

LHCとATLASの物理

山口大貴（東工大 D3）

高エネルギー春の学校

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はじめに

● はじめに

▶ 対象: 普通のM1

▶ 概要:

- 学生目線で、どんな実験をしているか
- 最新結果の一覧ではないので、ご容赦ください
(最新結果の一覧は[こちら](#)を見てください)

● 内容

▶ 興味の対象

▶ LHC

▶ ATLASとその物理

▶ これから

素粒子物理と標準模型

- 素粒子: 物質を構成する最小単位
- 標準模型: 素粒子の振舞いを記述する理論体系

▶ **クォーク&レプトン**: 物質を構成

▶ **ゲージ粒子**: 力を媒介

▶ **ヒッグス粒子**: 質量起源

- 2012年にATLAS&CMS実験で発見 (ノーベル賞へ)

▶ 多くの実験結果を精度良く説明

- 問題点: ダークマターやニュートリノ質量 (振動) を説明できないなど...

⇒ **標準模型を超えた物理があるはず**

- 標準模型の精密検証と、新しい物理 (素粒子) の探索

▶ **LHC**, Belle, T2K, KamLand-Zen, DeeMe, ANKOK, NEWAGE...
など世界各地で様々な実験を行っている

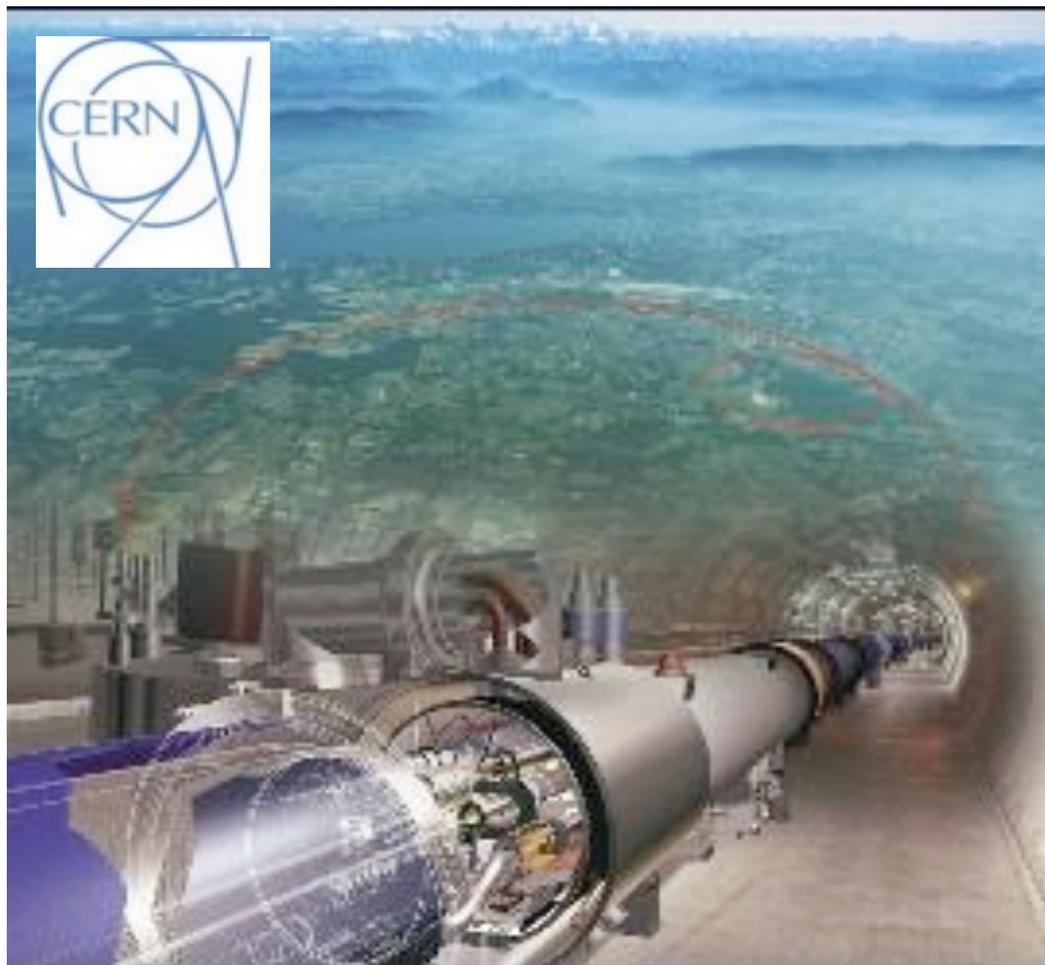


簡単な比較

● N = σ × L
生成される数 = 生成確率(E) × 試行回数(加速器)

エネルギーフロンティア

Large **H**adron **C**ollider



ヒッグス、新粒子探索

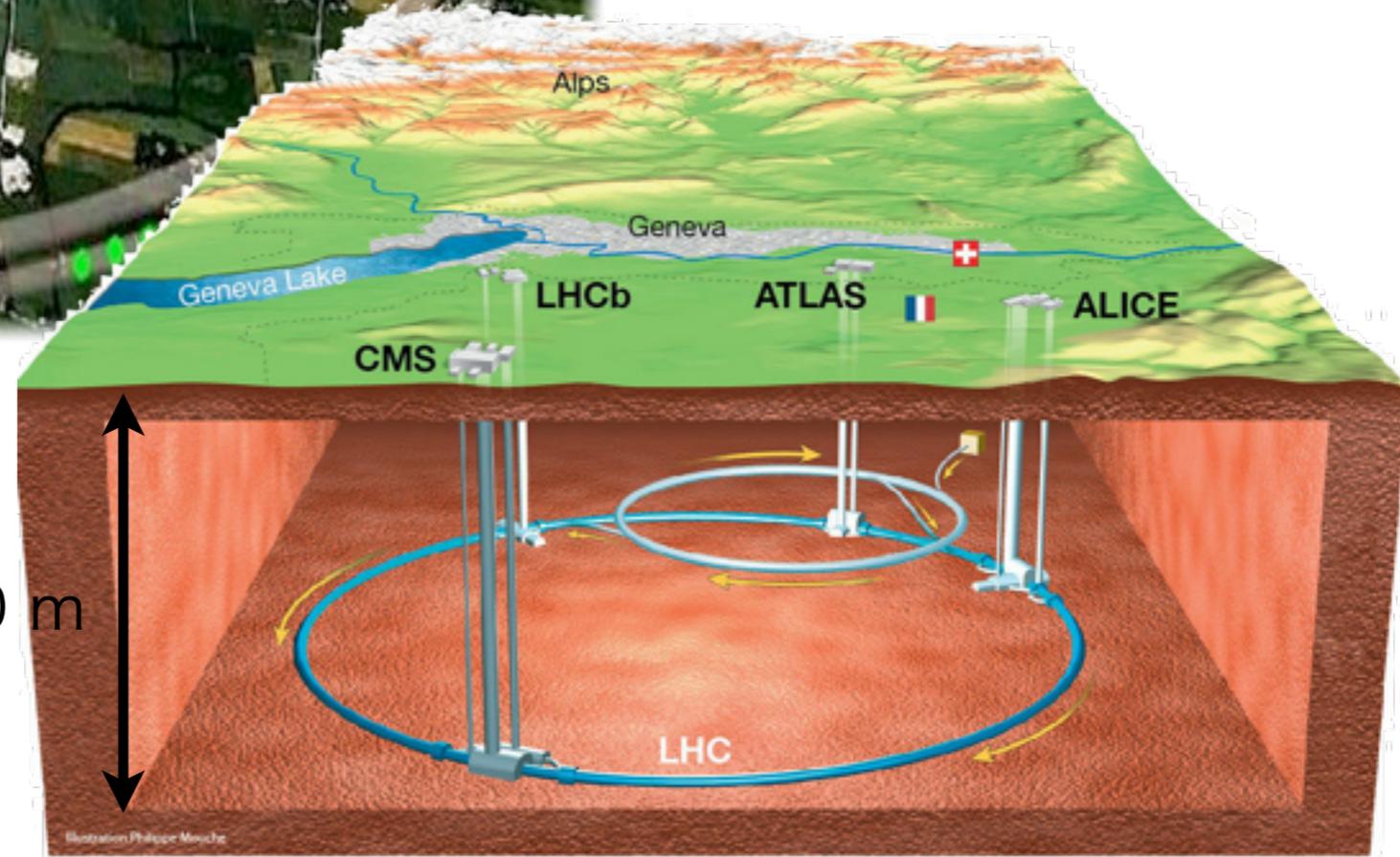
ルミノシティフロンティア

Super-KEKB



Bハドロン、稀崩壊事象

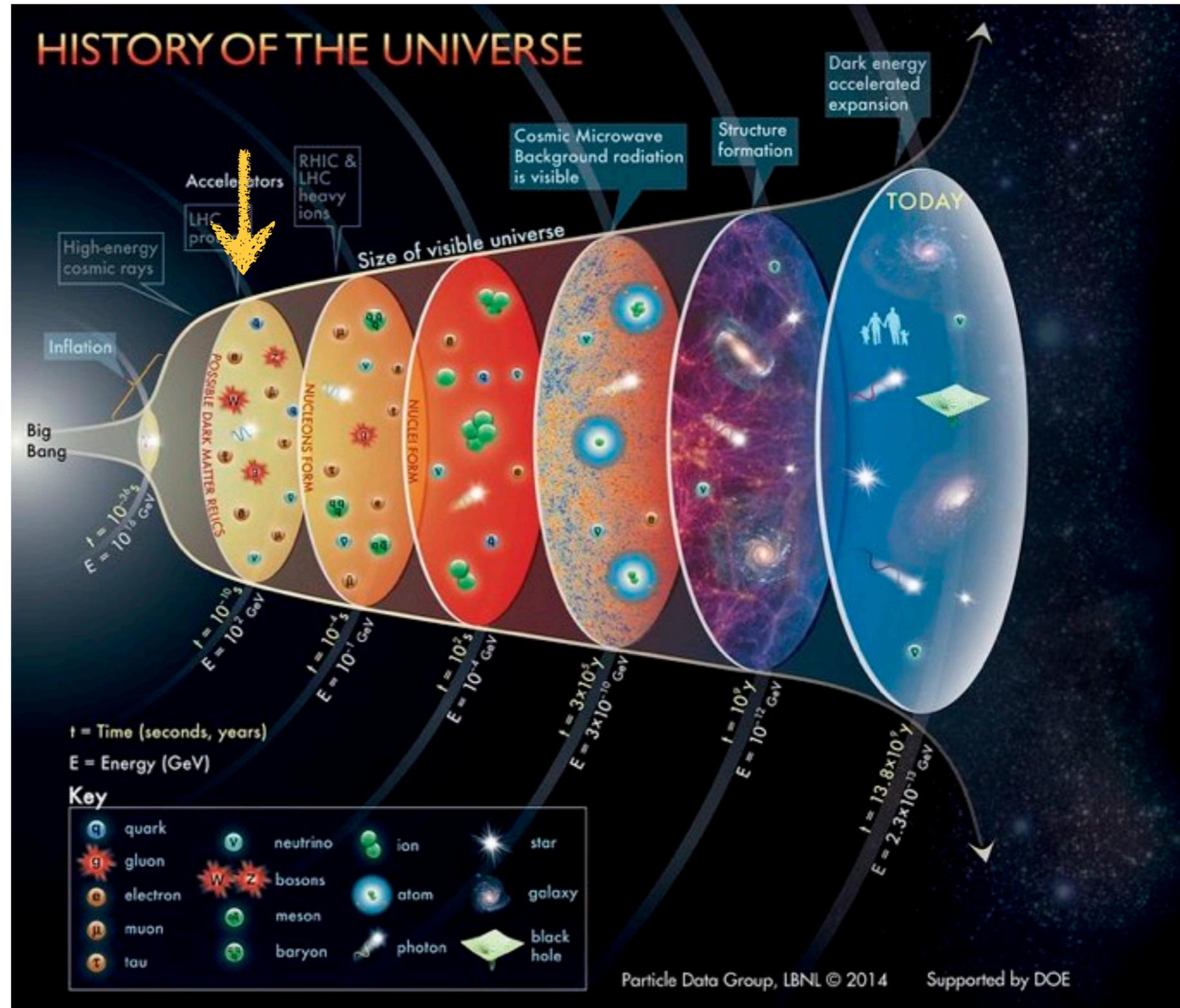
Large Hadron Collider



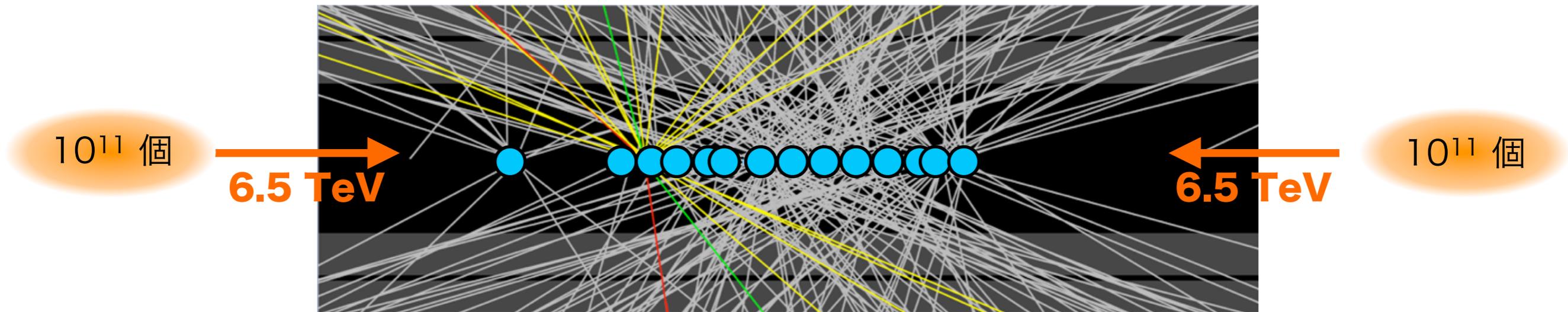
LHCで見たいもの

● 14 TeV
 ~ 10^{-12} 秒後の宇宙

▶ 初期宇宙で
 なにが起きていたか？

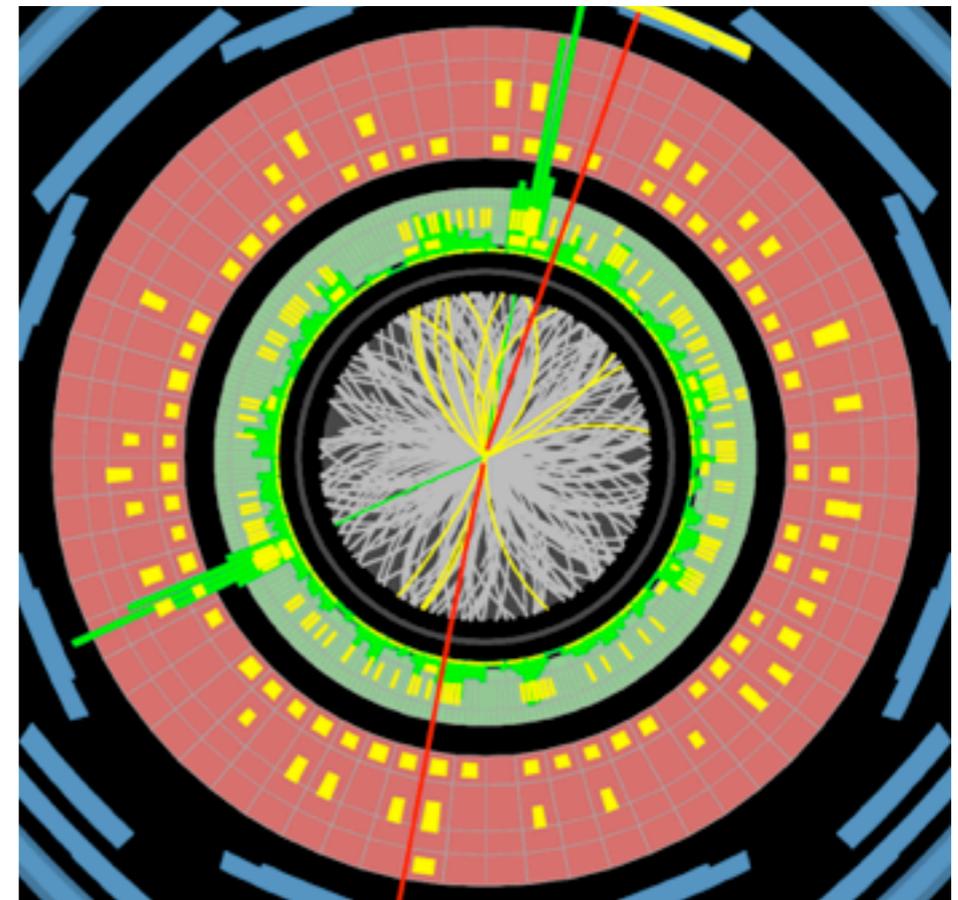


proton-proton 衝突

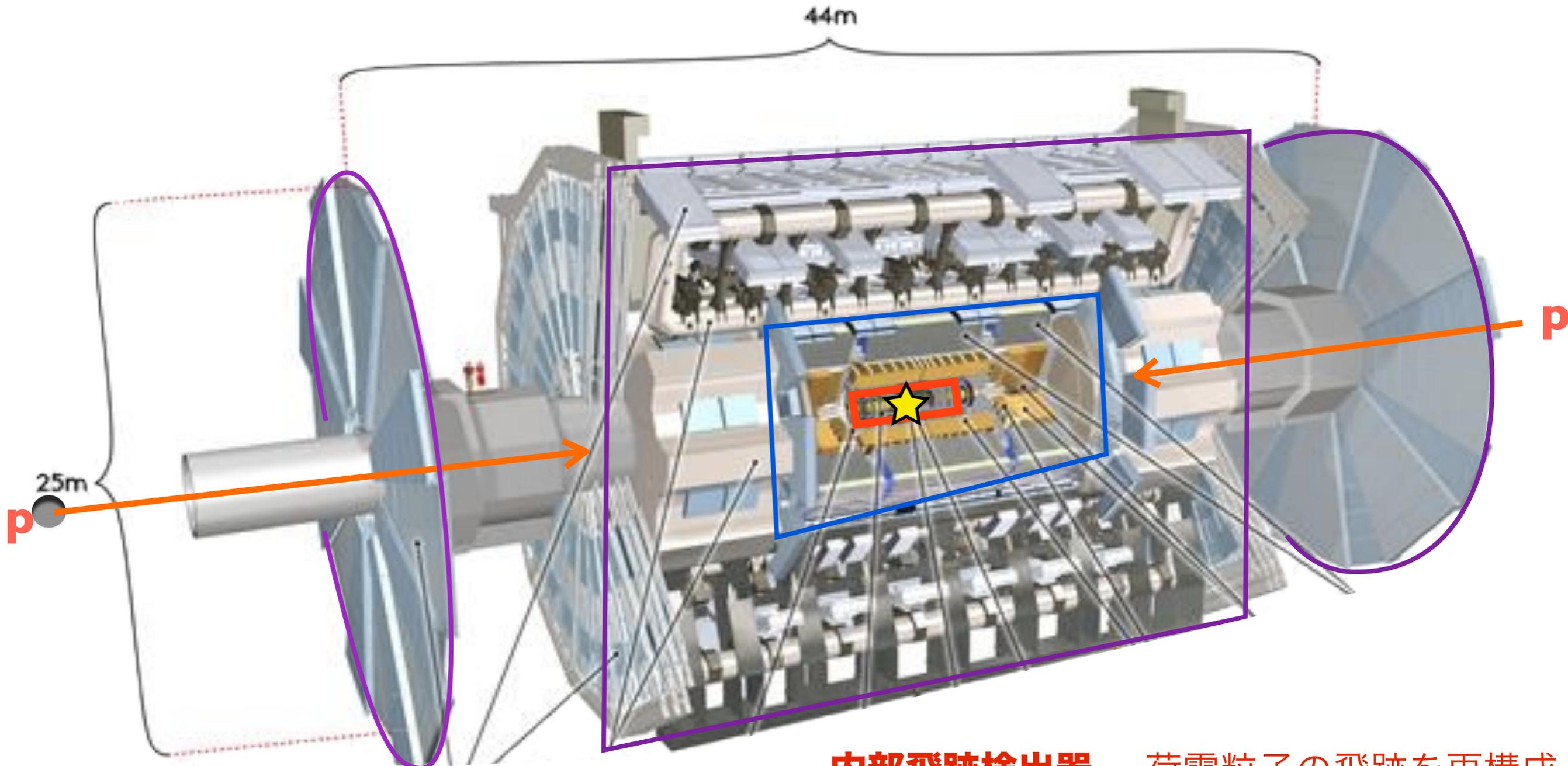


- 多くの種類の粒子が、様々な方向へ
- 検出器を衝突点周辺に置いて、衝突時に何が起きたかを調べる

▶ **出てきた粒子を隈なく捉えることが重要**



A Toroidal LHC Apparatus 検出器



内部飛跡検出器 ... 荷電粒子の飛跡を再構成

カロリメータ ... 粒子のエネルギー測定

ミューオン検出器 ... ミューオンの再構成

7000 t
~エッフェル塔

LS1 to Run2開始



現場の生活例

● ビームが出てるとき

	Mon	Tue	Wed	Thu	Fri
8h00	Daily Run	Daily Run	Daily Run	Daily Run	Daily Run
10h00	研究室			Pixel Activity	研究室
12h00					
14h00	Physics Ana.				
16h00	Pixel General	Physics Ana.	Data Quality		
18h00					

