The road to discovery at the LHC

The case of CMS

Filip Moortgat (ETH Zurich)

or

?

Road to discovery

So you want to discover new physics ….

Start with:

1) Build a powerful accelerator (energy and luminosity)
2) Build high performance detectors

Once this is done:

The roadmap:

1) Understand basic physics objects:
   electrons, muons, jets, b's, tau's, MET

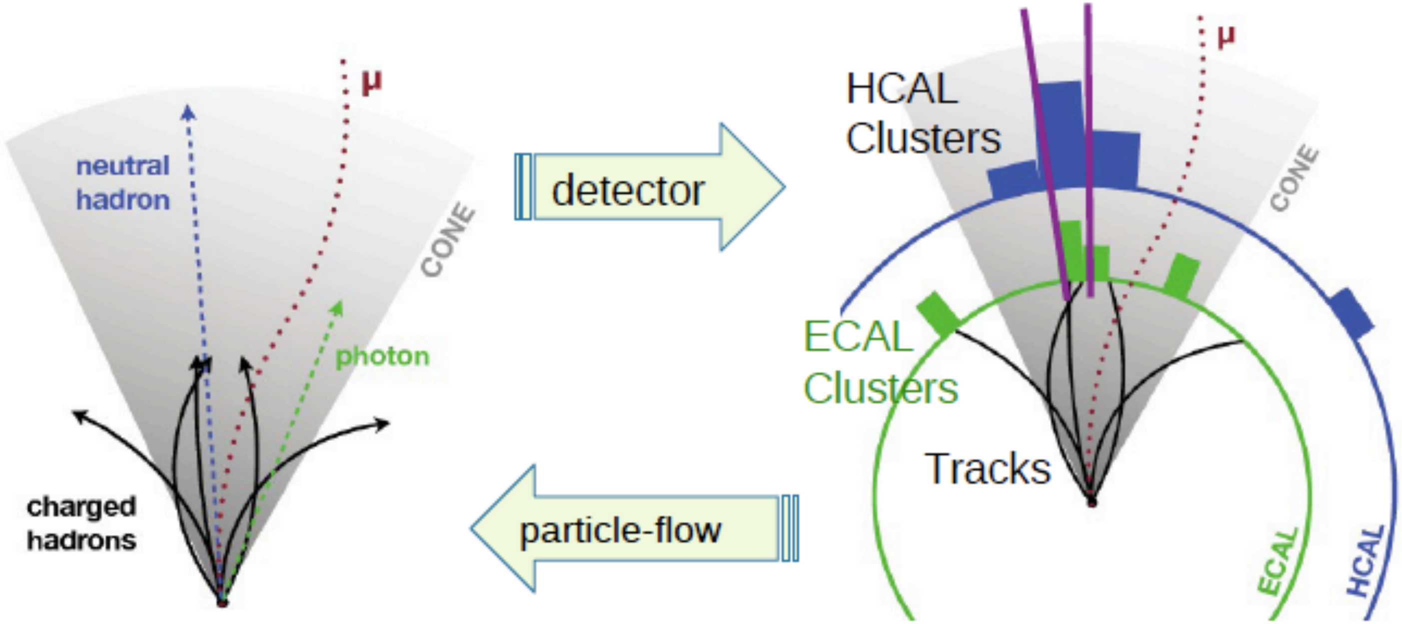
2) Understand the Standard Model (QCD, W, Z, top)

3) Start looking for anomalies … e.g. supersymmetry …

4) Interprete signals, measure properties

$\int \mathcal{L} dt$ (pb^{-1})

Particle Flow



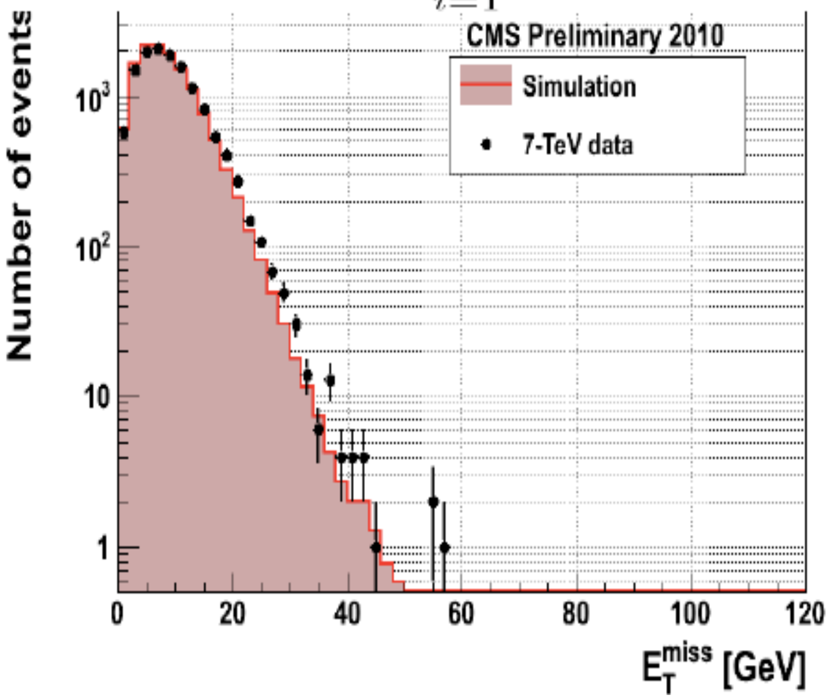
The list of individual particles is then used to build jets, to determine the missing transverse energy, to reconstruct and identify taus from their decay products, to tag b jets …

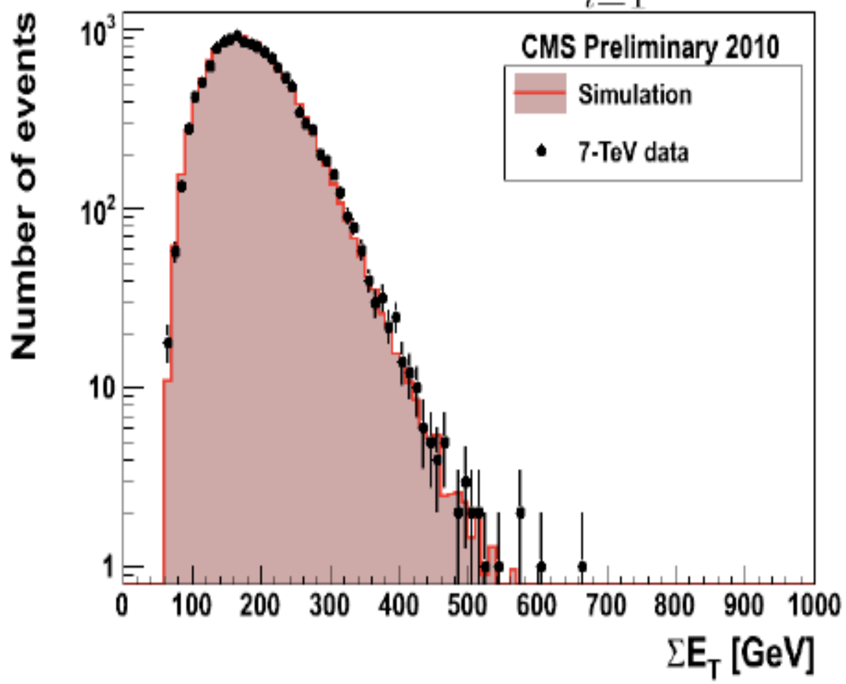
Particle Flow MET

$$\overrightarrow{E_T^{miss}} = -\sum_{i=1}^{N_{particles}} \overrightarrow{E_T^i}$$

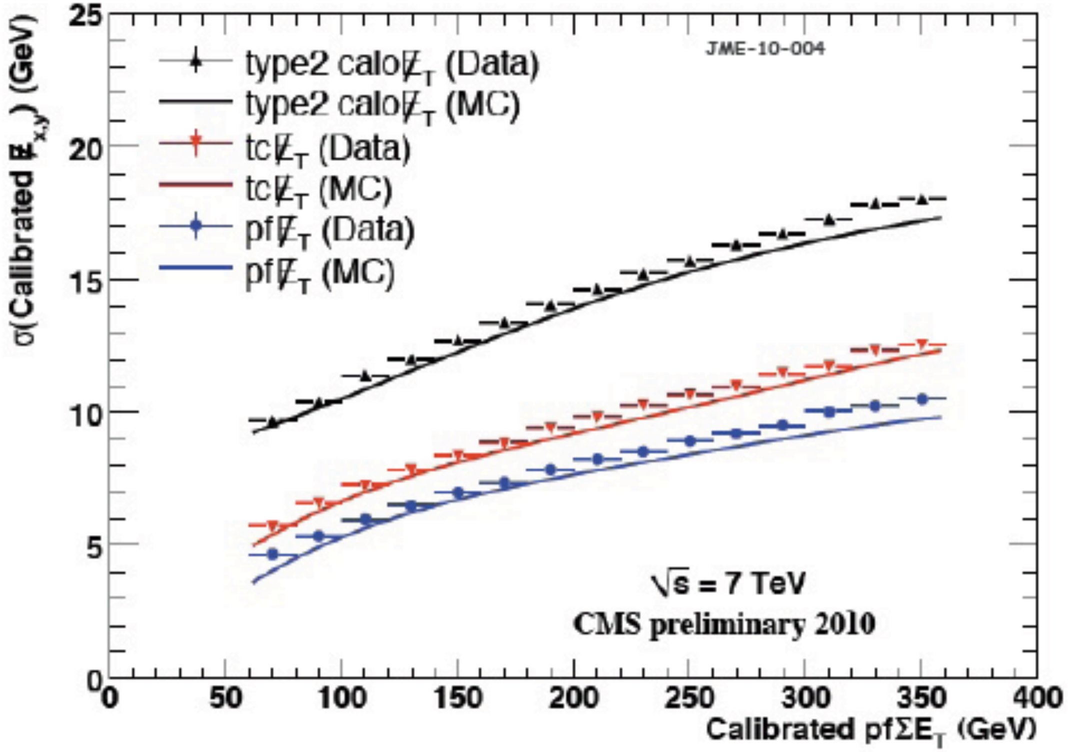
Di-jet events

$$\Sigma E_T = \sum_{i=1}^{N_{particles}} E_T^i$$

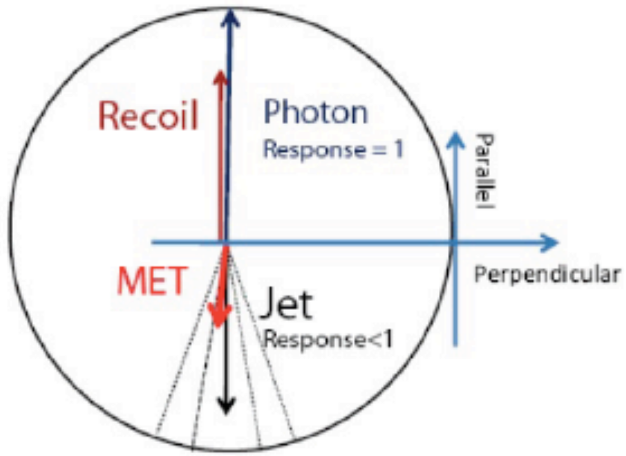




MET resolution



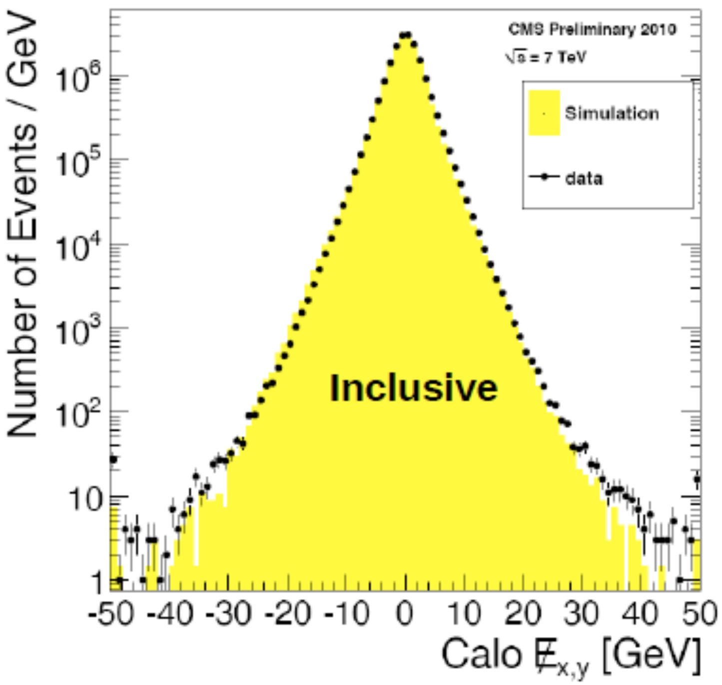
- PF SumE_T is calibrated to generator level Sum E_T
- Observed MET sigma is scaled by the MET scale obtained from photon+jets MC events:



=> PF MET has the best resolution.
Tc MET also shows significant impovement w.r.t. the calorimeter-only MET

Fit Gaussian:

Calo MET



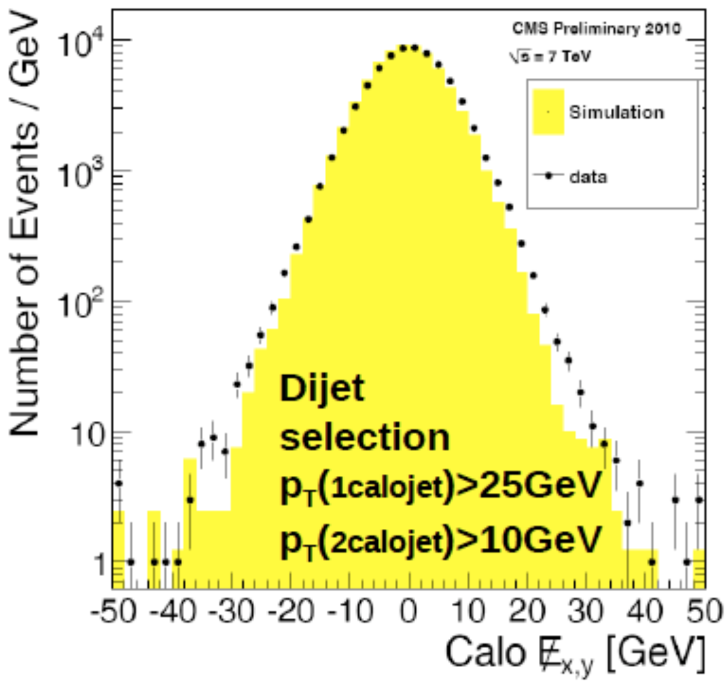
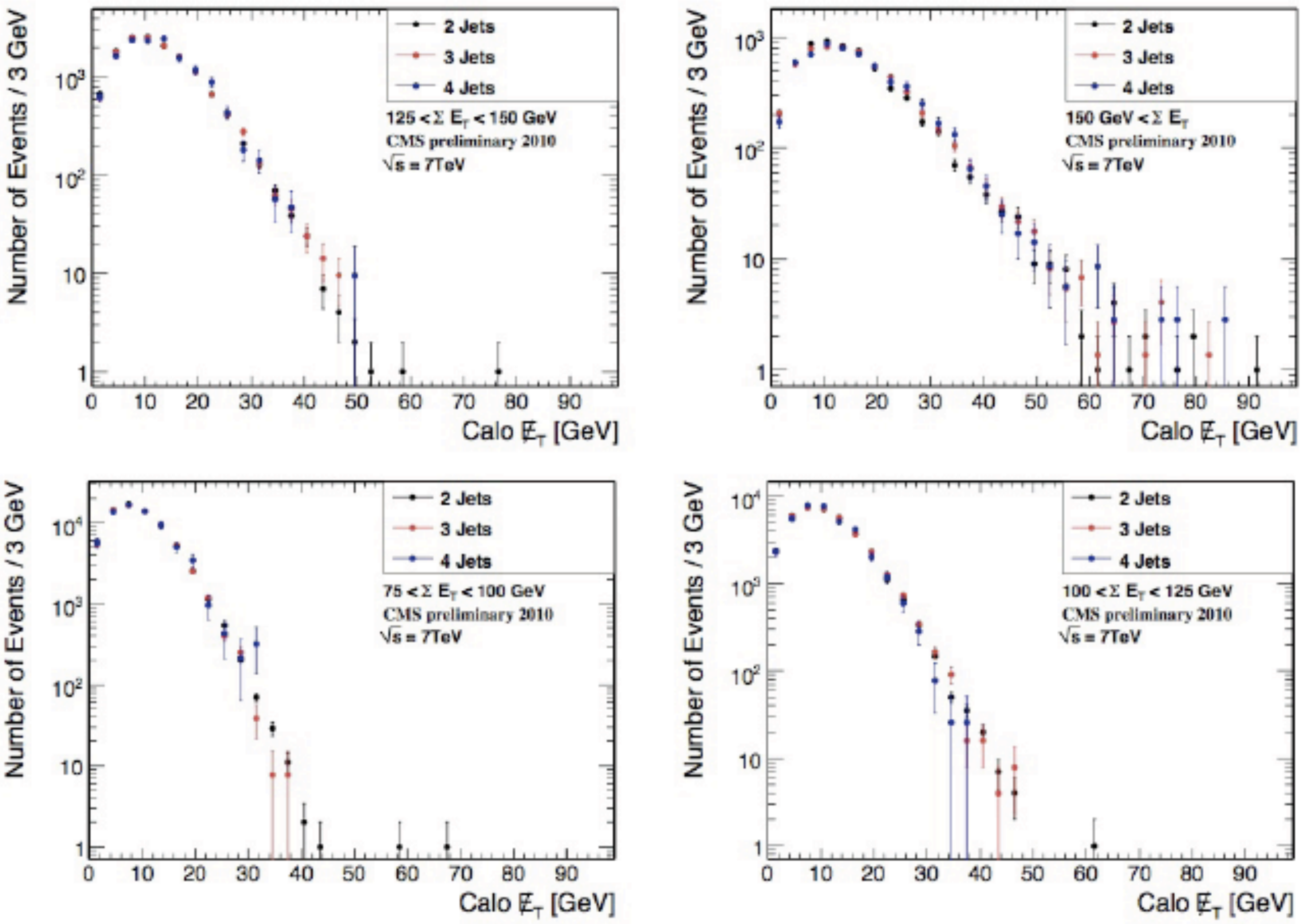


Figure: Data vs MC: Calo $\not{E}_x$, $\not{E}_y$ distributions

MET in multijets

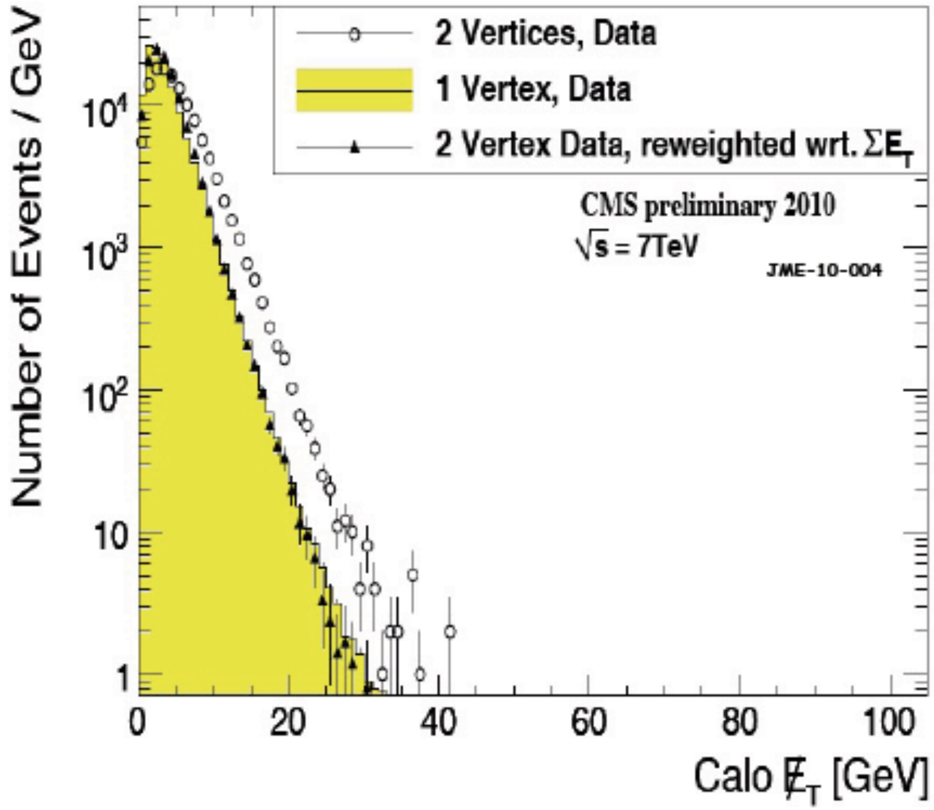


- Uncorrected Calo MET in jet events for different $SumE_T$ ranges
- Different jet multiplicity bins (jets w/p_T>20 GeV, |η|<3)

=> MET distribution "primarily" controlled by $SumE_T$, and not jet multiplicities

MET in pile-up conditions

Study of MET distribution in 1-and 2-vertex events in minimum-bias events

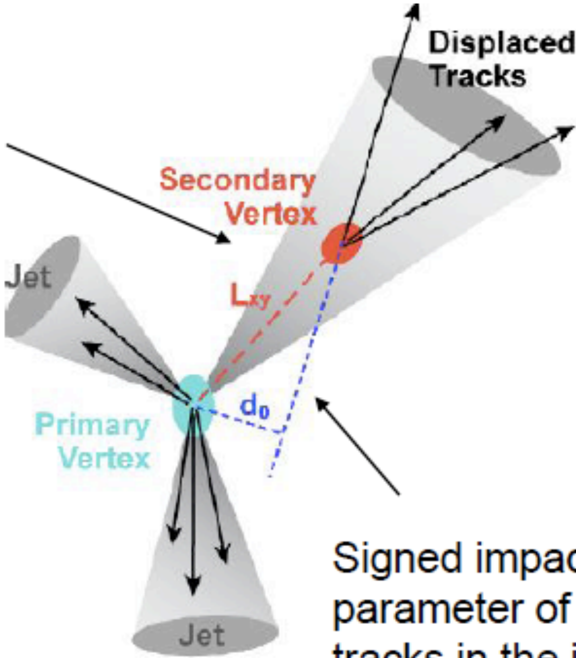


- MET distributions wider in 2-vertex events
- Reweight 2 vertex events so that the SumE_T distribution matches that of the 1 vertex events
- After reweighting, MET distribution agree between 1-vertex and 2-vertex events

=> Widening of MET distribution in 2-vertex events due to transverse energy increase in events

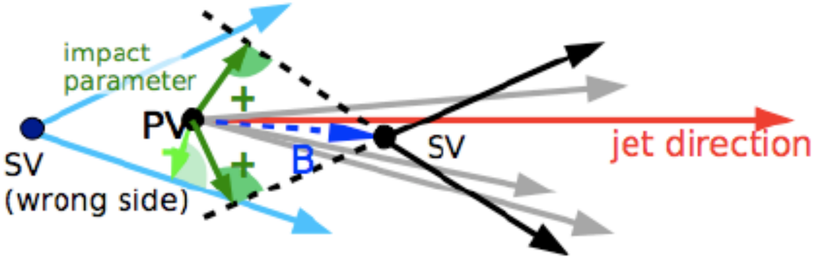
B-tagging

Signed decay length of secondary vertexes

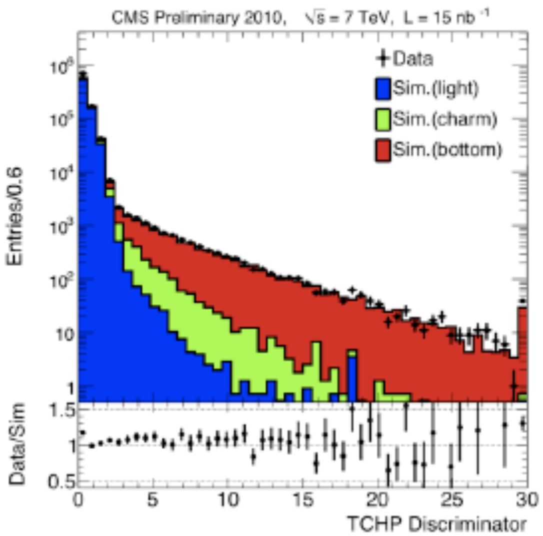


Signed impact parameter of tracks in the jet

Signs of Impact parameter and of vertex decay length are defined according to jet direction



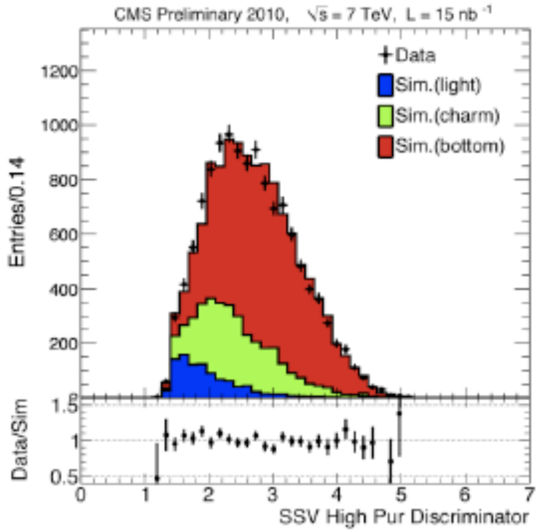
B-tag methods



Track Counting Algorithm

tags jets containing N tracks with Impact Parameter (IP) significance exceeding S

