Looking for SUSY

35 pb^{-1} recorded in 2010

Artist’s view

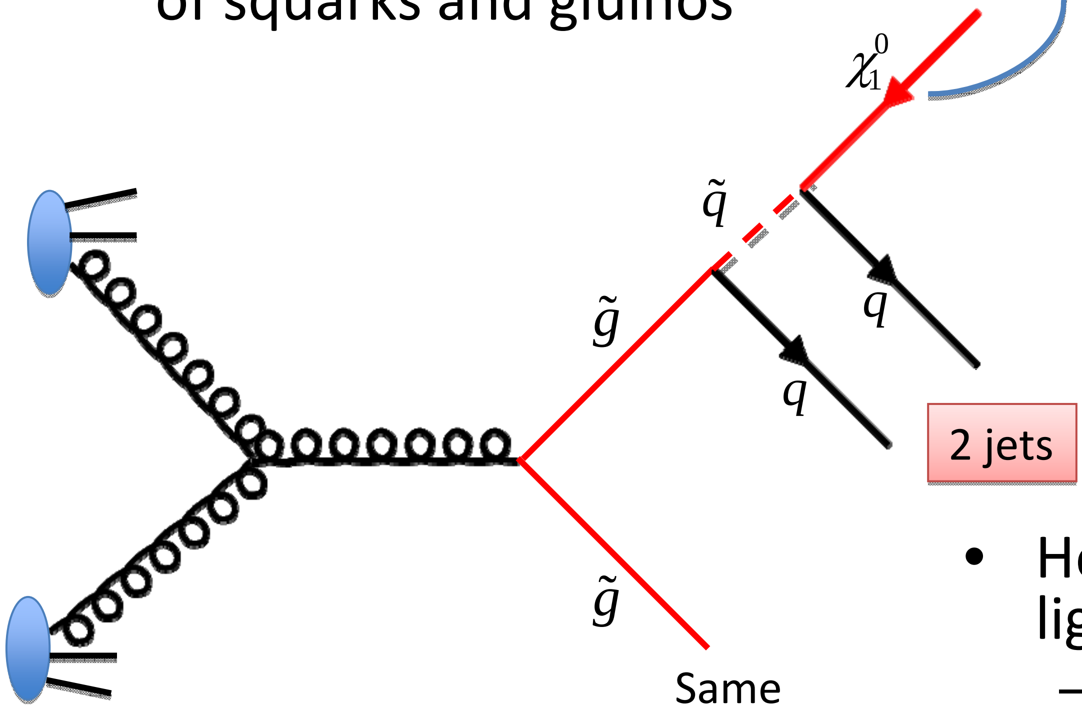
Colin Bernet (CERN, CNRS/LLR),
for the CMS collaboration

SUSY searches at hadron colliders

- Strong production of squarks and gluinos

Missing momentum

Weakly interacting only
Cannot decay if:
- it is the lightest SUSY particle (LSP)
- R-parity conserved
→ Invisible (dark matter candidate)

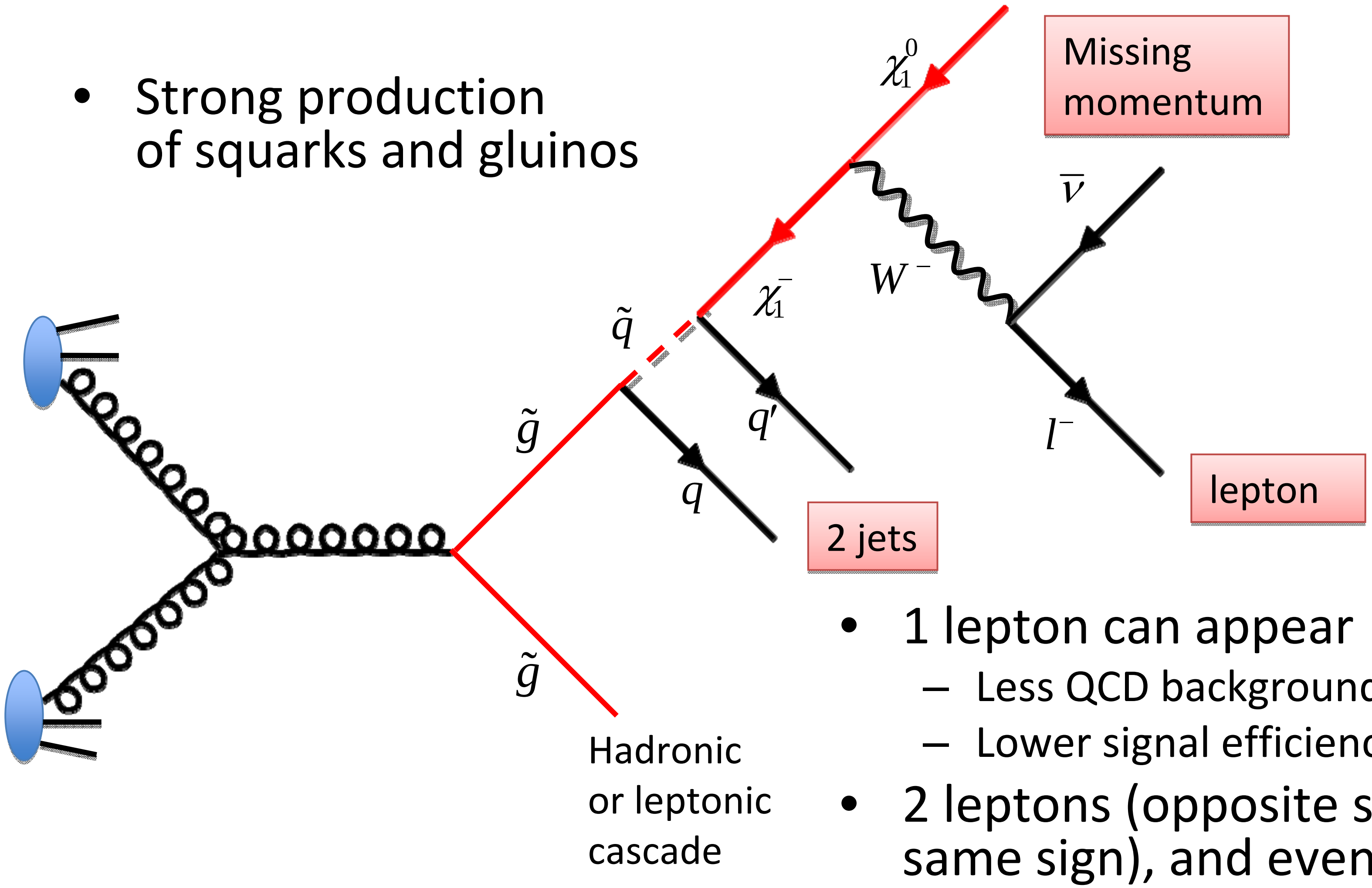


Same
Cascade
here

- Here, direct decay to the lightest neutralino (LSP)
  - Off mass-shell squark
- Fully hadronic final state
  - High QCD background

SUSY searches at hadron colliders

- Strong production of squarks and gluinos



- 1 lepton can appear
  - Less QCD background
  - Lower signal efficiency
- 2 leptons (opposite sign, same sign), and even more
  - Even less background
  - Even lower signal efficiency

The CMS Strategy

- Generic searches addressing most possible final states
- Robust physics objects
  - leptons, jets, missing momentum, τ's…
- Data-driven background prediction for all searches

  punch-line of this talk
- Well established statistical techniques

All Channels covered by CMS

c.f. Aspen

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

c.f. Moriond QCD

Di-leptons

Opposite sign

- e e
- μ μ
- e μ

Same sign

Lepton triggers

- e e
- μ μ
- e μ

HT triggers

- e e
- μ μ
- e μ
- e τ
- μ τ
- τ τ

Multileptons

Z

lepton + photon

Single lepton

ABCD

- e
- μ

Lepton spectrum

- e
- μ

R / MR (Razor)

- e
- μ

(di-)photons

Fully hadronic

αT

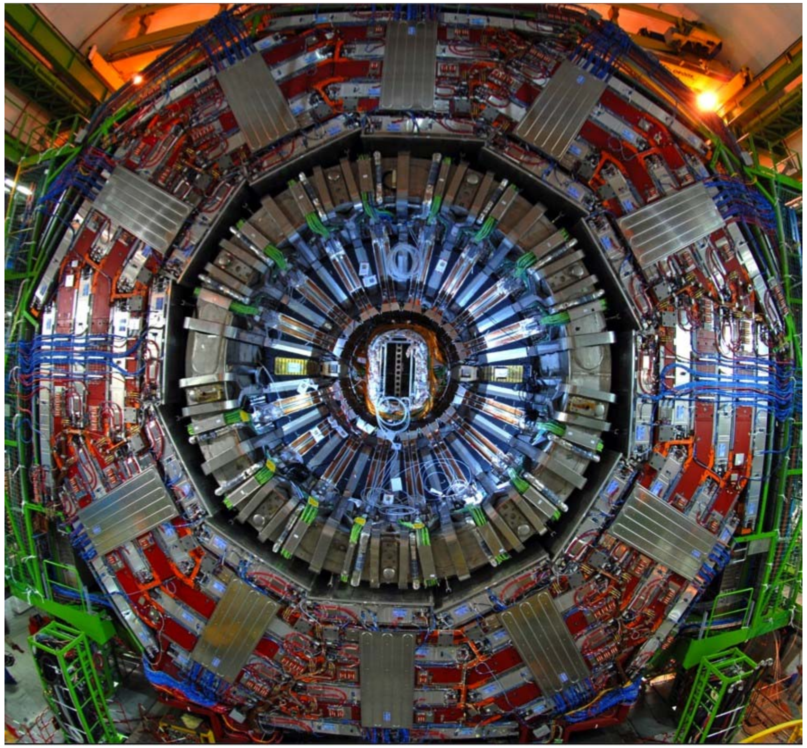
- incl.
- b

Jets + MET

- incl.
- b

R / MR (Razor)

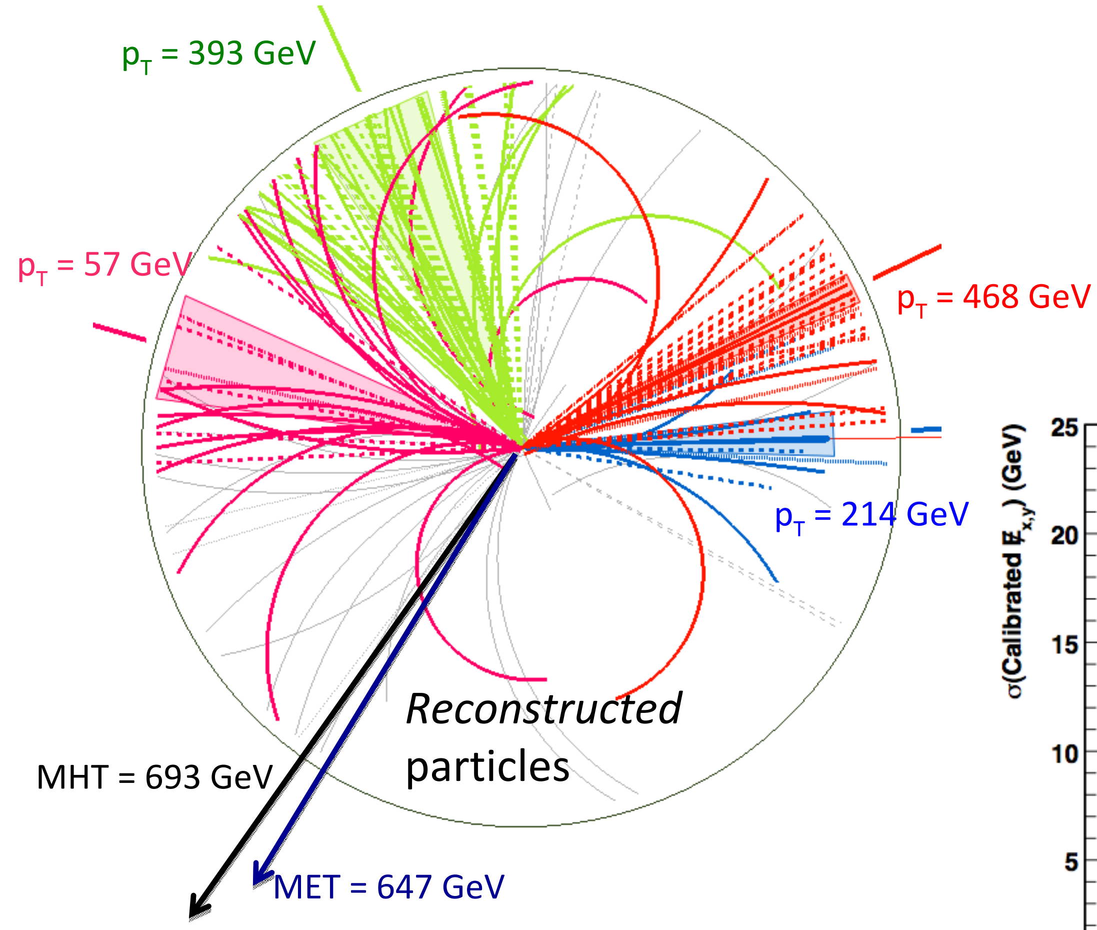
Outline



- **Object reconstruction**
- Multilepton searches
- 2-lepton searches
  - same sign + jets + "MET"
- 1-lepton search
  - e or mu + jets + "MET"
- 0-lepton search
  - jets + "MHT"
- Inclusive search
  - (e or mu) + jets, R & MR
- Limits / Interpretation

Physics objects definition

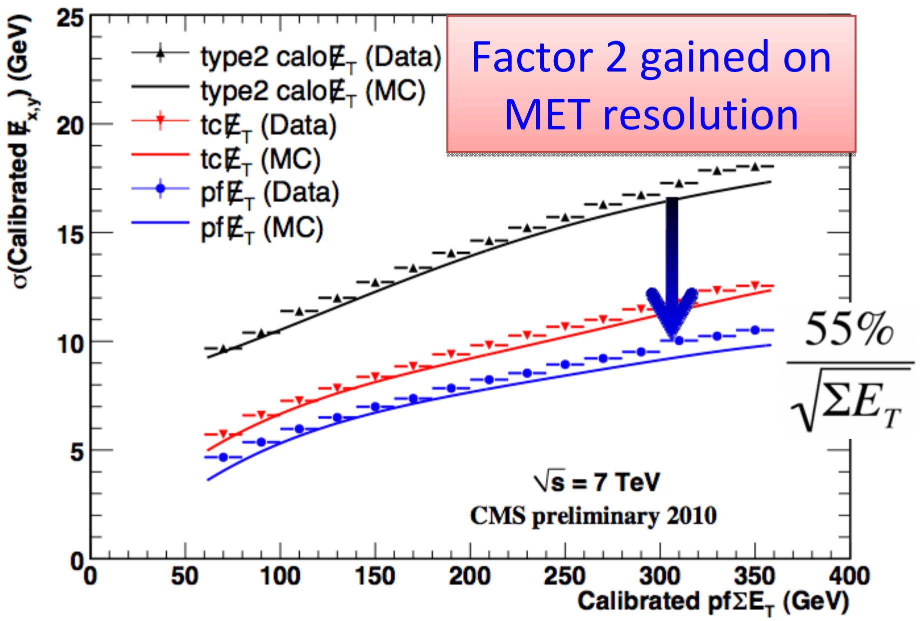
Highest MET multi-jet event
recorded in 2010



$$\vec{E}_T^{miss} = \overrightarrow{MET} = -\sum_{\text{All particles}} \vec{p}_T$$

$$\overrightarrow{MHT} = -\sum_{\text{Jets}} \vec{p}_T$$

$$HT = \sum_{\text{Jets}} p_T$$



Outline

- Object reconstruction
- Multilepton searches + jets, MET
- 2-lepton search
  - same sign + jets + “MET”
- 1-lepton search
  - e or mu + jets + “MET”
- 0-lepton search
  - jets + “MHT”
- Inclusive search
  - (e or mu) + jets, R & MR
- Limits / Interpretation

