A Search for Evidence of Supersymmetry Production as the Stop Pair on CMS

4th year seminar
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Outline

- Theory
  - The Standard Model
  - Supersymmetry
  - GMSB
- Experiment
  - CMS at LHC
- Analysis
  - RunI Results
  - RunII Progress

The Standard Model

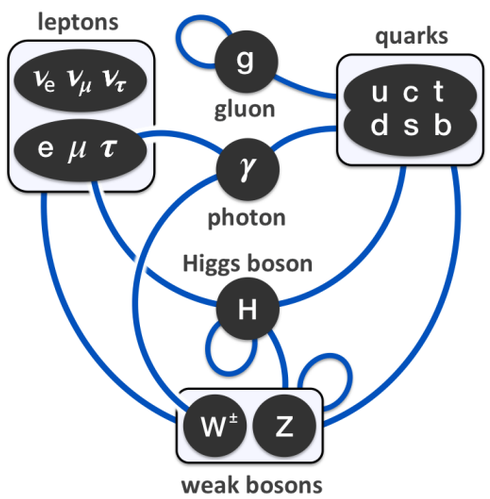
- It explains how the basic building blocks of matter interact under the government of the fundamental forces.

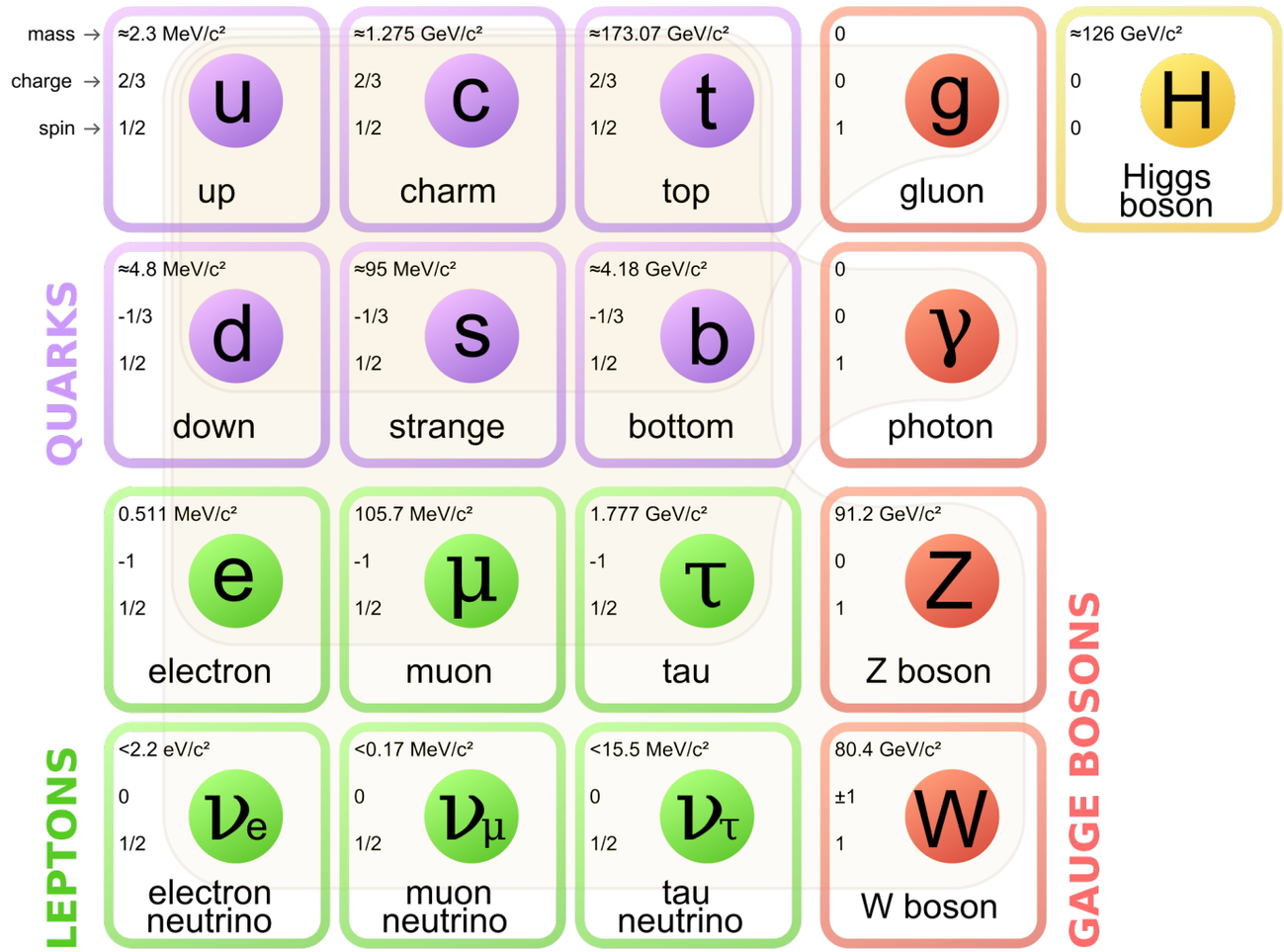
- In half century's development, it has successfully explained almost all experimental results and precisely predicted a wide variety of phenomena.

Physics cooking ingredients & recipe

The Standard Model

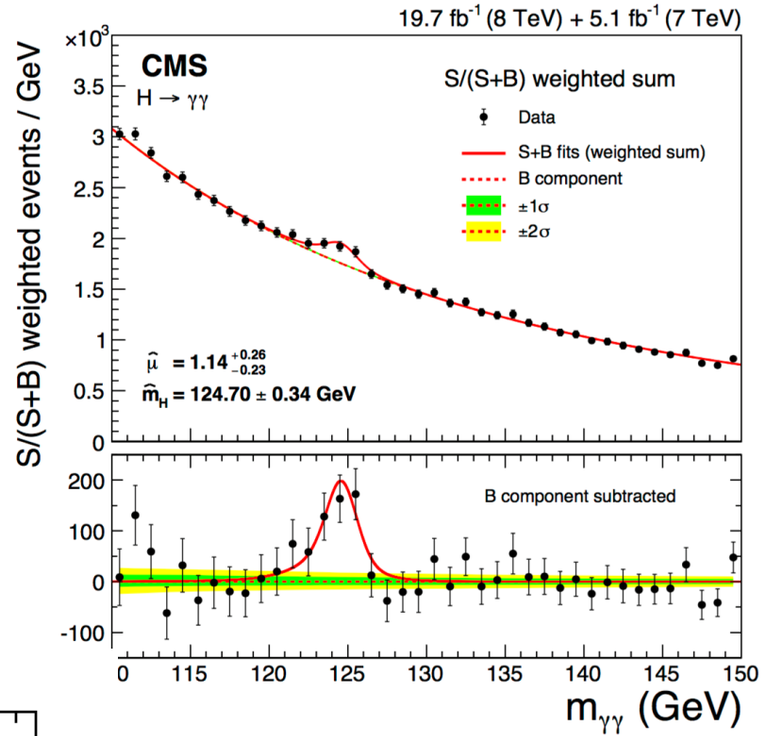
- SM: QFT of matter and its interactions
- $SU(3)_C$ x $SU(2)_L$ x $U(1)_Y$ gauge symmetry
  - $SU(3)_C$ – color charge
  - $SU(2)_L$ – weak isospin
  - $U(1)_Y$ – weak hypercharge
- Predicted Higgs particle



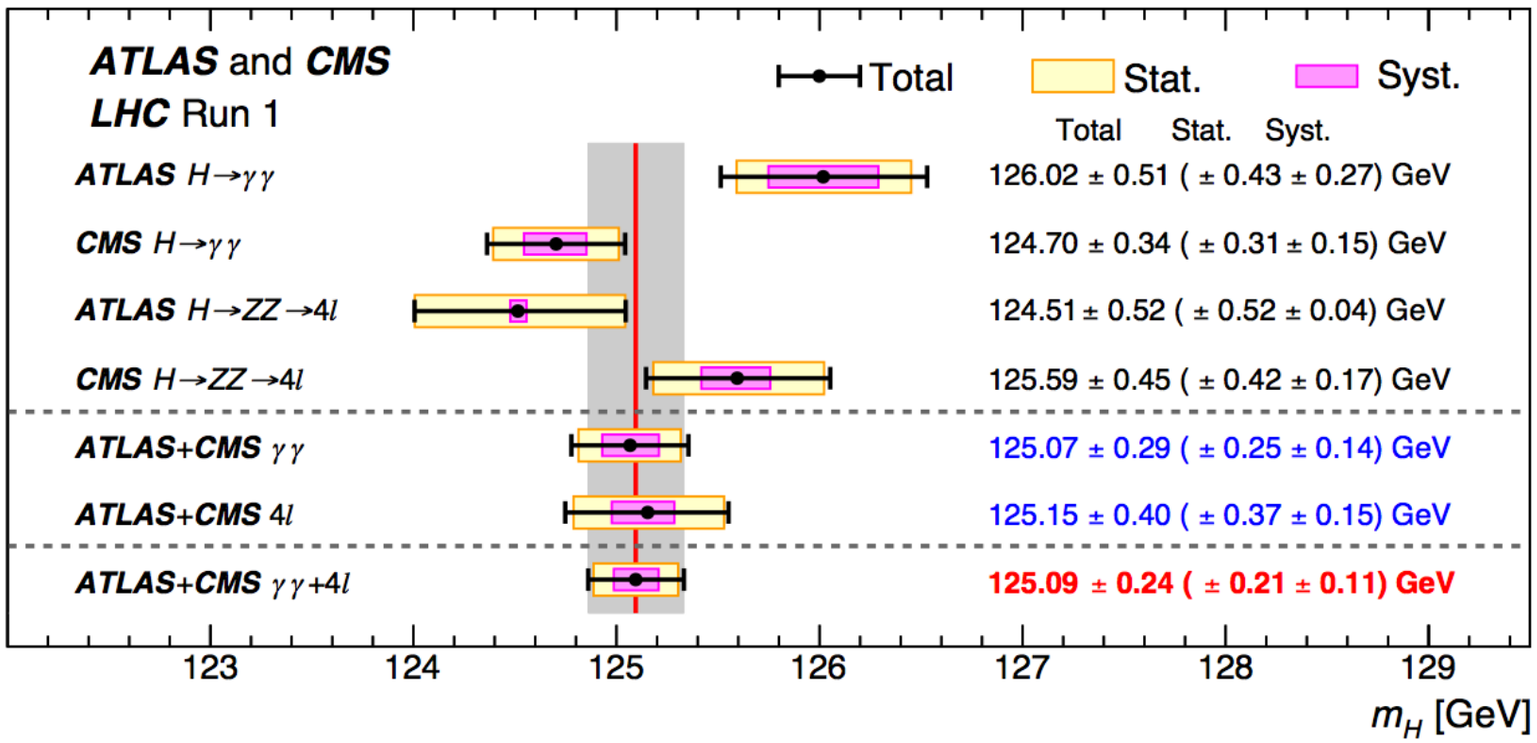


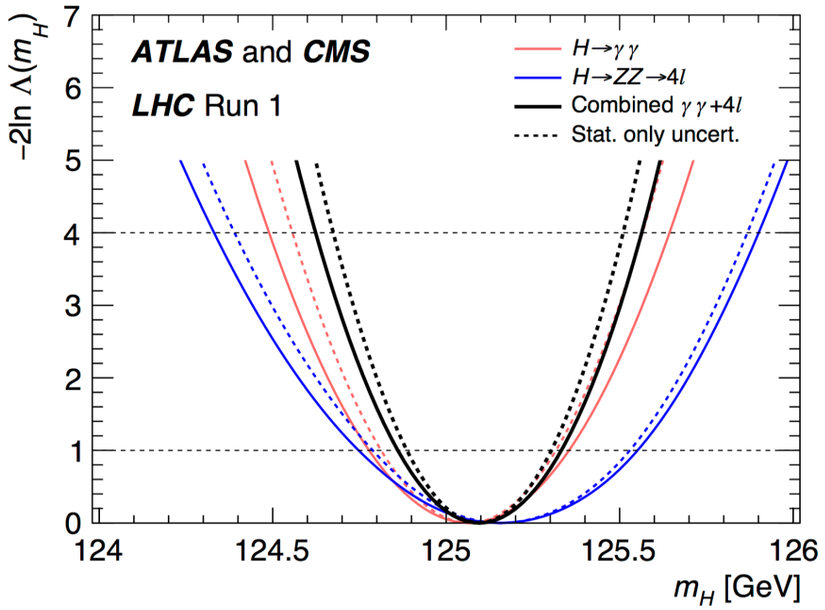
Higgs Discovery

- A candidate boson was announced being discovered on July 4th 2012
- Consistent with standard model higgs boson



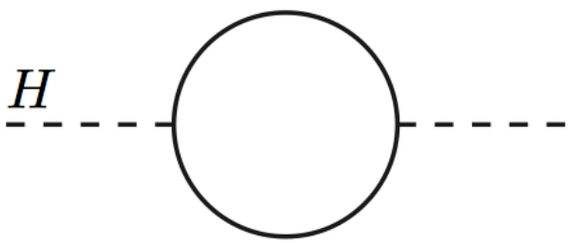
Combined Measurement of the Higgs Boson Mass in pp Collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS and CMS





The Hierarchy Problem

The Higgs boson receives mass corrections proportional to the highest energies squared in the Standard Model (the UV cutoff Λ_{UV})(to one-loop order):



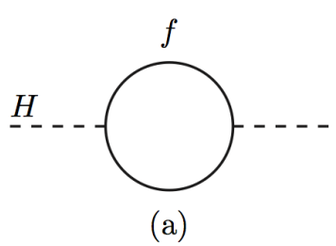
$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{\mathrm{UV}}^2 + \ldots.$$

- If the SM is valid up to the gravitational scale ($\Lambda_{UV} = M_{Planck} \sim 10^{19}$ GeV/c^2), how is the Higgs mass so light?
- More generally, why the electroweak scale is so different from the Plank mass?

- **No answer from SM**

The Hierarchy Problem

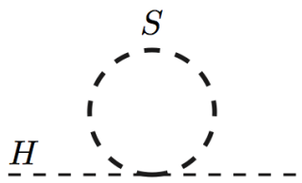
- One solution: new physics beyond SM
- Supersymmetry: a scalar partner to a fermion with the same quantum numbers and couplings:



(a)

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{\mathrm{UV}}^2 + \ldots.$$

+



(b)

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}\Lambda_{\mathrm{UV}}^2 + \ldots$$

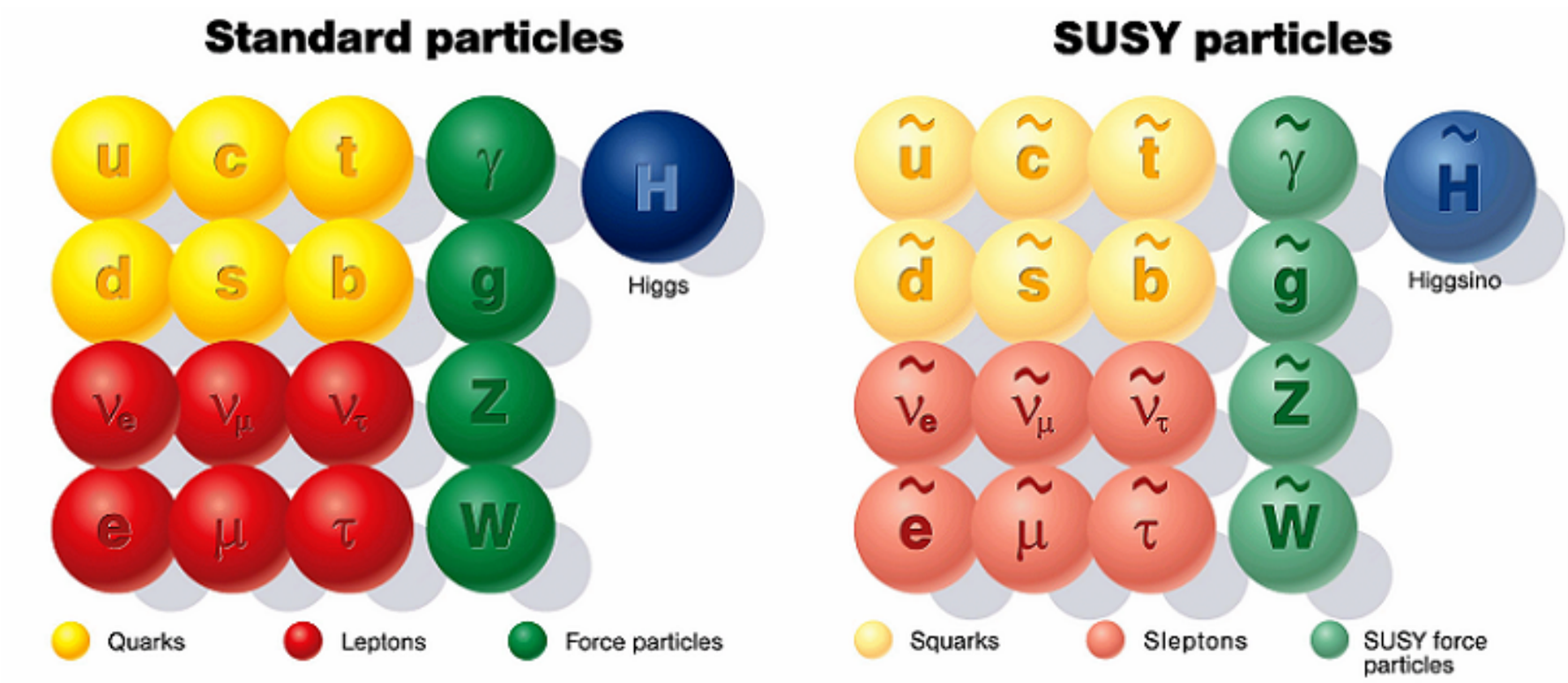
- The Higgs mass is sensitive to the heaviest particles it couples to, namely, the top quark
- If a scalar top is introduced (sTop), it would be best if it was not much heavier than the top! —> Light stop

Supersymmetry

- Supersymmetry(SUSY) introduces a partner particle for every SM particle.

$$Q\,|\text{Boson}\rangle = |\text{Fermion}\rangle \quad Q\,|\text{Fermion}\rangle = |\text{Boson}\rangle$$

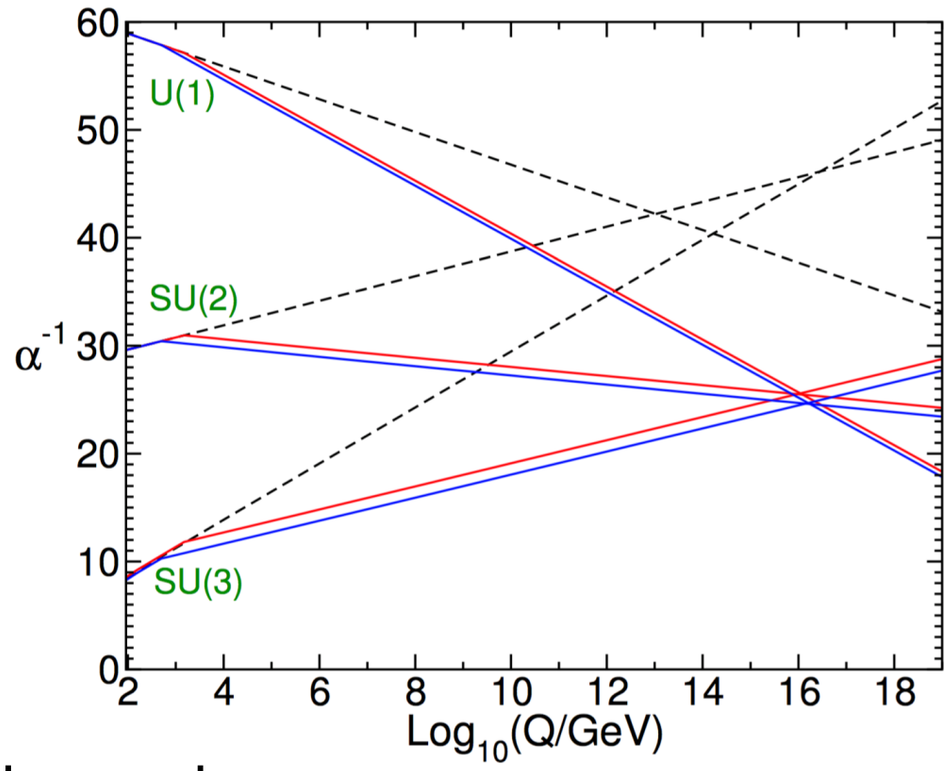
- All quadratically divergent Higgs mass terms cancel
- No Hierarchy problem!