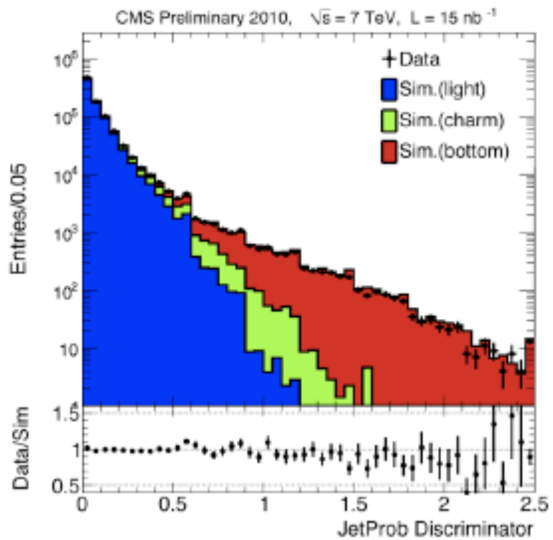
High Purity configuration: N=3



SSV Algorithm

tags jets according to the 3D flight distance significance of the reconstructed secondary vertex

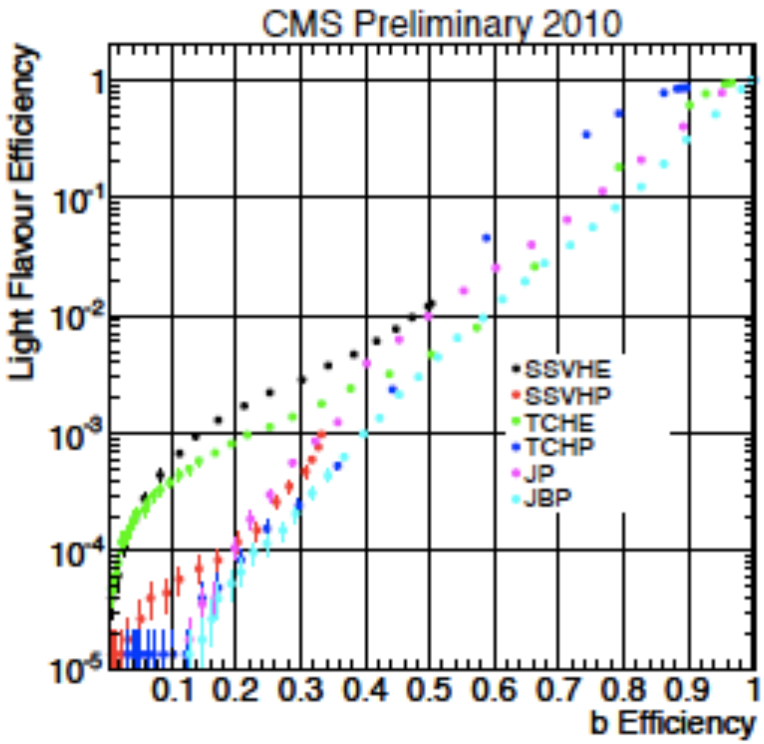
High Purity configuration:
Vertices with 3 or more tracks



Jet Probability Algorithm

tags jets according to the probability of all the tracks in the jet to originate from the primary vertex, given their IP significances

B-tag performance

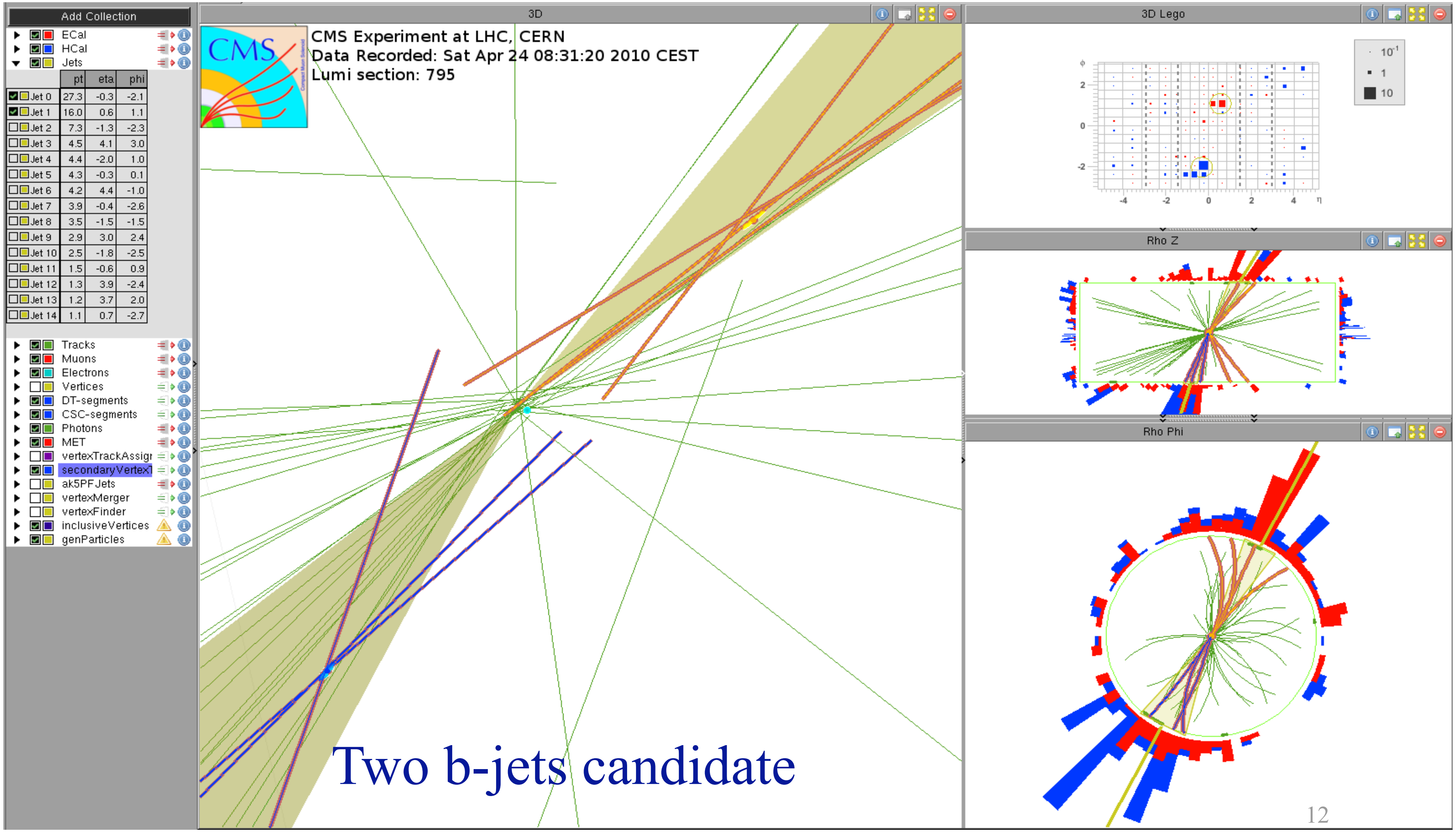


Monte Carlo simulation!

3 “working points” for each algorithm:

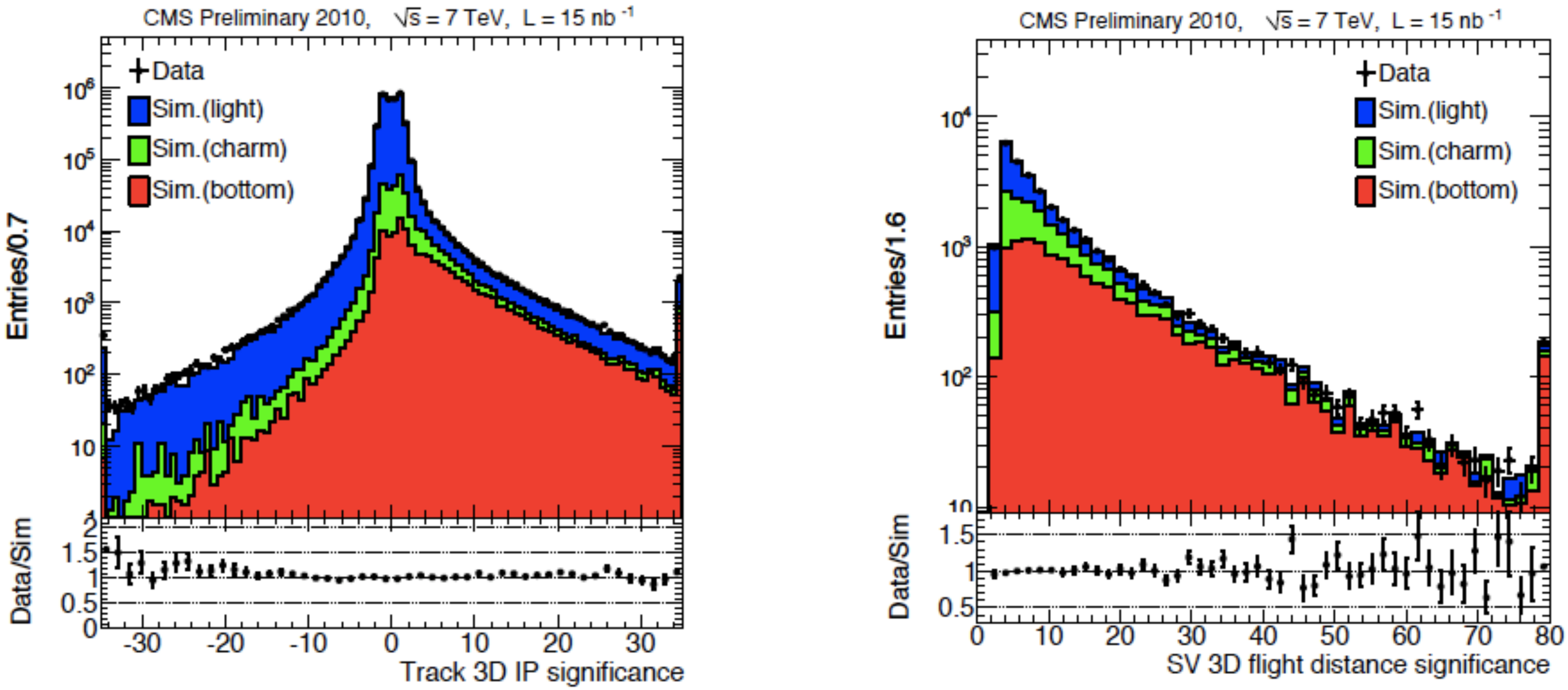
“loose” (mistag 10%), “medium” (mistag 1%), “tight” (mistag 0.1%)

b-jets event display



B-tag observables

Data:



Data/MC agreement is excellent, also for all other b-tagging variables

B-jet cross sections

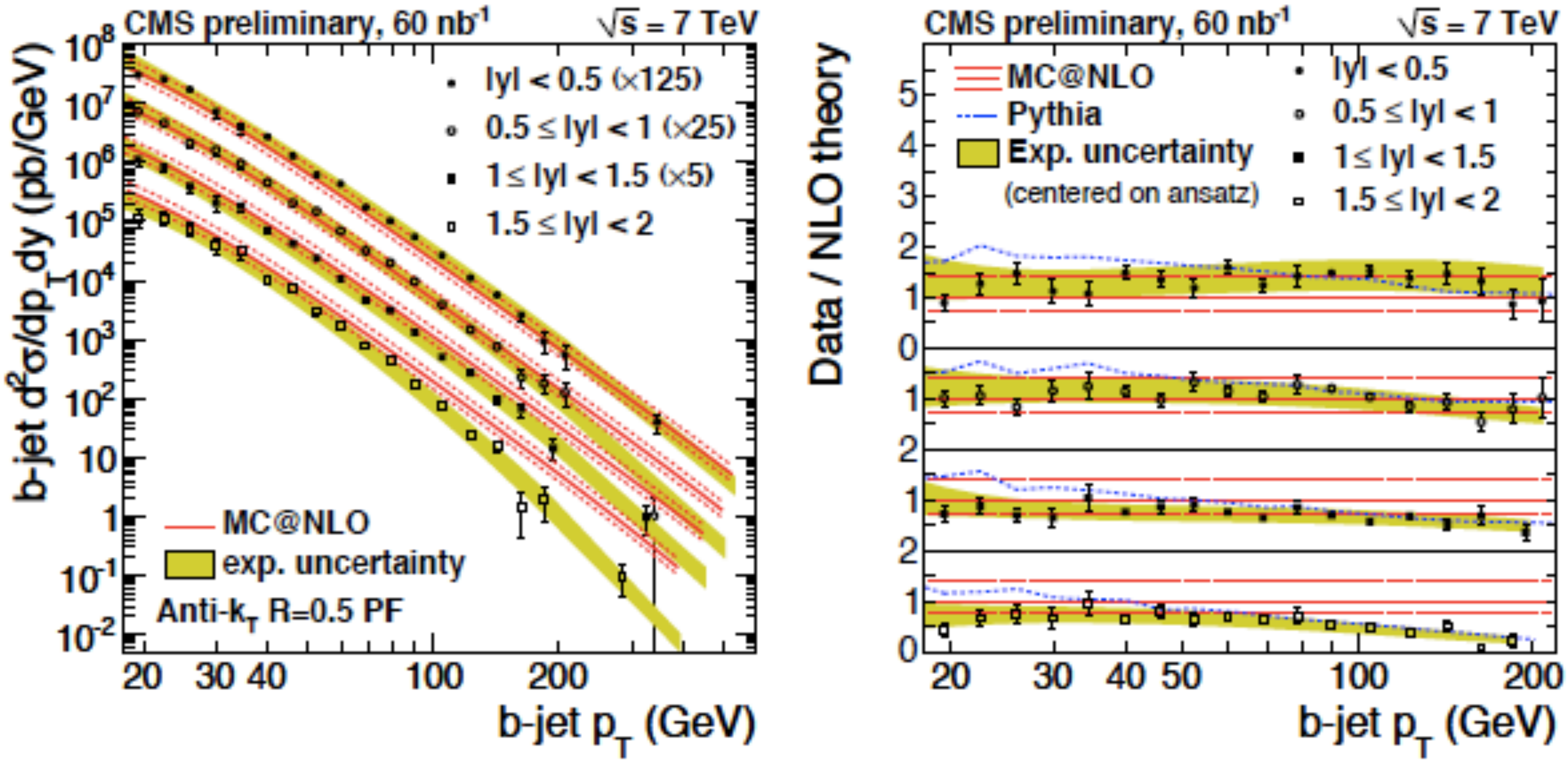


Figure 7: Measured b-jet cross section compared to the MC@NLO calculation, overlaid (left) and as a ratio (right). The Pythia prediction is also shown, for comparison.

Flavour ratios

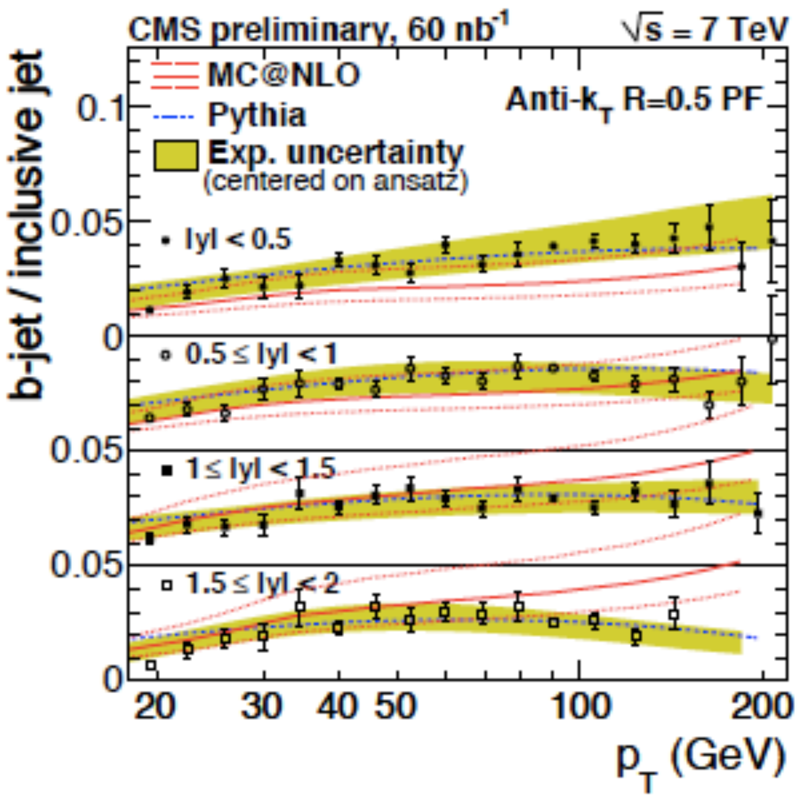


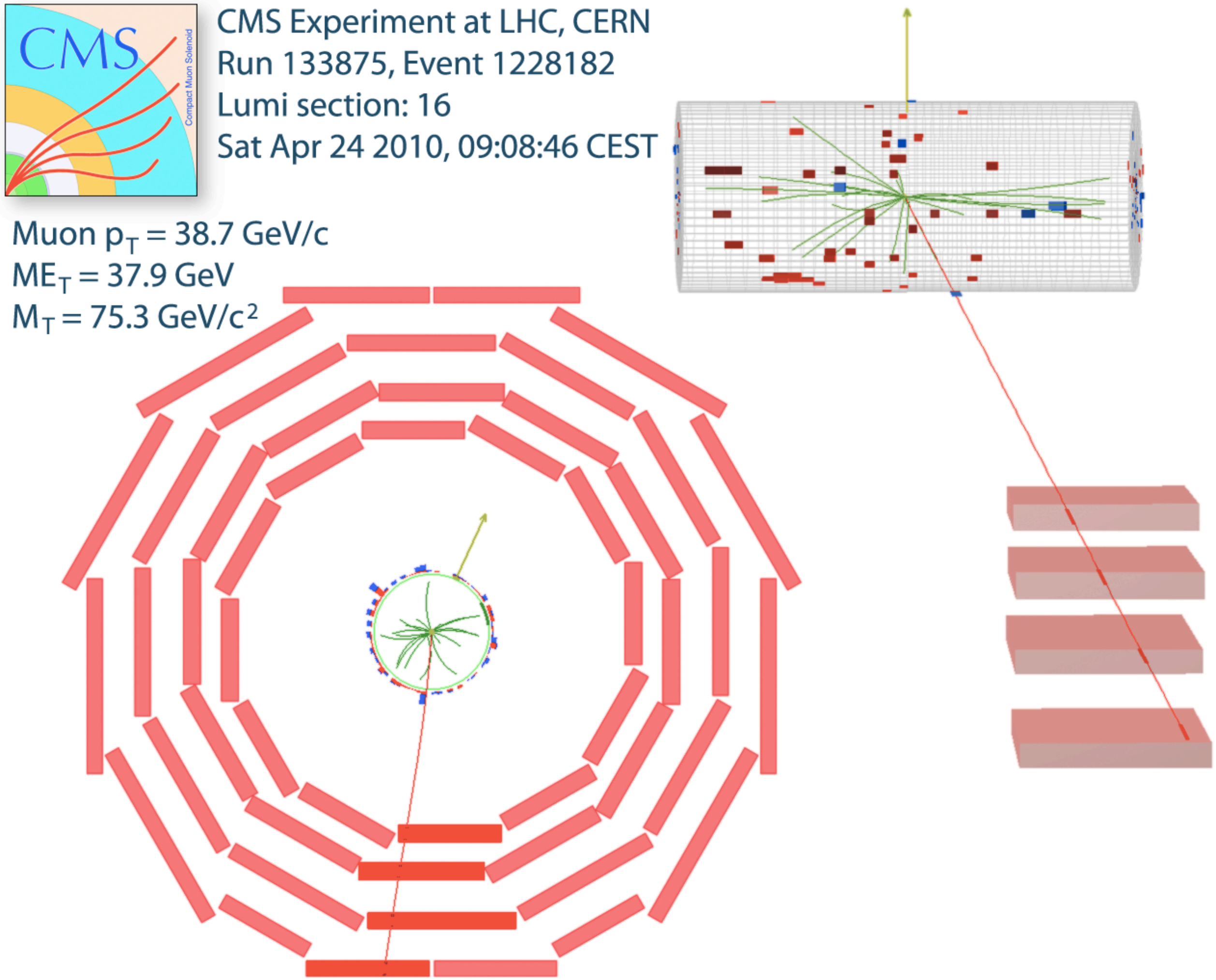
Figure 8: Measured b-jet cross section as a ratio to inclusive jet cross section. The NLO theory and Pythia MC predictions are shown for comparison.

Electroweak Physics

Accomplished so far (July 22, 2010) :

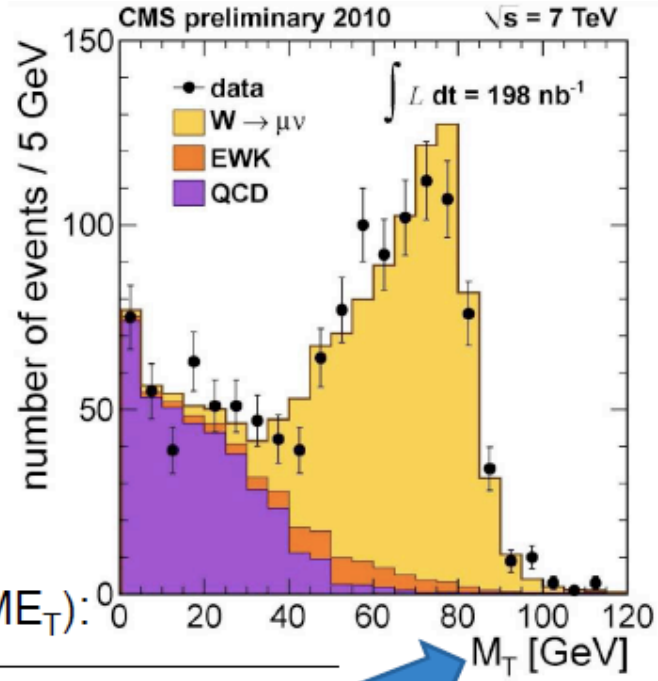
- **Muons**
  - $W \to \mu\nu$ event selection and cross-section determination
  - $Z \to \mu\mu$ event selection and cross-section determination
  - Systematic effects
- **Electrons**
  - $W \to e\nu$ event selection and cross-section determination
  - $Z \to ee$ event selection and cross-section determination
  - Systematic Effects
- **Measurements**
  - Combined results for cross-section and Ratios
  - W Charge Asymmetry
  - Associated V+Jets production

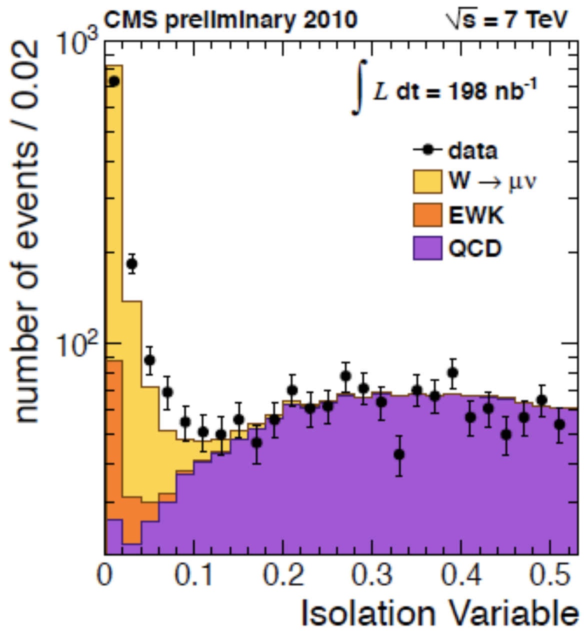
W to muon


CMS
CMS Experiment at LHC, CERN
Run 133875, Event 1228182
Lumi section: 16
Sat Apr 24 2010, 09:08:46 CEST
Muon $p_T = 38.7$ GeV/c
$ME_T = 37.9$ GeV
$M_T = 75.3$ GeV/c^2

W : muon channel

- Event triggered by Level1+HLT , $p_T > 9$ GeV
- **Selection Criteria** :
  - Muon $p_t > 20$ GeV, $|\eta| < 2.1$
  - Isolation $(\Sigma p_T\,(tk) + \Sigma E_T\,(had+em))/p_T < 15\%$
  - ME_T reconstructed using Pflow techniques
  - Drell Yan rejection (veto on events with a second muon of $p_T > 10$ GeV)





EWK = Drell-Yan, $W \to \tau\nu, Z \to \tau^+\tau^-$ and $t\bar{t}$.

