Slepton production via Vector Boson Fusion

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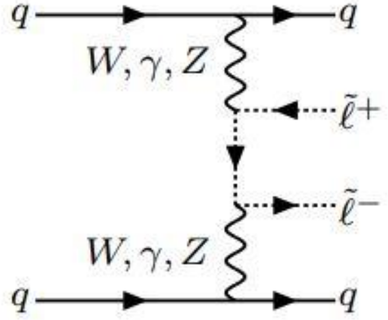
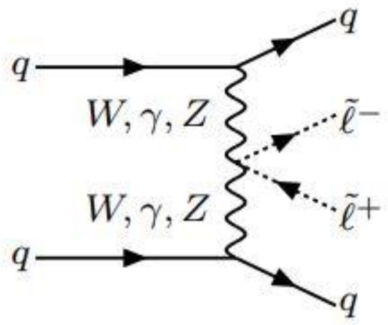
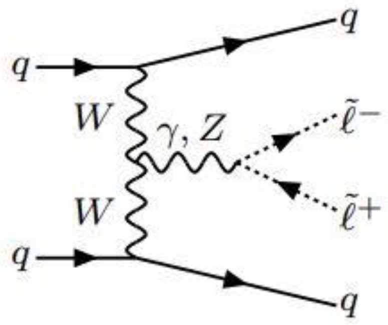
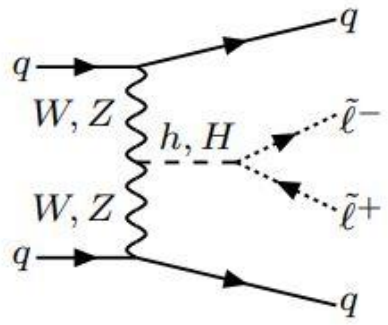
07.09.2021 Physik mit dem Large-Hadron-Collider HS









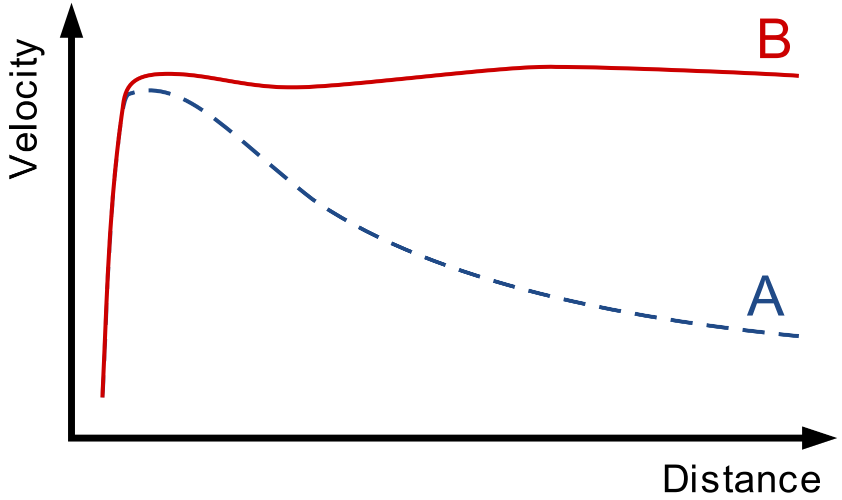
https://arxiv.org/pdf/hep-ph/0304192.pdf

Summary

- 1. Short introduction into Supersymmetry
  - Shortcomings of the Standard Model
  - The Minimal Supersymmetric standard model (MSSM)
- 2. Existing slepton searches
- 3. Studies on sleptons produced via vector-boson fusion (VBF)
  - Topology of VBF slepton production
  - Generator-level studies
  - Analysis strategy
  - Outlook

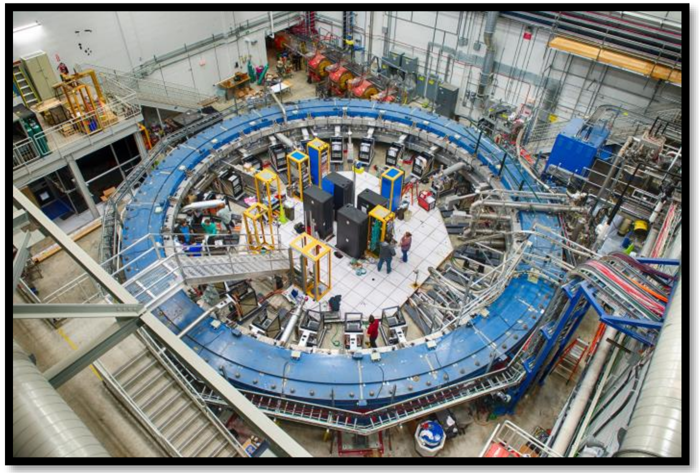
Shortcomings of the SM

- No candidate for dark matter in the SM
- Several measurements deviate from SM theory predicitons, such as the muon anomalous magnetic dipole moment (muon g-2)



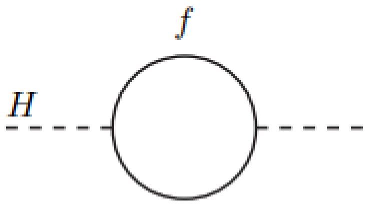
Velocity in rotating galaxies does not diminish with increasing distance from the centre.
If Kepler's laws are correct this hints to contributions from dark matter

https://en.wikipedia.org/wiki/Dark_matter#Observational_evidence



https://cerncourier.com/a/fermilab-strengthens-muon-g-2-anomaly/

Hierarchy problem of the SM



https://arxiv.org/pdf/hep-ph/9709356.pdf#page=3

- Higgs mass gets contributions from loop corrections
- $\Delta m_H{}^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda^2 + \ldots$ (contribution from fermionic loops)
- Contribution proportional to „cut-off" scale Λ where SM breaks down
- New physics required at least at the Planckscale $\Lambda = M_P \approx 10^{18} GeV$ where gravity becomes relevant

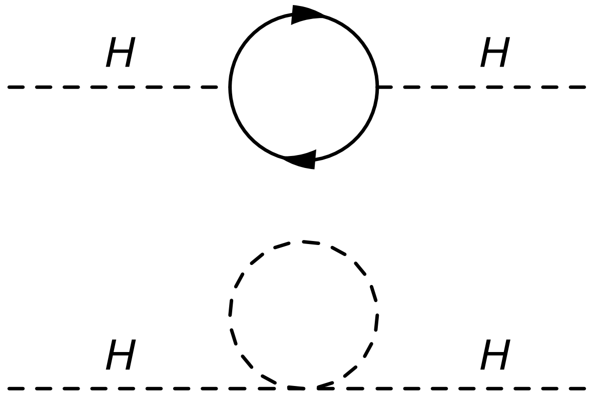
→ as Higgs mass is around weak scale v = 250 GeV, cancellations over 30 order of magnitude between Higgs mass and quadrative divergencies would be required („fine-tuning")

SUSY may mitigate need for fine-tuning

- For each loop in the SM exists a supersymmetric partner loop
- Loops from scalar particles have opposite signed contributions

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}\left[\Lambda_{\mathrm{UV}}^2 - 2m_S^2 \ln(\Lambda_{\mathrm{UV}}/m_S) + \ldots\right]$$

- Contributions could cancel each other out if we have additional scalar particles
- SUSY predicts scalar partners for the SM fermions



Fermionic SM loop

Corresponding scalar loop

https://arxiv.org/pdf/hep-ph/9709356.pdf#page=3

What is Supersymmetry (SUSY)?