MAPCERN



ATLAS



ATLAS & CMS

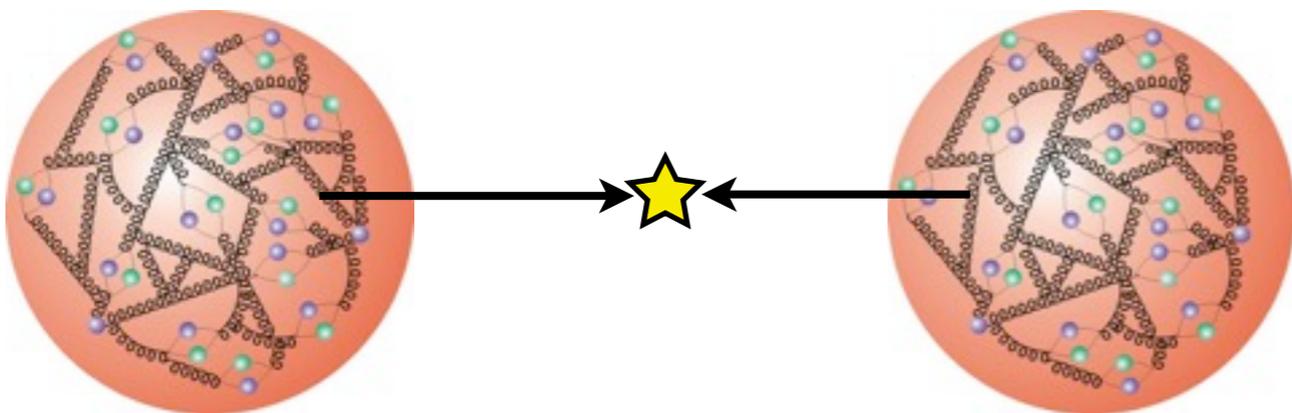
居室

トリガーの話

● **pp衝突のほとんどは興味がない事象**

▶ 陽子は複合粒子

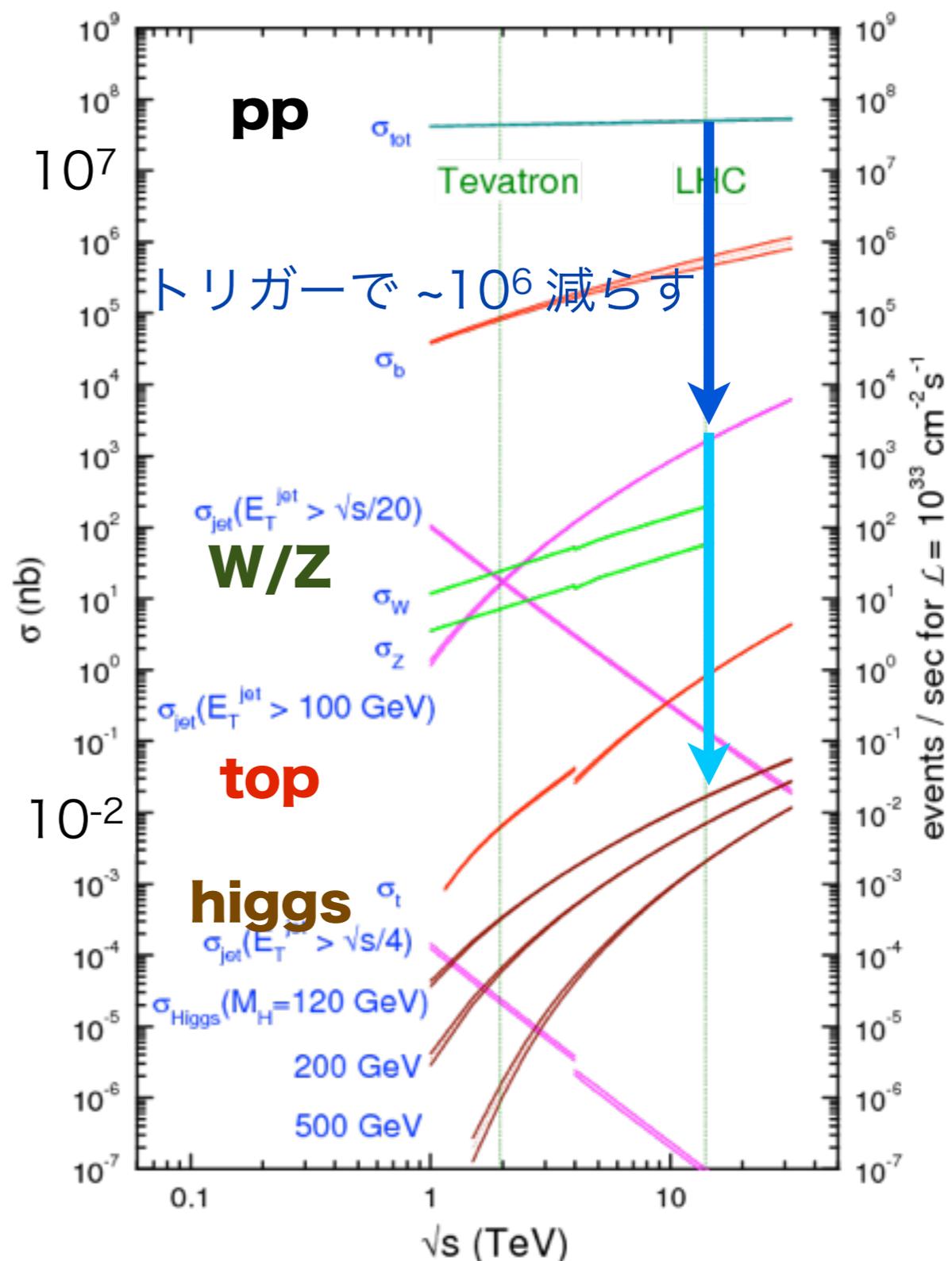
- 6.5 TeVの一部のエネルギーのみ反応に寄与
- ほとんどは低エネルギー



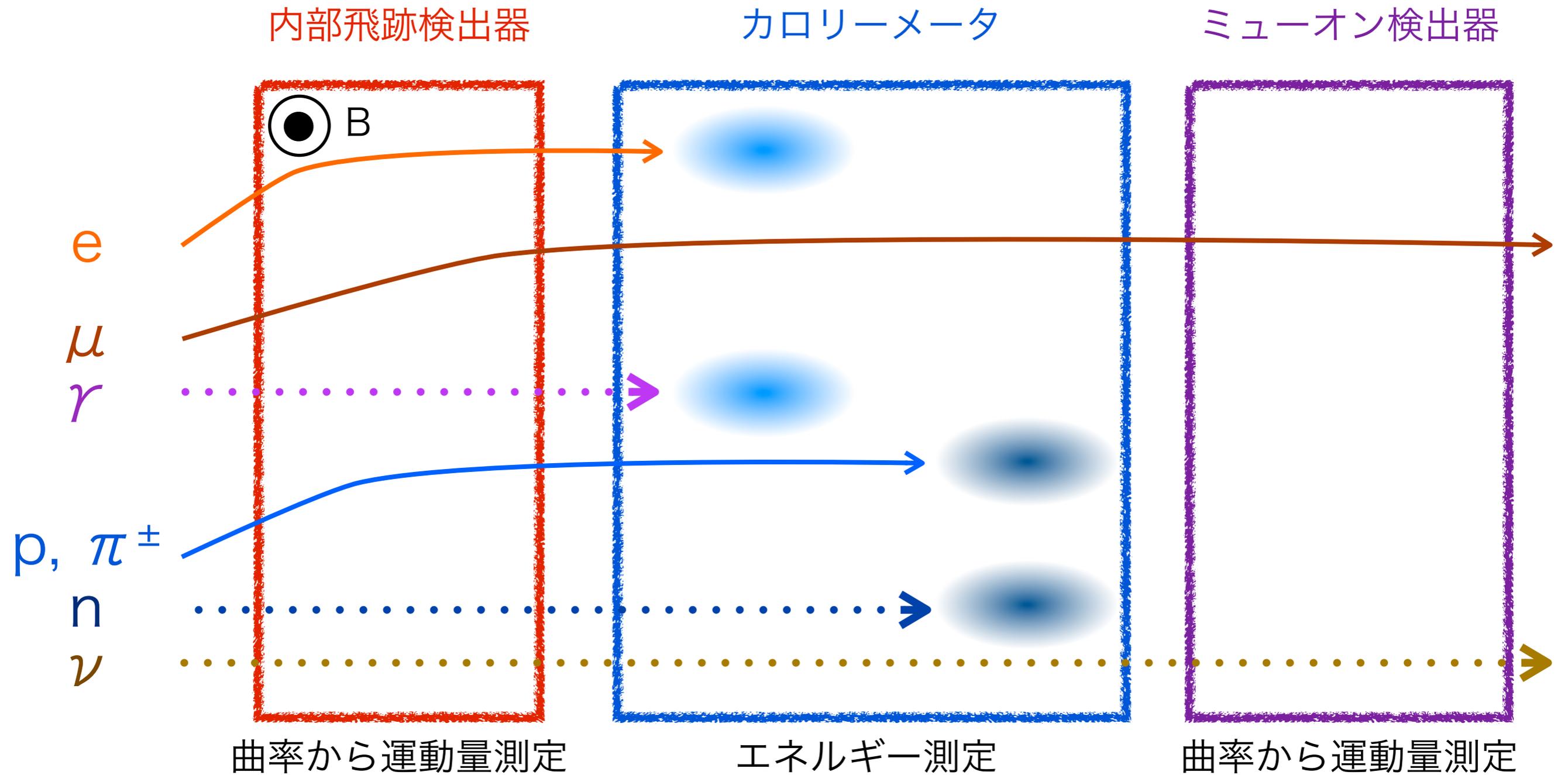
● トリガーシステム:
検出器の情報を使って
興味がありそうなイベントのみデータを保存

▶ ハード & ソフトで3段階

proton - (anti)proton cross sections



粒子の再構成



● 全ての検出器の情報から、粒子の種類や、その運動量とエネルギーを再構成する

物理解析の話

● 今までの簡単なまとめ

- LHCの物理を見るための検出器
- データ取得
- 粒子の再構成

▶ 「イベント毎に、どんな粒子が出てきたのか分かる」状態

● これから実際にどのように解析をしていくのか

▶ 「発見」の例: $\text{higgs} \rightarrow \gamma \gamma$

▶ 「探索」の例: mono-jet解析 (時間ないので飛ばすかも...)

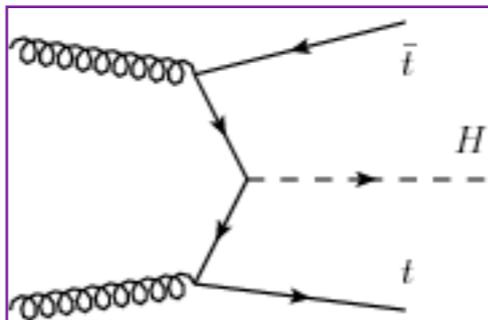
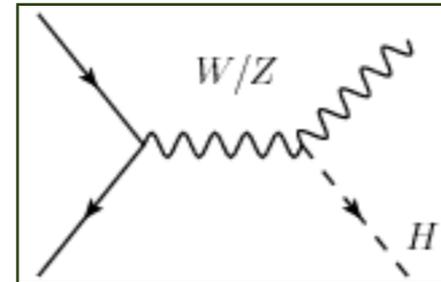
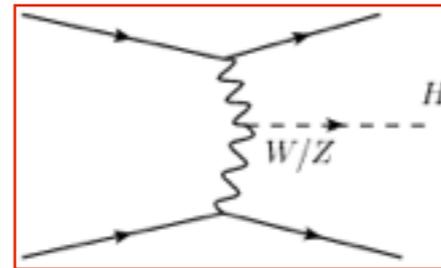
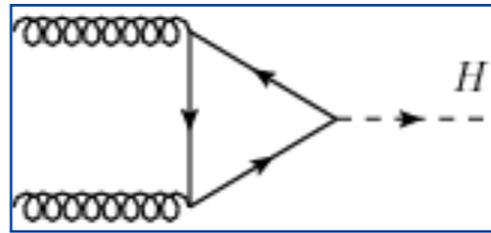
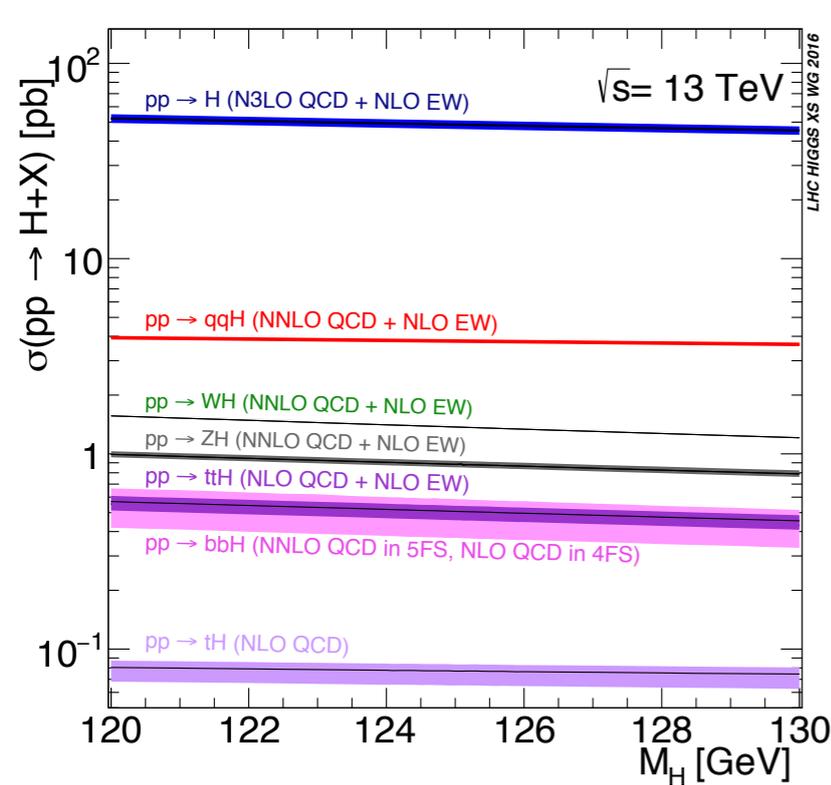
higgs \rightarrow $\gamma\gamma$ の例

生成と崩壊

$$\sigma \times L = N$$

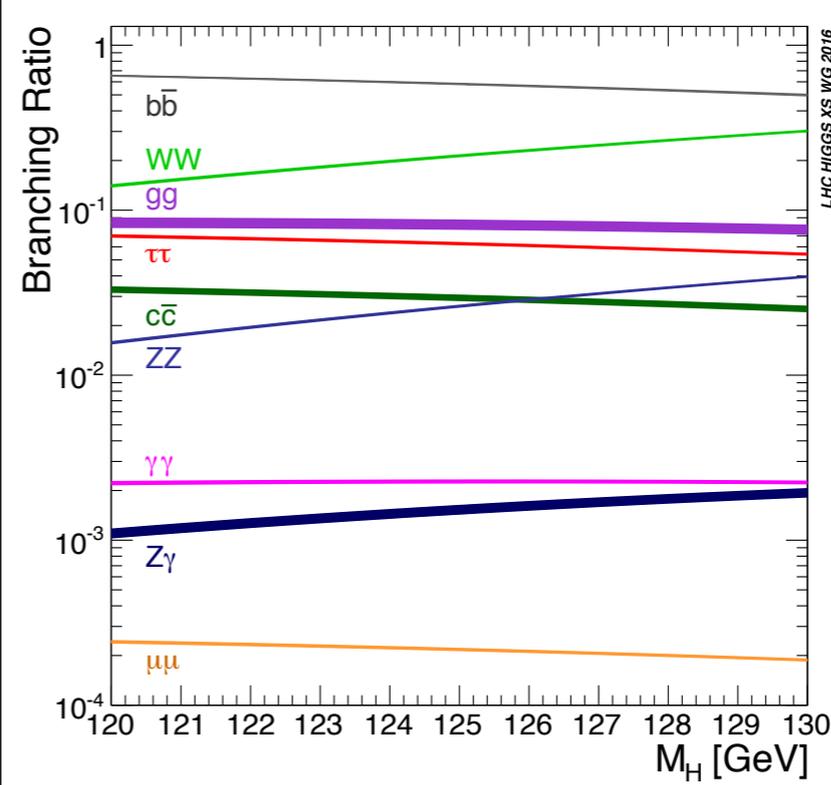
生成確率(E) × 試行回数(加速器) = 生成された数

生成



$\sigma(gg \rightarrow H) \sim 50 \text{ pb}$
 積分ルミノシティ: 35 fb^{-1}
 $= 35000 \text{ pb}^{-1}$
 とすると、ヒッグスは
 $50 \text{ [pb]} \times 35000 \text{ [pb}^{-1}]$
 $= 1750000$
 生成されている

崩壊

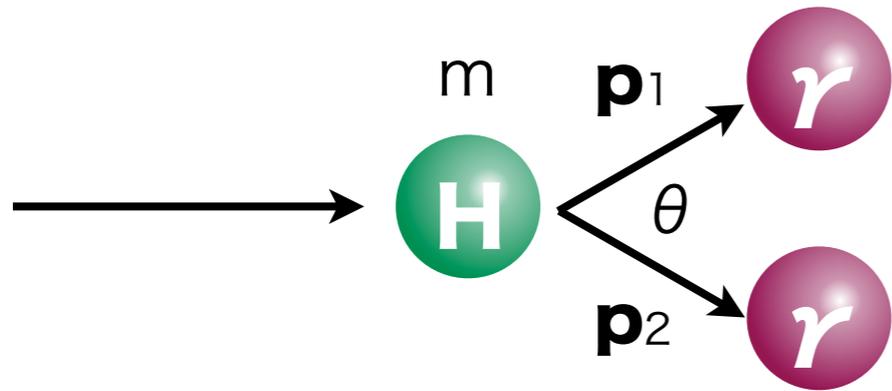


bb	~58%
WW(*)	~22%
$\tau\tau$	~6.3%
ZZ(*)	~2.6%
$\gamma\gamma$	~0.2%

今回は2つの光子に崩壊する事象を
 探索してみる

解析

- ターゲット: $higgs \rightarrow \gamma \gamma$
- 2つの光子をもつイベントを抽出
- 2つの光子で不変質量を計算

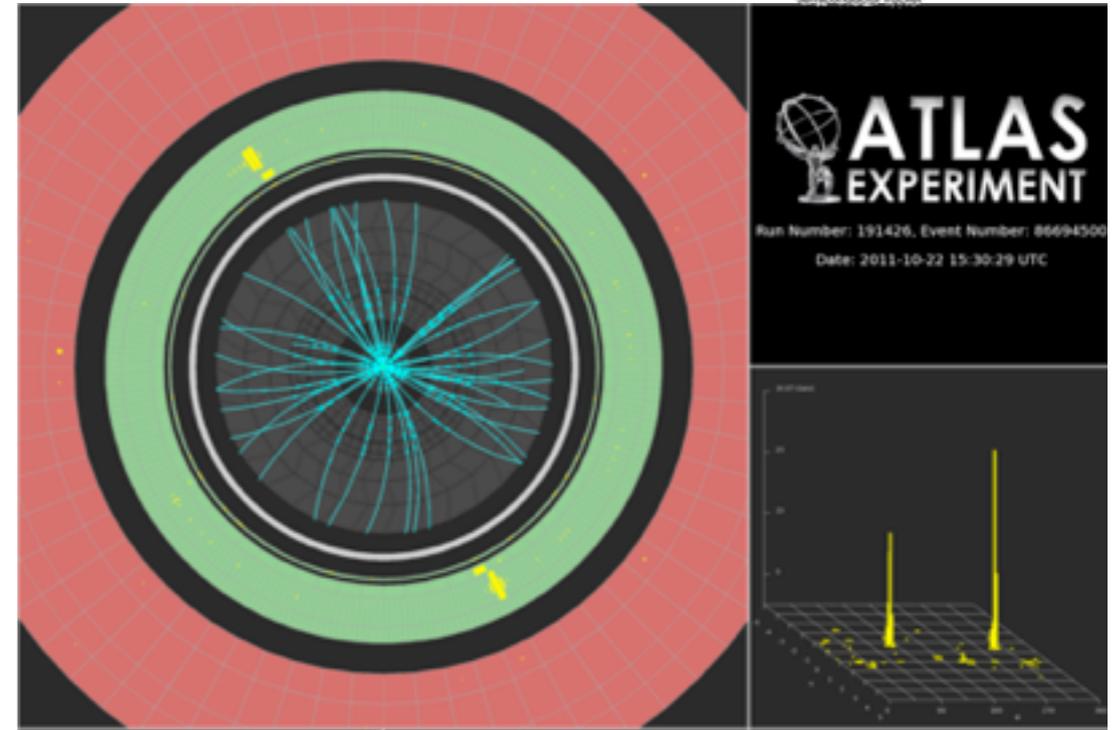
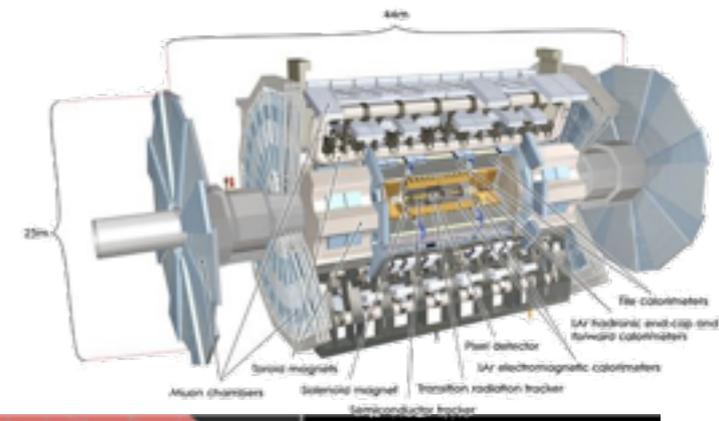


$$m^2 = (|\mathbf{p}_1| + |\mathbf{p}_2|)^2 - (\mathbf{p}_1 + \mathbf{p}_2)^2$$

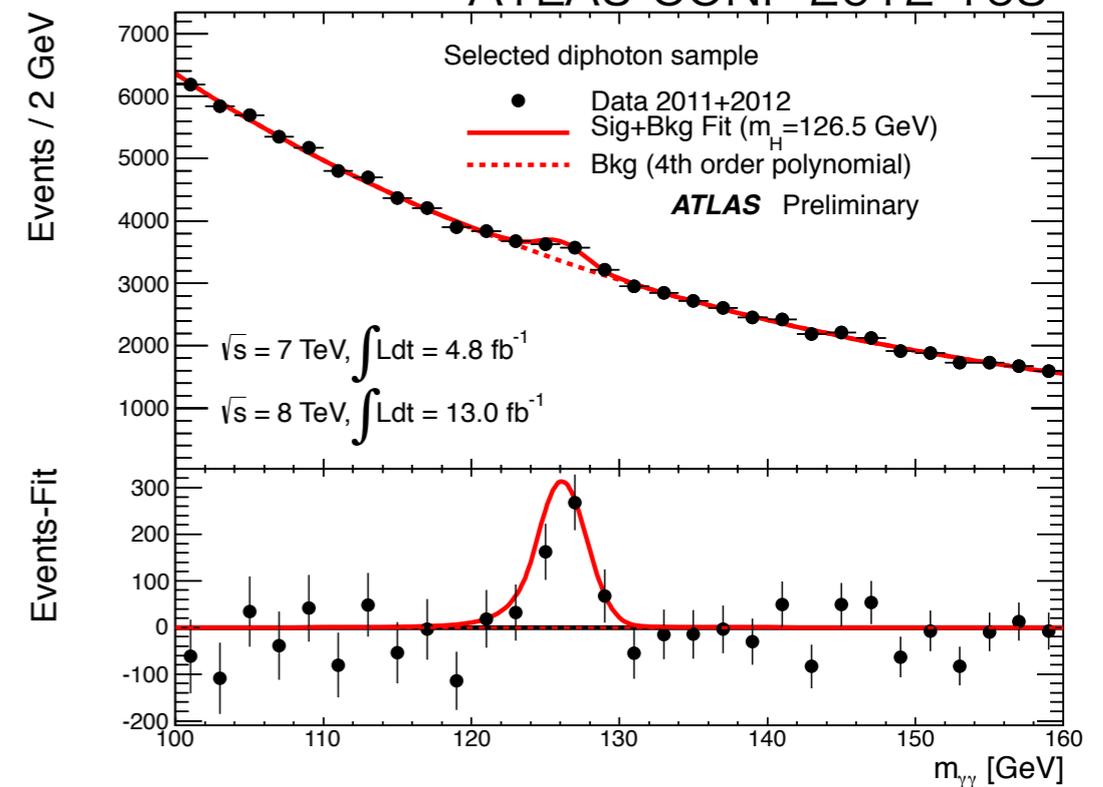
$$m = (2|\mathbf{p}_1||\mathbf{p}_2|(1 - \cos \theta))^{1/2}$$

- 確かにピークがある

▶ 発見??



ATLAS-CONF-2012-168

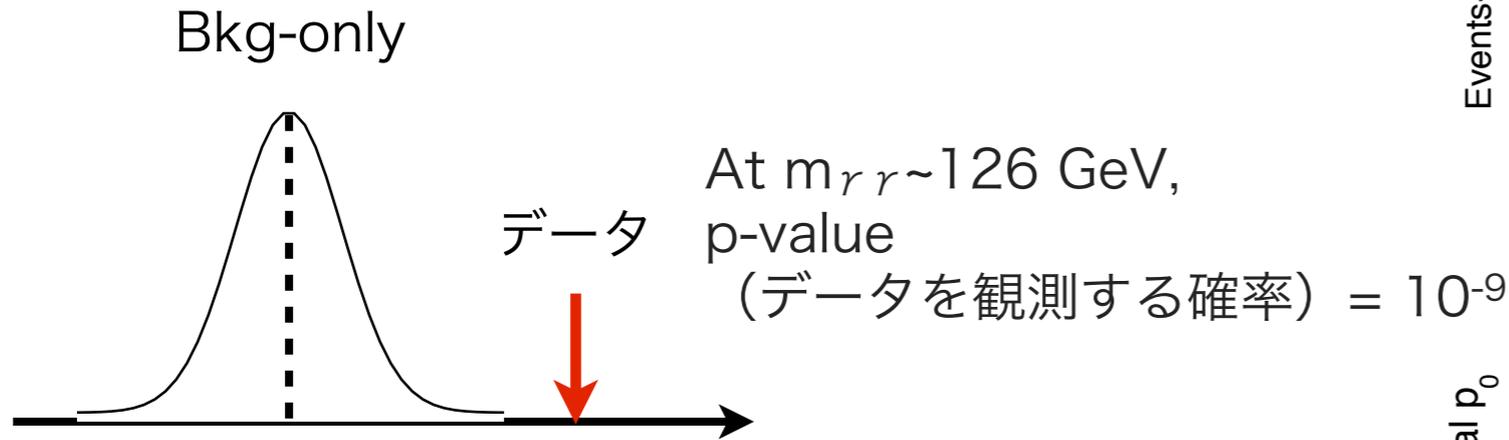


統計処理 (考え方だけ)

● バックグラウンドからデータがどれだけ離れているか？

● p-value:
Bkg-onlyの仮定のもとで観測した数を観測する確率

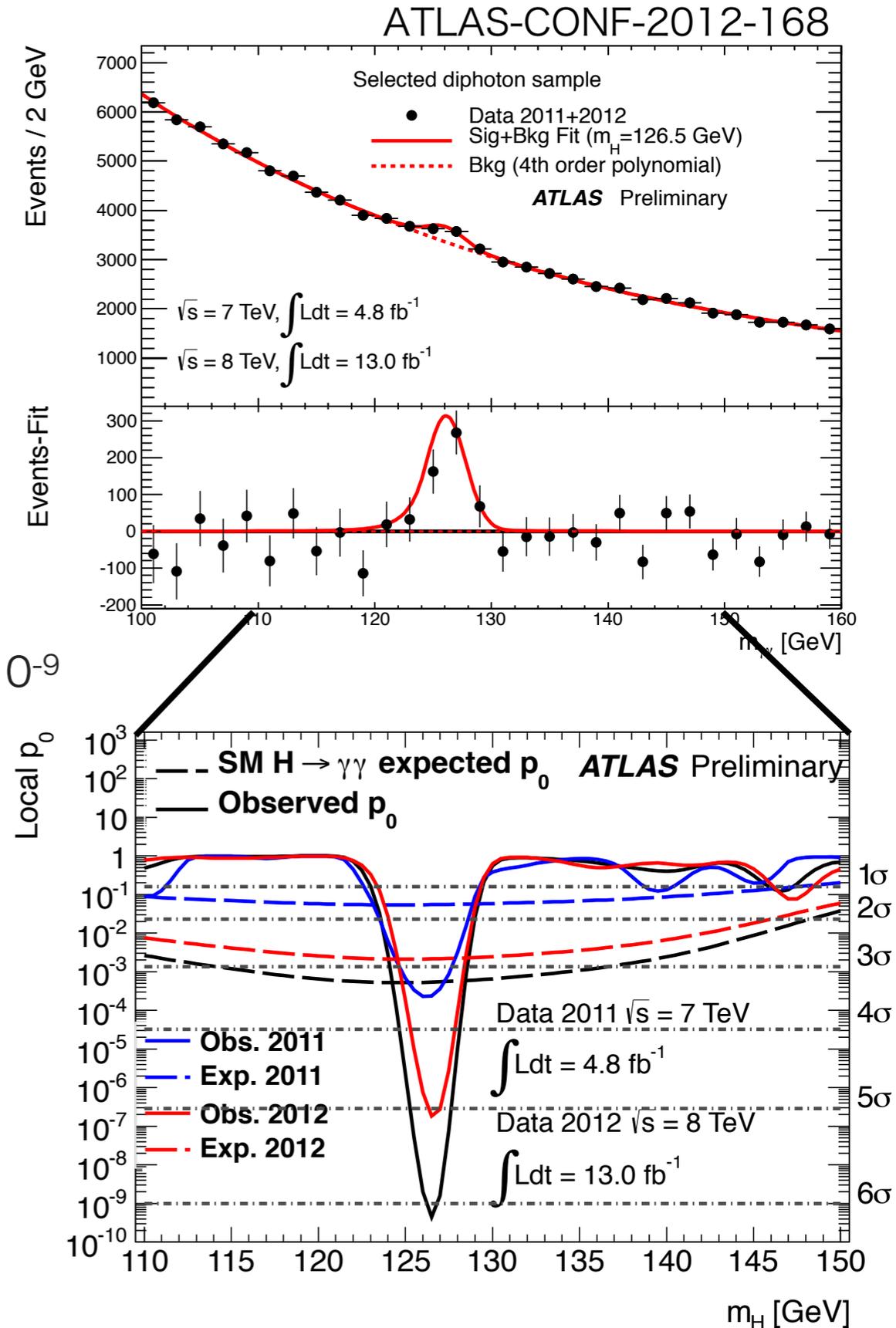
▶ Significance:
逸脱具合を標準正規分布のシグマで表した数



● Bkg-onlyでは観測した結果を説明できない
→ 仮説が間違ってる = Bkg-onlyではない
→ なにかある！

● 宣言:
 3σ (10^{-3}) ... "Evidence"
 5σ (10^{-7}) ... "Discovery"