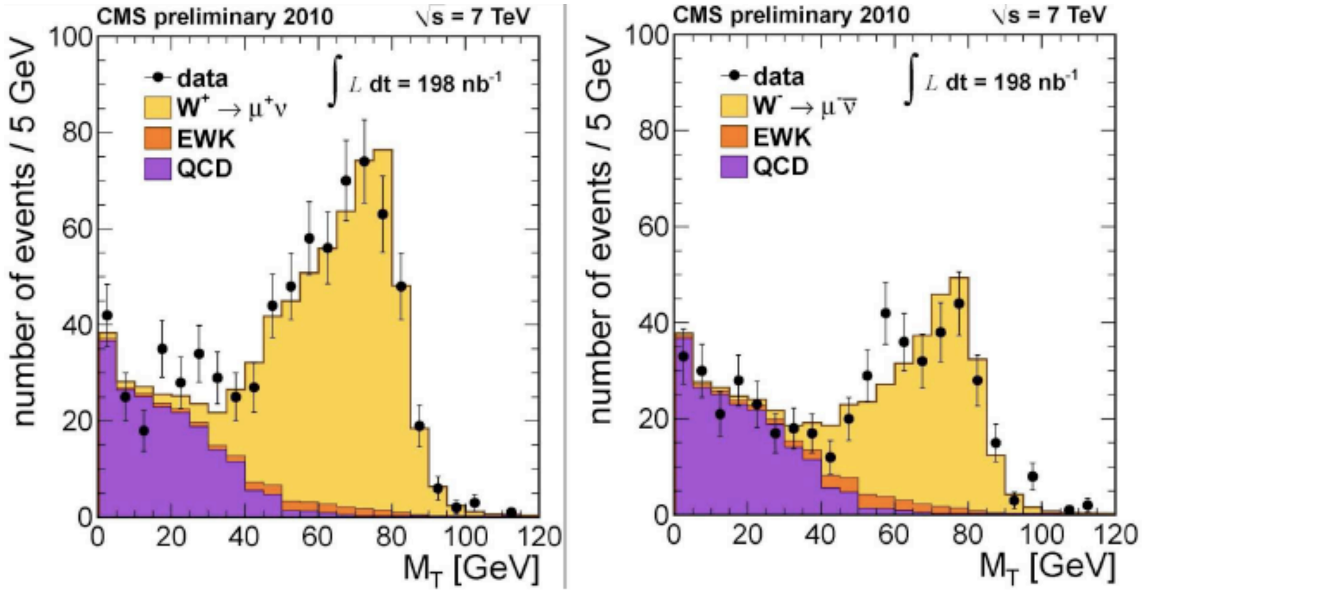
Transverse mass (μ, ME_T):

$$M_T = \sqrt{2p_T(\mu)\not{E}_T * (1 - \cos(\Delta\phi_{\mu,\not{E}_T}))}$$

- Main source of BG: QCD (b hadron decays)
- QCD MT Shape extracted from data (isolation inversion)
- W Signal and EWK MT shapes modeled from MC
- W Signal yield extracted through a Binned Likelihood fit to the MT distribution (Signal + QCD & EWK BGs)

W to muons

Separately μ^+ and μ^- :



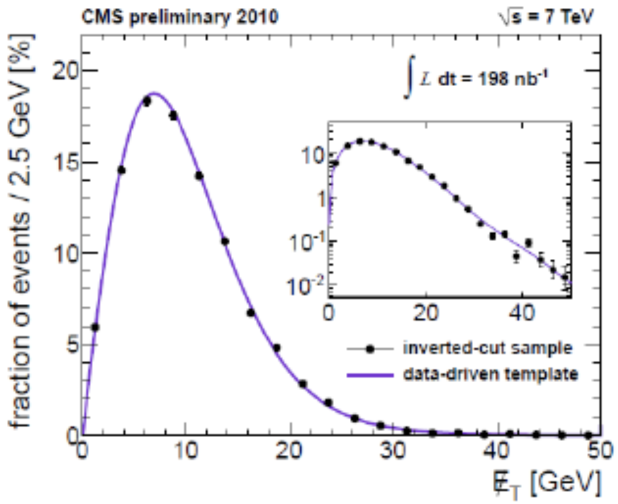
529 ± 24 W^+ Yield
289 ± 13 W^- Yield
(statistical error only)

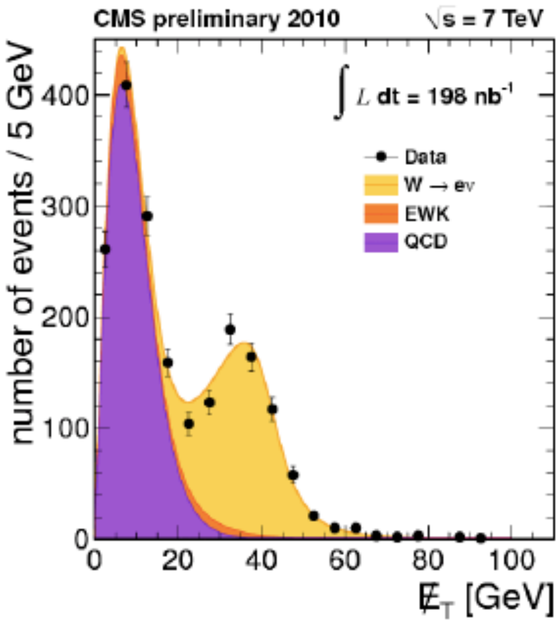
σ(pp→W+X→μv+X) = 9.14 ± 0.33 nb
R =1.69 ± 0.12

σ(W^+→μ^+v) = 5.75± 0.26 nb
σ(W^-→μ^-v) = 3.39± 0.15 nb

W : electron channel

- Events triggered by Level1 (ECAL) + HLT (E_T>15 GeV)
- Selection Criteria:
  - Electron E_T> 20 GeV
  - $|\eta| < 1.4442$ (Barrel), $1.566<|\eta|< 2.500$ (Endcap)
  - Isolation (independent cuts on track, em, had)
  - Drell Yan rejection (veto on events with a second electron of E_T>20 GeV)

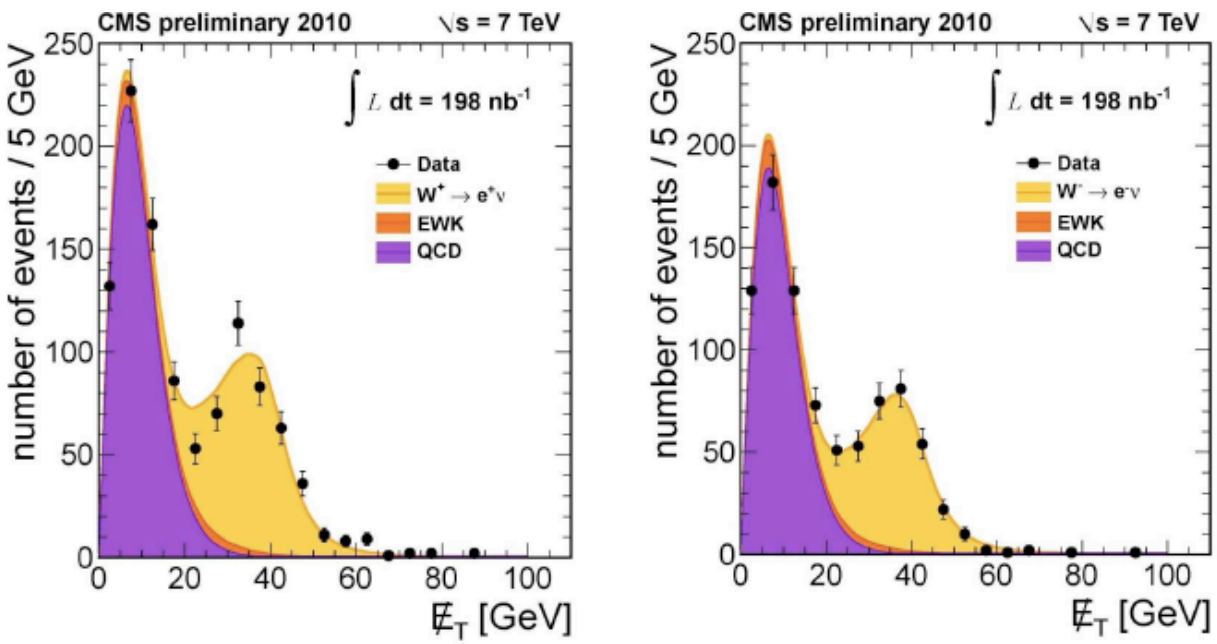




- QCD BG dominated by fake electrons
- Unbinned Likelihood fit to the ME_T distribution
- W Signal and ElectroWeak ME_T shape well modeled from Monte Carlo
- QCD background is parameterized through a modified Rayleigh distribution with E_T dependent resolution

W to electrons

Separately e^+ and e^- :



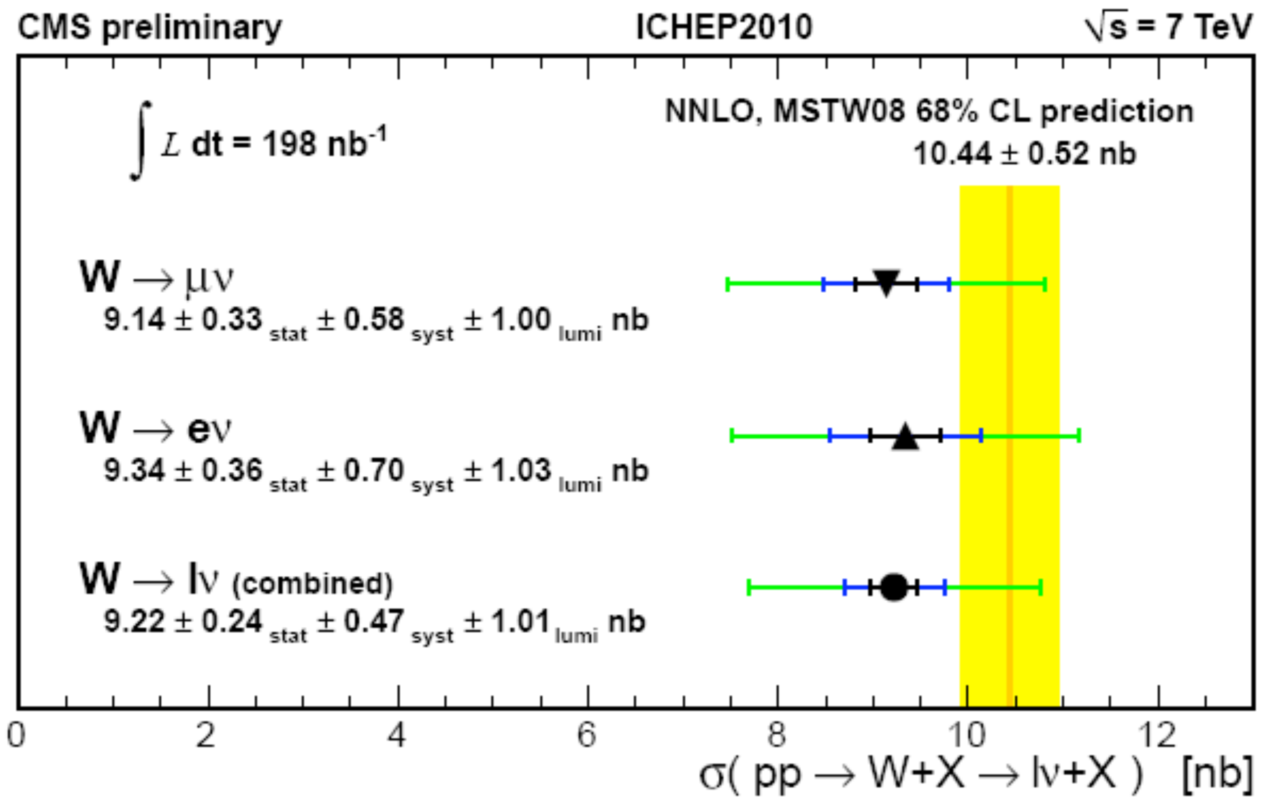
458±23 W^+ Yield
339±20 W^- Yield

(statistical error only)

σ(pp→W+X→eν+X) = 9.34 ± 0.36 nb
R = 1.26 ± 0.10

σ(W^+→e+ν) = 5.18 ± 0.26 nb
σ(W-→e-ν) = 4.13 ± 0.24 nb

W cross section



Remember: uncertainty from LHC luminosity (VdM) = 11%

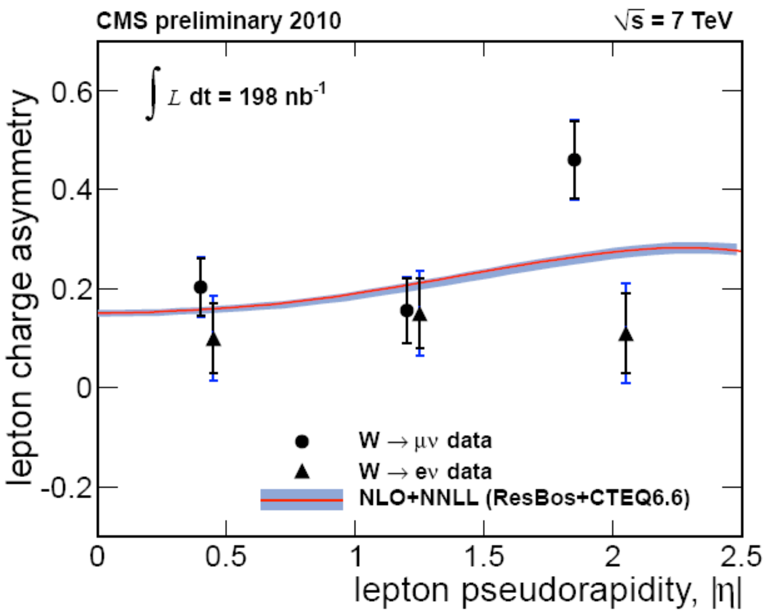
Systematic uncertainties

- Efficiencies and scales studied in Z events and recoil studies
- Background uncertainties from cut inversion studies and control samples
- PDF uncertainties evaluated via CTEQ66, MSTW08NLO, NNPDF2.0 sets

Source	$W \to \mu\nu$ (%)	$W \to e\nu$ (%)
Lepton reconstruction	3.0	6.1
Trigger Efficiency	3.2	0.6
Isolation Efficiency	0.5	1.1
Momentum/energy scale	1.0	2.7
MET scale and resolution	1.0	1.4
Background subtraction	3.5	2.2
PDF uncertainty in acceptance	2.0	2.0
Other theoretical uncertainties	1.4	1.3
Total systematic error	6.3	7.7
Luminosity uncertainty	11.0	11.0

W charge asymmetry

- W^+ and W^- charge asymmetry as a function of the lepton η provides a constraint on PDFs



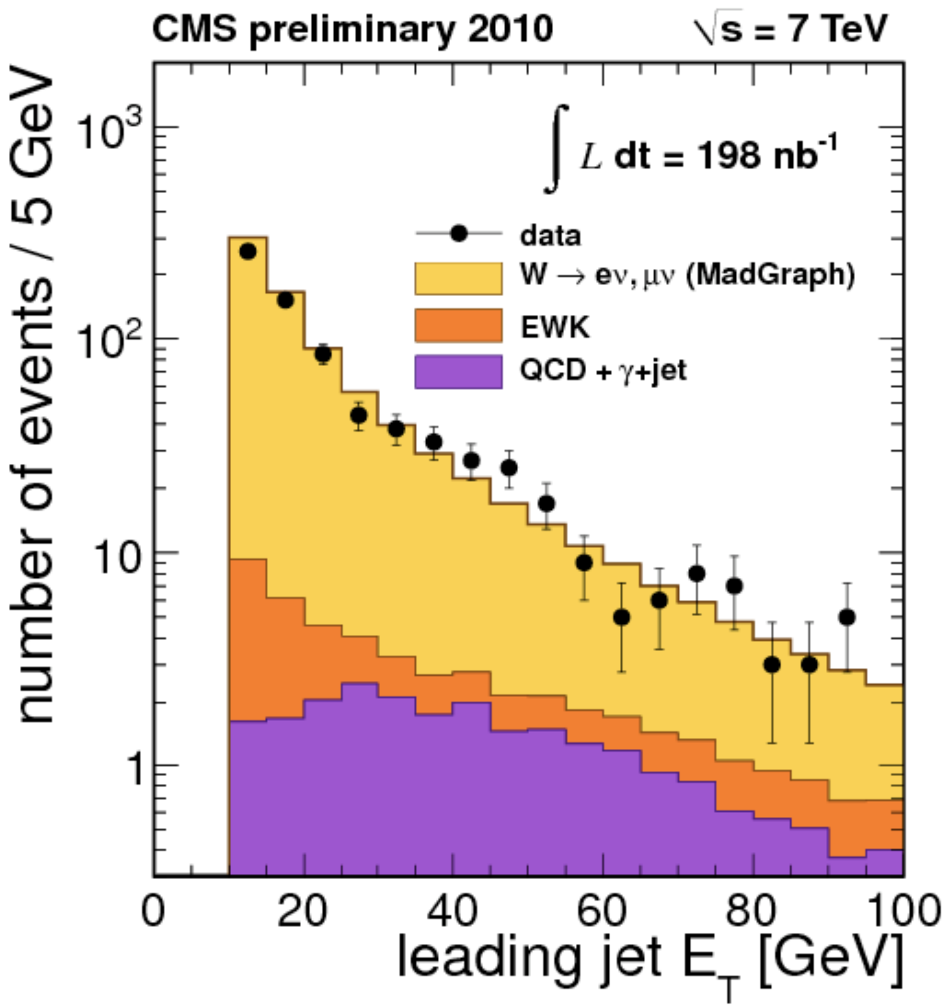
$$A(\eta) = \frac{d\sigma^{(+)}/d\eta_\ell - d\sigma^{(-)}/d\eta_\ell}{d\sigma^{(+)}/d\eta_\ell + d\sigma^{(-)}/d\eta_\ell}$$

Ratio of positive to negative reconstruction efficiencies compatible with unity within 5% (9%) for muons (electrons)

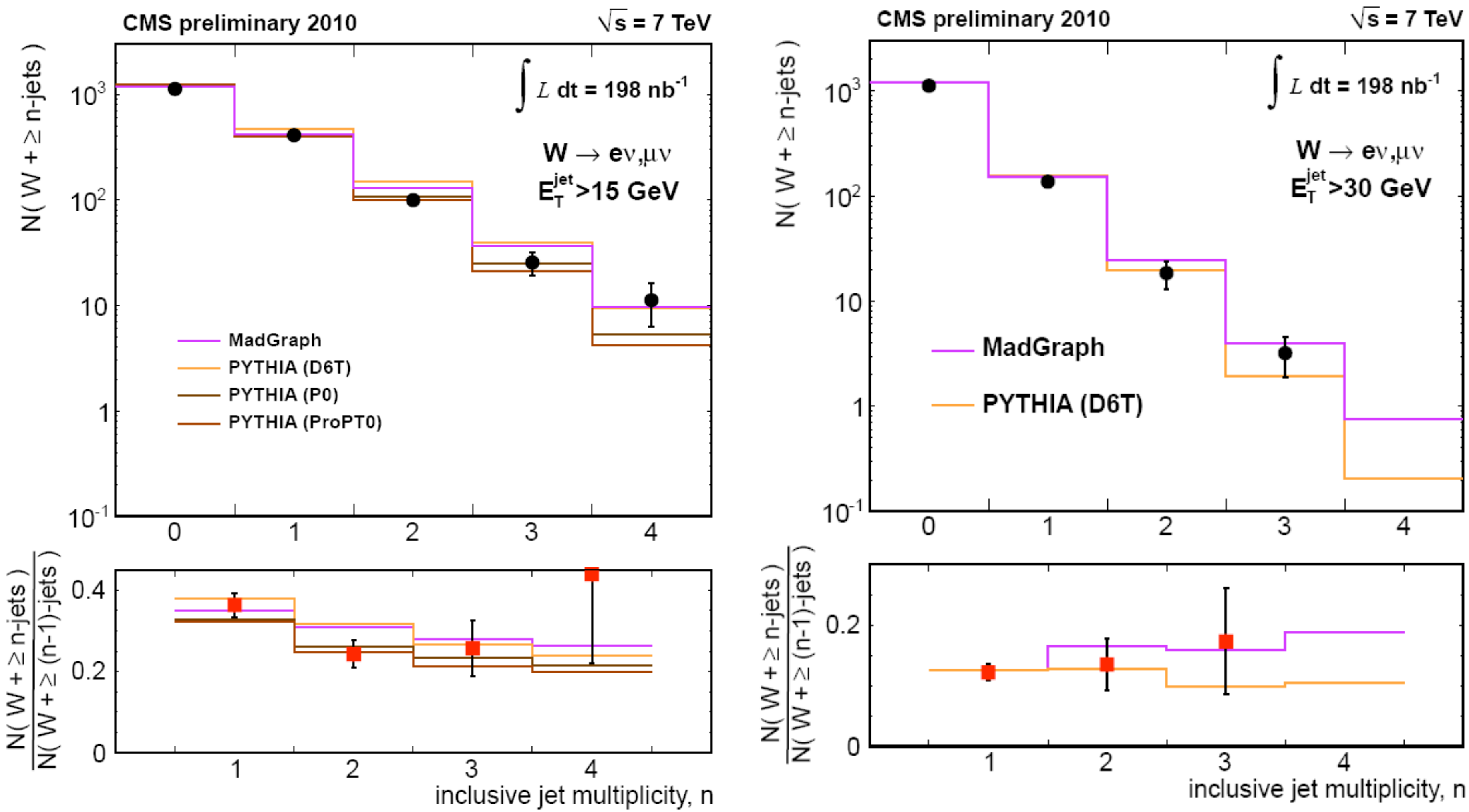
W+jets

- leading jet for W events (e,μ) with M_T> 50 GeV/c^2

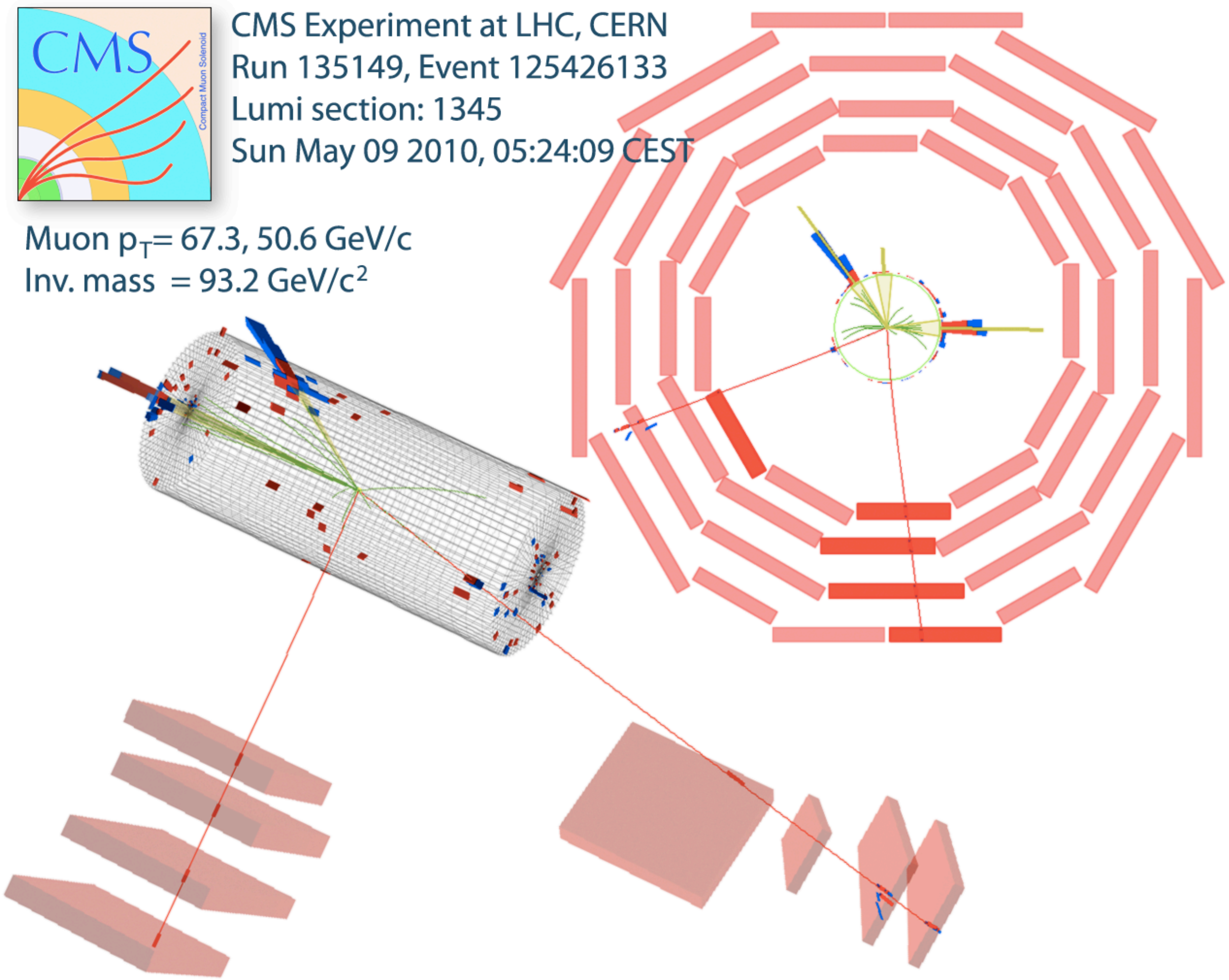
- Algorithm used: Anti-k_t (ΔR = 0.5) using Particle Flow Objects in $|\eta| < 2.5$



W+jets (2)

