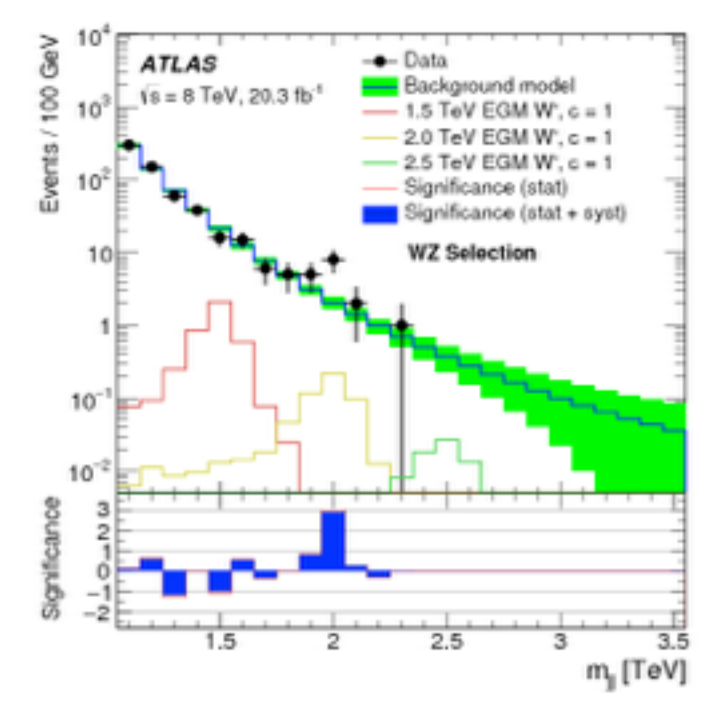
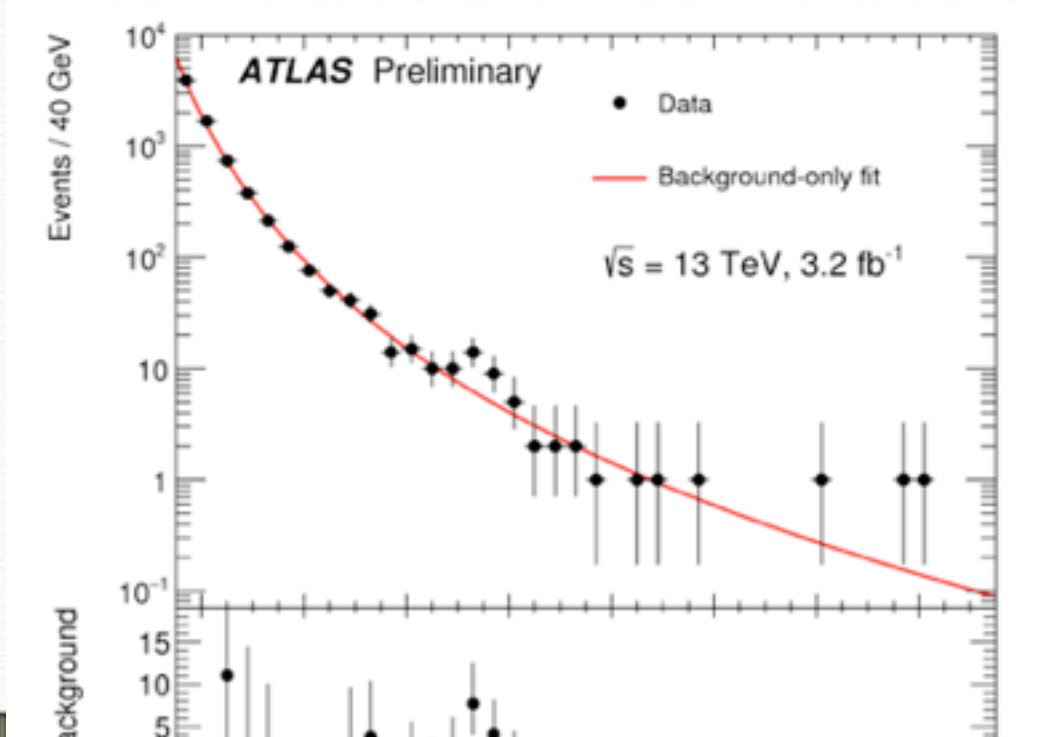
BSM search at LHC and its future

Mihoko Nojiri
KEK & IPMU

What LHC have done so far

- finding SM Higgs boson at 125GeV
- not finding SUSY ~TeV range tension with naturalness
- not finding any top partner <TeV range
- Finding ***“mostly harmless”*** peaks and excesses





Ok, Let's go out and enjoy the city

Foto 382996 www.bilderbuch-bonn.de (2012)

Well, be serious a)b)c) d)

a)We are in Germany.
b) I am supposed to be a Japanese
c) The physics is interesting.
d) X is demanding

Two things are wrong in SM

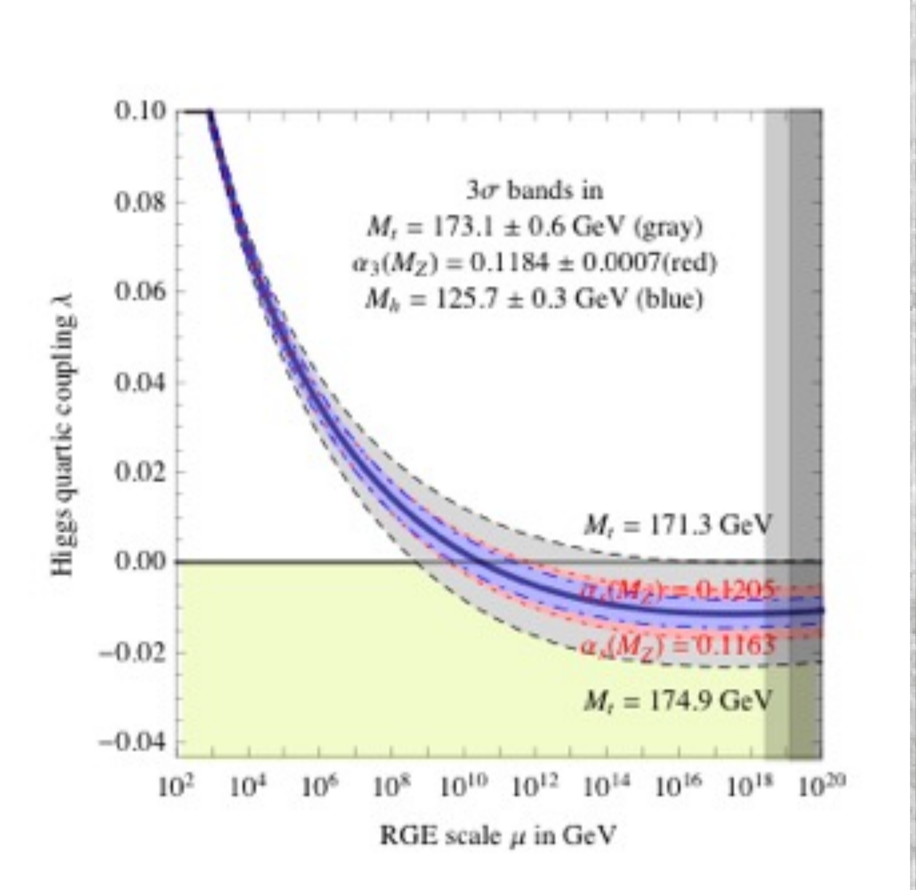
Supersymmetry provide some solution on two major problems of SM , but create another problem that we have not seen tit yet

- Wrong Vacuum of SM → SUSY V>0
  SM may sit in false vacuum for sufficiently long time, and there are lots of uncertainty on recent thermal history discussions.

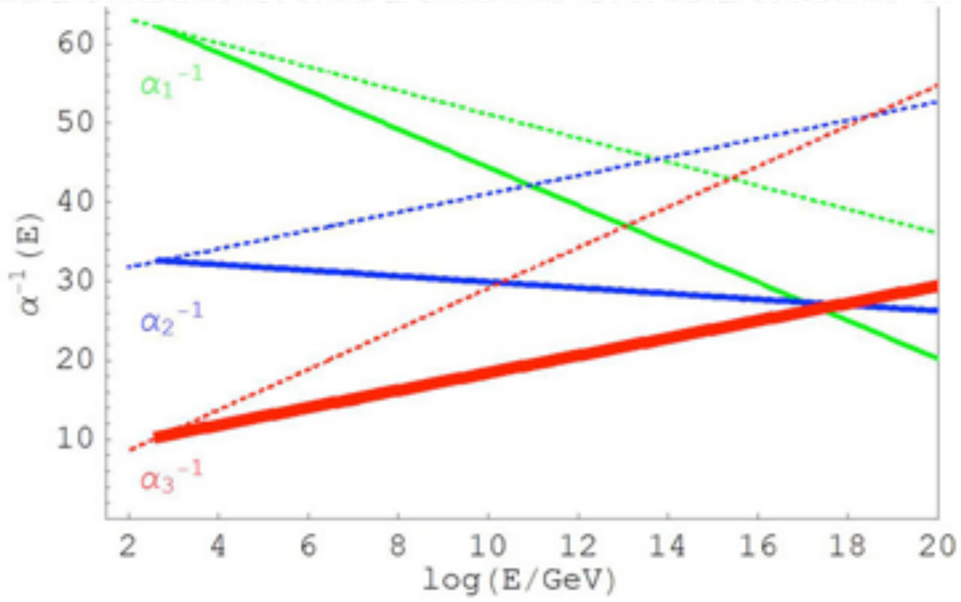
- No DM → SUSY R parity
  conservation and LSP dark matters

- gauge coupling unification.

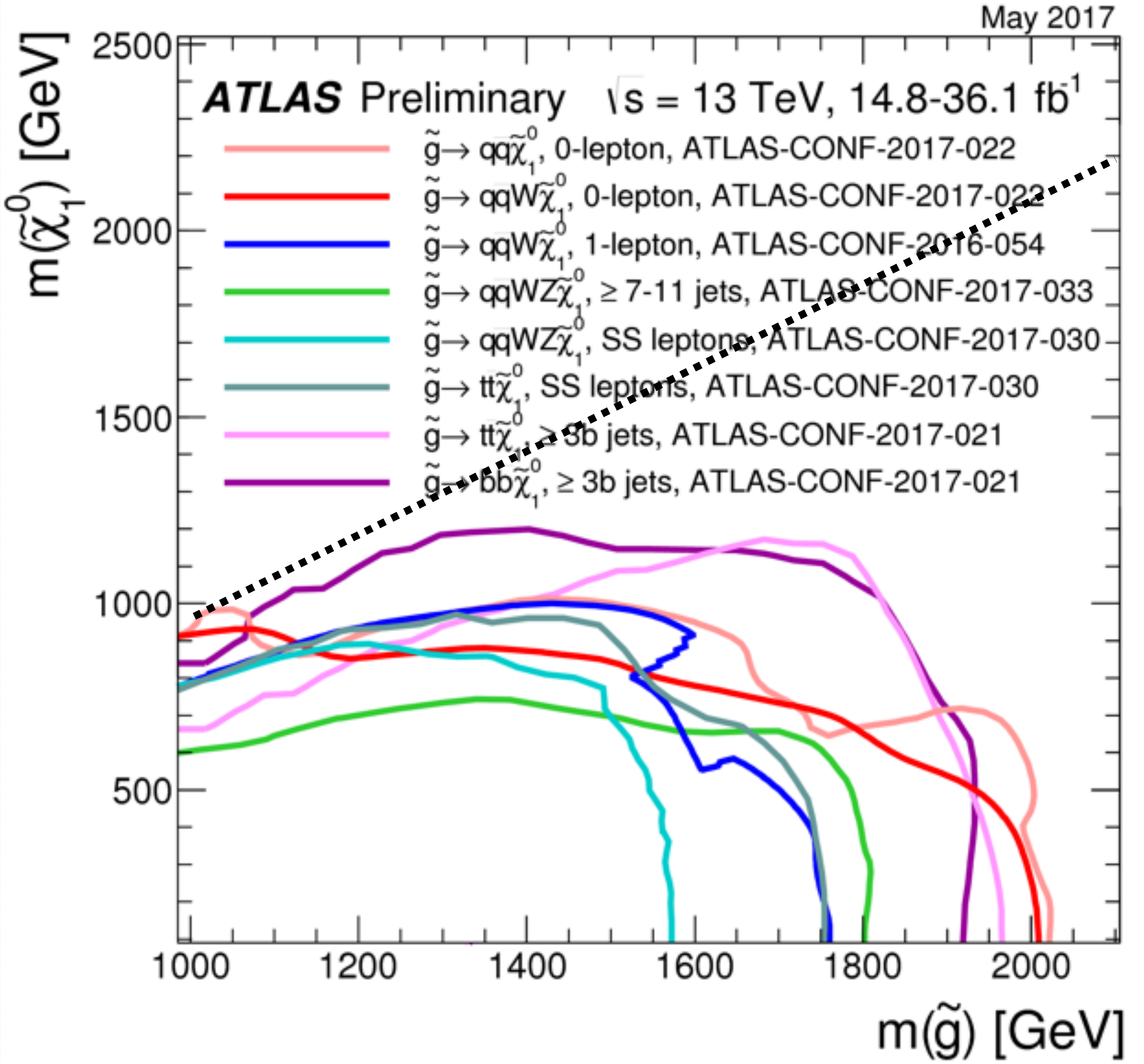
- but there are more another way to fix the SM problem.



gauge coupoing Unification

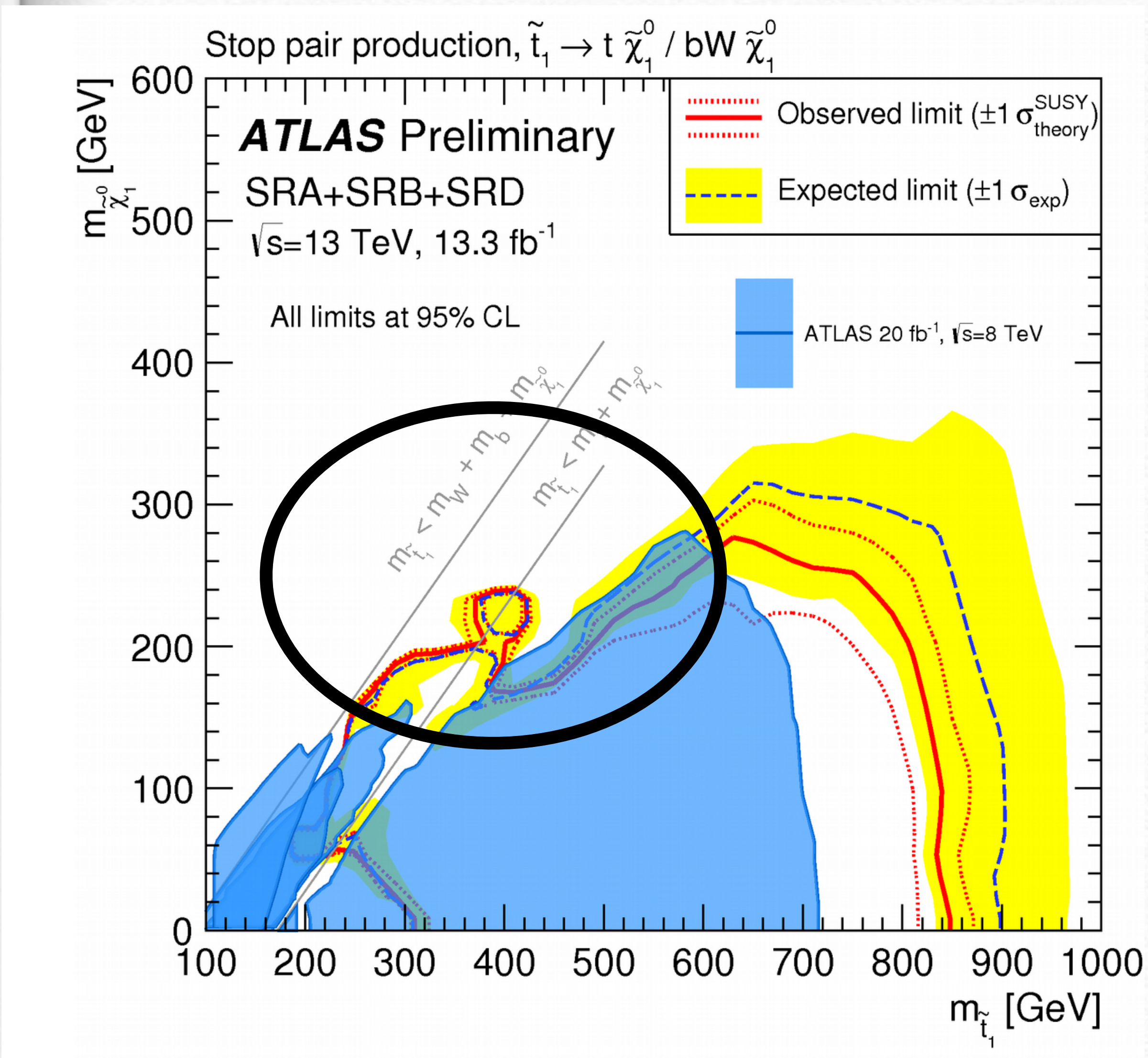


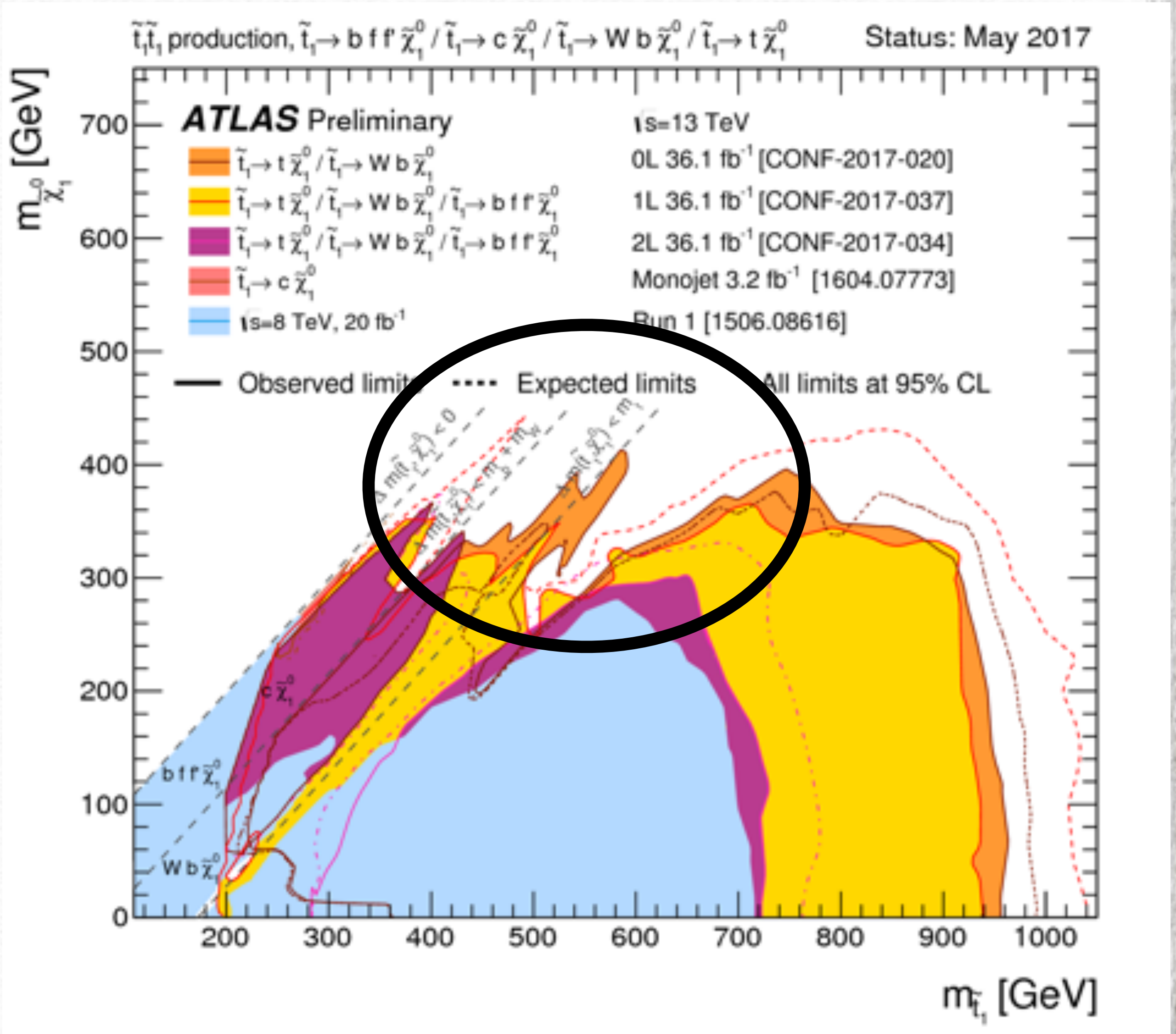
SUSY Limits:gluino



stop searches

1. Small production cross section, huge background from top
2. There is no hole in mstop ~ mt + mLSP region now
3. hadronic channel does better than leptonic
4. mono jet search(next slide)





