Searches with the First ATLAS Data

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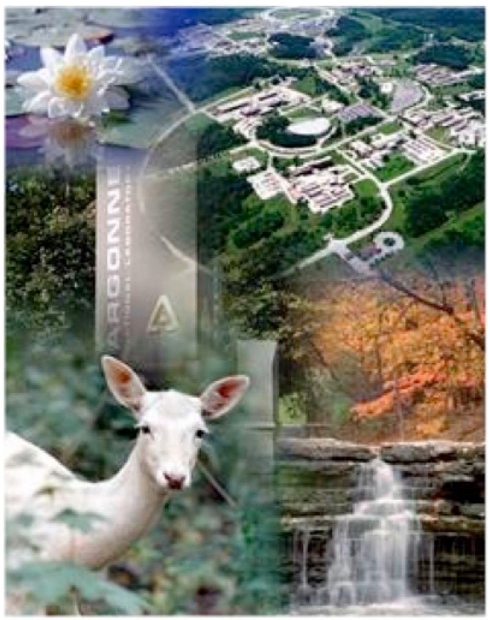


Argonne NATIONAL LABORATORY

CERN European Organization for Nuclear Research

Collider Physics 2009:
Joint Argonne & IIT Theory Institute
ANL, May 20th 2009

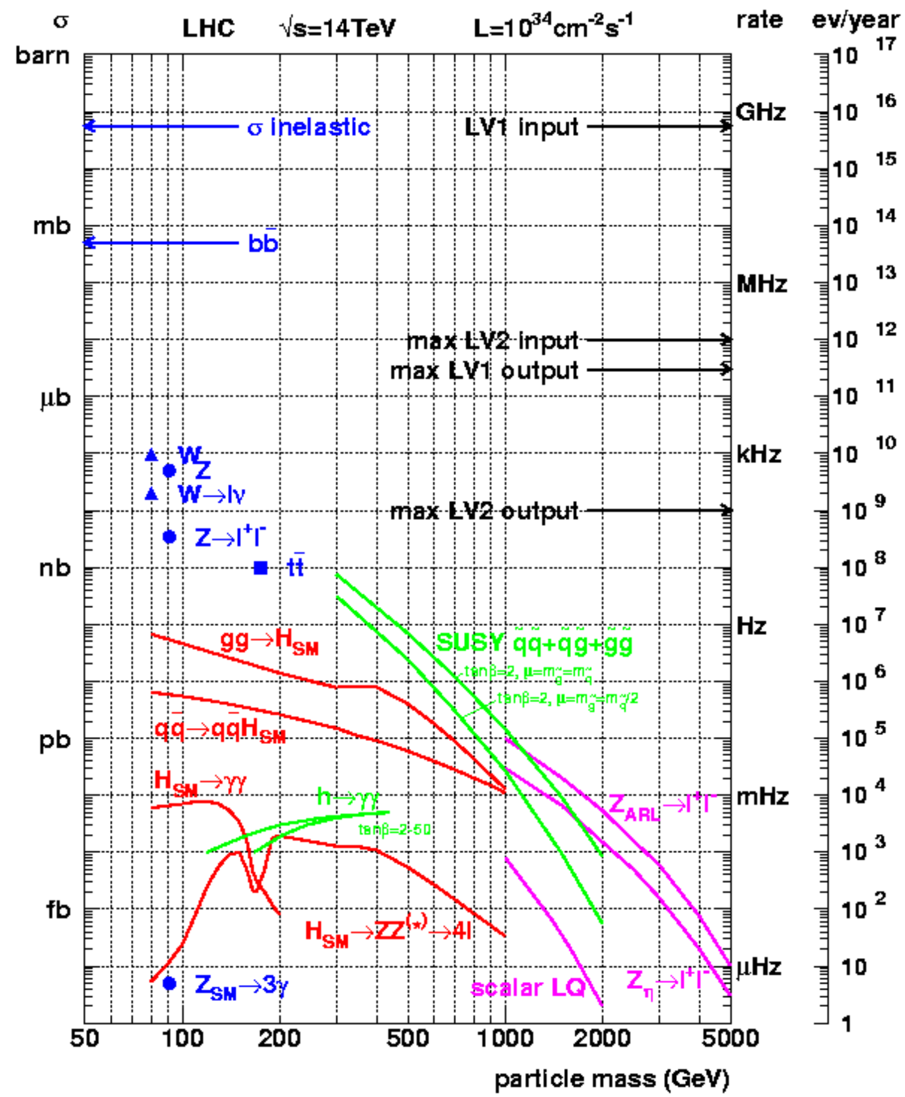
Outline

- Cross-Sections at the LHC
- Higgs searches
  - The SM Higgs with $H \rightarrow WW, ZZ$
- SUSY Searches
  - Search strategy
  - Data Driven Techniques
- Other Searches Beyond SM
  - Heavy Bosons
  - Same-Sign lepton pairs
  - Black holes…

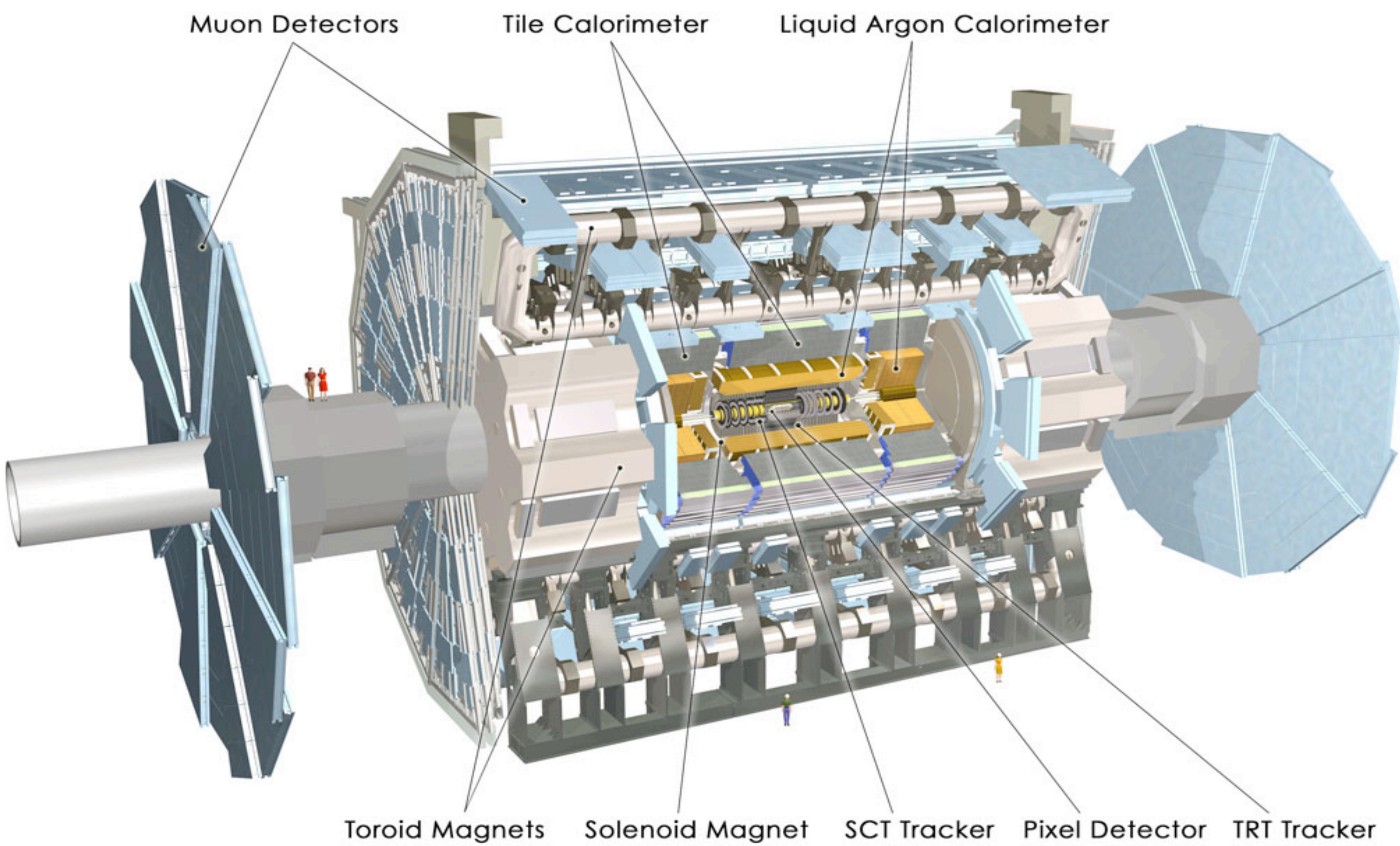
Estimates from "Expected Performance of the ATLAS experiment" for 14 TeV
http://arxiv.org/pdf/0901.0512
ATLAS is re-assessing sensitivity for 10 TeV and 200 pb^{-1}

Cross-Sections at the LHC

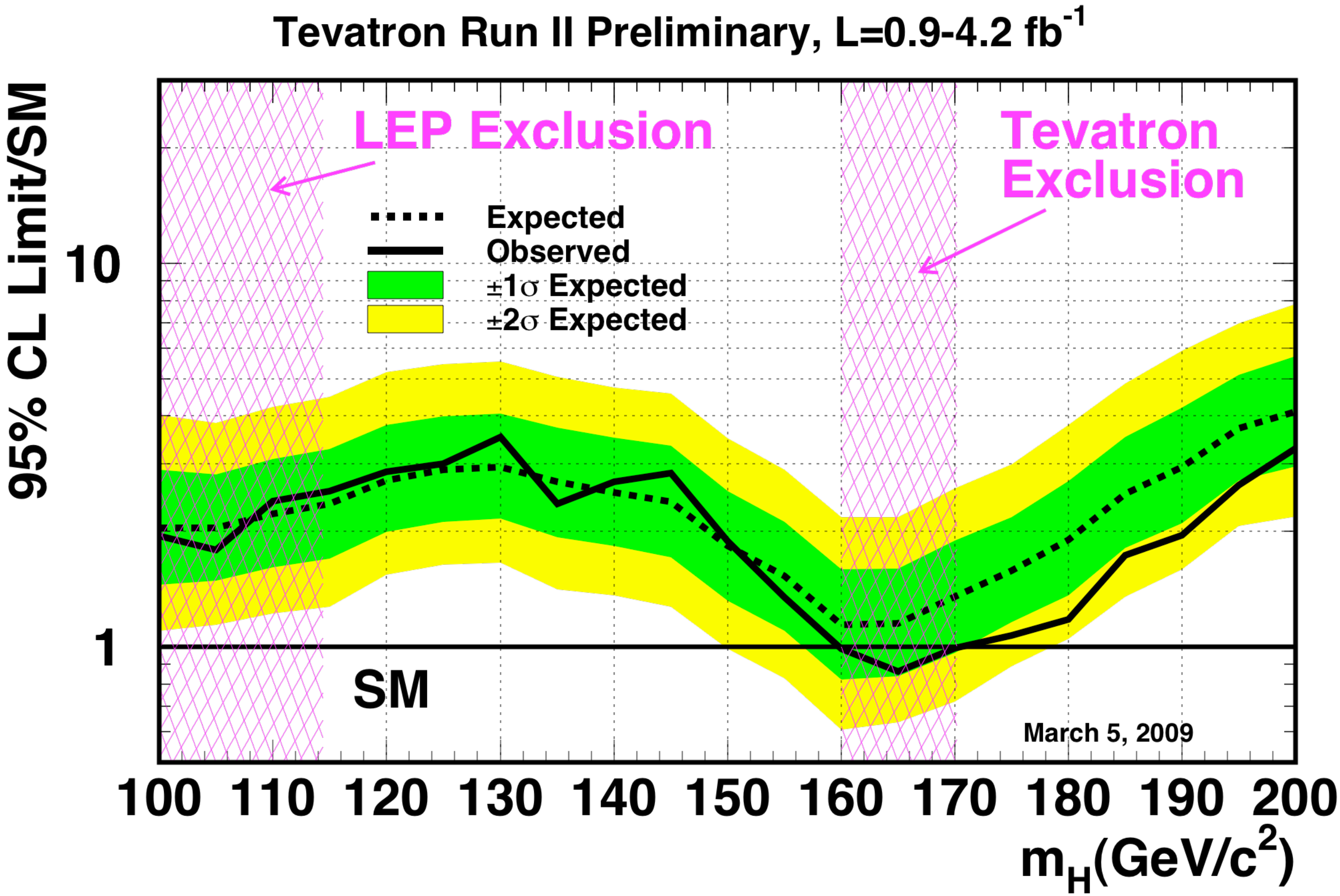
- ❑ **Search for Higgs and new physics hindered by huge background rates**
  - ❑ **Known SM particles produced much more copiously**
- ❑ **Need to rely on**
  - ❑ **Narrow resonances**
  - ❑ **Complex signatures**
    - **Leptons, jets, MET**
- ❑ **First, need to establish SM signatures**
  - ❑ **See Tom's talk**



The ATLAS Detector

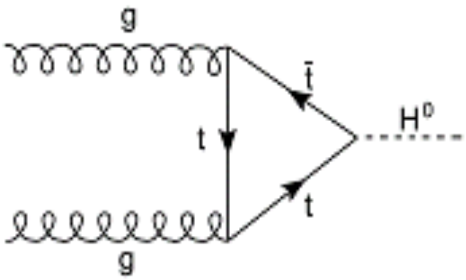


Higgs Searches

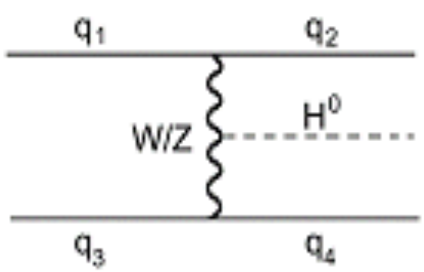

Tevatron Run II Preliminary, L=0.9-4.2 fb-1
95% CL Limit/SM
LEP Exclusion
Tevatron Exclusion
Expected
Observed
±1σ Expected
±2σ Expected
10
1
SM
March 5, 2009
100 110 120 130 140 150 160 170 180 190 200
mH(GeV/c2)

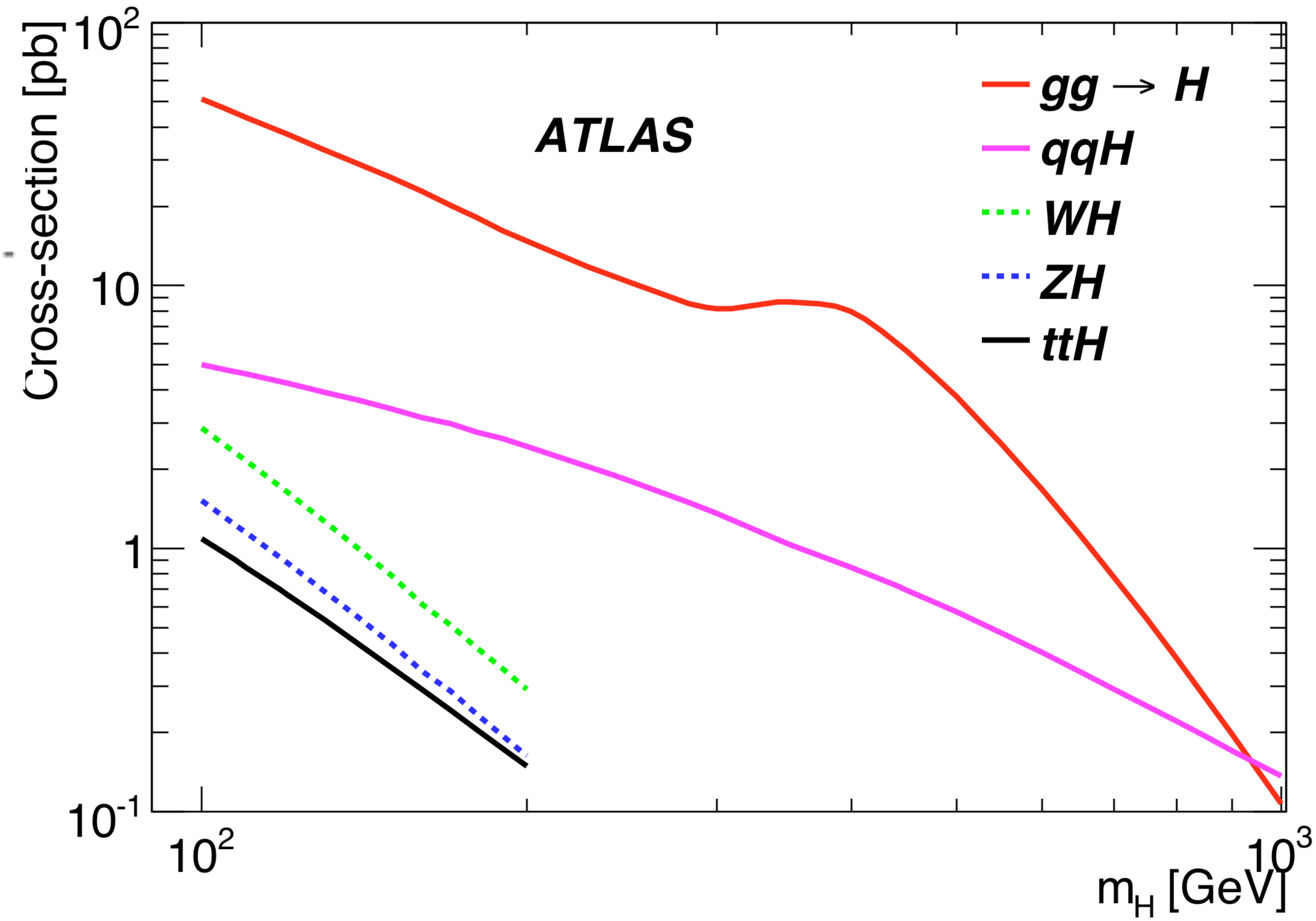
Higgs Production at LHC

Leading Process (gg fusion)

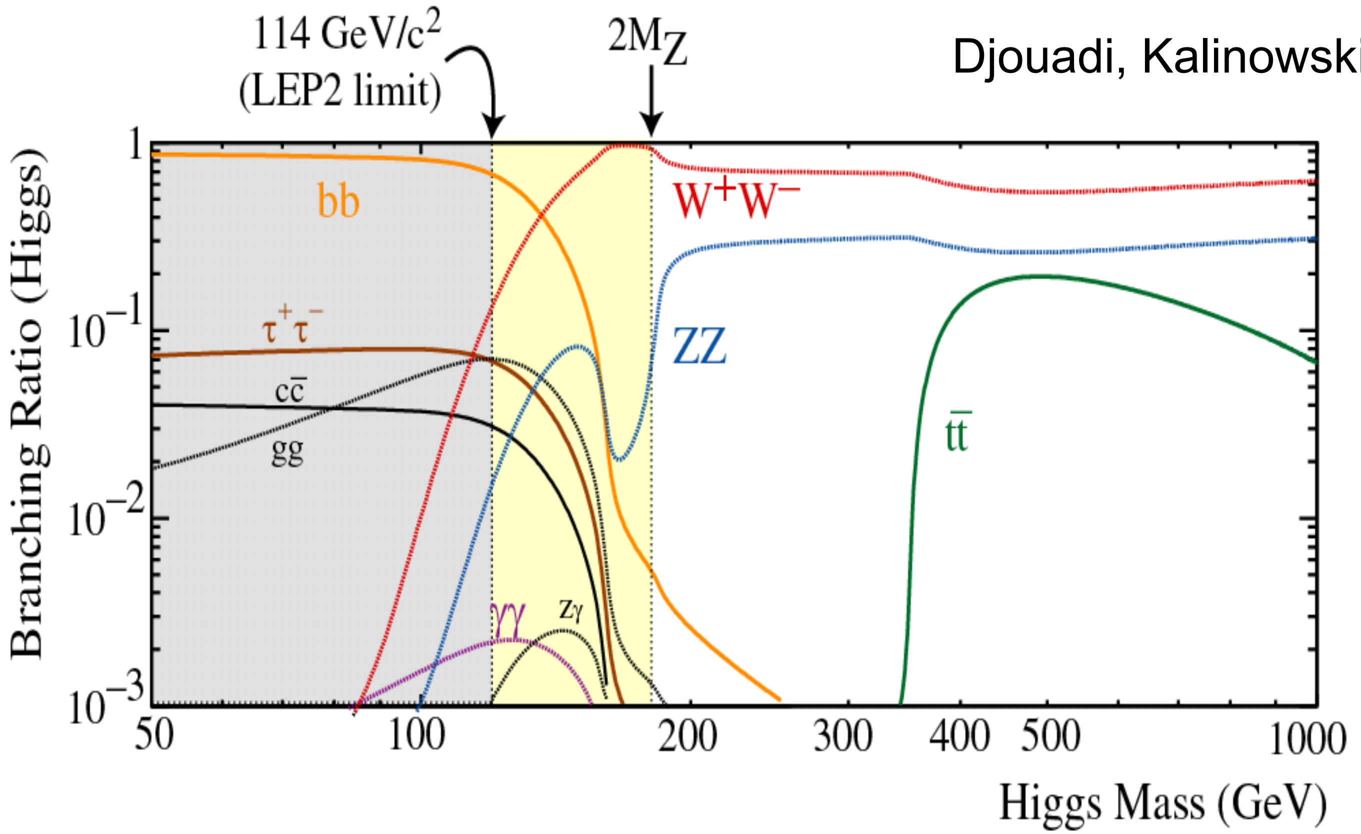


Sub-leading Process (VBF)





Main Decay Modes



Close to LEP limit:
$H \to \gamma\gamma, \tau\tau$

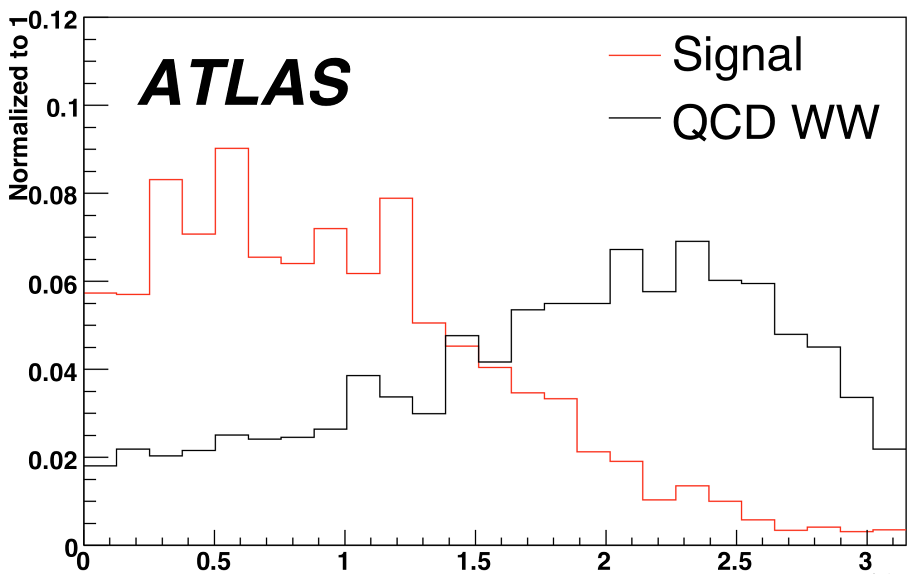
For M_H>140 GeV:
$H \to WW^{(*)}, ZZ^{(*)}$

Significant potential with the first data

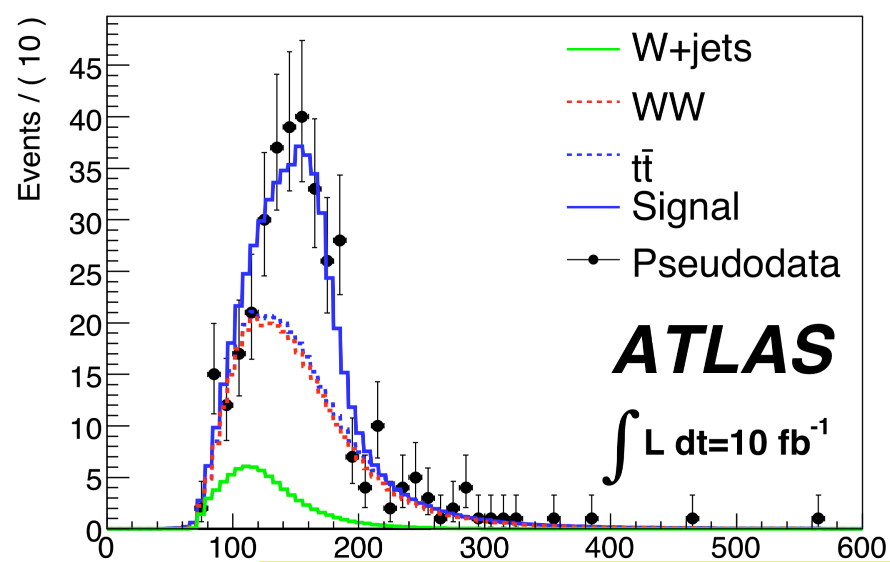
SM Higgs H→WW(*)→2l2ν

- Strong potential due to large signal yield, but no narrow resonance. Left basically with event counting experiment
  - Role of lepton ID, QCD rejection, jet vetoing/tagging, MET reconstruction for different jet multiplicities, top background rejections are crucial for this analysis

H→WW+0j



$\Delta\phi_{ll}$ (rad)



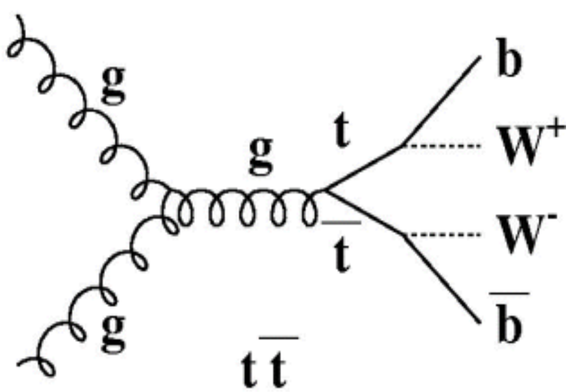
Transverse Mass (Gev)