● 6σ なので、「higgs $\rightarrow \gamma\gamma$ を発見」 (global p-valueの話は省)



mono-jetの例

探索の例 mono-jet

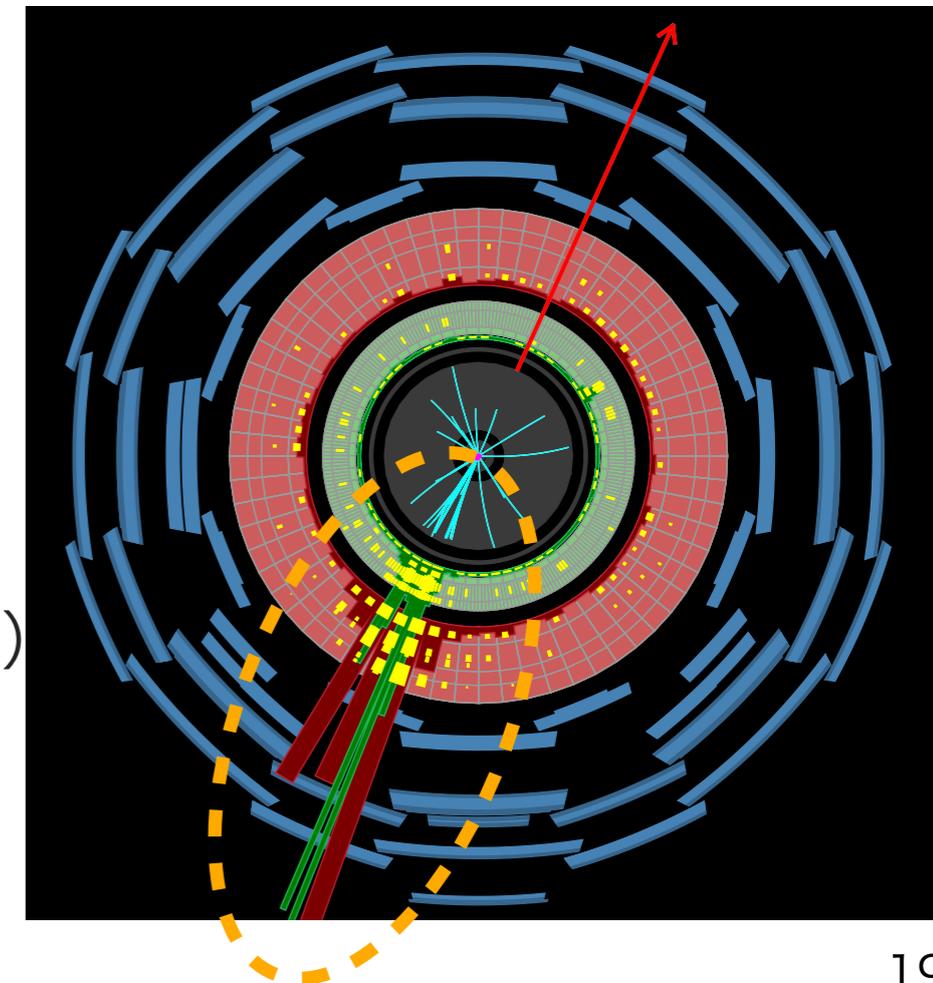
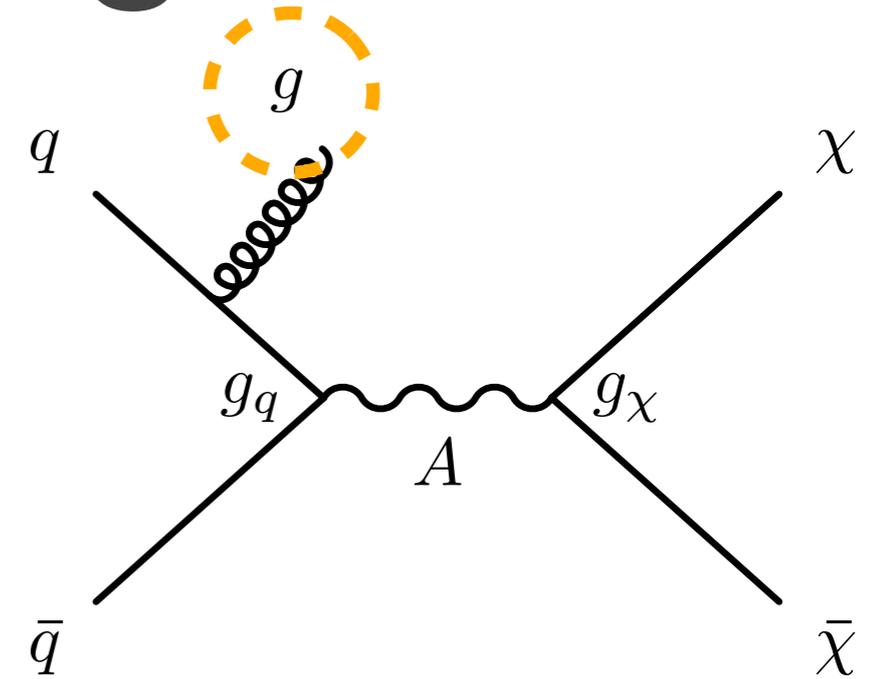
- 暗黒物質探索

- ▶ 陽子陽子が衝突
→ なにかある粒子Aが生成
→ WIMP (χ) が対生成

- WIMPは標準模型の粒子とほとんど相互作用しない
→ 検出器に信号を残さない (通り抜ける)

- どうやって探索するのか？

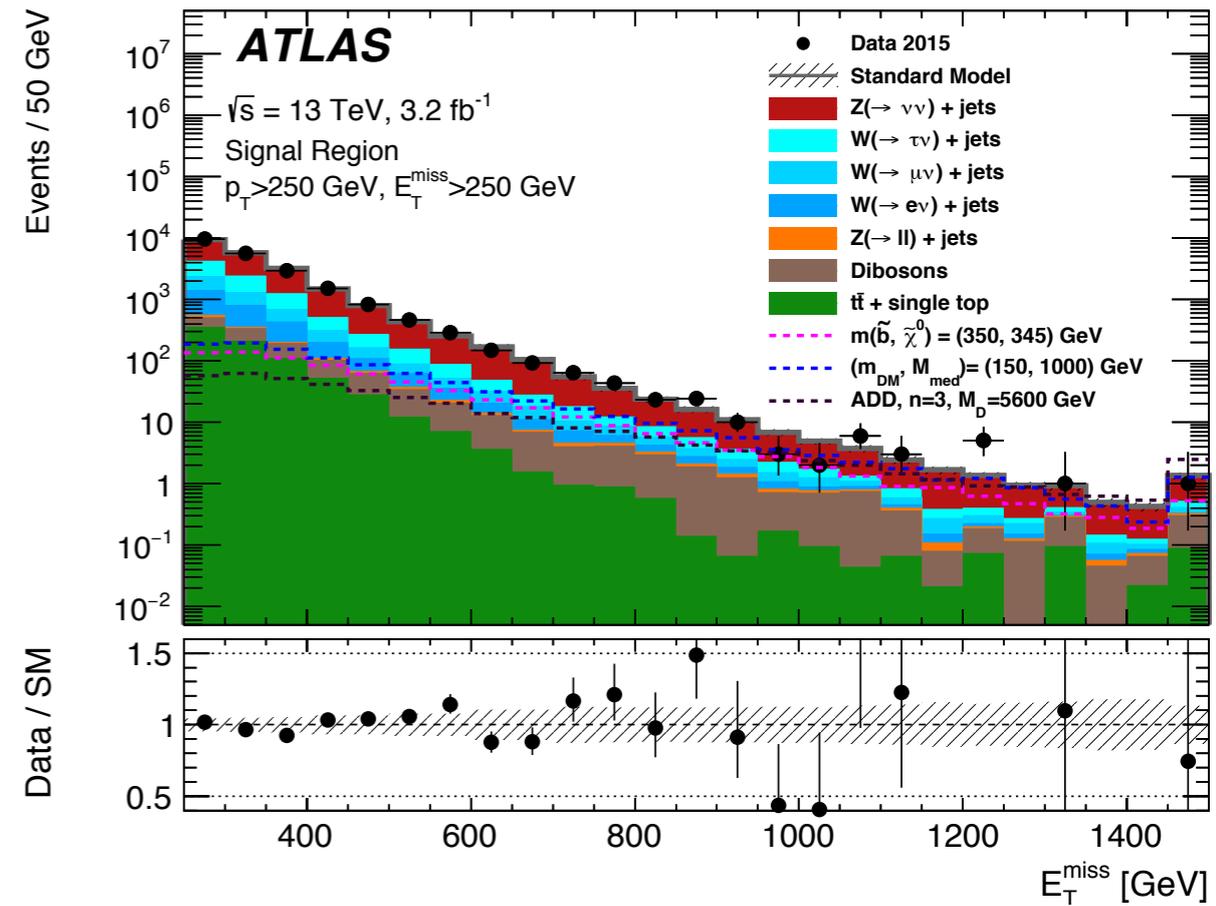
- ▶ 通り抜ける
→ 運動量保存則が成り立っていないようにみえる (ニュートリノも)
- ▶ 運動量のバランスから、
missing E_T (MET) or E_T^{miss}
(見えないものが持って行った横平面上のエネルギー)
を計算することで探索可能



探索の例 mono-jet

[Phys. Rev. D 94 \(2016\) 032005](#)

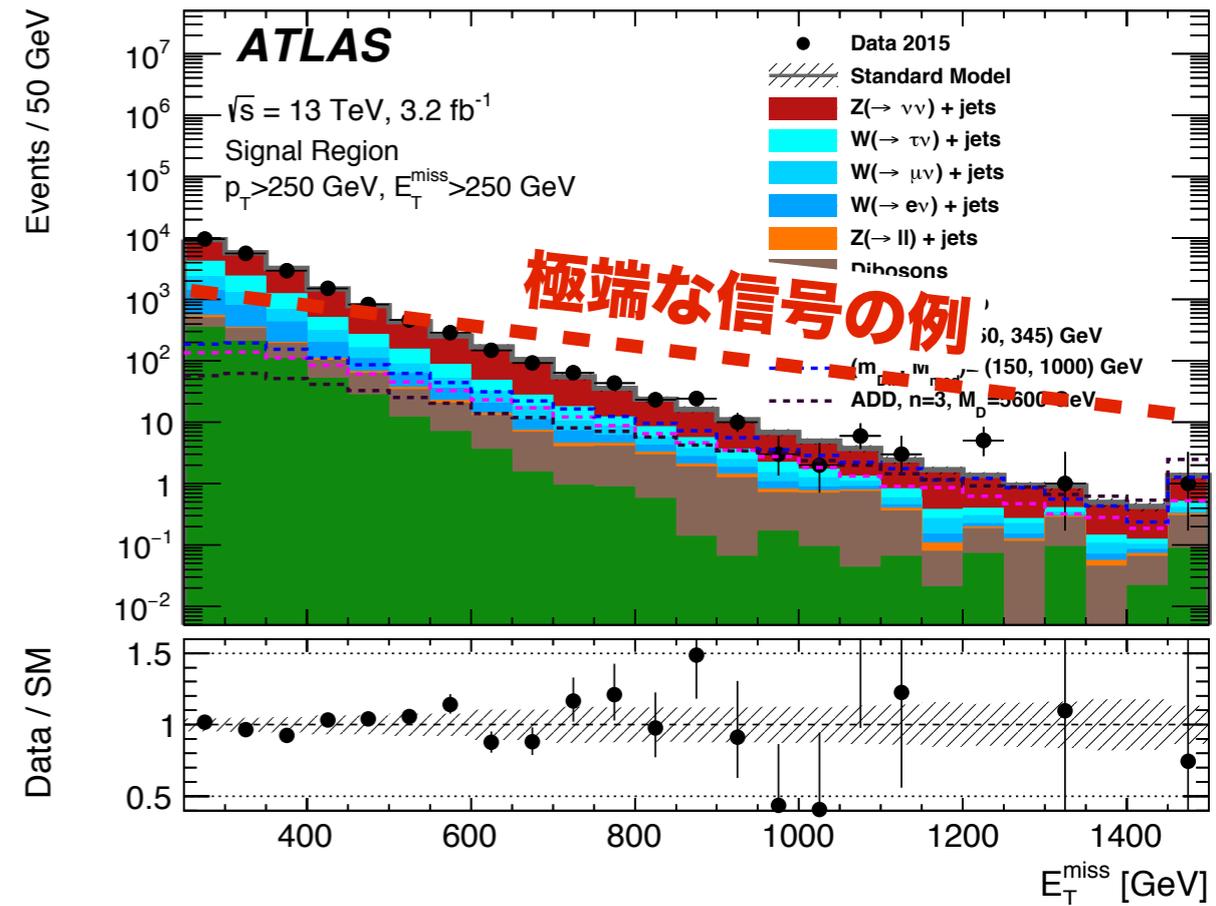
- 1つのジェットのみを含むようなイベントを抽出
- E_{T}^{miss} 分布を作成
→ 標準模型の予想とデータを比較
- ▶ 明らかな逸脱はなさそう ...
- 結論は「標準模型からのずれはなさそう」だけ？
→ 「信号事象がない」ということから
「理論に制限をつけることができる」



探索の例 mono-jet

[Phys. Rev. D 94 \(2016\) 032005](#)

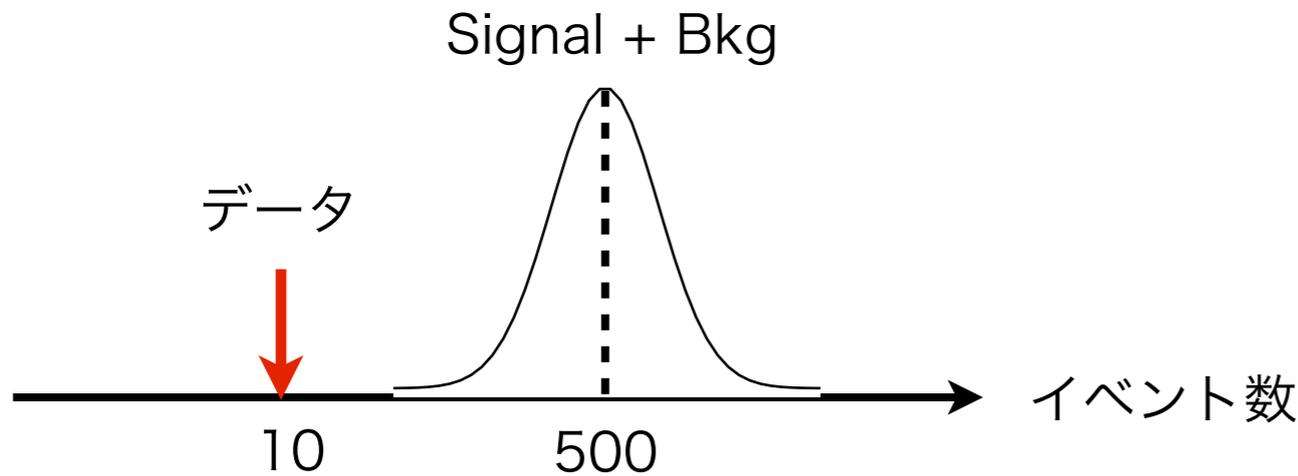
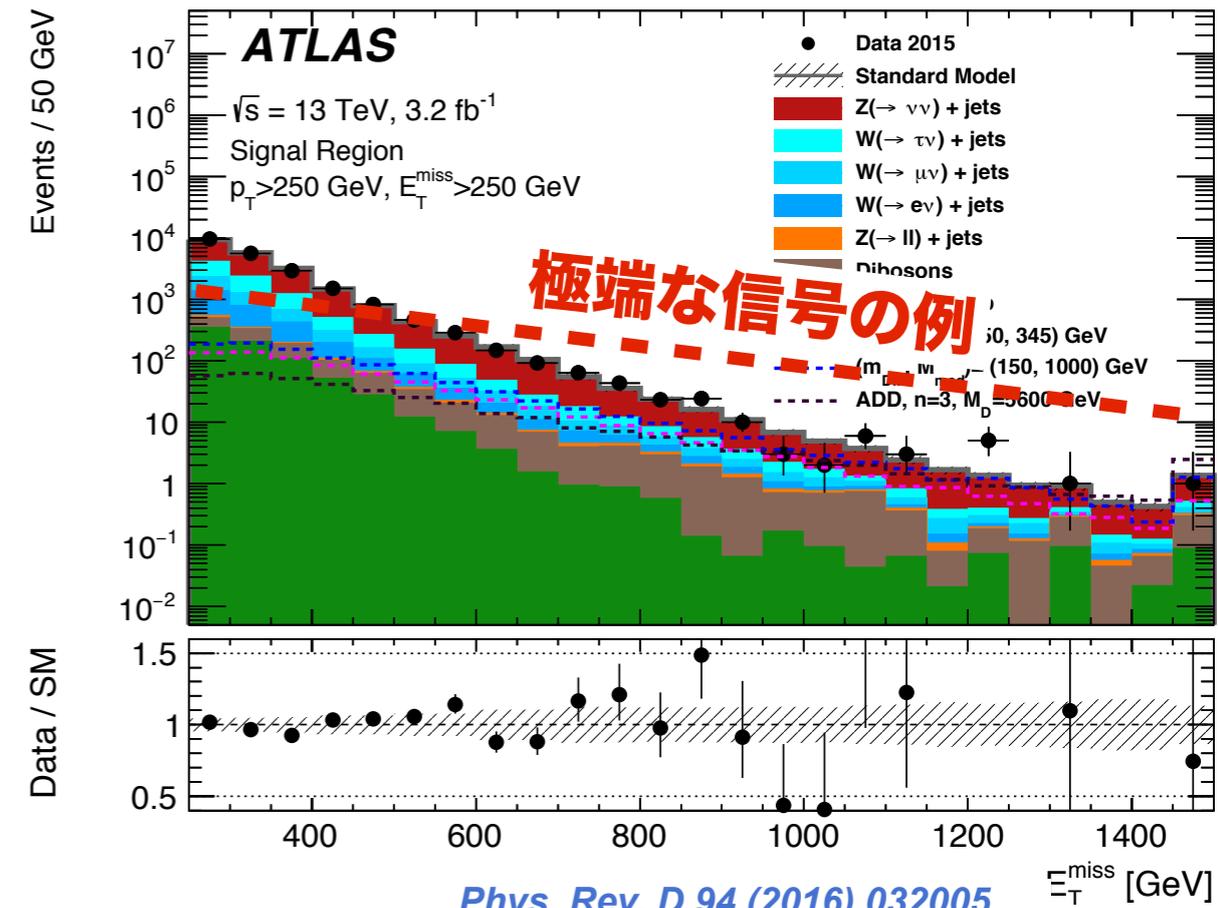
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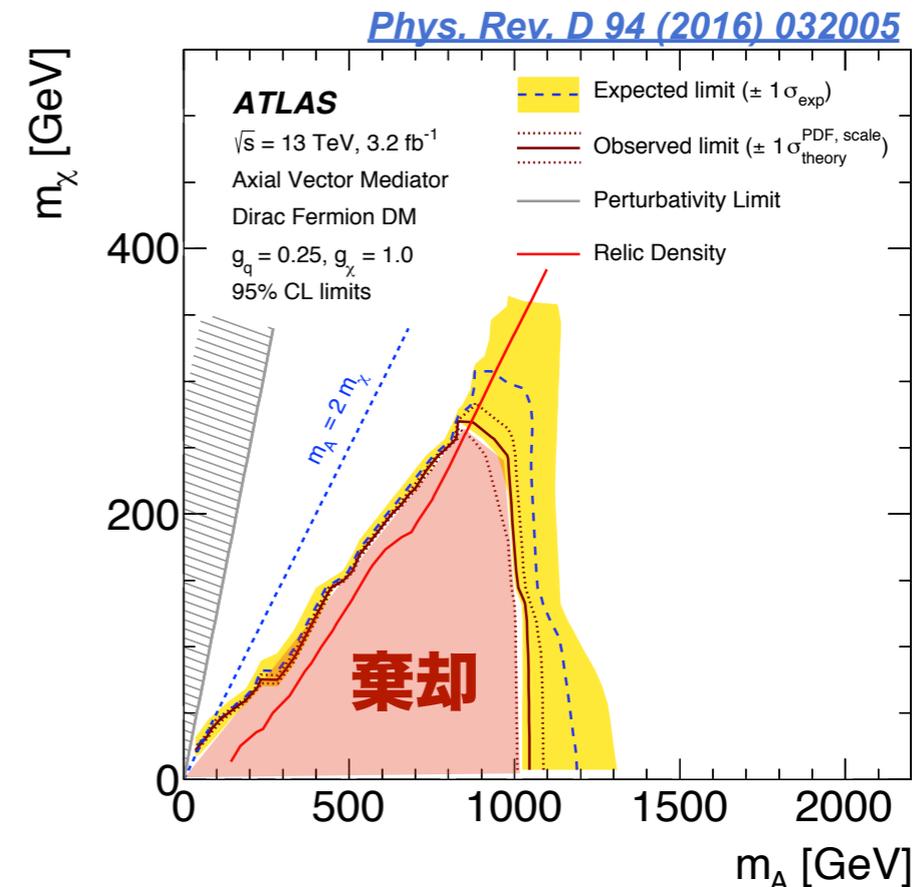
探索の例 mono-jet

Phys. Rev. D 94 (2016) 032005

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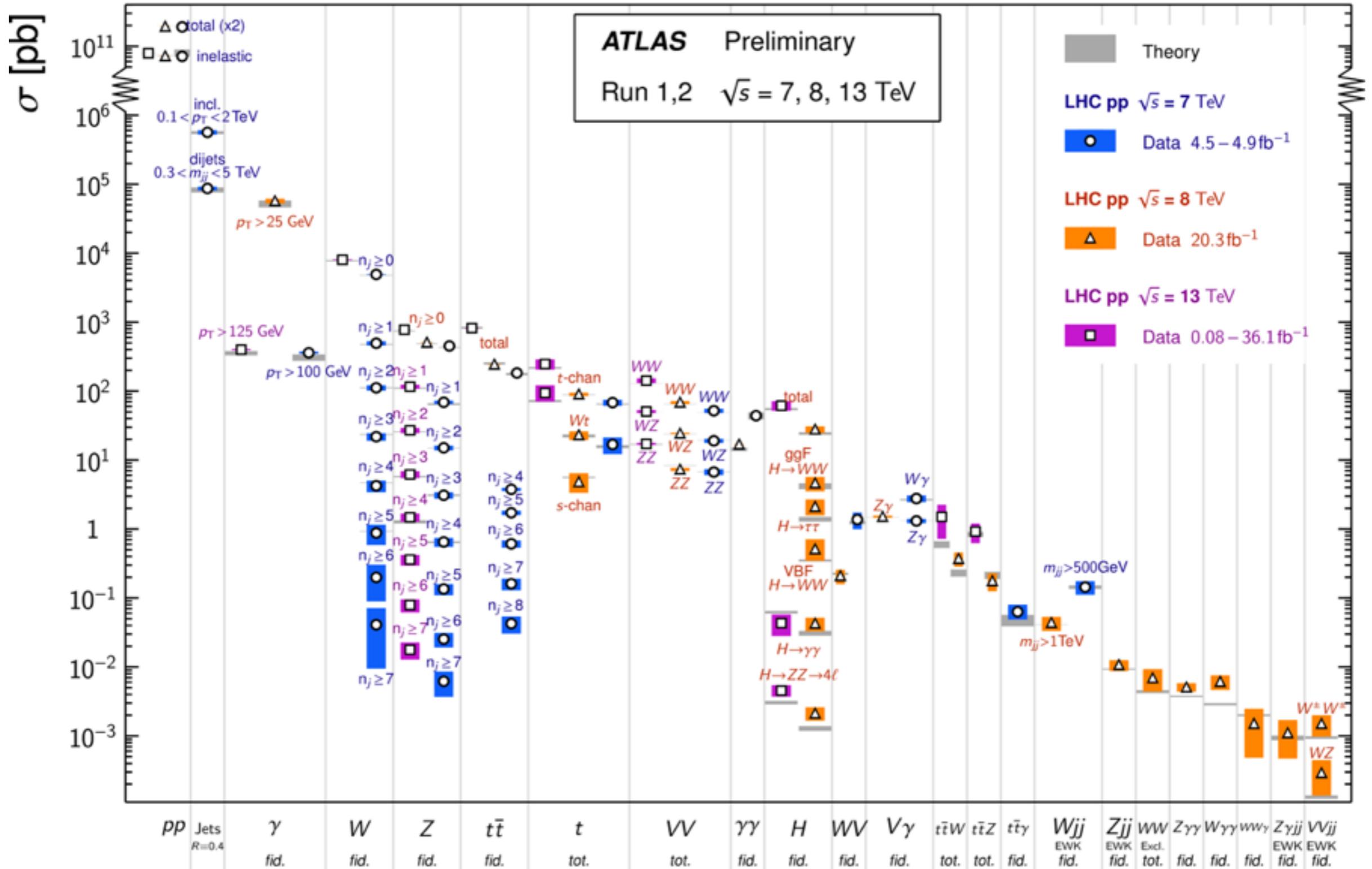
- S+Bでは観測した結果を説明できない
→ 仮説が間違ってる = S+Bではない
→ そんなSignalありえない
- ▶ 2σ (95%) を基準に棄却
「95% Confidence Levelで...を棄却」



