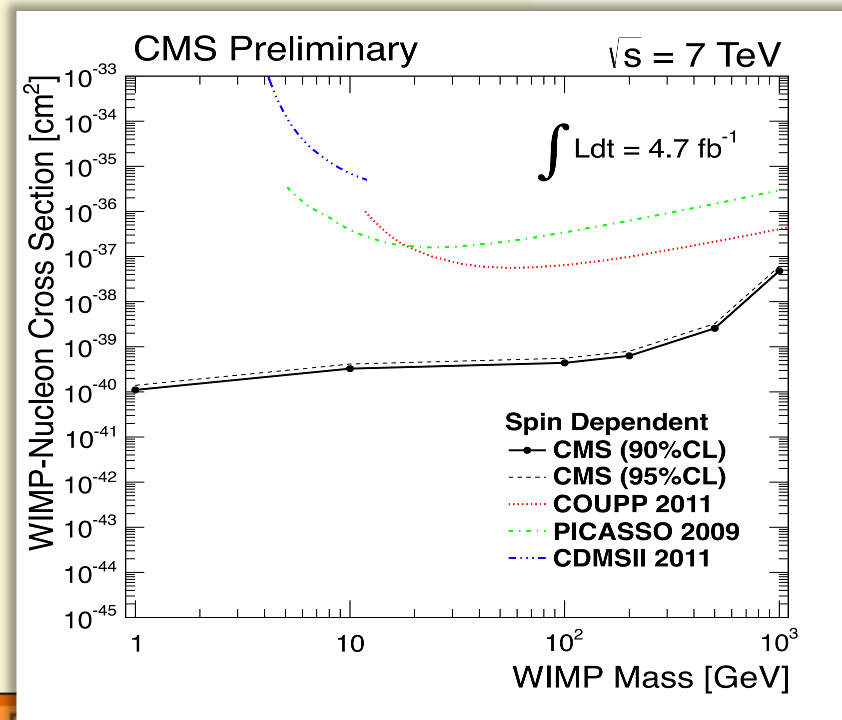


new

Extra Dimensions and WIMPs: γ+MET

- Good agreement between data and expectation
  - 71.9±9.1 (exp) and 73 (obs) events
- Exclude $M_D <$ **1.59-1.66** TeV for n=3-6 at 95%CL
- Limits on WIMP-nucleon interaction cross-section *(JHEP 1012:048(2010))*
  - Set limits on spin-independent (SD) and spin-dependent (SI) WIMP-nucleon xsection
  - Better sensitivity than direct detection experiments for spin-dependent case

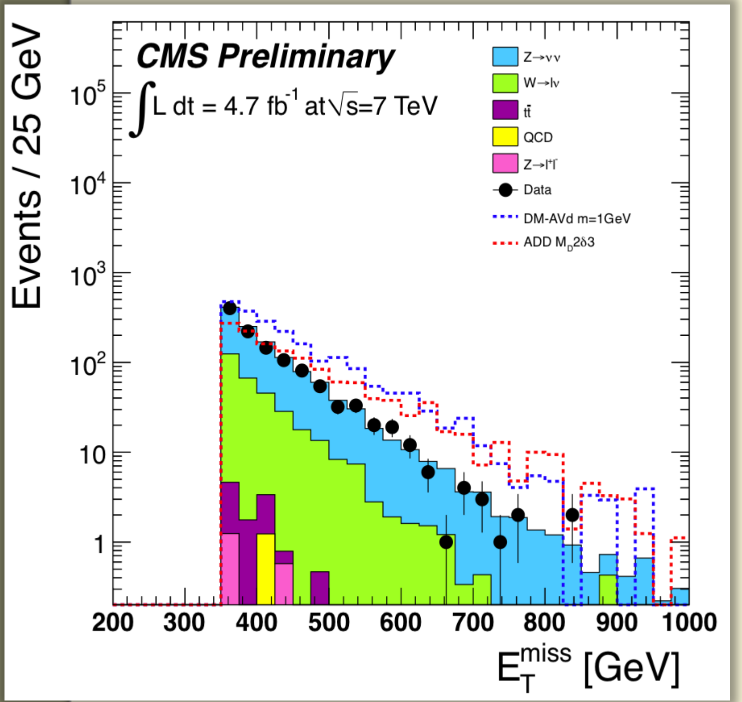


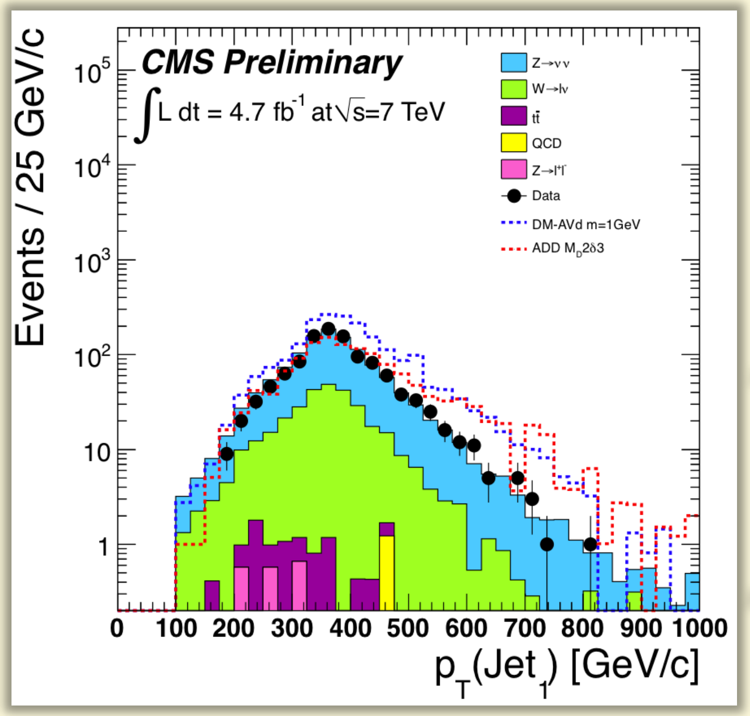


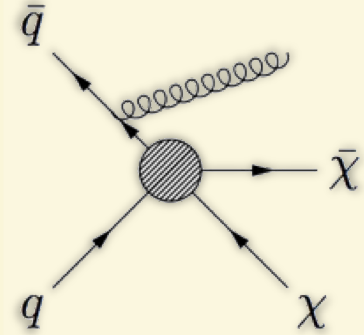
new

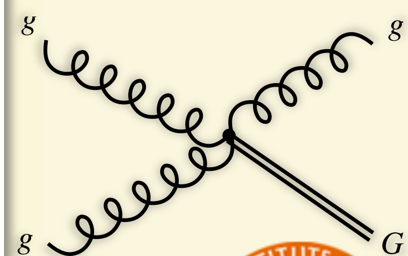
Extra Dimensions, DM and unparticles: monojet

- Similar to monophoton, but with a jet in the final state
- Main backgrounds from $Z \rightarrow \nu\nu$ and $W \rightarrow l\nu$ (lepton is lost, τ hadronic)
  - $Z \rightarrow \nu\nu$ is estimated from $Z \rightarrow \mu\mu$: similar kinematic characteristics
  - $W \rightarrow l\nu$ from $W \rightarrow \mu\nu$, understand the Data/MC scale factors









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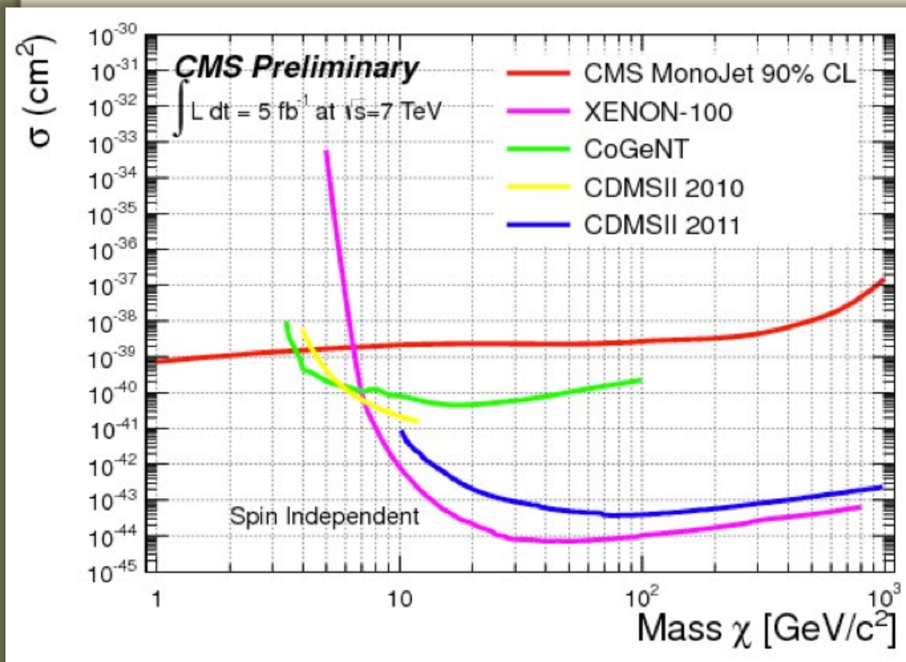
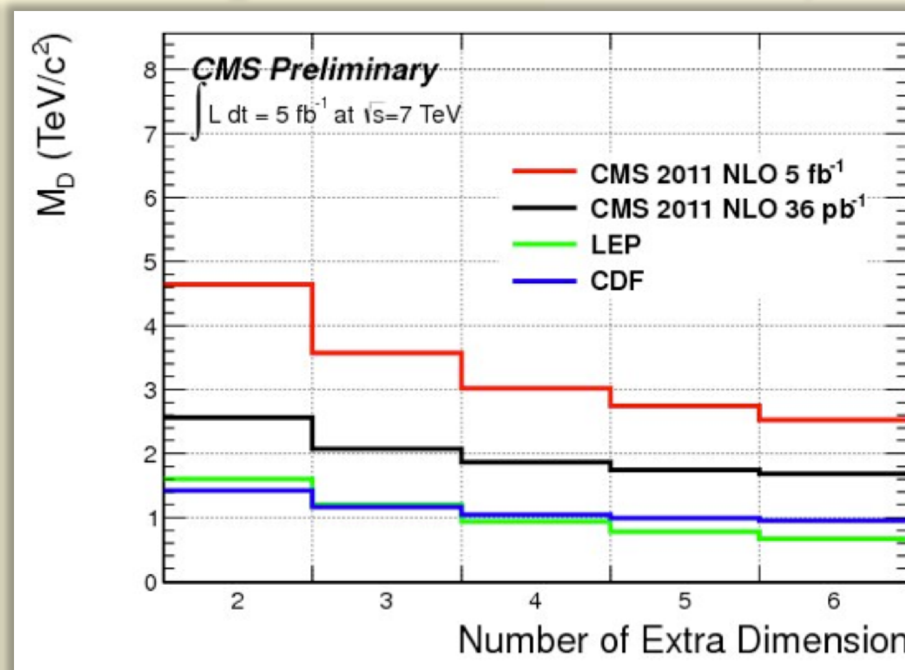
Extra Dimensions, DM and unparticles: monojet