excluded region depends on branching ratio you assume

Need to

1. Reduce branch into stop to t chi

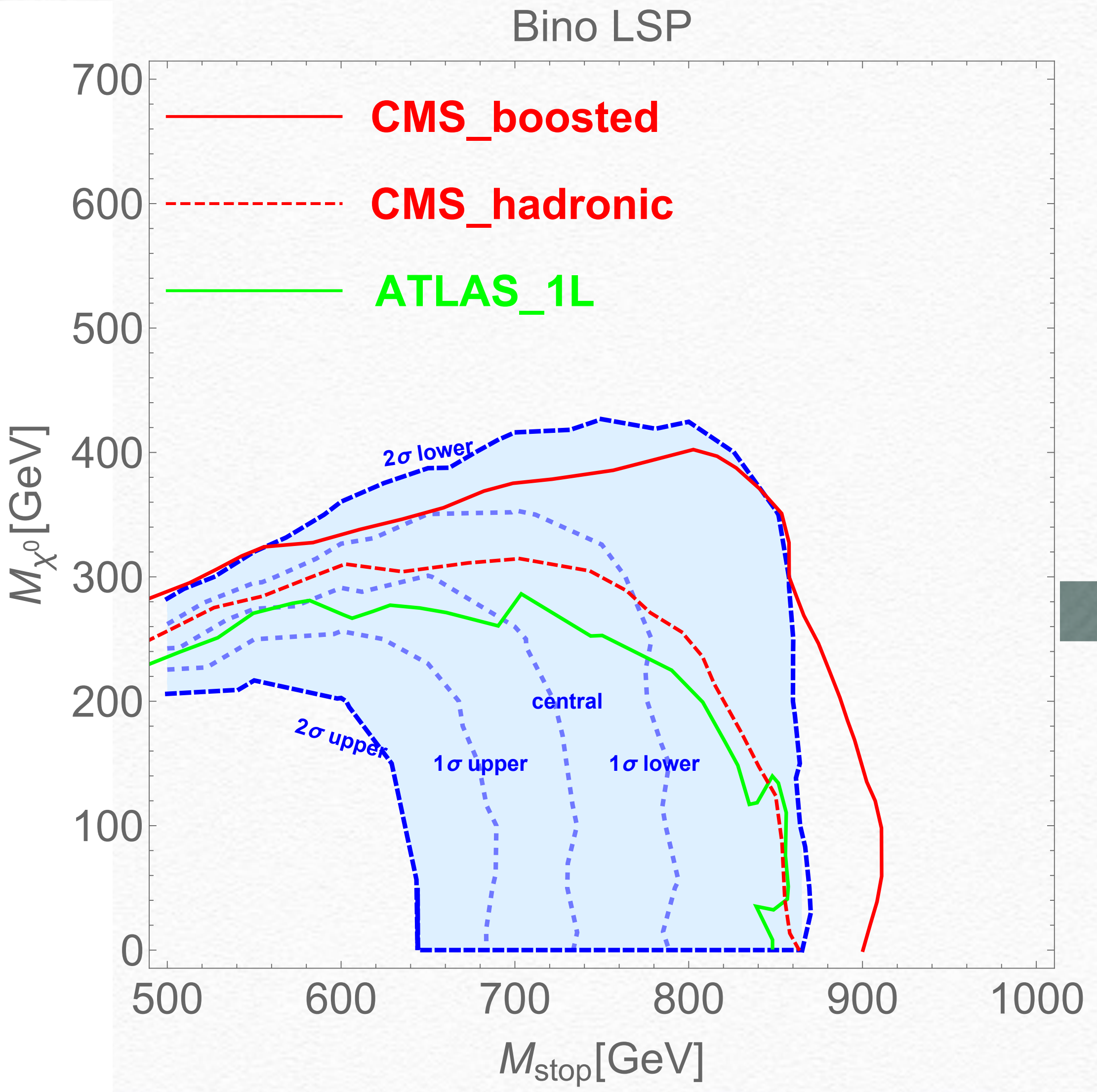
2. Keep lepton branch

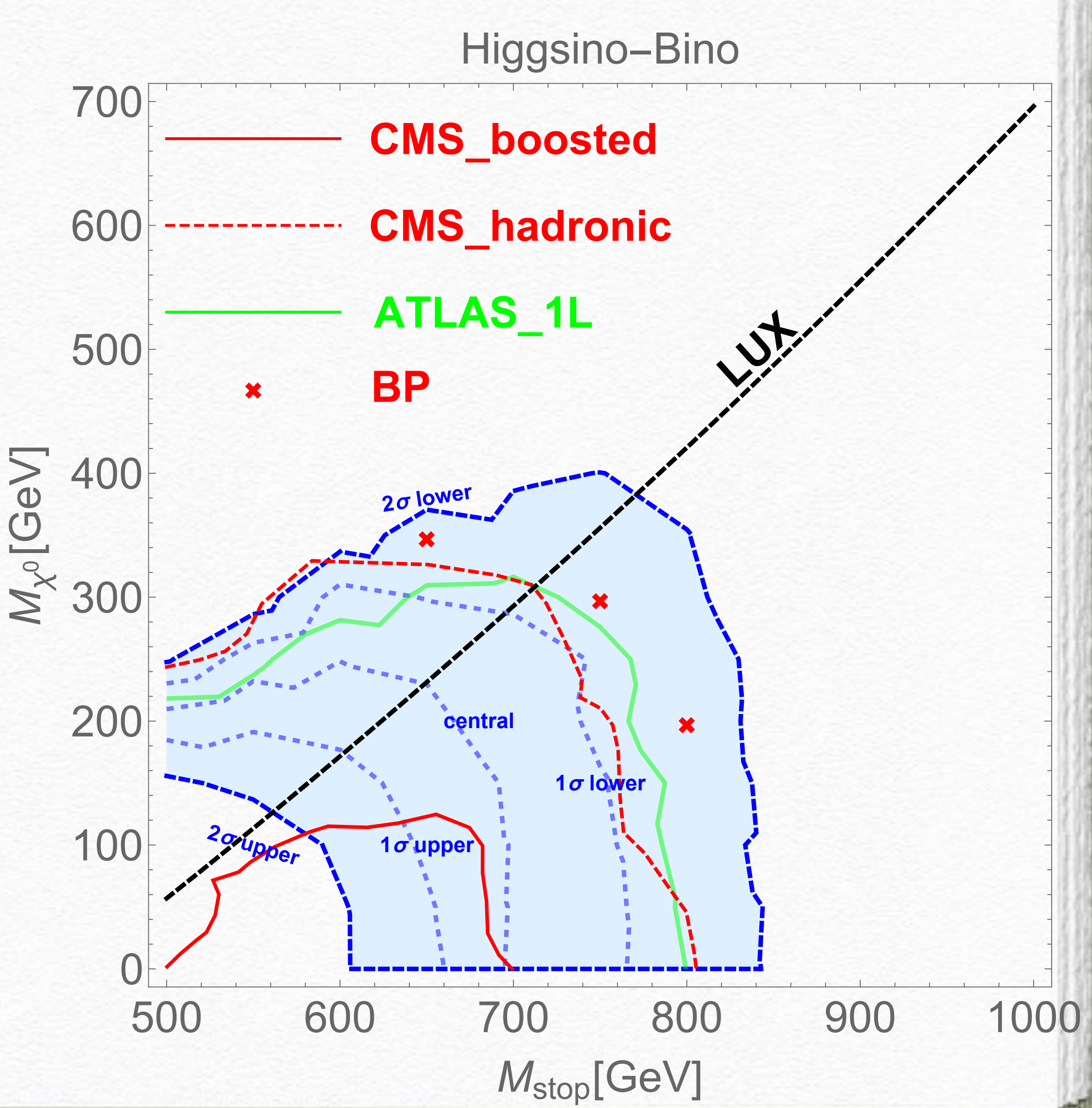
stop(right handed) →higgsino→ bino W .

*dark matter search constraints from Higgsino Bino mixing

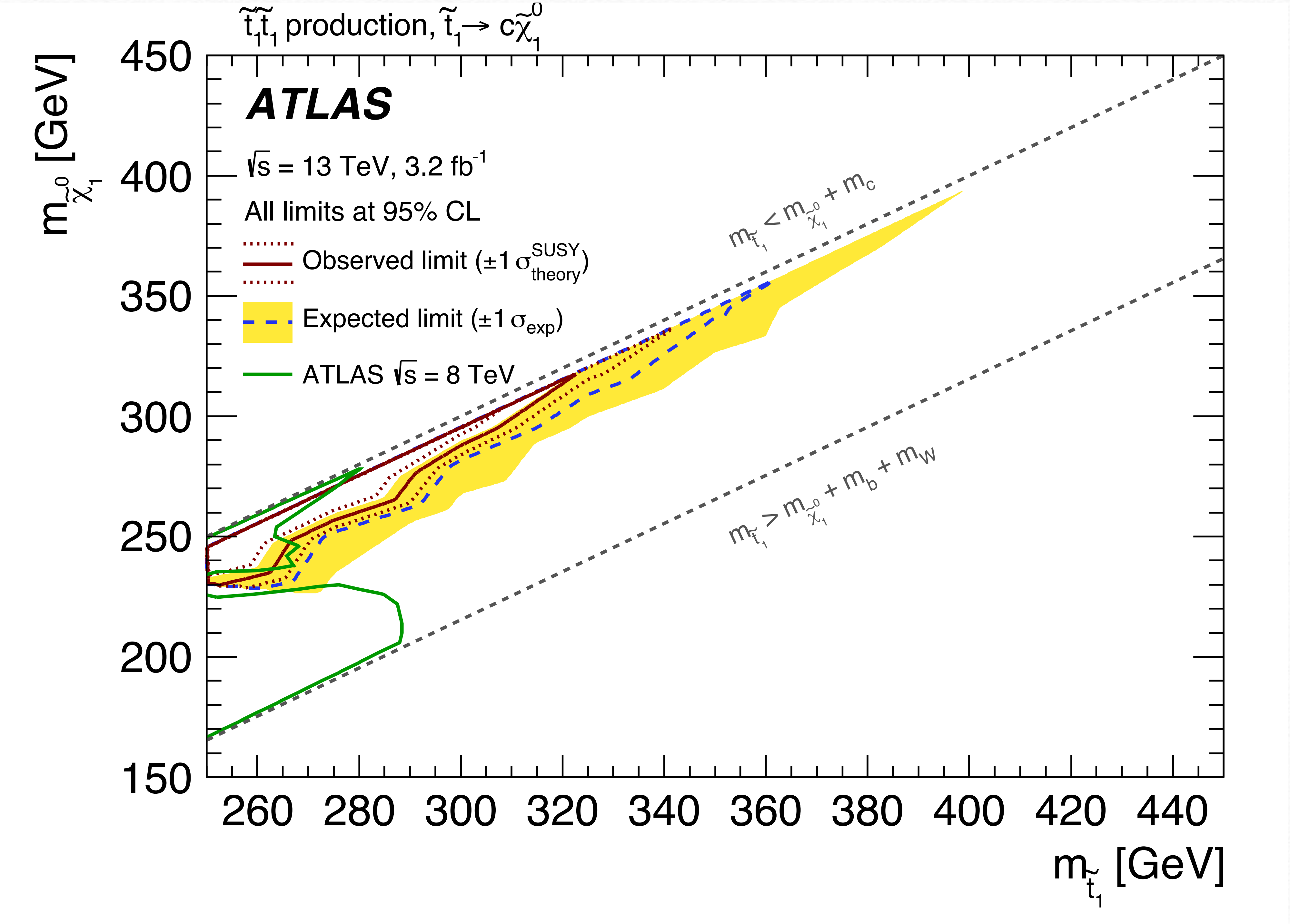
*Dark matter density can be adjusted by bin-slepton co-annihiliation

Han, Takeuchi, Yanagida, and MN

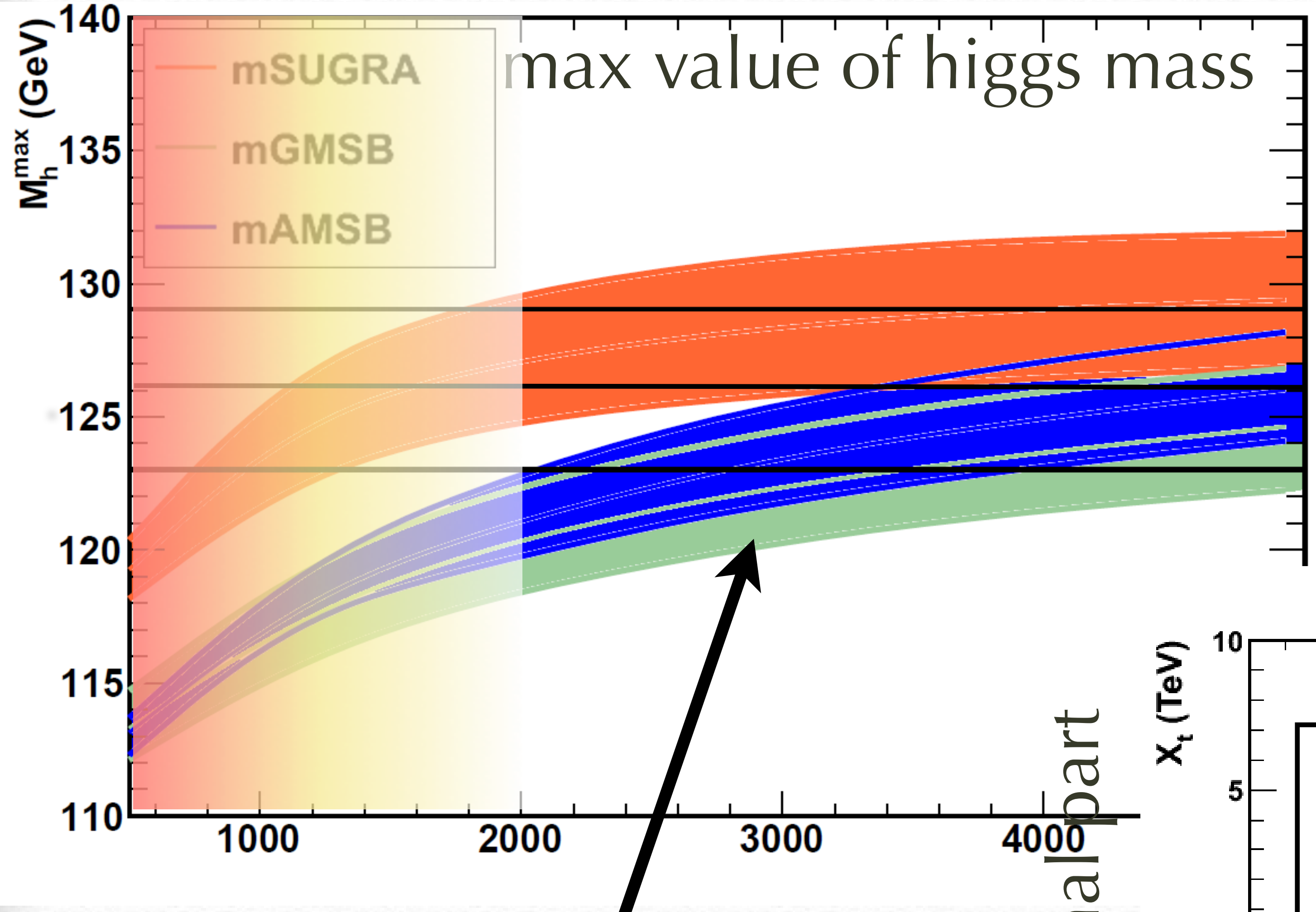




monojet search for stop



Higgs mass vs stop mass



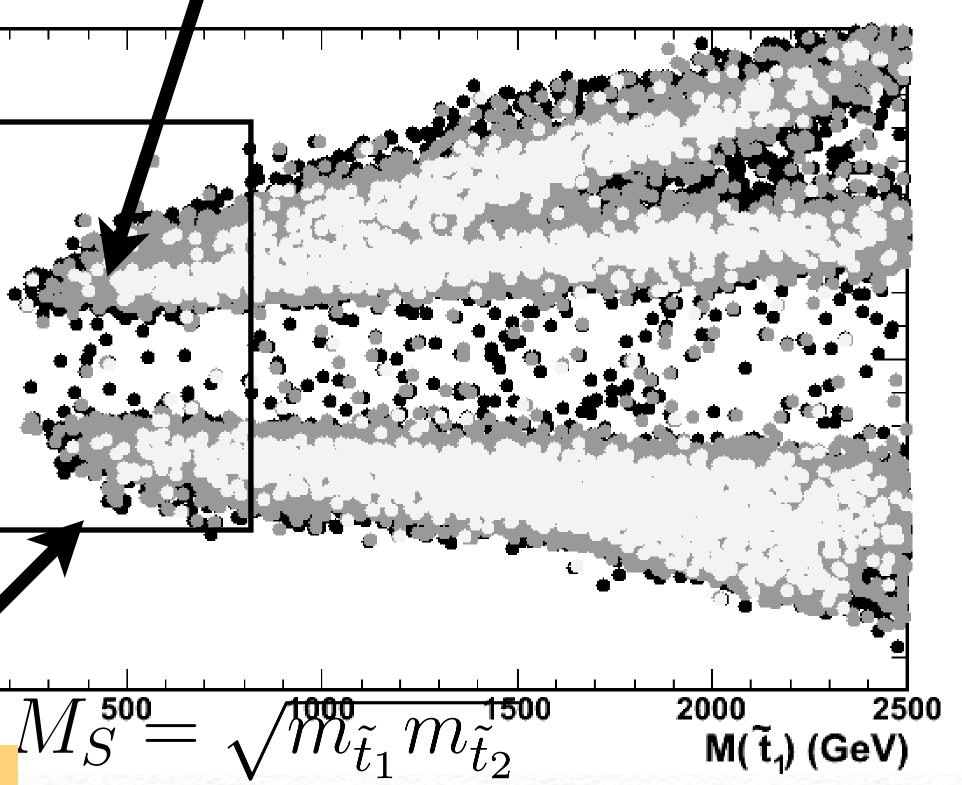
max value of higgs mass

} top mass uncertainty

GM →add additional matters?

AMSB → large squark mass

off diagonal part



$M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$

large stop mixing

Facing heavy scale SUSY
Recent debates on the calculation on the Higgs mass for very large SUSY scale

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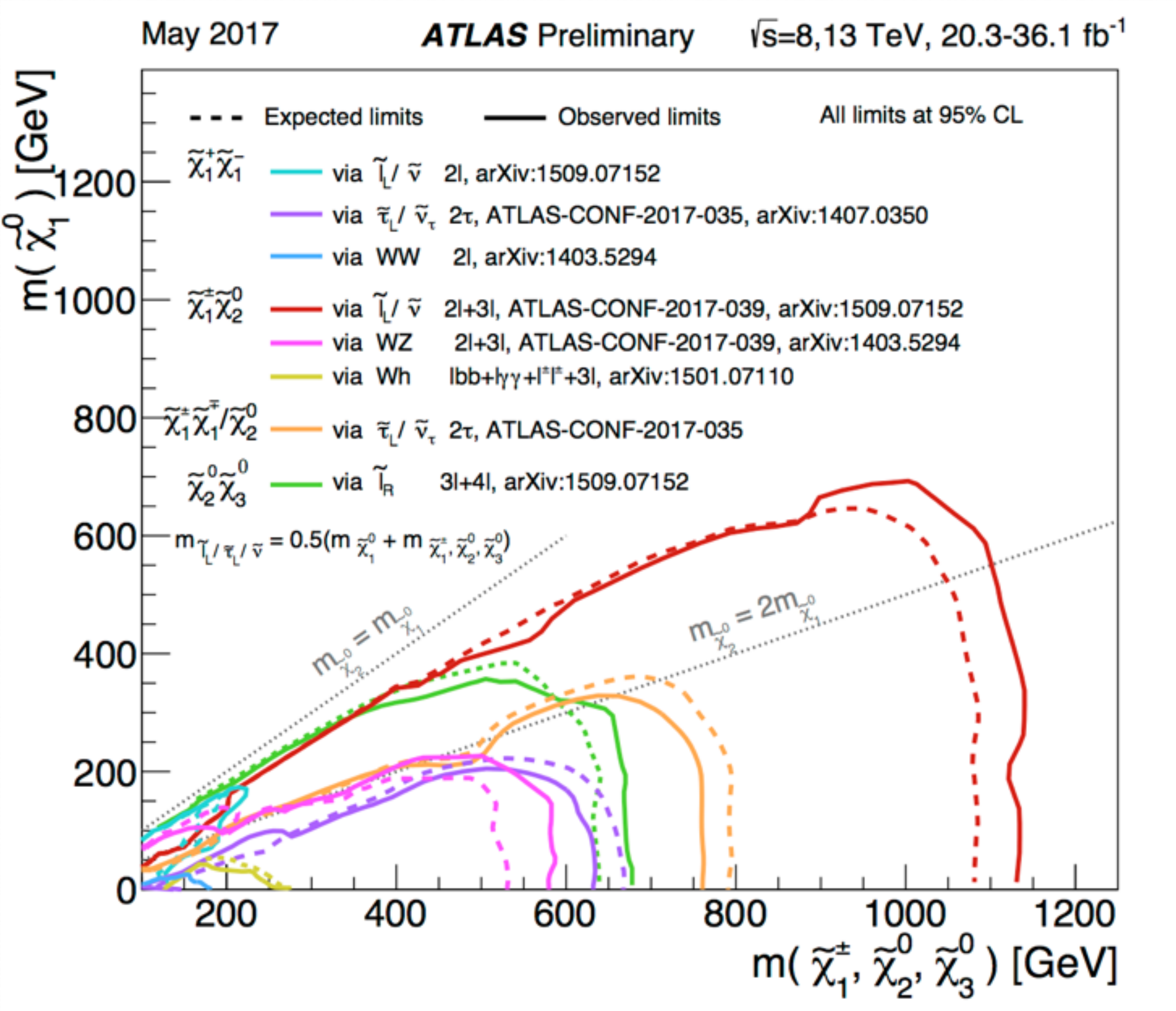
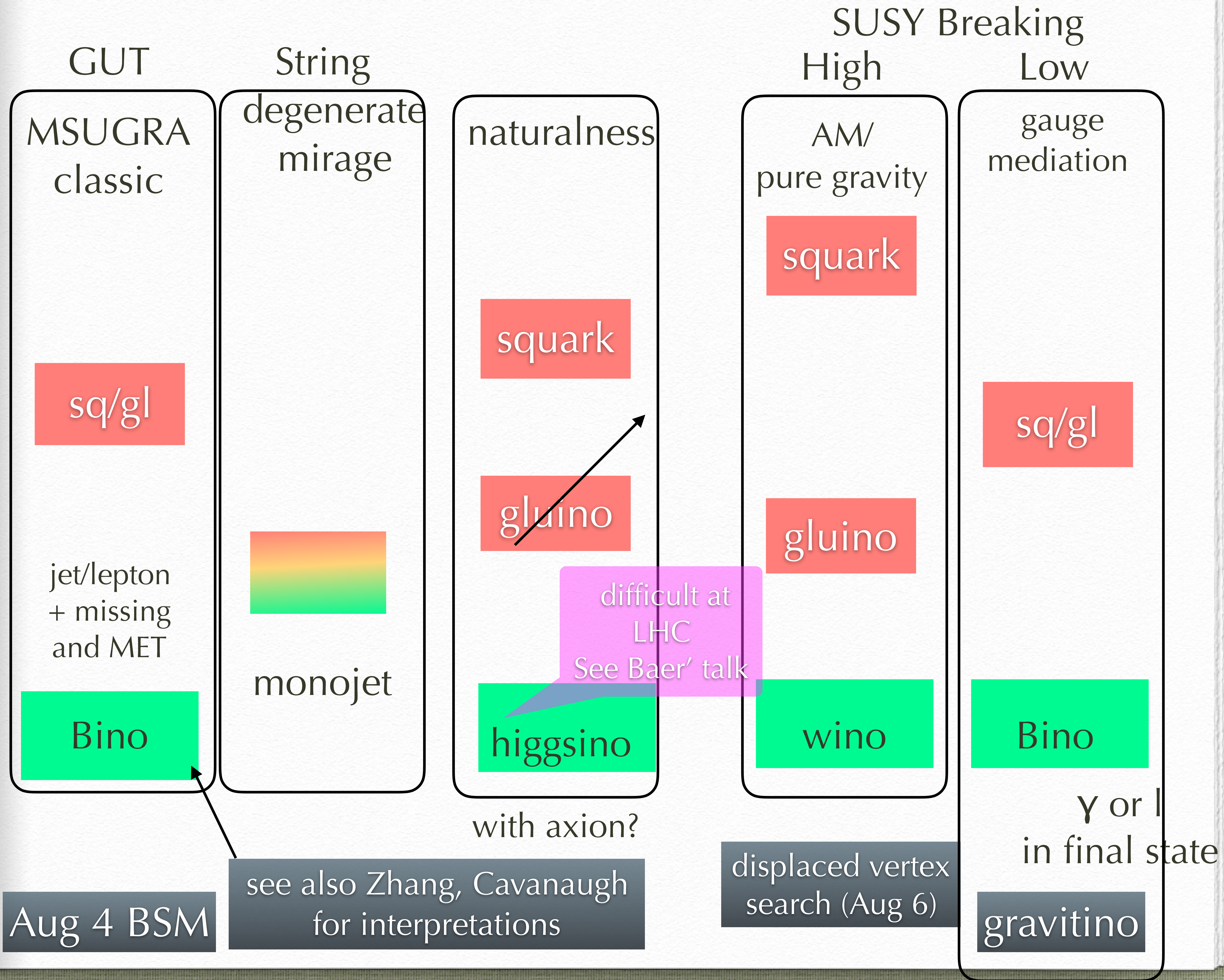