- One of the best studied extensions of the Standard Model (SM)
- Rather theoretical framework than one specific theory
- Predicts new particles: supersymmetric partners of the SM particles with spin differing by ½
- If SUSY is unbroken symmetry: particles would have same mass as SM particles

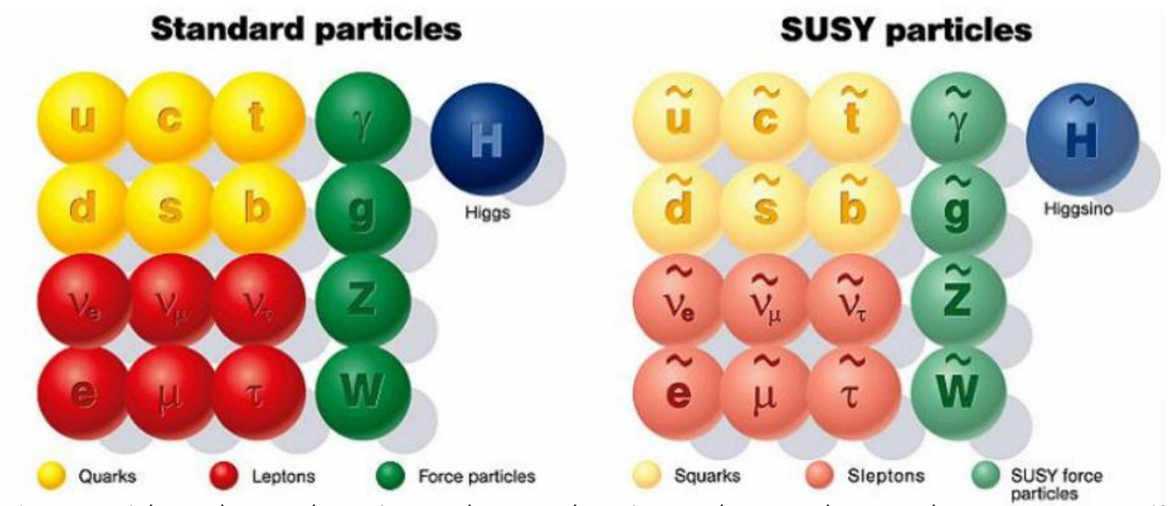
→ SUSY has to be softly broken to allow larger masses for SUSY partners

Brief introduction in MSSM

- Supersymmetric theory adding minimal number of additional particles possible
- Requires two Higgs SU(2) doublets (with superpartners)
- One SUSY partner for every other particle
- $|boson > \leftrightarrow |fermion >$

Brief introduction in MSSM

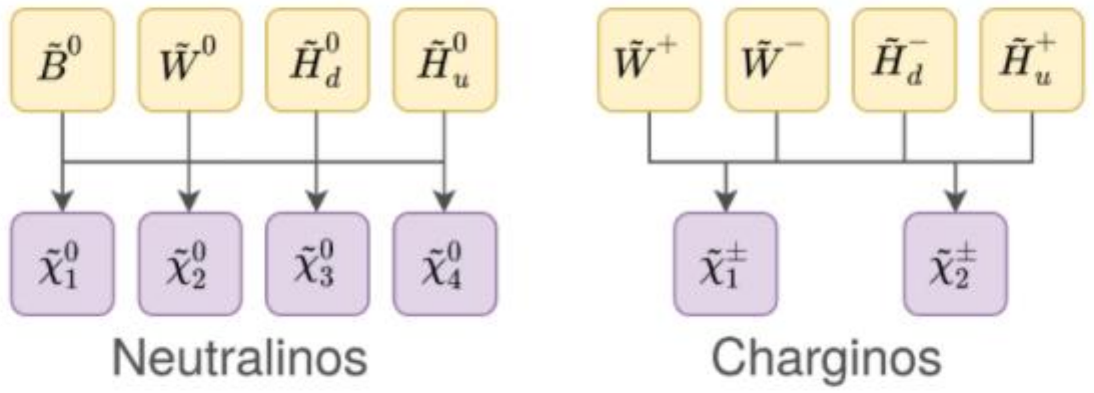
- Partners of SM bosons get appended by -ino (Higgsino, Bino, Wino)
- Partners of SM fermions get prepended by s- (sbottom, selectron, smuon)
- SUSY particle symbols are marked with an ~ on top



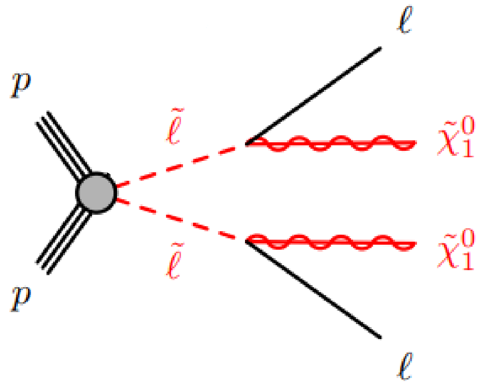
https://indico.cern.ch/event/607327/contributions/2447329/attachments/1414742/2165493/CoEPP2017-SUSY.pdf#page=3

Brief introduction in MSSM

- Due to electroweak-symmetry breaking: particles with same quantum numbers can mix
- Superpartners of charged SM gauge and Higgsbosons mix to charginos
- Superpartners of neutral SM gauge and Higgsbosons mix to neutralinos
- These are labelled ordered by their mass ($m_{\chi 1}$<$m_{\chi 2}$ etc.)



Brief introduction in MSSM



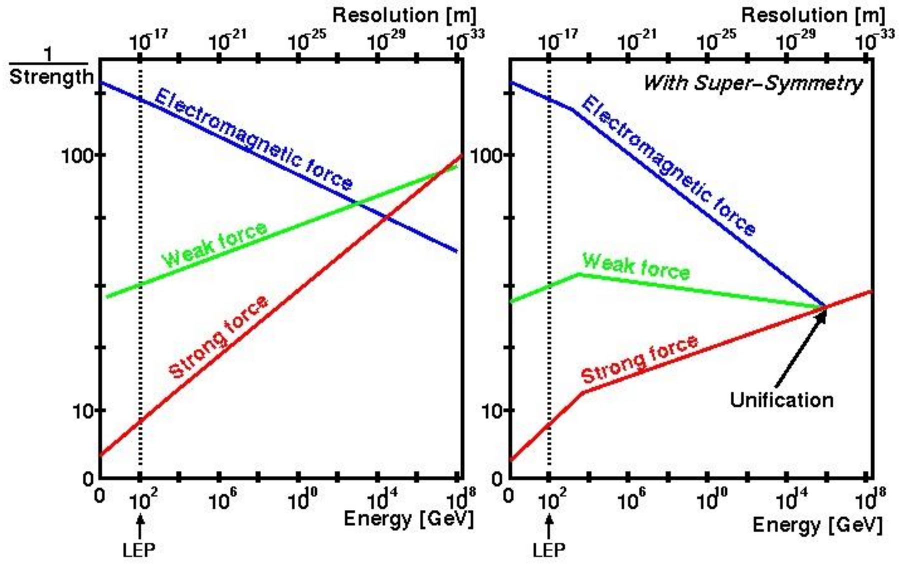
https://arxiv.org/pdf/1911.12606.pdf

- Conservation of R-Parity
- Needed to ensure B and L are conserved
- $P_R = (-1)^{3(B-L)+2s}$
- $P_R(SMparticle) = 1;\ P_R(SUSYparticle) = -1$
- Consequences
  - lightest SUSY particle (LSP) is stable
  - If the LSP is neutral -> candidate for black matter
  - Every other particle apart from LSP decays into states with uneven numbers of LSPs
  - In colliders only even numbers of sparticles can be produced