Other Benefits

- Dark matter candidates
  - SUSY model can introduce several weakly- interacting massive particles(WIMPs)

- Gauge unification
  - SUSY can offer a nearly-exact gauge coupling unification at ~10^{16} GeV



- SUSY Lagrangian can be built with both the fermion and boson processes, no renormalization is required as in SM

SUSY Breaking

- Including the necessary additional new particles that are able to be super-partners of those in the Standard Model,the simplest possible supersymmetric model consistent with the SM is the **Minimal Supersymmetric Standard Model** (MSSM)

- If Supersymmetry exists, it must be spontaneously broken at some high energy
- Several ways to introduce this breaking
  - **Gauge mediation (GMSB)** – hidden breaking sector communicates with the MSSM via the ordinary SM gauge interactions

SM Particle type	Particle	Symbol	Spin	R-Parity	Superpartner	Symbol	Spin	R-parity
Fermions	Quark	q	$\frac{1}{2}$	+1	Squark	$\tilde{q}$	0	-1
	Lepton	ℓ	$\frac{1}{2}$	+1	Slepton	$\tilde{\ell}$	0	-1
Bosons	W	W	1	+1	Wino	$\tilde{W}$	$\frac{1}{2}$	-1
	B	B	1	+1	Bino	$\tilde{B}$	$\frac{1}{2}$	-1
	Gluon	g	1	+1	Gluino	$\tilde{g}$	$\frac{1}{2}$	-1
Higgs bosons	Higgs	h_u, h_d	0	+1	Higgsinos	$\tilde{h}_u, \tilde{h}_d$	$\frac{1}{2}$	-1

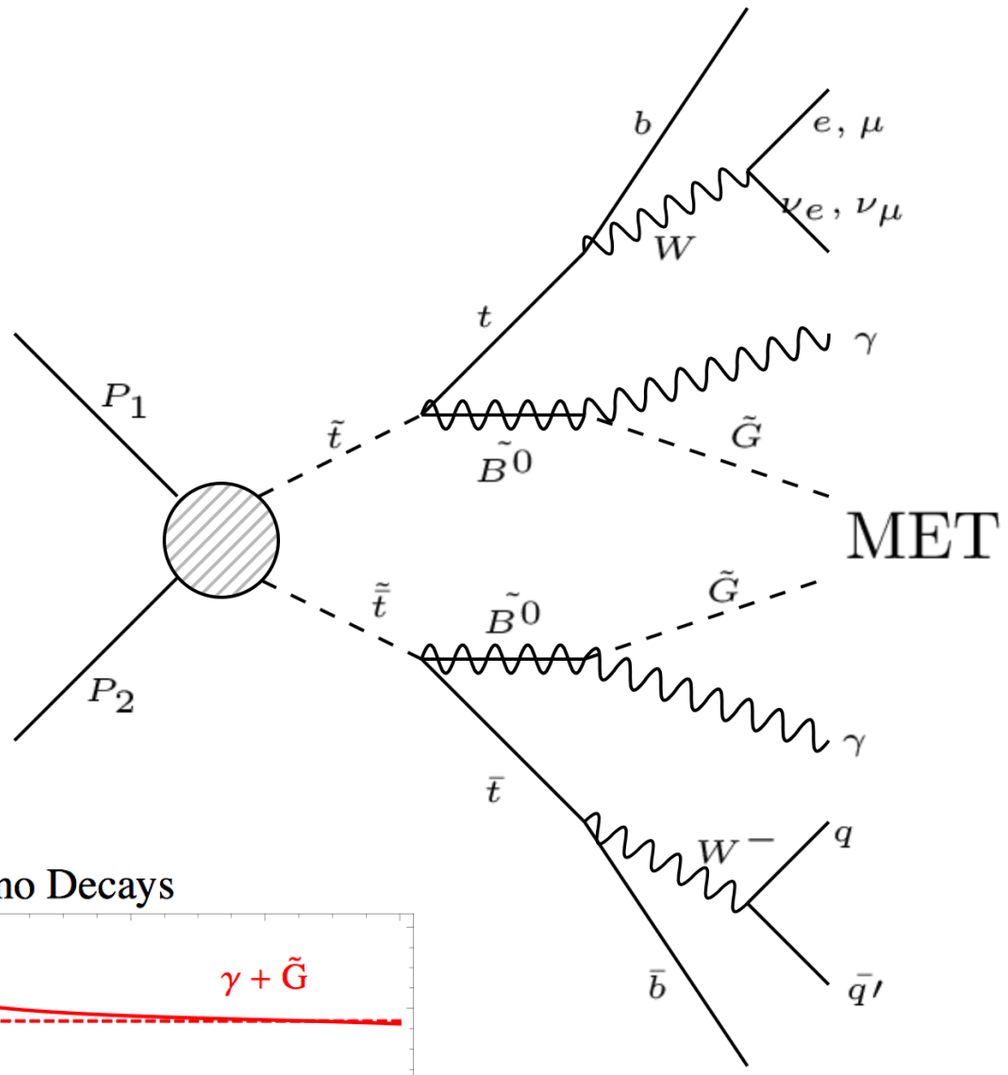
GMSB

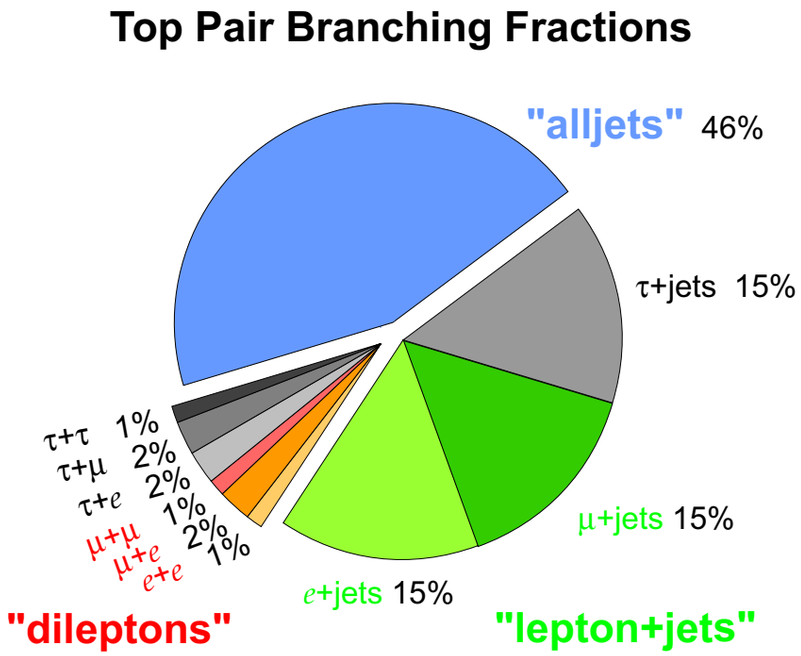
- Gaugino masses are generated in one-loop interactions
  - The stronger the coupling, the heavier the gaugino
- The electroweak gauginos (bino, wino) tend to be the **Next-to-Lightest SUSY Particle (NLSP)**
- The gravitino is the very light (eV – keV) **Lightest SUSY Particle (LSP)**

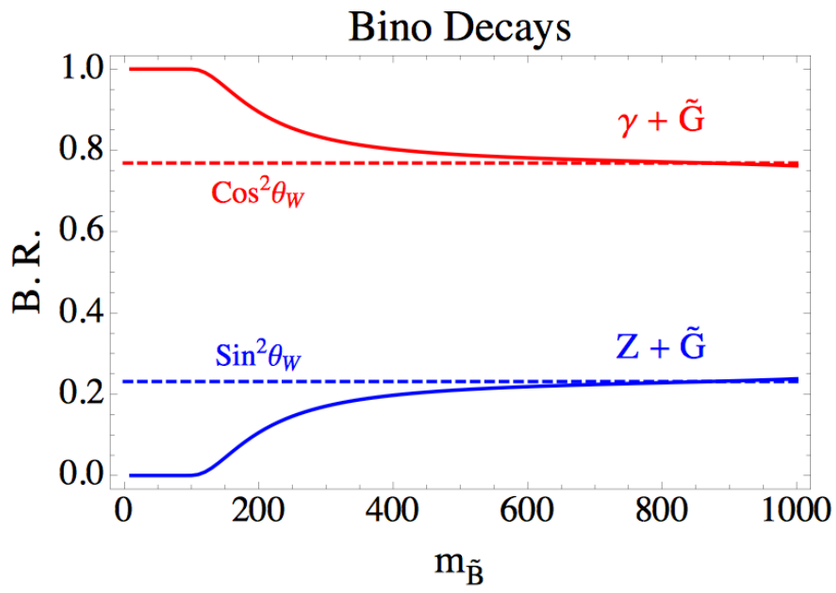
- **GMSB respects R-parity (acting in MSSM): $P_R=(-1)^{3(B-L)+2s}$**
- +1 for SM particles and -1 for SUSY particles
- Sparticles are produced in pairs in collider experiments
- All sparticles decay to the NLSP and then to the gravitino LSP
  - The gravitino LSP is absolutely stable
  - Dark matter candidate: The weakly-interacting LSP
  - Large Missing Transverse Momentum (MET)

GMSB

- Stop pair
- Bino like neutralino decay to photon and gravitino
- Semi-leptonic decay of the top quark pair







$$\vec{\not{E}}_{\mathrm{T}}^{\mathrm{raw}} = -\sum_{i \in \mathrm{all}} \vec{p}_{\mathrm{T}i}$$

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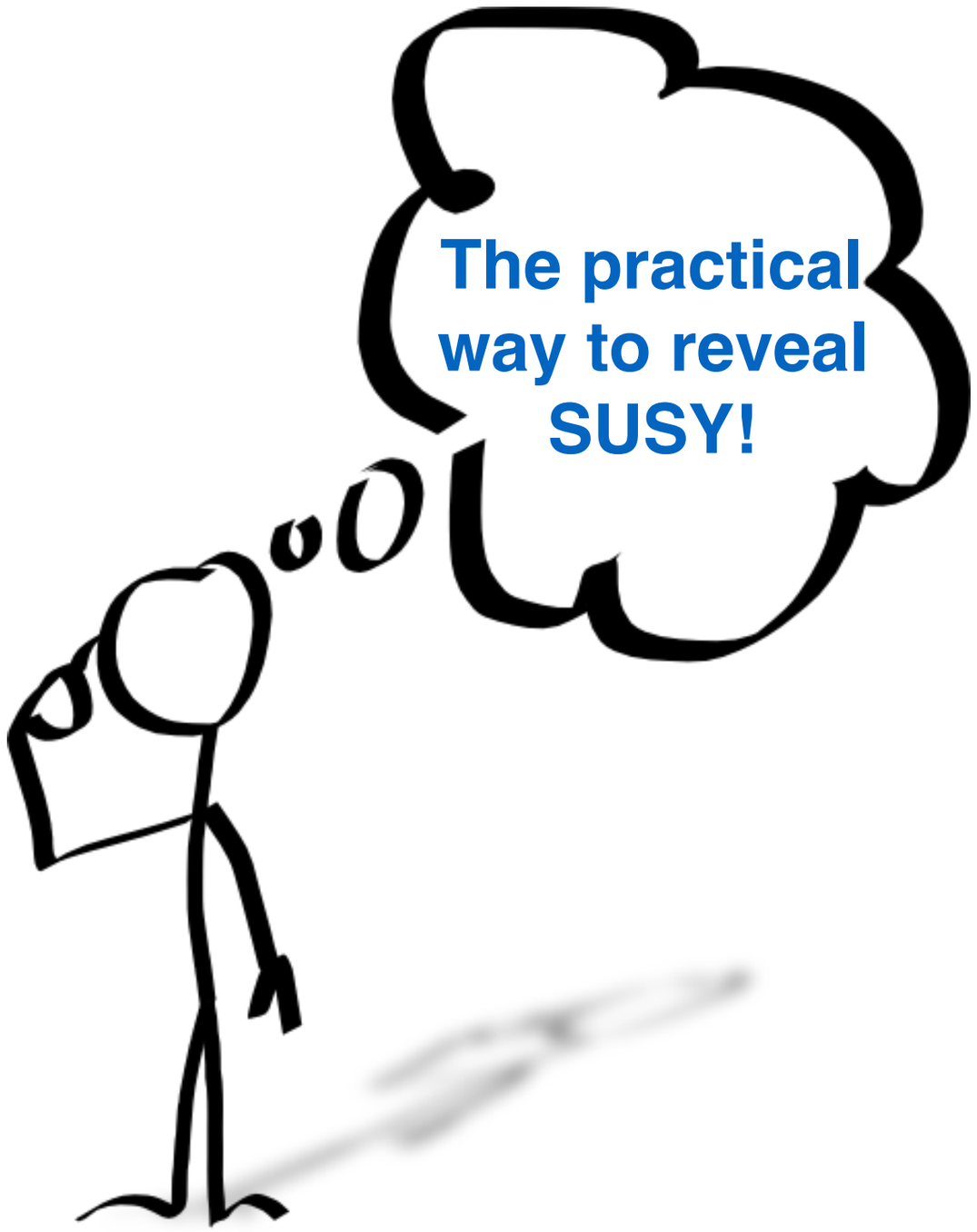
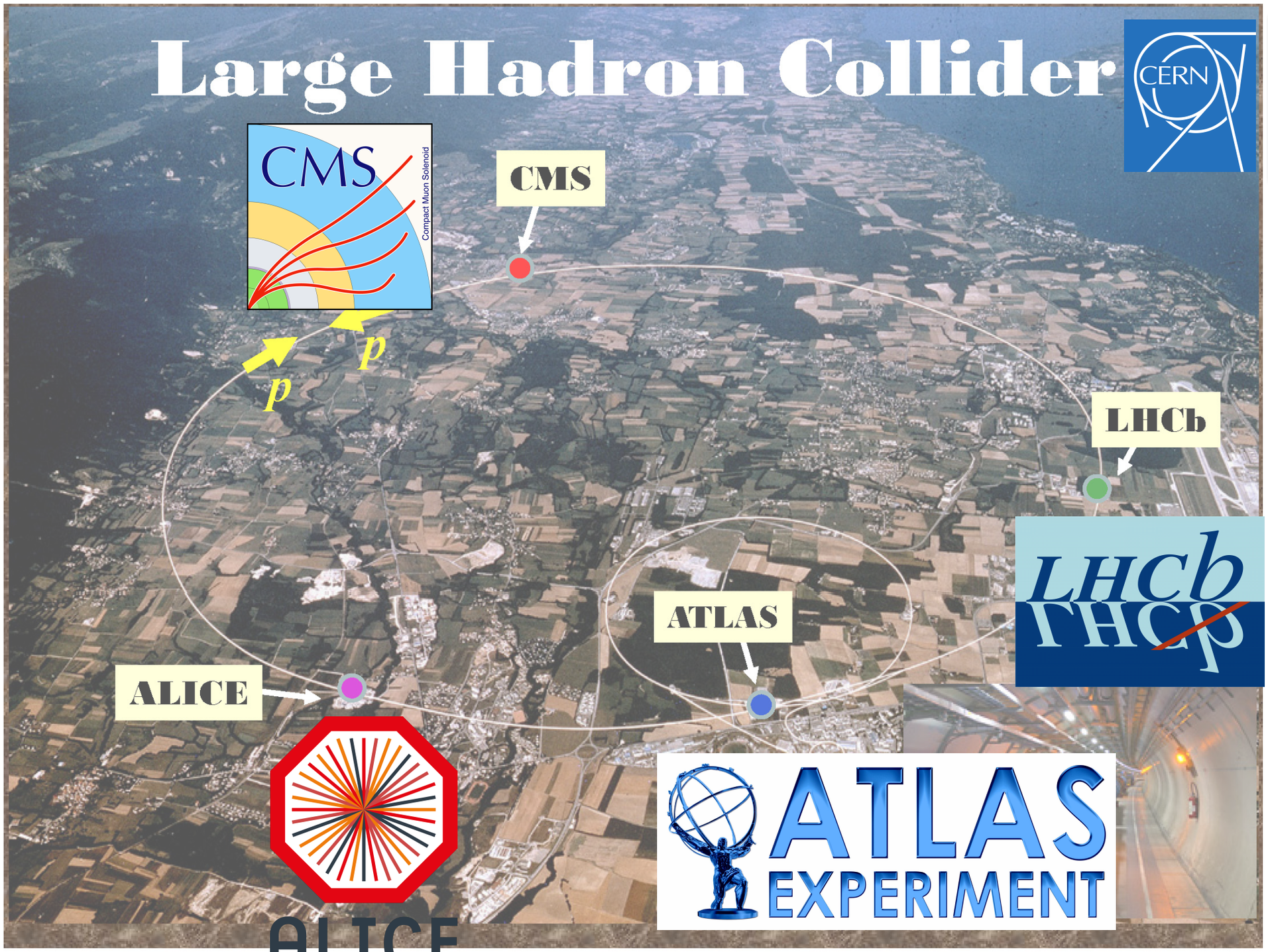
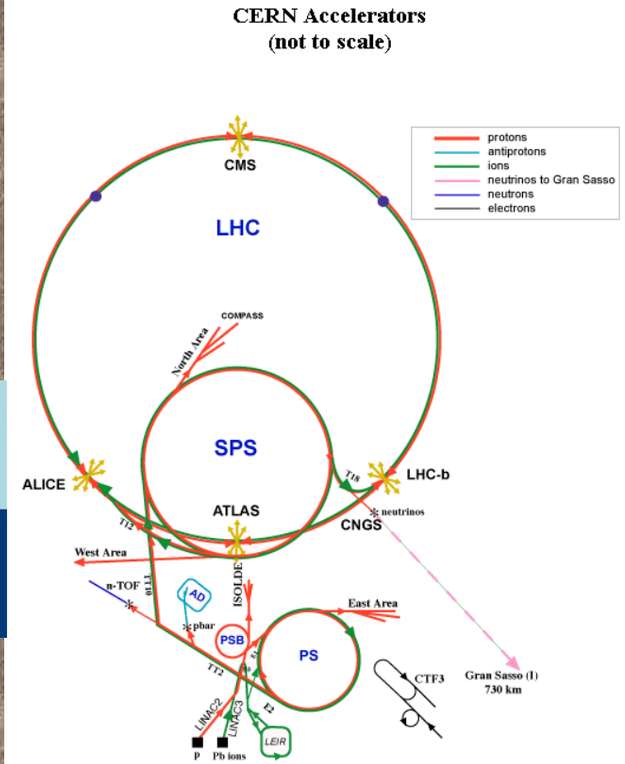
  - The Standard Model
  - Supersymmetry
    - GMSB
- Experiment
  - ☑ CMS at LHC
- Analysis
  - RunII Progress
  - RunI Results