May 2017
ATLAS Preliminary
$\sqrt{s}$=8,13 TeV, 20.3-36.1 fb^{-1}
Expected limits
Observed limits
All limits at 95% CL
$\tilde{\chi}_1^+\tilde{\chi}_1^-$
via $\tilde{l}_L / \tilde{\nu}$ 2l, arXiv:1509.07152
via $\tilde{\tau}_L / \tilde{\nu}_\tau$ 2τ, ATLAS-CONF-2017-035, arXiv:1407.0350
via WW 2l, arXiv:1403.5294
$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$
via $\tilde{l}_L / \tilde{\nu}$ 2l+3l, ATLAS-CONF-2017-039, arXiv:1509.07152
via WZ 2l+3l, ATLAS-CONF-2017-039, arXiv:1403.5294
via Wh lbb+lγγ+l$^\pm$l$^\pm$+3l, arXiv:1501.07110
$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0$
via $\tilde{\tau}_L / \tilde{\nu}_\tau$ 2τ, ATLAS-CONF-2017-035
$\tilde{\chi}_2^0\tilde{\chi}_3^0$
via $\tilde{l}_R$ 3l+4l, arXiv:1509.07152
$m_{\tilde{l}_L/\tilde{\tau}_L/\tilde{\nu}} = 0.5(m_{\tilde{\chi}_1^0} + m_{\tilde{\chi}_1^\pm,\tilde{\chi}_2^0,\tilde{\chi}_3^0})$
$m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^0}$
$m_{\tilde{\chi}_2^0} = 2m_{\tilde{\chi}_1^0}$
$m(\tilde{\chi}_1^0)$ [GeV]
0
200
400
600
800
1000
1200
200
400
600
800
1000
1200
$m(\tilde{\chi}_1^\pm, \tilde{\chi}_2^0, \tilde{\chi}_3^0)$ [GeV]



GUT

MSUGRA
classic

sq/gl

jet/lepton
+ missing
and MET

Bino

String

degenerate
mirage

monojet

naturalness

squark

gluino

higgsino

difficult at
LHC
See Baer' talk

with axion?

SUSY Breaking

High

AM/
pure gravity

squark

gluino

wino

displaced vertex
search (Aug 6)

Low

gauge
mediation

sq/gl

Bino

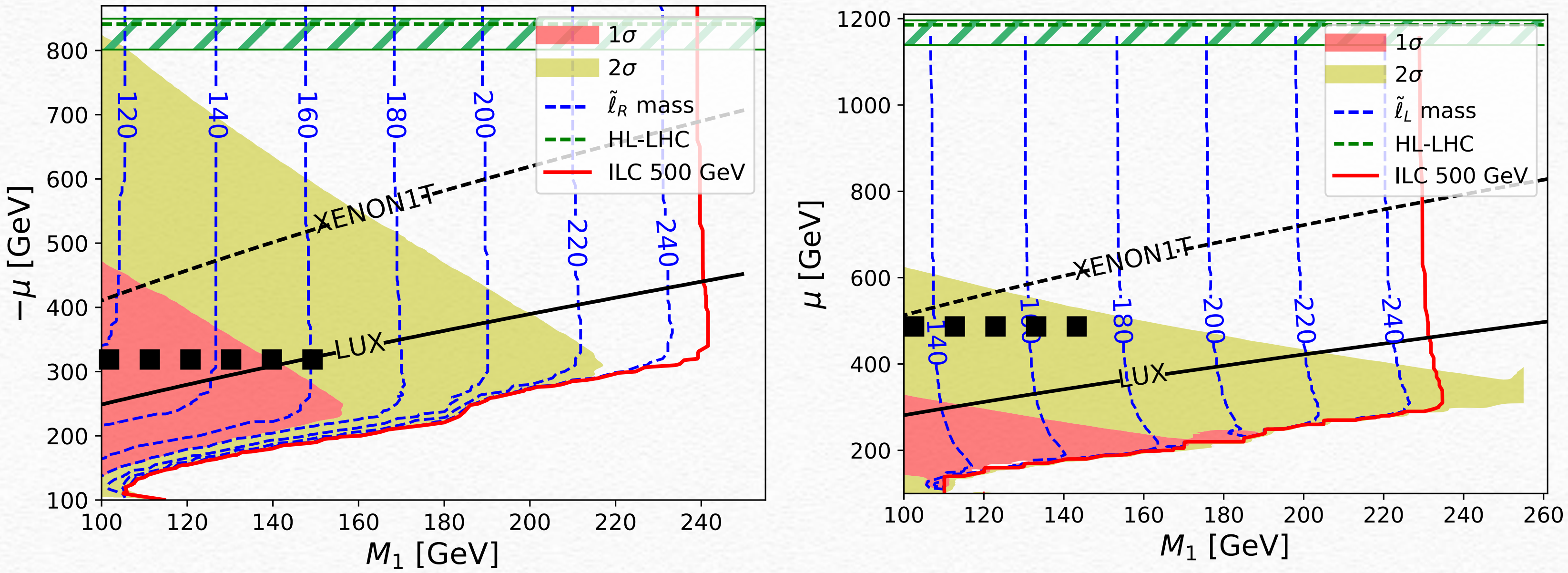
γ or l
in final state

gravitino

see also Zhang, Cavanaugh
for interpretations

Aug 4 BSM

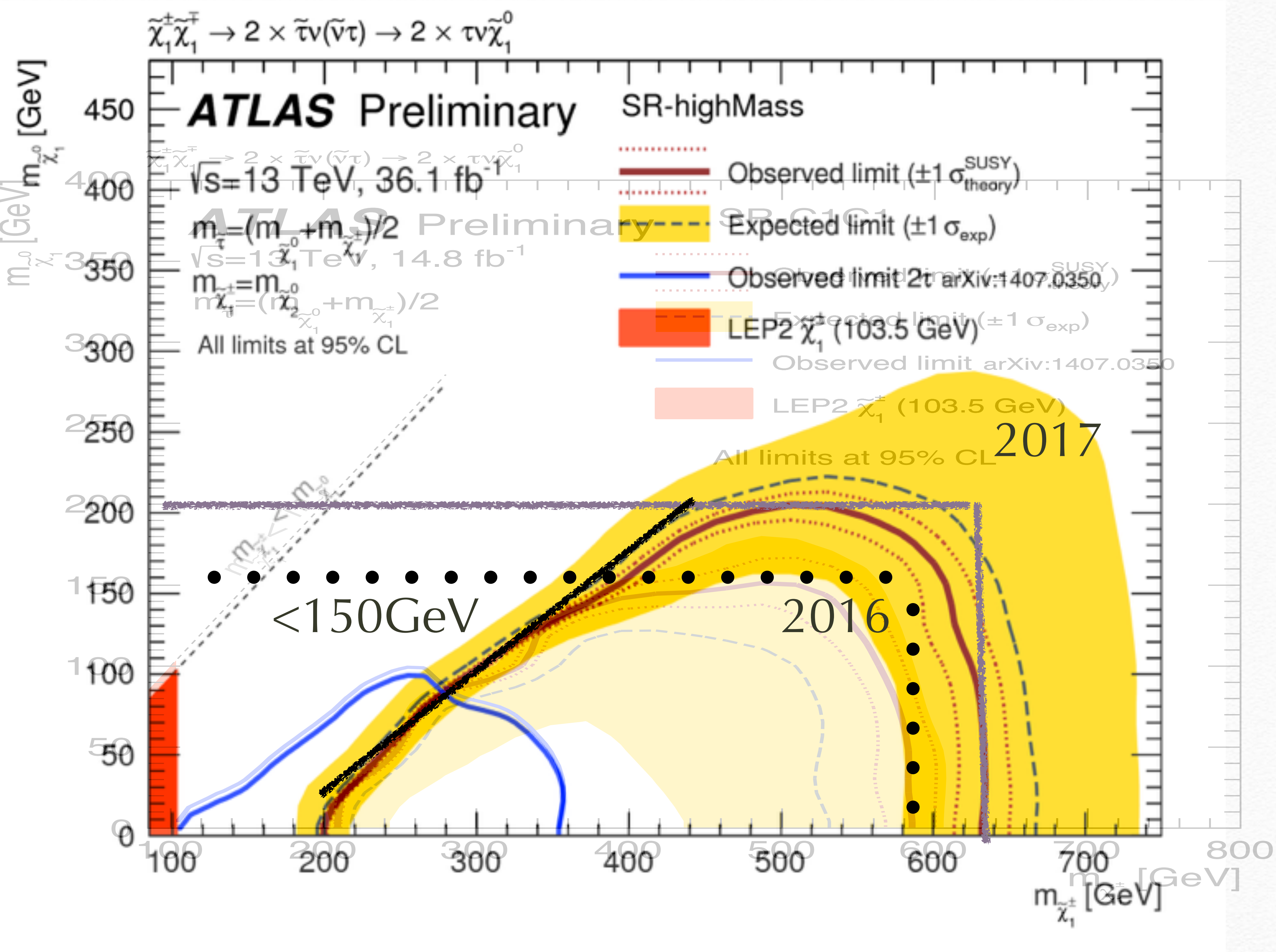
pull to lower scale. g-2 anomaly bino-Higgsino case



Limits by 2016

Figure 1: The parameter region of our interest for the BHR scenario (left panel) and BHL scenario (right panel), together with experimental constraints and future prospects. We use $\tan\beta = 40$ and $M_2 = 3\,\mathrm{TeV}$. The blue contours show the slepton mass $m_{\tilde\ell_R}$ or $m_{\tilde\ell_L}$ that gives $\Omega_{\rm LSP} = \Omega_{\rm DM}$. With the slepton mass, the muon $g-2$ discrepancy is explained within 1σ (2σ) uncertainty in the red (yellow) regions. The regions below the solid (dashed) lines are excluded (will be probed) by the LUX (XENON1T) experiment with 90% confidence level. The regions below the green dashed lines will be probed by the HL-LHC with $\sqrt{s} = 14\,\mathrm{TeV}$ and $\int\mathcal{L} = 3000\,\mathrm{fb}^{-1}$, assuming 30% systematic uncertainty from SM background; the green hatched regions correspond to different systematic uncertainties between 20% and 50%. The red solid line corresponds to $m_{\tilde\ell} = 248\,\mathrm{GeV}$, which will be probed at the ILC with $\sqrt{s} = 500\,\mathrm{GeV}$.

Endo , Hamaguchi, Iwamoto , Yanagi 1704.05287



2017

<150GeV

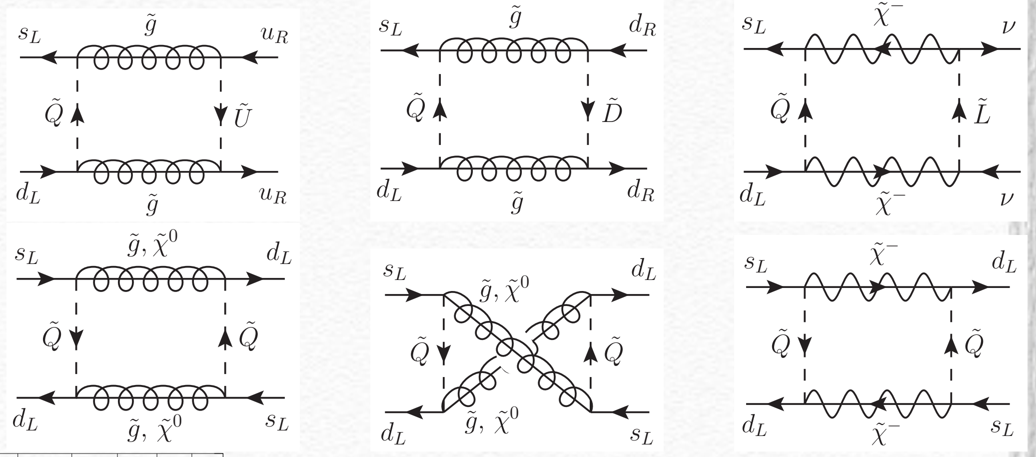
2016

need 200 GeV mass difference

K decay ε′/ε anomaly

SM $\mathrm{Re}\,(\epsilon'_K/\epsilon_K)_{\mathrm{SM}} = (1.06 \pm 4.66_{\mathrm{Lattice}} \pm 1.91_{\mathrm{NNLO}} \pm 0.59_{\mathrm{IV}} \pm 0.23_{m_t}) \times 10^{-4}$,

measured $\mathrm{Re}\,(\epsilon'_K/\epsilon_K)_{\mathrm{exp}} = (16.6 \pm 2.3) \times 10^{-4}$



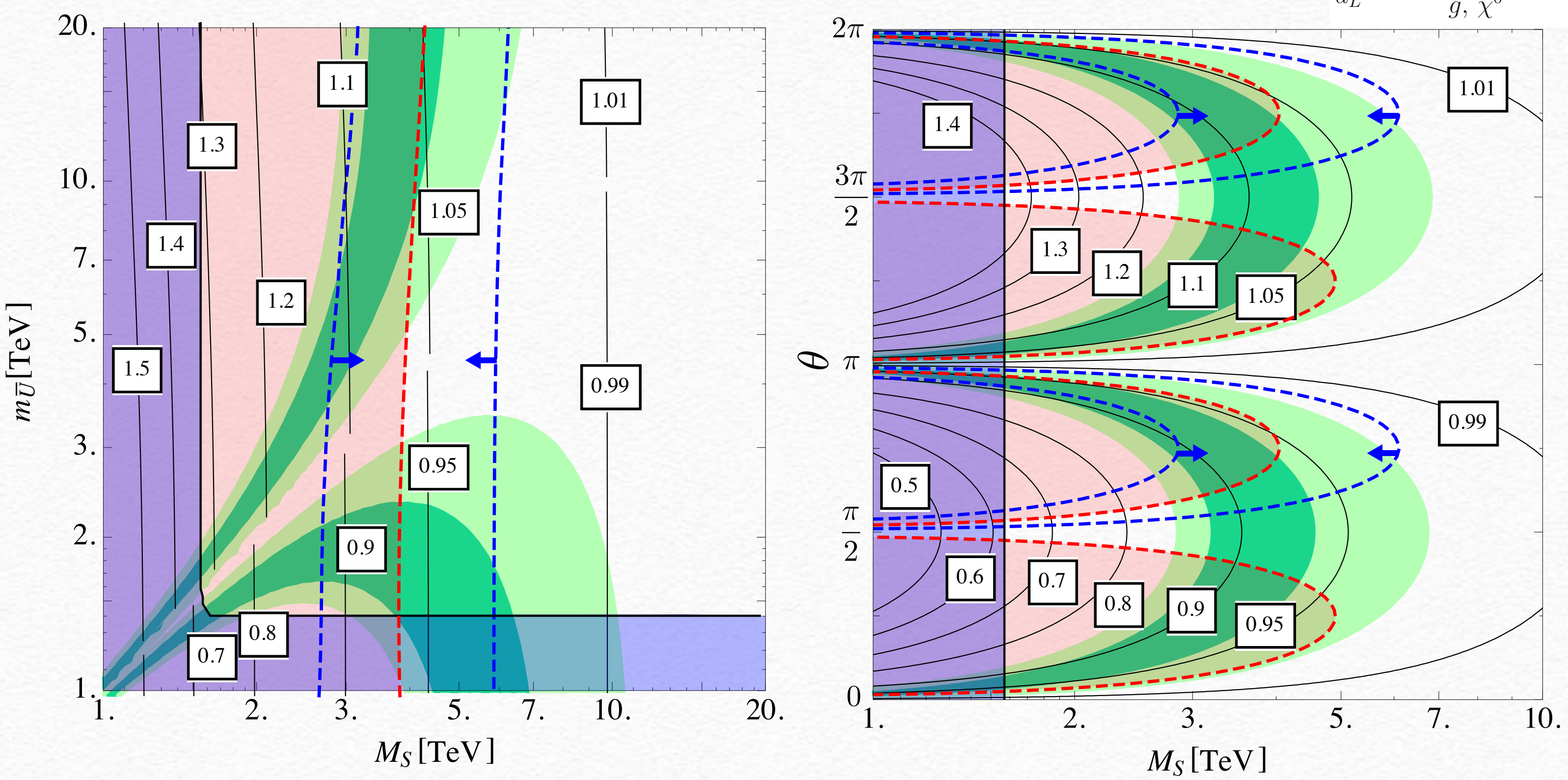


FIG. 2. Contours of $\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})/\mathcal{B}^{\mathrm{SM}}(K_L \to \pi^0\nu\bar{\nu})$. The ϵ'_K/ϵ_K discrepancy is resolved at the $1\,\sigma$ ($2\,\sigma$) level within the dark (light) green region. The red shaded region is excluded by ϵ_K at 95 % C.L. using the inclusive value $|V_{cb}|$, while the region between the blue-dashed lines can explain the ϵ_K discrepancy which is present if the exclusive determination of V_{cb} is used [42]. The blue shaded region is excluded by the current LHC results from CMS and ATLAS [39–41]. $M_3/M_S = 1.5$, $m_L = 300$ GeV and GUT relations among gaugino masses are used. In the *left* plot, $\Delta_{Q,12} = 0.1\exp(-i\pi/4)$ for $m_{\bar{U}} > m_{\bar{D}} = m_Q = M_S$ (upper branch) and $\Delta_{Q,12} = 0.1\exp(i3\pi/4)$ for $m_{\bar{U}} < m_{\bar{D}} = m_Q = M_S$ (lower branch). In the *right* plot, $|\Delta_{Q,12}| = 0.1$ is used, $m_{\bar{D}} = 2m_{\bar{U}} = 2m_Q = 2M_S$ (for $0 < \theta < \pi$) and $m_{\bar{U}} = 2m_{\bar{D}} = 2m_Q = 2M_S$ (for $\pi < \theta < 2\pi$).

High Luminosity or High Energy, or e+e-, or even muon ?