Brief introduction in MSSM

- Inverse gauge couplings do not meet in the SM
- But may with the additional particles in MSSM (Grand Unification)

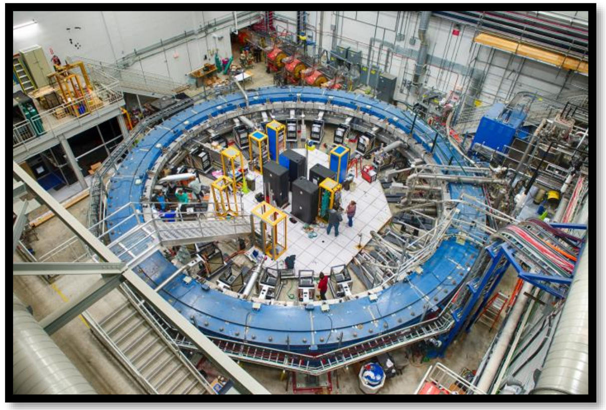
Standard model MSSM



https://i.stack.imgur.com/Ur0ol.gif

The inverse gauge couplings meet at 10^{16}GeV in the minimal supersymmetric standard model

2. Current slepton searches



https://cerncourier.com/a/fermilab-strengthens-muon-g-2-anomaly/

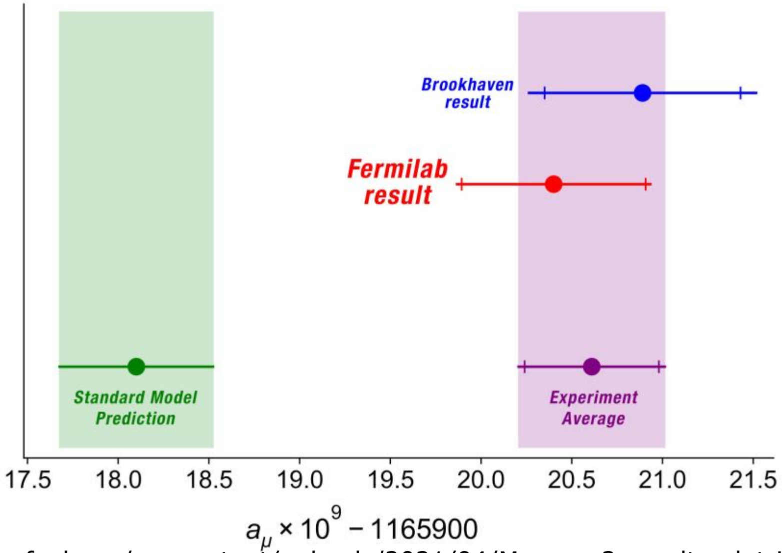
- Why search for sleptons?
- Potential solve for muon anomalous magnetic dipole moment (measured at muon g-2)
- $a_\mu \equiv \frac{g_\mu - 2}{2}$

Results:

$a_\mu^{\text{FNAL}} = 116\,592\,040(54) \times 10^{-11}$

4.2 σ deviation (combined)

→ Probability 1:100000 for SM-only explanation



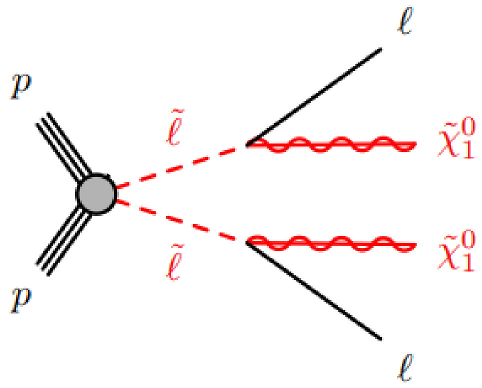
https://news.fnal.gov/wp-content/uploads/2021/04/Muon-g-2-results-plot.jpg

- Contributions to a_μ from light smuons could explain the observed deviation

Current slepton searches

- Sleptons are already part of the LHC search program
- Model considered:
  - R-Parity conserved
  - Neutralino is LSP
  - Only first two generations (Smuon, Selectron)
- Search for slepton pair production
- Event kinematics highly dependant on mass splitting $\Delta M = m(\tilde{\ell}_{L,R}) - m(\tilde{\chi}_1^0)$
  - Large ΔM -> high energetic leptons low $E_{T miss}$
  - low ΔM -> soft leptons, high $E_{T miss}$

→ different search strategies required!



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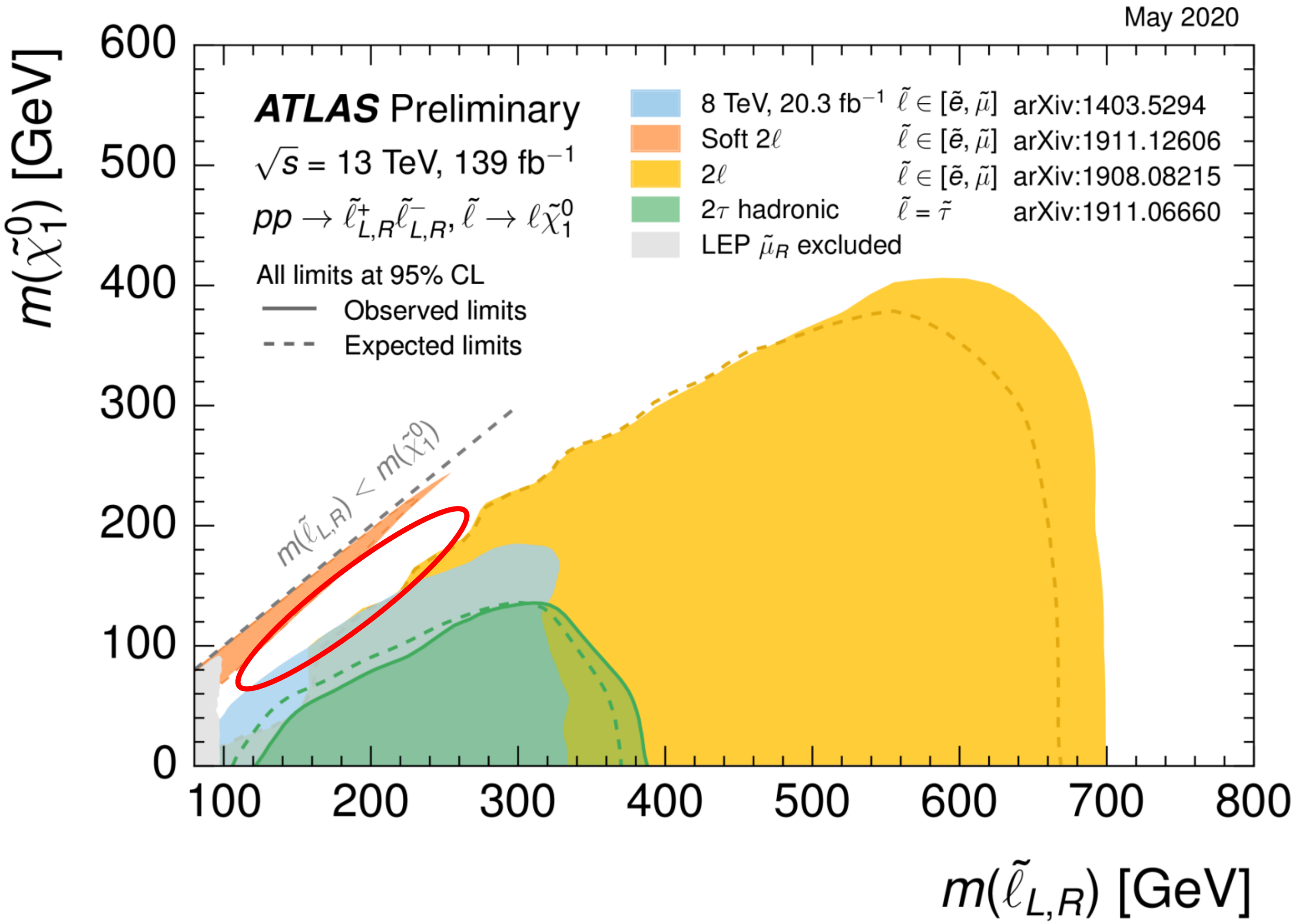
Current slepton searches



