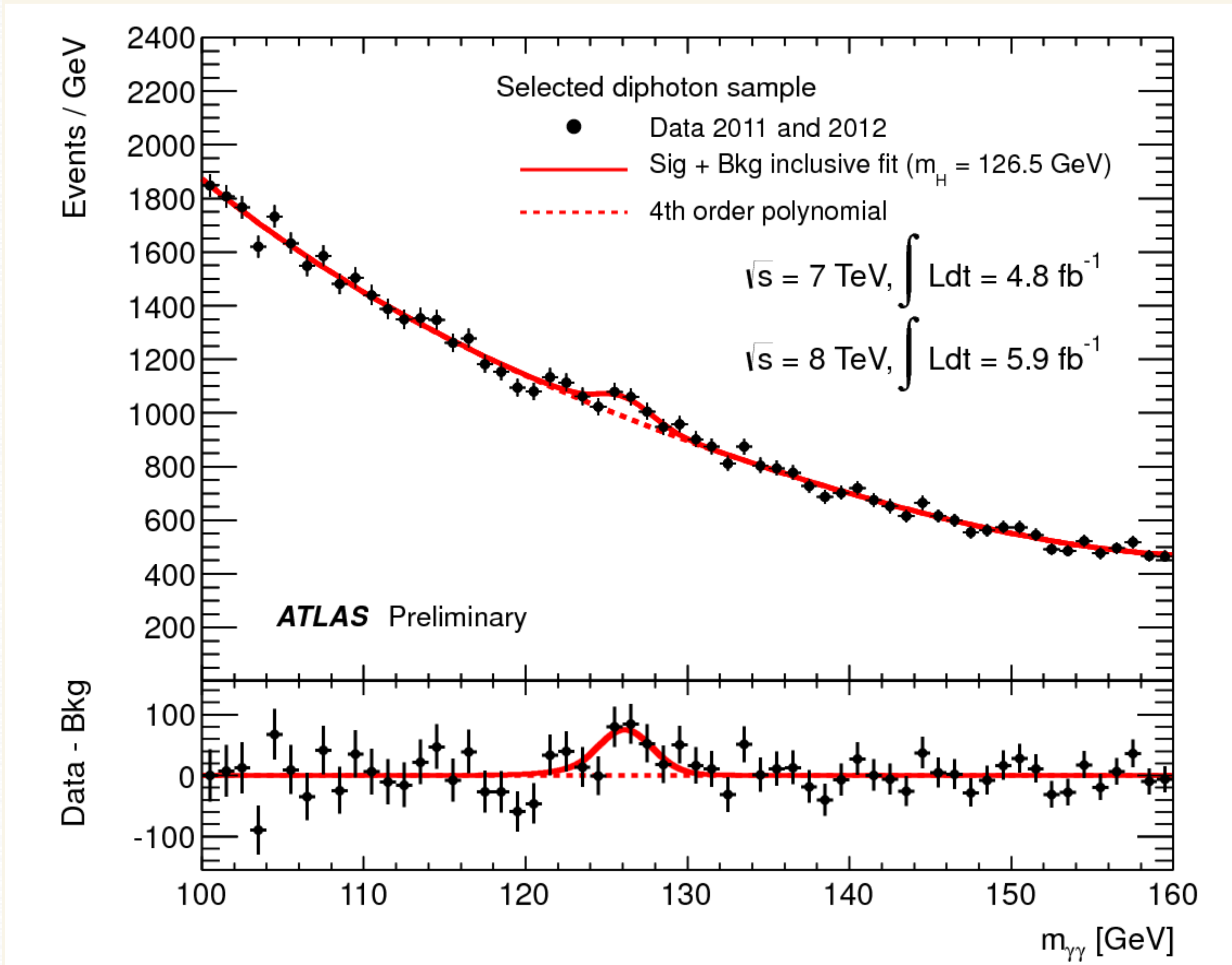
LHC physics and beyond

Mihoko Nojiri
KEK & IPMU

success of LHC

NY Times

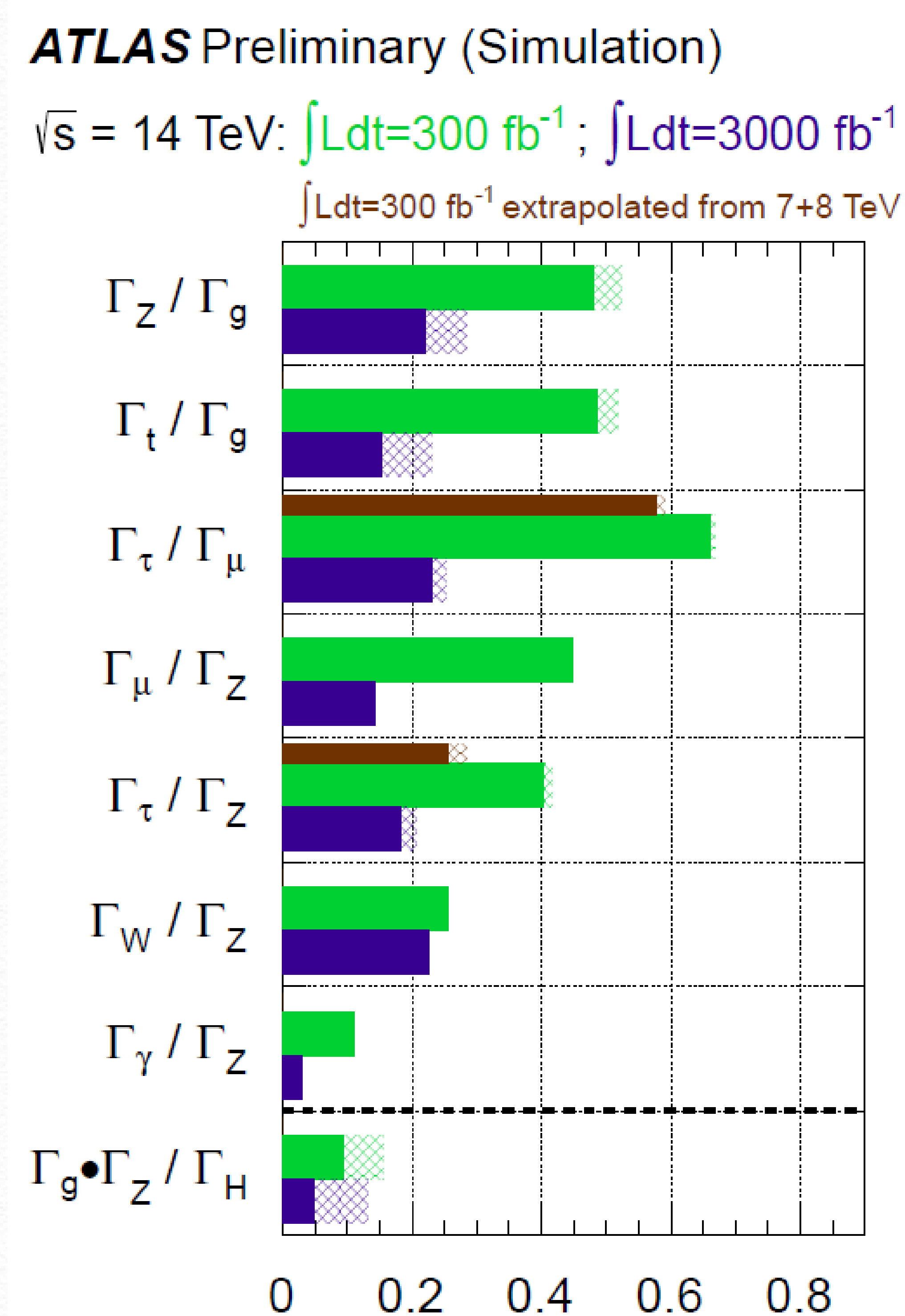
discovery of Higgs boson



Higgs boson と top quark は標準模型のフロンティア

今後のLHC への期待

- 統計は圧倒的
- 系統誤差は大きい→QCDの高次計算が大事.
- 系統誤差は比率で改善



300 fb^{-1} :

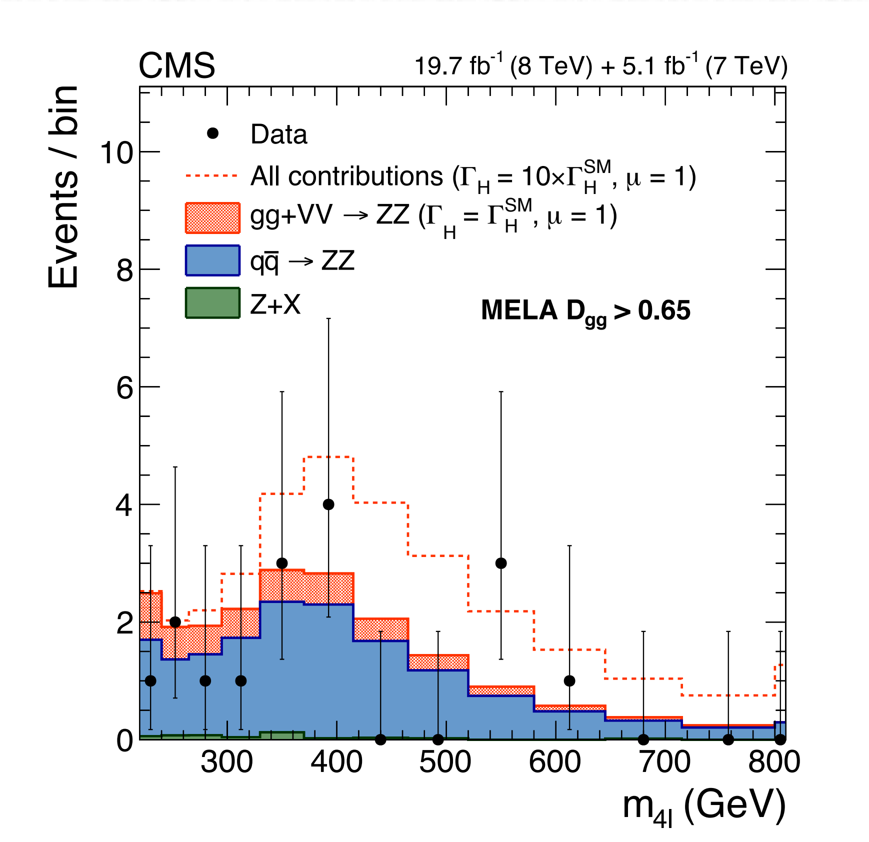
Observable	ATLAS	CMS-1	CMS-2
$\sigma(gg)\cdot BR(\gamma\gamma)$	$12 \oplus 19$	$6 \oplus 12.3$	$3 \oplus 6.2$
$\sigma(WW)\cdot BR(\gamma\gamma)$	$47 \oplus 15$	$20 \oplus 2.4$	$14 \oplus 1.2$
$\sigma(gg)\cdot BR(WW)$	$8 \oplus 18$	$6 \oplus 12.3$	$5 \oplus 6.2$
$\sigma(WW)\cdot BR(WW)$	$20 \oplus 8$	$35 \oplus 2.4$	$28 \oplus 1.2$
$\sigma(gg)\cdot BR(ZZ)$	$6 \oplus 11$	$7 \oplus 12.3$	$5 \oplus 6.2$
$\sigma(WW)\cdot BR(ZZ)$	$31 \oplus 13$	$12 \oplus 2.4$	$10 \oplus 1.2$
$\sigma(gg)\cdot BR(\tau\tau)$	—	$13 \oplus 12.3$	$6 \oplus 6.2$
$\sigma(WW)\cdot BR(\tau\tau)$	$16 \oplus 15$	$16 \oplus 2.4$	$9 \oplus 1.2$
$\sigma(Wh)\cdot BR(b\bar{b})$	—	$17 \oplus 3.8$	$14 \oplus 1.7$
$\sigma(t\bar{t}h)\cdot BR(b\bar{b})$	—	$60 \oplus 11.7$	$50 \oplus 5.9$
$\sigma(t\bar{t}h)\cdot BR(\gamma\gamma)$	$54 \oplus 10$	$40 \oplus 11.7$	$38 \oplus 5.9$
$\sigma(Zh)\cdot BR(invis)$	—	$16 \oplus 4.3$	$11 \oplus 2.2$

3000 fb^{-1} :

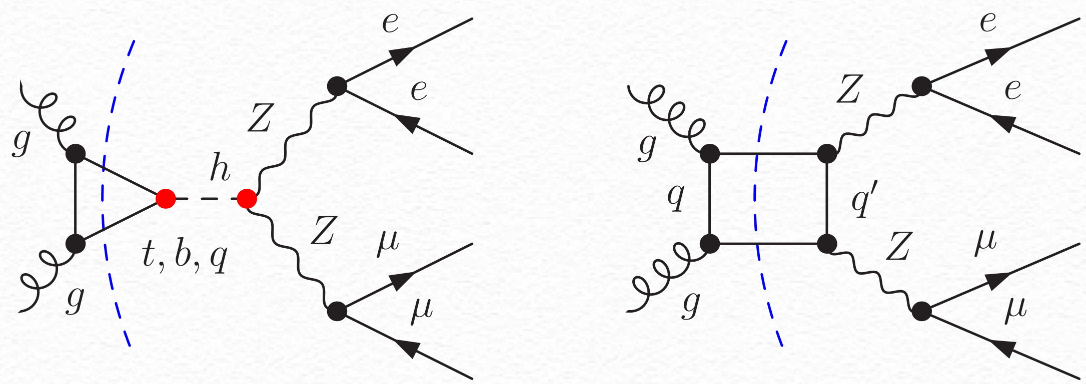
最近ちょっと気になった解析

(Higgs のoff shell width)

"higgs の幅だけ10倍いじったら gg-> ZZ 断面積が
たくさん変わるからHiggs の幅に制限がついた"

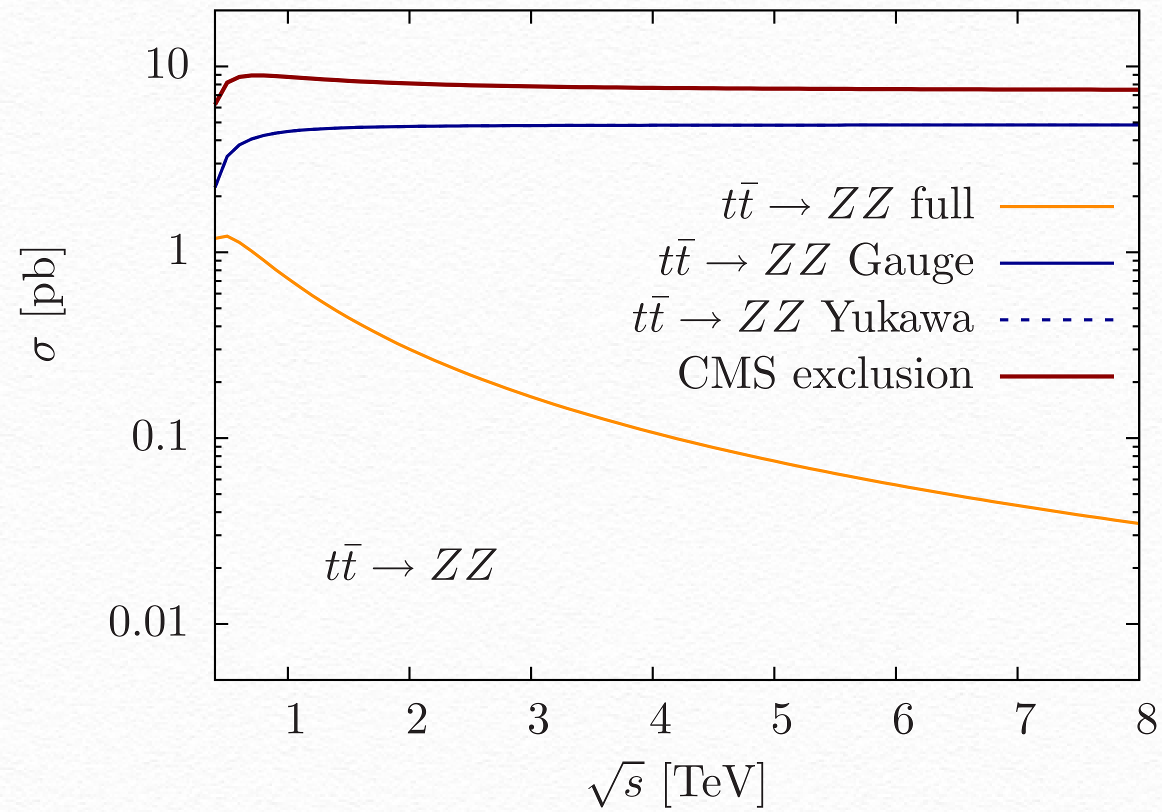


amplitude の 盛大な cancellation
をてこにしている



CMS 1405.3455

- model independent も考えもの
- complete theory が必要



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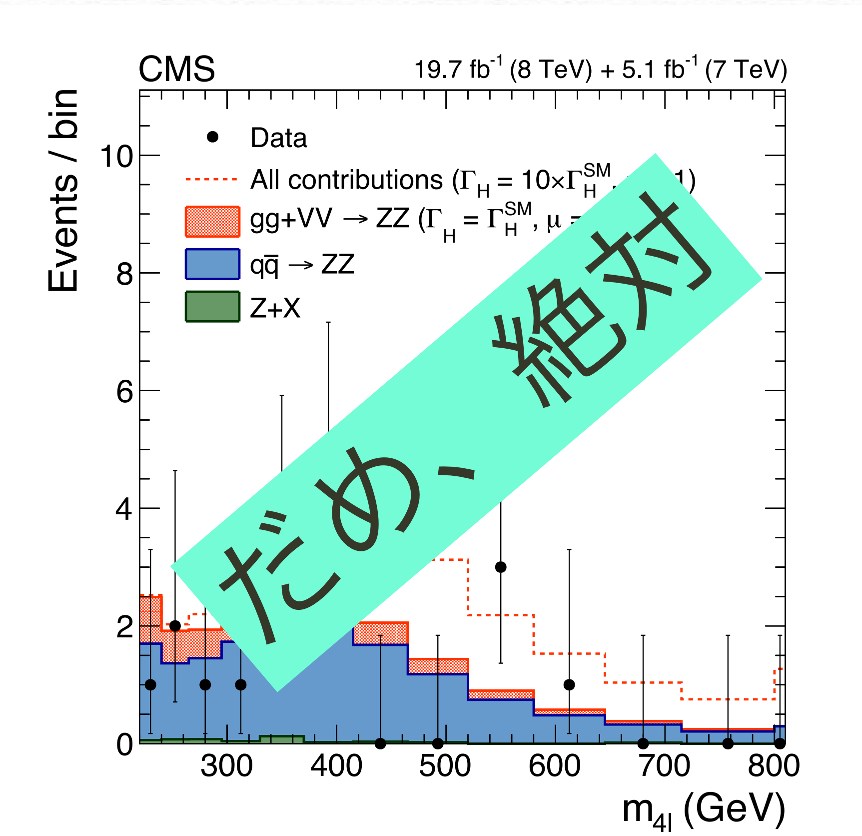

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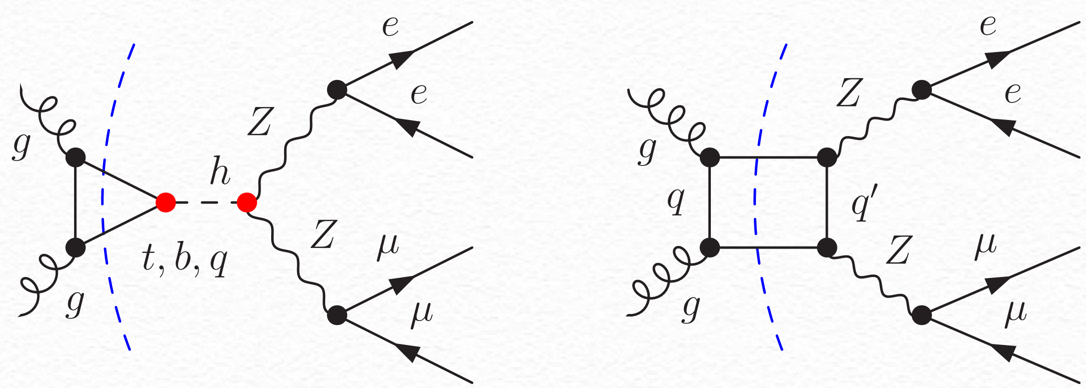
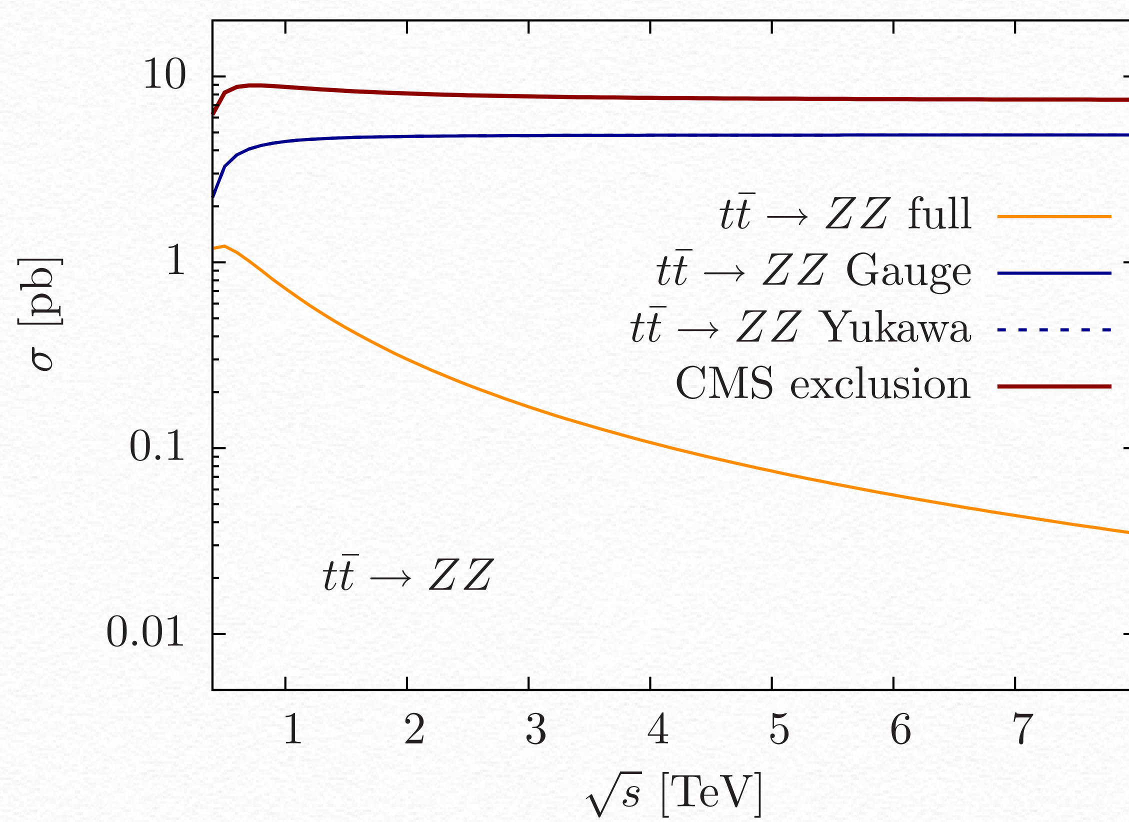
amplitude の 盛大な cancellation をてこにしている