LHC



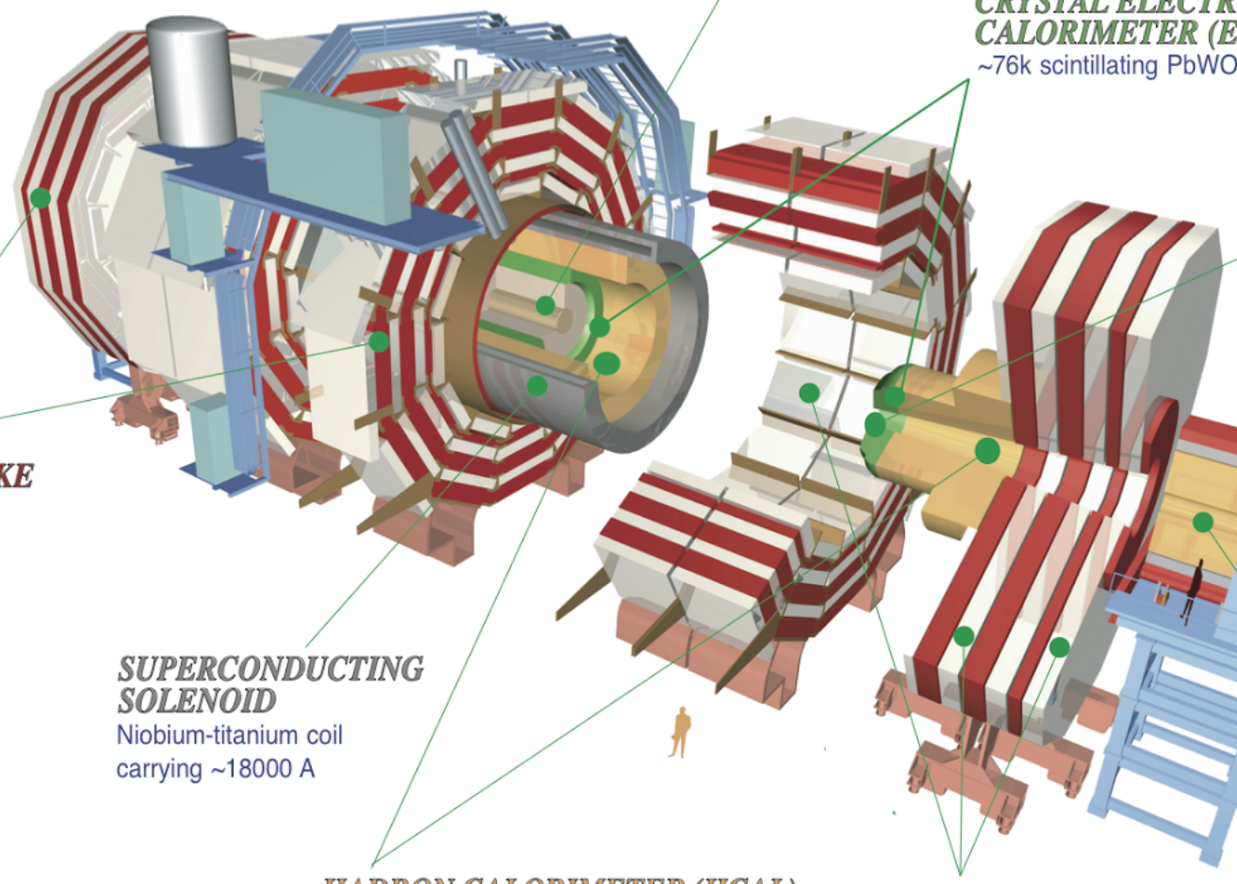
Run I: 2009-2013
Run II: 2015-onward



LHC: Large Hadron Collider
SPS: Super Proton Synchrotron
AD: Antiproton Decelerator
ISOLDE: Isotope Seperator OnLine DEvice
PSB: Proton Synchrotron Booster
PS: Proton Synchrotron
LINAC: LINear ACcelerator
LEIR: Low Energy Ion Ring
CNGS: Cern Neutrinos to Gran Sasso

CMS Detector

Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons



SILICON TRACKER
Pixels (100 x 150 μm²)
~1m² ~66M channels
Microstrips (80-180μm)
~200m² ~9.6M channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76k scintillating $PbWO_4$ crystals

PRESHOWER
Silicon strips
~16m² ~137k channels

STEEL RETURN YOKE
~13000 tonnes

SUPERCONDUCTING SOLENOID
Niobium-titanium coil
carrying ~18000 A

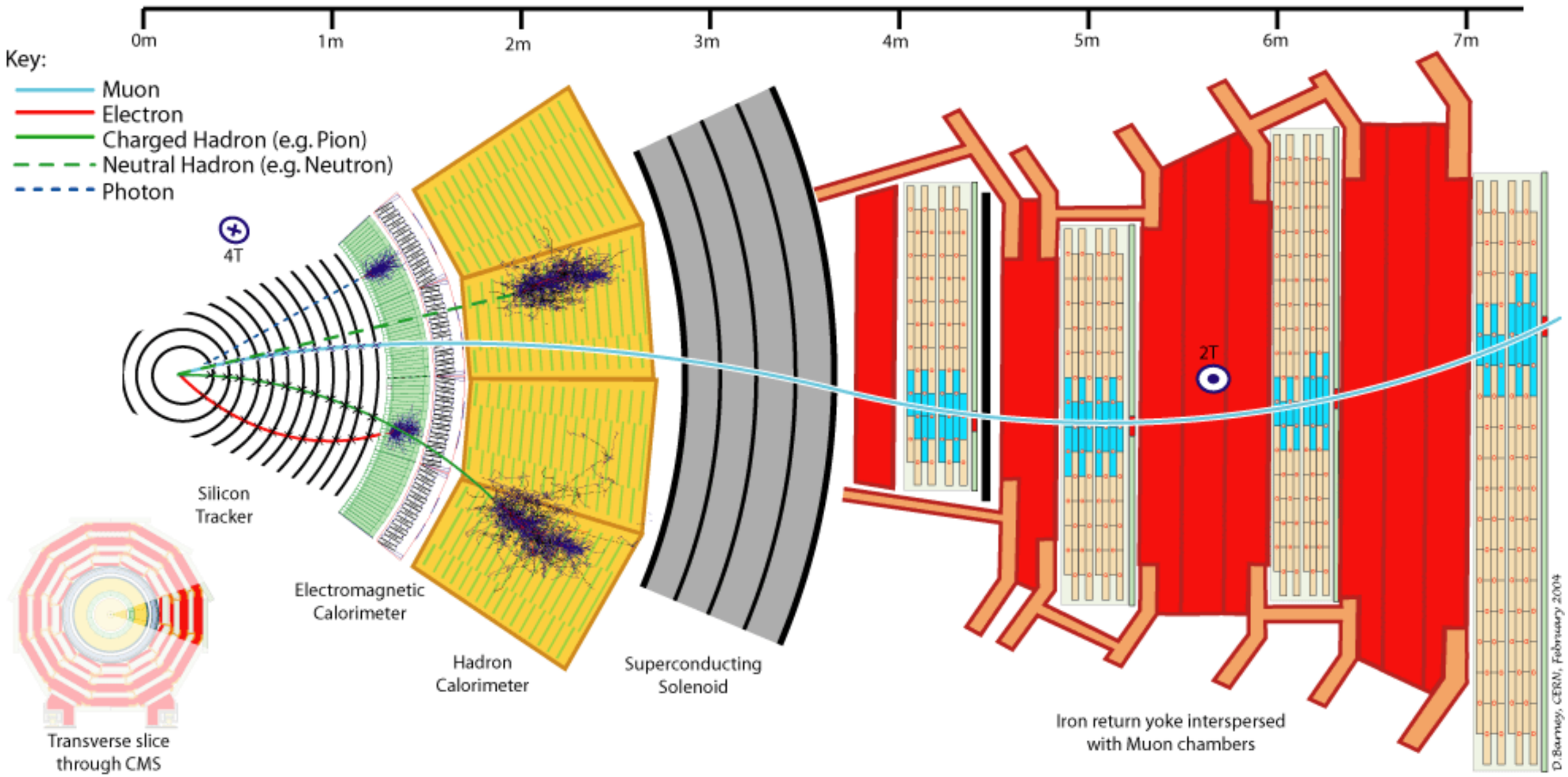
HADRON CALORIMETER (HCAL)
Brass + plastic scintillator
~7k channels

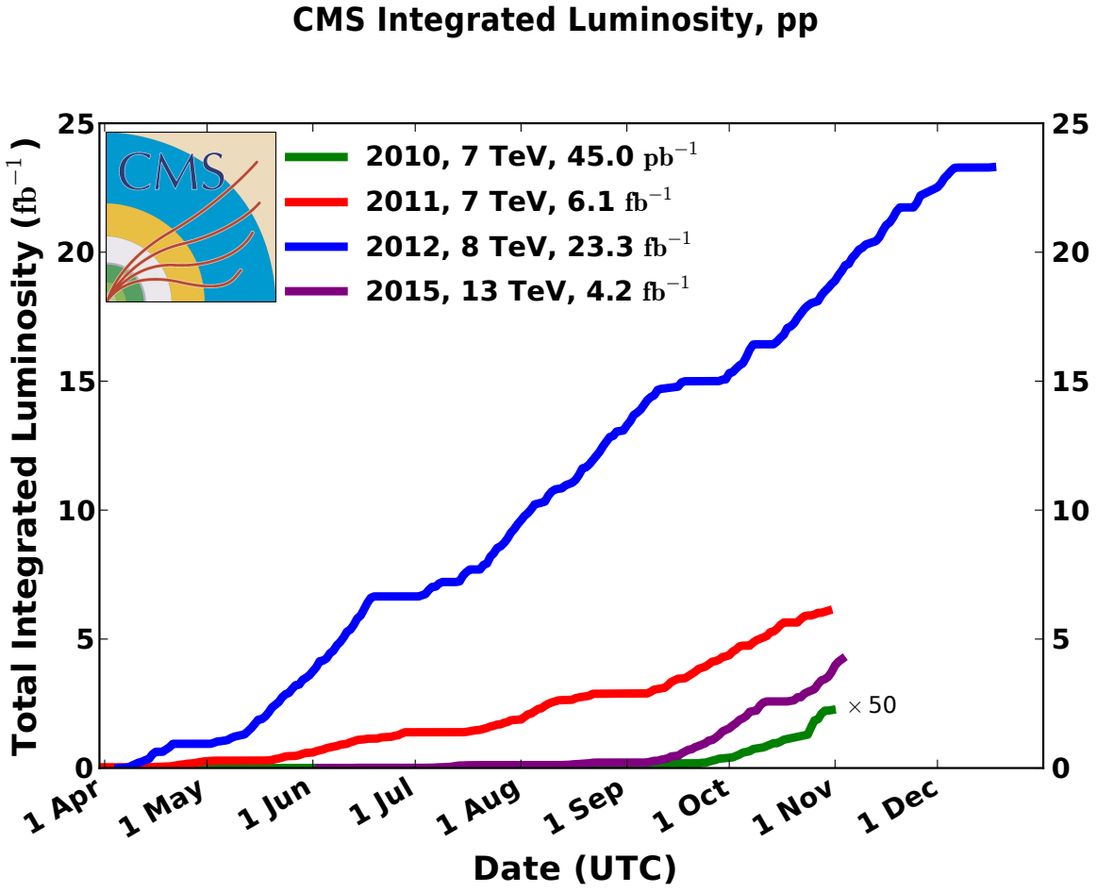
FORWARD CALORIMETER
Steel + quartz fibres
~2k channels

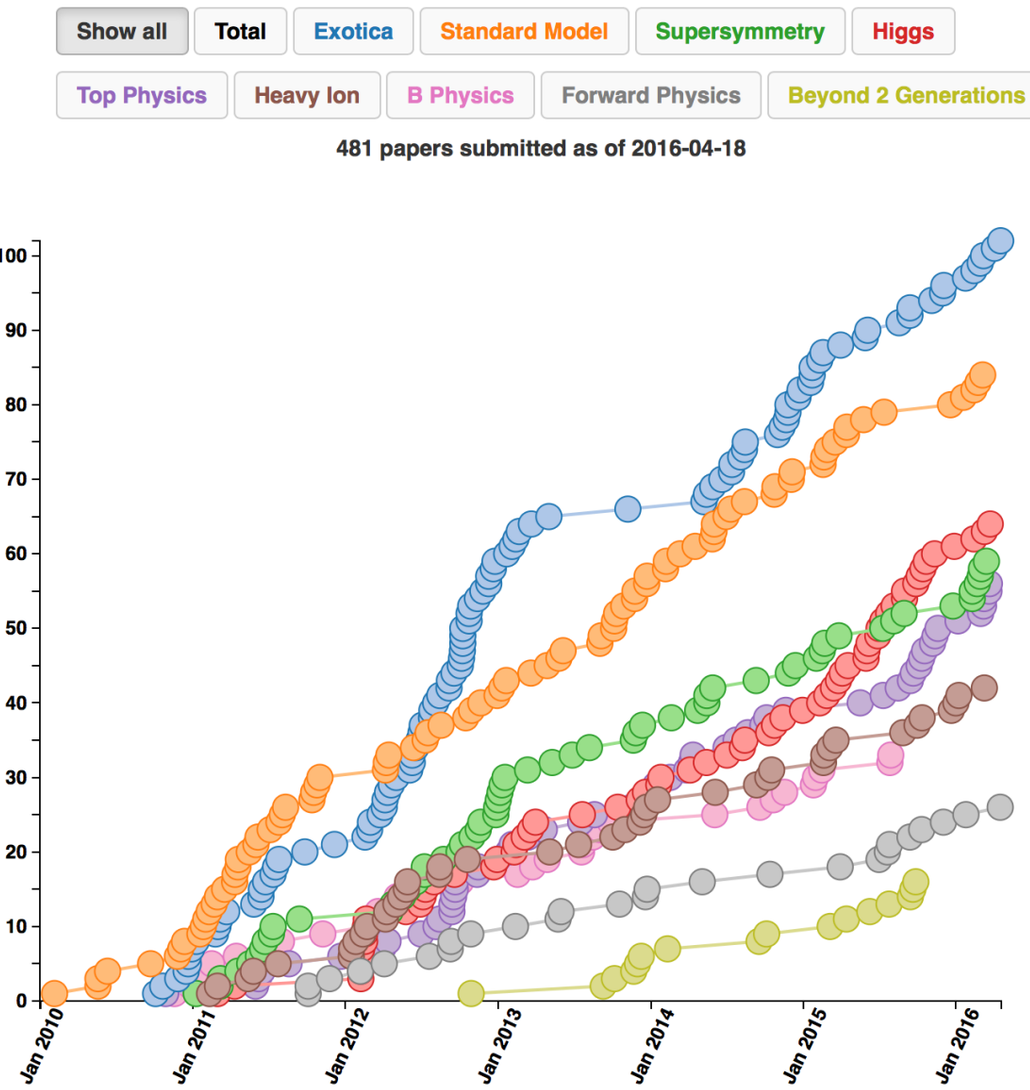
MUON CHAMBERS
Barrel: 250 Drift Tube & 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip & 432 Resistive Plate Chambers

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

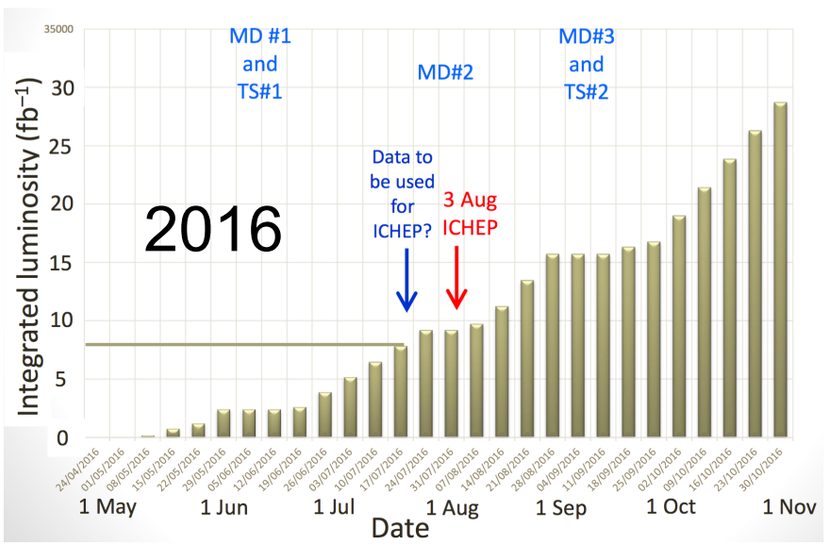
CMS


0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004





$$\frac{dR}{dt} = \mathcal{L}\,\sigma_P$$



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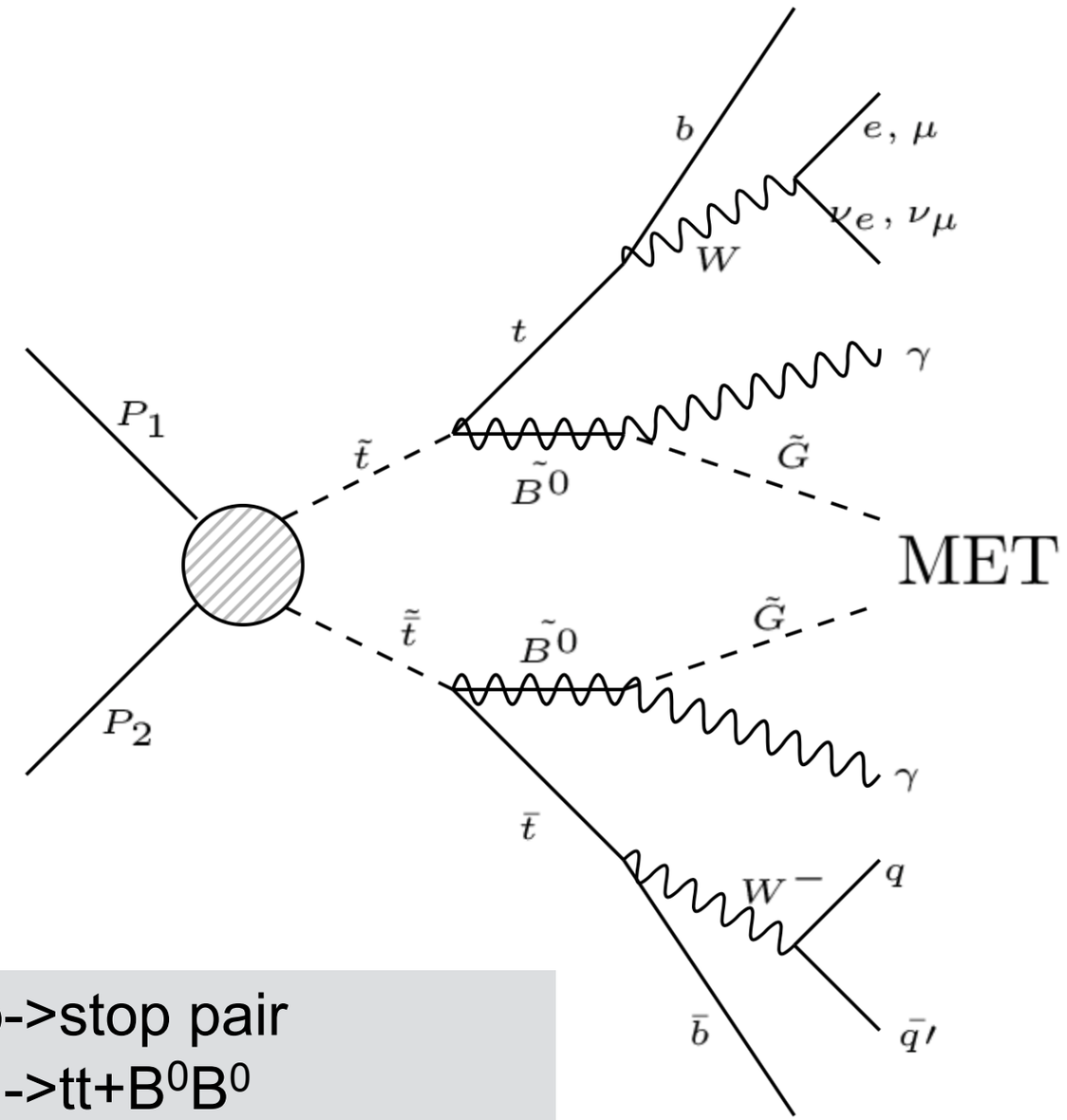
Analysis Overview



pp->stop pair
->tt+B^0B^0
->bbWW+$\gamma\gamma$+MET
->bbjj$\ell\nu$+$\gamma\gamma$+MET

