Exotics Searches with CMS

Jim Brooke
Birmingham, 21st May 2014

CMS Physics Program 2011

Measurements
- QCD
- Electroweak
- Heavy flavour
- Heavy Ions

Searches
- Higgs
- SUSY
- Exotics

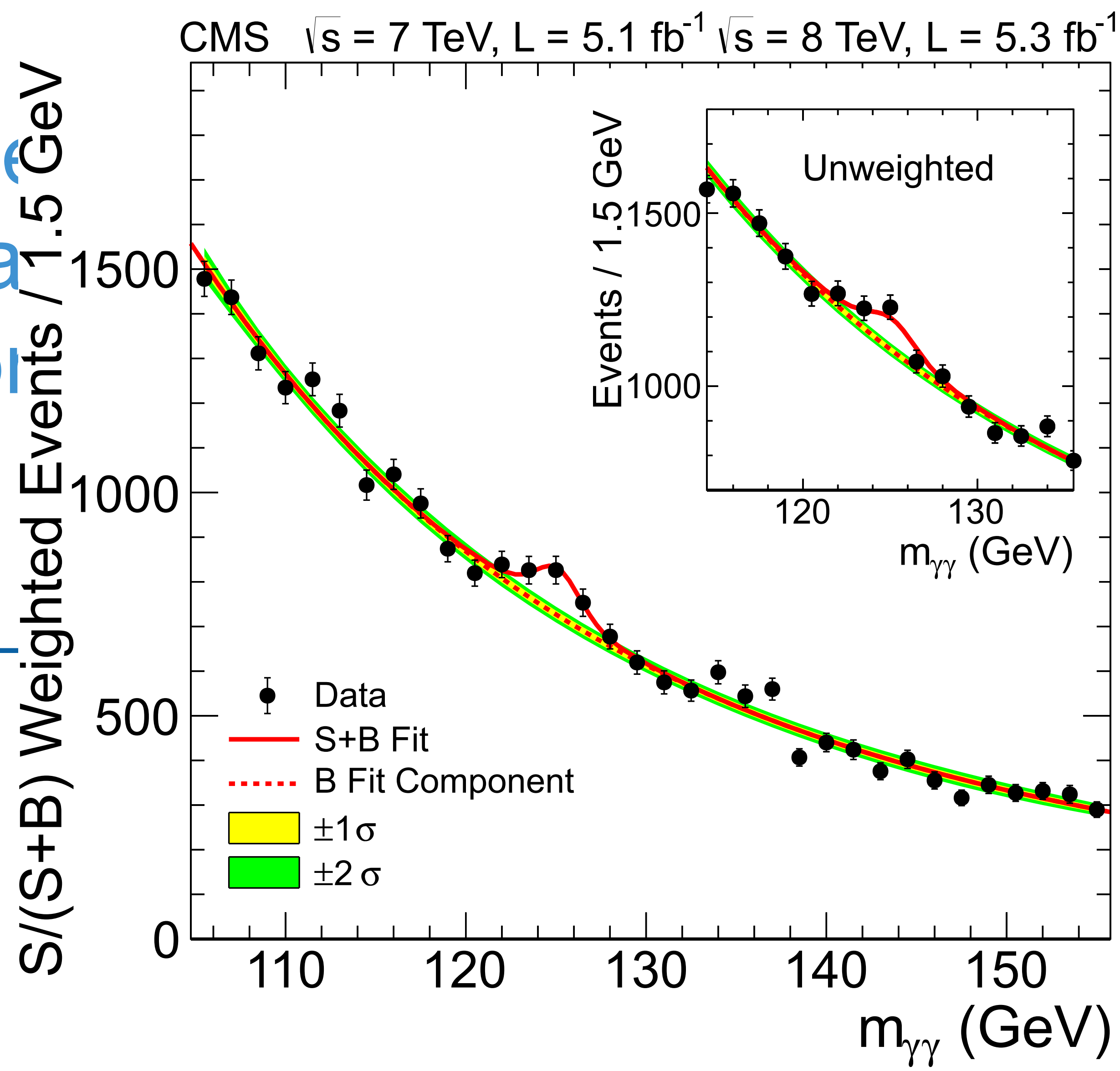
CMS Physics Program 2012

Measurements

- QCD
- Electrowe
- Heavy fla
- Heavy Io

Searches

- s
- Y
- ics



CMS Physics Program post-2012

Measurements
- QCD
- Electroweak
- Heavy flavour
- Heavy Ions
- Higgs

Searches
- Higgs
- SUSY
- Exotics

Exotics @ CMS

Measurements
- QCD
- Electroweak
- Heavy flavour
- Heavy Ions
- Higgs

Searches
- Higgs
- SUSY
- Exotics

Searches for everything other than Higgs & SUSY

Exotics @ CMS

Measurements
- QCD
- Electroweak
- Heavy flavour
- Heavy Ions
- Higgs

Searches
- Higgs
- SUSY
- Exotics

Searches for everything
~~other than Higgs & SUSY~~

Leave no stone unturned

Why Search for Exotics?

Glueballs

Hidden Valleys

Large Extra Dimensions

R-hadrons

Quirks

Colorons

Unparticles

Leave no stone unturned

Dark matter

Leptoquarks

Dark photons

Microscopic black holes

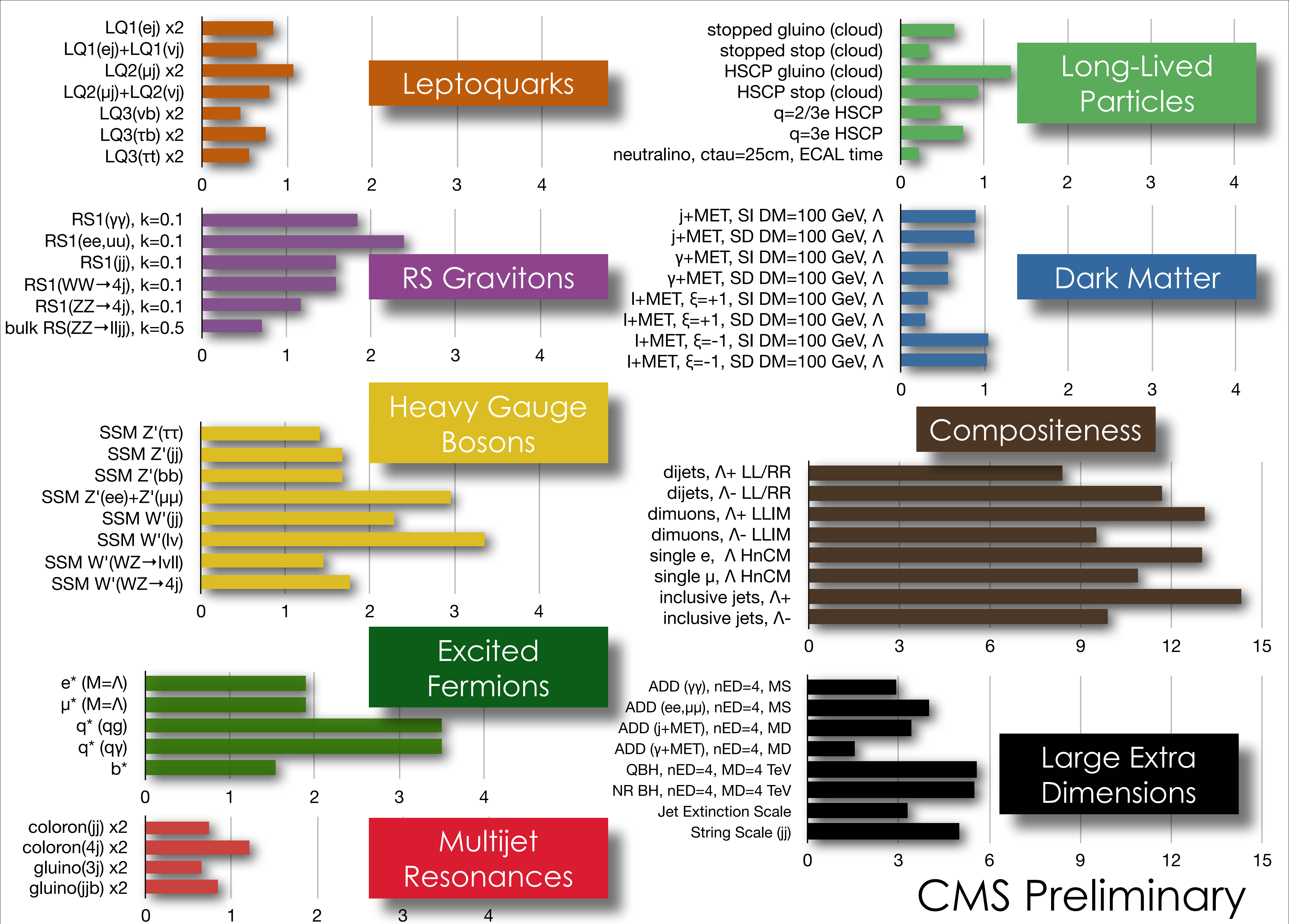
Stringballs

Monopoles

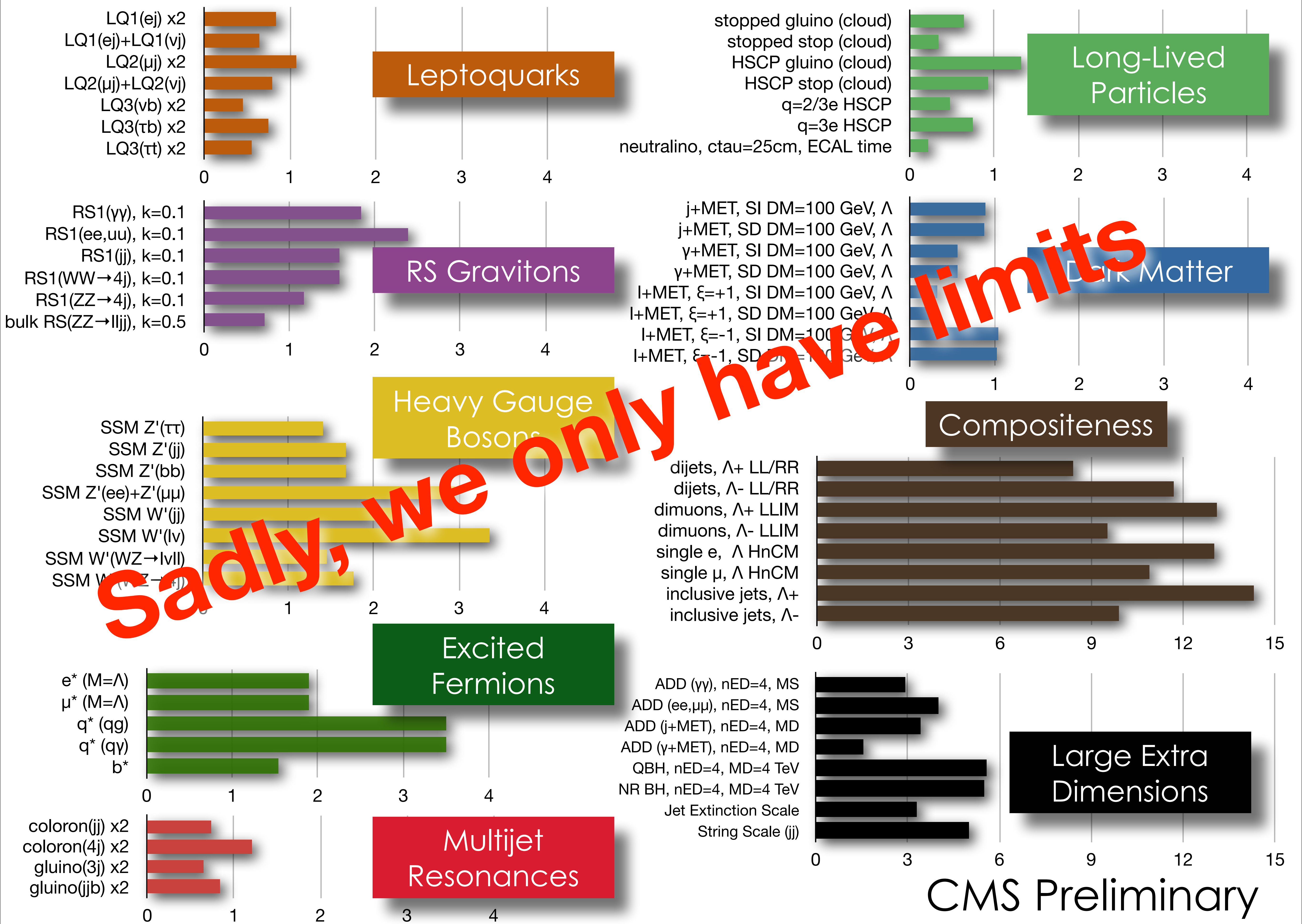
Compositeness

How to Search for Exotics

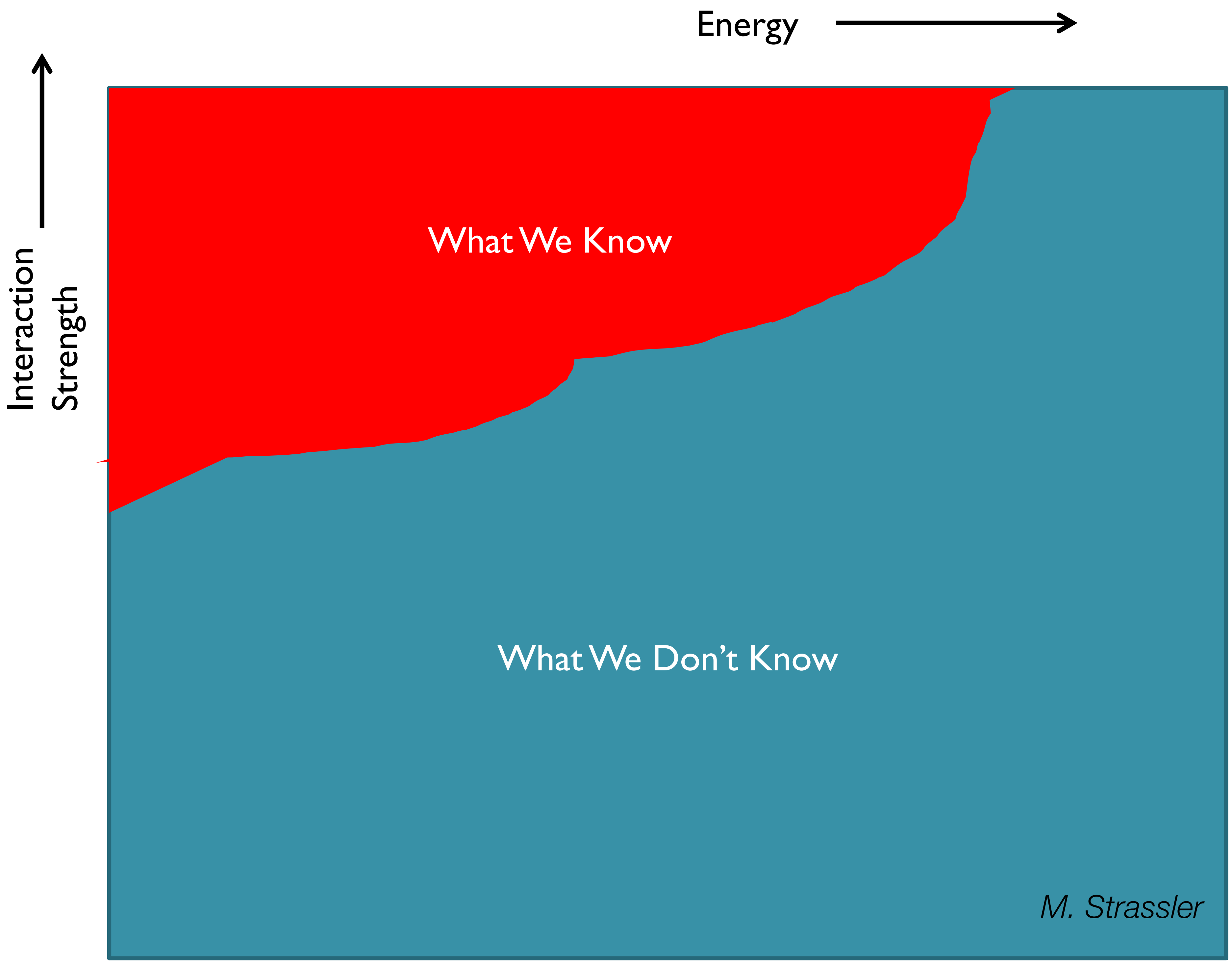
- Search for broad excess or resonance
  - Familiar final states : **e^+e^-, $\mu^+\mu^-$, bb, dijet, e+MET, μ+MET, top-like ...**
  - Unexpected : **e+jet, μ+jet, e+μ, high multiplicities, ...**
- Measure properties of particles directly
  - **anomolous dE/dx, timing, weird tracks, displaced vertices, etc.**
  - (Obviously they need to be at least meta-stable for this...)
- Exotic decay modes of known particles



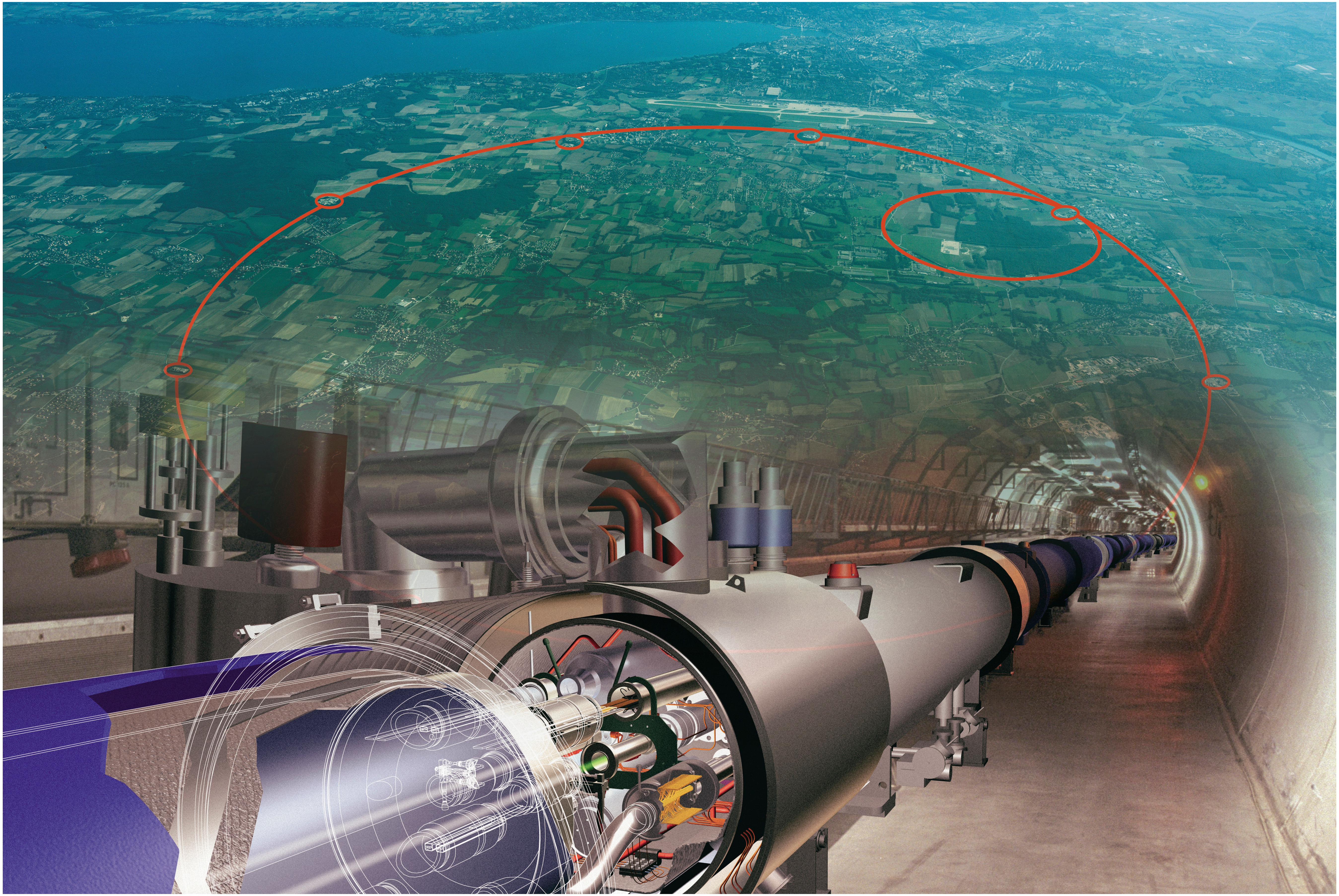
CMS Exotica Physics Group Summary – March, 2014


Leptoquarks
LQ1(ej) x2
LQ1(ej)+LQ1(νj)
LQ2(μj) x2
LQ2(μj)+LQ2(νj)
LQ3(νb) x2
LQ3(τb) x2
LQ3(τt) x2
Long-Lived Particles
stopped gluino (cloud)
stopped stop (cloud)
HSCP gluino (cloud)
HSCP stop (cloud)
q=2/3e HSCP
q=3e HSCP
neutralino, ctau=25cm, ECAL time
RS Gravitons
RS1(γγ), k=0.1
RS1(ee,μμ), k=0.1
RS1(jj), k=0.1
RS1(WW→4j), k=0.1
RS1(ZZ→4j), k=0.1
bulk RS(ZZ→llјј), k=0.5
Dark Matter
j+MET, SI DM=100 GeV, Λ
j+MET, SD DM=100 GeV, Λ
γ+MET, SI DM=100 GeV, Λ
γ+MET, SD DM=100 GeV, Λ
l+MET, ξ=+1, SI DM=100 GeV, Λ
l+MET, ξ=+1, SD DM=100 GeV, Λ
Heavy Gauge Bosons
SSM Z'(ττ)
SSM Z'(jj)
SSM Z'(bb)
SSM Z'(ee)+Z'(μμ)
SSM W'(jj)
SSM W'(lν)
SSM W'(WZ→lνll)
Compositeness
dijets, Λ+ LL/RR
dijets, Λ- LL/RR
dimuons, Λ+ LLIM
dimuons, Λ- LLIM
single e, Λ HnCM
single μ, Λ HnCM
inclusive jets, Λ+
inclusive jets, Λ-
Excited Fermions
e* (M=Λ)
μ* (M=Λ)
q* (qg)
q* (qγ)
b*
Large Extra Dimensions
ADD (γγ), nED=4, MS
ADD (ee,μμ), nED=4, MS
ADD (j+MET), nED=4, MD
ADD (γ+MET), nED=4, MD
QBH, nED=4, MD=4 TeV
NR BH, nED=4, MD=4 TeV
Jet Extinction Scale
String Scale (jj)
Multijet Resonances
coloron(jj) x2
coloron(4j) x2
gluino(3j) x2
gluino(jjb) x2
Sadly, we only have limits
CMS Preliminary