Multi-Leptons: e, μ, τ

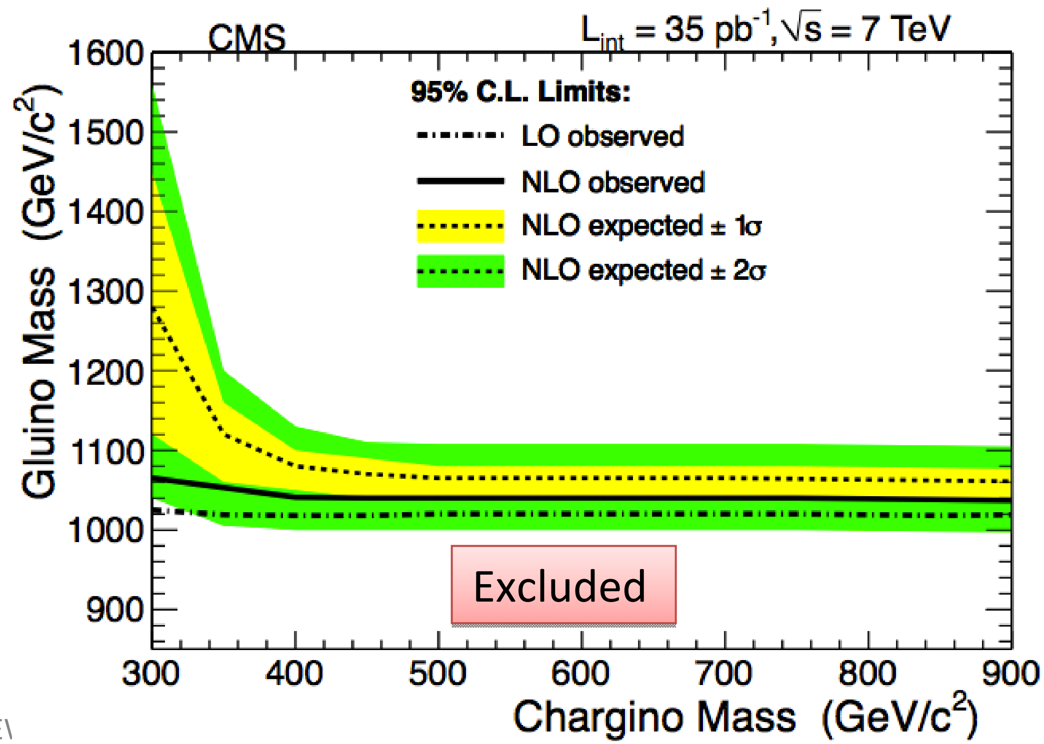
- Baseline selection:
  - 3+ isolated leptons, pT > 8 GeV/c
  - 2 search regions:
    - MET > 50 GeV OR
    - HT > 200 GeV
  - 55 independent channels

Background prediction and results table in back-up

GMSM: LSP = gravitino
If NLSP = sleptons:

$$2 \times (\chi^0 \rightarrow \tilde{l}^+ \tilde{l}^- \rightarrow g g l l)$$

Copious source of 4 lepton events

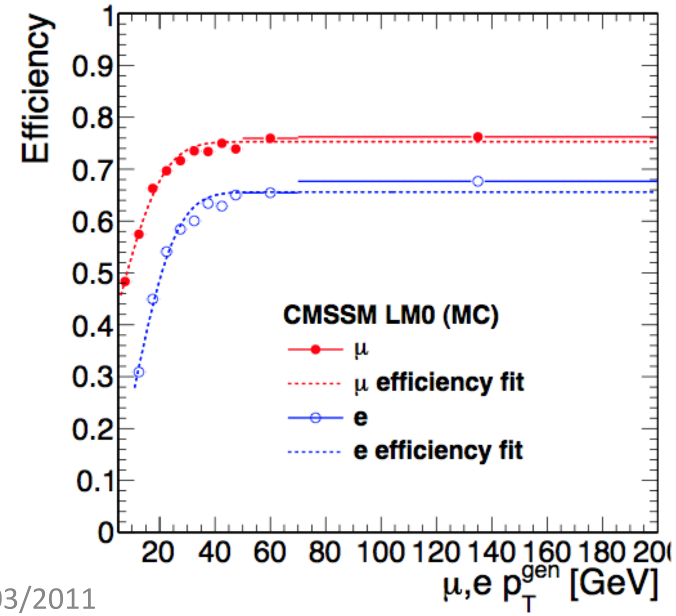


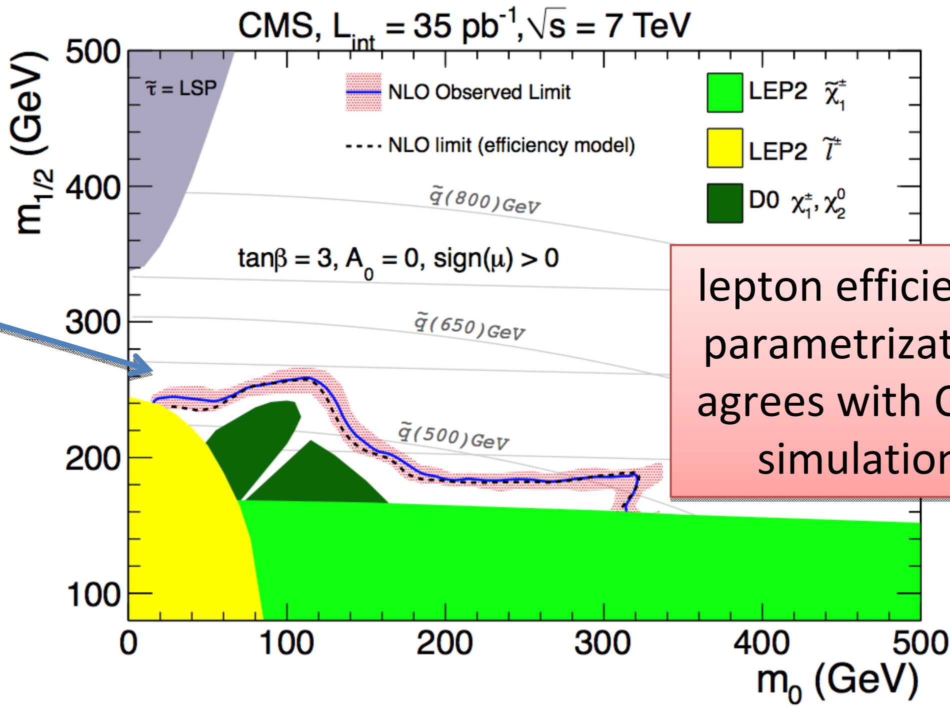
2 Leptons, same sign

data-driven method in back-up

- Baseline selection:
  - 2 same sign, isolated leptons (e or μ)
    - $p_{T,1}>20$, $p_{T,2} > 10$ GeV
  - ≥ 2 jets:
    - $p_T > 30$ GeV, $|\eta|<2.5$
  - MET:
    - > 30 GeV (ee and μμ)
    - > 20 GeV (eμ)
- Main backgrounds:
  - ttbar (lepton from b)

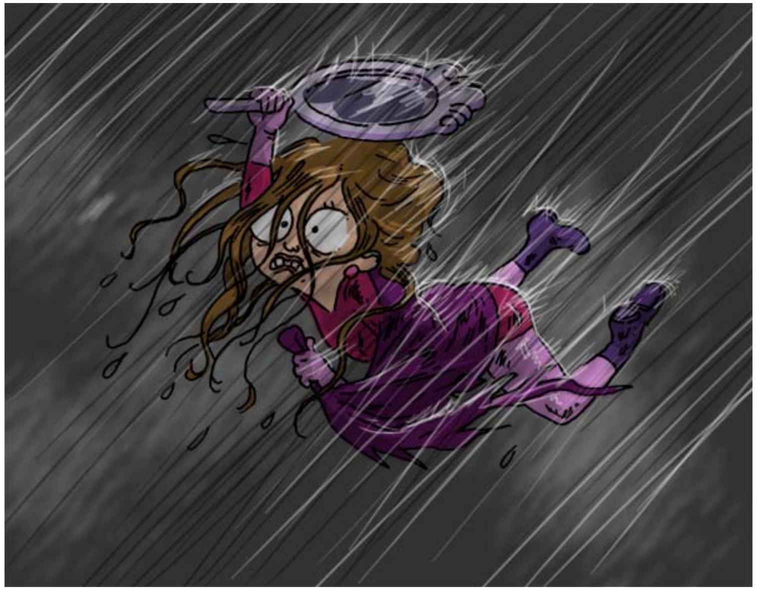
	expected	Observed
MET>80 GeV	1.2 ± 0.8	0
HT>200 GeV	0.97 ± 0.74	1





lepton efficiency parametrization agrees with CMS simulation

Outline



- For each analysis:
  - Selection & main background
  - A nice idea in some details
  - Number of events expected and observed.

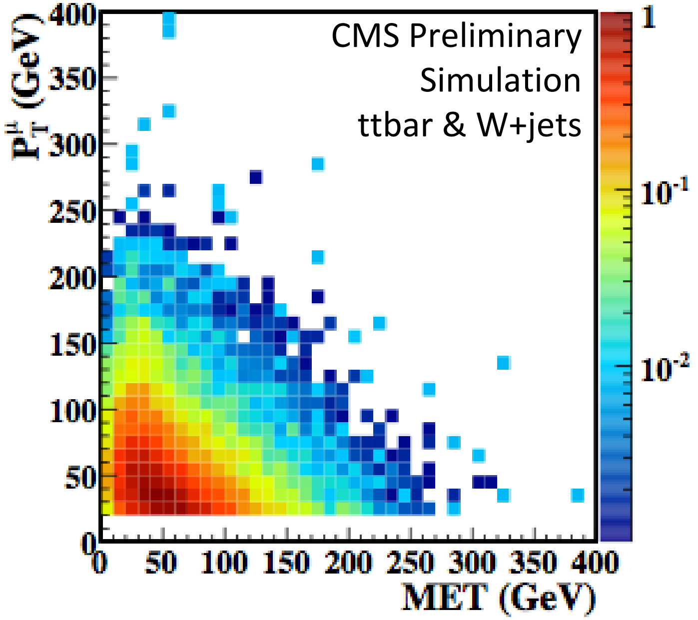
- Object reconstruction
- Multilepton searches
- 2-lepton searches
  - same sign + jets + "MET"
- 1-lepton search
  - e or mu + jets + "MET"
- 0-lepton search
  - jets + "MHT"
- Inclusive search
  - (e or mu) + jets, R & MR
- Limits / Interpretation

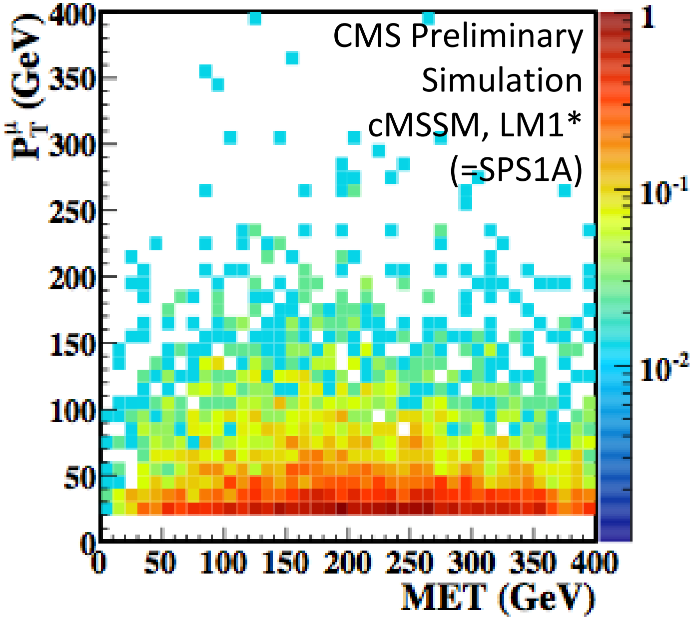
1 lepton

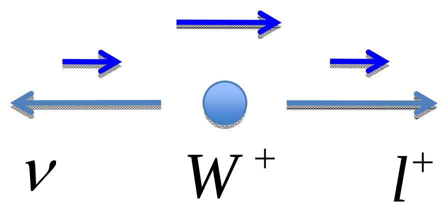
Analysis principles – the lepton spectrum method

- Baseline selection:
  - Isolated lepton:
    - pT > 20 GeV
  - 4 jets:
    - pT > 30 GeV, |η|<2.4

- Main backgrounds
  - ttbar, W+jets .
  - Use the muon pT spectrum to predict the MET spectrum
    - MET resolution and W polarization accounted for.





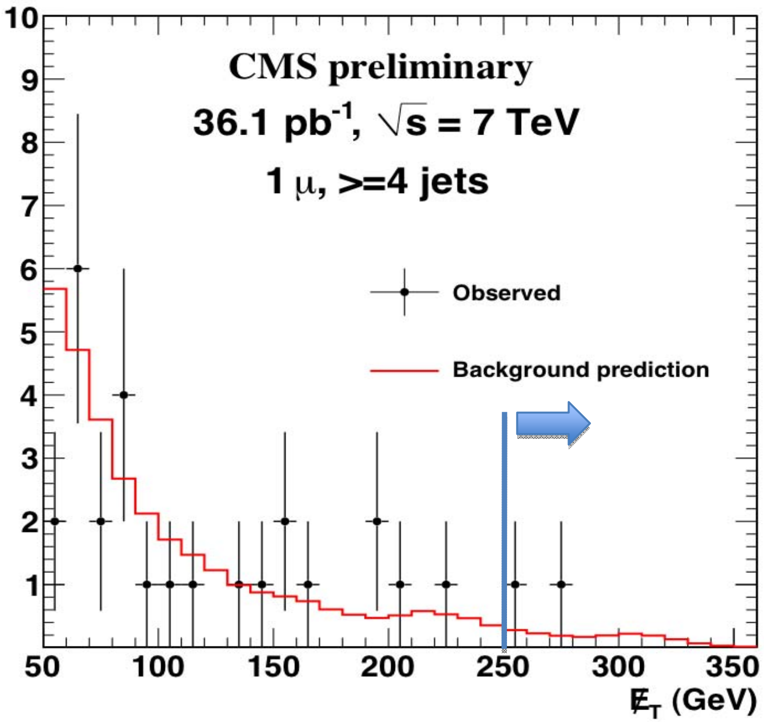


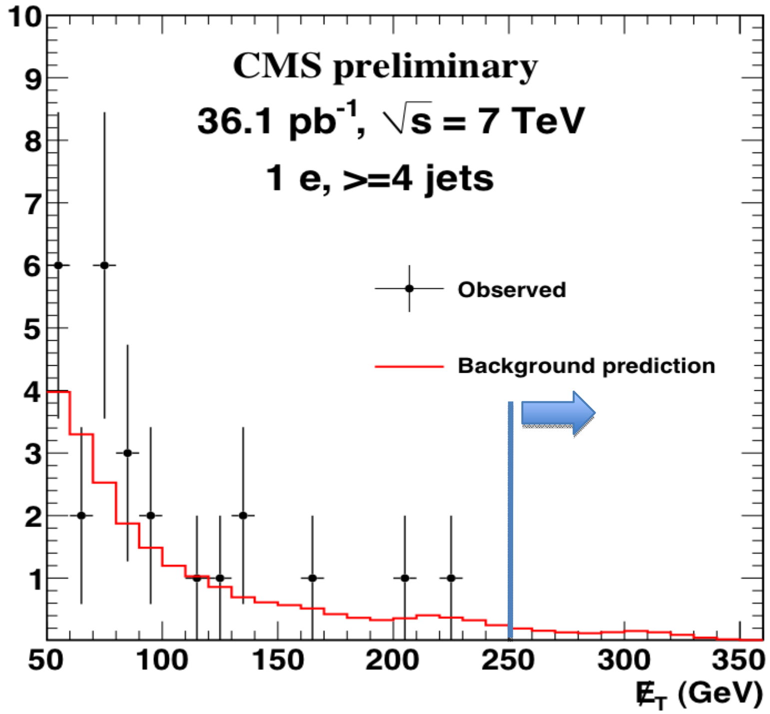
Very low signal contamination

*cMSSM: $m_0 = 60\,\text{GeV}$, $m_{1/2} = 250\,\text{GeV}$, $A_0 = 0$, $\tan\beta = 10$ and $\text{sign}(\mu) > 0$

1 lepton

Results





	expected	Observed
μ	2.1 ± 1.5	2
e	1.5 ± 1.2	0

Observation compatible with background prediction

Outline

- For each analysis:
  - Selection & main background
  - A nice idea in some details
  - Number of events expected and observed.