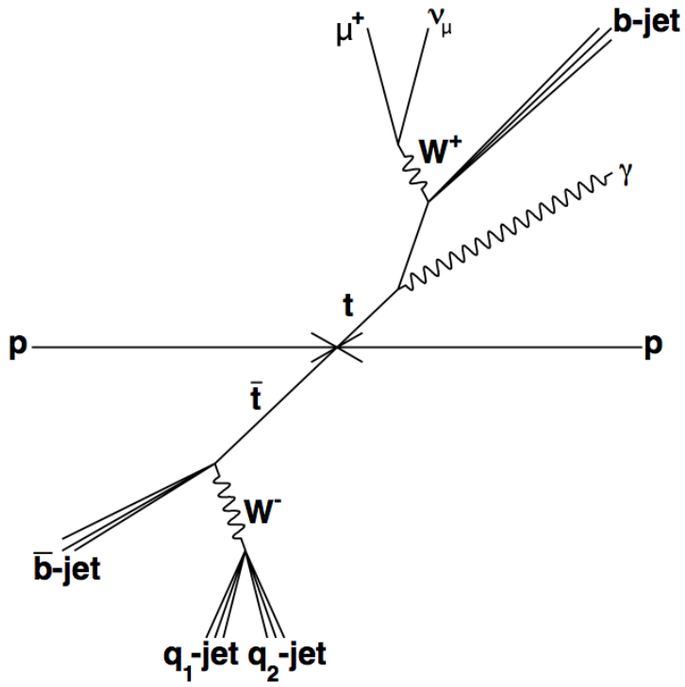
Signature:

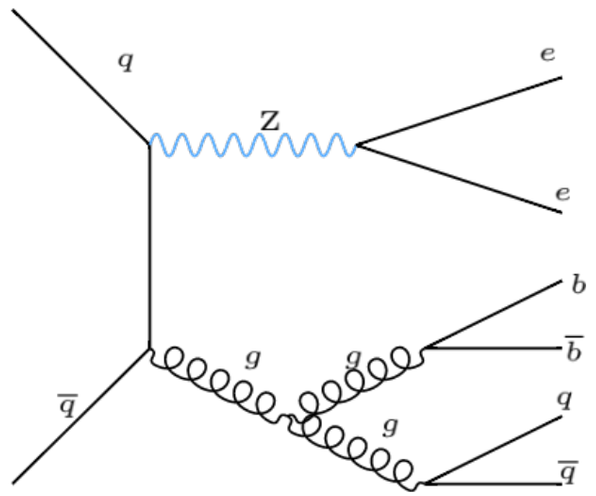
- one or more photons
- exact one lepton(electron or muon)
- two b-quark tagged jets
- additional jets
- Missing transverse momentum(MET)

To find SUSY: goal is to observe an excess of events at high MET region

Backgrounds

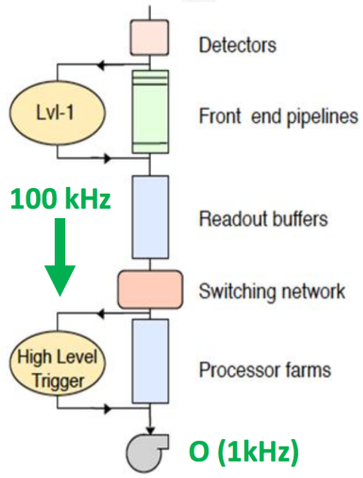
- Monte Carlo simulated
- Dominant:
  - tt+$\gamma(\gamma)$
  - tt+jets(mis-identified as γ)
- Sub-dominant
  - Wγ, Zγ, Z+jets
- Others:
  - tt+W/Z
  - W+jets
  - Di-boson(WW,WZ,ZZ)
  - Single top





Event Preselection

- Trigger on lepton
  - Electron channel: Data & MC: electron_ P_T>23GeV/c
  - Muon channel: Data & MC: muon_P_T>20GeV/c
- Required exact one tight isolated 30GeV/c lepton
- Veto events with additional 10GeV/c loose lepton
- Required at least three 30GeV/c jets
  - At least one of the selected jets is b-tagged



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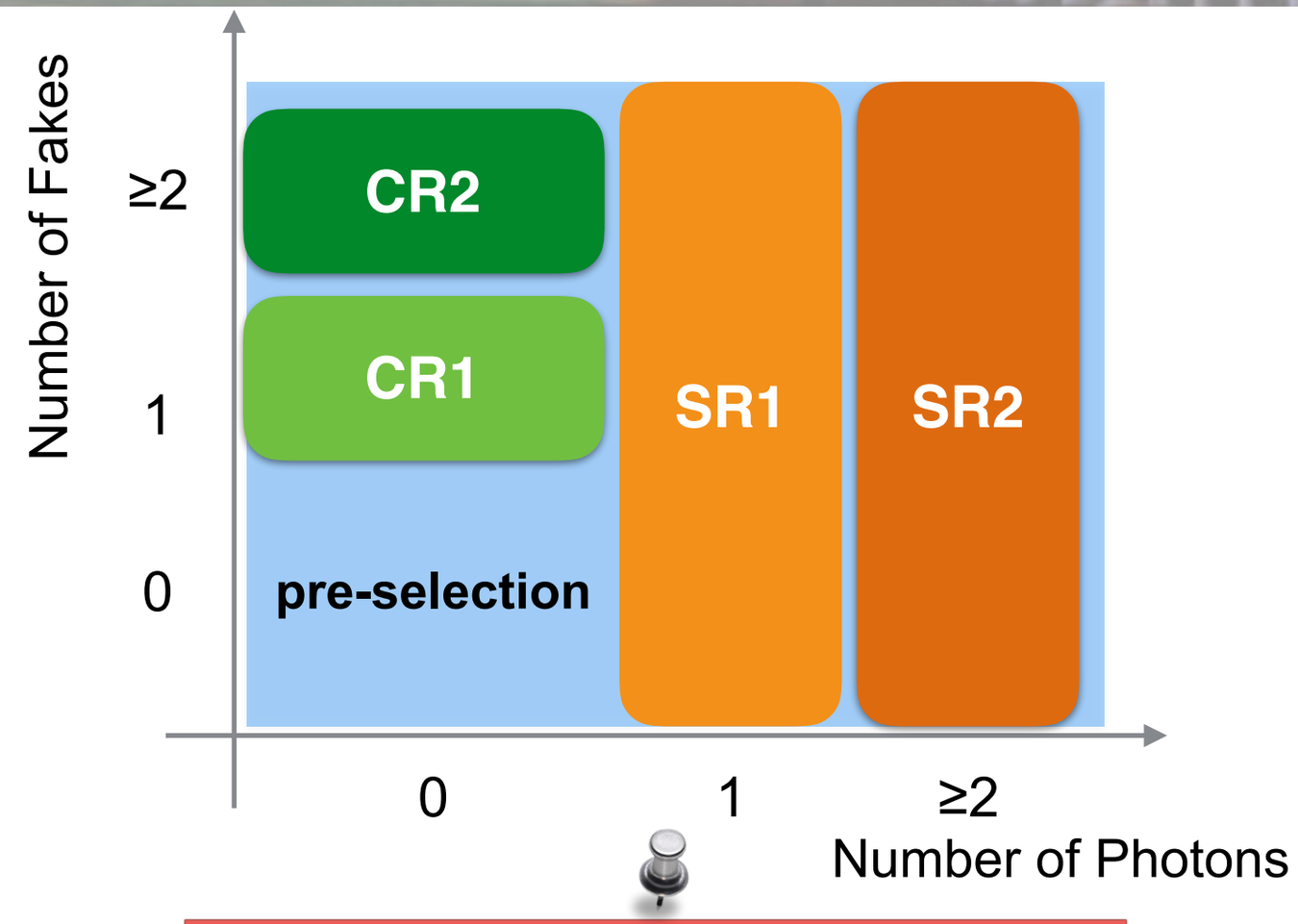
To pick out clean events

Photon selection

Signal Photon (Loose)
- Et>20
- |eta|<1.4442 (restrict barrel only)
- dR(pho,ele)>0.3

“fake” photon
- Similar to signal photon
- Require to fail
  - either: Shower shape variable
  - or: Charged hadron isolation

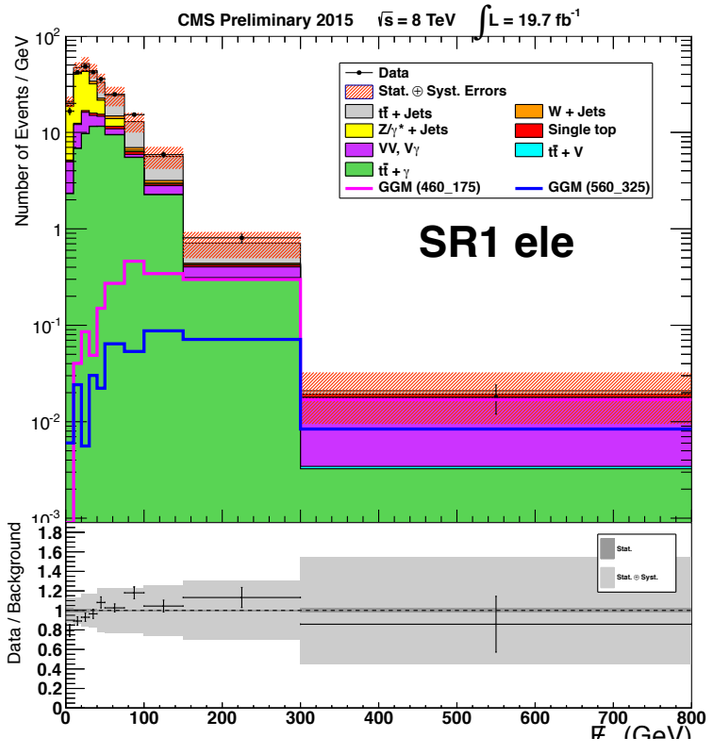


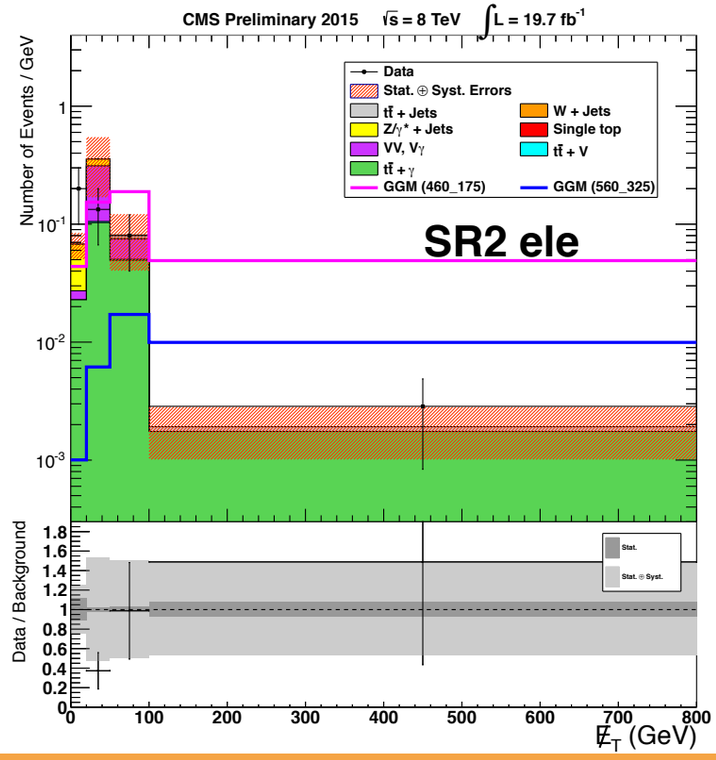
- **Categorize events regions**
- **Signal regions:**
  - **SR1: N(γ) = 1**
  - **SR2: N(γ) ≥ 2**
- **Control regions:**
  - **Veto photons in control regions**
  - **CR1: N(f) = 1**
  - **CR2: N(f) ≥ 2**

RunI Results

- Run I: 8TeV,19.7fb^{-1}
- Electron Channel

Channel	Pre-selection	SR1	SR2
QCD	$53129 \pm 230 \pm 53131$	–	–
$t\bar{t}$ + jets	$217189 \pm 466 \pm 8990$	$901 \pm 30 \pm 51$	$0.47 \pm 0.68 \pm 0.09$
W + jets	$90652 \pm 301 \pm 13846$	$100 \pm 10 \pm 16$	–
Z + jets	$13355 \pm 116 \pm 198$	$816 \pm 29 \pm 19$	$1.80 \pm 1.34 \pm 0.24$
Single t	$22281 \pm 149 \pm 1256$	$63 \pm 8 \pm 5$	–
Diboson	$1736 \pm 42 \pm 184$	$14.9 \pm 3.9 \pm 1.5$	$0.11 \pm 0.33 \pm 0.05$
$V\gamma$	$2677 \pm 52 \pm 1843$	$239 \pm 15 \pm 169$	$6.2 \pm 2.5 \pm 4.5$
$t\bar{t} + W$	$338 \pm 18 \pm 107$	$3.8 \pm 1.9 \pm 1.2$	$0.03 \pm 0.16 \pm 0.02$
$t\bar{t} + Z$	$265 \pm 16 \pm 28$	$4.3 \pm 2.1 \pm 0.5$	$0.09 \pm 0.30 \pm 0.02$
$t\bar{t} + \gamma$	$3292 \pm 57 \pm 1674$	$953 \pm 31 \pm 485$	$7.3 \pm 2.7 \pm 3.7$
Total Background	$404914 \pm 636 \pm 55707$	$3095 \pm 56 \pm 516$	$16.0 \pm 4.0 \pm 5.8$
GMSB (460_175)	$158 \pm 13 \pm 11$	$82 \pm 9 \pm 6$	$44 \pm 7 \pm 3$
GMSB (560_325)	$41 \pm 6 \pm 3$	$21 \pm 5 \pm 2$	$7.4 \pm 2.7 \pm 0.5$
Data	404337	3266	14

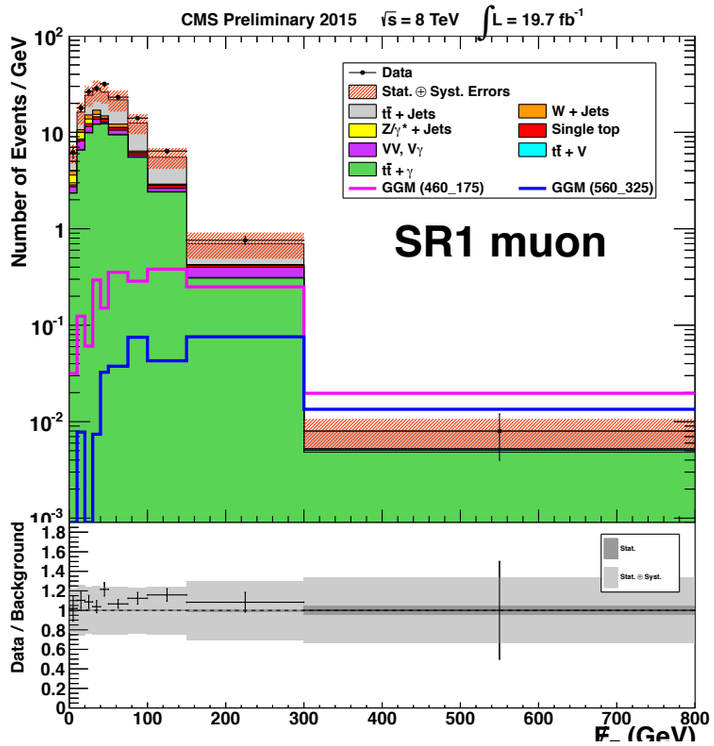


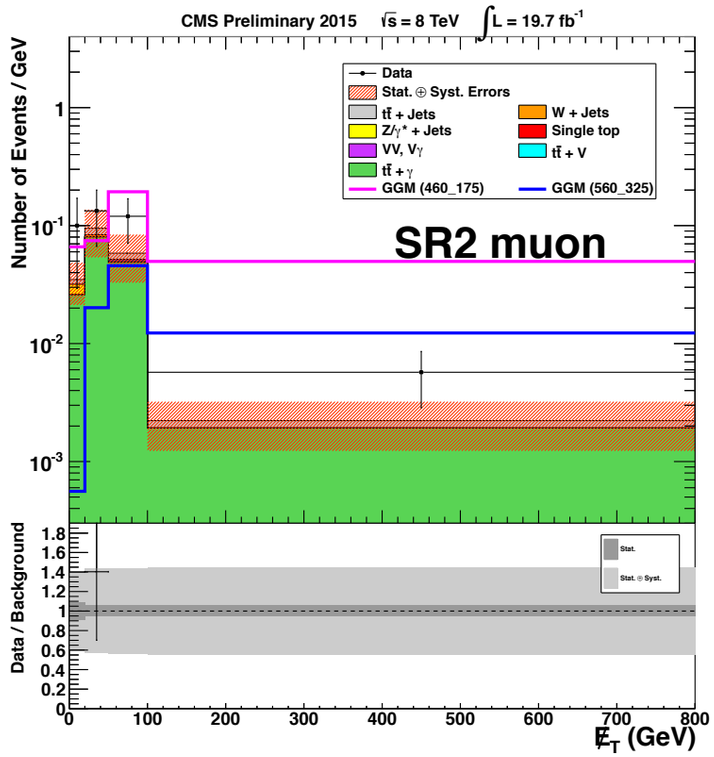


RunI Results

- Muon Channel

Channel	Pre-selection	SR1	SR2
QCD	14291 ± 298	–	–
$t\bar{t}$ + jets	235482 ± 476	944 ± 4	0.95 ± 0.12
W + jets	90256 ± 515	83 ± 2	0.11 ± 0.01
Z + jets	10376 ± 61	100 ± 1	0.22 ± 0.00
Single t	23399 ± 30	67 ± 2	–
Diboson	1731 ± 2	7.8 ± 0.1	0.08 ± 0.00
$V\gamma$	3092 ± 18	192 ± 3	–
$t\bar{t} + W$	355 ± 1	3.8 ± 0.1	0.04 ± 0.00
$t\bar{t} + Z$	262 ± 1	2.8 ± 0.1	–
$t\bar{t} + \gamma$	3182 ± 4	973 ± 2	6.7 ± 0.2
Total Background	382426 ± 765	2374 ± 6	8.1 ± 0.3
GMSB (460_175)	155 ± 3	80 ± 2	43 ± 2
GMSB (560_325)	44 ± 1	22 ± 1	10.7 ± 0.6
Data	381772	2475	16