I will be talking about “Technology” or “Theory” that enable **the success** of LHC

~“Precision QCD”

- QCD Matrix element calculation
- NNLO corrections
- Jet and soft physics

Collider Physics in 2010 is different those in '00

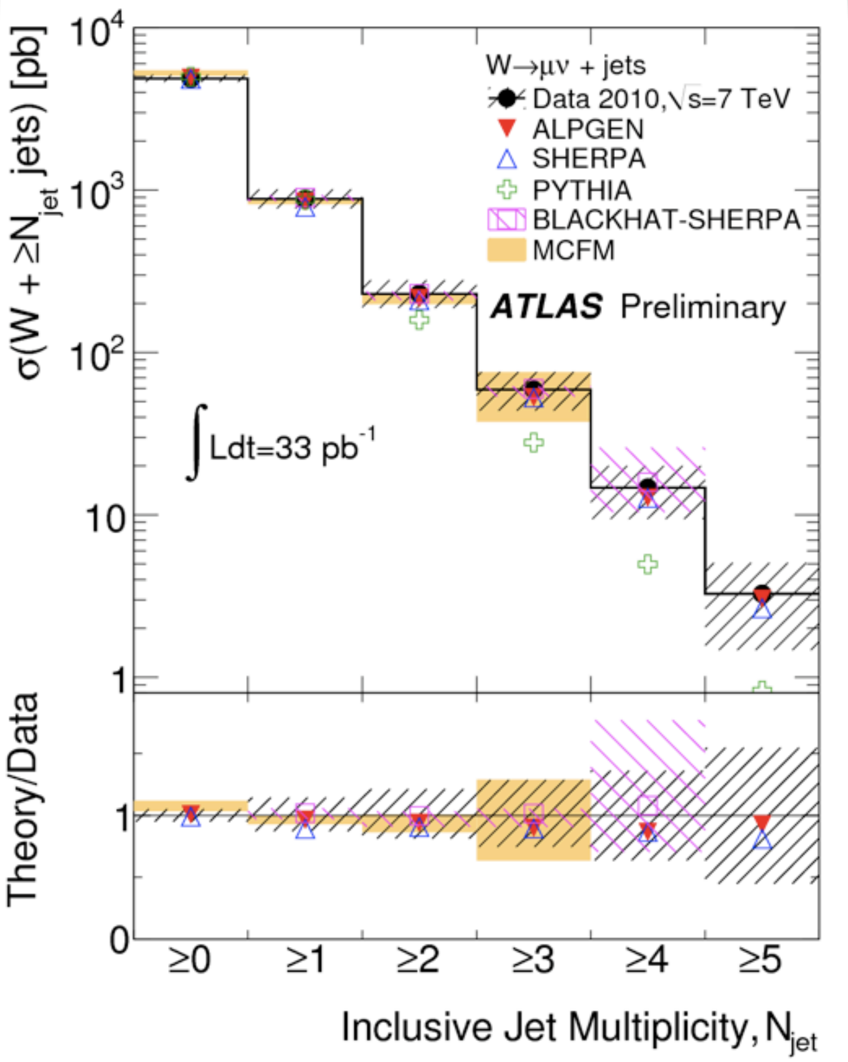
- In 90's: We do not know how to calculate multijet processes at the hadron collider precisely. "I do not trust hadron collider physics" is typical attitudes in e+e-collider funs in 90's.

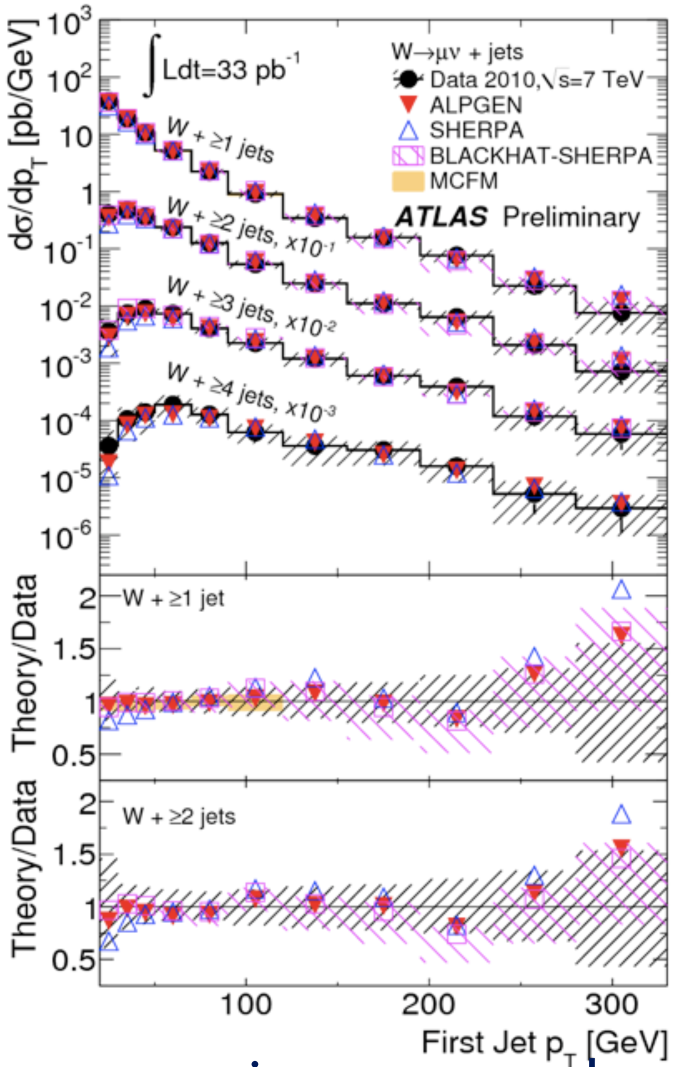
photo 1972

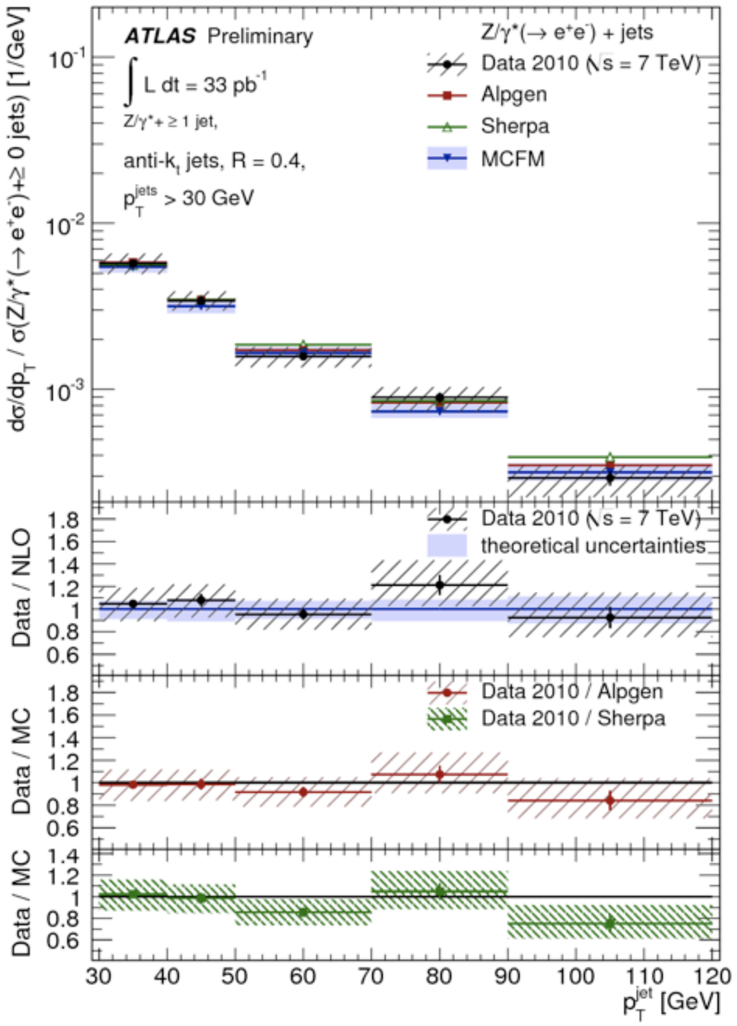
- Now: we understand higher oder QCD (multijet process) and its NLO correction better
- This also means **we do not "discover" anything until we should discover** them. (unlike the era of SPS)
- We can also "calibrate" using plenty of data.

W/Z + jet results

This is where we are







dominant systematics

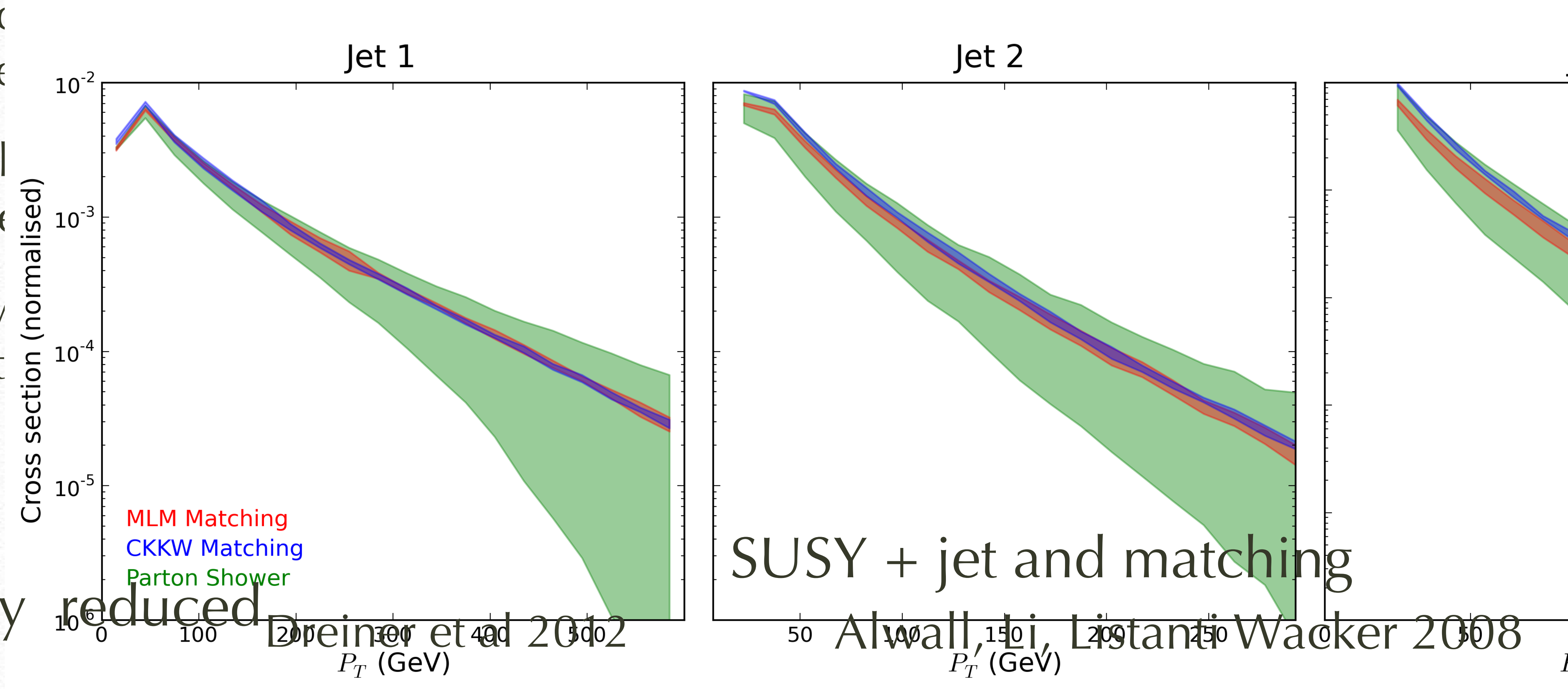
- JES: 8(26)% for $N_j \geq 1(4)$
- jets from pile-up ≈7%
- lep. reco. ≈ 2%
- QCD bkgd ≈ 2%
- unfolding ≈ 2%

- cross section measured as a function of several kinematic variables (see end of this talk)
- very good agreement with NLO predictions from MCFM and Blackhat-Sherpa in the total and differential cross sections
- good agreement with matched LO prediction from AlpGen and Sherpa once normalized to the NNLO prediction
- Poor agreement with LO PYTHIA in the high jet multiplicity

key component I :

Parton shower Matrix element matching

- For typic
  processe
- Original
  but large
- Better w
  element
- Applied



SUSY + jet and matching

uncertainty reduced

Dreiner et al 2012

Alwall, Li, Listanti Wacker 2008

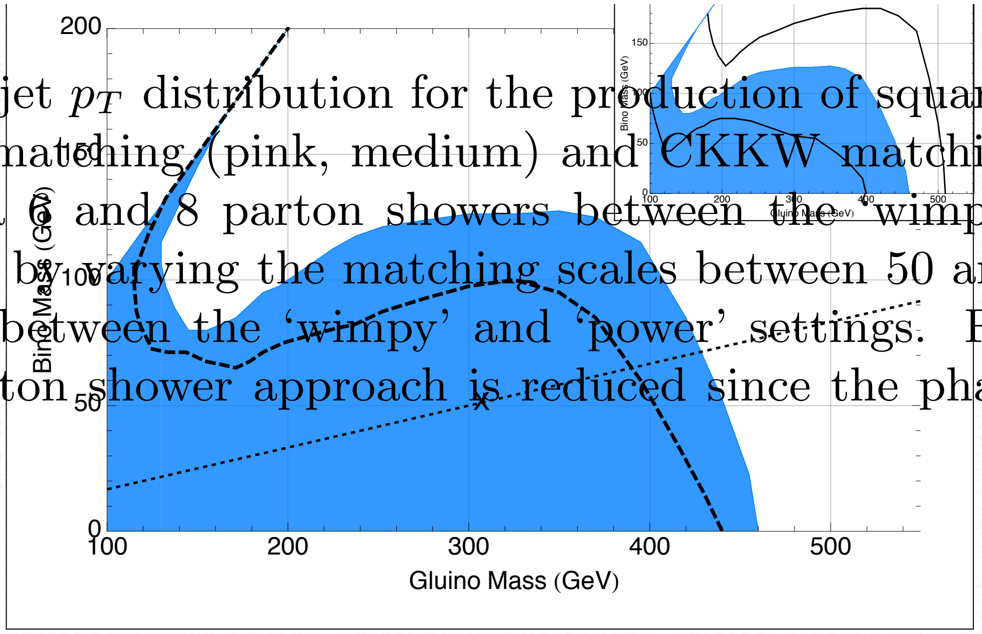


Fig. 1: A comparison of the uncertainty in the ISR jet p_T distribution for the production of squarks
the parton shower prediction (green, light), MLM matching (pink, medium) and CKKW matching
shower uncertainty is found by varying the Pythia 6 and 8 parton showers between the 'wimpy'
The matching uncertainties are found in both cases by varying the matching scales between 50 and
for MLM matching by varying the parton shower between the 'wimpy' and 'power' settings. For
unmatched jet), the relative uncertainty of the parton shower approach is reduced since the phase
better constrained.

Key component 2
NLO, NNLO, NNLL

NLO wish list (2005~ complited in 2012,
and we also have them in MC (means, NLL)
for almost all processes you need.

1) multiple jets (up to 4 jets)

2) a gauge boson and up to 5 jets

3) multiple gauge bosons in association with jets (up to VV + 2j)

4) top quarks in association with jets (up to two) and gauge bosons (W,Z, photon)

5) Higgs and jets

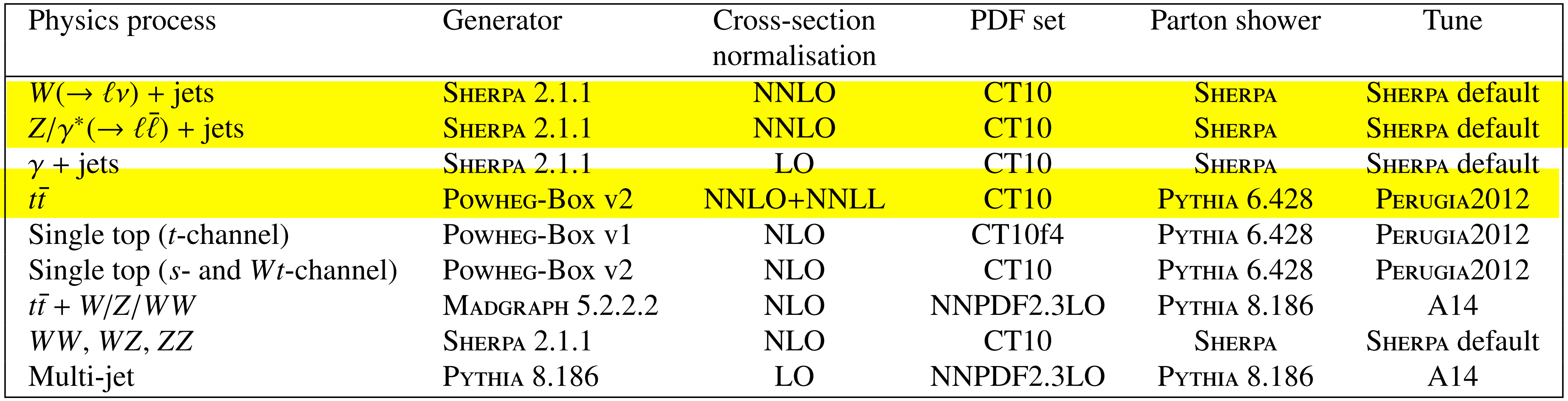
たいへんよくできました

LO O(100 %) error
NLO O(10%) error
NNLO O(1%) error

very good historical records that additional NLO calculation provide the better fit to the the data.

NLO computing is demanding, but our WS (Xenon E5, 12core) does Tp Tp + 1jet (pT> 20
in NLO using Madgraph MC @NLO O(10^4)events 2 hours.

background modeling at 13TeV is different from that of 8TeV



Physics process	Generator	Cross-section normalisation	PDF set	Parton shower	Tune
$W(\to \ell\nu)$ + jets	Sherpa 2.1.1	NNLO	CT10	Sherpa	Sherpa default
$Z/\gamma^*(\to \ell\bar{\ell})$ + jets	Sherpa 2.1.1	NNLO	CT10	Sherpa	Sherpa default
γ + jets	Sherpa 2.1.1	LO	CT10	Sherpa	Sherpa default
$t\bar{t}$	Powheg-Box v2	NNLO+NNLL	CT10	Pythia 6.428	Perugia2012
Single top (t-channel)	Powheg-Box v1	NLO	CT10f4	Pythia 6.428	Perugia2012
Single top (s- and Wt-channel)	Powheg-Box v2	NLO	CT10	Pythia 6.428	Perugia2012
$t\bar{t} + W/Z/WW$	MadGraph 5.2.2.2	NLO	NNPDF2.3LO	Pythia 8.186	A14
WW, WZ, ZZ	Sherpa 2.1.1	NLO	CT10	Sherpa	Sherpa default
Multi-jet	Pythia 8.186	LO	NNPDF2.3LO	Pythia 8.186	A14

on going progress on reducing the theoretical uncertainty on the background

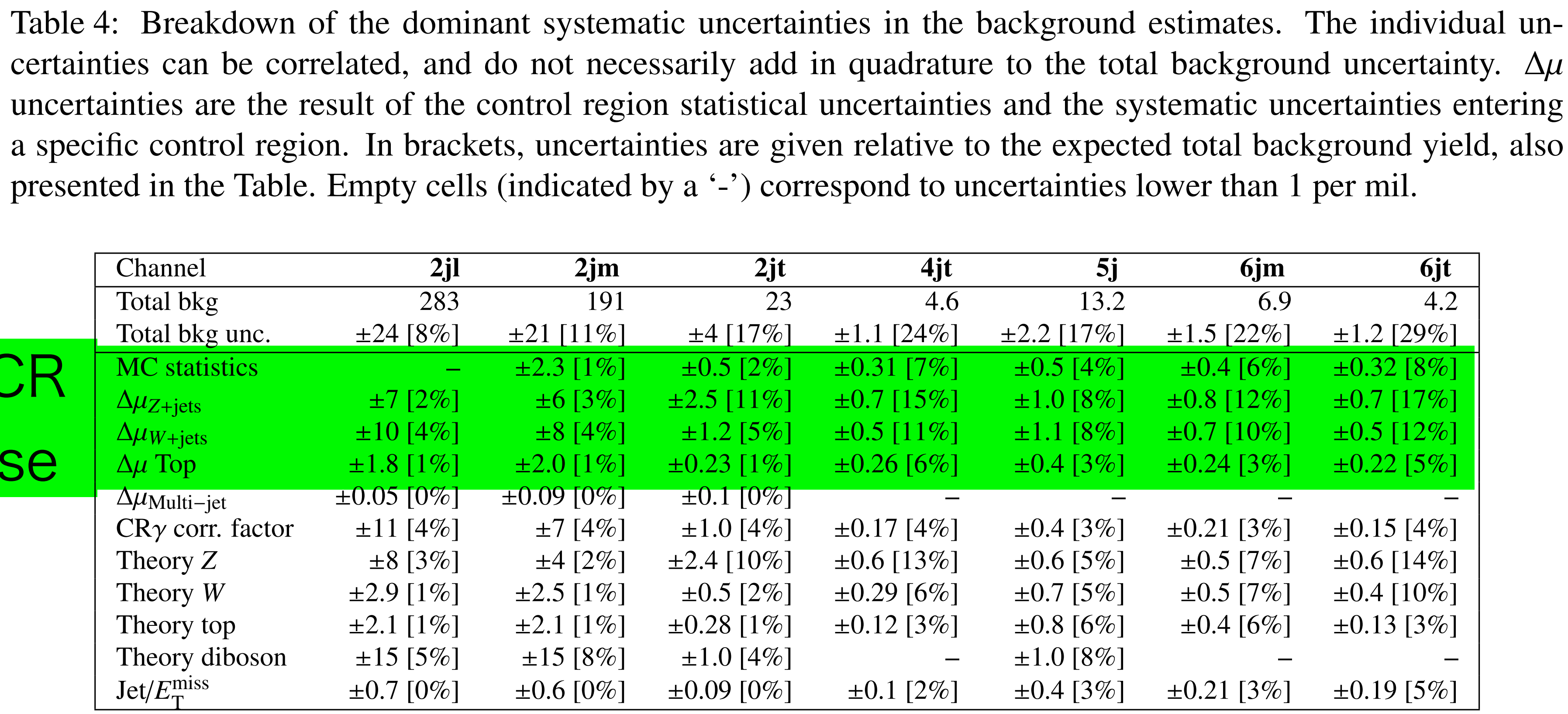
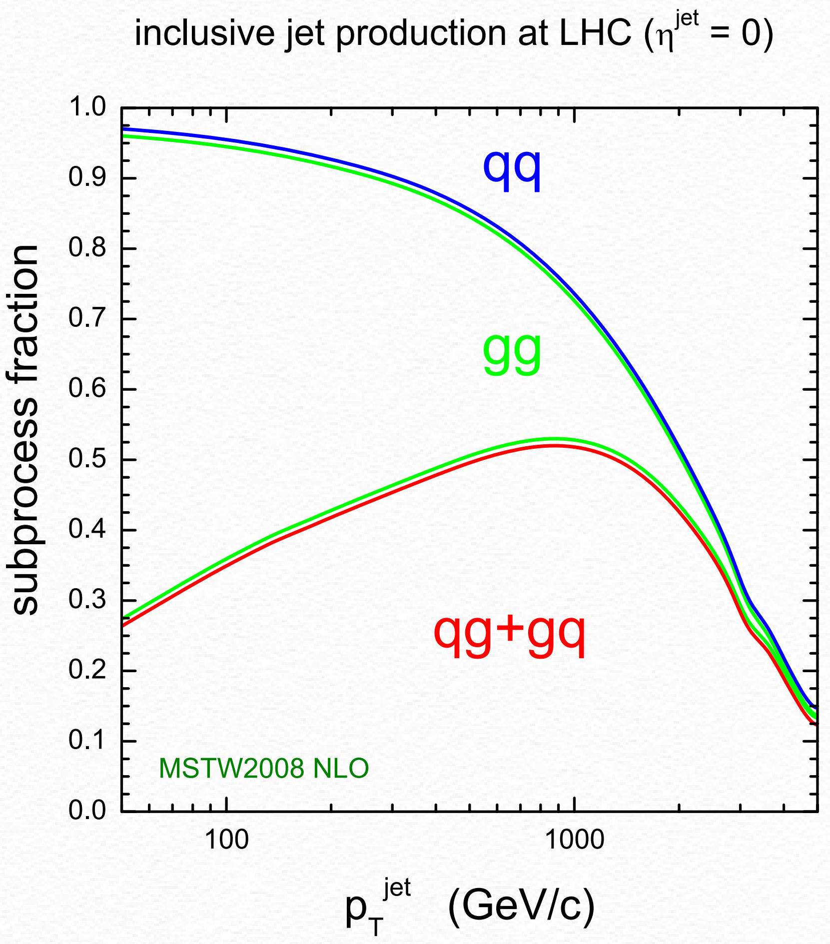


Table 4: Breakdown of the dominant systematic uncertainties in the background estimates. The individual uncertainties can be correlated, and do not necessarily add in quadrature to the total background uncertainty. $\Delta\mu$ uncertainties are the result of the control region statistical uncertainties and the systematic uncertainties entering a specific control region. In brackets, uncertainties are given relative to the expected total background yield, also presented in the Table. Empty cells (indicated by a '-') correspond to uncertainties lower than 1 per mil.