Background Suppression and Extraction

- Not able to use side-bands to subtract background. This makes signal extraction more challenging. Need to rely on data rather than on theoretical predictions
- Definition & understanding of control samples is crucial
  - Use large $\Delta\phi_{ll}$ and M_{ll} regions to extrapolate to signal-like region
    - Minimize theoretical uncertainties
    - Working on more methods minimize further dependence on MC

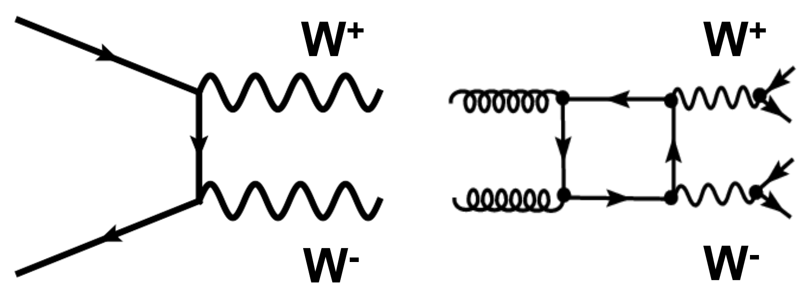
ttbar suppression

- Jet veto (understand low P_T jets)
- B-tagging for control samples
  - Working on methods that don't need the use of b-tagging



Non-resonant WW suppression

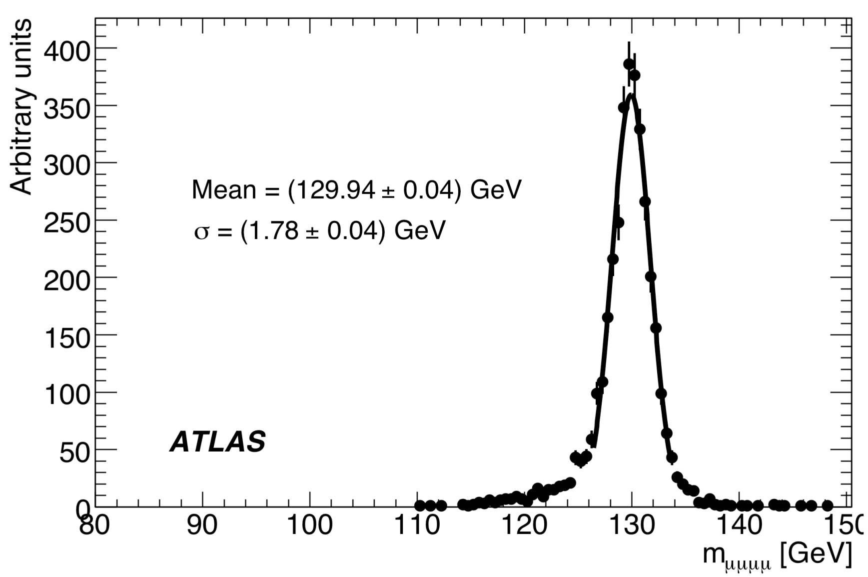
- $\Delta\phi_{ll}$ and M_{ll} very important variables
- Transverse momentum of WW system
  - Higgs production is harder. Missing E_T reconstruction plays a significant role here



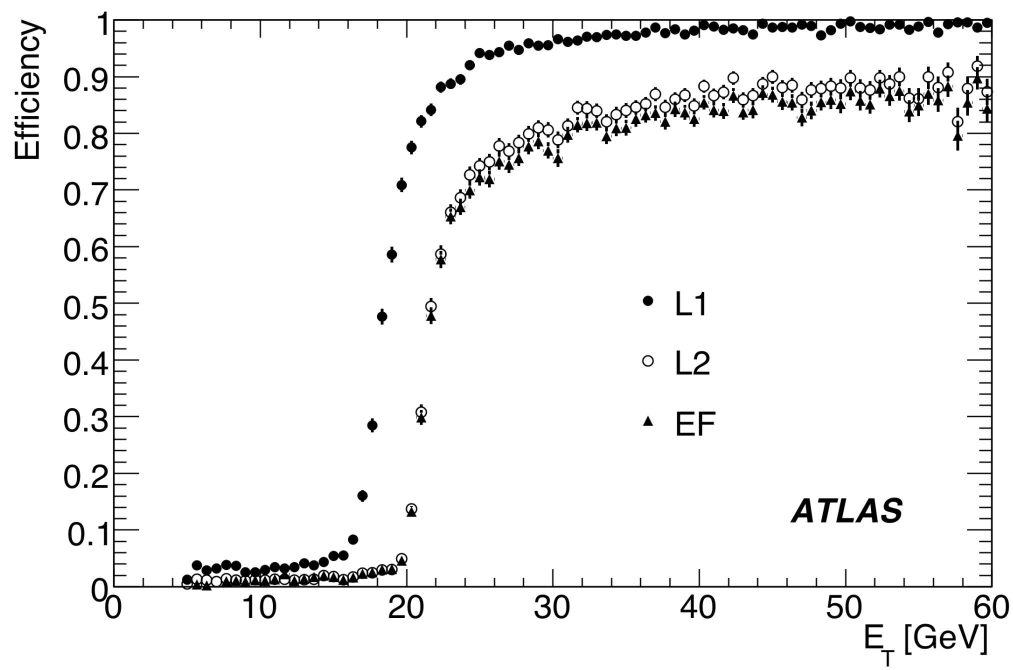
SM Higgs→ZZ$^{(*)}$→4l

- Able to reconstruct a narrow resonance, with mass resolution close to 1%. Can achieve excellent signal-to-background > 1
  - **Major issues: Lepton ID and rejection of semi-leptonic decays of B decays. Suppress reducible background Zbb,tt→4l**

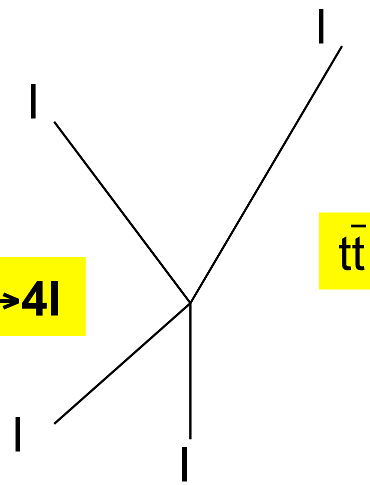
H[**130** GeV]→4μ



Electron efficiency

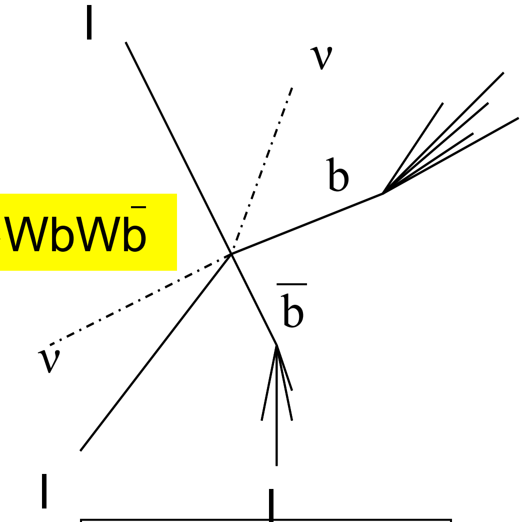


$ZZ^*/\gamma^* \rightarrow 4l$



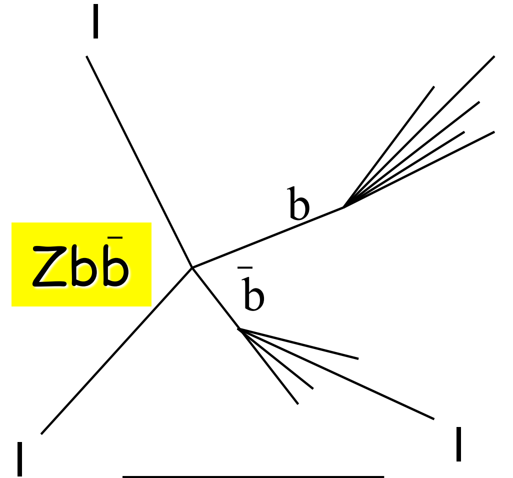
Continuum Irreducible

$t\bar{t} \rightarrow WbW\bar{b}$



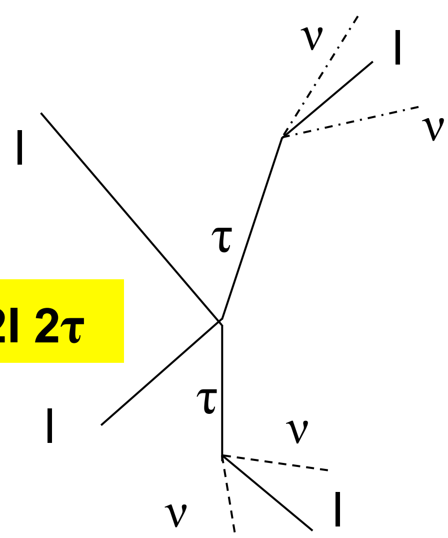
Non-Resonant reducible

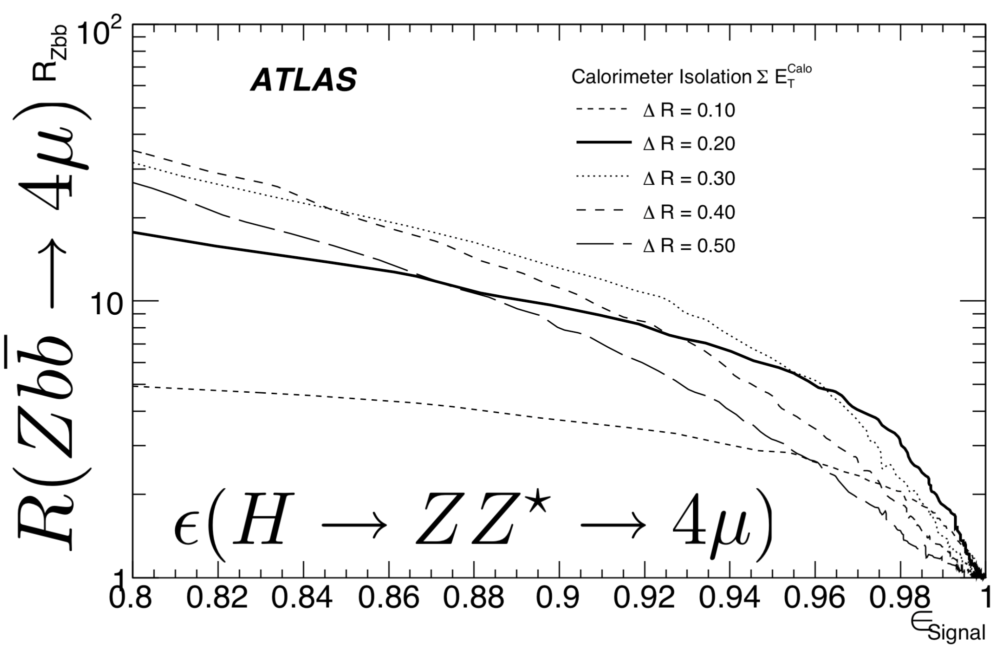
$Zb\bar{b}$

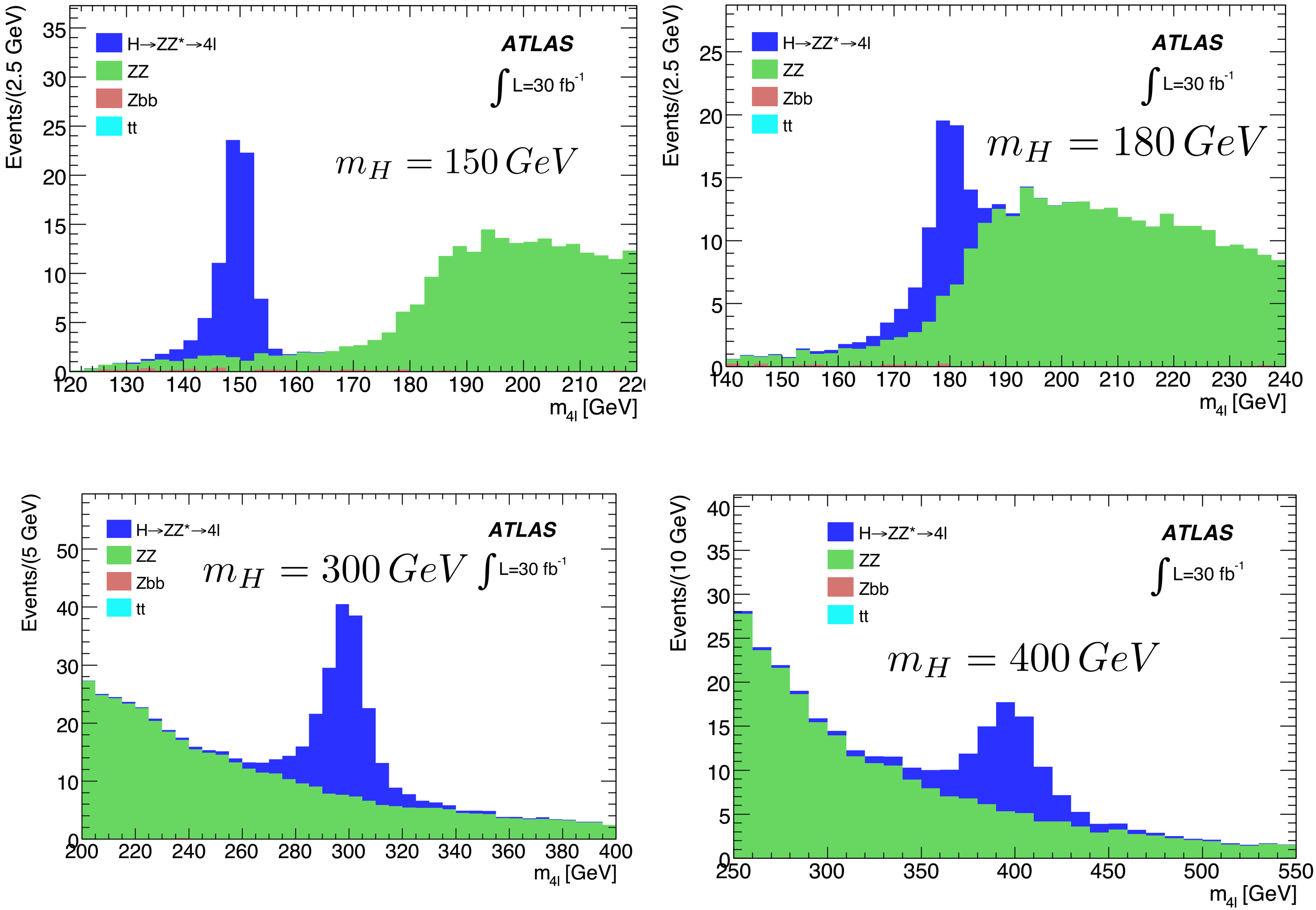


Resonant reducible

$ZZ^*/\gamma^* \rightarrow 2l\ 2\tau$





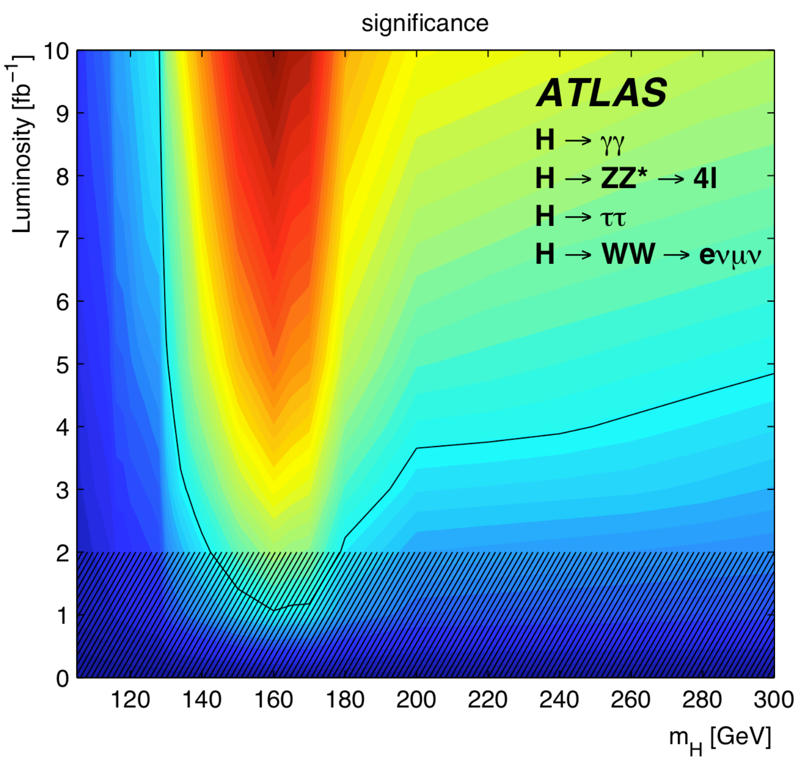


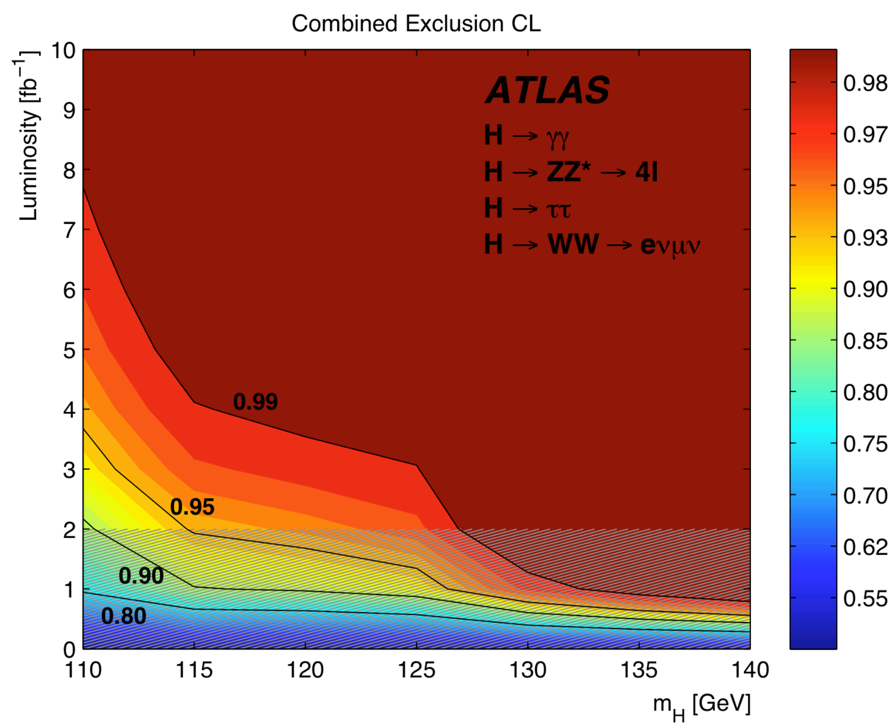
Events/(2.5 GeV)
H→ZZ*→4l
ZZ
Zbb
tt
ATLAS
∫L=30 fb-1
$m_H = 150\,GeV$
m4l [GeV]
Events/(2.5 GeV)
H→ZZ*→4l
ZZ
Zbb
tt
ATLAS
∫L=30 fb-1
$m_H = 180\,GeV$
m4l [GeV]
Events/(5 GeV)
H→ZZ*→4l
ZZ
Zbb
tt
ATLAS
$m_H = 300\,GeV$
∫L=30 fb-1
m4l [GeV]
Events/(10 GeV)
H→ZZ*→4l
ZZ
Zbb
tt
ATLAS
∫L=30 fb-1
$m_H = 400\,GeV$
m4l [GeV]

Overall Sensitivity to SM Higgs

Results obtained for 14 TeV

$H \to WW^{(*)}, ZZ^{(*)}$ dominate sensitivity for M_H>140 GeV





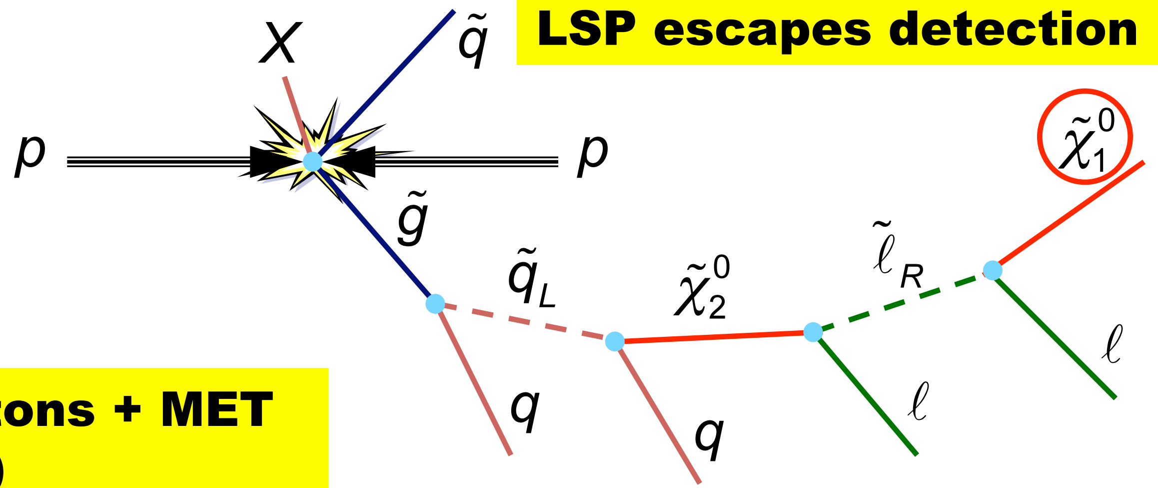
Preliminary studies seem to indicate that ATLAS has the potential to exclude the SM Higgs with M_H around 160 GeV with 10 TeV center of mass energy and 200 pb^{-1} of integrated luminosity

SUSY Searches

Characteristic SUSY “Cascades” at the LHC

- Long decay chains and large mass differences between SUSY states
  - Many high P_T objects observed (leptons, jets, b-jets)
- If R-Parity conserved LSP (lightest neutralino in mSUGRA) stable and sparticles pair produced → requires energy 2 × SUSY mass
  - Since no exotic strong or EM bound states have been observed, the LSP should be neutral and colourless. LSP, like heavy neutrino
  - Large MET signature (c.f. W→lν)
- Closest equivalent SM signature t-tbar decay (t→Wb)

LSP escapes detection →MET

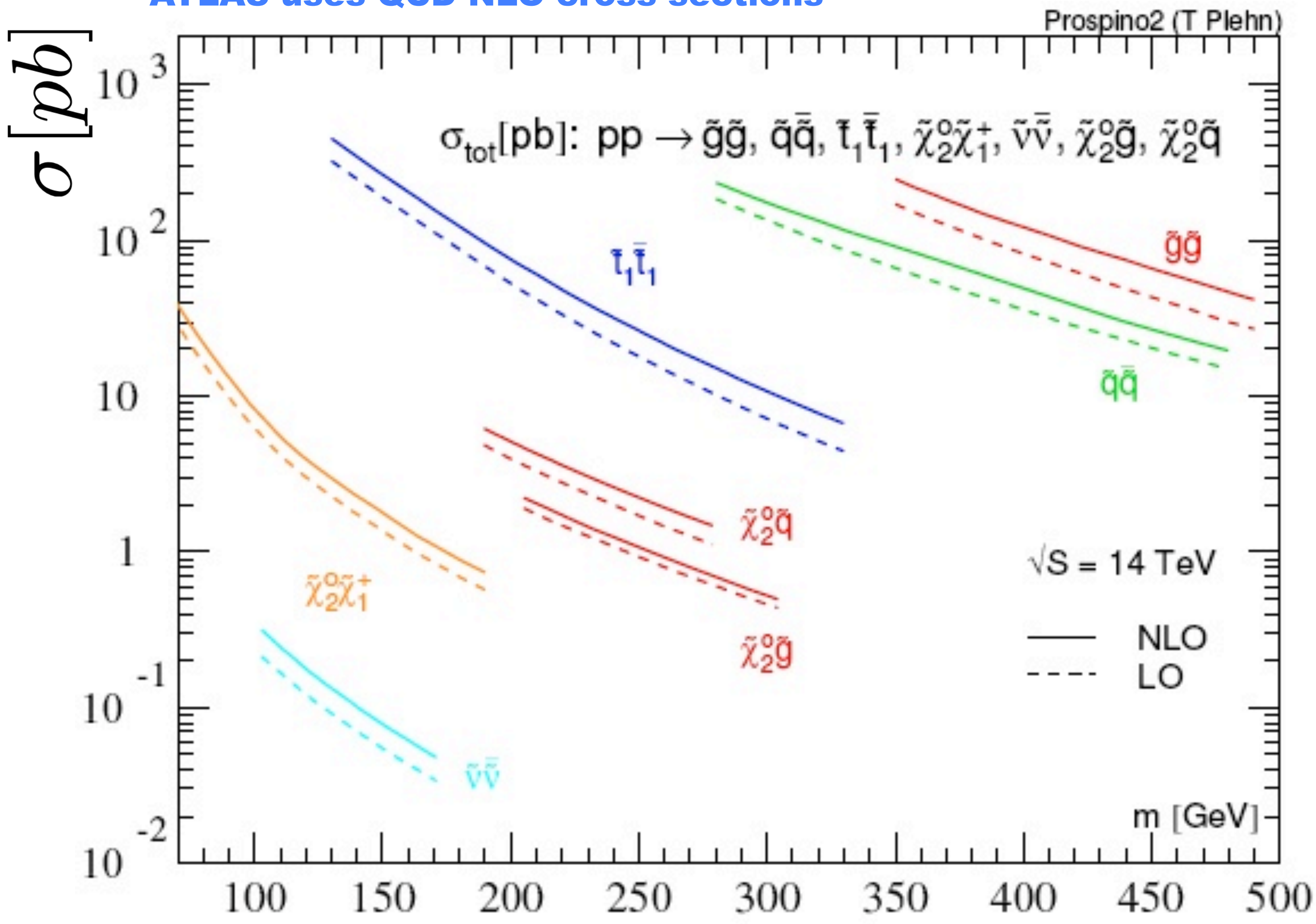


Jets + Leptons + MET
(b-jet) (τ)

“Typical” SUSY decay chain at the LHC

mSUGRA Cross-sections

- **Strongly interacting sparticles** (squarks, gluinos) **dominate production**
  - **Cross-sections driven by sparticle masses**
    - **ATLAS uses QCD NLO cross-sections**