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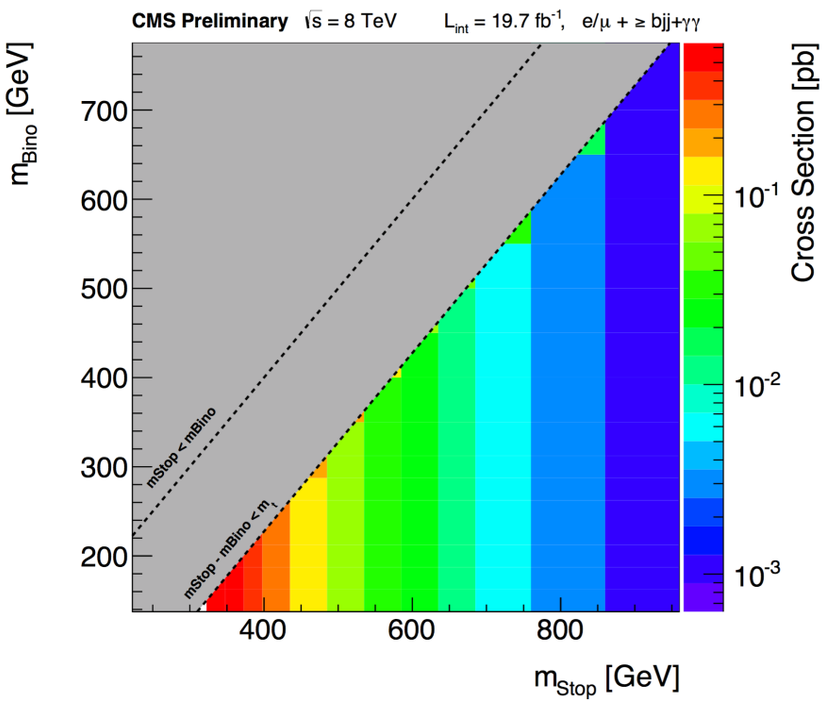
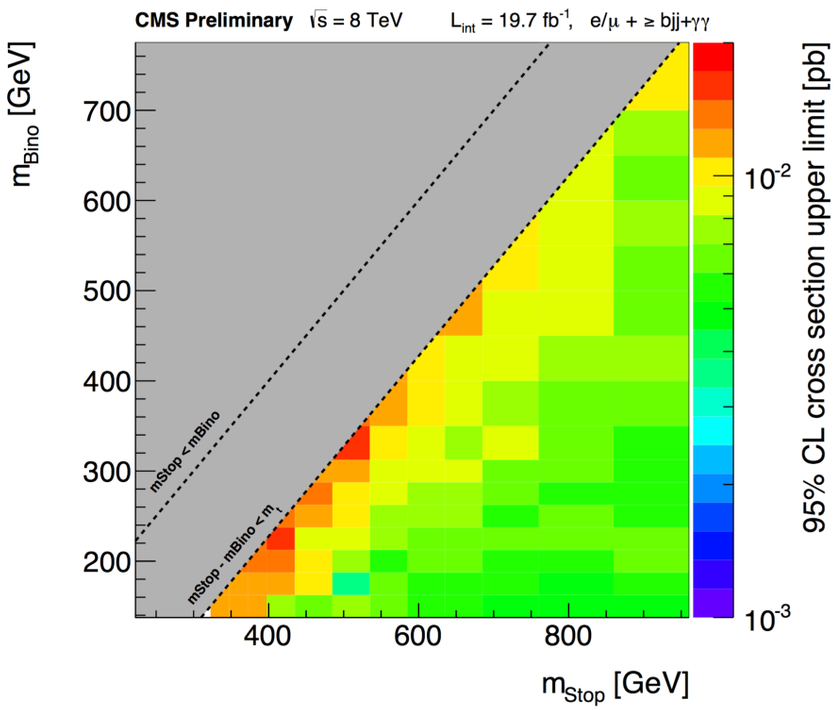
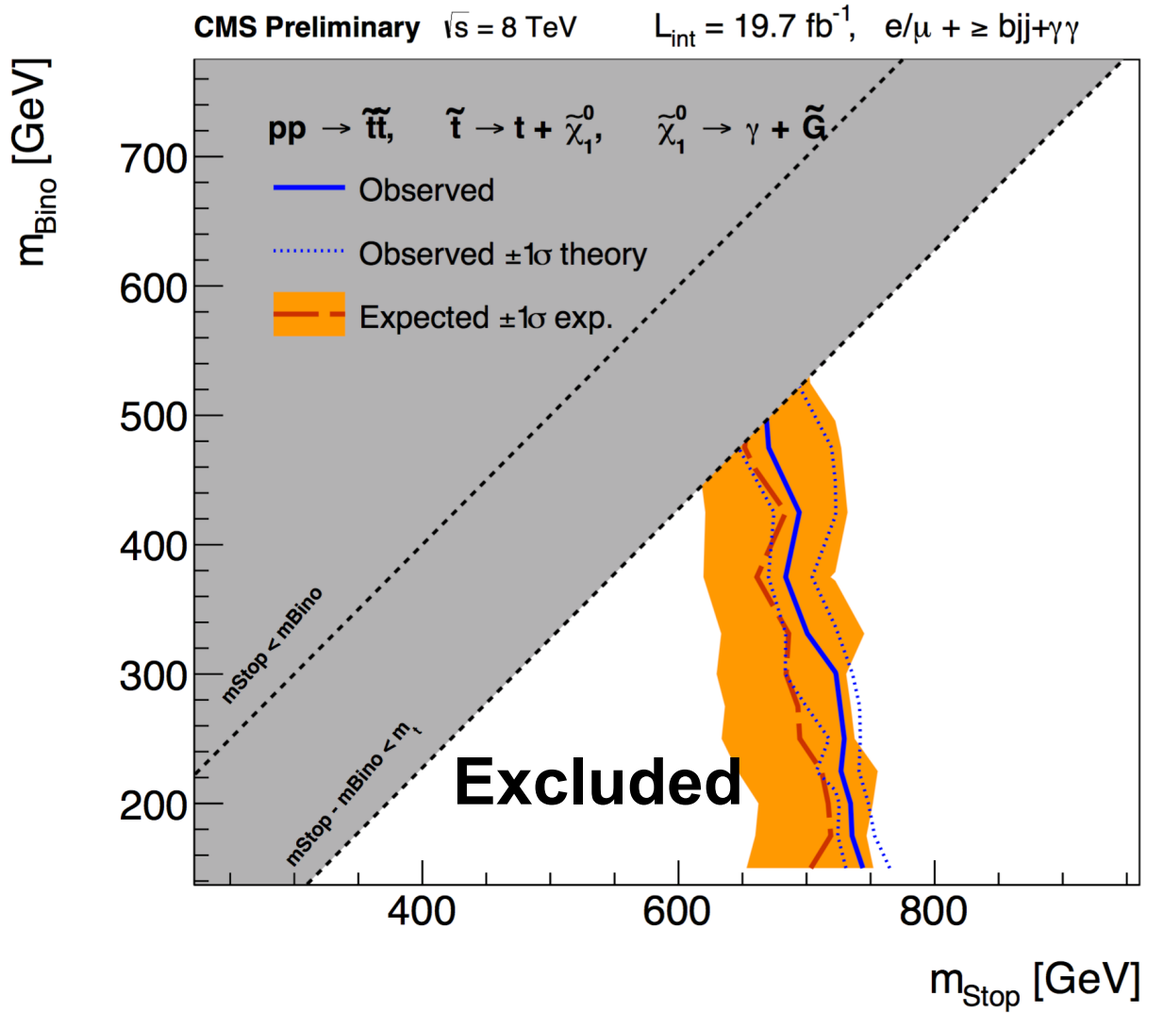




- No significant excess in the shape of the MET distribution is observed

- Interpret into exclusion contour
- Pushed exclusion in stop mass up to ~ 650 – 750 GeV



RunII Progress

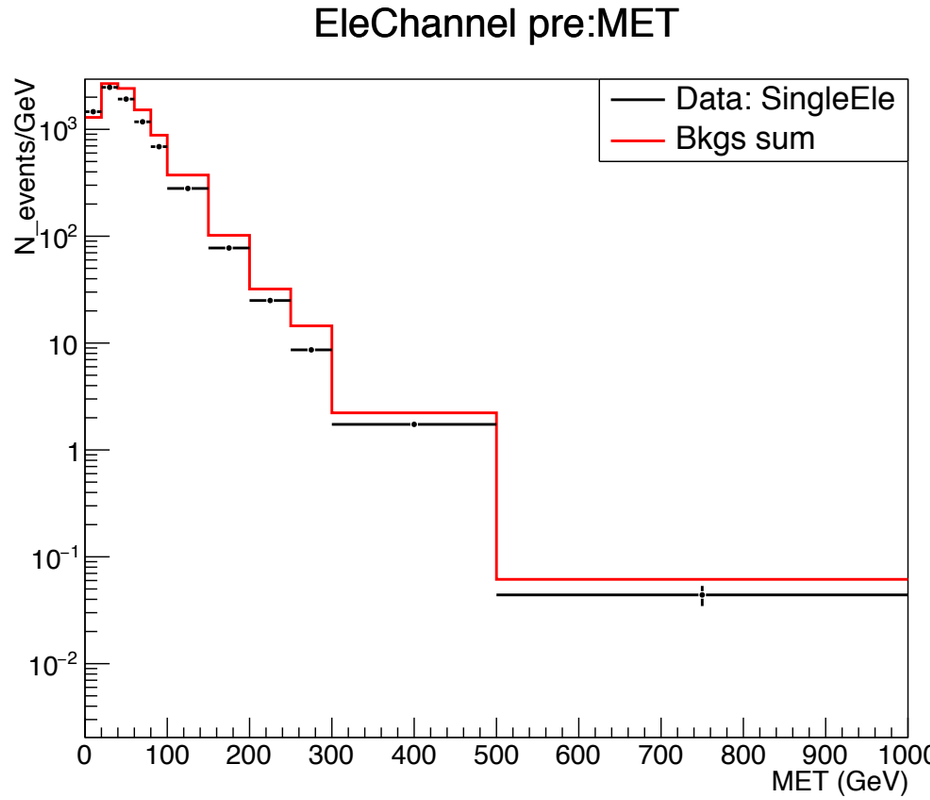
2015 datasets with 13TeV, 25ns bunch crossing
Have investigated the data and some background samples

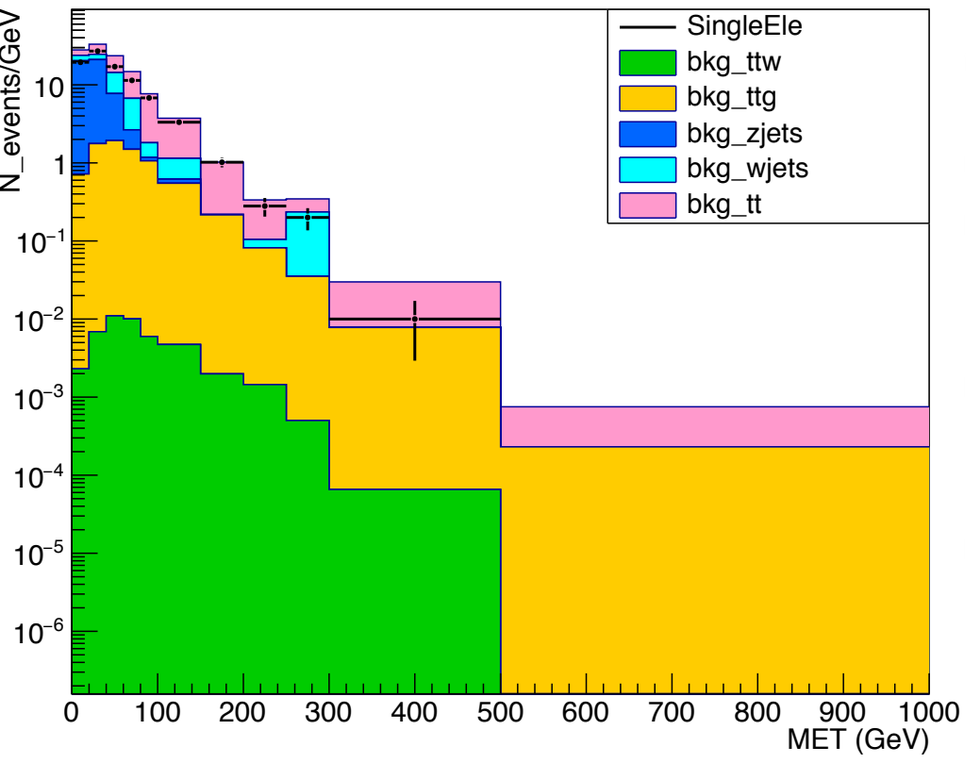
		Xsec(pb)	Event number	Lumi(/fb)
Data	**Muon channel**			1.731
	Electron channel			2.67
Backgrounds	**tt+γ**	3.697	4832230	1307
	ttjets	831.76	19757190	23.75
	z+jets	6025.2	28747969	4.77
	ttw->lnu	0.2043	252908	1238
	wjets->lnu	61526.7	24184766	0.4

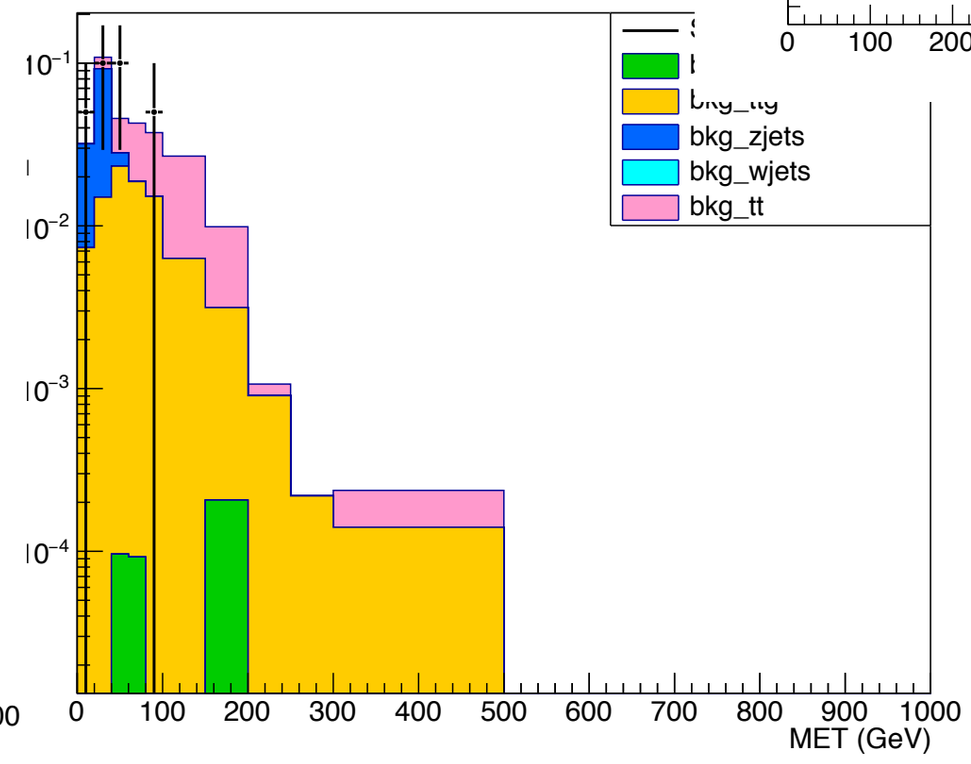
RunII Progress

Very preliminary results: Electron channel

Channel	Pre_selection	SR1	SR2
tt	114745.761488	910.560126846	2.99507947769
ttw	52.9618943584	1.16971822686	0.0144644710464
ttg	569.294645331	184.027870123	2.13820276189
zjets	14296.7258355	922.936046308	2.13362199907
wjets	72721.8888044	403.205799998	0.0
bkgsum	202386.632668	2421.8995615	7.28136870969
data	174288	1879	6





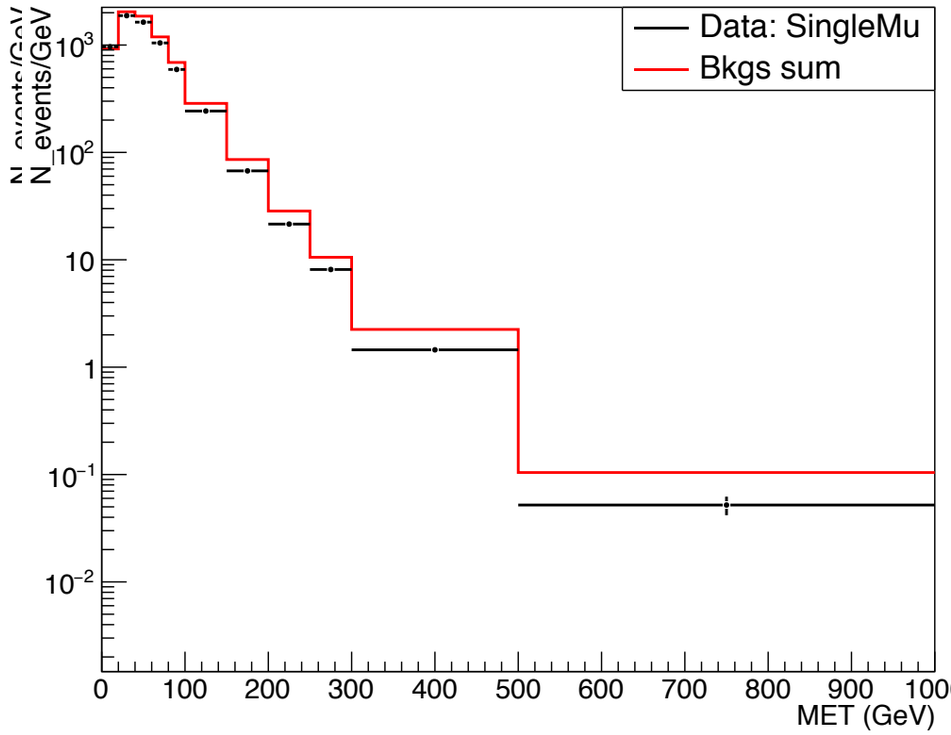


RunII Progress

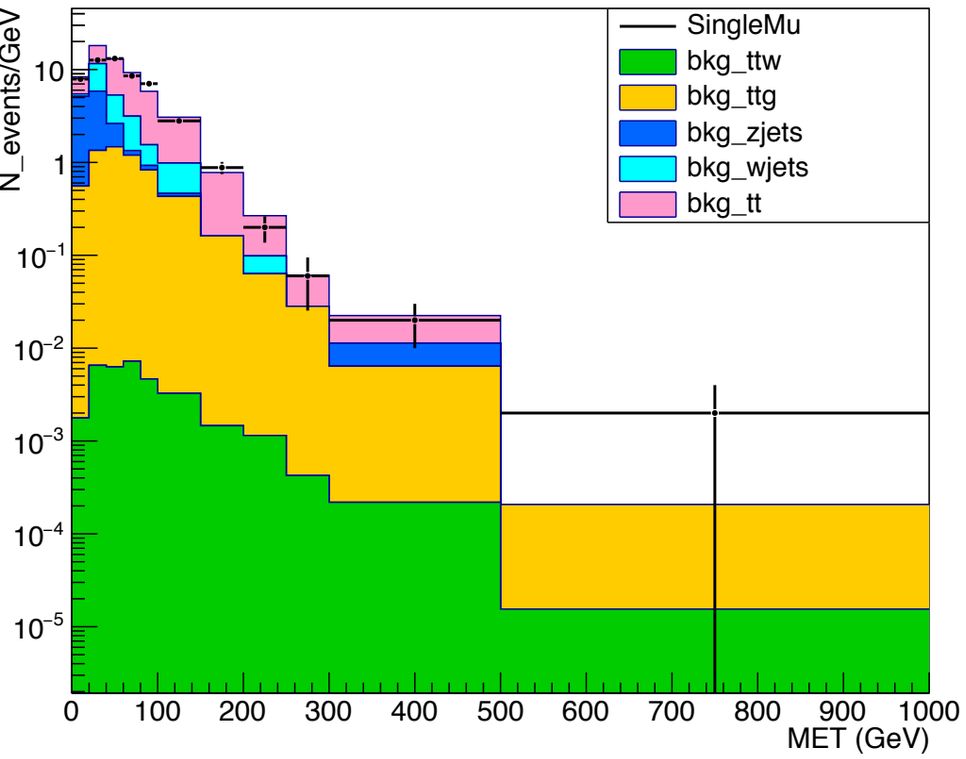
Very preliminary results: Muon channel

Channel	Pre_selection	SR1	SR2
tt	91187.3019031	699.662832842	2.47430143029
ttw	39.0427912031	0.896072854267	0.00194193115457
ttg	423.732913342	142.76224154	1.55054300742
zjets	6373.37888429	212.000186751	0.787970152419
wjets	56978.22801	251.295646774	0.0
bkgsum	155001.684502	1306.61698076	4.81475652128
data	139591	1188	7