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2021-007/fig_14.png

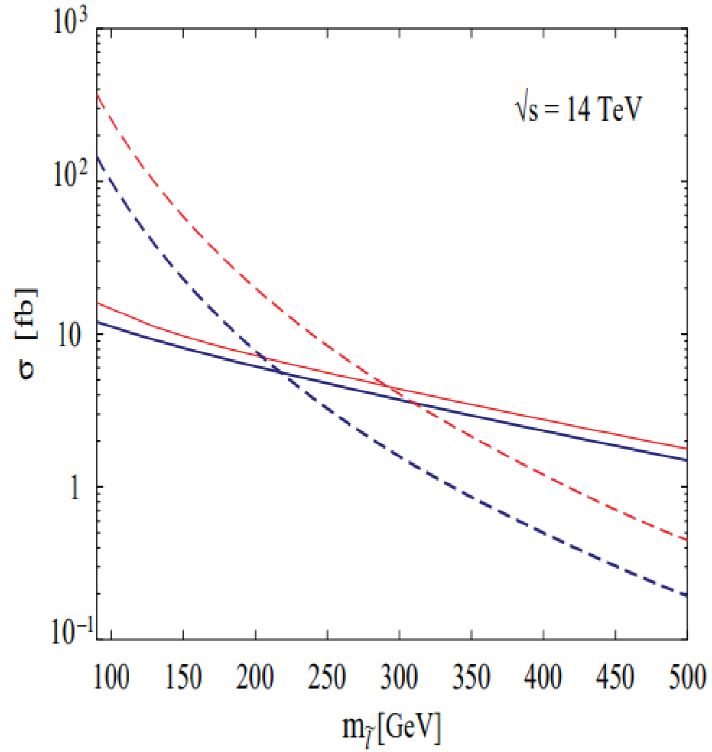
Soft 2lepton at $m(\tilde{\ell}_{L,R}) >\approx m(\tilde{\chi}^{0}_{1})$
With initial state radiation (ISR)

Hard 2lepton at $m(\tilde{\ell}_{L,R}) \gg m(\tilde{\chi}^{0}_{1})$

Sensitivity gap between regions,
may need new approaches
→ consider sleptons produced via VBF

Cross-section for VBF slepton production

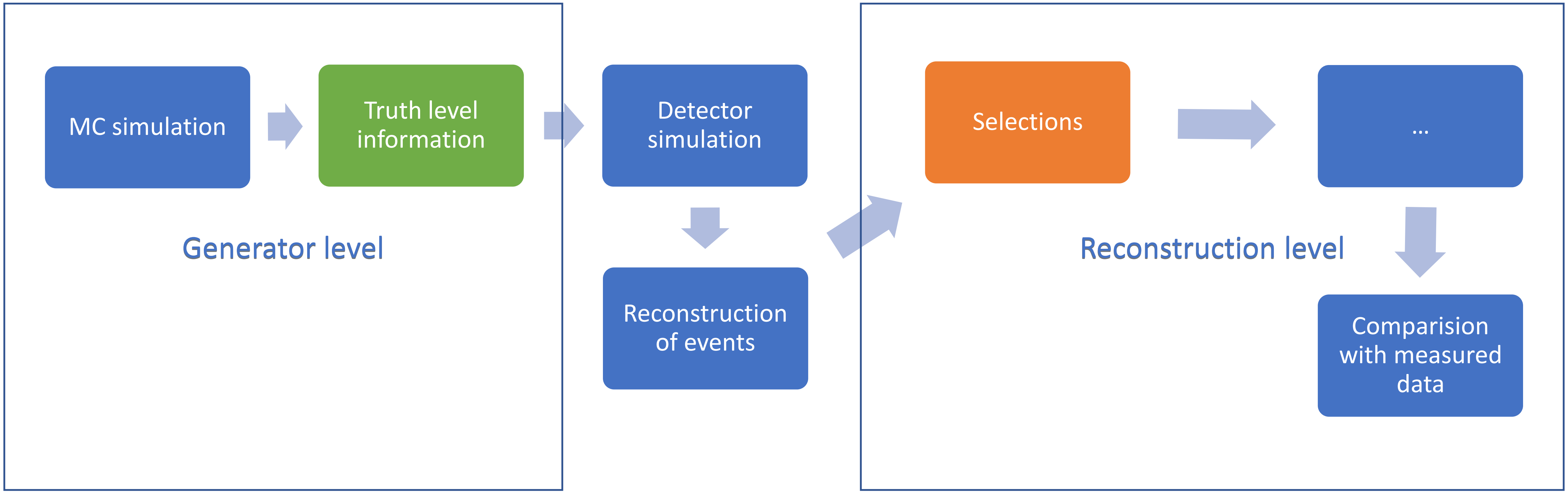
- Based on paper arXiv:hep-ph/0304192v2 18 Aug 2003



Dashed lines show the cross-section of the Drell-Yan process. The solid lines show the VBF slepton cross-section. At high slepton masses the VBF topology overtakes the Drell-Yan process. Upper and lower curves show process for left or right handed slepton respectively

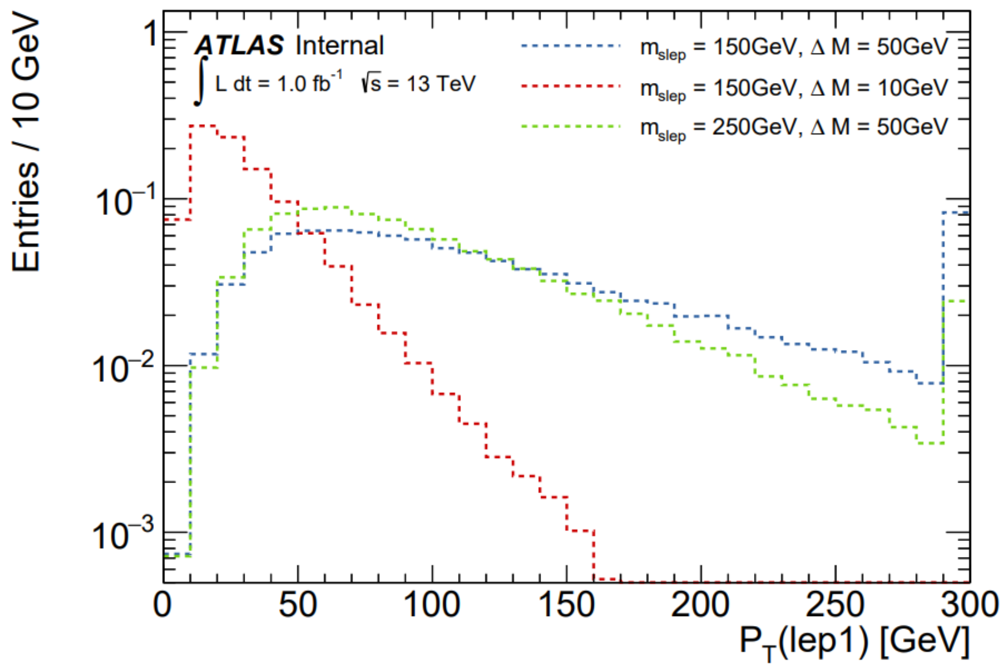
https://arxiv.org/pdf/hep-ph/0304192.pdf