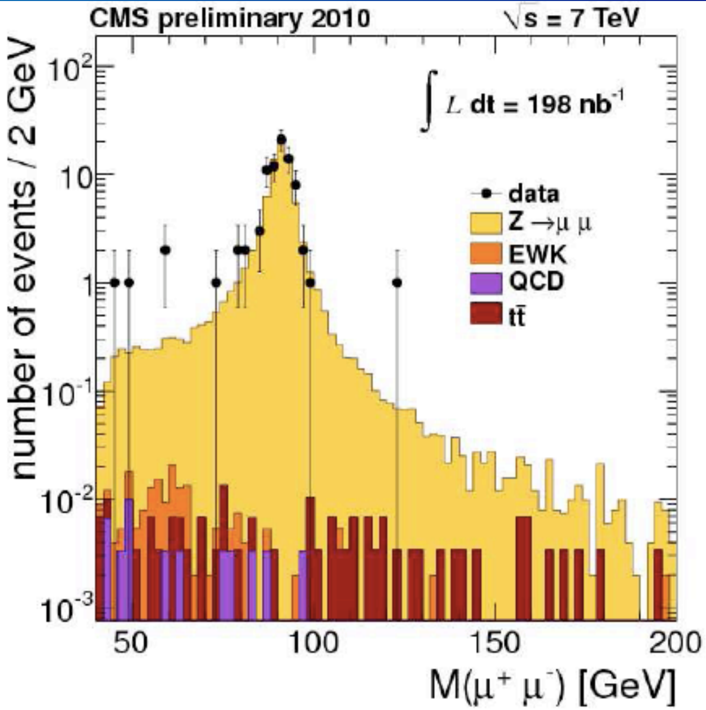

CMS preliminary 2010
$\sqrt{s}$ = 7 TeV
$\int L$ dt = 198 nb^{-1}
W → eν,μν
E_T^{jet}>15 GeV
MadGraph
PYTHIA (D6T)
PYTHIA (P0)
PYTHIA (ProPT0)
N(W + ≥ n-jets)
N(W + ≥ n-jets) / N(W + ≥ (n-1)-jets)
inclusive jet multiplicity, n
CMS preliminary 2010
$\sqrt{s}$ = 7 TeV
$\int L$ dt = 198 nb^{-1}
W → eν,μν
E_T^{jet}>30 GeV
MadGraph
PYTHIA (D6T)
N(W + ≥ n-jets)
N(W + ≥ n-jets) / N(W + ≥ (n-1)-jets)
inclusive jet multiplicity, n

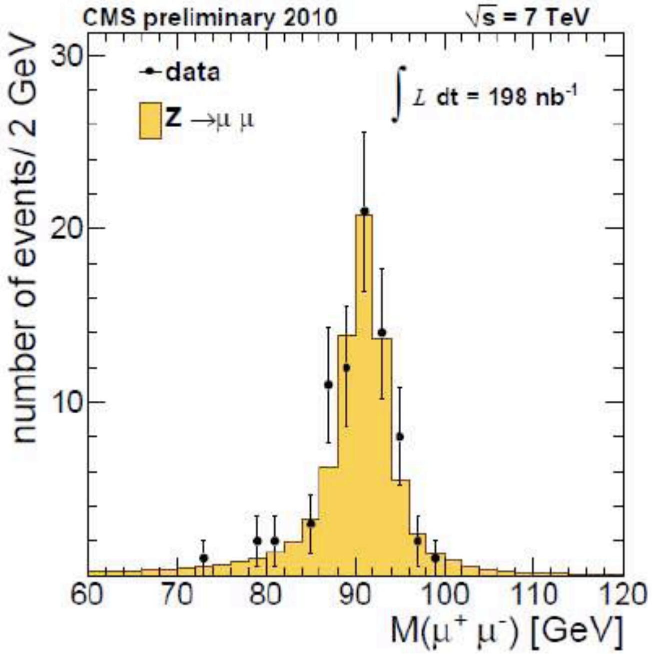
Z+2 jets


CMS
CMS Experiment at LHC, CERN
Run 135149, Event 125426133
Lumi section: 1345
Sun May 09 2010, 05:24:09 CEST
Muon p_T= 67.3, 50.6 GeV/c
Inv. mass = 93.2 GeV/c^2

Z : muon channel

- Event triggered by Level1 (Muon)+HLT (Muon+Tracker), $p_T > 9$ GeV
- **Selection Criteria**
  - 2 muons $p_t > 20$ GeV
  - Opposite charge muons
  - At least one in $|\eta| < 2.1$
  - Track-Based isolation ($\Sigma p_T < 3$ GeV)

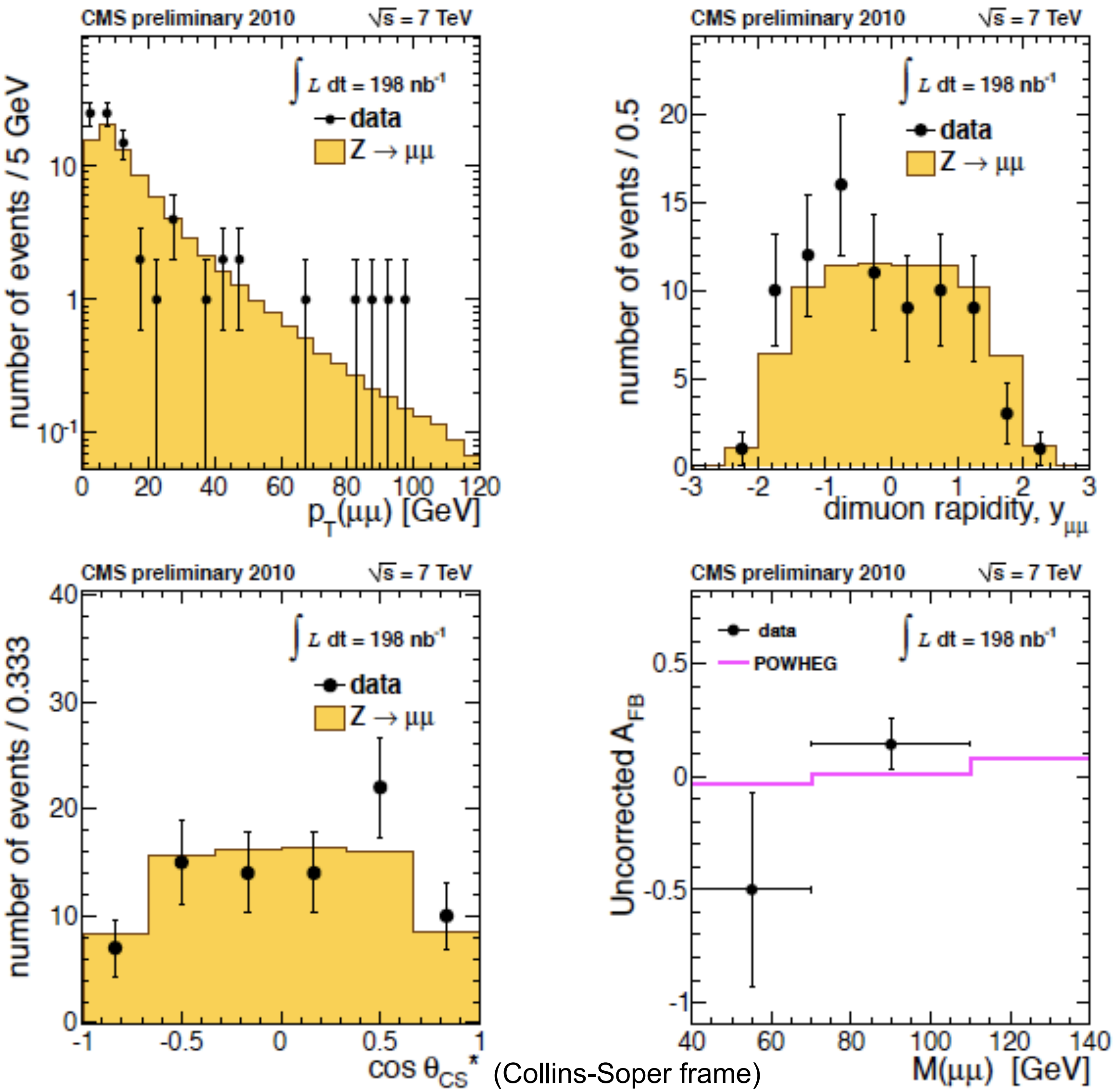




- Background negligible (~0.3%)
- 77 Events selected the invariant mass range $m_{\mu\mu}$ (60,120) GeV

$\sigma(pp \to Z+X \to \mu\mu+X) = 0.88 \pm 0.10$ nb

Differential distributions



Many powerful differential measurements possible for dileptons

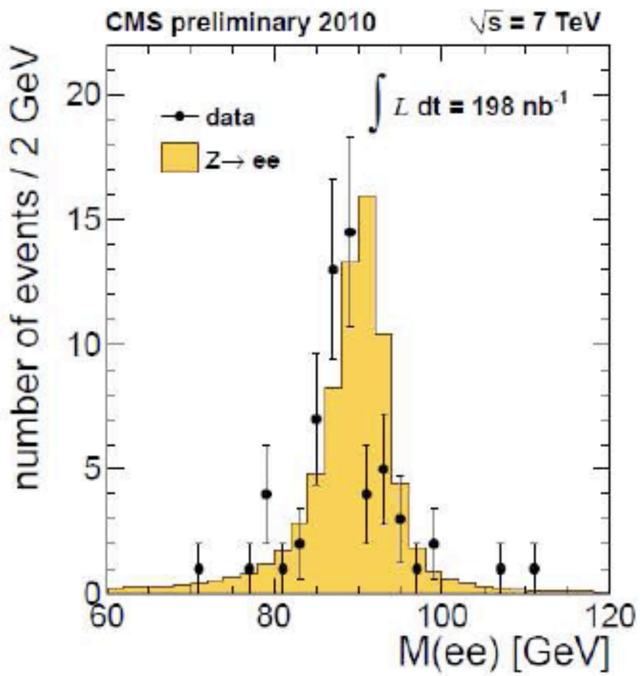
$$\frac{d\sigma(Z \rightarrow l^+ l^-)}{d\cos\theta_{CS}}$$

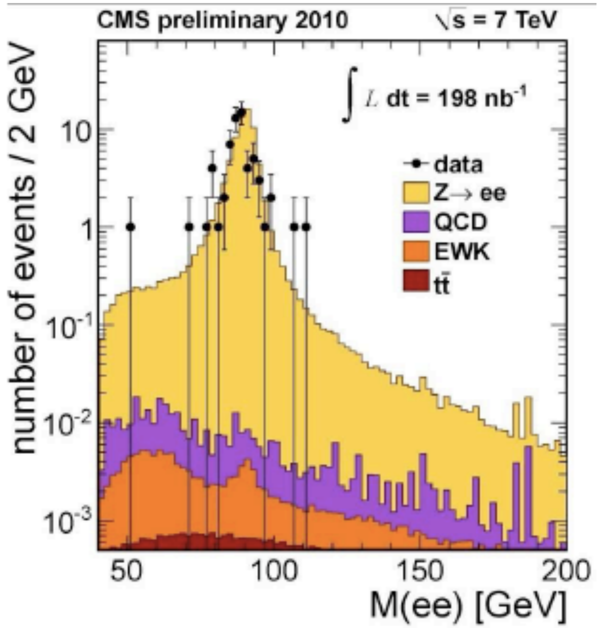
$$\frac{d\sigma(Z \rightarrow l^+ l^-)}{d q_T}$$

$$\frac{d\sigma(Z \rightarrow l^+ l^-)}{d Y}$$

Z to electrons

- Events trigger by Level1 (ECAL) + HLT (E_T>15 GeV)
- **Selection Criteria**
  - 2 electrons with E_T>20 GeV
  - Isolated (independently on tracker and calorimeters)

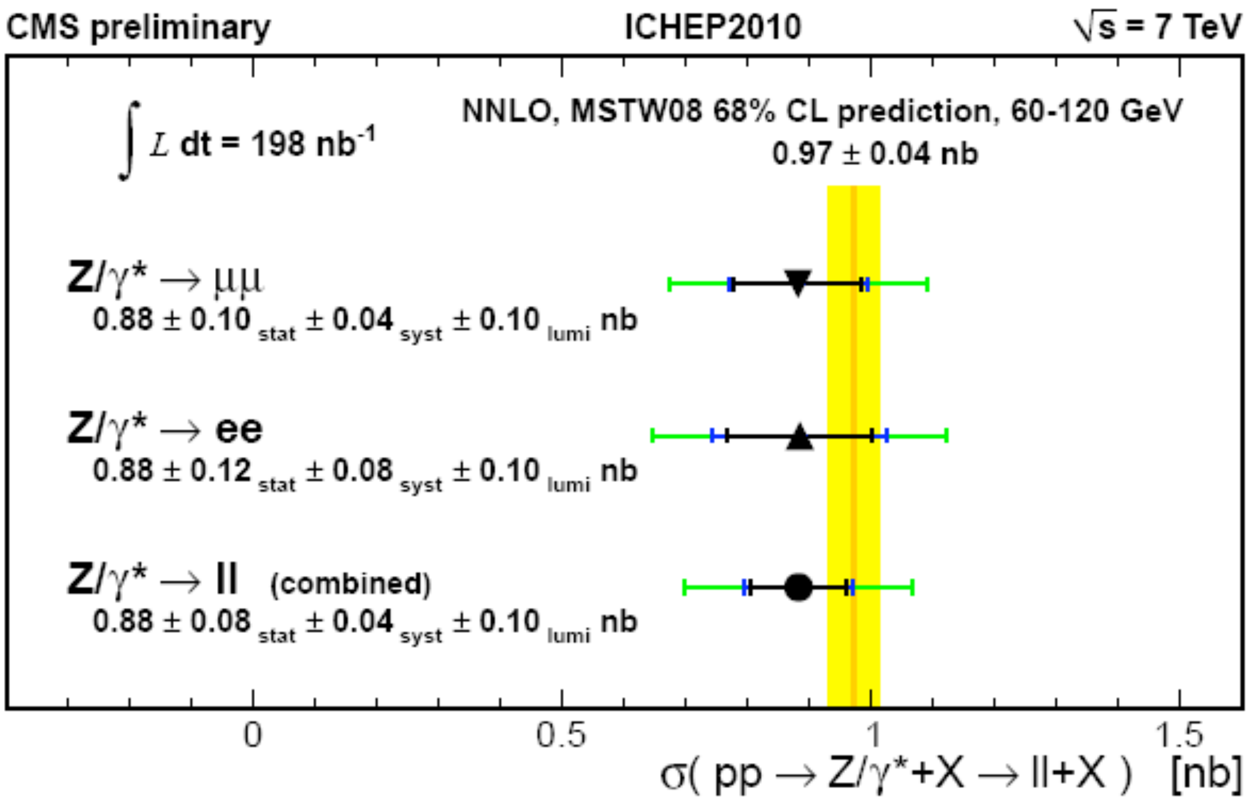




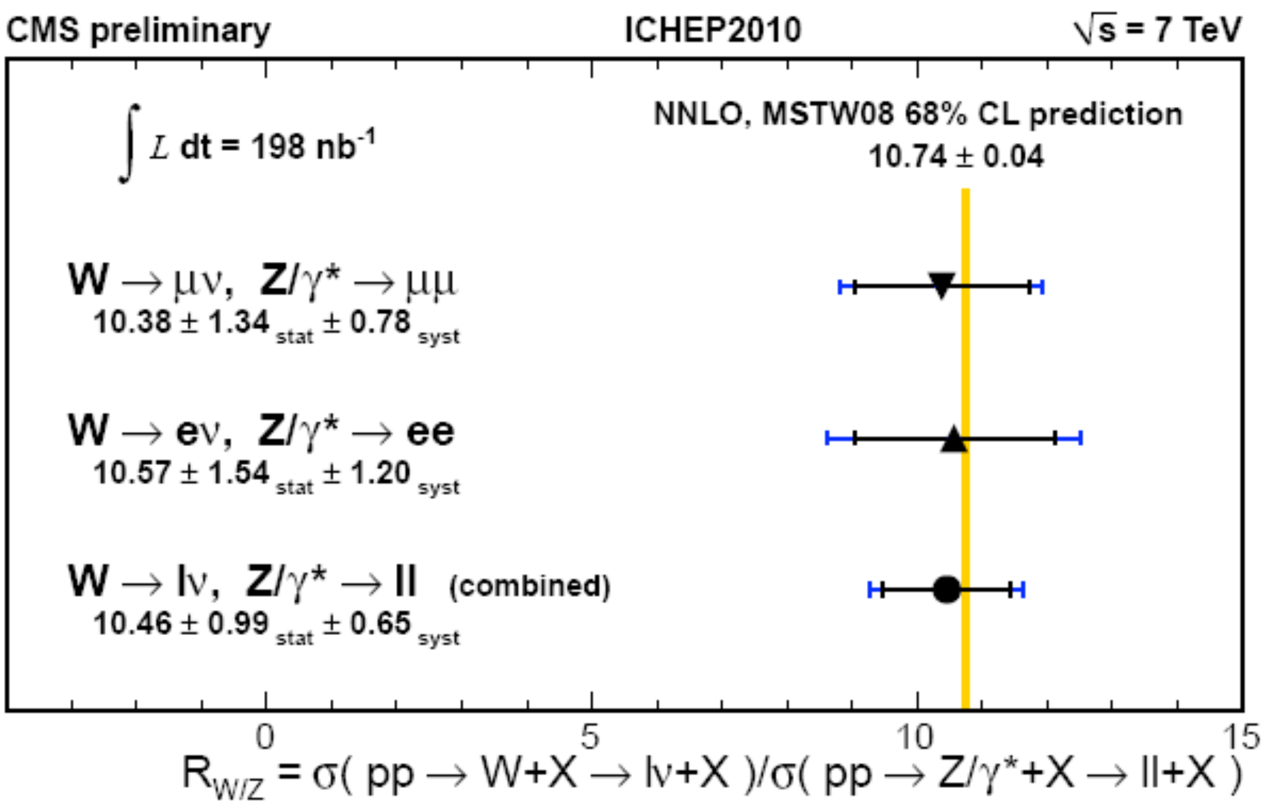
- Background negligible
- 61 events selected in the Invariant mass range m_{ee} (60,120)

σ(pp→Z+X→ee+X) =0.88 ± 0.11 nb

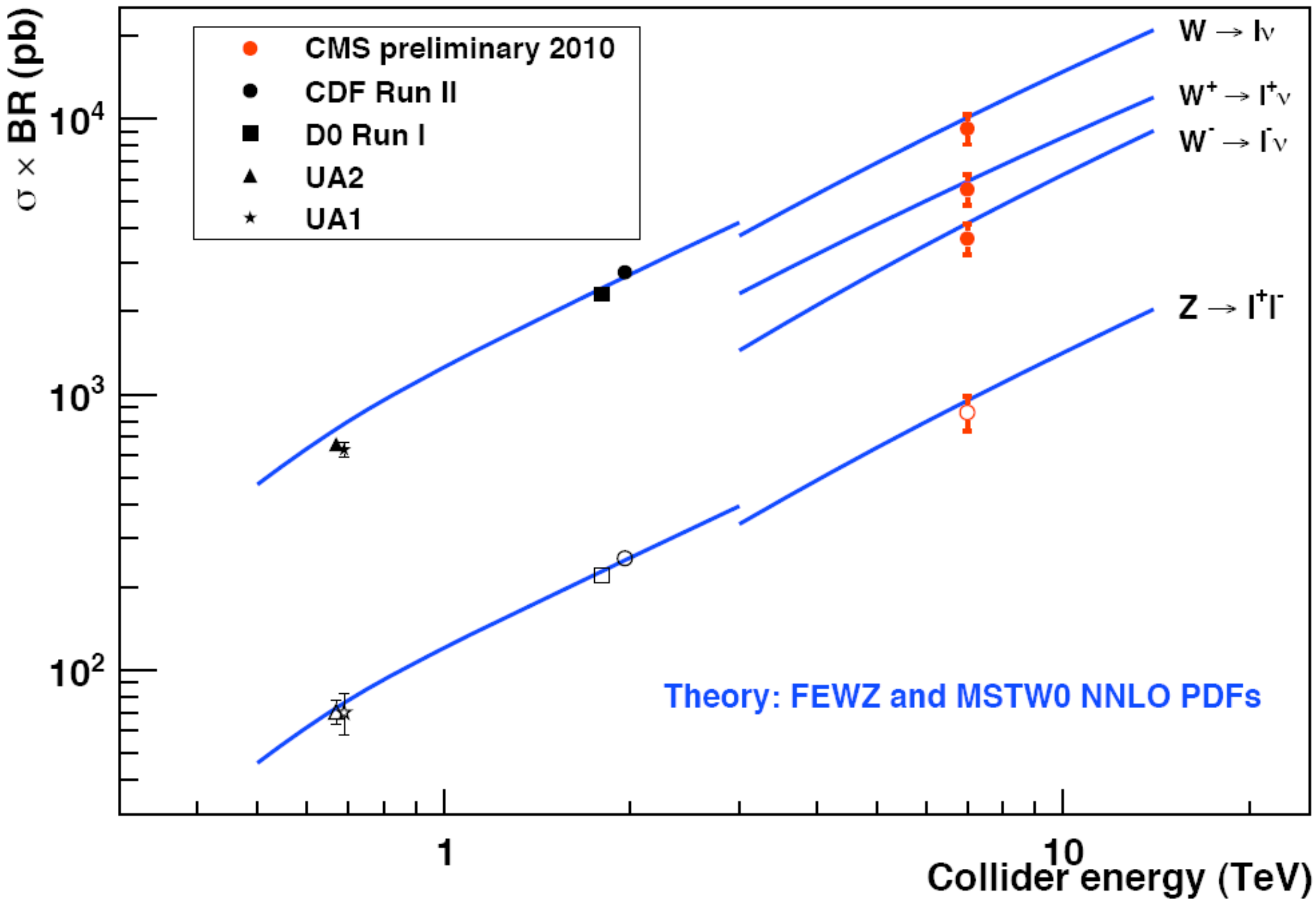
Z cross section



W/Z ratios


CMS preliminary
ICHEP2010
$\sqrt{s}$ = 7 TeV
$\int L\, dt$ = 198 nb^{-1}
NNLO, MSTW08 68% CL prediction
10.74 ± 0.04
$W \to \mu\nu$, $Z/\gamma^* \to \mu\mu$
10.38 ± 1.34 $_{stat}$ ± 0.78 $_{syst}$
$W \to e\nu$, $Z/\gamma^* \to ee$
10.57 ± 1.54 $_{stat}$ ± 1.20 $_{syst}$
$W \to l\nu$, $Z/\gamma^* \to ll$ (combined)
10.46 ± 0.99 $_{stat}$ ± 0.65 $_{syst}$
0
5
10
15
$R_{W/Z} = \sigma(pp \to W+X \to l\nu+X)/\sigma(pp \to Z/\gamma^*+X \to ll+X)$

W/Z cross section



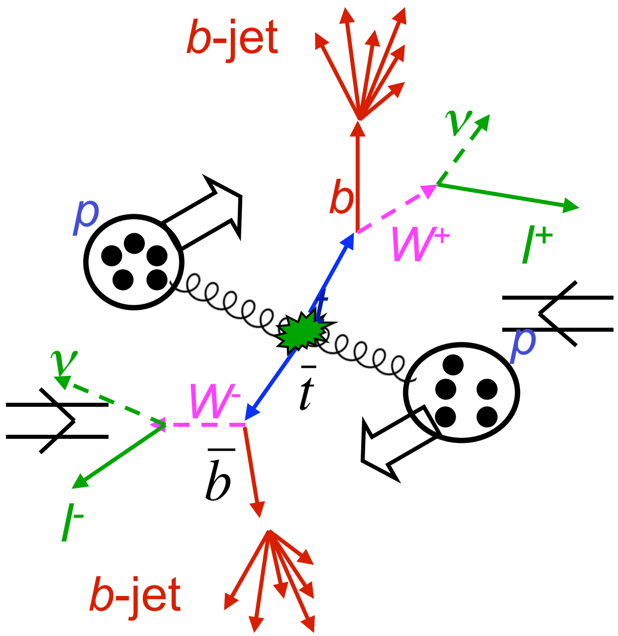
Top : dilepton selection

- Dilepton channels: *ee, μμ, eμ*
  - Triggers: μ+X (p_T > 9 GeV/c) or e/γ+X (E_T > 15 GeV)
  - 2 isolated,oppositely charged leptons (l = e,μ) of good quality
    - p_T(l) > 20 GeV/c
    - $|\eta_\mu| < 2.5$, $|\eta_e| < 2.4$
    - Relative isolation:

Detected energy around lepton

$$\text{Rel.isol.} = \frac{\overbrace{\sum_{R<0.3} p_T^{\text{track}} + \sum_{R<0.3} p_T^{\text{ECAL}} + \sum_{R<0.3} p_T^{\text{HCAL}}}}{p_T(\text{lepton})} < 15\ \%$$

  - Missing transverse energy (MET)
    - using Track Corrected MET
    - MET > 30 (20) GeV (in $e\mu$+X)