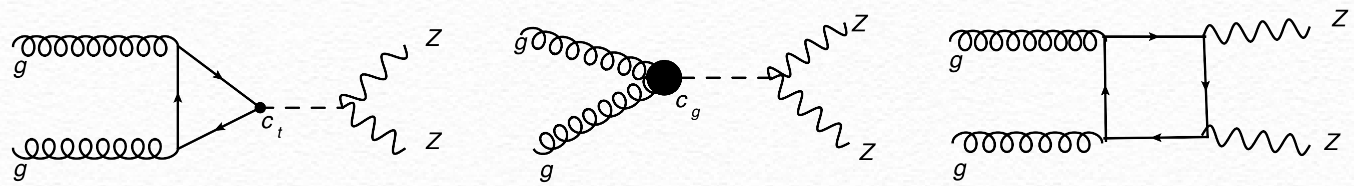
- model independent も考えもの
- complete theory が必要

高次元operator への制限

$$\mathcal{L}^{\text{dim-6}} = c_y \frac{y_t|H|^2}{v^2}\bar{Q}_L \widetilde{H} t_R + \text{h.c.} + \frac{c_g g_s^2}{48\pi^2 v^2}|H|^2 G_{\mu\nu}G^{\mu\nu} + \tilde{c}_g \frac{g_s^2}{32\pi^2 v^2}|H|^2 G_{\mu\nu}\tilde{G}^{\mu\nu}\,,$$

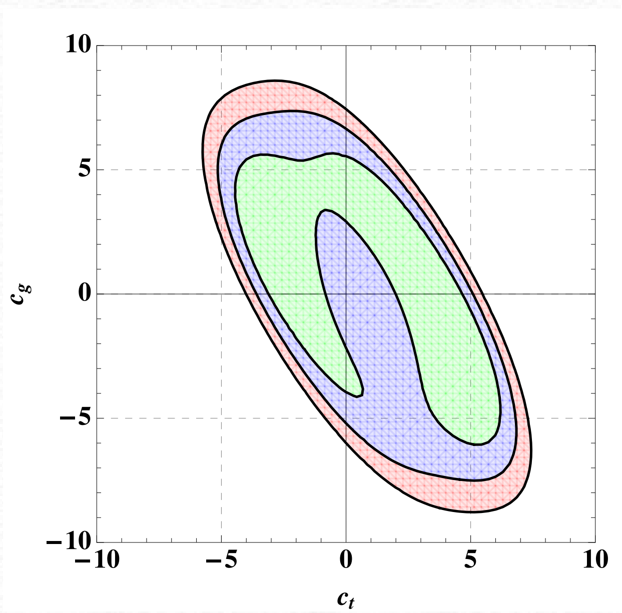
Higgs production $\sigma \sim |c_t + c_g|^2\,.$ ct と g が相関すると制限がつかない

ZZ 生成の高エネルギー挙動

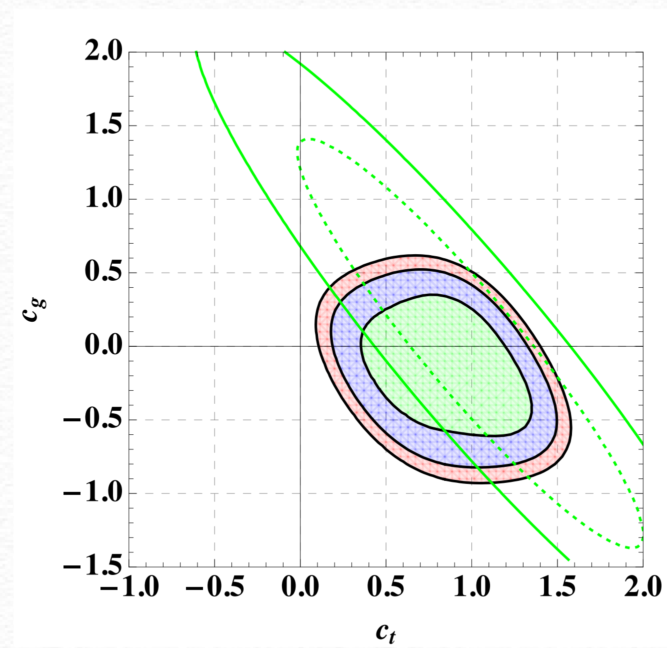


$$\mathcal{M}^{++00}_{c_t} \sim \log^2 \frac{\hat{s}}{m_t^2}, \qquad \mathcal{M}^{++00}_{c_g} \sim \hat{s}\,,$$

8TeVCMS

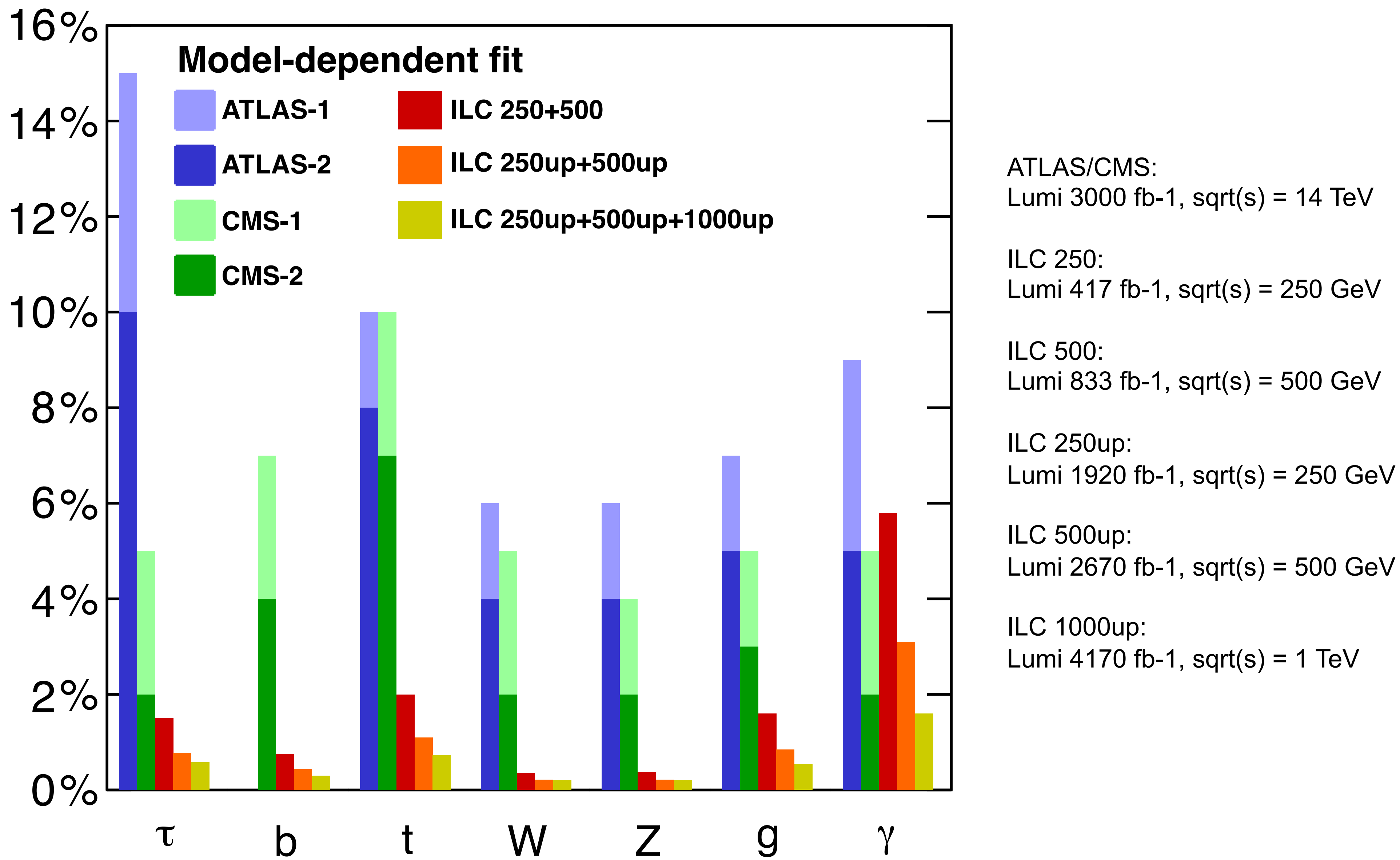


14TeV 3ab-1



もしILCができたらどうなるか

Higgs Couplings (1/2)



t の coupling と W のcoupling の測定には、500GeV が必要

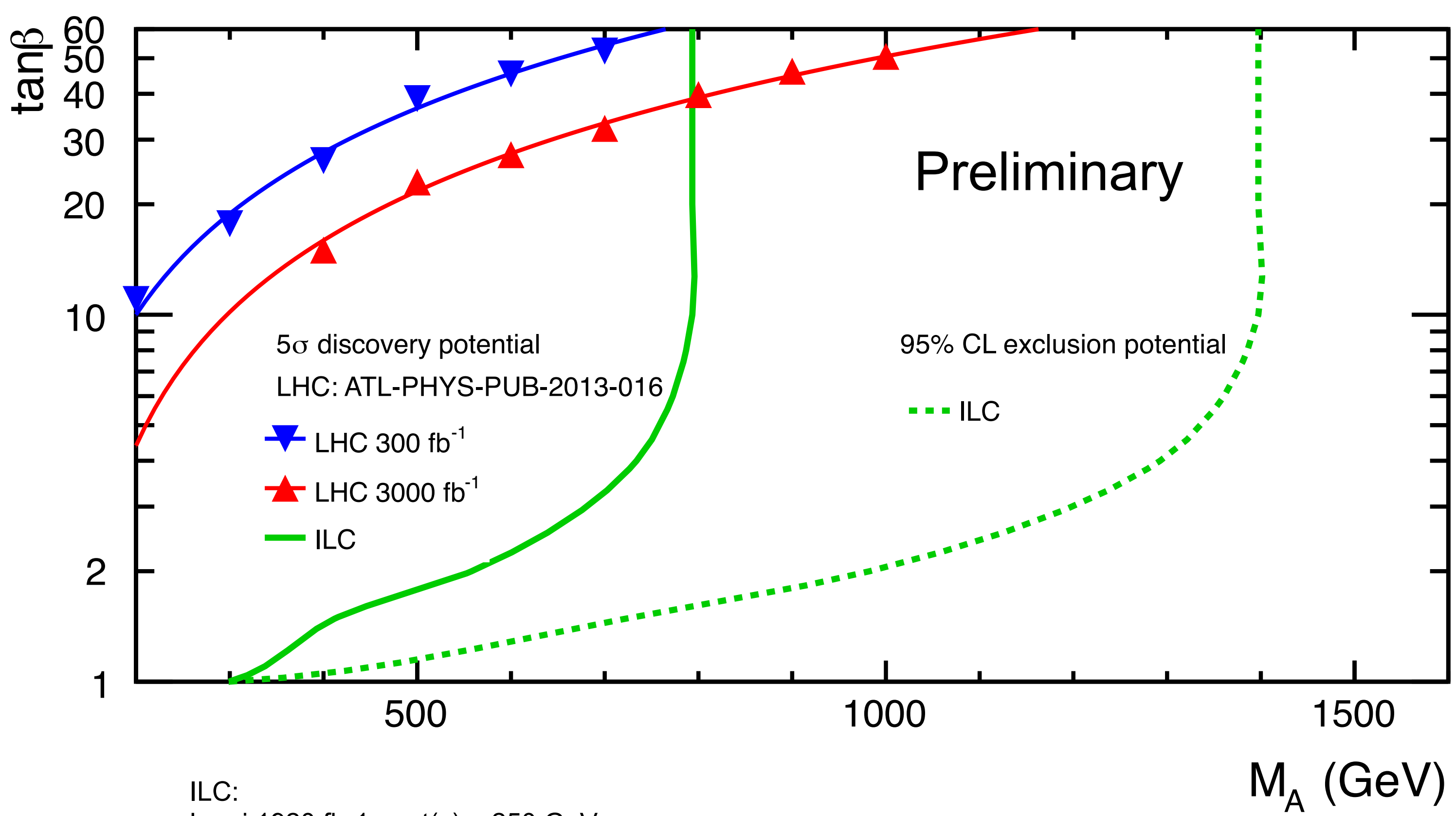
LHC の Γ(γ)/Γ(Z)を使うと g(γγH) がさらに改善。

Higgs sector に関わる模型

- SUSY 2 Higgs doublet 模型

Heavy Higgs Mass Reach

- **LHC:** Heavy Higgs direct search
- **ILC:** Indirect search via effect on Higgs couplings BR(h→WW)/BR(h→bb) and BR(h→WW)/BR(h→ττ)



ILC:
Lumi 1920 fb-1, sqrt(s) = 250 GeV
Lumi 2670 fb-1, sqrt(s) = 500 GeV

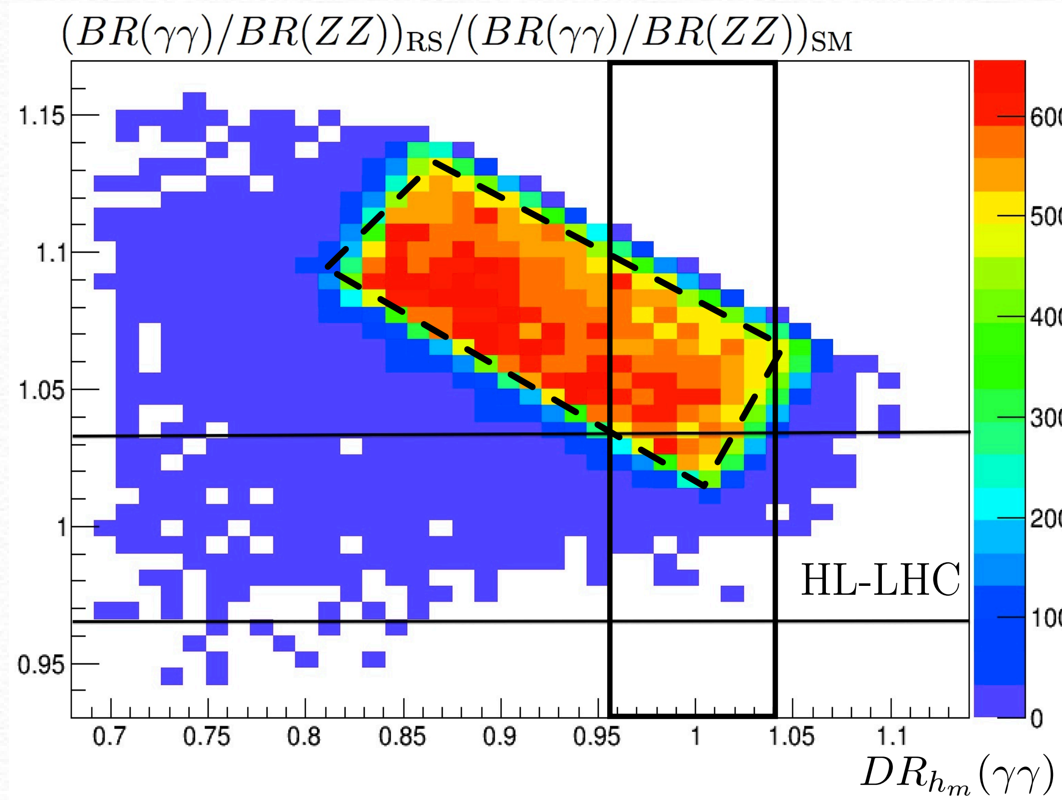
tree level の計算

この他に1loop 補正が
tanbeta =50 MA=500GeV で5%
くらいあっても不思議ではない

top mass の測定もhiggs sector を決める上で重要

Example: 10TeV RS with higgs radion mixing

- 5dim RS && bulk Fermions &&Raidon-Higgs mixing.
- KK contribution to Higgs decay though loop, large KK yukawa
- Radion: direct coupling to gauge bosons.



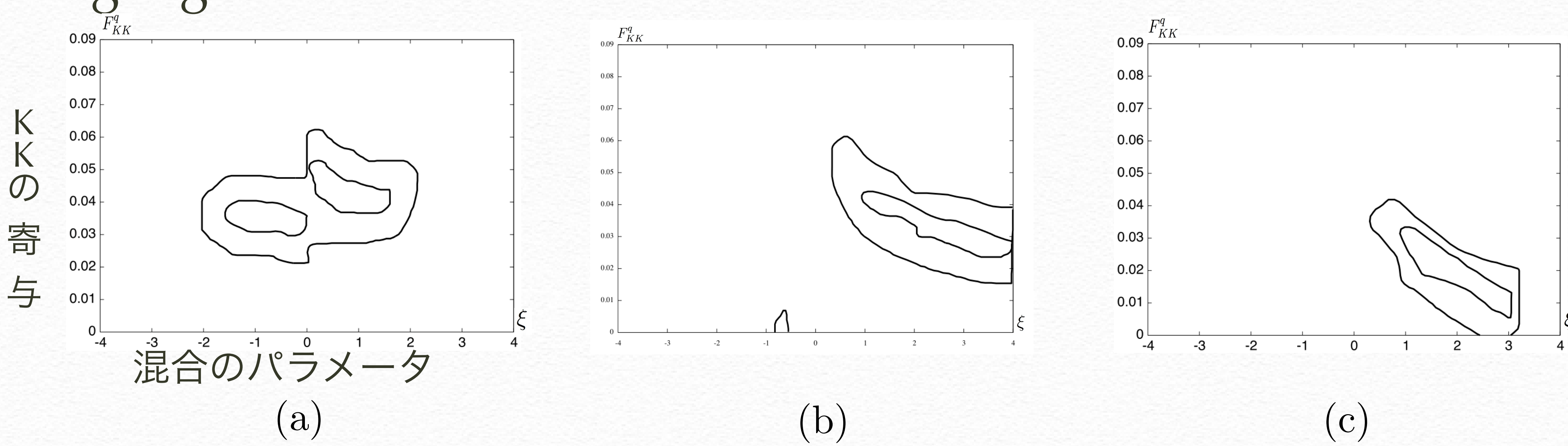


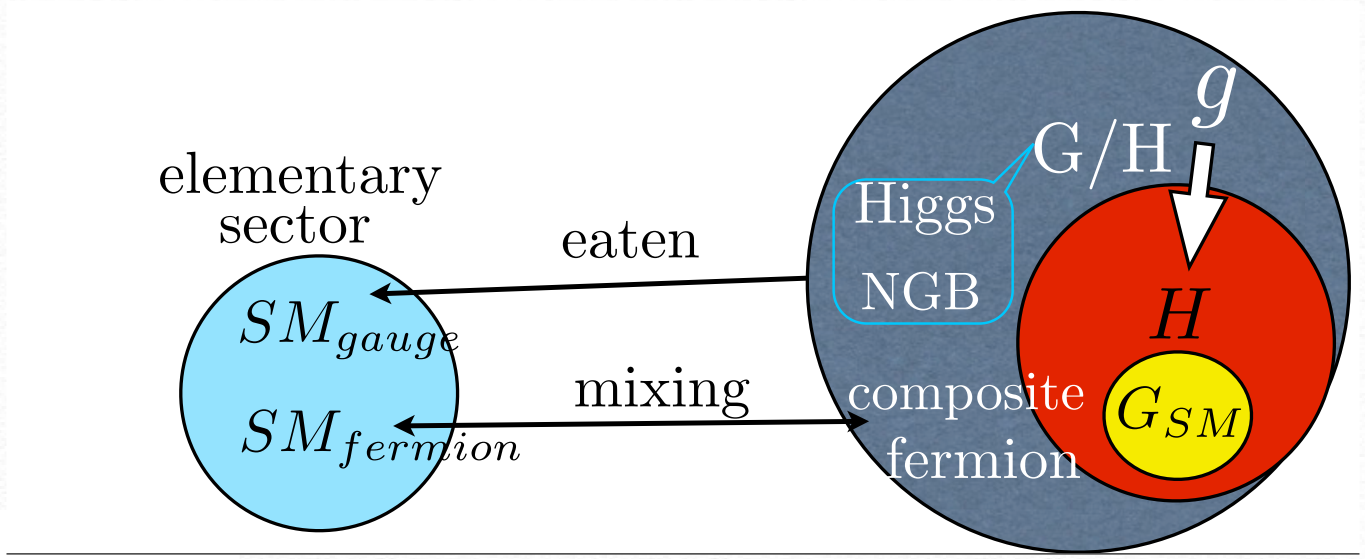
FIG. 8: Contours of constant $\Delta\chi^2 = 1$ and $\Delta\chi^2 = 4$ in F^q_{KK} and ξ plane at (a) Point I, (b) II

Minimal Composite Higgs Model (MCHM)