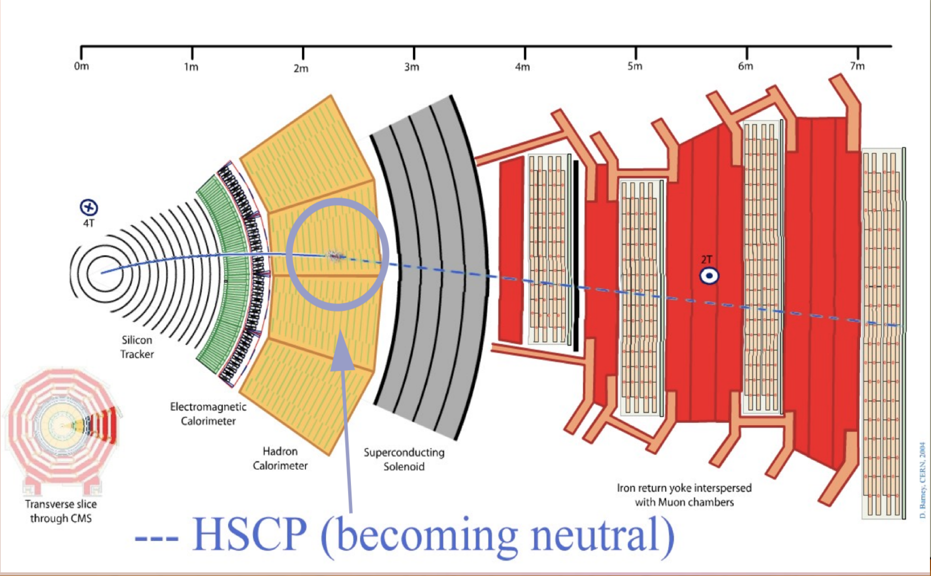


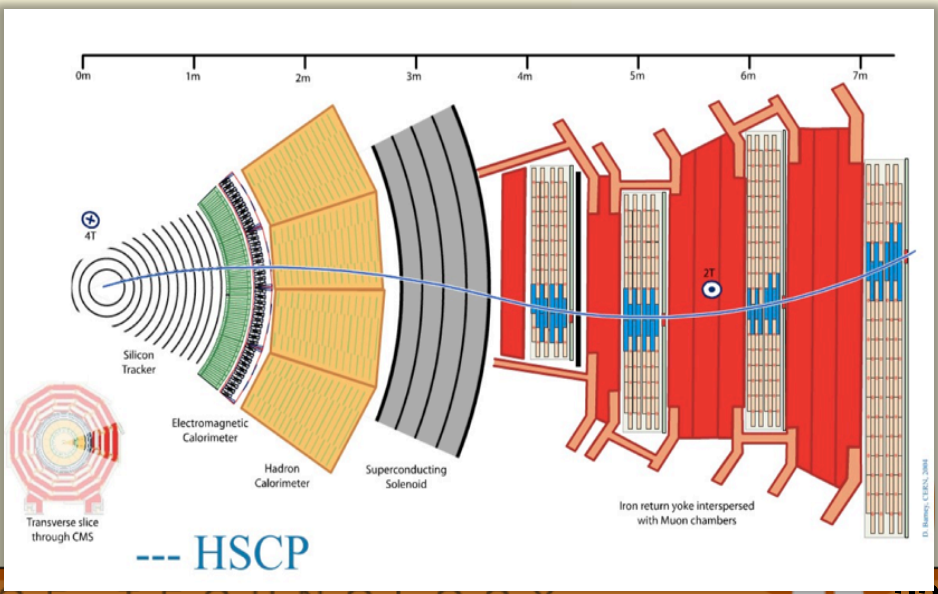


- Exclude large parameter space:
  - M_D<**4.45-2.46** TeV for number of extra dimensions δ = 2-6 (*ADD*)
  - Exclude Λ_U < **28.5-1.16** TeV for scale dimensions d_U=1.4-1.9 (*unparticles*)
  - Best limits below **3.5** GeV for SI DM models (hard for the direct detection experiments)
  - **Most stringent** constraints over 1-1000 GeV mass for SD DM models

Heavy stable charged particles

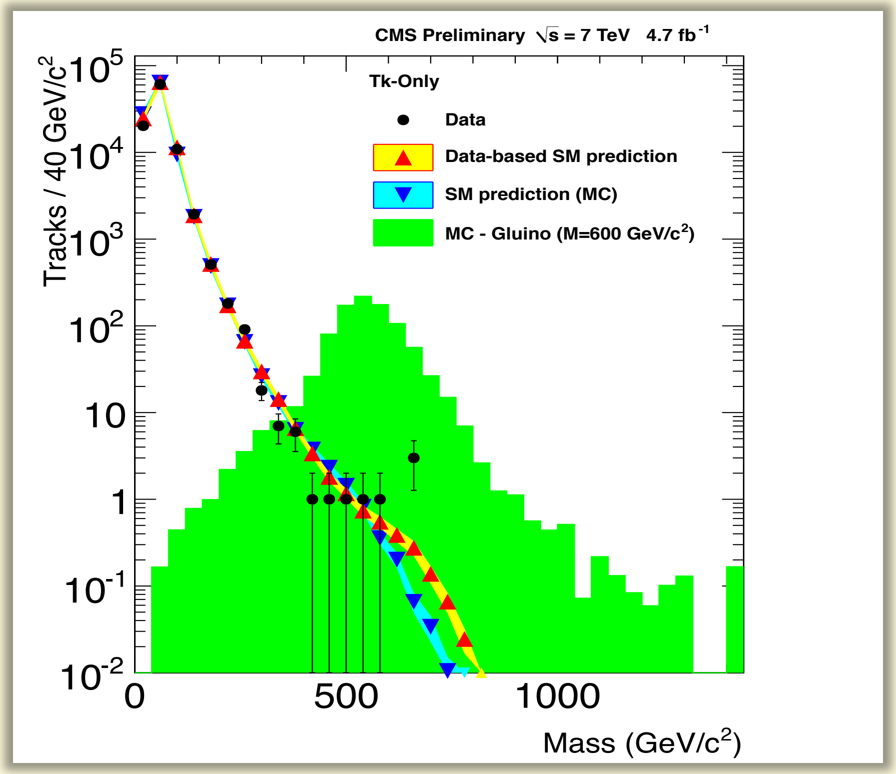
- Small coupling or mass splitting between NLSP and LSP → stable NLSP
  - Various versions of SUSY (GMSB, split SUSY), UED and other extensions to SM
- R-hadron: bound state of strongly interacting particle
  - Squarks or gluinos hadronize with SM quarks/gluons
- Characteristics: high momentum, but slower than light
  - High dE/dx (heavy particle) and long TOF to the muon system (slow)
  - Charge exchange possible in material
- Two approaches: tracker only and full tracking (with muon hits)+ TOF

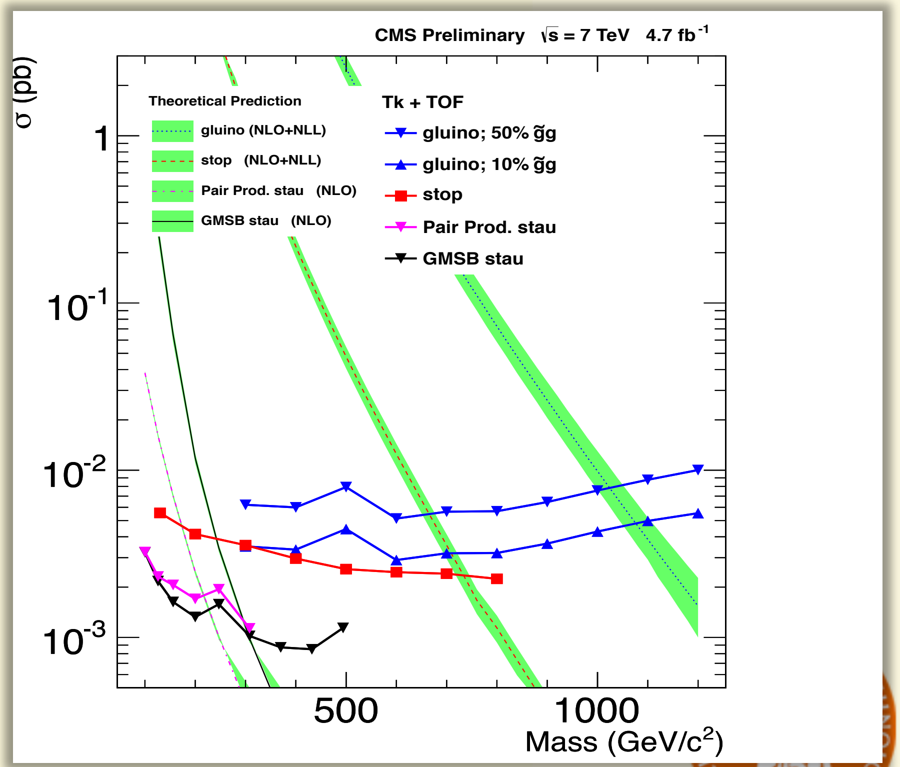




Heavy stable charged particles

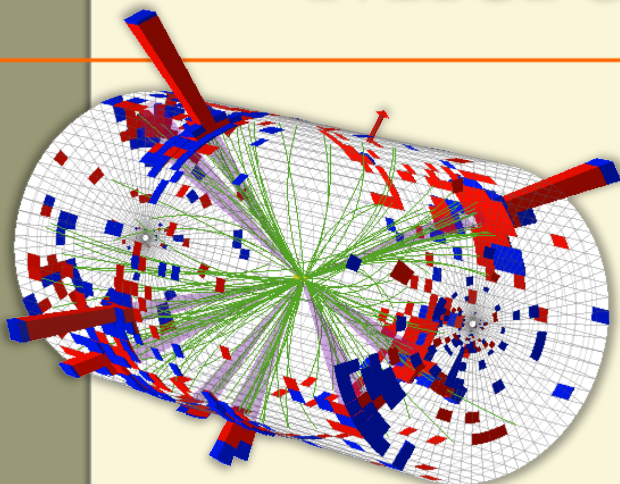
- Counting experiment in a mass window in [M_{RECO}-2σ, 2000 GeV]
  - Select candidates with large p_T, large dE/dx, and large TOF
- Observations consistent with expected data-driven background
  - Limits on many models: M(glu)>**1091** GeV, M(stop)>**734** GeV, M(stau) > **221** GeV.
  - Exclude stable gluino < **923** GeV that becomes neutral before reaching muon detectors.