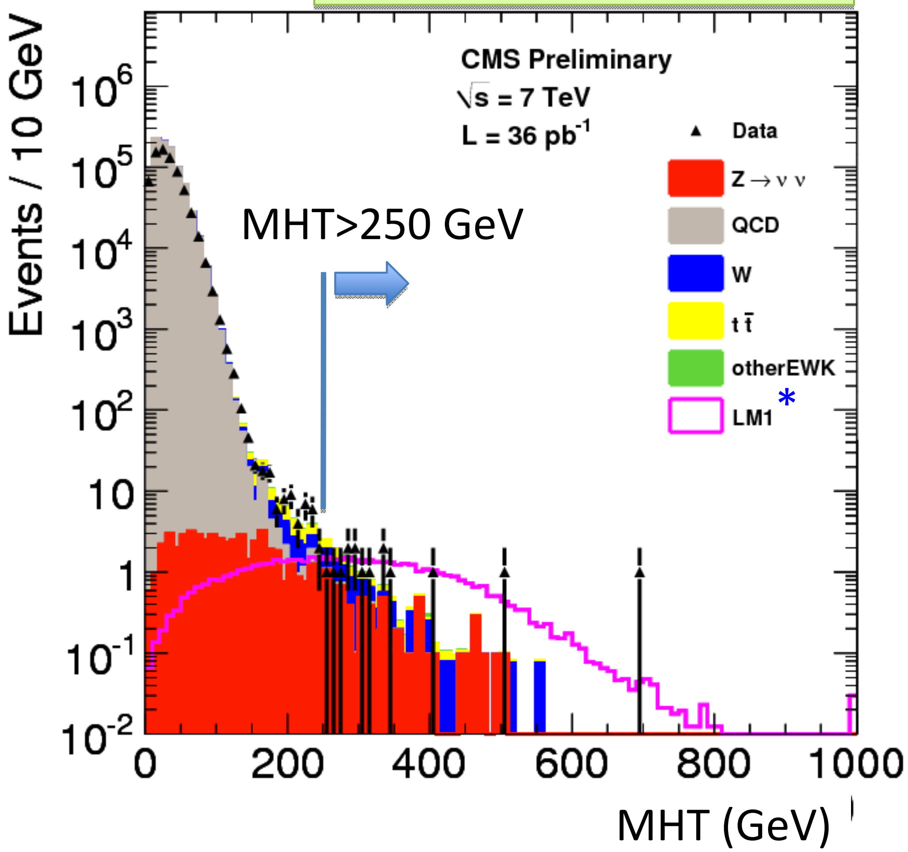
- Object reconstruction
- Multilepton searches
- 2-lepton searches
  - same sign + jets + "MET"
- 1-lepton search
  - e or mu + jets + "MET"
- 0-lepton search
  - jets + "MHT"
- Inclusive search
  - (e or mu) + jets, R & MR
- Limits / Interpretation

0 lepton: Jets + MHT

Principle

Just an illustration. background prediction fully data-driven

- Baseline selection
  - $\geq$ 3 jets
    - $|\eta| < 2.5$
    - $p_T > 50$ GeV
  - $H_T >$ 300 GeV
    - HT trigger fully efficient
  - Veto isolated e or μ
  - $\Delta\varphi(j1,2, MHT) > 0.3$
    - $\Delta\varphi(j3, MHT) > 0.5$
  - Event cleaning



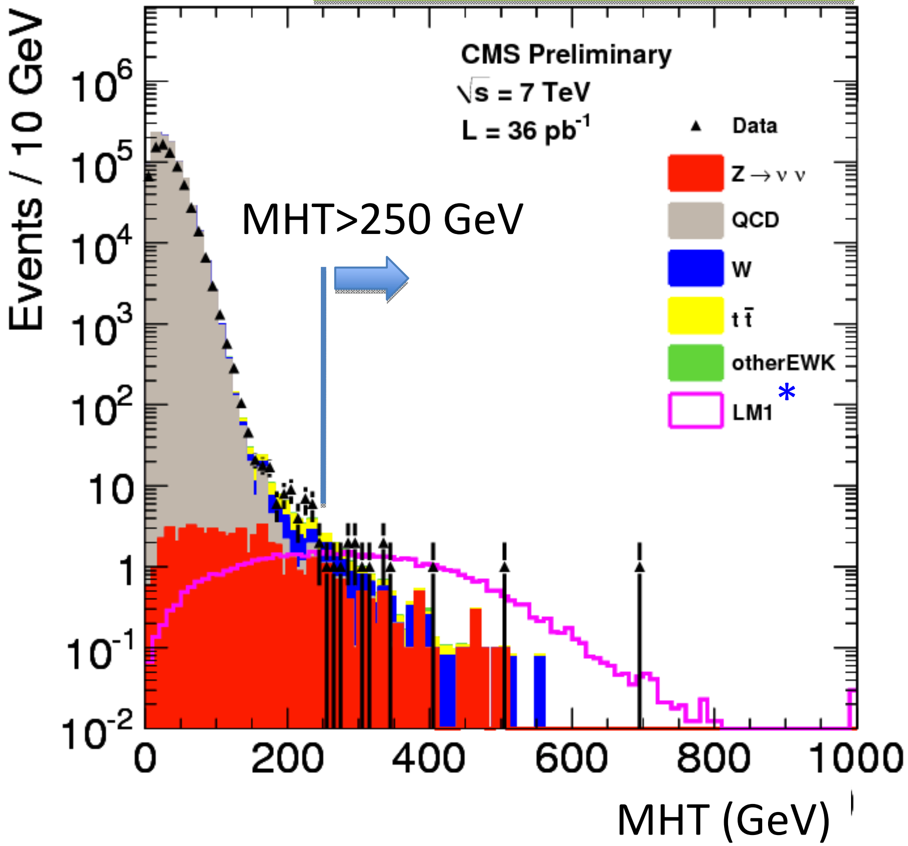
*cMSSM: $m_0 = 60\,\text{GeV}$, $m_{1/2} = 250\,\text{GeV}$, $A_0 = 0$, $\tan\beta = 10$ and $\text{sign}(\mu) > 0$.

0 lepton: Jets + MET

Background & Results

Just an illustration. background prediction fully data-driven

- QCD: next slide
- Z→νν + jets:
  - Z→ll (W→lν + jets):
    - Ignore leptons (correct for W/Z)
    - Small stat, used as x-check
  - γ + jets:
    - Ignore photon, correct for γ/Z
- W + jets (including top):
  μ + jets:
  - Lost leptons:
    - Ignore μ
    - Use e-μ universality
    - lepton ε corrected for, obtained from tag & probe
  - W → τ hadronic decay
    - Replace μ by simulated τ had.

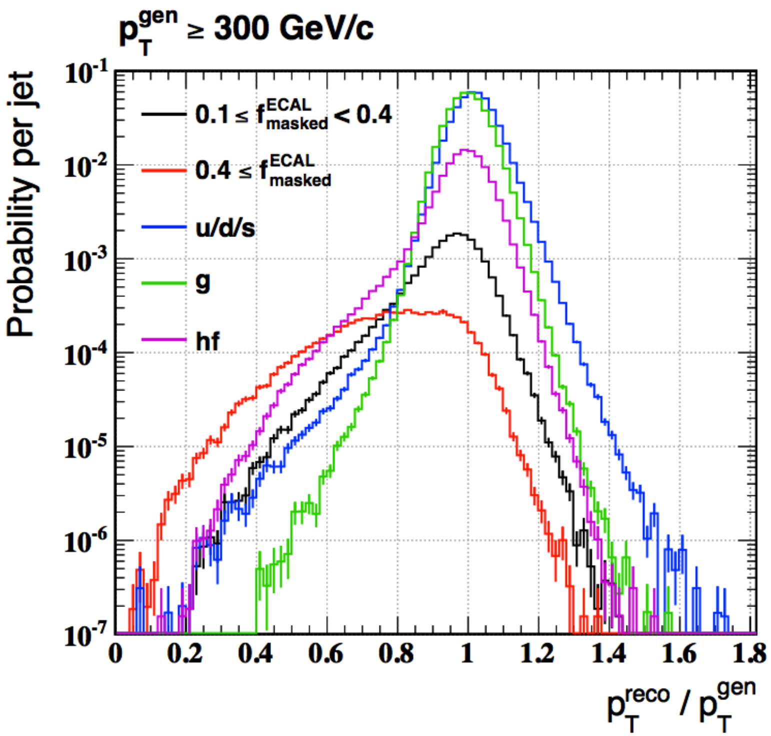


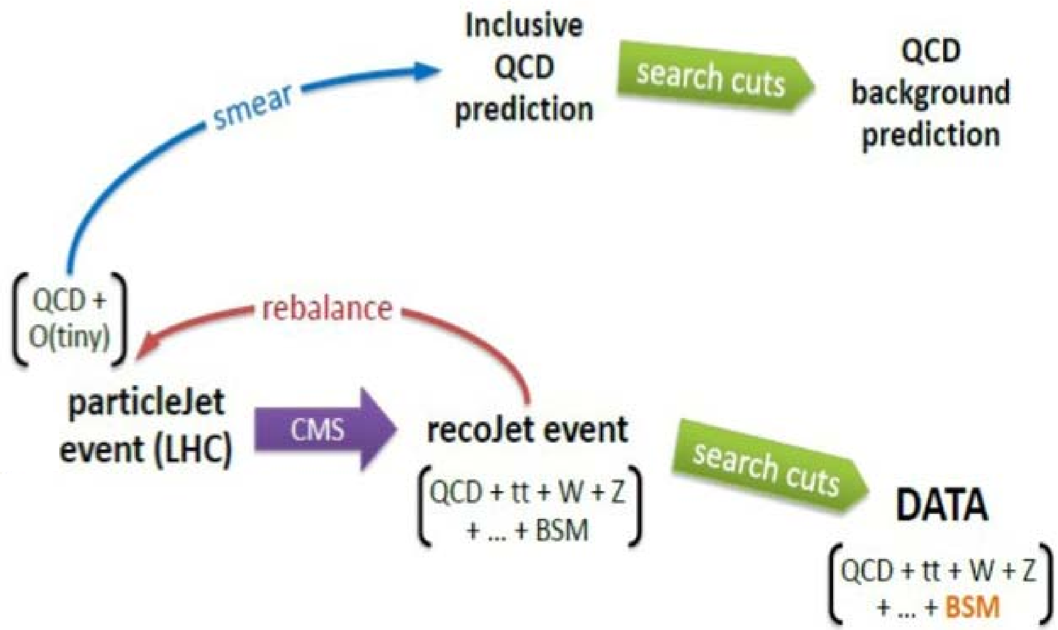
	expected	Observed
MHT>250 GeV	18.8 ± 3.5	15

*cMSSM: $m_0 = 60\,\mathrm{GeV}$, $m_{1/2} = 250\,\mathrm{GeV}$, $A_0 = 0$, $\tan\beta = 10$ and $\mathrm{sign}(\mu) > 0$,

0 lepton: Jets + MHT

Rebalance+smear QCD prediction





- Jet resolution distributions from simulation, and corrected using data:
  - di-jet asymmetry,
  - photon + jet

Closure in the simulation: 20% in the MHT tail

Outline

- For each analysis:
  - Selection & main background
  - A nice idea in some details
  - Number of events expected and observed.

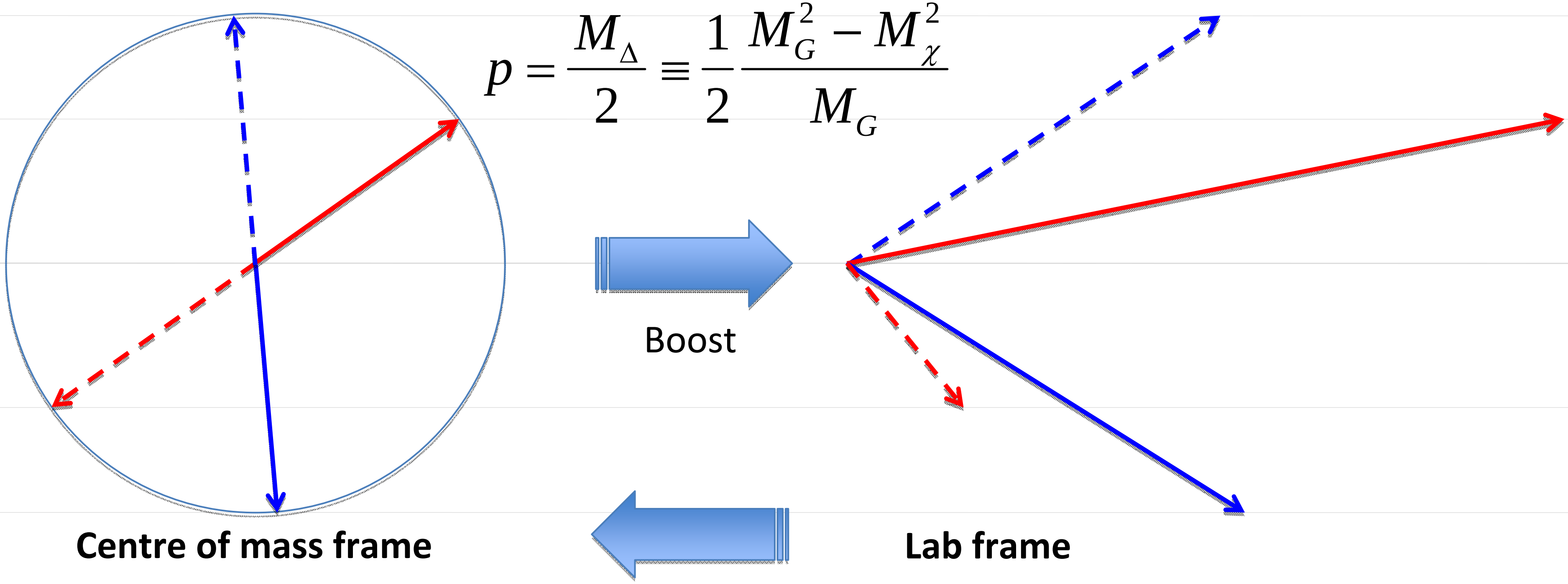
- Object reconstruction
- Multilepton searches
- 2-lepton searches
  - same sign + jets + “MET”
- 1-lepton search
  - e or mu + jets + “MET”
- 0-lepton search
  - jets + “MHT”
- Inclusive search
  - (e or mu) + jets, R & MR
- Limits / Interpretation

http://arxiv.org/abs/1006.2727v1

0 or 1 lepton: R&M_R

M_R definition: Signal

$$p = \frac{M_\Delta}{2} \equiv \frac{1}{2}\frac{M_G^2 - M_\chi^2}{M_G}$$



2 massive particles:
- produced at rest
- decaying to a visible and an invisible part