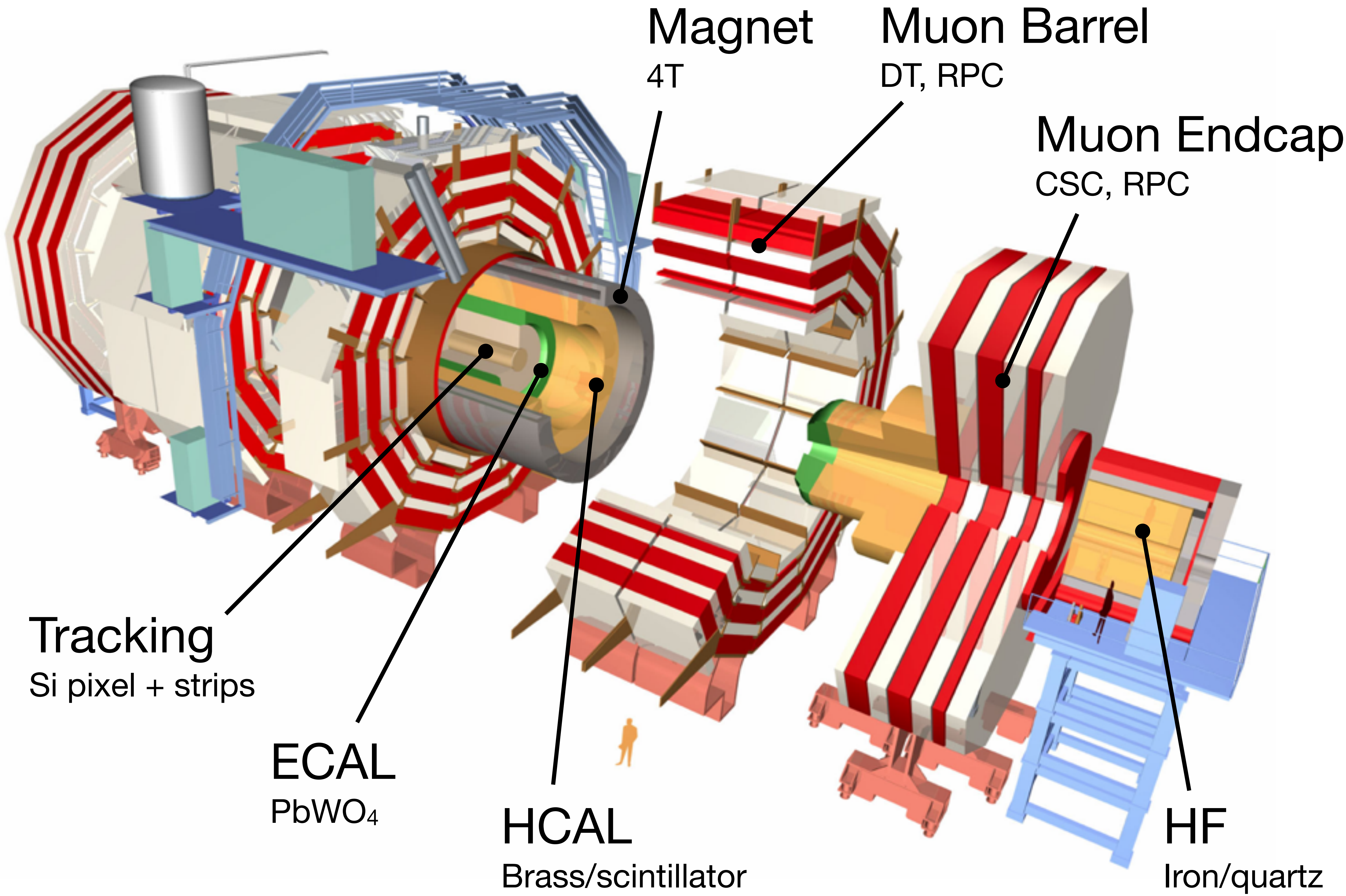
What we (don't) know



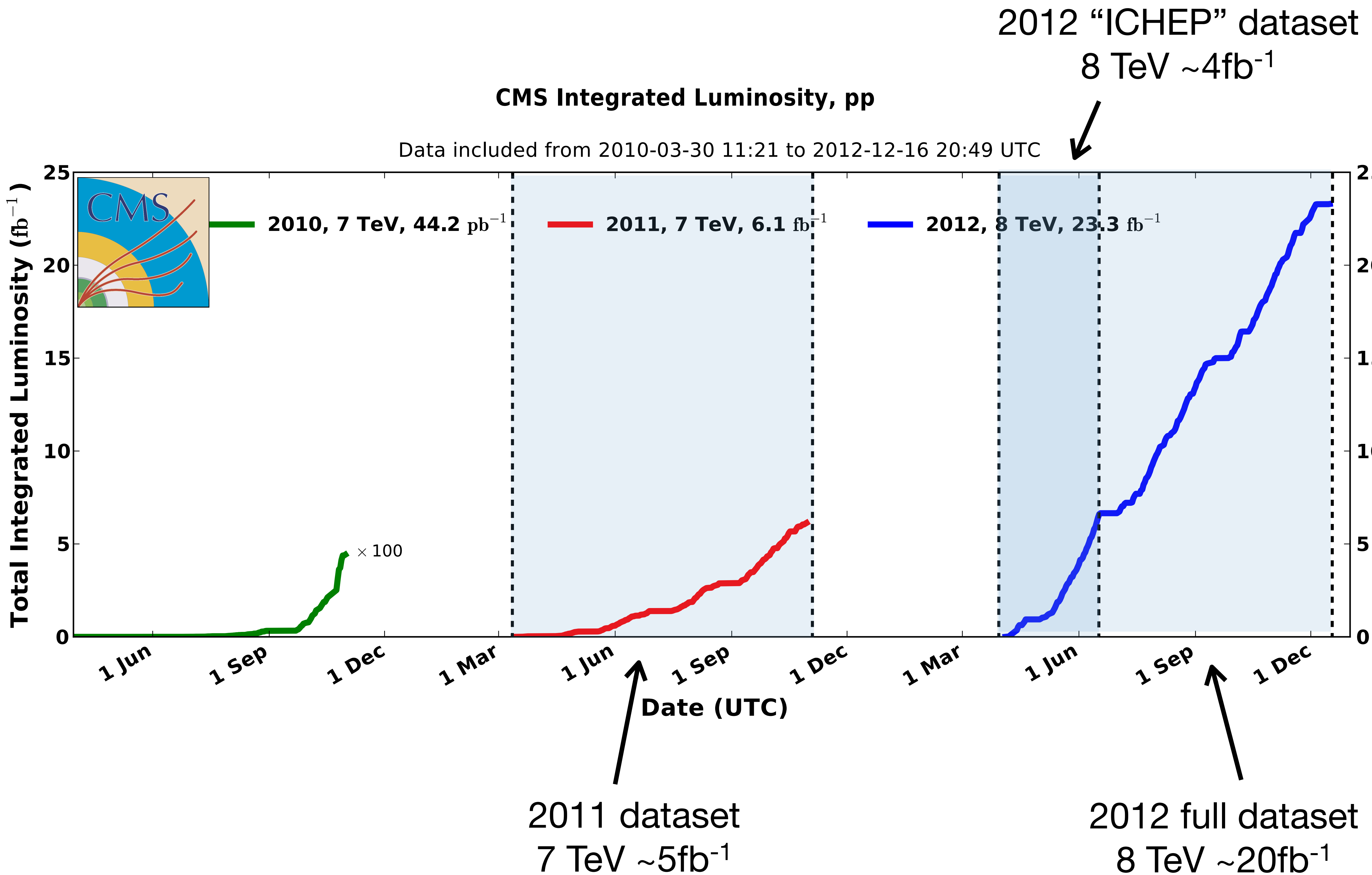
Large Hadron Collider



Compact Muon Solenoid



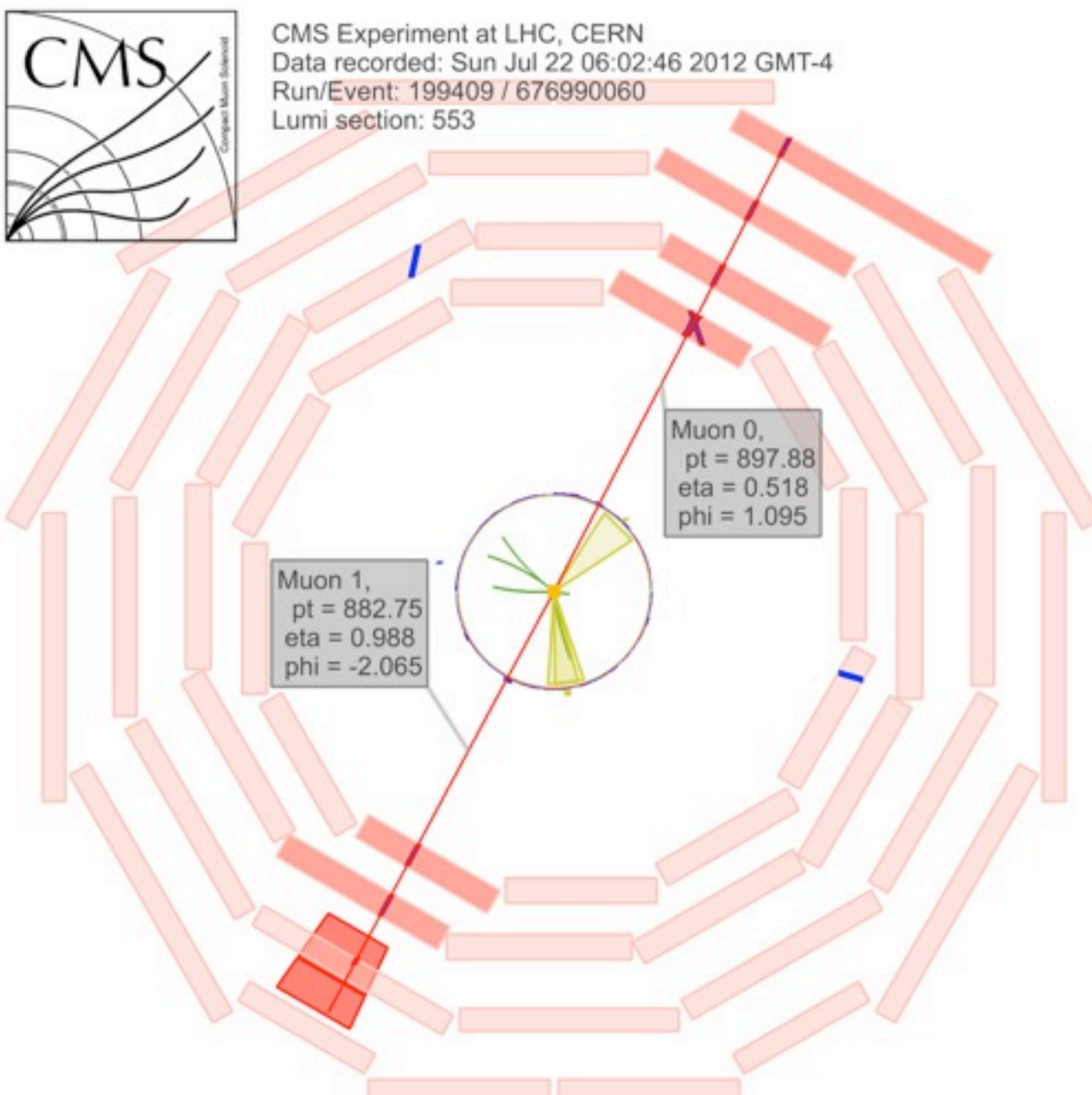
Integrated Luminosity



Familiar Final States

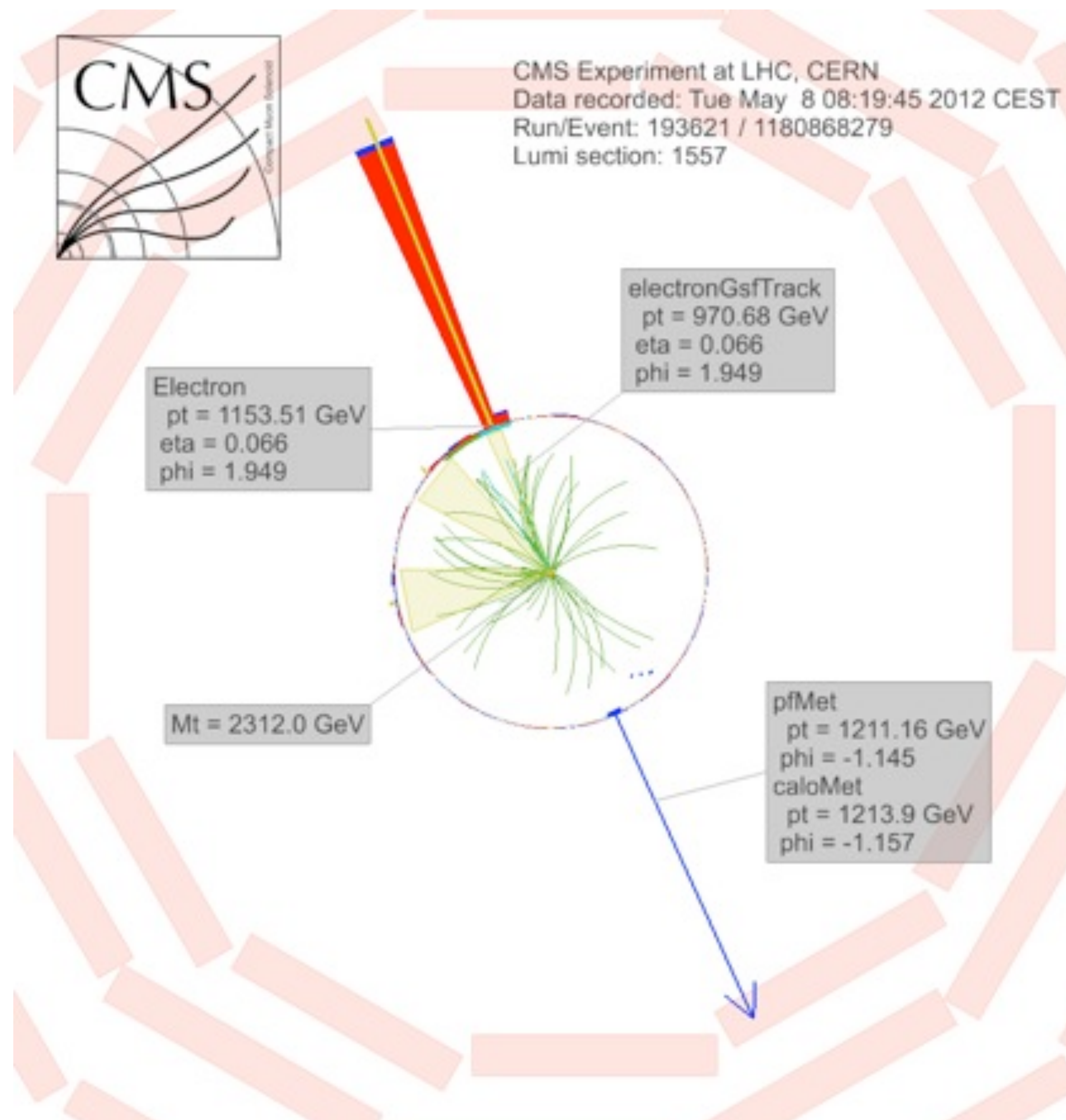
Familiar Final States

Di-lepton



$M_{\mu\mu}$ = 1.824 TeV

Lepton + E_T^{miss}



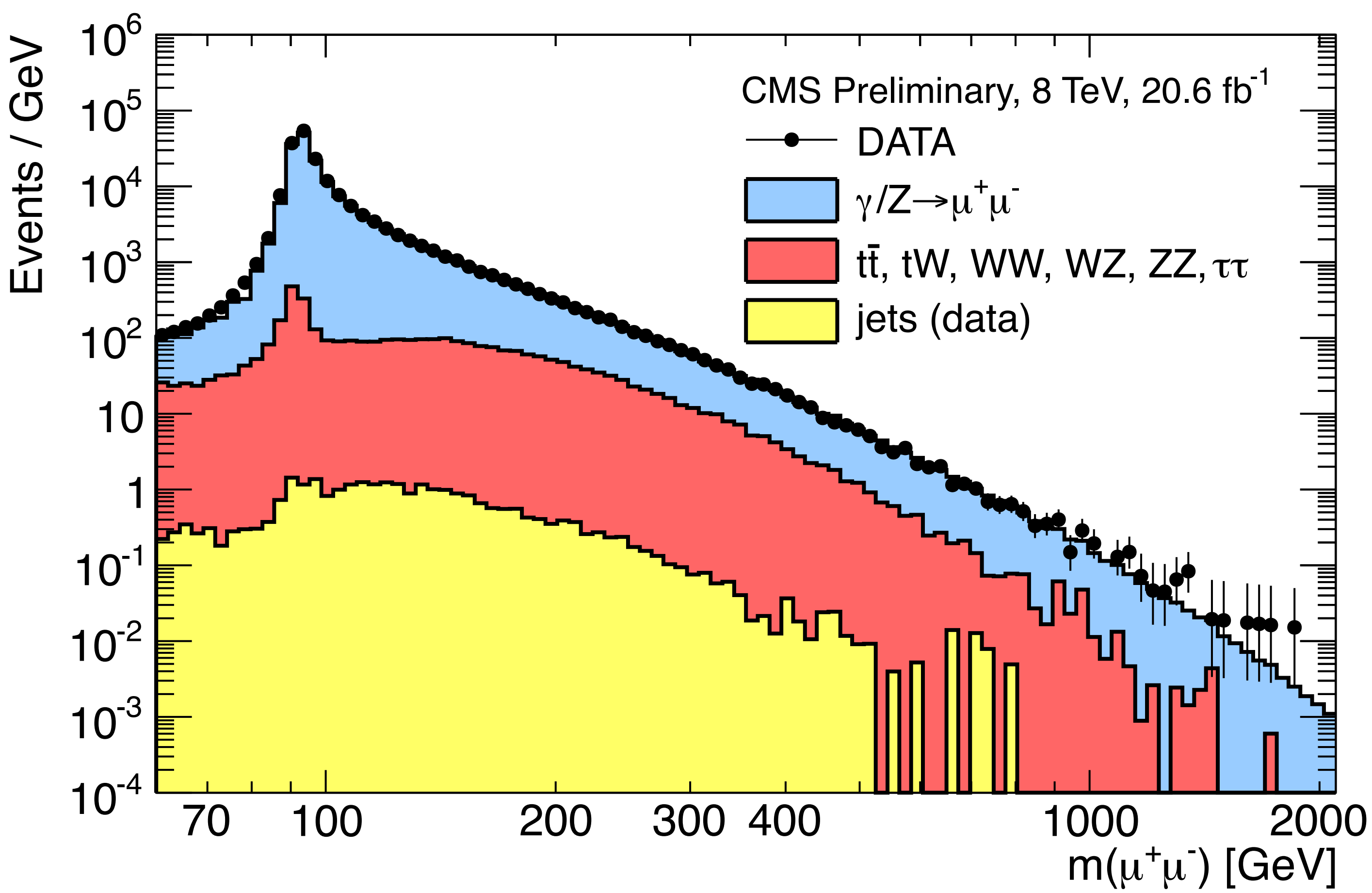
m_T = 2.31 TeV

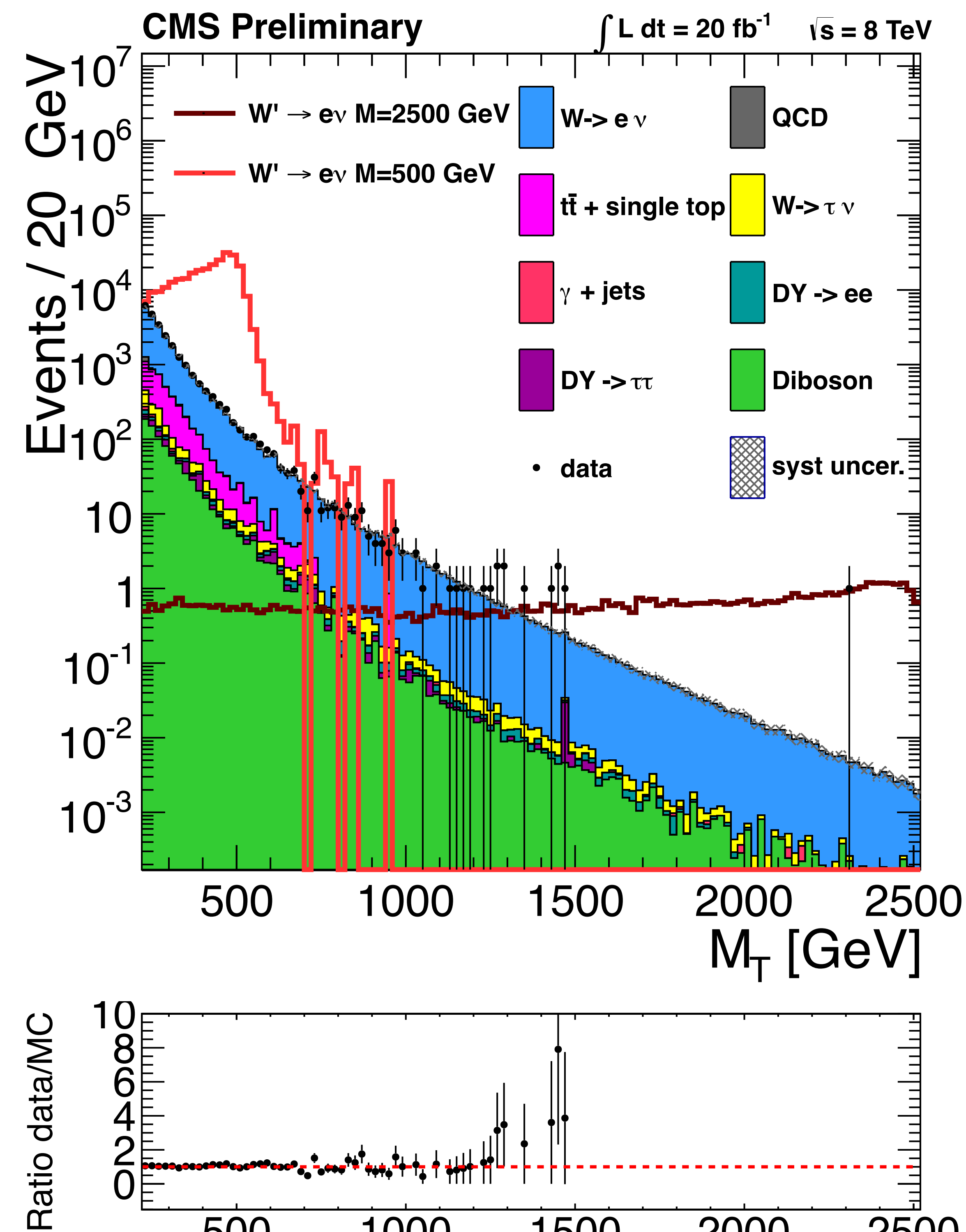
Familiar Final States

CMS-PAS-EXO-12-060

CMS-PAS-EXO-12-061

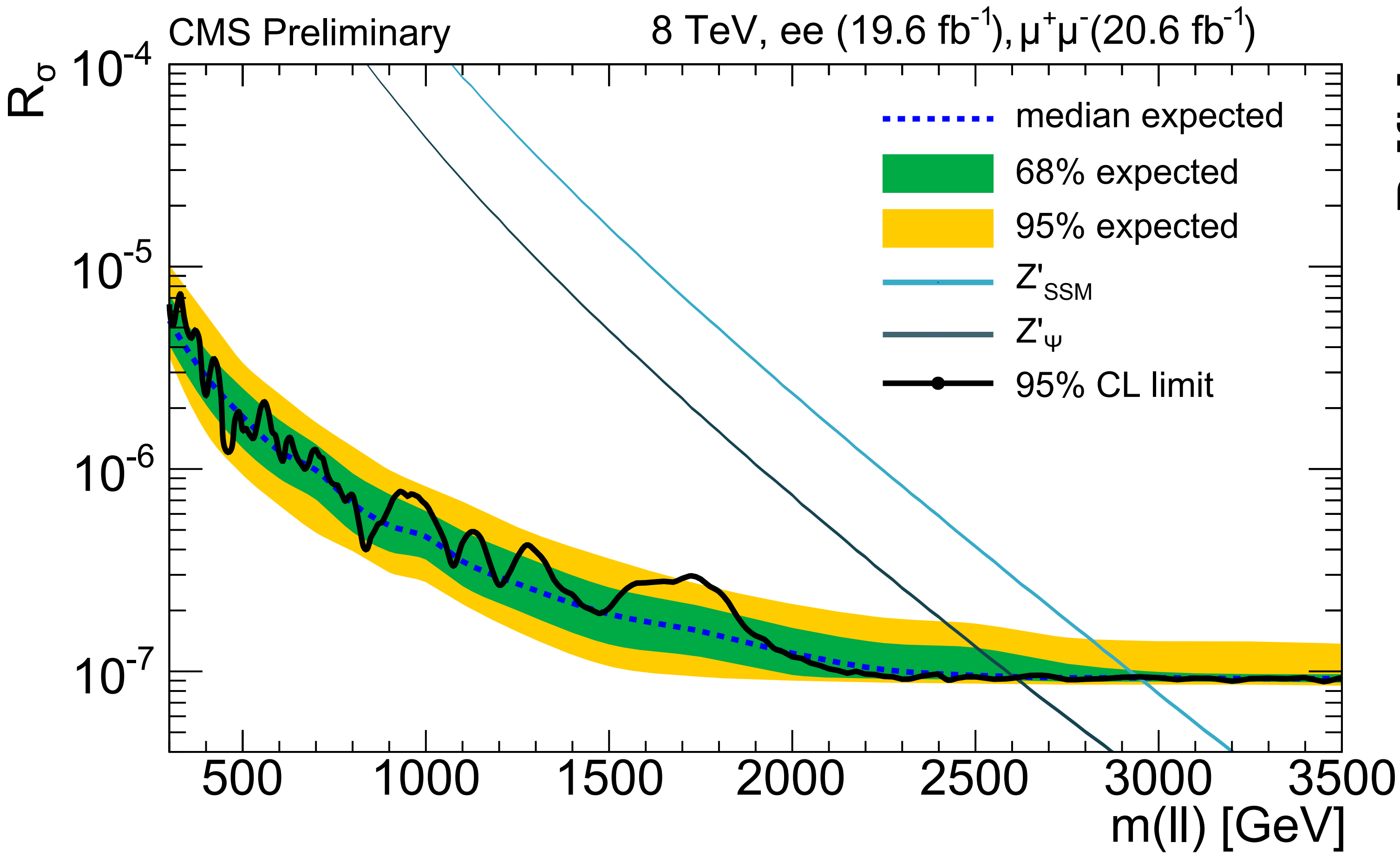
University of BRISTOL

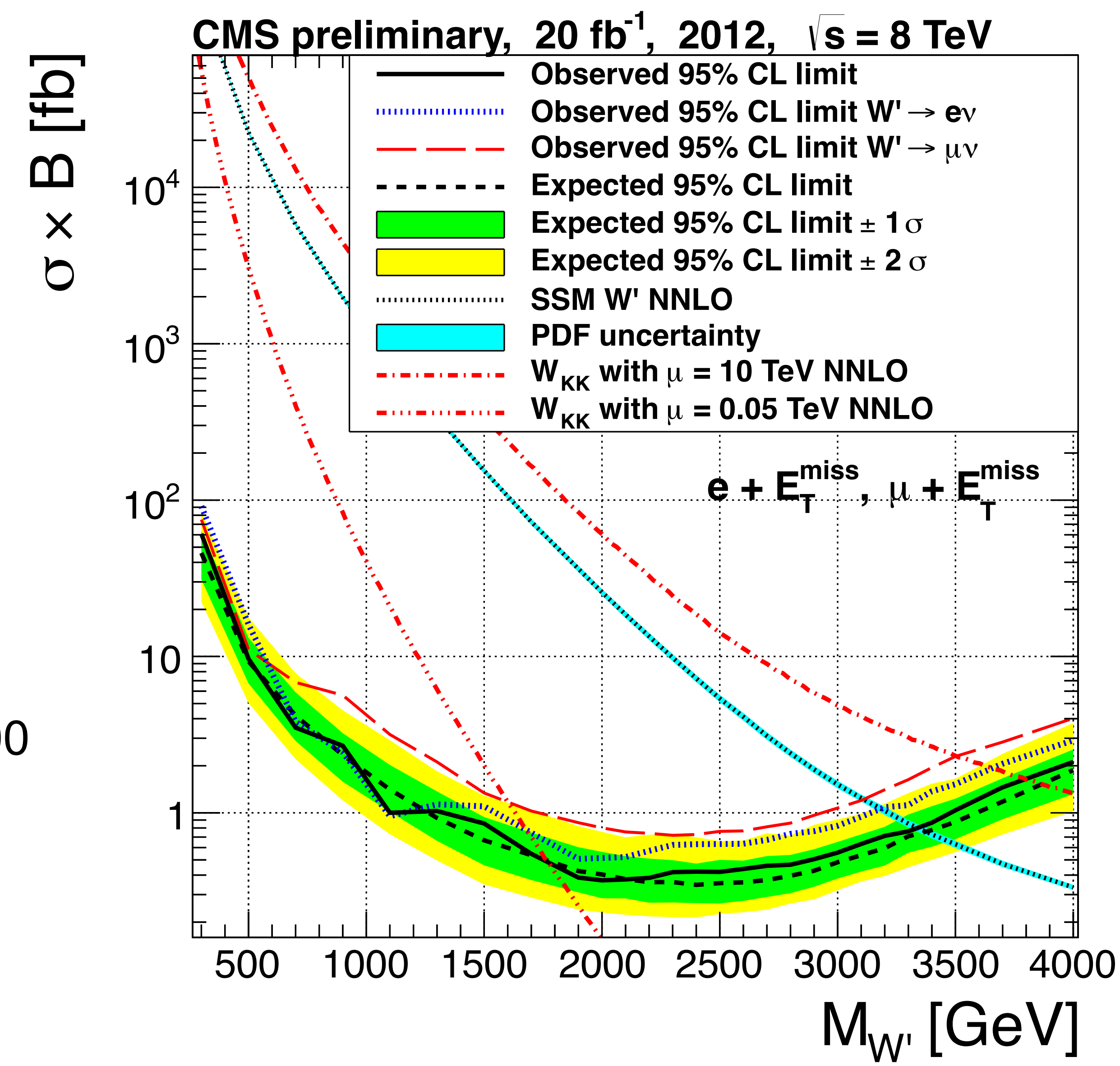




- Perform "bump hunts" in
  - Dilepton invariant mass spectrum
  - Lepton+ E_T^{miss} m_T distribution
- Background shapes taken from MC and normalised to control regions in data

Familiar Final States

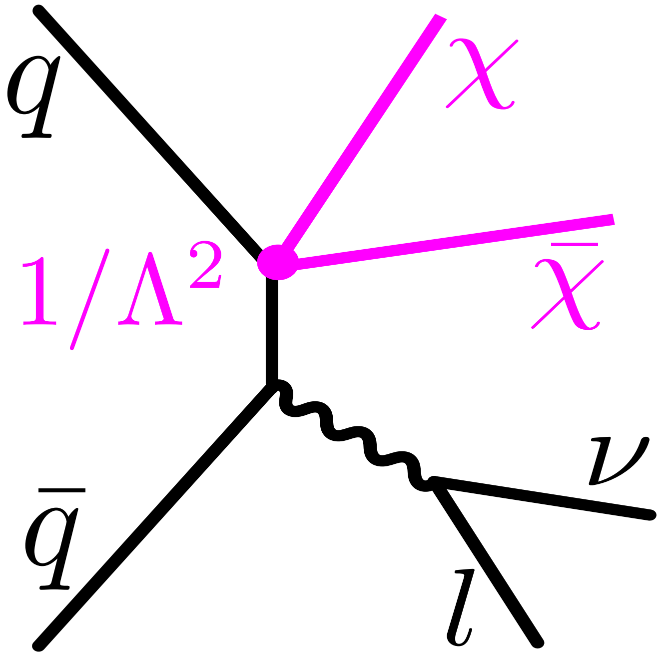




- No evidence for a signal ☹
- Set limits on a variety of BSM physics
  - Z'_{SSM}, Z'_ψ, W'_{SSM}, W_{KK}
- **Alternative interpretation of lepton + E_T^{miss} → W + E_T^{miss}**

Dark Matter Signatures

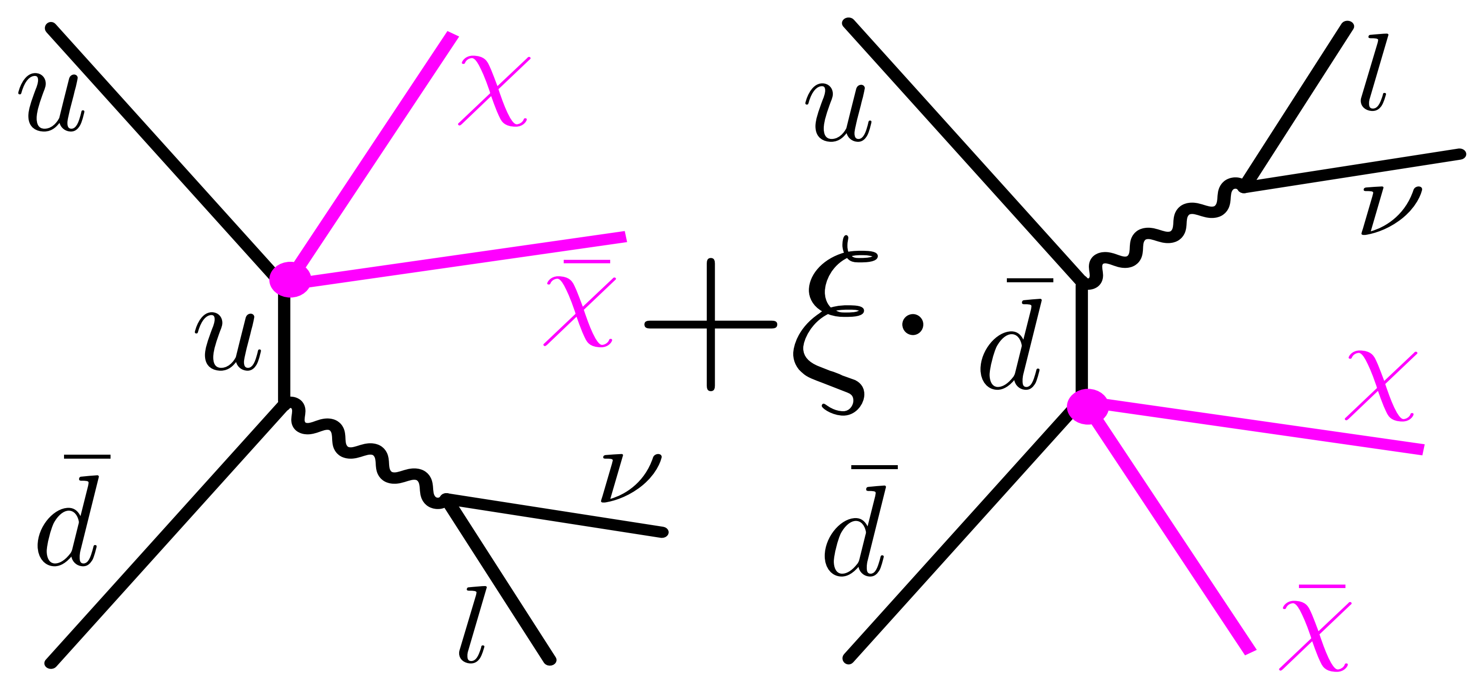
Dark Matter



Lepton+MET final state is a signature of W+invisible, eg. $W\chi^0\chi^0$

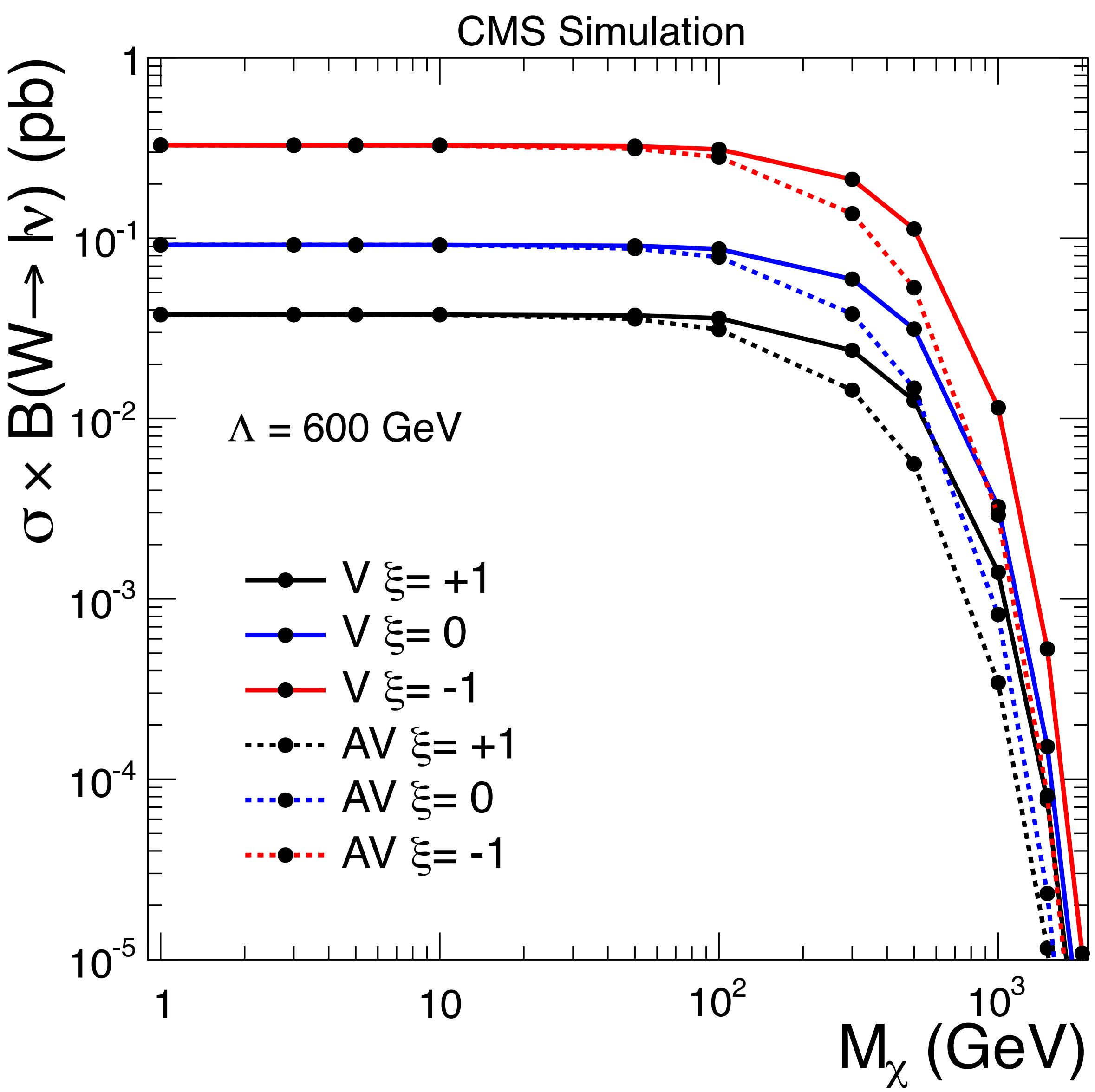
DM production characterised using effective field theory with vector or axial-vector couplings

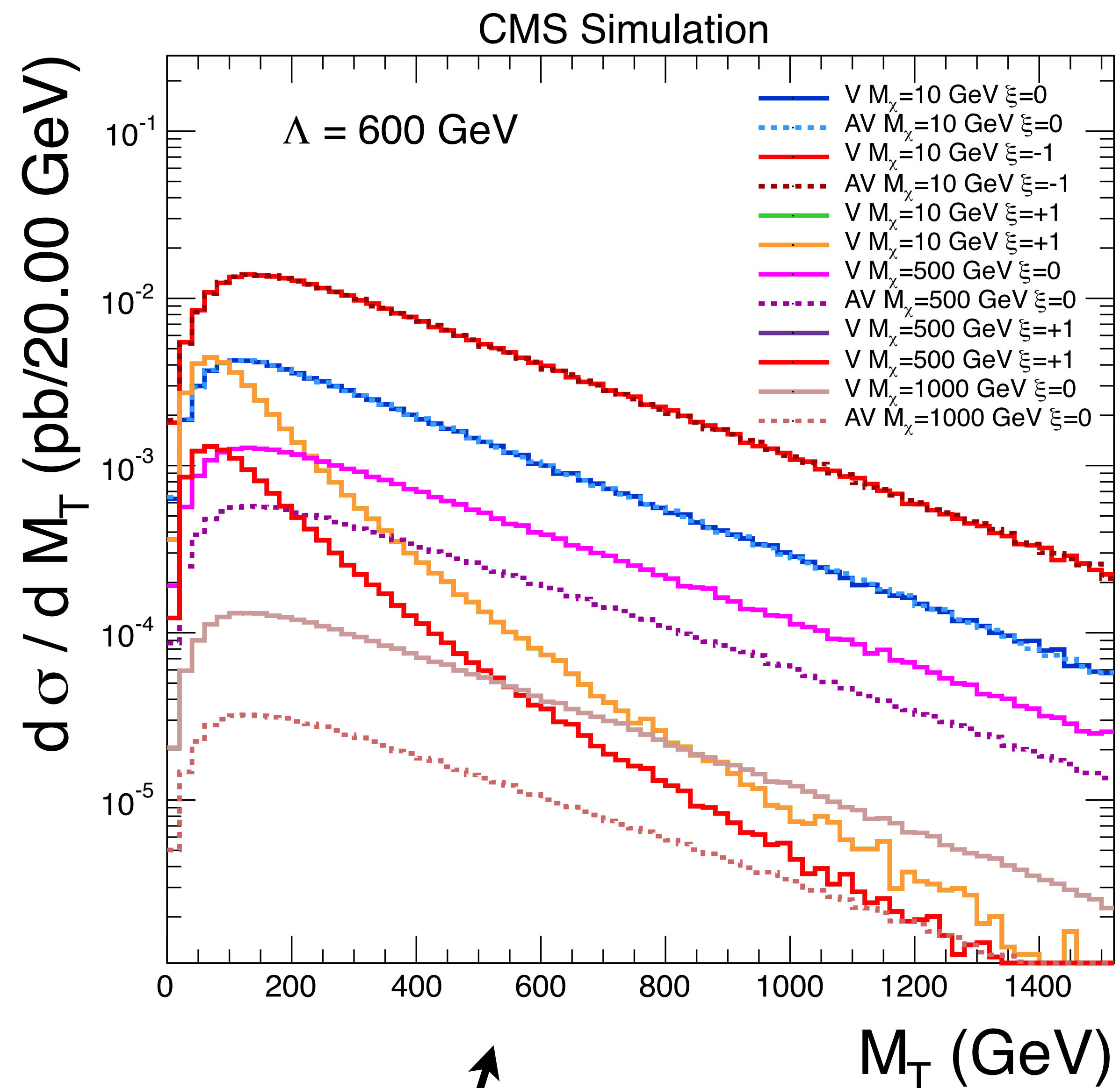
For W+MET search :
DM couplings to u and d may be different.
Interference characterised through parameter ξ



Monolepton

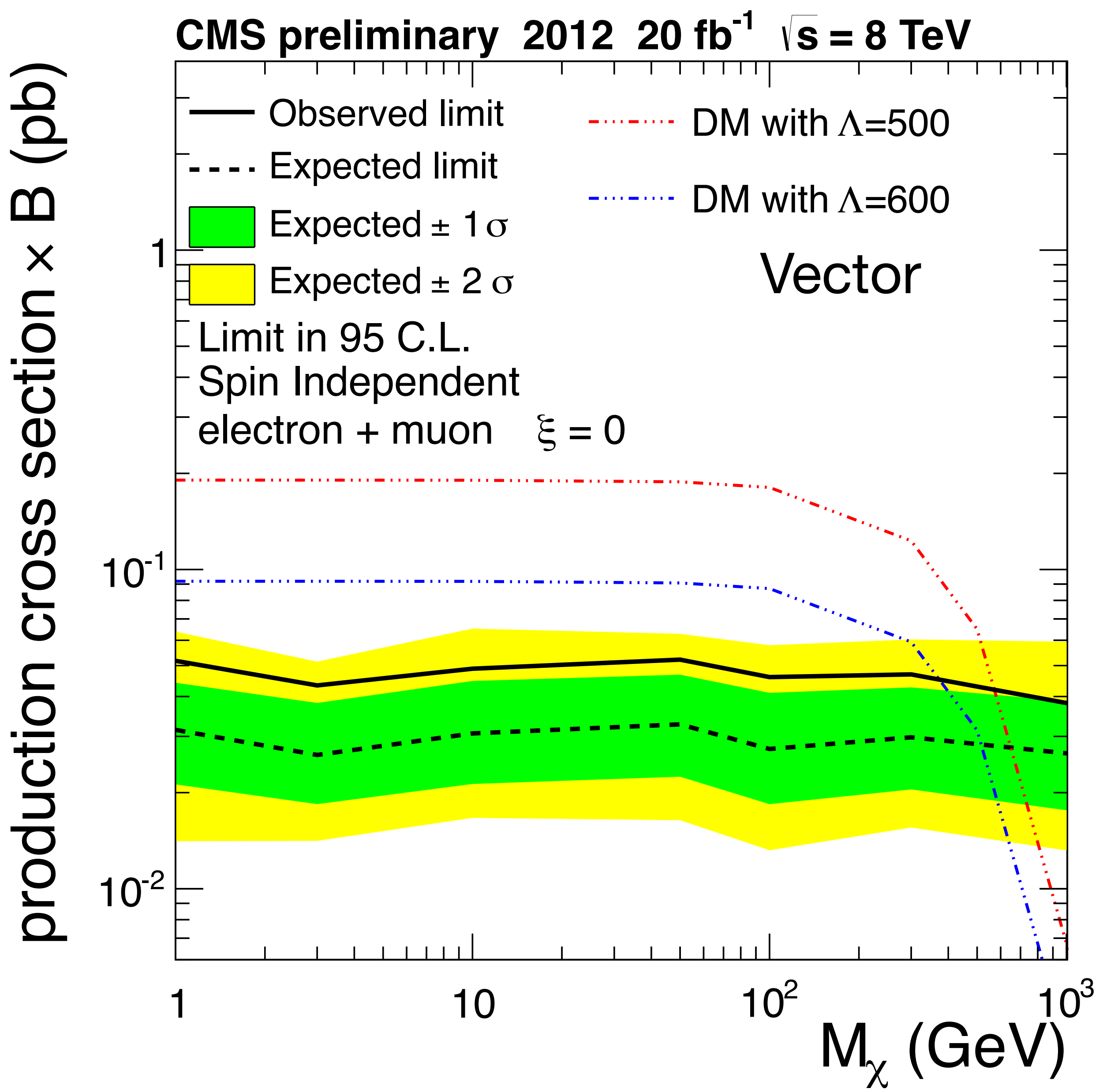
CMS-PAS-EXO-13-004

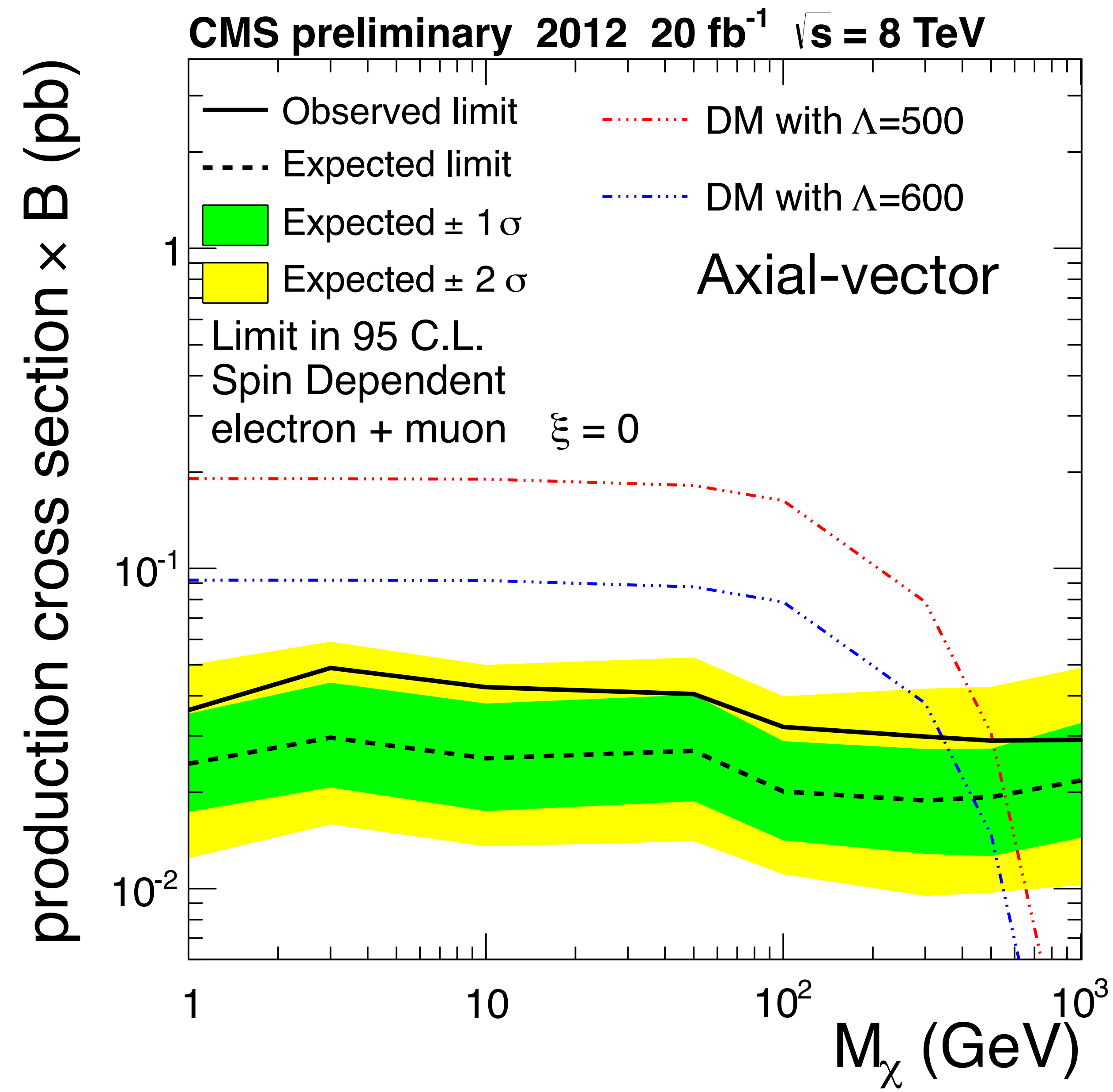




For $M\chi > 100$ GeV, AV has lower cross-section than V
m_T distribution falls more steeply for $\xi = +1$

CMS-PAS-EXO-13-004

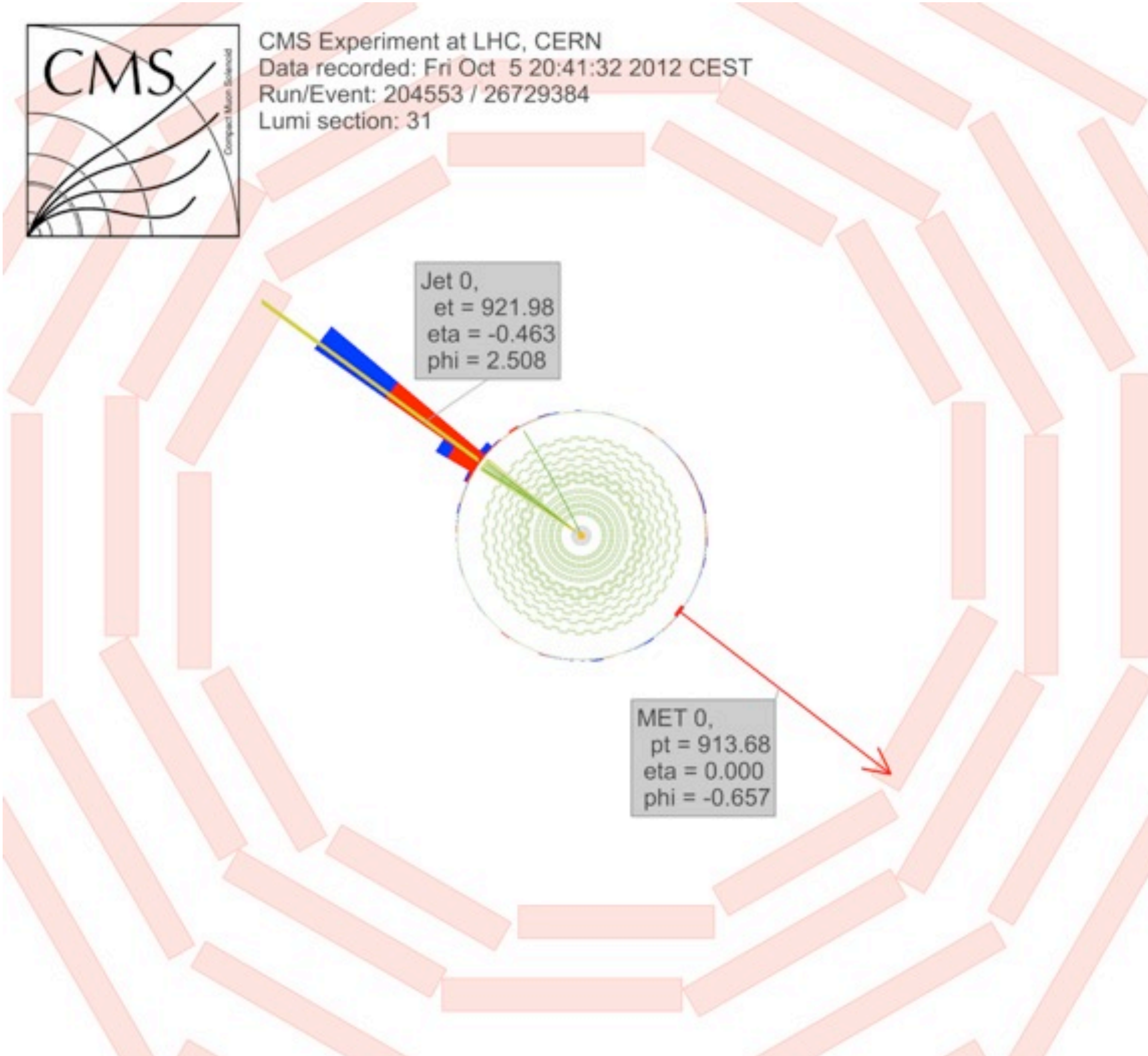




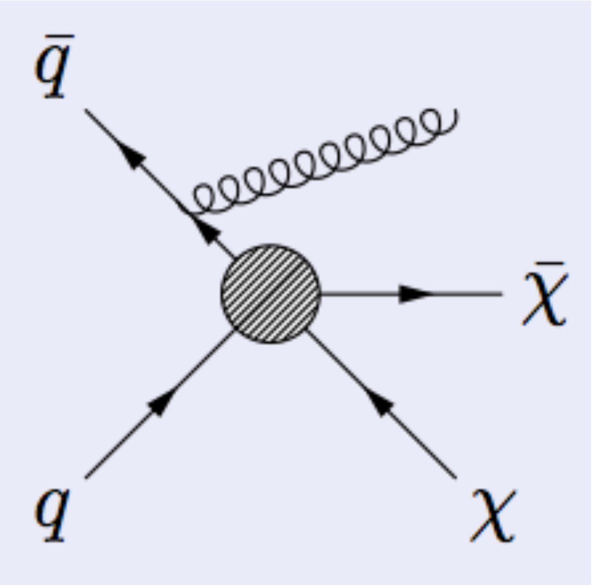
Set limits on σ.BF as function of DM mass,
for V and AV, ξ = -1, 0, +1