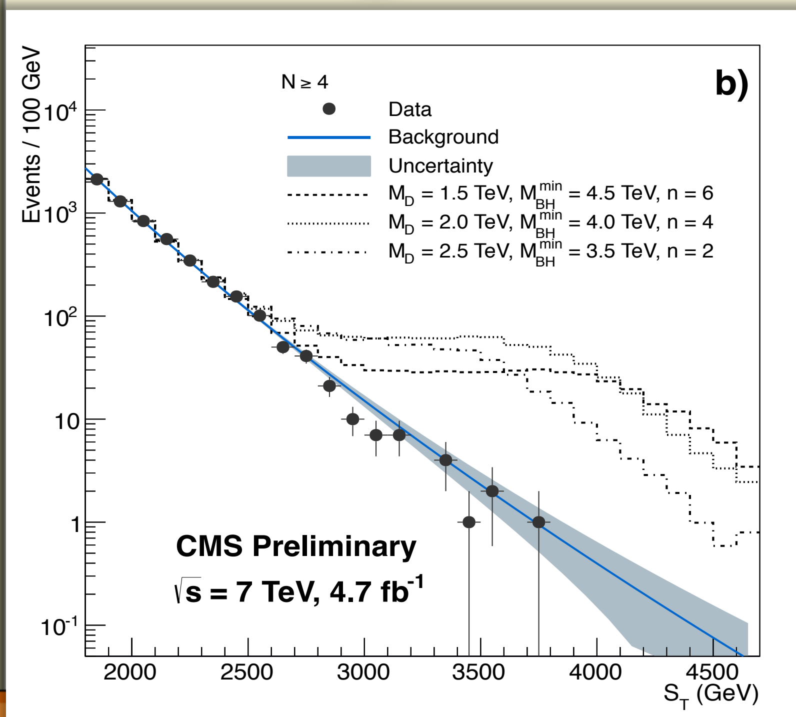


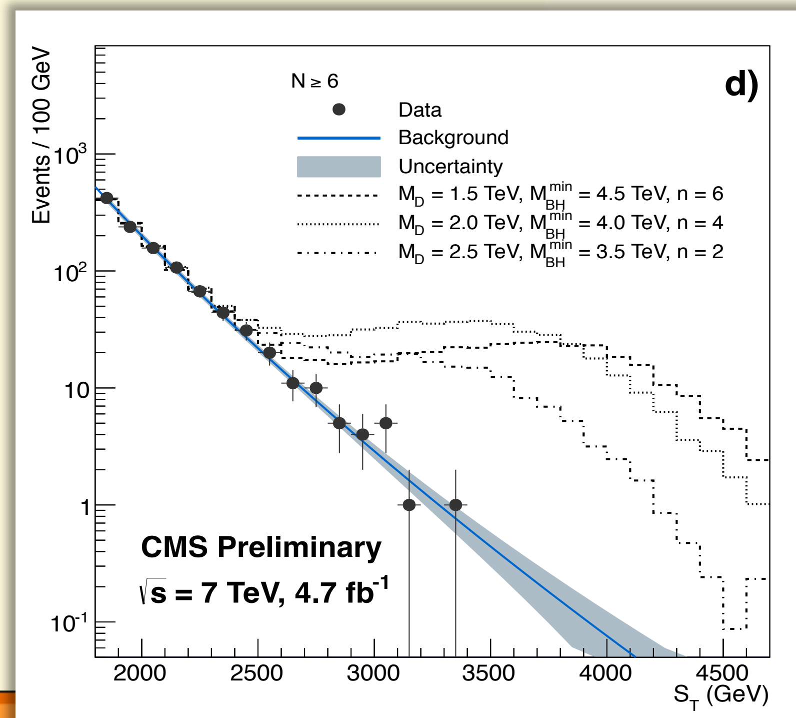
CMS-PAS-EXO-11-071, 4.7 fb^{-1}

Microscopic black holes



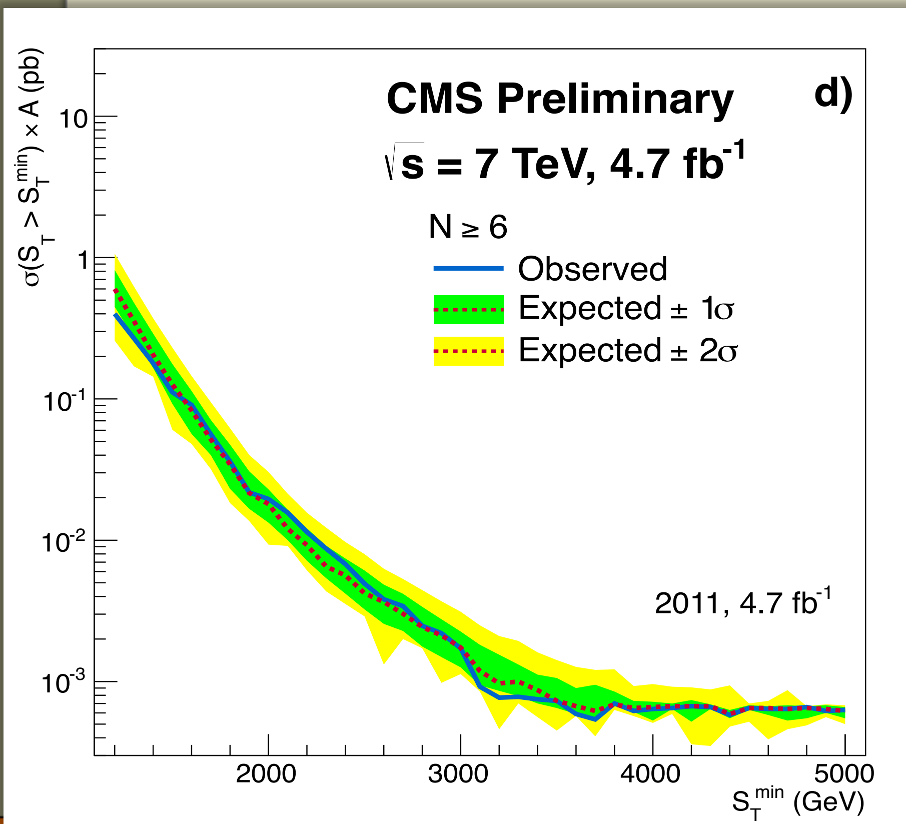
- $S_T = \sum E_T$ (jets, e, μ, γ, ν; E_T>50GeV) used for search
  - Democratic decay via Hawking radiation
- QCD multijet production is the main background
  - S_T multiplicity invariance: shape of S_T is independent of N
  - Use S_T=1200-1800 GeV, N = 2, 3 data → background shape

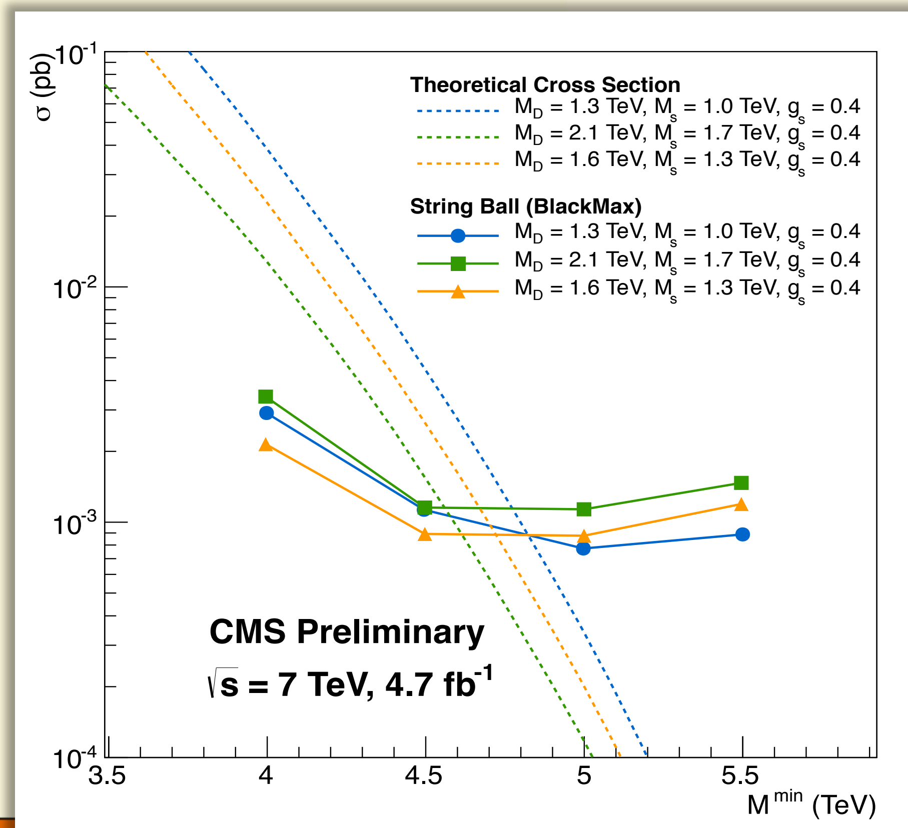




Microscopic black holes

- Model-independent limits for high-S_T and high-N searches: ~0.6 fb at high S_T
- Semi-classical and quantum black holes exclude < **3.8–5.3** TeV limit range
- Exclude string balls with masses below **4.6** to **4.8** TeV

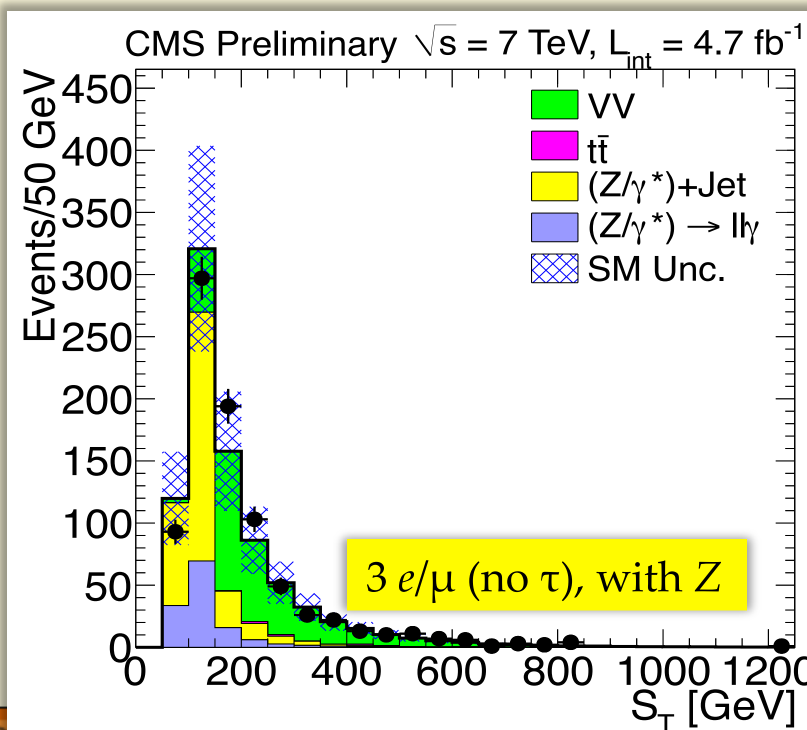


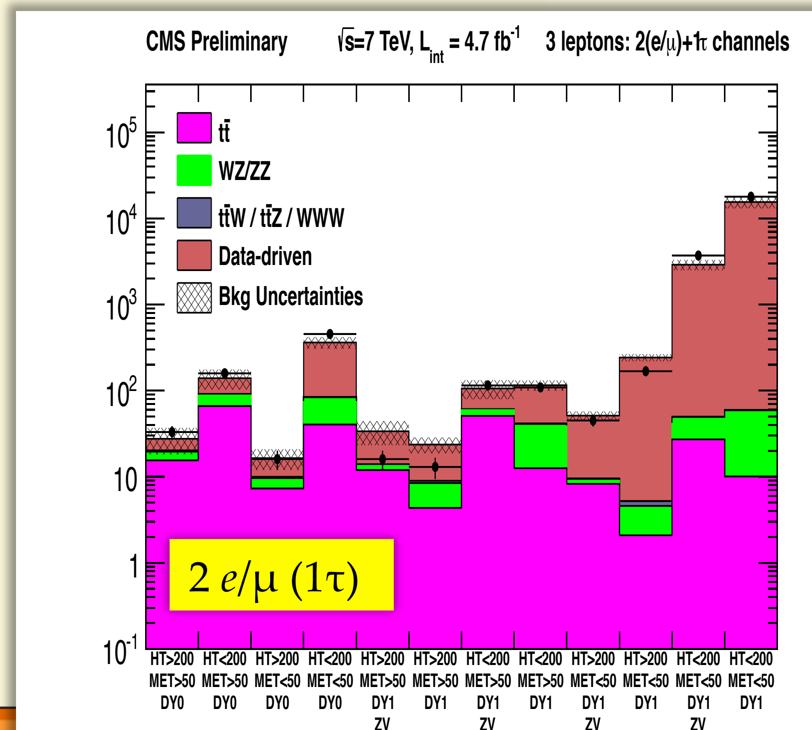


new

Multileptons

- A "*generic*", low-background signature (≥3 leptons, *e*, μ, τ)
    - R-Parity-conserving & RPV-SUSY, GMSB, mSUGRA, high tanβ (taus)
- Exclusive channels binned in: S_T, lepton charge, Z/no-Z
- MC (tt, VV+jets) and data-driven (V+jets, Zγ, QCD) background models