Experimental Strategy

Inclusive Searches

Search for deviations from the Standard Model

Fully hadronic channel
Lepton veto

1 lepton + Jets

2 lepton + Jets
Same Sign + Opposite sign

3 lepton
Jet veto and jets

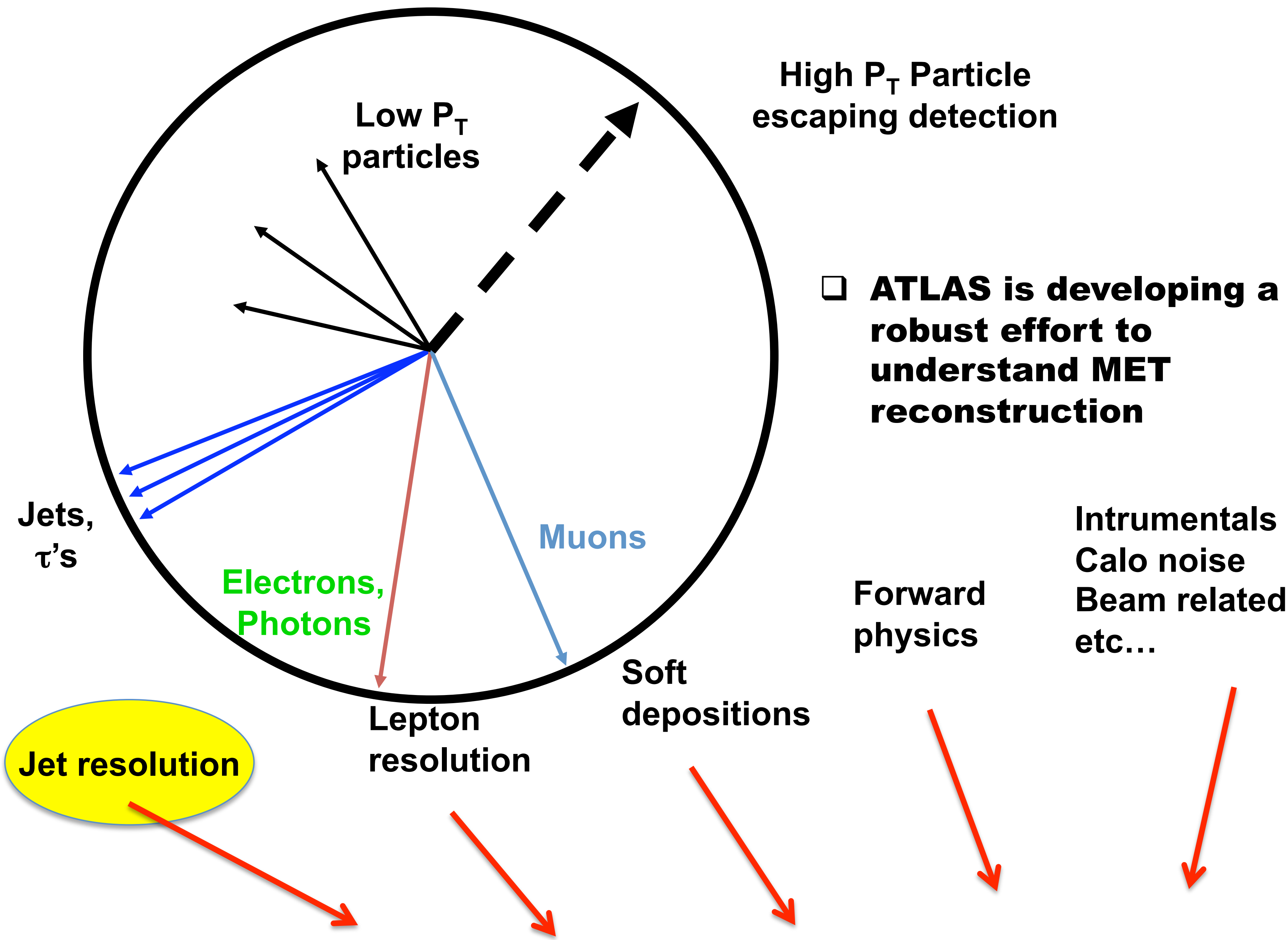
Etc…

Assume 1fb^{-1} of data and 14 TeV
Re-evaluation with 10 TeV and in progress

Exclusive Search

Understand properties like mass
Limited in pp-collisions

Great progress in defining data-driven methods to extract SM backgrounds in interesting corners of the phase-space

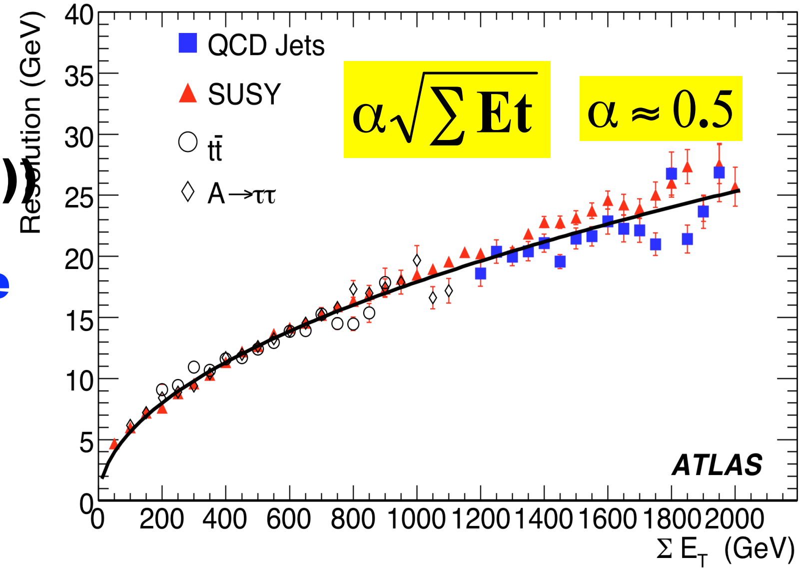


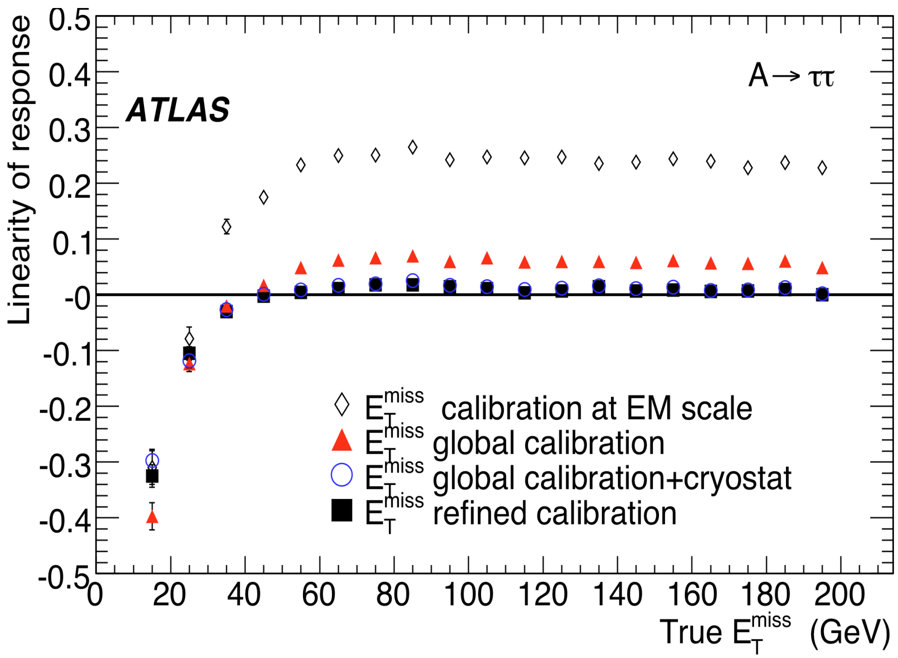
- **ATLAS is developing a robust effort to understand MET reconstruction**

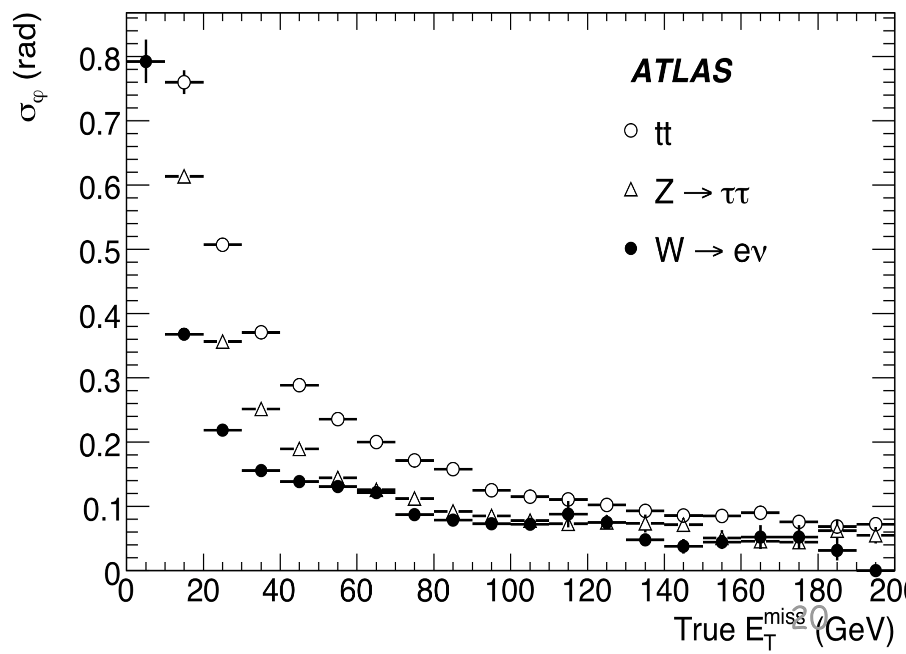
$$\sigma(MET) \approx \sigma^{Jet} \oplus \sigma^{Lep} \oplus \sigma^{Soft} \oplus \sigma^{Forw} \oplus \sigma^{Other}$$

MET Performance

- **Resolution = σ(MET (Rec)-MET(truth))**
  - **Degradation for large (high pt jets) and very low SumET regions (noise suppression method)**
- **Linearity =(MET (truth)-MET(Rec))/ MET (truth) within 5%**
- **Angular resolution**
  - **100 mrad for EtMiss> ~ 80 GeV**
- **Obserseve Dependence on event topology**



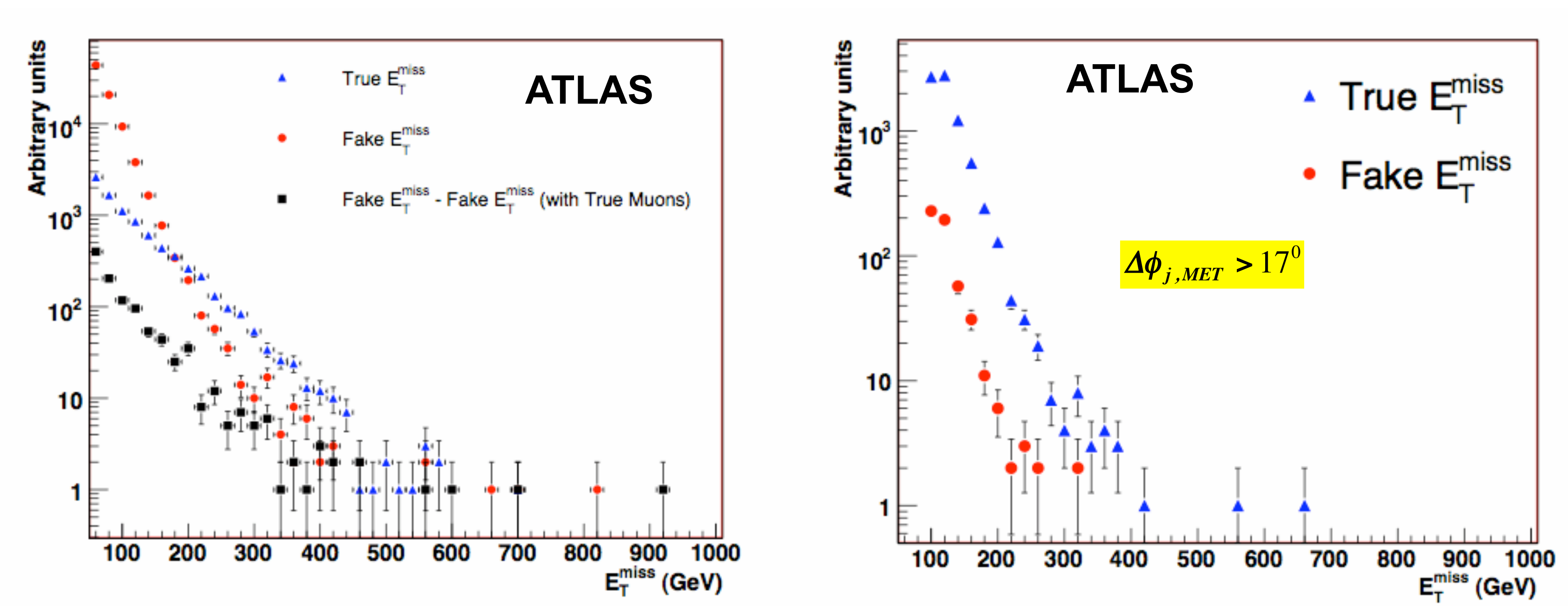




Fake MET

- The identification, suppression and prediction of fake MET is one of the most complex problems for experimentalists, even after the event clean up. This has strong implications on SUSY searches

Study with QCD di-jets with $560 < E_T < 1120$ GeV

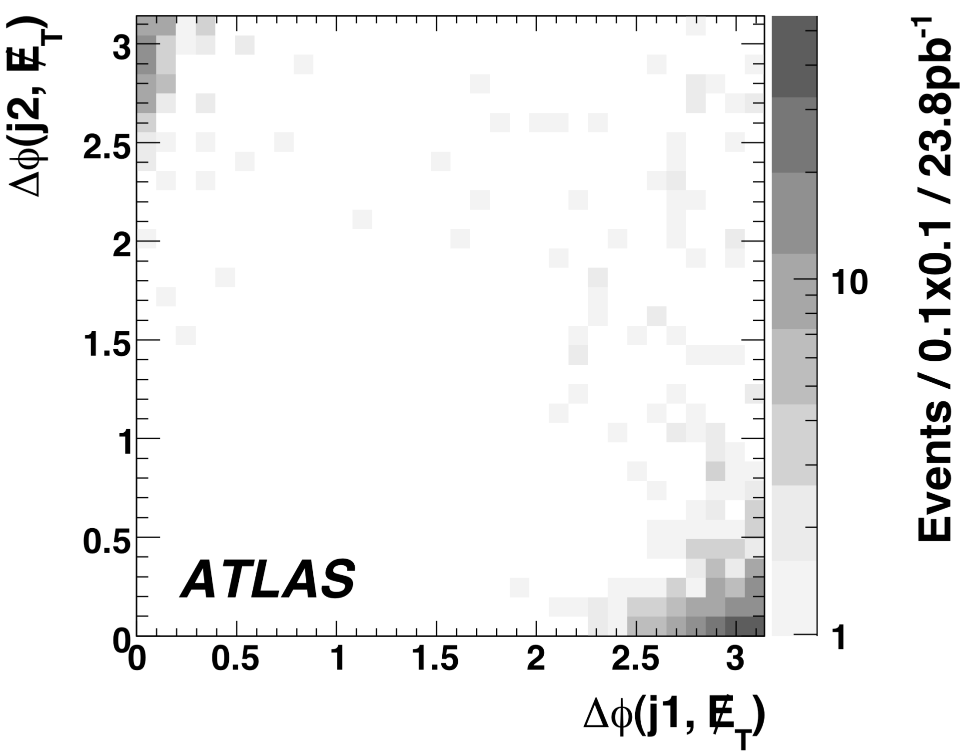


Suppression of Fake MET

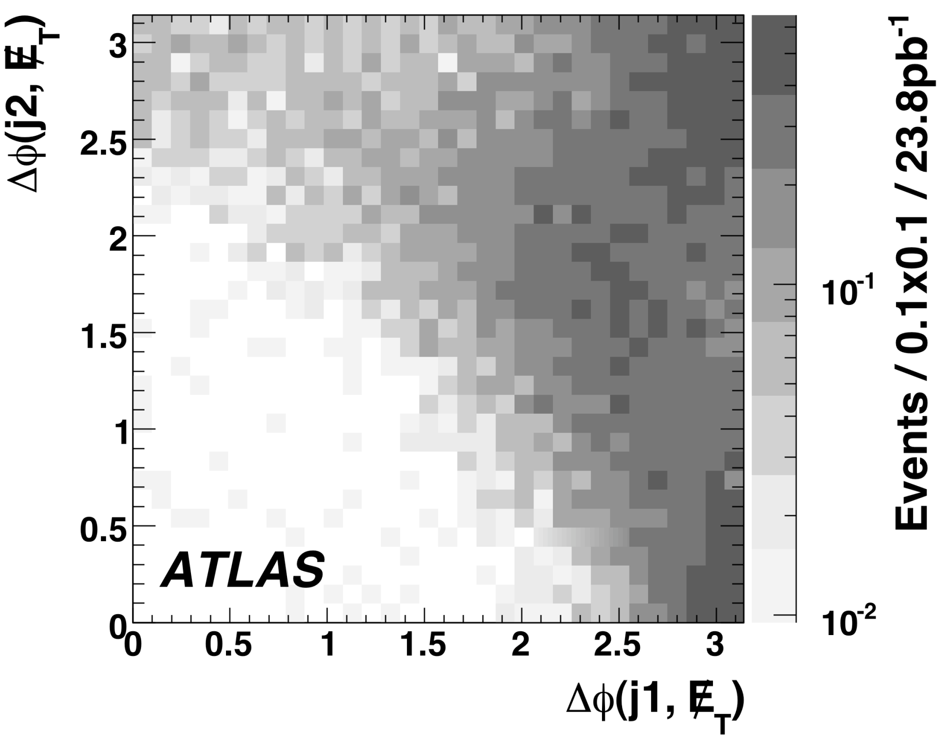
- Fake MET due to Jet resolution effects tends to point along the direction of the jet. Cuts on the opening angle between the jets and the MET are very effective in fake MET in multi-jet topologies, corresponding to SUSY searches

MET>100 GeV

QCD multi-jets



SUSY SU3



Inclusive Search with Zero Leptons

- **Four jets** $(P_T > 100, 50, 50, 50) GeV$
- **Lepton veto (e,mu)**

$$MET > 100GeV; MET > 0.2M_{Eff}$$

$$\Delta\phi(j, MET) > 0.2$$

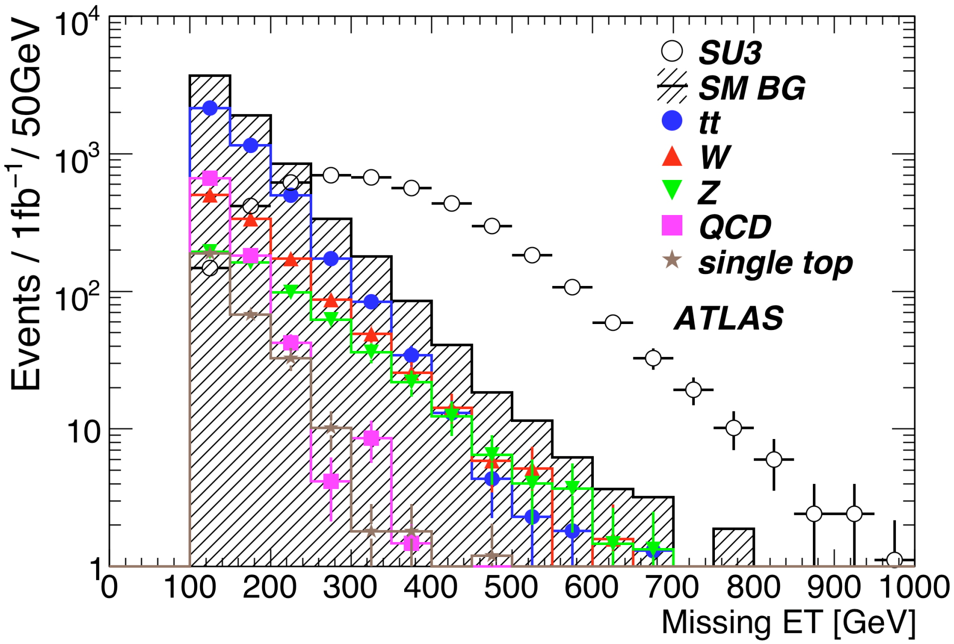
$$S_T > 0.2$$

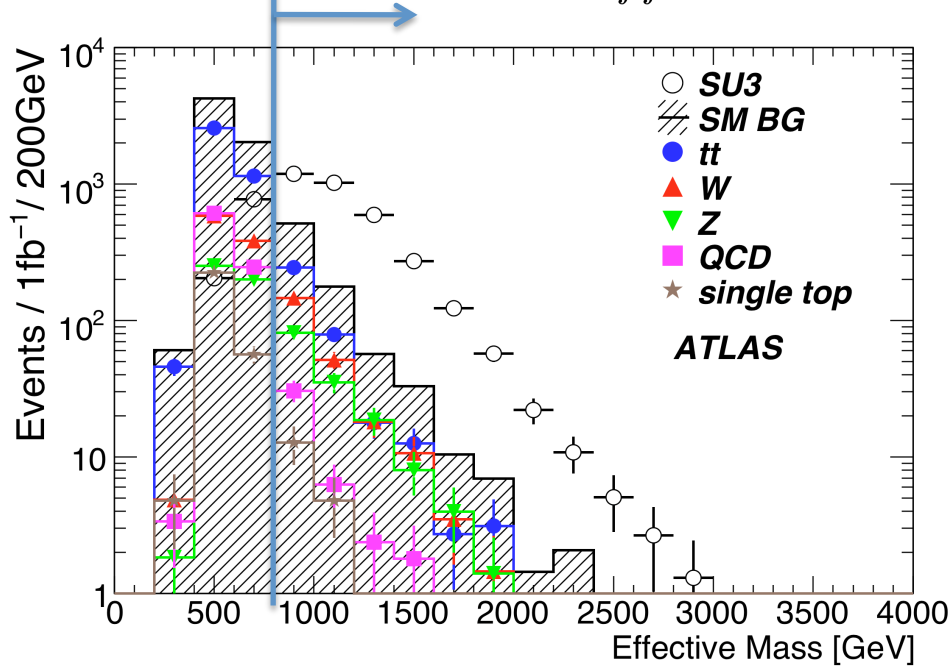
$$M_{eff} = \sum_{i=1}^{4} P_{Tj} + MET$$

Benchmark point

$$SU3 : m_0 = 100, m_{1/2} = 300,$$
$$\tan\beta = 6, A = -300, \mu > 0$$

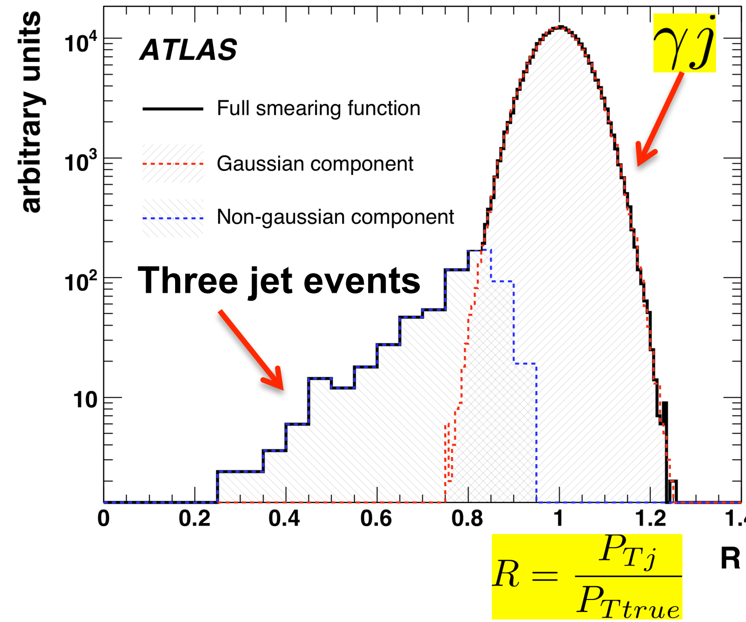
Typical cut $M_{eff} > 800GeV$

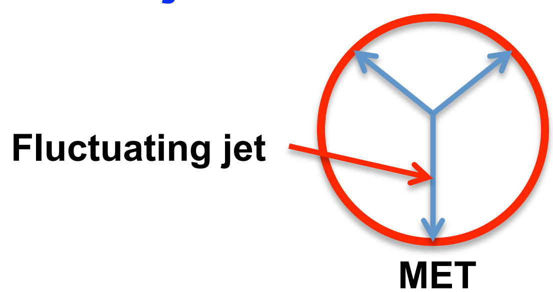




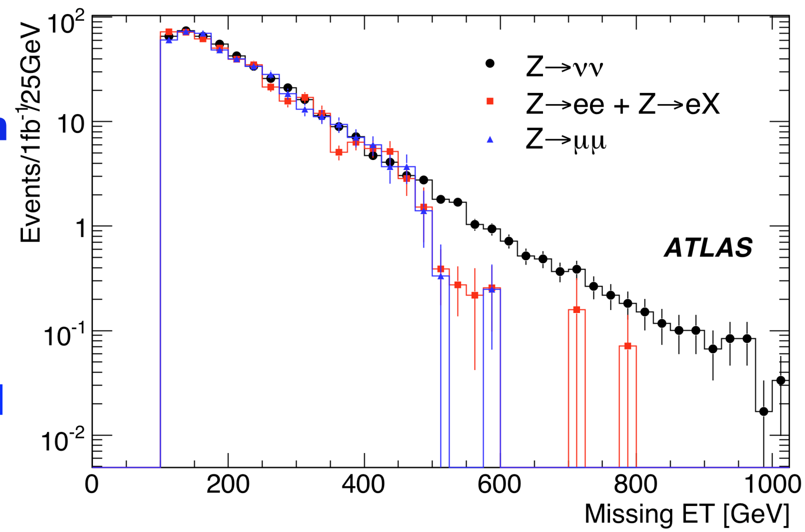
Data Driven Background Extraction

- **QCD extraction:**
  - **Get Gaussian resolution from γjet**
  - **Get non-Gaussian response from three jet events with only one jet parallel to the vector of the reconstructed MET**
  - **Smear jet P_T in four jet events with small MET**