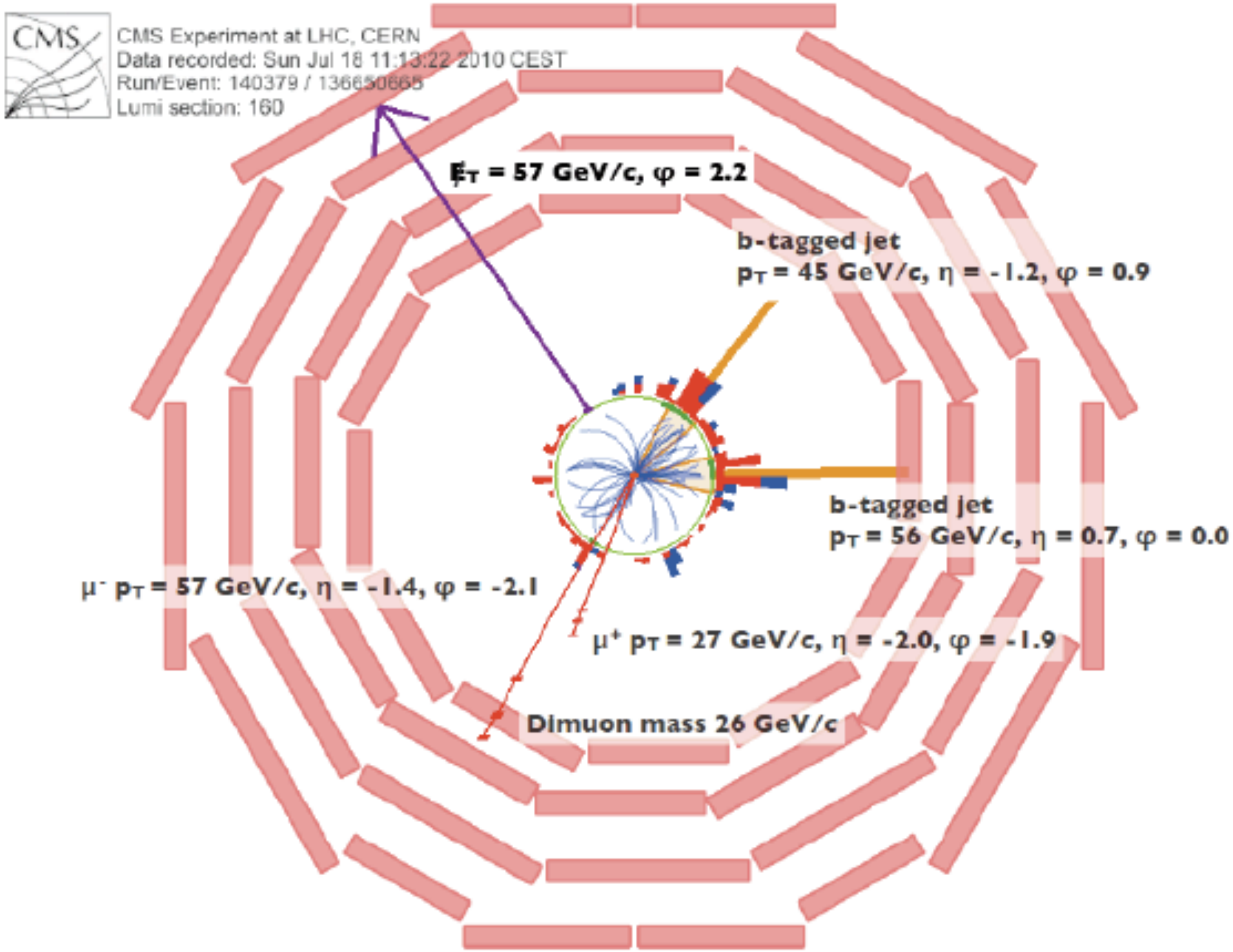


- *Z*-boson veto:
  - 76 < $M_{ee,\mu\mu}$ < 106 GeV/c²
- Count additional jets:
  - anti-k_T jets, R = 0.5

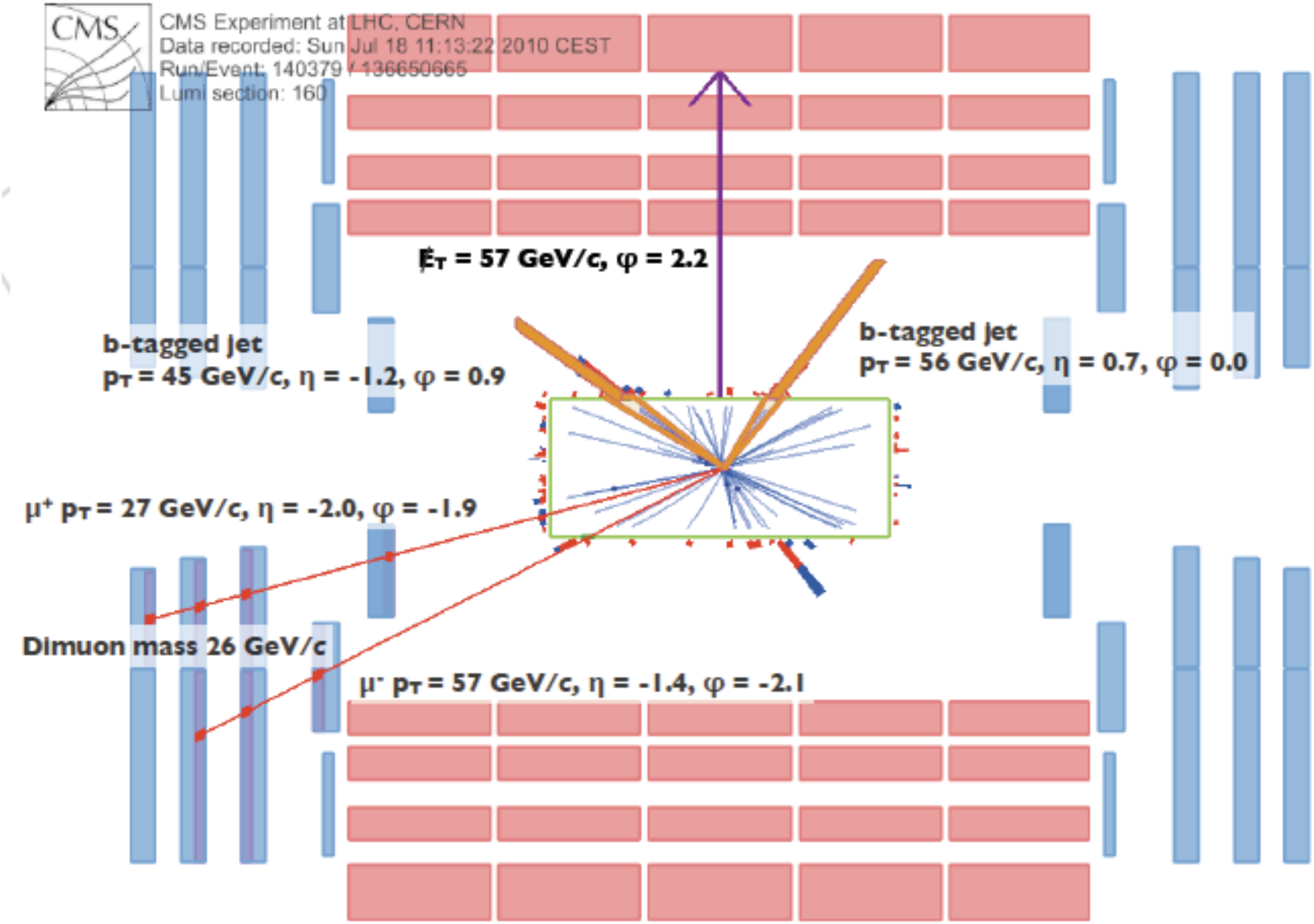
    $|\eta| < 2.4$, p_T > 30 GeV/c

  ≥ 2 jets typical for ttbar

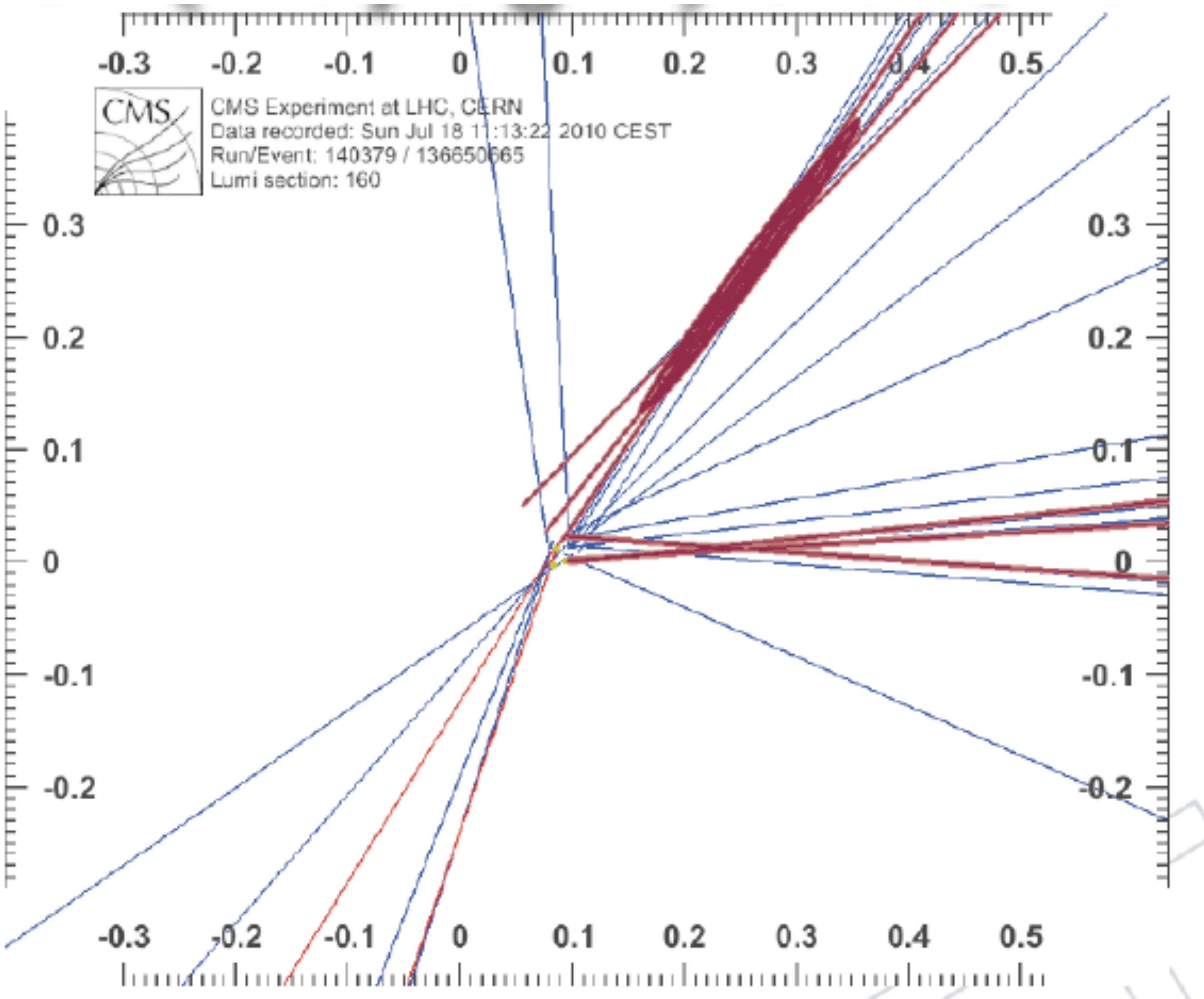
Top: dilepton candidate



Side view

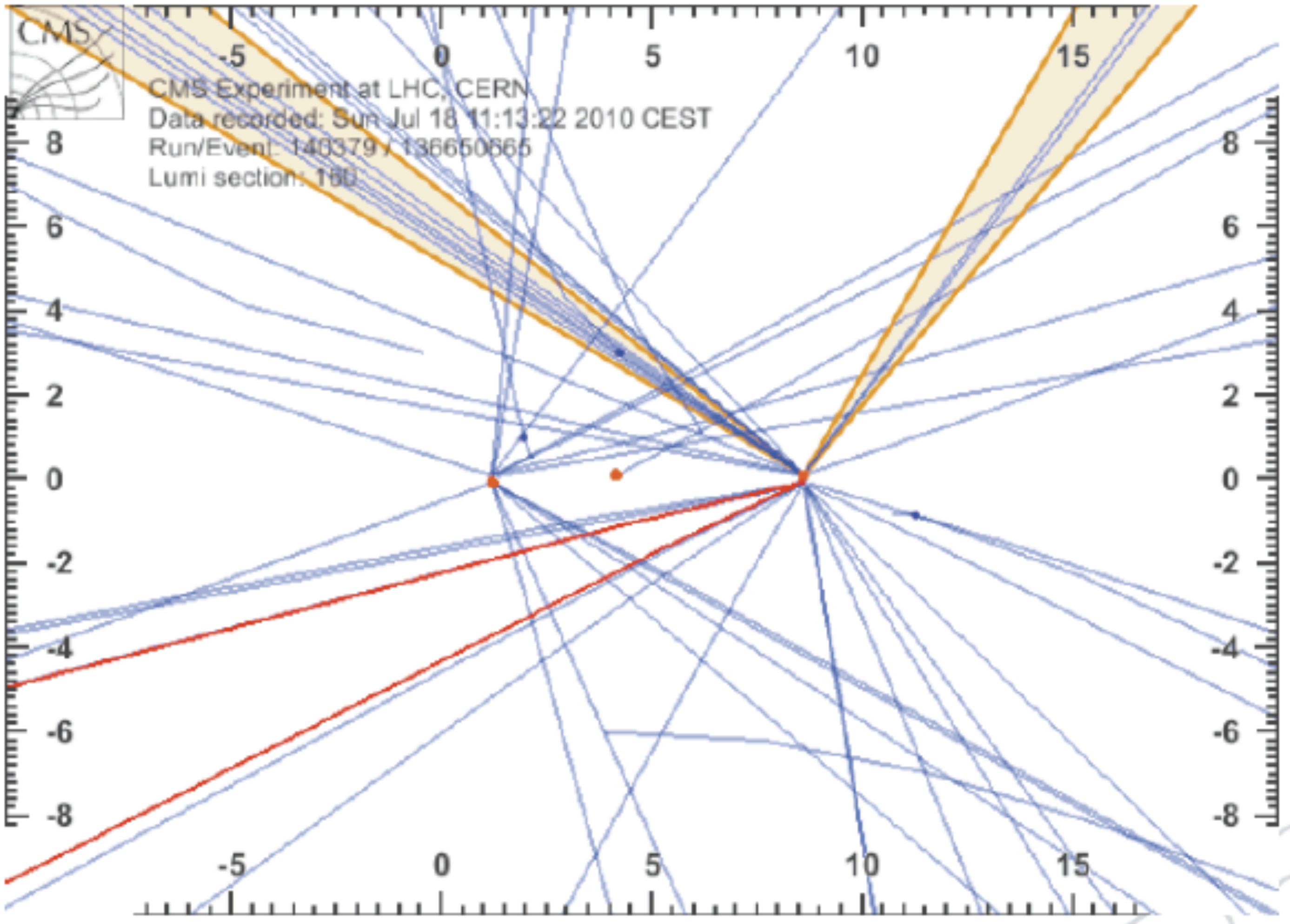

CMS Experiment at LHC, CERN
Data recorded: Sun Jul 18 11:13:22 2010 CEST
Run/Event: 140379 / 136650665
Lumi section: 160
$\not{E}_T$ = 57 GeV/c, φ = 2.2
b-tagged jet
p_T = 45 GeV/c, η = -1.2, φ = 0.9
b-tagged jet
p_T = 56 GeV/c, η = 0.7, φ = 0.0
μ^+ p_T = 27 GeV/c, η = -2.0, φ = -1.9
Dimuon mass 26 GeV/c
μ^- p_T = 57 GeV/c, η = -1.4, φ = -2.1

zoom



CMS Experiment at LHC, CERN
Data recorded: Sun Jul 18 11:13:22 2010 CEST
Run/Event: 140379 / 136650665
Lumi section: 160
-0.3 -0.2 -0.1 0 0.1 0.2 0.3 0.4 0.5
0.3 0.2 0.1 0 -0.1 -0.2

Side view : zoom

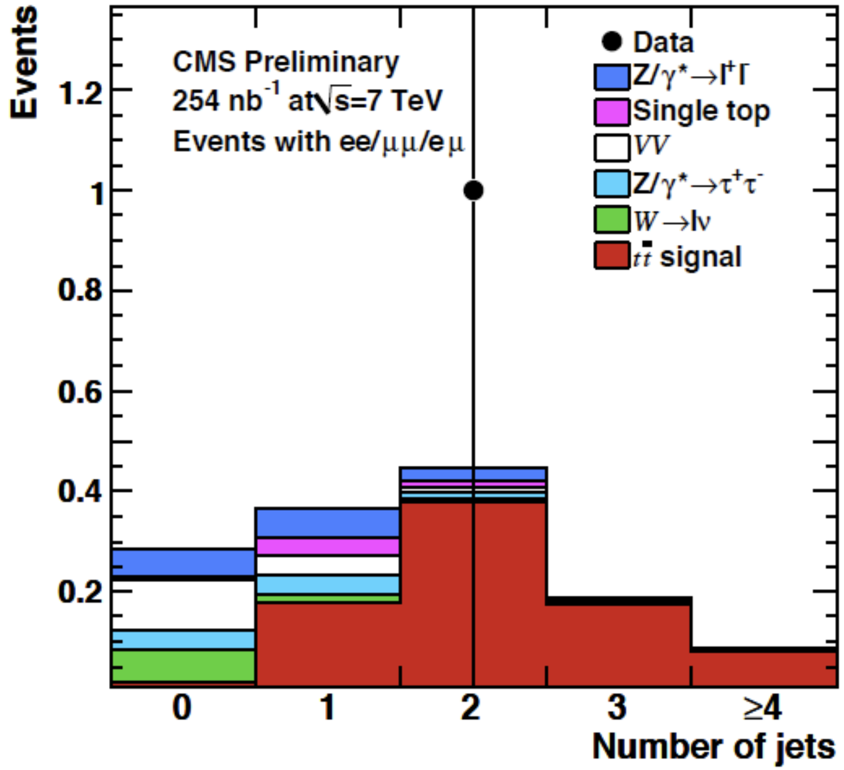


B-tag multiplicity

OK, but that's one event.

How much background is expected?

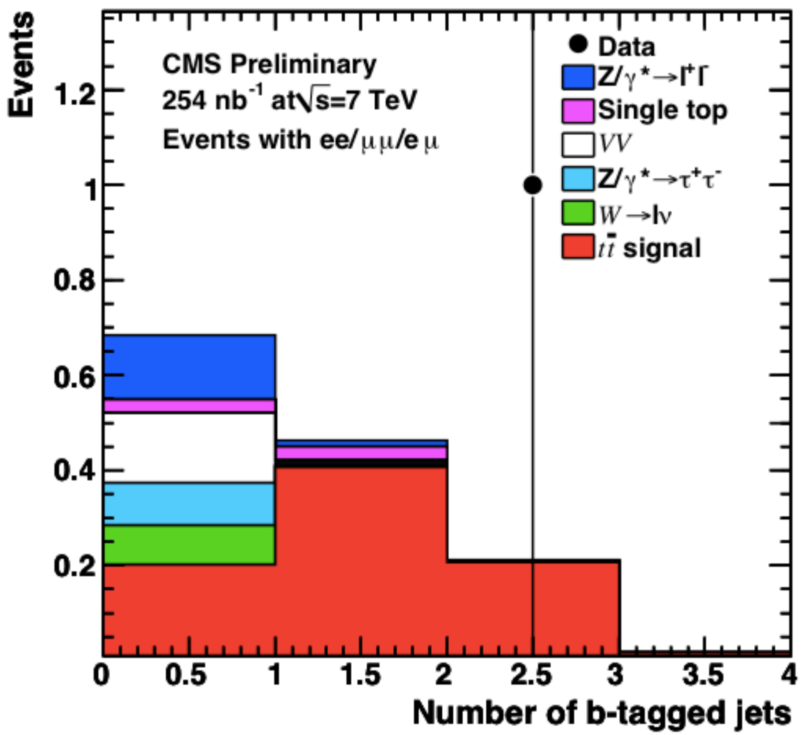
With standard di-lepton selection:
S/B = 5/1 (10/1 for e/mu)



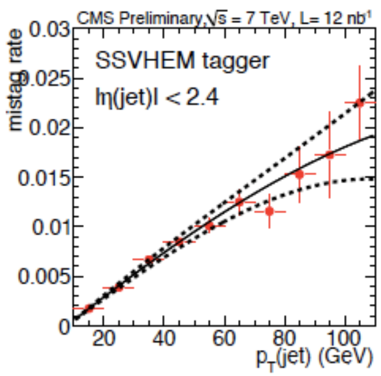
B-tag multiplicity

… and after b-tagging:

B-tagging algorithm used:
simple secondary vertex tagger, "high eff."
(i.e. made of ≥2 tracks),
medium working point
Efficiency ~ 40%



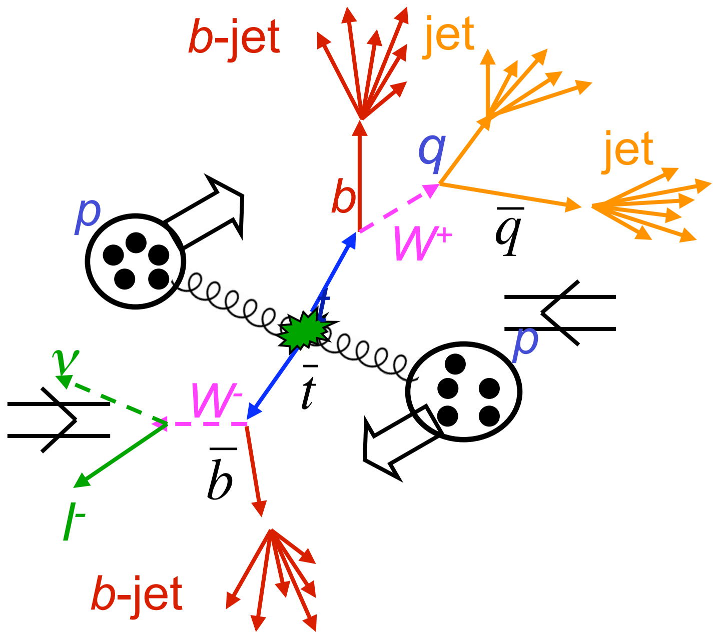
Mistag rate:



Top: semi-leptonic

- Channels: *e*+jets, *μ*+jets
  - Ask for exactly 1 prompt, isolated electron (muon) of good quality
  - Very similar selection of *e*,*μ* as before, but
    - tightened ID requirements and isolation:
      - Rel.isol. < 10%(*e*), 5%(*μ*)

      due to larger backgrounds
    - p_T(e) > 30 GeV/c
    - $p_T(\mu)$ > 20 GeV/c, $|\eta_\mu| < 2.1$
  - Do not apply (yet) any requirement of significant missing transverse energy (MET)

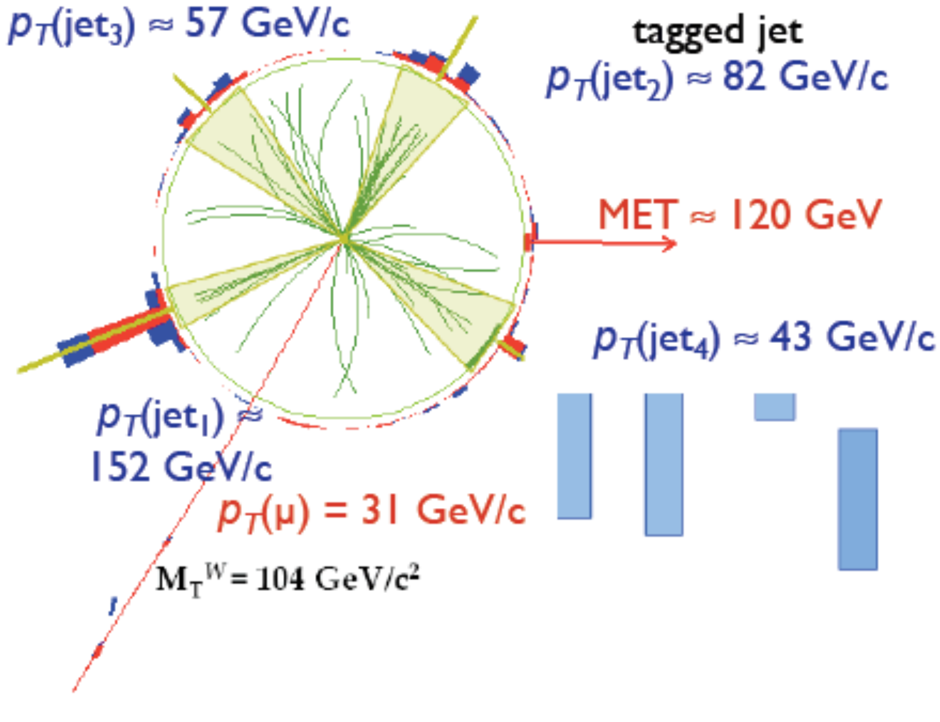


- Count additional jets
  - anti-k_T jets, R = 0.5

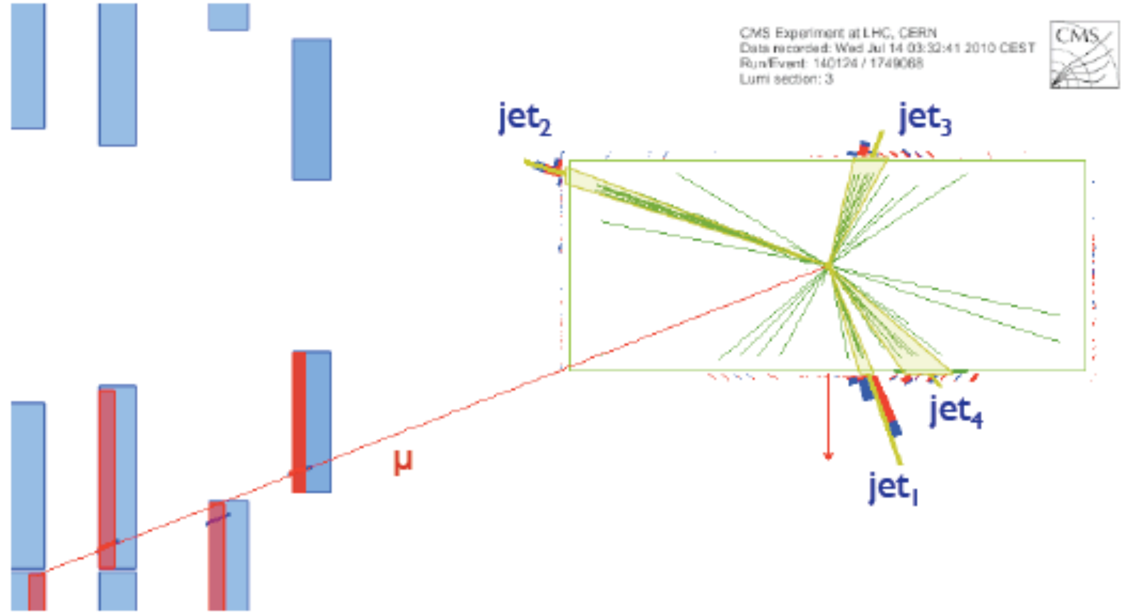
    $|\eta|$ < 2.4, p_T > 30 GeV/c

≥ 4 jets is typical for ttbar

Top μ+jet candidate

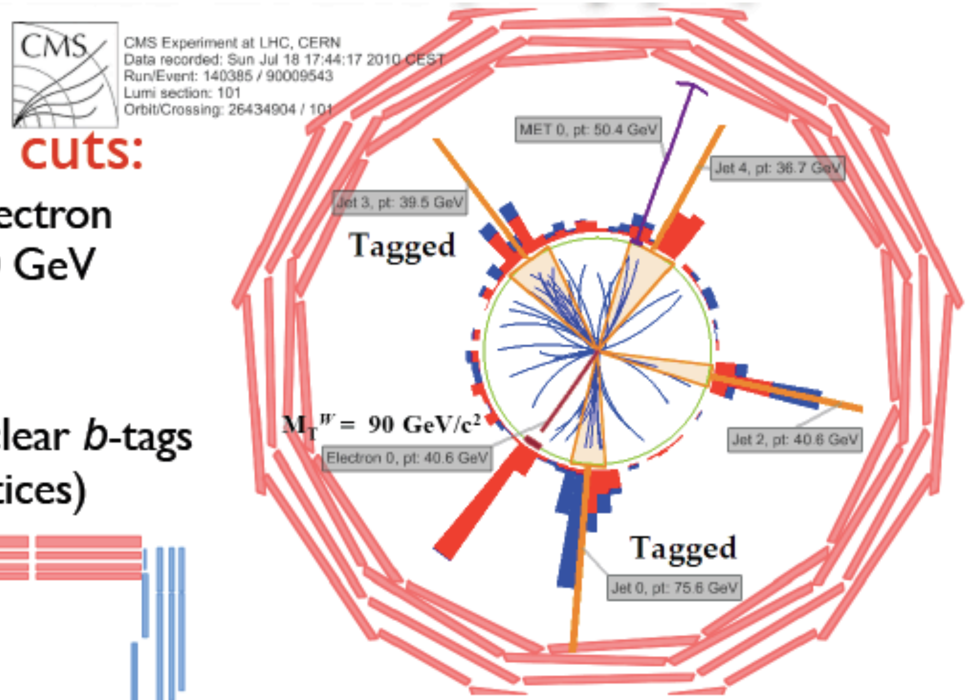


1 high-momentum muon
significant MET
$m_T(W) = 104$ GeV/c²
4 high-p_T jets,
one of which with good b-tag