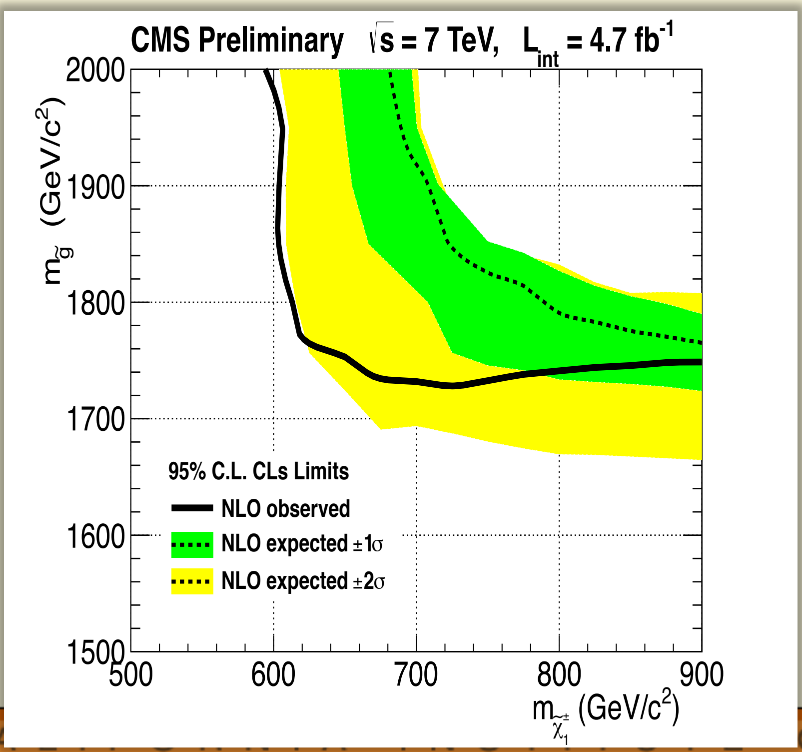


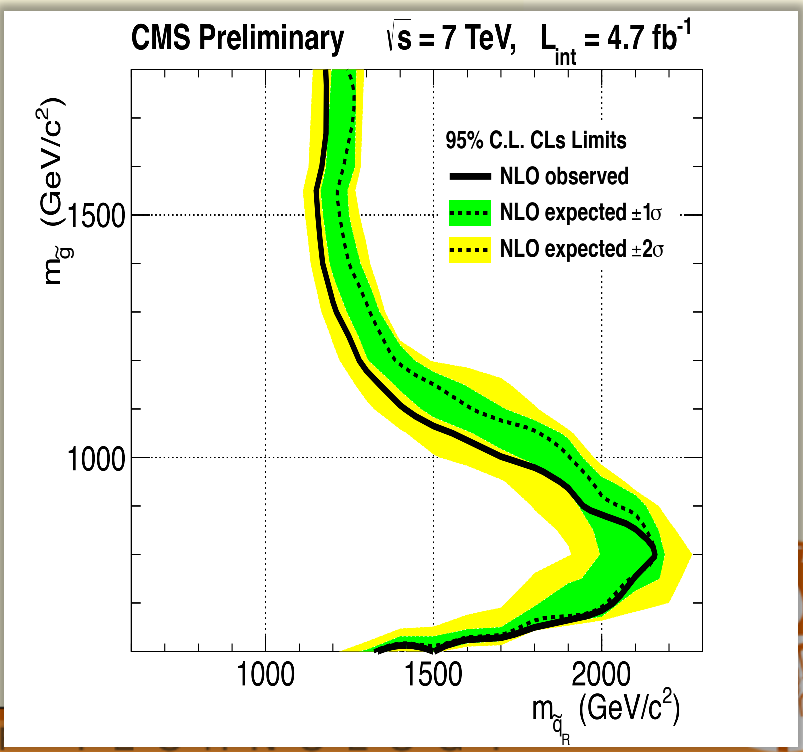


new

Multileptons

- Overall, a good agreement of data with background model
- Divide into exclusive channels
  - Any specific new-physics model may produce excess events only in some channels
- Exclude RPV couplings and H-RPV for M_{squark},M_{gluino}<**1** TeV





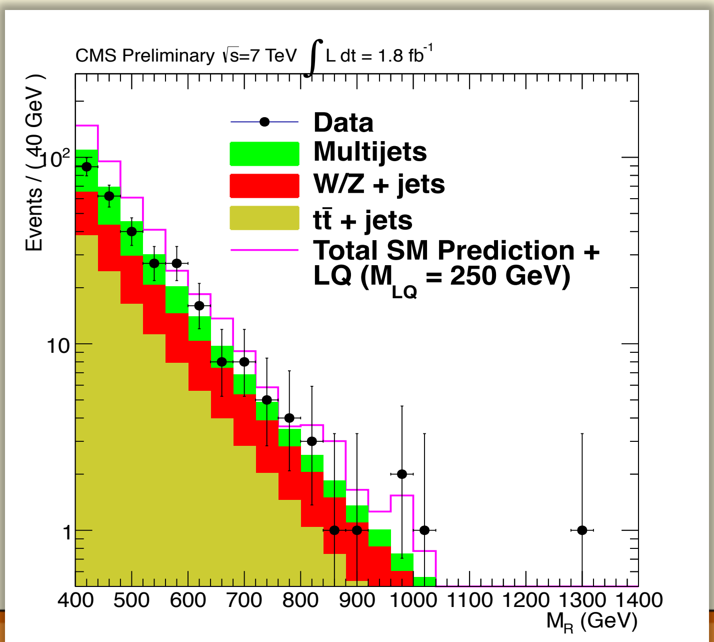
Scalar Leptoquarks: 3rd gen

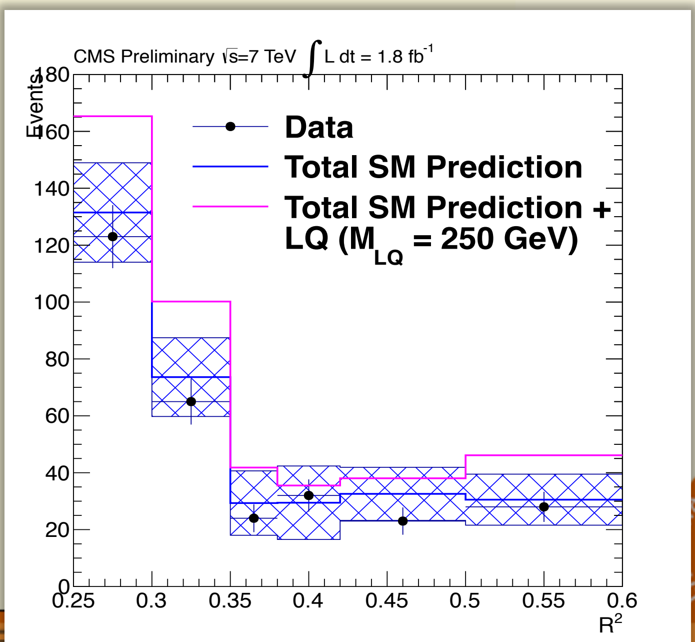
- $LQ_3 \rightarrow b\nu_\tau$: jets and MET in the final state
- Main sources of backgrounds
  - Fake MET: mismeasured jets from QCD *b*-jets
  - Real MET: W/Z+*b*-jets, top pair production
- Use R/M_R variables to search for signal
  - Largest backgrounds derived from independent sample in data

$$M_R \equiv \sqrt{(E_{j_1} + E_{j_2})^2 - (p_z^{j_1} + p_z^{j_2})^2}$$

$$M_T^R \equiv \sqrt{\frac{\not{E}_T(p_T^{j1} + p_T^{j2}) - \vec{\not{E}}_T \cdot (\vec{p}_T^{\,j1} + \vec{p}_T^{\,j2})}{2}}$$

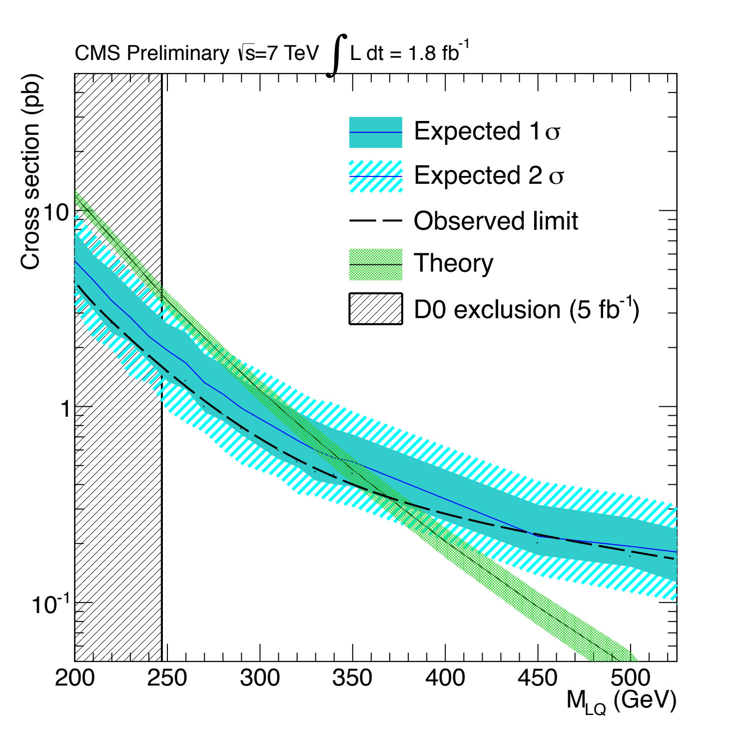
$$R \equiv \frac{M_T^R}{M_R}$$

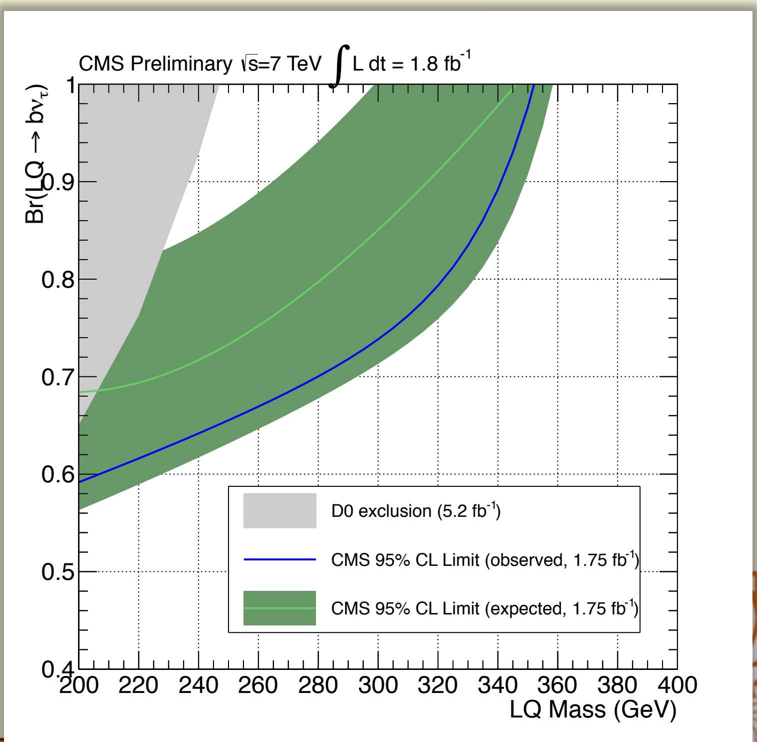




Scalar Leptoquarks: 3rd gen

- Search for signal in the sample with no leptons, two *b*-tagged jets
- No significant excess over background prediction is observed
  - Expected yield: **326.98 ±30.98**, observed: **295**
- Exclude scalar leptoquarks with masses below **350** GeV (β=1).