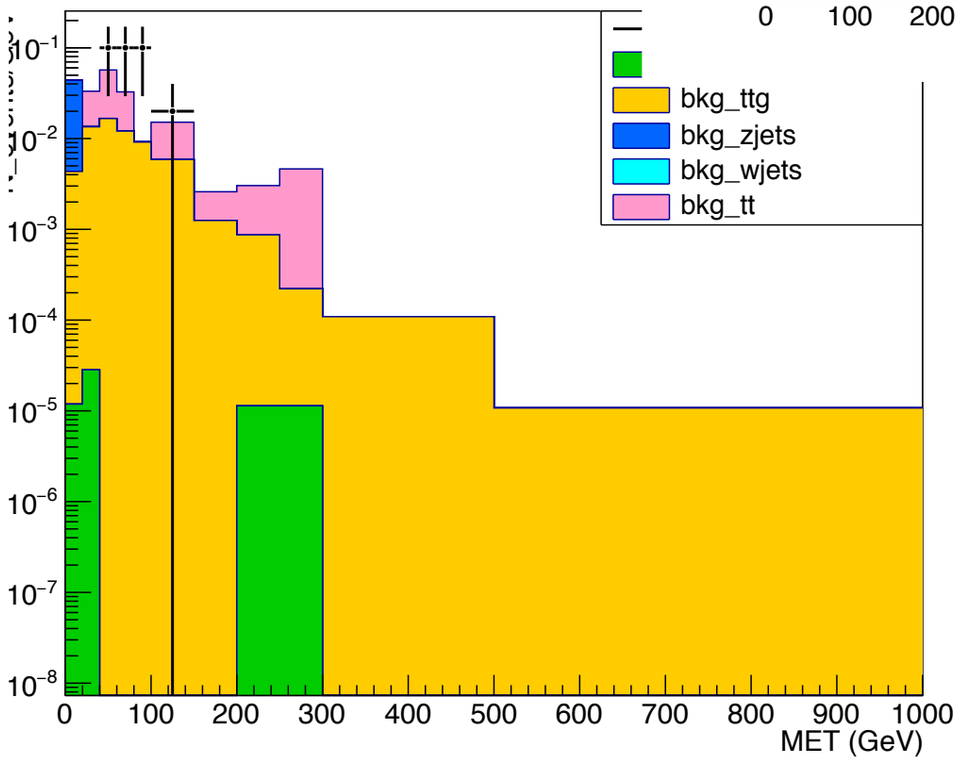
MuChannel pre:MET



MuChannel SR1:MET



MuChannel SR2:ME



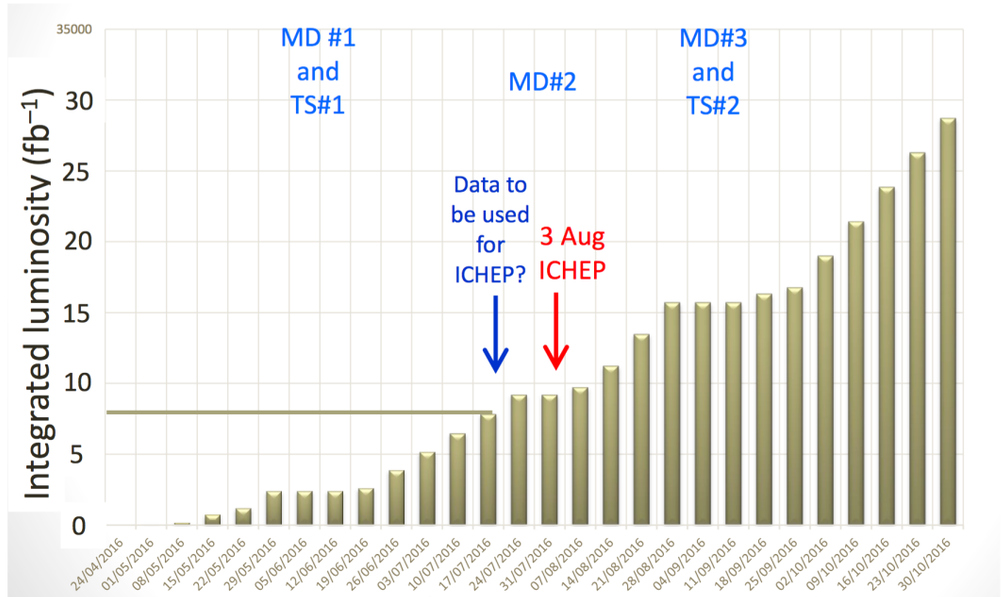
RunII Progress

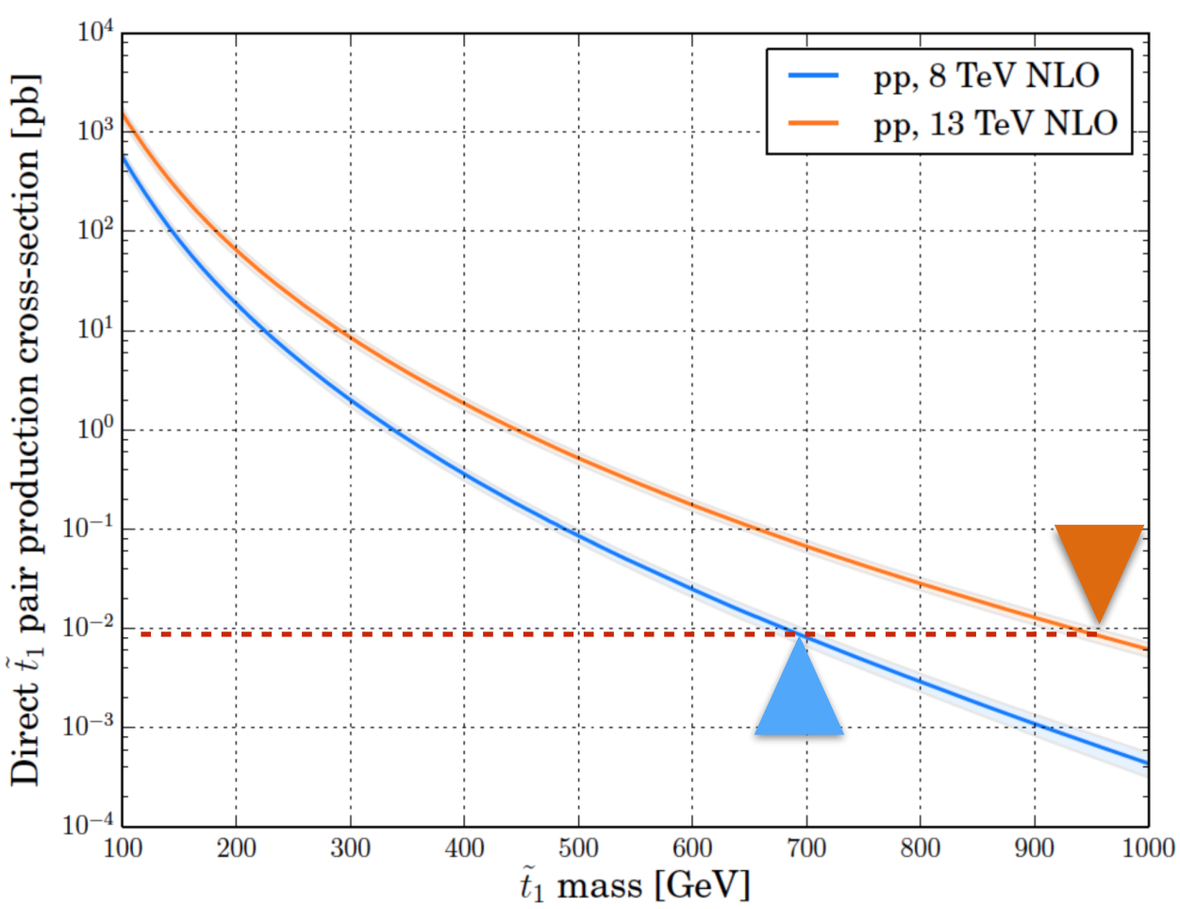
Very preliminary results:

- MET shapes agree between backgrounds sum and data
- Event numbers: sum of backgrounds is over data expected:
- Data is quite limited
- To describe the data accurately, need to investigate Monte Carlo Bkgs: efficiencies, reweighting, scale factors…

Outlook

- By the end of 2016, expect to accumulate integrated lumi ~30fb^{-1}
- More and more data…
- **SUSY might be around the corner**





If no susy, and with the similar signal events yield, can push up the exclusion

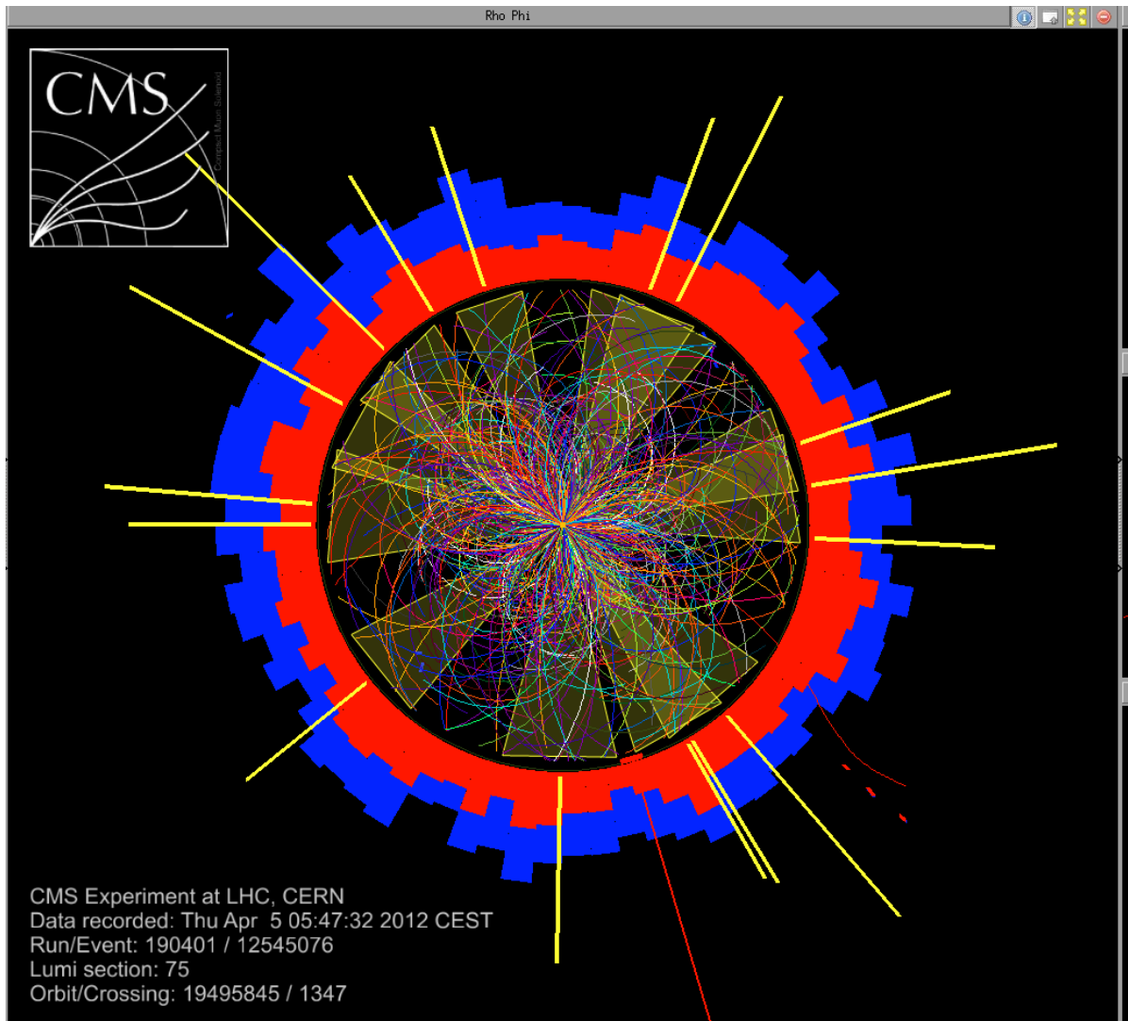
8TeV exclusion

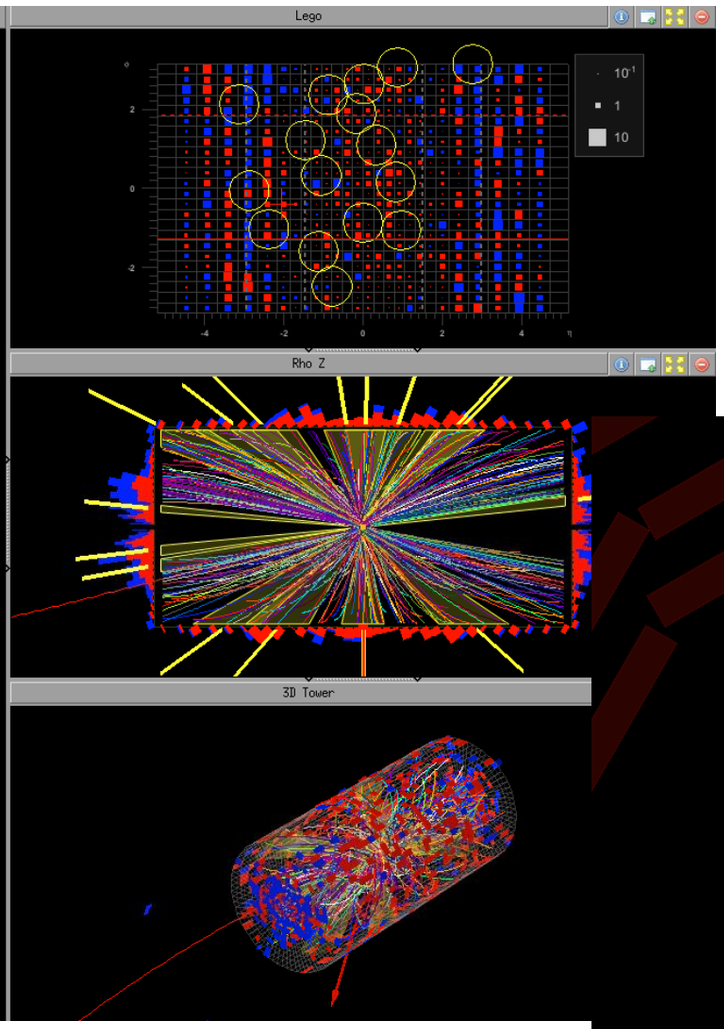
13TeV exclusion

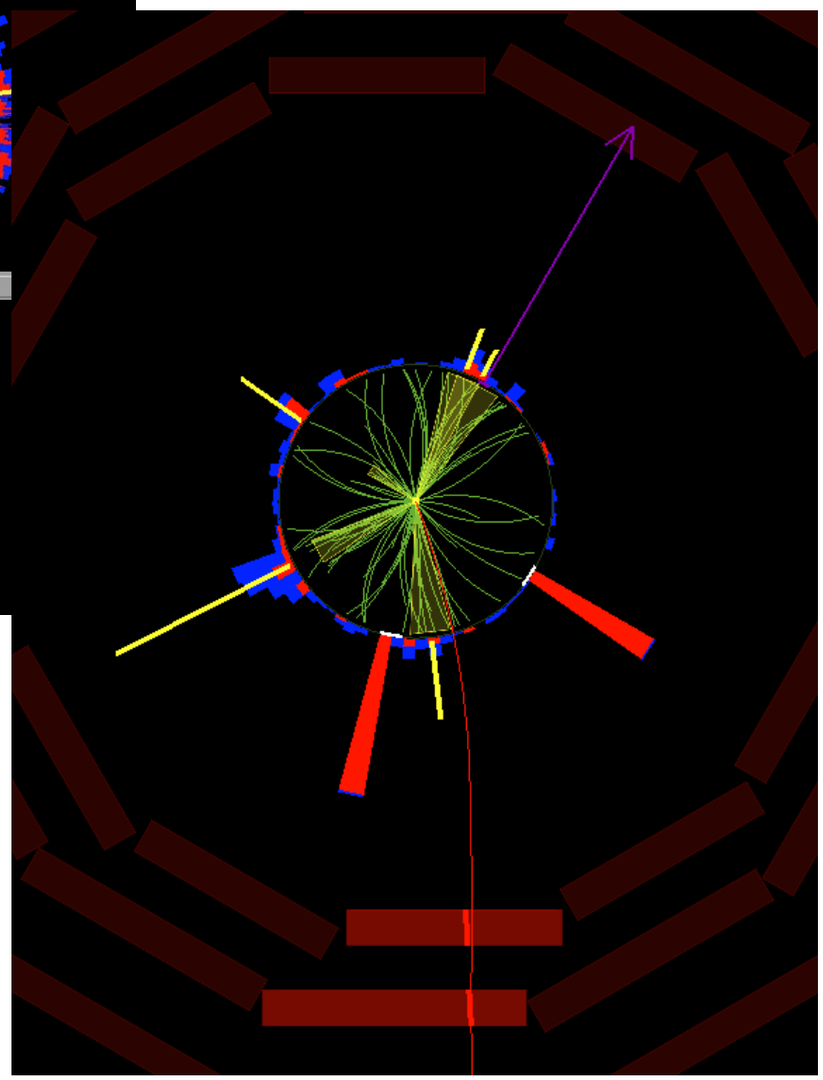
Thank You!

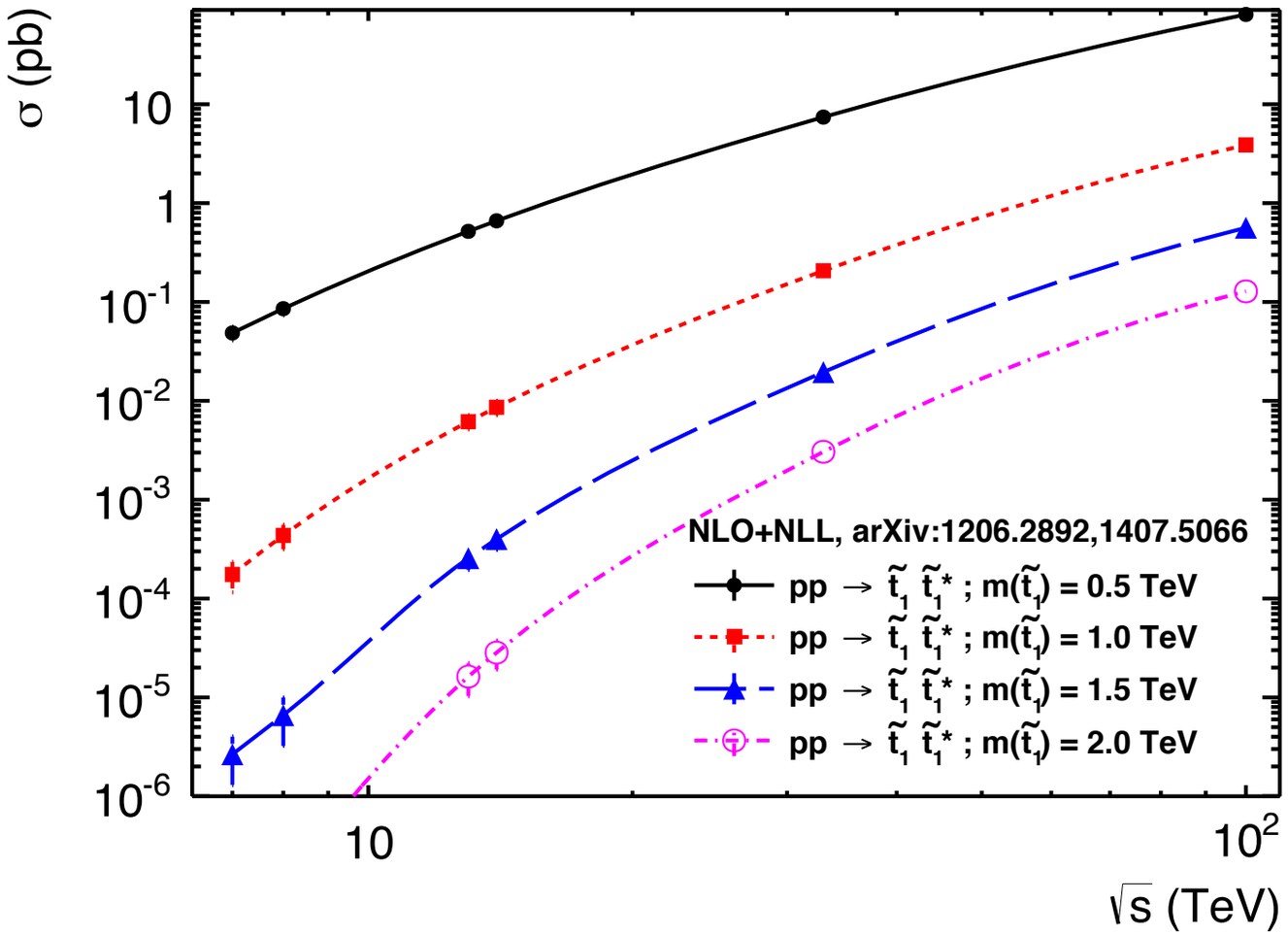
(Back up)