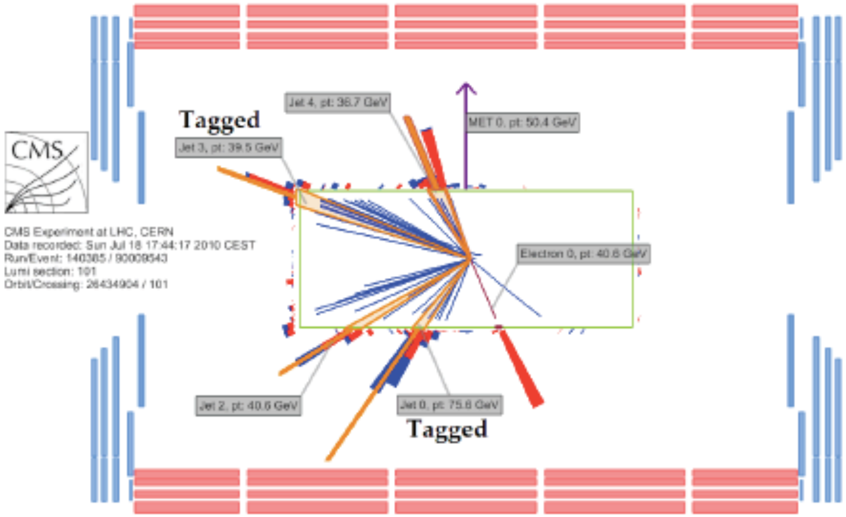
prelim. reconstructed mass is in the range 200–210 GeV/c²

Top e+jets candidate



Event passes all cuts:

1 high-momentum electron
significant MET ≈ 50 GeV
large m_T(W)
4 high-p_T jets,
two of which with good/clear *b*-tags
(and secondary vertices)



M3 ≈ 230 GeV/c²

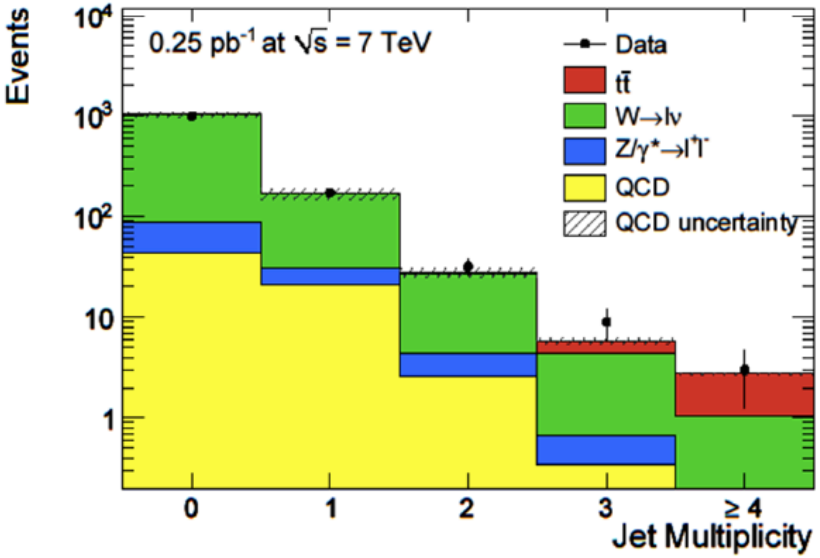
m_T(W) ≈ 77 GeV/c²

Mass of 2 untagged jets ≈ 102 GeV/c²

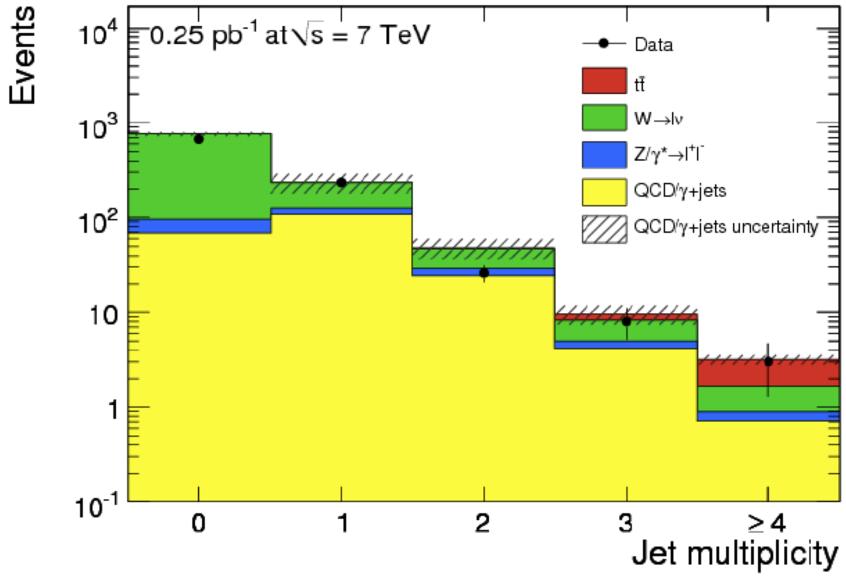
m(jjj) ≈ 208, 232 GeV/c²
(for the two 3-jet combinations)

Jet multiplicities

μ + jets

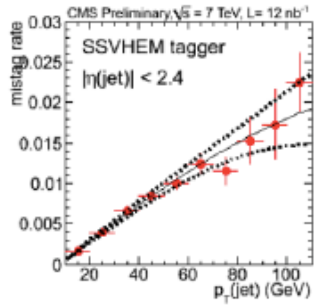


e + jets

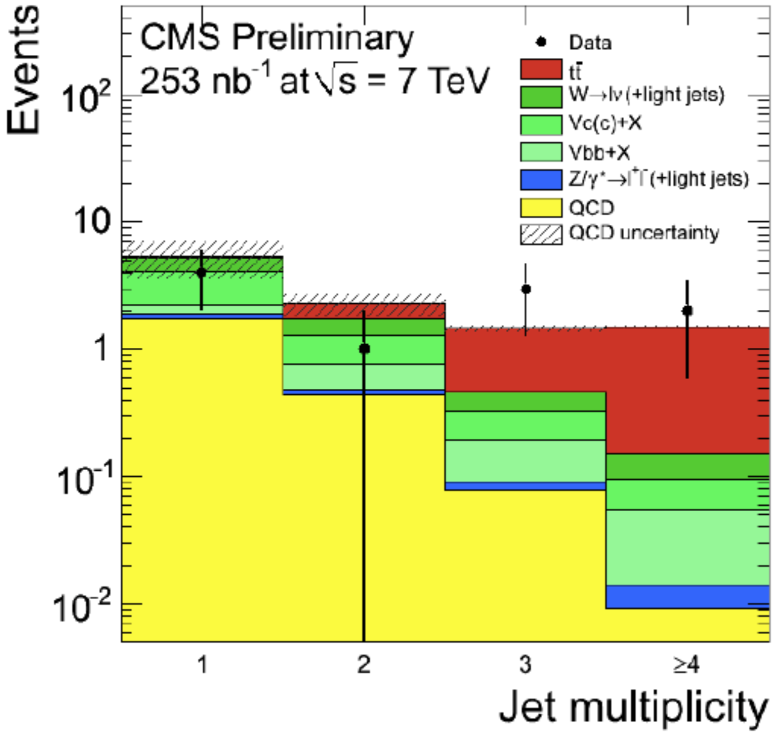


Jet mult. after b-tag

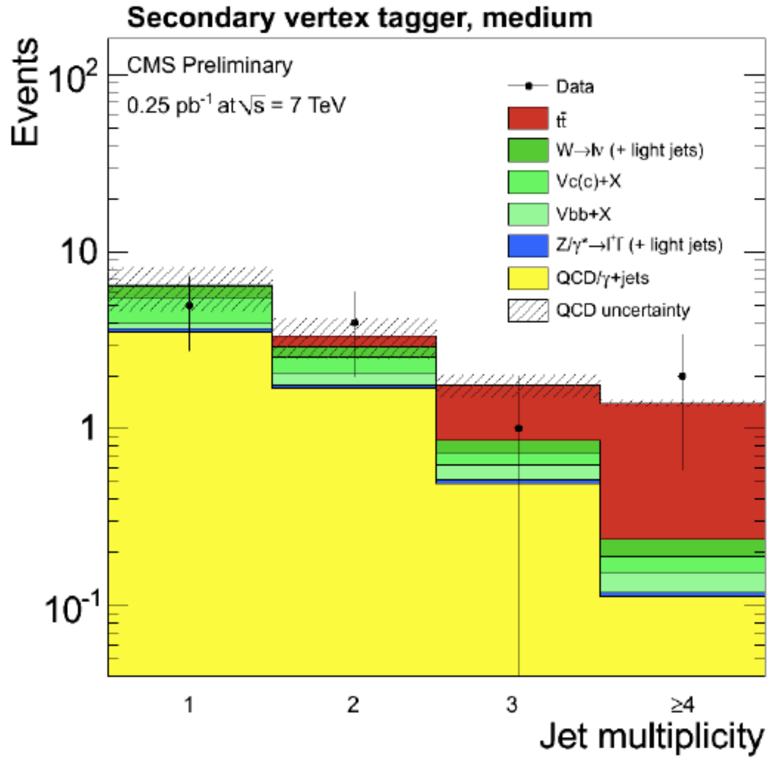
B-tagging algorithm used: simple secondary vertex tagger, "high eff." (i.e. made of ≥2 tracks), medium working point



μ + jets



e + jets



Top: status for 0.25 pb^{-1}

- Top in dilepton final state
  - ✓ Selection: two opposite sign good isolated leptons (e/mu) pt>20GeV/c each, nJet>=2 (can use >=1 too), Z-veto in ee and mumu, MET>30 (ee/mumu) 20 (emu)
  - ✓ Expect about 3 events in 1 pb^{-1} with about 5:1 S:Bgd (10:1 in emu) without b-tagging
- ==> about 0.8 signal events expected in 0.25 pb^{-1} <== observe 1 !

- Top in e+jets and mu+jets
  - ✓ Selection: good isolated e (pt>30GeV/c) or mu (pt>20 GeV/c), >= 4 jets
    - Large QCD background implies tighter ID and isolation required compared to dileptons
    - B-tagging is quite helpful
  - ✓ Expect about 6(e)+7(mu) with about 7+4 background events in 1 pb^{-1} without b-tagging
- ==> about 1.5e +1.7mu signal events and about 3 backgrounds <== observe 6 !

Supersymmetry

One of the most appealing extensions of the Standard Model:

TeV-scale supersymmetry

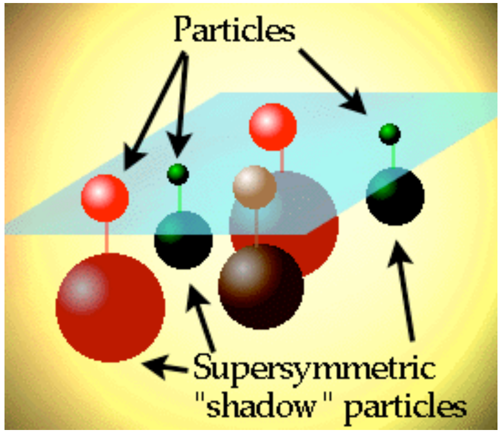
[= a symmetry between fermions and bosons,
duplicates the SM particle spectrum, but not the couplings]

Solves several problems at once:

- hierarchy problem
- opening towards a theory of gravity
- unification of gauge couplings
- dark matter candidate (=lightest susy particle or LSP)
- allows to explain why the Higgs mechanism works

SUSY particles

Need to introduce new particles :



leptons (f) → sleptons (b) $(\tilde{l}, \tilde{q})$
quarks (f) → squarks (b)
gauge bosons (b) → gauginos (f) } neutralinos
Higgs bosons (b) → higgsinos (f) } charginos

$(\chi_1^0, \chi_2^0, \chi_3^0, \chi_4^0)$

$(\chi_1^\pm, \chi_2^\pm)$

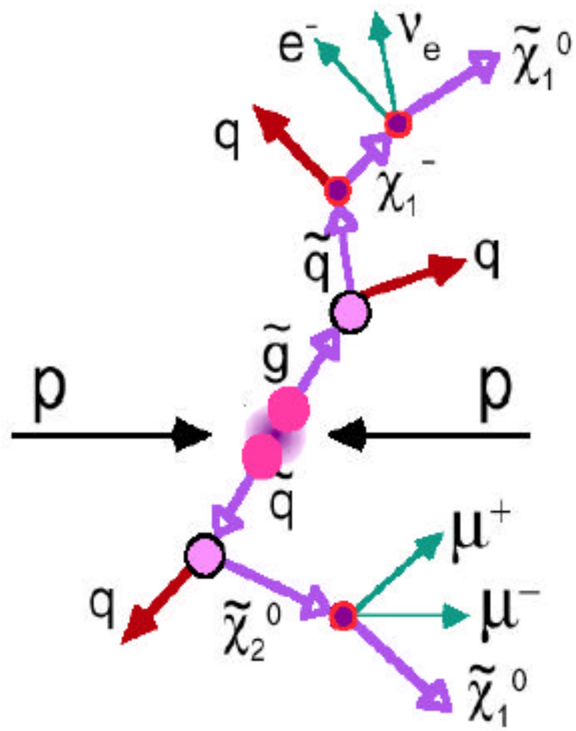
(f = fermion, b = boson)

General characteristics of R-parity conserving SUSY:

• sparticles pair-produced and LSP stable
→ large amount of missing transverse energy

• coloured sparticles are copiously produced and cascade down to the LSP with emission of many hard jets and often leptons

→ Generic SUSY signatures are
E_T^{miss} + multi-jets (and multi-leptons)



SUSY at the LHC?

Two types of signatures at the LHC:

- Missing Transverse Energy signals: “standard” WIMP neutralino (also: lightest KK particle, lightest T-odd parity particle, …)
- long-lived heavy charged particles : stau, R-hadrons (GMSB, split-susy, …)

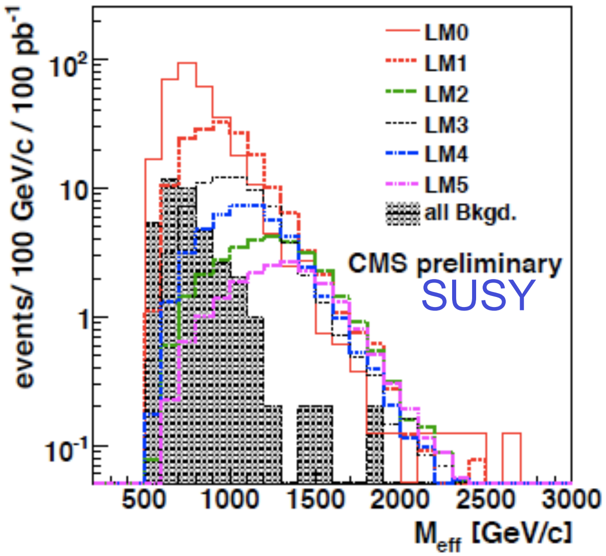
Goal of the LHC:

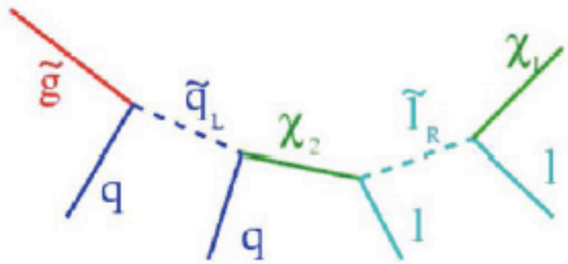
1) *Discovery*
2) *Measure properties, identify underlying physics*

A typical SUSY selection

Event selection :

- large missing E_T (MET): O(> 200 GeV) (→ LSP)
  - MET challenging to control at startup
- at least 3 hard jets (→ cascade decays)
  - 3 may not always be optimal
- N leptons (according to investigated topology)
  - growing N: reduces QCD background
- angular or event shape variables for background rejection
  - top background probably the most challenging





Main backgrounds: tt+jets, W+jets, Z+jets, QCD (multijet)

SUSY seaches

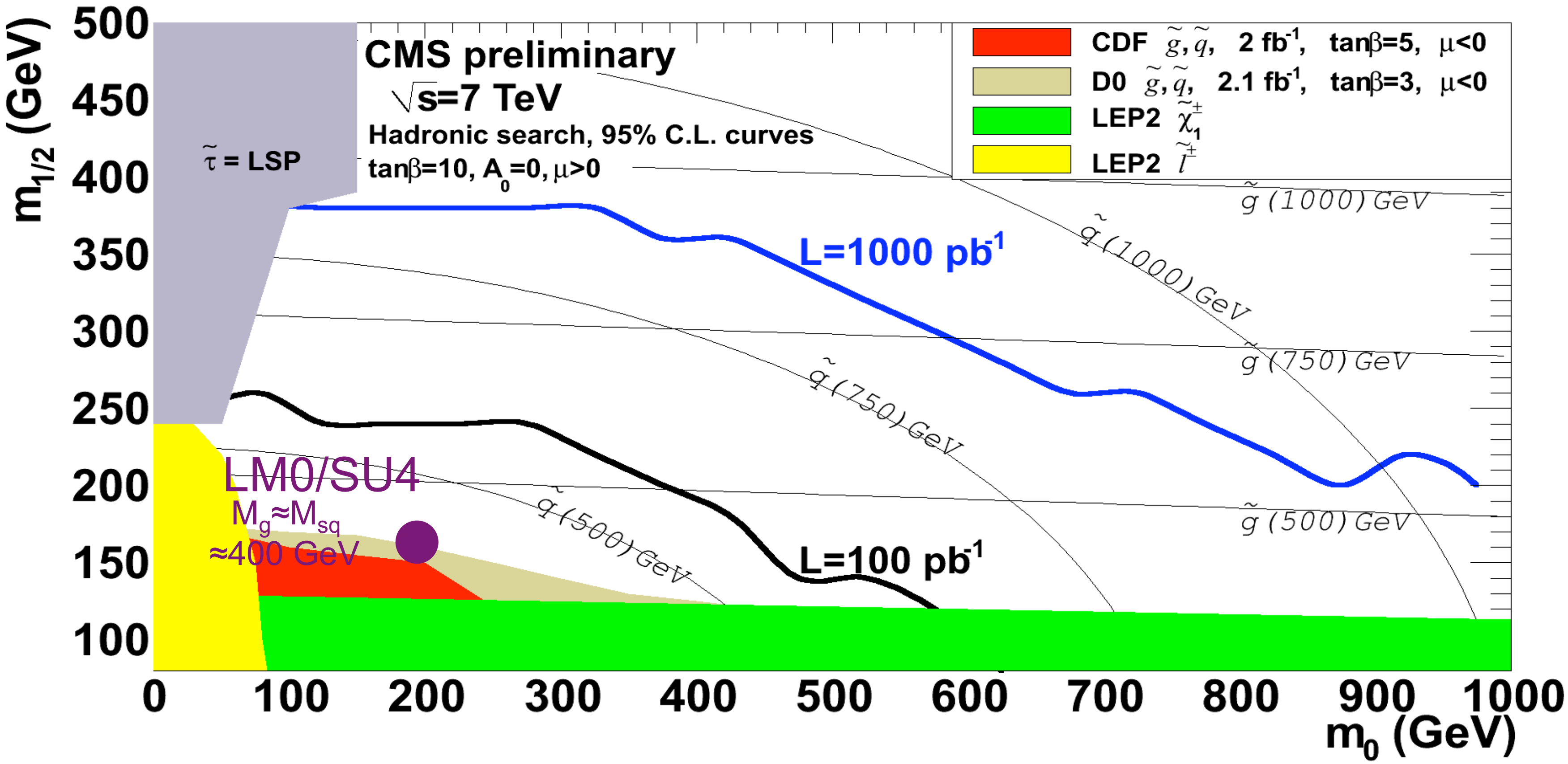
Searches considered in CMS in the near future:

0 leptons	1 lepton	2 leptons	≥3 leptons
• Exclusive 2-jets • Inclusive Jets • Photons + Jets		• Like-sign • Opposite sign	

Approach

- For many background measurements, we (mostly) do not want to (only) rely on
  - Predicted cross sections (especially for QCD)
  - Predicted kinematical distributions
- Major emphasis on “Data-driven background determinations”
  - Rely on control samples in the data, sometimes with some assistance from Monte Carlo
  - May suffer from limitations (statistical or systematic) that reduce the precision of the measurement. Will evolve rapidly w/more data.

Inclusive Jet + MET reach



- 95% CL exclusion for all-hadronic search (≥ 3 jets + MET + e/μ veto)
- Systematic uncertainty of 50% assumed on Standard Model background
- *Sensitivity significantly beyond previous experiments (~50/pb to surpass Tevatron)*

Hadronic SUSY

$N_{leptons}$=0 : largest signal cross section, but beware of QCD!