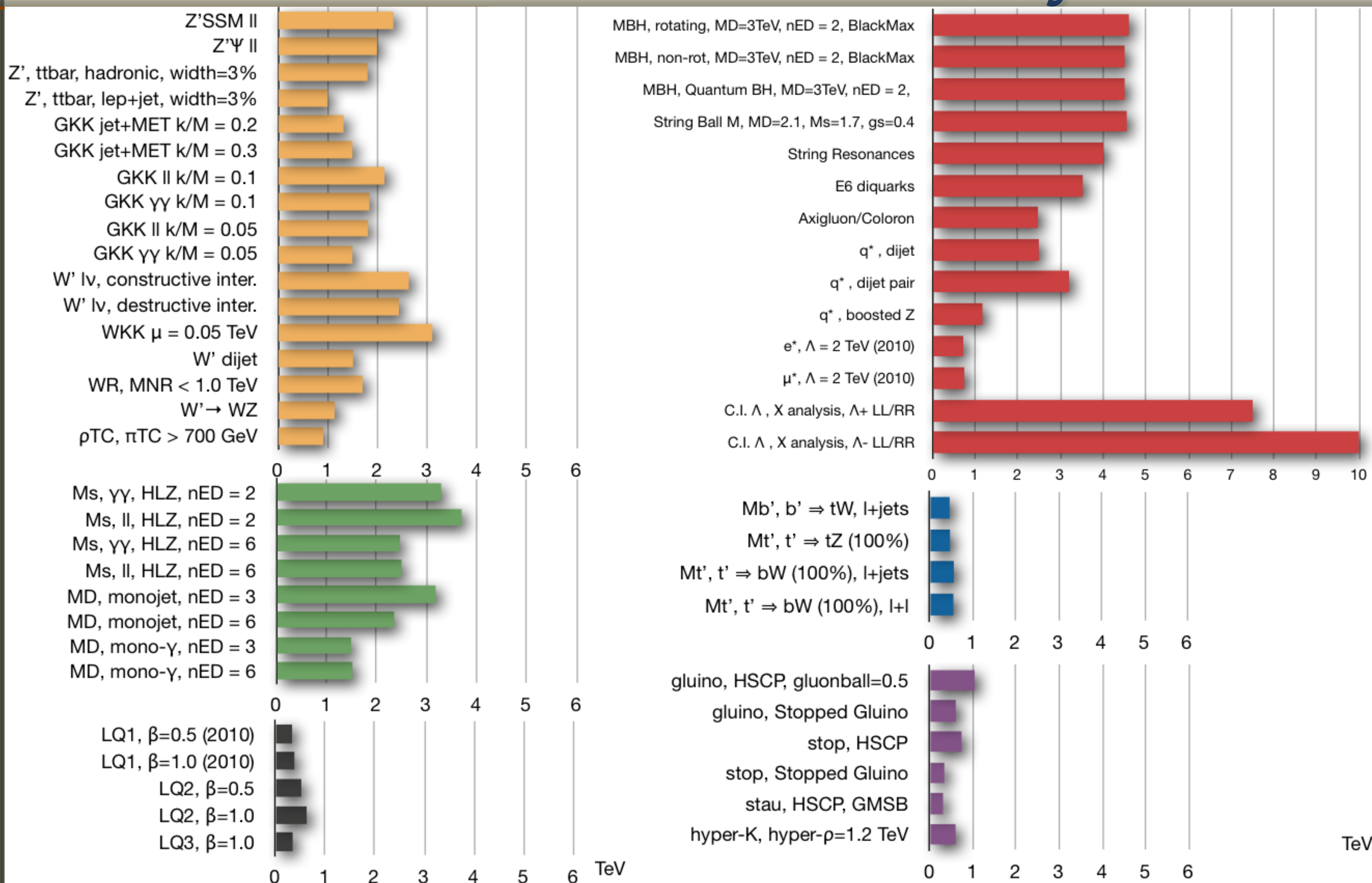


Conclusion

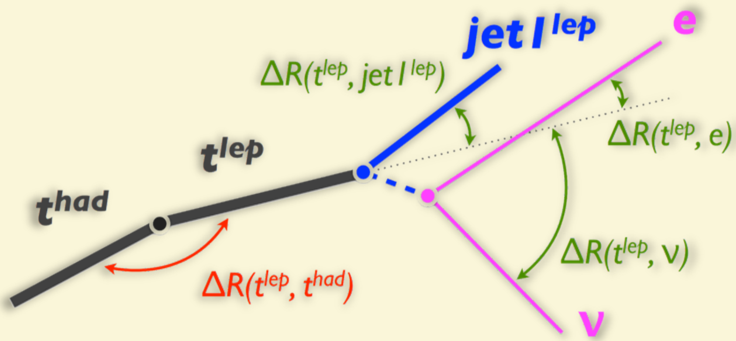
- Search for deviations from SM in wide range of final states
  - After two years of LHC, the SM is **alive and well**
  - No departures from the known physics yet
  - Have excluded a wide range of BSM parameters, mass scales
- New physics may appear any time
  - LHC run at $\sqrt{s}$=8TeV in 2012 → higher mass scales
  - X3 larger statistics in 2012 → smaller cross-sections
- An exciting year ahead for the BSM searches in CMS

Backup

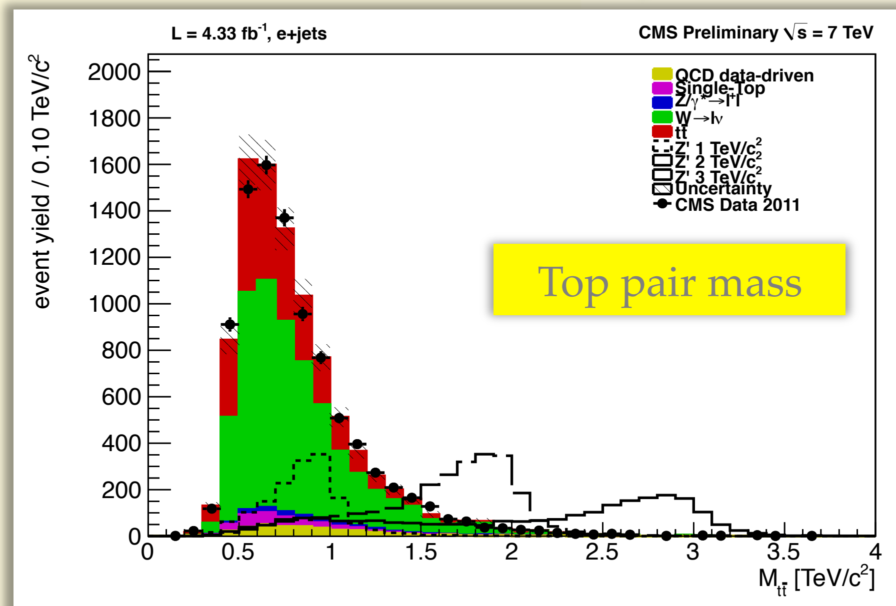
CMS BSM summary



Heavy resonances: $Z' \rightarrow t\bar{t}$: e+jets



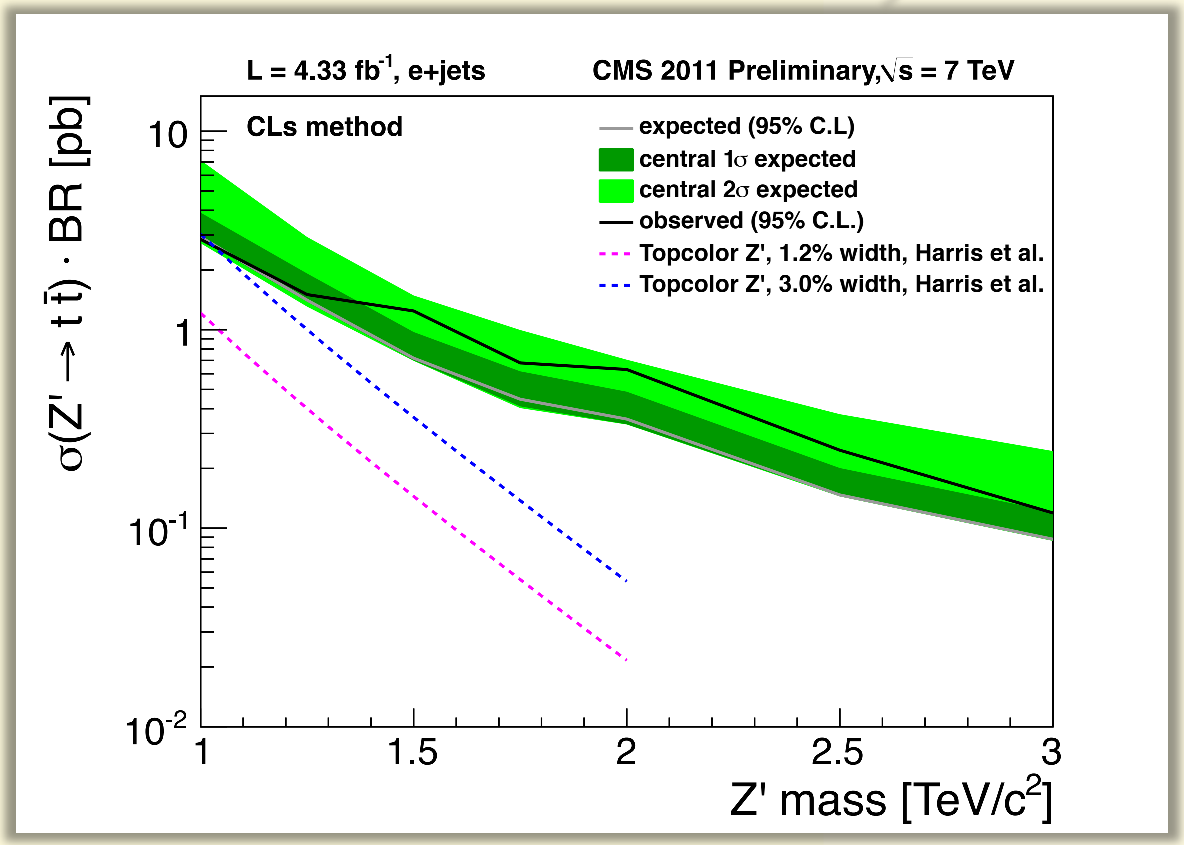
HT^{lep}>150 GeV, MET>50 GeV
p^T_e>70 GeV, p^T_{j1}>150GeV, p^T_{j2}>5GeV
p^T_{top}>100 GeV



- Assign each object in the event to the leptonic or hadronic top candidate
  - Minimize ΔRs on the side of leptonic top decay: collinear ele+2jets+neutrino
  - Maximize $\Delta R(t^{lep},t^{had})$: favor back-to-back decays
- Backgrounds: W/Z+jets, top (pair and single), QCD
  - QCD shape derived from data in the orthogonal sample
  - Template fit to extract the absolute normalization of QCD background
  - Reject QCD using topological cuts: $\Delta\phi(e$, MET) and $\Delta\phi$(jet, MET)

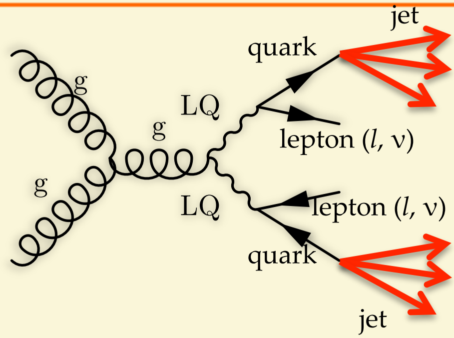
Heavy resonances: $Z' \rightarrow t\bar{t}$: e+jets

Sample	Event Yield
Z', $M = 1\,\mathrm{TeV}/c^2$	153 ± 2
Z', $M = 1.5\,\mathrm{TeV}/c^2$	244 ± 3
Z', $M = 2\,\mathrm{TeV}/c^2$	273 ± 3
Z', $M = 3\,\mathrm{TeV}/c^2$	229 ± 3
Single Top	285 ± 4
W+jets	5408 ± 105
Z+jets	152 ± 8
$t\bar{t}$	2707 ± 29
Total MC	8551 ± 109
QCD data-driven	375 ± 16
Total Background	8927 ± 111
Data 2011	9236

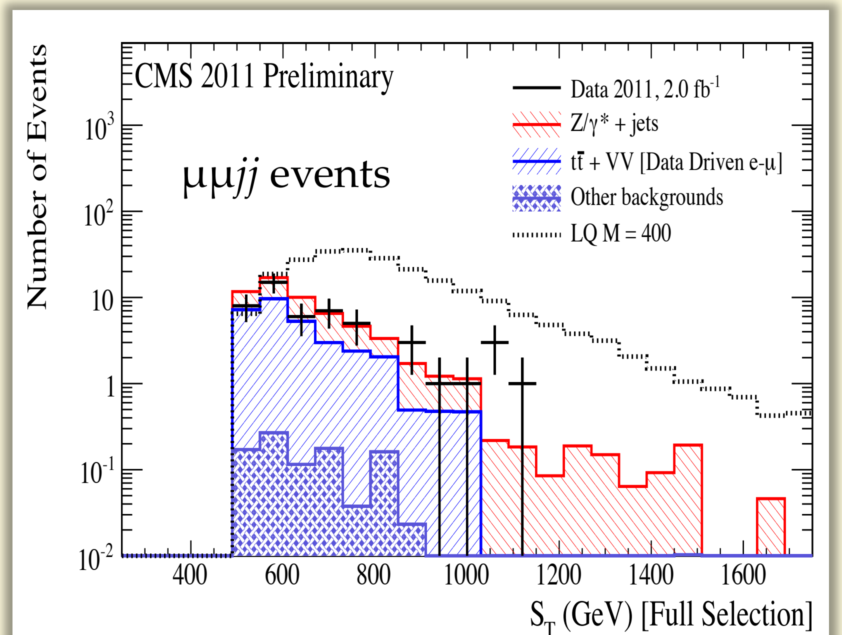


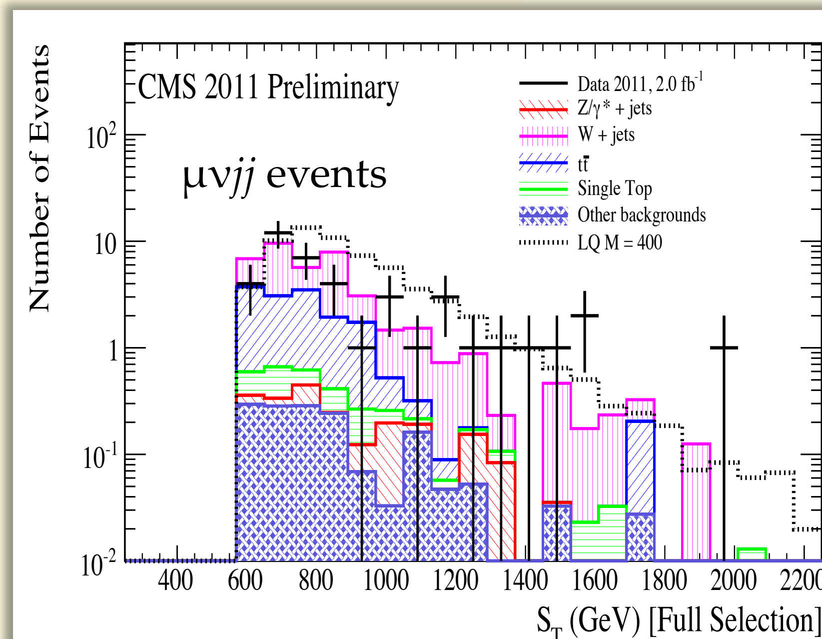
- Good agreement of data with the background model
  - Set upper limits on Z' production cross-section as a function of mass
- Exclude xsections of: **2.85** pb for $M_{Z'}$=**1** TeV; **0.63** pb for $M_{Z'}$=**2** TeV