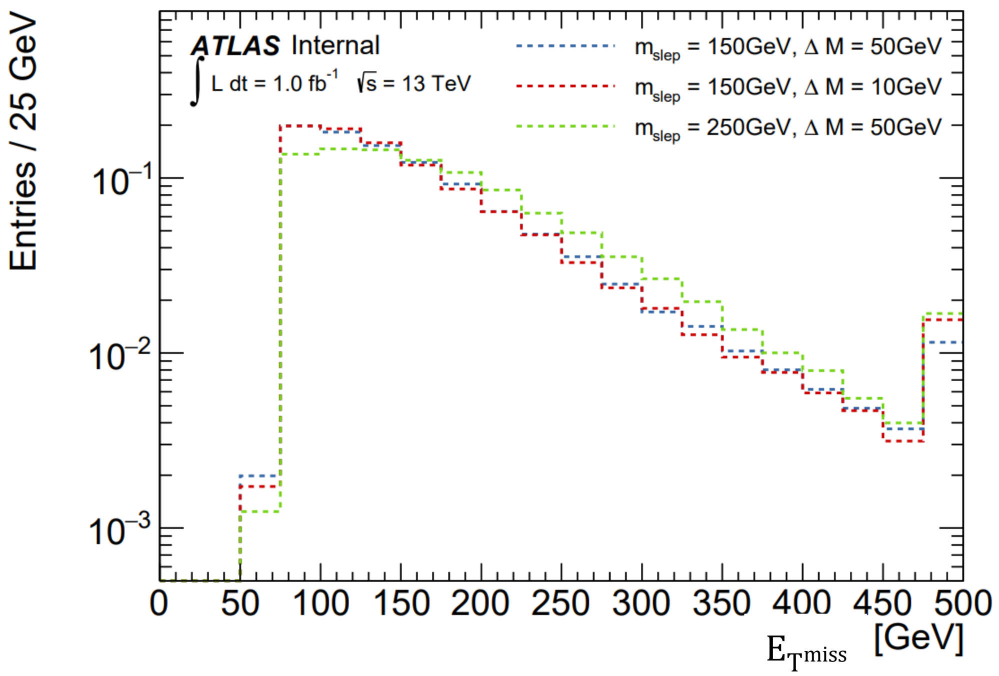
Reminder:
Analysis chain in High Energy Physics



Generator level studies

- Visualize dependency of kinematics in VBF slepton production on ΔM and $m(\tilde{l})$
- Missing transverse momentum is only low to not dependent on $m(\tilde{X}_1^0)$
- Lepton system gets harder with larger ΔM





Analysis Event Selection

- Main purpose: search for phase space with as little background and as much signal as possible

→ Apply kinematic restrictions ("cuts") on reconstructed observables

- Representative mass splitting of $\Delta M = 30\ GeV\ (m_{slep} = 200GeV)$ used for optimization
- Preselection (loose selection based on the basic event topology)
- To be sensitive to signal, need much tighter requirements
- Define signal enriched region, Signal Region (SR) on top of the preselection

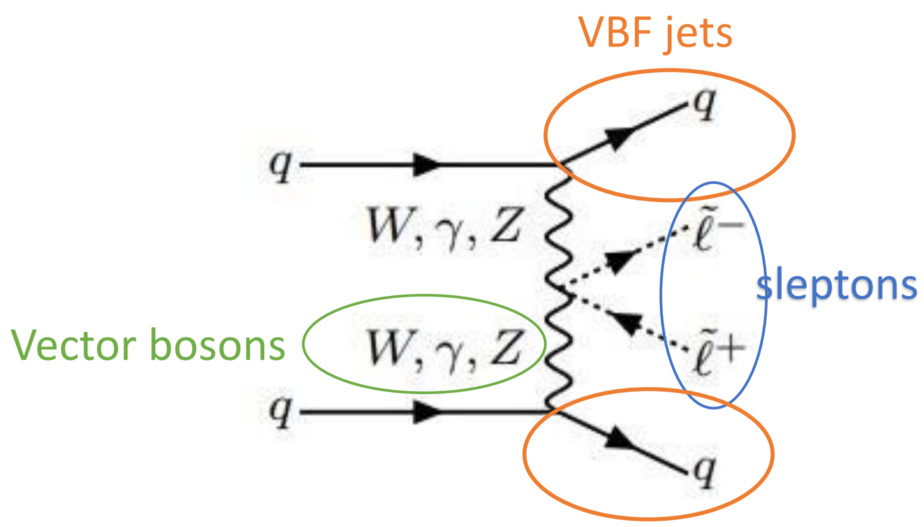
Topology of VBF slepton production

Vector boson fusion

- 2 back-to-back jets (different hemispheres of detector)
- Large invariant jet mass m_{jj}
- Not b-tagged

Slepton production

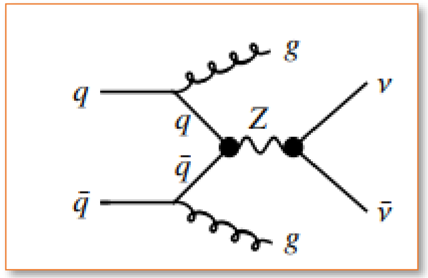
- 2 sleptons get produced
- Decay into a SM lepton and a neutralino each



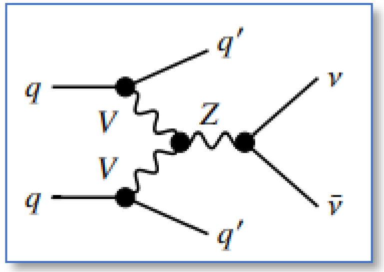
https://arxiv.org/pdf/hep-ph/0304192.pdf

Main Backgrounds

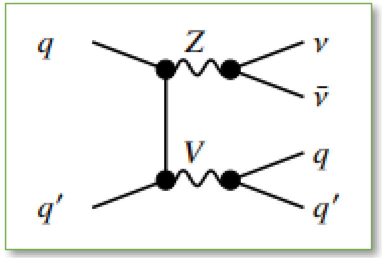
- Z -> ll + 2 jets
- W-> $l\nu$ + 2 jets
  - Strong processes $\propto \alpha_{EW}^2$
  - Electroweak (EW) $\propto \alpha_{EW}^4$
- Diboson (one decays into ll and one decays into 2 jets)
- Top production processes