Boost back to the frame where the momentum of the 2 jets is equal

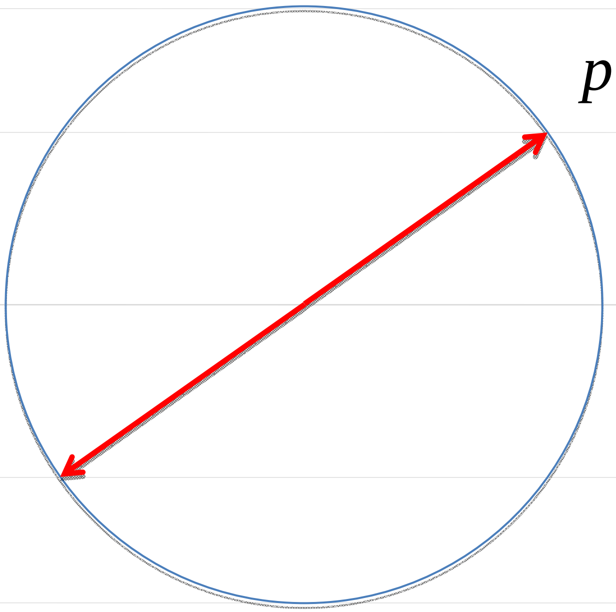
$M_R \equiv 2p$
is peaking

http://arxiv.org/abs/1006.2727v1

0 or 1 lepton: R&M_R

M_R definition: QCD di-jet

$$p = \frac{\sqrt{\hat{s}}}{2}$$



Boost

More than 2 objects?
Build 2 "hemispheres"

Centre of mass frame

two jets, back to back

Boost back to the frame where the momentum of the 2 jets is equal

Lab frame

$$M_R \equiv 2p = \sqrt{\hat{s}}$$

falls as a power law

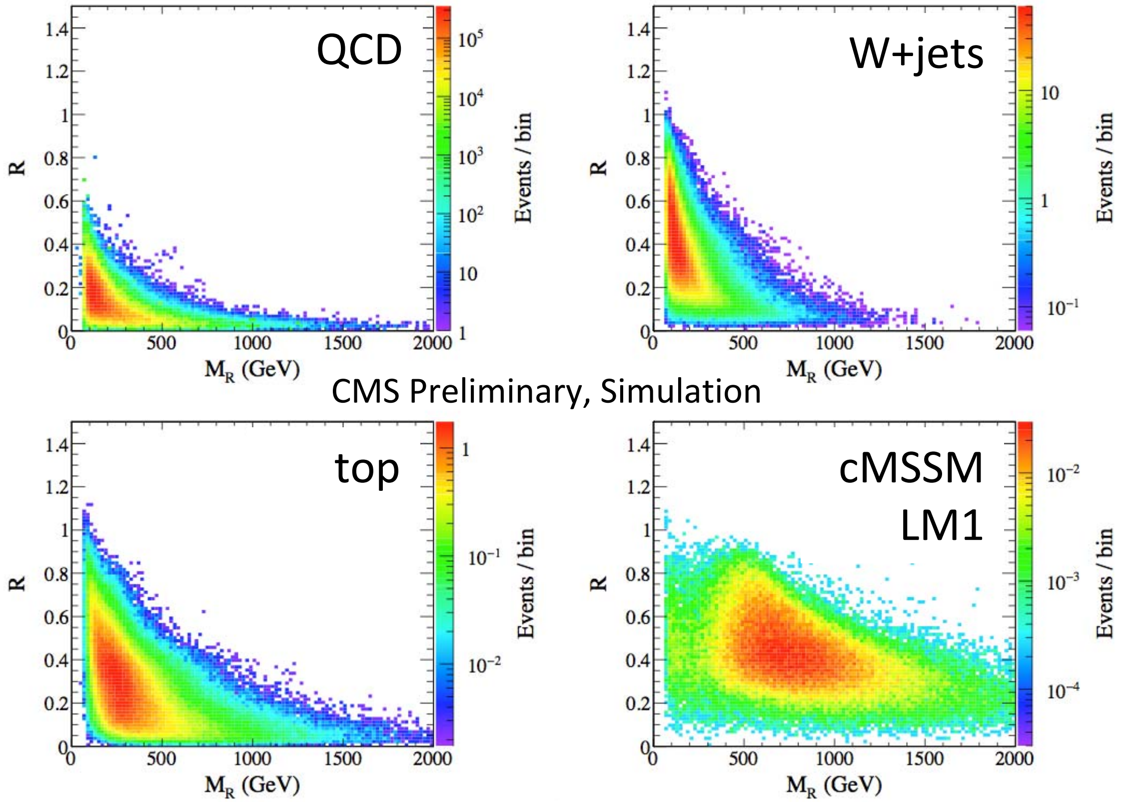
http://arxiv.org/abs/1006.2727v1

0 or 1 lepton: R&M_R

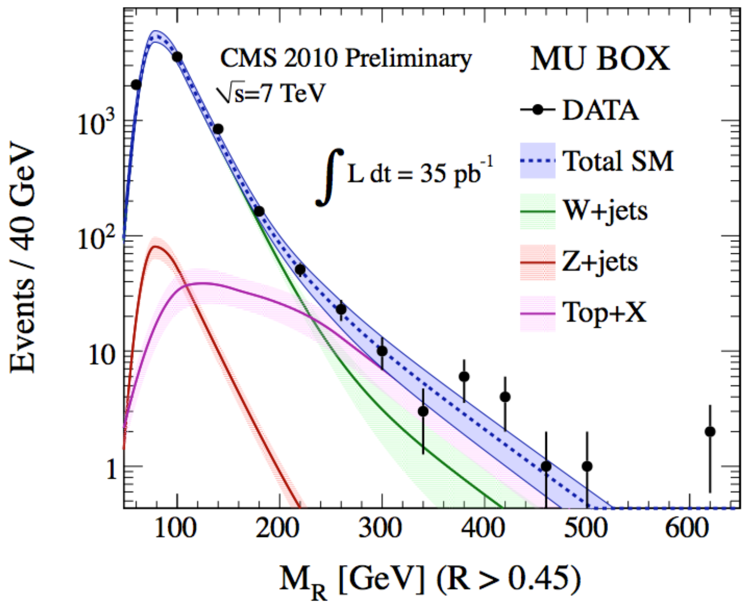
New discriminating variables

R = M_R^T / M_R
Max value: 1

Removes QCD



Background Shapes and normalization extracted from data

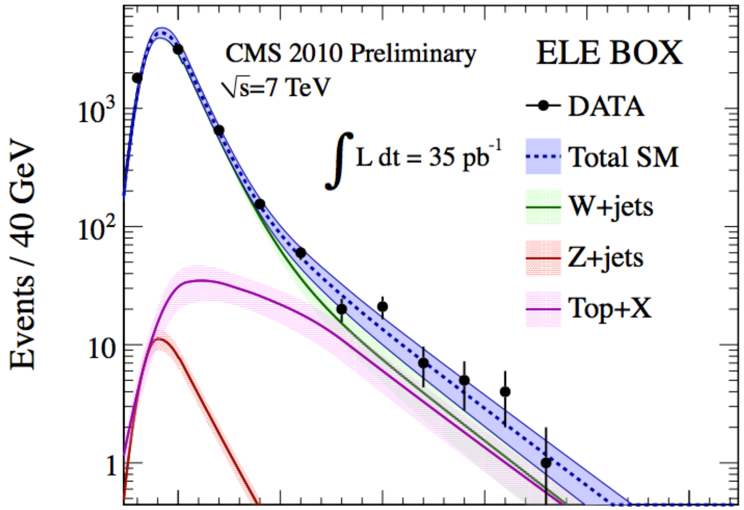


M_R ~ $$M_\Delta \equiv \frac{M_q^2 - M_\chi^2}{M_q}$$

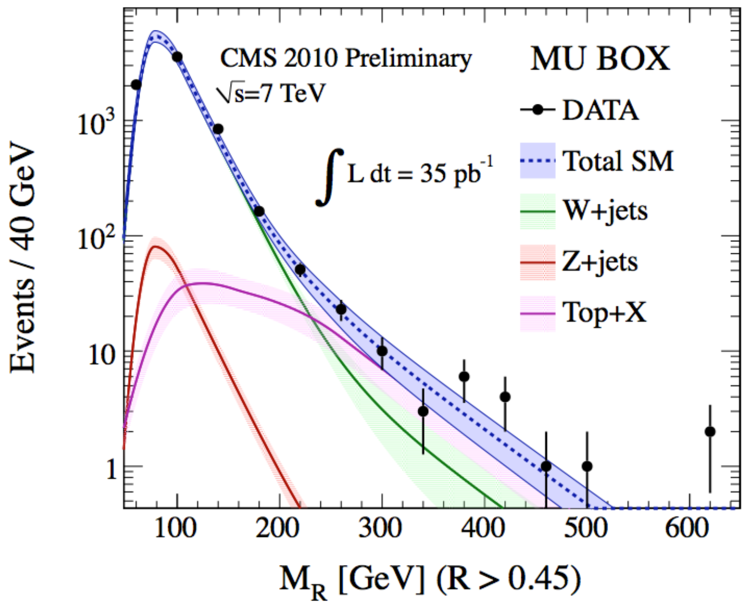
Peaking for signal

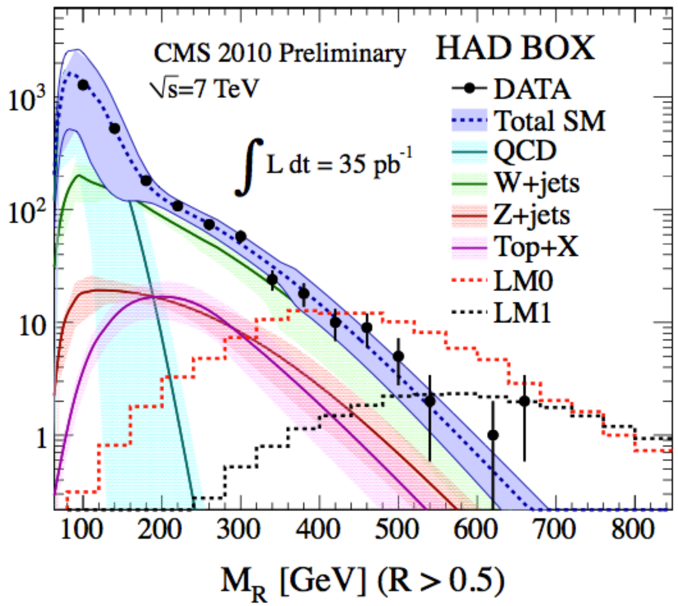
0 or 1 lepton: R&M_R

Results



	R cut	M_R cut	Expected	Observed
MU	0.45	500	0.51 ± 0.20	3
ELE	0.45	500	0.63 ± 0.23	0
HAD	0.5	500	5.5 ± 1.4	7





3 different searches.

Background in HAD box predicted using MU box.

No excess observed.

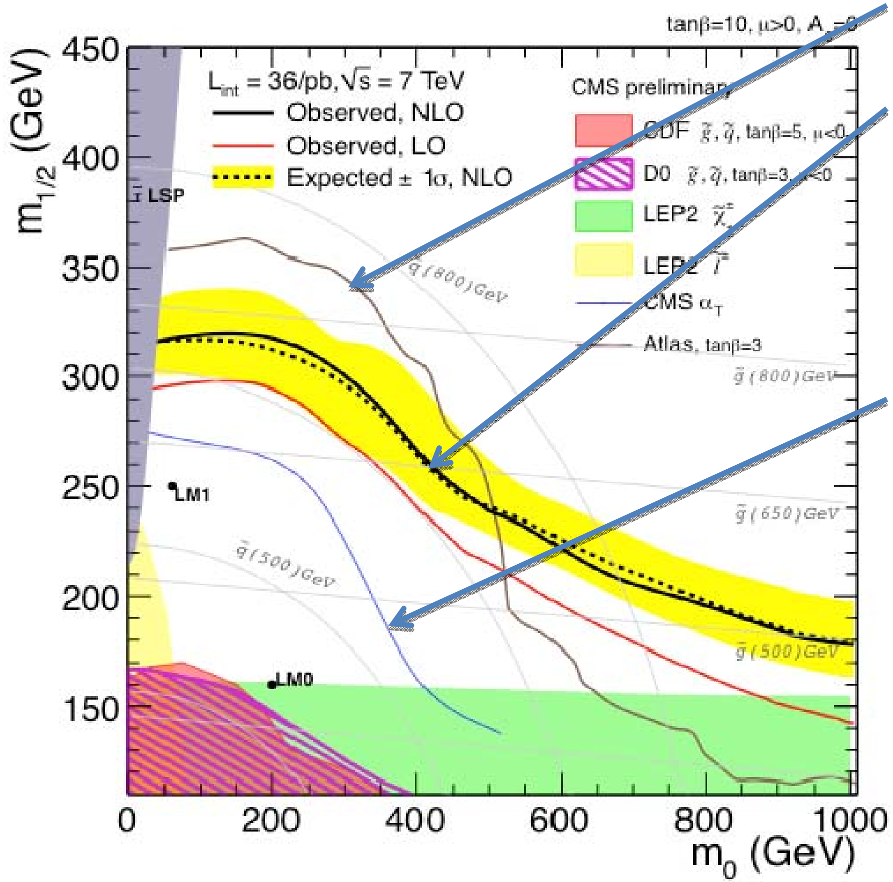
Outline

- For each analysis:
  - Selection & main background
  - A nice idea in some details
  - Number of events expected and observed.