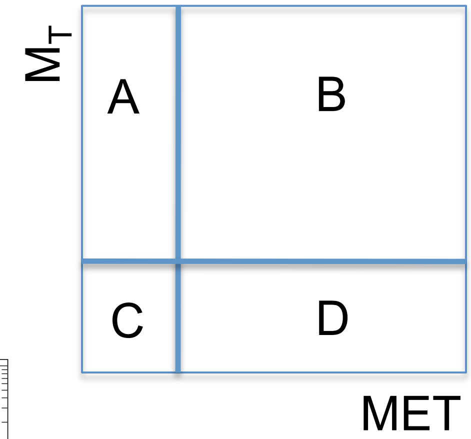


- **Z(→νν)+jets with Z(→ll)+jets:**
  - **Select Z(→ll) events with same cuts on jets as those for the SUSY analysis**
  - **Correct for difference in acceptance due to tagging leptons and the different branching ratios**
  - **Low statistics, which can be remedied by fitting MET shape**

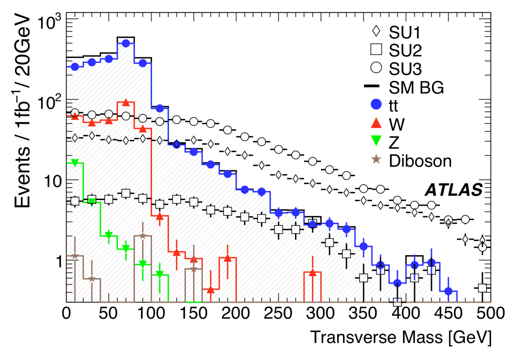


Inclusive Search with one Lepton

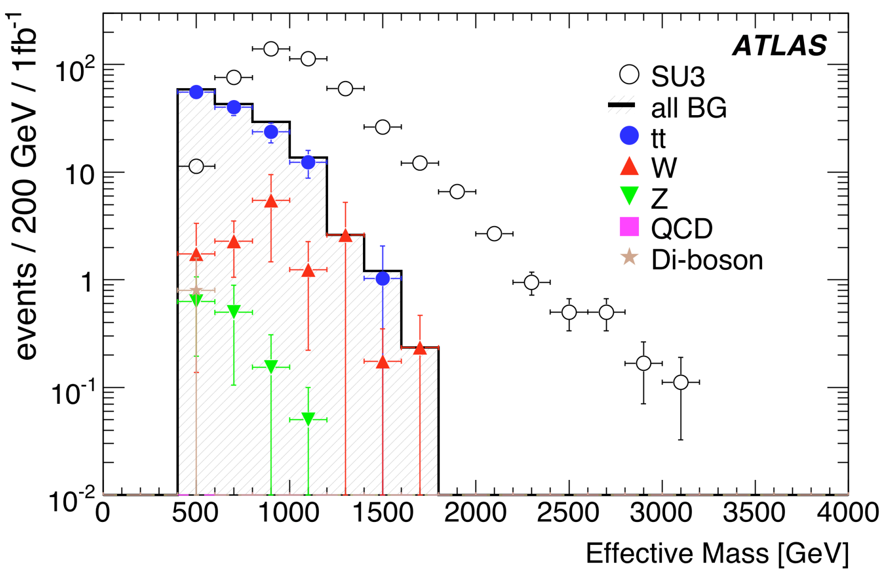
- Zero lepton signature is the least model dependent. However, backgrounds in Lepton +jets+MET may be easier to control
  - tt+jets is the dominant background, QCD negligible
  - Need to use data-driven techniques to extract backgrounds
    - Use weakly correlated variables

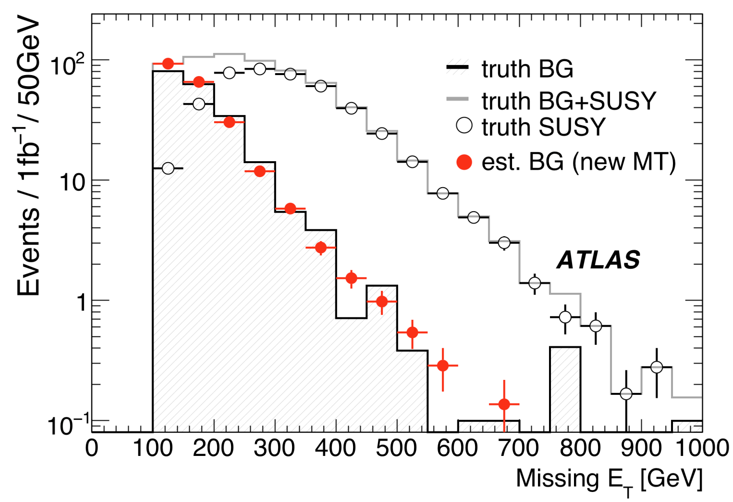


$$N(B) = N(D) \times \frac{N(A)}{N(C)}$$



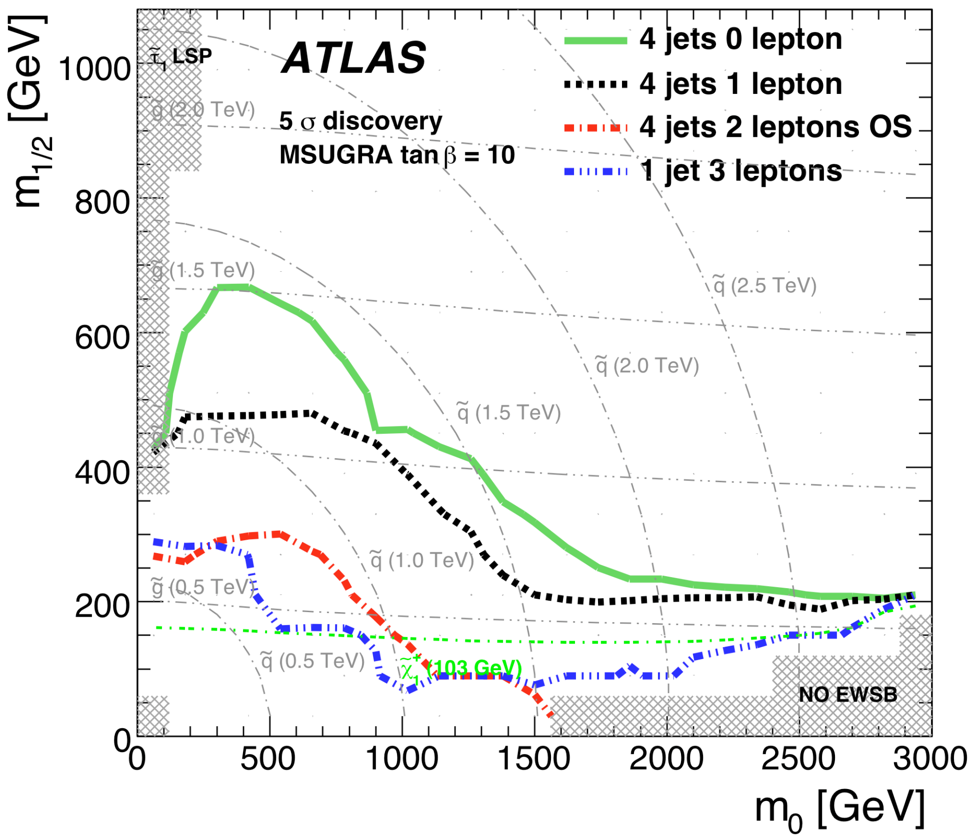
- Results below after application of same cuts at in the 0-lepton analysis

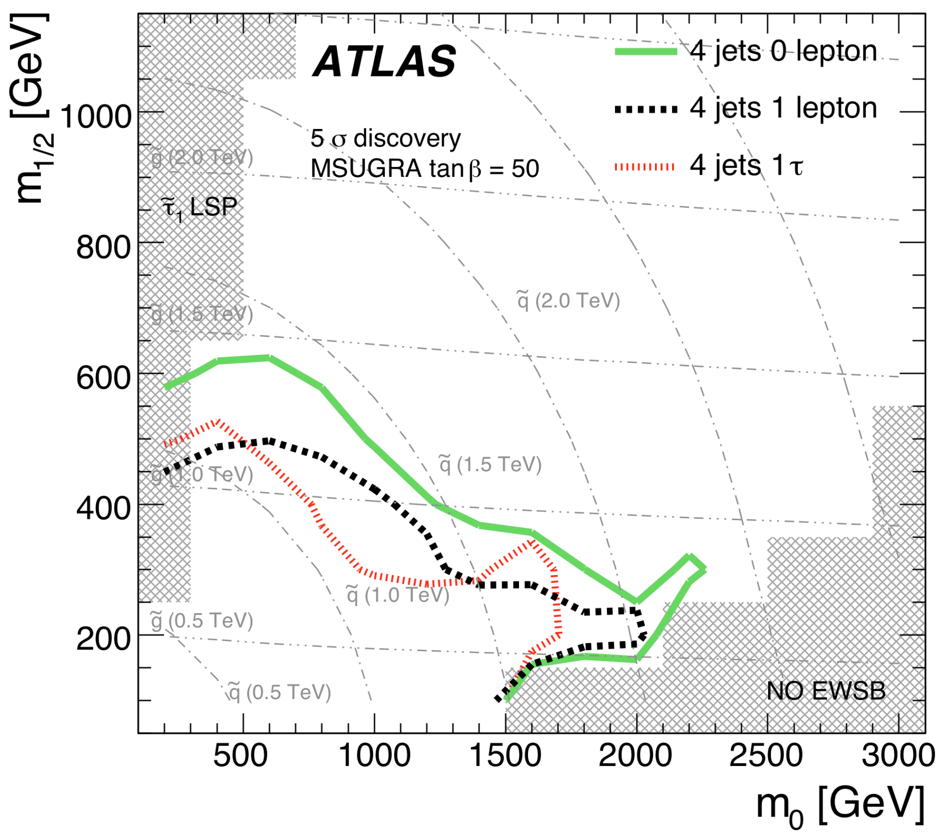




mSUGRA reach of ATLAS (1 fb^{-1})

- ATLAS reach estimates in terms of 5σ contours with 1fb^{-1} include=ing uncertainties from background extractions
  - QCD: 50%
  - tt, V+jets: 20%



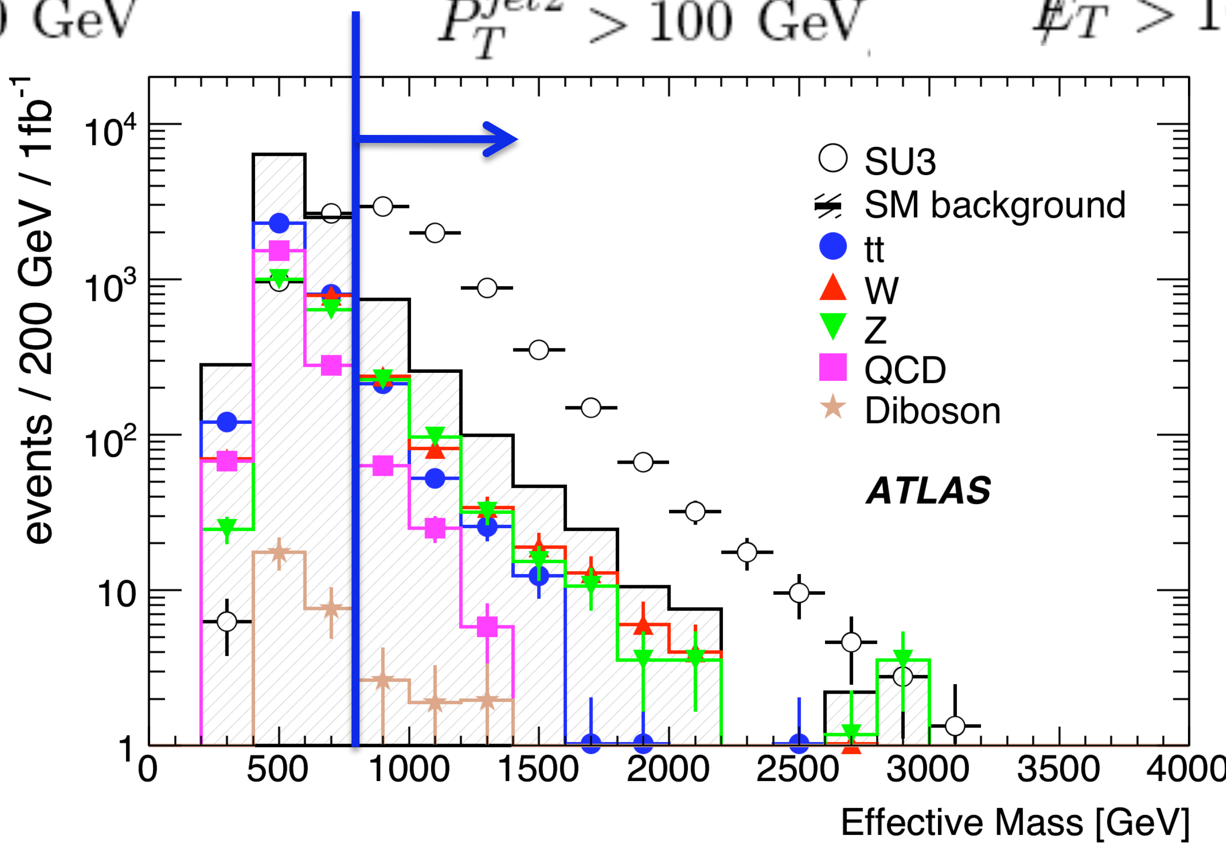


0-lepton Search: di-jet, three-jet

- Di-jet, three-jet search relatively new at ATLAS
- Use both Meff and also m_{T2} as an alternative

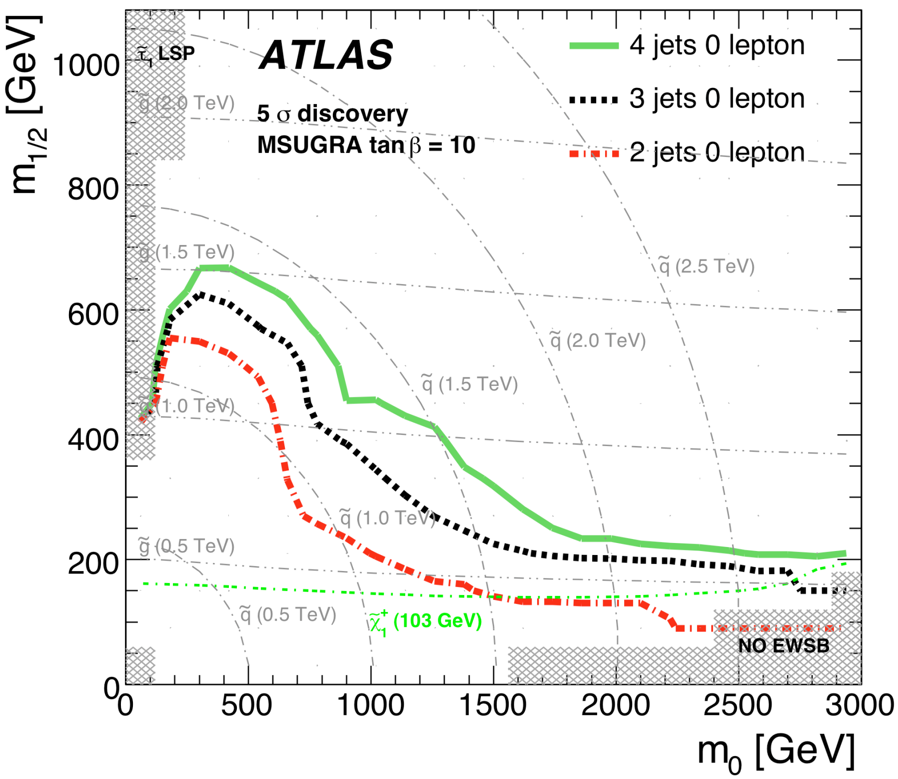
$$m_{T2}^2 \equiv \min_{\not{q}_T^{(1)}+\not{q}_T^{(2)}=\not{E}_T} \left[\max\left\{ m_T^2(\mathrm{p}_T^\alpha, \not{q}_T^{(1)}; m_\alpha, m_\chi),\ m_T^2(\mathrm{p}_T^\beta, \not{q}_T^{(2)}; m_\beta, m_\chi) \right\} \right]$$

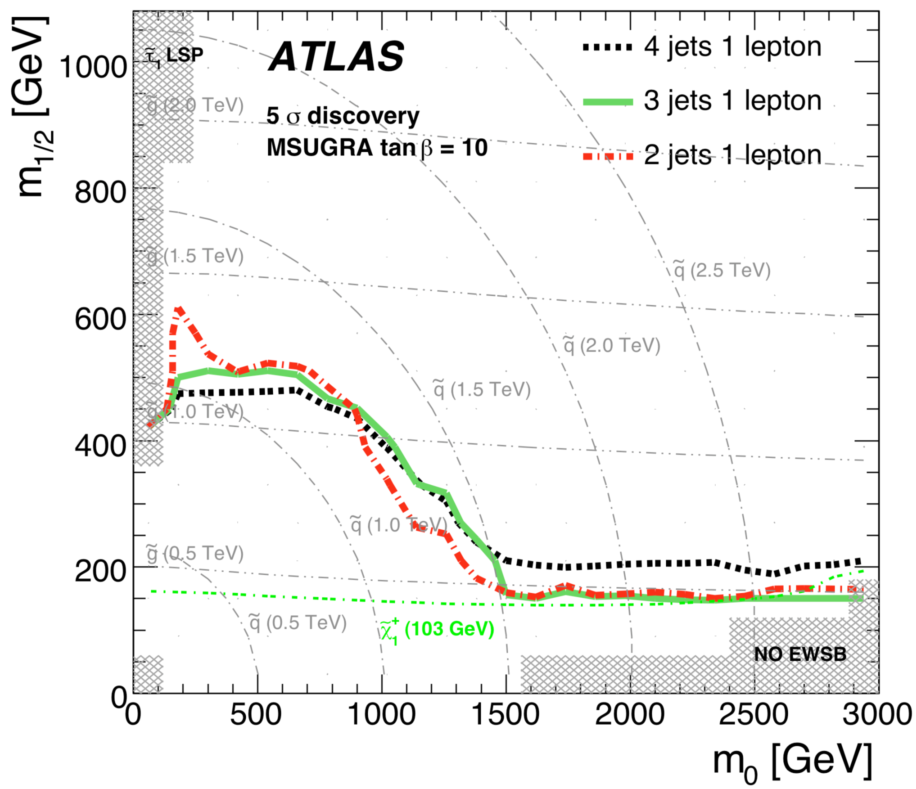
$P_T^{jet1} > 150$ GeV $\quad P_T^{jet2} > 100$ GeV $\quad \not{E}_T > 100$ GeV



mSUGRA reach of ATLAS (cont)

- ATLAS has evaluated the reach of searches with less jet multiplicities (2,3)
  - Demonstrated significant sensitivity for mSUGRA





Other Searches Beyond the Standard Model

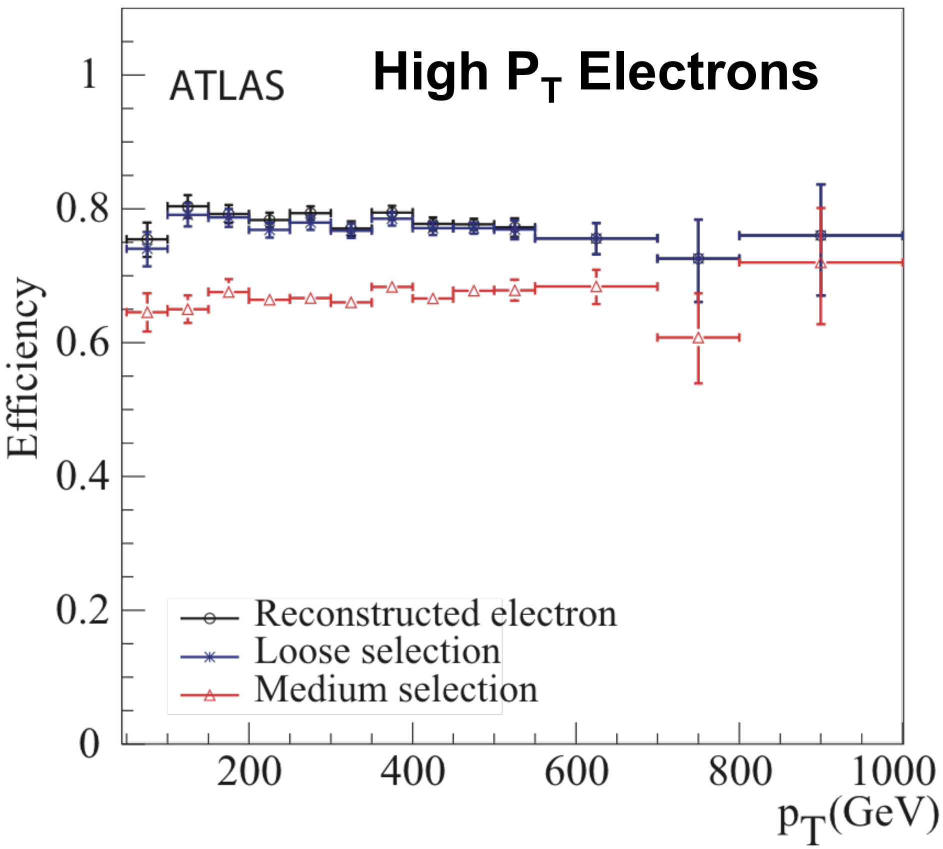
Heavy Boson Resonances

- Direct and indirect searches for Heavy Bosons, is one of the most common and generic way to address physics BSM
  - Indirect searches dominated studies in e+e- of the Z* shape, BF symmetry, etc…
  - Direct searches via l^+l^- bumps or shoulders

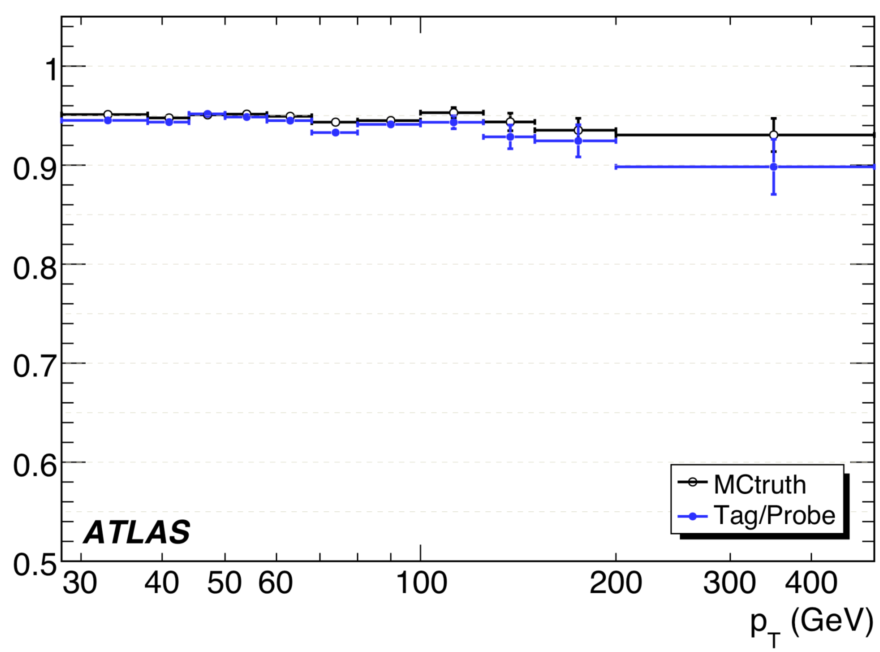
Z' Model	Indirect Searches (GeV)	Direct Searches (GeV)	
		e^+e^- Colliders	p^+p^- Colliders
Z'_χ	680	781	864
Z'_ψ	481	366	853
Z'_η	619	515	933
Z'_{LRSM}	804	518	–
Z'_{SSM}	1787	1018	966

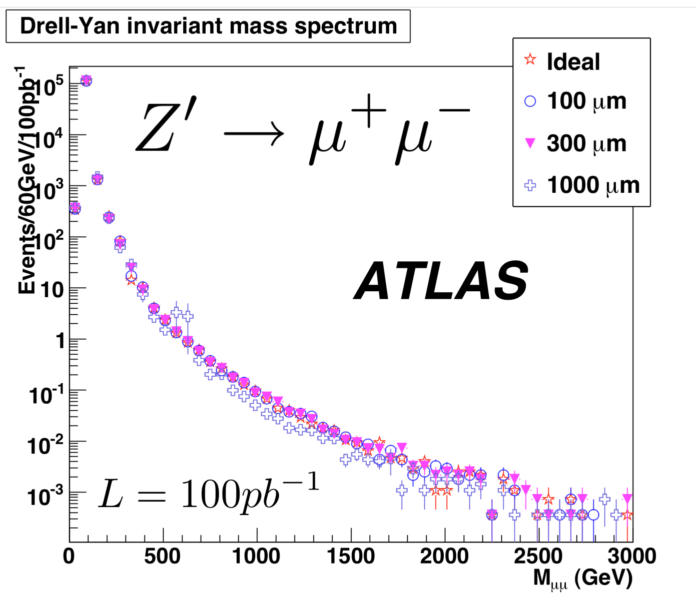
Experimental Aspects

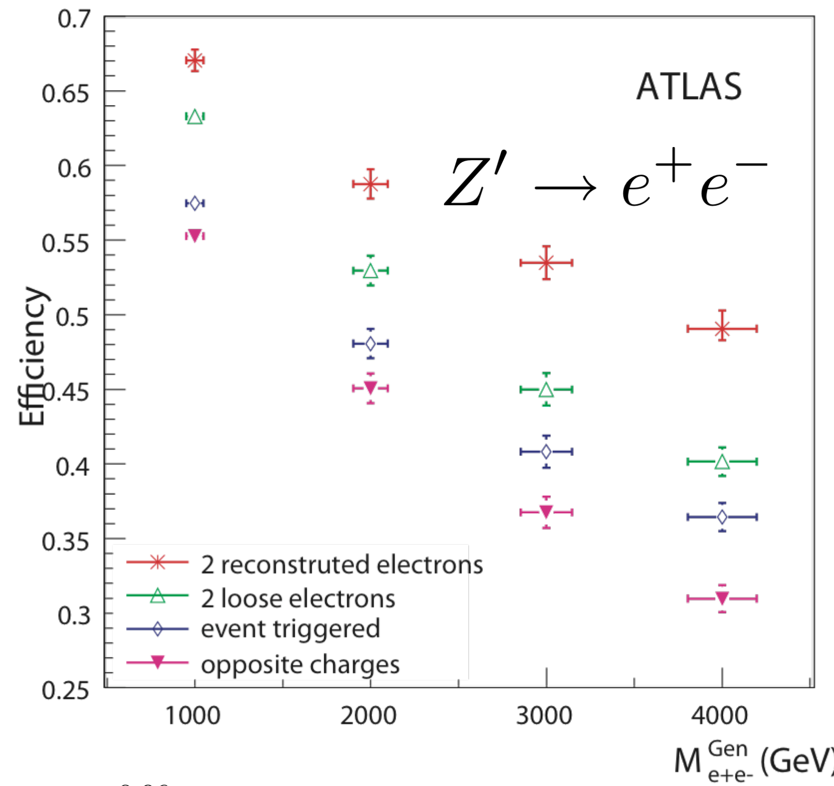
- The reconstruction and identification of high P_T leptons becomes a crucial issue
  - Lepton linearity, resolution at high P_T
  - Lepton efficiency
    - Use tag and probe method with Z events