Scalar Leptoquarks: 2nd gen



- Carry both baryon and lepton numbers
  - Quark+ charged lepton: BR=β, OR
  - Quark + neutrino: BR = 1-β
  - Pair production: insensitive to Yukawa couplings λ
- Data-driven backgrounds if possible, some from MC normalized to data.
- Use $S_T = p_T(l_1)+p_T(l_2)+p_T(j_1)+p_T(j_2)$ as the discriminating variable ($l=\mu$ *or* ν)

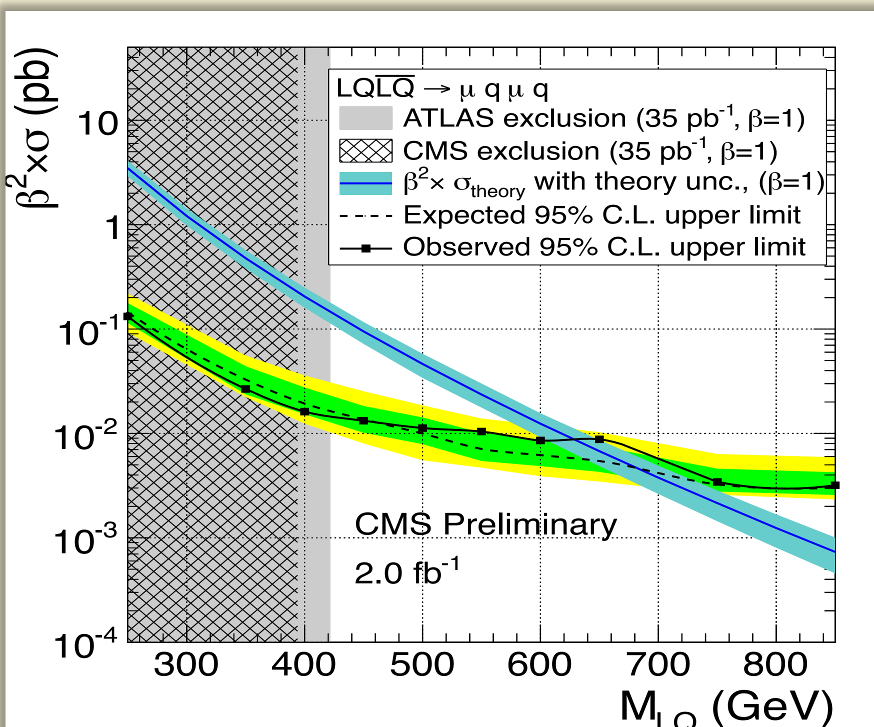


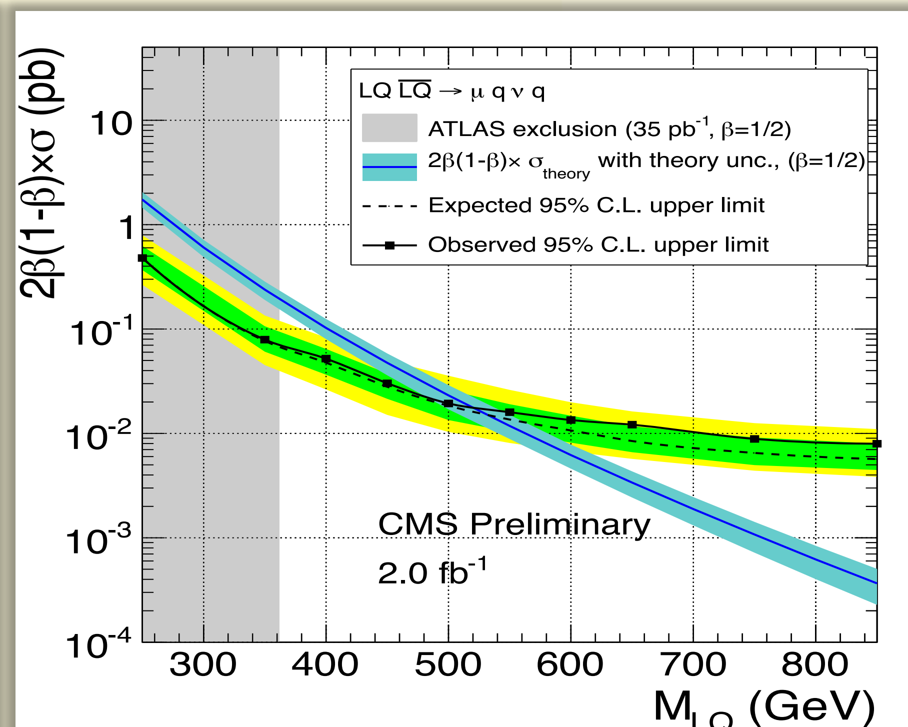


CMS-PAS-EXO-11-028, 2.0 fb^{-1}

Scalar Leptoquarks: 2nd gen

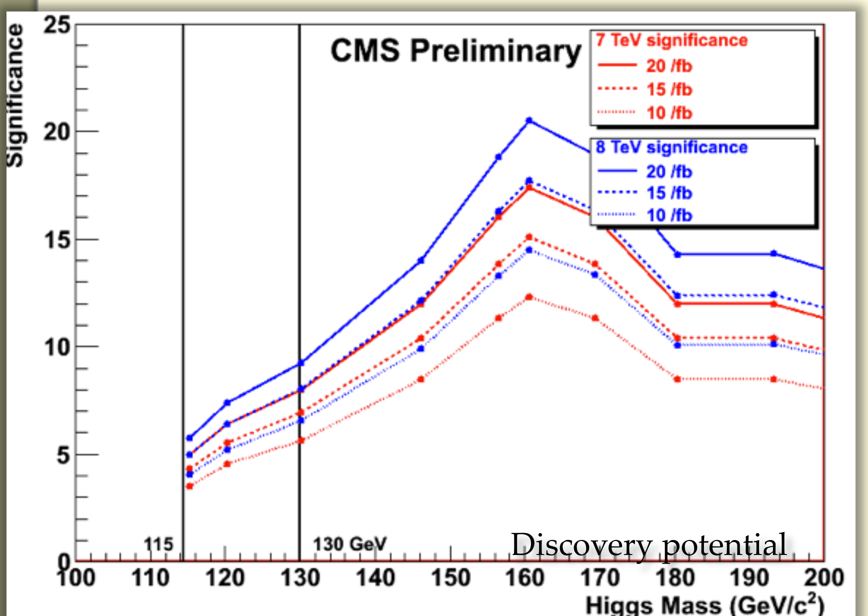
- No excess observed: optimize for best S/√S+B
  - Signal region optimized in S_T, $M_{\mu\mu}$ (or MET), and min(M_μ,jet) for each LQ mass
- Exclude masses below **632** (**523**) GeV with the assumption that β = 1(0.5).

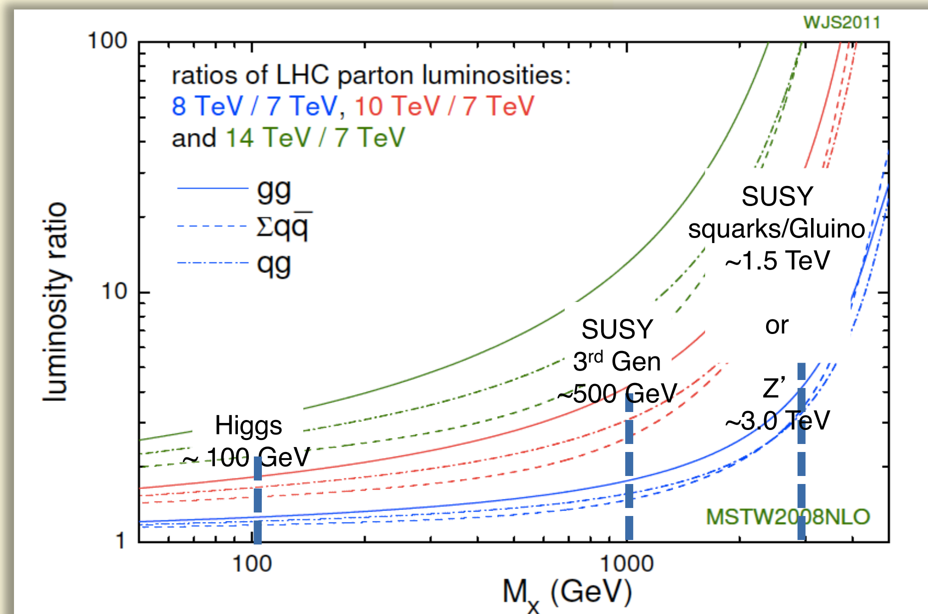




Prospects for 2012 run

- 2011 was an amazing year for CMS physics program
  - Published 5 papers (with 2011 data), ~130 papers in review, ~40 public notes
  - Unfortunately, no NP has yet, but the room for Higgs boson is getting smaller
- 2012 data will allow to find or rule out the SM Higgs boson
- Likely scenario: increase √s to 8TeV
  - More luminosity, higher mass scales of NP accessible, higher x-sections for NP