- Object reconstruction
- Multilepton searches
- 2-lepton searches
  - same sign + jets + "MET"
- 1-lepton search
  - e or mu + jets + "MET"
- 0-lepton search
  - jets + "MHT"
- Inclusive search
  - (e or mu) + jets, R & MR
- **Limits / Interpretation**

Limits in the cMSSM

"jets+MHT" fully hadronic analysis

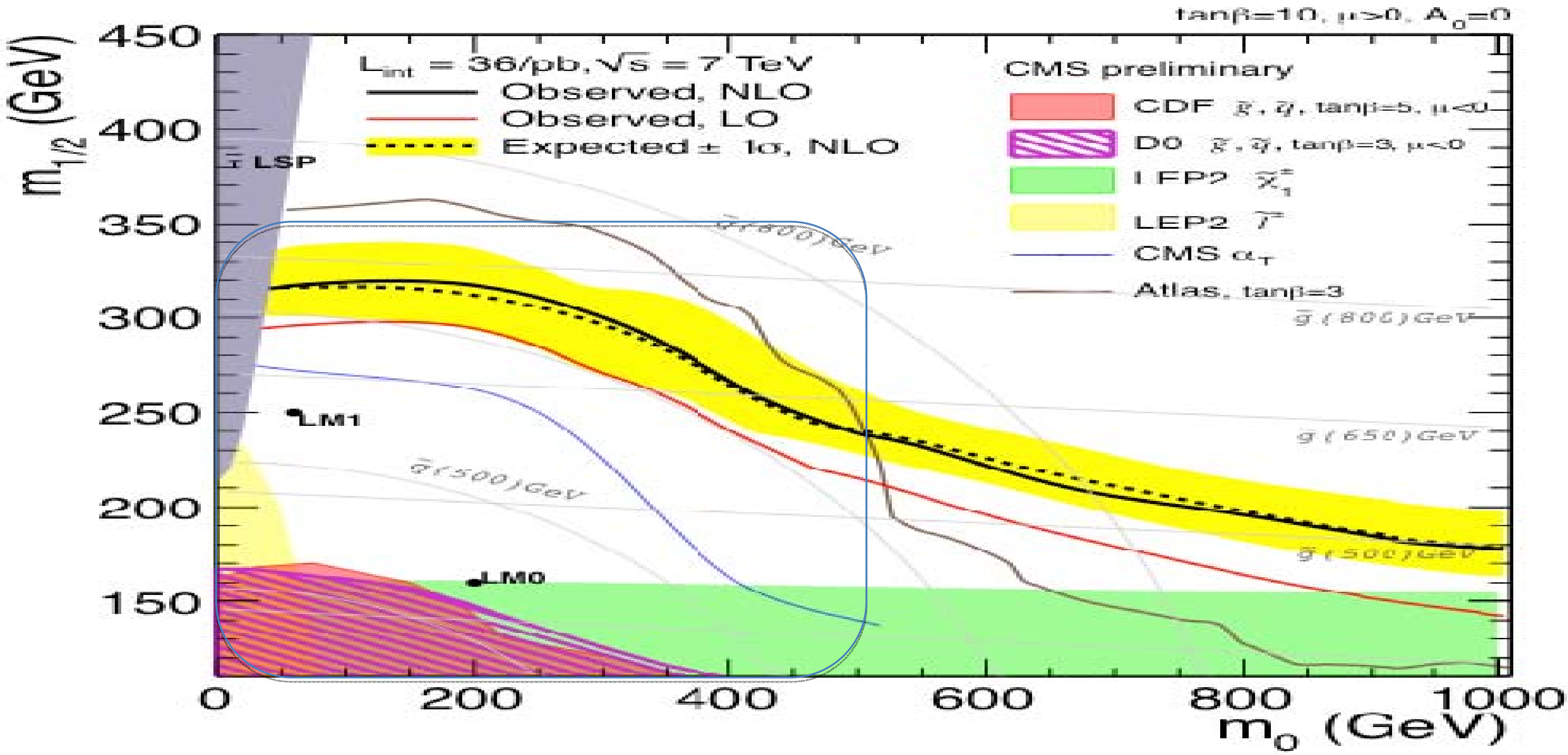


- ATLAS observed limit
- good agreement between expected and observed limit
- α_T analysis:
  - designed for fast discovery (QCD killer)
    - submitted beg. Jan
    - accepted last week

Limits in the cMSSM

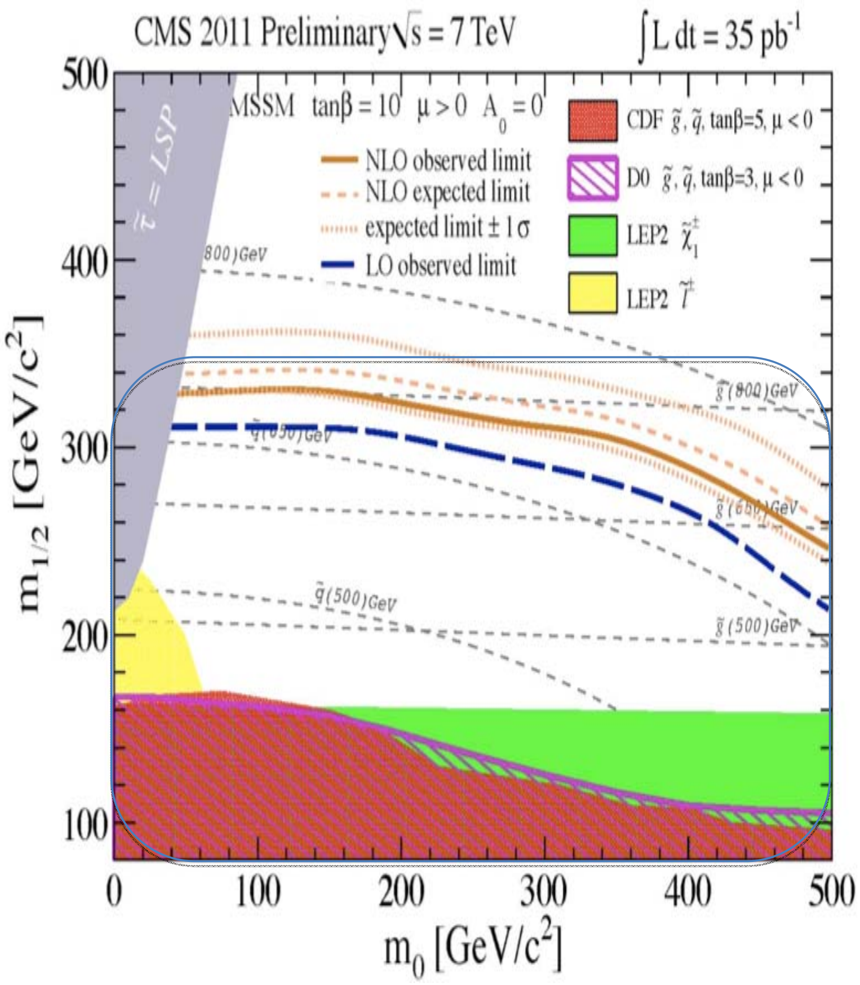
“jets+MHT” fully hadronic analysis

Same plot as in prev. slide. Stretched for easy comparison with the next one



Limits in the CMSSM

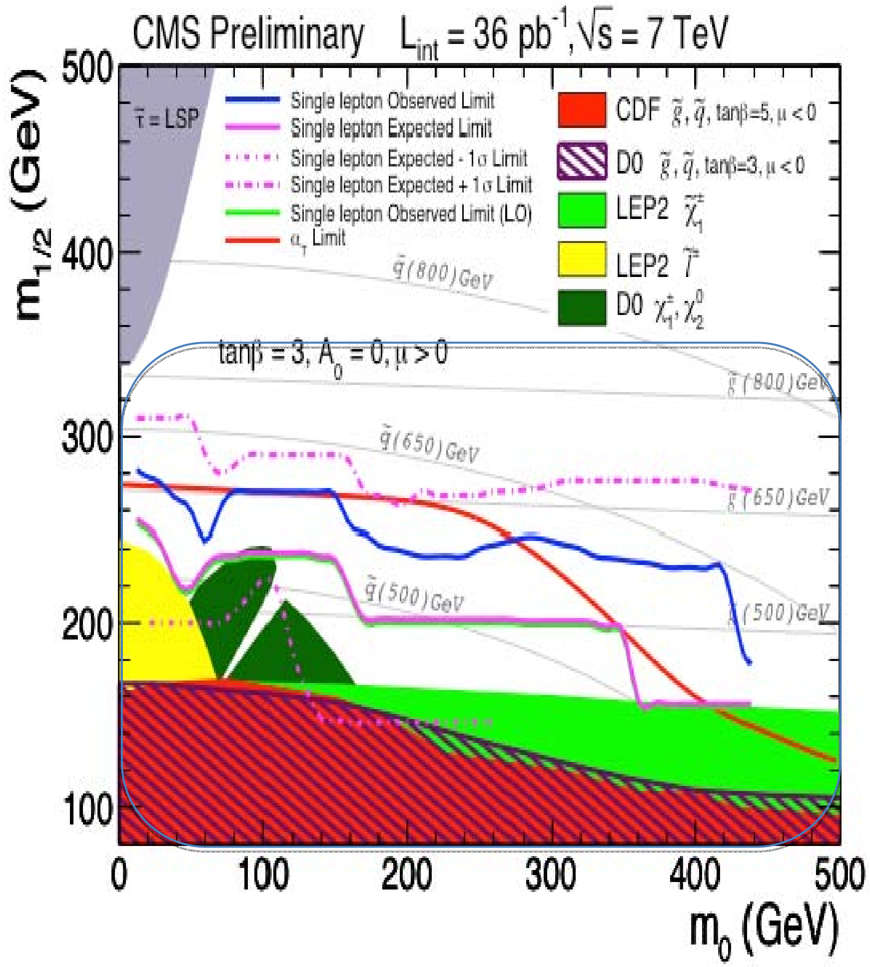
“R&MR” fully hadronic analysis



- Roughly the same limits as for the “jets + MHT” analysis
- Complementary
- Full scan up to m_0 = 1 TeV on the way

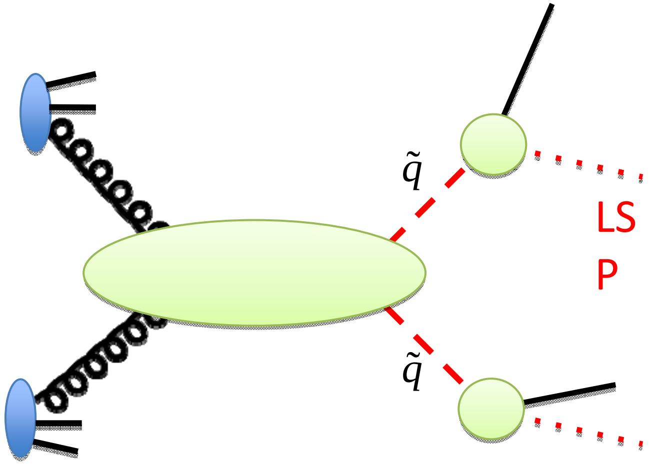
Limits in the CMSSM

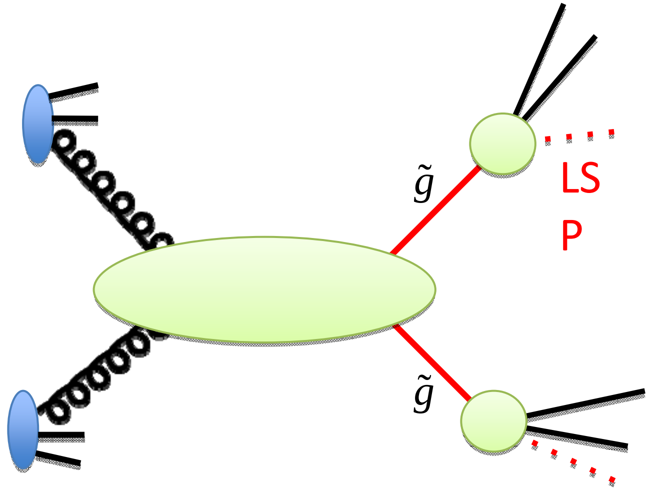
1 lepton + jets

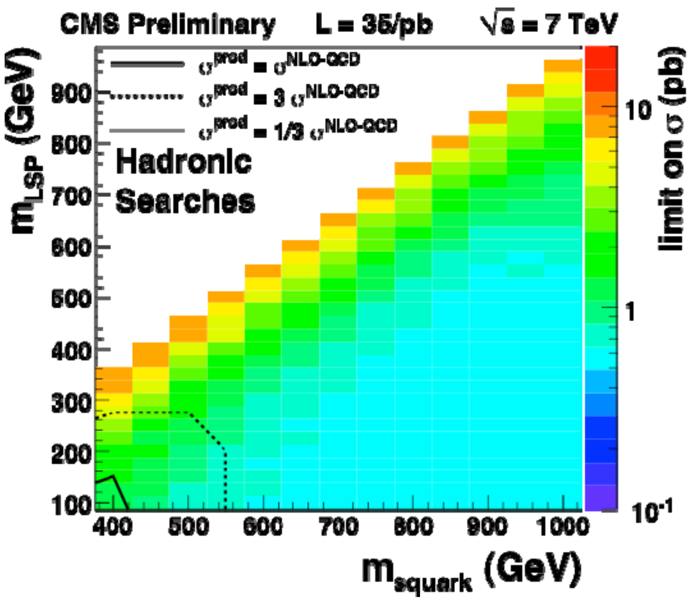


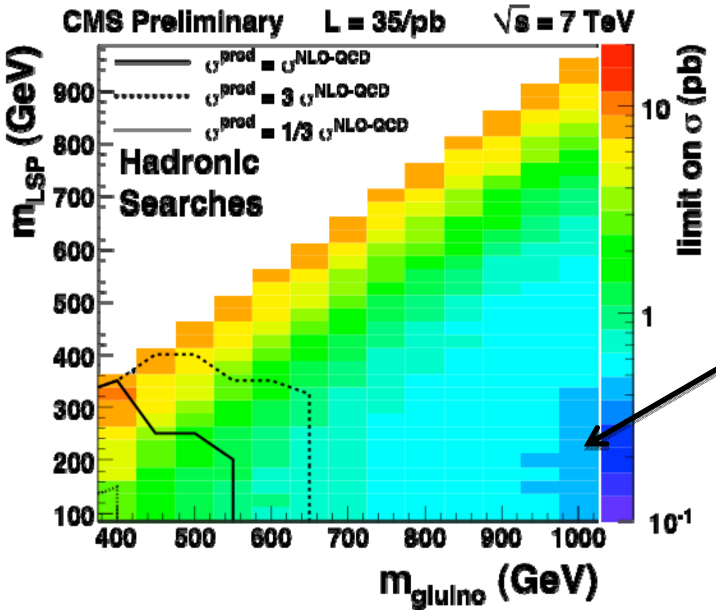
Simplified Models

Focus on the topology, put a limit on cross-section





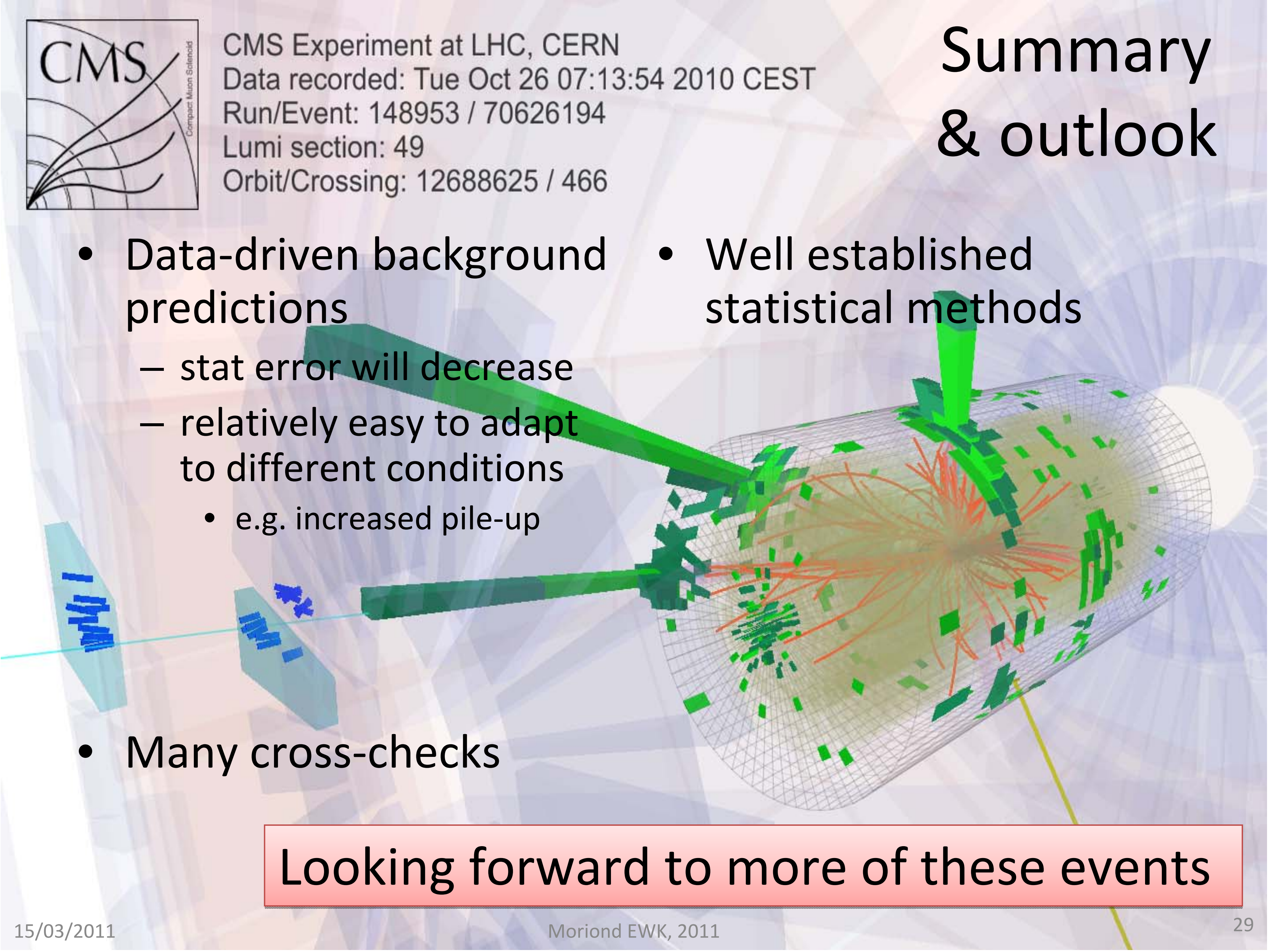




Combined results for:
- αT,
- jets + MHT
- R & MR

example: for this LSP and gluino mass, excluding all models giving $\sigma > 0.5\ pb^{-1}$