ATLASの成果 標準模型の検証

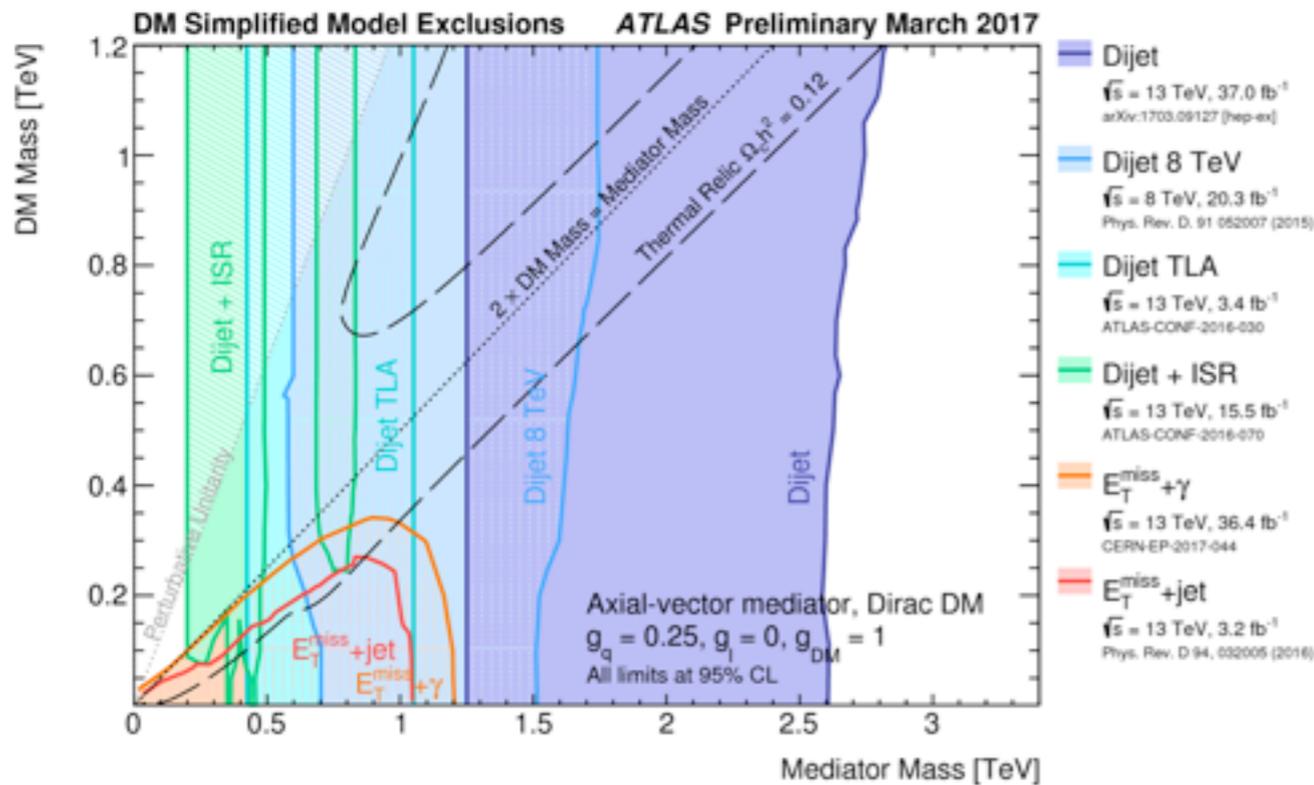
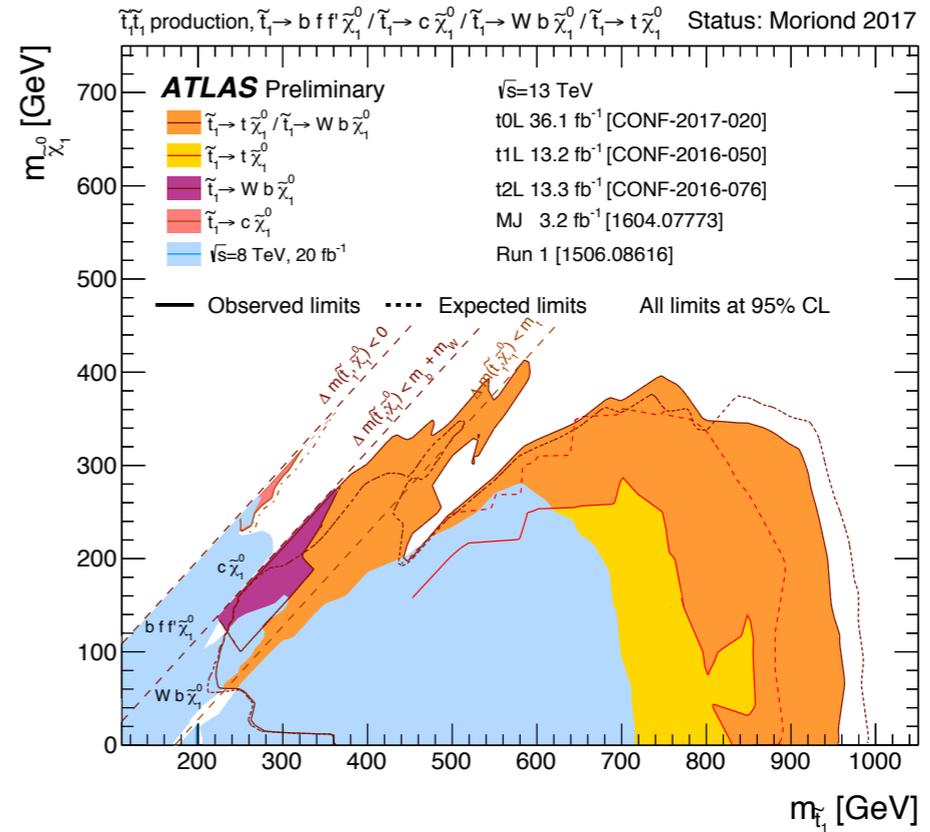
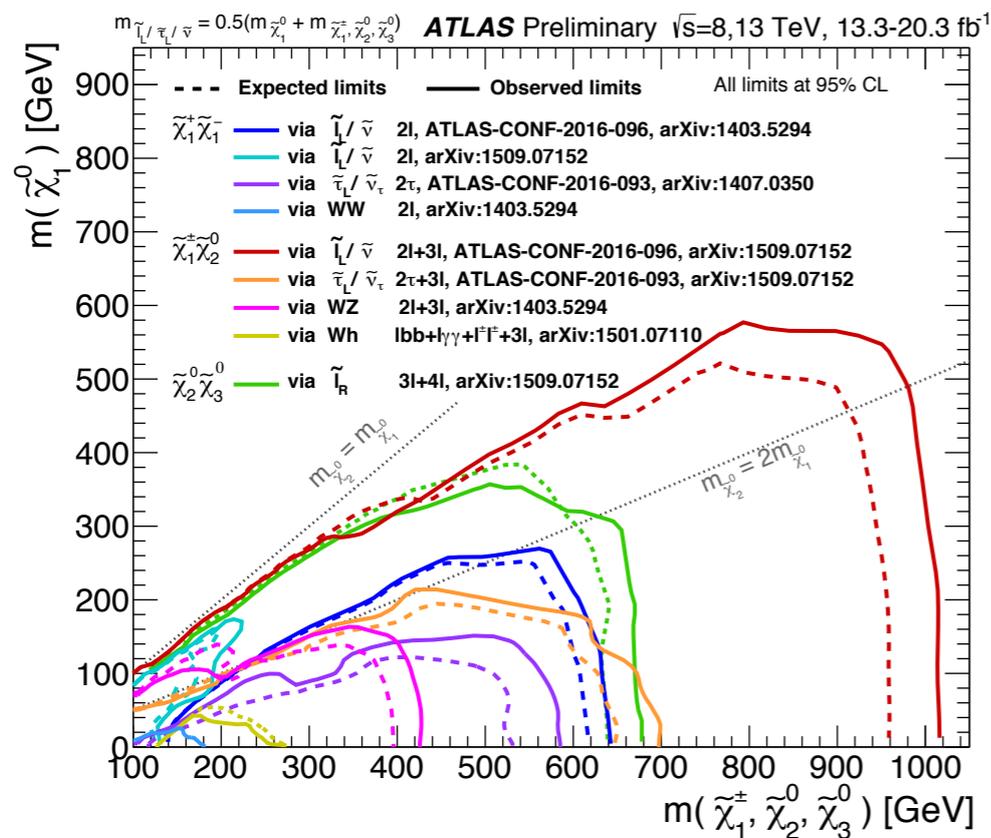
Standard Model Production Cross Section Measurements

Status: May 2017



標準模型の予測とデータがぴったしあっている！

ATLASの成果 新粒子探索



ATLAS Exotics Searches* - 95% CL Exclusion
Status: August 2016

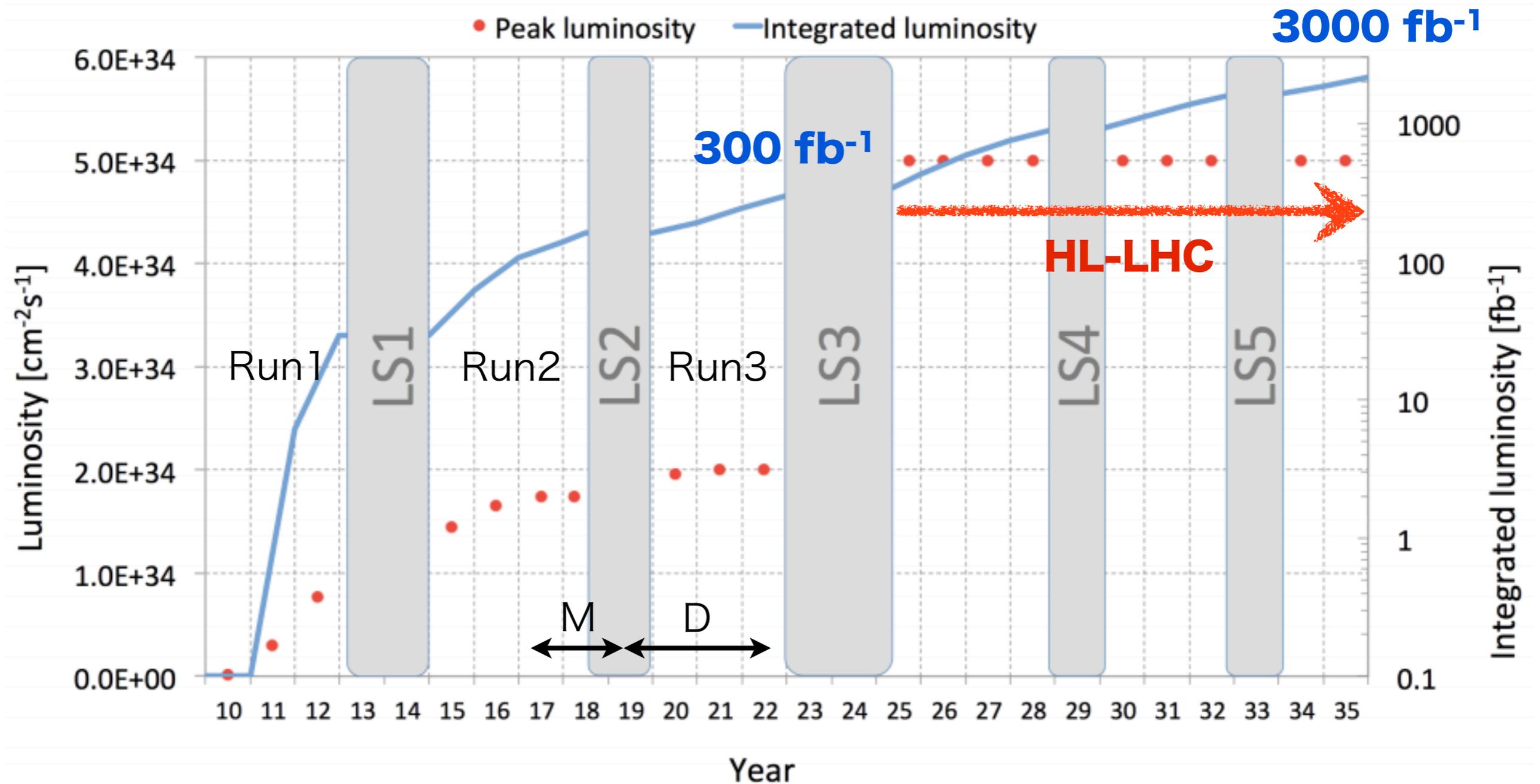
ATLAS Preliminary
 $\sqrt{s} = 8, 13$ TeV
 $\int \mathcal{L} dt = (3.2 - 20.3) \text{ fb}^{-1}$

Model	l, γ	Jets [†]	E_T^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference
Extra dimensions	ADD $G_{KK} + g/q$	-	$\geq 1j$	Yes	3.2	M_{pl} 6.58 TeV $n=2$
	ADD non-resonant ll	$2e, \mu$	-	-	20.3	M_{pl} 4.7 TeV $n=3$ HLZ
	ADD QBH $\rightarrow lq$	$1e, \mu$	$2j$	-	15.7	M_{pl} 5.2 TeV $n=6$
	ADD QBH	$1e, \mu$	$2j$	-	3.2	M_{pl} 8.7 TeV $n=6$
	ADD BH high Σp_T	$\geq 1e, \mu$	$\geq 2j$	-	3.2	M_{pl} 8.2 TeV $n=6, M_{\text{pl}} = 3 \text{ TeV, rot BH}$
	ADD BH multijet	$\geq 1e, \mu$	$\geq 3j$	-	3.6	M_{pl} 9.55 TeV $n=6, M_{\text{pl}} = 3 \text{ TeV, rot BH}$
	RS1 $G_{KK} \rightarrow ll$	$2e, \mu$	-	-	20.3	G_{KK} mass 2.68 TeV $k/\overline{M}_{\text{pl}} = 0.1$
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2γ	-	-	3.2	G_{KK} mass 3.2 TeV $k/\overline{M}_{\text{pl}} = 0.1$
	Bulk RS $G_{KK} \rightarrow WW \rightarrow qq/\nu$	$1e, \mu$	1J	Yes	13.3	G_{KK} mass 1.24 TeV $k/\overline{M}_{\text{pl}} = 1.0$
	Bulk RS $G_{KK} \rightarrow HH \rightarrow bbbb$	-	4b	-	13.3	G_{KK} mass 360-960 GeV $k/\overline{M}_{\text{pl}} = 1.0$
Bulk RS $G_{KK} \rightarrow tt$	$1e, \mu$	$\geq 1b, \geq 1J/2$	Yes	20.3	G_{KK} mass 2.2 TeV BR = 0.925	
2UED / RPP	$1e, \mu$	$\geq 2b, \geq 4j$	Yes	3.2	KK mass 1.46 TeV Tier(1,1), BR($A^{(1)} \rightarrow tt$) = 1	
Gauge bosons	SSM $Z' \rightarrow ll$	$2e, \mu$	-	-	13.3	Z' mass 4.05 TeV
	SSM $Z' \rightarrow \tau\tau$	2τ	-	-	19.5	Z' mass 2.02 TeV
	Leptoquark $Z' \rightarrow bb$	-	2b	-	3.2	Z' mass 1.5 TeV
	SSM $W' \rightarrow l\nu$	$1e, \mu$	-	Yes	13.3	W' mass 4.74 TeV
	HVT $W' \rightarrow WZ \rightarrow qq/\nu$ model A	$0e, \mu$	1J	Yes	13.2	W' mass 2.4 TeV
	HVT $W' \rightarrow WZ \rightarrow qq/\nu$ model B	-	2J	-	15.5	W' mass 3.0 TeV
	HVT $V' \rightarrow WH/ZH$ model B	multi-channel	-	-	3.2	V' mass 2.31 TeV
	LRSM $W'_q \rightarrow l\nu$	$1e, \mu$	2b-0-1j	Yes	20.3	W'_q mass 1.92 TeV
	LRSM $W'_q \rightarrow tb$	$0e, \mu$	$\geq 1b, 1j$	Yes	20.3	W'_q mass 1.76 TeV
	CI	CI $qqqq$	-	2j	-	15.7
CI $llqq$		$2e, \mu$	-	-	3.2	A 25.2 TeV $\eta_{LL} = -1$
DM	Axial-vector mediator (Dirac DM)	$0e, \mu, 1\gamma$	$\geq 1j$	Yes	3.2	m_{pl} 1.0 TeV $g_u = 0.25, g_s = -1.0, m(\chi) < 250 \text{ GeV}$
	Axial-vector mediator (Dirac DM)	$0e, \mu, 1\gamma$	1j	Yes	3.2	m_{pl} 710 GeV $g_u = 0.25, g_s = -1.0, m(\chi) < 150 \text{ GeV}$
	ZZ $\chi\chi$ EFT (Dirac DM)	$0e, \mu$	1J, $\leq 1j$	Yes	3.2	m_{pl} 550 GeV $m(\chi) < 150 \text{ GeV}$
LQ	Scalar LQ 1 st gen	$2e$	$\geq 2j$	-	3.2	LQ mass 1.1 TeV $\beta = 1$
	Scalar LQ 2 nd gen	2μ	$\geq 2j$	-	3.2	LQ mass 1.05 TeV $\beta = 1$
	Scalar LQ 3 rd gen	$1e, \mu$	$\geq 1b, \geq 3j$	Yes	20.3	LQ mass 640 GeV $\beta = 0$
	VLO $TT \rightarrow H + X$	$1e, \mu$	$\geq 2b, \geq 3j$	Yes	20.3	T mass 655 GeV T in (TB) doublet
	VLO $YY \rightarrow W + X$	$1e, \mu$	$\geq 1b, \geq 3j$	Yes	20.3	Y mass 770 GeV Y in (BY) doublet
Heavy quarks	VLO $BB \rightarrow H + X$	$1e, \mu$	$\geq 2b, \geq 3j$	Yes	20.3	B mass 735 GeV isospin singlet
	VLO $BB \rightarrow Z + X$	$2\tau, 3e, \mu, \tau$	$\geq 2b$	-	20.3	B mass 755 GeV B in (BY) doublet
	VLO $QQ \rightarrow WqWq$	$1e, \mu$	$\geq 4j$	Yes	20.3	Q mass 690 GeV
	VLO $T_{3/2} T_{3/2} \rightarrow WWt$	$2(SS)/\geq 3e, \mu$	$\geq 1b, \geq 1j$	Yes	3.2	$T_{3/2}$ mass 990 GeV
	Excited fermions	Excited quark $q^* \rightarrow q\gamma$	1γ	1j	-	3.2
Excited quark $q^* \rightarrow qg$		$1e, \mu$	$\geq 1b, \geq 3j$	-	15.7	q^* mass 5.6 TeV
Excited quark $q^* \rightarrow qg$		$1e, \mu$	1b, 1j	-	8.8	q^* mass 2.3 TeV
Excited quark $b^* \rightarrow Wt$		$1\tau, 2e, \mu$	1b, 2-0j	Yes	20.3	b^* mass 1.5 TeV $f_u = f_s = f_c = 1$
Excited lepton l^*		$3e, \mu, \tau$	-	-	20.3	l^* mass 3.0 TeV $\Lambda = 3.0 \text{ TeV}$
Other	Excited lepton ν^*	$3e, \mu, \tau$	-	-	20.3	ν^* mass 1.6 TeV $\Lambda = 1.6 \text{ TeV}$
	LSTC $a\gamma \rightarrow W\gamma$	$1e, \mu, 1\gamma$	-	Yes	20.3	$a\gamma$ mass 960 GeV
	LRSM Majorana ν	$2e, \mu$	2j	-	13.3	ν^c mass 2.0 TeV
	Higgs triplet $H^{\pm\pm} \rightarrow ee$	$2e$ (SS)	-	-	20.3	$H^{\pm\pm}$ mass 570 GeV $m(W_h) = 2.4 \text{ TeV, no mixing}$
	Higgs triplet $H^{\pm\pm} \rightarrow ll$	$3e, \mu, \tau$	-	-	20.3	$H^{\pm\pm}$ mass 400 GeV DY production, BR($H^{\pm\pm} \rightarrow ee$) = 1
Monopole (non-res prod)	$1e, \mu$	1b	Yes	20.3	spin-1/2 invisible particle mass 657 GeV DY production, BR($H^{\pm\pm} \rightarrow \tau\tau$) = 1	
Multi-charged particles	-	-	-	20.3	multi-charged particle mass 785 GeV $\alpha_{\text{em}} = 0.2$	
Magnetic monopoles	-	-	-	7.0	monopole mass 1.34 TeV DY production, $ g = 5e$	

*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.
†Small-radius (large-radius) jets are denoted by the letter j (J).

いまのところ、新粒子発見の兆候はなし

これから



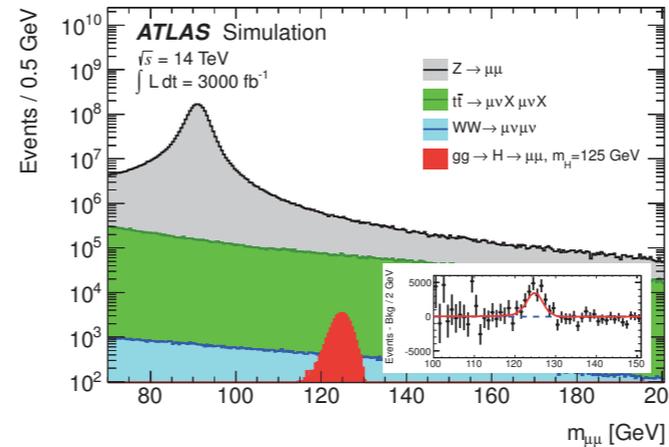
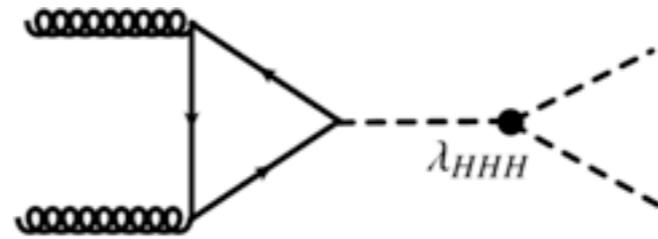
● 今M1だと、LS2をまたいでRun3→D卒業