Strong Zvv



EW Zvv



Diboson

https://cds.cern.ch/record/2715447/files/ATLAS-CONF-2020-008.pdf

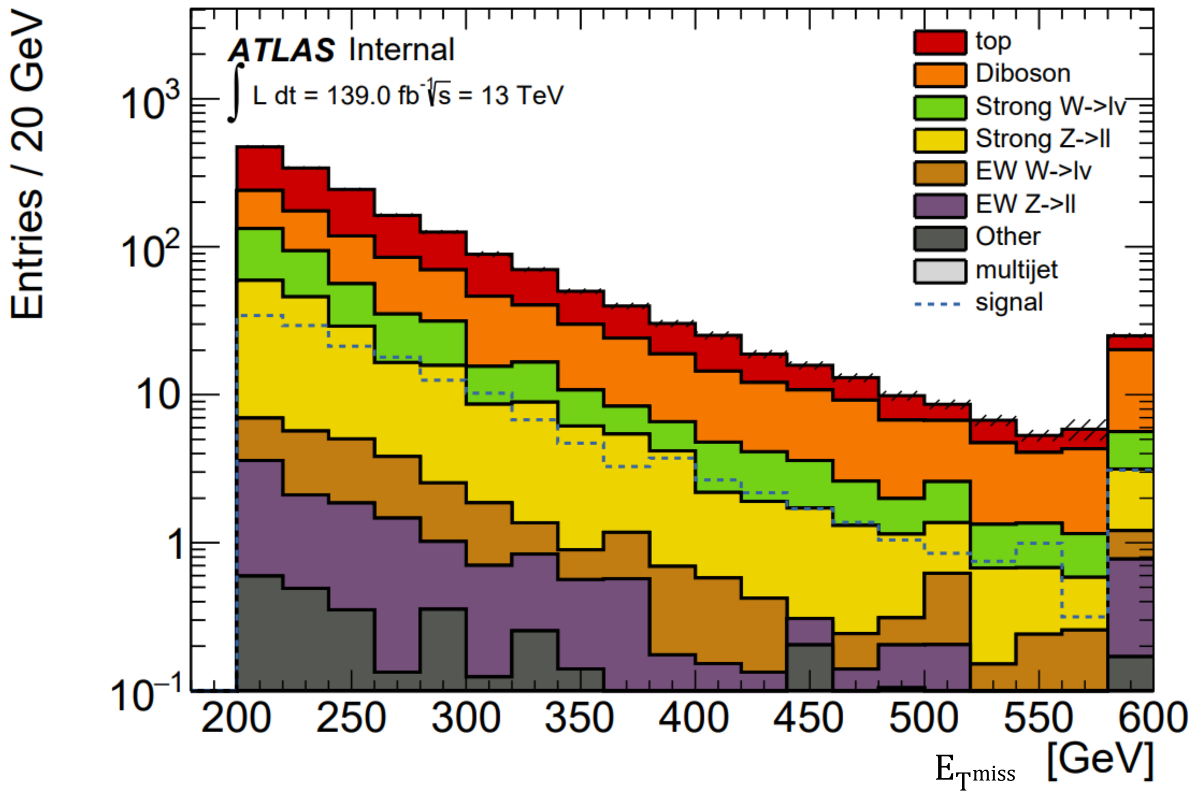
Preselection (signal)

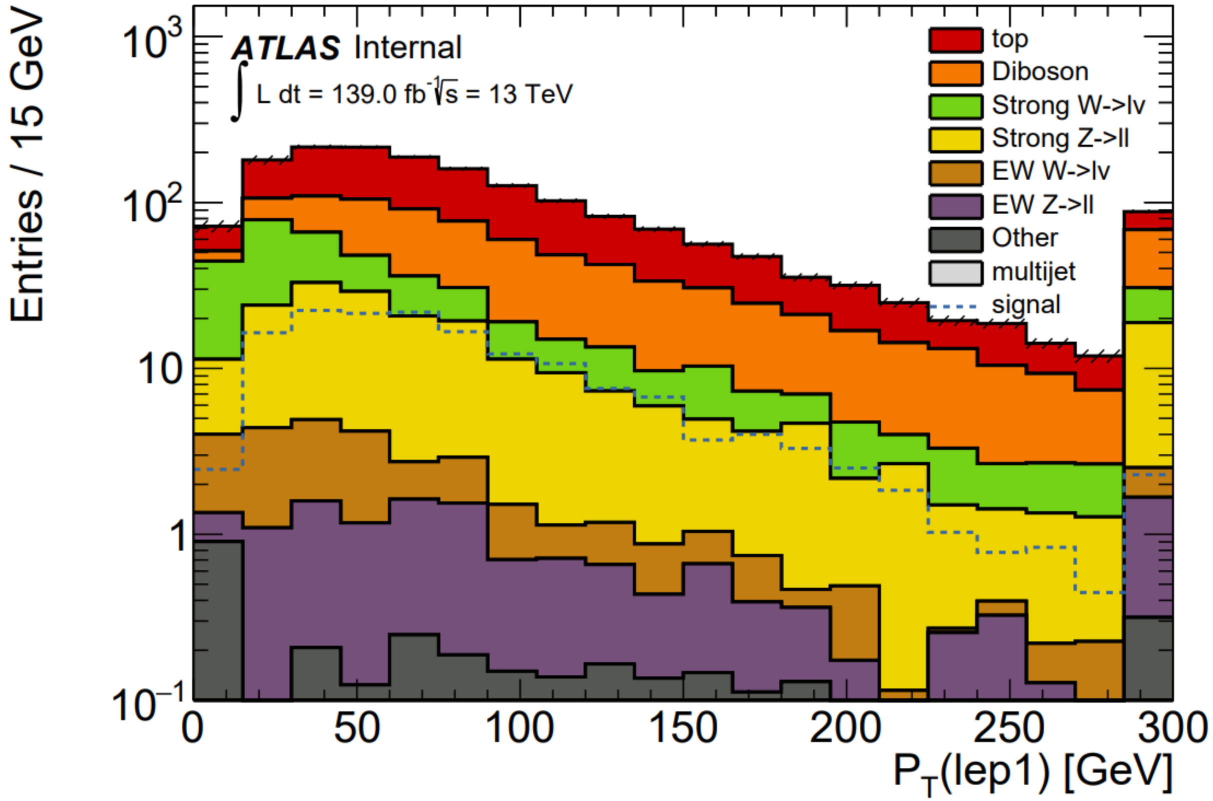
Initial signal events: cross-section · luminosity

Selection	Percentage left of total signal
Missing transverse momentum related cuts	34.0%
VBF topology	30.5% (89.7% of preceding cut)
lepton related	27.7% (90.5% of preceding cut)

→ 27.7% of the signal events remain while background events are rejected

Preselection Histograms





Signal to background ratio is still far too low to separate new physics from the Standard Model background

→ Selection needs to be further enhanced

→ use significance function to quantify how good the selection separates signal from background

Significance

- related to probability how likely it is that an potential observation can be explained by the background-only hypotheses
- $Significance \approx \frac{s}{\delta b}$ (s = amount of signal events, δb = error in background events)
- $\delta b \sim$ b = amount of background events

→to improve the significance, minimize background while preserving as much signal as possible