Summary & outlook



- Data-driven background predictions
  - stat error will decrease
  - relatively easy to adapt to different conditions
    - e.g. increased pile-up
- Many cross-checks
- Well established statistical methods

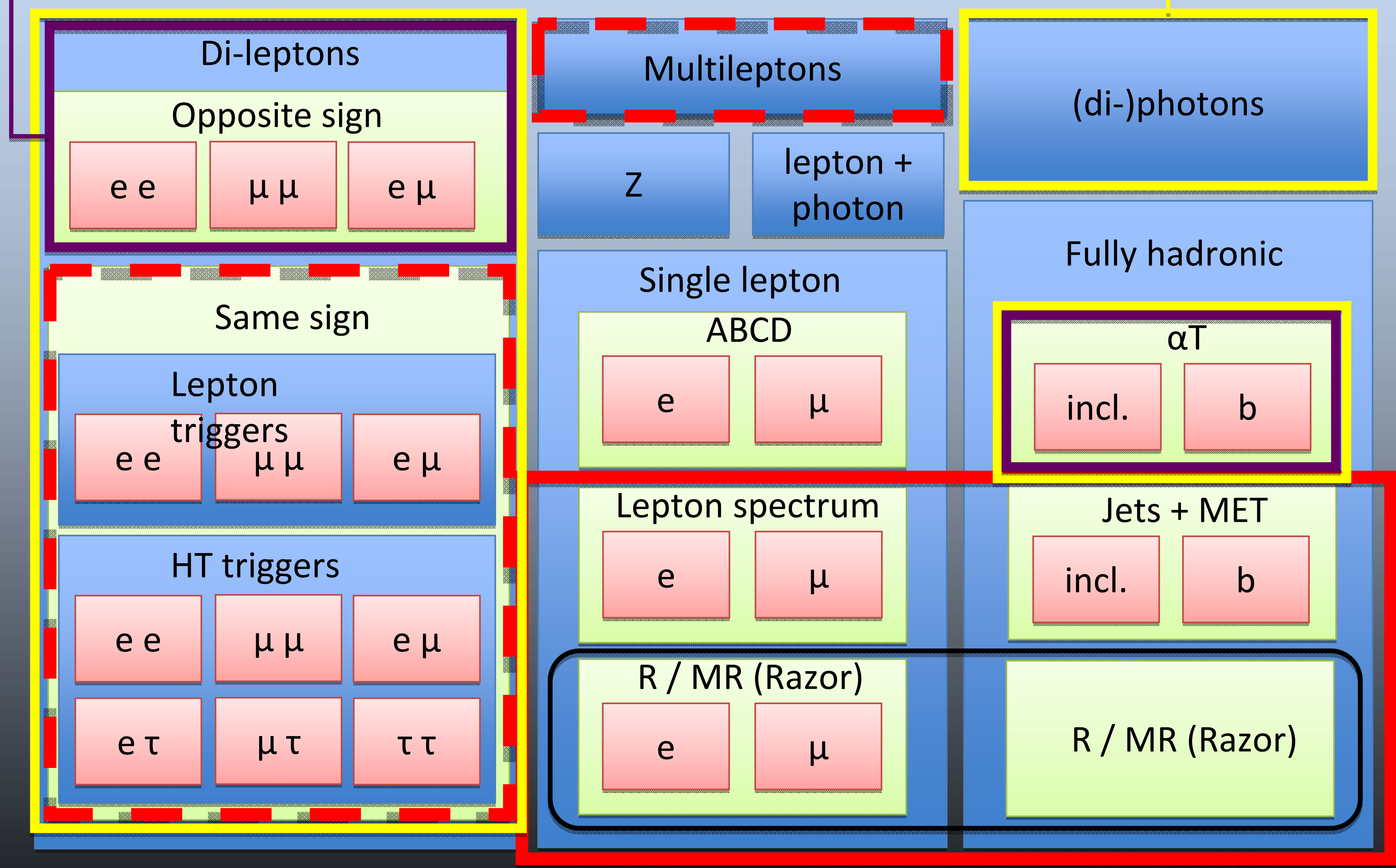
Looking forward to more of these events

All Channels covered by CMS

c.f. Aspen

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

c.f. Moriond QCD



Back-up

Multi-Leptons: e, μ, τ

More details

Background prediction

- Z+jets:
  - Channels without τ
    - fake lepton from a jet
    - dijet events → probability f for an isolated track to fake a lepton
    - Background prediction: $N_{di\text{-}lepton} \cdot f \cdot N_{tracks}$
  - Channels with τ
    - Isolation sideband
- ttbar and VV+jets
  - Small contribution, well controlled in simulation
  - ttbar simulation controlled on OS-OF events in data

Systematic errors

- Shared by all channels
  - luminosity: 11%
  - renormalization scale: 10%
  - pdfs: <14%
  - trigger efficiency: 5%
- Lepton efficiency from tag & probe:
  - muons: 1.5 to 3%
  - electrons: up to 10%
  - tau: up to 30% (stat limited)
- Jet energy scale (HT): < 14%

Multi-Leptons: e, μ, τ

Backgrounds, expected signals, observed events

MET>50 GeV HT>200 GeV

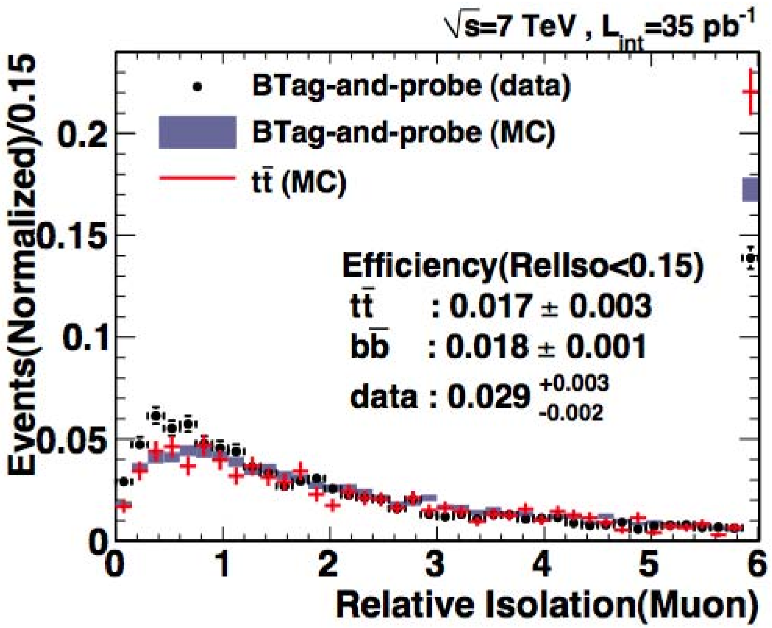
	After Lepton ID Requirement					Inclusive		Hadronic		ML01 Signals	
	Z+jets	$t\bar{t}$	VV+jets	ΣSM	Data	ΣSM	Data	ΣSM	Data	Incl.	Hadr.
Channel	3-lepton channels										
$ll(OS)e$	1.7	0.1	1.2	4.4 ± 1.5	6	0.1 ± 0.1	0	0.2 ± 0.1	1	121.4	141.5
$ll(OS)\mu$	2.83	0.2	1.7	4.7 ± 0.5	6	0.10 ± 0.1	0	0.1 ± 0.1	0	123.6	120.8
$ll(OS)T$	121.5	0.5	0.7	123 ± 16	127	0.4 ± 0.1	0	–	–	80.5	–
$ll(OS)\tau$	476	2.7	3.9	484 ± 77	442	–	–	0.6 ± 0.2	1	–	68
$ll'T$	0.72	0.5	0.2	1.7 ± 0.7	3	0.4 ± 0.2	2	–	–	18.6	–
$ll'\tau$	4.7	2.9	0.6	11.2 ± 2.5	10	–	–	0.4 ± 0.1	1	–	12.3
$ll(SS)l'$	0.13	0.1	0.0	0.2 ± 0.1	0	0.2 ± 0.1	0	0	0	2.8	2.8
$ll(SS)T$	0.25	0.0	0.1	0.7 ± 0.4	3	0.1 ± 0.1	0	–	–	9.0	–
$ll(SS)\tau$	1.4	0.0	0.1	3.0 ± 1.1	3	–	–	0.0 ± 0.1	0	–	6.9
$\Sigma\, lll(T)$	127.1	1.4	3.8	135 ± 16	145	1.3 ± 0.2	2	–	–	355.9	–
$\Sigma\, lll(\tau)$	486.8	6.0	7.5	507 ± 77	467	–	–	1.3 ± 0.3	3	–	349.5
lTT	47.1	0.33	0.1	48 ± 9	30	0.4 ± 0.1	0	–	–	8.0	–
Channel	4-lepton channels										
$llll$	0	0	0.2	0.2 ± 0.1	2	0	0	0	0	163.9	149.2
$lllT$	0	0	0.1	0.1 ± 0.1	0	0	0	–	–	62.3	–
$lll\tau$	0	0	0.1	0.1 ± 0.1	0	–	–	0	0	–	33.2
$llTT$	0	0	0	0.0 ± 0.1	0	0	0	–	–	20.6	–
$ll\tau\tau$	3.1	0.1	0.1	3.2 ± 0.7	5	–	–	0	0	–	16.8
$\Sigma\, llll(T)$	0	0	0.3	0.3 ± 0.1	2	0	0	–	–	246.8	–
$\Sigma\, llll(\tau)$	3.1	0.1	0.4	3.5 ± 0.7	5	–	–	0	0		199.2

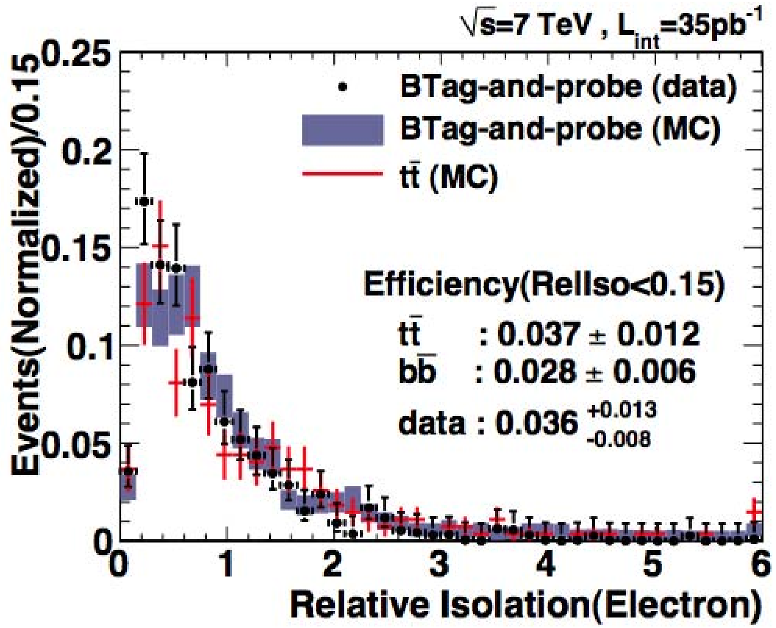
2 Leptons, same sign

data-driven background estimation: single fake lepton

- all cuts applied
- but: one of the leptons not isolated → N events
- prediction: $N \frac{\varepsilon_{iso}}{1-\varepsilon_{iso}}$

- ε_{iso} from "b tag & probe:
  - one b-tagged jet away from the lepton
    - dominated by QCD
  - reweight to the ttbar kinematics





2 Leptons, same sign

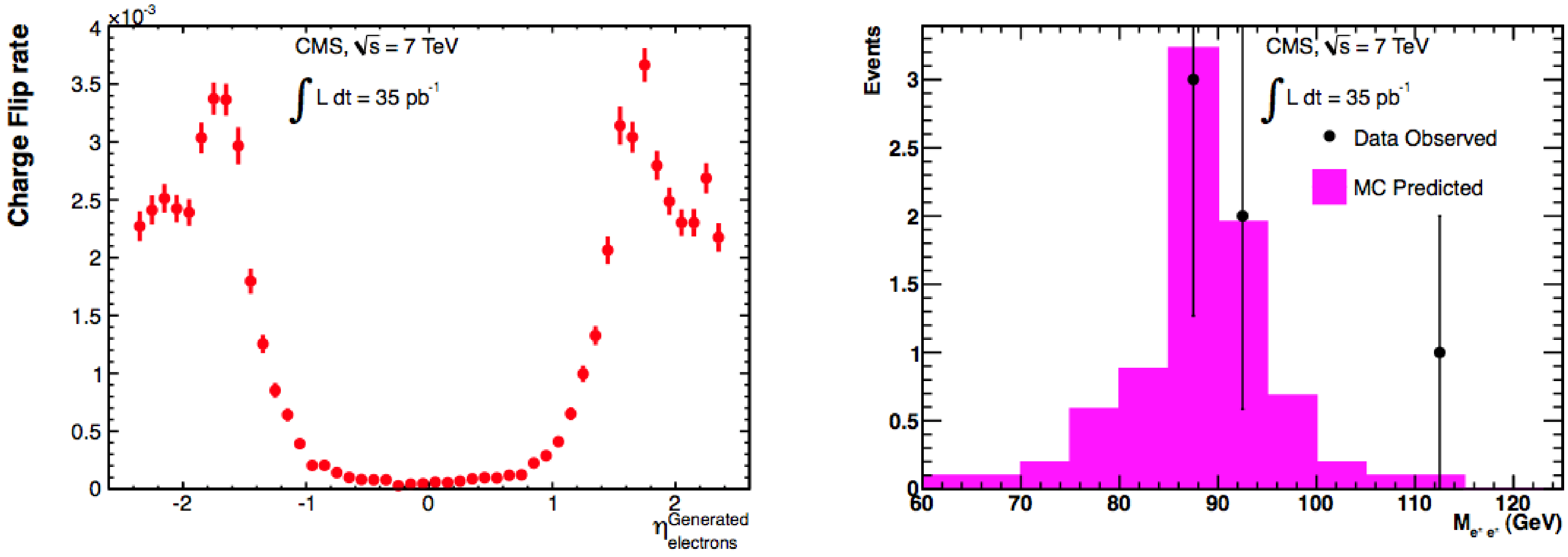


Figure 6: (Left) The probability to mismeasure the electron charge as a function of η in the P_T range 10−100 GeV, as obtained from Monte Carlo simulation. (Right) Same-sign *ee* invariant mass distribution in data compared with $Z \to ee$ Monte Carlo expectations.