Efficiency for e.g. SPS1a: 13%

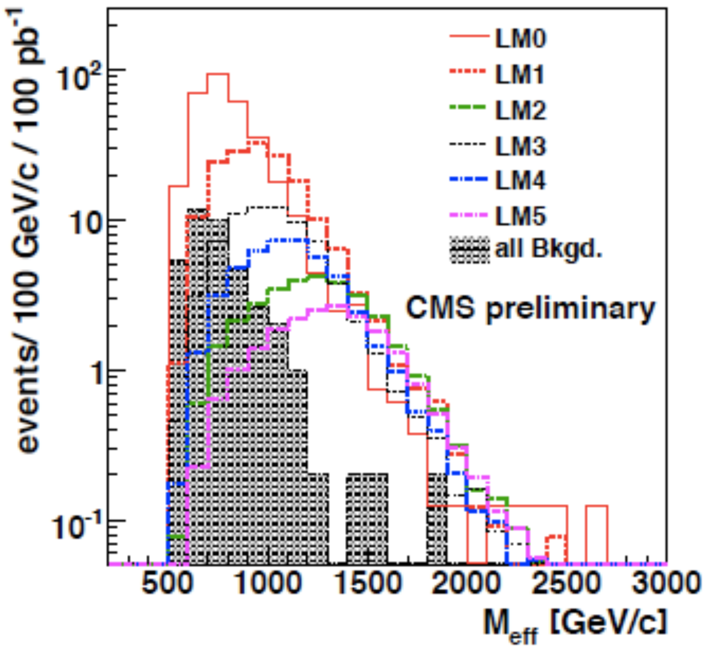
(SPS1a = LM1)

Event Selection:

- MET > 200 GeV
- ≥ 3 jets ($|\eta|$ < 1.7/3/3) with E_T > 180/110/30 GeV
- HT (= $E_{T,j2}+E_{T,j3}+E_{T,j4}$+MET) > 500 GeV
- indirect lepton veto
- cleanup and QCD rejection (see next slide)

Main backgrounds:

- QCD multijets: MET due to mis-measurements or jet resolution
- Z+jets: $Z \to \nu\nu$ irreducible
- tt+jets: hadronic or lost lepton(s)
- W+jets: hadronic or lost lepton



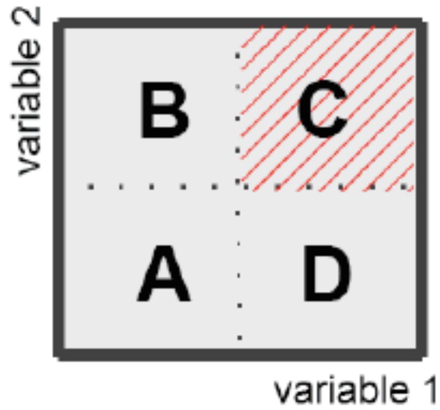
ABCD method

Examples of data-driven methods:

- often "ABCD" method used:

Idea:
IF variable 1
and variable 2
are uncorrelated:

$$C = D \cdot \frac{B}{A}$$



Avoid signal contamination in A,B,D

- variables for hadronic search: MET, Rsum, $\Delta\phi$(jj), $\Delta\phi$(hemisphere), …
- variables for leptonic search: lepton isolation, impact parameter, MET, …
- correlations to be studied

New variables

CMS PAS SUS-09-001

L. Randall and D. Tucker-Smith, "Dijet Searches for Supersymmetry at the LHC," Phys. Rev. Lett. **101 (2008) 221803.**

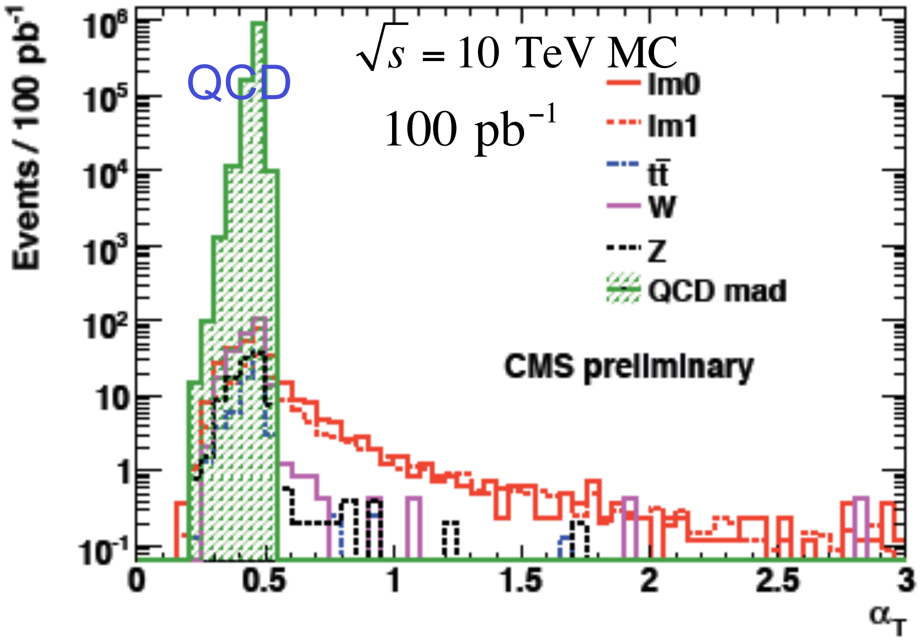
- Dijet analysis

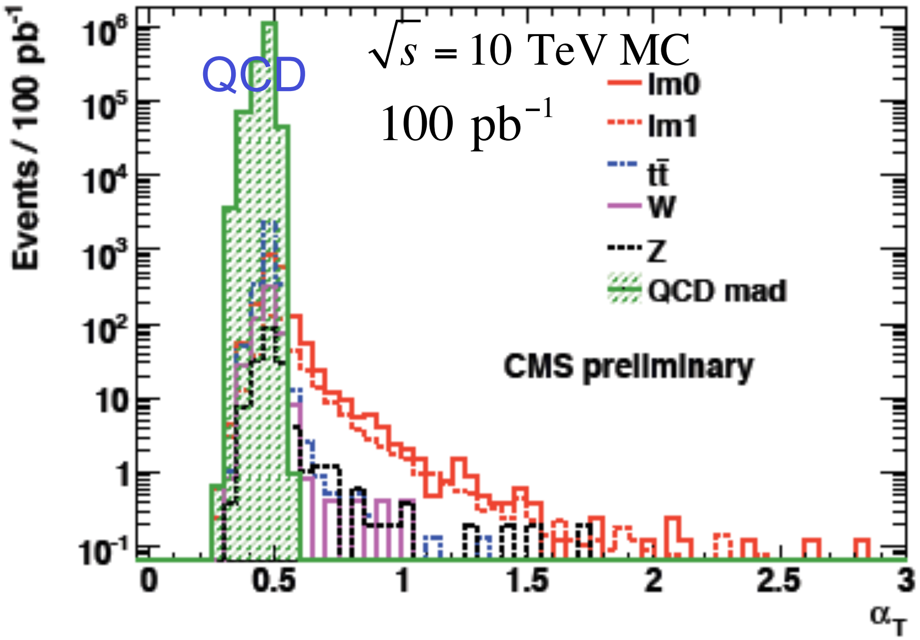
$$\alpha_T \equiv E_T^{j_2} / M_T(j_1 j_2) = \frac{\sqrt{E_T^{j_2} / E_T^{j_1}}}{\sqrt{2(1-\cos\Delta\varphi)}}$$

- N=3-6 jets: form two pseudo-jets
- minimize

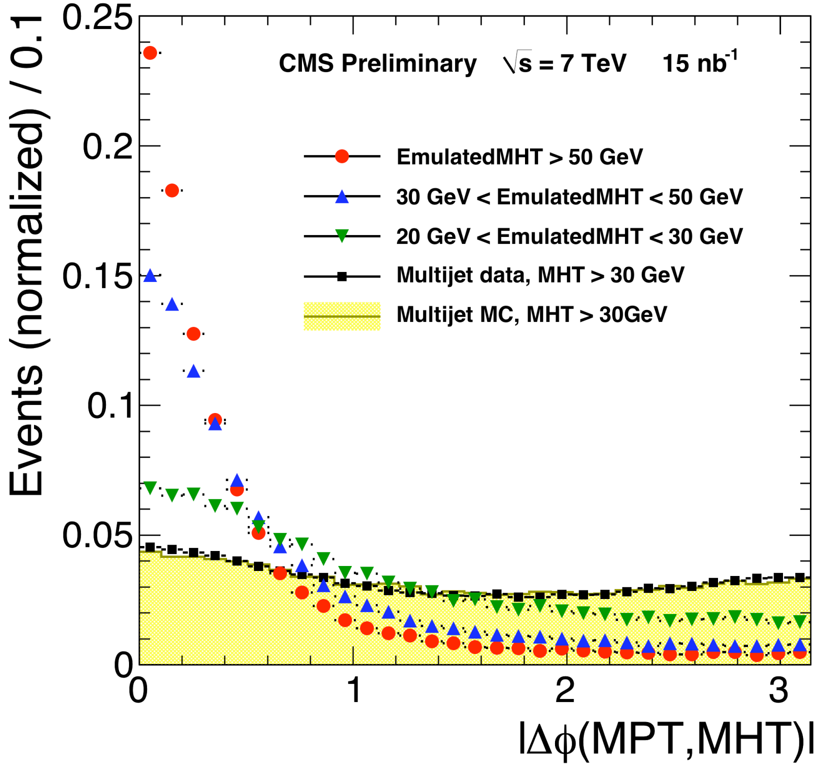
$$\Delta HT = E_T^{pj1} - E_T^{pj2}$$

$$\alpha_T \equiv \frac{1}{2}\frac{HT - \Delta HT}{\sqrt{HT^2 - MHT^2}}$$





Double-checking MET



- Independent measurement of missing momentum from Tracker & Calorimeter

$$\mathrm{MHT} = \left| -\sum_i \vec{p}_{\mathrm{T}}(\mathrm{jet}_i) \right|$$

$$\mathrm{MPT} \equiv \left| -\textstyle\sum_i \vec{p}_{\mathrm{T}}(\mathrm{track}_i) \right|$$

- Compare the direction of MPT and MHT, Δϕ(MPT,MHT)

✓ Very little correlation between the directions of MPT and MHT when no real MHT is present (QCD)

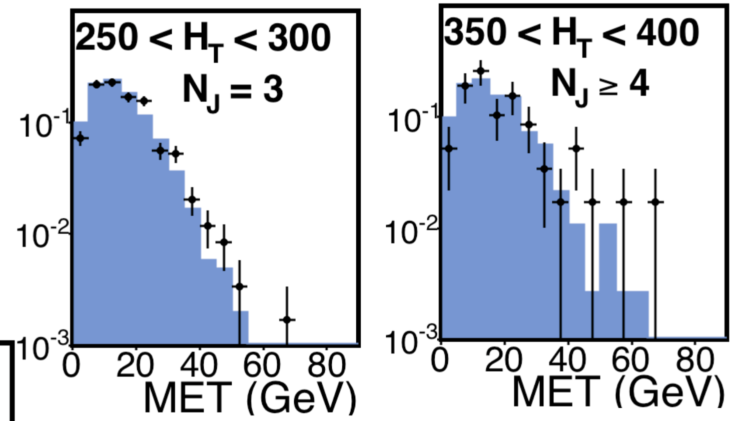
✓ peaks towards zero for real MHT (emulated by removing a random jet)

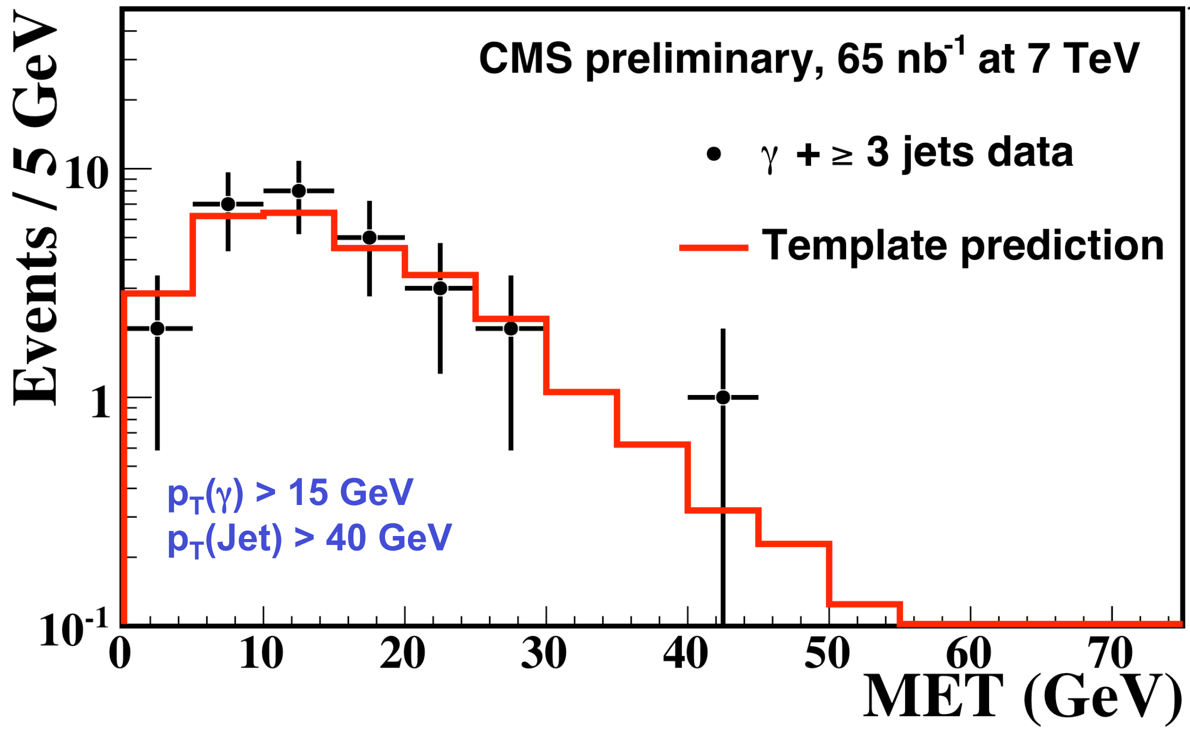
✓ Also useful to remove events with a fake MHT due to noise in the calorimeter

Predicting MET tails

- Can we predict MET due to jet mis-measurements?
- Test: use MET templates from multi-jet events to predict MET for **γ+jets events**

MET templates from multi-jet events





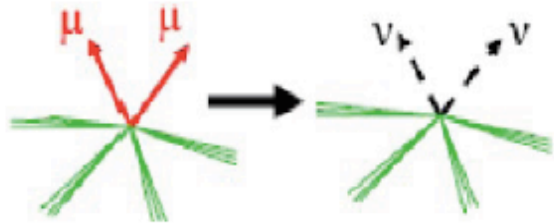
✓ Good agreement between predicted and observed distributions:
for MET > 15 GeV
predicted = 12.5
observed = 11

Bckg rejection?

Data-driven estimation from Z+jets

"standard candle": use $Z \to \mu\mu$

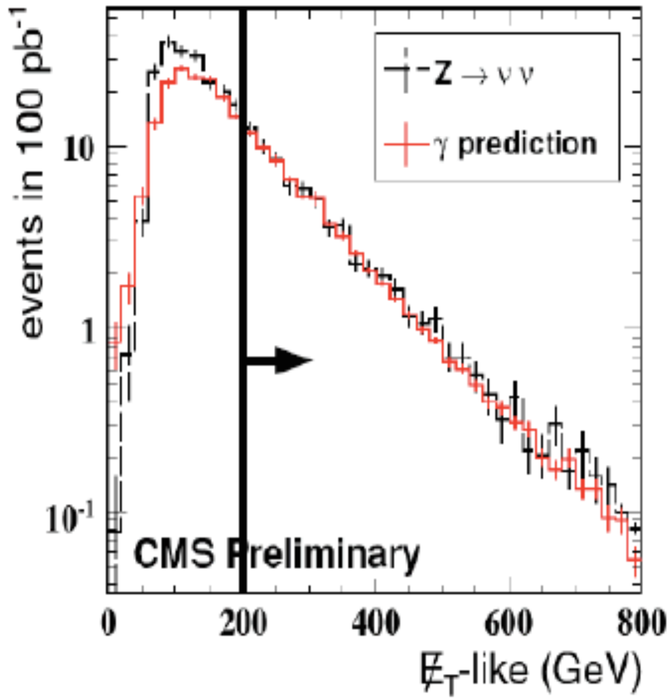
- replace leptons by neutrinos (and correct for acceptance using MC)
- total uncertainty ~20% for 1fb^{-1} statistics limited: $BR(Z \to \mu\mu) = 1/6\ BR(Z \to \nu\nu)$



New: data-driven estimation from W,γ+jets

assumption: bosonic events at high Pt look similar → use W,γ+jets

- gain in statistics (→ 100 pb^{-1} analyses) $\sigma(W+2j) = 3\ \sigma(Z+2j) = 0.8\ \sigma(\gamma+2j)$
- complementary to the above (other backgrounds/other triggers)
- beware of signal contamination



$Z \to \nu\nu$ background estimate (100 pb^{-1})	
MC-truth	35
From γ+jets	29 ± 3 (stat) ± 5 (sys)
From W+jets	35 ± 10 (stat) ± 8 (sys) ± 3 (theory)

2l OS SUSY

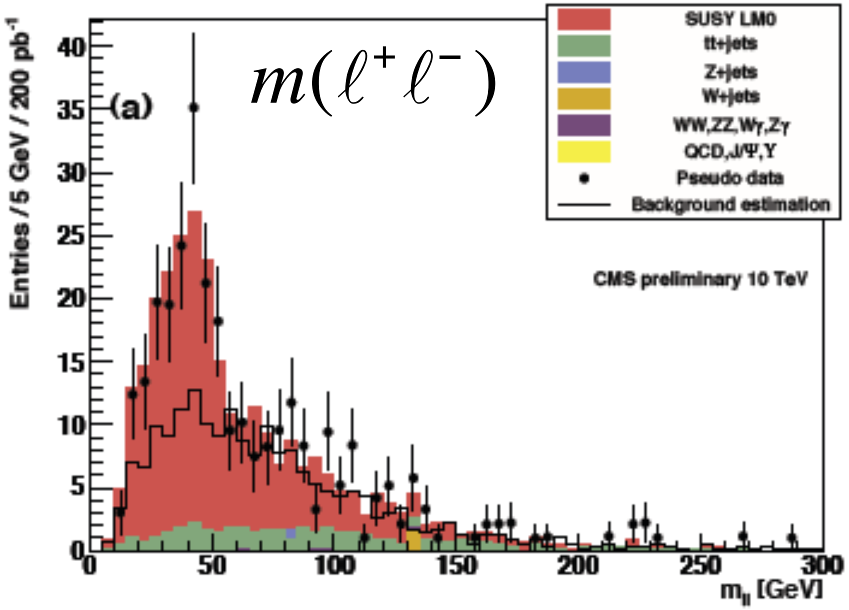
- Traditional approach: search for opp. sign, same flavor leptons from correlated SUSY production:

$$\tilde{\chi}_2^0 \rightarrow \ell^+ \tilde{\ell}^-; \quad \tilde{\ell}^- \rightarrow \ell^- \tilde{\chi}_1^0$$

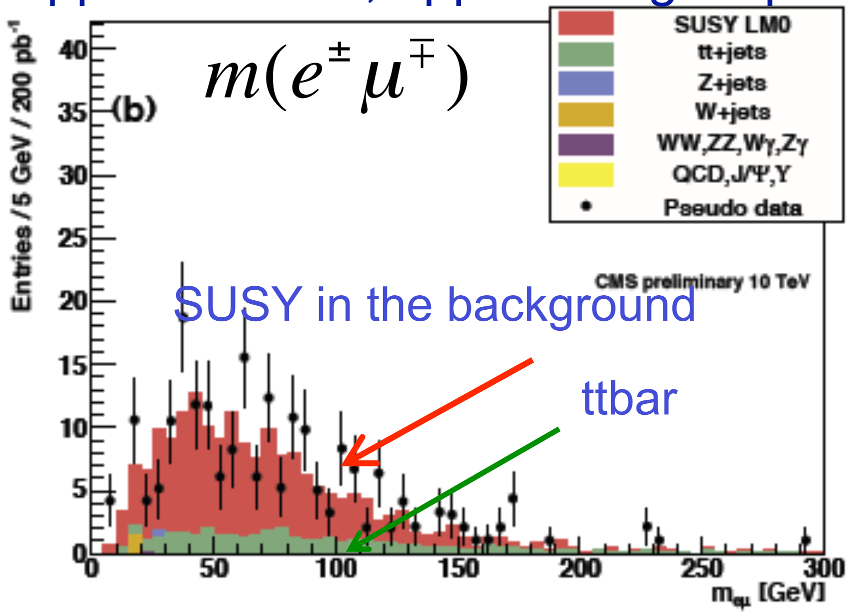
slepton on-shell: seq. 2-body decays
slepton off-shell: 3-body decay

- Background estimations from eμ control sample.

Same flavor; opposite sign leptons



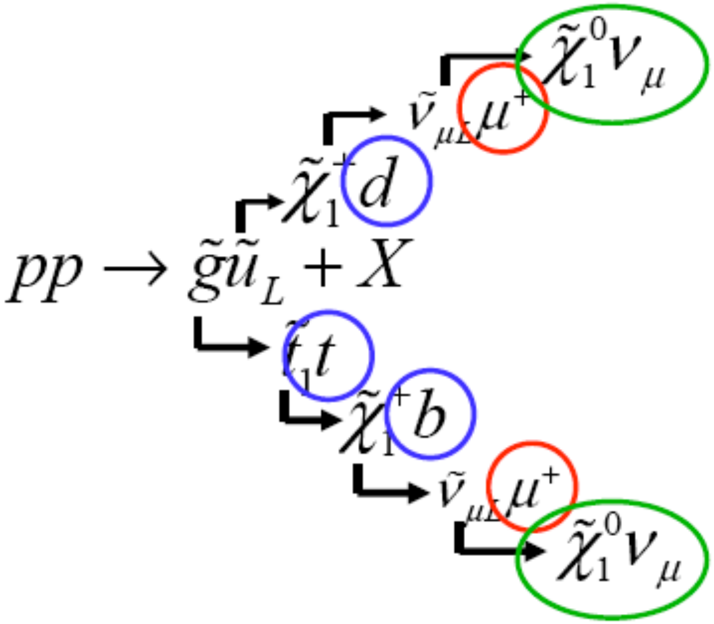
Opposite flavor; opposite sign leptons



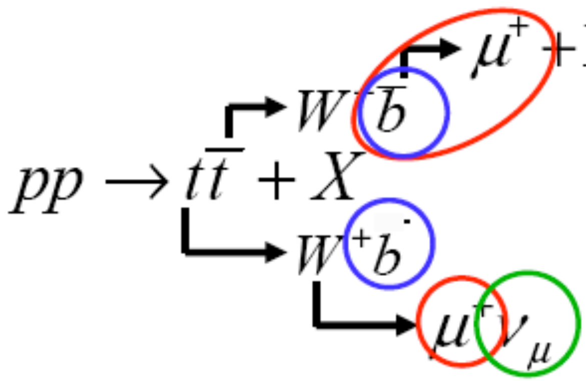
Same-sign dileptons

Classic SUSY signature; very low SM background.
Largest background: ttbar

Signal:



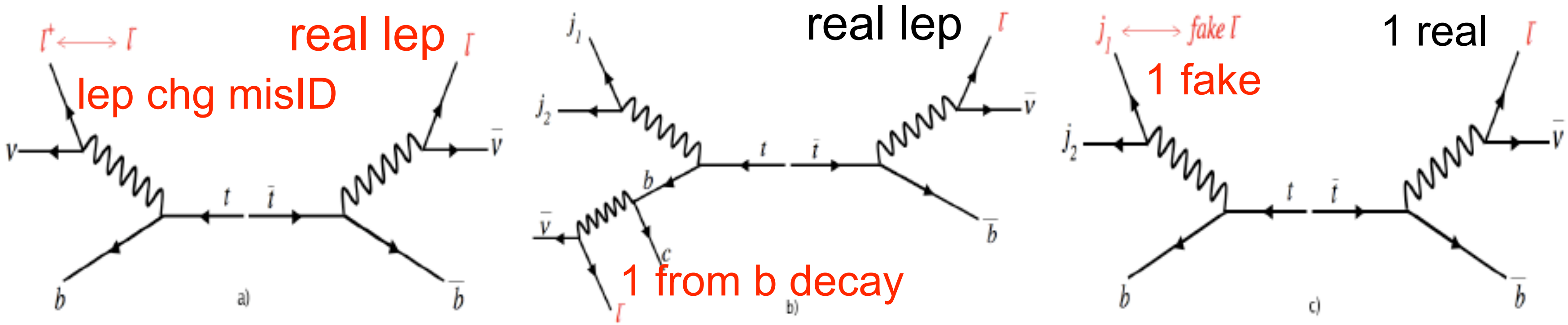
Background:



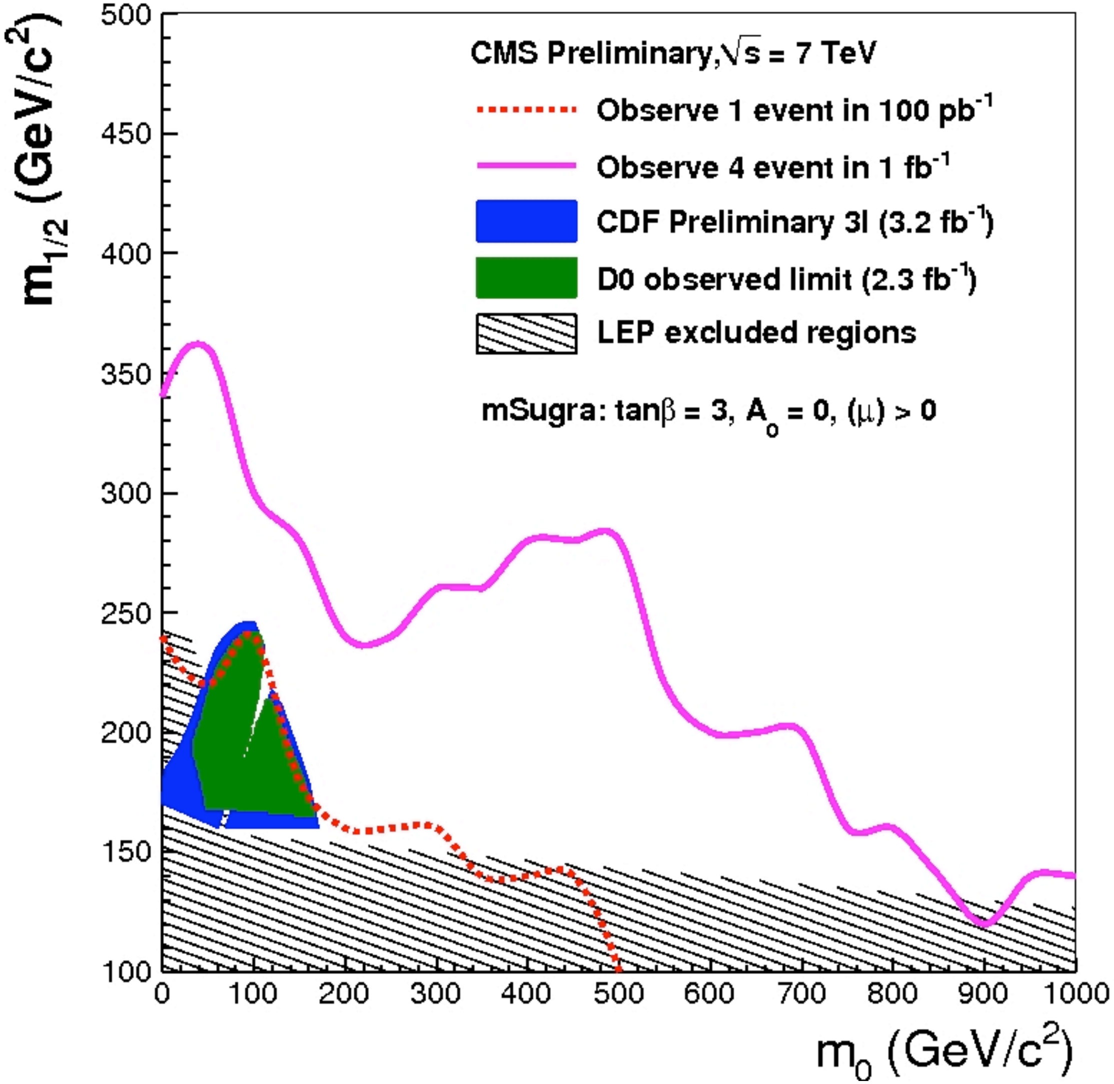
→ ask for 2 SS leptons + hard jets + E_T^{miss}