Monojet

CMS-PAS-EXO-12-048

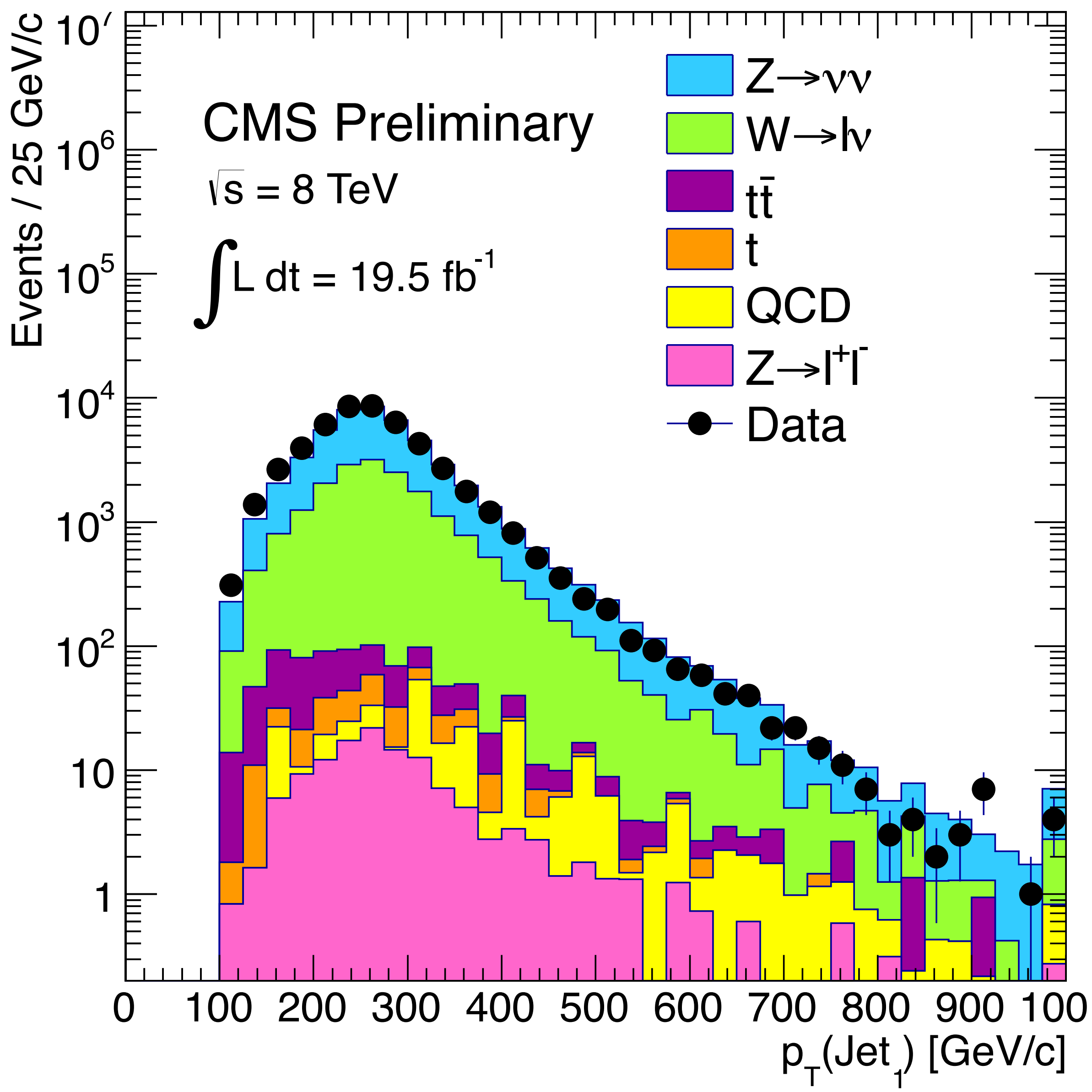


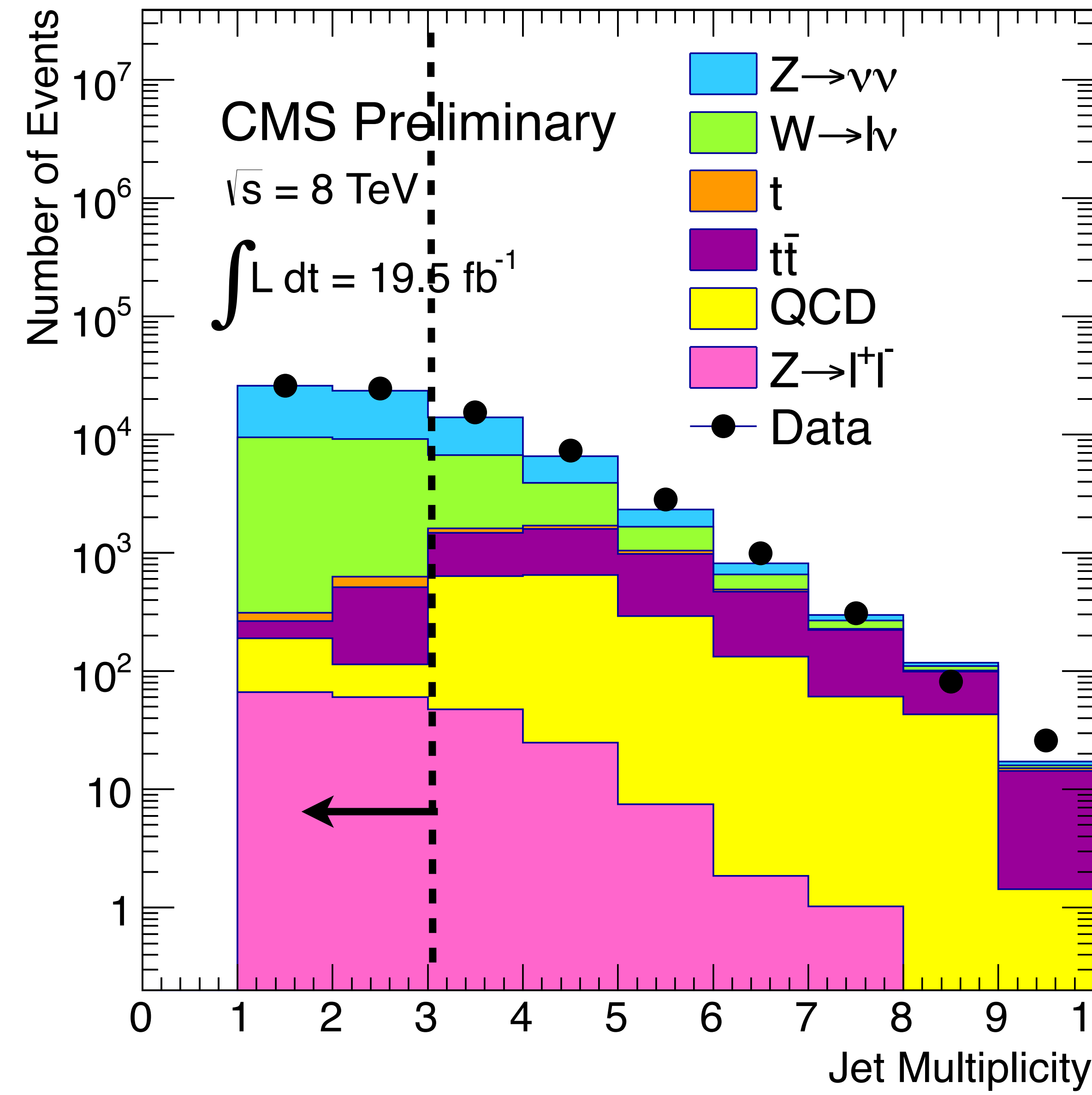
Single jet can result from initial state radiation



Monojet

CMS-PAS-EXO-12-048





$jet_1\ p_T > 110$ GeV, $\eta < 2.4$

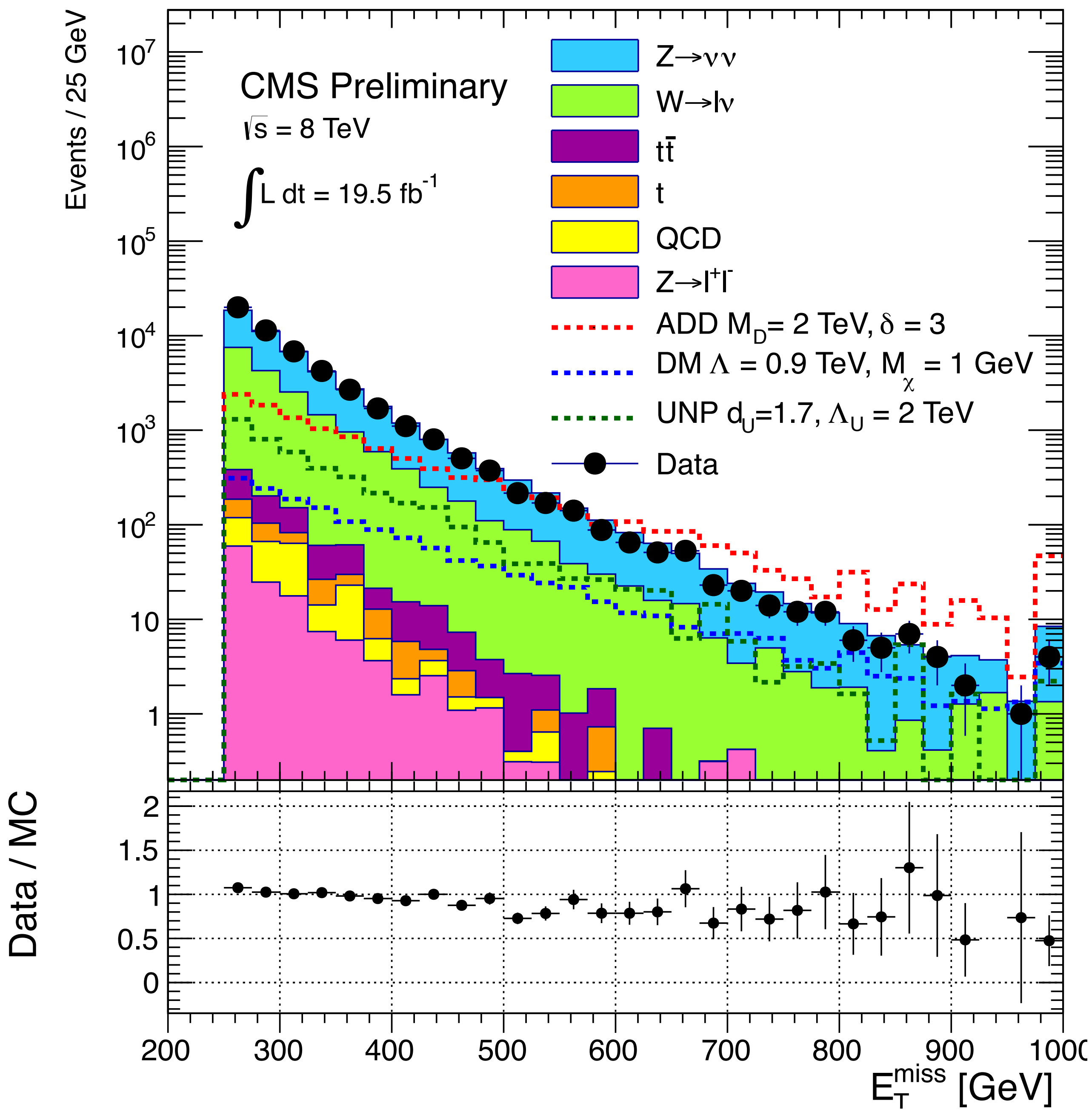
N_{jet} (30 GeV) < 3

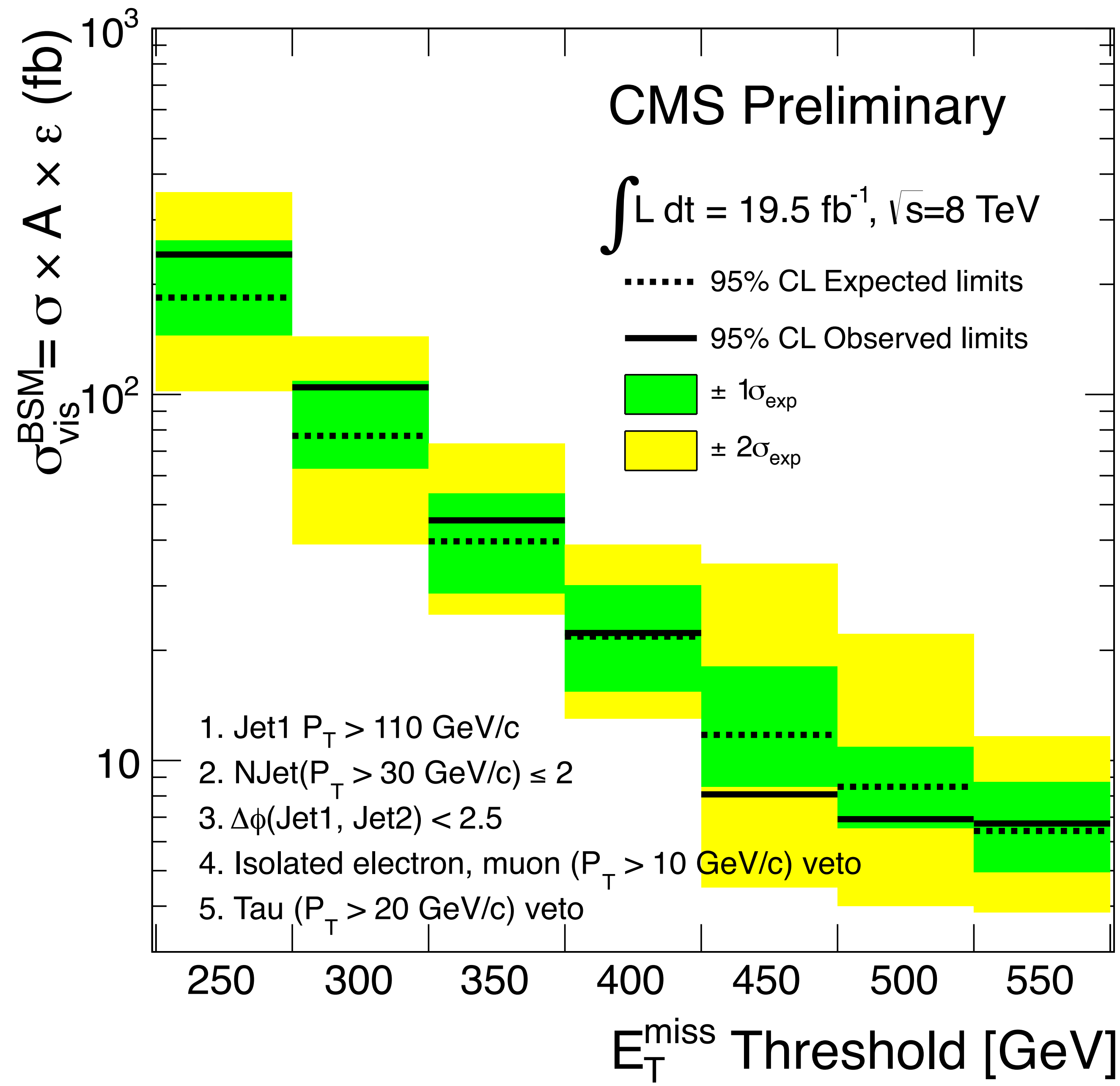
$\Delta\phi(j1,j2) < 2.5$

lepton veto : e, μ (10 GeV), τ (20 GeV)

Monojet

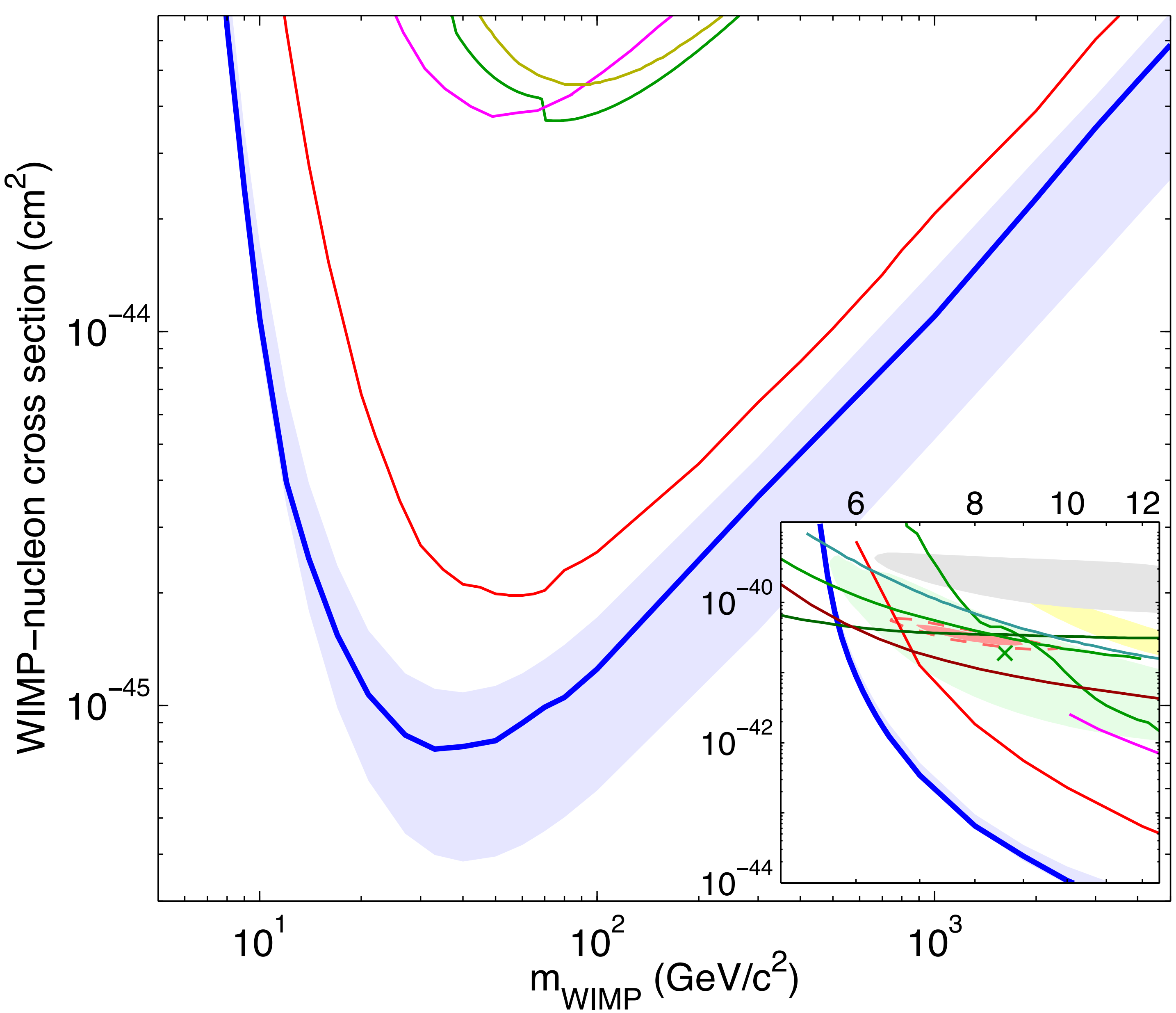
CMS-PAS-EXO-12-048





Perform a counting experiment
for several E_T^{miss} thresholds

LUX - *Phys. Rev. Lett.* ***112***, *091303 (2014)*

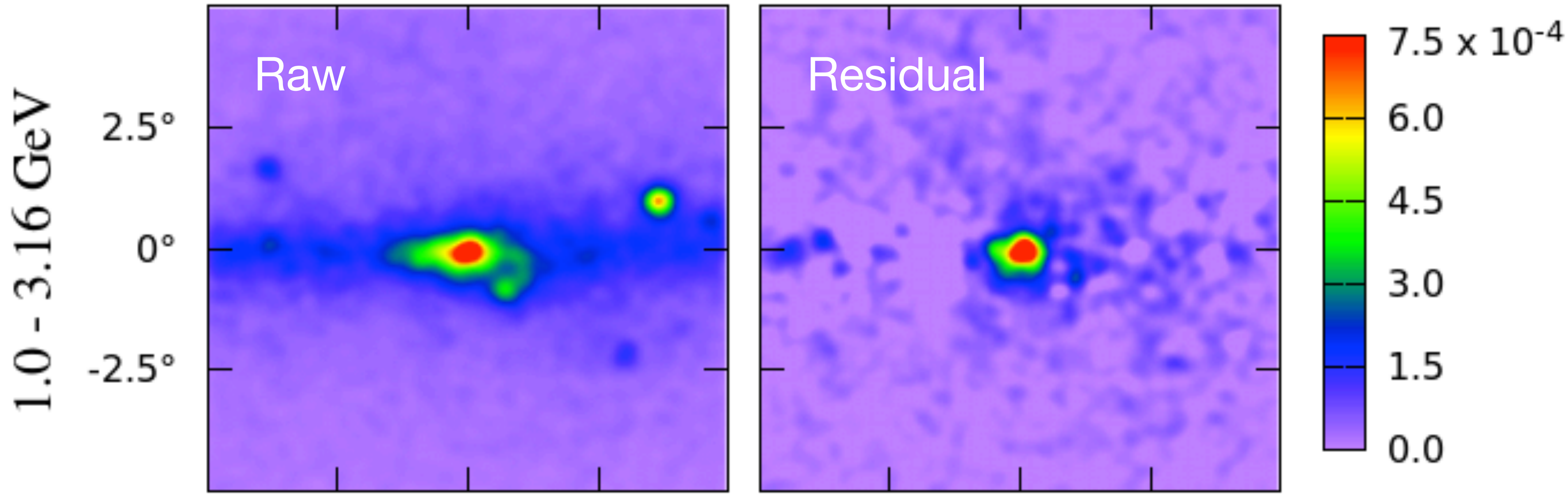


Search for galactic halo WIMPs interacting with matter in the lab

Edelweiss II [44] (dark yellow line), CDMS II [45] (green line), ZEPLIN-III [46] (magenta line), CDMSlite [47] (dark green line), XENON10 S2-only [20] (brown line), SIMPLE [48] (light blue line) and XENON100 100 live-day [49] (orange line), and 225 live-day [50] (red line) results. The inset (same axis units) also shows the regions measured from annual modulation in CoGeNT [51] (light red, shaded), along with exclusion limits from low threshold re-analysis of CDMS II data [52] (upper green line), 95% allowed region from CDMS II silicon detectors [53] (green shaded) and centroid (green x), 90% allowed region from CRESST II [54] (yellow shaded) and DAMA/LIBRA allowed region [55] interpreted by [56] (grey shaded). Results sourced from DMTools [57].

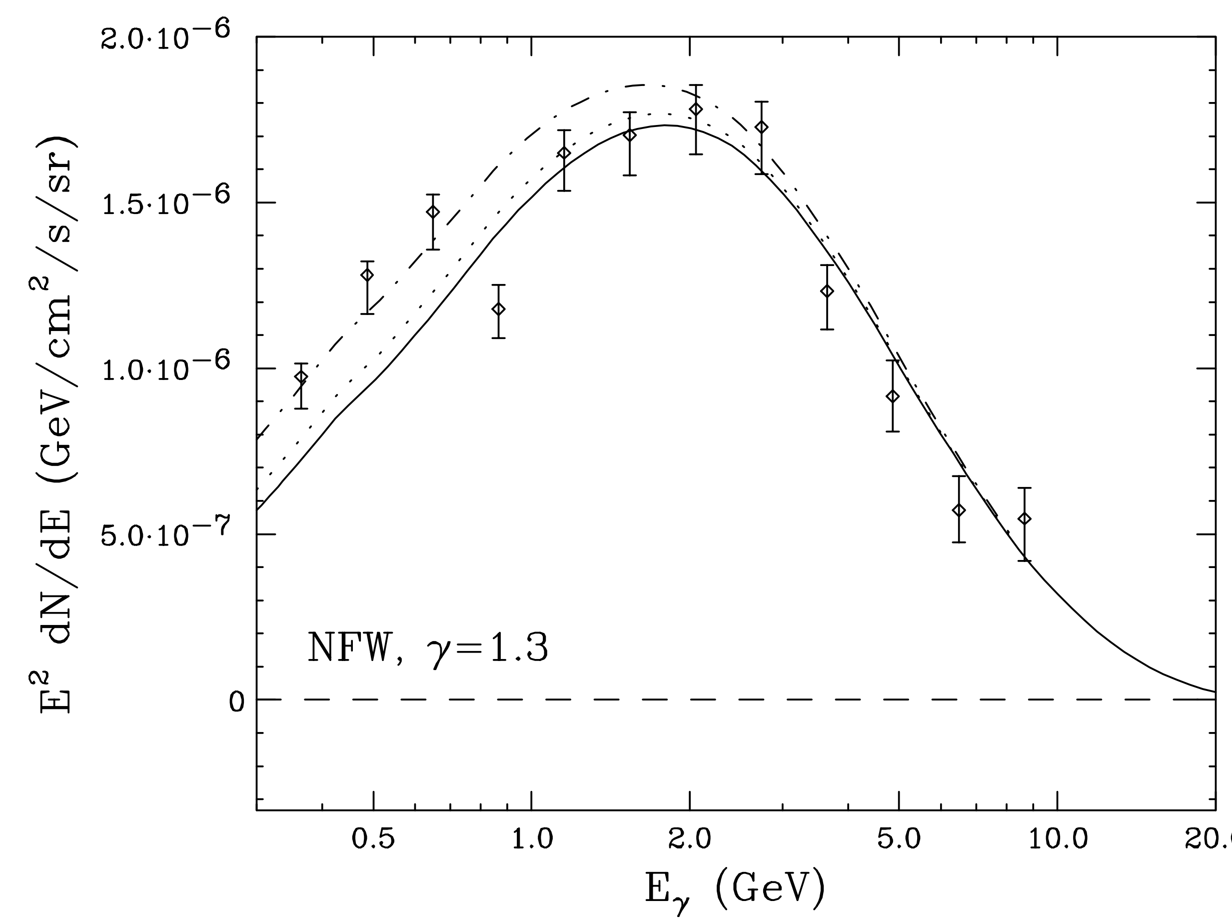
Indirect DM Searches

arXiv:1402.6703 [astro-ph.HE]



Observe a gamma-ray excess from galactic centre in the Fermi-LAT data

Compare observed spectrum with DM annihilation model
$\chi^0\chi^0 \rightarrow bb$, m_χ = 35.25 GeV



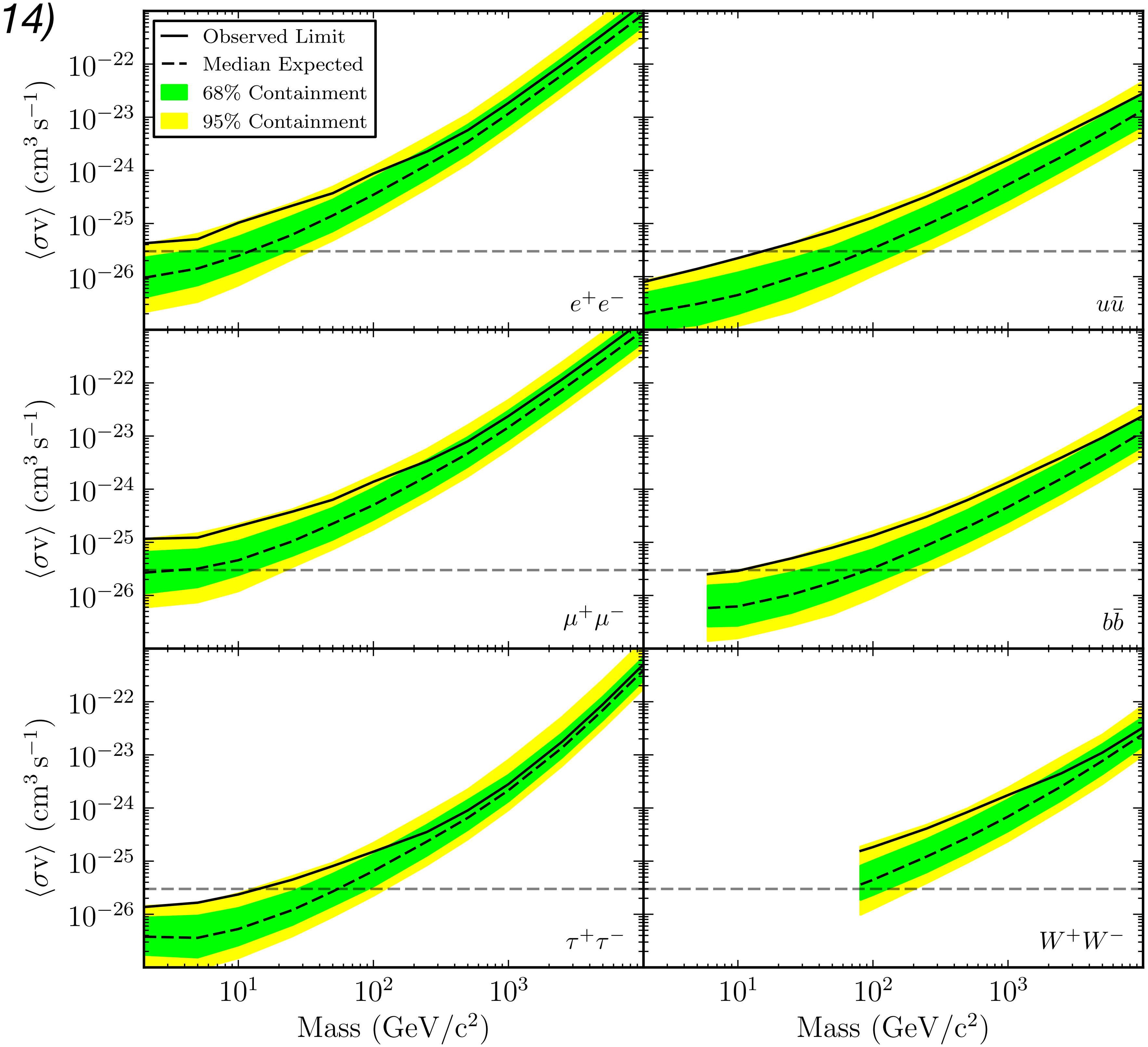
Indirect DM Searches

Phys. Rev. D 89, 042001 (2014)

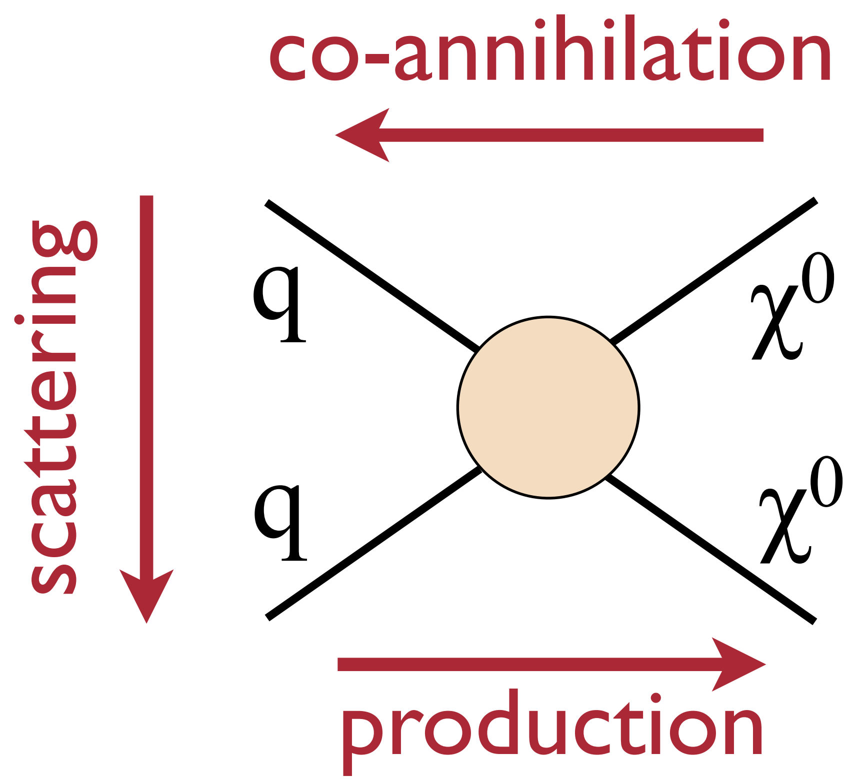
Fermi-LAT
Gamma-ray data from 25 dwarf spheroidal galaxies

Set limits on DM co-annihilation cross-section

Expectation from primordial DM abundance :
~3 × 10^{-26} cm^{3}s^{-1}



All these searches probe the same interaction...

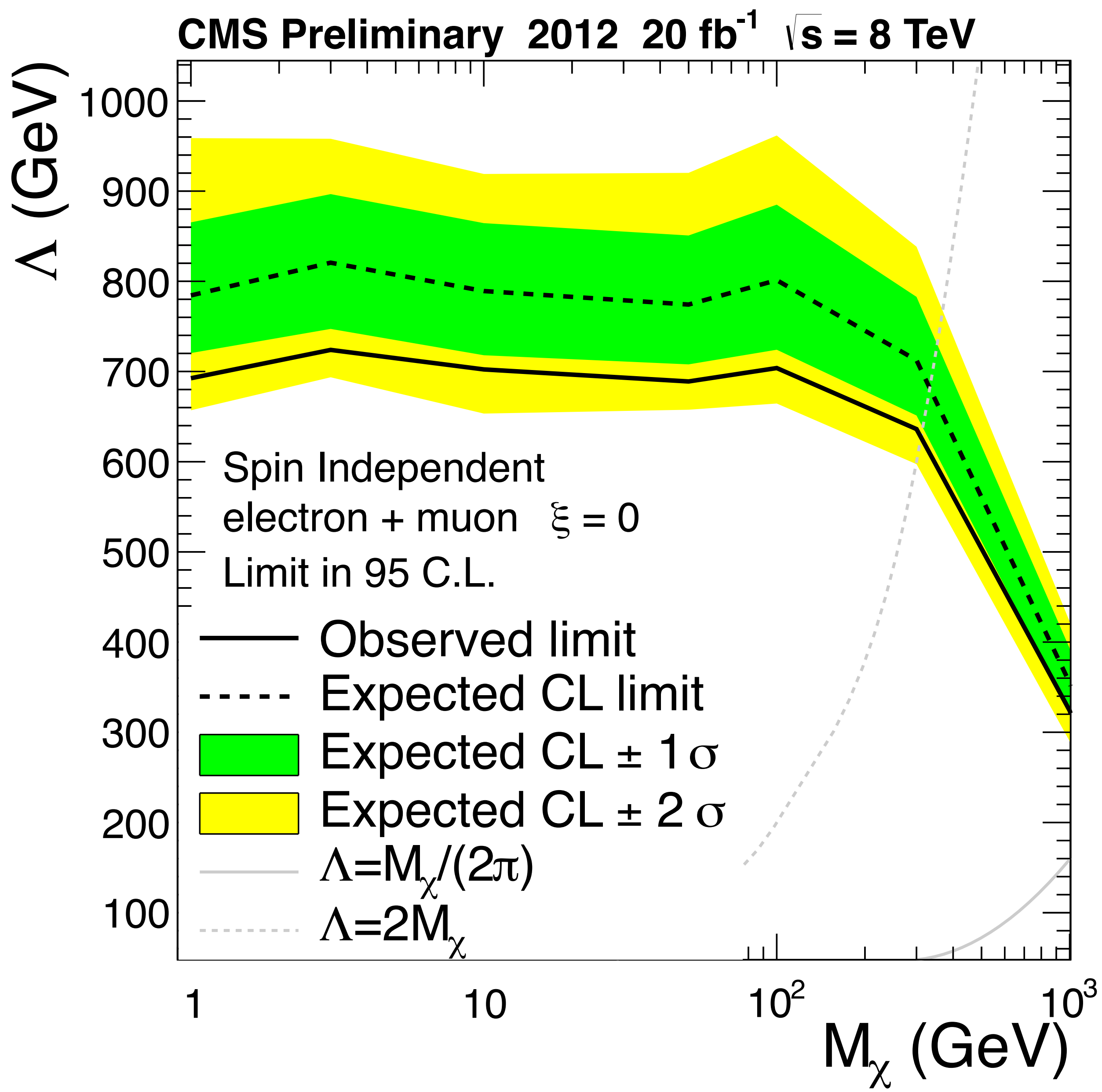


Use the effective field theory to convert limits on $\sigma(pp \rightarrow \chi^0\chi^0)$ to limits on $\sigma(\chi^0$-nucleon) and compare with direct detection expts (scattering)

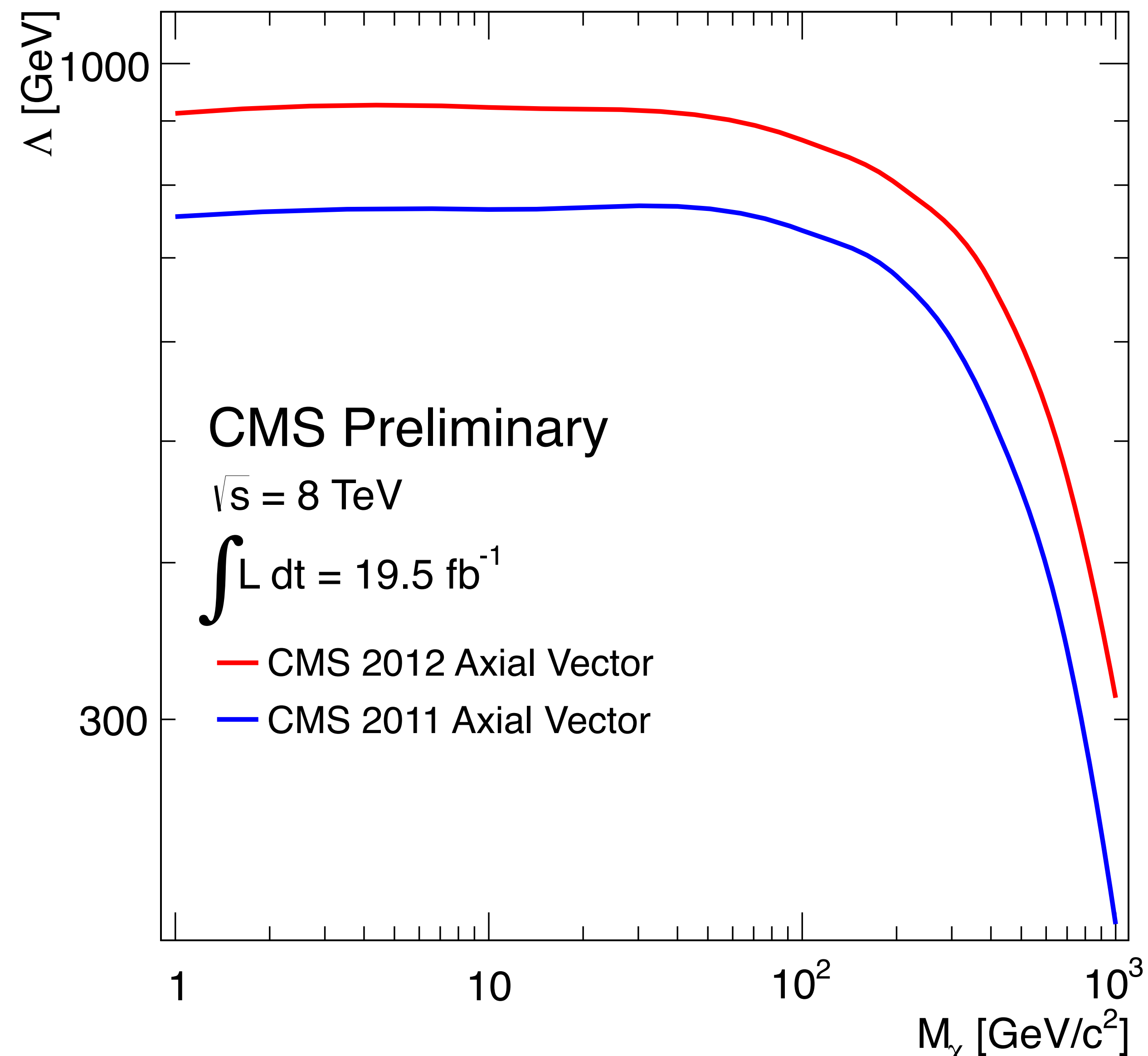
DM-nucleon Limits

CMS-PAS-EXO-13-004
CMS-PAS-EXO-12-048

University of BRISTOL



Mono-lepton V

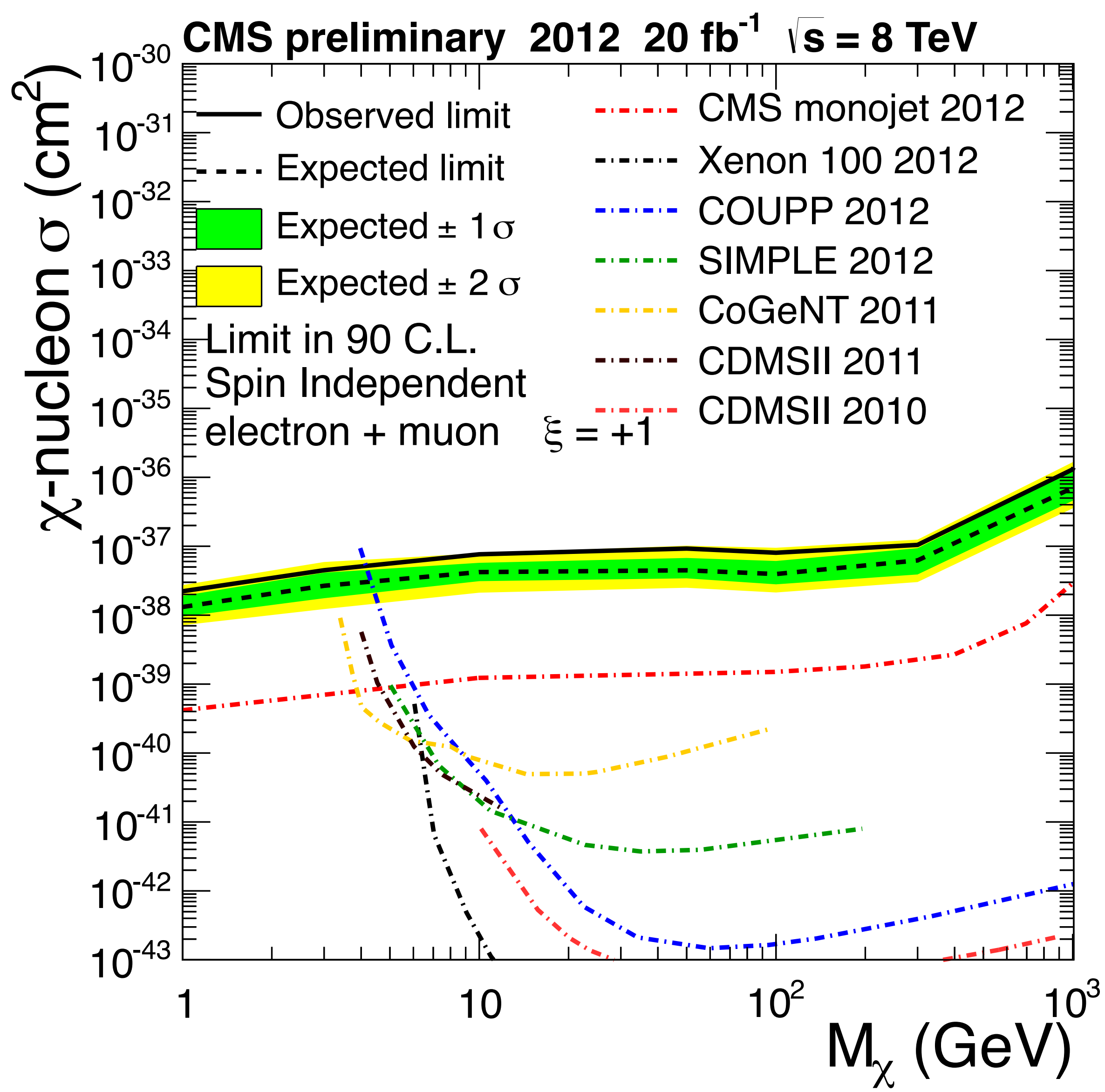


Mono-jet AV

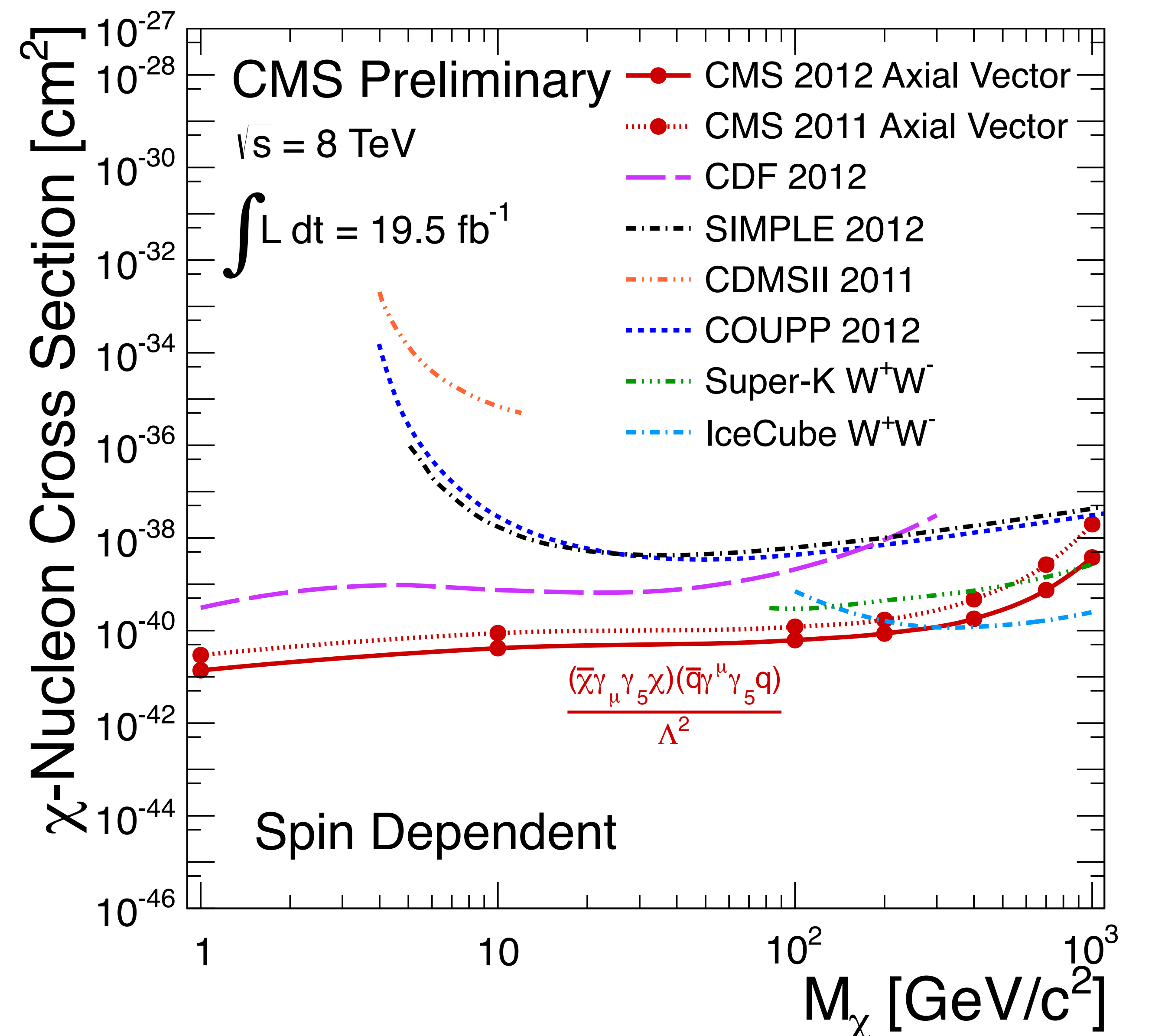
Convert limits on σ.BF to limits in Λ-M_χ plane