2 Leptons, same sign

Results, including tau channels

Table 2: Data and Monte Carlo yields summarized for all analyses.

Search Region	ee	$\mu\mu$	$e\mu$	total	95% C.L. UL Yield
Lepton Trigger					
$\not{E}_T > 80$ GeV					
MC	0.05	0.07	0.23	0.35	(7.3 for LM0)
BG predicted	**0.23 $\pm$ 0.35**	**0.23 $\pm$ 0.26**	**0.74 $\pm$ 0.55**	**1.2 $\pm$ 0.8**	
observed	**0**	**0**	**0**	**0**	**3.1**
$H_T > 200$ GeV					
MC	0.04	0.10	0.17	0.32	(9.6 for LM0)
BG predicted	**0.71 $\pm$ 0.58**	**0.01 $\pm$ 0.24**	**0.25 $\pm$ 0.27**	**0.97 $\pm$ 0.74**	
observed	**0**	**0**	**1**	**1**	**4.4**
H_T Trigger					
Low-p_T					
MC	0.05	0.16	0.21	0.41	(9.1 for LM0)
BG predicted	**0.10 $\pm$ 0.07**	**0.30 $\pm$ 0.13**	**0.40 $\pm$ 0.18**	**0.80 $\pm$ 0.31**	
observed	**1**	**0**	**0**	**1**	**4.5**
	$e\tau$	$\mu\tau$	$\tau\tau$	total	95% C.L. UL Yield
τ enriched					
MC	0.36	0.47	0.08	0.91	(2.0 for LM0)
BG predicted	**0.10 $\pm$ 0.10**	**0.17 $\pm$ 0.14**	**0.02 $\pm$ 0.01**	**0.29 $\pm$ 0.17**	
observed	**0**	**0**	**0**	**0**	**3.4**

Additional cuts for HT trigger:

HT>300 GeV
MET>30 GeV

HT>350 GeV
MET>50 GeV

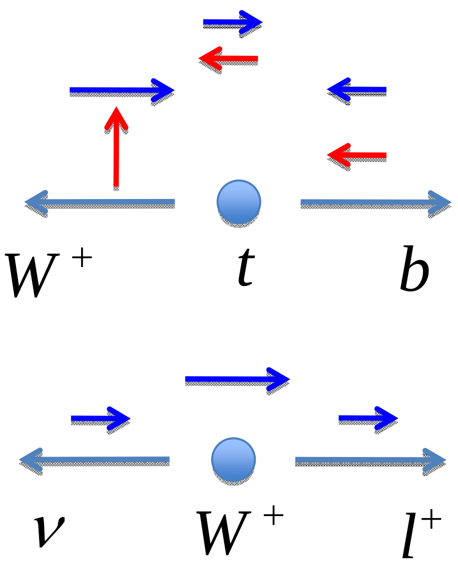
The HT trigger allows to reach low pT leptons and taus

1 lepton search

More on the lepton spectrum method

- W polarization very well known for ttbar [1]
- Not the case for W+jets
  - – polarized pdf uncertainty
- No need to correct for W polarization to get MC closure in this analysis

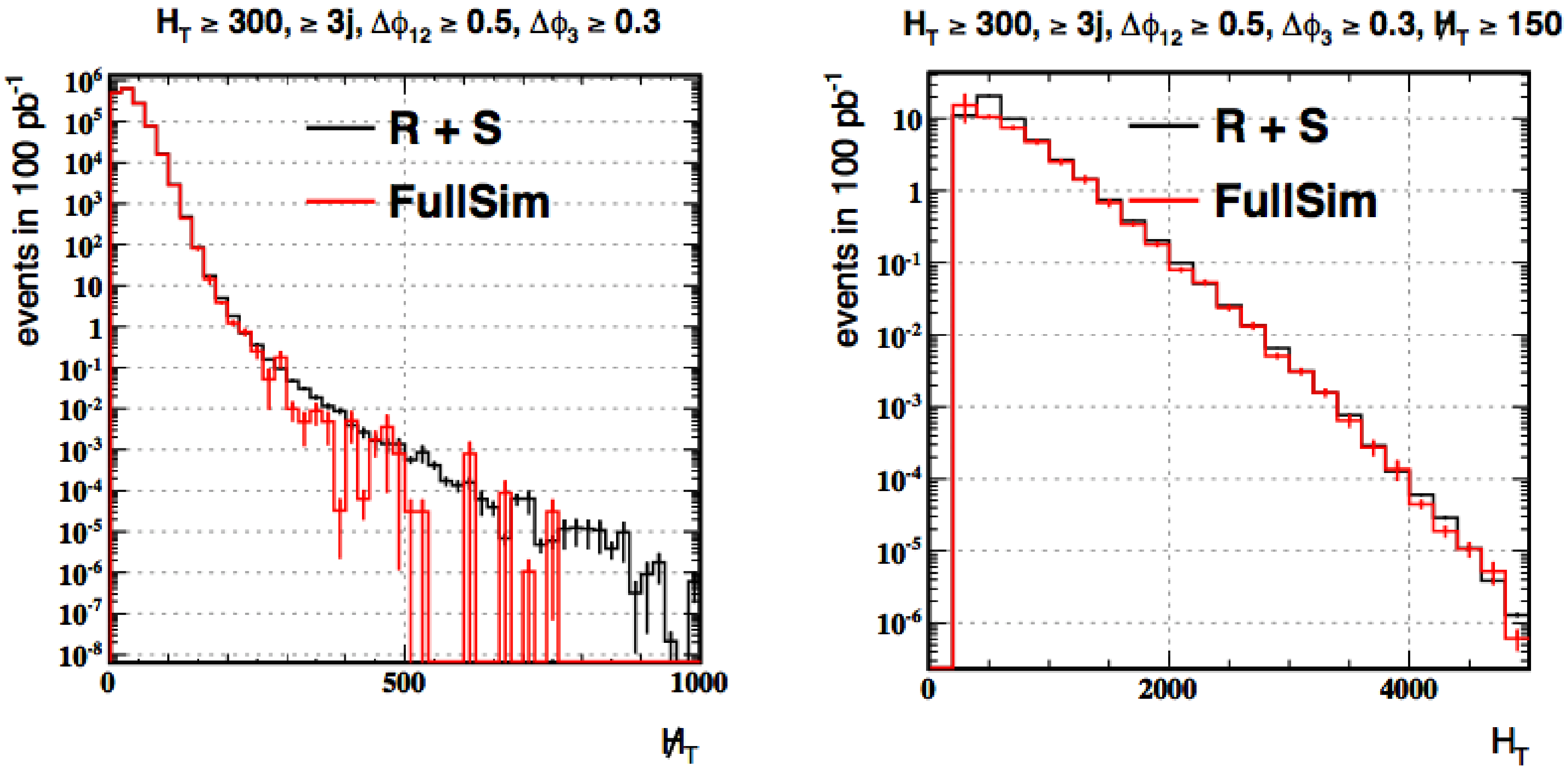
$$
\begin{aligned}
f_{\lambda=0} &= 0.687 \pm 0.005, \\
f_{\lambda=-1} &= 0.311 \pm 0.005, \\
f_{\lambda=+1} &= 0.0017 \pm 0.0001
\end{aligned}
$$



[1] A. Czarnecki, J. Korner, and J. Piclum, "Helicity fractions of W bosons from top quark decays at next-to-next-to leading order in QCD", *Phys. Rev.* **D 81** (2010) 111503(R).

0 lepton: Jets + MET

Rebalance+smear QCD prediction: closure test



- lack of closure taken into account as a systematic error

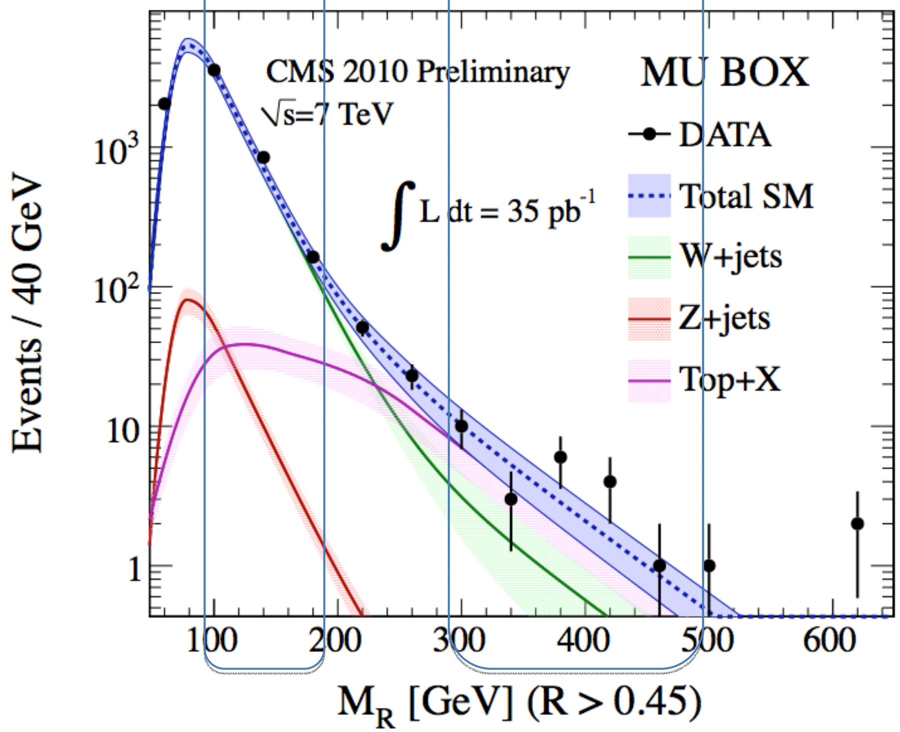
R&MR

Data-driven background estimation

Same slope for
- Z→ll + jets
- 1st W + jets component

The lepton enters the computation of R and MR

Slope directly measurable



Same slope for
- Top+X
- 2nd W + jets Component
- Z→νν in HAD Box

The lepton does not enter R and MR

Slope measured by ignoring the lepton

Data/MC correction to
1st W+jets slope
Z + jets slope

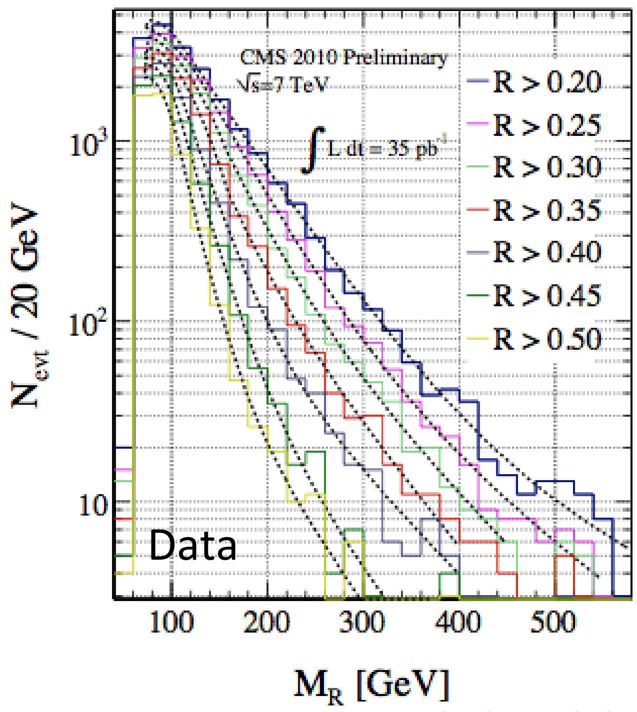
Data/MC correction to
2nd W+jets slope
Top+X slope

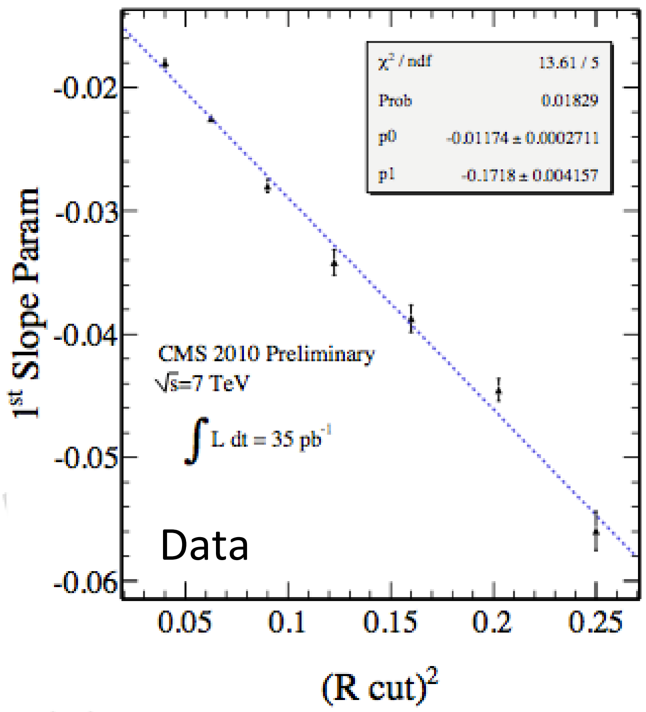
R&MR

Data-driven background estimation

- W+jets dominated (>90%)
- Fit with 2 exponentials
- Extract the 1st component

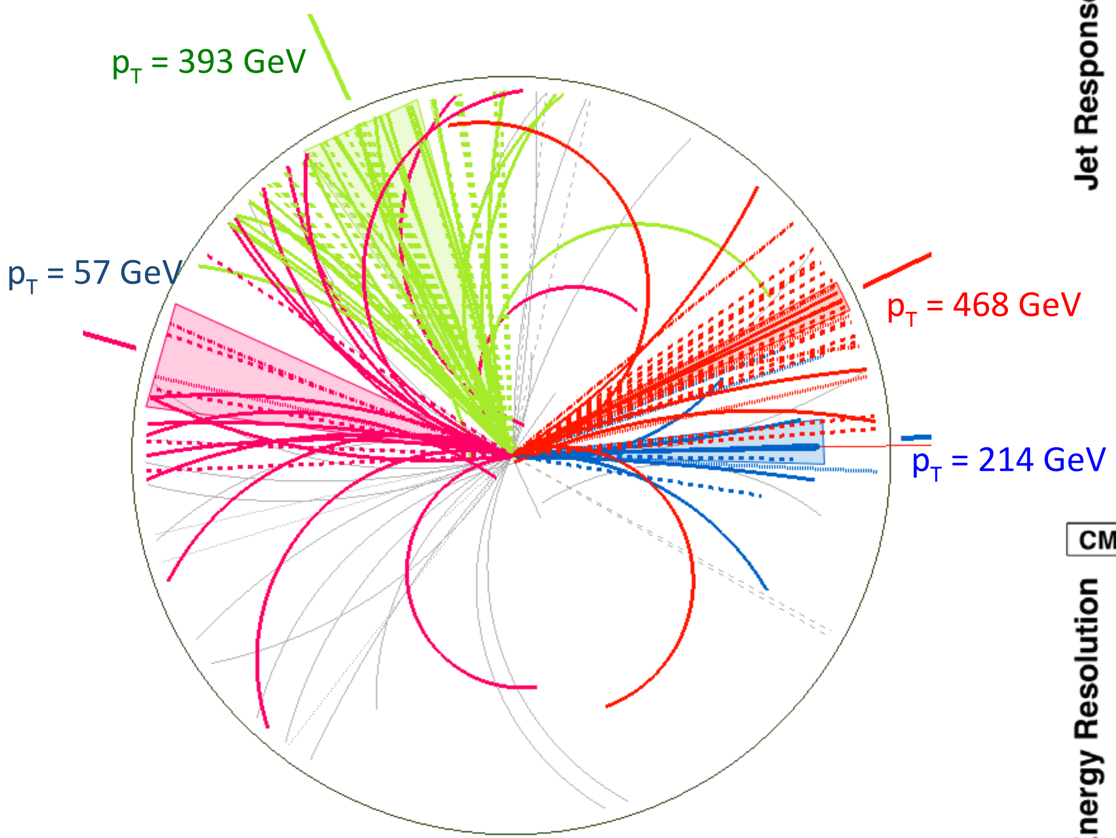
- Plot as a function of (R cut)^2
- Correction factors:
  - p0 (data) / p0 (MC)
  - p1 (data) / p1 (MC)