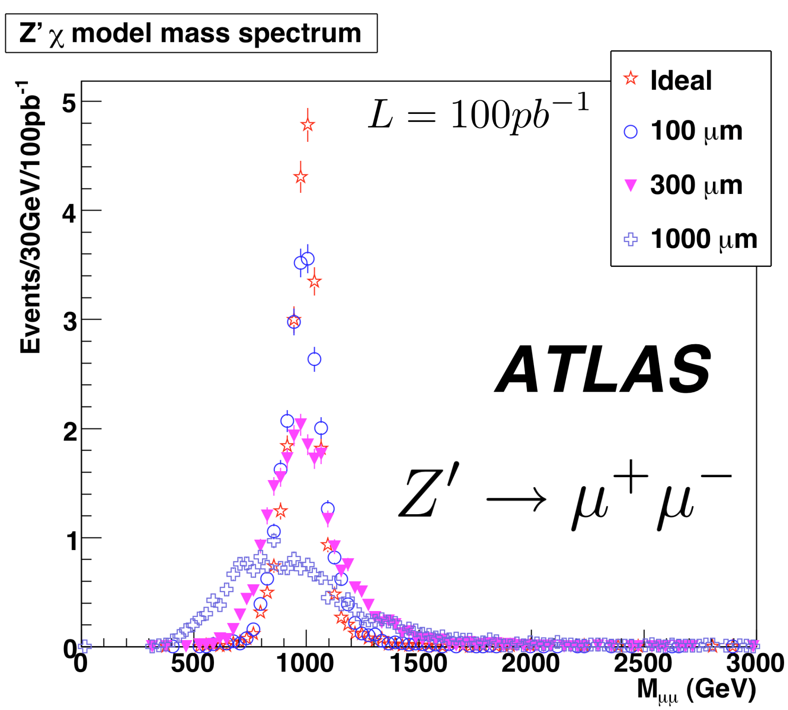
High P_T Muons

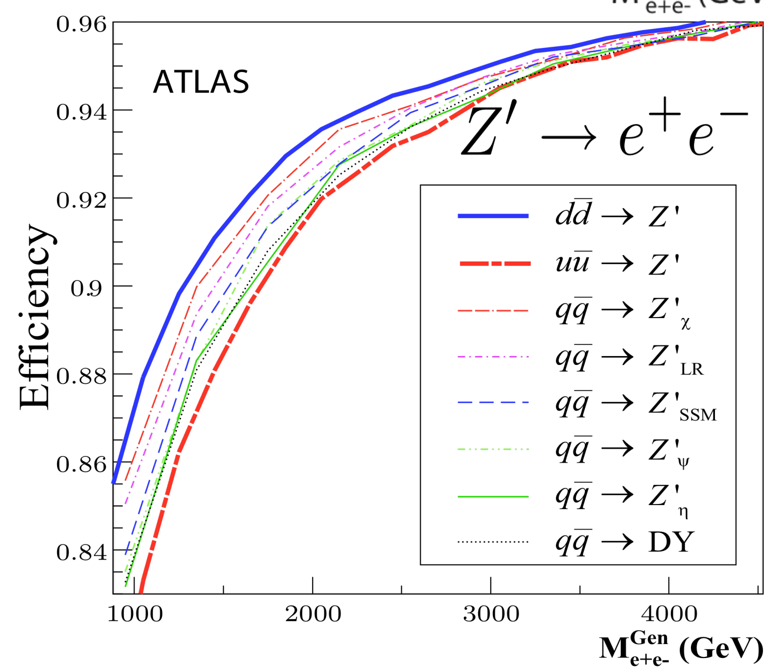






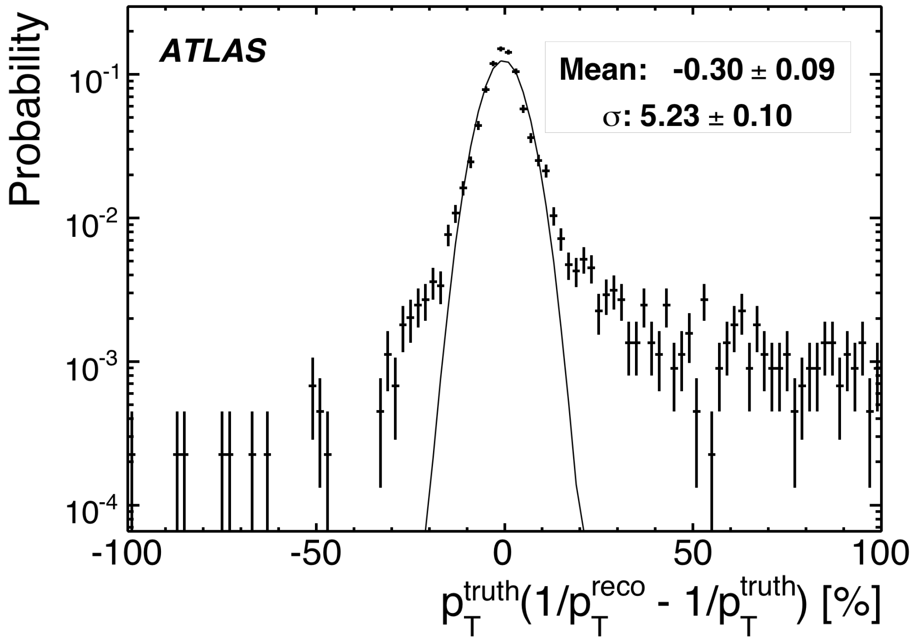
Effect of alignment of muon system

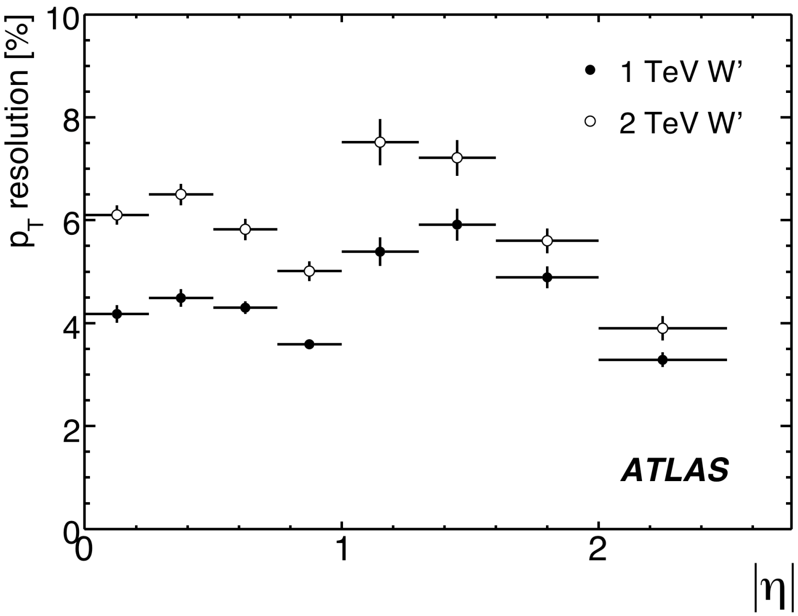




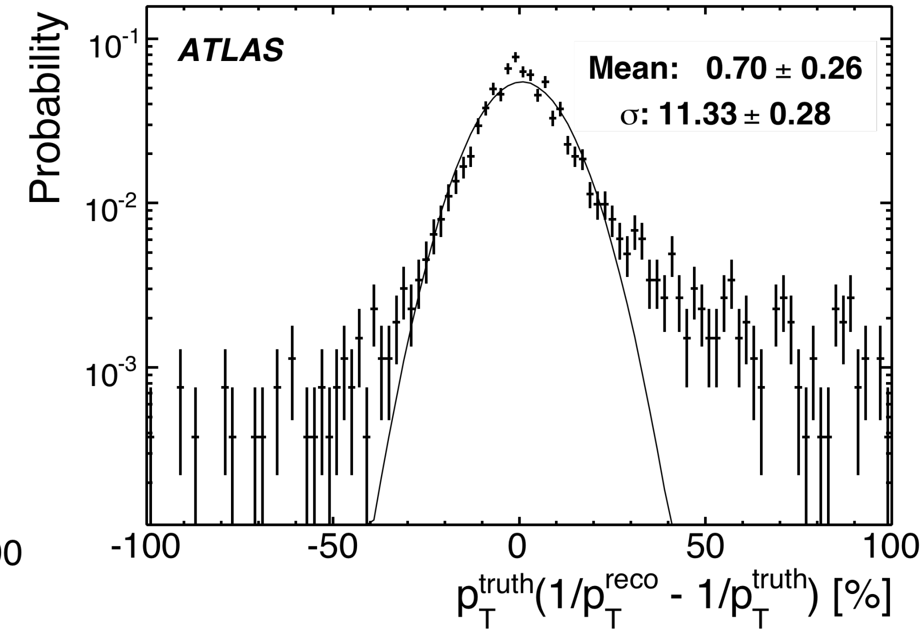
High P_T Muons with ATLAS

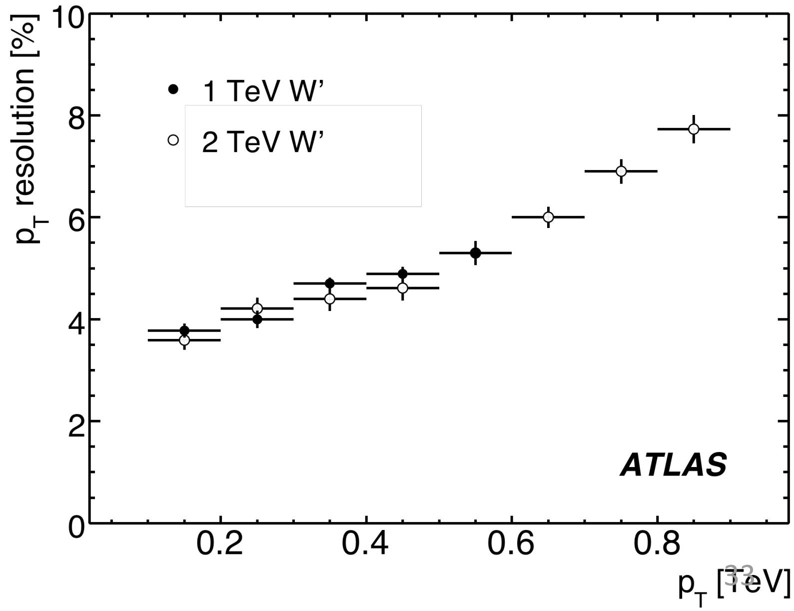
p_T < 400 GeV





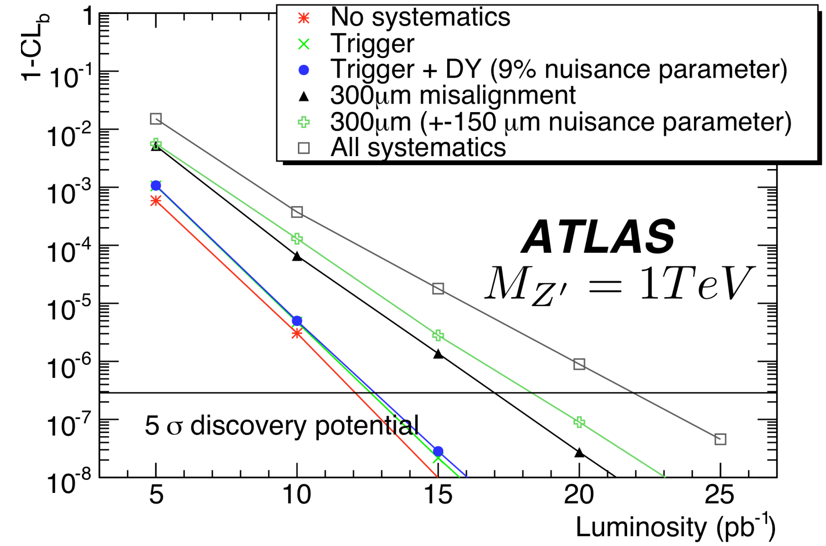
p_T > 800 GeV



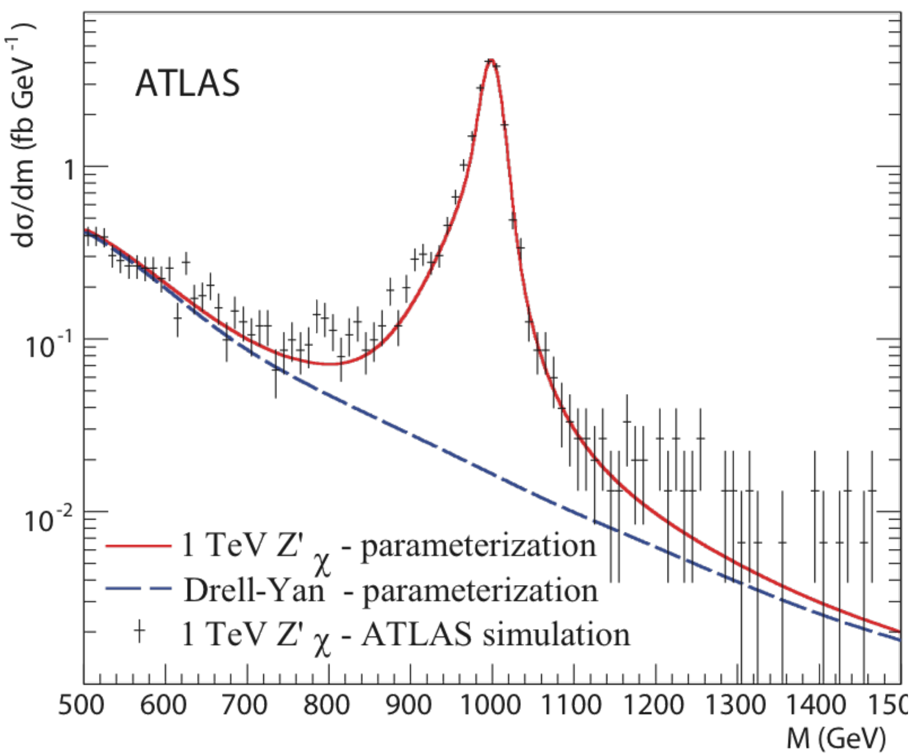


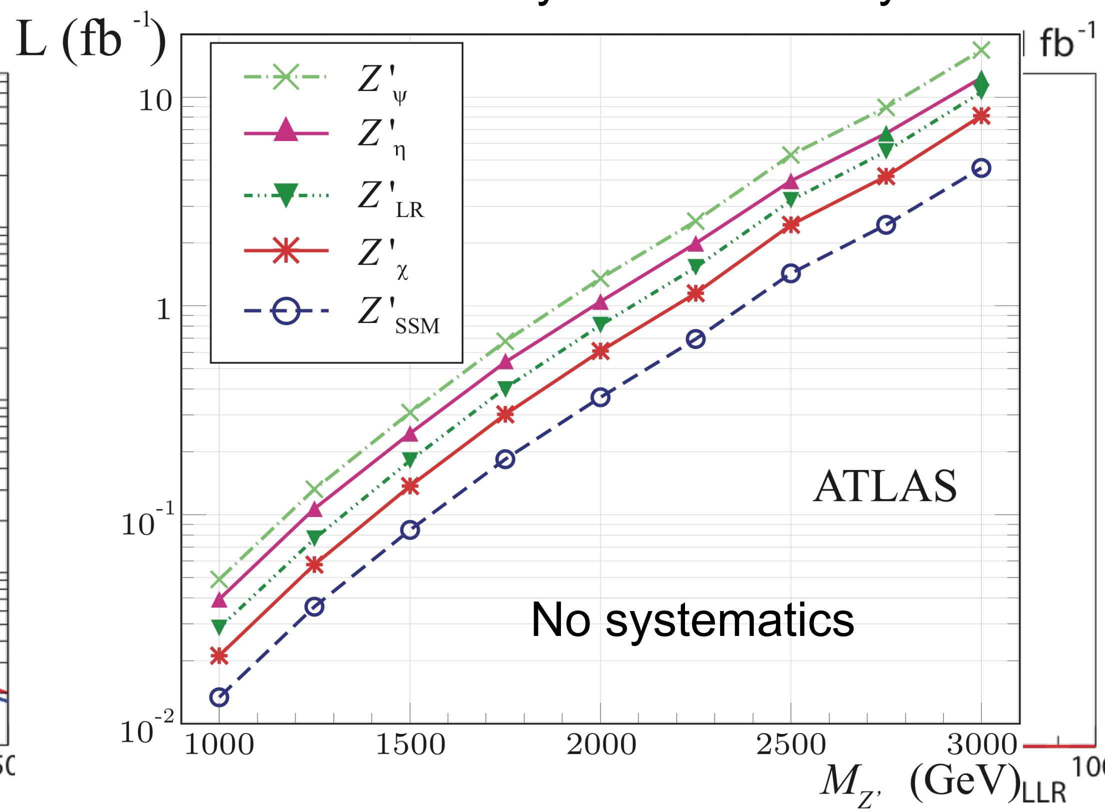
ATLAS Reach

- **Sensitivity to SSM Z' with $M_{Z'}$ =1 Tev with ~20 pb^{-1}**
  - **Consider both event counting and fit-based results**
  - **Systematics included**



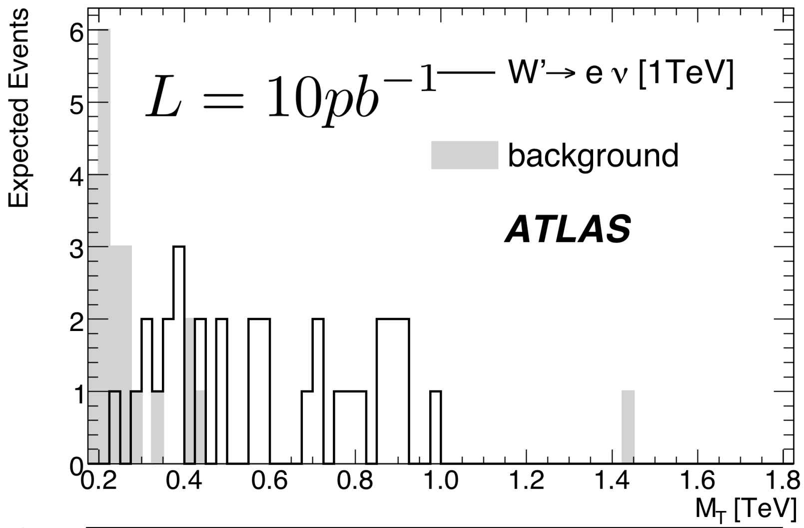
Luminosity or 5σ discovery



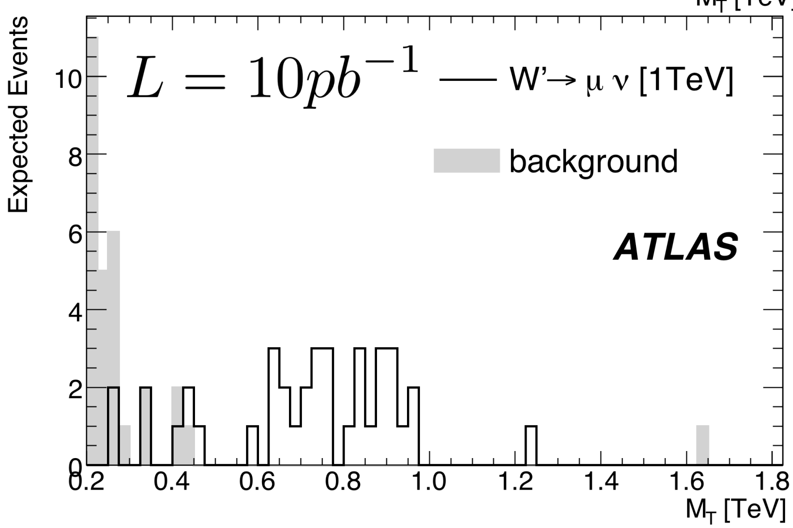


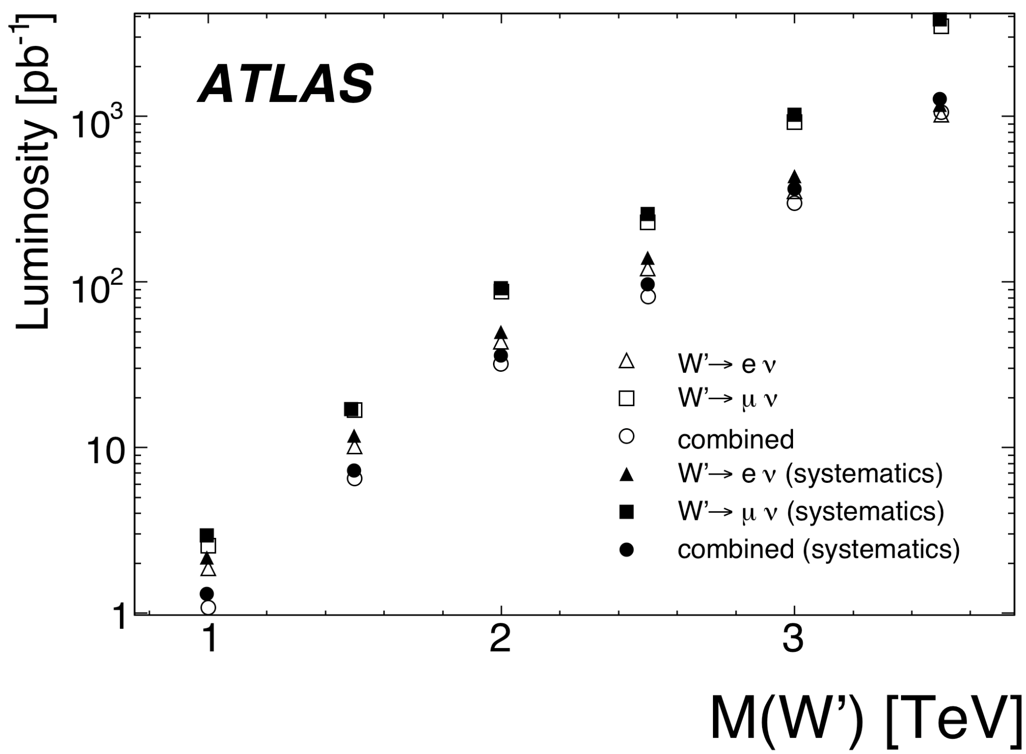
Heavy Boson W'→lν (l=e,μ)

Use the transverse mass as the main discriminator to disentangle the continuum background from the resonant backgrounds



$$M_T = \sqrt{2 p_{Tl} MET (1 - \cos(\Delta\phi_{l,MET}))}$$





Some models consider heavy resonances coupling preferentially to the third generation, i.e. Z'→ττ. Use two mass reconstruction methods.