DM-nucleon Limits

CMS-PAS-EXO-13-004
CMS-PAS-EXO-12-048



Monolepton V



Monojet AV

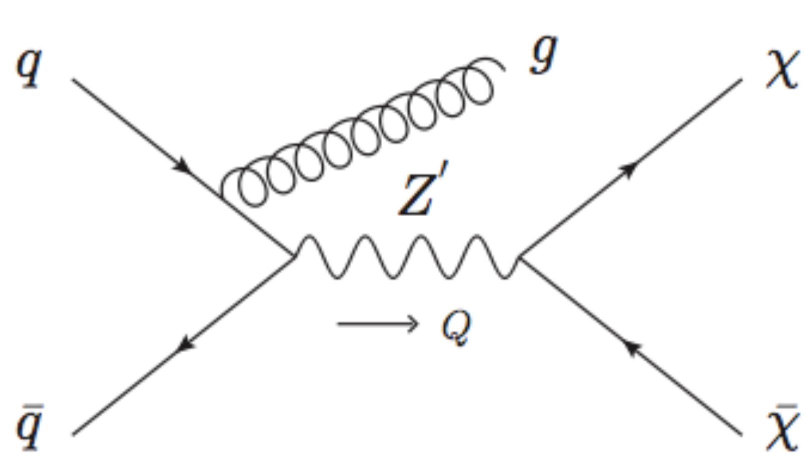
Also have results for :
monolepton AV, monojet (V, S), monophoton (V, AV), monotop (V, S), tt+MET

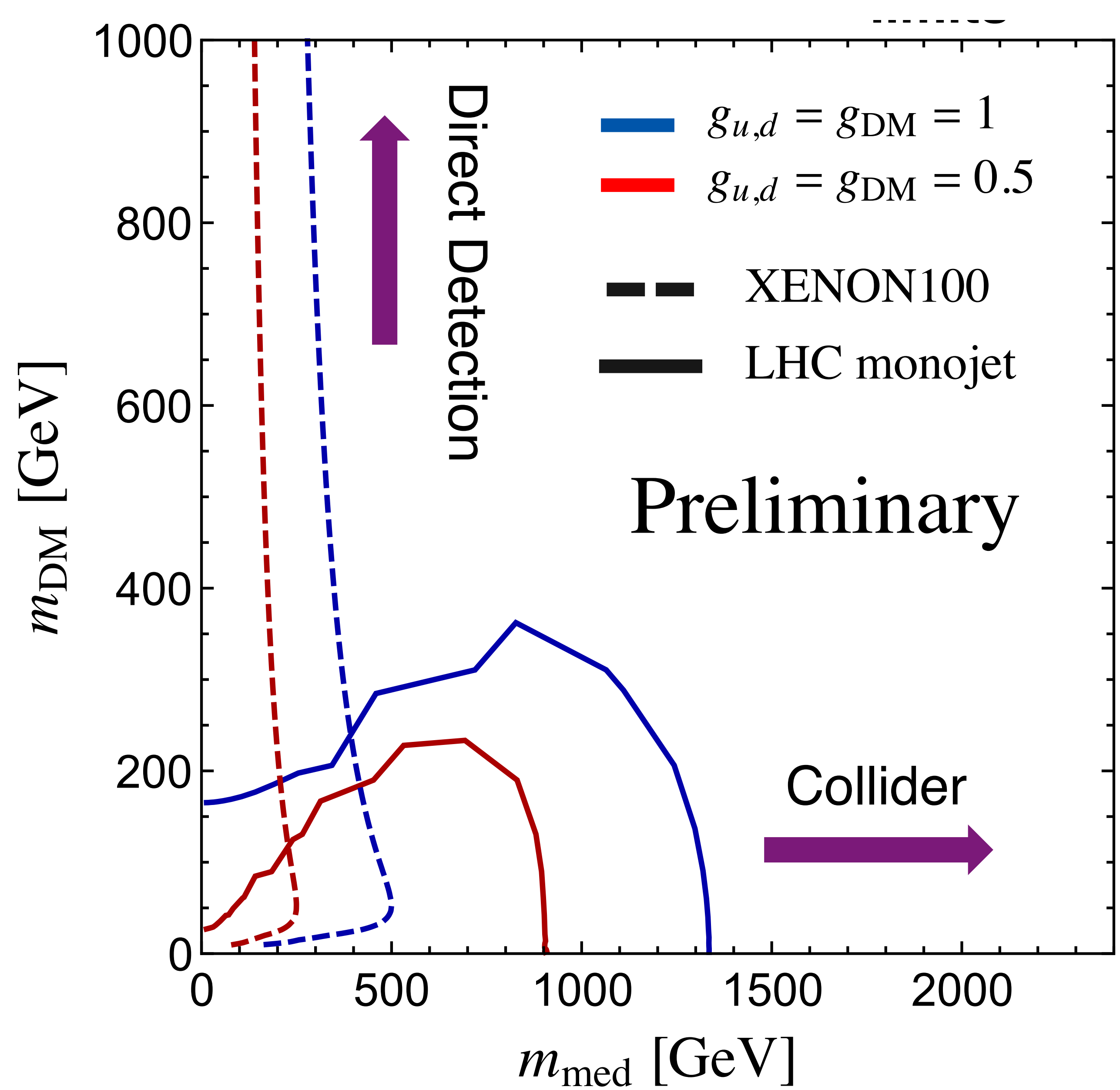
Caveat

- Several papers discuss validity of the effective field theory
  - eg Buchmuller, Dolan, McCabe : arXiv:1308.6799
  - EFT is only valid for high mediator mass
  - (Also, valid region has $\Gamma_{med}/m_{med} > 1$!)

- Collider limits on $\sigma(\chi^0$-nucleon)
  - Need to be taken with a pinch of salt !

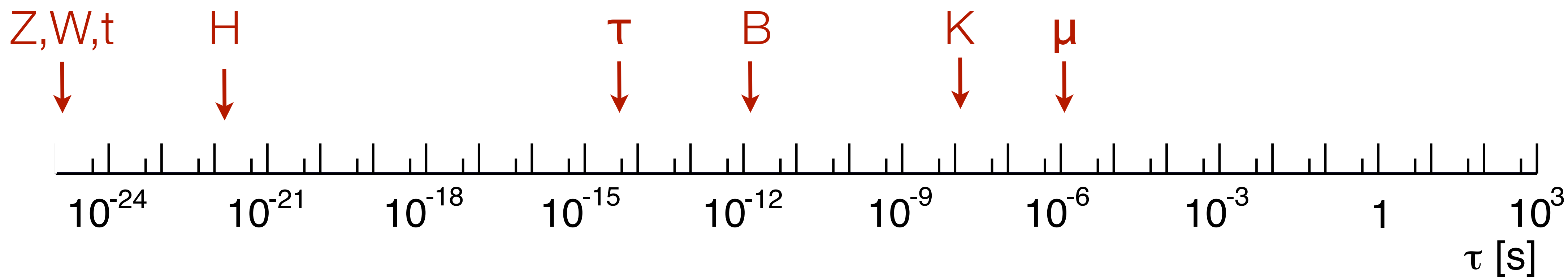
- Proposal from paper above
  - Present limits using simplified models
  - Parameters : m_{med}, m_χ , g_q, g_χ, Γ_{med}





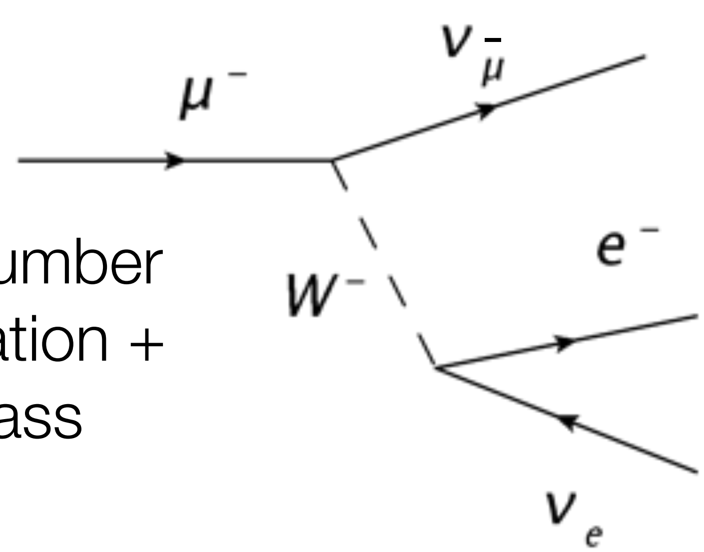
Long Lived Particles

Long Lived Particles

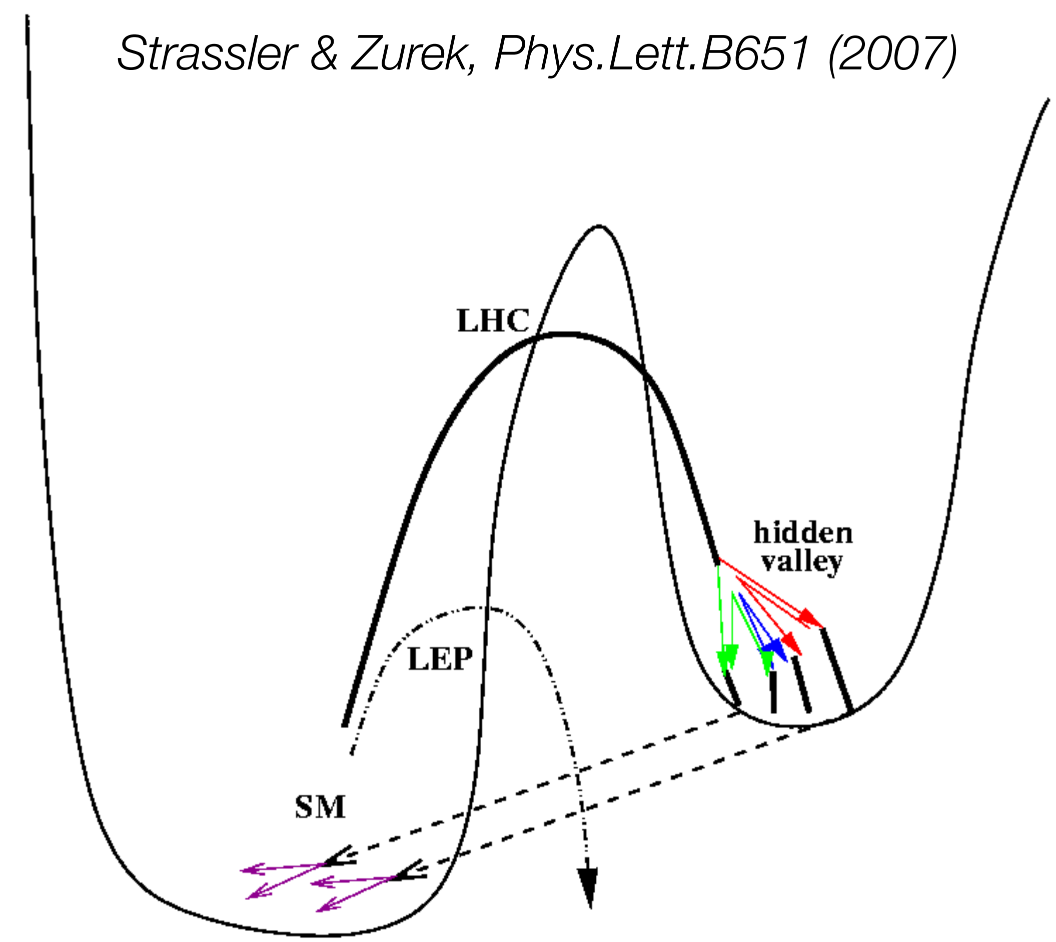


- Long lifetimes are common in the SM
  - Constrained interactions + potential barrier

lepton number conservation + W mass



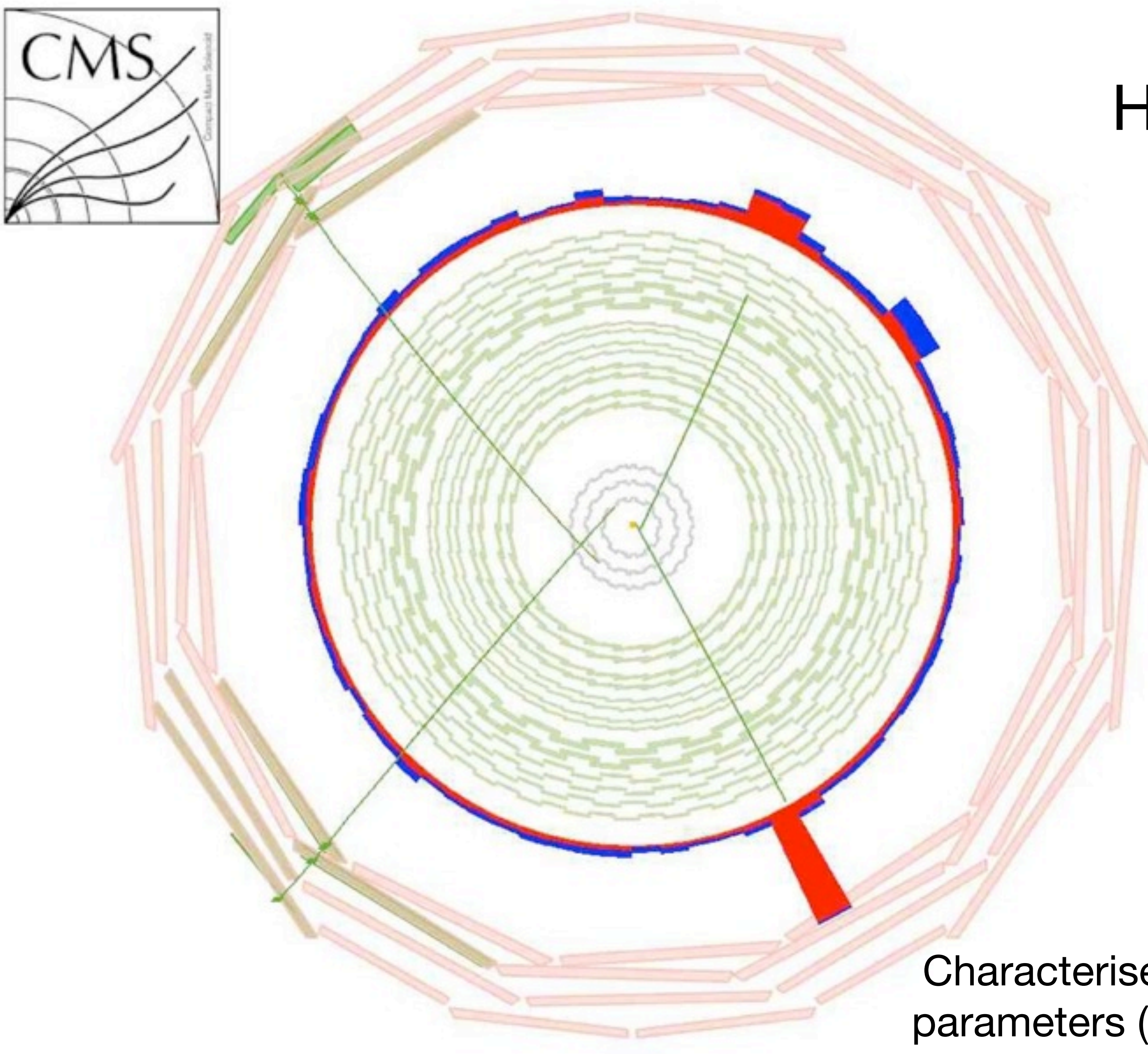
Strassler & Zurek, Phys.Lett.B651 (2007)



- **We should expect them in BSM scenarios !**
  - Split SUSY, GMSB, RPV, ...

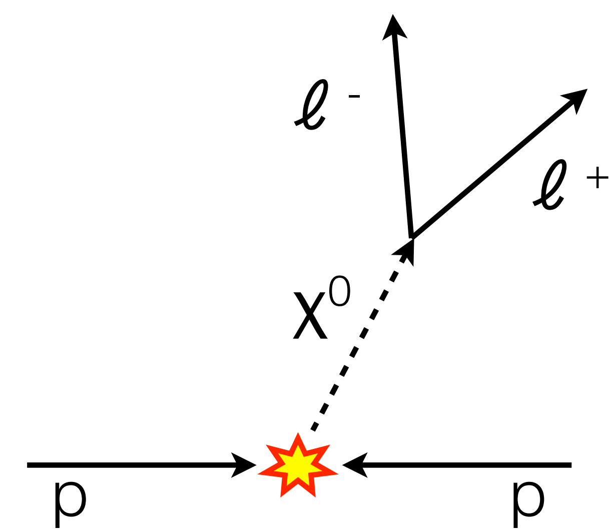
Displaced Dileptons

Displaced Dileptons



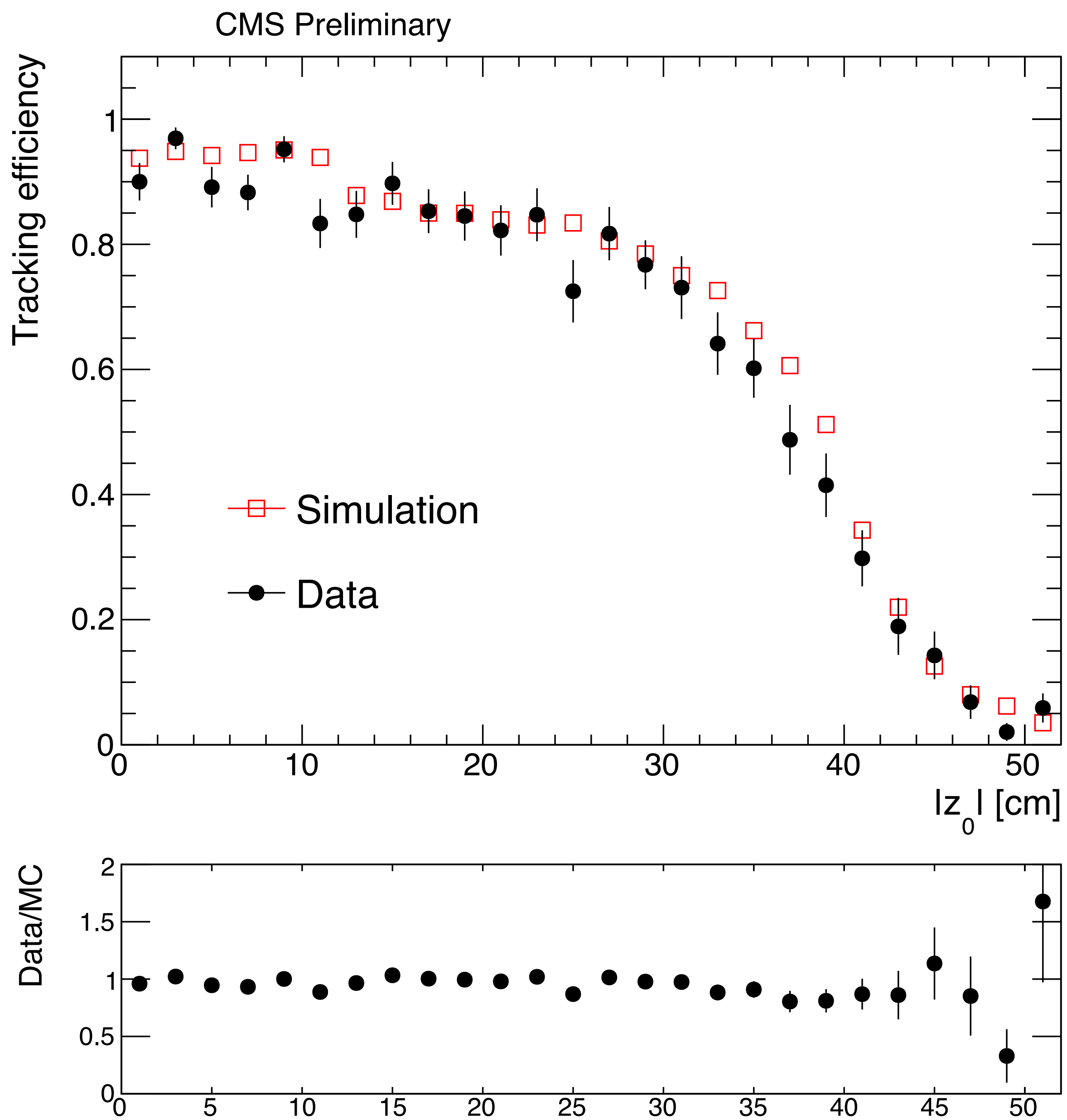
Simulated

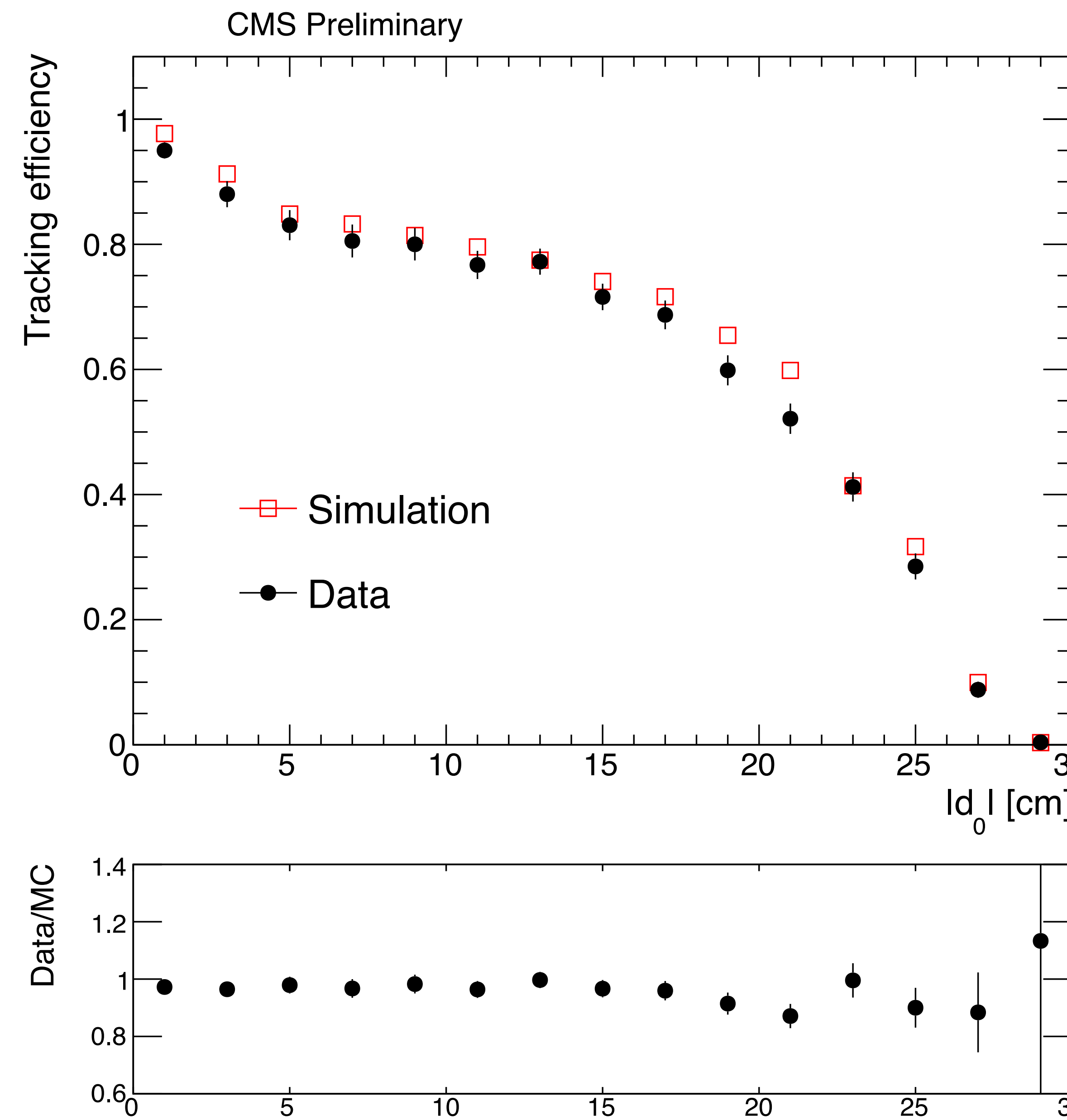
$H^0 \rightarrow X^0 X^0 \rightarrow \mu^+ \mu^- e^+ e^-$



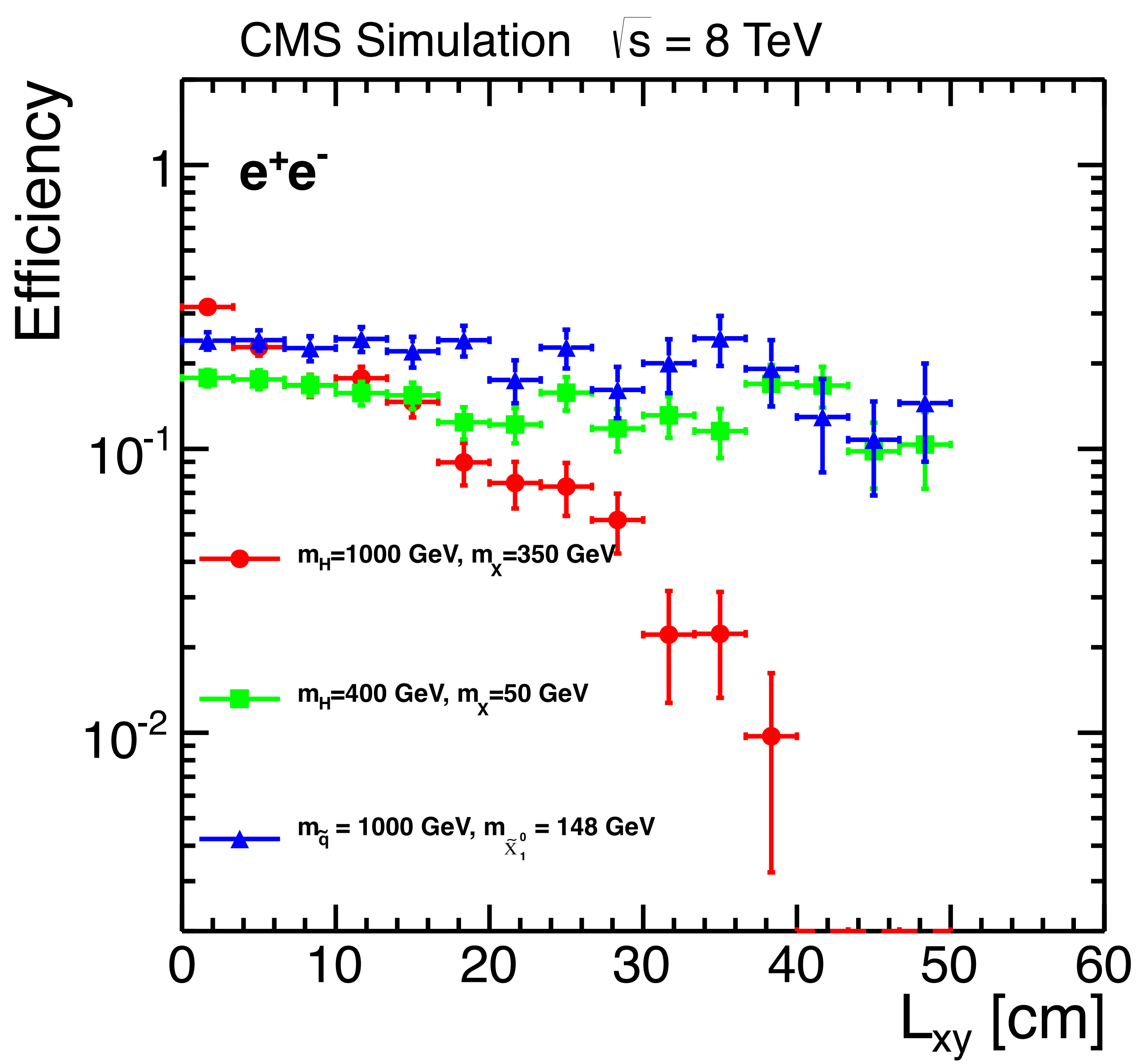
Characterise X^0 decay with track impact parameters (d_0, z_0) and decay length (L_{XY})

Require good tracking efficiency for high impact parameter tracks

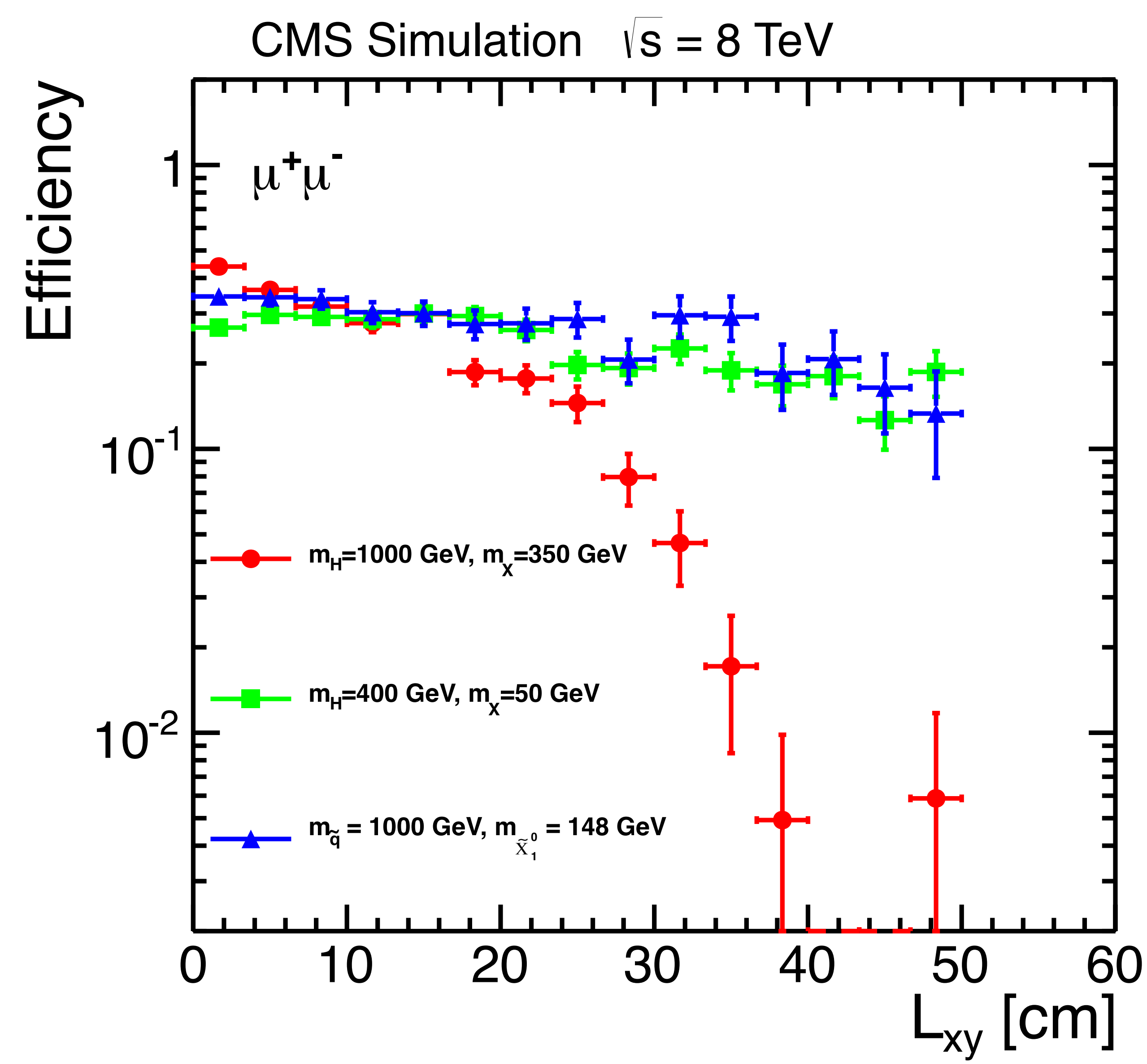




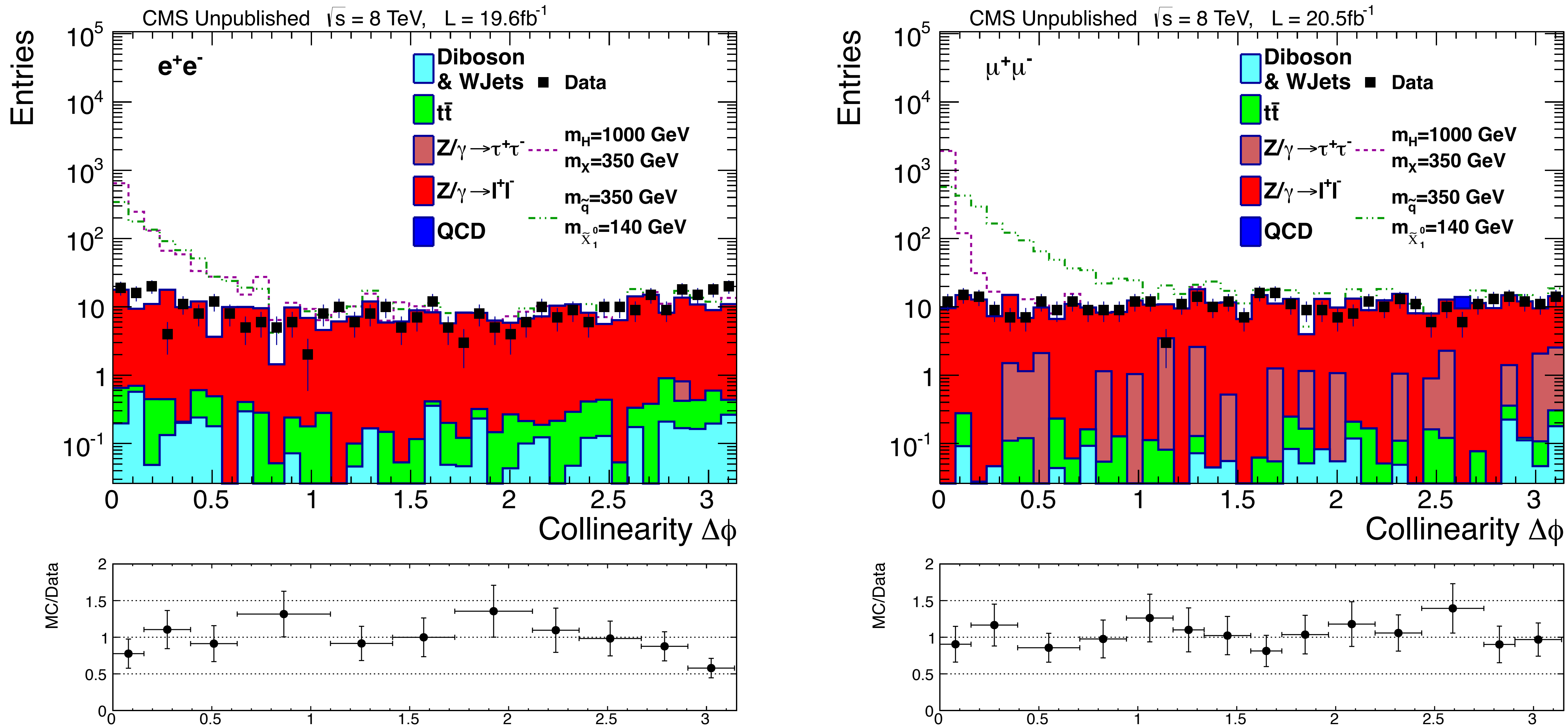
Tracking efficiency measured from cosmics



ECAL $E_T(1,2) > 40,25$ GeV
Track $p_T(1,2) > 36,21$ GeV
Track RelIso < 0.1 (0.04 < R < 0.3)
Track $|d_0/\sigma_d| > 12$
Secondary vertex χ^2/dof < 10
$\Delta\phi > \pi/2$



Track $p_T(1,2) > 26$ GeV
Track RelIso < 0.1 (0.03 < R < 0.3)
Track $|d_0/\sigma_d| > 12$
Secondary vertex χ^2/dof < 5
$\Delta\phi > \pi/2$