Significance

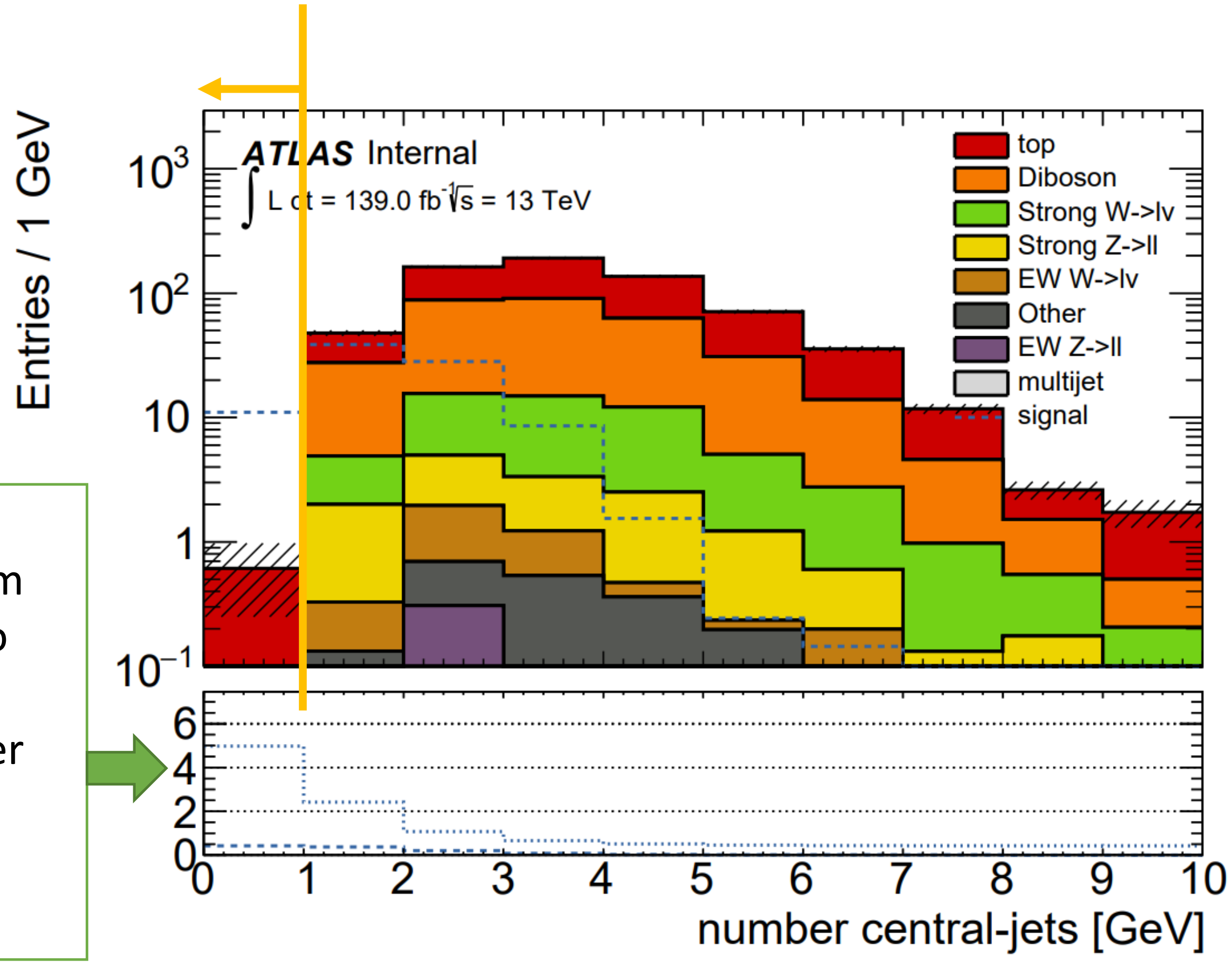
- More accurate:
- assumed systematic error of 30% of background events
- δb = statistical error of MC predictions
- $\sigma \equiv \sqrt{\delta b^2 + (0.3 \cdot b)^2}$
- $n \equiv b + s$
- $S(s, \delta b, b) \equiv \sqrt{2 \cdot n \cdot \log\left(n \frac{b+\sigma^2}{b^2+n \cdot \sigma^2}\right) - b^2 \sigma^2 \log\left(1 + \frac{\sigma^2 s}{b \cdot (b+\sigma^2)}\right)}$

Signal region

- Add additional cuts that maximize significance function
- No jets with $|\eta| \leq 2.8$ (central jet)
- Invariant lepton mass $m_{ll} \geq 60\ \mathrm{GeV}$
- Transverse momentum of leading VBF-tagged jet $P_T(jet1) \geq 70\ GeV$

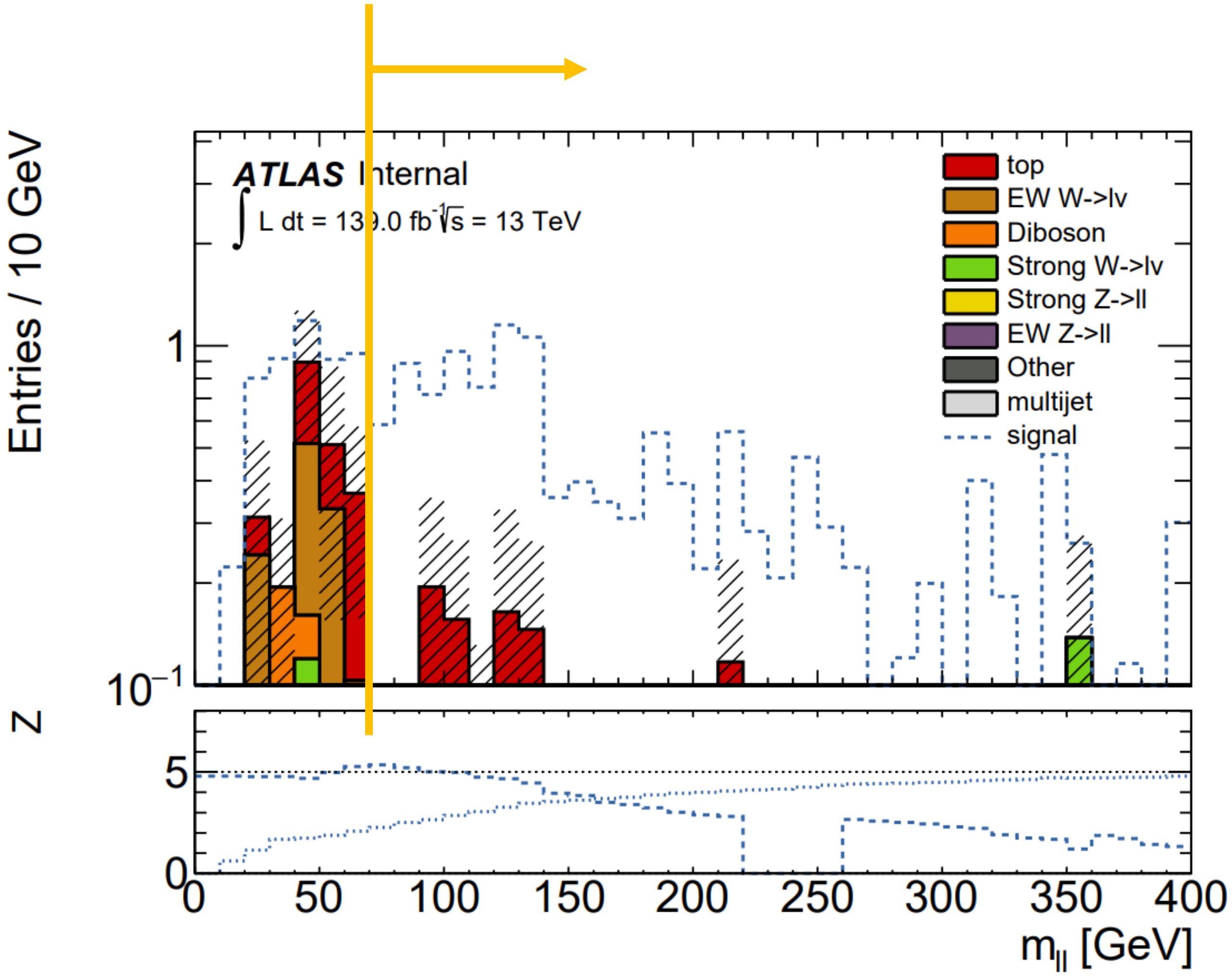
→ use histograms with all requirements except one in order to validate the cut position with the significance function (N-1 plots)