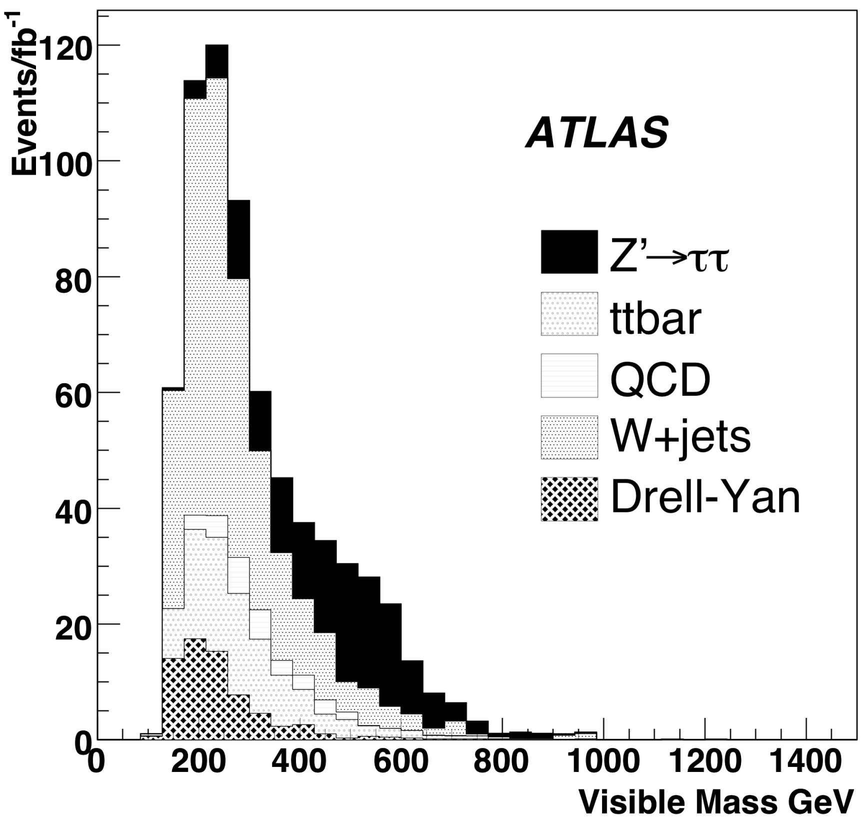
The collinear approximation is used to build up the event-by-event invariant mass. The fraction of the τ momentum carried by the visible decay daughters, x_ℓ and x_h, are calculated with the following formulas:

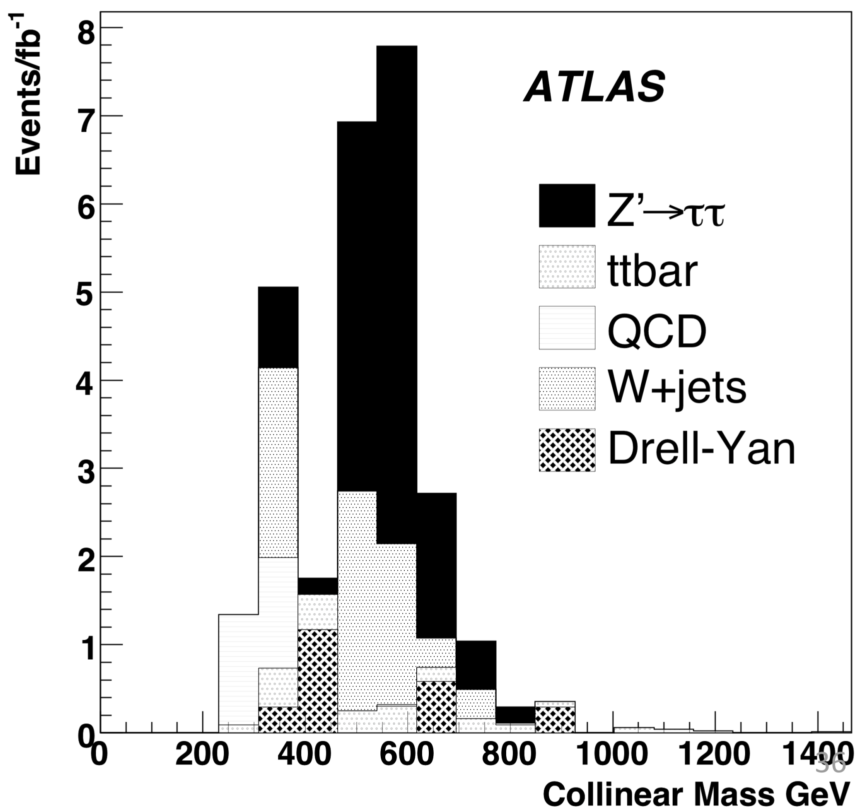
$$\not{p}_T = (\not{E}_{T_x}, \not{E}_{T_y}, 0, |\not{E}_T|)$$

$$x_\ell = \frac{p_{x,\ell}p_{y,h} - p_{x,h}p_{y,\ell}}{p_{y,h}p_{x,\ell} + p_{y,h}\not{p}_x - p_{x,h}p_{y,\ell} - p_{x,h}\not{p}_y}, \quad x_h = \frac{p_{x,\ell}p_{y,h} - p_{x,h}p_{y,\ell}}{p_{y,h}p_{x,\ell} + p_{x,\ell}\not{p}_y - p_{x,h}p_{y,\ell} - p_{y,\ell}\not{p}_x}.$$

$$m_{vis} = \sqrt{(p_\ell + p_h + \not{p}_T)^2}$$

$$m_{\tau\tau} = \frac{m_{\ell,h}}{\sqrt{x_\ell x_h}}.$$

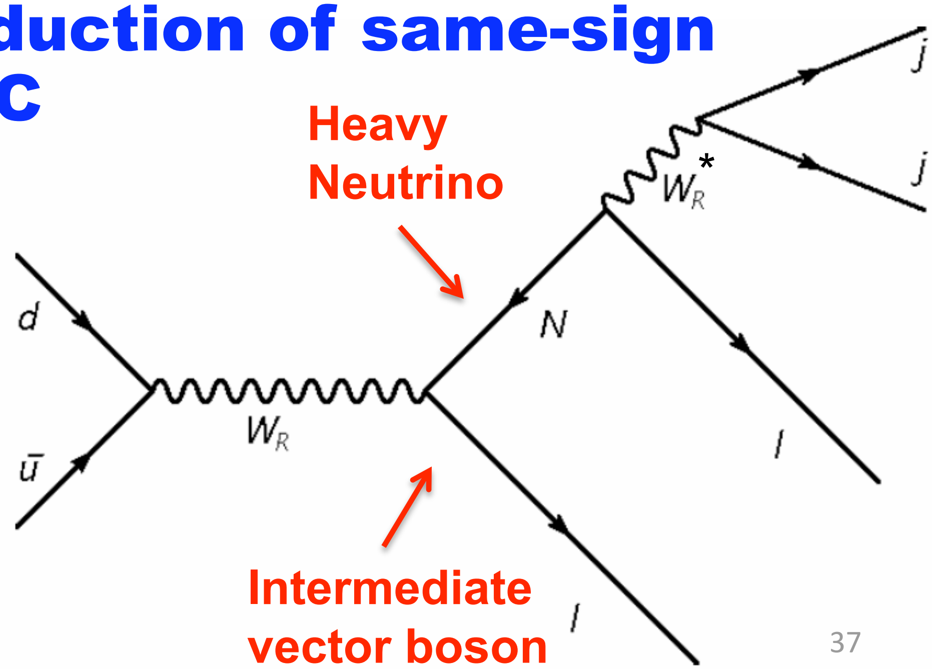




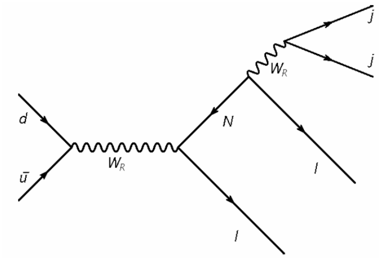
Left-Right Symmetric Models

- LRSM conserve parity at high energies by introducing three new heavy right-handed Majorana neutrinos. The masses of the left-handed neutrinos are explained by the see saw mechanism
  - The lepton number L is violated ($\Delta L=2$)
  - This leads to the production of same-sign lepton pairs a the LHC

The most generic way of producing same-sign lepton pairs within LRSM models

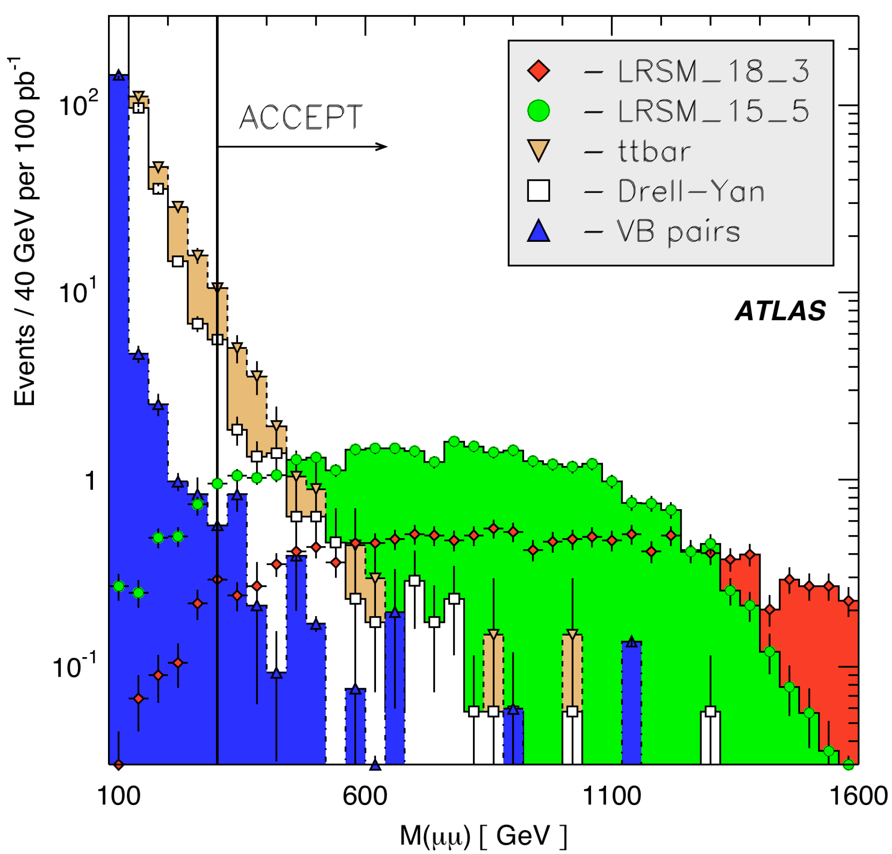


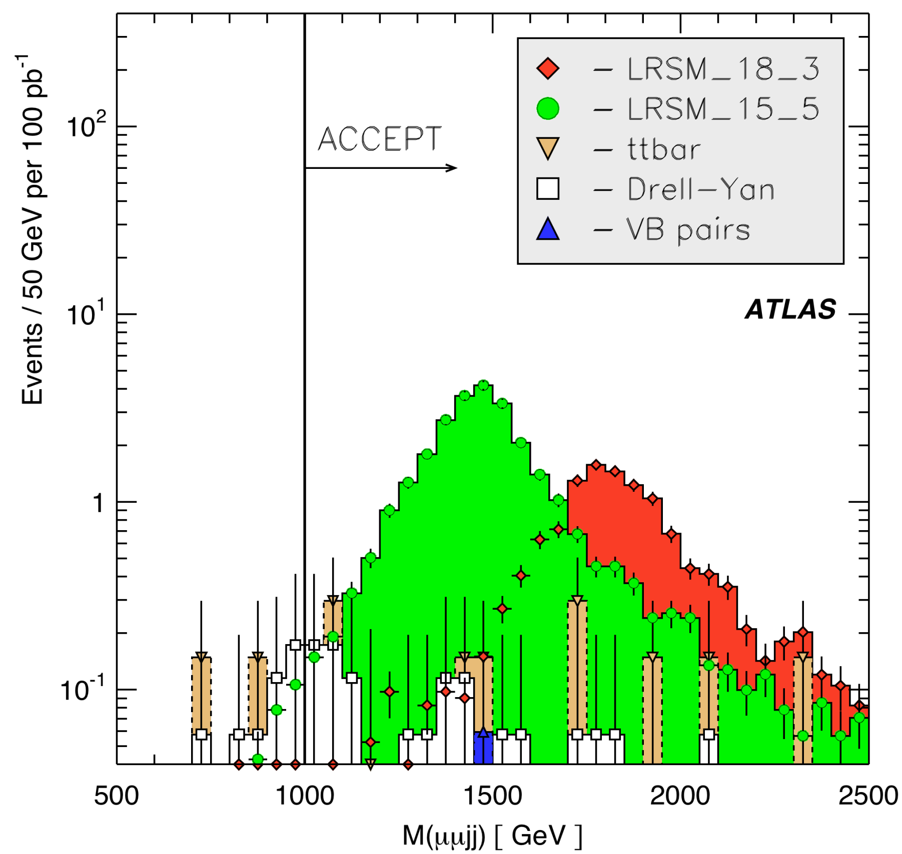
Analog to neutrino-less beta decay



Same-Sign Lepton Pairs

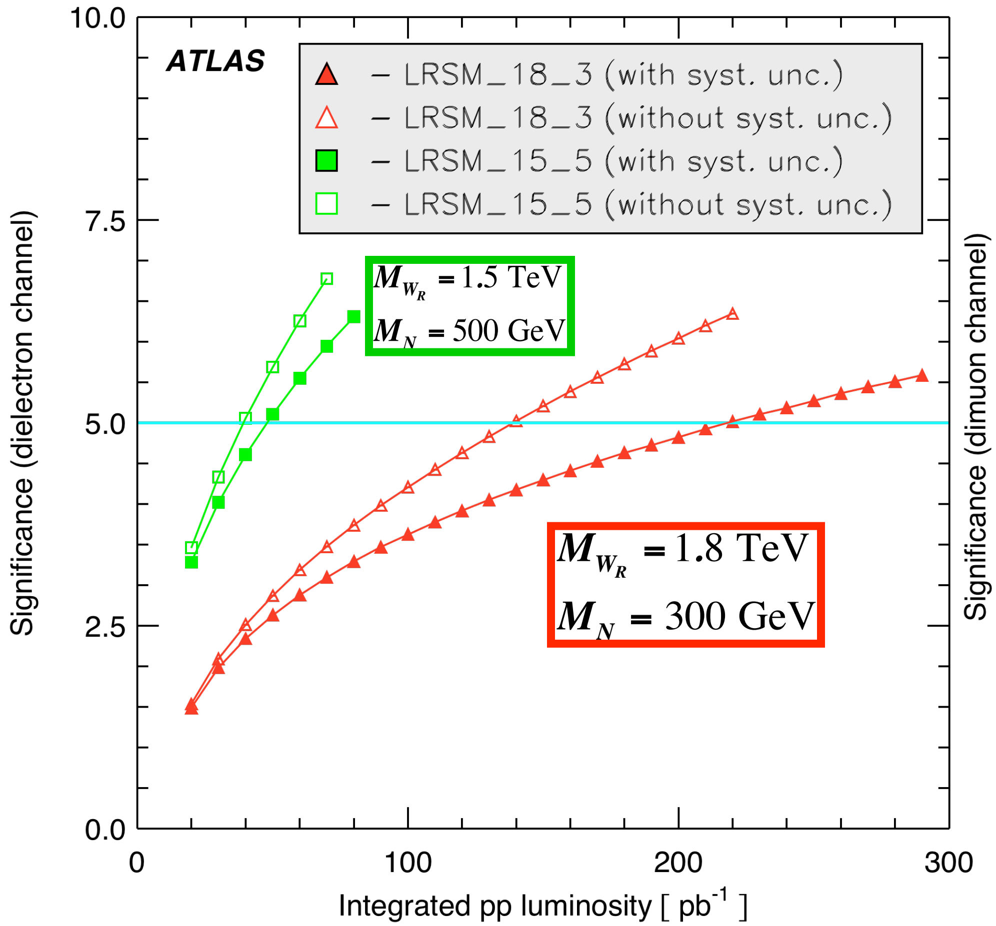
- Several cuts can provide a good signal-to-background
  - Scalar sum of P_T of leading jets and leptons, invariant mass of leptons, etc...
  - Peak structure in the invariant mass of the jets and leptons

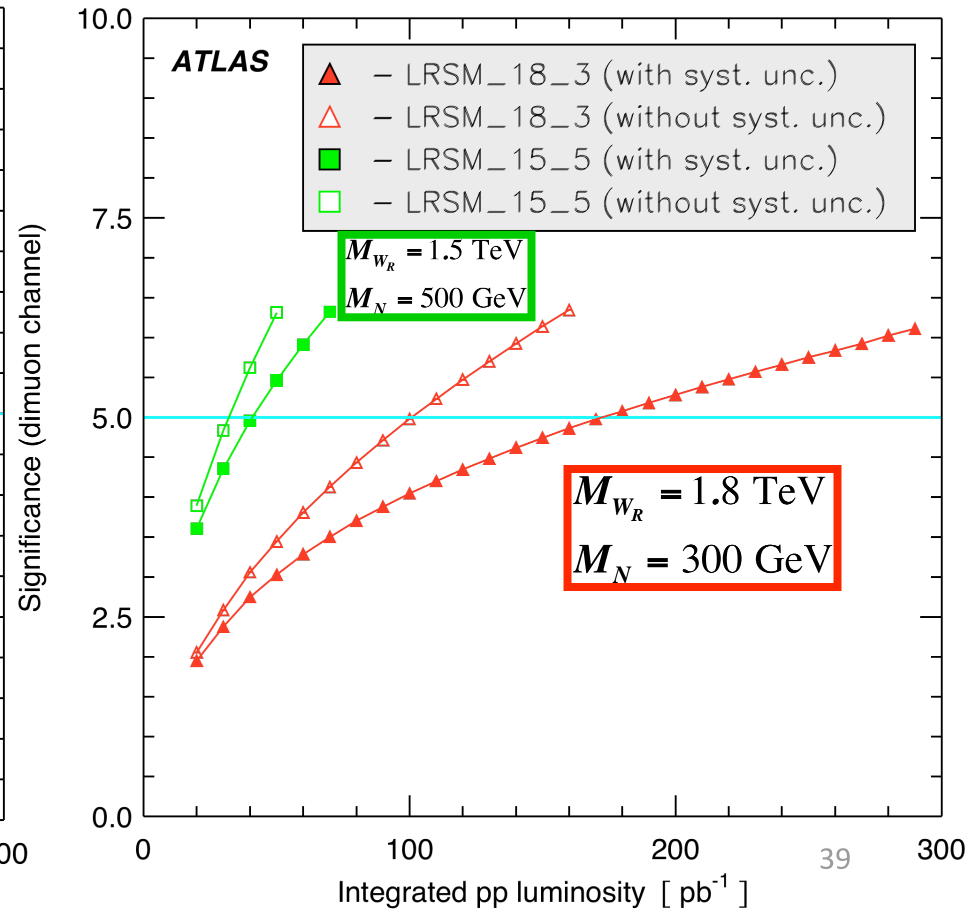




Same-Sign Lepton Pairs

Sensitivity for different assumptions of the masses of W_R and N, with and without systematic errors



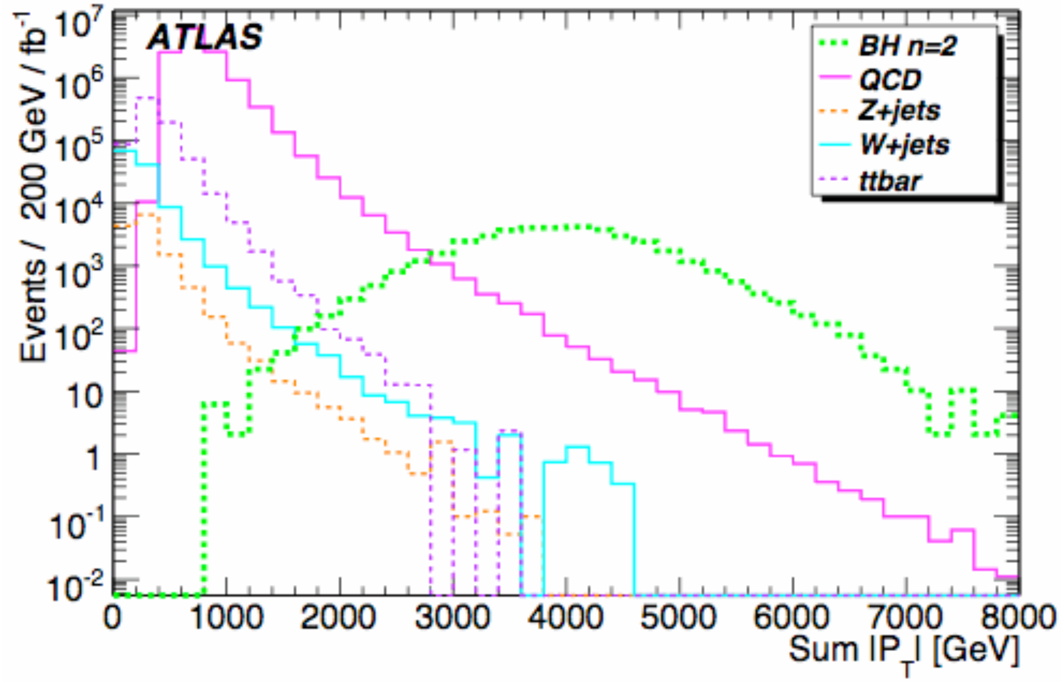


Search for Black Holes

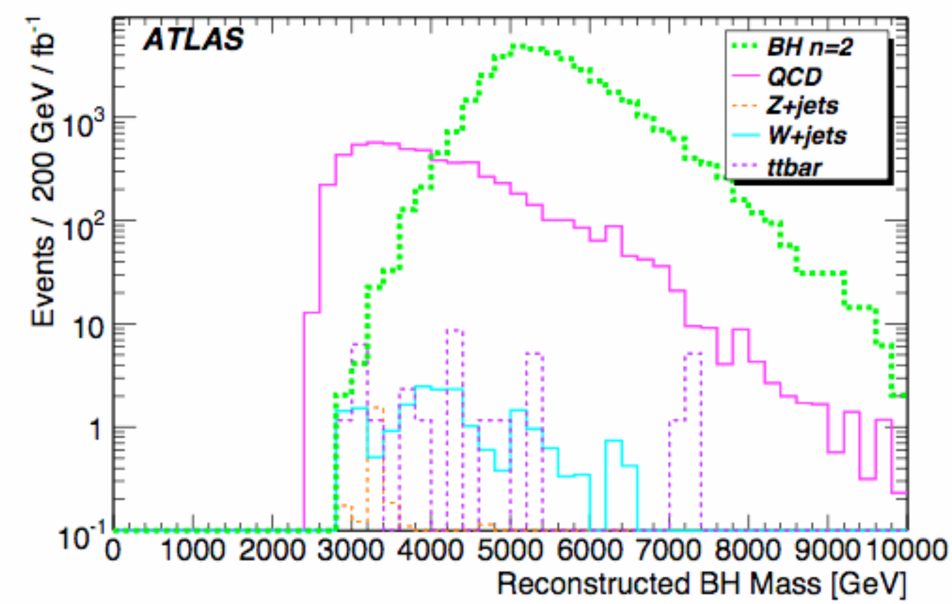
$$\text{Sum } |P_T| = \sum |\mathbf{p}_T|$$

$$p_{BH} = \sum_{i=\text{objects}} p_i + (\not{E}_T, \not{E}_{Tx}, \not{E}_{Ty}, 0) ,$$