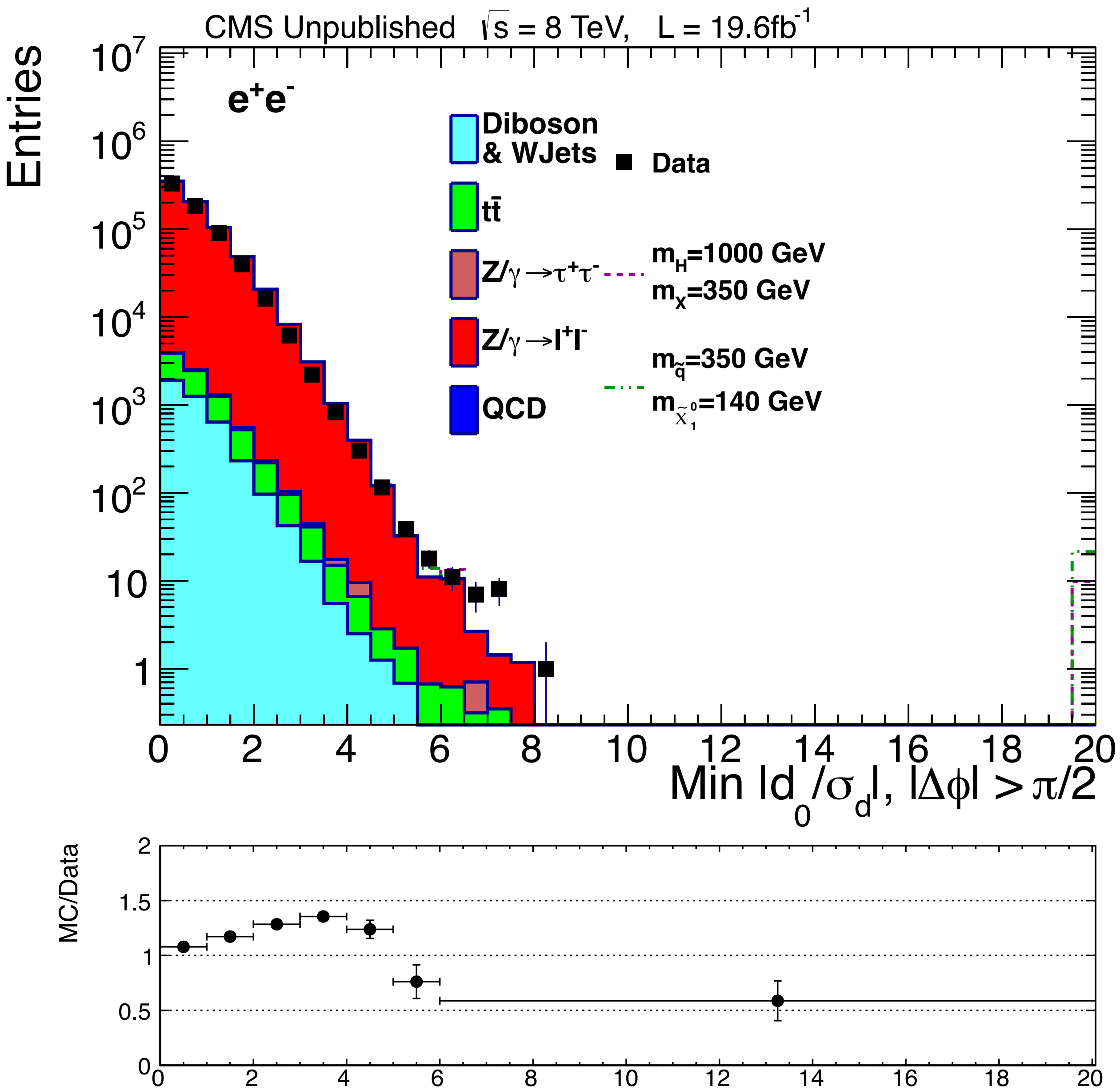


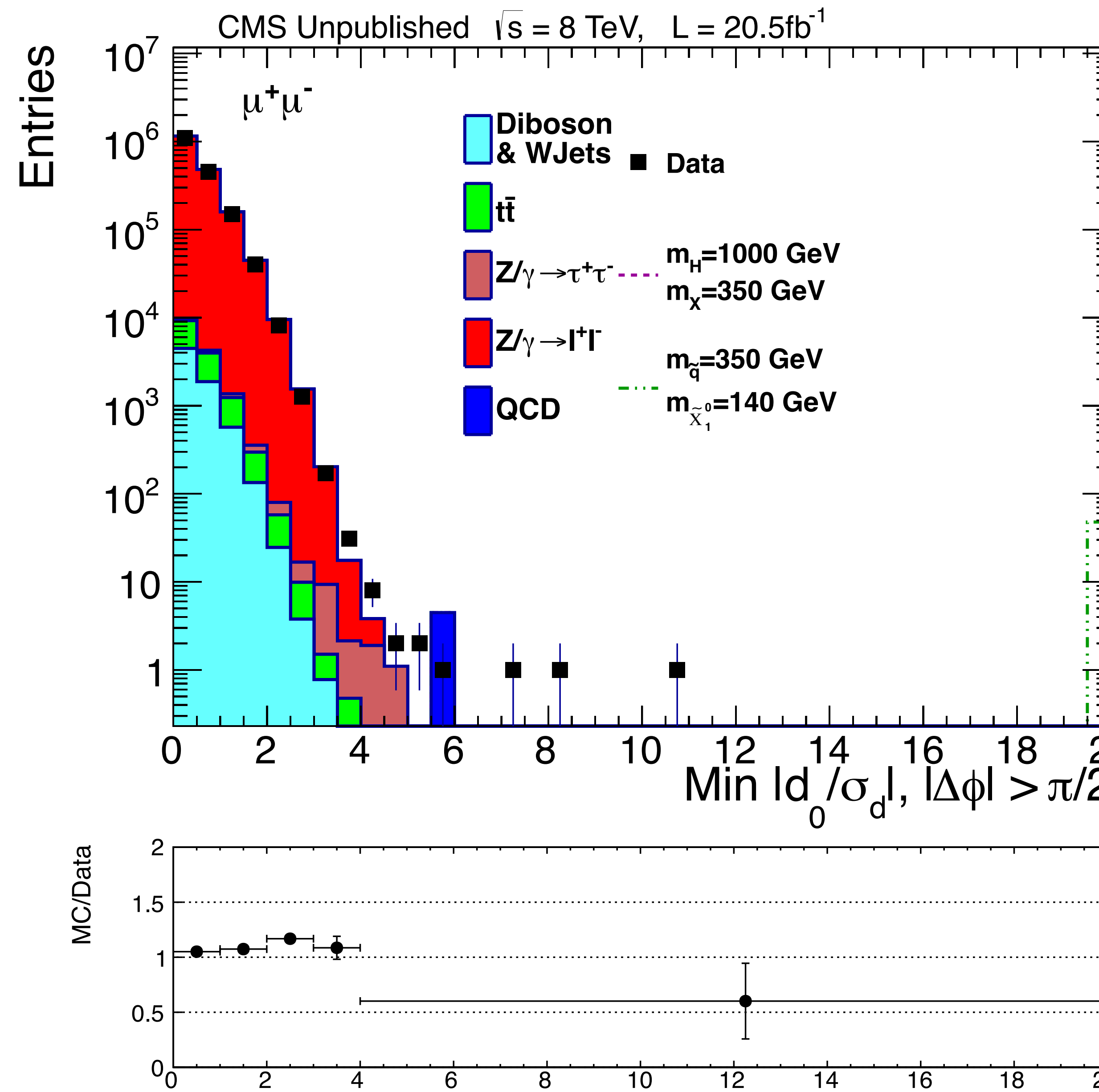
Inverted cut on $|d_0/\sigma_d|$ - ie. prompt tracks

- Azimuthal separation between dilepton momentum vector and displaced vertex vector
- Signal at small values - define control region with **$\Delta\phi > \pi/2$**
- **Background populates signal and control regions equally**

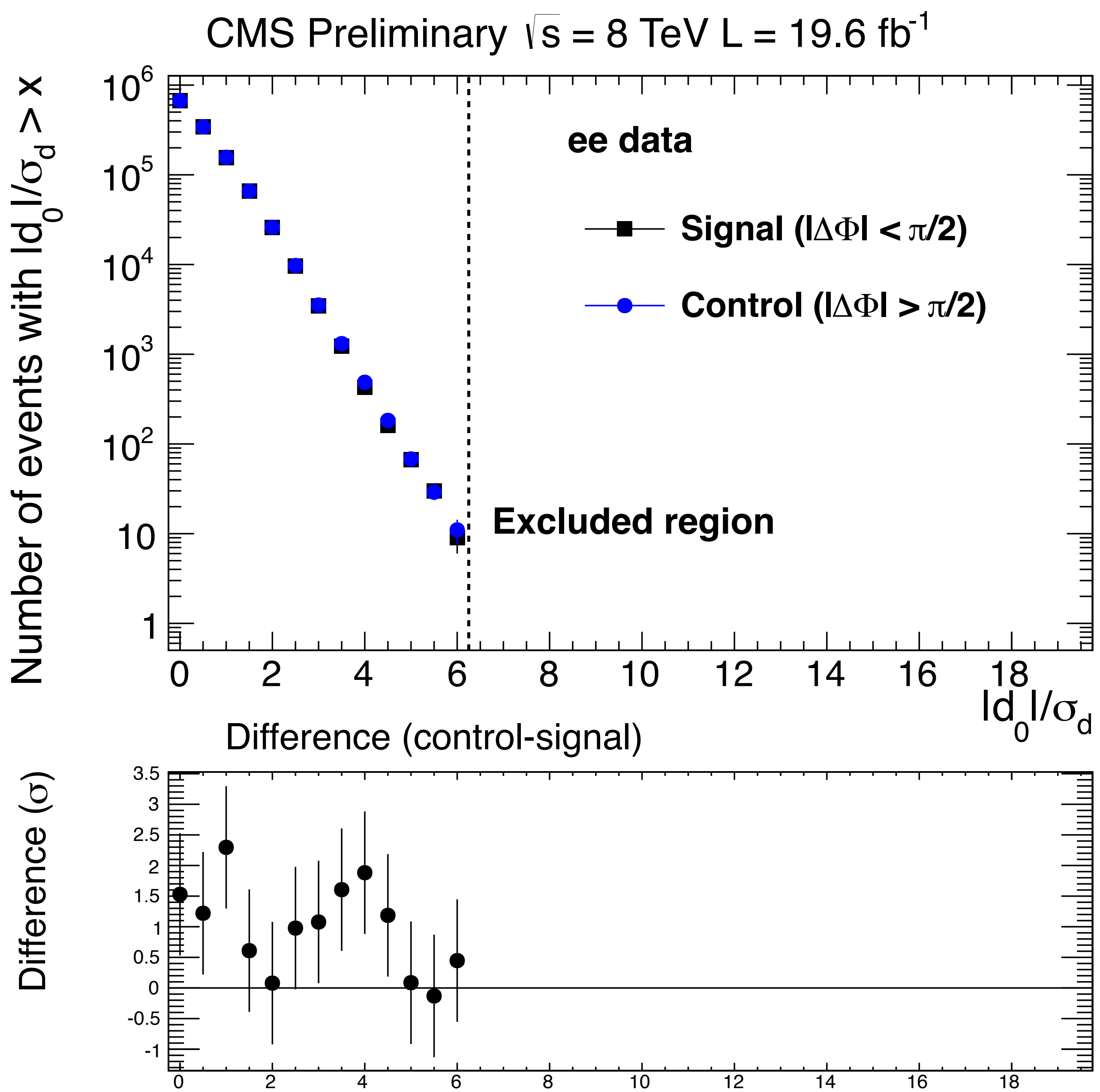
Displaced Dileptons

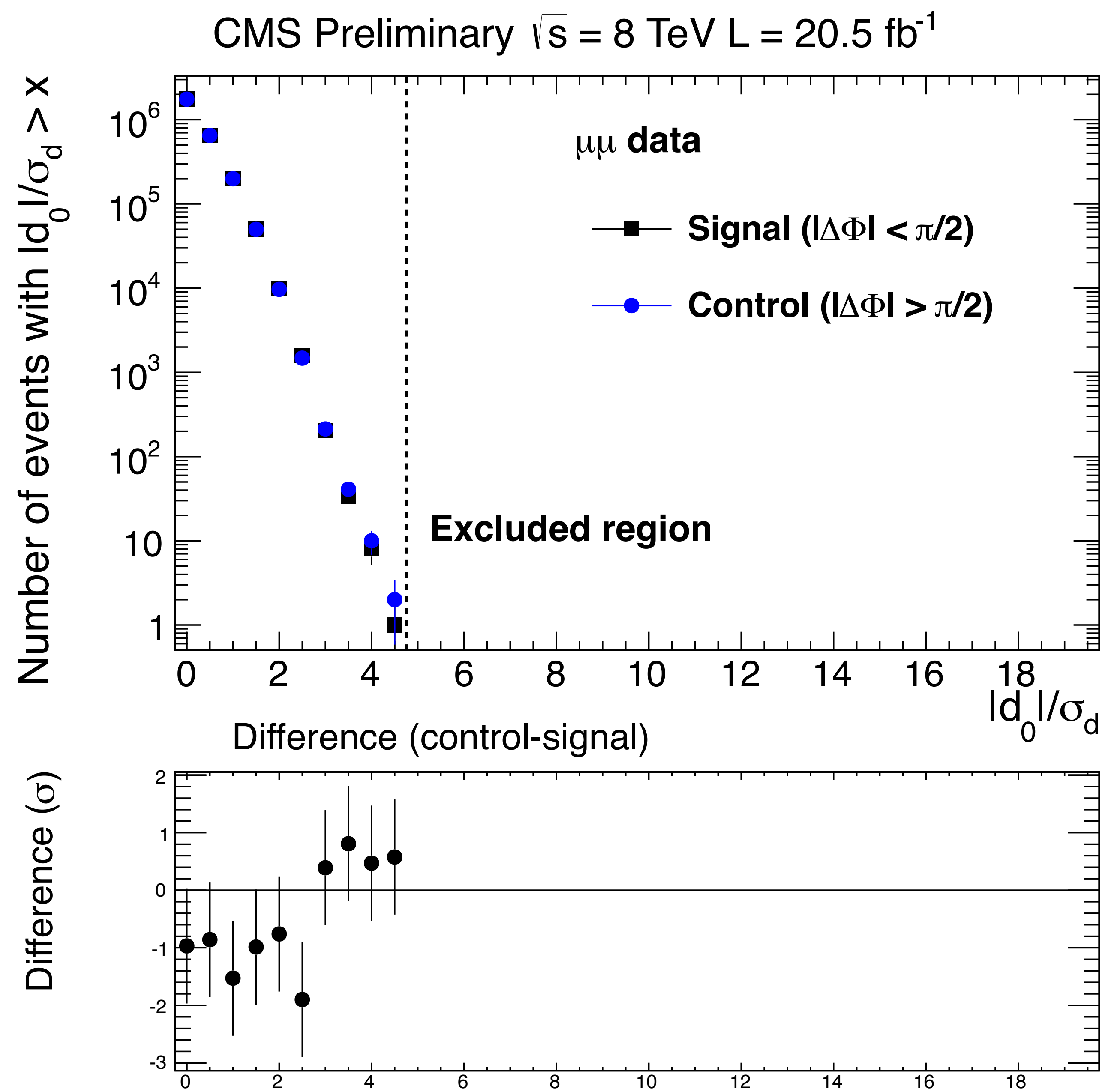
CMS-PAS-EXO-12-037





- Data and MC in control region **: $\Delta\phi > \pi/2$**

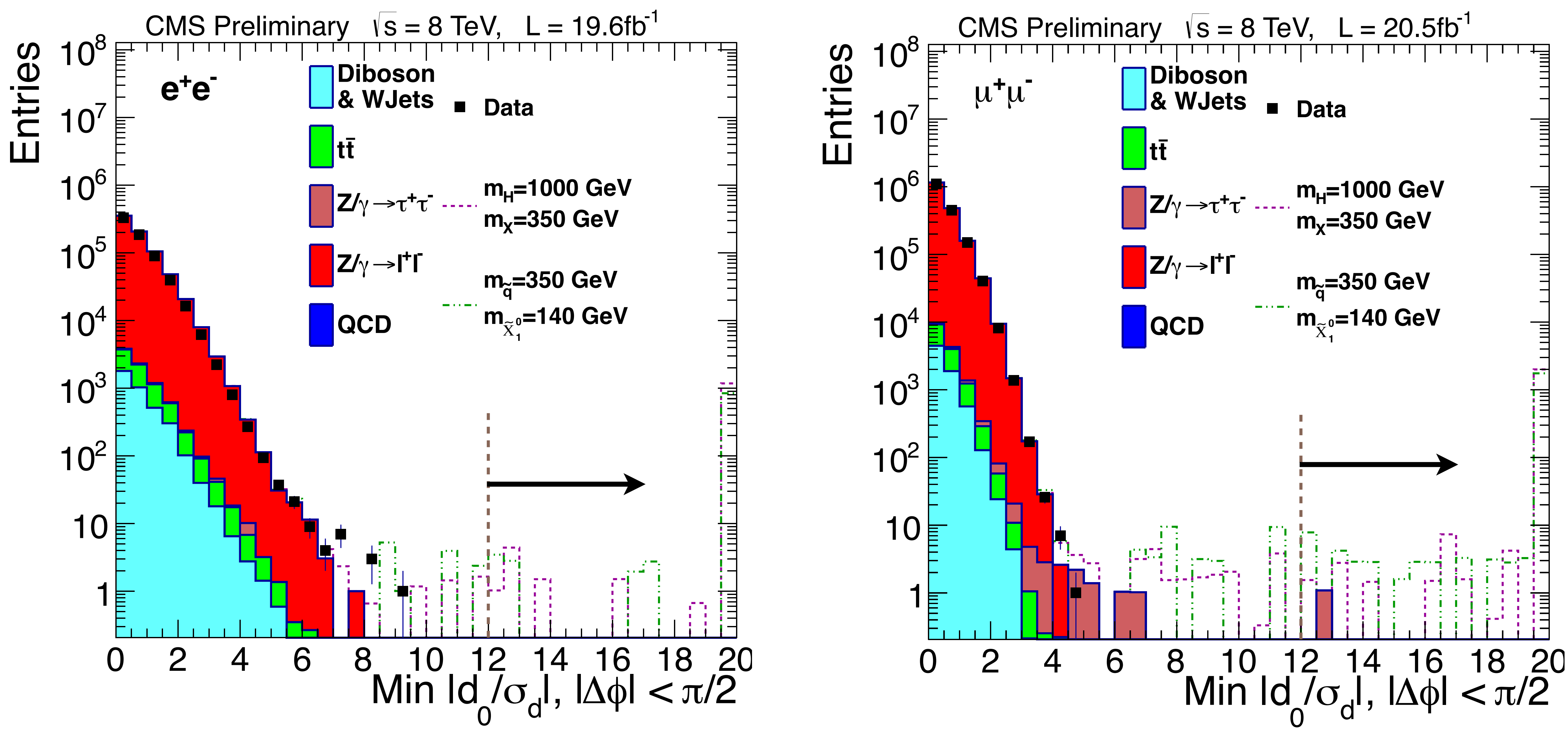




Tail cumulative distributions in control and pseudo-signal regions
(ie. minimum transverse impact parameter significance $|d_0/\sigma_d| < 6$)

Displaced Dileptons

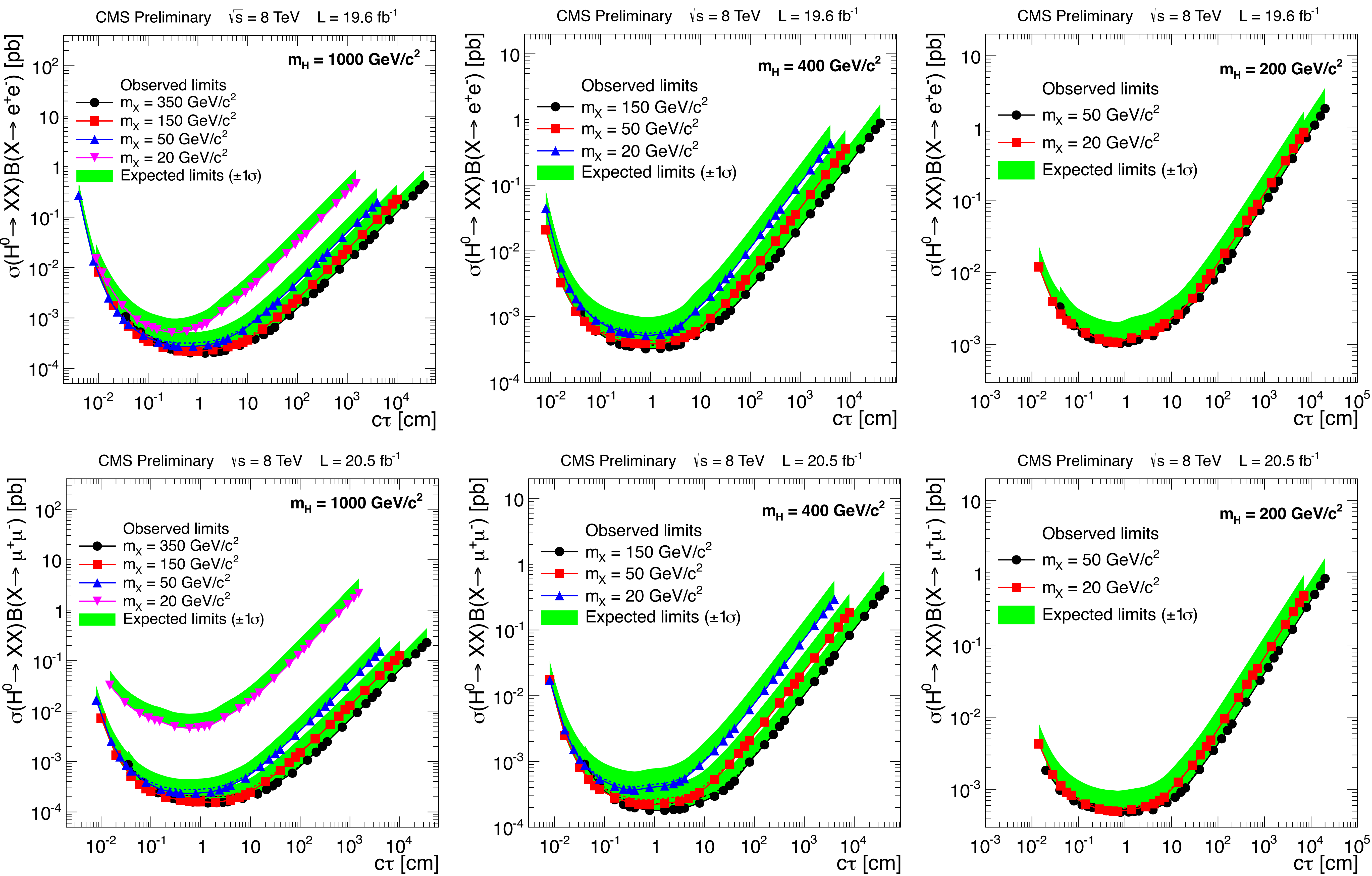
CMS-PAS-EXO-12-037



Transverse impact parameter distributions in the signal region ($\Delta\phi < \pi/2$)

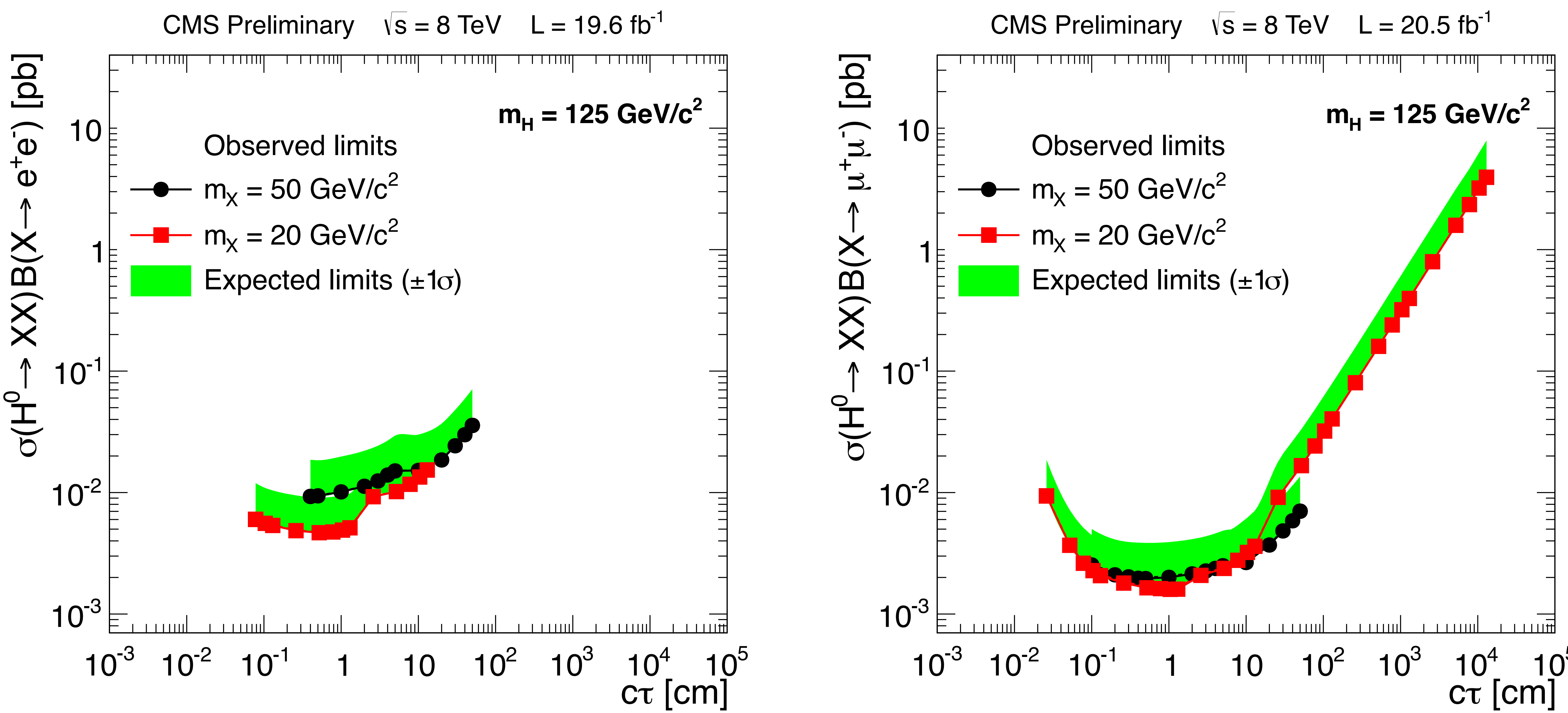
Displaced Dileptons

CMS-PAS-EXO-12-037



Displaced Dileptons

CMS-PAS-EXO-12-037



Limits on exotic decays of H_{125} !

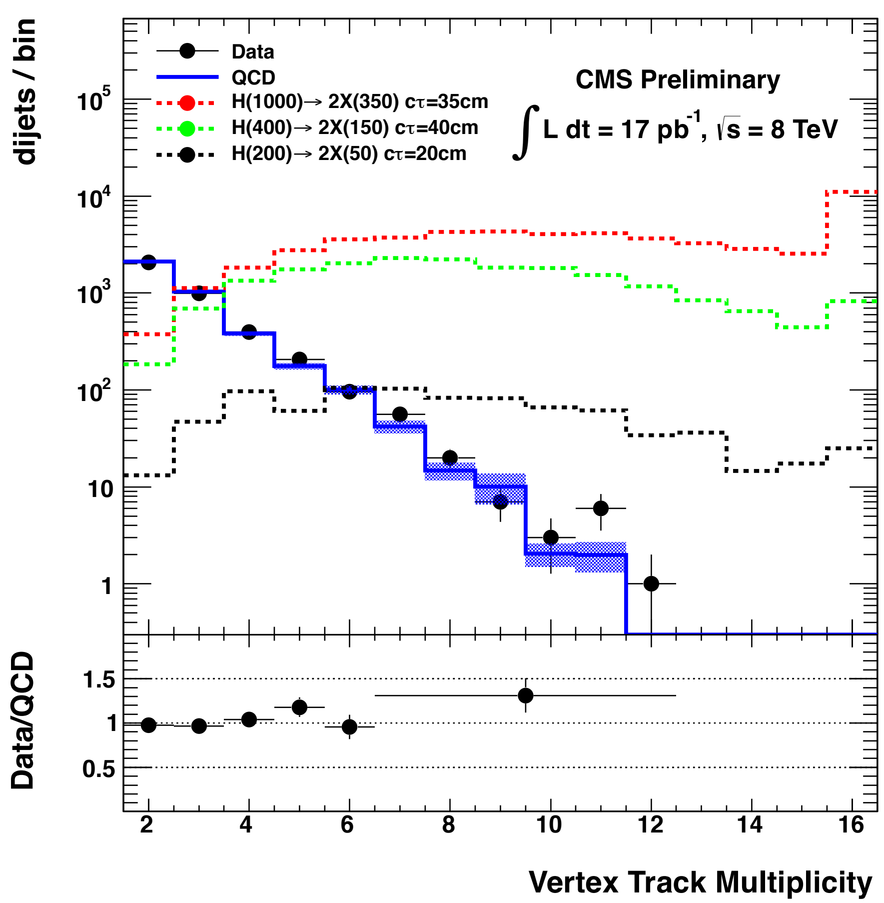
Displaced Dijets

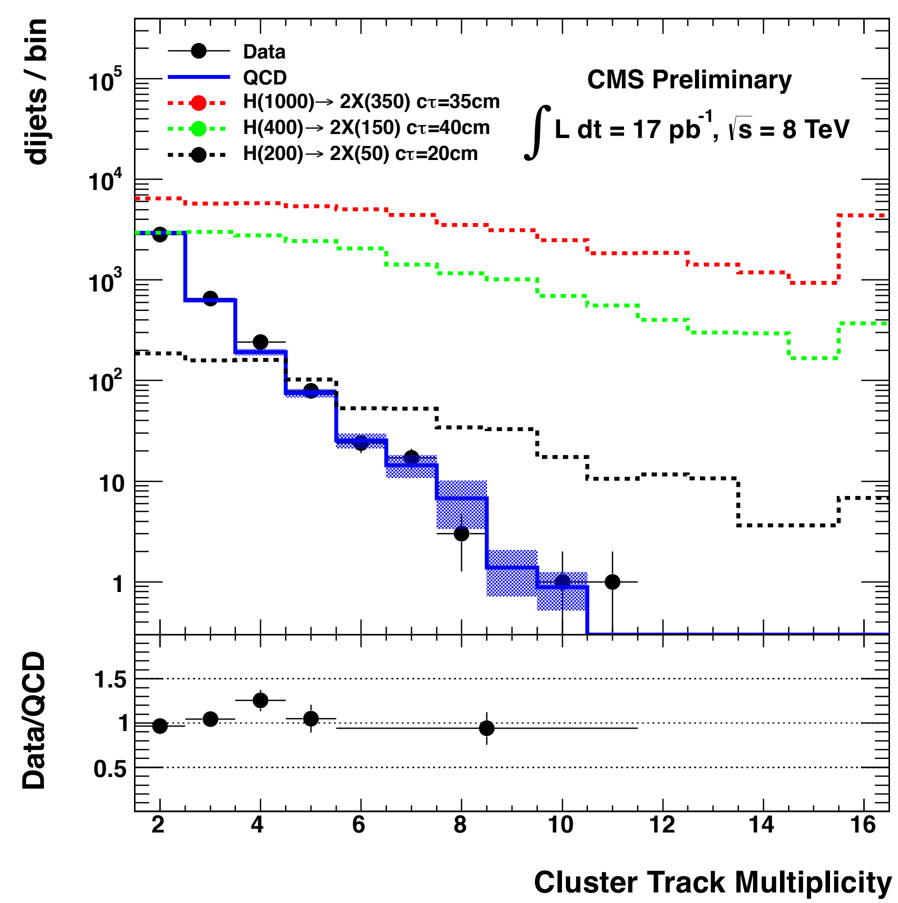
Displaced Dijets

[CMS-PAS-EXO-12-038]

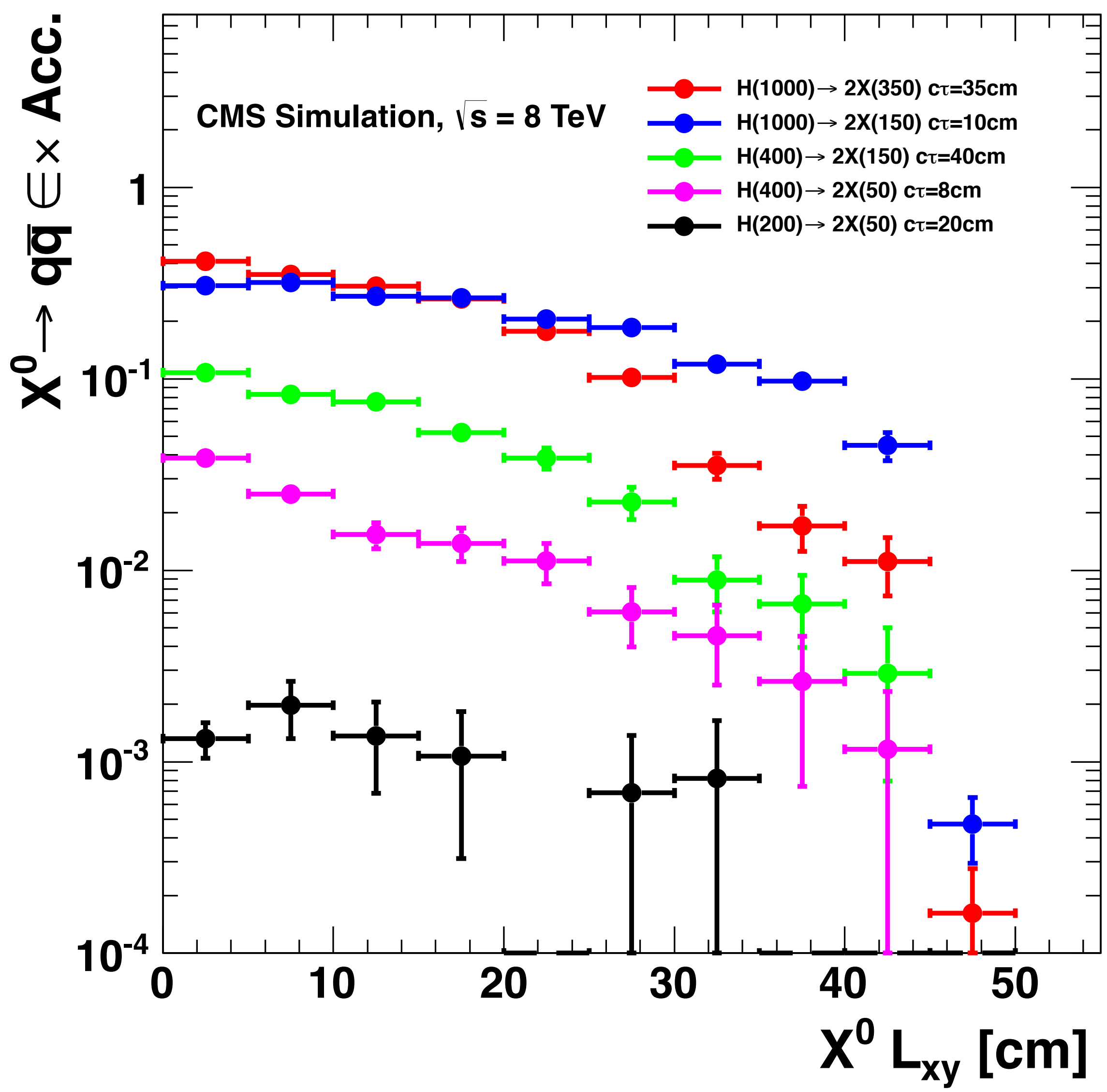
University of BRISTOL

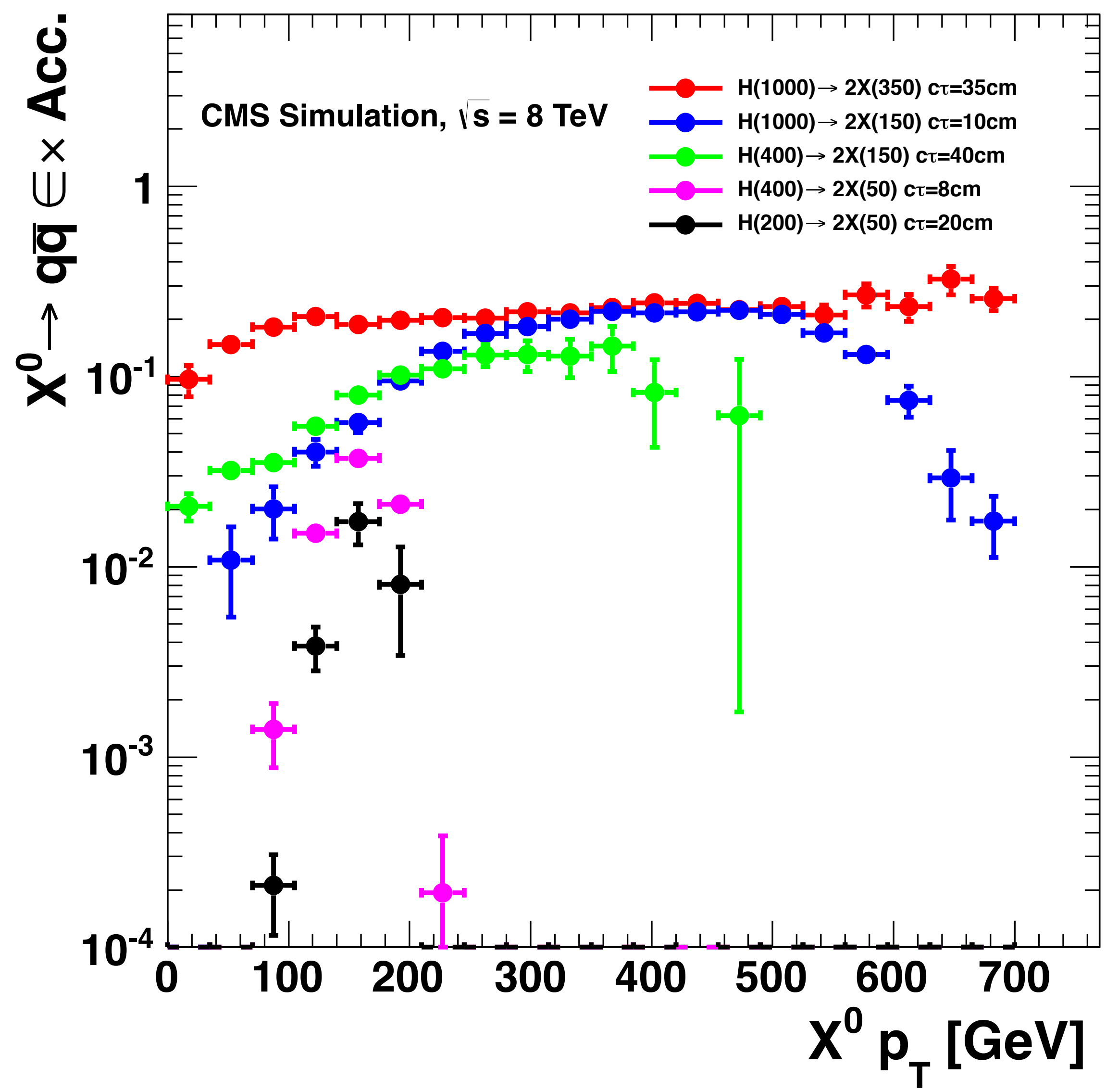
- Select events with two jets with good tracks and a common secondary vertex
  - Jet pT(1,2) > 60 GeV, η < 2
  - Vertex $\chi 2$/dof < 5
- Remainder of selection based on 3 orthogonal criteria
  - 1. Jet 1 : N prompt tracks, “prompt energy fraction”
  - 2. Jet 2 : N prompt tracks, “prompt energy fraction”
  - 3. Vertex/cluster likelihood discriminant (based on four variables)
- Background estimation then based on an extended ABCD using these 3 criteria





Displaced Jets





Simulated

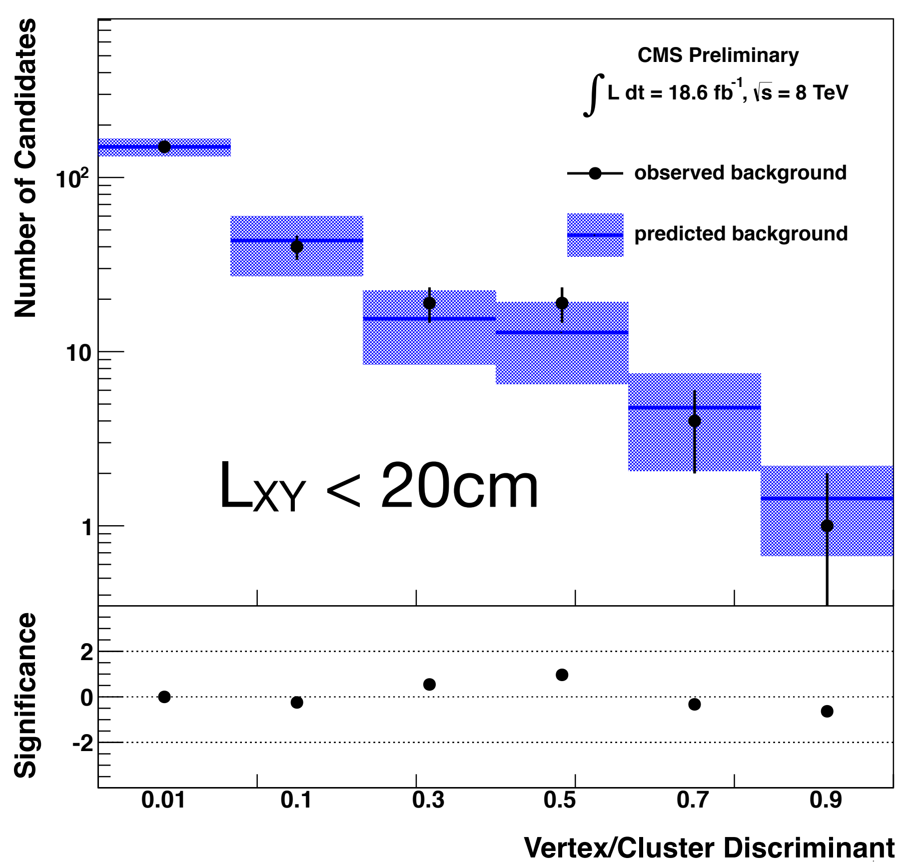
$H^0 \rightarrow X^0 X^0 \rightarrow qqqq$

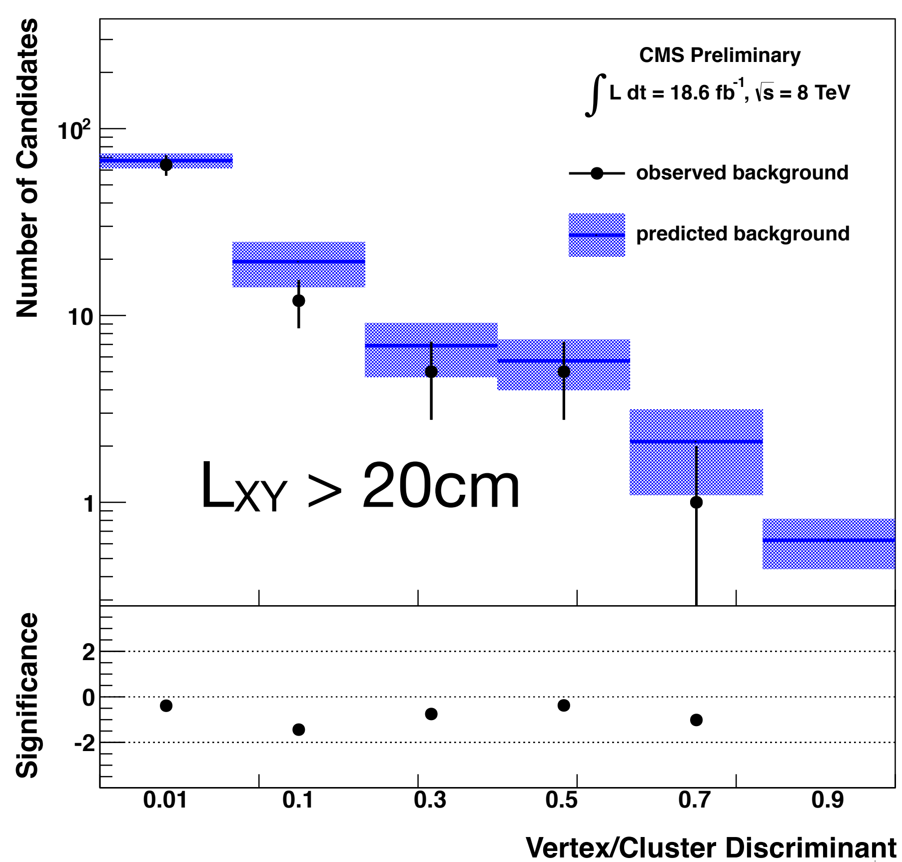
Background estimates :

$\mathbf{L_{xy}}$	**< 20 cm(low)**	**> 20 cm(high)**
prompt tracks	≤ 1	≤ 1
prompt energy fraction	< 0.15	< 0.09
vertex/cluster disc.	> 0.9	> 0.8
expected background	$1.60 \pm 0.26(stat.) \pm 0.51(syst.)$	$1.14 \pm 0.15(stat.) \pm 0.52(syst.)$
observed	**2**	**1**

Table 1: Predicted background and the number of observed candidates for optimised selections.