No central jets

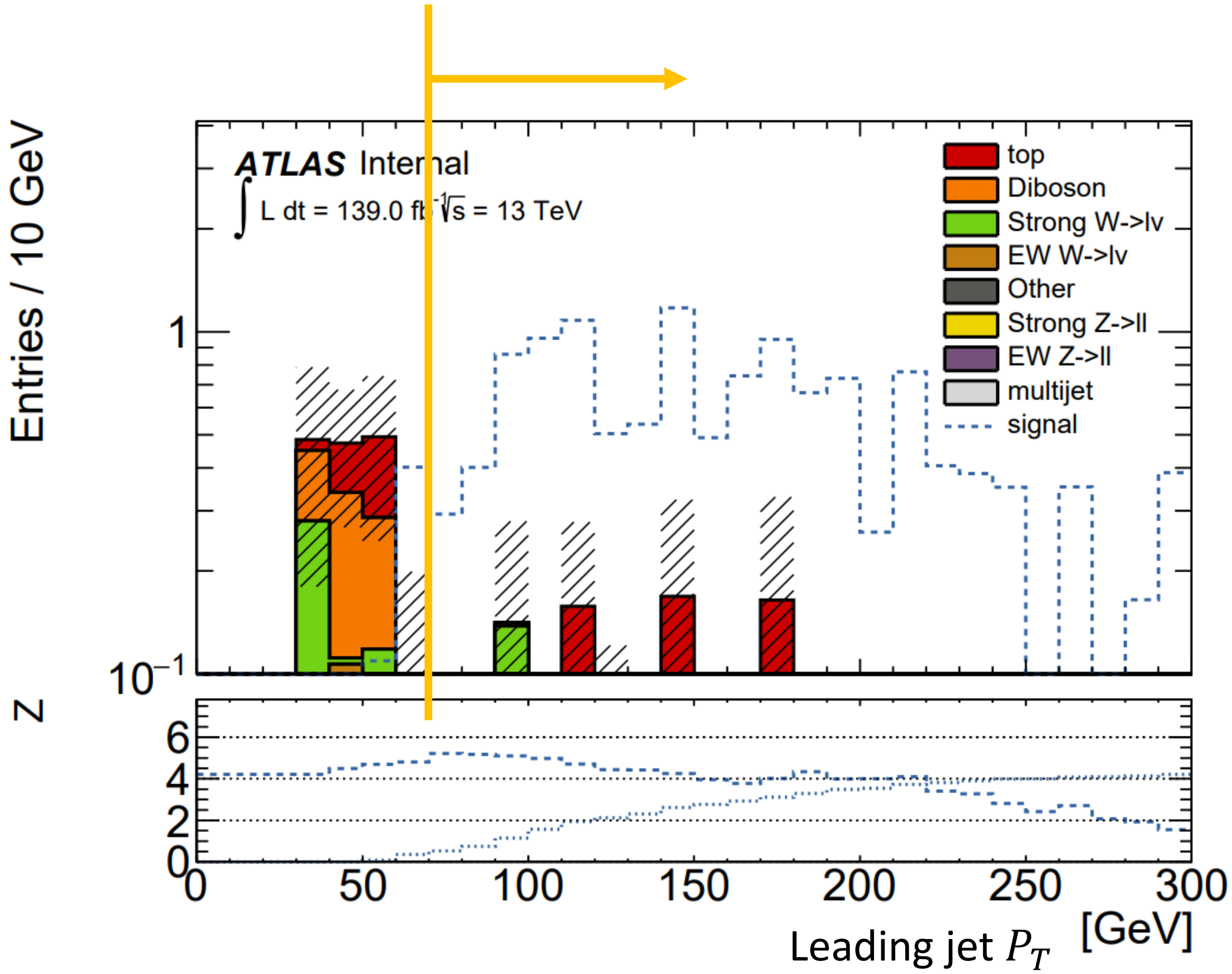


Significance (Z)
Perform a cut at the maximum of the significance function to optimize the region.
Dotted-line: reject region after x-value
Dashed-line: reject region before x-value

Cut on invariant lepton mass

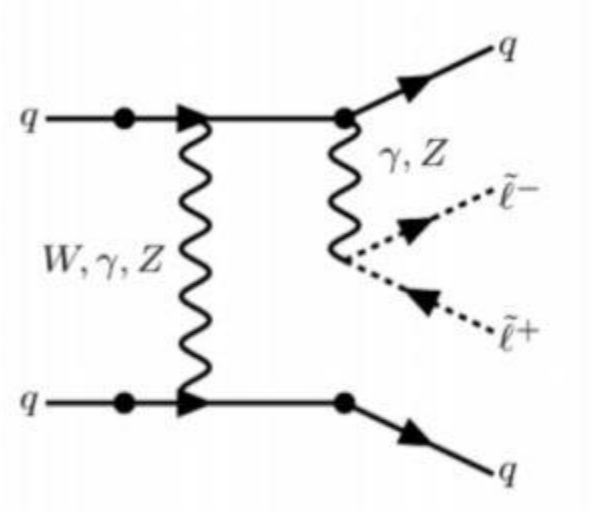


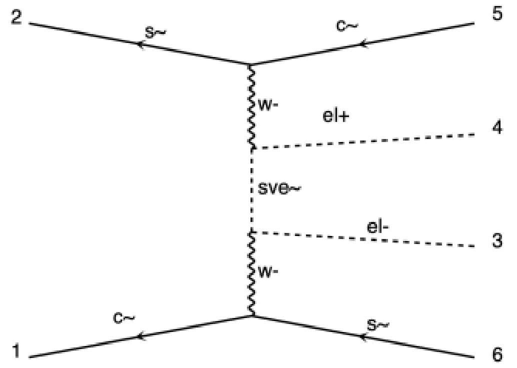
Cut on leading VBF-tagged jet $P_T(jet1)$



Caveat: Contribution of sneutrino process

- Prediction of VBF slepton Cross-section wrong!
- Simplified models shown before are decoupled in regards to the other SUSY particles (masses assumed to be far higher)
- For sneutrinos applies however $m_{\tilde{\nu}} \leq m_{\tilde{l}}$
- Recent papers call out mentioned paper (arXiv:hep-ph/0304192v2 18 Aug 2003): cross-section reduced (by factor ~ 30) due to destructive interference with sneutrino diagrams





Outlook

- Redo SR optimization with "realistic" signal sample, containing light sneutrinos (no huge sensitivity expected because of lowered cross-section)
- Consider additional variables for optimization such as m_{T2}
- Maybe VBF slepton production interesting for High-Luminosity LHC

Thank you for your attention!

Special thanks to Michael Holzbock and Prof. Kroha