Event display









- stop pair cross section

$$m_{\tilde{\chi}_1^0} = M_1 - \frac{m_Z^2 \sin^2\theta_W (M_1 + \mu \sin 2\beta)}{\mu^2 - M_1^2} + \dots$$

$$m_{\tilde{\chi}_2^0} = M_2 - \frac{m_W^2 (M_2 + \mu \sin 2\beta)}{\mu^2 - M_2^2} + \dots$$

$$m_{\tilde{\chi}_3^0} = |\mu| + \frac{m_Z^2 (\mathrm{sgn}(\mu) - \sin 2\beta)(\mu + M_1 \cos^2\theta_W + M_2 \sin^2\theta_W)}{2(\mu + M_1)(\mu + M_2)} + \dots$$

$$m_{\tilde{\chi}_4^0} = |\mu| + \frac{m_Z^2 (\mathrm{sgn})\mu) + \sin 2\beta)(\mu - M_1 \cos^2\theta_W - M_2 \sin^2\theta_W)}{2(\mu - M_1)(\mu - M_2)} + \dots$$

$$m^2_{\tilde{\chi}_1^\pm} = M_2 - \frac{m_W^2 (M_2 + \mu \sin 2\beta)}{\mu^2 - M_2^2} + \dots$$

$$m^2_{\tilde{\chi}_2^\pm} = |\mu| + \frac{m_W^2 \mathrm{sgn}(\mu)(\mu + M_2 \sin 2\beta)}{\mu^2 - M_2^2} + \dots$$

‘bino-like’ ($\tilde{\chi}^0_1$)

‘wino-like’ ($\tilde{\chi}^0_2$)

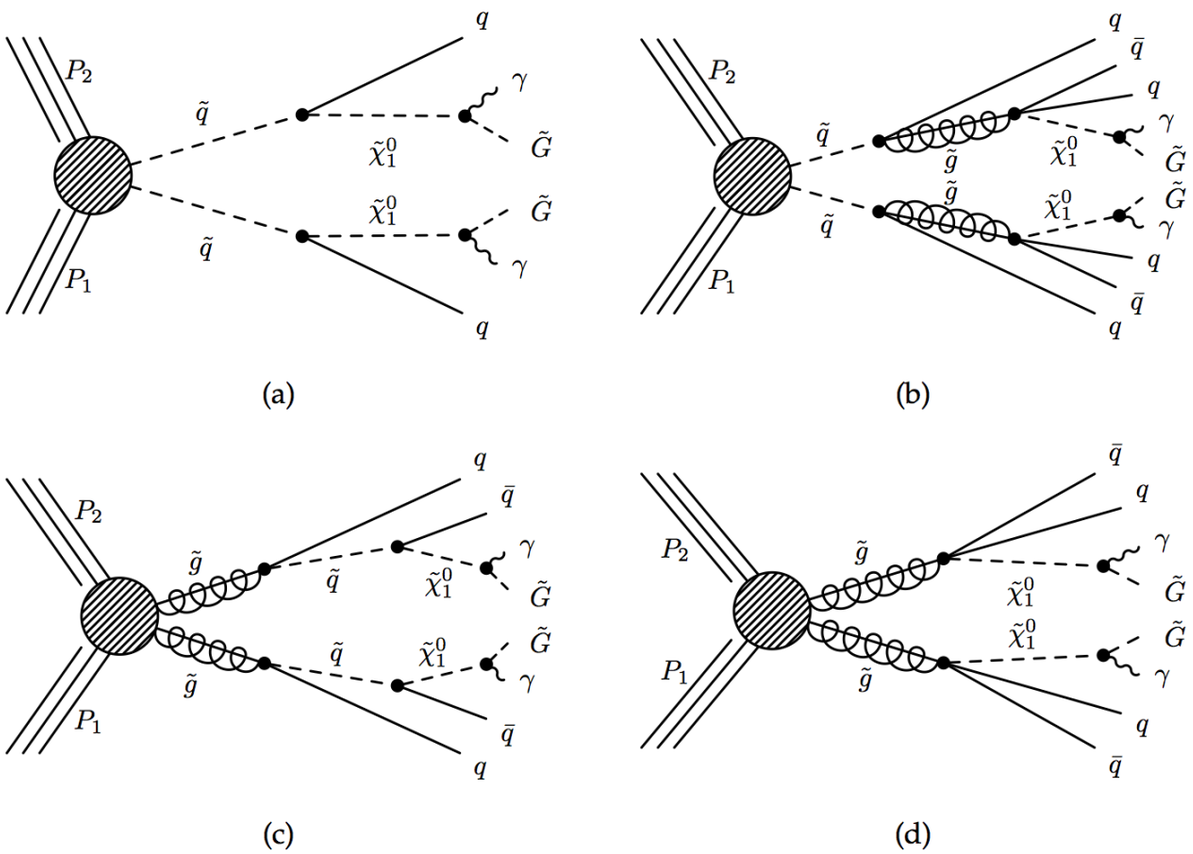
‘higgsino-like’ mixture $\tilde{\chi}^0_3$, $\tilde{\chi}^0_4$

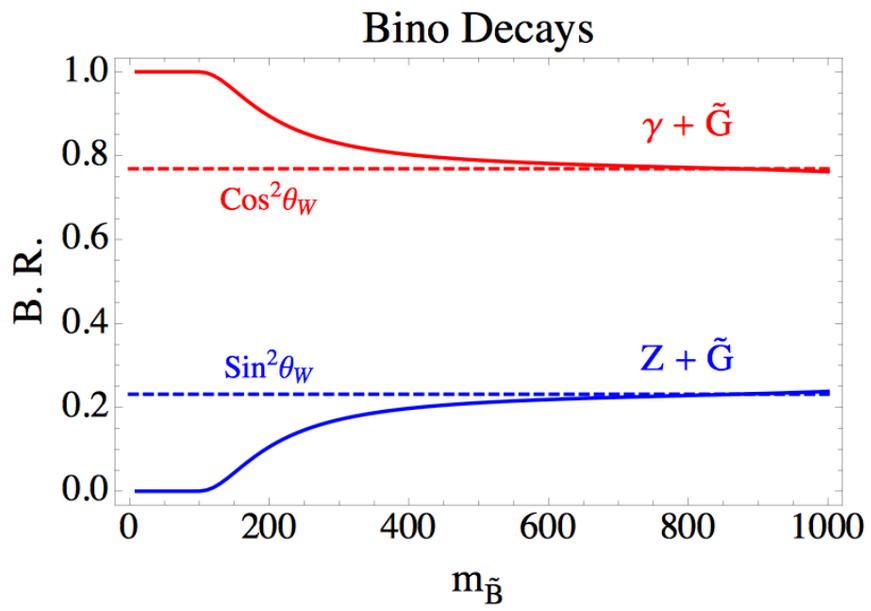
charginos are a wino-like $\tilde{\chi}^\pm_1$

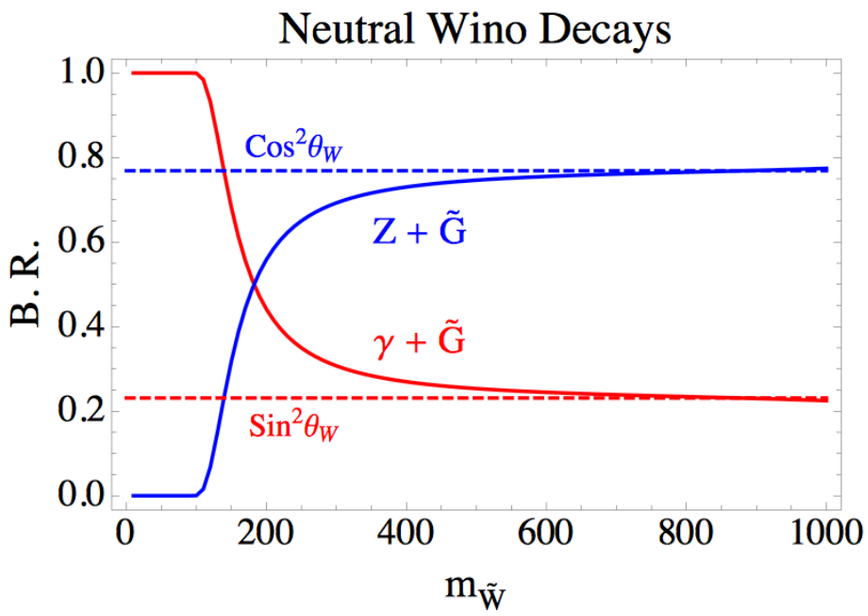
higgsino-like $\tilde{\chi}^\pm_2$

GMSB

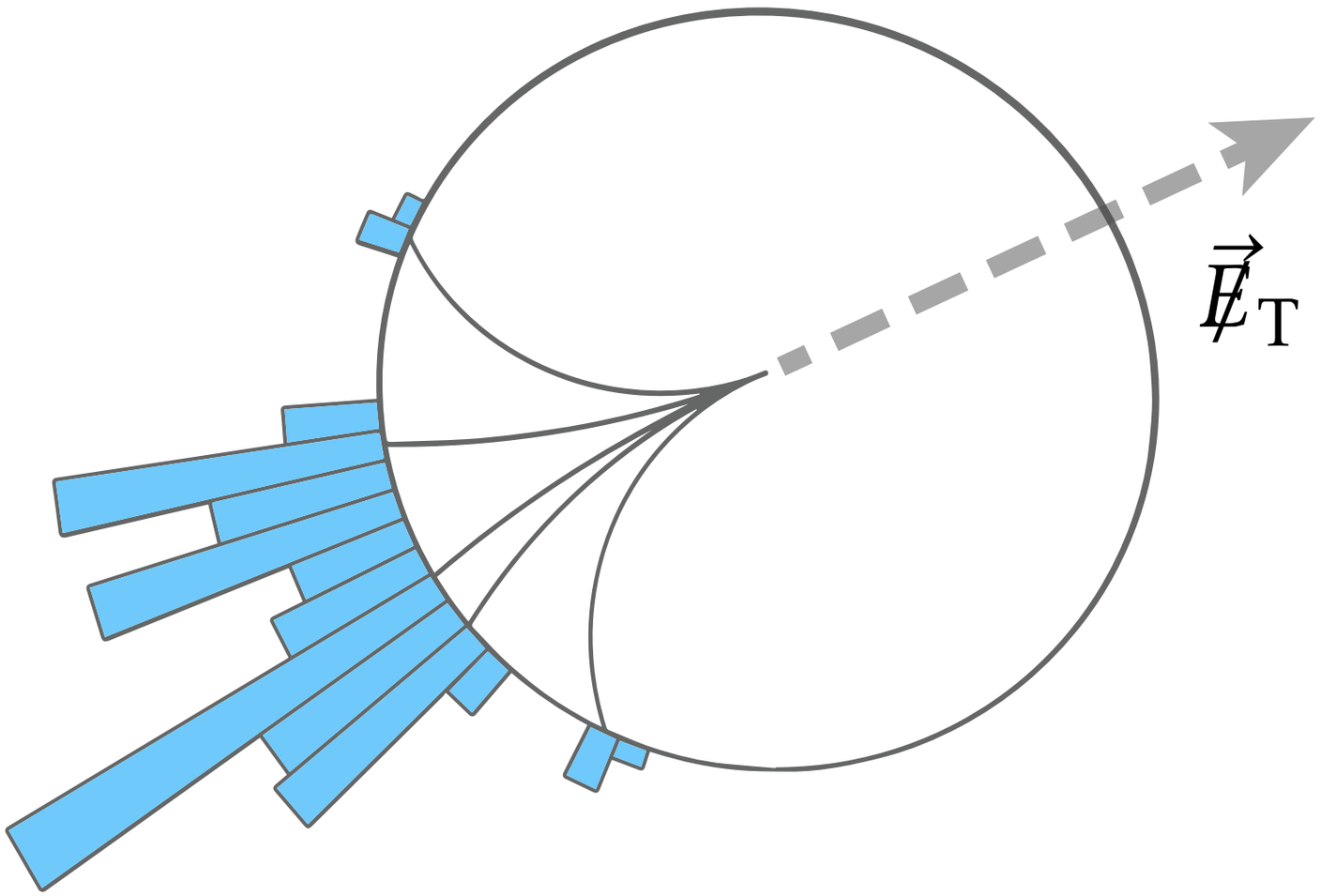
Topologies: for the bino like neutralino...







MET

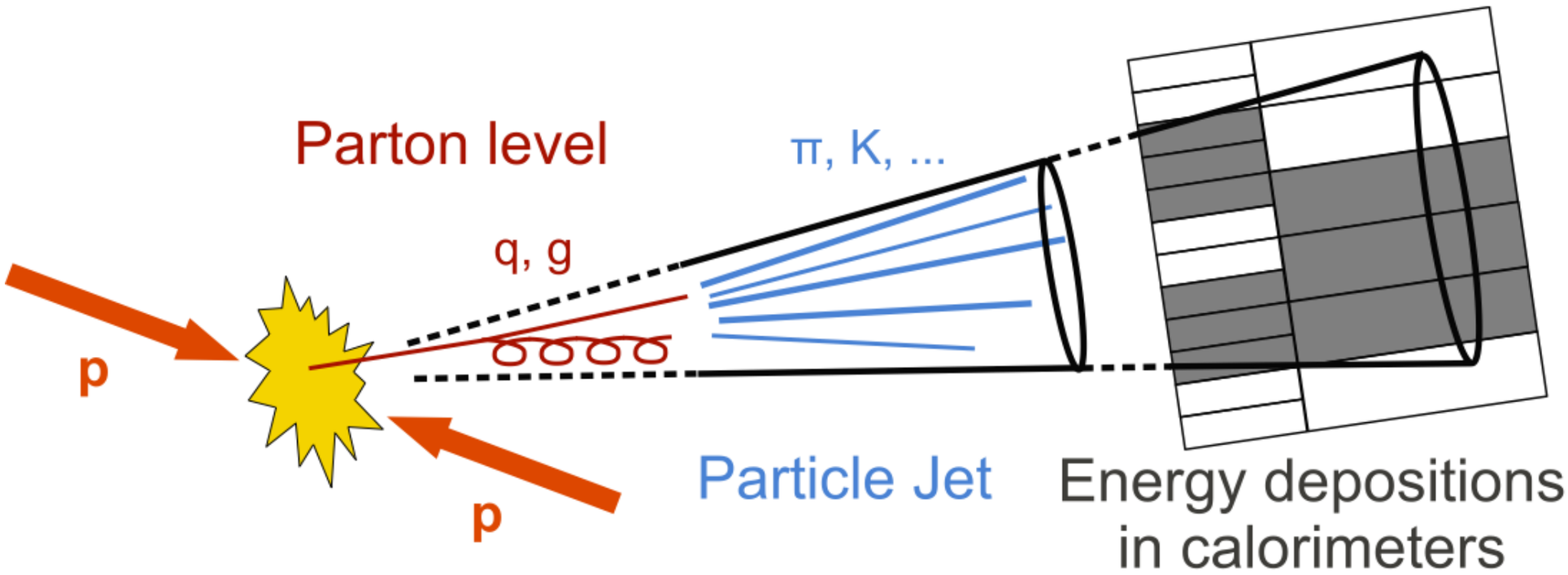


$$\vec{\not{E}}_{\mathrm{T}}^{\mathrm{raw}} = -\sum_{i \in \mathrm{all}} \vec{p}_{\mathrm{T}i}$$

Raw MET is the negative of the vector sum of of all reconstructed particles

Missing transverse momentum (MET) is the imbalance in the transverse momentum of all *visible* particles, particles which interact with the electromagnetic or strong forces, in the final state of collisions. Because momentum is conserved in each direction, MET is the transverse momentum that must have been carried by something *invisible*. Neutrinos, for example, are invisible particles

Jet



Sketch of pp-collision and resulting collimated spray of particles, a jet.

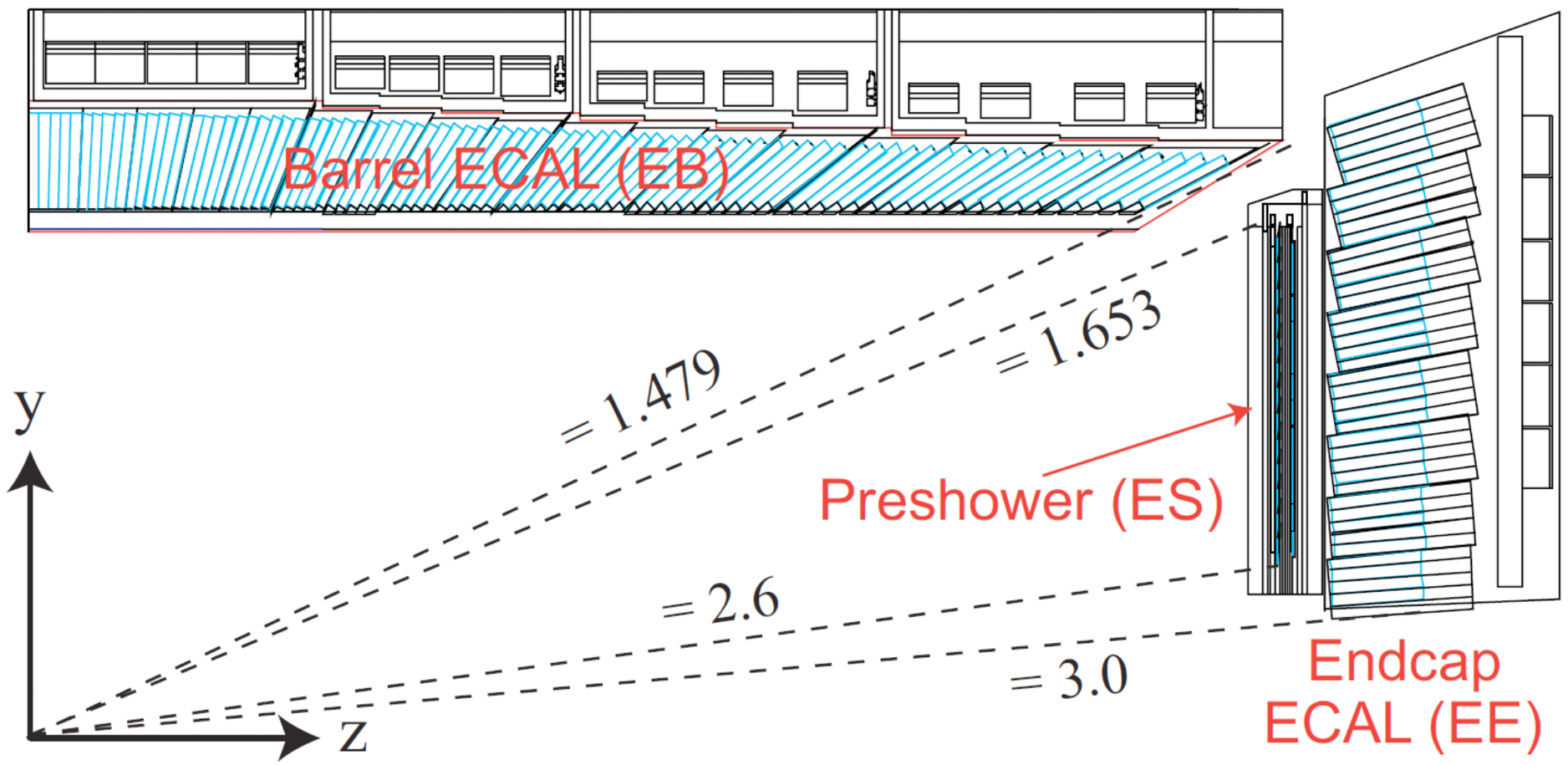
Analysis Objets

Muon	Tight	Loose
Pt	>30	>10
|eta|	<2.1	<2.5
POG ID	Tight	Loose
PF RelIso(dR0.4	0.15	0.25