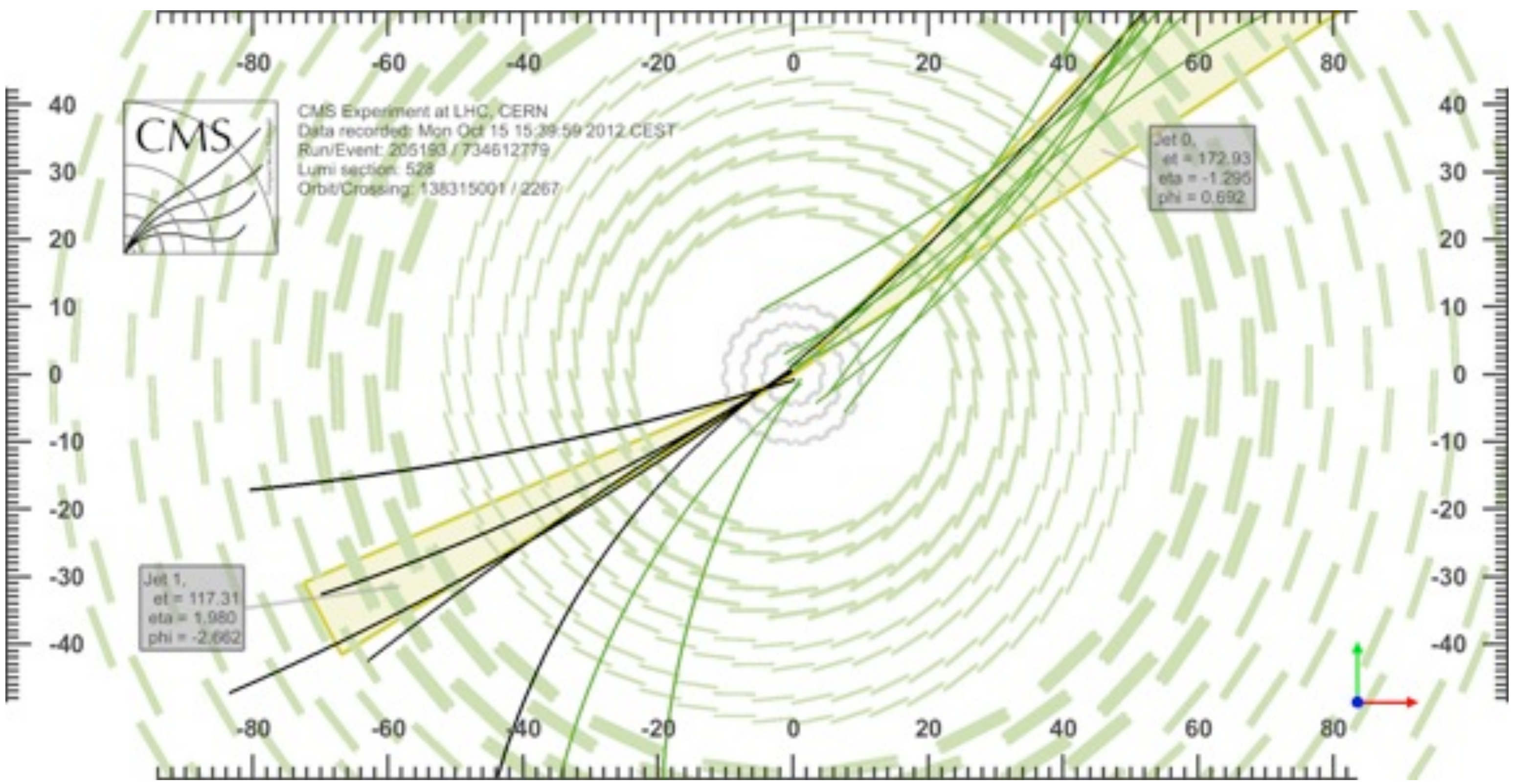
Cross-check in control region with inverted missing hits requirement :



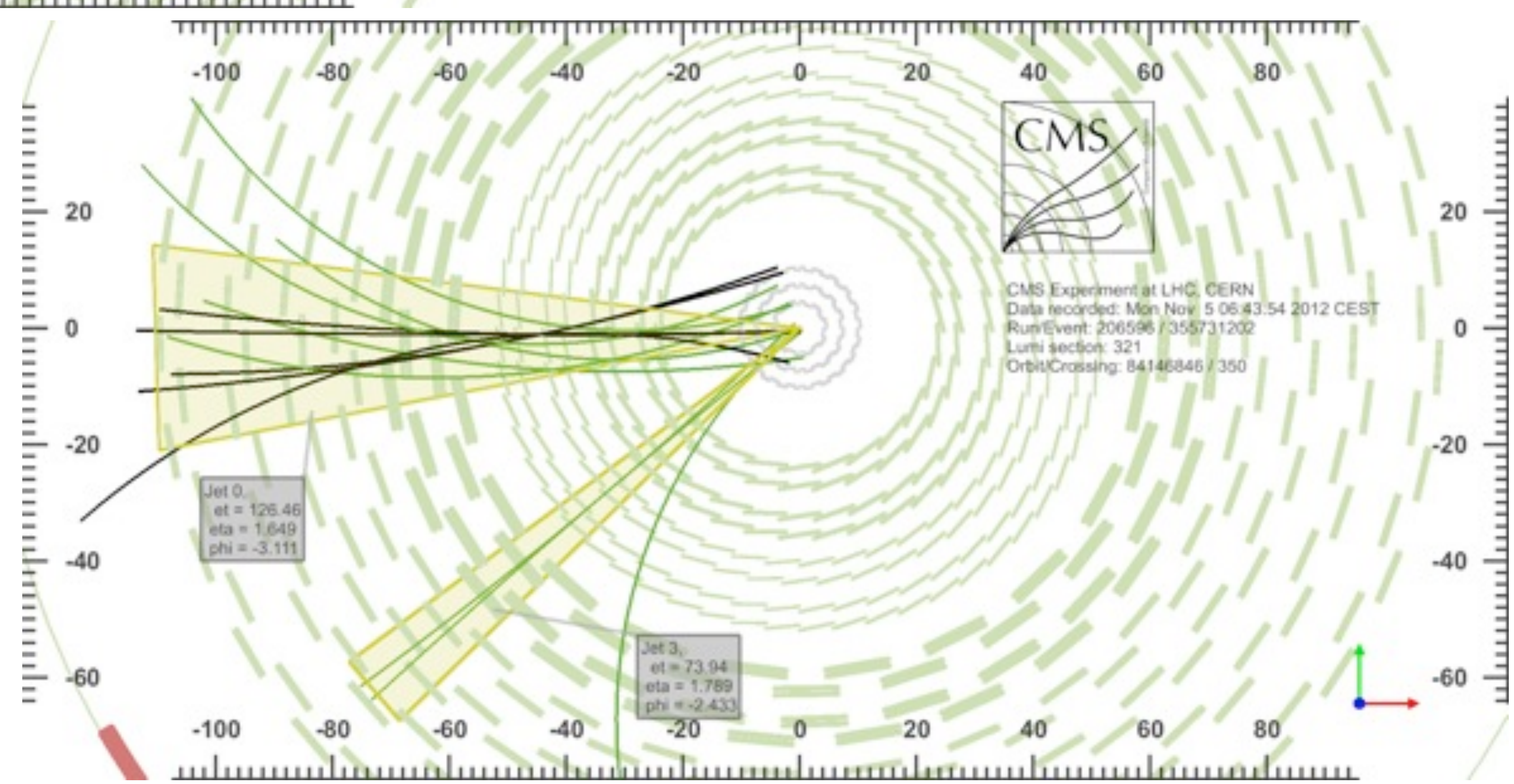


[CMS-PAS-EXO-12-038](CMS-PAS-EXO-12-038)

University of BRISTOL



Signal event in low L_{XY} category

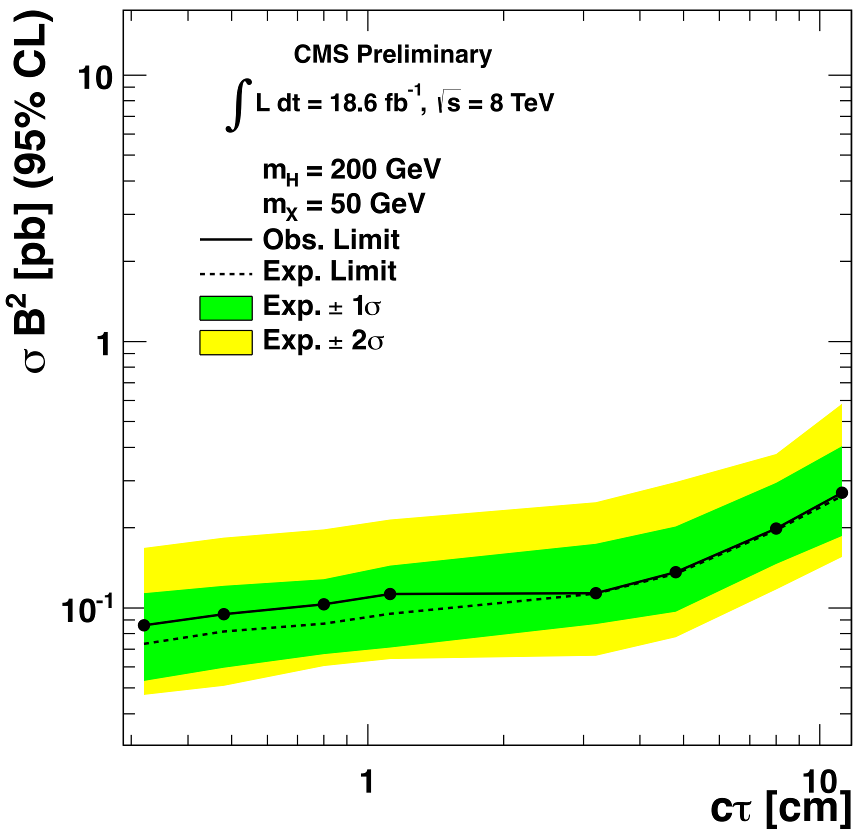


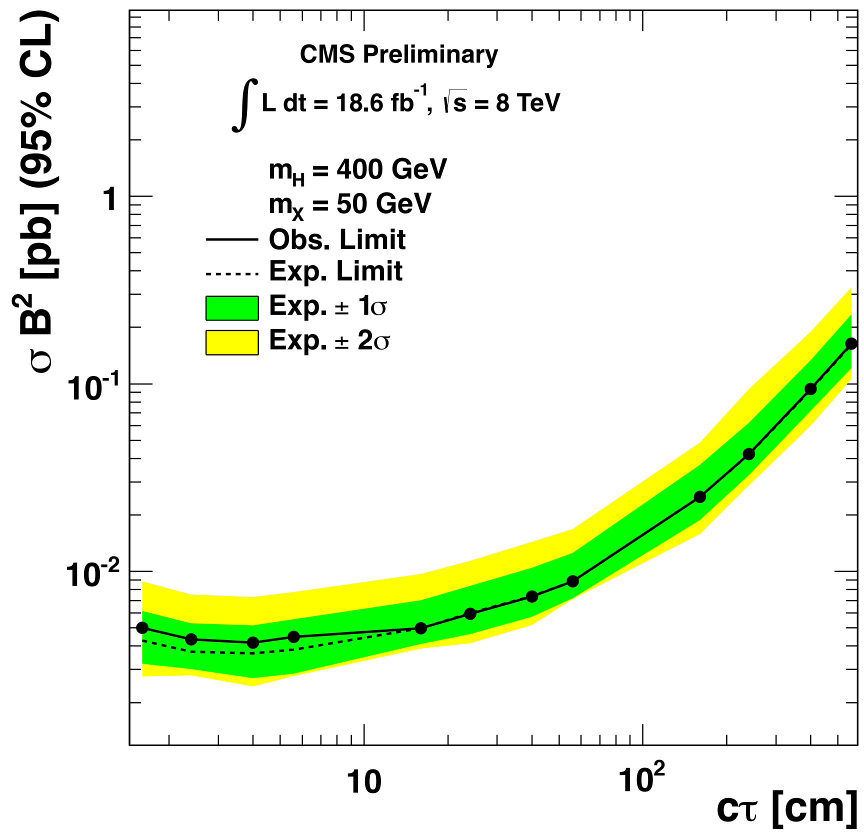
Signal event in high L_{XY} category

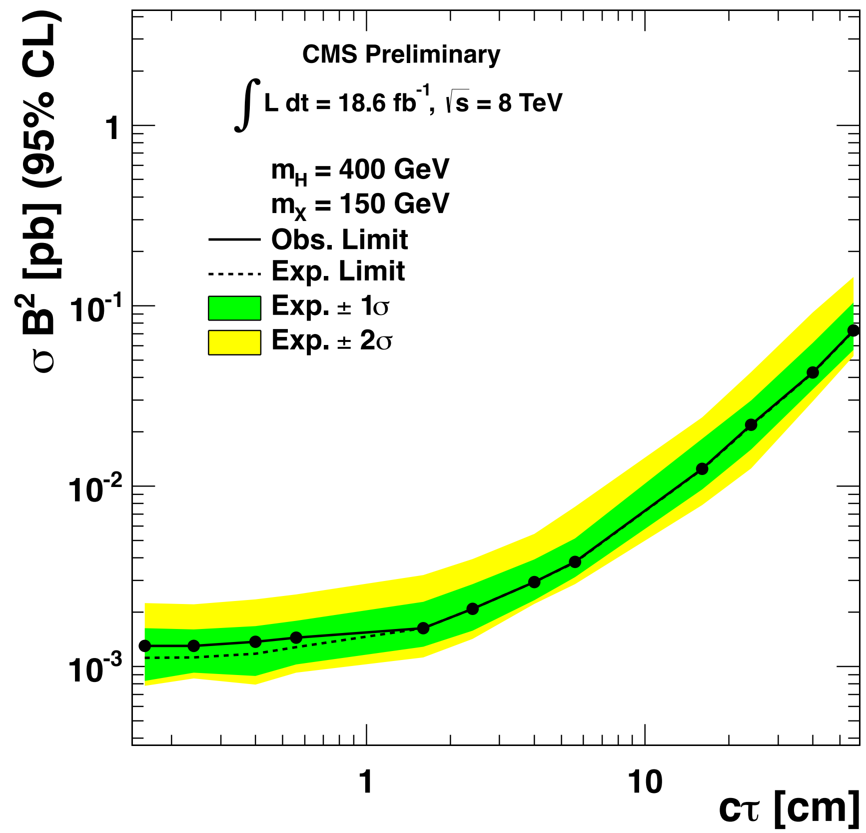
Displaced Jets

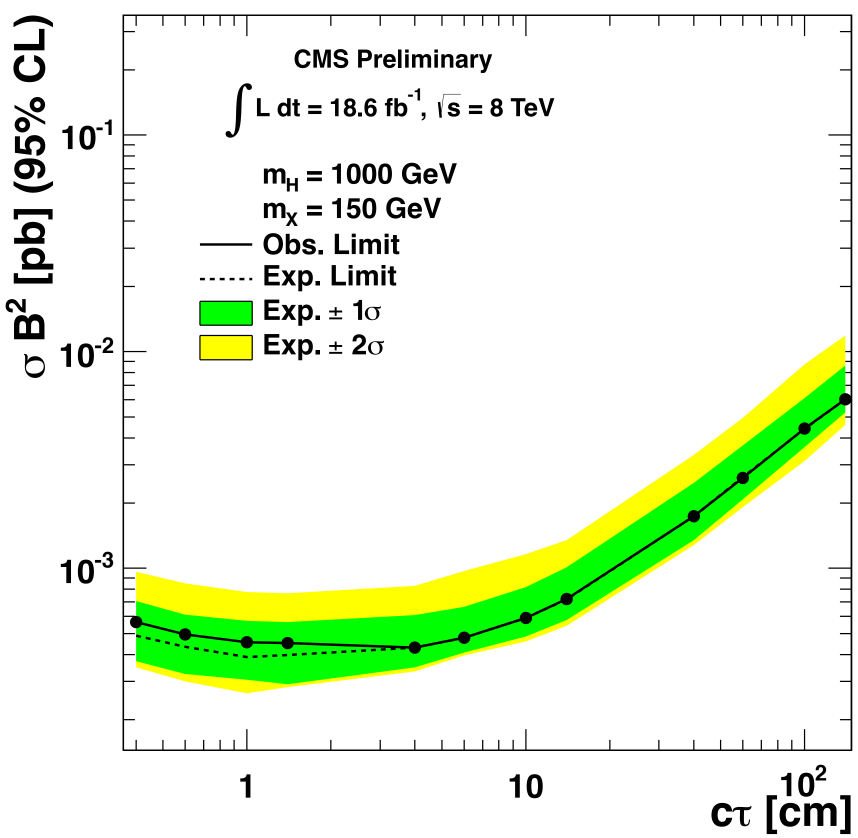
CMS-PAS-EXO-12-038

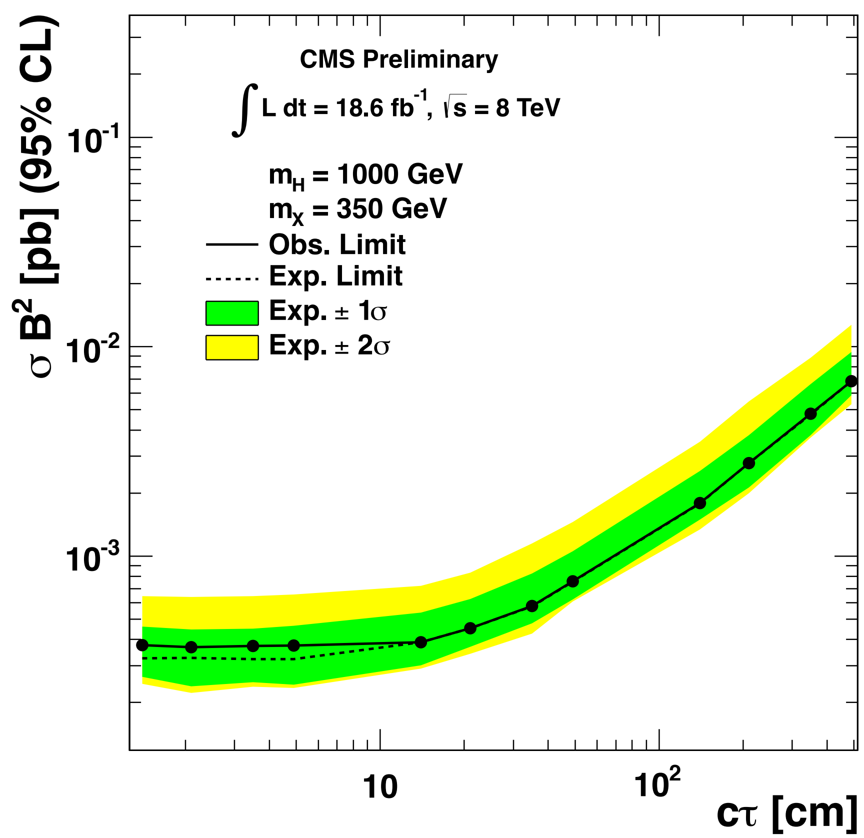
University of BRISTOL











- Limits for a selection of signal hypotheses

Stable Massive Particles

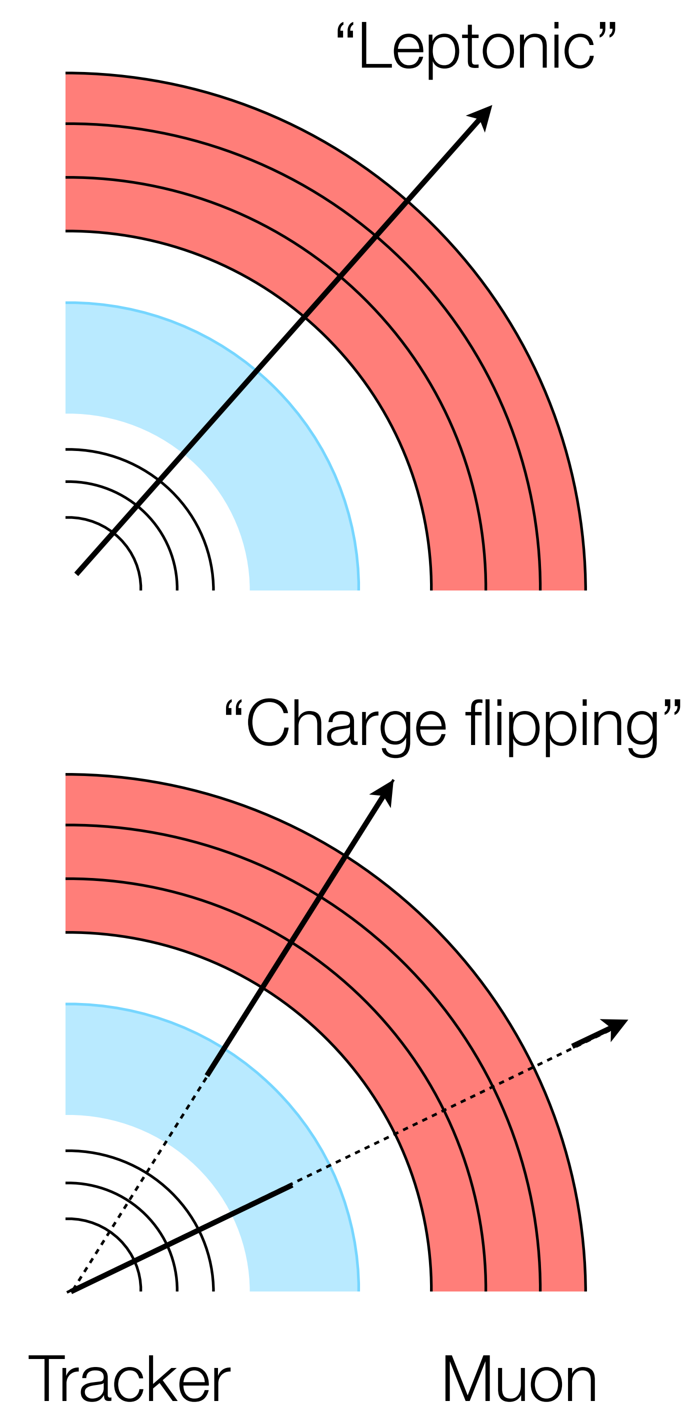
Stable Massive Particles JHEP 07 (2013) 122

- Identify a (meta)-stable charged particle as it traverse the detector

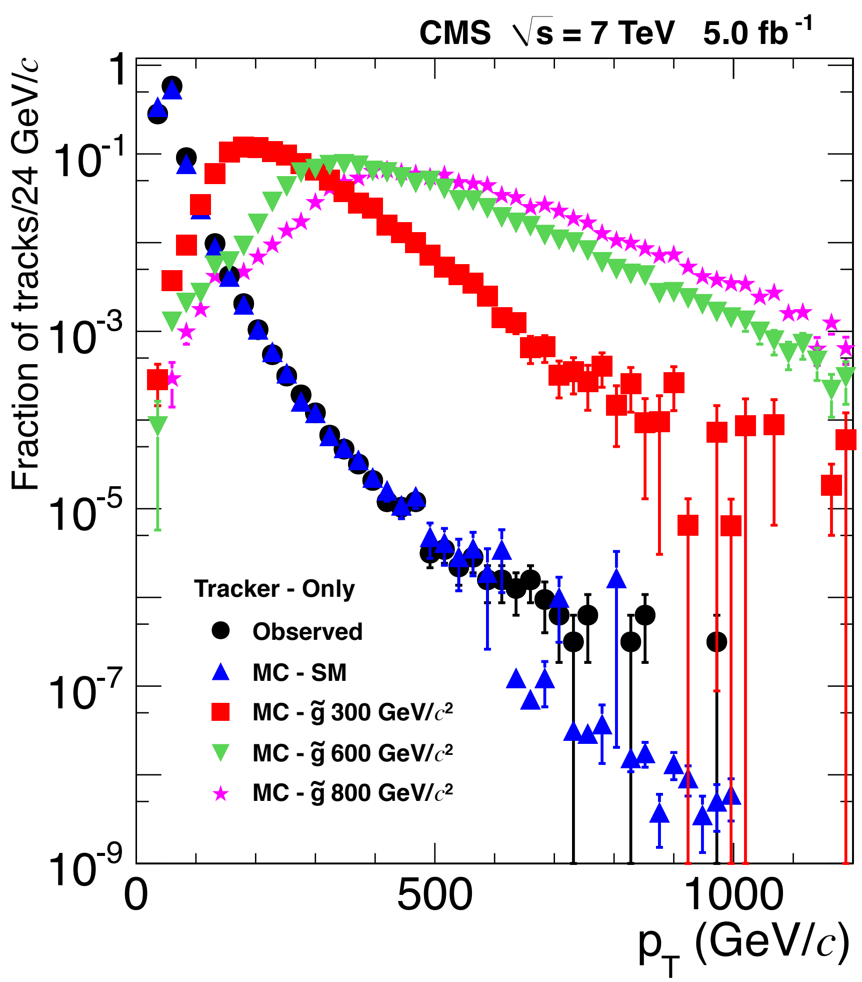
- Examples
  - R-hadrons
  - Long lived stau
  - Vector-like confining gauge theories

- SMP signature
  - High momentum
  - Highly ionising
  - Long time-of-flight

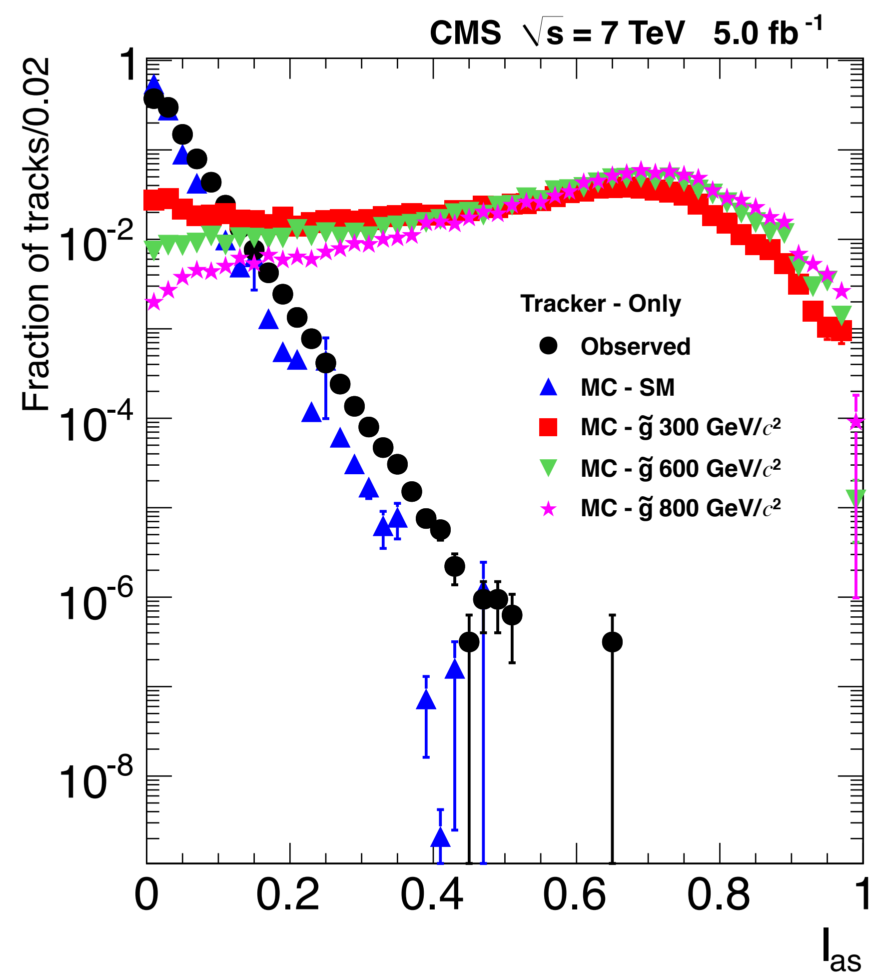
- Special case of strongly interacting R-hadrons
  - Nuclear interactions with material may change flavour
  - Neutral <=> Charged
  - Multiple analyses :
    - “Tracker-only”, “TOF-only”, “Tracker+TOF”



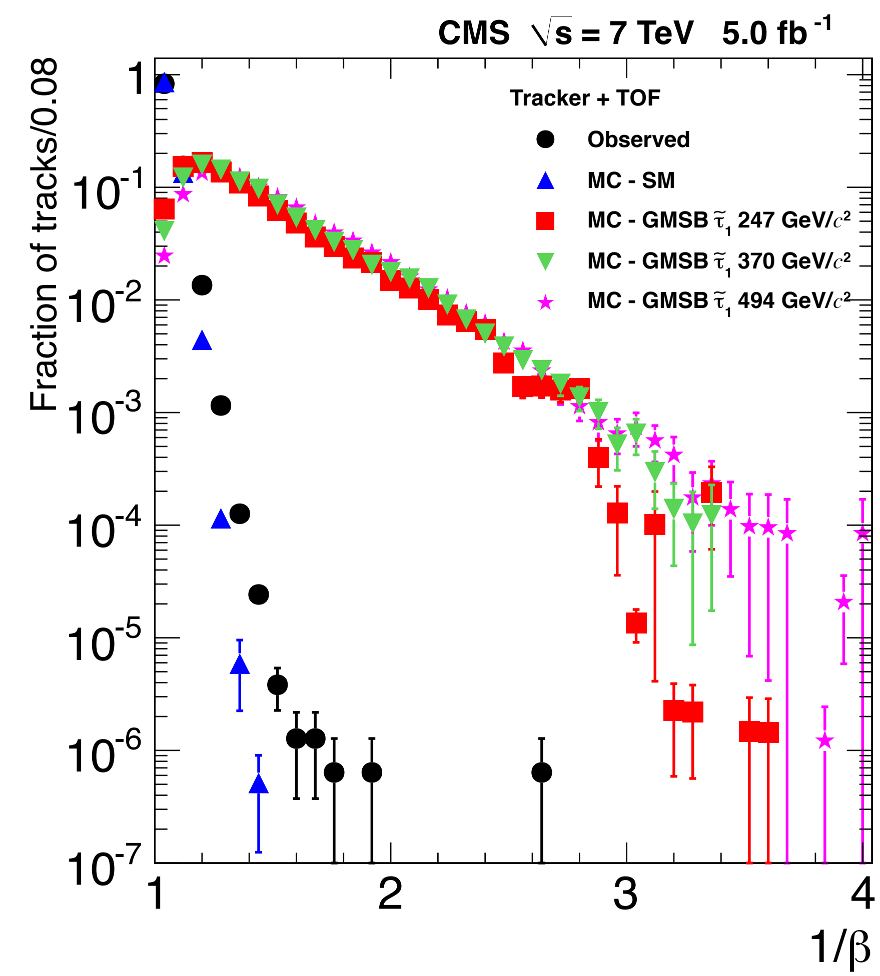
High momentum



Highly ionising

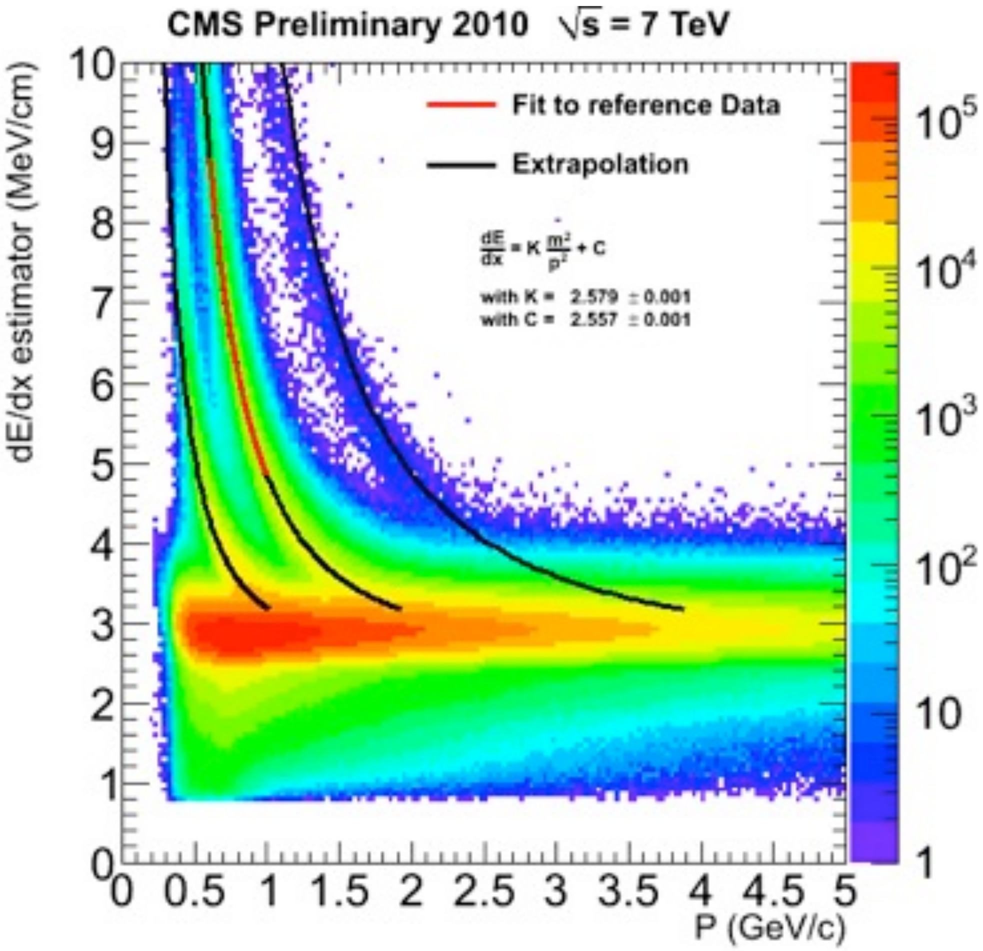


Long TOF

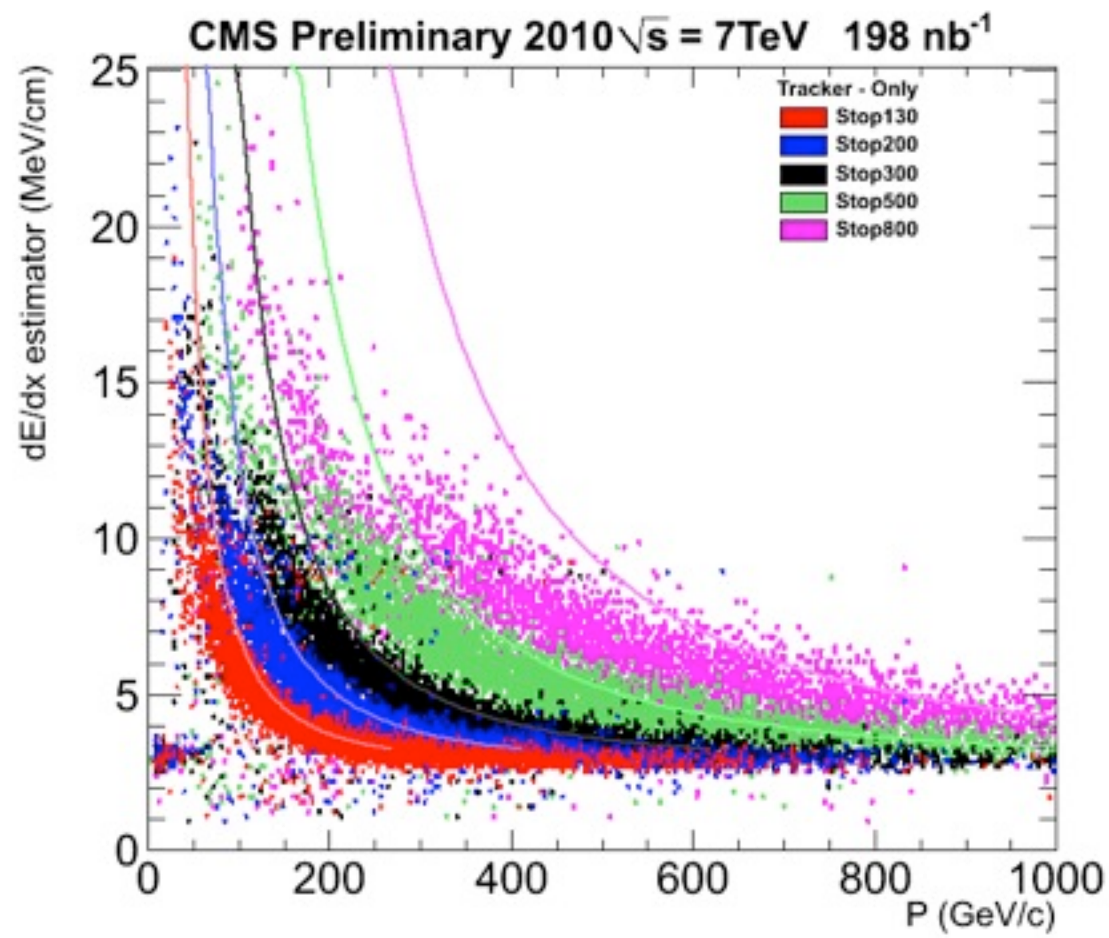


Plots from *Phys. Lett. B 713 (2012) 408*

University of BRISTOL

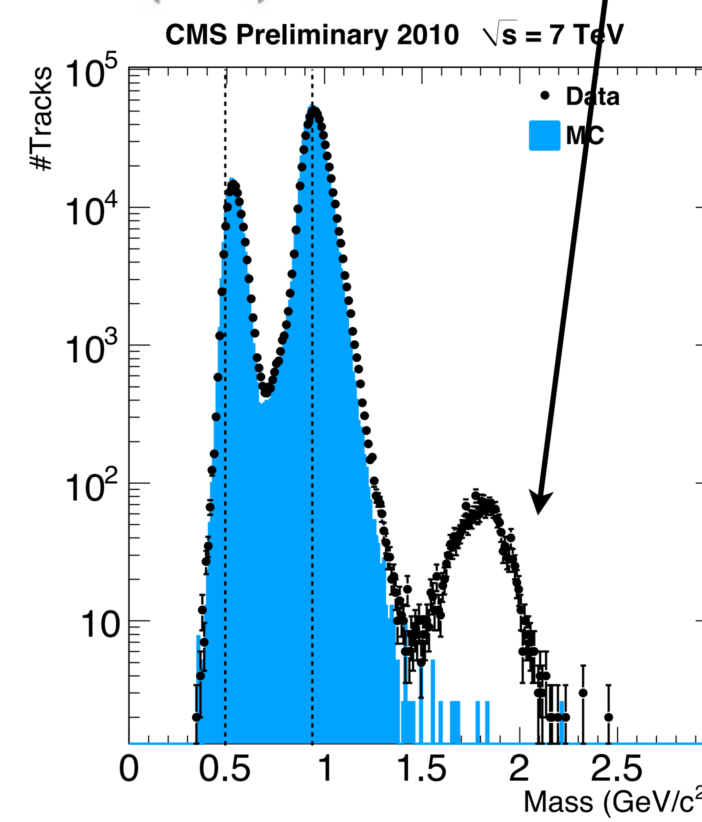


min-bias data



...and stop MC

Discovery of the deuteron!