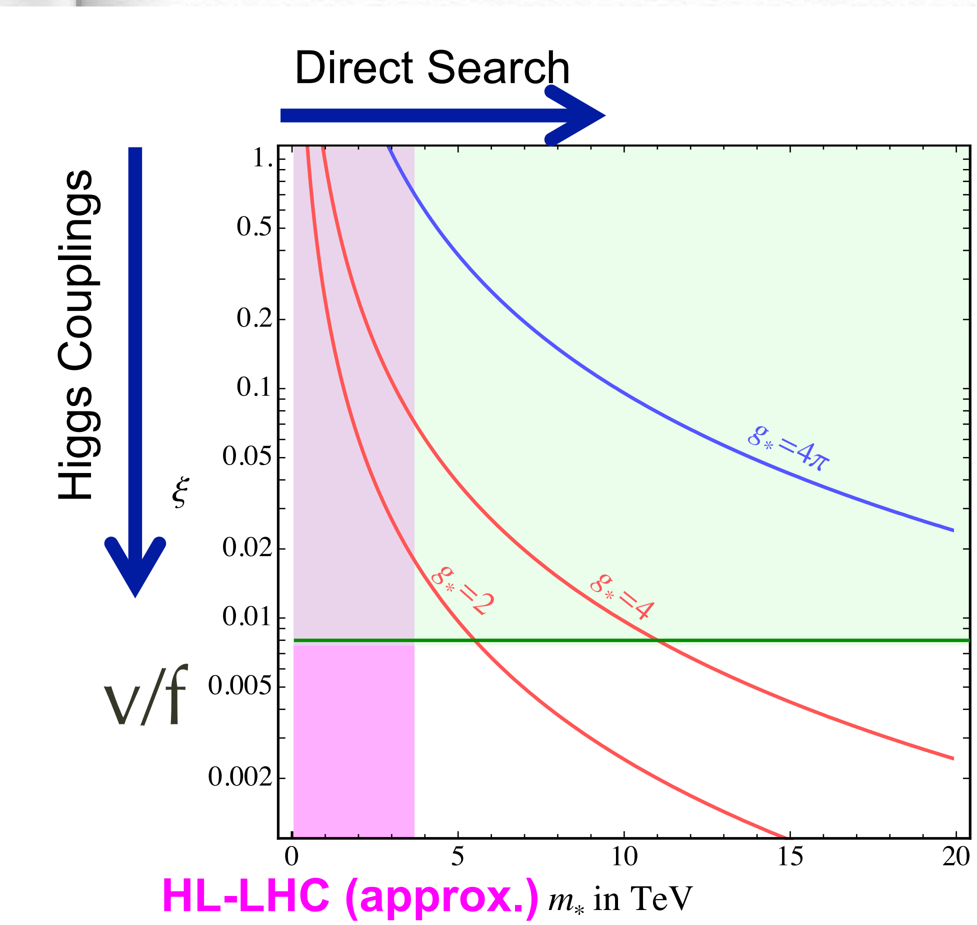
SO(5)x U(1)x→ SO(4)x U(1)x

$$\Sigma = \Sigma_0 e^{\Pi/f}$$

$$\Sigma = (0,\ 0,\ 0,\ \sin\frac{h(x)}{f}, \cos\frac{h(x)}{f})$$



4 NG-> SU(2) doublet
1 higgs + 3 NG



$$\xi = \frac{g_*^2}{m_*^2} v^2$$ =v2/f2

$$\frac{g_{hVV}}{g_{h_{SM}VV}} = \sqrt{1-\xi}$$

ILC

$$\frac{\Delta g_{hVV}}{g_{hVV}} = 0.4\%$$

v/f ~ 0.09 くらいまで
リーチがある

top partner of MCHM

MCHM5 arXiv:1110.5646

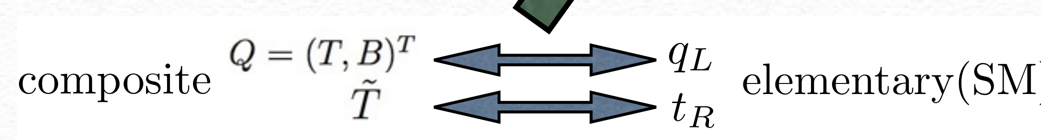
$$\Psi = \frac{1}{\sqrt{2}}\begin{pmatrix} B-X \\ i(B+X) \\ T+U \\ i(T-U) \\ \sqrt{2}\tilde{T} \end{pmatrix}$$

field	T^3_L	T^3_R	X	$Y = T^3_R + X$	$Q_{EM} = T^3_L + Y$
X	$1/2$	$1/2$	$2/3$	$7/6$	$5/3$
U	$-1/2$	$1/2$	$2/3$	$7/6$	$2/3$
T	$1/2$	$-1/2$	$2/3$	$1/6$	$2/3$
B	$-1/2$	$-1/2$	$2/3$	$1/6$	$-1/3$
$\tilde{T}$	0	0	$2/3$	$2/3$	$2/3$

(2, 2) — rows X, U, T, B

(1, 1) — row $\tilde{T}$

$$\mathcal{L}_{Yukawa+Mass} = \underbrace{-Yf(\bar{\Psi}_L\Sigma^T)(\Sigma\Psi_R)}_{\text{(proto) yukawa}} \underbrace{- M\bar{\Psi}_L\Psi_R}_{\text{vector mass}} \underbrace{- \Delta_L\bar{q}_L Q_R - \Delta_R\bar{\tilde{T}}_L t_R}_{\text{mixing}}$$



bR とmixing をいれるには 10=4+6 表現も必要

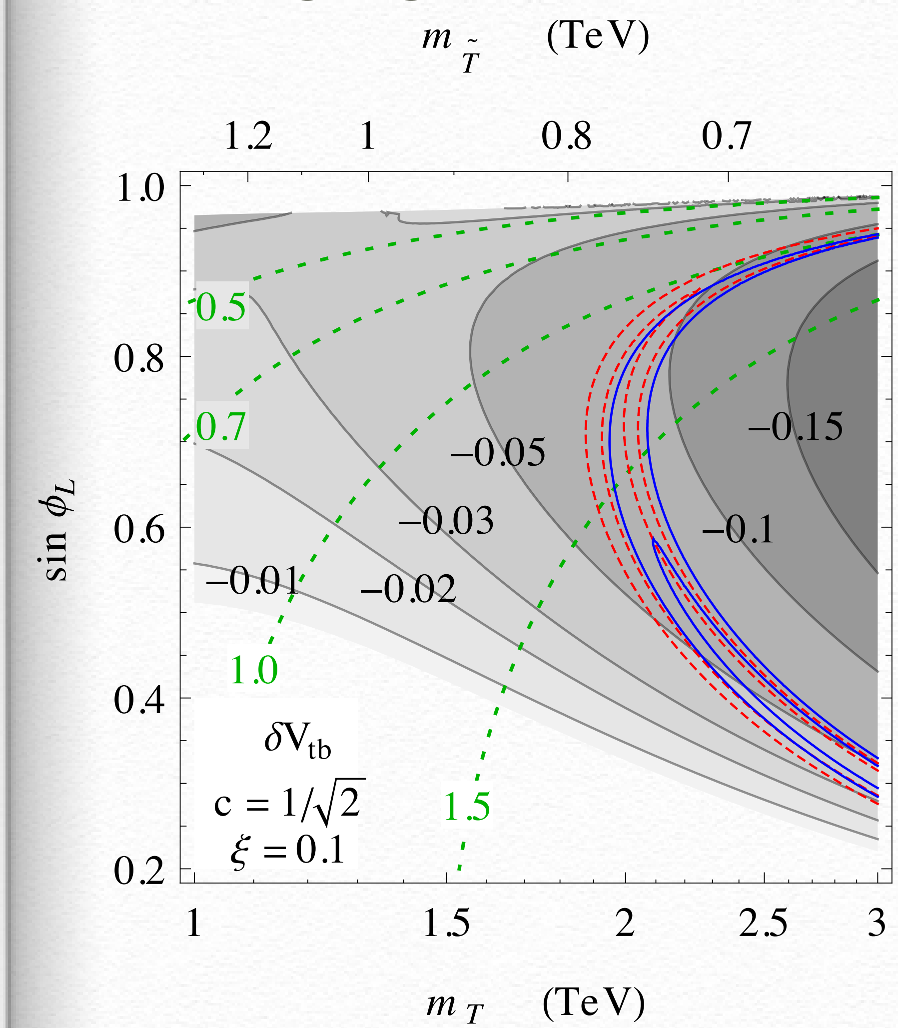
主たる制限 T, S, Zbb

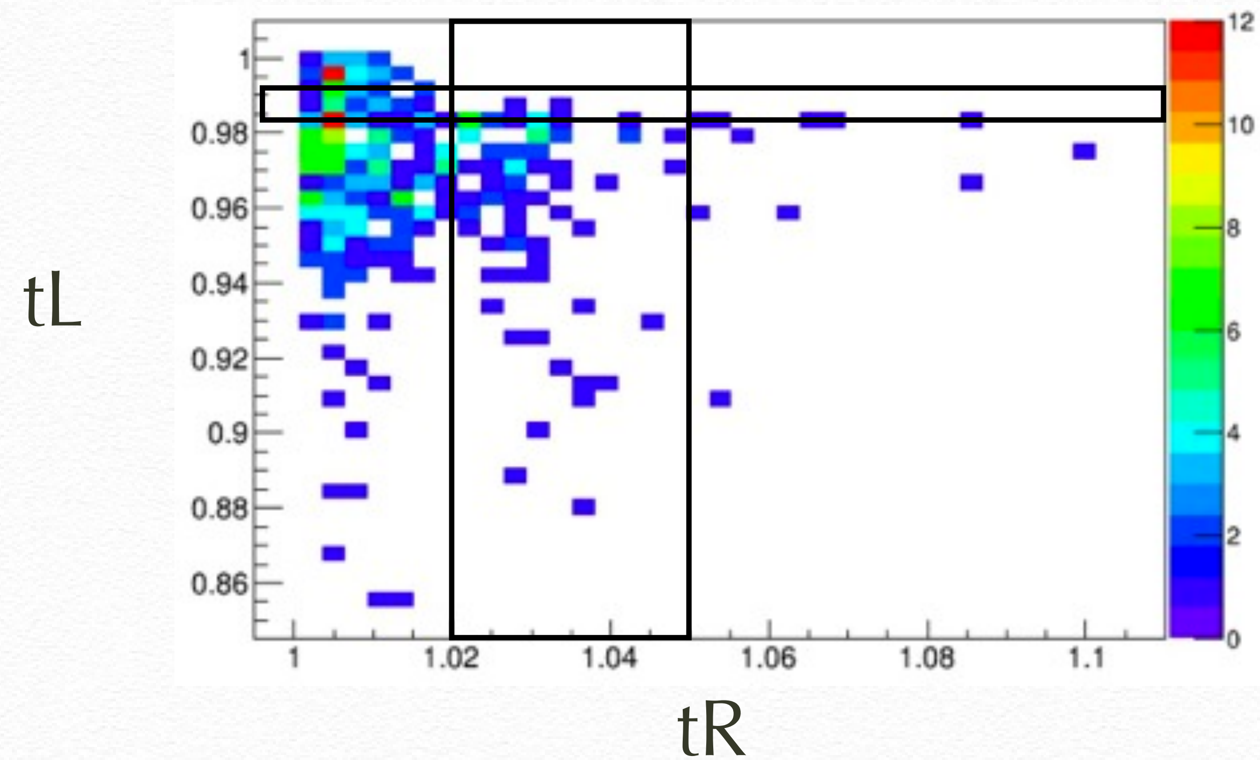
interesting effect on Hgg, Hγγ, Htt

ttZ coupling in MCHM

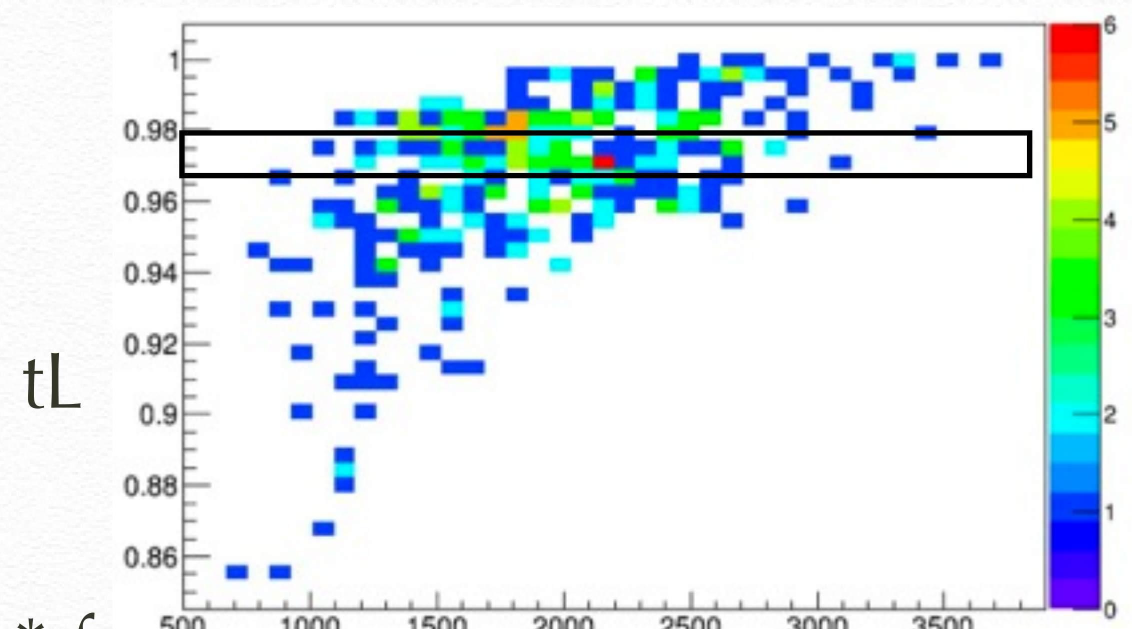
Kubota in progress

$\delta g_{tL}/g_{tL}$ =-0.05~-0.1





ILC precision
Left coupling 0.6%
Right coupling 1.4%

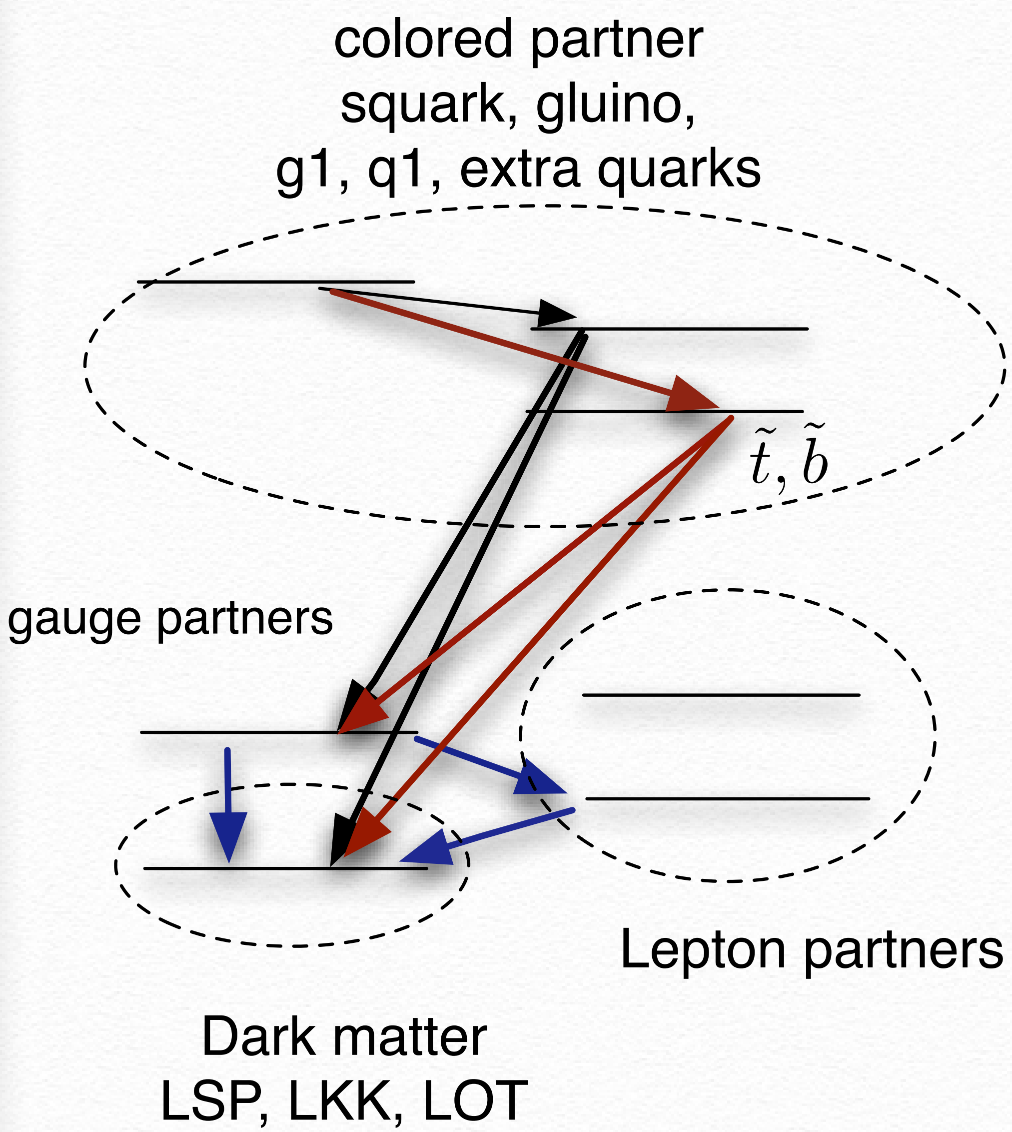


scan over Y,M,Δ, g*,f..
fix top mass, mH..

top partner mass

SUSY

On going
"Dark matter (SUSY) searches"



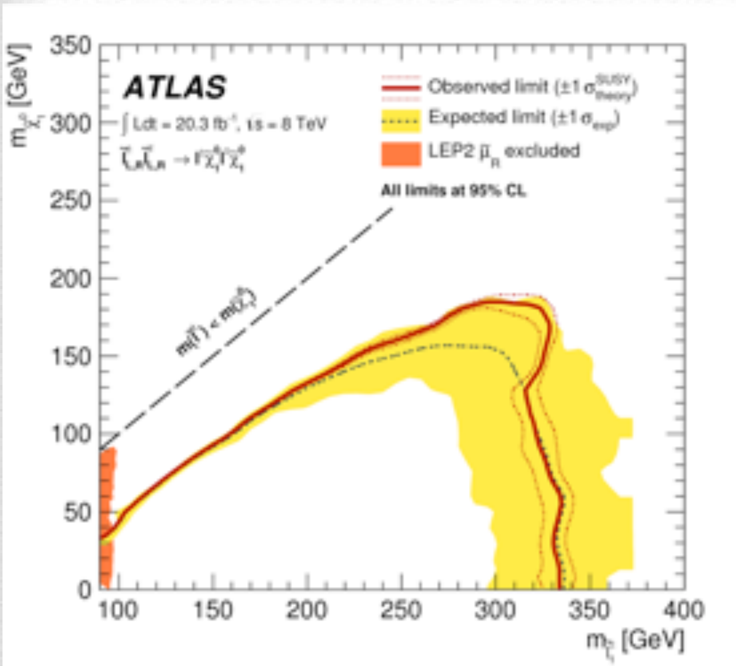
- **"SUSY signature"**
  - "Models with new colored particles decaying into a stable neutral particle-- LSP"
- Some of "New physics" are migrated into SUSY category.
- Signal:
  High P_T jets hiph P_T leptons and E_{Tmiss}

assume mass difference is large

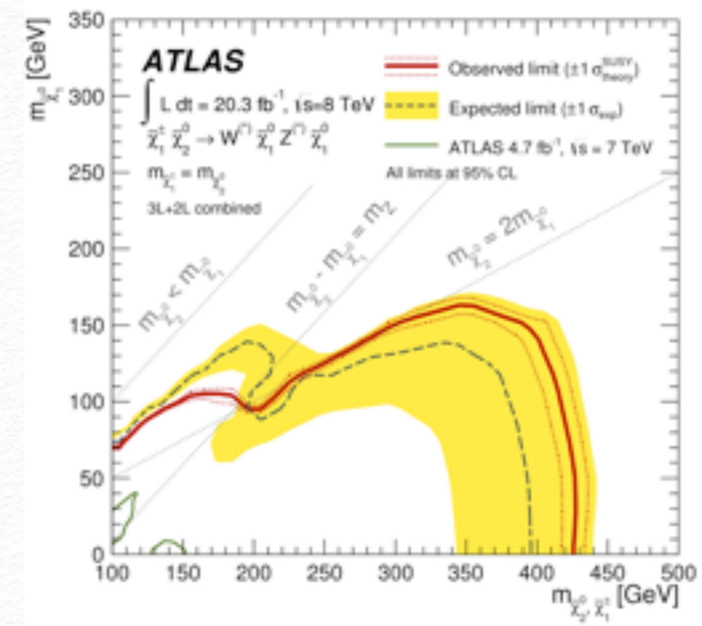
if there are R parity violation, we have additional jets and leptons instead of E_{Tmiss}