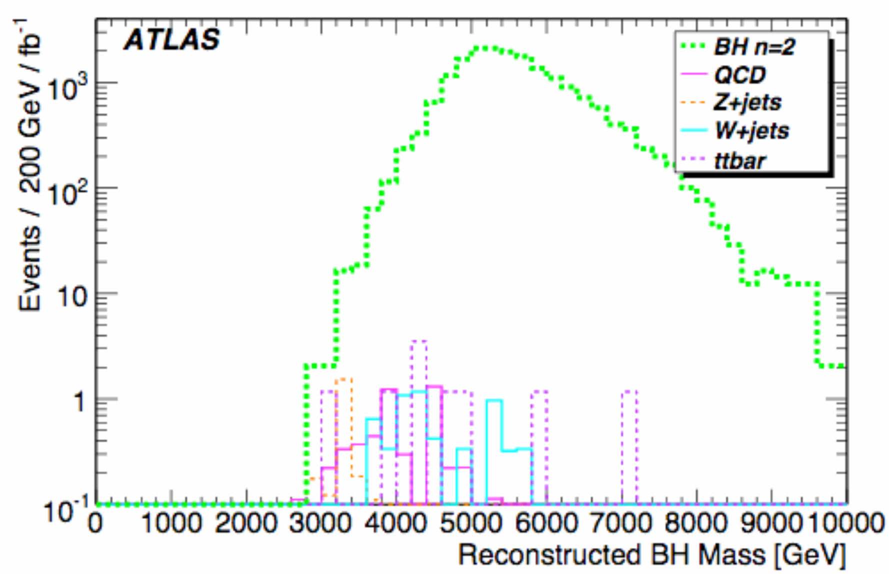
$$m_{BH} = \sqrt{p_{BH}^2} .$$



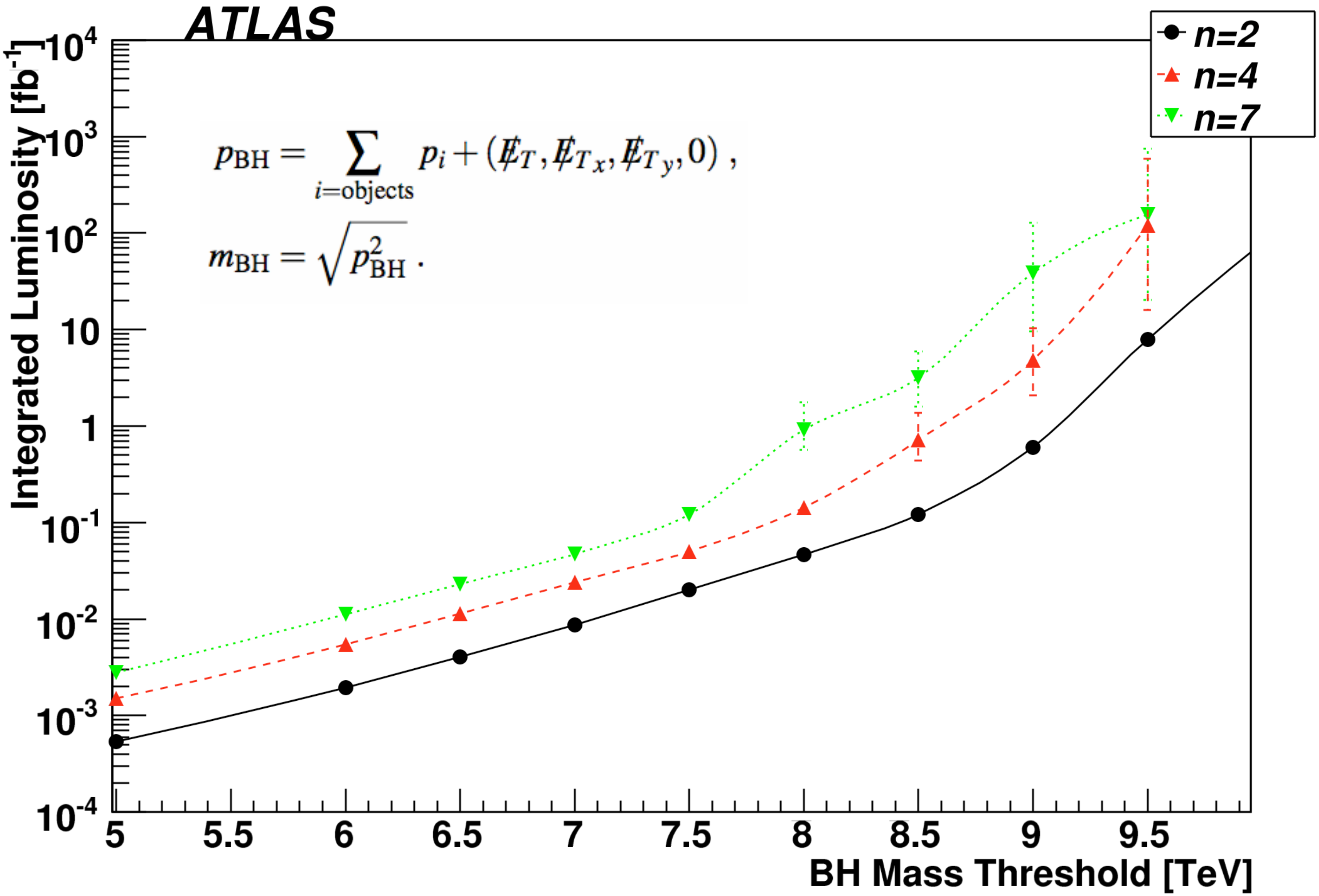
$$\sum |p_T| > 2.5 \text{ TeV}$$



$$\sum |p_T| > 2.5 \text{ TeV} \;\; \& \;\; p_T^{Lepton} > 50 \text{ GeV}$$



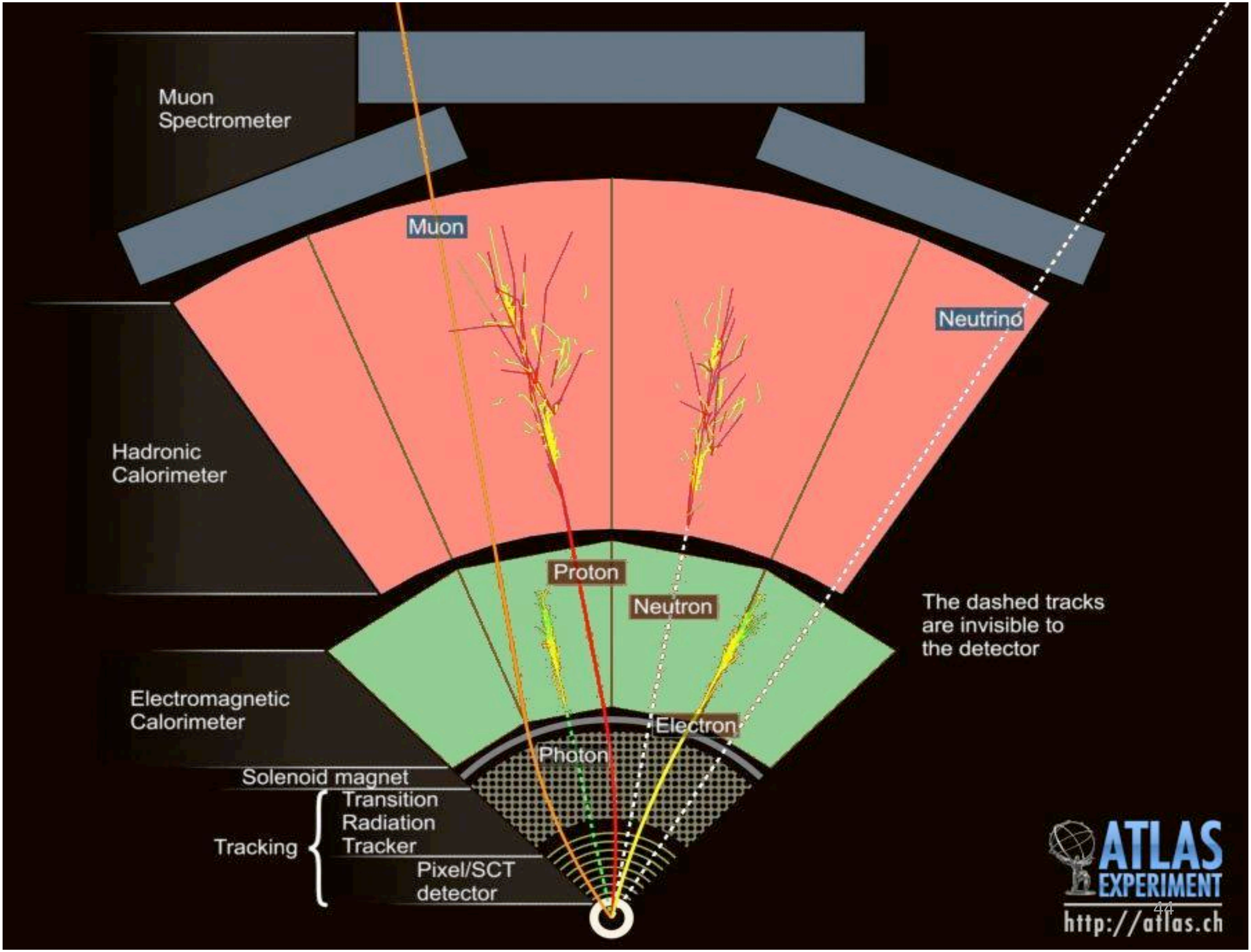
ATLAS Reach

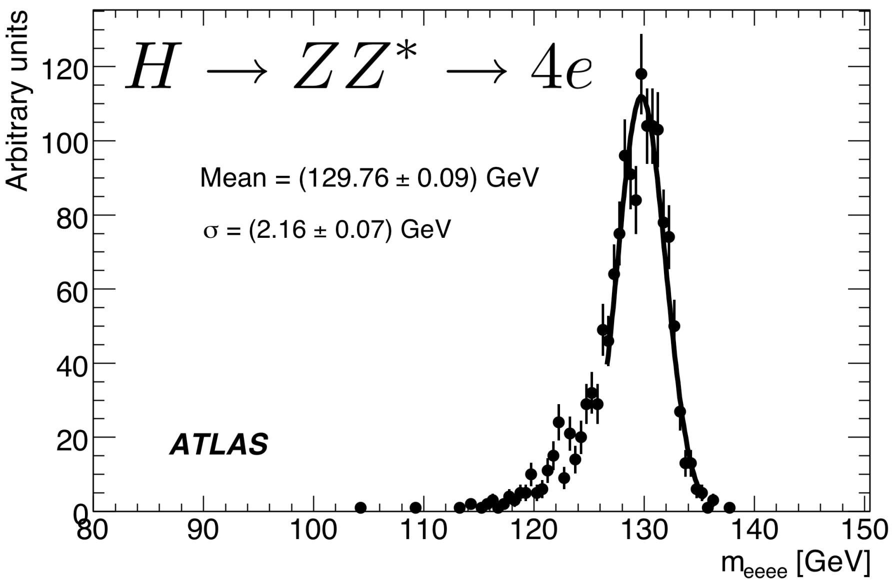

ATLAS
Integrated Luminosity [fb^{-1}]
10^{4}
10^{3}
10^{2}
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
5
5.5
6
6.5
7
7.5
8
8.5
9
9.5
BH Mass Threshold [TeV]
n=2
n=4
n=7
$p_{\mathrm{BH}} = \sum_{i=\mathrm{objects}} p_i + (\not{E}_T, \not{E}_{Tx}, \not{E}_{Ty}, 0)$,
$m_{\mathrm{BH}} = \sqrt{p_{\mathrm{BH}}^2}$.

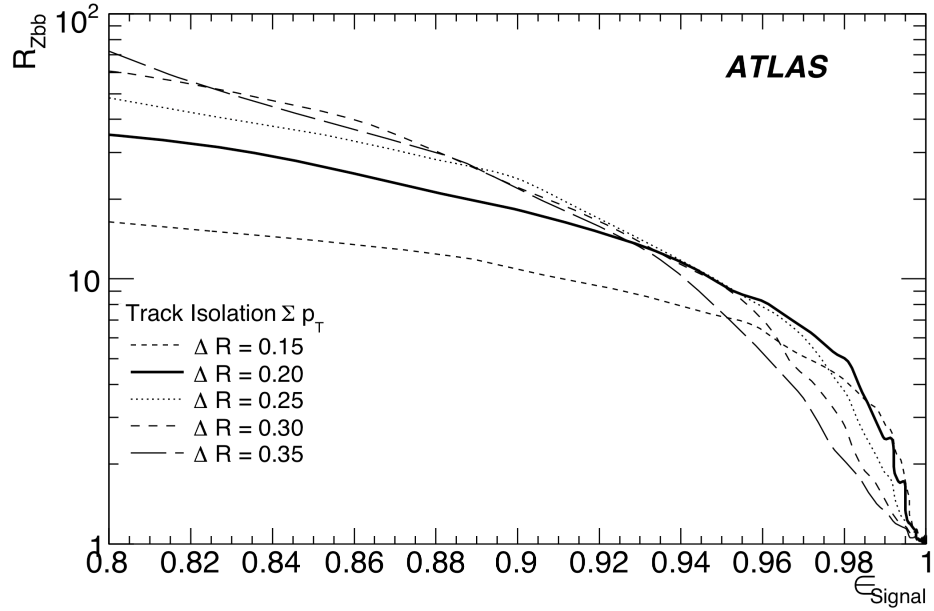
Outlook and Conclusions

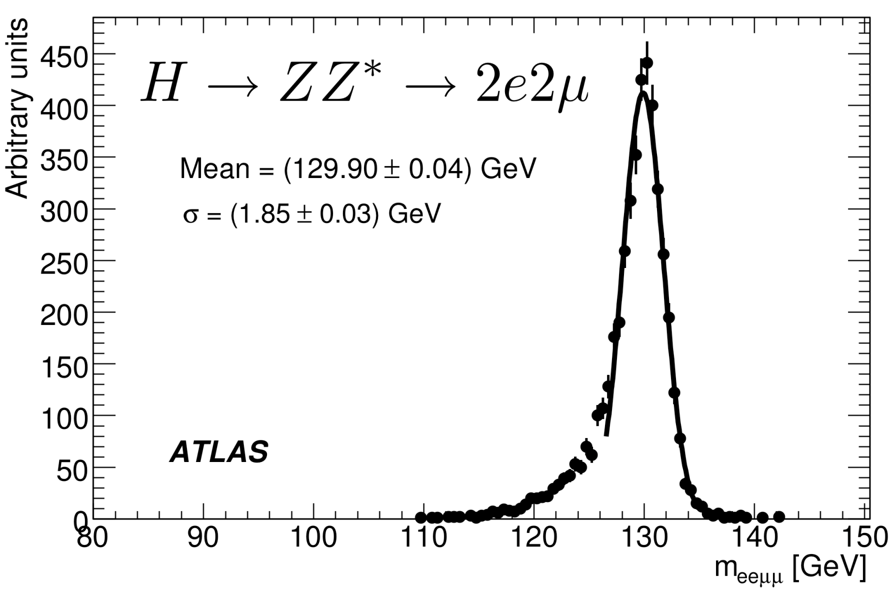
- The physics potential of the LHC is breath taking
- The first priority of the ATLAS collaboration with the first data is to establish the Standard Model candles. As we gain confidence rich windows of opportunity will open:
  - First searches for the SM Higgs boson with ZZ,WW decays
    - May exclude SM Higgs with 10 TeV and 200 pb^{-1} for M_H~160 GeV
  - Inclusive SUSY searches gives sensitivity to $M(\tilde{g},\tilde{s})$~1-1.5 TeV with less than 1fb^{-1} of data
    - Complex signatures that will require a good understanding of the detector performance and SM backgrounds
    - ATLAS has defined control samples and data-driven methods for the extraction of SM backgrounds and different signatures
  - Searches for other physics beyond the SM yield strong potential with 1pb^{-1}-1fb^{-1} of data
    - Searches for heavy boson, Majorana neutrinos, Leptoquarks, Black Holes, et...
- Will produce anti-matter, but the Vatican will be safe!

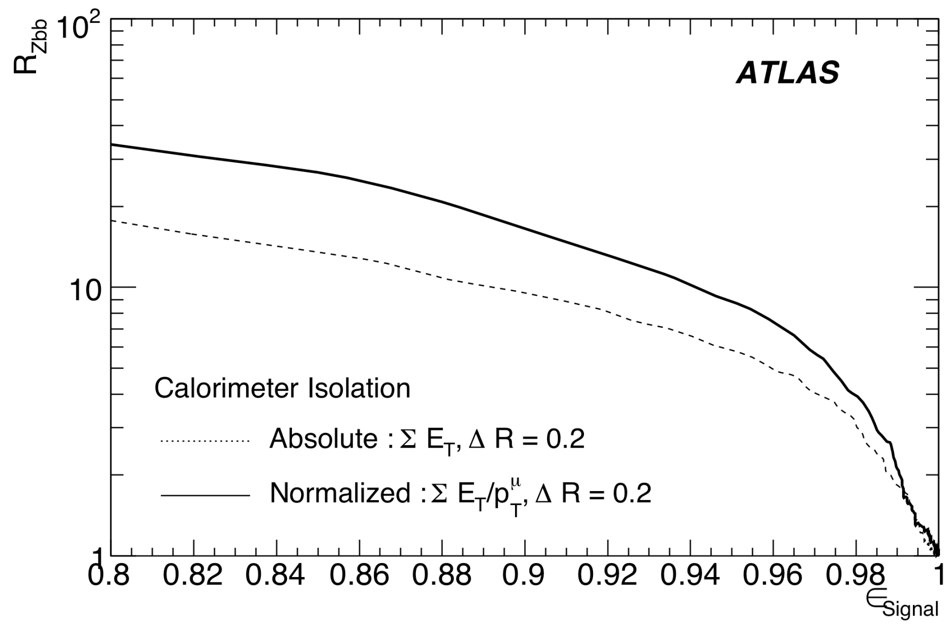
Extra Slides


Muon
Spectrometer
Muon
Hadronic
Calorimeter
Neutrino
Proton
Neutron
The dashed tracks
are invisible to
the detector
Electromagnetic
Calorimeter
Electron
Photon
Solenoid magnet
Transition
Radiation
Tracker
Tracking
Pixel/SCT
detector
ATLAS
EXPERIMENT
http://atlas.ch

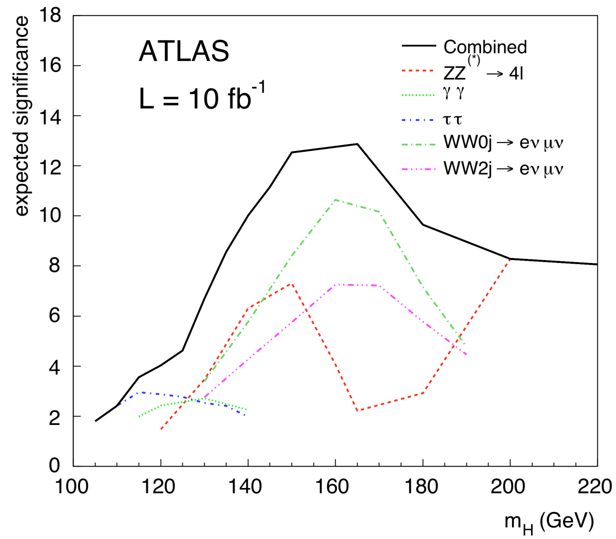

$H \rightarrow ZZ^* \rightarrow 4e$
Mean = (129.76 ± 0.09) GeV
σ = (2.16 ± 0.07) GeV
ATLAS
Arbitrary units
m_eeee [GeV]

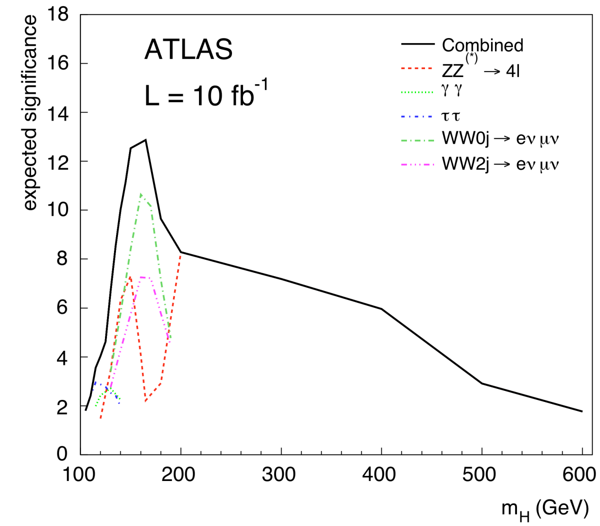

ATLAS
R_Zbb
Track Isolation Σ p_T
Δ R = 0.15
Δ R = 0.20
Δ R = 0.25
Δ R = 0.30
Δ R = 0.35
ε_Signal

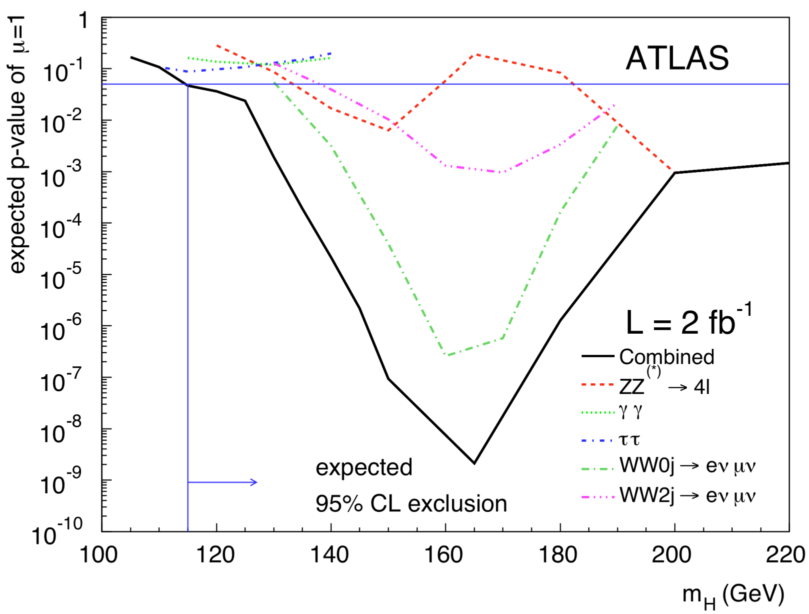

$H \rightarrow ZZ^* \rightarrow 2e2\mu$
Mean = (129.90 ± 0.04) GeV
σ = (1.85 ± 0.03) GeV
ATLAS
Arbitrary units
m_eeμμ [GeV]

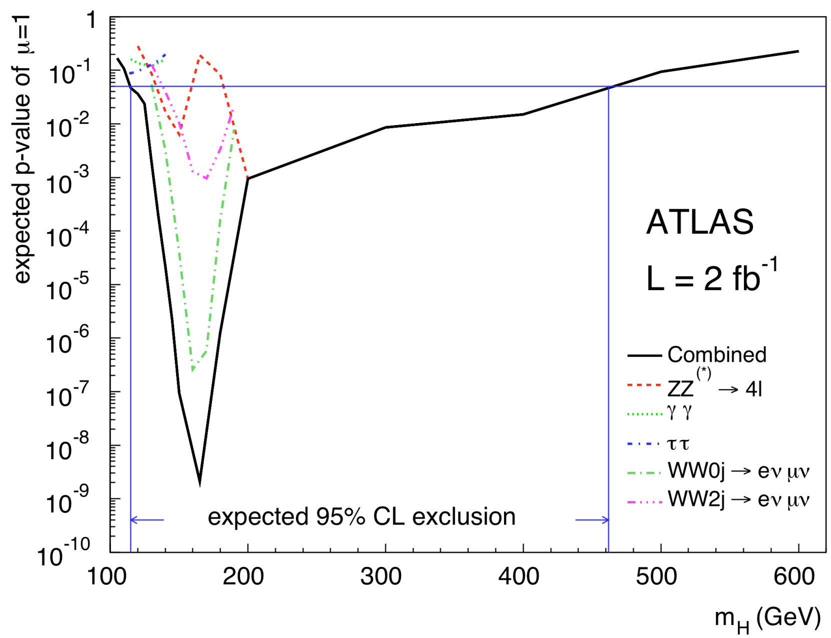

ATLAS
R_Zbb
Calorimeter Isolation
Absolute : Σ E_T, Δ R = 0.2
Normalized : Σ E_T/p_T^μ, Δ R = 0.2
ε_Signal

ATLAS Sensitivity to SM Higgs









Are We happy with the SM?

- The SM as it is does not solve a number of fundamental questions/problems
  - Quadratic divergences of the Higgs mass
    - Higgs mass grows with scale of new physics
  - Does not explain the origin of the neutrino mass
  - Does not explain dark matter in the universe
  - Does not explain dark origin in the universe
    - The universe expanding at an accelerated rate
  - How about gravity?
  - Unification of fundamental interactions
    - This is probably more of a philosophical issue
  - Why three generations?
  - Etc…

MSUGRA - Parameters

The MSSM has 105 masses, phases and mixing angles.
This is a reflection of us not knowing how SUSY is broken – we just put in the most general set of masses and soft SUSY breaking terms into the Lagrangian. This makes things rather hard for experimental (pre-data) analysis, so normally one assumes some well motivated model of SUSY breaking.

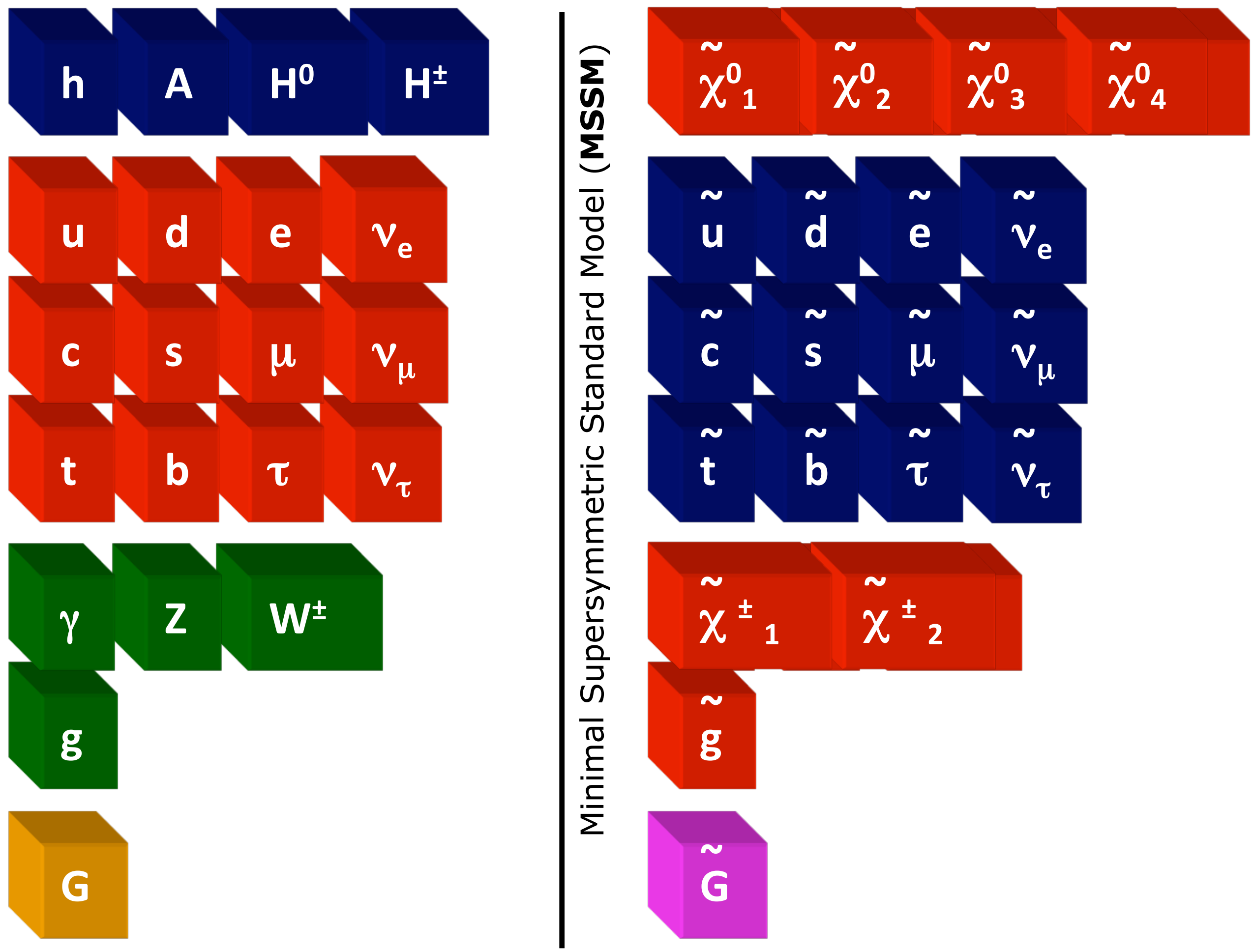
A popular choice is mSUGRA, which is useful for analysis

- m_0 : universal scalar mass at GUT scale
- $m_{1/2}$: universal gaugino mass at GUT scale
- $\tan\beta$: ratio of Higgs vacuum expectation value
- sgn μ: sign of Higgsino mass parameter
- A_0 : universal s-fermion mass mixing parameter
- M(SUSY) < 1 TeV for LSP
- Take account of limits from LEP and TEVATRON

MSUGRA Particles

- SUSY gives rise to partners of SM states with opposite spin-statistics but otherwise same Quantum Numbers.

- Expect SUSY partners to have same masses as SM states
  - Not observed!
  - SUSY must be a broken symmetry at low energy
- Higgs sector also expanded
- Colour-code
  - Spin-0
  - Spin-1/2
  - Spin-1
  - Spin-2
  - Spin-3/2



Note: all scalar particles with same *e*-charge, *R*-parity and colour quantum number can mix !