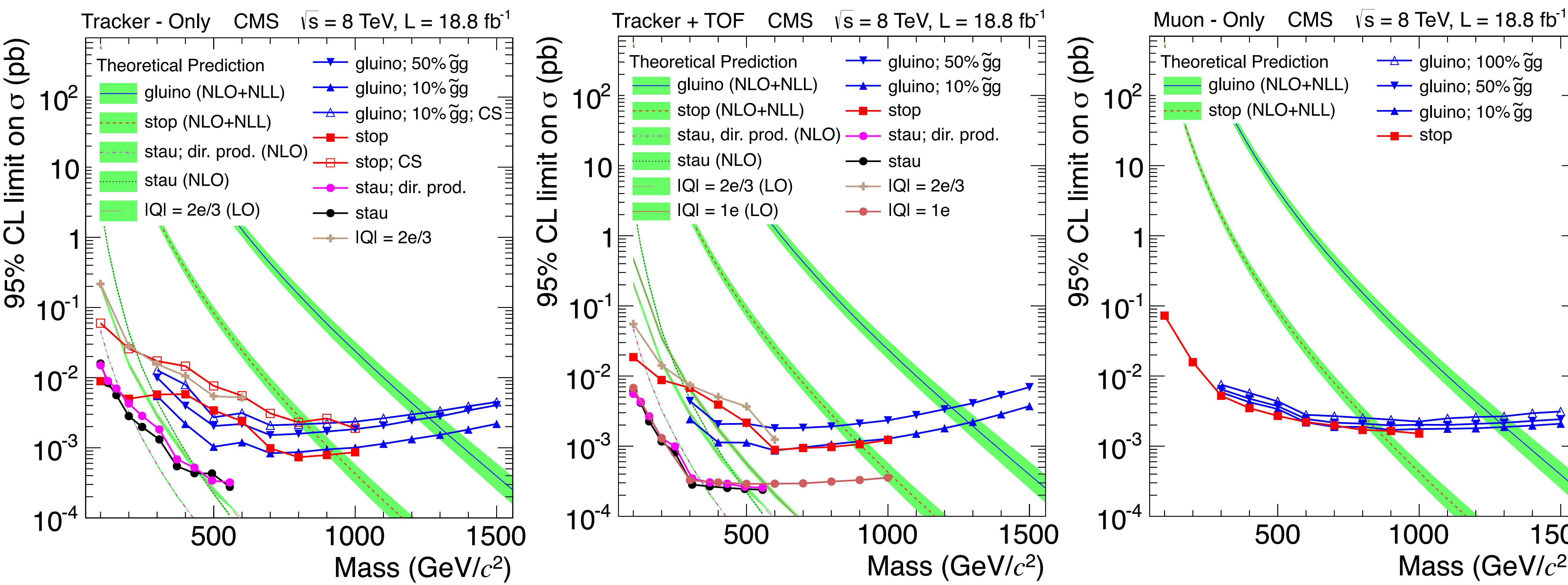


- Mass reconstruction
  - Approximate Bethe-Bloch formula before minimum
  - Extract parameters by fitting to the proton line
- Search for tracks with high mass

Plots from *CMS-PAS-EXO-10-004*

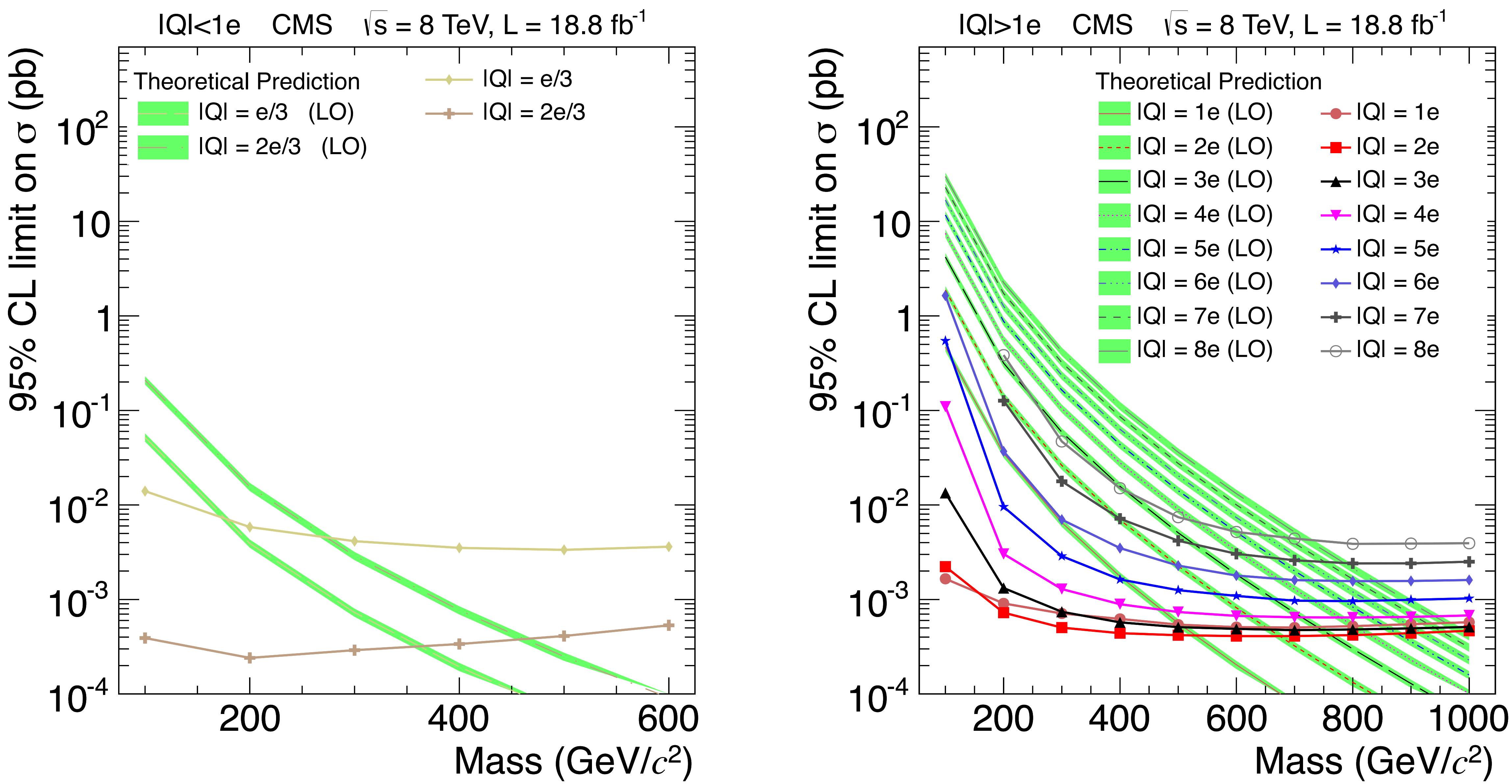
JHEP 07 (2013) 122

- Standard interpretation in terms of gluino, stop, stau (GMSB)
  - Inc. “charge suppressed” model of R-hadron nuclear interactions (any interaction results in a neutral R-hadron)
  - Different fractions of gluino/gluon initial states



Tracker only *Tracker+TOF* *TOF-only*

Paper includes combined 7 TeV (5 fb^{-1}) + 8 TeV (19 fb^{-1}) result



- Limits on DY production of charged particles with Q != 1
  - Neutral under SU(3) and $SU(2)_L$, only couple to Z and photon

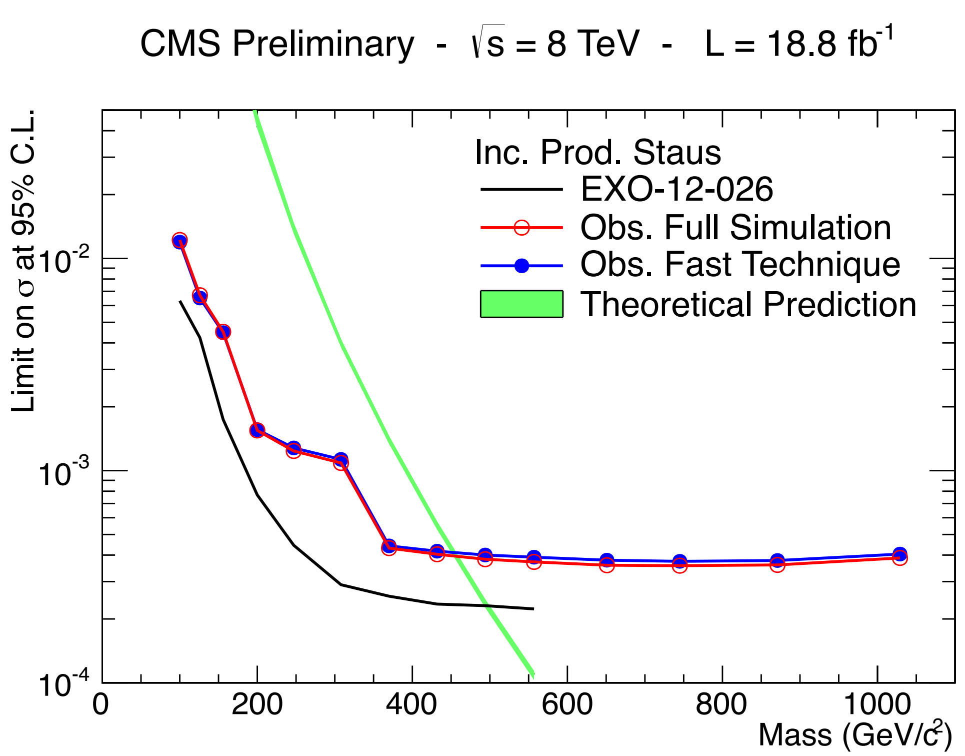
Paper includes combined 7 TeV (5 fb^{-1}) + 8 TeV (19 fb^{-1}) result

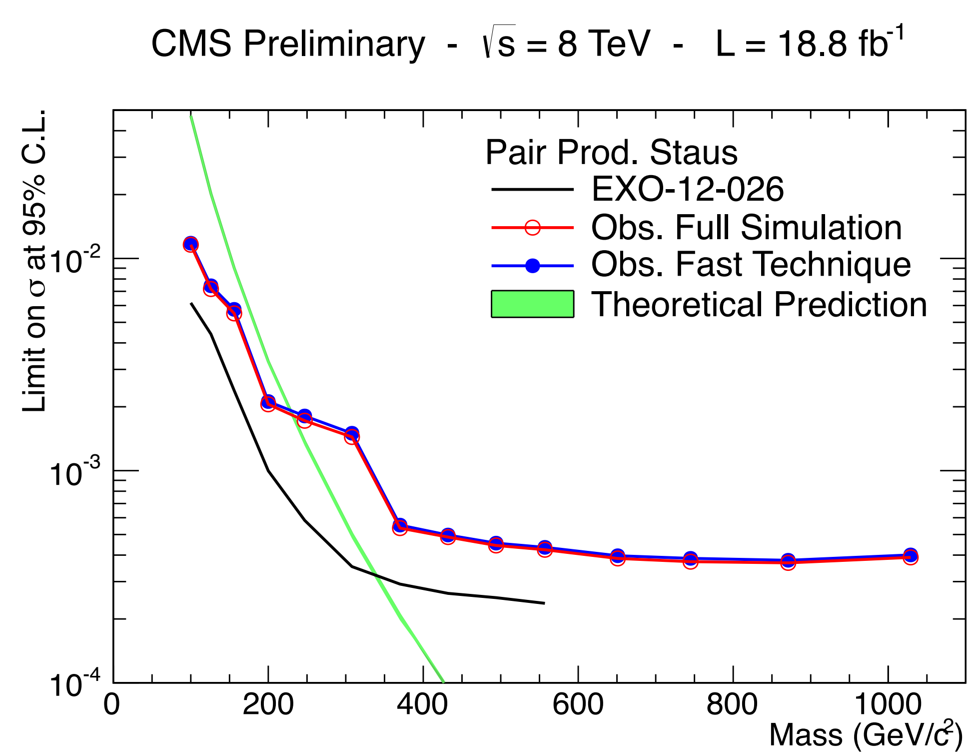
SMPs in pMSSM

CMS-PAS-EXO-13-006

University of BRISTOL

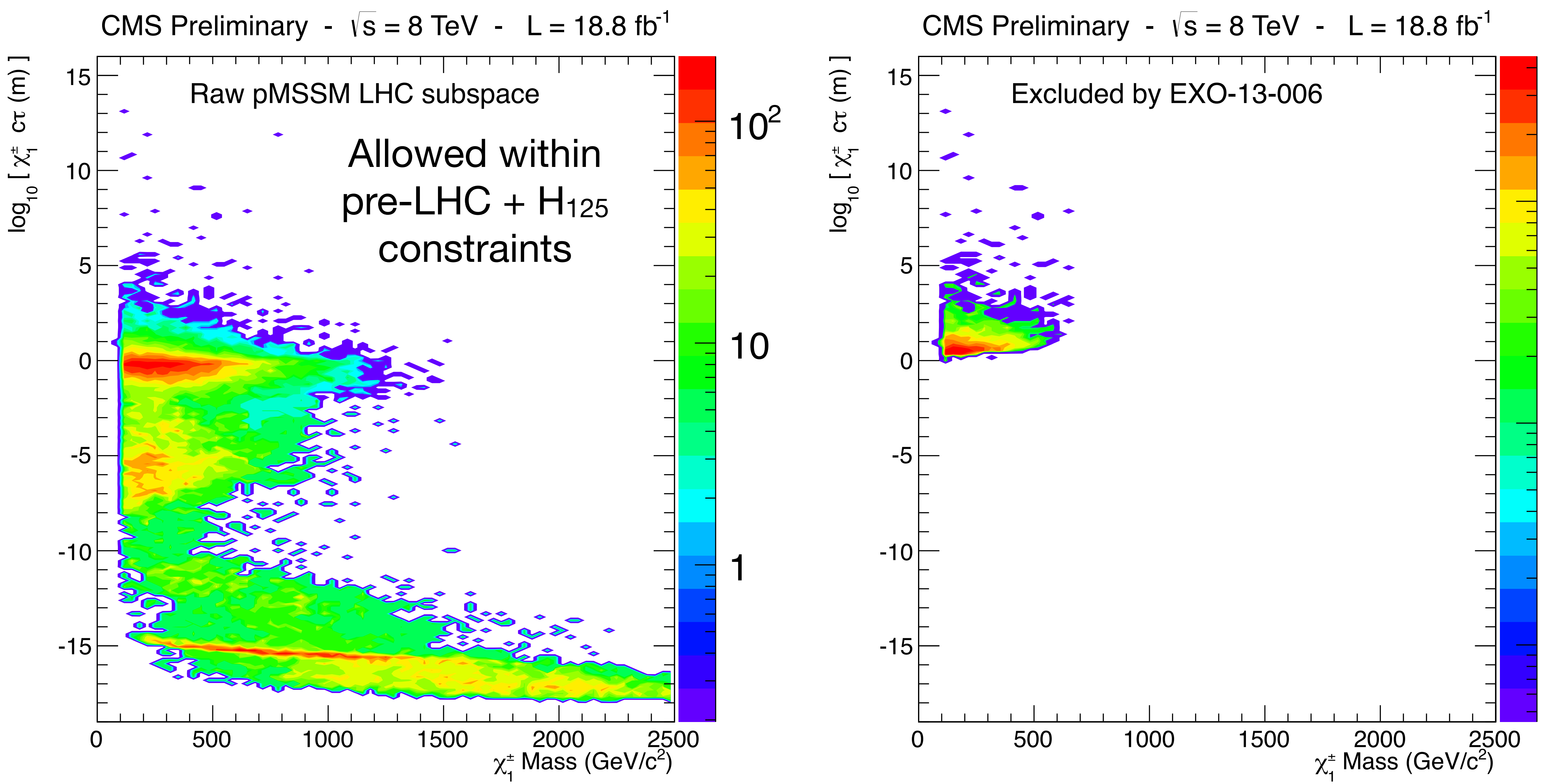
- The analysis is sensitive to large fraction of SUSY parameter space
- Acceptances for results on previous slides are estimated using full GEANT simulation
  - Detector effects are important and complex (eg. amount of material traversed)
  - This is impractical for parameter space scans
- Instead parameterise acceptance as function of individual particle properties
  - This is valid for lepton-like particles
  - Use large full simulation samples to parameterise acceptance of Tracker+TOF analysis in bins of **p_T, β, η**
  - Use this to re-cast Tracker+TOF result for any given model





SMPs in pMSSM

CMS-PAS-EXO-13-006

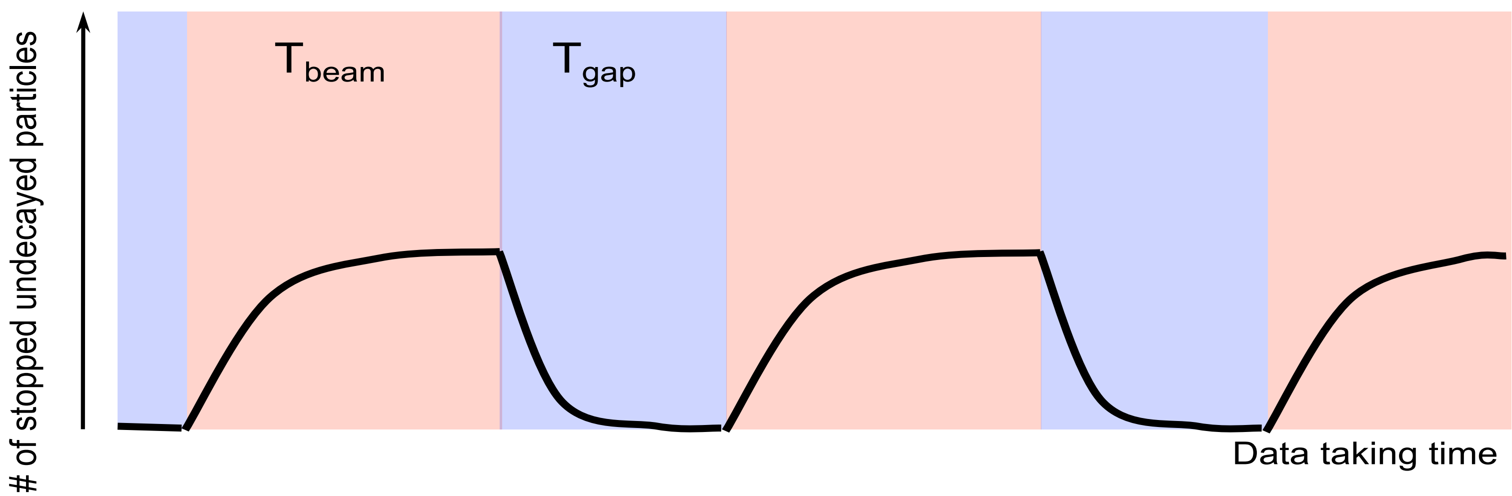


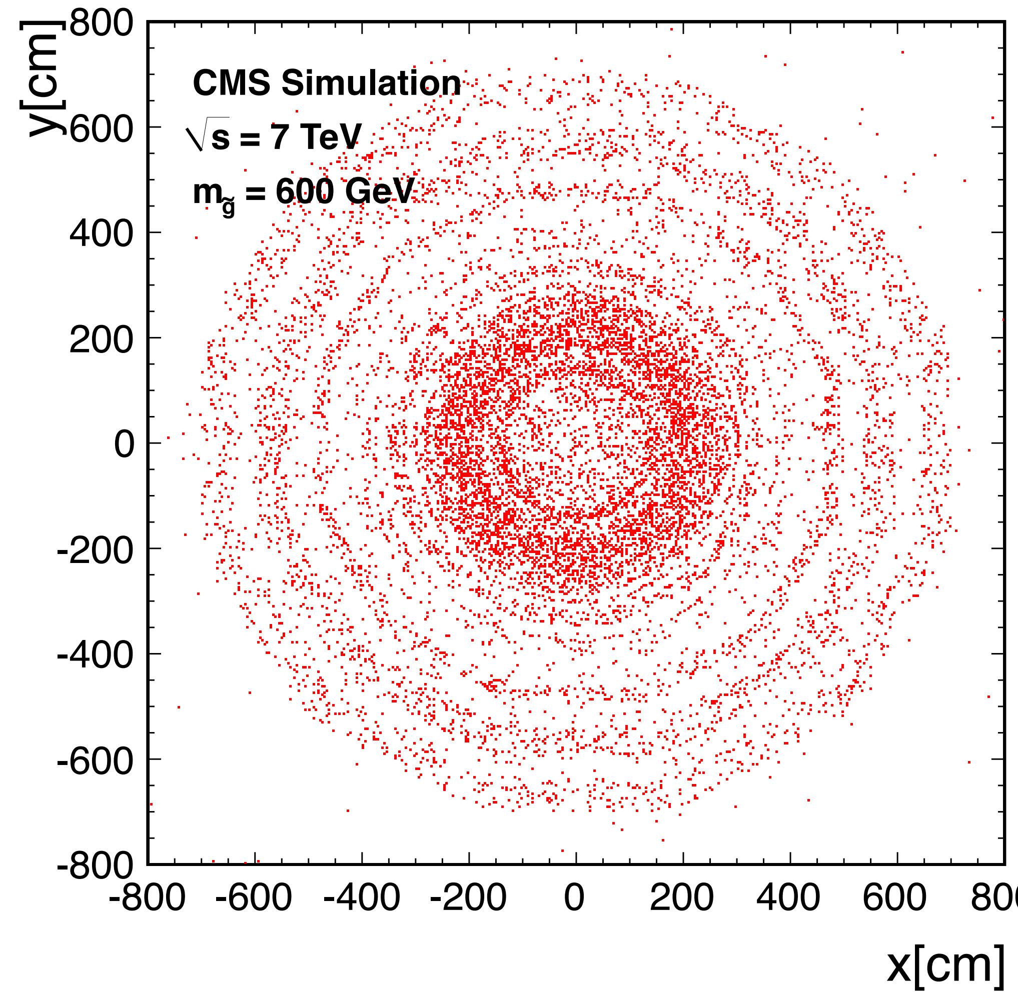
Chargino mass/lifetime exclusion map
pMSSM = 19 parameter SUSY model

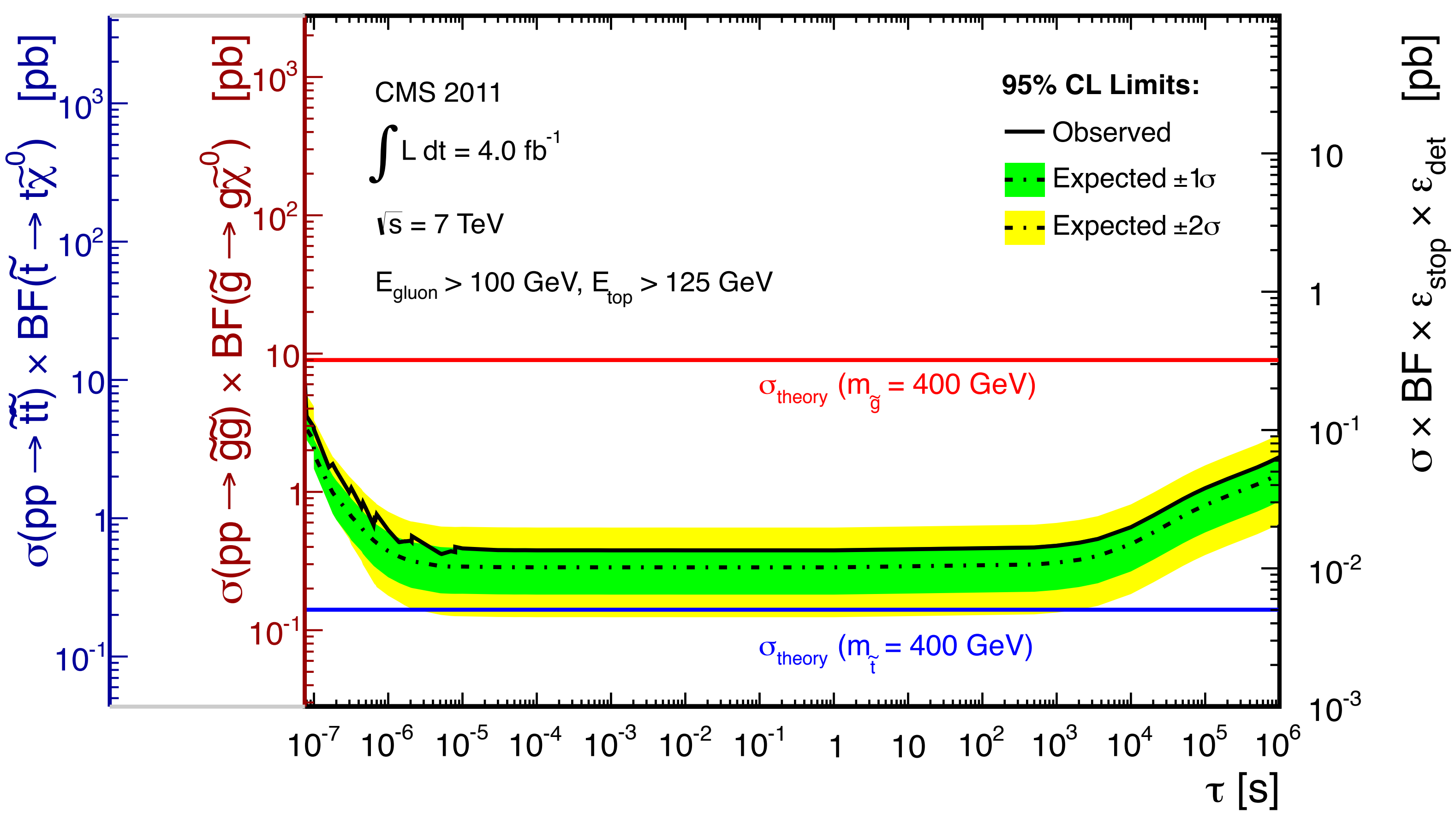
Other Long Lived Searches

Stopped SMPs

JHEP 8 (2012) 26



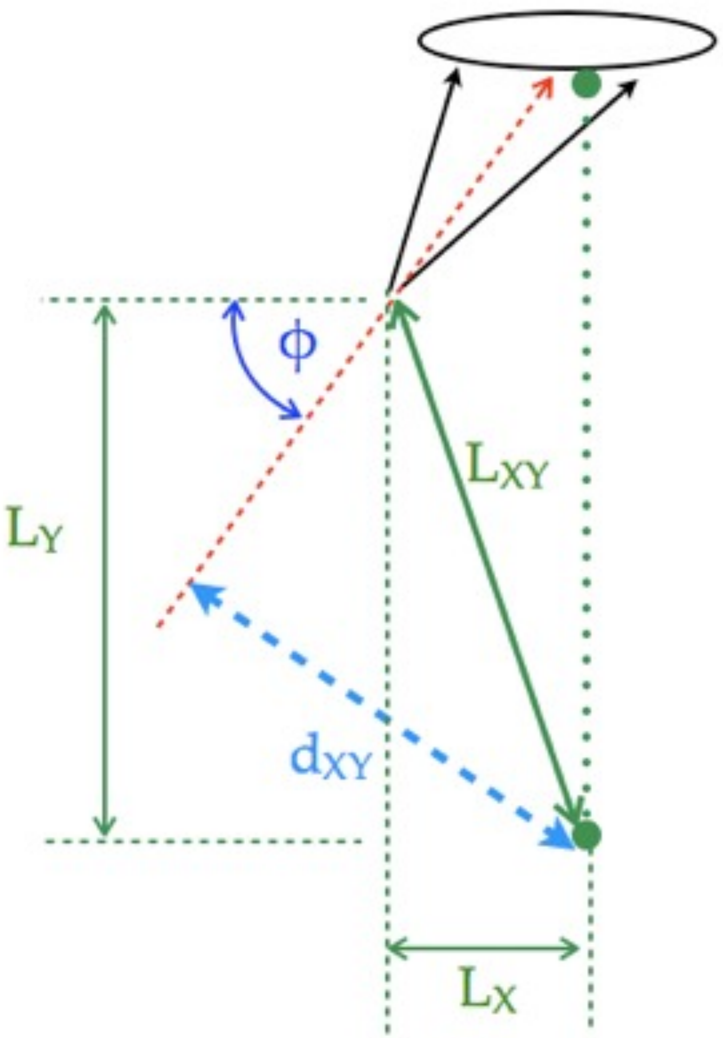




- Highly ionising particles may stop in the detector
- Search during periods of no collisions
- Trigger includes a "no collision" condition using BPTX monitors

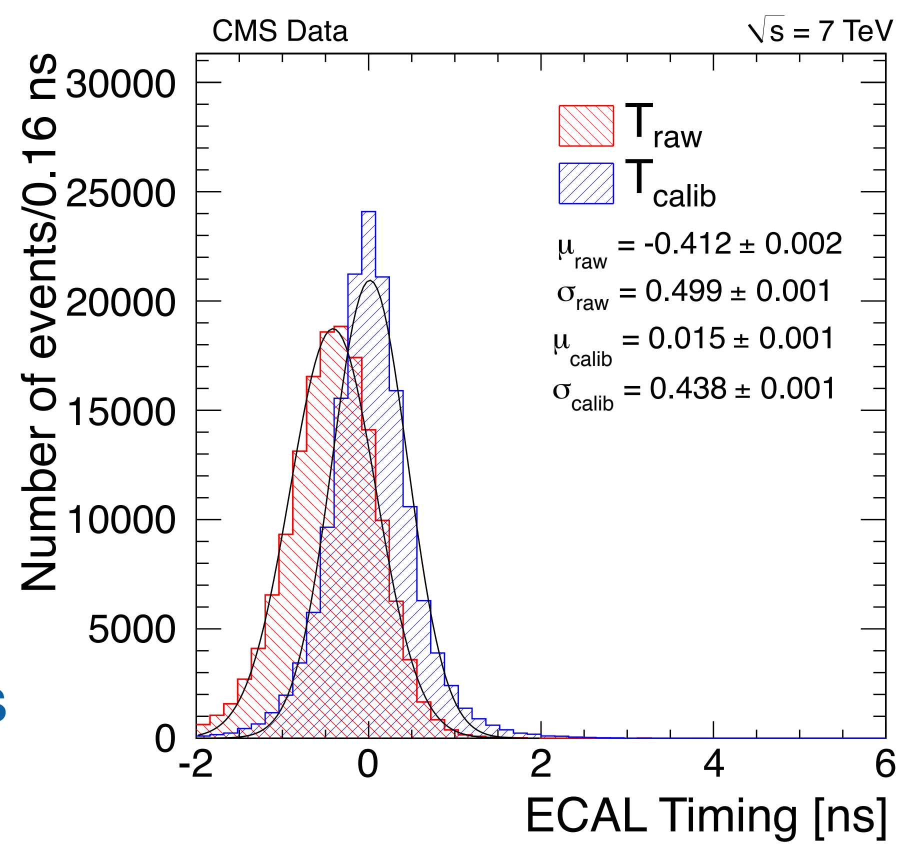
arXiv:1207.0627

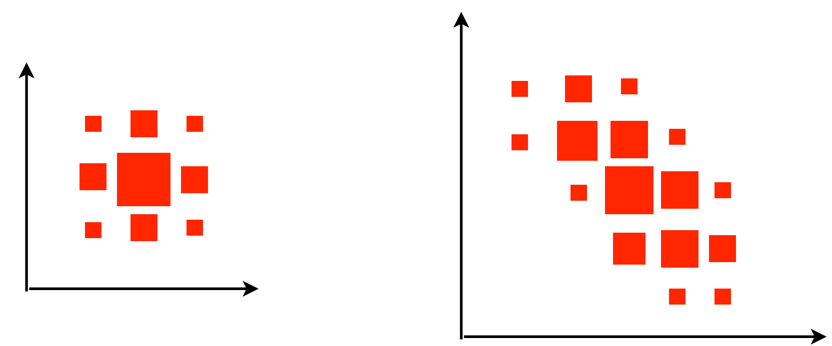
Searching for a neutral long lived particle (eg X^0) that decays to photon + invisible particle (eg $\tilde{G}$)