Production of W, Z, and top with additional jets would be significant background

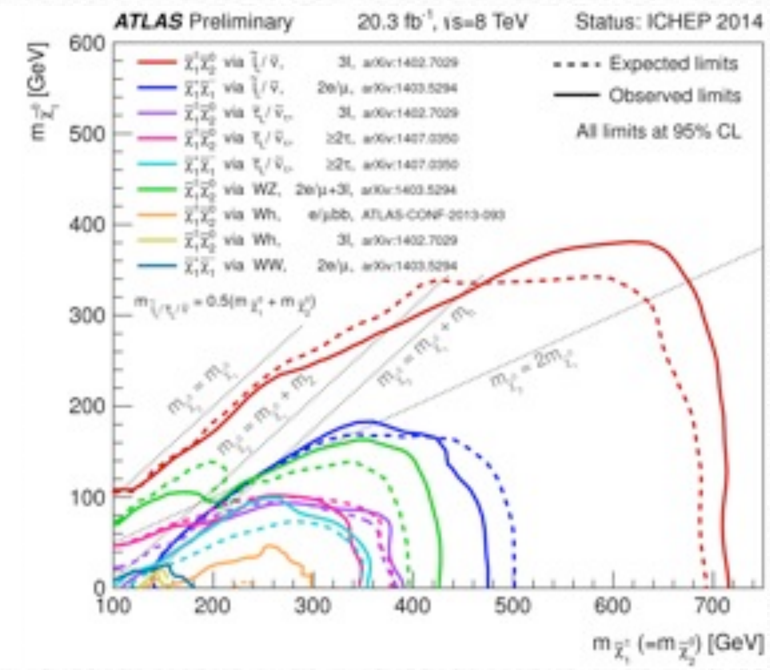
EW SUSY and dark matter



2l



テキスト



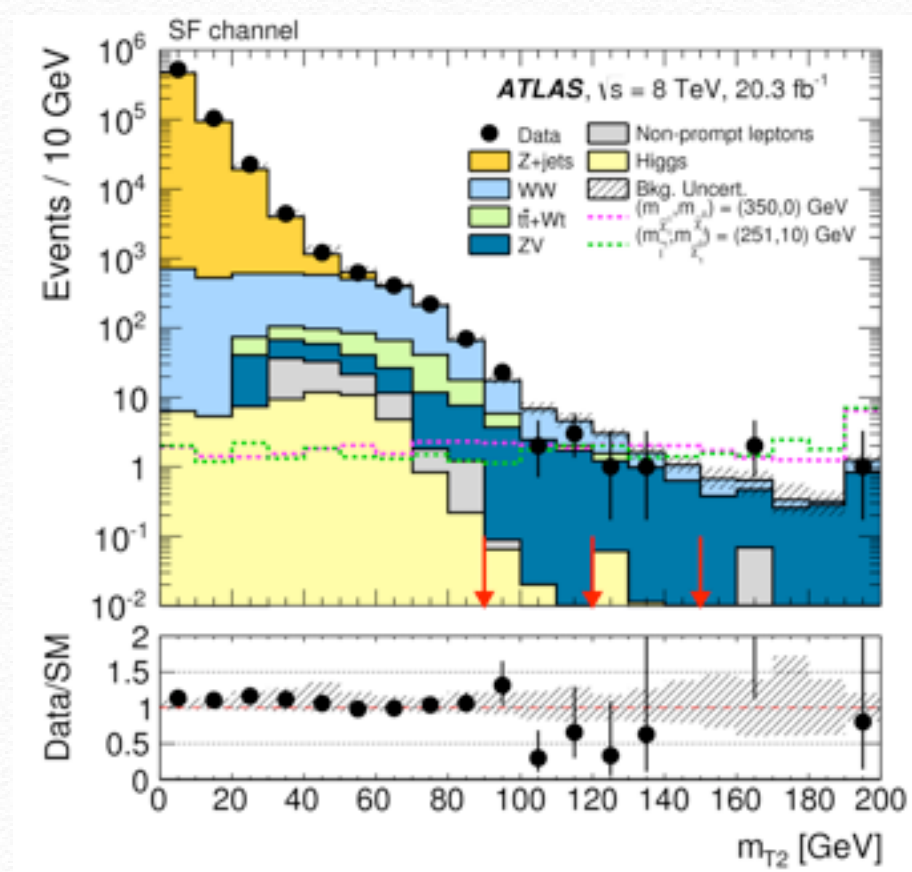
Reach up to 350 GeV for slepton

Note however

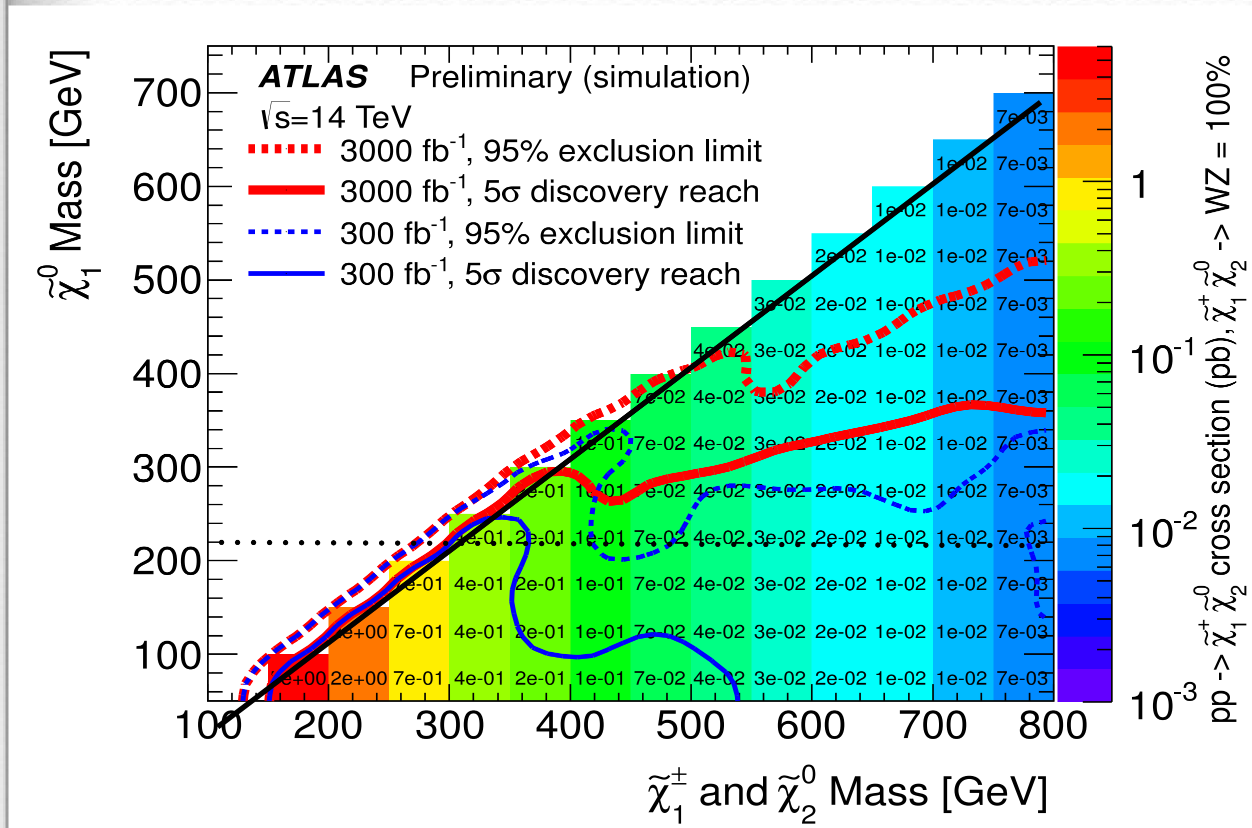
Mass difference 50 GeV required due to the overlap with W and Z's

(ILC is more sensitive to those.)

chargino は案外 limit 悪い　(M2=2M1と思うと)

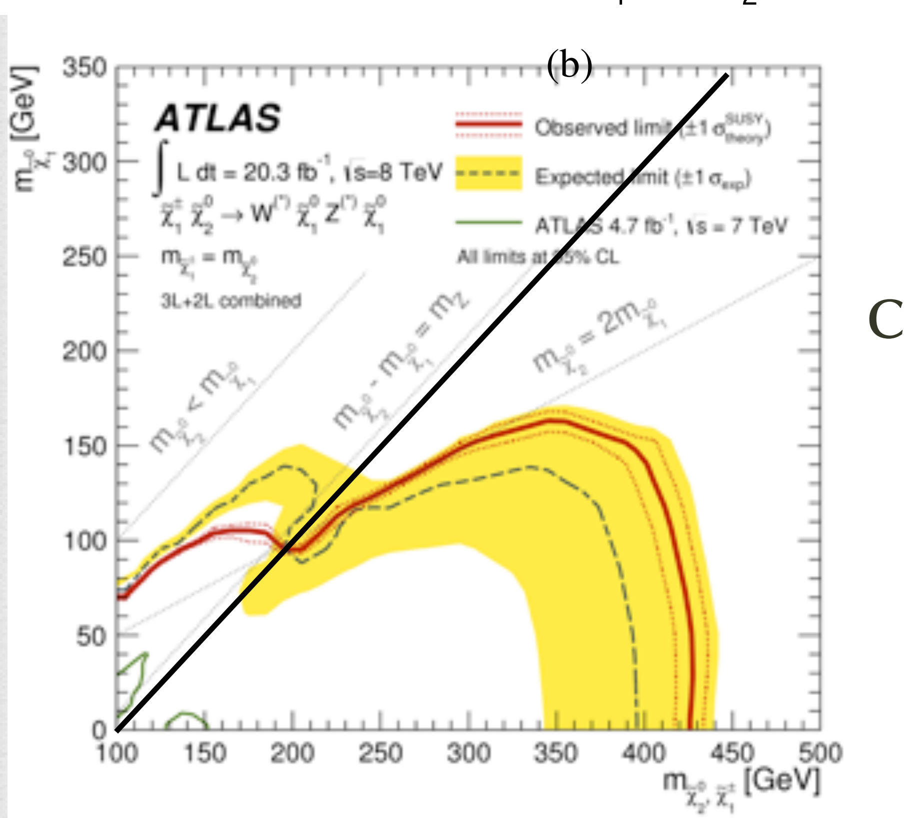


EW SUSY at HL-LHC



extension at HL-LHC (up to 3000fb^{-1}) because lepton trigger rate will be kept

LHC will be sensitive to Lepton channel !



current limit

Object(s)	Trigger	Estimated Rate no L1Track	Estimated Rate with L1Track
e	EM20	200 kHz	40 kHz
γ	EM40	20 kHz	10 kHz*
μ	MU20	> 40 kHz	10 kHz
τ	TAU50	50 kHz	20 kHz
ee	2EM10	40 kHz	< 1 kHz
$\gamma\gamma$	2EM10	as above	~5 kHz*
$e\mu$	EM10_MU6	30 kHz	< 1 kHz
$\mu\mu$	2MU10	4 kHz	< 1 kHz
$\tau\tau$	2TAU15I	40 kHz	2 kHz
Other	JET + MET	~ 100 kHz	~ 100 kHz
Total		~ 500 kHz	~ 200 kHz

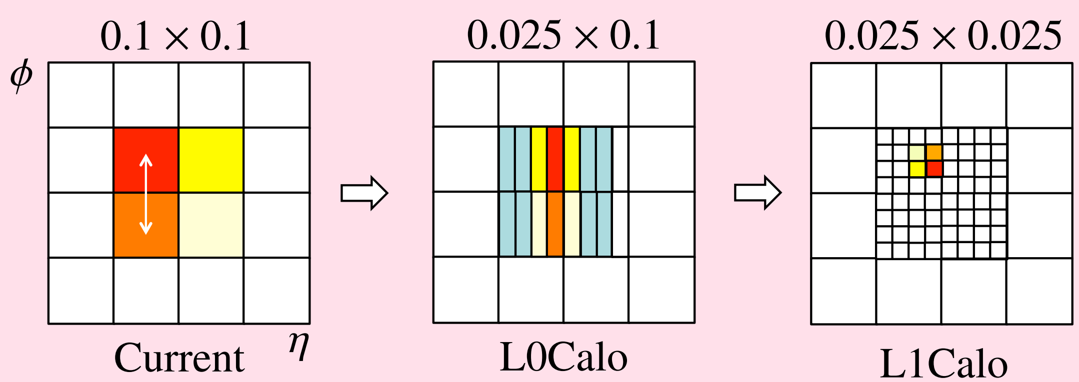
Table 2.3: The expected Level-1 trigger rates at 7×10^{34} cm^{-2} s^{-1} for the baseline split L

HL-LHC (1000->3000 fb^{-1}) backup

- 2018年 14TeV L~2x10^{34} cm^{-2}s^{-1} 25ns (Phse 1)
- 2022年 L~5x10^{34} cm^{-2}s^{-1} (Phase II)
- strong intention to keep trigger as low as possible for Higgs physics

This is not free!

Ex ATLAS ECal



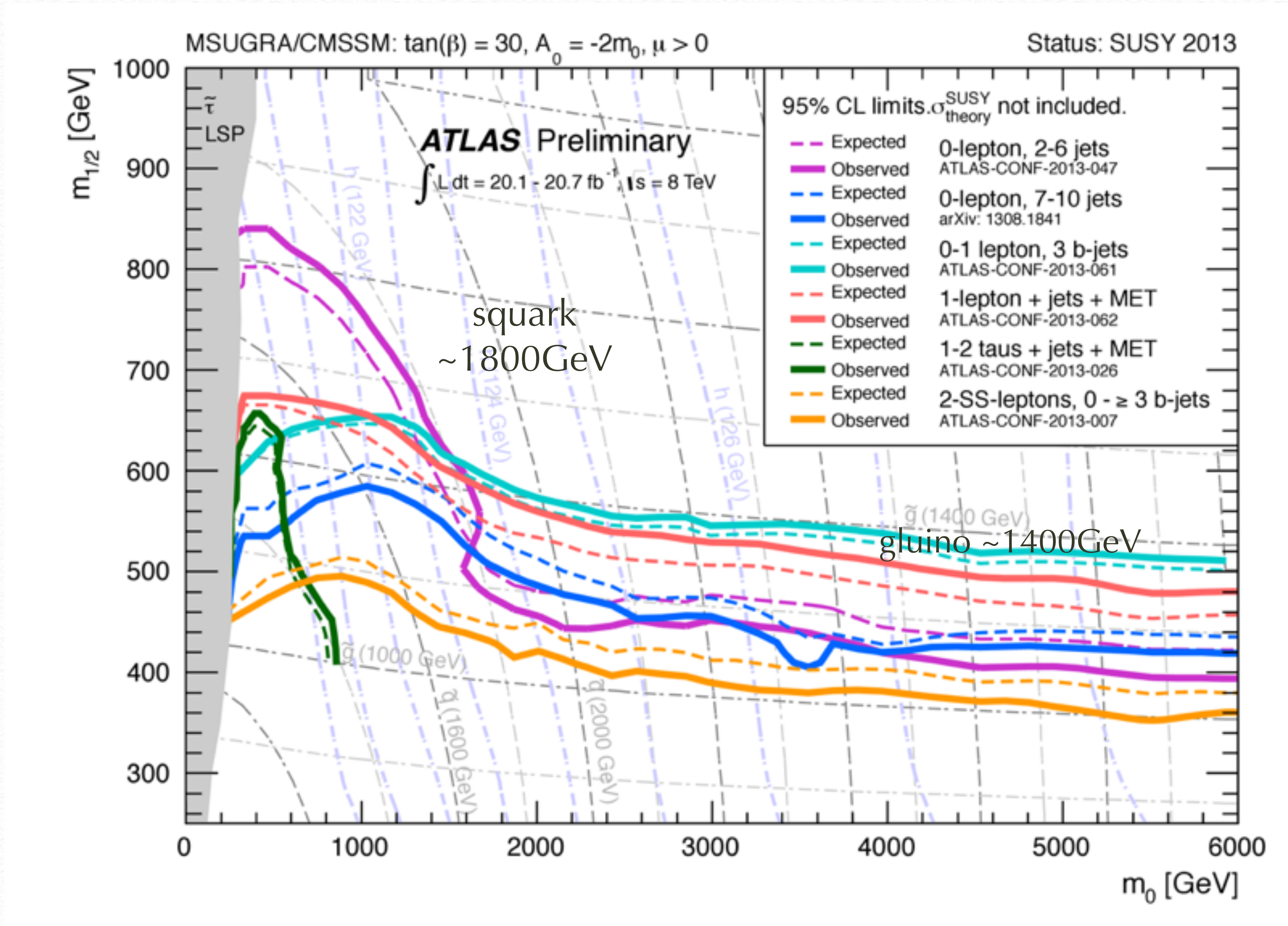
Muon....

muon new small wheel
for 1 mrad resolution

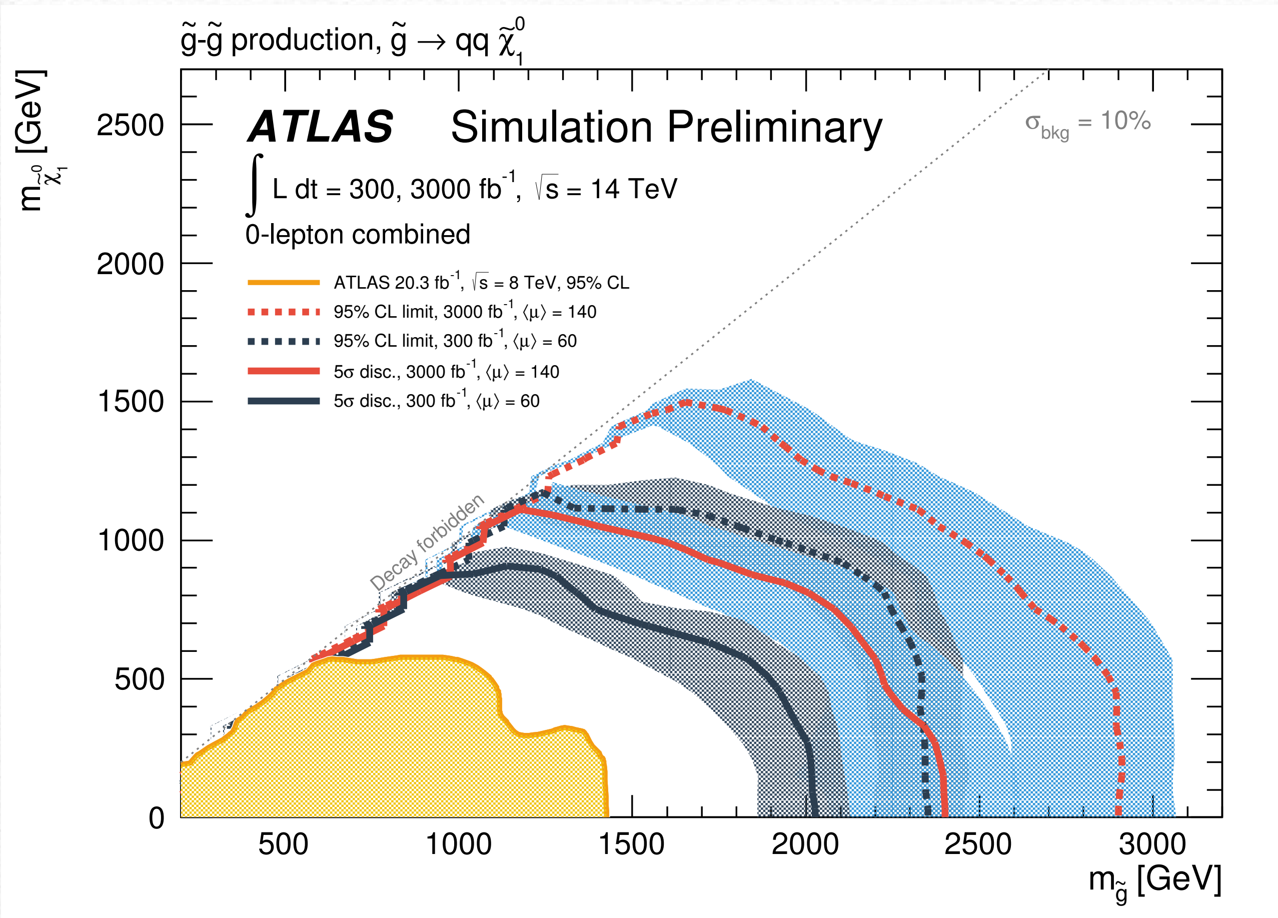
Figure 2.5: The EM granularity available in the current, Phase-II Level-0 and Phase-II Level-1 EM triggers.

Object(s)	Trigger	Estimated Rate no L1Track	Estimated Rate with L1Track
e	EM20	200 kHz	40 kHz
γ	EM40	20 kHz	10 kHz*
μ	MU20	$>$ 40 kHz	10 kHz
τ	TAU50	50 kHz	20 kHz
ee	2EM10	40 kHz	$<$ 1 kHz

jet +missing channel



LHC 13TeV



(a) $\tilde{q}\tilde{q}$

gluino

scalar top

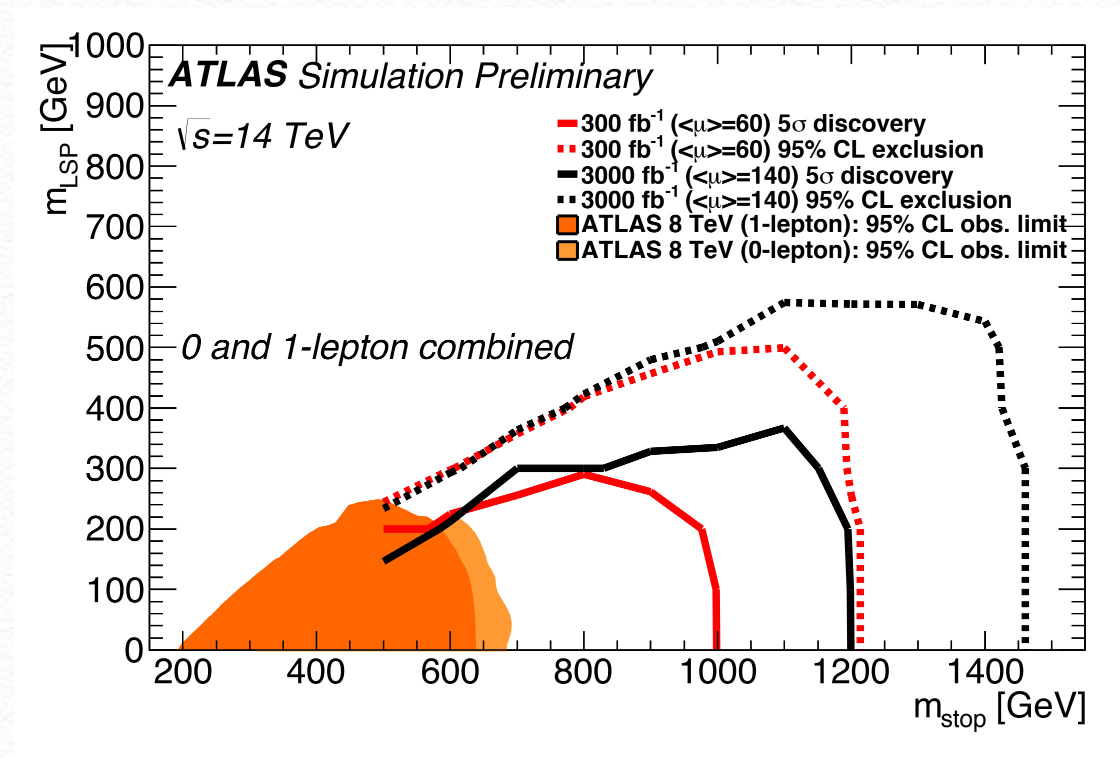


Figure 5: The 95% CL exclusion limits (dashed) and 5σ discovery reach (solid) for 3 3000 fb^{-1} (black) in the $\tilde{t}$, $\tilde{\chi}_1^0$ mass plane assuming $\tilde{t} \rightarrow t + \tilde{\chi}_1^0$ with a branching rati results are shown for the combination of the 1-lepton and 0-lepton analyses. The obse the analyses of 8 TeV data are also shown.