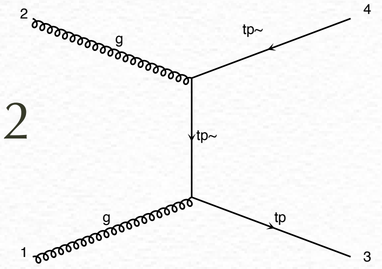
Channel	**2jl**	**2jm**	**2jt**	**4jt**	**5j**	**6jm**	**6jt**
Total bkg	283	191	23	4.6	13.2	6.9	4.2
Total bkg unc.	±24 [8%]	±21 [11%]	±4 [17%]	±1.1 [24%]	±2.2 [17%]	±1.5 [22%]	±1.2 [29%]
MC statistics	–	±2.3 [1%]	±0.5 [2%]	±0.31 [7%]	±0.5 [4%]	±0.4 [6%]	±0.32 [8%]
$\Delta\mu_{Z+\text{jets}}$	±7 [2%]	±6 [3%]	±2.5 [11%]	±0.7 [15%]	±1.0 [8%]	±0.8 [12%]	±0.7 [17%]
$\Delta\mu_{W+\text{jets}}$	±10 [4%]	±8 [4%]	±1.2 [5%]	±0.5 [11%]	±1.1 [8%]	±0.7 [10%]	±0.5 [12%]
$\Delta\mu$ Top	±1.8 [1%]	±2.0 [1%]	±0.23 [1%]	±0.26 [6%]	±0.4 [3%]	±0.24 [3%]	±0.22 [5%]
$\Delta\mu_{\text{Multi-jet}}$	±0.05 [0%]	±0.09 [0%]	±0.1 [0%]	–	–	–	–
CRγ corr. factor	±11 [4%]	±7 [4%]	±1.0 [4%]	±0.17 [4%]	±0.4 [3%]	±0.21 [3%]	±0.15 [4%]
Theory Z	±8 [3%]	±4 [2%]	±2.4 [10%]	±0.6 [13%]	±0.6 [5%]	±0.5 [7%]	±0.6 [14%]
Theory W	±2.9 [1%]	±2.5 [1%]	±0.5 [2%]	±0.29 [6%]	±0.7 [5%]	±0.5 [7%]	±0.4 [10%]
Theory top	±2.1 [1%]	±2.1 [1%]	±0.28 [1%]	±0.12 [3%]	±0.8 [6%]	±0.4 [6%]	±0.13 [3%]
Theory diboson	±15 [5%]	±15 [8%]	±1.0 [4%]	–	±1.0 [8%]	–	–
Jet/$E_{\text{T}}^{\text{miss}}$	±0.7 [0%]	±0.6 [0%]	±0.09 [0%]	±0.1 [2%]	±0.4 [3%]	±0.21 [3%]	±0.19 [5%]

statistics in CR
improve these

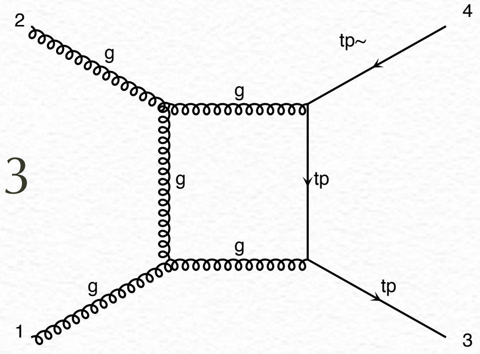


- **leading order processes may NOT be favored by PDF:** therefore, the correction tend to be large.
- in each NLO level, additional tree level process with higher order in alpha_s comes in up to NNLO→ need up to + 2 jet in your amplitude calculation to cover all possible initial state.
- MC(NLL, NNLL etc) : need to take care showers, which overlap with NLO real emission diagrams.
- **To obtain "Accurate" NNLO PDF requires higher order correction to all relevant processes.**

LO αs^2



NLO αs^3



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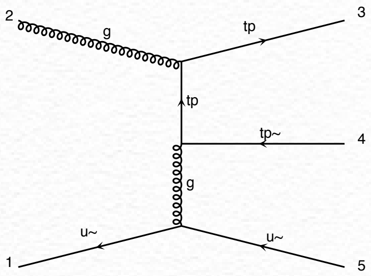


vert real

Why am I talking about this
High Luminosity run and Systematical errors

- High Luminosity is possible but No large energy increase for a moment.
- Significance is expressed at S/√(B + (δ B)^2) where δB is systematical error of the background

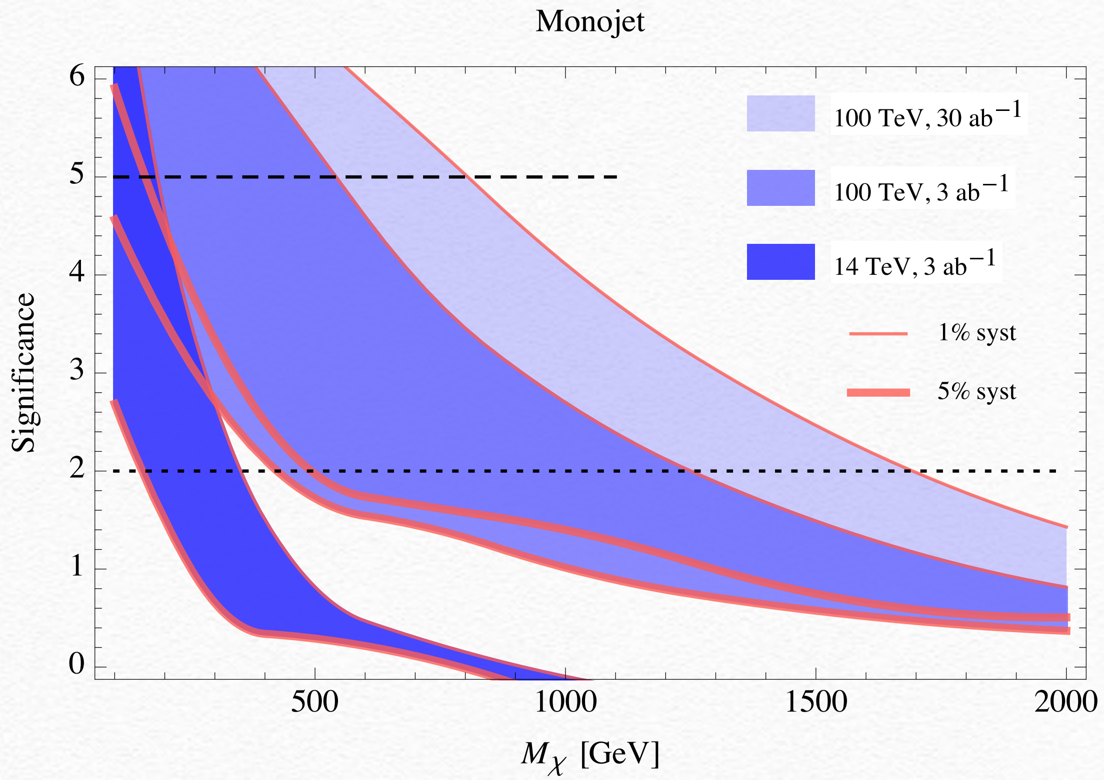


Figure 2. Reach of monojet searches.

Cirelli et al ‘14

- We need “control” on both theoretical and experimental error to see the deviation

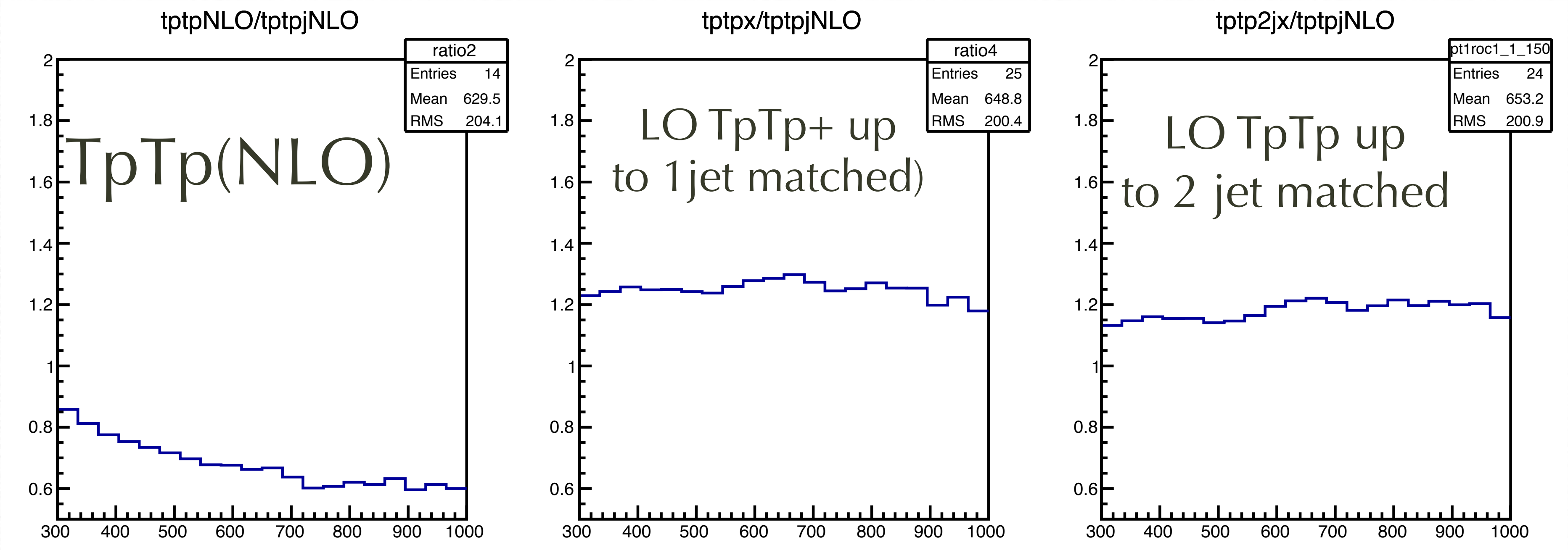
NLO simplified models with a colored particle and a DM

- the main process: XX+ jet, X is gluino, top partner, stop, or even sgluino.
- MC@NLO ⇐NLO UFO :XX+ jet NLO with matrix element level jet pT cut (say, 200GeV). the main process: XX+ jet, X is gluino, top partner, stop, or even sgluino.
- MC@NLO ⇐NLO UFO :XX+ jet NLO with matrix element level jet pT cut (say, 200GeV).
  - real + virtual XX+ jet (NLO), XX+ 2 partons (LO)

with R Ruiz, Sun Hak Lim, Amit Chakraborty(Madgraph)
Frank Krauss,Silvan Kuttimalai(Sherpa side)

signal cross section LO→NLO
top partner decaying into scalar DM

ratio to Tp Tp + 1jet (NLO) for mTp=600GeV leading jet pT cut > 300GeV



pT cut

Madgraph 2.5.4
(older one has bags)

using canonical choice of tree level cross section

TpTp+ up to 1 jet 0.126pb(canonical choice) +0.055pb- 0.46pb (no PDF error

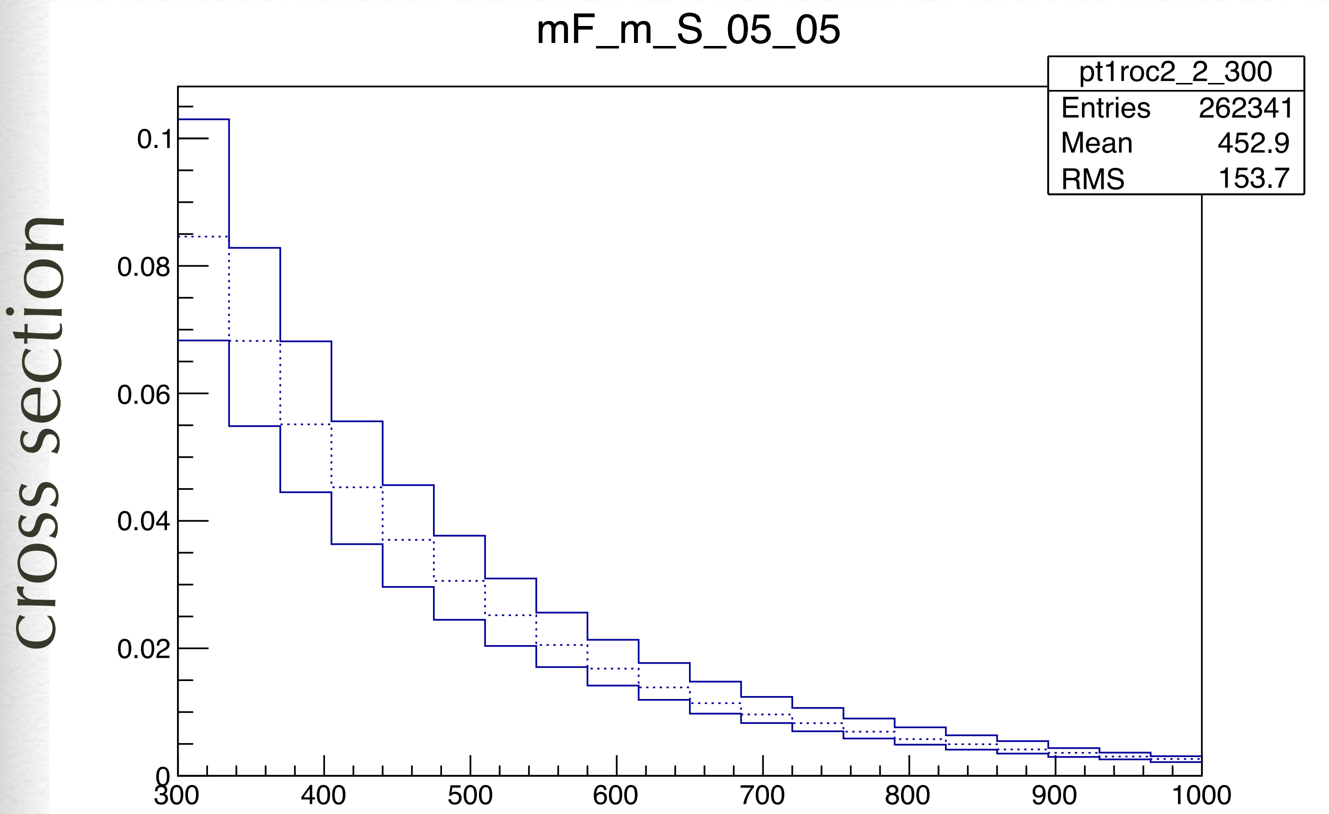
TpTp+ up to 2 jet 0.105 pb + 0.154-0.047pb (error is bigger for high pT)

TpTp NLO 0.0726+ 0.0175-0.014 (missing high pT component) +24% -19.3%

(scale dependence of cross section before the cut is smaller 1.237+0.120-0.142pb, in NNLO, it will be around half.)

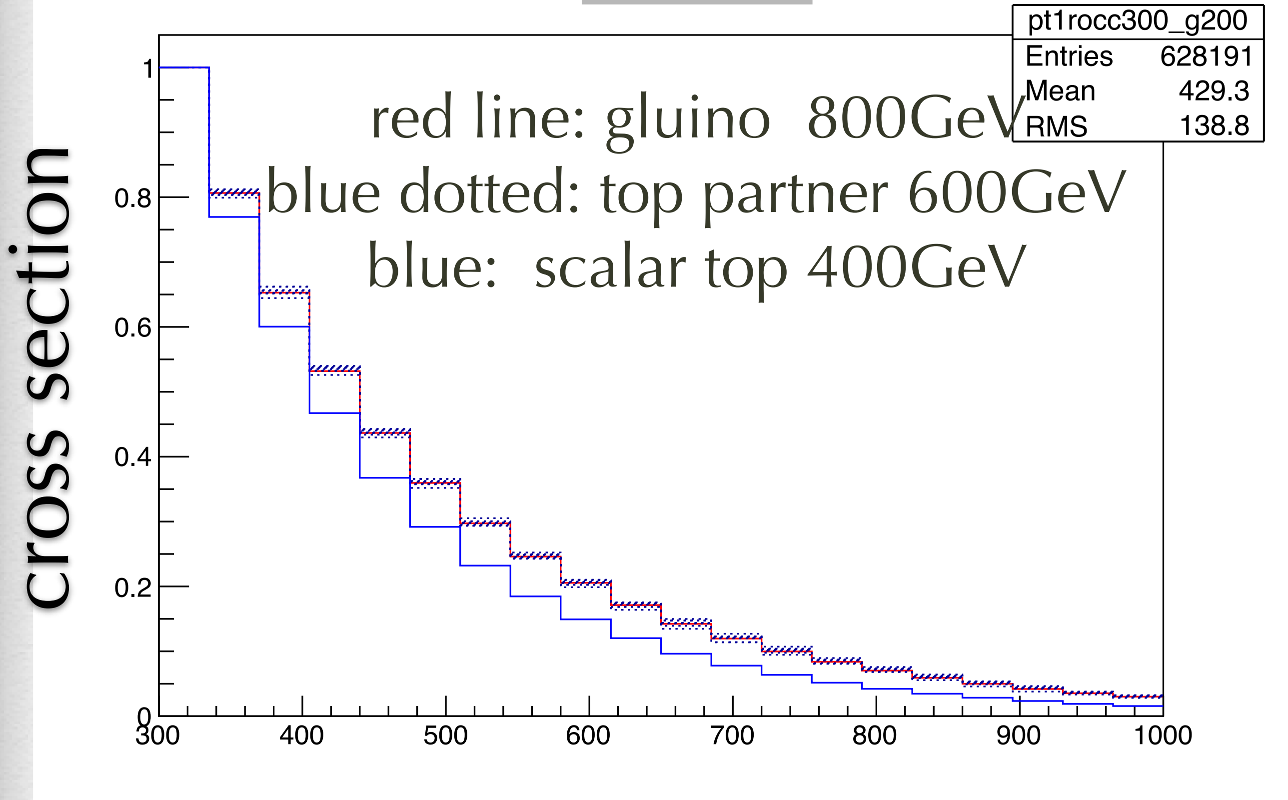
TpTp j NLO 0.0846 + 0.0184-0.0163 (acceptable level) +22% -19.2%

The error on the pT1 distribution



pt cut

scale error of cross section is 20% (ptcut> 300GeV)



red line: gluino 800GeV
blue dotted: top partner 600GeV
blue: scalar top 400GeV

by normalizing cross section to 1, scale dependence of the shape of the shape is small

stop and gluino may be distinguished if pdf error is small.