▶ Run3に向けた準備 & 最新のデータを使った物理解析ができそう

High Luminosity-LHC

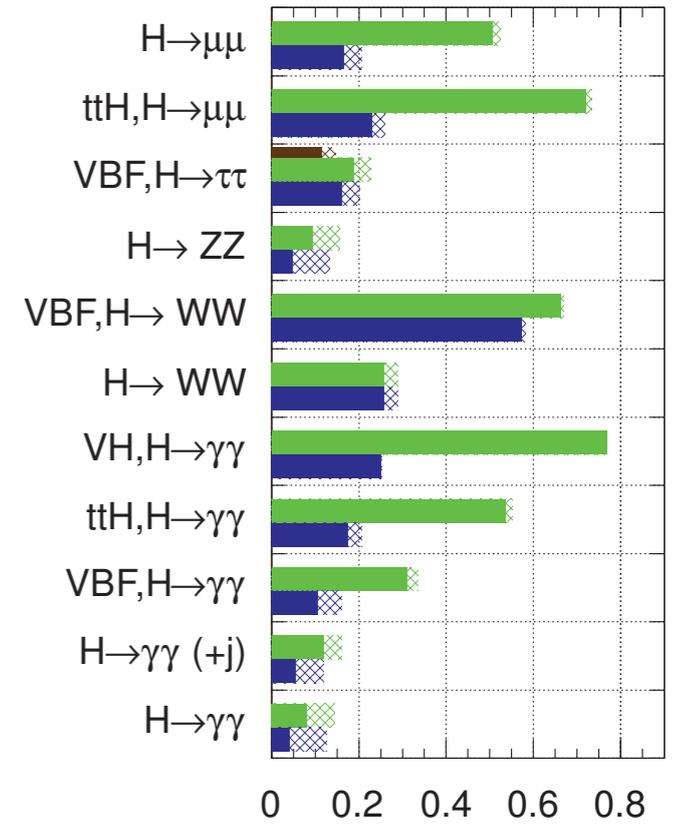
● ヒッグスの物理

- ▶ 精密測定
- ▶ ヒッグスの自己結合測定
- ▶ レアな崩壊モード探索: $\mu\mu$
 - 3000 fb^{-1} で 5σ 超えそう

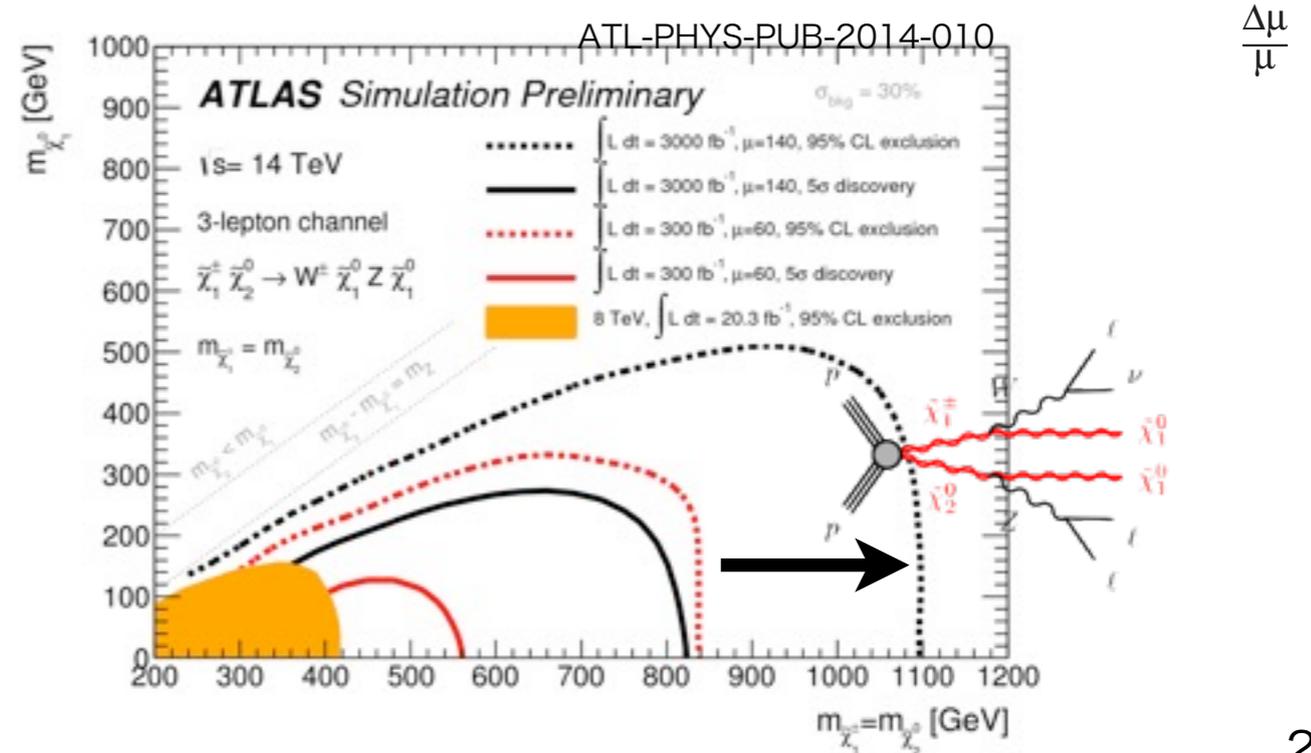
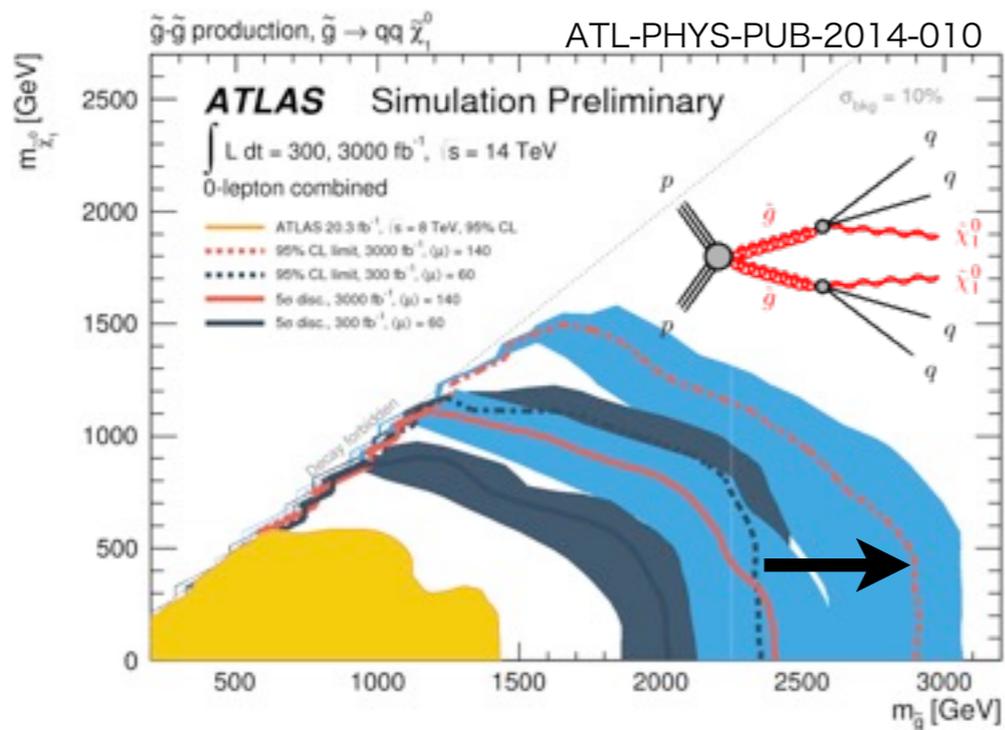


ATLAS Simulation

$\sqrt{s} = 14 \text{ TeV}$: $\int L dt = 300 \text{ fb}^{-1}$; $\int L dt = 3000 \text{ fb}^{-1}$
 $\int L dt = 300 \text{ fb}^{-1}$ extrapolated from 7+8 TeV



● 新物理探索 ... 超対称性粒子の探索の例



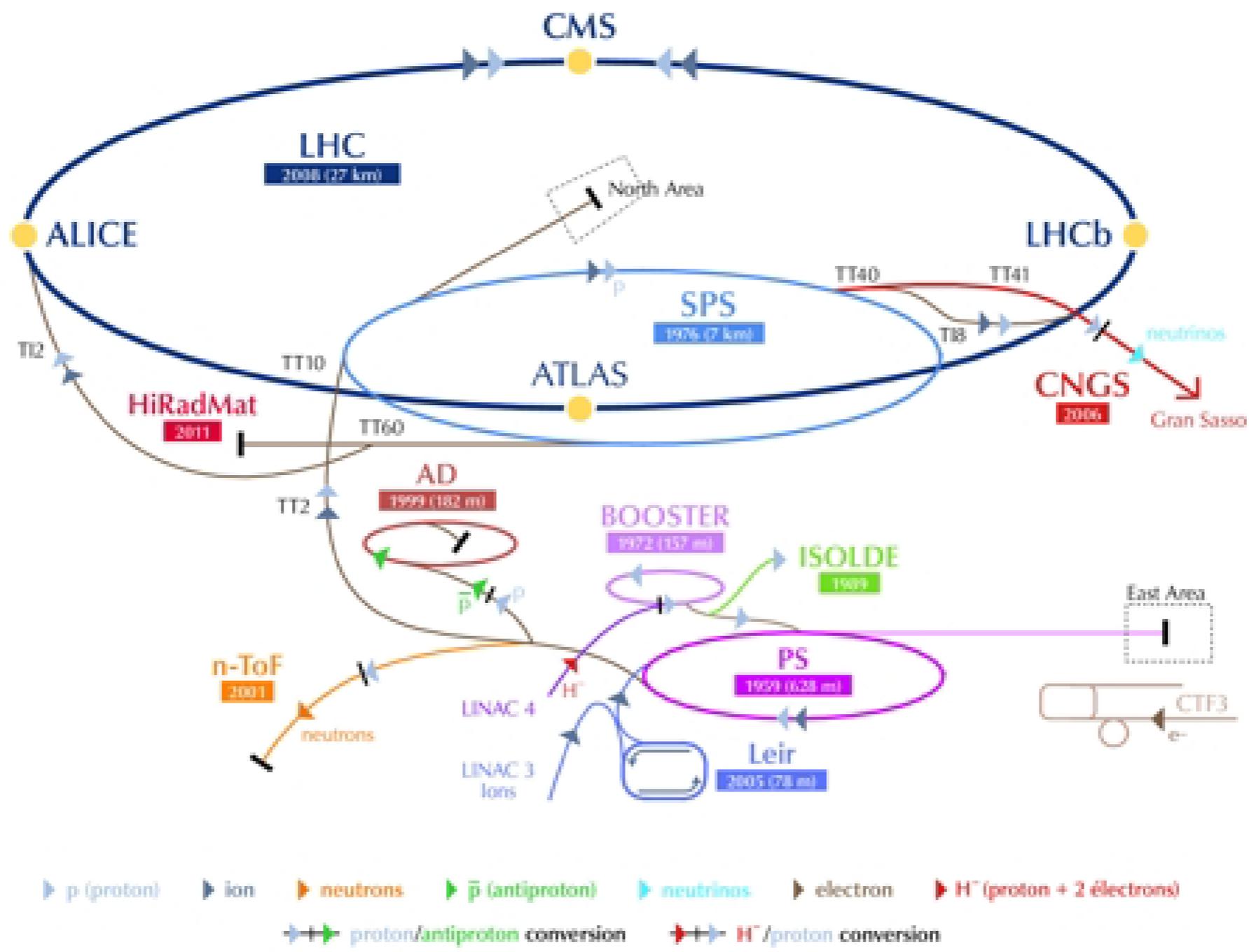
まとめ

- 世界最大の重心系エネルギーを実現するLHCを使ってATLAS実験を行っている
 - ▶ **素粒子標準模型の検証**
 - ▶ **未発見の新しい物理/素粒子の探索**
- 実際にどんなことをしているか？
 - ▶ トリガー、データ取得、再構成、 higgs \rightarrow $\gamma \gamma$ の例
- 現在、これ以外にも**たくさんの解析**が行なわれている
 - ▶ 興味がある方は[こちら](#)
- 将来、**できることはたくさんある**
 - ▶ Run3の準備と解析、HL-LHCに向けたアップグレード、HL-LHCの物理解析、....
- もっと知りたいな...と思った方はいつでも聞いてください！

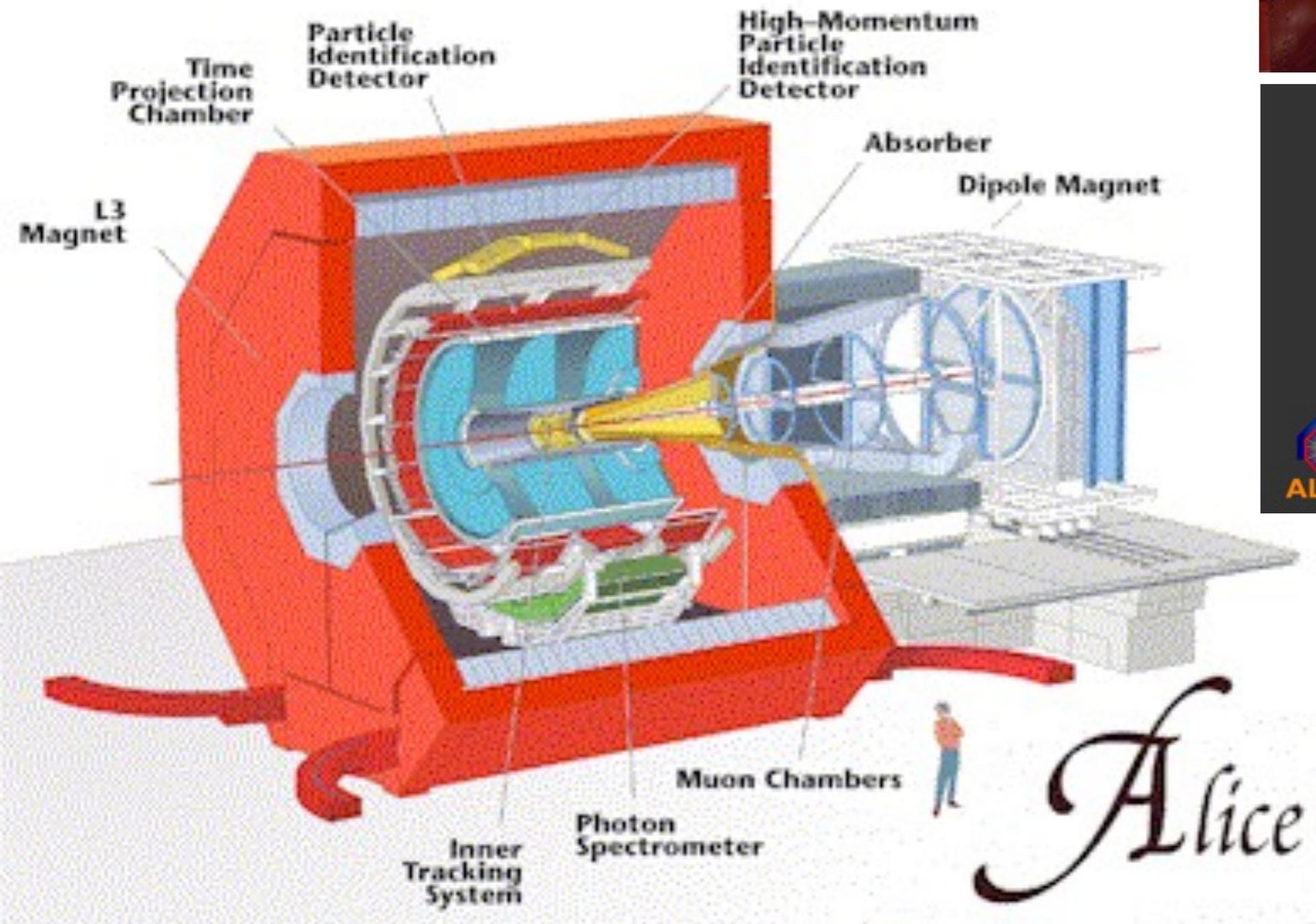
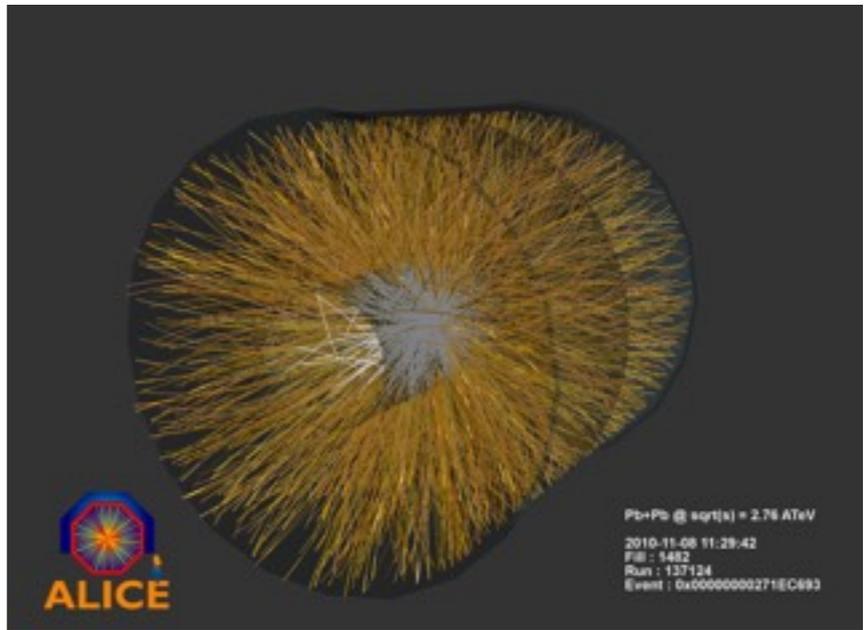
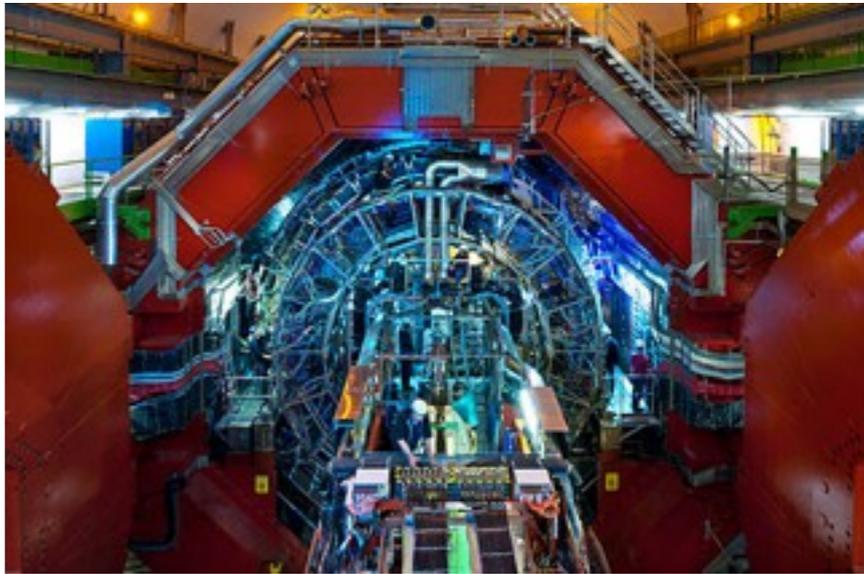
ご清聴ありがとうございました

Back Up

LHC

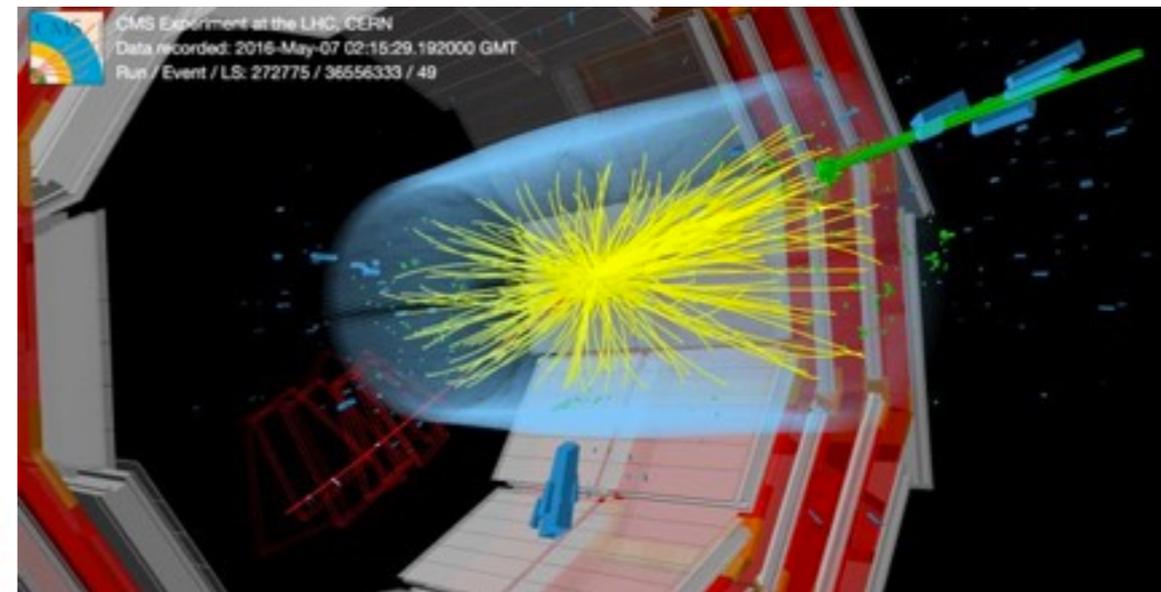
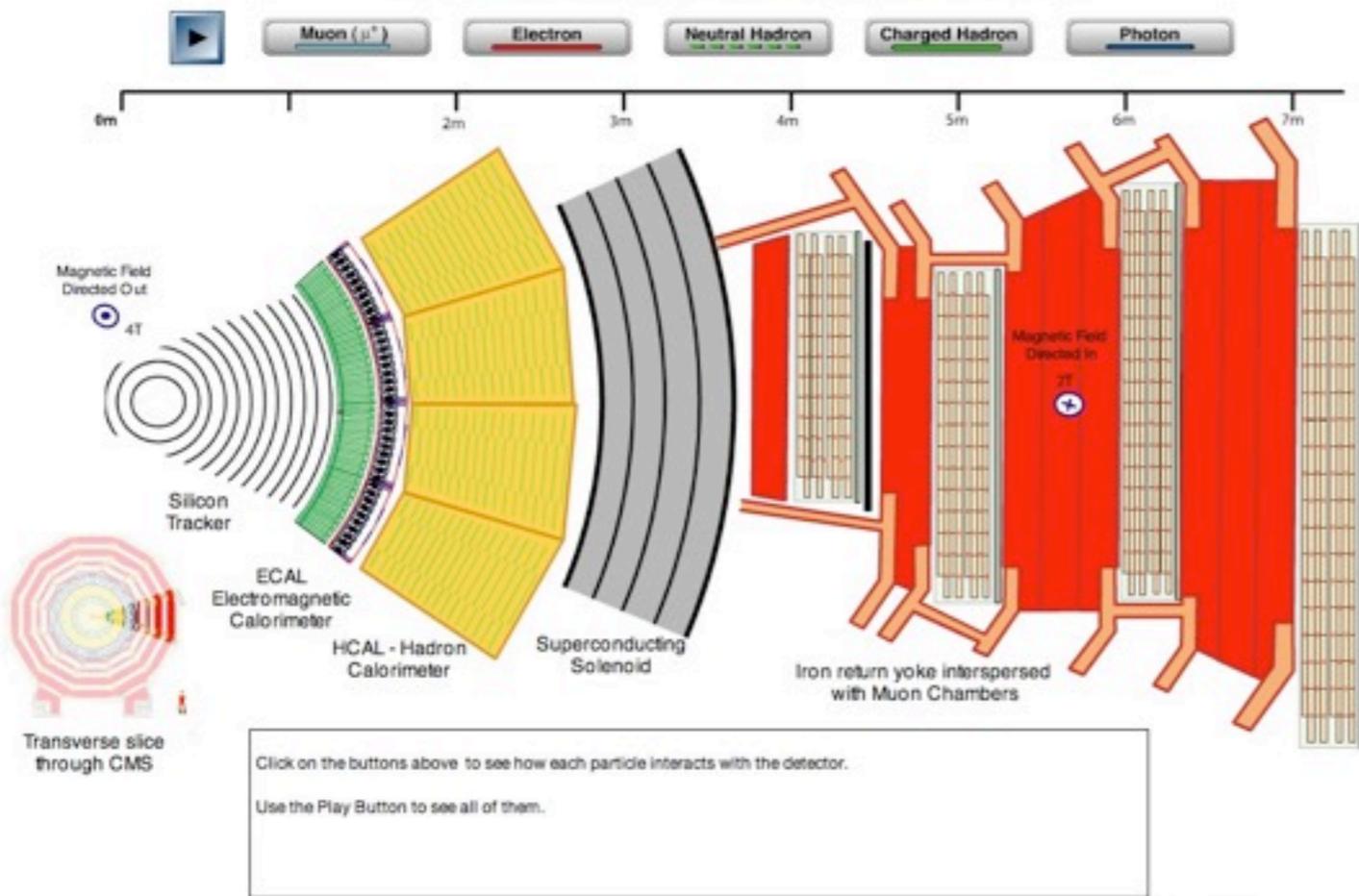
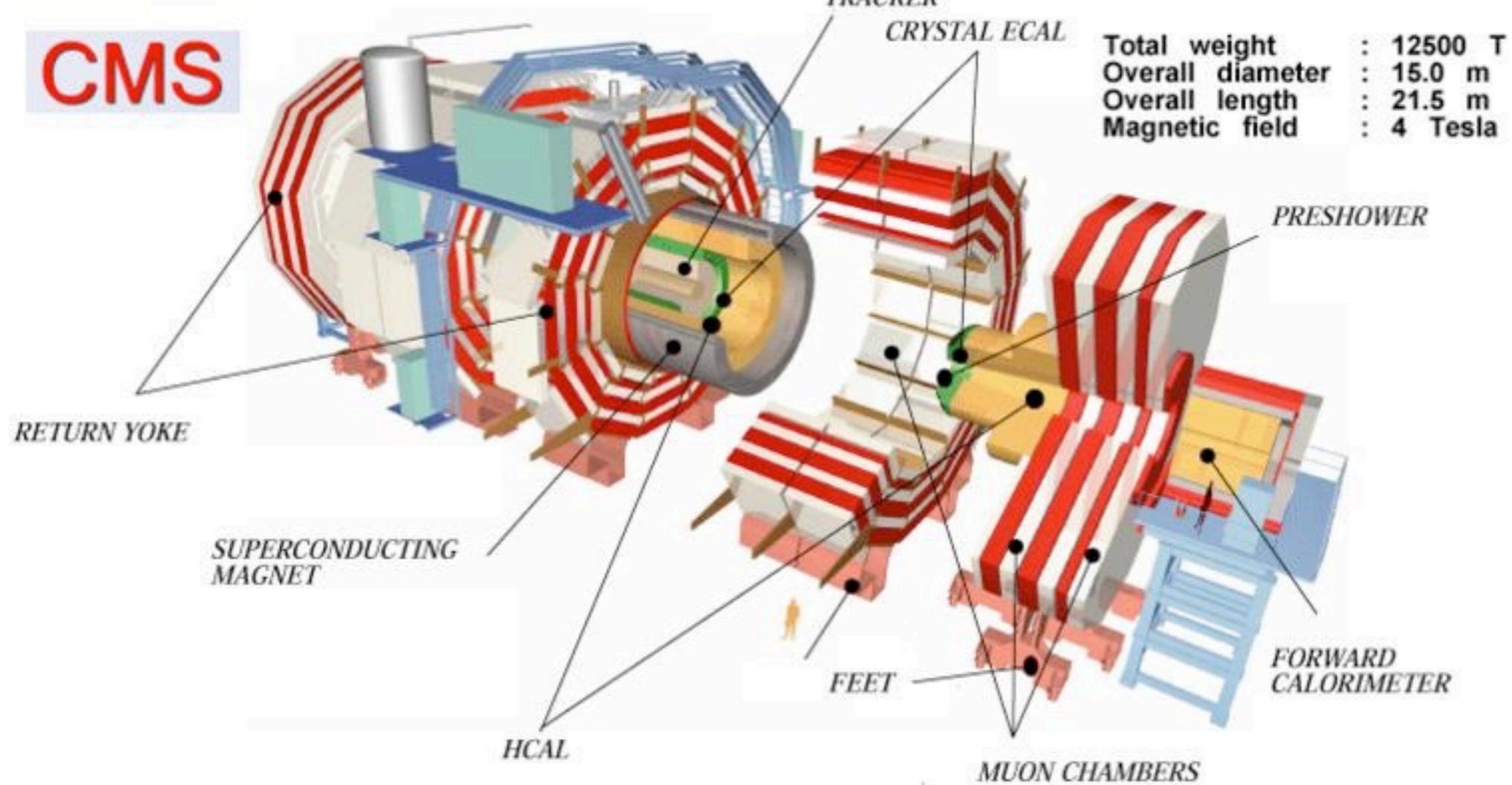