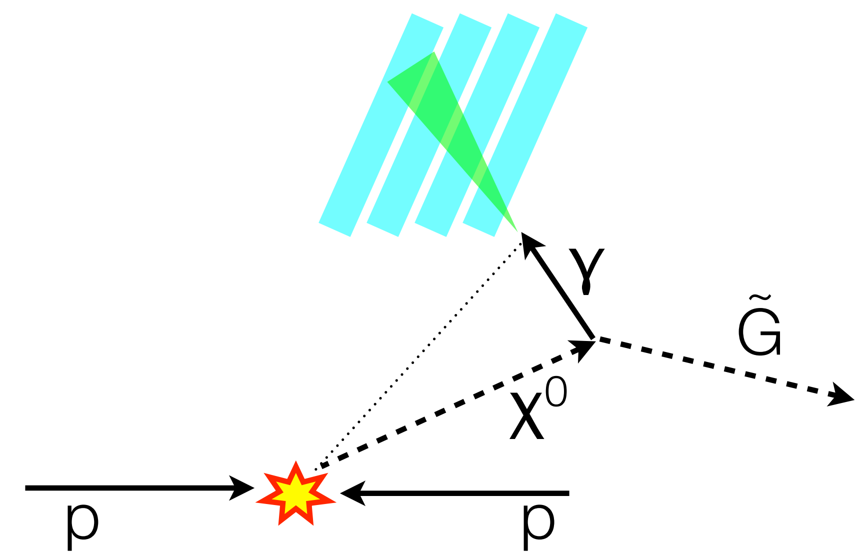


Reconstruct photon direction from conversions

Use ECAL signal time to estimate TOF



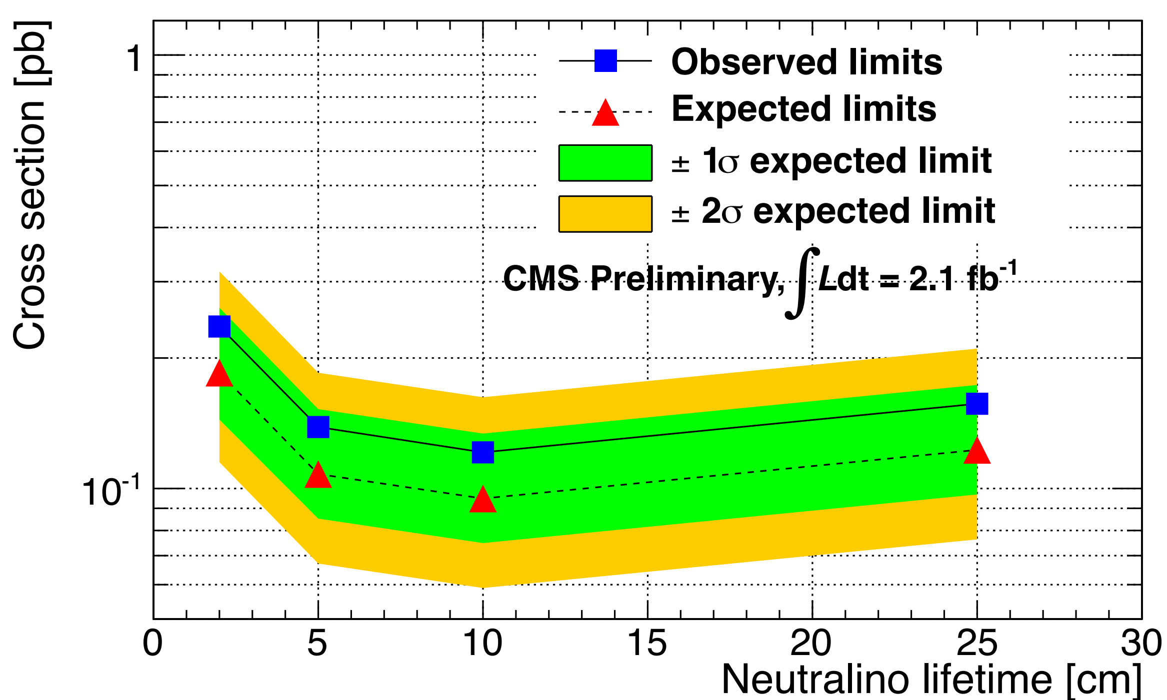




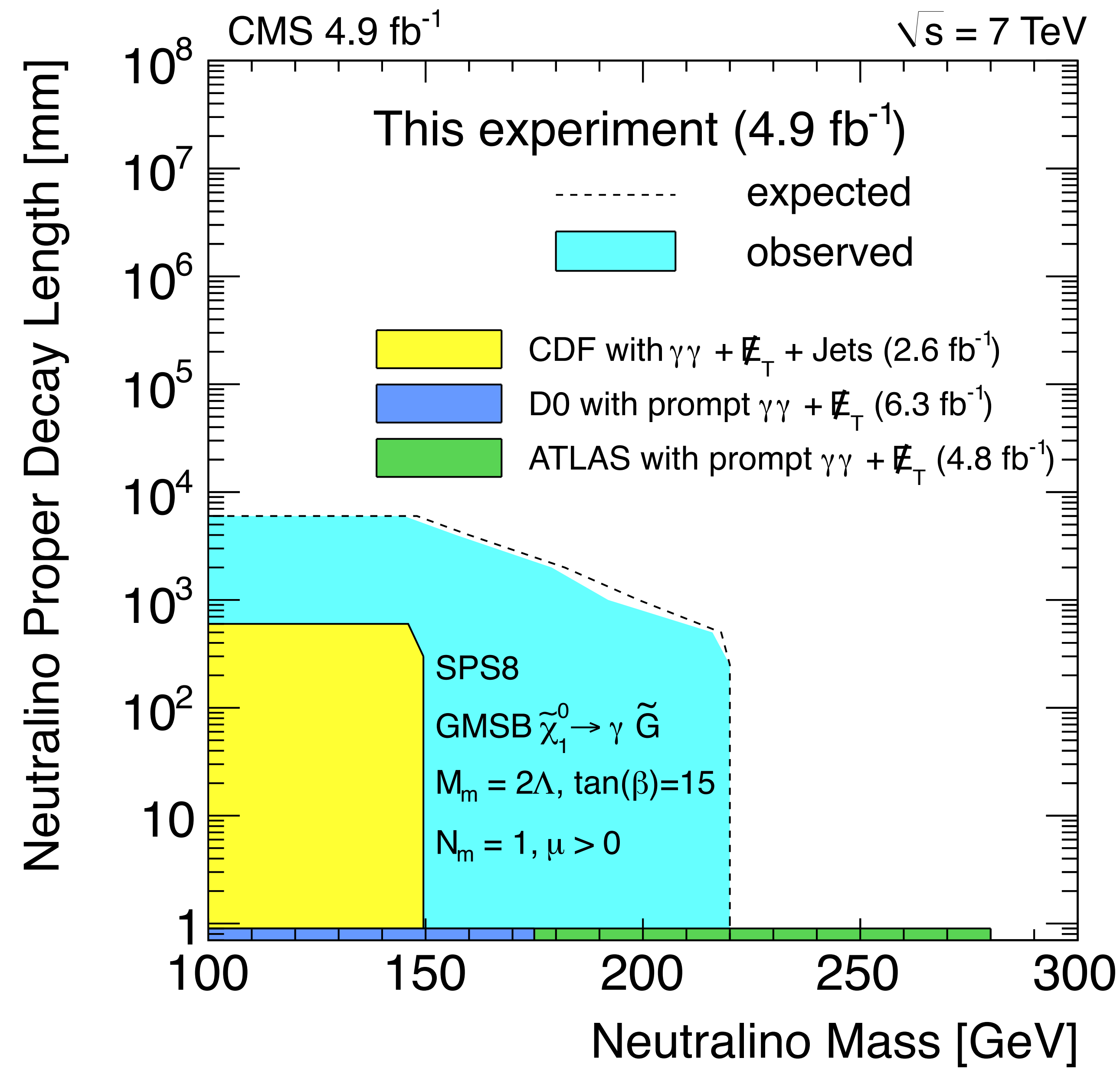
Use cluster shape in ECAL

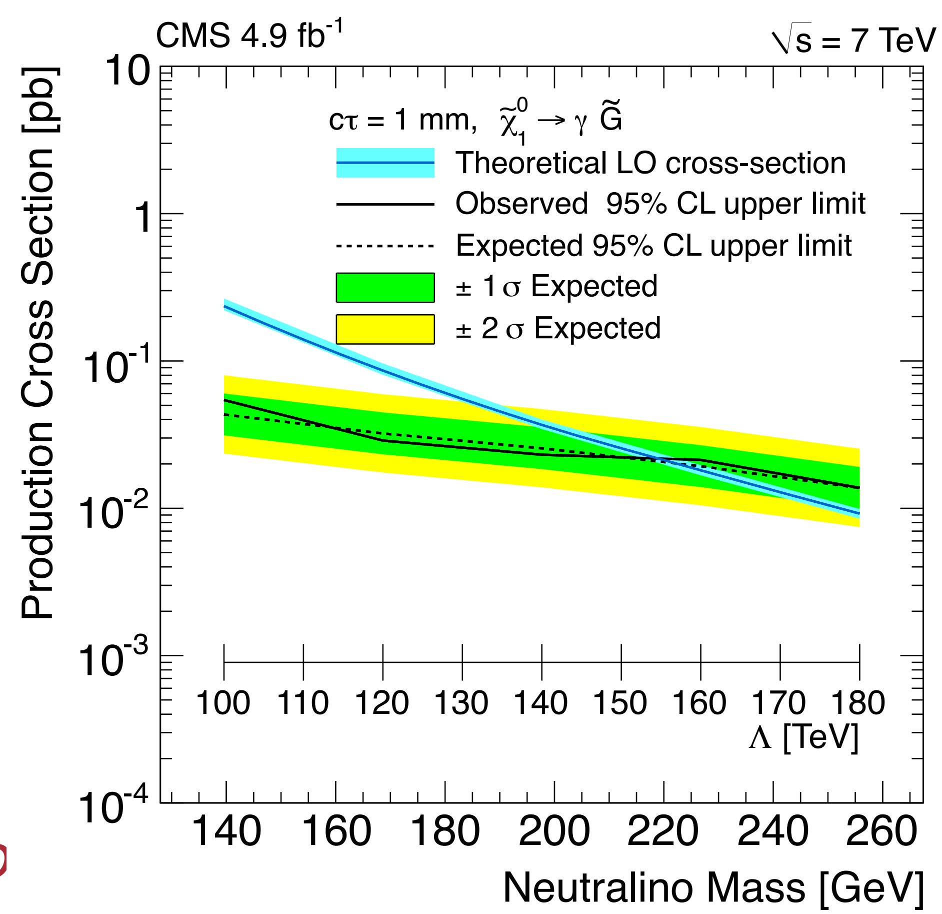
Displaced Photons

arXiv:1212.1838



Conversions



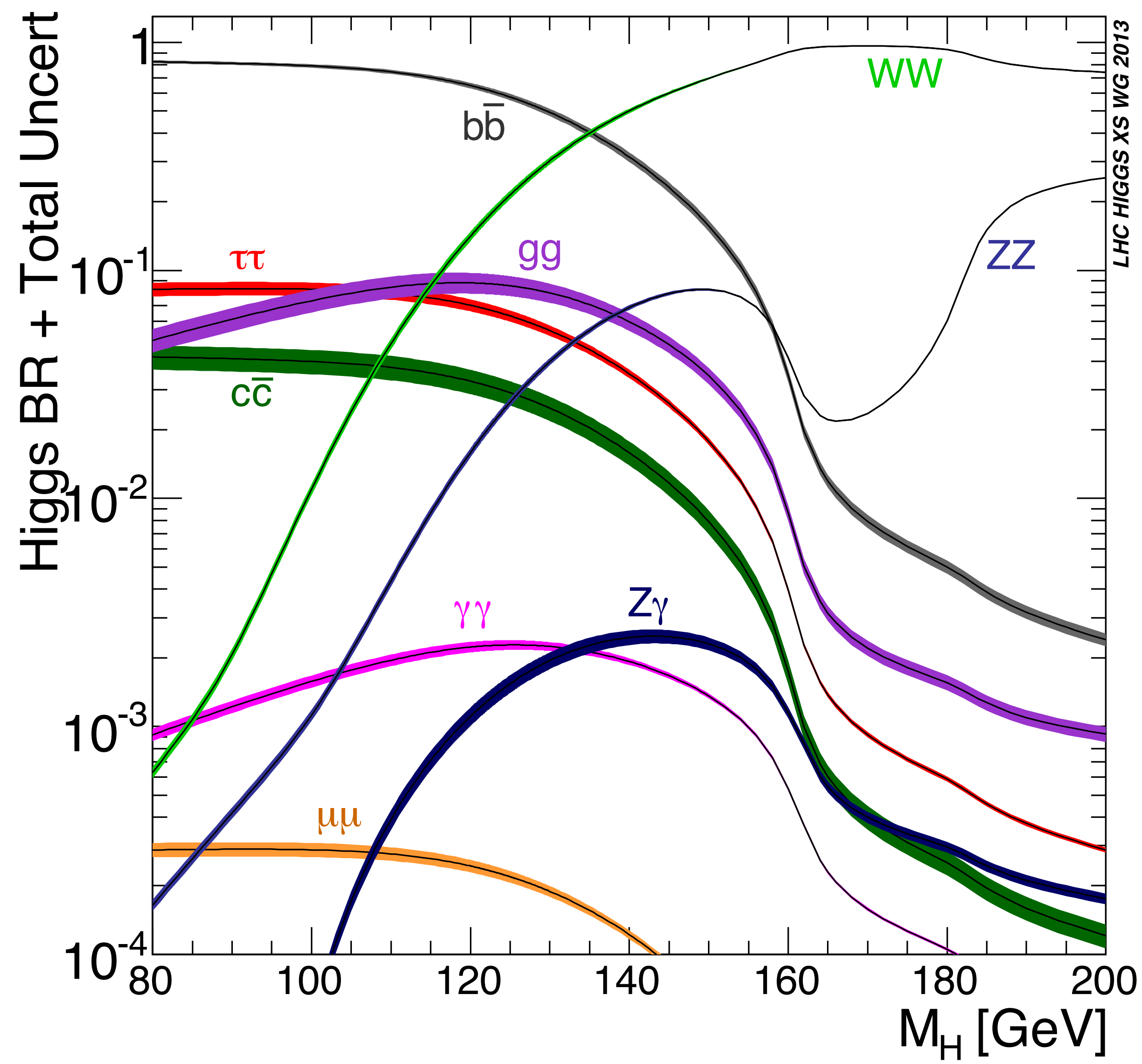


ECAL time + cluster shape

Exotic Higgs Decays

Exotic Higgs Decays

- We know there must be BSM physics
- We know Higgs bosons couple to mass
- H_{125} is one of the least well measured SM particles...



We should be looking for exotic decay modes !

See arXiv:1312.4992 for comprehensive survey

Exotic Higgs Decays

- SM modes
  - $H_{125} \rightarrow \mu\mu$, $H_{125} \rightarrow ee$
- h125 → γ+MET
- H → invisible
  - VBF, Z(ll)H, Z(bb)H, monojet, ttH
- Charged H
  - $H^{+/-} \rightarrow cs, cb, tb, \tau\nu$
- $H_{125} \rightarrow XX \rightarrow \gamma\gamma\gamma\gamma$
- LFV in $H \rightarrow \mu\tau$
- 2HDM
  - $H \rightarrow h_{125}h_{125}$, $A \rightarrow Zh_{125} \rightarrow$ multi-leptons, γ
  - A → Zh(125) → llbb
  - heavy H → ZA → llbb
  - heavy H → ZA → $ll\tau\tau$
- NMSSM
  - H_2 (125) → $H_2H_1 \rightarrow 4\tau$
  - H → a1a1 → 4μ
  - $H_3 \rightarrow H_2(125)H_1(60\text{-}125) \rightarrow bbbb$
  - $H_2(125) \rightarrow a_1a_1 \rightarrow \gamma\gamma\gamma\gamma$
  - H1 → $\gamma\gamma$
  - $H_2(125) \rightarrow H_1H_1 \rightarrow 4\tau$, $2\tau 2b$, $2\mu 2b$, 4b
- MSSM
  - H → hh → $\gamma\gamma bb$

Invisible Higgs

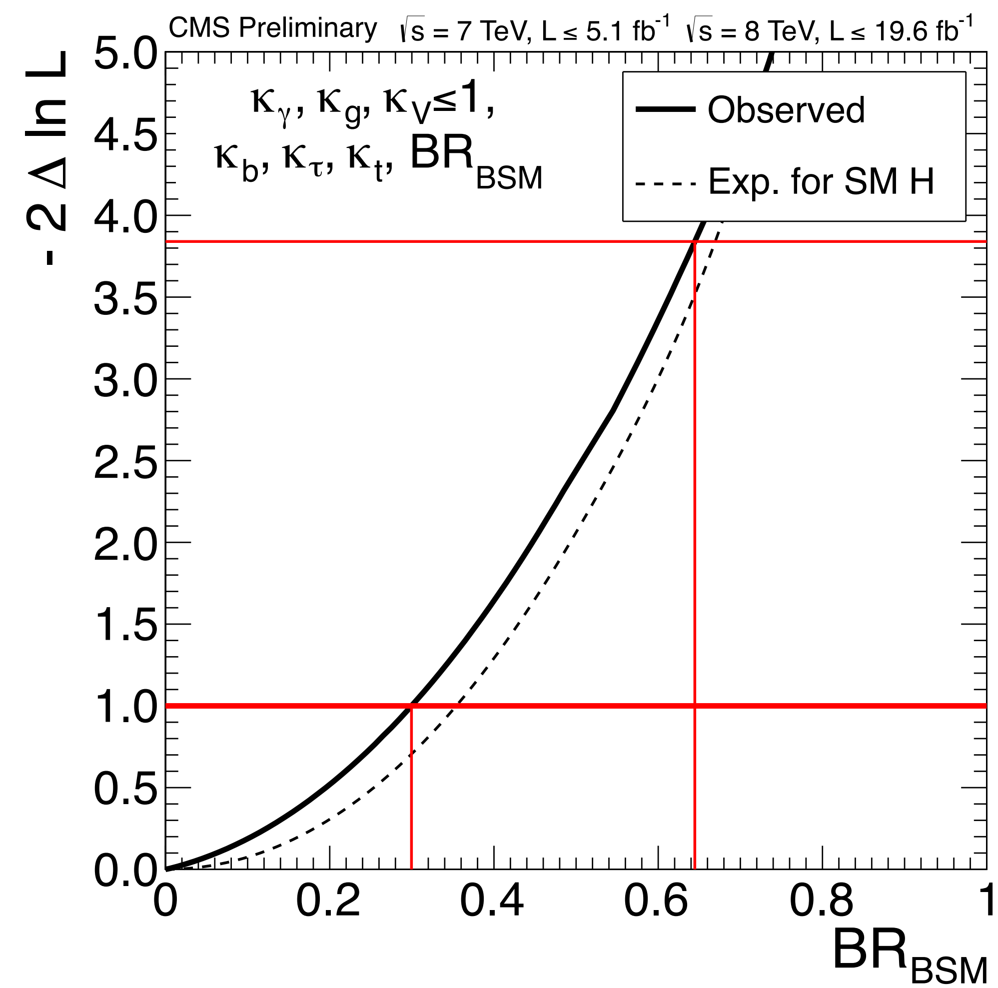
arXiv:1404.1344

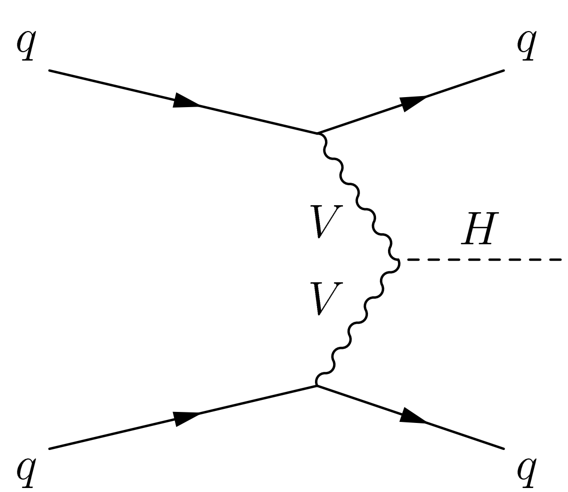
Invisible decay modes are well motivated by the existence of dark matter !

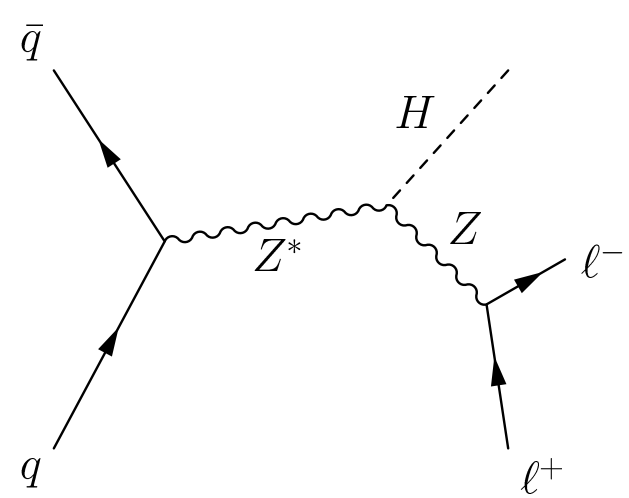
Already have indirect limits from fits to visible decay modes

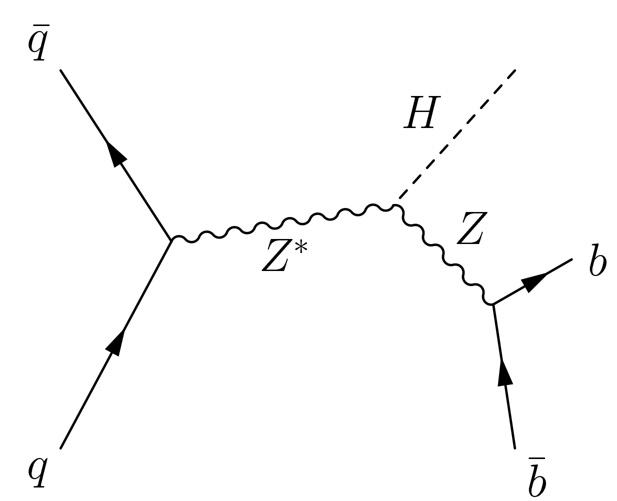
We search in ZH and vector boson fusion production modes

- With Z→ll and Z→bb final states







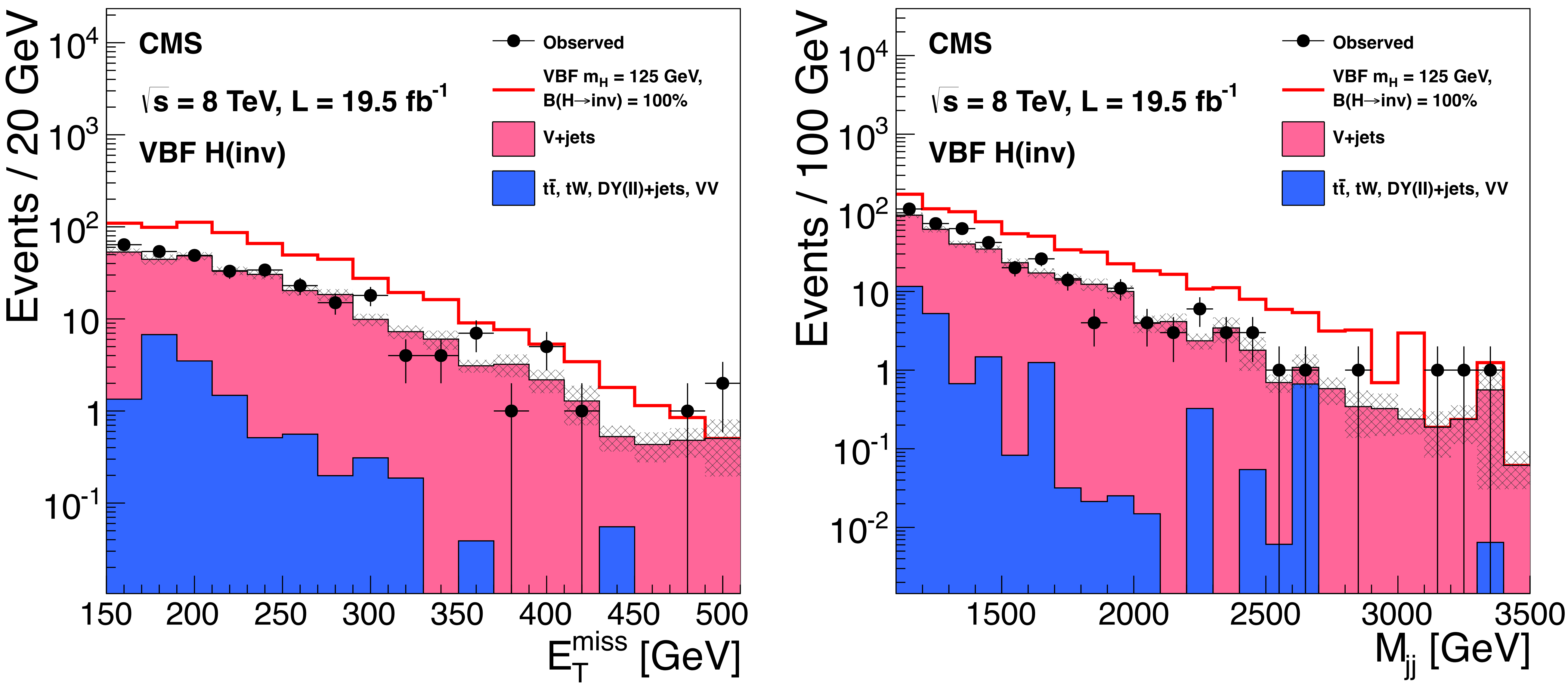


Invisible Higgs

VBF jet topology

p_T > 50 GeV, fwd-bkwd, $\Delta\eta_{jj}$ > 4.2, M_{jj} > 1100 GeV, $\Delta\phi_{jj}$ < 1.0, 30 GeV CJV

E_T^{miss} > 130 GeV



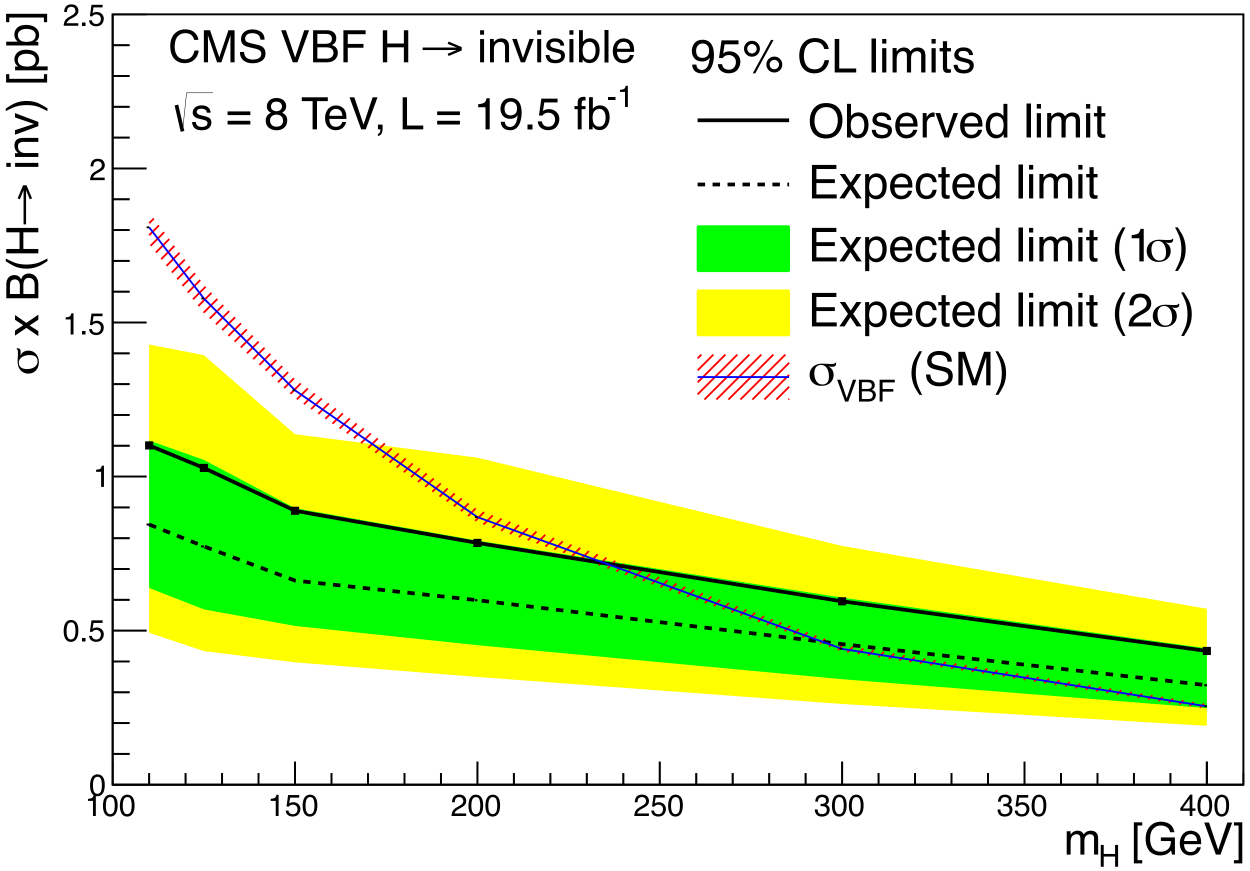
V+jets backgrounds -> control regions with visible leptons

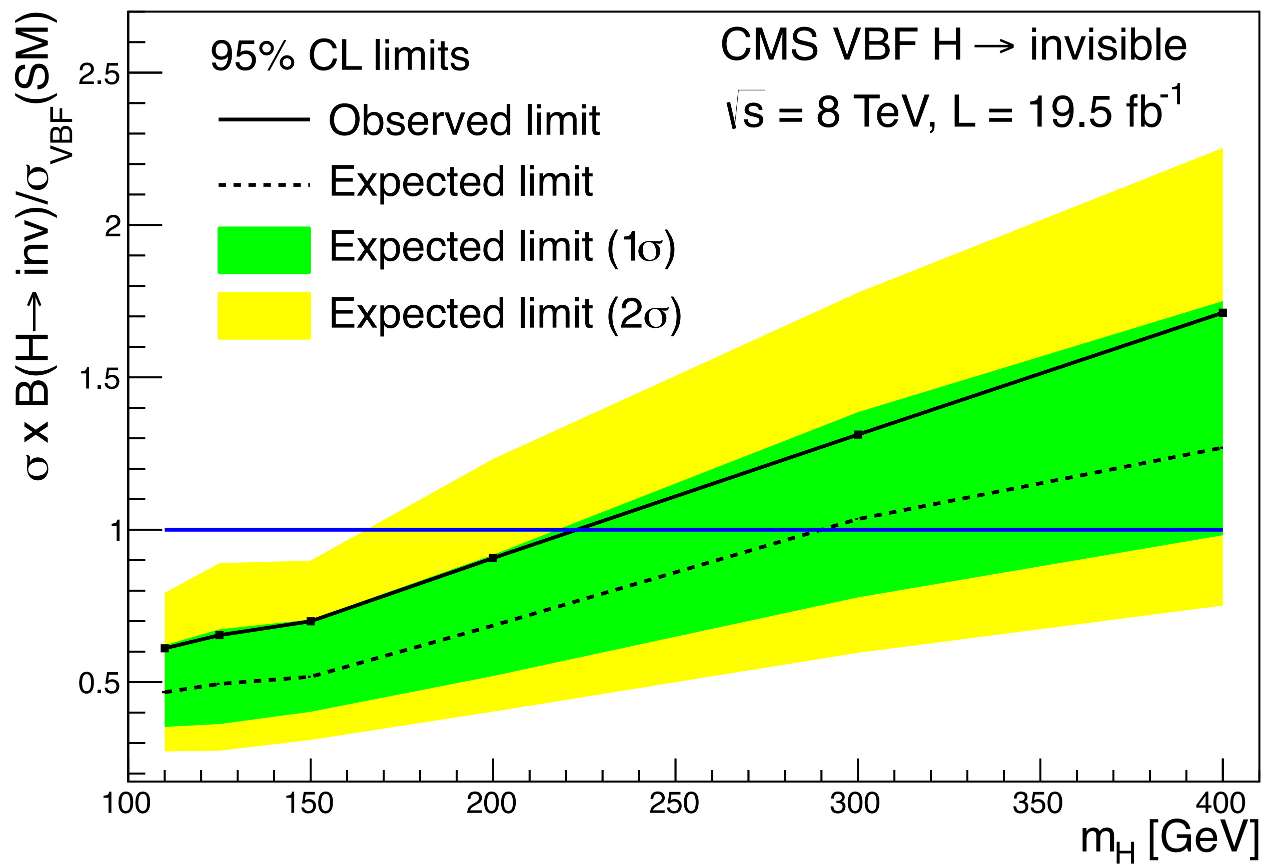
QCD multijet -> ABCD method

Remainder -> MC

Invisible Higgs

arXiv:1404.1344

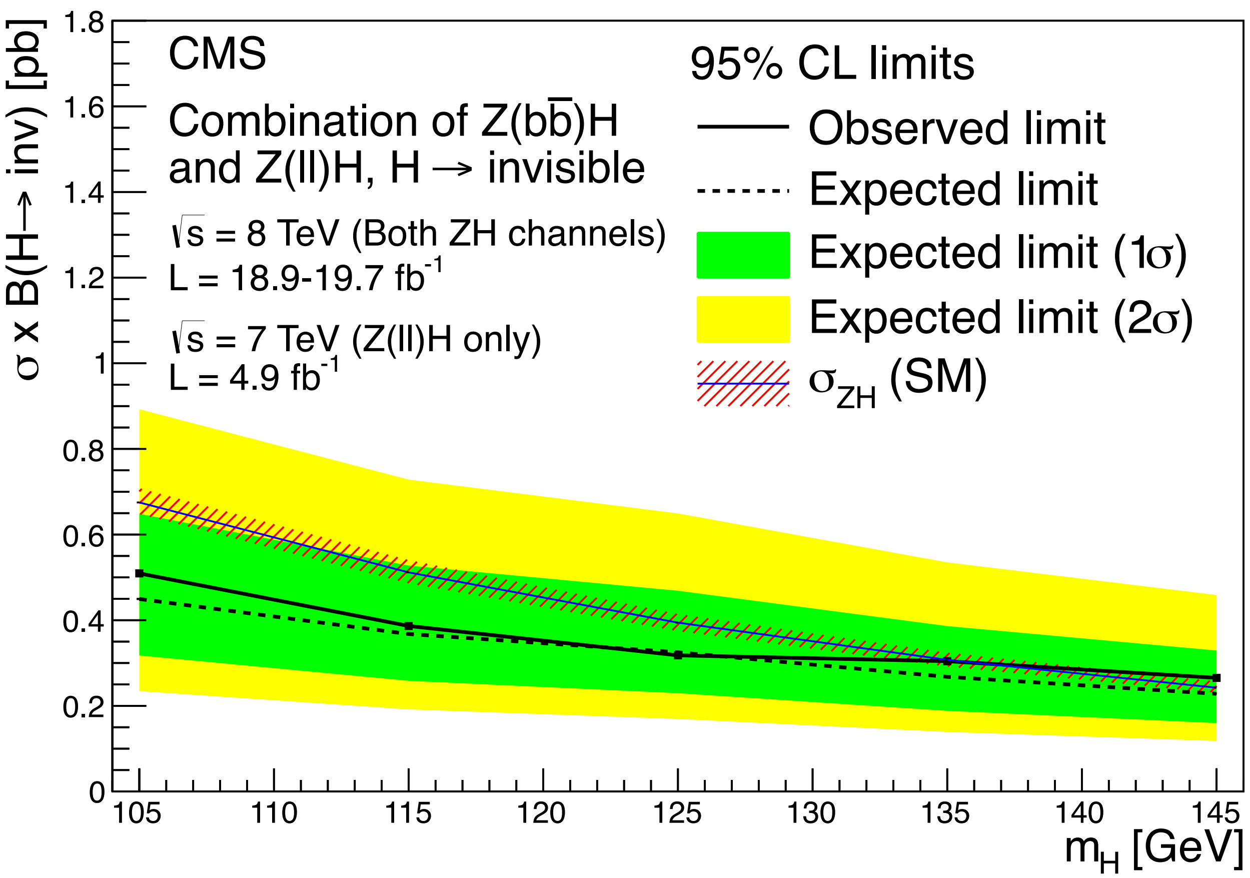


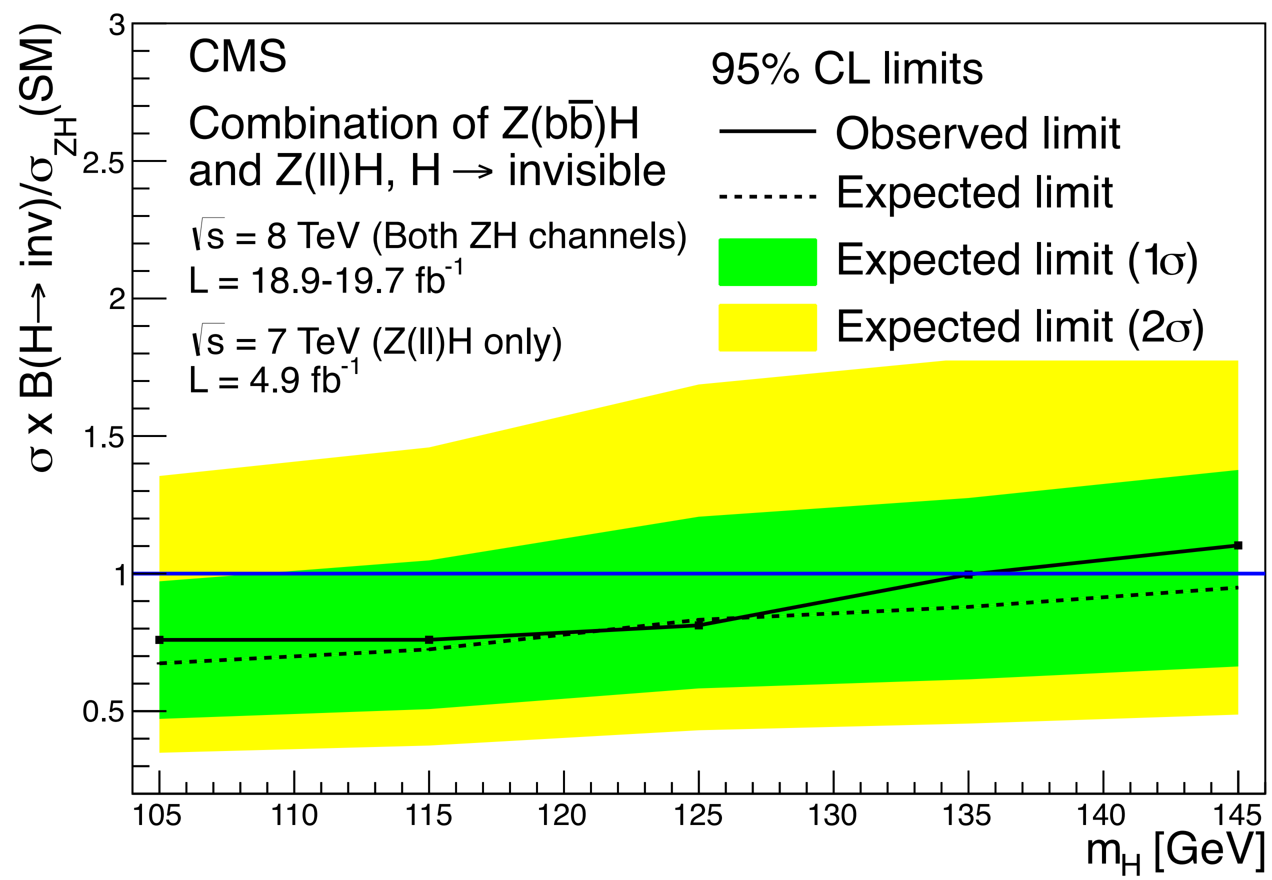


Limits on $\sigma\times BF$ and $\sigma\times BF/\sigma_{SM}$

$BF(H_{125}\rightarrow inv) < 0.65$ obs (0.49 exp) arXiv:1404.1344

University of BRISTOL



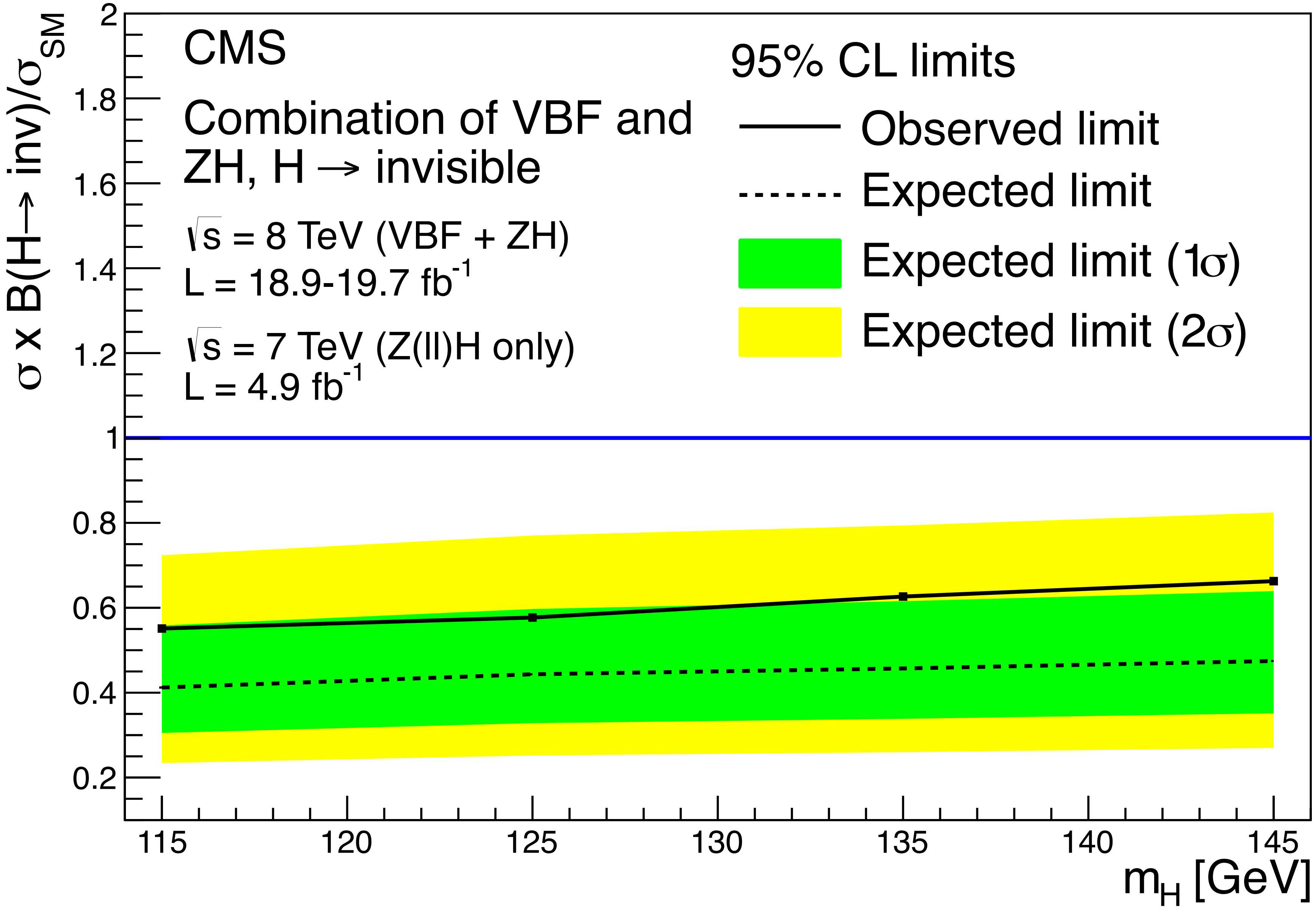


Combination of Z(ll)H and Z(bb)H

BF(H_{125}→inv) < 0.81 obs (0.83 exp)

Invisible Higgs

arXiv:1404.1344

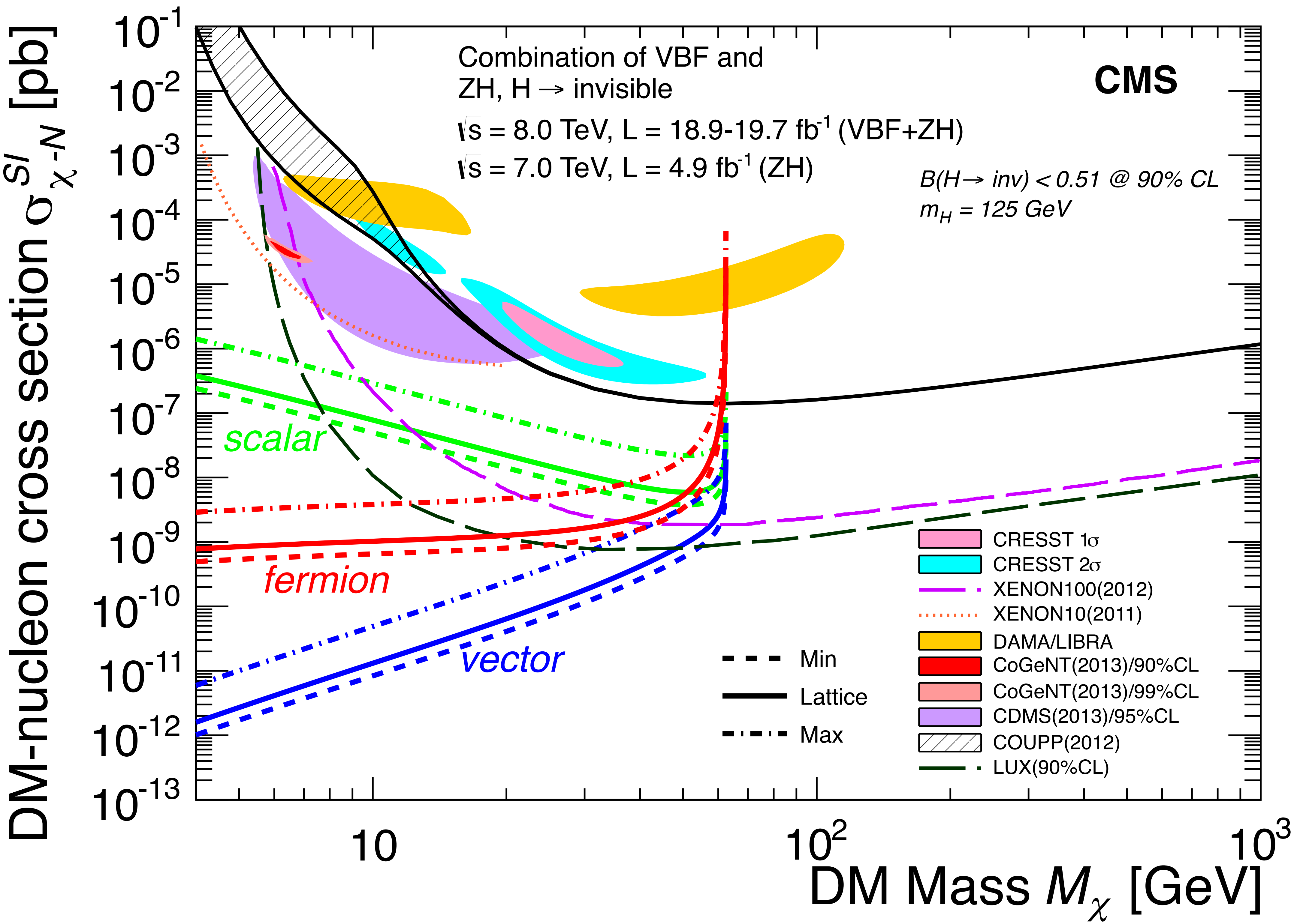


BF(H_{125}→inv) < 0.58 obs (0.44 exp)

Future plans : combination with indirect limits !

Invisible Higgs

arXiv:1404.1344



Conclusion

- Try to leave no stone unturned !

- Search for new physics using a wide range of methods
  - Familiar final states & unfamiliar final states
  - **Directly detect particles with anomolous properties**
  - **Exotic decays of 125 GeV Higgs !**

- No signals yet...
  - Hope for some hints in Run 2