Jet Physics

Jet physics

- mergning “nearby objects to form a jet” → kT, CA, and finally Anti KT, infrared and collinear safe algorithem

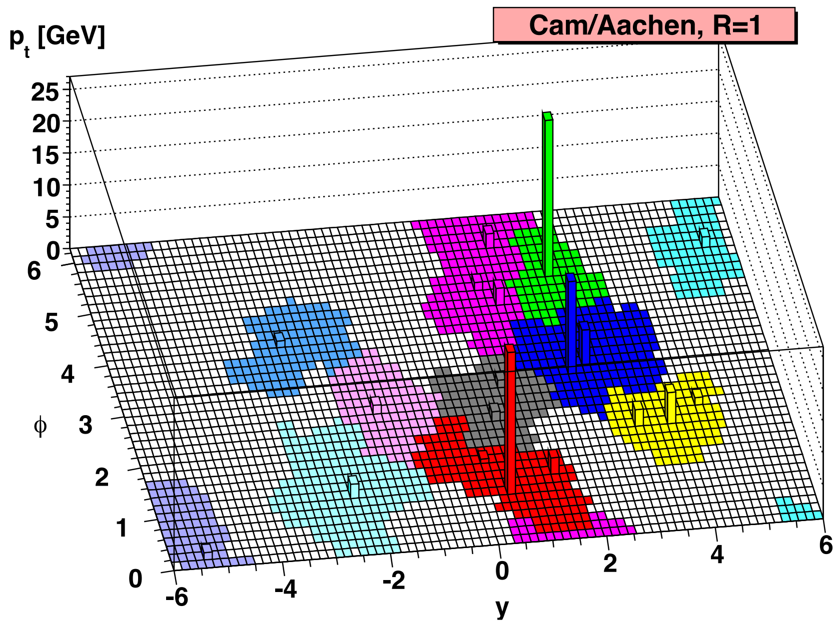
$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p}) \frac{\Delta R_{ij}^2}{R^2}, \qquad \Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

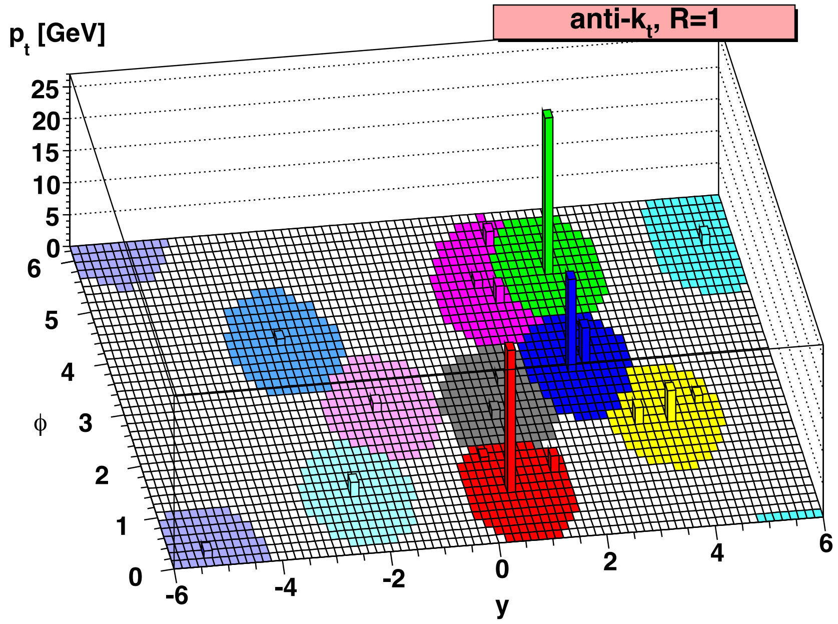
$$d_{iB} = p_{ti}^{2p},$$

CA(p=0) small angle first: motivated by angular ordering

KT(p=1) small angle or soft (good at e+e-)

Anti kt(-1) bias to high pT (similar to cone)





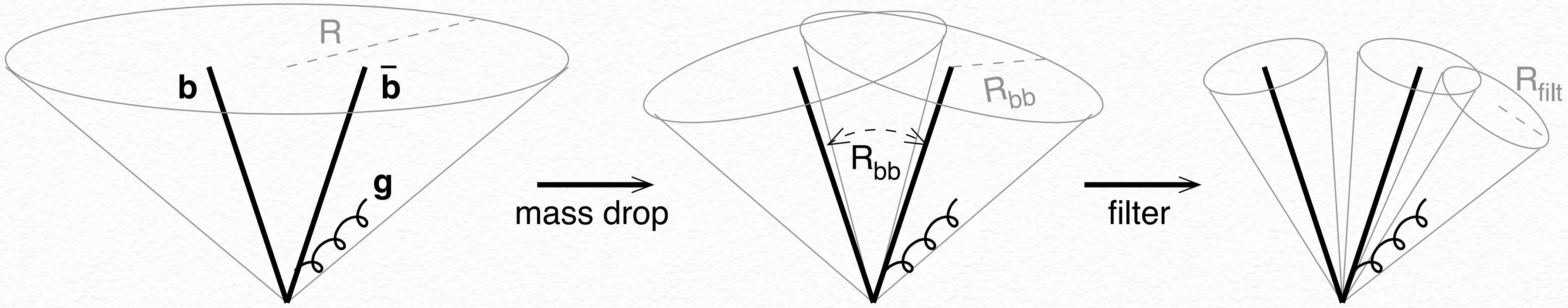
Fastjet (2005~)
The code using Voronoi diagram to find out nearest pairs efficiently reducing total time order of particle N from naive N^3

My slide in 2007

jet substructure

Butterworth, Ellis, Raklev hep-ph/0702150.
Butterworth, Davison, Rubin, Salam, 0802.2470

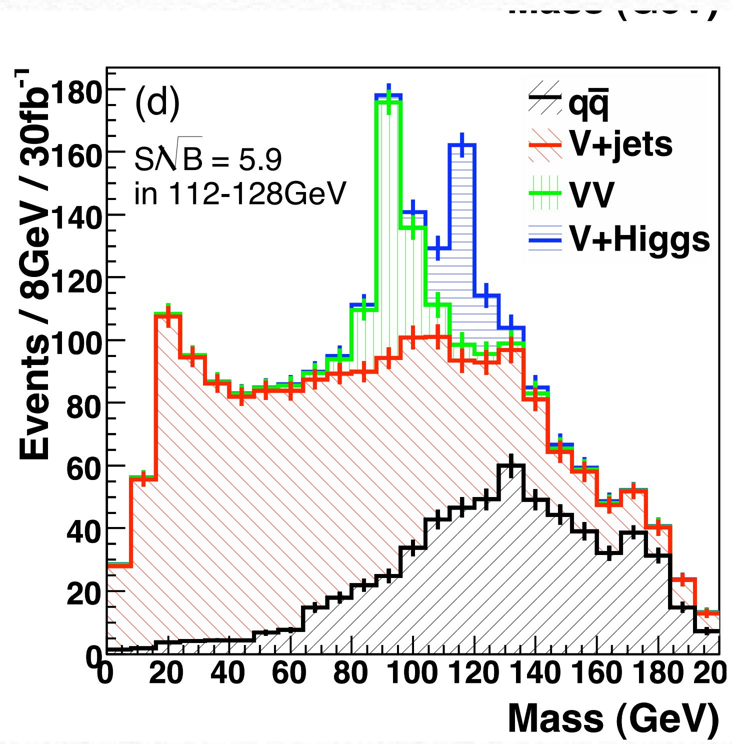
ex: pp→WH, ZH



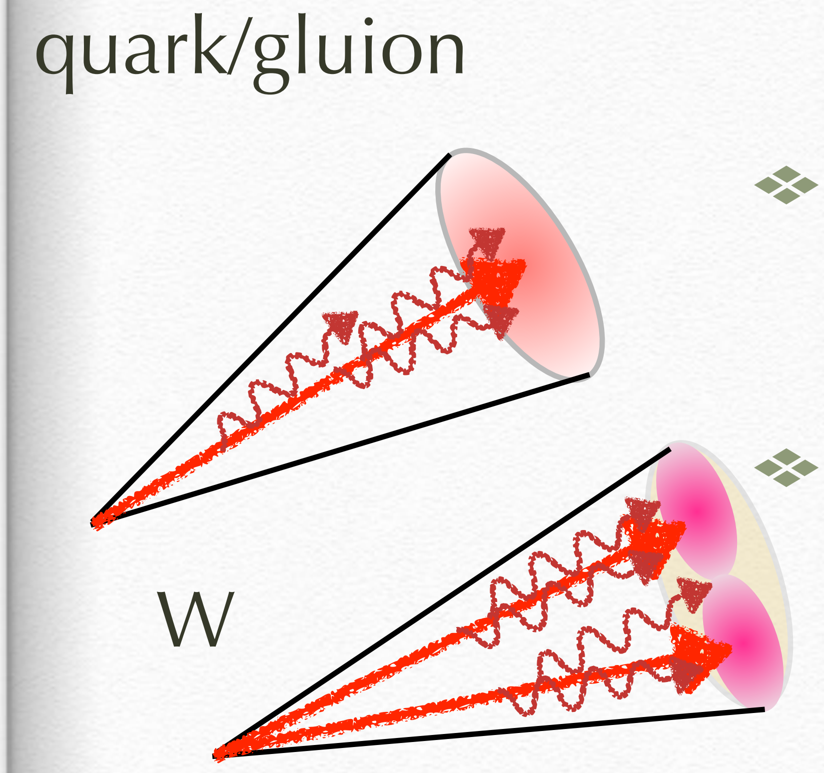
1)take somewhat large R~1.2 select massive jet**(boosted objects)**

2) look for the scale with significant mass drop + symmetric jet. **(reject QCD).**

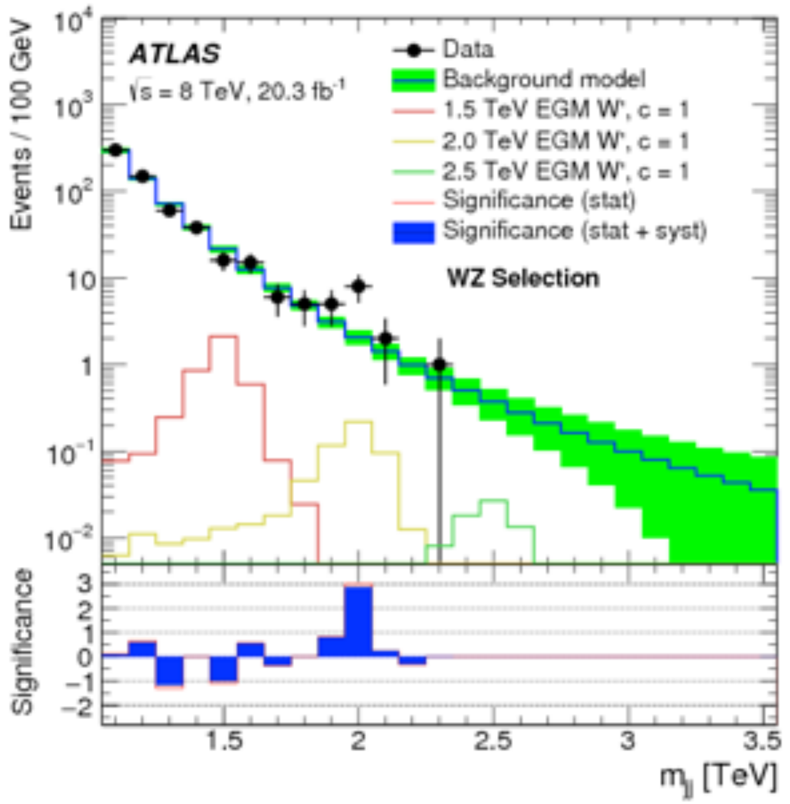
3) select additional jets further to find hard activity but kill underlying events. **(mass resolution)**

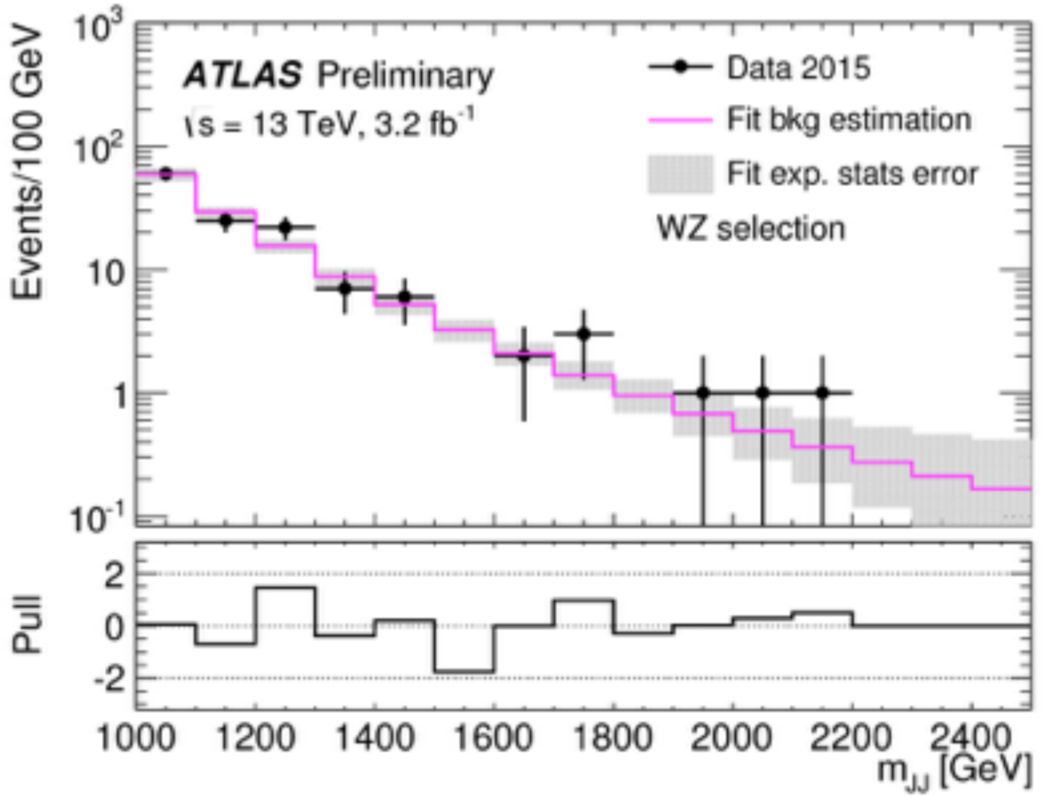


Leaning from “fakes”
2TeV Gauge bosons and subjet analysis



- ATLAS diboson excess, use the mass drop and grooming to find out W.
- N_{tr} also used: IR unsafe (still some kind of voodoo there)





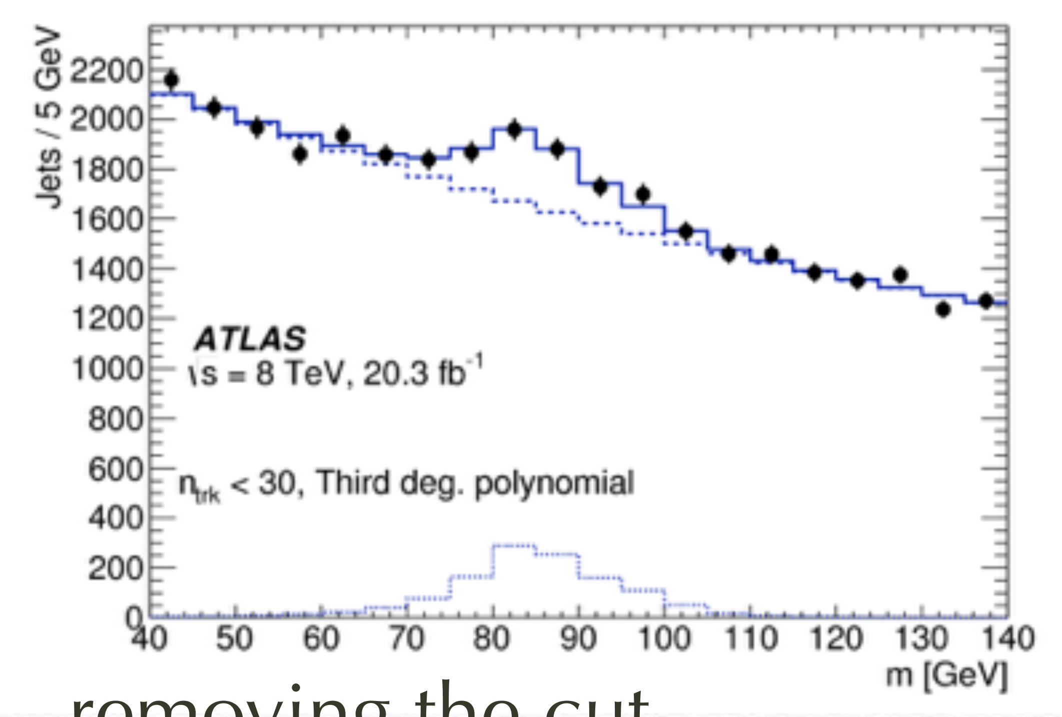
Calibrating background rejection

O(10^3) rejection of the QCD background.

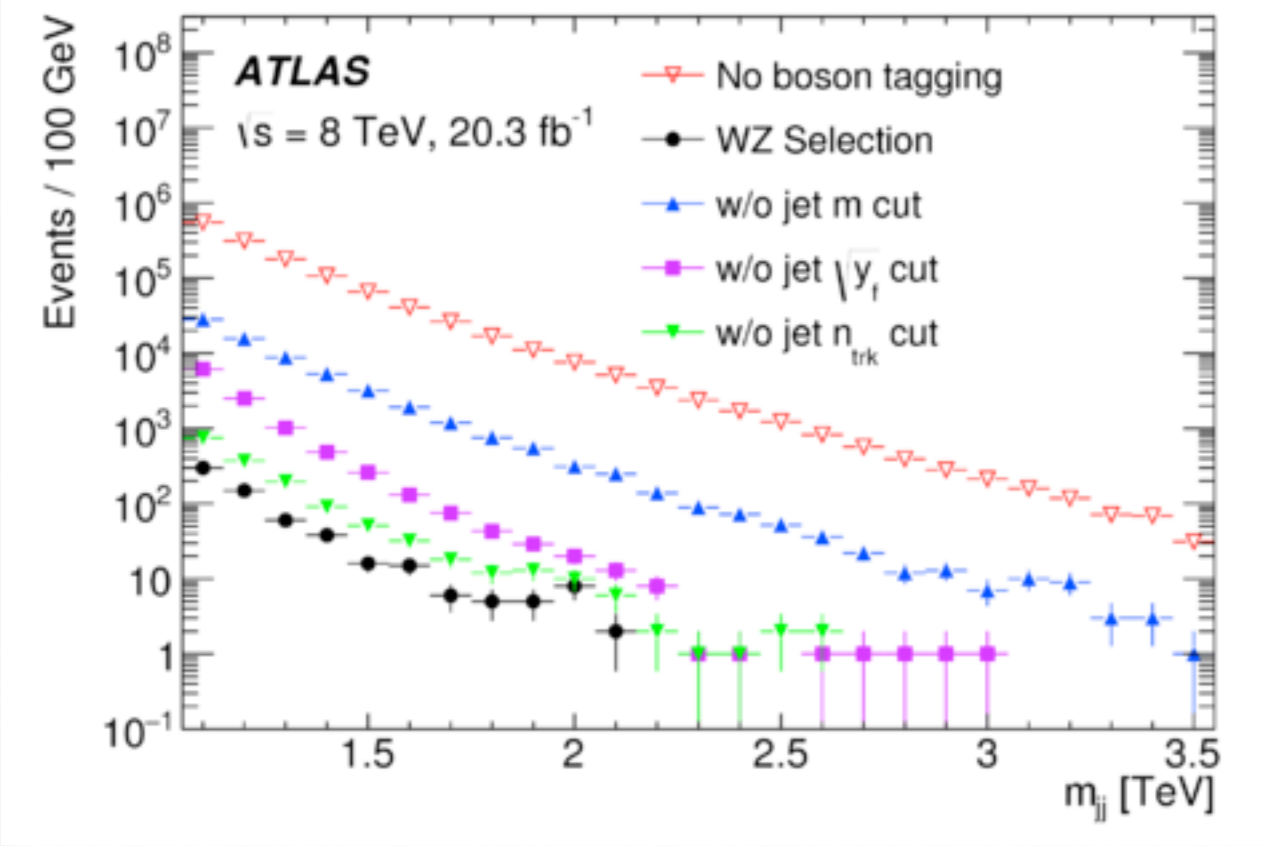
Note: Rejection rate should depend on the fraction of quark and gluon jets

Number of track cut(soft physics) is useful at the end

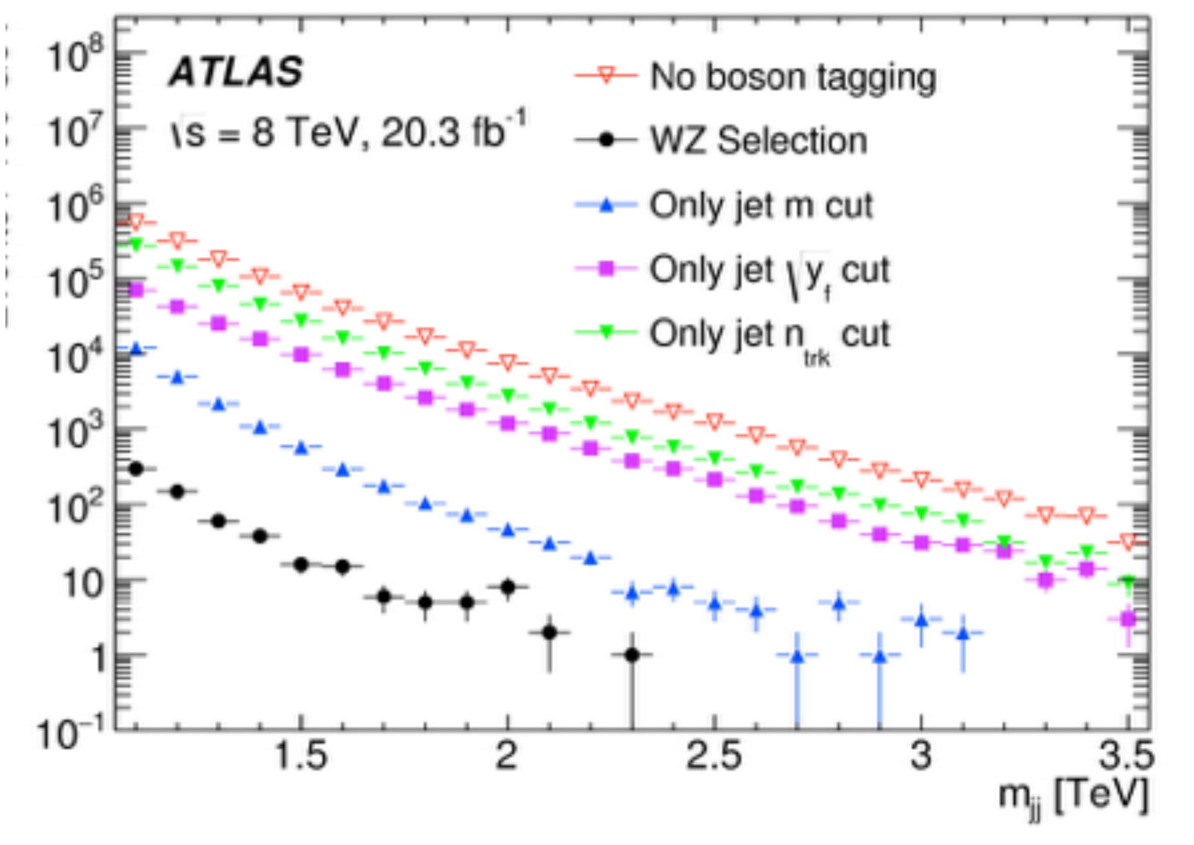
final cuts



adding cuts



removing the cut



Meeting soft physics

quark gluon separation

if we can distinguish quark jet is quark
ex： gluino→ qq X

- quark and gluon initiated jet are different: In parton shower, quark split into hard quark and soft gluon and gluon split into two gluon more equally.