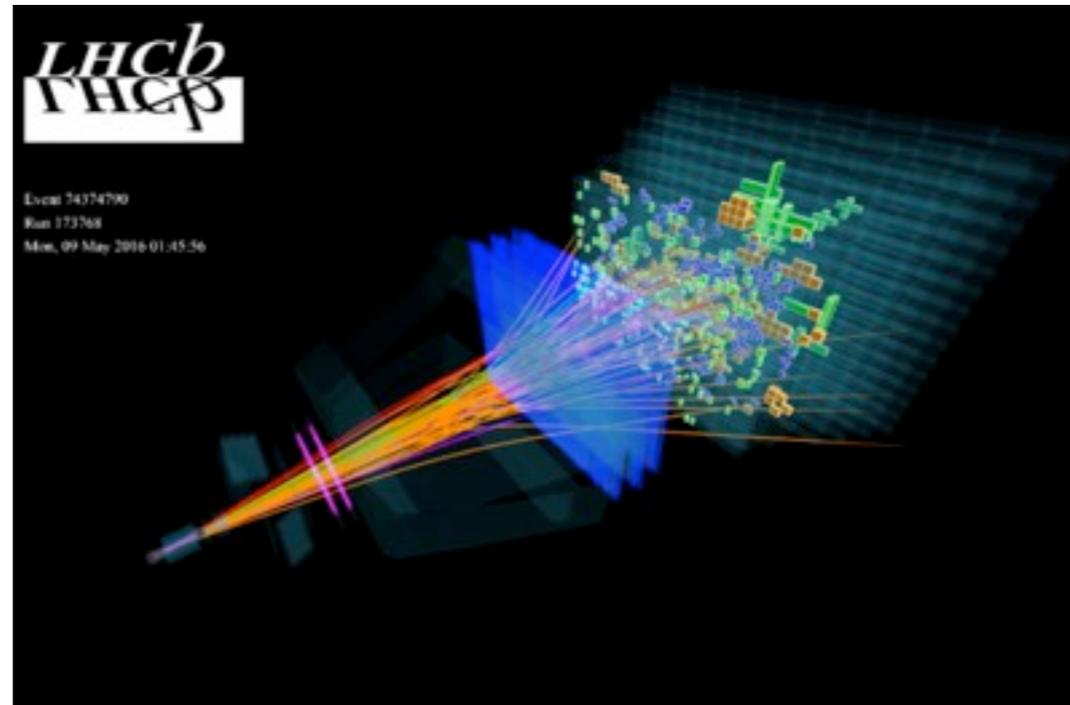
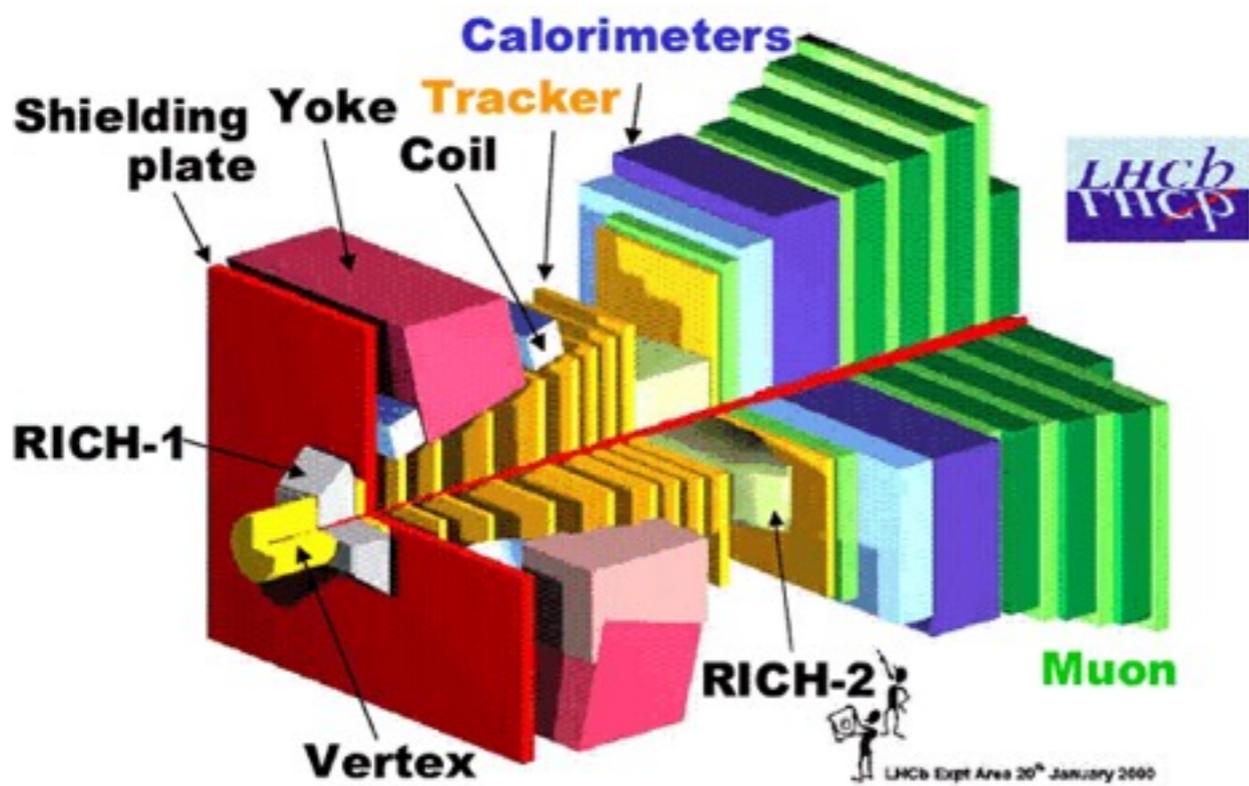
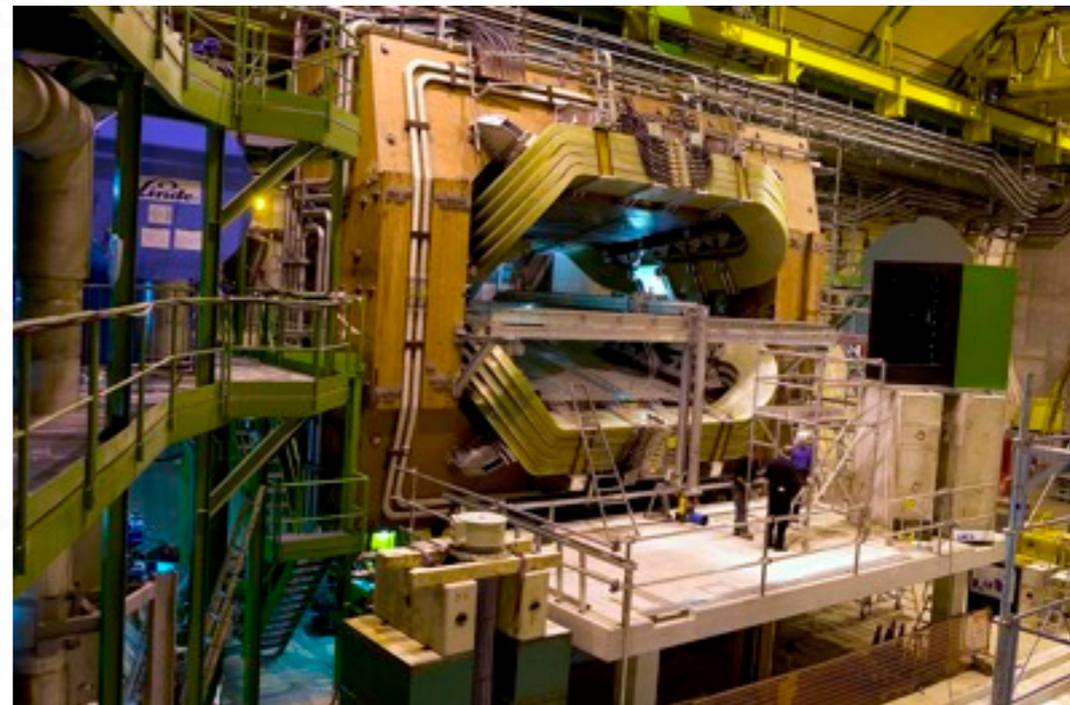
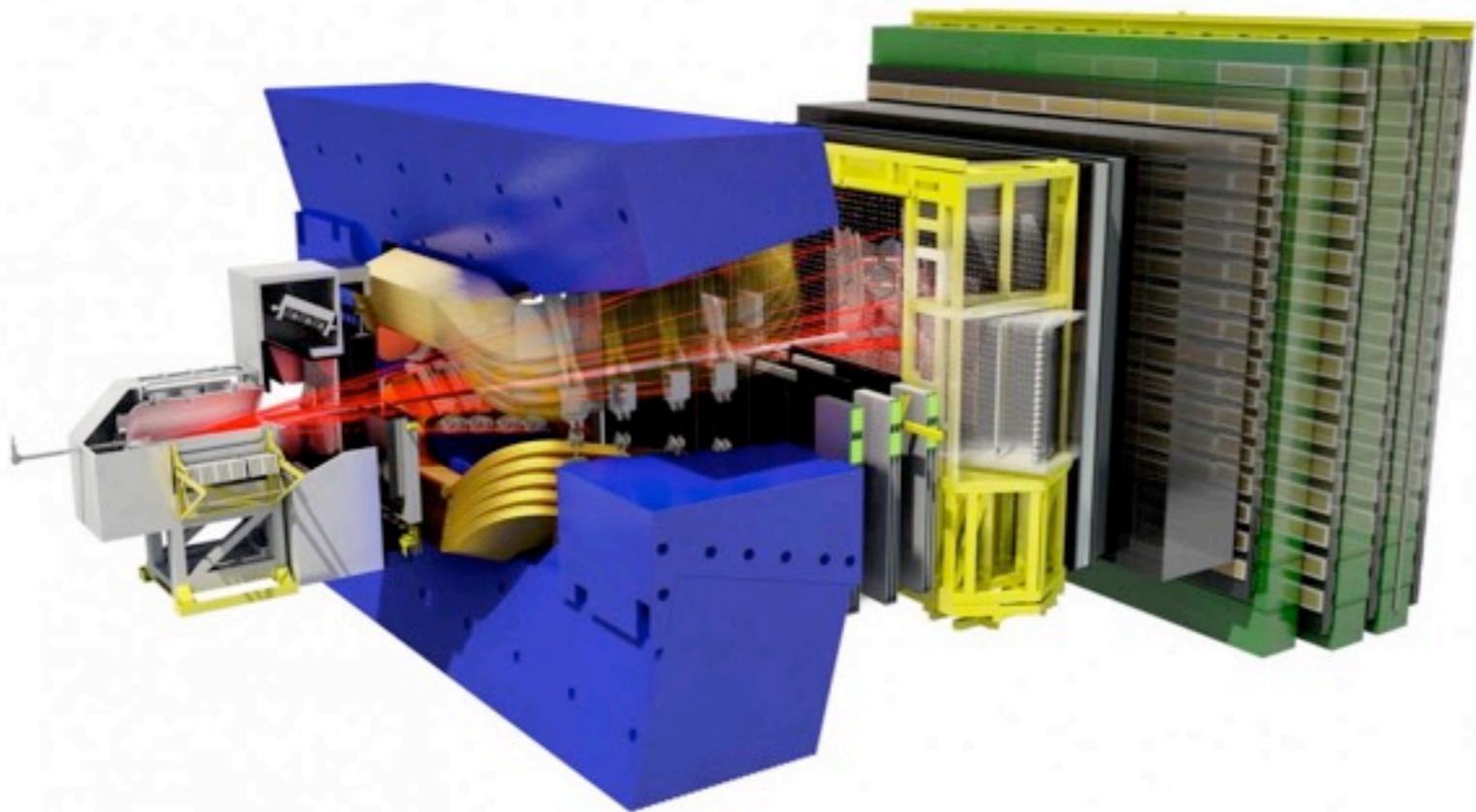
- LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron
- AD Antiproton Decelerator CTF3 Cbc Test Facility CNGS Cern Neutrinos to Gran Sasso ISOLDE Isotope Separator OnLine DEvice
- LEIR Low Energy Ion Ring LINAC Linear ACcelerator n-ToF Neutrons Time Of Flight HiRadMat High-Radiation to Materials

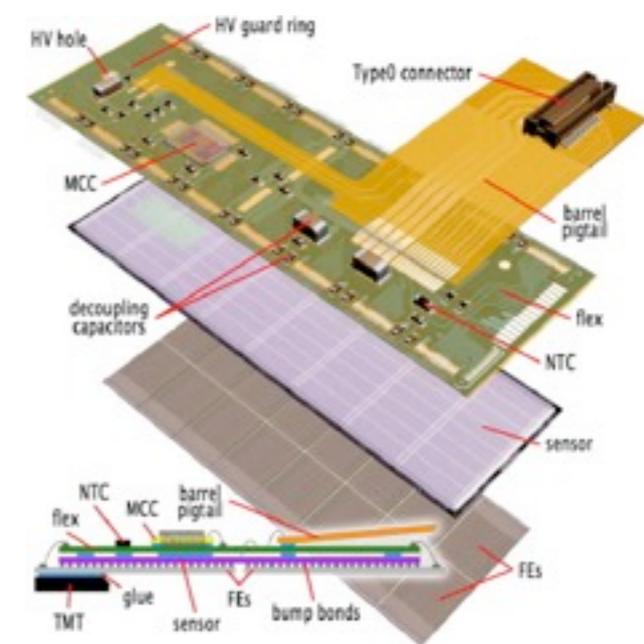
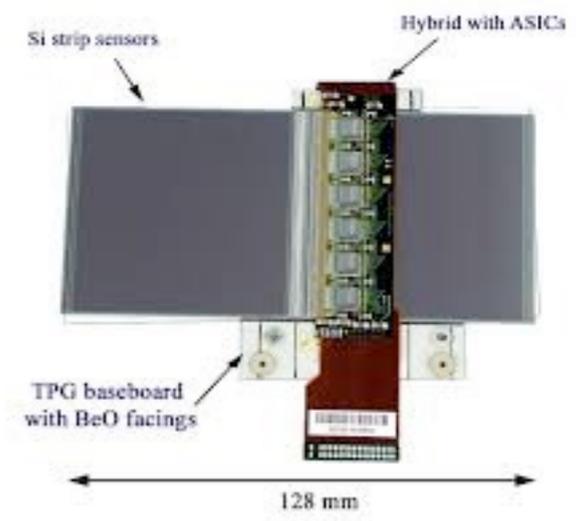
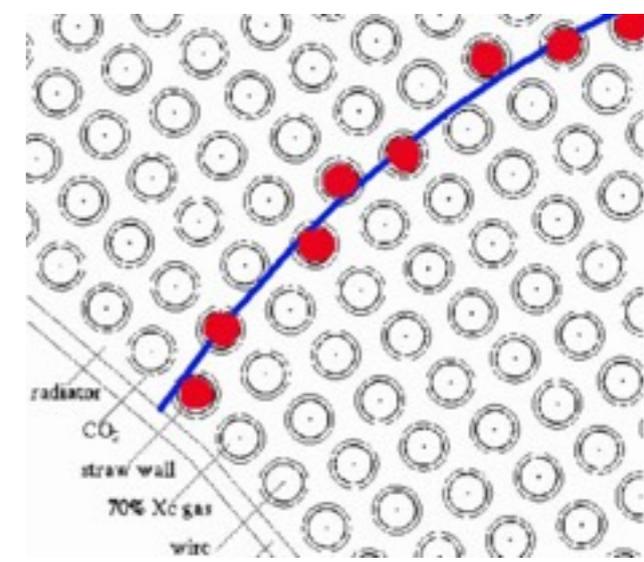
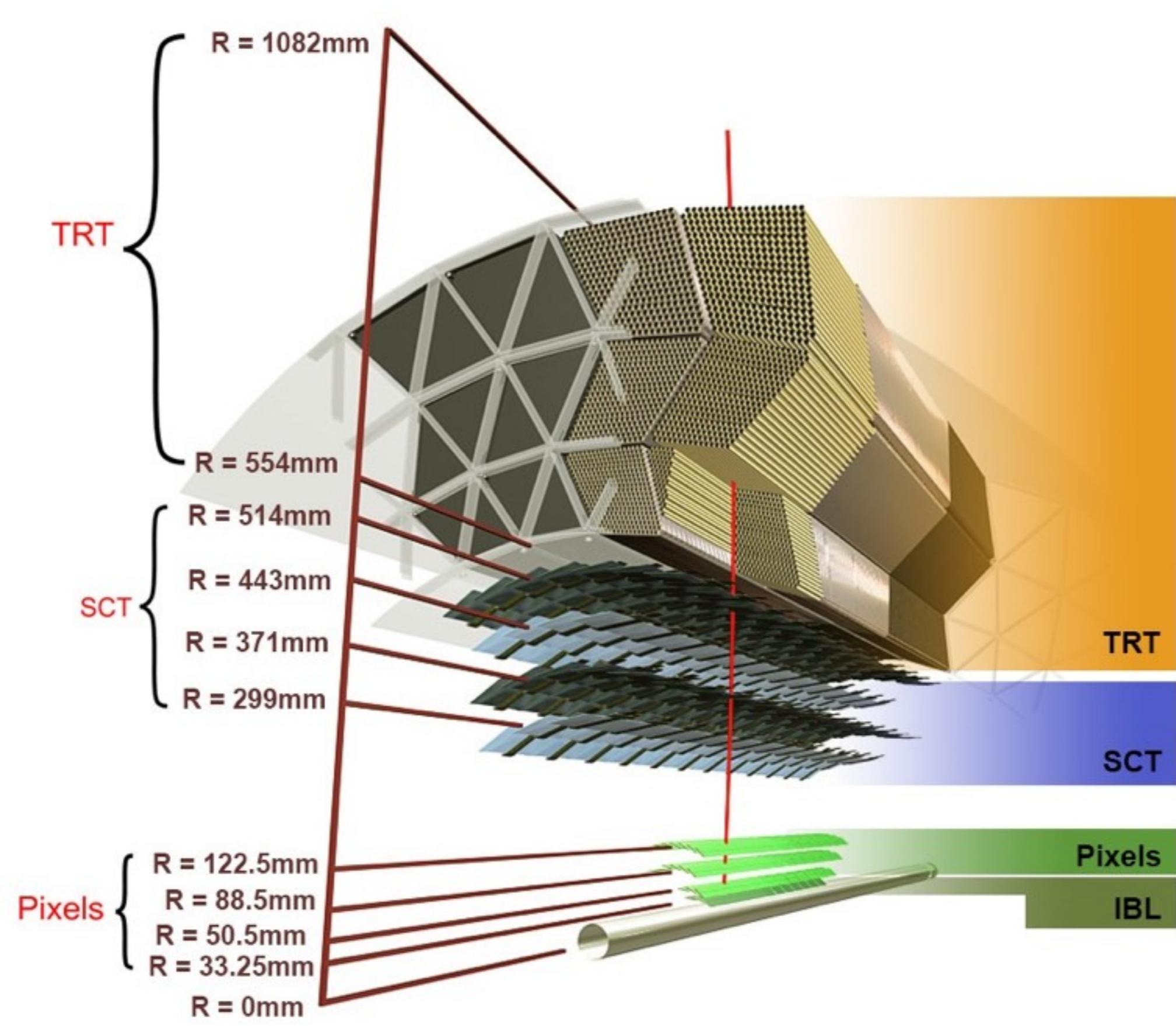


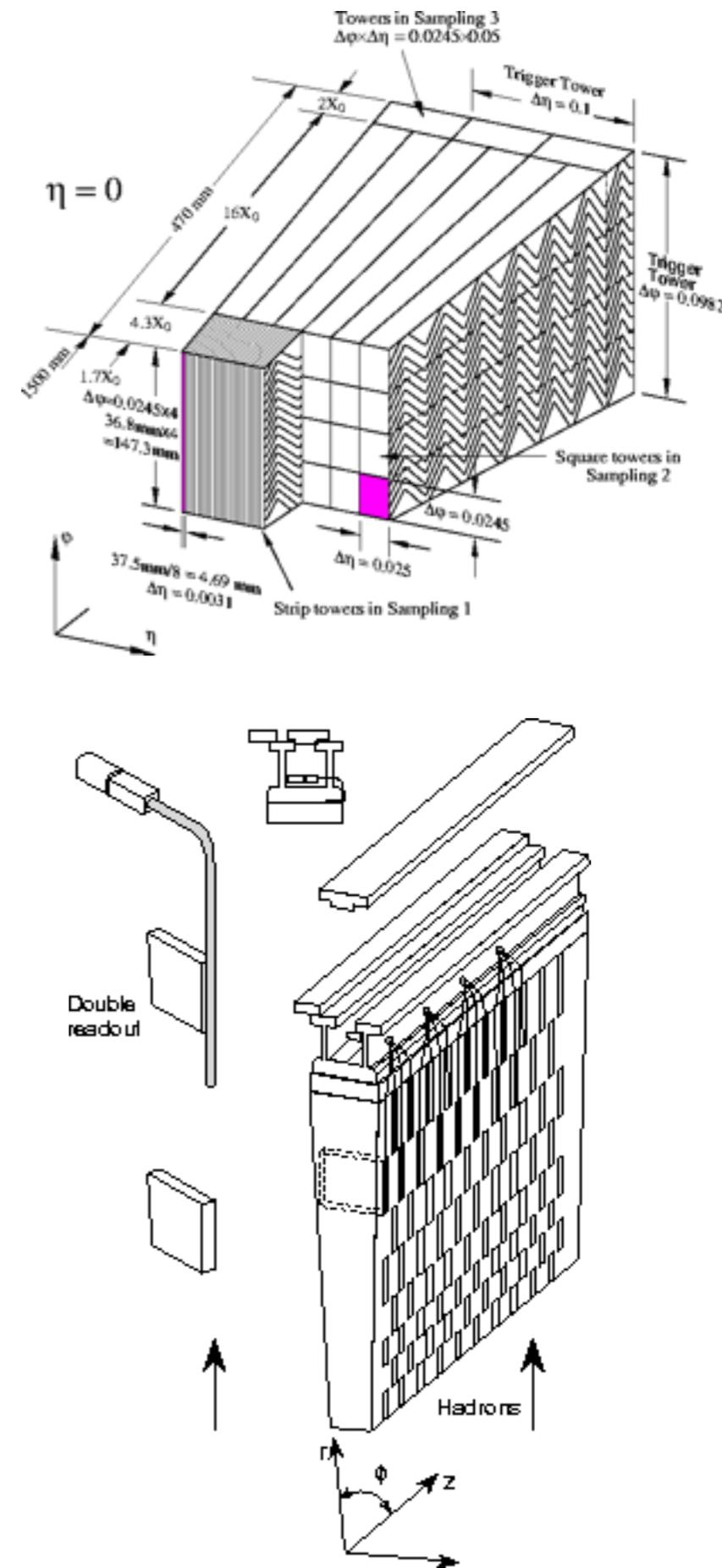
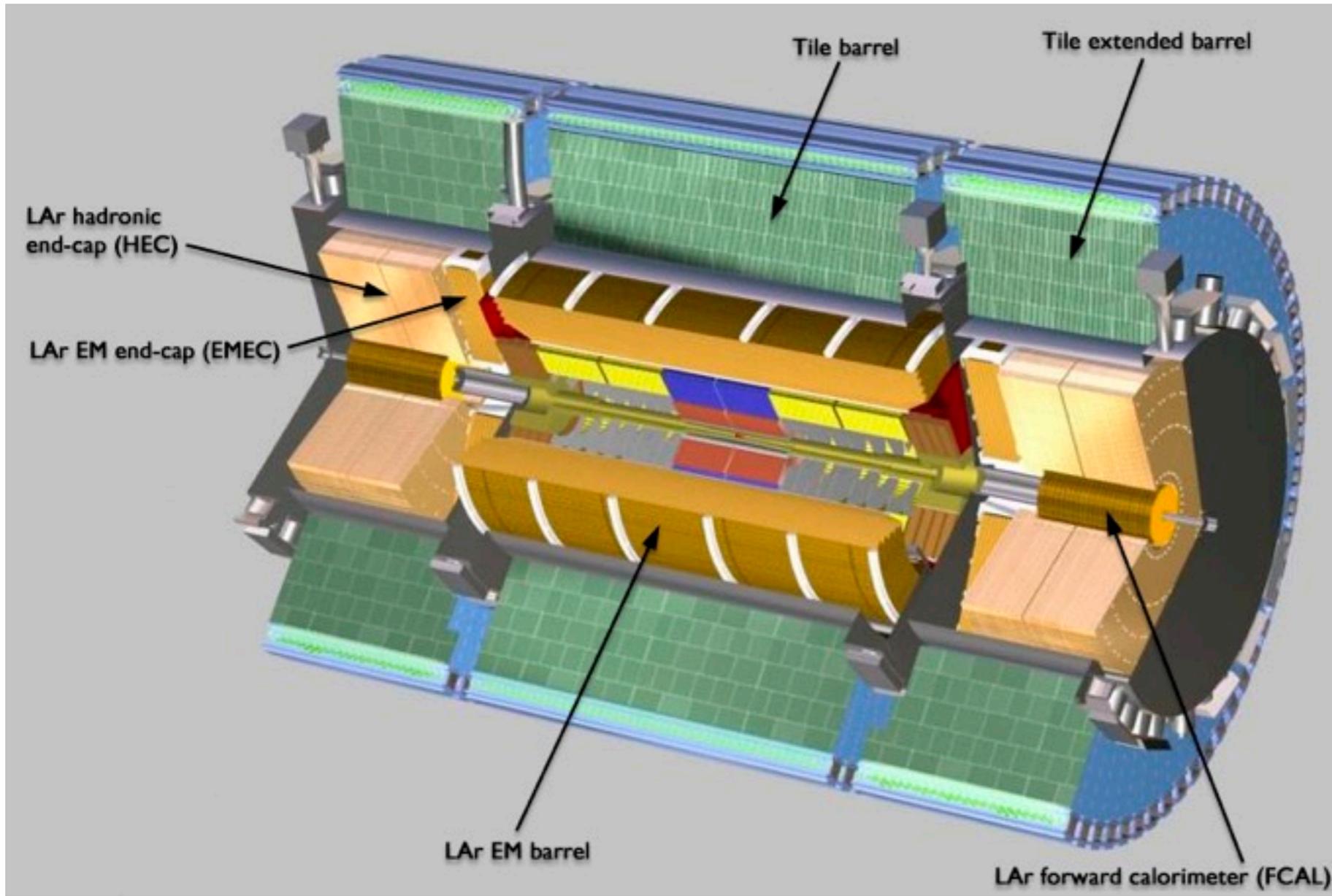
Alice