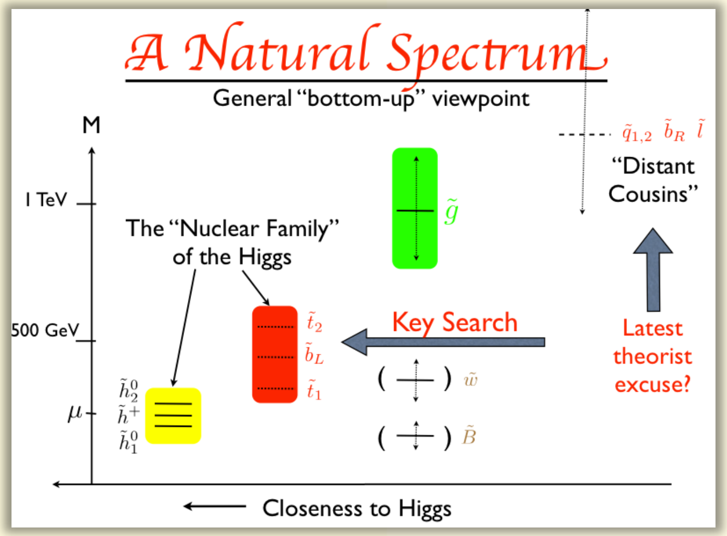


Prospects for 2012 run

- E.g.: Z′ estimated 95% CL mass limits for 20fb^{-1} are extended by ~300 GeV

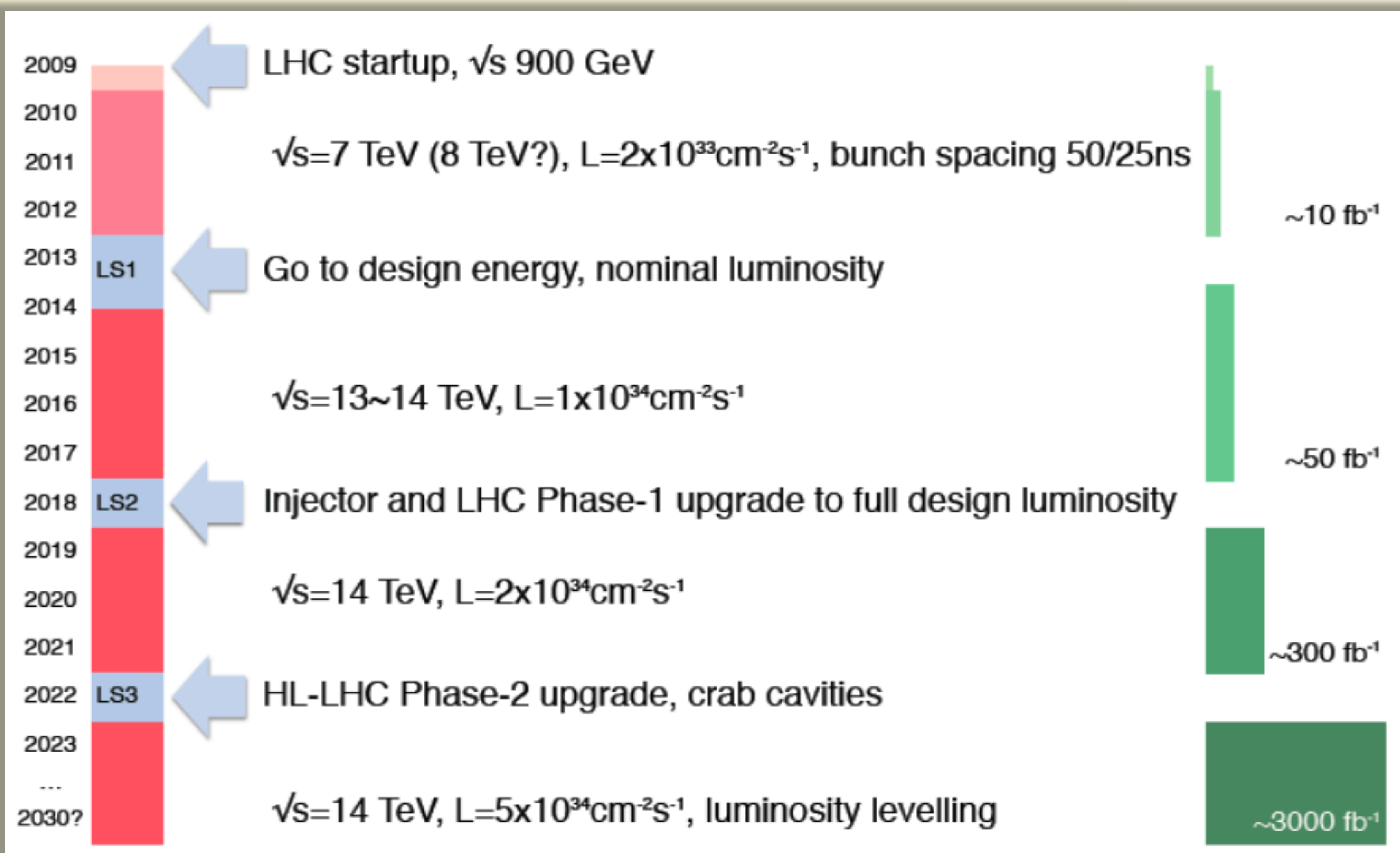
Model	√s=7 TeV	√s=8 TeV
Z'_{SSM}	2450 (GeV)	2750 (GeV)
Z'_{Ψ}	2150	2350
G_{KK} (k=0.1)	2250	2550

- Increase of 1TeV in √s has a big impact
  - Searches can probe much higher probability PDF regions
  - ~25% increase for M_H~100 GeV
    - Probe wider mass range for BSM Higgs
    - Look for rarer decay channels
  - For 1.5 TeV gluino get x4 in statistics relative
    - 2.5σ hint → 5σ discovery



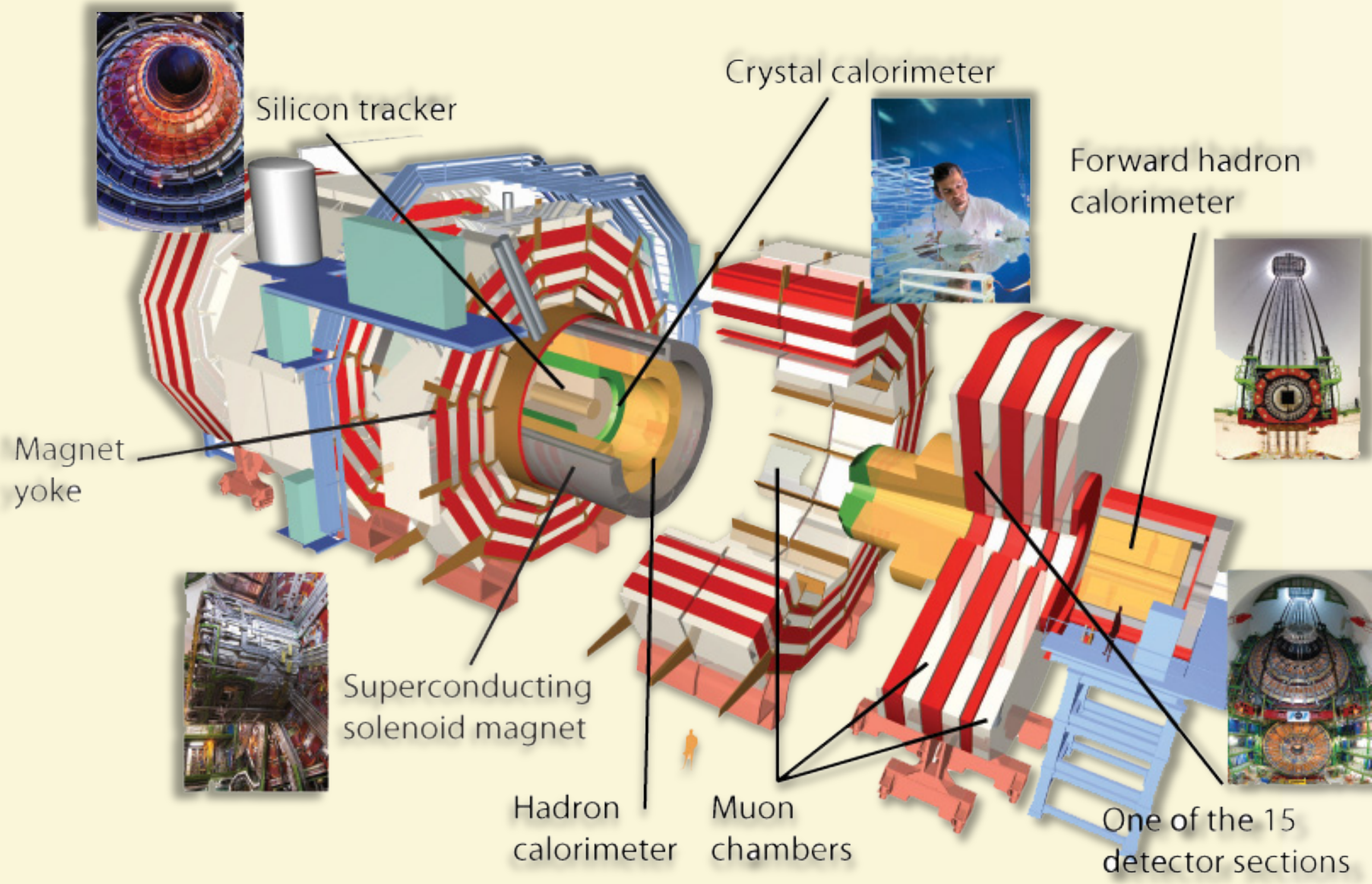
- Stop pairs: a key but challenging channel
  - Up to ~500 GeV is *"natural"*
  - 8 TeV → ~50-80% more signal, better S/B

Looking ahead…



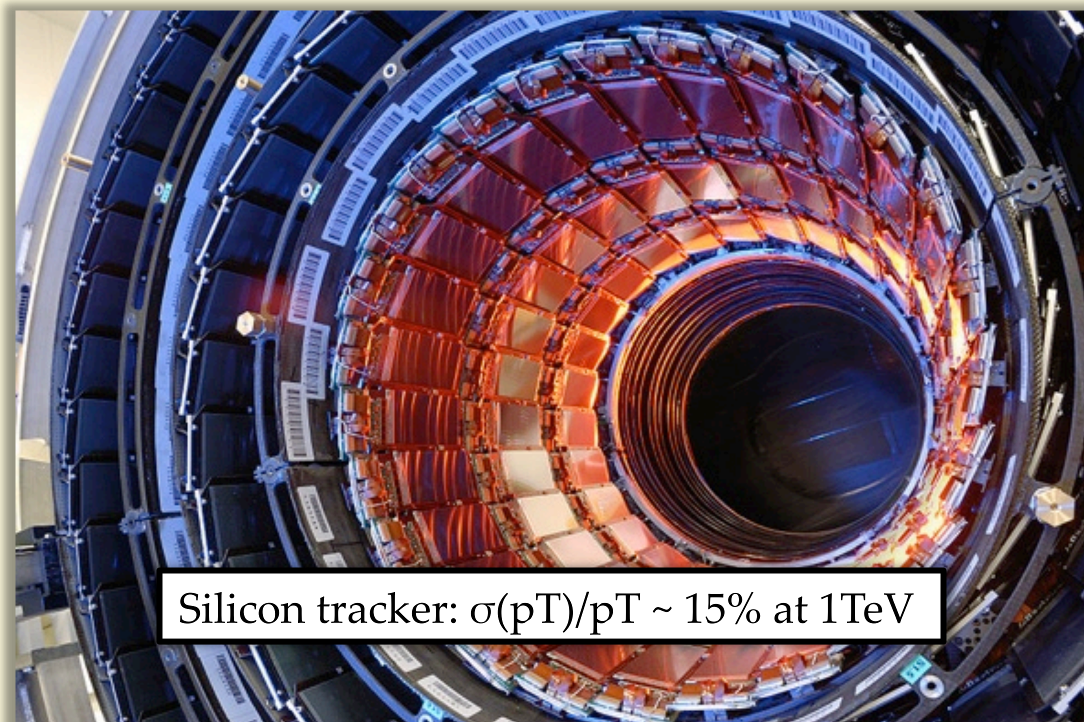
The Compact Muon Solenoid (CMS)

- A "*general purpose*" detector to cover full physics program with LHC

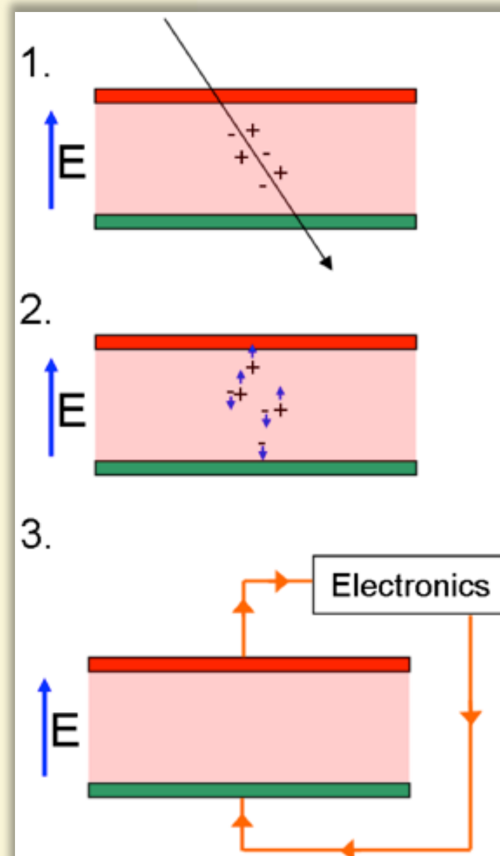


Measuring the products of collisions

- Where did the particle originate from?→ **tracking detectors**
  - Long-lived particles travel substantial distance before decaying
  - For precise reconstruction of objects' P_T need to know origin precisely