- ME level pp-> gluino gluino-> 4q +missing: background Z+jets more gluons.

Process	$f_q^{j_1}$	$f_q^{j_2}$	$f_q^{j_3}$	$f_q^{j_4}$
$\tilde{g}\tilde{g}$+jets	0.92	0.87	0.77	0.64
Z+jets	0.64	0.55	0.27	0.16

contamination of ISR especially compressed spectrum

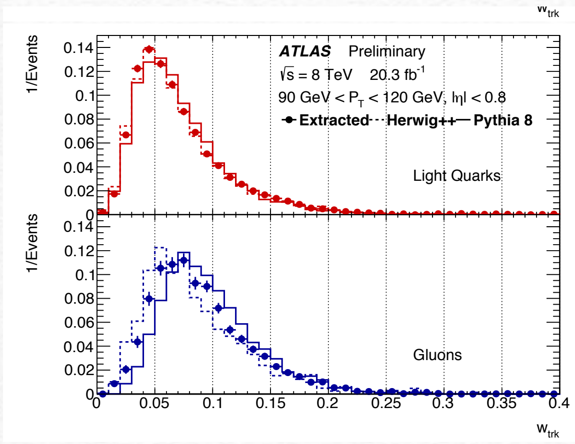
background also contains quark especially for the leading jet.

(Mgluino, Mchi) =(1750 GeV,750GeV) Meff> 1.8TeV

(we have checked Matrix level ISR
generation is not necessary for this level of compressed spectrum

(Fraction is calculated following parton shower history)

Minimum Validation Analysis



QCD prediction with re-sum

$$C_\beta = \frac{\sum_{i,j\in \rm jet} E_{\mathrm{T},i} E_{\mathrm{T},j} (\Delta R_{i,j})^\beta}{\left(\sum_{i\in \rm jet} E_{\mathrm{T},i}\right)^2}$$

soft physics

$$n_{\rm trk} = \sum_{\rm trk\in jet}$$

$$w_{\rm calo} = \frac{\sum_{\rm const\in jet} p_{\rm T,const} \Delta R_{\rm const,jet}}{\sum_{\rm const\in jet} p_{\rm T,const}}$$

…………

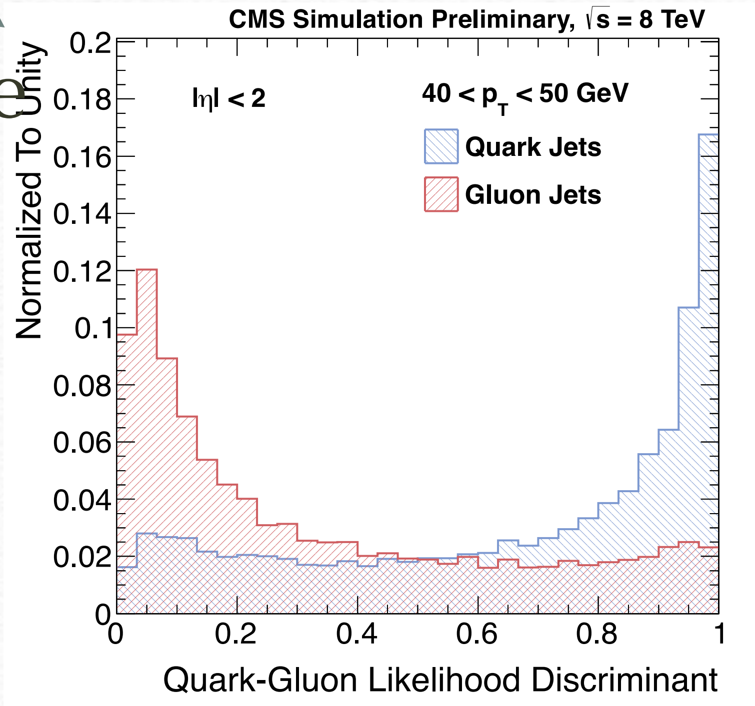
$$w_{\rm trk} = \frac{\sum_{\rm trk\in jet} p_{\rm T,trk} \Delta R_{\rm trk,jet}}{\sum_{\rm trk\in jet} p_{\rm T,trk}}$$

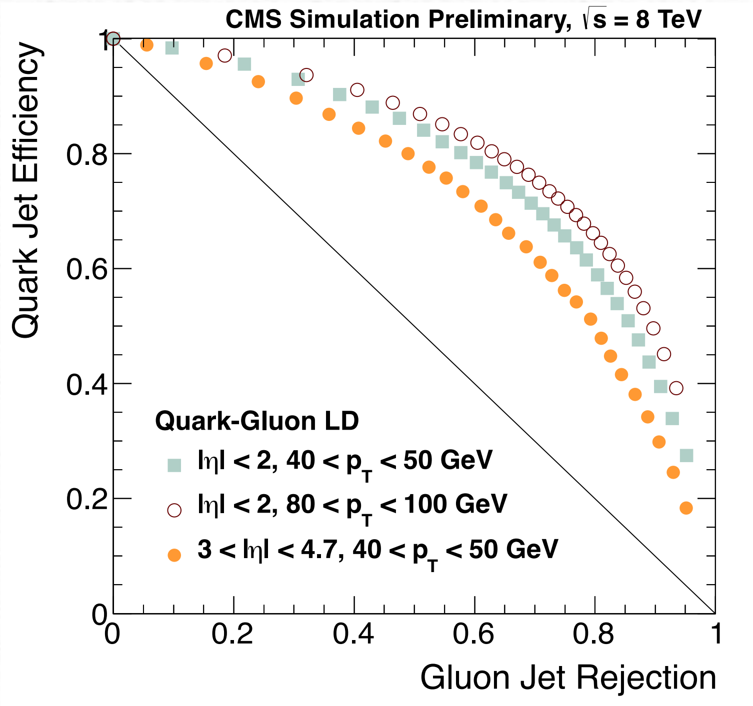
experimentally different

ROC

build a function which give gluon jet ~0 an quark~1

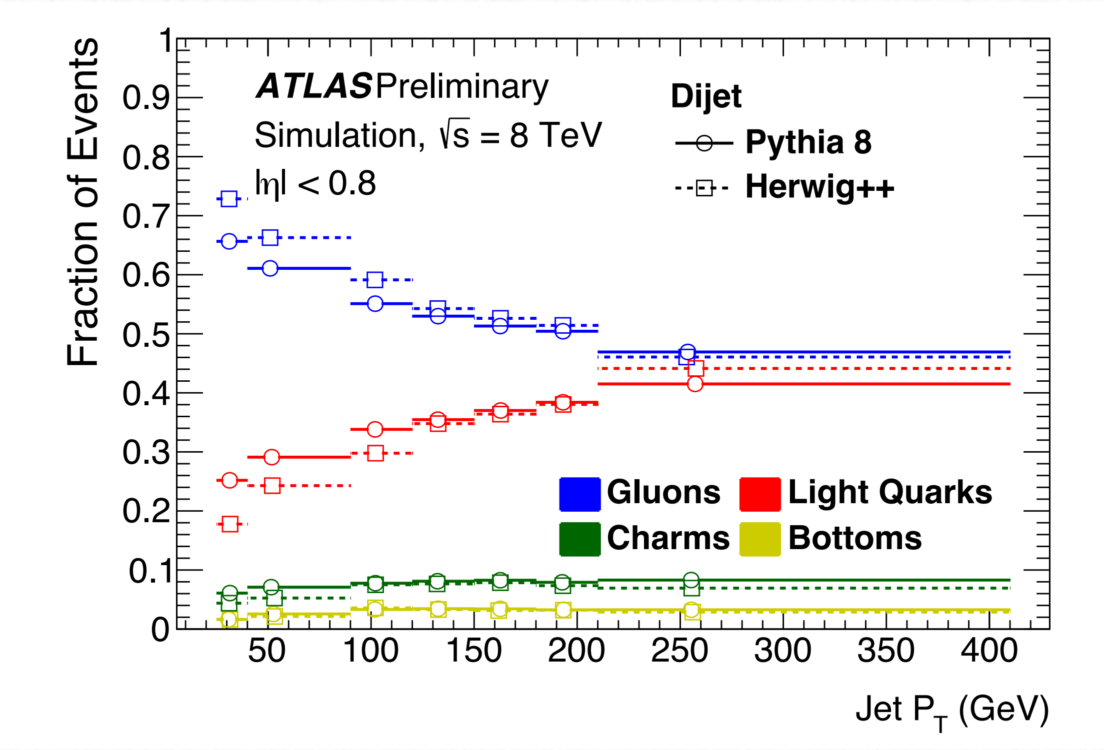
This function depend on method you use to build the function

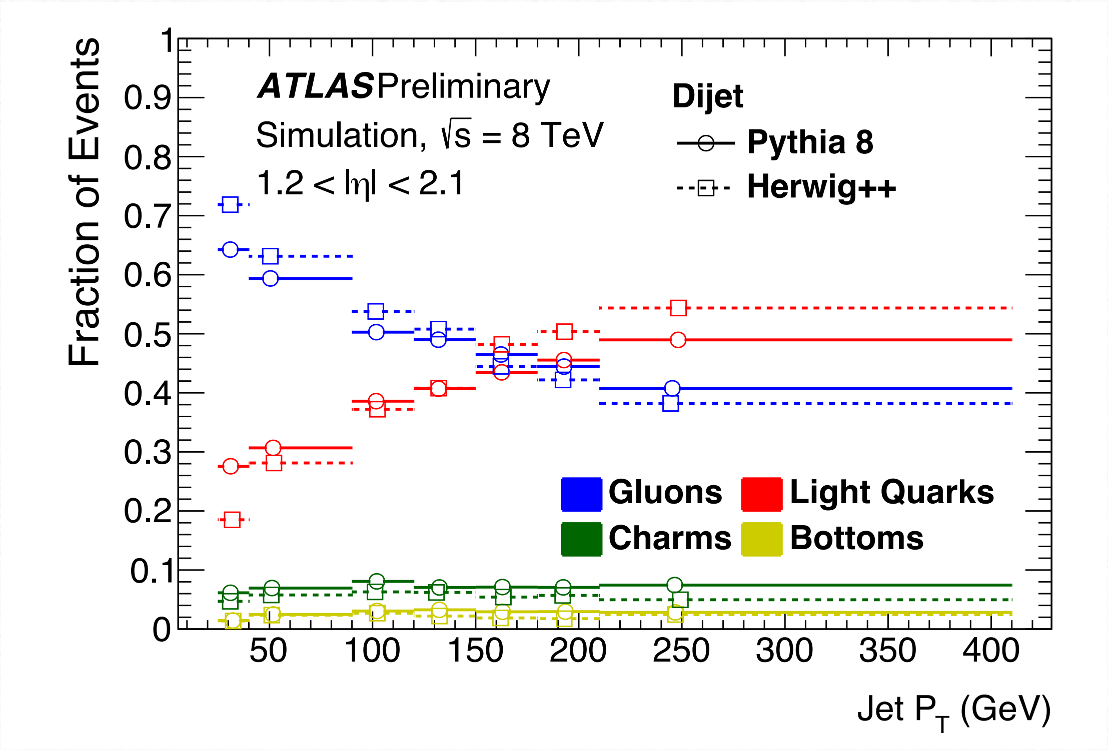


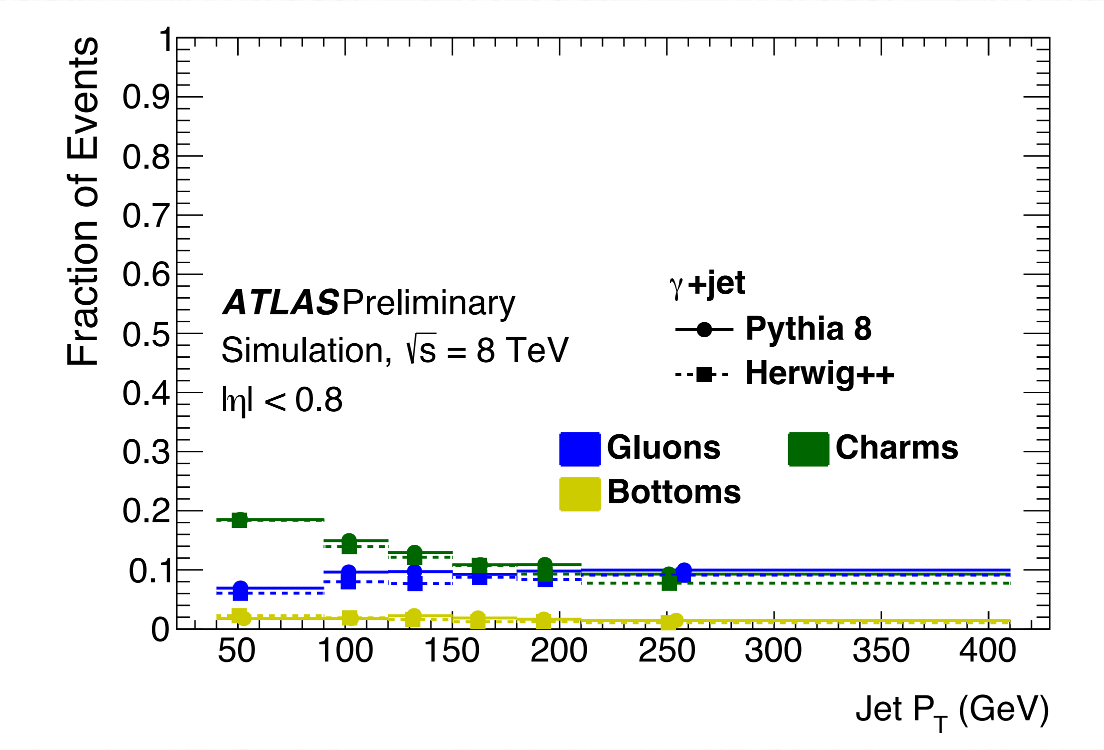


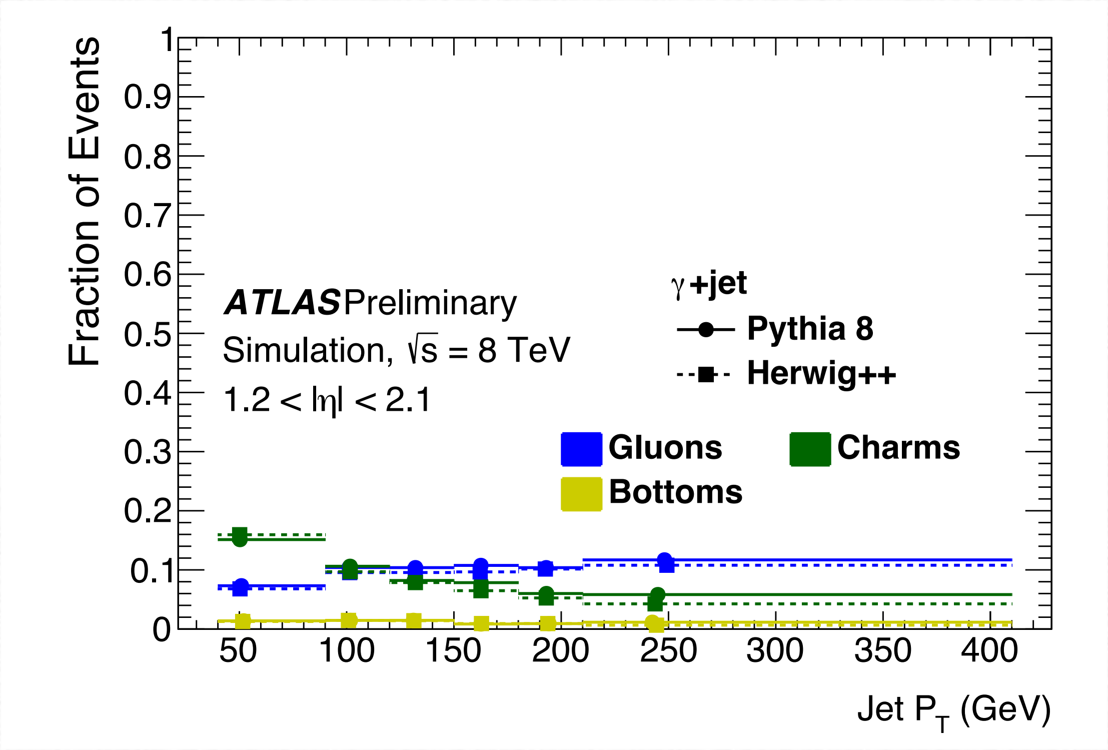
mostly gluons ↔ mostly quark

There is a calibration samples…









Why I am talking about this

- High Luminosity is possible but No large energy increase for a moment.
- Significance is expressed at $S/\sqrt{B + (\delta B)^2}$ where δB is systematical error of the background
  - clean channel extend with luminosity. → Theoretical error will reduce drastically at NNLO
  - **New methods which can reduce background independently might also be useful.**

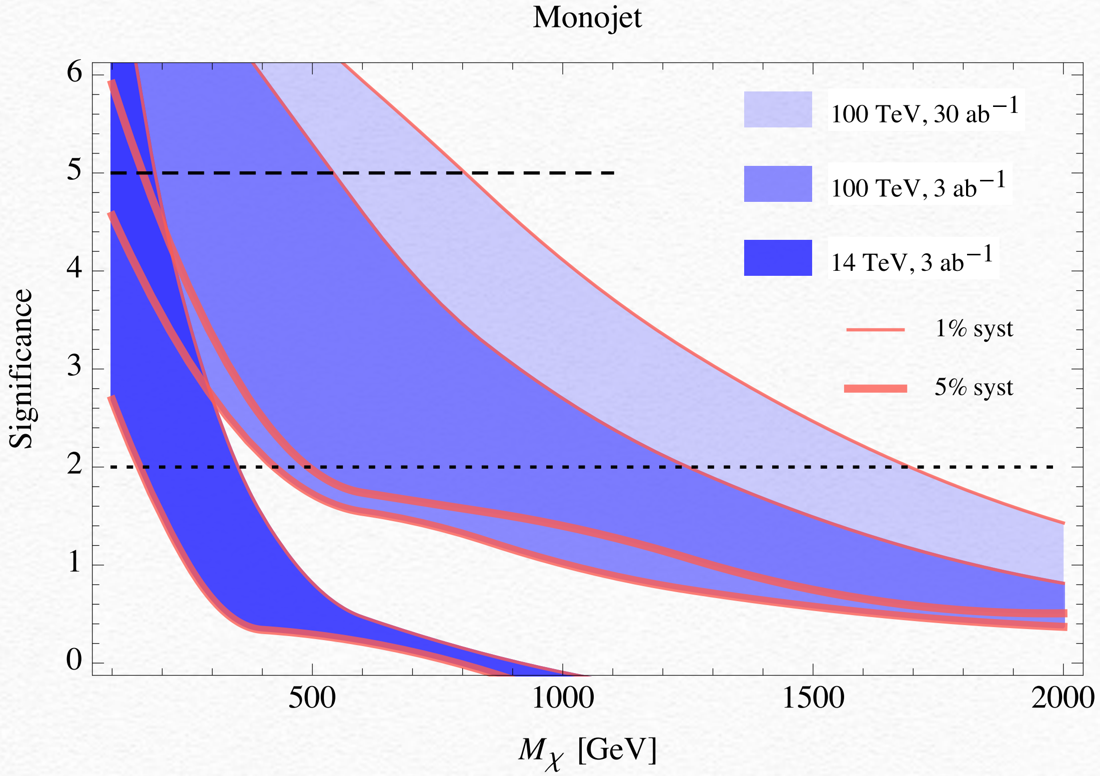
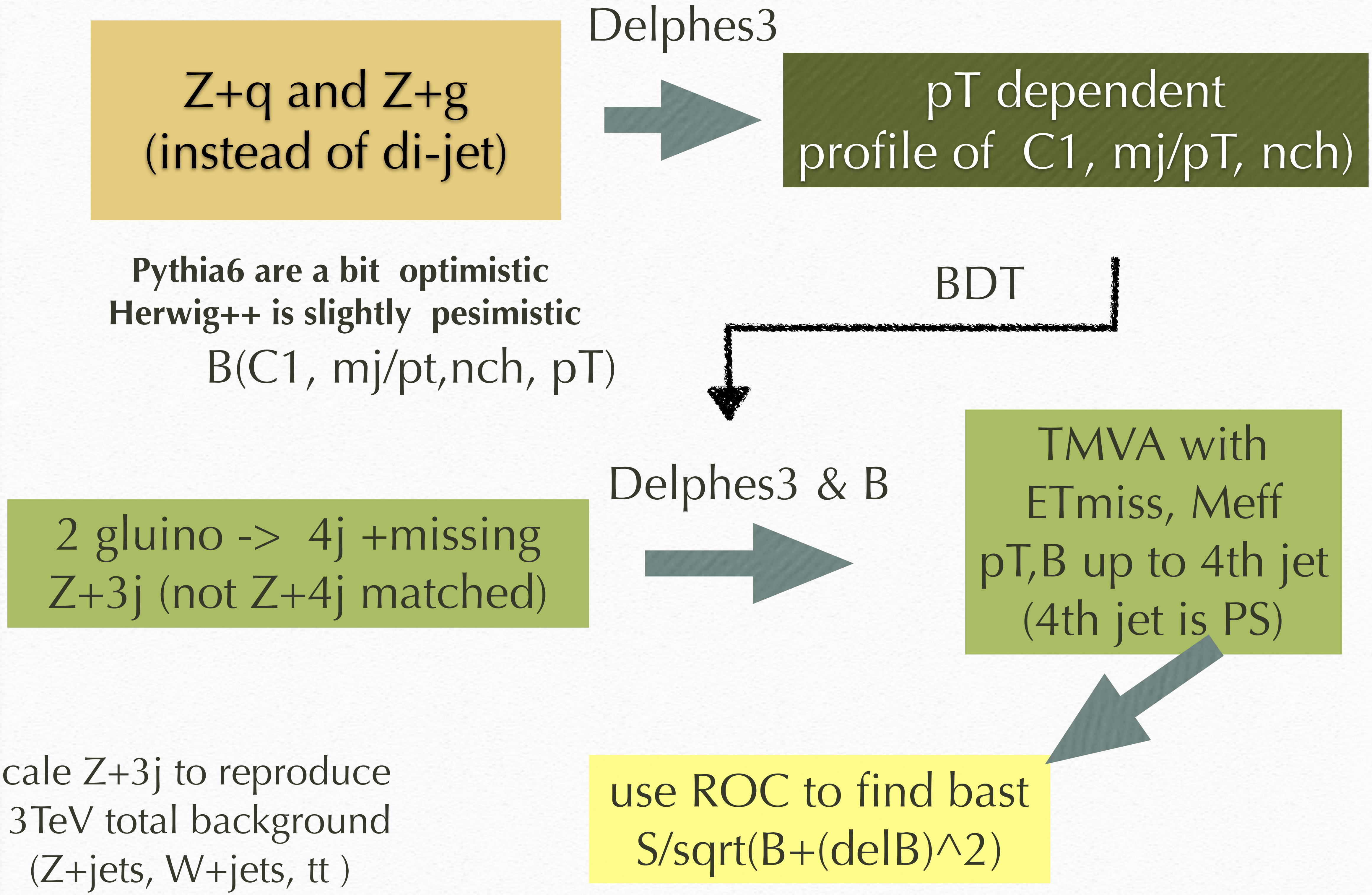


Figure 2. Reach of monojet searches.