CMS









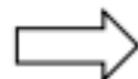
[6.5] ハドロン・シャワー

- 電子、光子などは電磁シャワーを、ハドロン(バリオン、メソン)はハドロン・シャワーを形成

λ は原子核相互作用長 (nuclear interaction length) とも呼ぶ

- 強い相互作用により、**多重粒子**生成
- 放射長(X_0)の代わりに、**吸収長(λ)**を用いる一般的に

$$\lambda \gg X_0$$



物質	X_0 (gcm ⁻²)	λ (gcm ⁻²)	密度 (gcm ⁻³)	X_0 (cm)	λ (cm)
ヘリウム	94.3	65.1	0.125	754.4	520.8
カーボン	42.7	86.3	2.27	18.8	38.0
アルミニウム	24.0	106.4	2.70	8.9	39.4
鉄	13.8	131.9	7.87	1.75	16.8
鉛	6.4	194	11.4	0.56	17.0

放射長、吸収長、密度

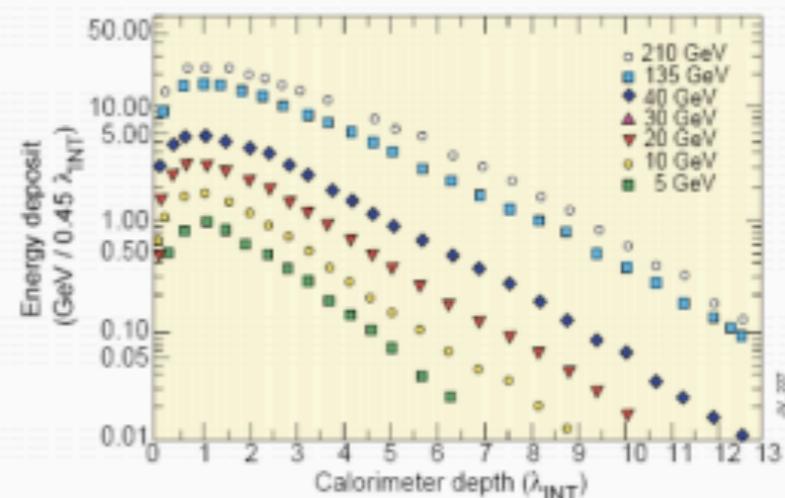
- 電磁シャワー長 \ll ハドロンシャワー長
(通常、電磁カロリメータが内側にあり、ハドロンカロリメータが外側にある理由) **選べ(議論1min)**

- 表から、電磁に**鉛**、ハドロンに**鉄**の組み合わせが標準

- 全エネルギーを評価するためには、シャワー全体を覆う必要がある。およそ**10 λ** の深さがないと、エネルギーを逃してしまう

ハドロンシャワー長 NIM A263 (1988)102

WA78 : 5.4 λ of 10mm U / 5mm Scint + 8 λ of 25mm Fe / 5mm Scint



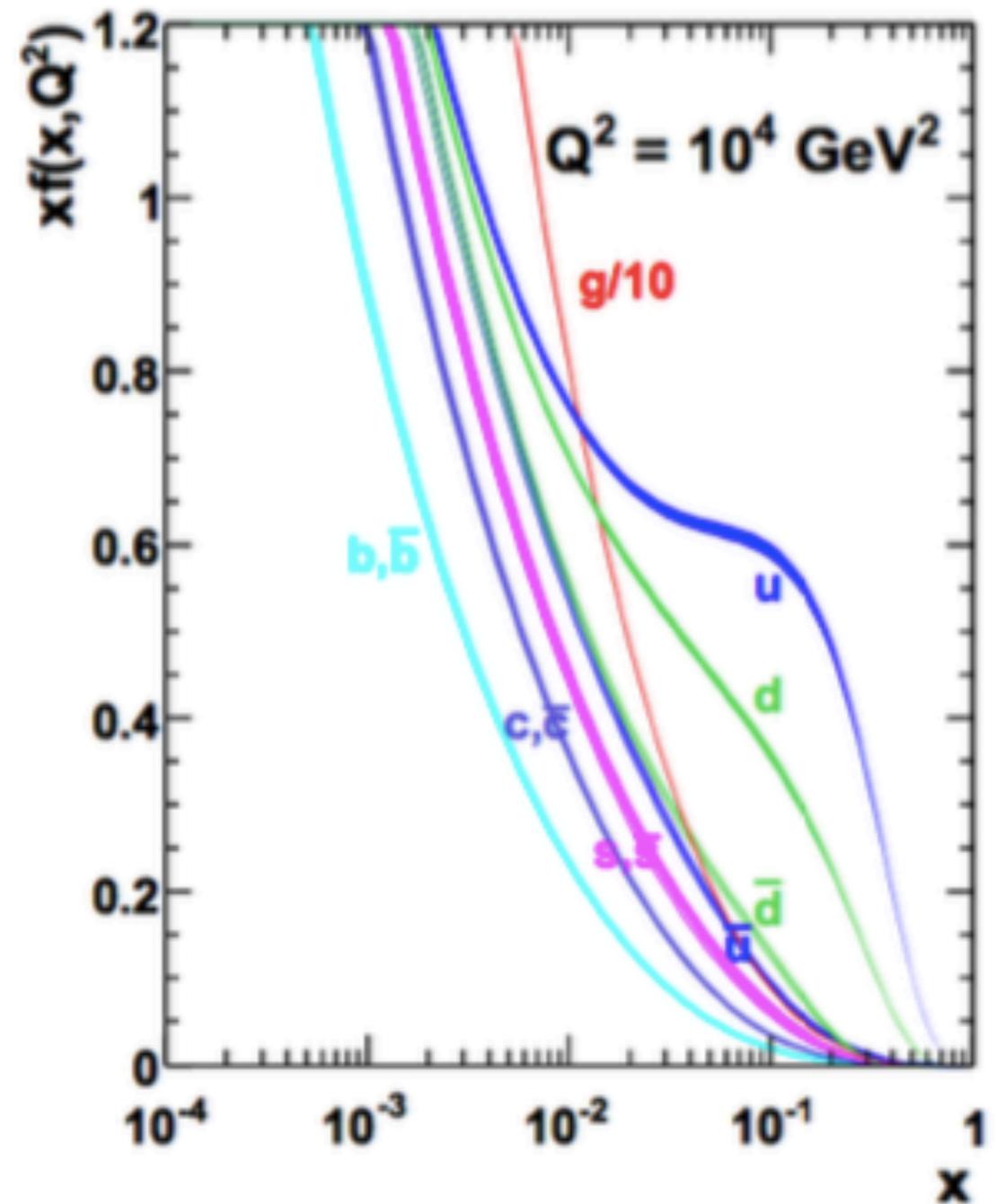
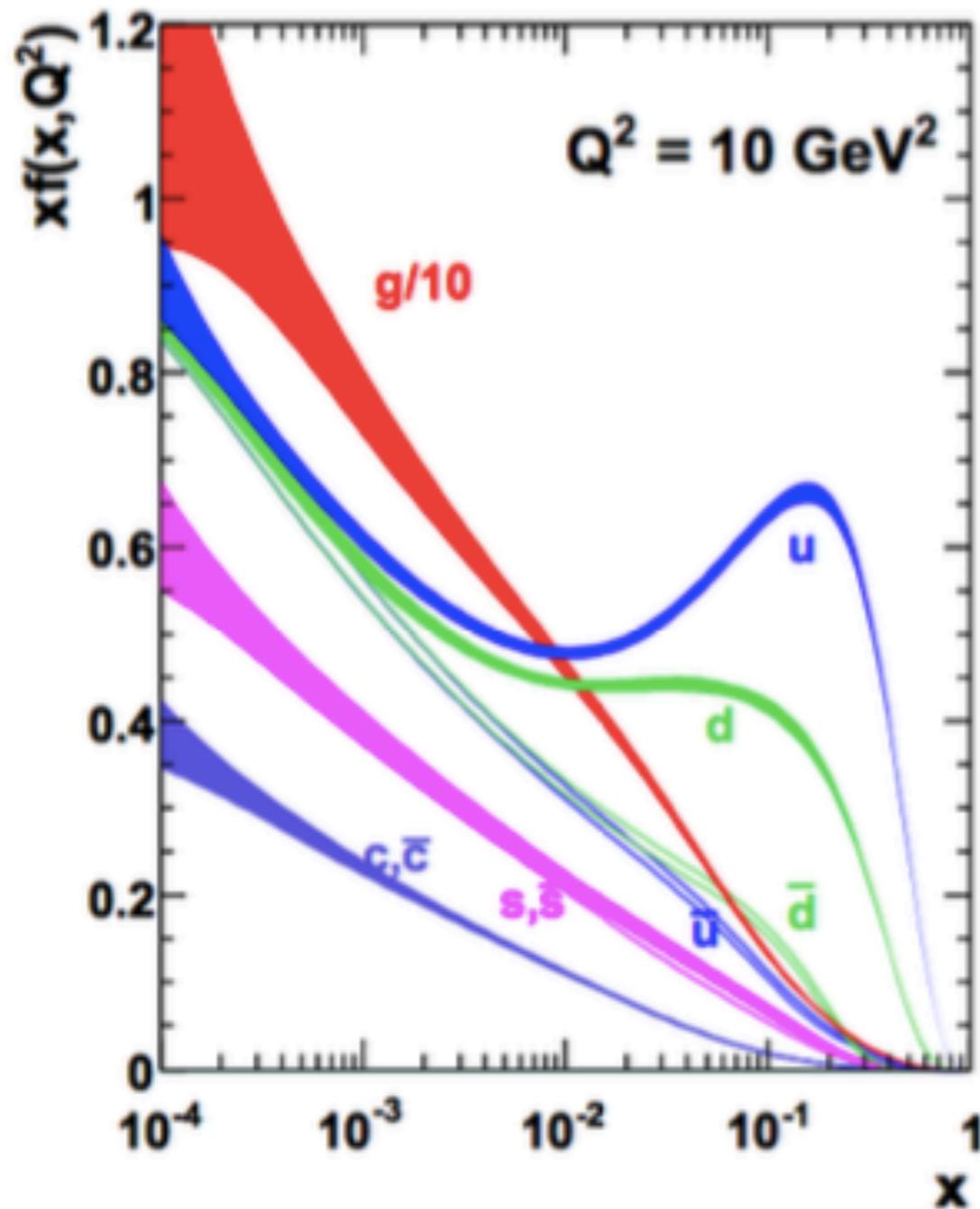
データの話

- データ ... 各検出器のヒット情報の集合
 - ▶ 生データ ... 毎秒500 MB → 年間100 PB
- シミュレーション
 - ▶ 信号事象用、バックグラウンド用、...
- 世界中の研究者がいつでもどこからでもアクセスできる
 - ▶ 世界各地のデータセンターに分散して保存
 - ▶ ユーザーはどこに何が保存されているか気にせずアクセスできるクラウドコンピューティング / グリッドコンピューティング



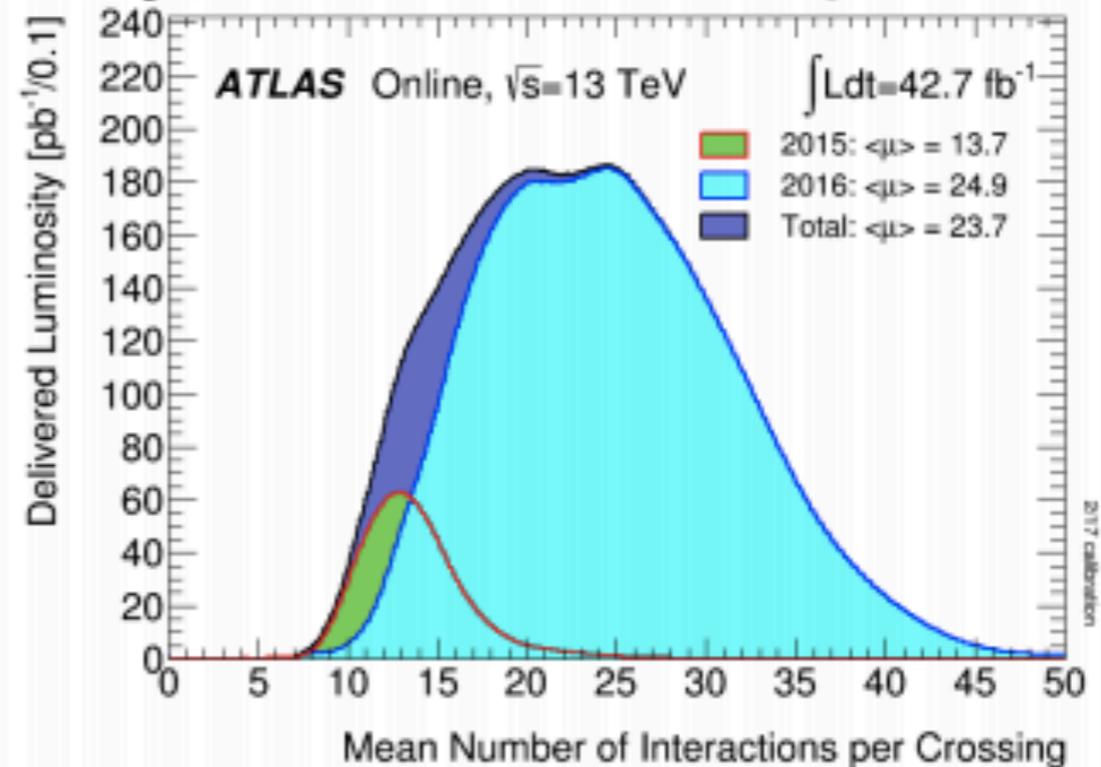
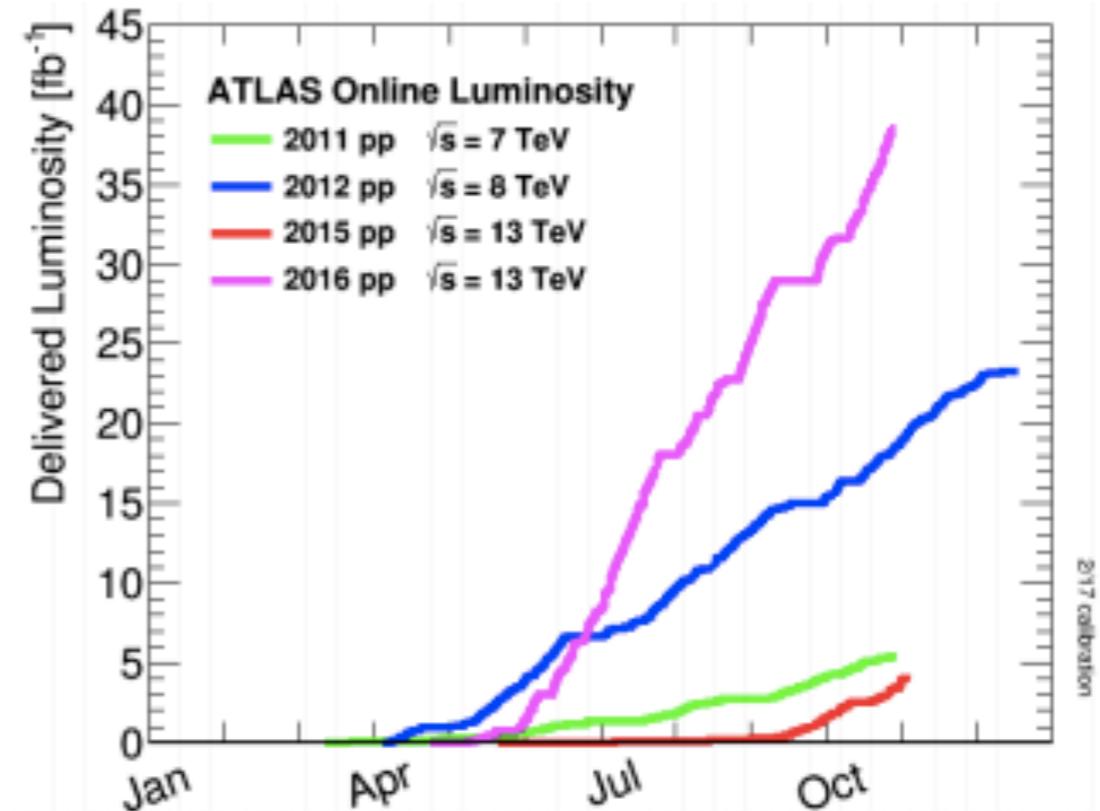
Parton distribution func.

MSTW 2008 NLO PDFs (68% C.L.)



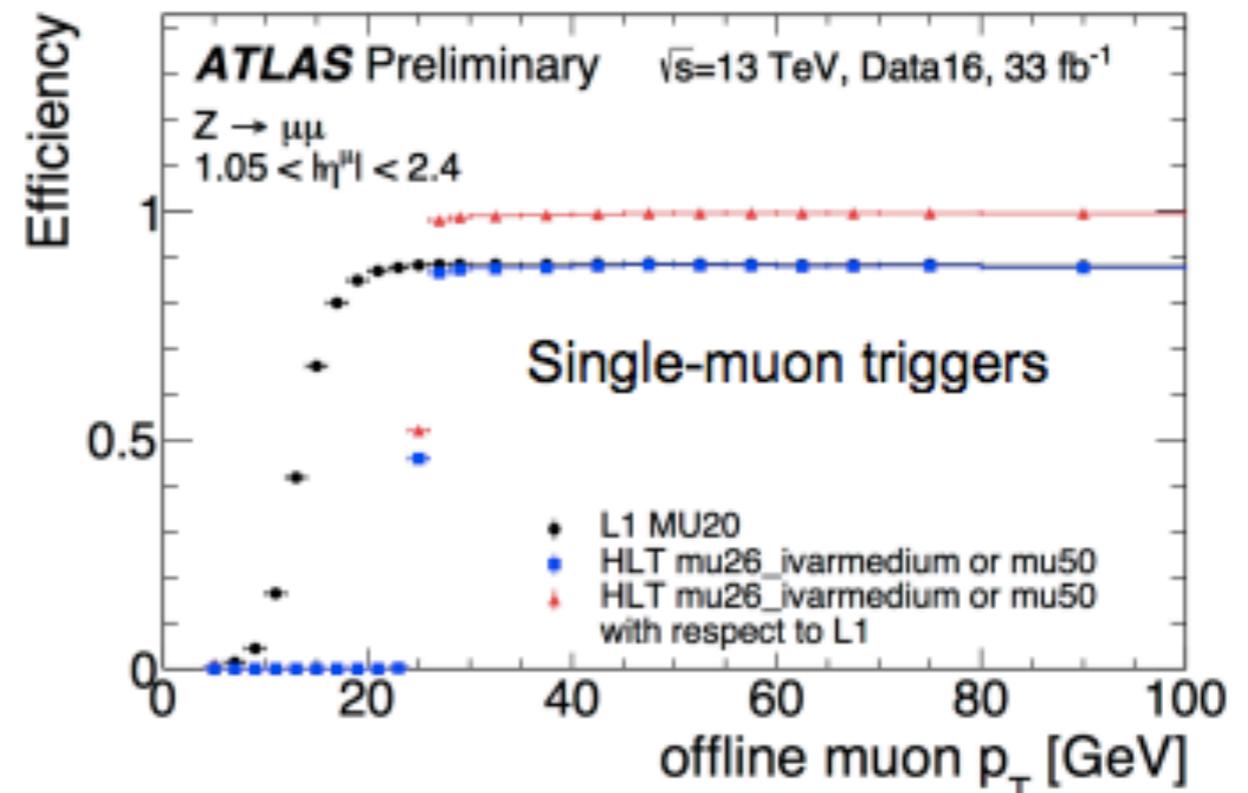
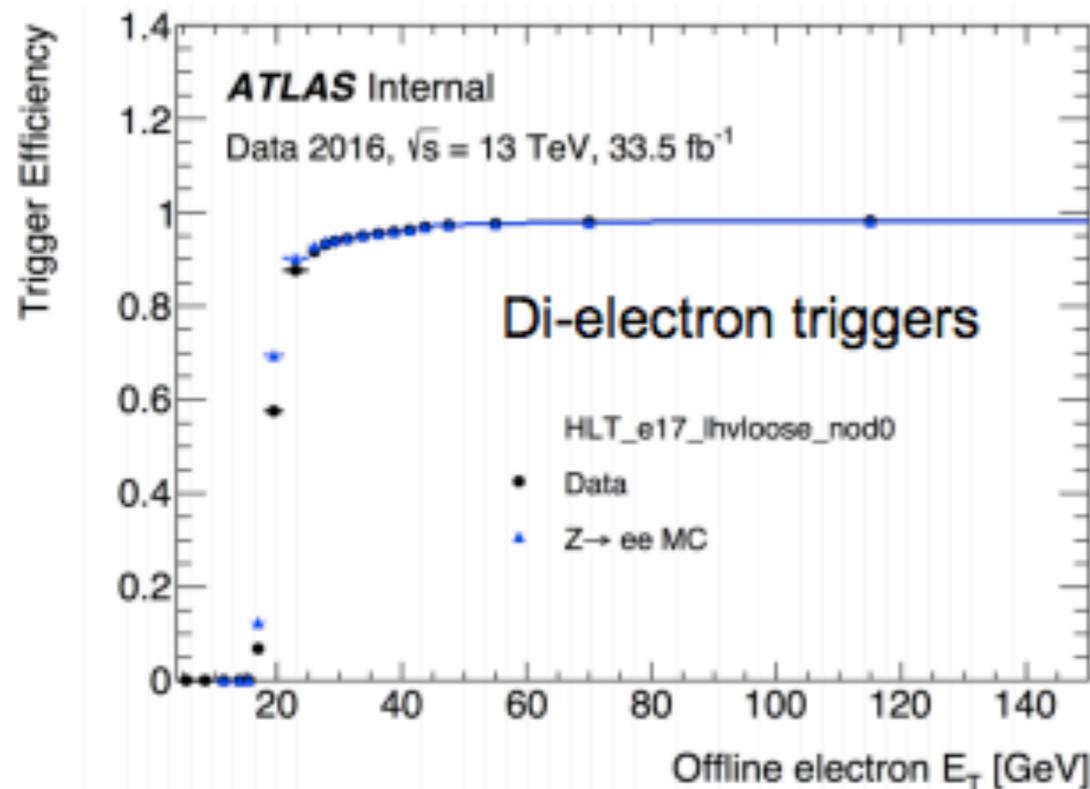
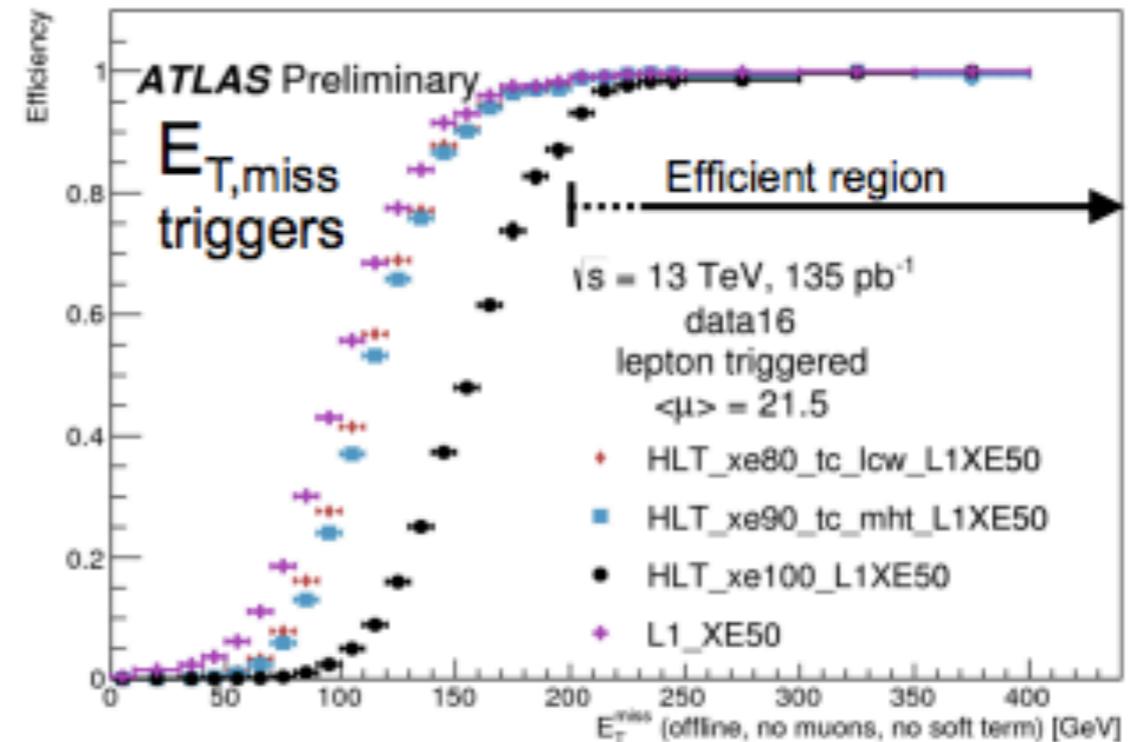
Data-taking 2015/2016