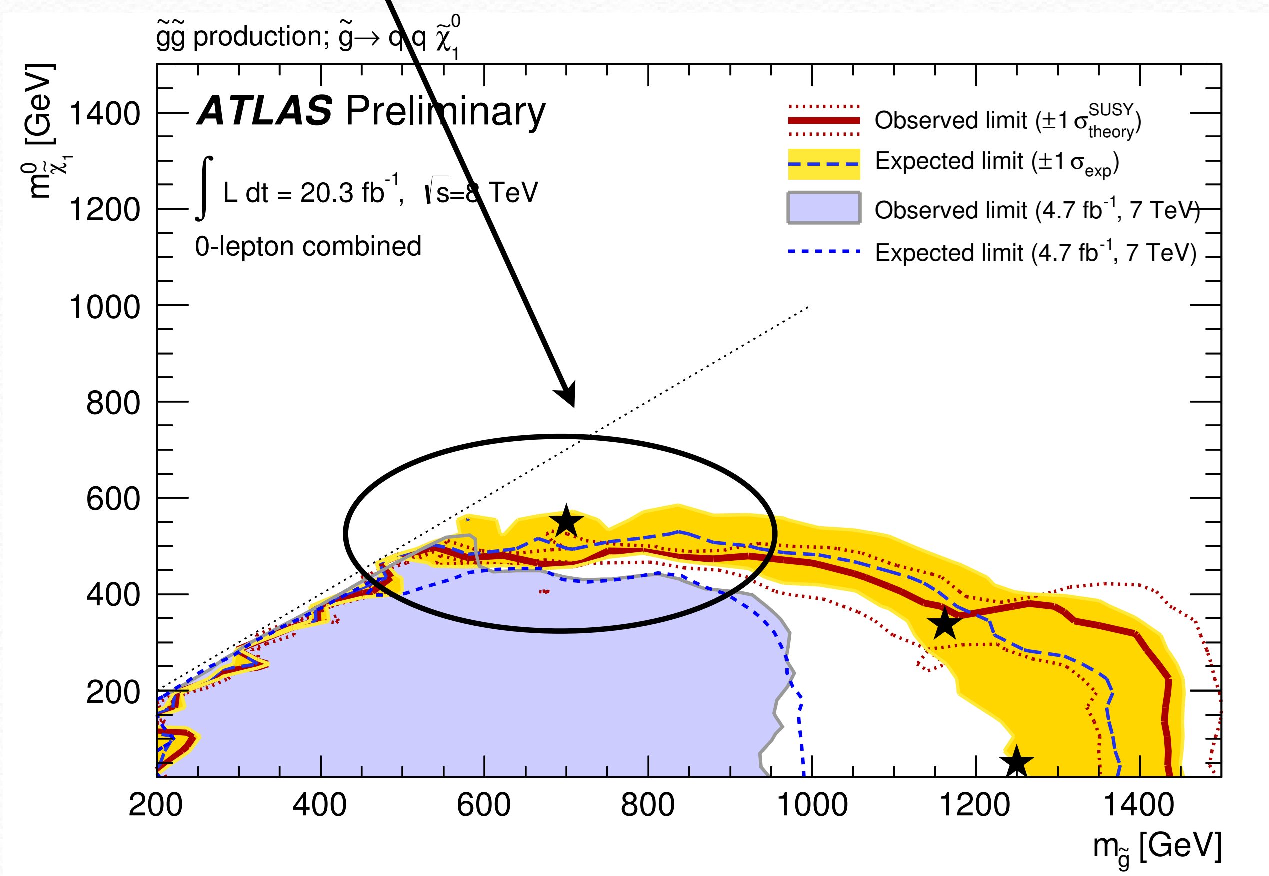
The limit on the mass depends on the assumption of light LSP

軽い超対称粒子があっても

みえないとすればここ

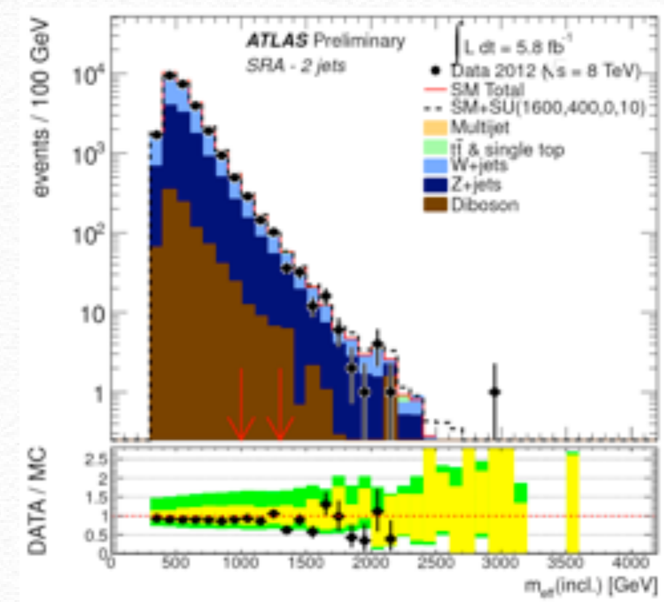
Meff, ETmiss
が小さい

dark matter mass



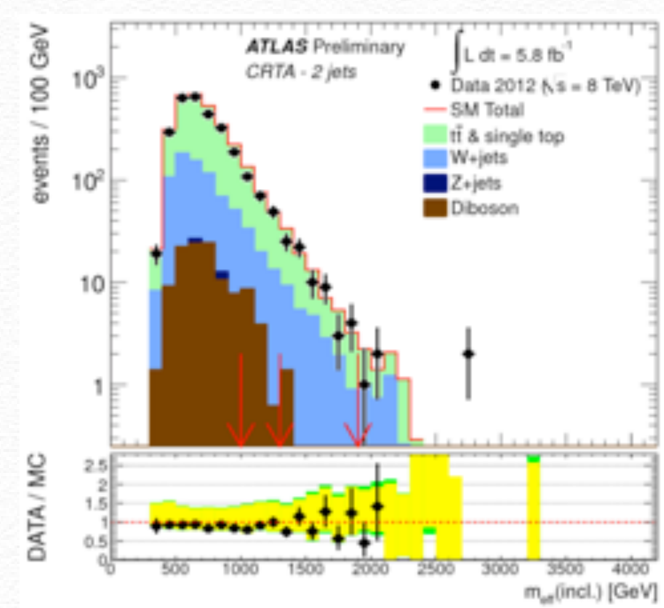
gluino mass

signal



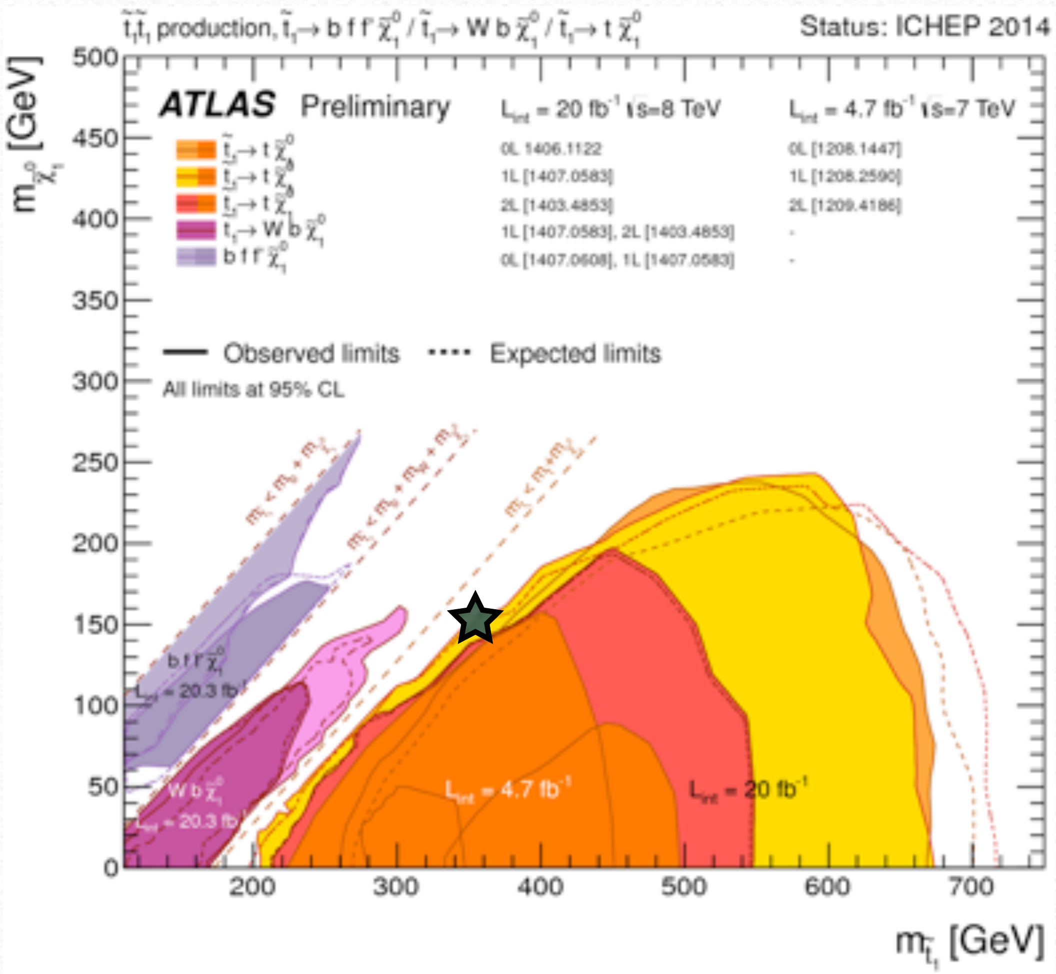
Meff=sum of pT of the jet and missing ET

control

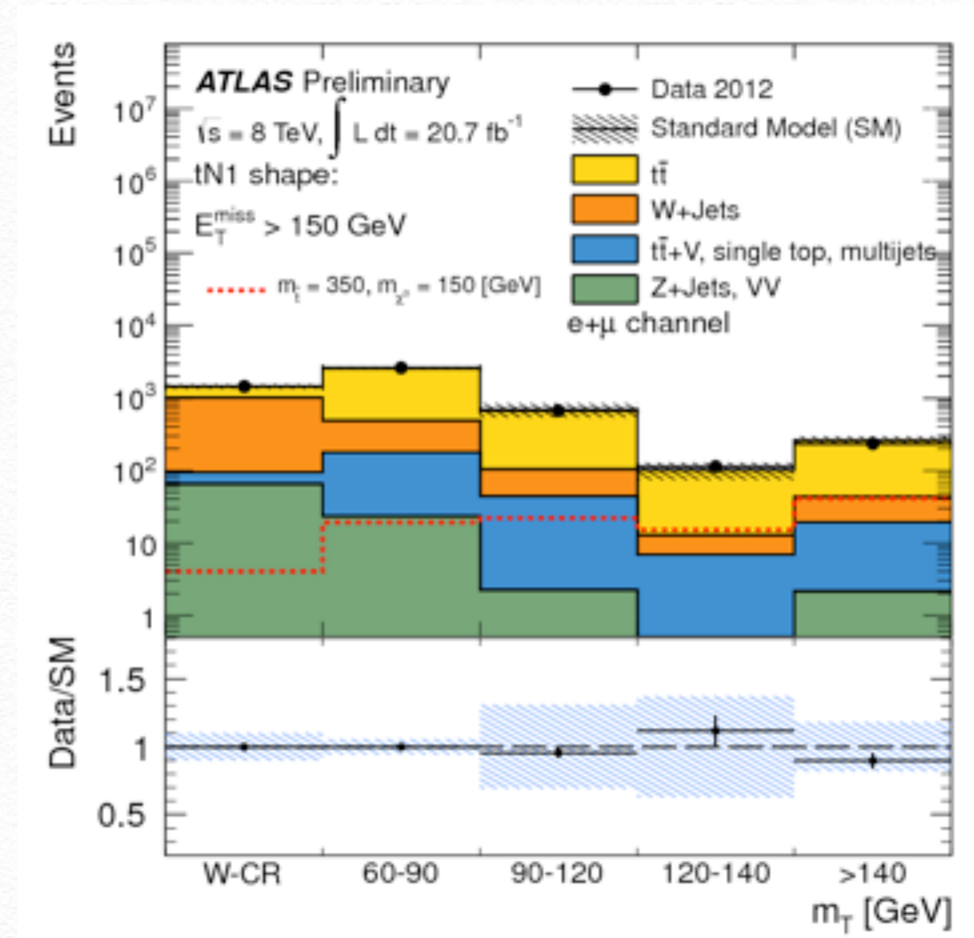


Light SUSY confronts real data
M(SUSY) > 1.5TeV Mstop~ 650GeV GeV

The bound is model independent



exclude up to the region
where mstop~mLSP+mt +30GeV



stop 350GeV and LSP 150GeV
There are no region with
S/N>0.1 in this plot!

The limit relys on understanding of background

I am not sure I take this limit but it is still nice to see such efforts

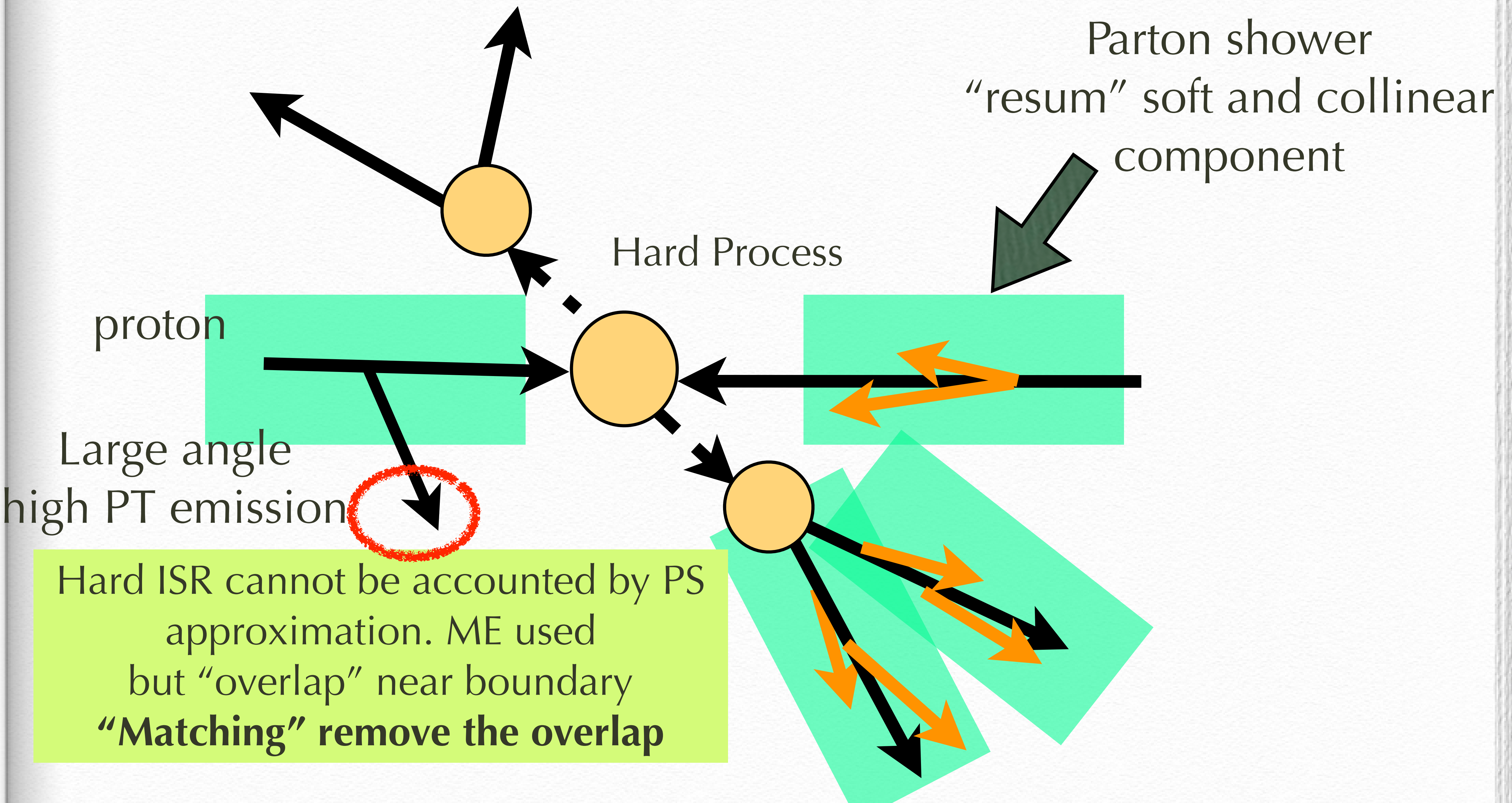
QCD technique for BSM discovery

Matching

ISR tag

jet structure

background estimation powered by “Matching”



The inclusion of additional emission to the SM process is important when we rely on the cut on P_{T3}, P_{T4} and inclusive quantity like H_T, Meff...

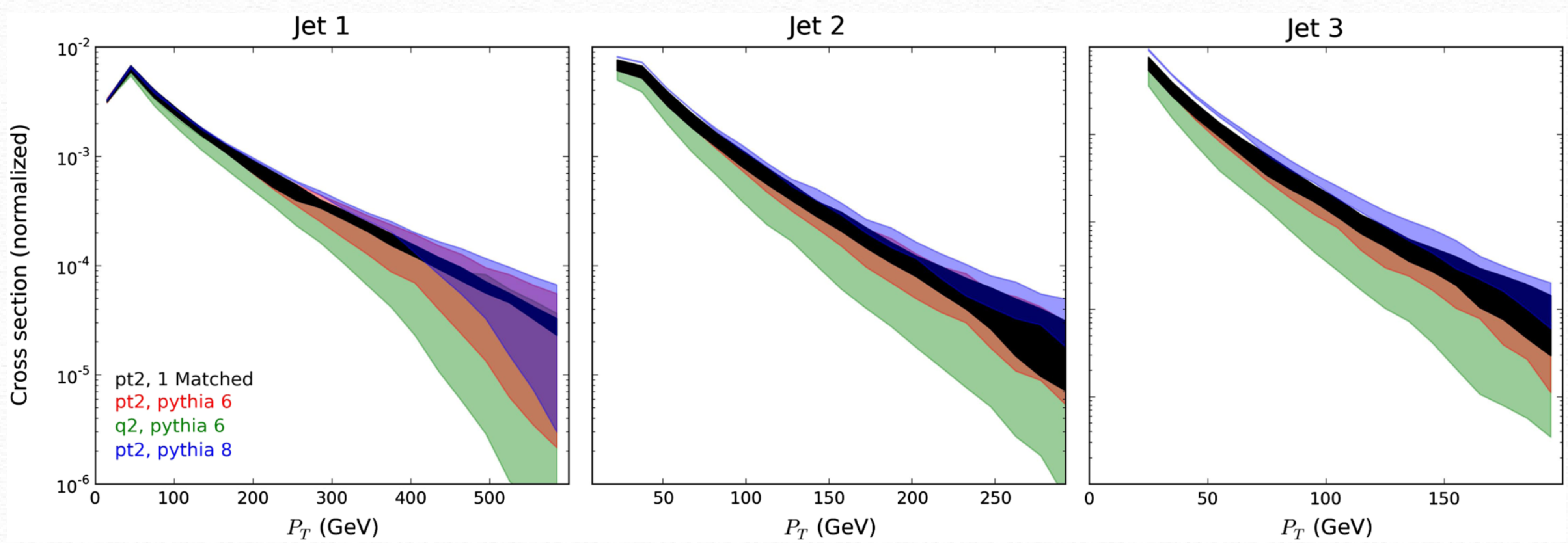
MLM

CKKW 2001

Prediction of ISR:Matching reduce the generator dependence

- gluino production pp-> gg something
- Parton shower sum soft and collinear divergences, emit initial and final state radiation, but it is only approximation.
- from hard process to final state different scales and ordering (mass, angle, PT) and starting scale (in pythia)
- by doing matching, one obtain stable prediction on the PT distribution of the jets

DREINER, KRÄMER AND TATTERSALL PHYSICAL REVIEW D **87,** 035006 (2013)



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DREINER, KRÄMER AND TATTERSALL PHYSICAL REVIEW D **87,** 035006 (2013)

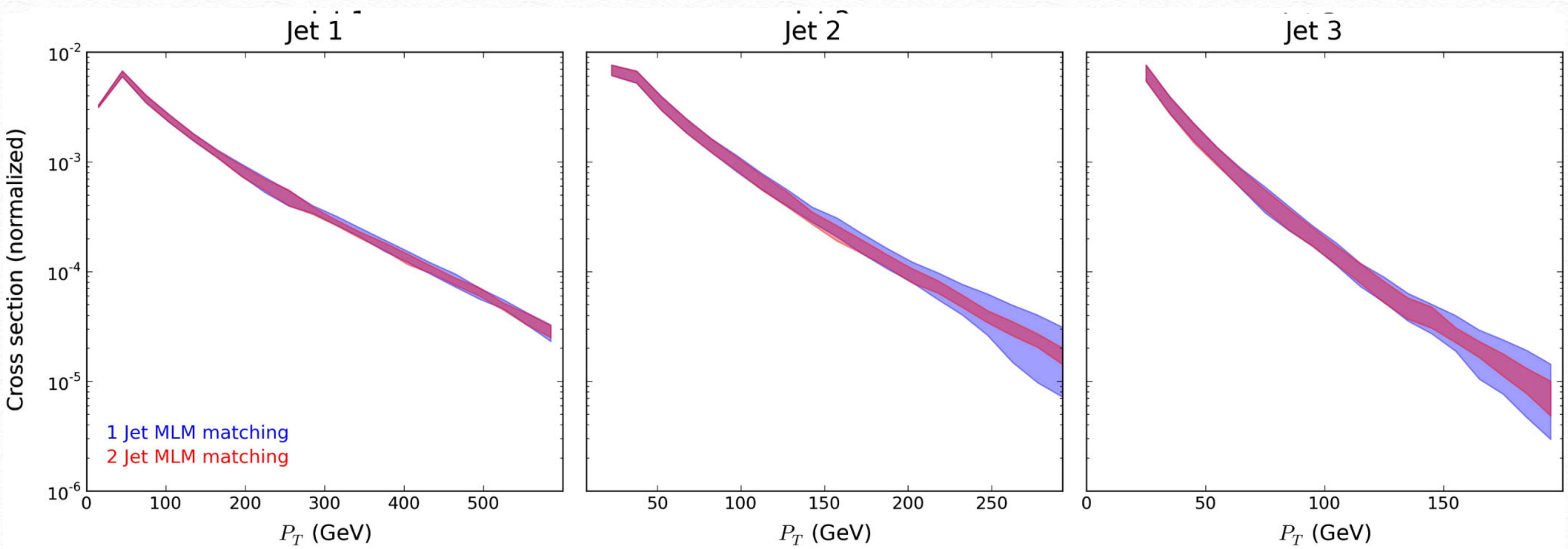
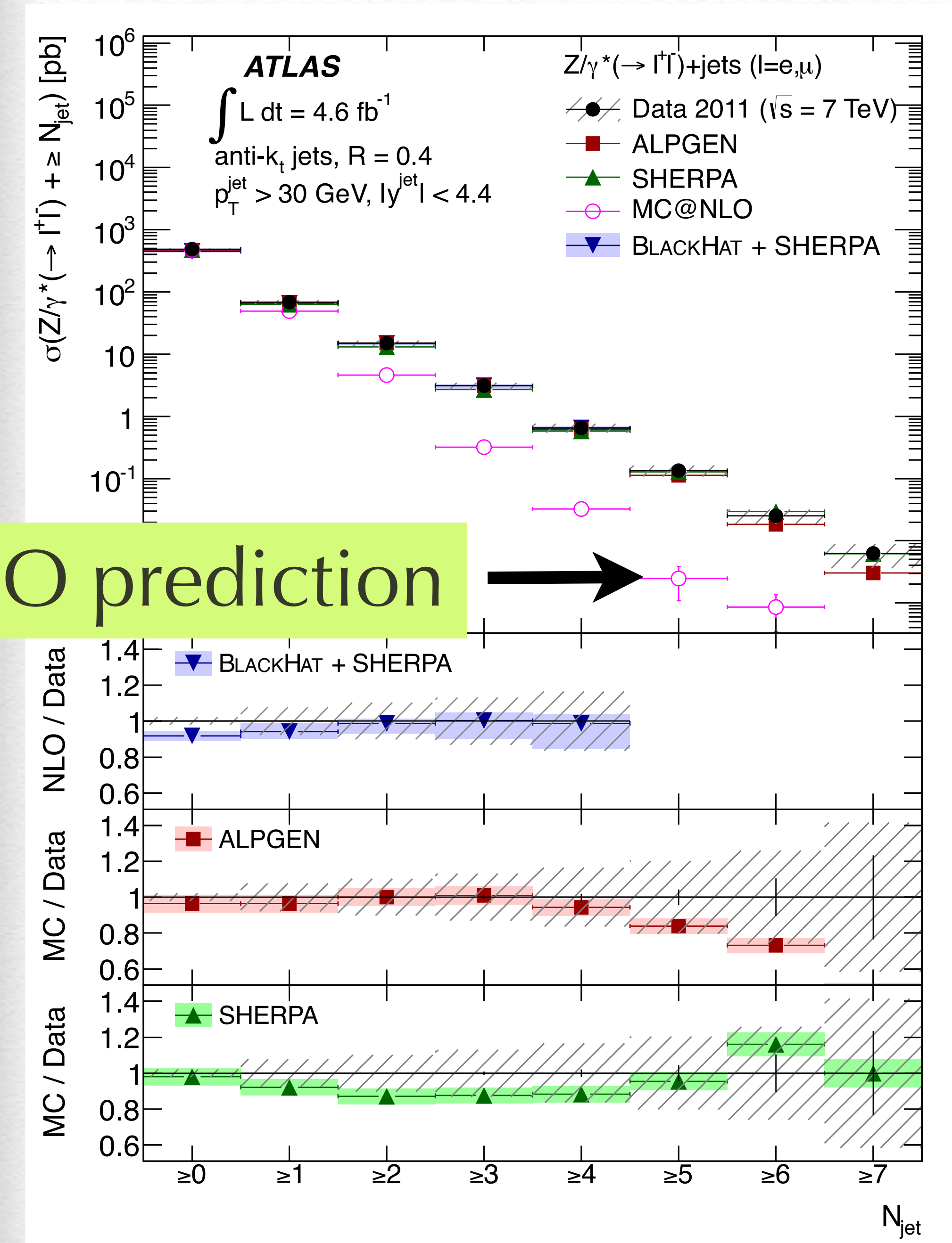