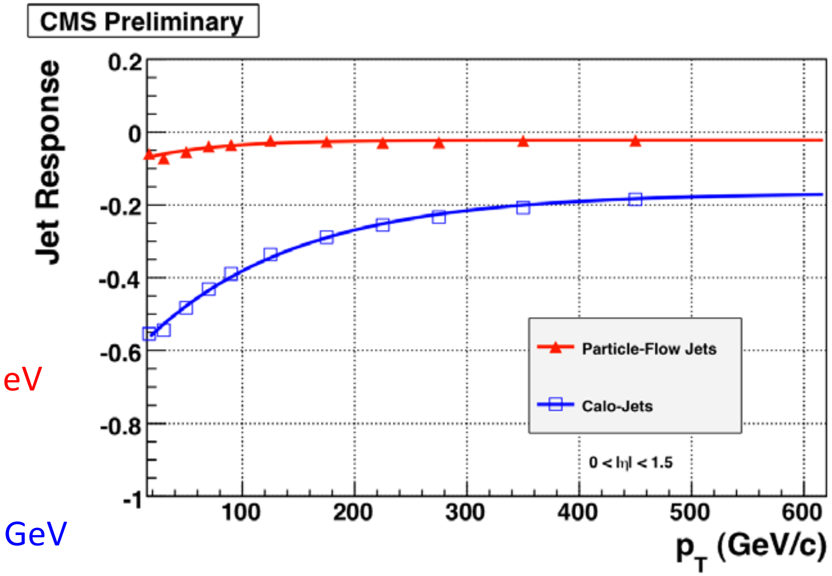


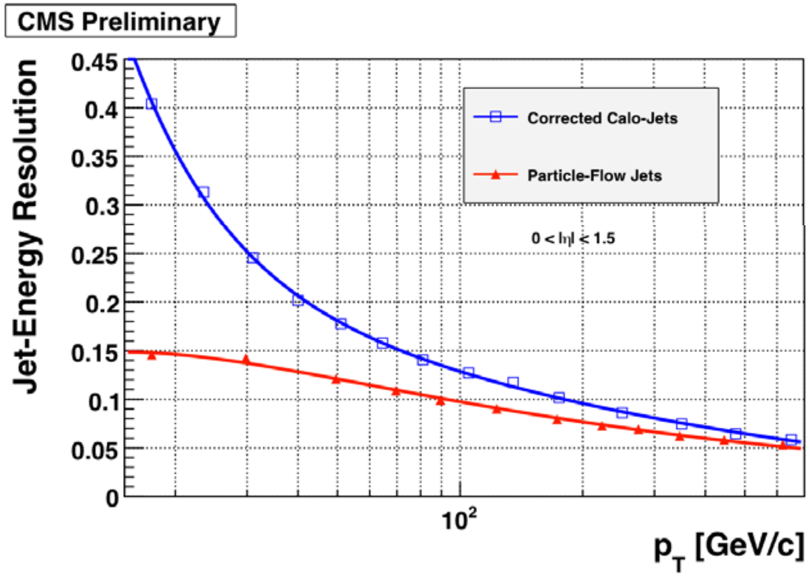
Reconstructed Particle Jets

Showing jets with pT > 50 GeV/c



An event recorded in 2010

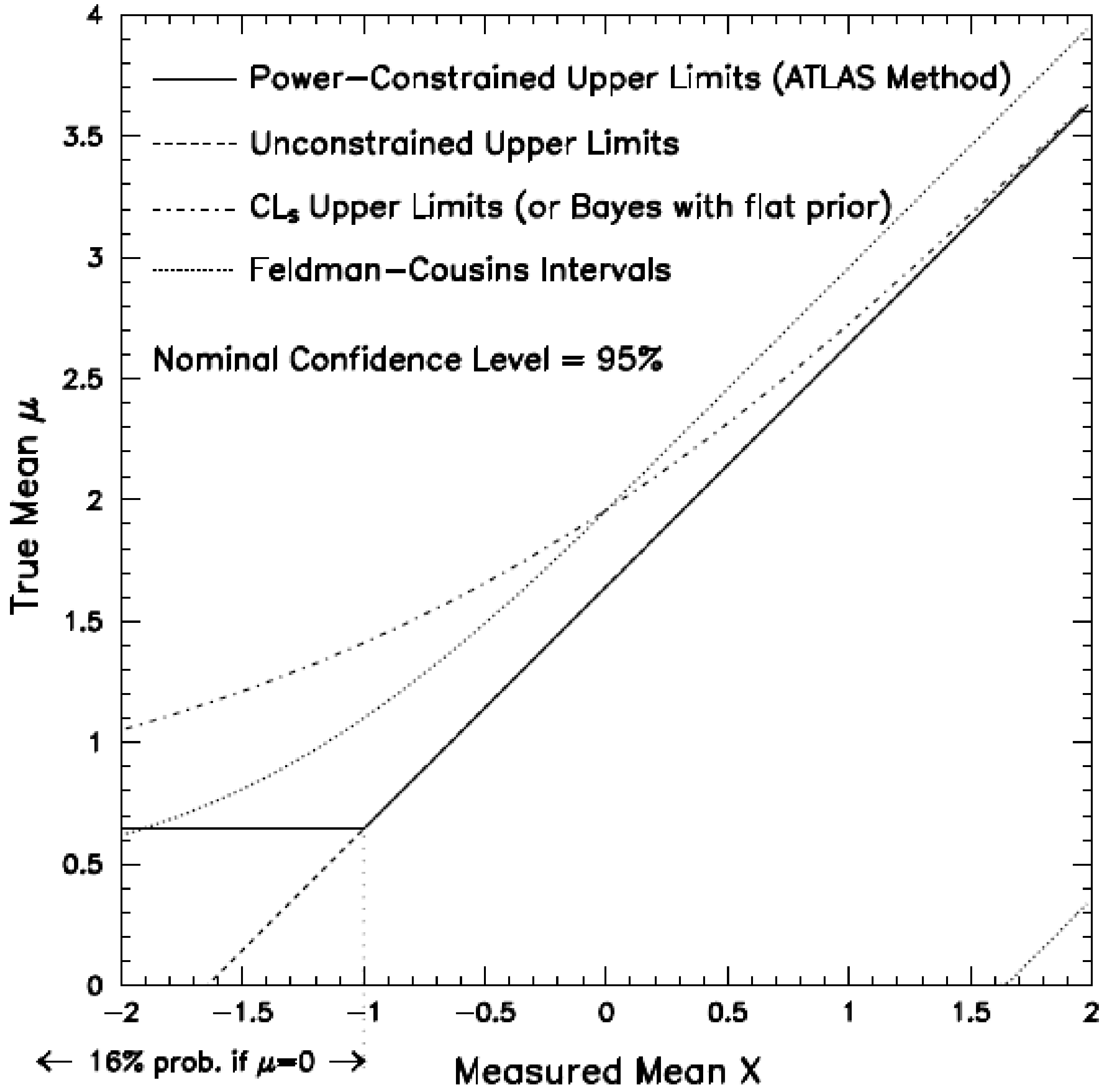




Intervals and Limits for a Physically Bounded μ

- Prototype: measurement x is unbiased Gaussian estimate of μ. (Let σ=1.) What is 95% C.L. Upper Limit (UL)?
- 1986: Six methods for UL surveyed by V. Highland (VH) include U.L. = max(0, x + 1.64) and U.L. = max(0,x) + 1.64.
- RPP 1986: Bayesian: uniform prior on the mean μ for $\mu \geq 0$, prior prob = 0 for μ<0. (VH's other five not mentioned.)
- 1994,96: 3 ad-hoc frequentist recipes, one using max(x,0).
- 1998: Feldman & Cousins (FC) "Unified Approach" in (Kendall and Stuart) replaces ad hoc frequentist
- 2002: CLS from LEP added to Bayesian and FC.
- CMS Statistics Committee recommends using (at least) one of the three (red) methods in 2002-present PDG RPP.
- ATLAS SC method implies U.L. = max(0, x + 1.64) before power constraint (PC), U.L. = max(-1,x) + 1.64 after PC.

Comparison of ATLAS PCL with the three methods in PDG



(Atlas unconstrained U.L. is zero, not null, for x < -1.64)

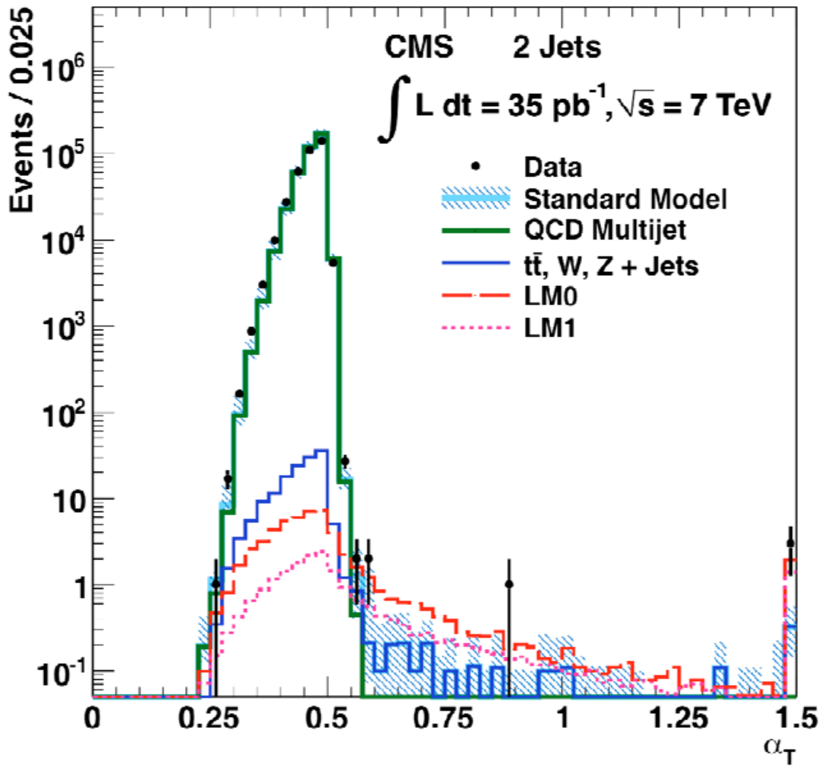
ATLAS PCL re-opens discussion on use of diagonal line along with ad hoc constraint, out of favor for many years, not recommended by CMS SC.

CMS and ATLAS SC's are reviewing arguments and what has been learned in 25+ years. Academic statisticians have commented as well.

Just tip of iceberg: Poisson example brings in other issues. Nuisance parameters yet more. Choice of test statistic varies.

α_T fully hadronic analysis

α_T variable



- The α_T analysis was optimized for fast discovery
  - goal was: kill QCD
  - first LHC SUSY paper
    - http://arxiv.org/pdf/1101.1628.pdf

$$\alpha_T = \sqrt{\frac{E_{T,2}}{2E_{T,1}(1-\cos(\phi))}}$$

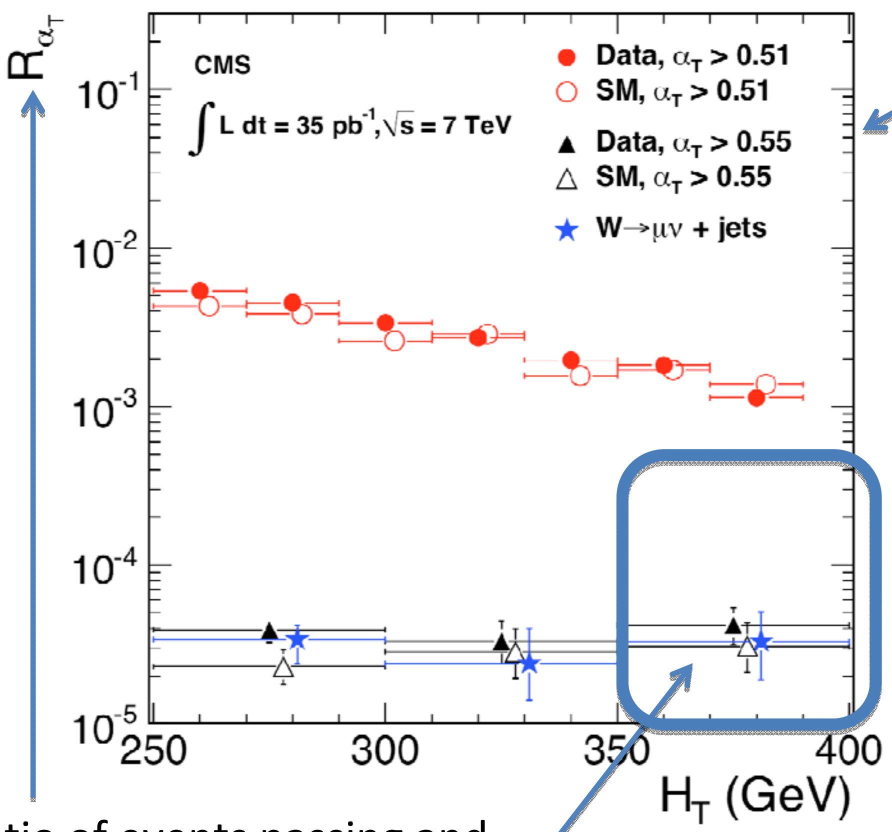
QCD:

α_T = 0.5 if jets are back-to-back and well measured

α_T <0.5 if energy mismeasurement

α_T fully hadronic analysis

Data-driven background estimation



ratio of events passing and failing the α_T cut , extrapolated to search region

- Inclusive: α_T ratio
- $Z \to \nu\nu$ + jets:
  - γ + jets:
    - Ignore photon, correct for γ/Z
  - $W \to l\nu$ + jets x-check
- W + jets (incl. top):
  - Select a μ+jets sample in data and MC passing the final selections
  - Number of events in search region:

$$N_{\text{data}}^{\text{W; had}} = N_{\text{MC}}^{\text{W; had}} / N_{\text{MC}}^{\text{W; }\mu} \times N_{\text{data}}^{\text{W; }\mu} \approx 0.86 \times N_{\text{data}}^{\text{W; }\mu}$$