SS dileptons

Reliable data-driven background estimate is critical.
Key issues: fake leptons & electron charge misID



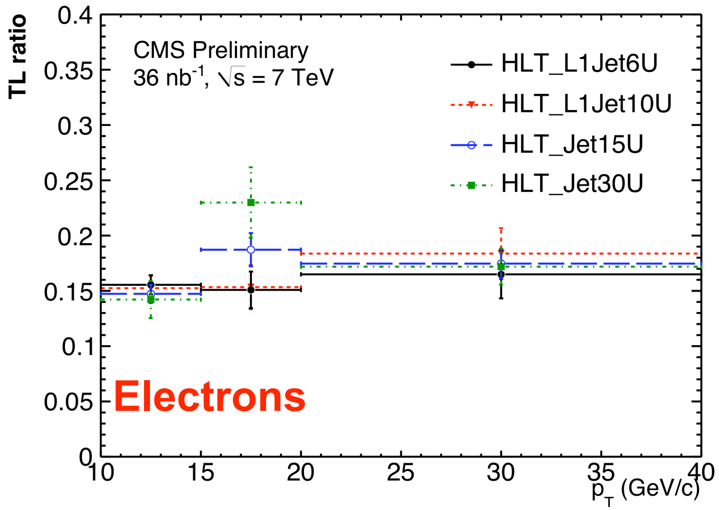
SS dileptons

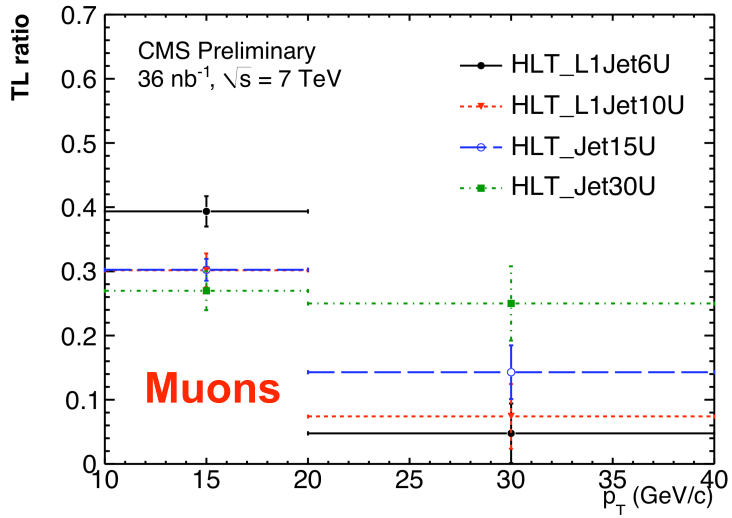


Fake ratio method

Use a control sample (loose lepton-id & isolation) to measure efficiency of passing all analysis cuts (“TL ratio”), as a function of lepton kinematics.

Monitor measured Tight-to-Loose-Ratios using different jet-triggered samples.





Predictions obtained using HLT_Jet15U

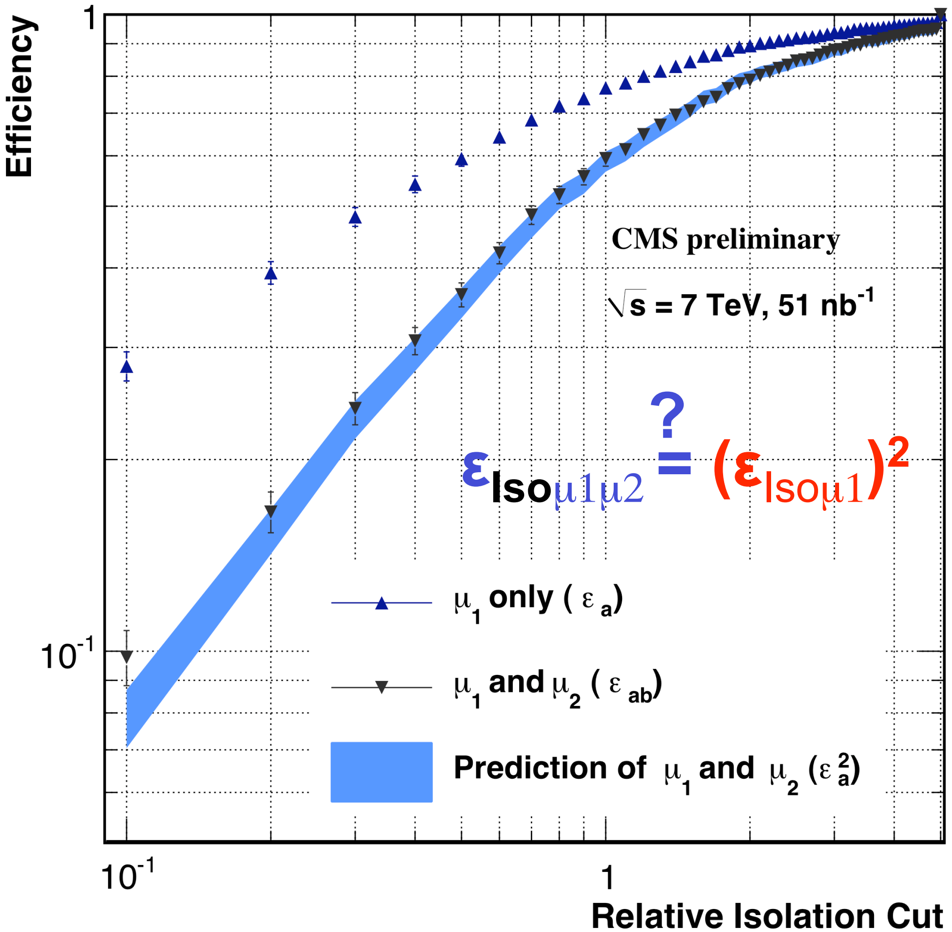
Channel	Predicted	Observed
ee	$0.43^{+0.18}_{-0.14}$	0
$e\mu$	$0.14^{+0.18}_{-0.09}$	1
$\mu\mu$	$0.22^{+0.51}_{-0.18}$	0

✓ Measured TL ratio is stable within 50%

✓ Predicted & observed number of SS di-lepton events consistent

Factorisation?

- Exploit the fact that some selection cuts are uncorrelated ➔ selection efficiency for each cut can be measured in control samples



IsoCut(μ_1) : Isolation of μ_1 , $\varepsilon_{Iso\mu1}$

IsoCut(μ_2) : Isolation of μ_2 , $\varepsilon_{Iso\mu2}$

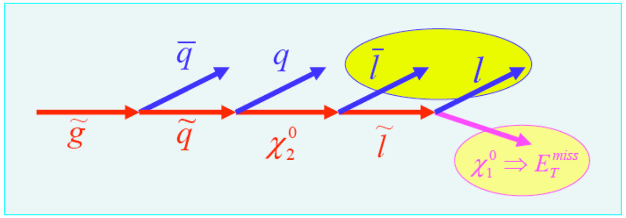
METCut : third jet and MET, ε_{MET}

$$\varepsilon_{AllCuts} = \varepsilon_{Iso\mu1} \cdot \varepsilon_{Iso\mu2} \cdot \varepsilon_{MET}$$

- test the factorization of cuts IsoCut(μ_1) and IsoCut(μ_2), no jet & MET requirement yet

✓ data indicates isolation of the μ_1 and μ_2 can be factorized

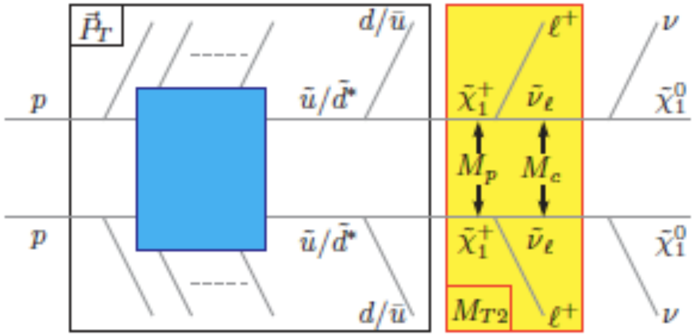
Mass reconstruction



- Kinematic endpoint technique (classic)
- More recent: polynomial method (2003), wedgebox (2003), kink in M_{T2} distribution (2008)

Example of new method for sparticle reconstruction @ the LHC:

- *Precision sparticle spectroscopy in the inclusive same-sign dilepton channel at LHC,* K. Matchev, FM, L. Pape, M. Park, hep-ph 0909.4300



SUSY properties @ LHC

Courtesy of K. Matchev

Missing momenta reconstruction?	Mass measurements		Spin measurements
	Inclusive	2 symmetric chains	
None	Inv. mass endpoints and boundary lines		Inv. mass shapes
	M_{eff}, M_{est}, H_T	Wedgebox	
Approximate	S_{min}, M_{Tgen}	M_{T2}, M_{2C}, M_{3C}, M_{CT}, $M_{T2}(n,p,c)$	As usual
Exact	?	Polynomial method	As usual

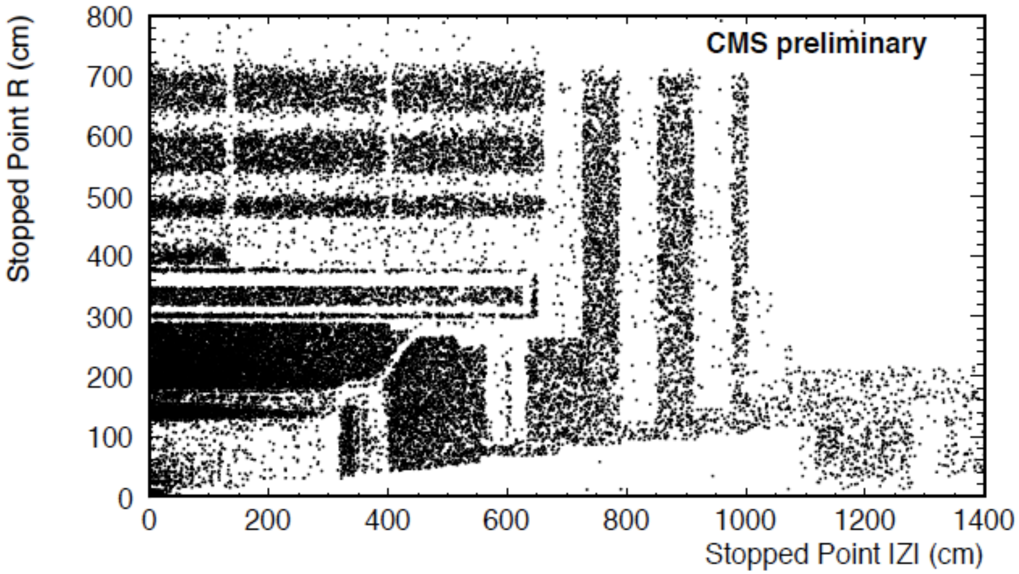
pessimism → optimism (down the rows)

pessimism → optimism (across the columns)

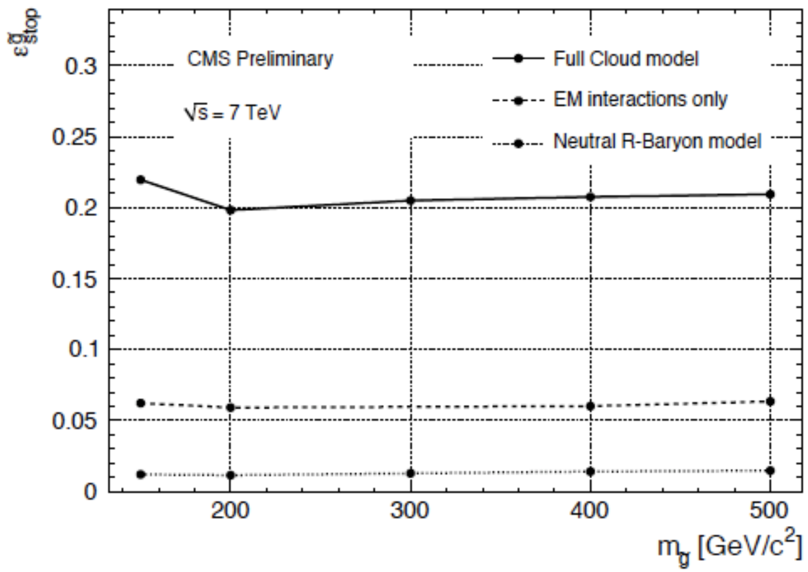
Stopped gluinos

CMS PAS EXO-09-001

Where do R-hadrons stop?



R-hadron stopping efficiency

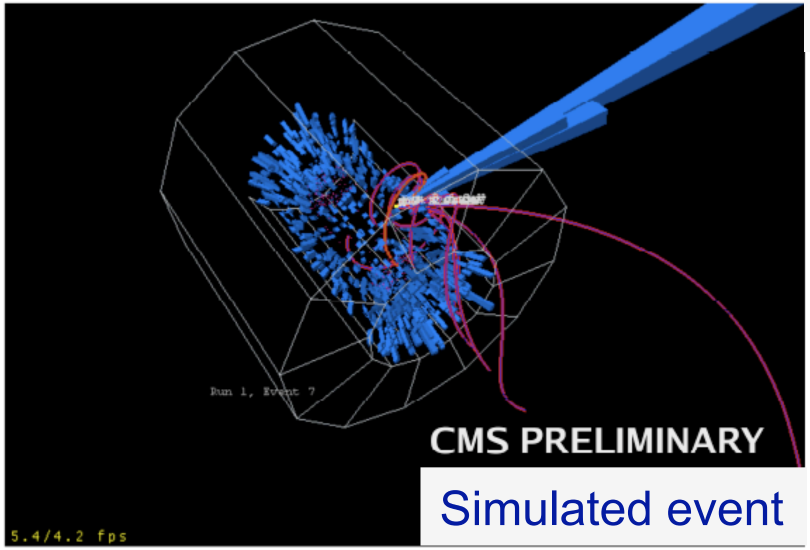


- Offline analysis based on hadronic calorimeter (HCAL) energy deposit, shower shape, and pulse shape.
- Efficiency after all cuts: 17% of stopped gluinos.

$(m_{\tilde{g}} = 200,\ m_{\chi^0} = 100\ \mathrm{GeV})$

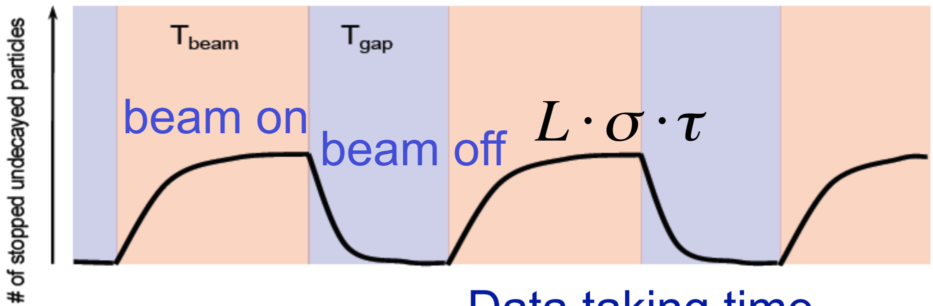
Stopped gluinos (2)

CMS PAS EXO-09-001



Simulated event

Num stopped undecayed particles



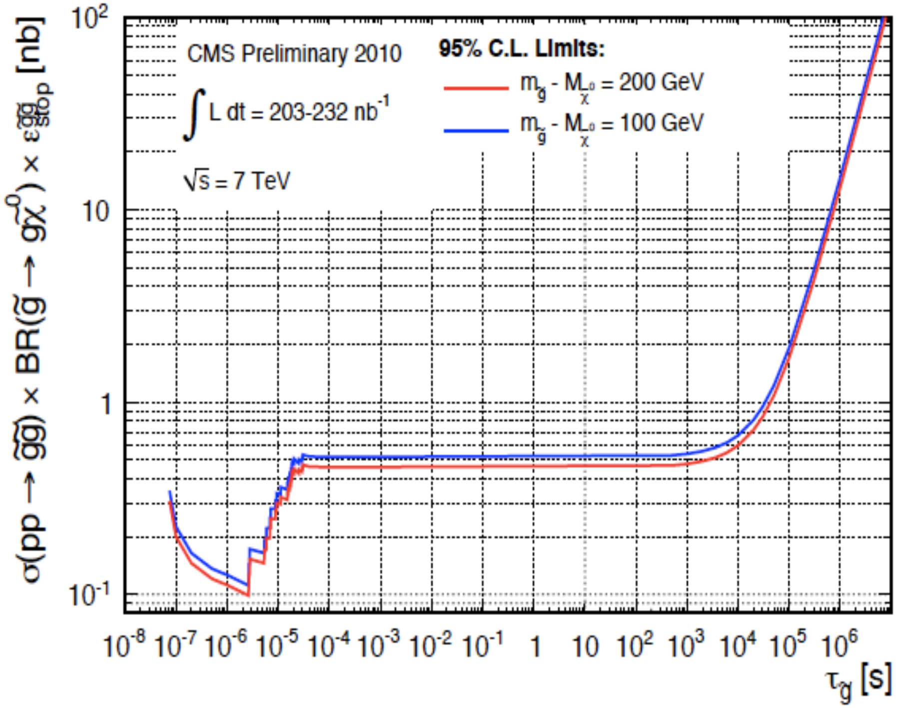
Data taking time

$$\frac{S}{\sqrt{B}} \propto \frac{L \cdot t}{\sqrt{t}} \propto L\sqrt{t} \qquad t_{5\sigma} \propto L^2$$

- Trigger: calorimeter (HCAL) energy + out of LHC collision times (beam gaps+interfill periods). Use coincidence of beam pick-up monitors upstream of CMS to veto pp.
- Dominant background: cosmic rays+instrumental noise (both studied during extensive CMS cosmic ray running in 2008-2009). $R_{background} \approx 4 \times 10^{-4}$ Hz.

Stopped gluinos (3)

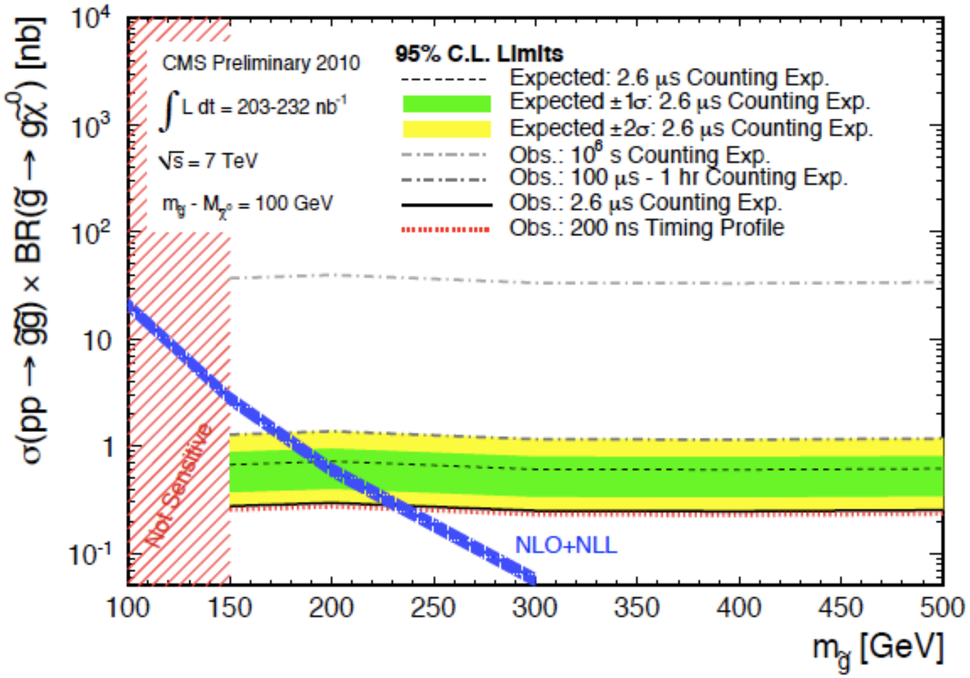
Result: model-independent limit



Beamgap exp’t: τ≈1μs→hours

interfill exp’t: τ≈hours→weeks

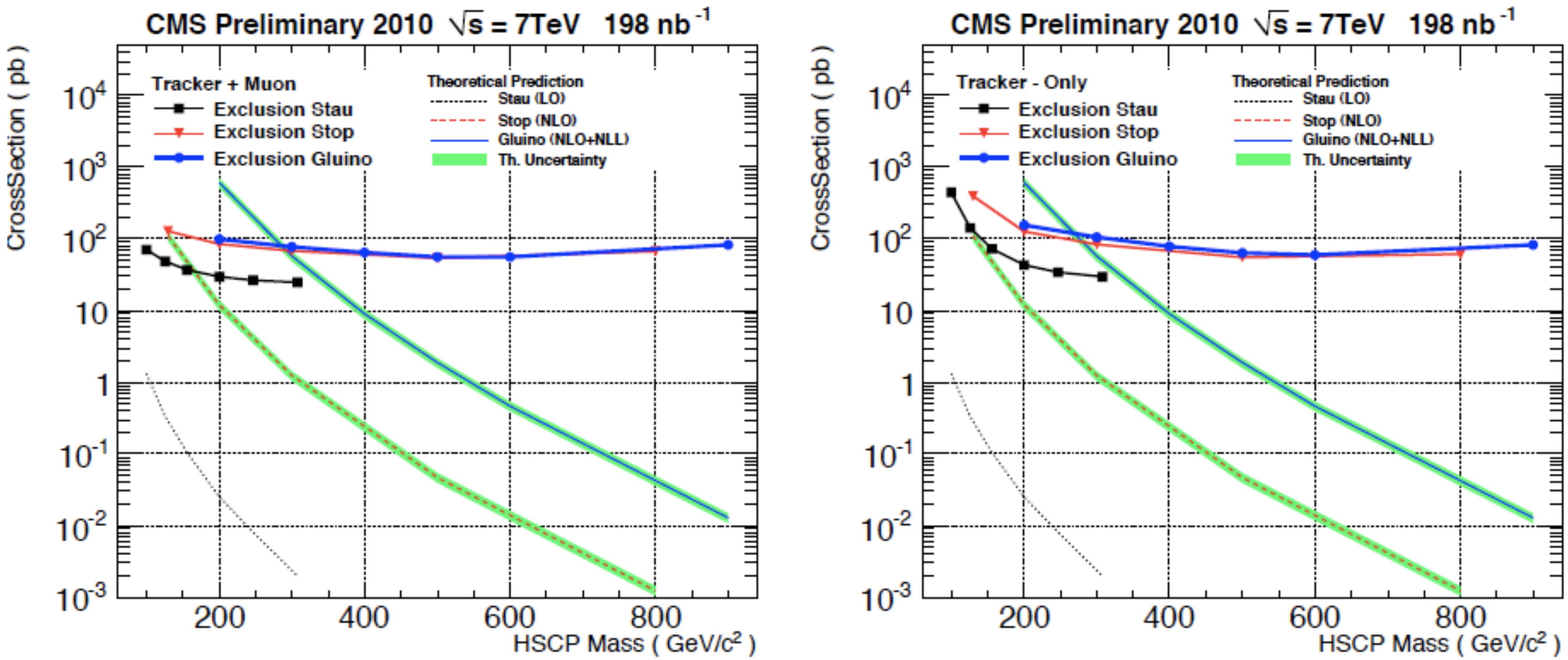
Significance vs. gluino mass



Take few key lifetimes and take $m_{\tilde{g}} - M_{\tilde{\chi}^0} = 100$ GeV

→ exclude gluino masses below ~225 GeV

HSCP



- We use the null result to place 95% CL limits on the production cross-section of stau, stop and gluino, using a Bayesian method
  - For tk+muon (tk-only) analysis, a 95% CL lower limit on the gluino mass is set at 284 (271) GeV/c^2

Conclusion

- After many years of preparations, the LHC has started producing collisions at 7 TeV
- CMS detector in excellent shape:
  - Basic physics objects understood
  - Agreement with simulations remarkably good
  - Still preparing many data-driven background control methods
- First physics results appearing
  - We've covered Particle Physics up to the '80s

  (W/Z) – now entering the '90s (top)
- expect to be able to extend Tevatron searches for SUSY starting ~ end of the year

Conclusion (2)

The road to discovery might still be long …

… but at least we've started driving!