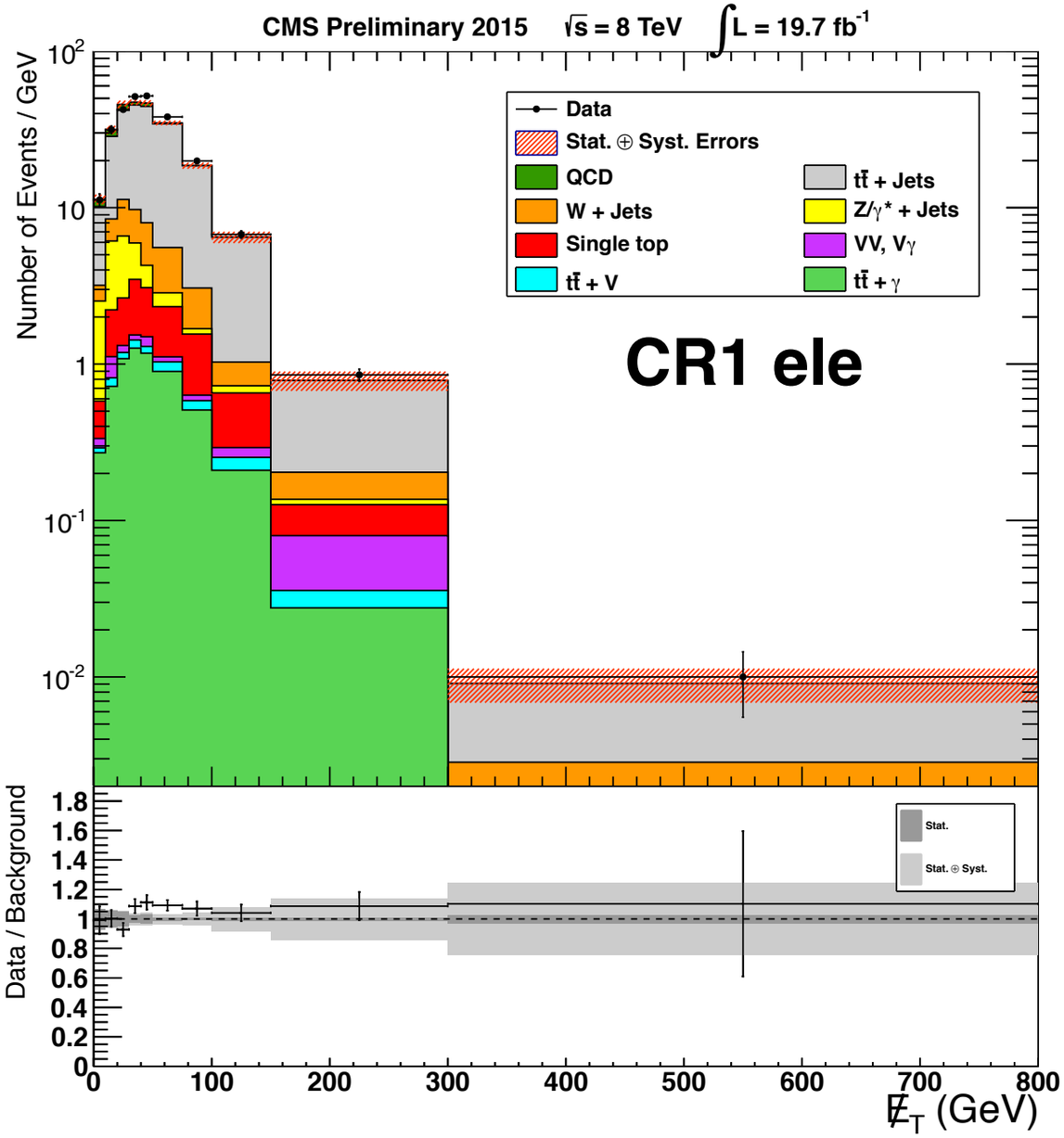
Electron	Tight	Loose
Pt	>30	>10
|eta|	<2.5	<2.5
POG ID	Tight	Loose

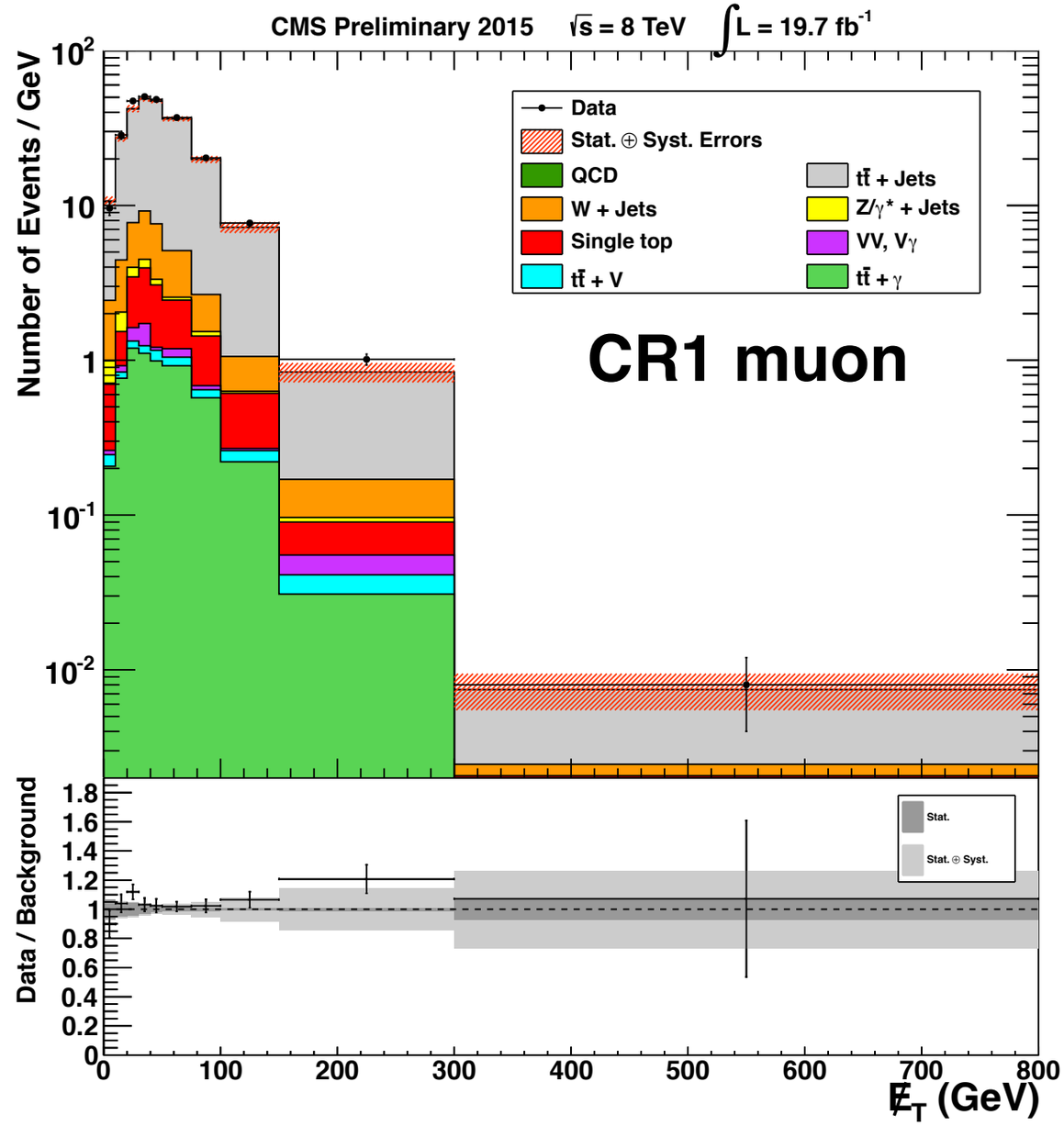
Jet (Loose)
- Pt>30
- |eta|<2.4
- pass jetPF LooseId
- bjet csvm>0.89

Photon (Loose)
- Et>20
- |eta|<1.4442 (restrict barrel only)
- pass ElectronVeto
- POG Loose Id
- dR(pho,mu)>0.3


Barrel ECAL (EB)
= 1.479
= 1.653
Preshower (ES)
= 2.6
= 3.0
Endcap
ECAL (EE)
y
z

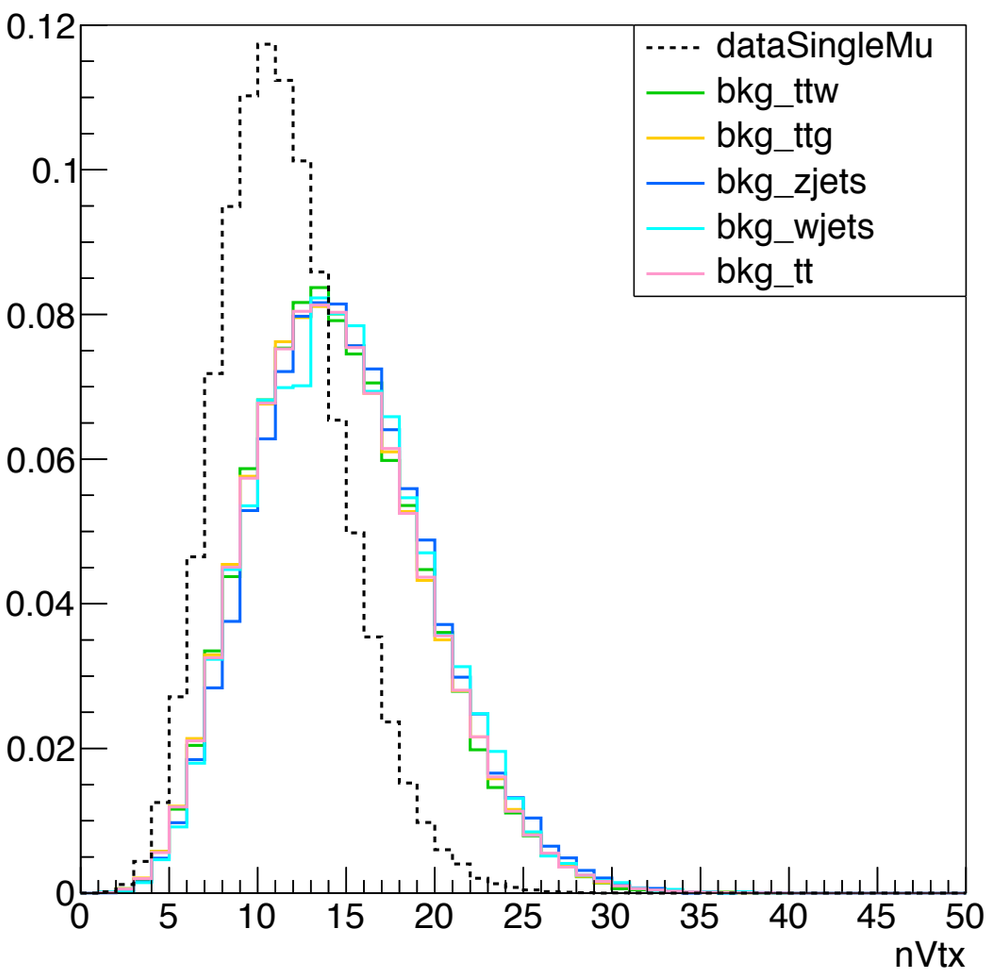
RUN I

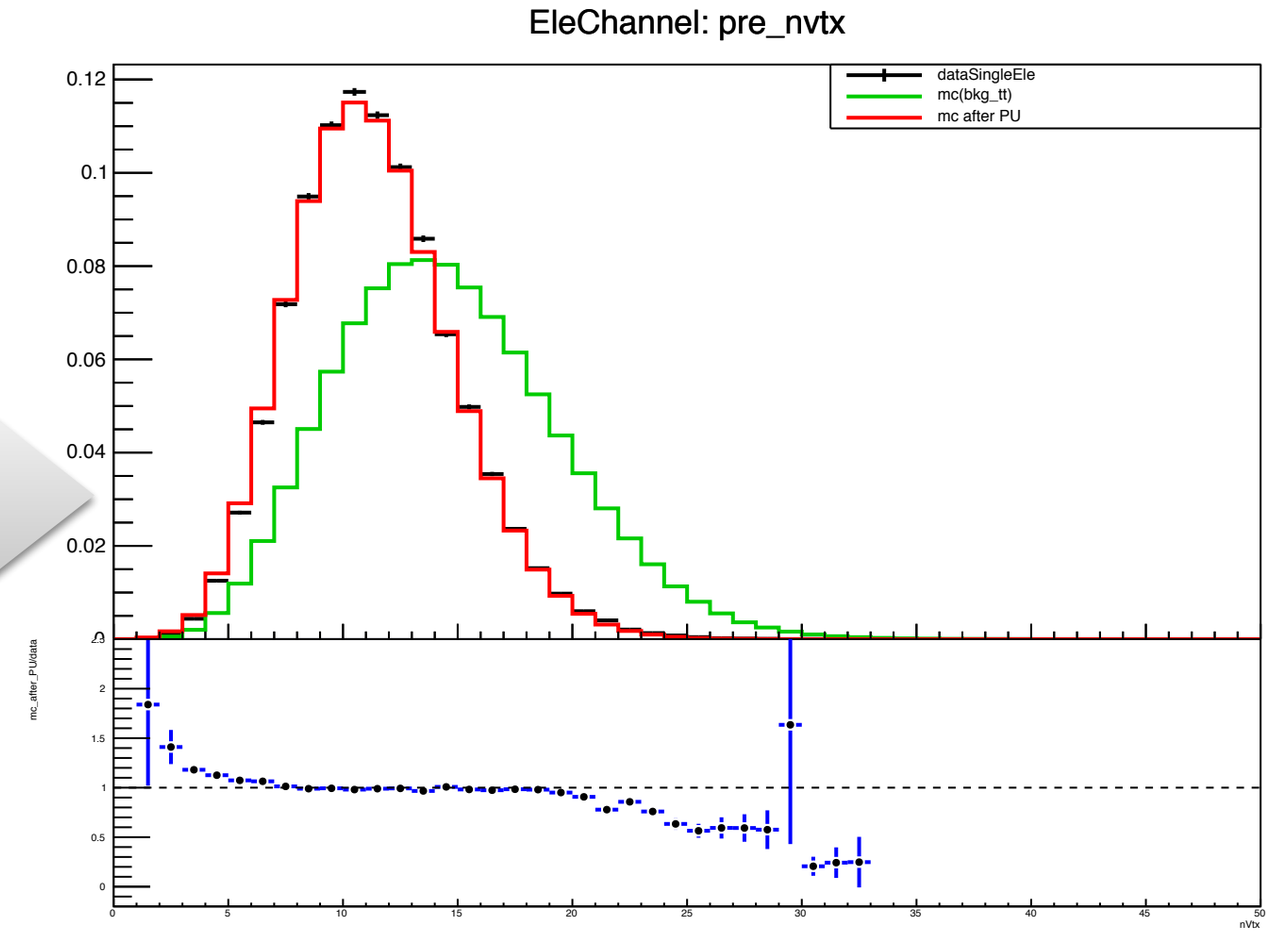

CMS Preliminary 2015 √s = 8 TeV ∫L = 19.7 fb-1
Number of Events / GeV
Data
Stat. ⊕ Syst. Errors
QCD
W + Jets
Single top
tt̄ + V
tt̄ + Jets
Z/γ* + Jets
VV, Vγ
tt̄ + γ
CR1 ele
Data / Background
Stat.
Stat. ⊕ Syst.
E̸T (GeV)


CMS Preliminary 2015 √s = 8 TeV ∫L = 19.7 fb-1
Number of Events / GeV
Data
Stat. ⊕ Syst. Errors
QCD
W + Jets
Single top
tt̄ + V
tt̄ + Jets
Z/γ* + Jets
VV, Vγ
tt̄ + γ
CR1 muon
Data / Background
Stat.
Stat. ⊕ Syst.
E̸T (GeV)

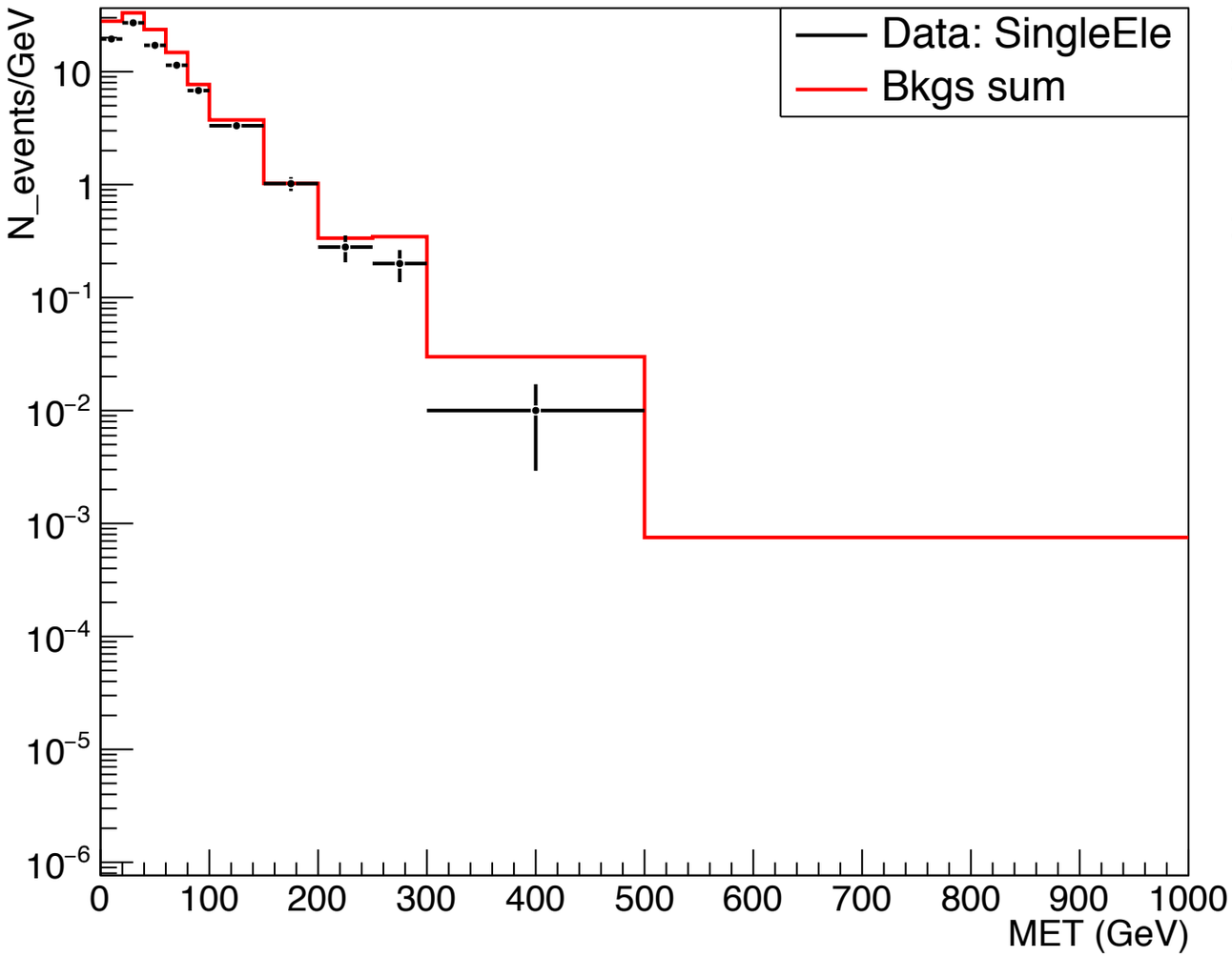
Pileup reweighting

- Due to the very high instantaneous luminosity, the interactions that occur in each bunch crossing can be up to ~20
- Monte Carlo samples simulate the pileup based on expected data pileup, however, might not well describe the “real” pileup, so need to reweight the MC to get close to data.





EleChannel SR1:MET



MuChannel SR1:MET