FIG. 3 (color online). Comparison of the uncertainty associated with one jet and two jet MLM matching. The uncertainty is found by

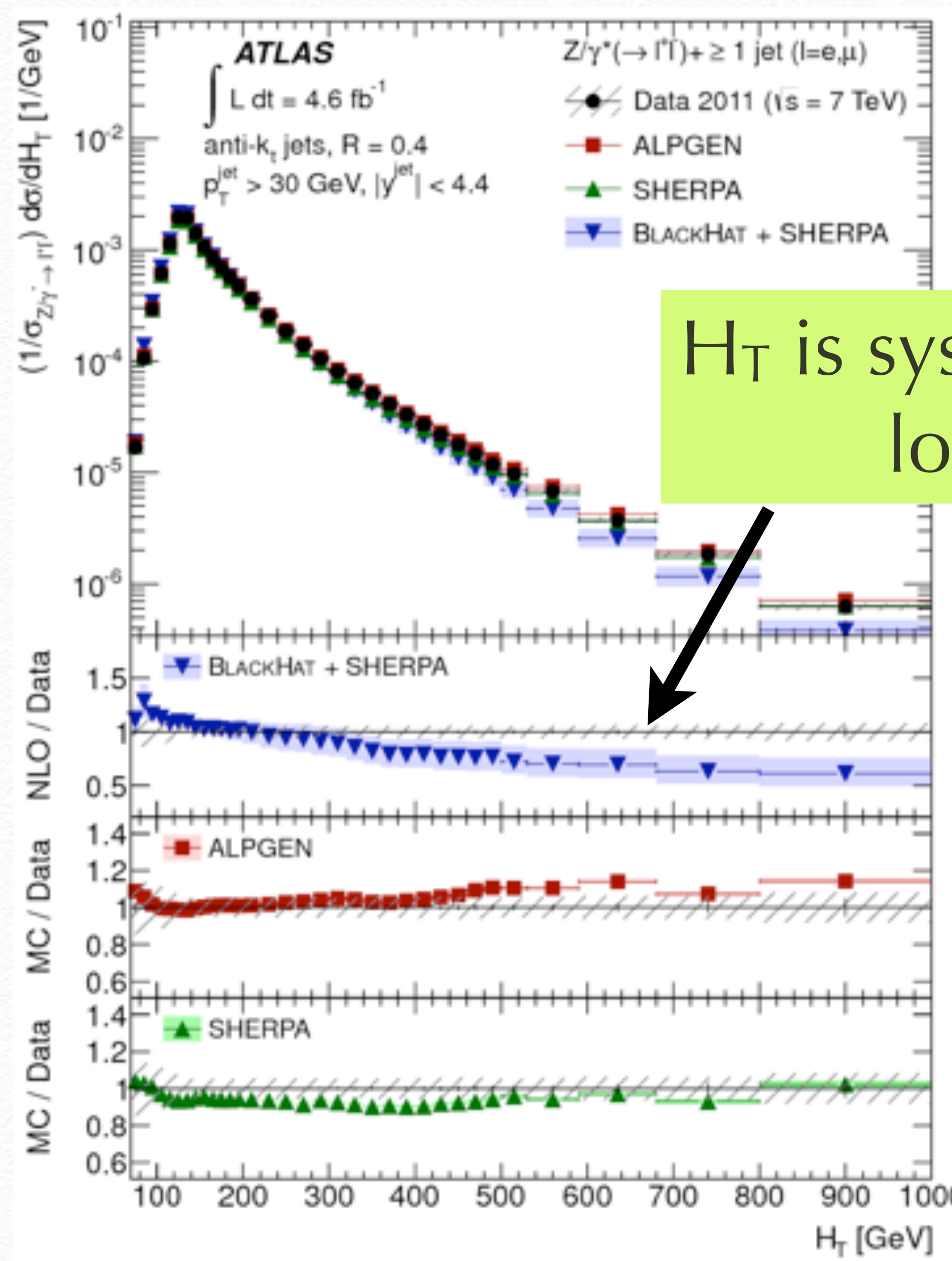
14年7月29日火曜日

.... but still some disagreement

コライダー物理は走りながら体裁を整えている



NLO prediction



H_T is systematically low yet

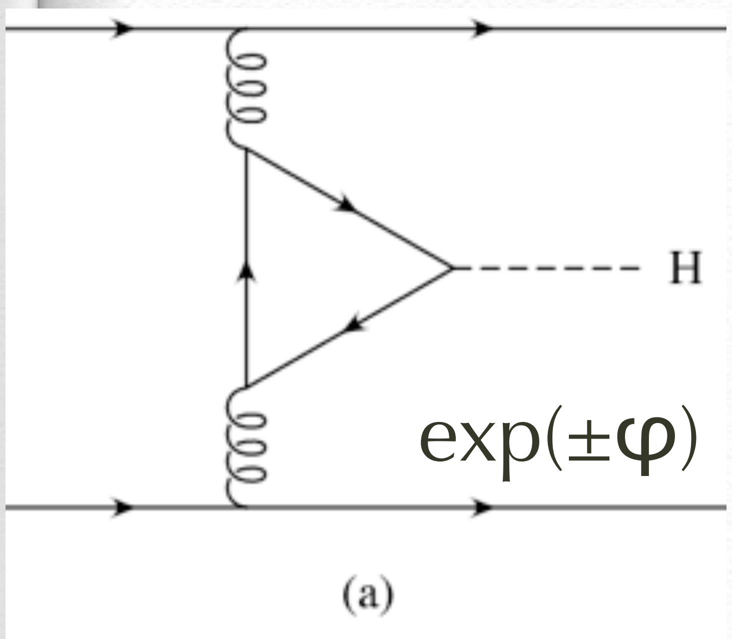
NLO

Tree

Tree

ATLAS 1304.7098

ISR jet in Higgs Production
Azimuthal angle correlation



A+/- B cos $2\Delta\varphi_{12}$

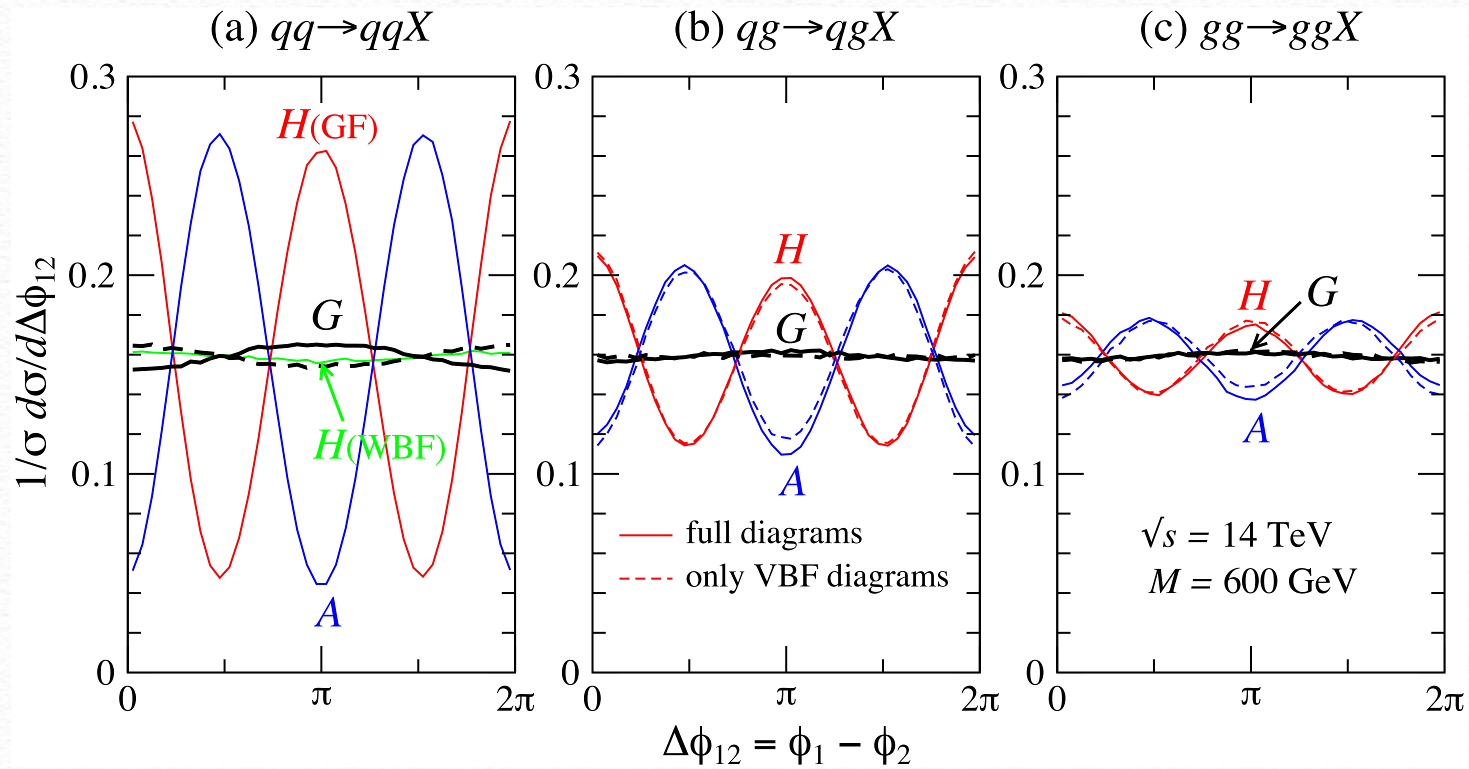
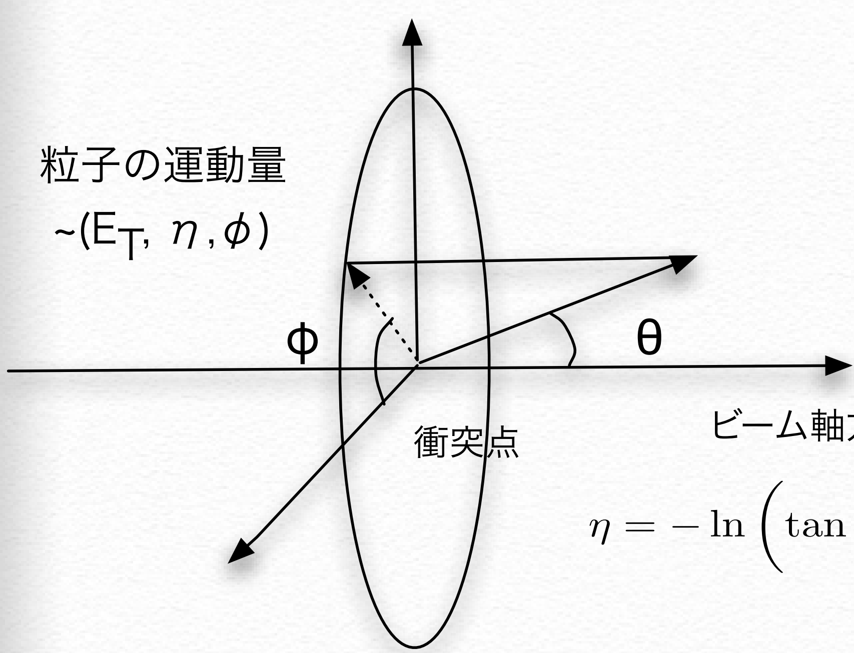


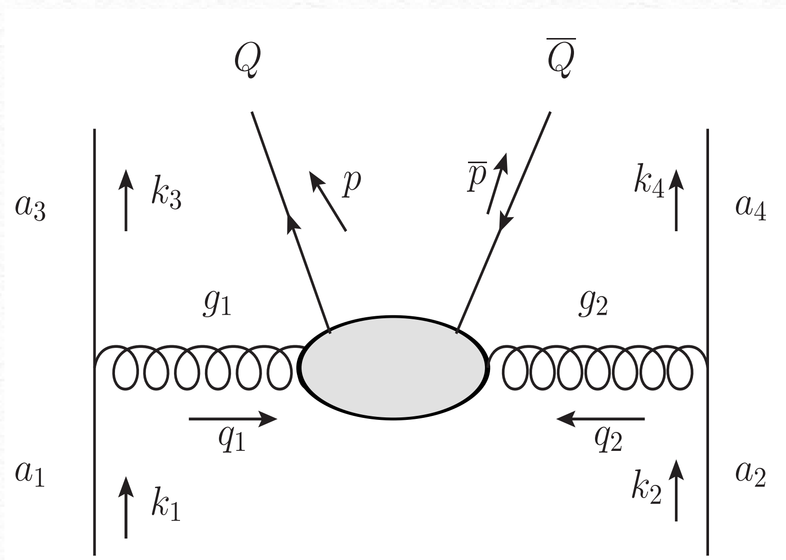
Figure 5: Normalized azimuthal correlations $\Delta\phi_{12}$ (mod 2π) between the two tagging jets in the $pp \to jjX$ process at the LHC, where the selection cuts (5.1) and (5.2) with $\Delta\eta_{jj\min} = 4$ are imposed. For the massive-graviton productions, the additional p_{T_j} cut (5.3) is also imposed. The distributions for each subprocess with the full diagrams (solid lines) and with the only VBF diagrams (dashed lines) are shown.



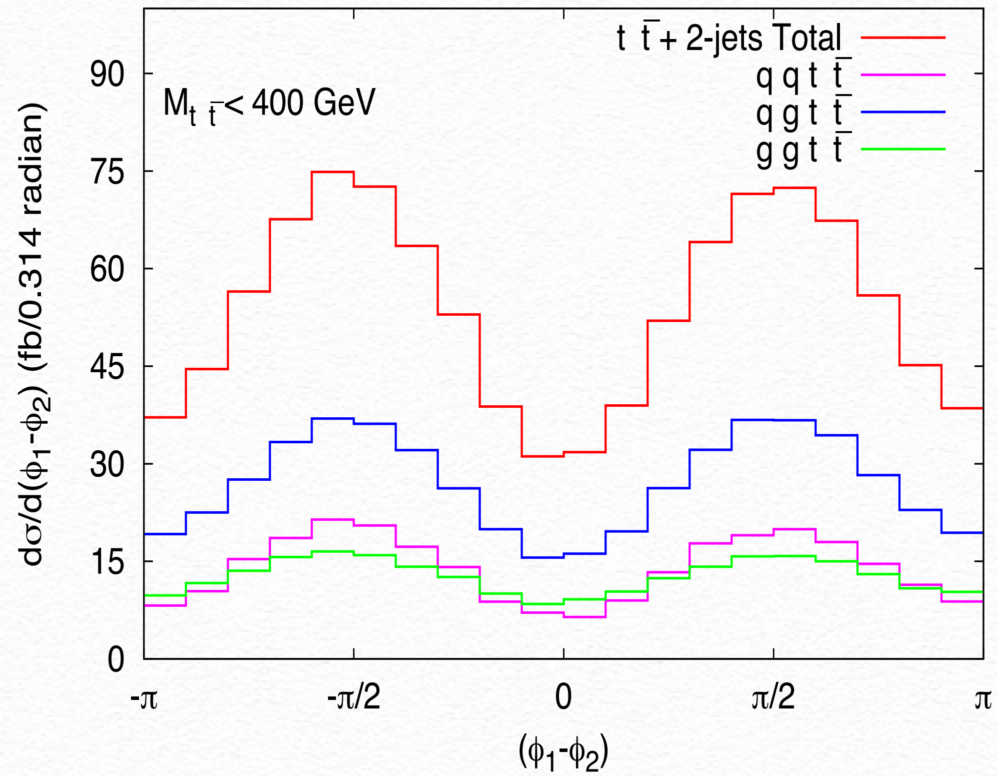
$$\eta = -\ln\left(\tan\frac{\theta}{2}\right)$$

ISR with SUSY

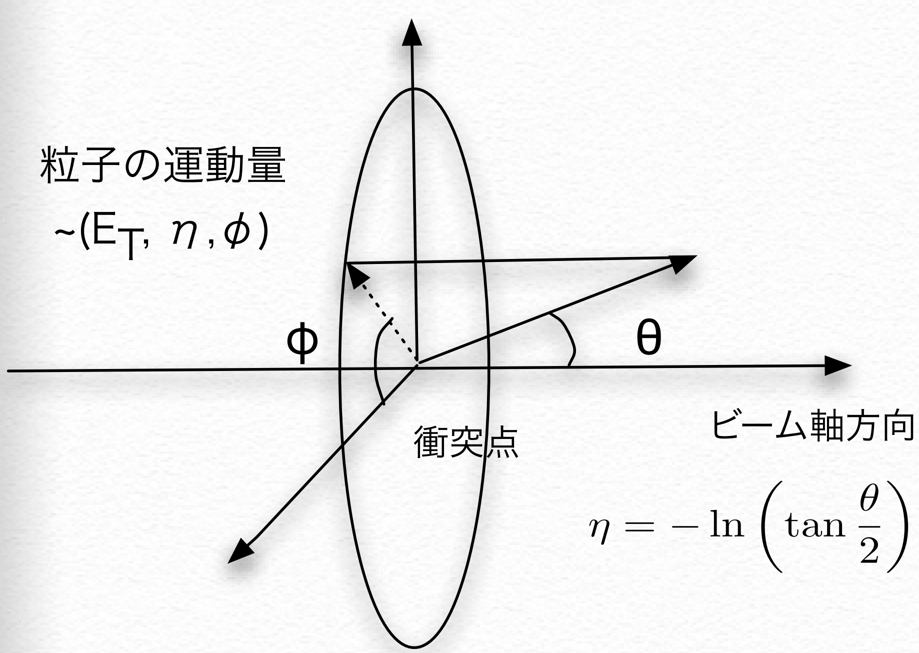
Hagiwara Mukhopadhy
JHEP 2013



ISR の角分布は実は特徴的



tt + 2 jet process, two jet in the forward direction shows some spin correlation



spin 0 CP odd amplitude shows spin correlation 1 +A cos(2Δφ)

ISR jet correlation in SUSY

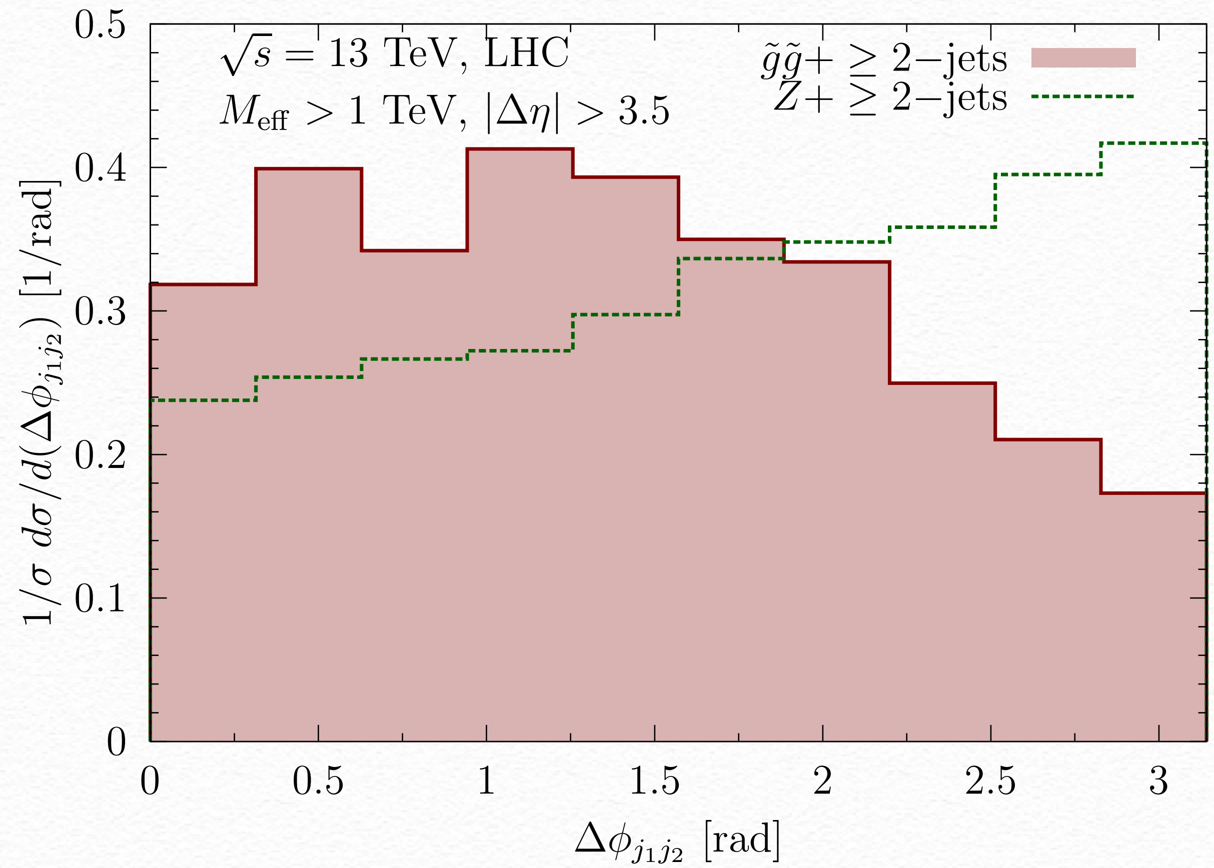


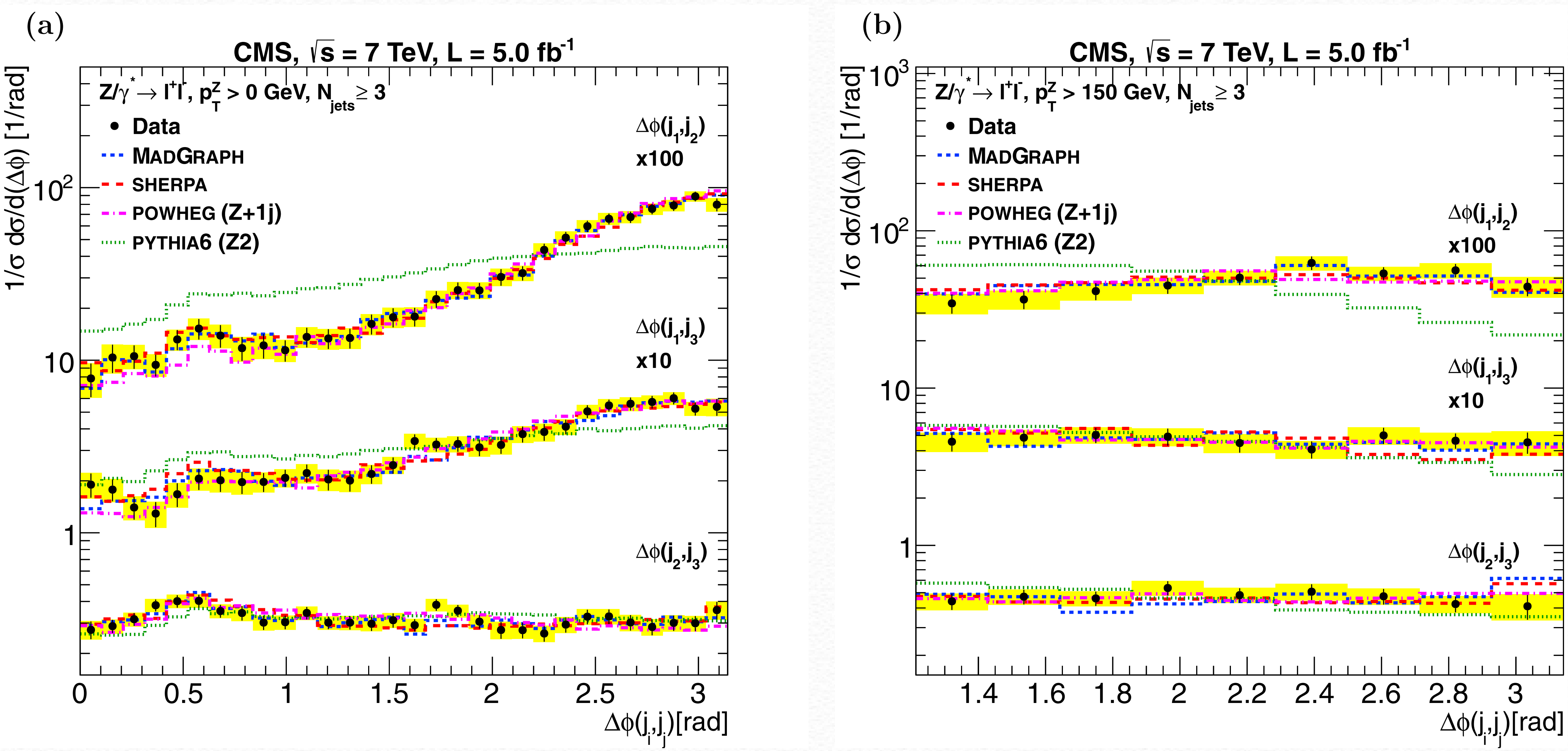
Figure 2: *Normalized* $|\Delta\phi_{j_1 j_2}|$ *distributions for* $\tilde{g}\tilde{g}+ \geq 2-$*jets in signal Point-A (shaded region) and the dominant* $Z+ \geq 2-$*jets background (green dashed) for the* 13 *TeV LHC. The distributions are shown after the jet-*p_T, $\not{E}_T$, $M_{\rm eff} > 1$ *TeV and* $|\Delta\eta_{j_1 j_2}| > 3.5$ *cuts.*

jet selection: take leading 3jets, and select two forward ones.