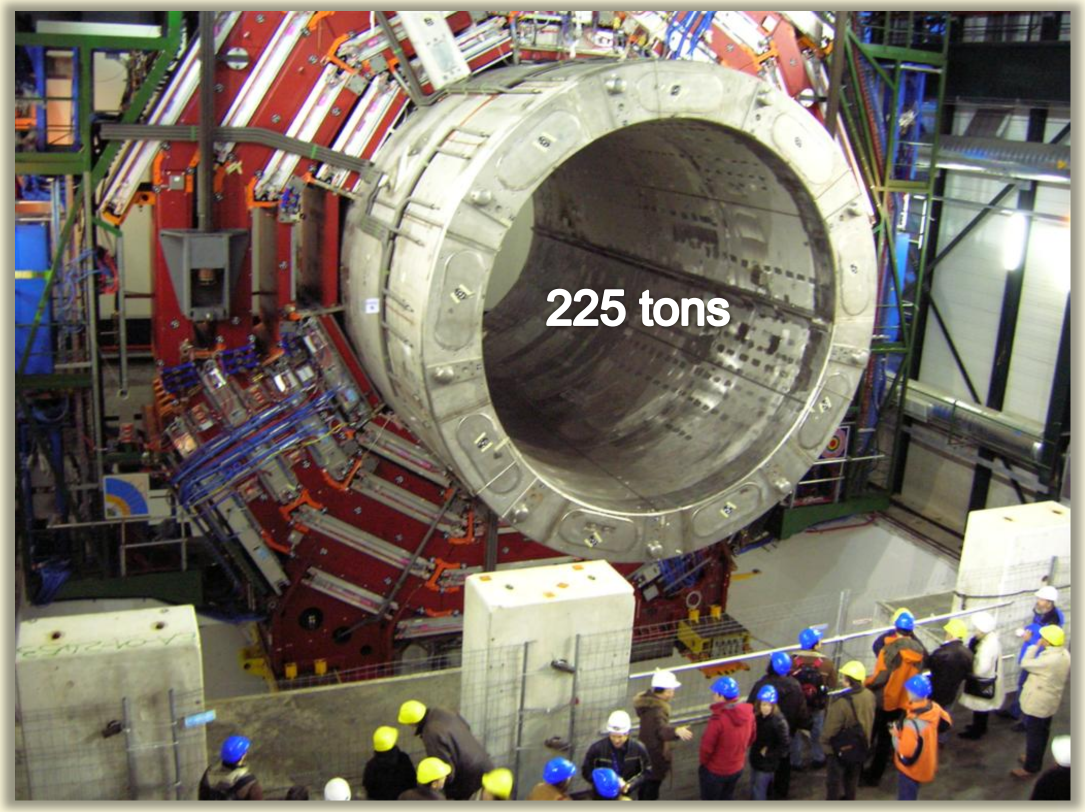


CMS all silicon tracker



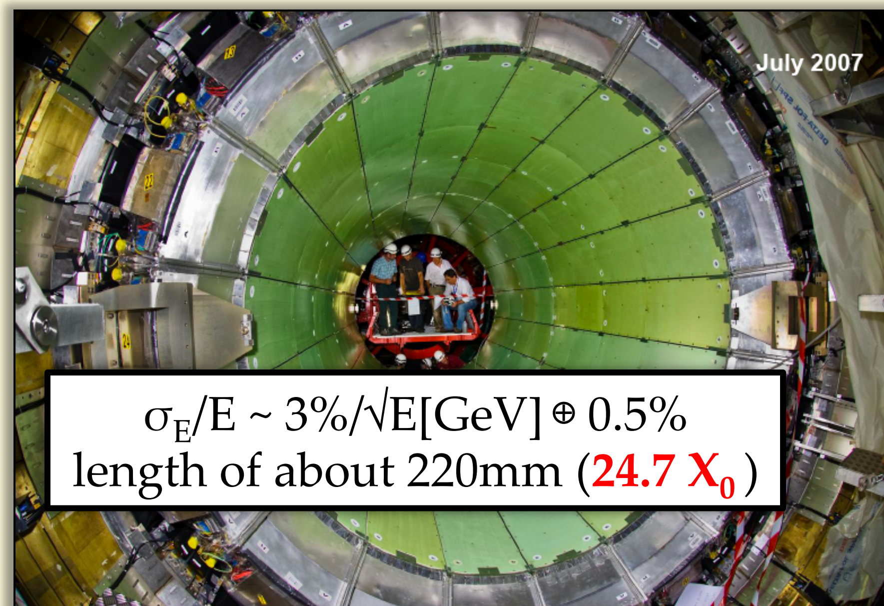
Measuring the products of collisions

- Momenta of the particles→ **tracking detectors and magnet**
  - The higher the magnetic field, the better we can measure: $R = p/(qB)$
  - CMS magnetic field: **3.8 Tesla**



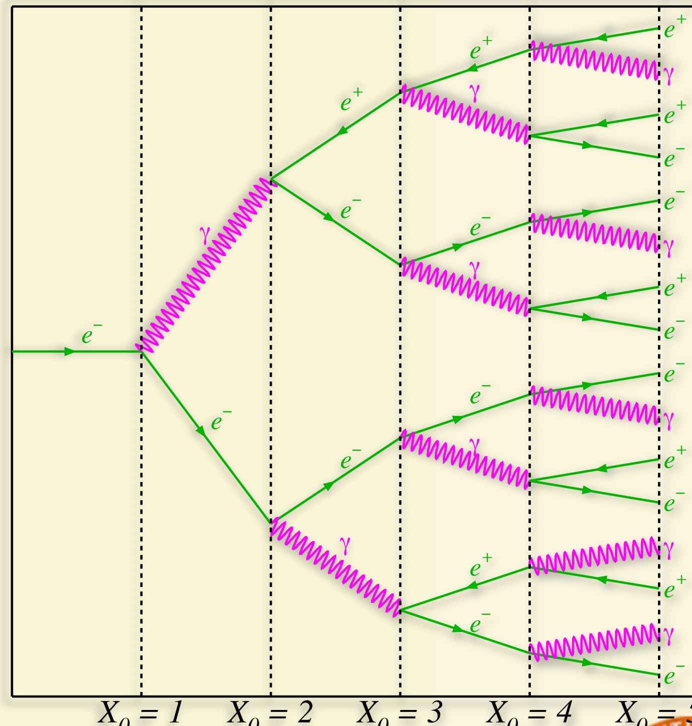
Measuring the products of collisions

- Energy of all particles produced in the collision
  - Photons and pions measured in **electromagnetic calorimeters**
  - homogeneous Lead-Tungstate crystal



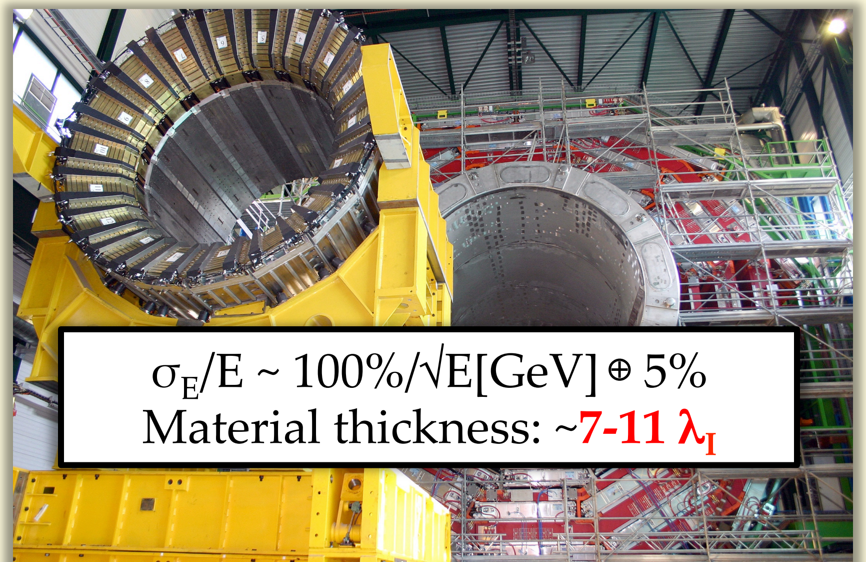
$\sigma_E/E \sim 3\%/\sqrt{E[\mathrm{GeV}]} \oplus 0.5\%$
length of about 220mm (**24.7 X_0**)

CME Electromagnetic calorimeter



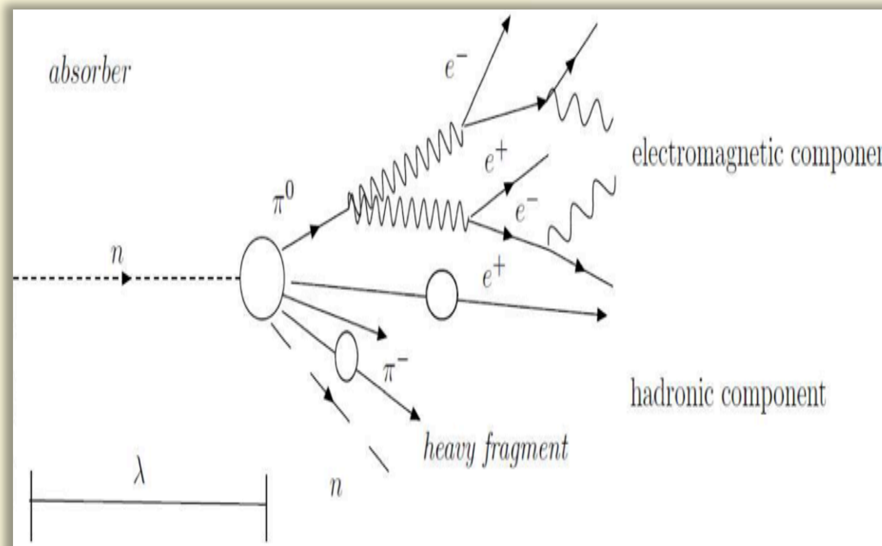
Measuring the products of collisions

- Energy of all particles produced in the collision
  - Strongly interacting hadrons measured in **hadronic calorimeter**



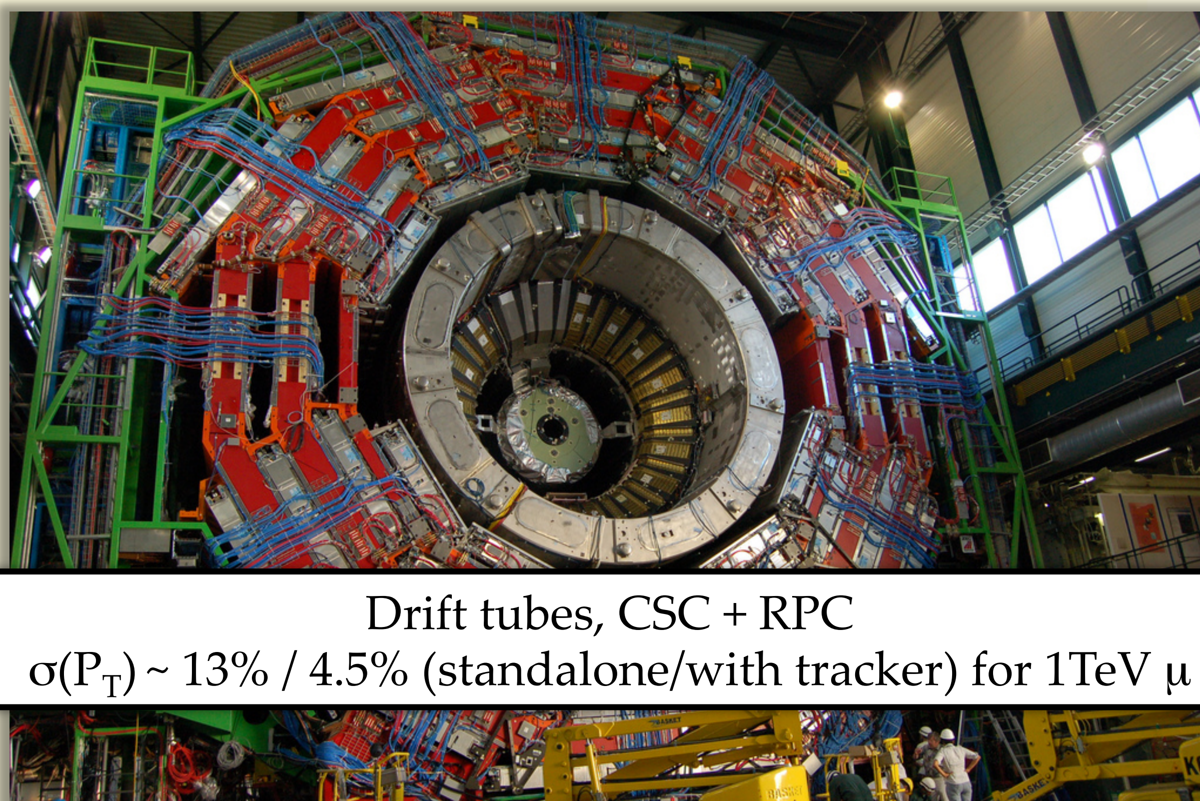
$\sigma_E/E \sim 100\%/\sqrt{E[\mathrm{GeV}]} \oplus 5\%$
Material thickness: ~**7-11 λ_I**

CMS Hadronic calorimeter



Measuring the products of collisions

- **Muon detectors** at the outermost edges of the detector
  - Negligible energy loss in the calorimeters: minimum ionizing particles
  - Combine measurements in the inner tracker with hits in the outermost detector



Drift tubes, CSC + RPC
$\sigma(P_T) \sim 13\% / 4.5\%$ (standalone/with tracker) for 1TeV μ

M_T for W′ including interference

- constructive interference increases the W′ cross section
- destructive interference would yield lower cross sections