Cirelli et al '14

Checking if this is useful for BSM (gluino search)

Bhattacherjee, Mukhopadhyay, Nojiri, Sakaki, Webber (2016)



Z+q and Z+g
(instead of di-jet)

Delphes3

pT dependent
profile of C1, mj/pT, nch)

BDT

Pythia6 are a bit optimistic
Herwig++ is slightly pesimistic

B(C1, mj/pt,nch, pT)

2 gluino -> 4j +missing
Z+3j (not Z+4j matched)

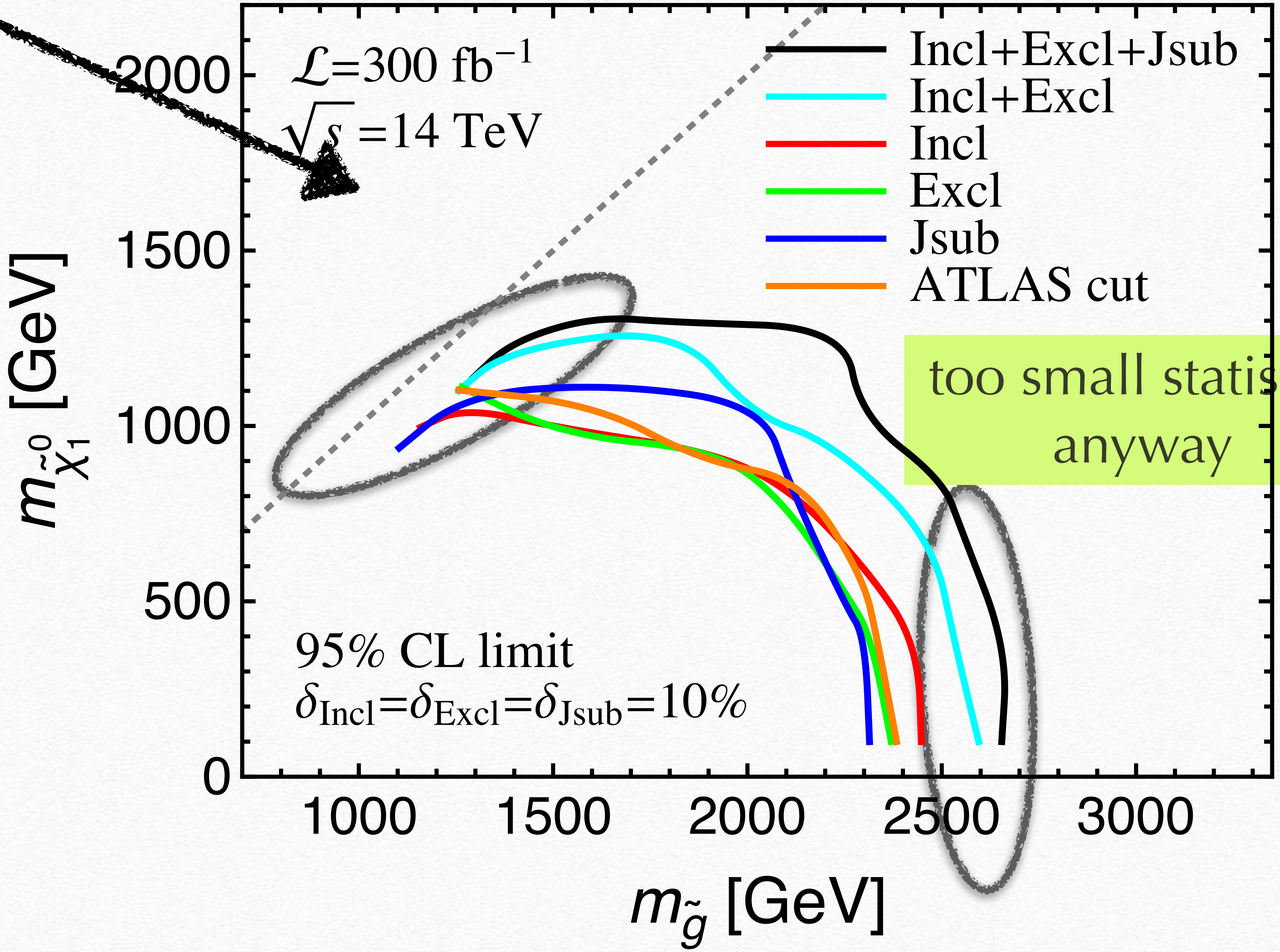
Delphes3 & B

TMVA with
ETmiss, Meff
pT,B up to 4th jet
(4th jet is PS)

use ROC to find bast
S/sqrt(B+(delB)^2)

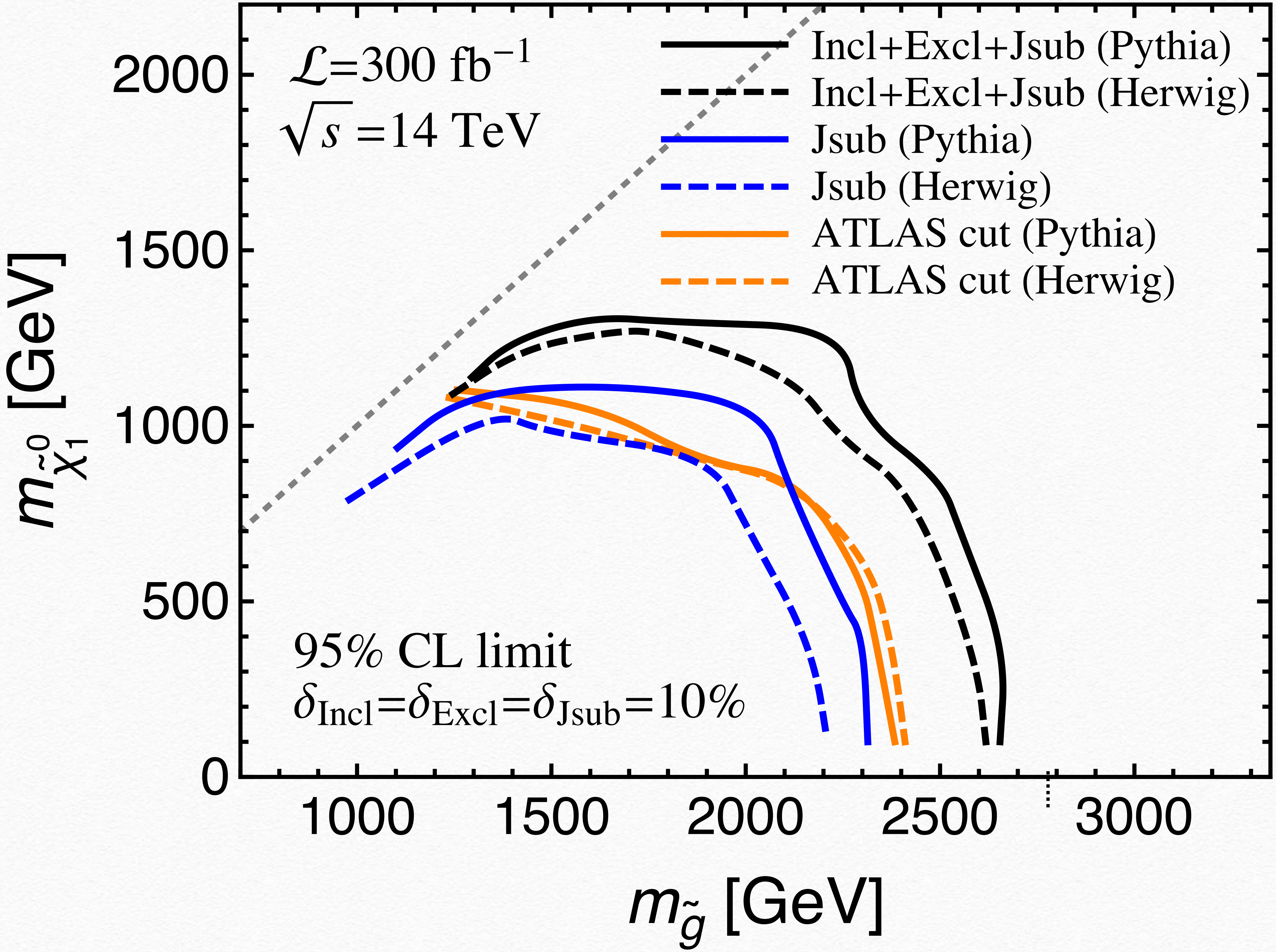
scale Z+3j to reproduce
13TeV total background
(Z+jets, W+jets, tt)

not much
improvement
ISR is important here



too small statistics
anyway

generator dependence

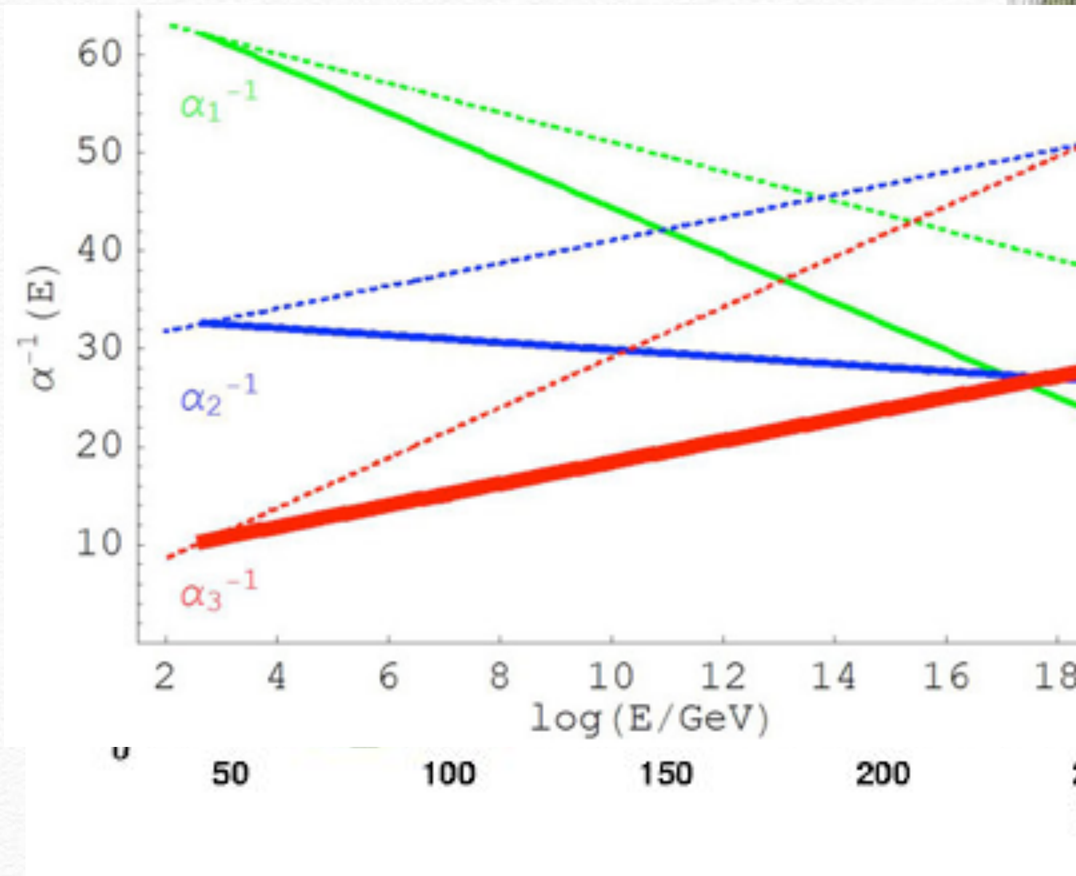


Systematics added 30% for most later lines

At the end

Looking back LEP era again

EW precision



- No deviation of standard model. **Field Theory win. Light higgs boson was suggested.**
- People started to believe SUSY and thought **neutralino** as standard dark matter candidate.
- Technicolor became difficult and people have left to **effective theory: Little Higgs model/composite model:** Higgs boson is NG boson of some global symmetry **without specifying** the origin of symmetry breaking
- **Important Lessons** have been learned from this approach
  - top sector need to be enlarged → **top partner**
  - Z2 symmetry separating new sector from SM sector → TeV scale new physics **(stable spin 1 particle as dark matter)**

12 years (= 6 years+ 2 year budget + 2 (delay) + 2 (He) between LEP and LHC

It was fan time

SUSY

- development of Gauge Mediation: **Low energy SUSY breaking,** and gravitino dark matter (spin 3/2, Late decay, connection to BBN)
- Anomaly Mediation :**suppressed gaugino mass,** wino dark matter, moduli decay
- Little Hierarchy argument ,natural SUSY?

Extra dim

- Warped Extra dimension(1998, 1999) Planck scale → EW scale. Yukawa coupling can have geometrical meaning, U(1) gauge boson KK dark matter

Composite Models

- Little Higgs models (2001) & Minimal composite models

We also start to confuse about DM

Effective theory and Simplified models of DM

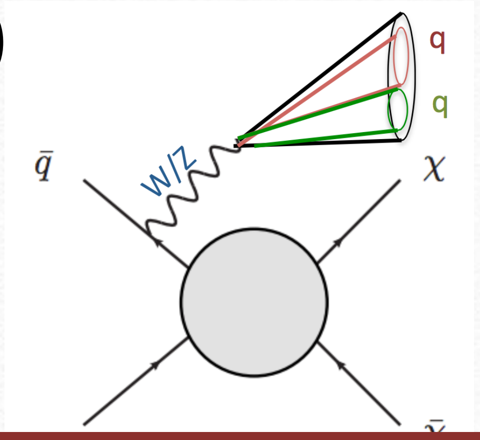
- Recently, theorists are busy to make effective theories or simplified models.
- This is useful especially when 1) production cross sections and branching ratios are not sensitive to the model details 2) limits are not sensitive to the simplified model assumptions.
- But you may get into wrong direction if you use effective theory to emphasizing the one which is unlikely to exists theoretically.

Effective Theory used in funny ways

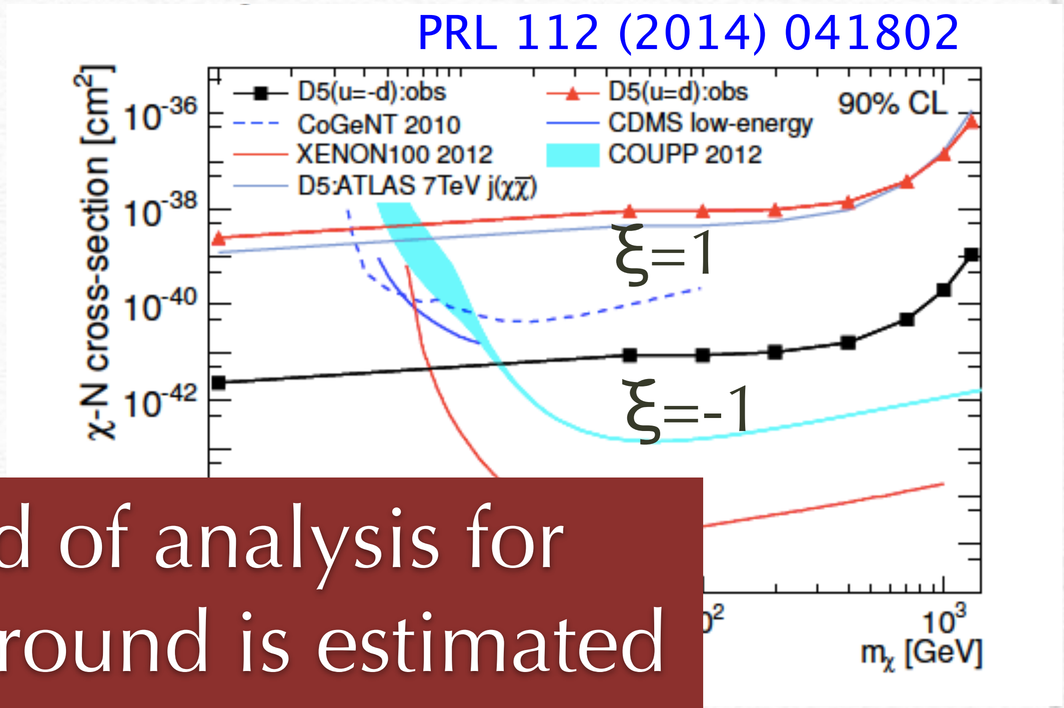
1. gauge symmetry violated

Amplitude increase as **ε**~ E/mW

$$\frac{1}{\Lambda^2}\,\overline{\chi}\gamma_\mu\chi\;\left(\overline{u}\gamma^\mu u + \xi\,\overline{d}\gamma^\mu d\right)$$



PRL 112 (2014) 041802



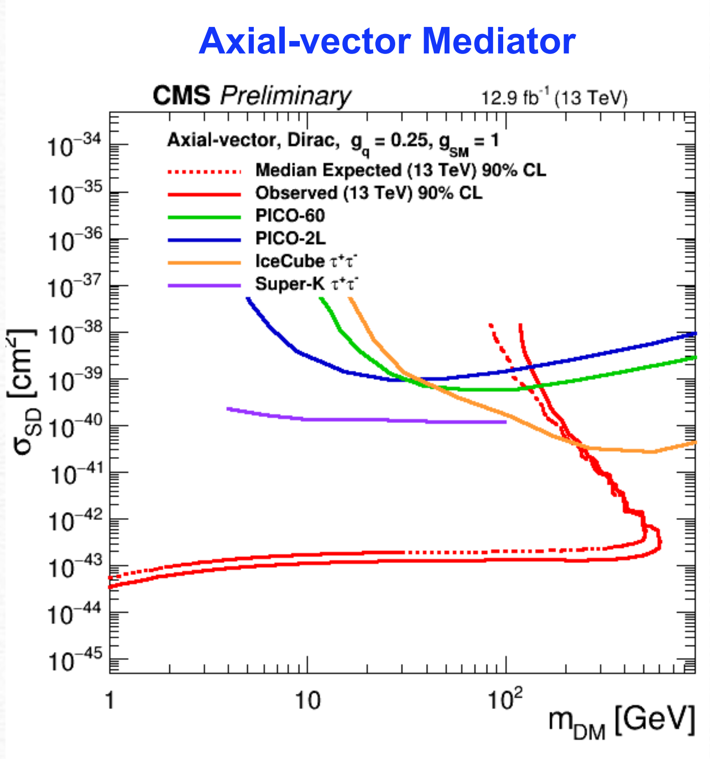
It is a bit funny to have this kind of analysis for the dark matter signal while background is estimated seriously using NNLO, NLO, …

2.

$$\mathcal{L}_{\rm VDM} = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu - \frac{\lambda_{VH}}{2}V_\mu V^\mu H^\dagger H - \frac{\lambda_V}{4}(V_\mu V^\mu)^2$$

3 Axial vector gauge boson (invented to make LHC results nice)

another example is Higgw width "measurement"



Summary

- Overall **LHC is successful**. It is based on solid science, especially, precision EW calculation, higher order QCD, development of MC tools. fantastic job compared with our expectations at 23 years ago(at the time of SSC cancellation)
- Anomaly are more abundant in flavor physics now. Are there something more to be developed? Or are we in the “who ordered this” situation?
- **Is understanding good/excluded regions in effective/ simplified theory enough to justify the existence of HEP on the earth?**