Need glgl+3j (matched) and Z+3j(matched) amplitude calculation

because parton shower does not remember the spin correlation.

azimuthal correlation of Z+>2jet is observed CMS



Study of gluino gluino production signal and background simulation

- Signal gluino + 3jets (2jet for forward correlation, 1 jet for missing PT, Δm=20GeV
- background Z+ 3jet, top, W
- Z production is most important background

ETmiss 300GeV jet pt 200GeV

	Z	W	tt	SM	gluino mass 800	gluino mass 1000	S/B
Cut-B							
$M_{\rm eff} > 1250$ GeV	310.82	202.59	86.26	599.67	42.80	9.84	0.07
$+\lvert\Delta\eta_{j_1j_2}\rvert > 3.5$	7.55	2.03	4.01	13.59	2.55	0.51	0.19
$+\lvert\Delta\phi_{j_1j_2}\rvert < \pi/2$	2.91	0.68	0	3.59	1.44	0.29	0.40

“ Jet structure”

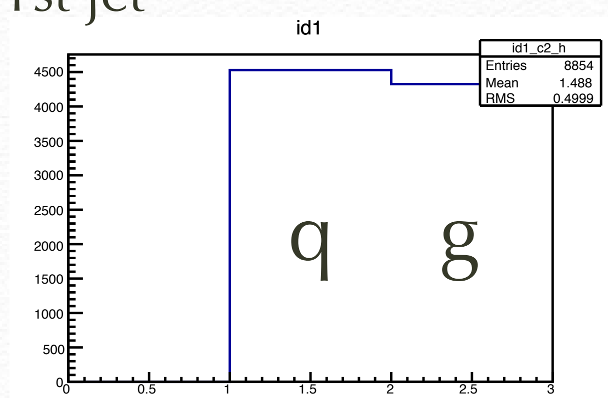
SUSY process のバックグラウンドについて考えてみる

- Main background : Z+ jets. highest pT ジェットは殆どクオーク
- gluino productiongg→ gluino gluino　のISR は相当gluon .
- クオークとグルーオンが区別できるなら、background を減らす方法の一つになるかも

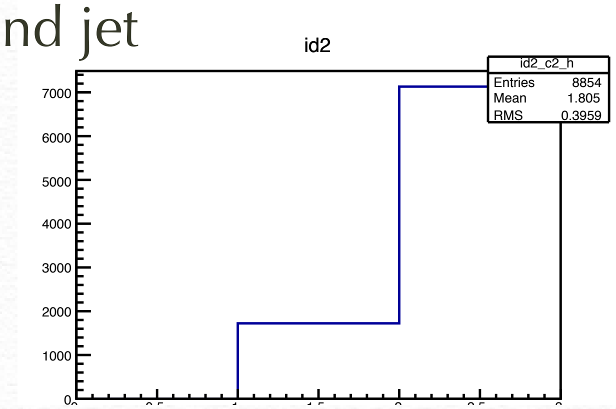
gluino production

z+3j

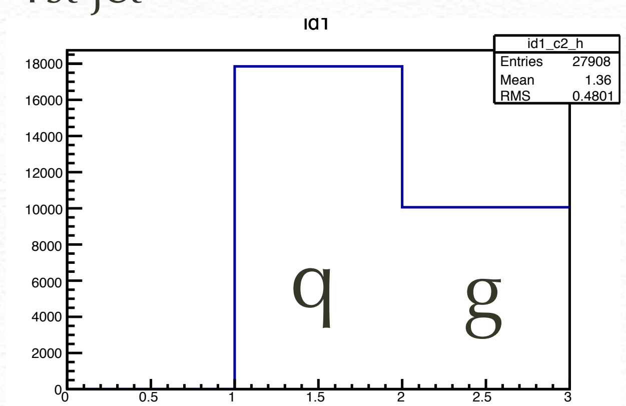
1st jet



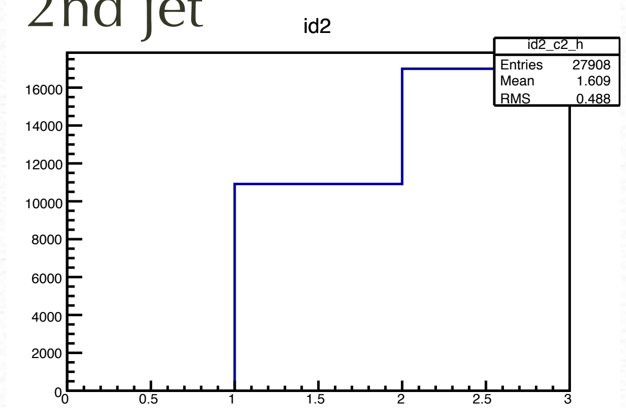
2nd jet



1st jet



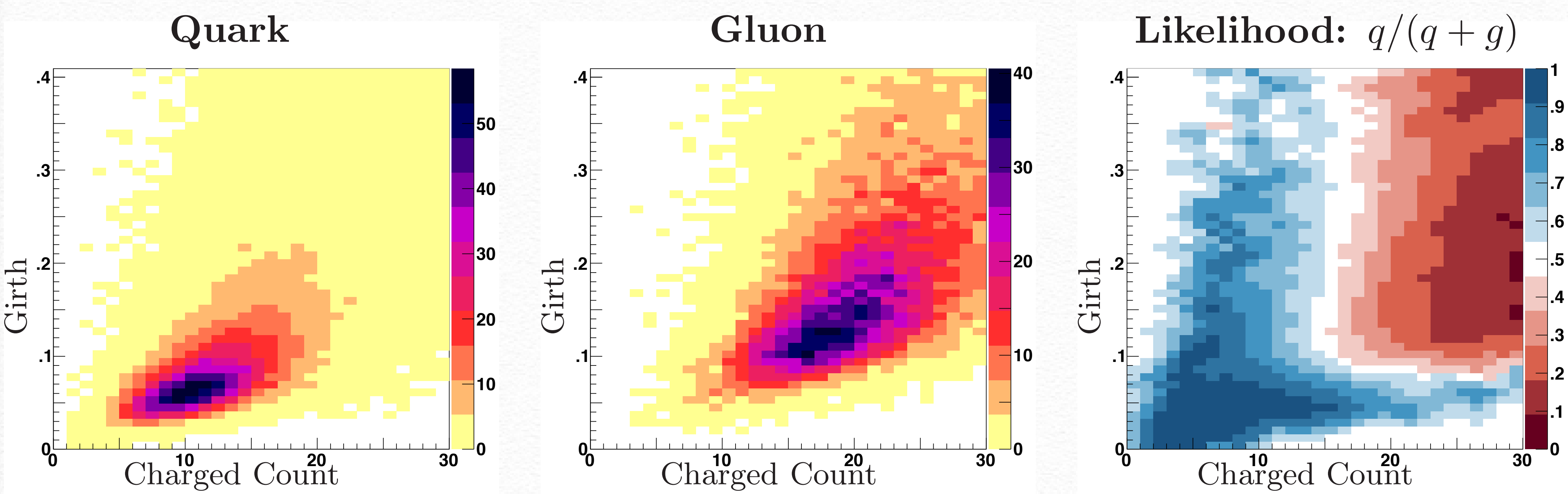
2nd jet



逆に gluino が LSP と縮退していない領域であれば、シグナルは4つ目のジェットまでクオーク background はグルオンより

quark and gluon jet substructure

“gluon jet” : more charged tracks and broader than “quark jet”



Girth :

$$g = \sum_{i \in \text{jet}} \frac{p_T^i}{p_T^{jet}} r_i \ .$$

Using MVA
(説明はあとで)

arXive 1211.7038 Gallicchio and Schwartz

理論的には

- Number of charged tracks
  - QCD calculations starts some 30 years ago
- “Jet width” broadness of the jet

Girth : $g = \sum_{i \in \text{jet}} \frac{p_T^i}{p_T^{jet}} r_i \ .$

More recent quantities

$C_1^{(\beta)} = \sum_{i<j\in J} p_{Ti}\, p_{Tj} (\Delta R_{ij})^{\beta}$

Larkoski et al JHEP 1306.108(2013)

Probability to emit n hadron at scale Q

$$\Phi_i(Q,u) \equiv \sum_{n=0}^{\infty} P_{n,i}(Q) u^n \ ,$$

evolution equation

-> n_g/n_q~2

$$Q\partial\Phi_q(Q,u)/\partial Q = \int_{Q_0/Q}^{1-Q_0/Q} dz\ (\alpha_s/\pi) P_{qq}(z) \times \{\Phi_q(zQ,u)\Phi_g((1-z)Q,u) - \Phi_q(Q,u)\}\ , \quad (4)$$

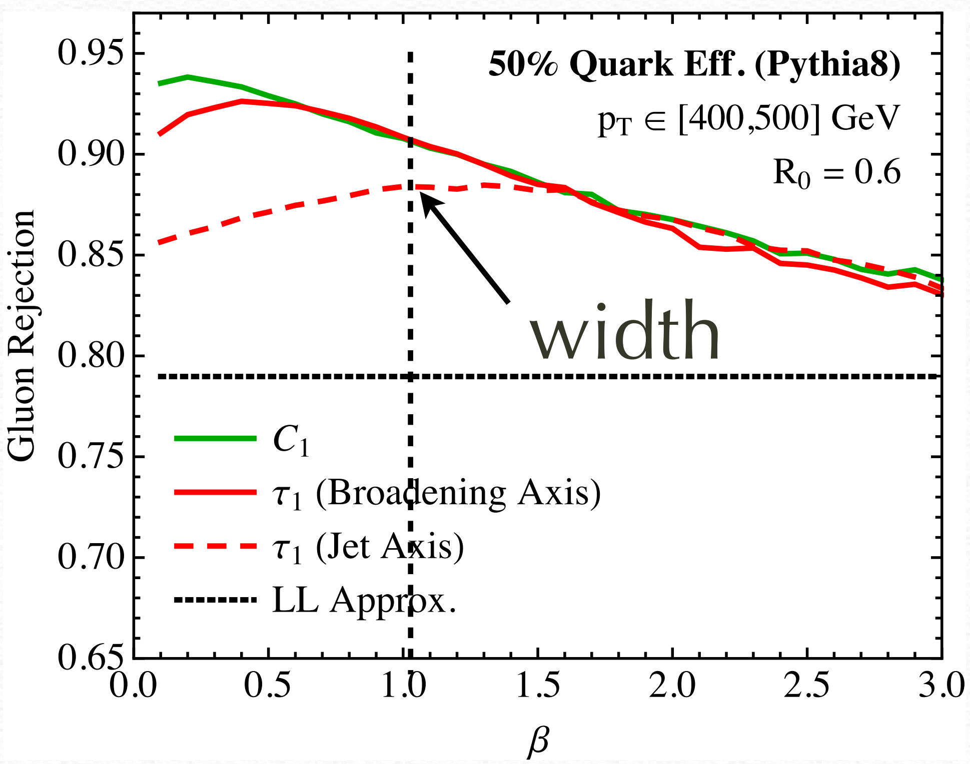
$$Q\partial\Phi_g(Q,u)/\partial Q = \int_{Q_0/Q}^{1-Q_0/Q} dz\ (\alpha_s/\pi) \times \{P_{gg}(z)[\Phi_g(zQ,u)\Phi_g((1-z)Q,u) - \Phi_g(Q,u)] + P_{qg}(z)[\Phi_q(zQ,u)\Phi_q((1-z)Q,u) - \Phi_g(Q,u)]\}\ ,$$

この効果が QCD MC にどのように実装されているか

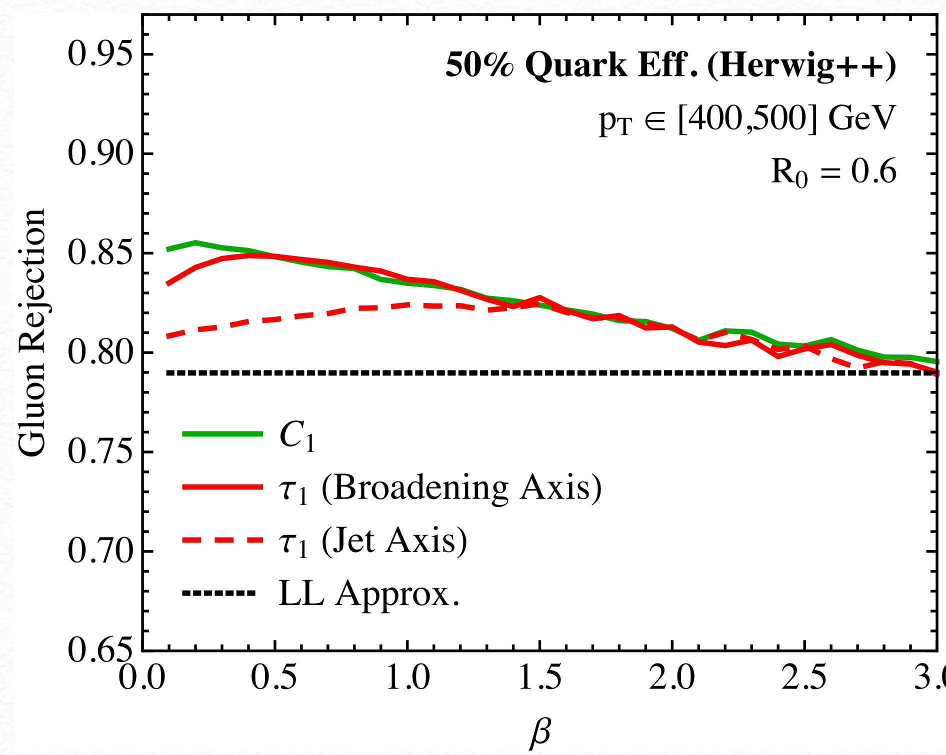
Using C1 instead of Jet width

default Herwig ++ predicts less rejection

max C1



(b)



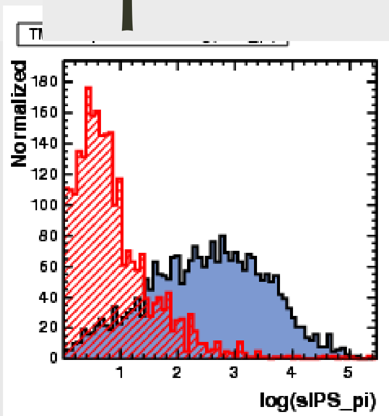
(b)

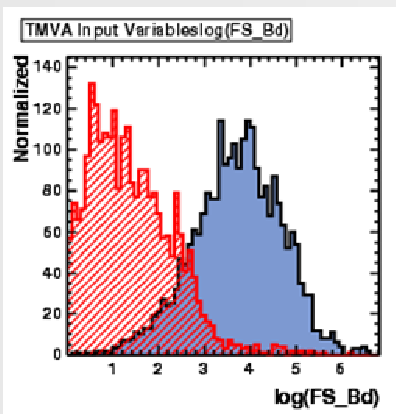
Even after Pythia turning some difference remains

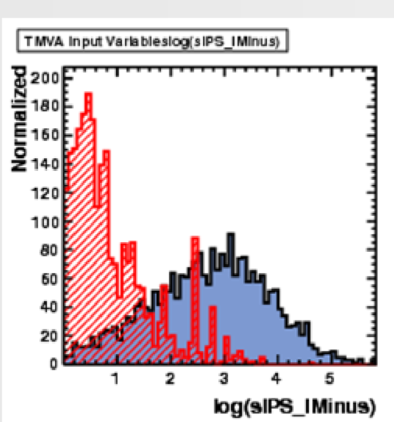
結果はMC によって違うようだ。

(jet 周りのアクティビティの大小も実は違うので検討中)

quark gluon separation にはMVA 解析をつかう







$\mathbb{R}^D$

"feature space"

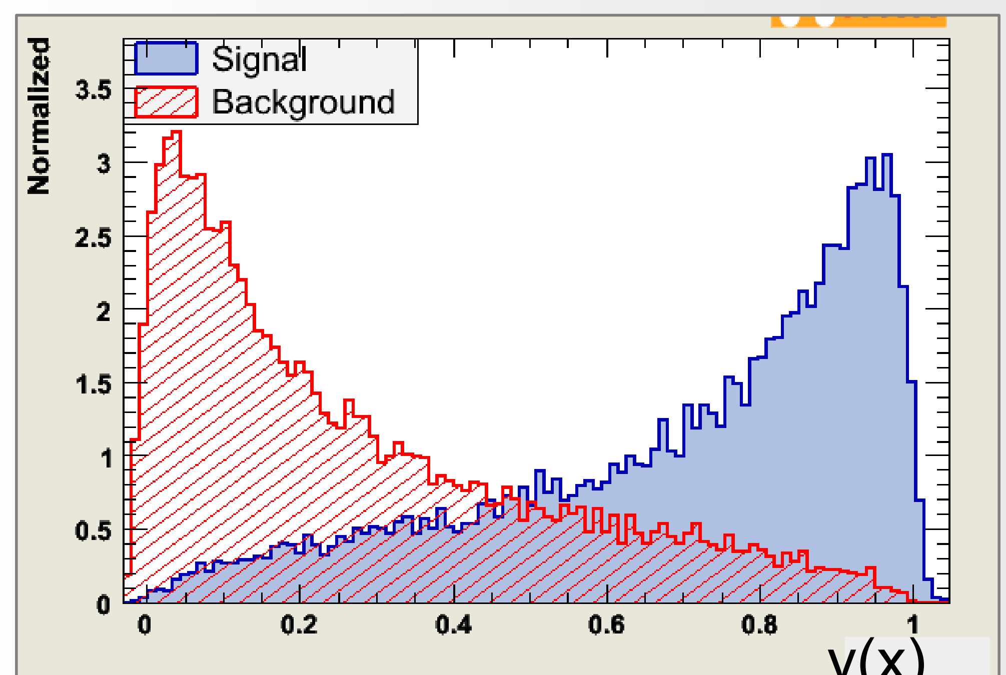
- Each event, if Signal or Background, has "D" measured variables.
- Find a mapping from D-dimensional input/observable/"feature" space to one dimensional output → class lables

y(x): $R^n \rightarrow R$:

→ $\mathbb{R}$

most general form
$y = y(\mathbf{x})$; $\mathbf{x} \in \mathbb{R}^D$
$\mathbf{x}=\{x_1,\ldots,x_D\}$: input variables

- If one histogramms the resulting y(x) values:

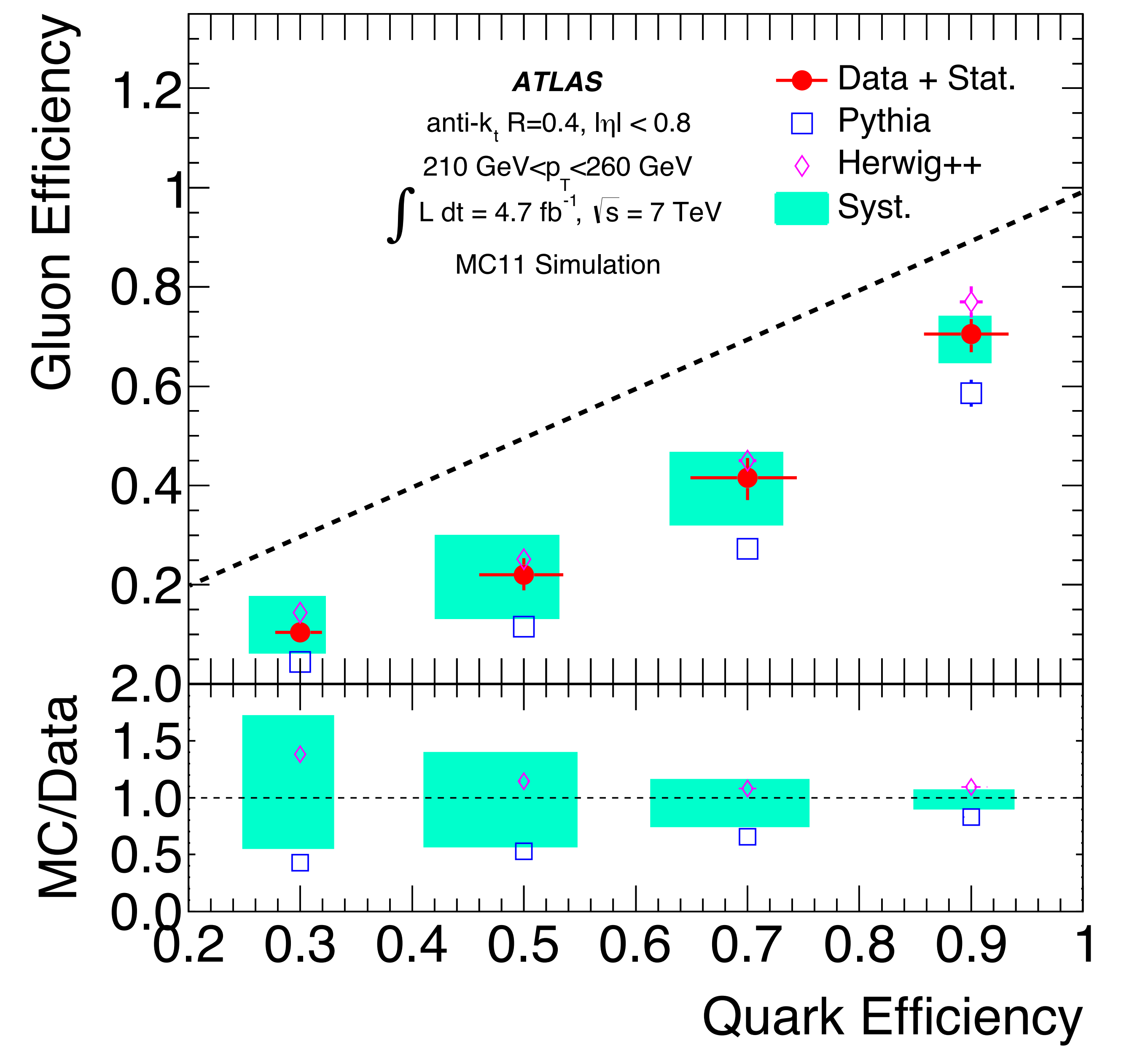


- Who sees how this would look like for the regression problem?