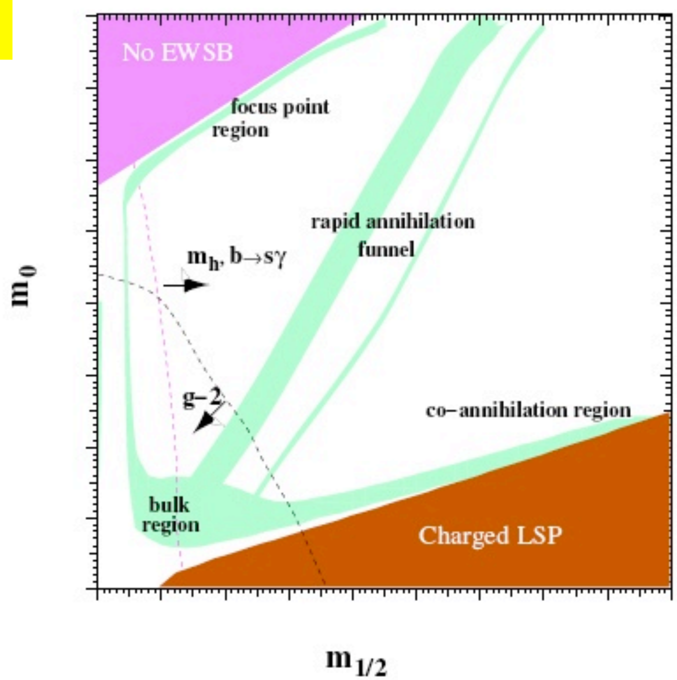
ATLAS mSUGRA Benchmarks

G.Polesello

Large annihilation sross-section required by WMAP data

Boost annihilation via quasi-degeneracy of a sparticle with $\tilde{\chi}_1^0$, or large higgsino content of $\tilde{\chi}_1^0$

Regions in mSUGRA $(m_{1/2}, m_0)$ plane with acceptable $\tilde{\chi}_1^0$ relic density (e.g. Ellis et al.):



- SU3: Bulk region. Annihilation dominated by slepton exchange, easy LHC signatures fom $\tilde{\chi}_2^0 \to \tilde{\ell}\ell$
- SU1: Coannihilation region. Small $m(\tilde{\chi}_1^0) - m(\tilde{\tau})$ (1-10 Gev). Dominant processes $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to \tau\tau$, $\tilde{\chi}_1^0\tilde{\tau} \to \tau\gamma$ Similar to bulk, but softer leptons!
- SU6: Funnel region. $m(\tilde{\chi}_1^0) \simeq m(H/A)/2$ at high $\tan\beta$ Annihilation through resonant heavy Higgs exchange. Heavy higgs at the LHC observable up to ∼800 GeV
- SU2: Focus Point high m_0, large higgsino content, annihilation through coupling to W/Z Sfermions outside LHC reach, study gluino decays.
- SU4: Light point. Not inspired by cosmology. Mass scale ~ 400 GeV, at limit of Tevatron reach

Generic SUSY Signatures

(A) Light sneutrinos/sleptons

$\tilde{q}_L \to \tilde{\chi}_1^+ / \tilde{\chi}_2^0 \to \tilde{\nu}+l / \tilde{l}+l$

>>Lepton enriched

(B) Direct decay

$\tilde{q}_R \to \tilde{\chi}_1^0+q$

>> Lepton depleted

(C) Light Stop/Sbottom

$\tilde{g} \to \tilde{t}+t \to \tilde{\chi}_2^+ + b \to \tilde{\chi}_2^0 + W / \tilde{\chi}_1^+ + Z$

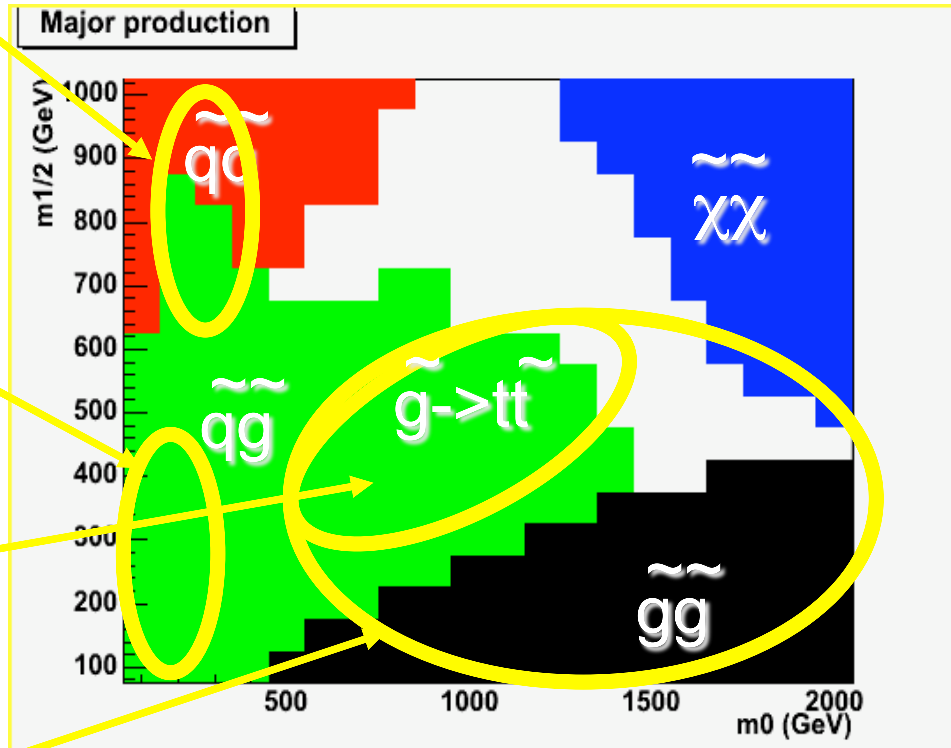
>> Lepton/b-jet enriched

(D) gluino production/decay

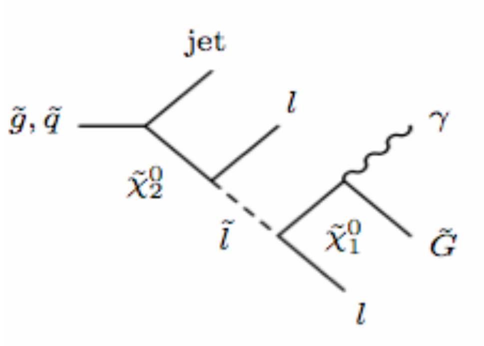
$\tilde{g} \to \tilde{\chi}_n^+ / \tilde{\chi}_n^0 + qq$

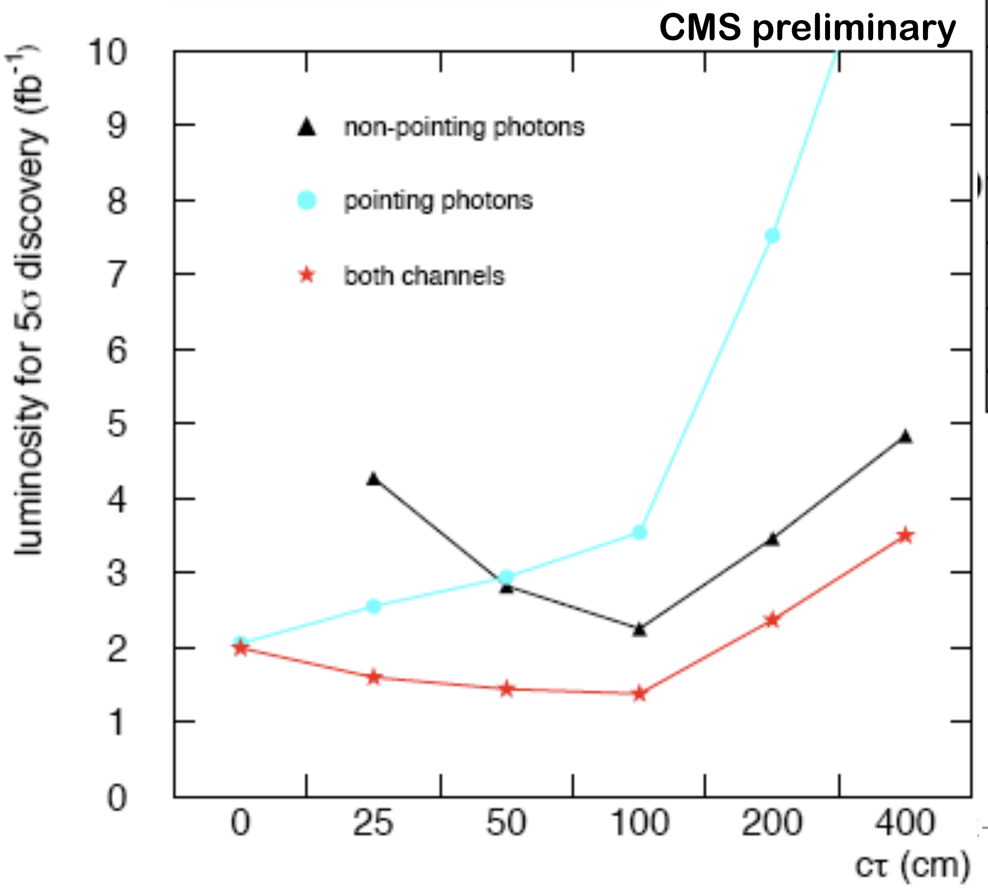
>> Multi-jets

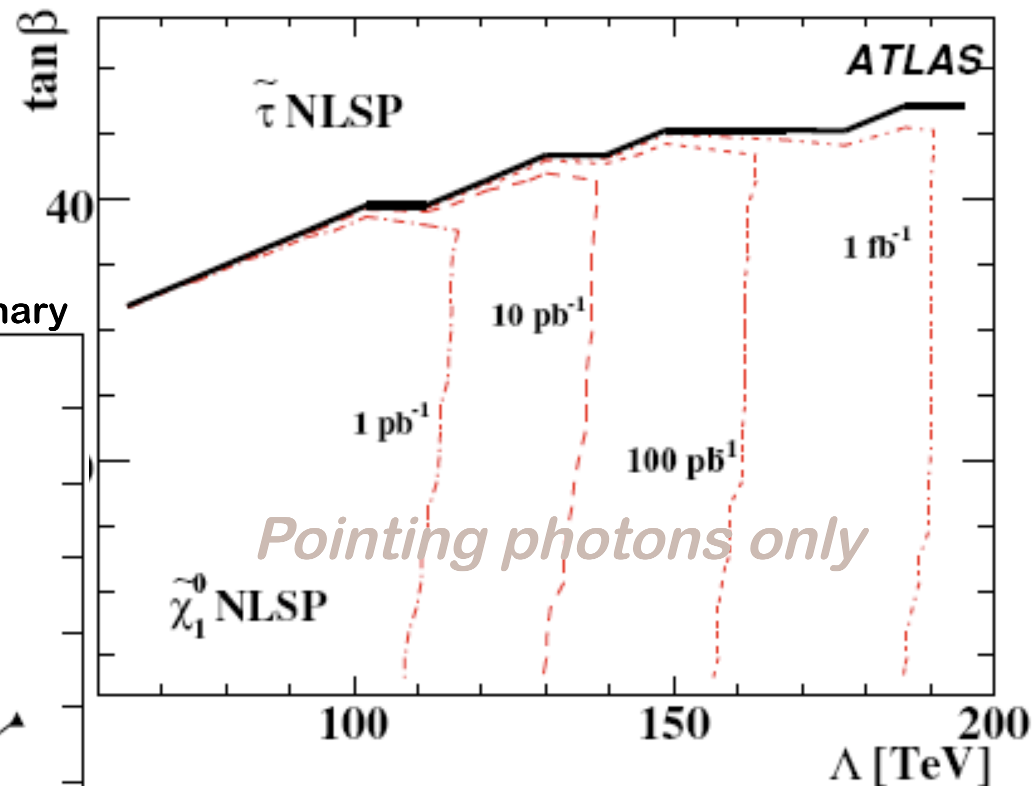
Leading Production

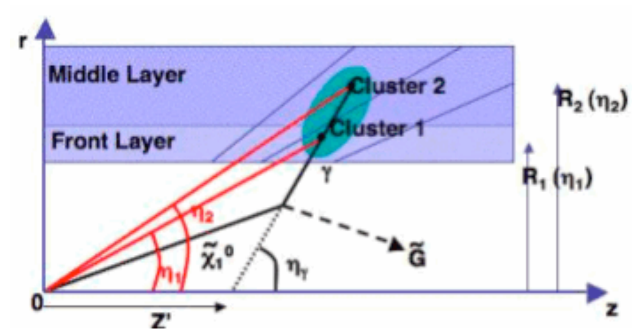


GMSB: Reach at ATLAS and CMS







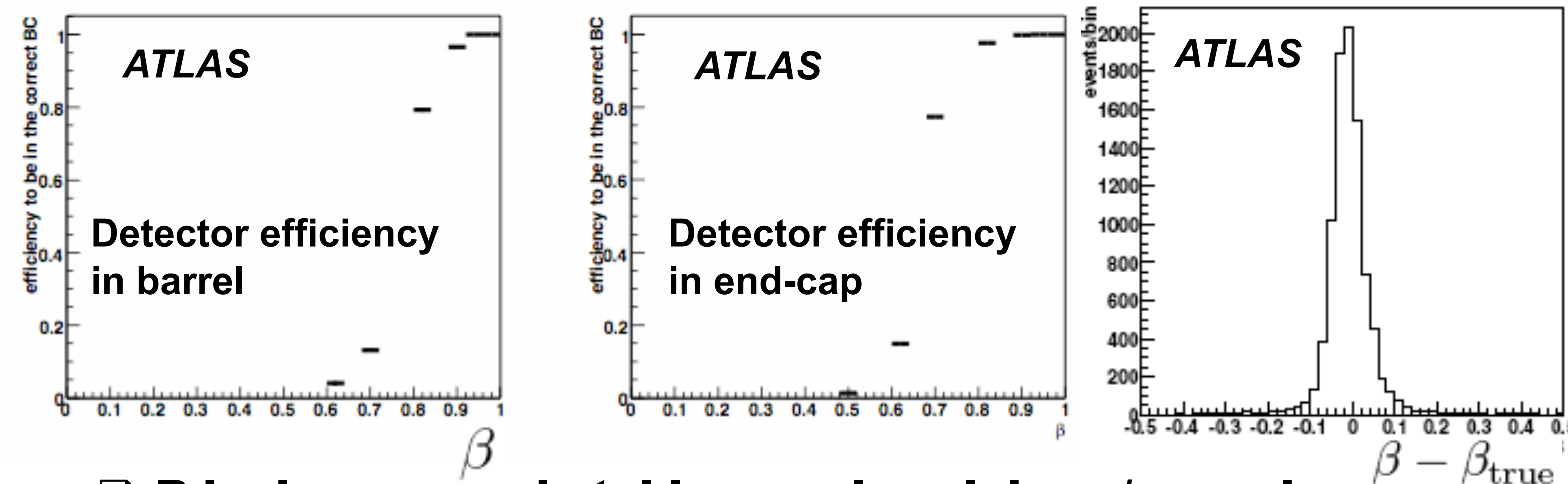


Leptonic (Quasi-) Stable Massive Particles and R-hadrons (ATLAS)

- Many models predict massive leptonic stable particles
- Signature: penetrating tracks with high P_T and low beta
- Signal in parts of detector in different bunch crossings
  - At the trigger level:
    - L1: require regular muon high P_T trigger (95% efficient)
    - L2: use TOF information from RPC's (barrel only, ~50% eff.)

Leptonic (Quasi-) Stable Massive Particles and R-hadrons (ATLAS)

- ❑ **Dedicated muon-like reconstruction**
  - ❑ **Like at L2 with β and mass constraints**
  - ❑ **Minimize χ^2 w/r/t hit position and time of arrival**



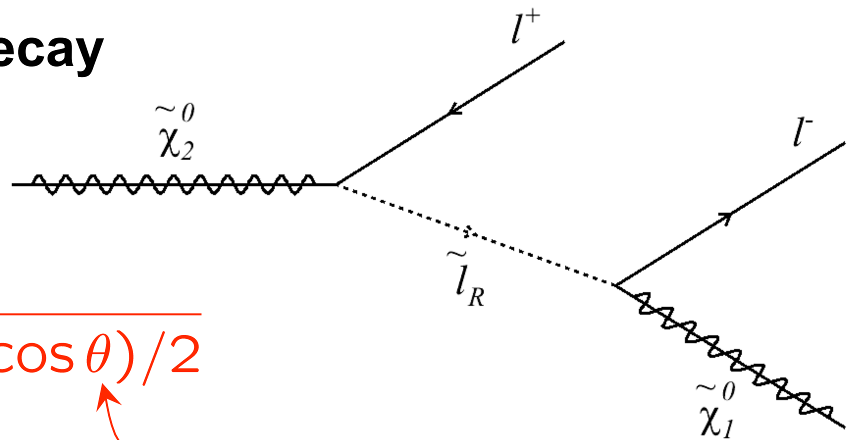
- ❑ **R-hadrons: quasi-stable massive gluinos / squarks**
  - ❑ **Approx. 20 nuclear interactions traversing ATLAS**
  - ❑ **Charge flipping effects / neutral fractions of particle path!**
  - ❑ **Track stubs / unmatched track segments**

SUSY Mass Measurement

- There are two problems when attempting to measure SUSY masses at proton colliders
  - Missing energy and momentum
  - We do not know the center of mass of the collisions
- We cannot use traditional methods by means of invariant mass distributions of SUSY particles
- Instead we may use end-points of invariant mass distributions

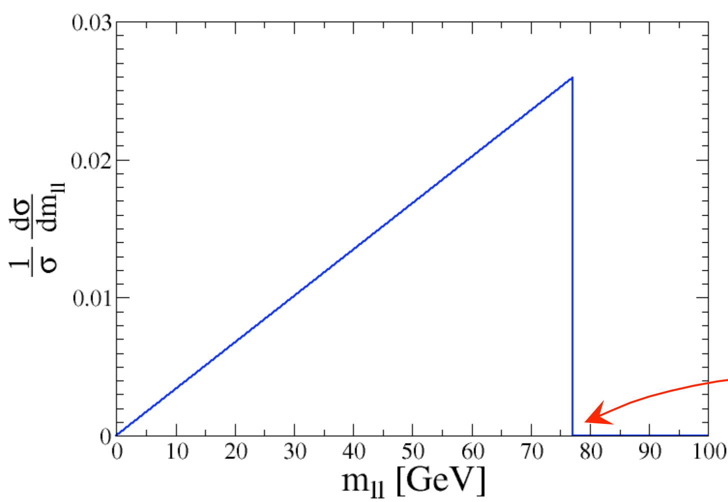
Basic idea:

e.g. consider the decay



$$m_{ll} = m_{ll}^{\max}\sqrt{(1-\cos\theta)/2}$$

angle between leptons

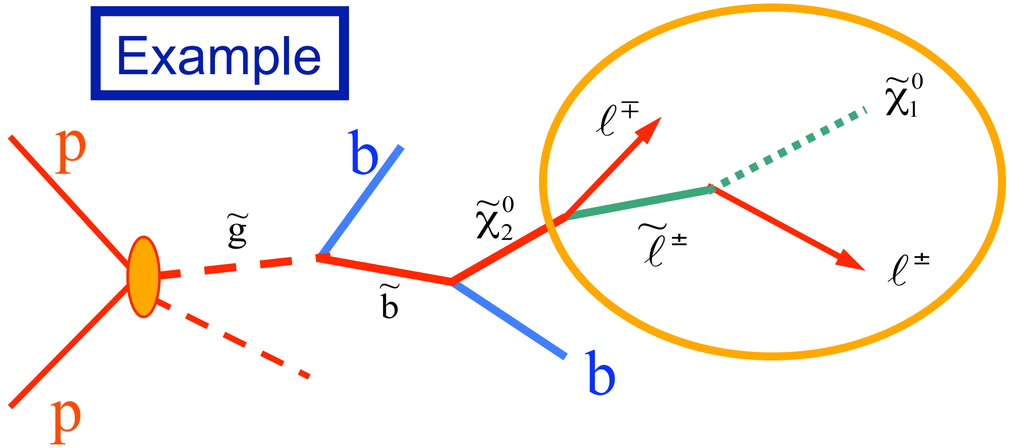


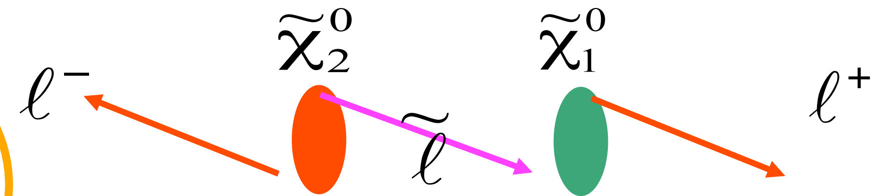
m_{ll} is maximized when leptons are back-to-back in slepton rest frame

$$\left(m_{ll}^{\max}\right)^2 = \left(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{l}_R}^2\right)\left(m_{\tilde{l}_R}^2 - m_{\tilde{\chi}_1^0}^2\right)/m_{\tilde{l}_R}^2$$

Sparticle Reconstruction

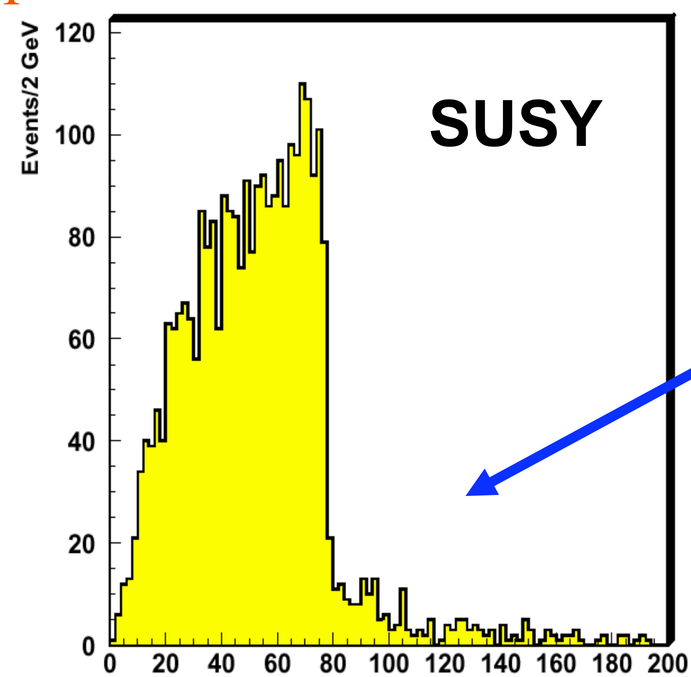
Example





Problem χ_1^0 measurement!
It escapes detection like a neutrino!
Use kinematic formulae...

$$M_{\ell^+\ell^-}^{max} = \frac{\sqrt{(M_{\tilde{\chi}_2^0}^2 - M_{\tilde{\ell}}^2)(M_{\tilde{\ell}}^2 - M_{\tilde{\chi}_1^0}^2)}}{M_{\tilde{\ell}}}$$

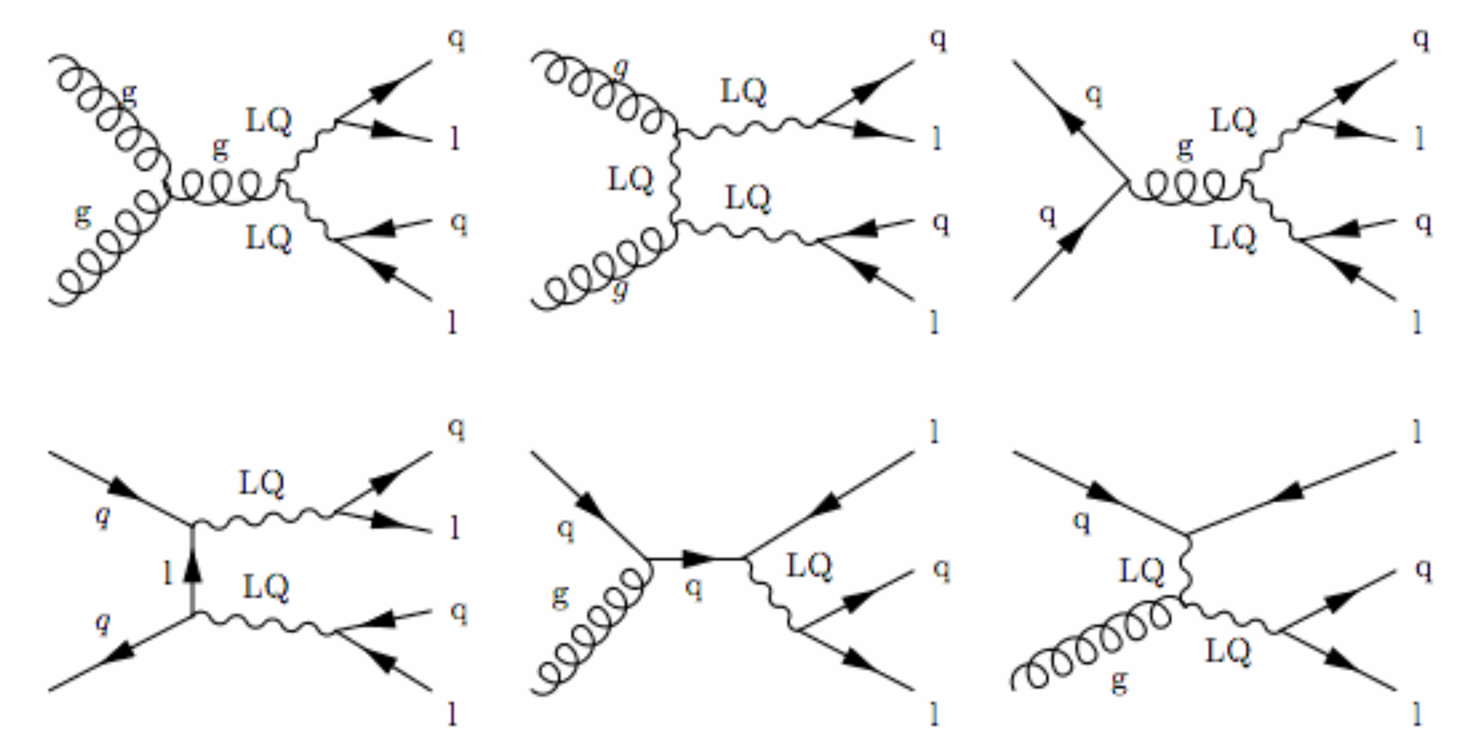


$M(e^+e^-) + M(\mu^+\mu^-)$

Don't be afraid of endpoints (it's kinematics) !

Searches for Lepto-Quarks

The symmetry between leptons and quarks impels some to consider bosons carrying both lepton and quark quantum numbers. This includes a fractional electric charge.
At proton-proton colliders leptoquarks can be produced doubly(via the strong interaction) or singly (via the lepton-quark coupling).
Usually experiments consider decays into electrons and muons



Search for Lepto-Quark pair production