実験的に決めてみる

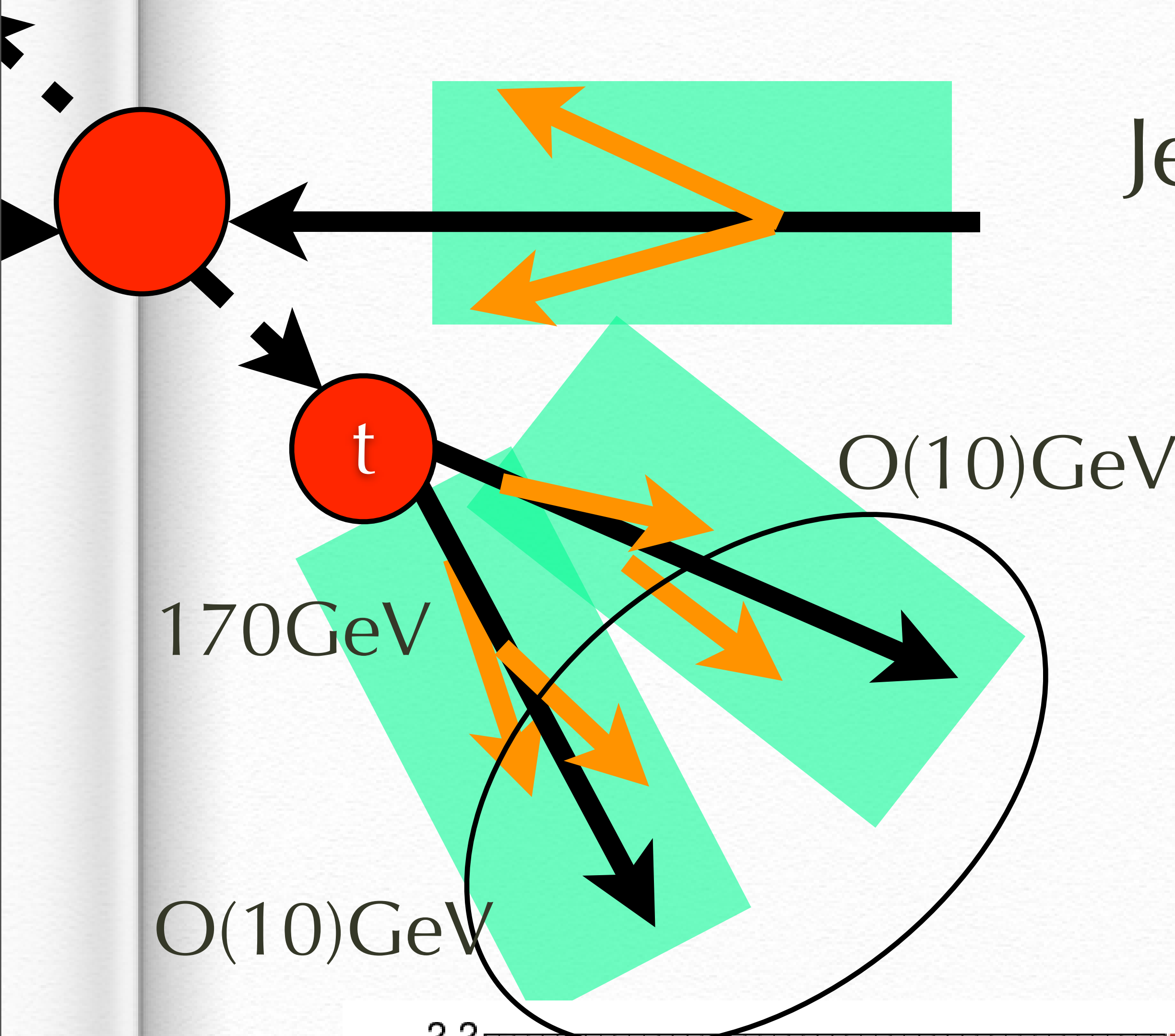
quark を残して、どのくらいgluon
をreject できるか

quark: γj event
gluon: dijet evnet



代表的なMC である
Pythia(pt ordering) と
Herwig(angular ordering)
で予言が相当違う

現実は中間だが、
quark efficiency 50% の
現実的領域ではHerwig
が正しいっぽい



Jet substructureとどこが違うか

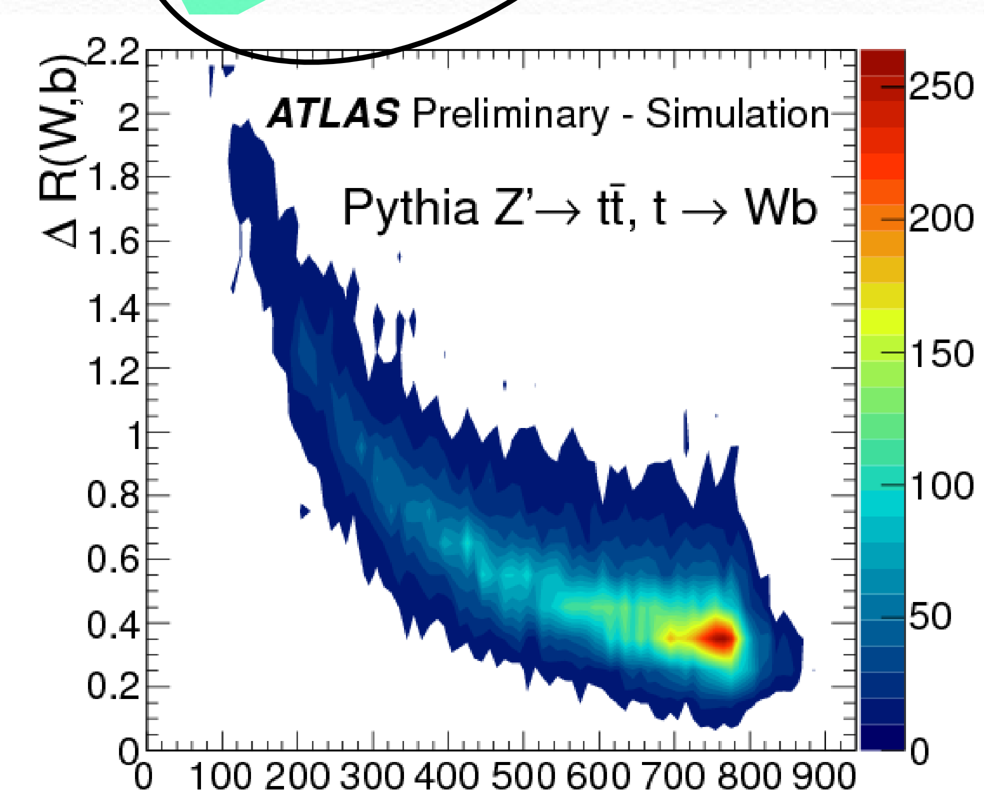
heavier particle search-> high P_T top, W, Z

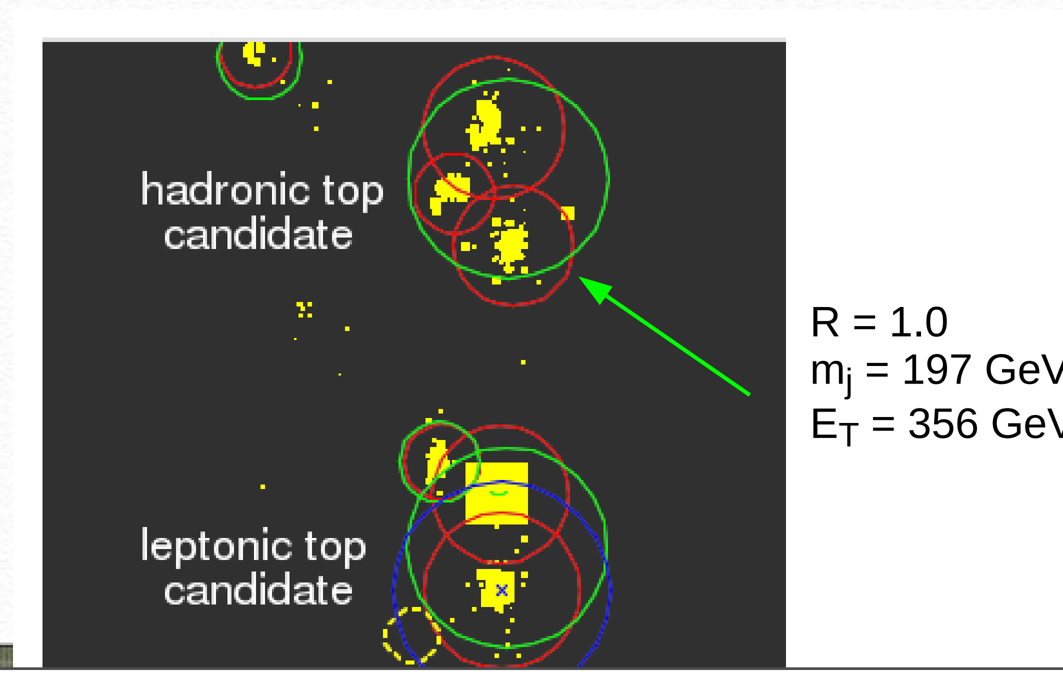
The boosted t, W, Z maybe identified as a single jet
but there are structures inside =**mass drop**

一見jet 的なものの中にある

ハードプロセスを狙っていて、

予言は安定





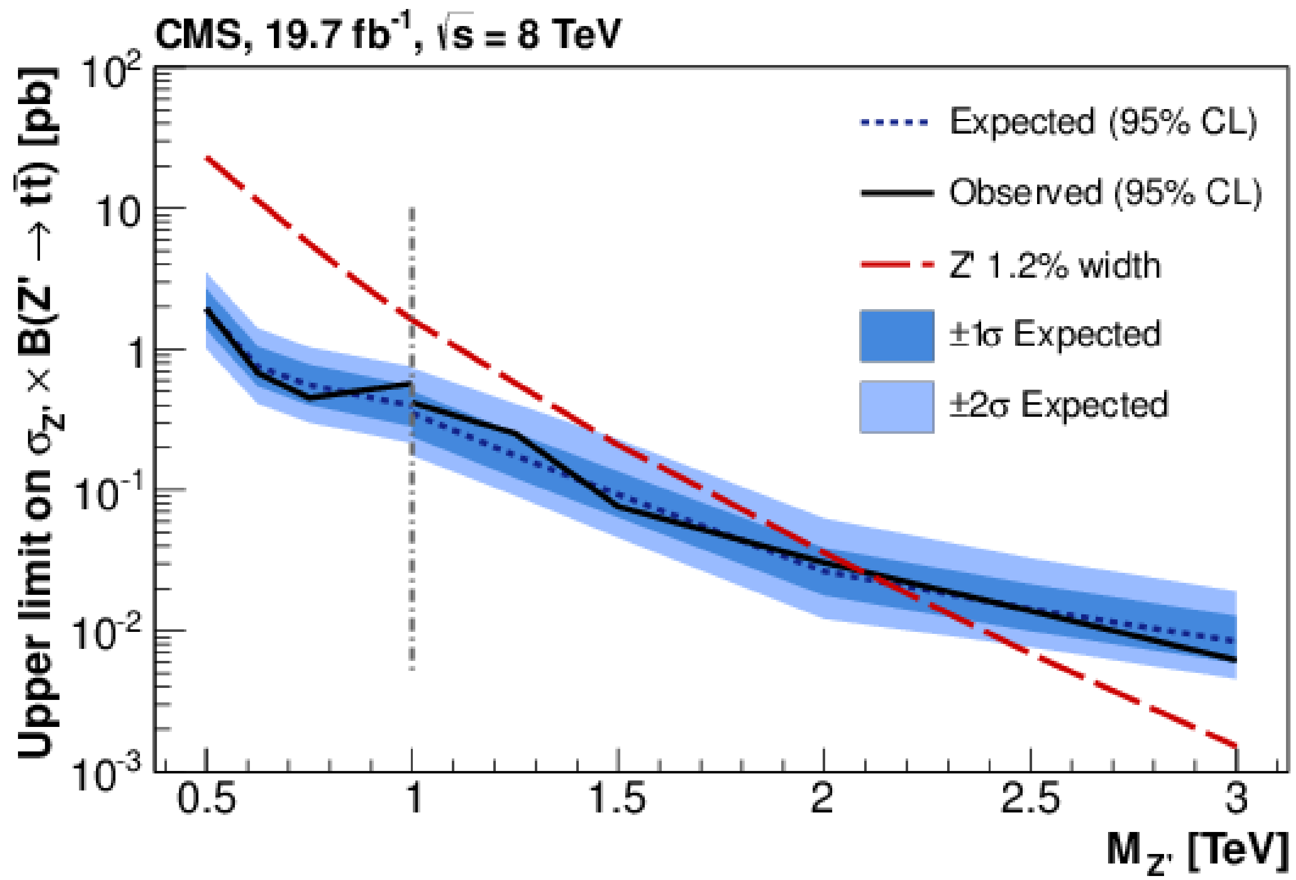
Combined Limits

Jet substructure はすでに

あちこちで使われている

quark gluon separation は

もう少し練習が必要



Limits:

- Narrow Topcolor Z': m>2.1 (2.1 expected) TeV
- Topcolor Z' with 10% width: m>2.7 (2.6) TeV
- RS Kaluza-Klein gluon: m>2.5 (2.4) TeV
- S=σ(SM+BSM)/σ(SM) <1.2 at 95% CL for $m_{t\bar{t}}$>1 TeV

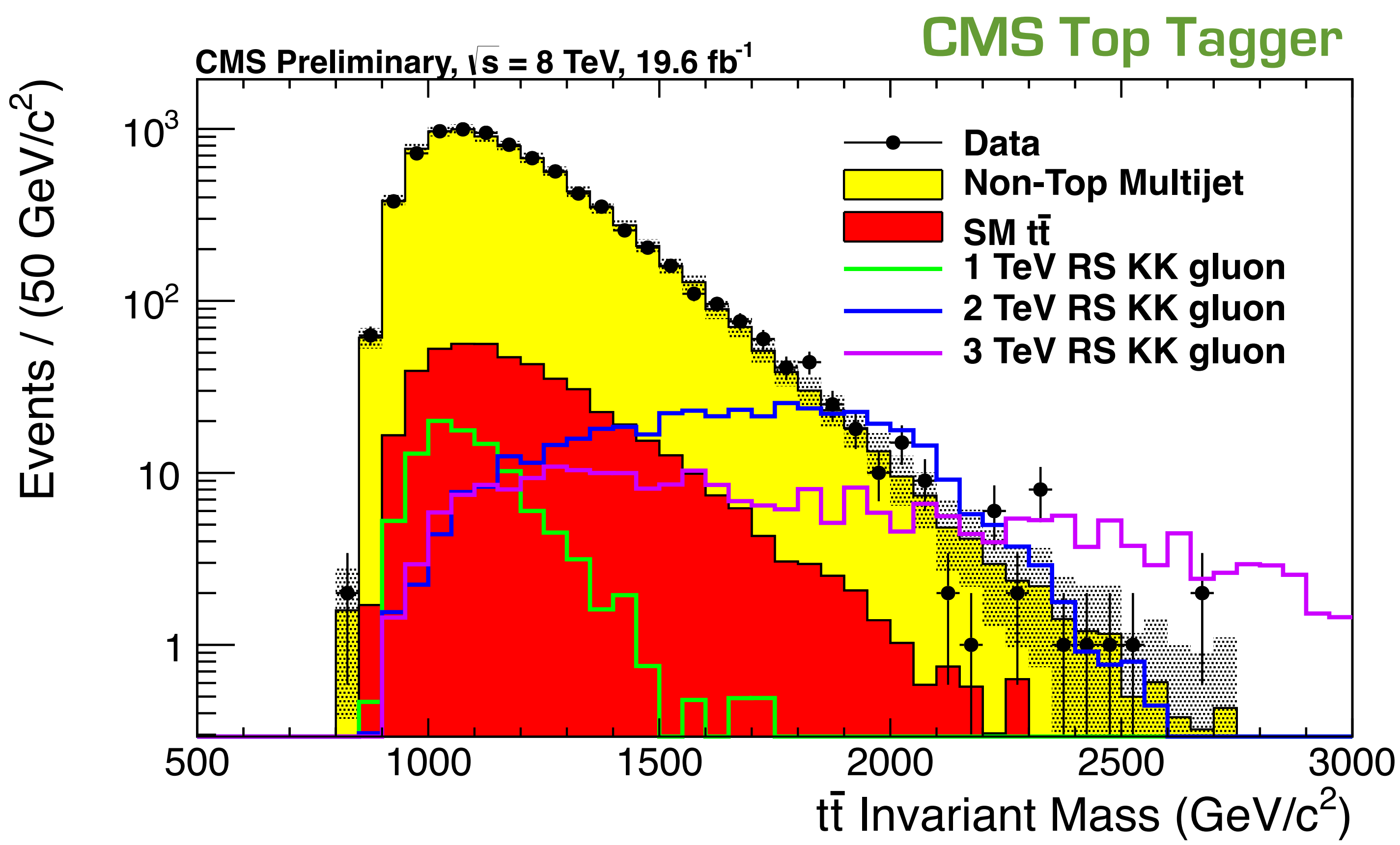
14年7月29日火曜日

Combined Limits

Jet substructure はすでに
あちこちで使われている

quark gluon separation は
もう少し練習が必要

channels



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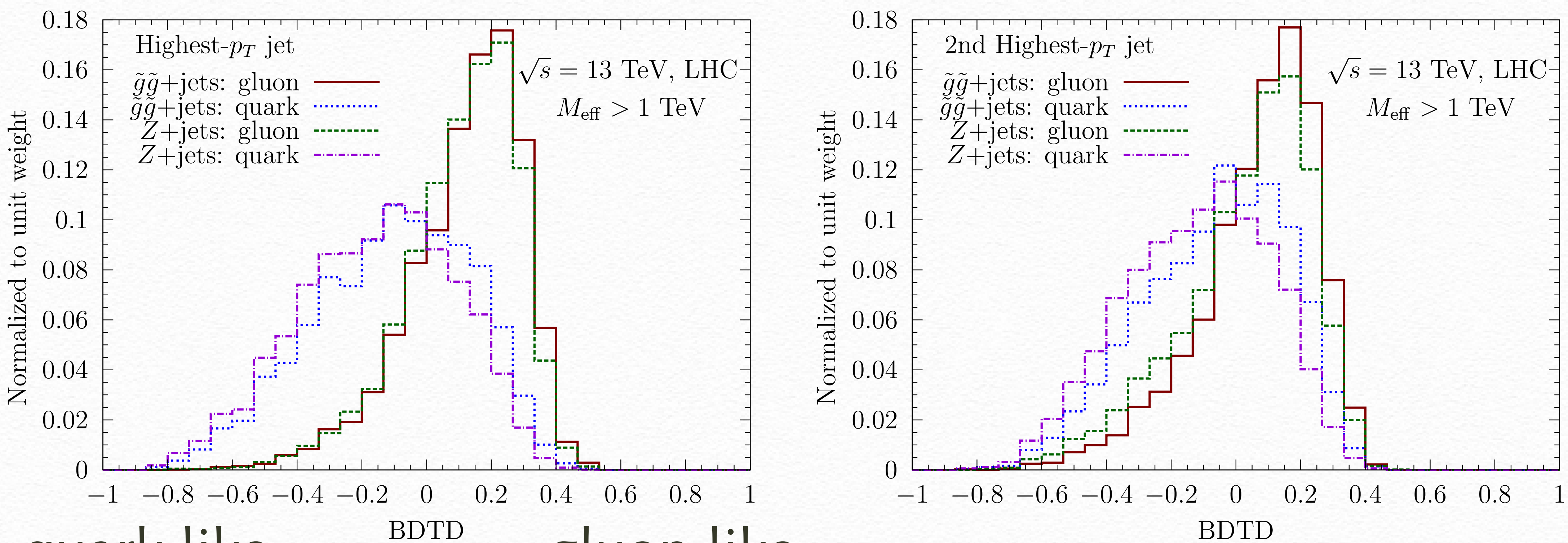
14年7月29日火曜日

ISR における quark gluon jet separation



quark like gluon like

Figure 3: *Normalized (to unit weight) distribution of the BDTD variable for the $\tilde{g}\tilde{g}$ signal*

MVA distribution of quark(gluon) from Z+ jets and gluino ISR are essentially the same. It is possible to reject quark keeping gluons

after the jet-p_T, $\not{E}_T$ and the $M_{\rm eff} > 1$ TeV cuts, for 13 TeV LHC. The quark and gluon

S/N improved by factor of 2 for BDTD> 0.15

σ(Z):σ(gl) =36.5:7.9

まとめ

- LHC 14TeV -> Extend new particle search significantly
- HL-LHC (3000fb-1) High Luminosity machine good for lepton channel
- ILC if it is build, good facility to Higgs and top sector. Top sector is important for composite context.
- QCD technology ISR, quark gluon separation,,,