- Record performance of the LHC in 2016:
 - **1680 hours** of **13 TeV** stable beams data-taking in 2016!
 - Peak instantaneous luminosity of **$1.38 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$**
 - Pile-up of up to **50** interactions per crossing
- Excellent Run-2 data-taking campaign for ATLAS:
 - **$3.9 \text{ fb}^{-1} + 35.6 \text{ fb}^{-1}$** recorded in 2015 + 2016
 - In total **36.1 fb^{-1}** (i.e. 91.4%) *good* for **SUSY searches!**

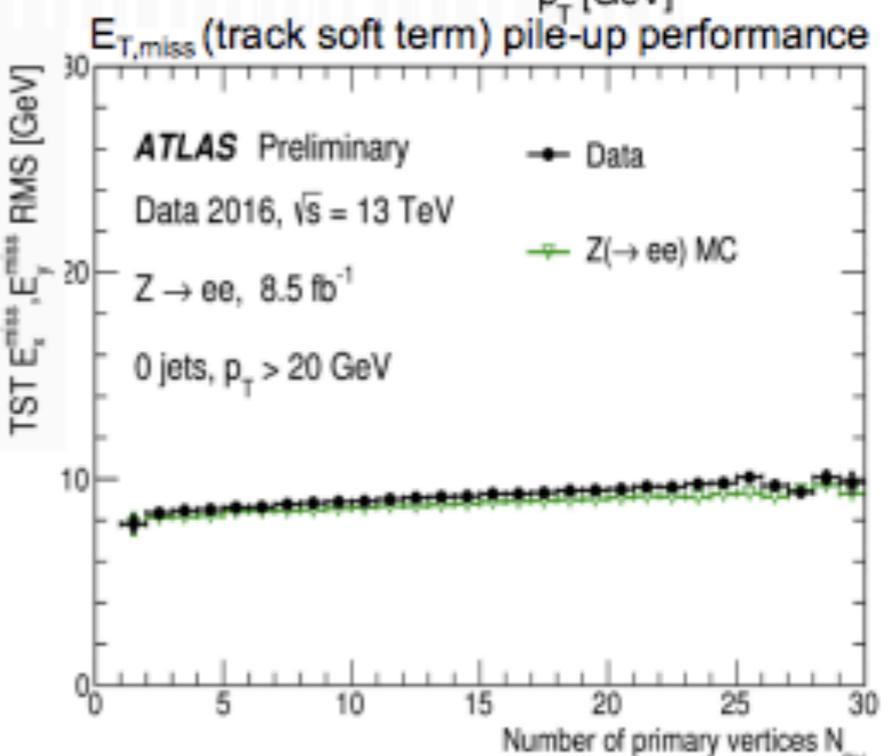
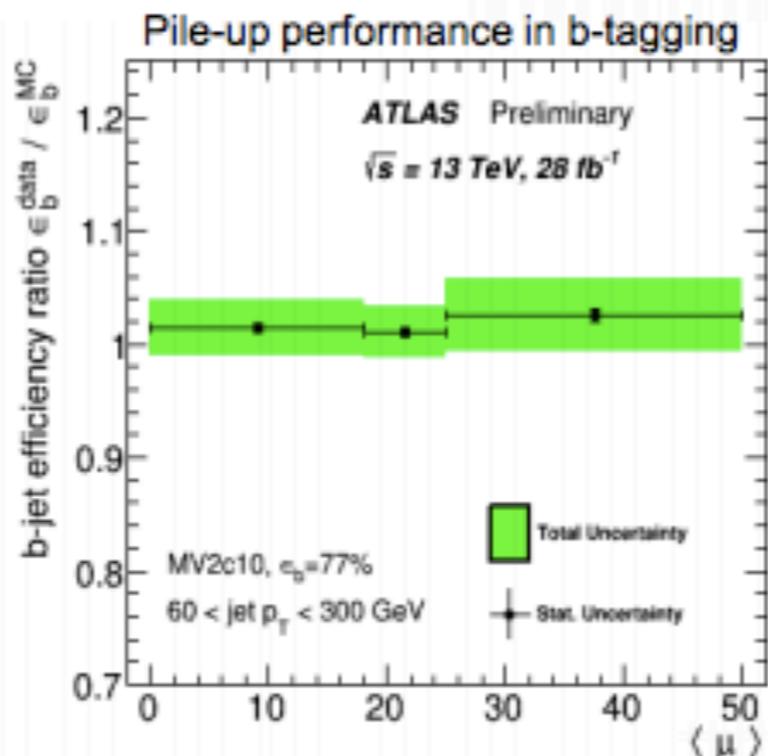
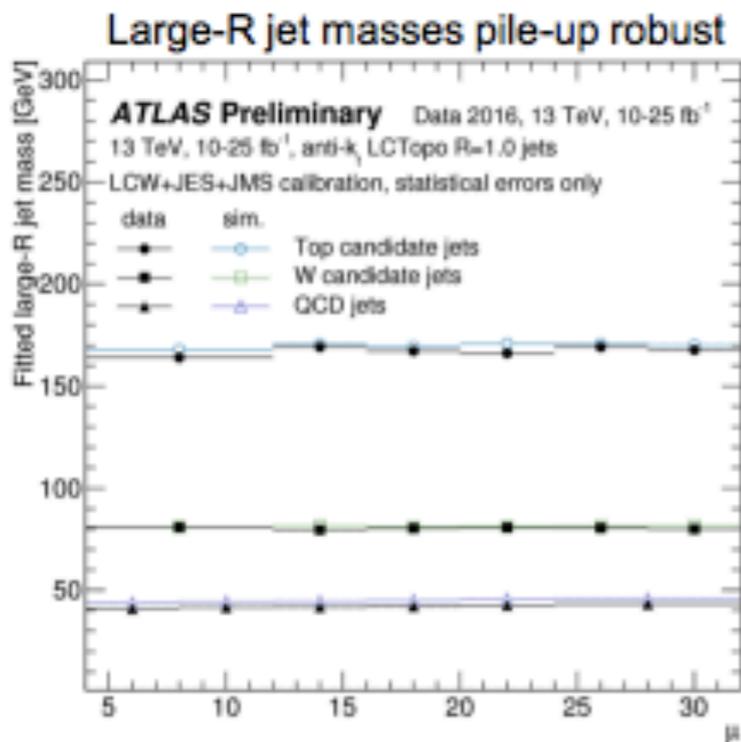
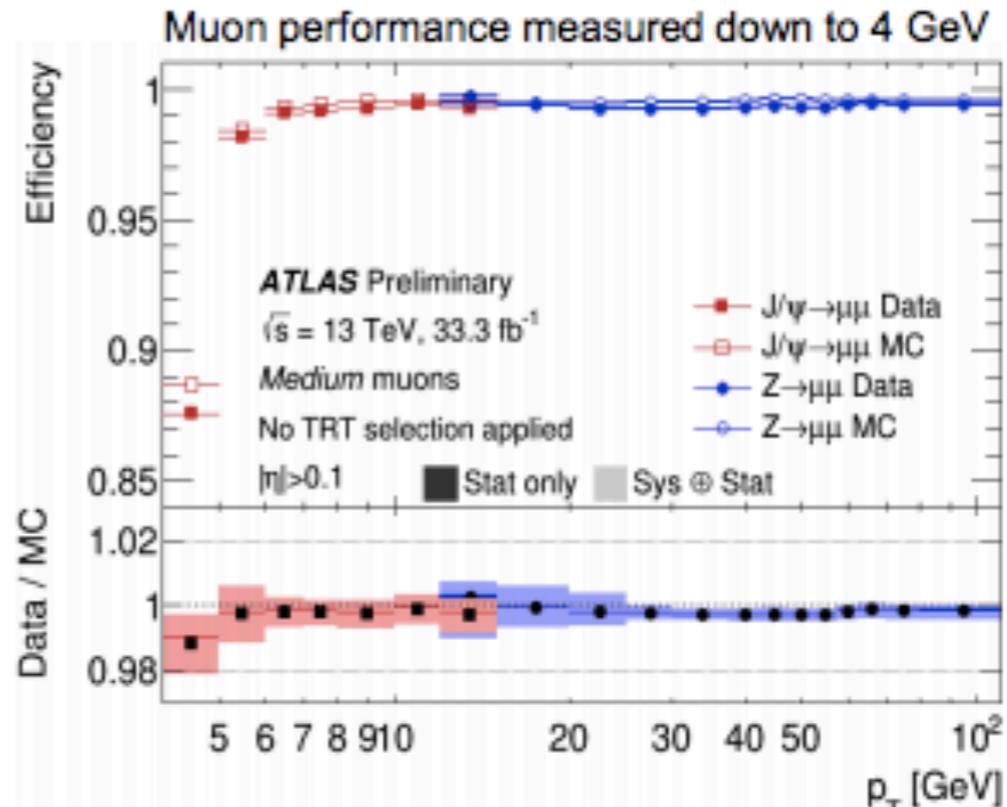
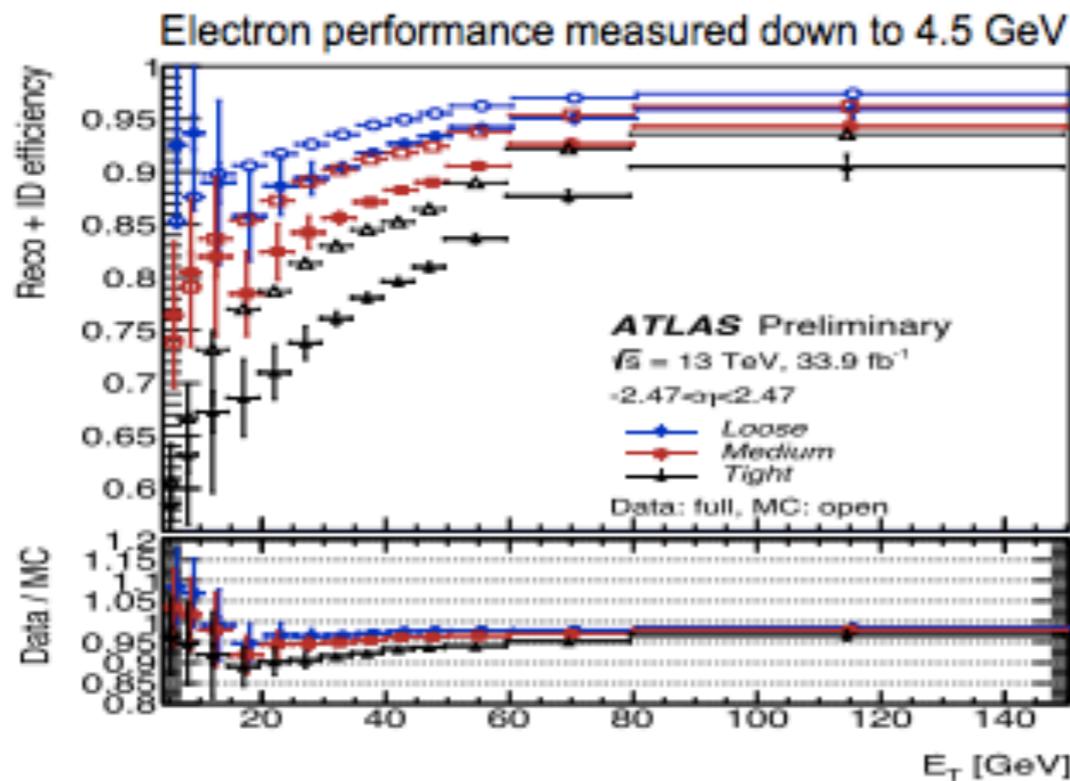


Trigger Performance Highlights

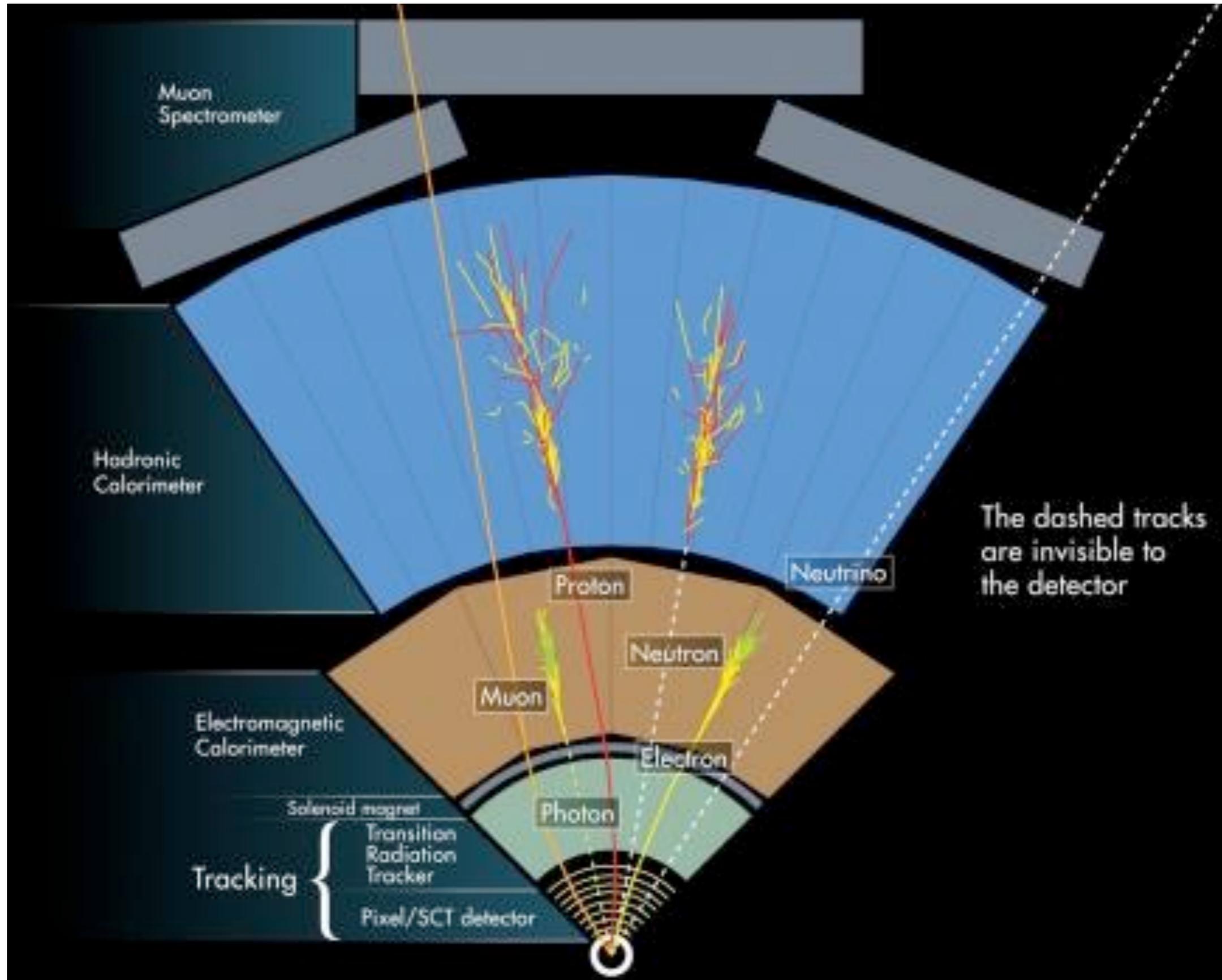
- **ATLAS trigger and DAQ** systems form the basis for a successful data-taking
- Major **challenge** in 2016: **Maintain trigger performance** in fierce luminosity & pile-up conditions
- Main physics triggers for SUSY searches: **Generic $E_{T,miss}$, jet, lepton triggers**



Detector Performance Highlights



粒子の再構成



ATLAS SUSY Searches* - 95% CL Lower Limits

May 2017

ATLAS Preliminary

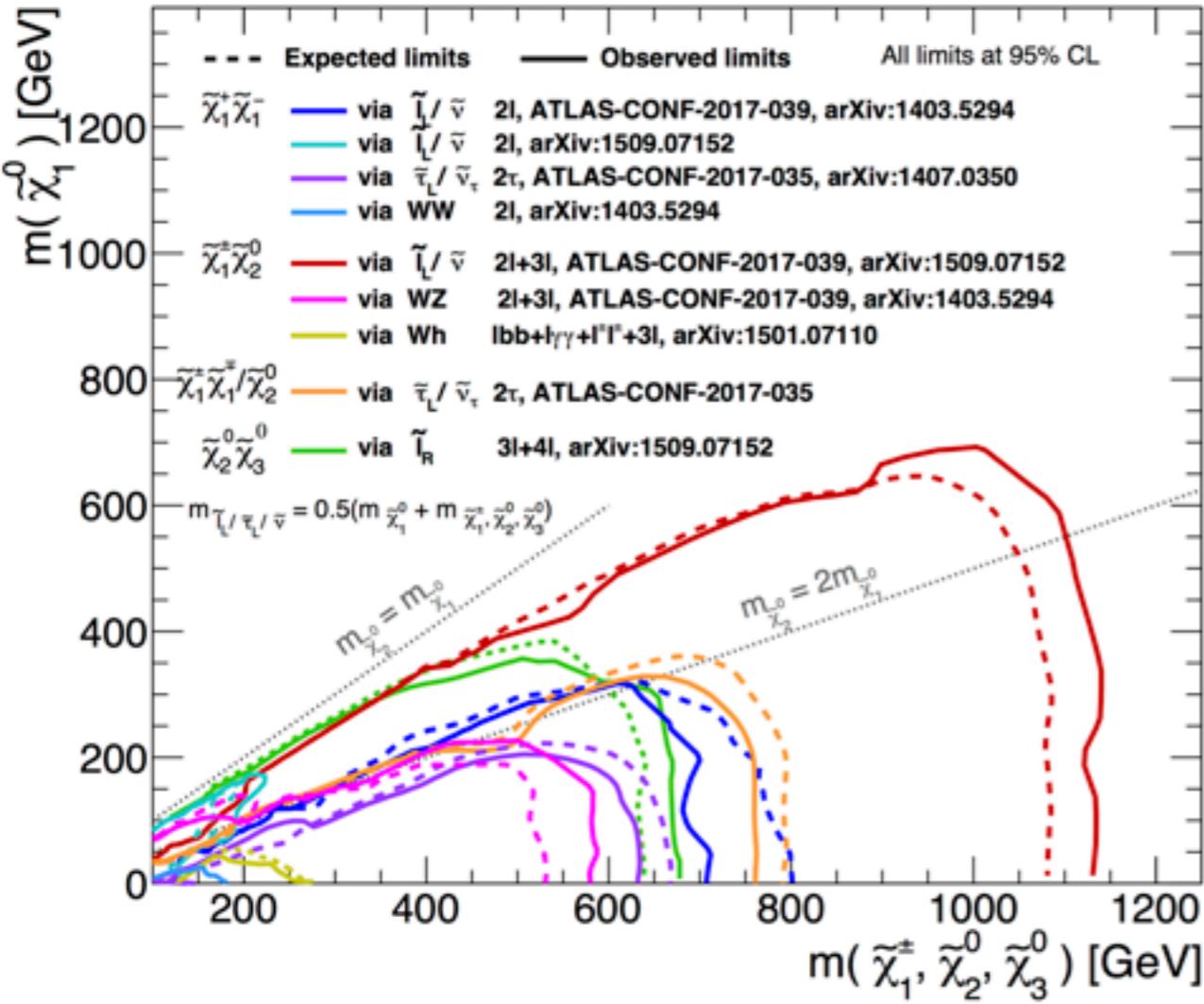
$\sqrt{s} = 7, 8, 13$ TeV

Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L} d\mathcal{L} [\text{fb}^{-1}]$	Mass limit	$\sqrt{s} = 7, 8$ TeV	$\sqrt{s} = 13$ TeV	Reference	
Inclusive Searches	MSUGRA/CMSSM	0-3 $e, \mu/1-2 \tau$	2-10 jets/3 b	Yes	20.3	\tilde{g}, \tilde{g}	1.85 TeV	$m(\tilde{g})=m(\tilde{g})$	1507.05525
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	\tilde{q}	1.57 TeV	$m(\tilde{q}) < 200 \text{ GeV}, m(1^{\text{st}} \text{ gen. } \tilde{q})=m(2^{\text{nd}} \text{ gen. } \tilde{q})$	ATLAS-CONF-2017-022
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	3.2	\tilde{q}	608 GeV	$m(\tilde{q})-m(\tilde{\chi}_1^0) < 5 \text{ GeV}$	1604.07773
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	\tilde{g}	2.02 TeV	$m(\tilde{g}) < 200 \text{ GeV}$	ATLAS-CONF-2017-022
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0 \rightarrow q\tilde{q}W^{\pm}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	\tilde{g}	2.01 TeV	$m(\tilde{g}) < 200 \text{ GeV}, m(\tilde{g}^*)=0.5(m(\tilde{g})+m(\tilde{g}))$	ATLAS-CONF-2017-022
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell\ell/\nu\nu)\tilde{\chi}_1^0$	3 e, μ	4 jets	-	36.1	\tilde{g}	1.825 TeV	$m(\tilde{g}) < 400 \text{ GeV}$	ATLAS-CONF-2017-030
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}WZ\tilde{\chi}_1^0$	0	7-11 jets	Yes	36.1	\tilde{g}	1.8 TeV	$m(\tilde{g}) < 400 \text{ GeV}$	ATLAS-CONF-2017-033
	GMSB ($\tilde{\ell}$ NLSP)	1-2 $\tau + 0-1 \ell$	0-2 jets	Yes	3.2	\tilde{g}	2.0 TeV	$m(\tilde{g}) < 400 \text{ GeV}$	1607.05979
	GGM (bino NLSP)	2 γ	-	Yes	3.2	\tilde{g}	1.65 TeV	$c\tau(\text{NLSP}) < 0.1 \text{ mm}$	1606.09150
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	\tilde{g}	1.37 TeV	$m(\tilde{g}) < 950 \text{ GeV}, c\tau(\text{NLSP}) < 0.1 \text{ mm}, \mu < 0$	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	13.3	\tilde{g}	1.8 TeV	$m(\tilde{g}) > 680 \text{ GeV}, c\tau(\text{NLSP}) < 0.1 \text{ mm}, \mu > 0$	ATLAS-CONF-2016-066
GGM (higgsino NLSP)	2 e, μ (Z)	2 jets	Yes	20.3	\tilde{g}	900 GeV	$m(\text{NLSP}) > 430 \text{ GeV}$	1503.03290	
Gravitino LSP	0	mono-jet	Yes	20.3	$\tilde{g}^{1/2}$ scale	865 GeV	$m(\tilde{g}) > 1.8 \times 10^{-4} \text{ eV}, m(\tilde{g})=m(\tilde{g})=1.5 \text{ TeV}$	1502.01518	
3 rd gen. \tilde{g} med.	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow b\tilde{b}\tilde{\chi}_1^0$	0	3 b	Yes	36.1	\tilde{g}	1.92 TeV	$m(\tilde{g}) < 600 \text{ GeV}$	ATLAS-CONF-2017-021
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	36.1	\tilde{g}	1.97 TeV	$m(\tilde{g}) < 200 \text{ GeV}$	ATLAS-CONF-2017-021
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow b\tilde{b}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	20.1	\tilde{g}	1.37 TeV	$m(\tilde{g}) < 300 \text{ GeV}$	1407.0600
3 rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$	0	2 b	Yes	36.1	\tilde{b}_1	950 GeV	$m(\tilde{b}_1) < 420 \text{ GeV}$	ATLAS-CONF-2017-038
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow t\tilde{\chi}_1^0$	2 e, μ (SS)	1 b	Yes	36.1	\tilde{b}_1	275-700 GeV	$m(\tilde{b}_1) < 200 \text{ GeV}, m(\tilde{b}_1^*) = m(\tilde{b}_1) + 100 \text{ GeV}$	ATLAS-CONF-2017-030
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{\chi}_1^0$	0-2 e, μ	1-2 b	Yes	4.7/13.3	\tilde{t}_1	117-170 GeV	$m(\tilde{t}_1) = 2m(\tilde{b}_1), m(\tilde{t}_1) = 55 \text{ GeV}$	1209.2102, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e, μ	0-2 jets/1-2 b	Yes	20.3/36.1	\tilde{t}_1	90-198 GeV	$m(\tilde{t}_1) = 1 \text{ GeV}$	1505.06616, ATLAS-CONF-2017-020
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$	0	mono-jet	Yes	3.2	\tilde{t}_1	90-323 GeV	$m(\tilde{t}_1)-m(\tilde{\chi}_1^0) = 5 \text{ GeV}$	1604.07773
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e, μ (Z)	1 b	Yes	20.3	\tilde{t}_1	150-600 GeV	$m(\tilde{t}_1) > 150 \text{ GeV}$	1403.5222
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	3 e, μ (Z)	1 b	Yes	36.1	\tilde{t}_2	290-790 GeV	$m(\tilde{t}_2) = 0 \text{ GeV}$	ATLAS-CONF-2017-019
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$	1-2 e, μ	4 b	Yes	36.1	\tilde{t}_2	320-880 GeV	$m(\tilde{t}_2) = 0 \text{ GeV}$	ATLAS-CONF-2017-019
EW direct	$\tilde{\chi}_{1,2}^{\pm}\tilde{\chi}_{1,2}^{\pm}, \tilde{\chi} \rightarrow \ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	36.1	$\tilde{\chi}$	90-440 GeV	$m(\tilde{\chi}_1^0) = 0$	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0 \rightarrow \tilde{\chi}_1^0(\ell\nu)$	2 e, μ	0	Yes	36.1	$\tilde{\chi}_1^{\pm}$	710 GeV	$m(\tilde{\chi}_1^0) = 0, m(\tilde{\chi}_1^{\pm}) = 0.5(m(\tilde{\chi}_1^0) + m(\tilde{\chi}_1^{\pm}))$	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0, \tilde{\chi}_1^0 \rightarrow \tilde{\chi}_1^0(\tau\nu), \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0(\nu\nu)$	2 τ	-	Yes	36.1	$\tilde{\chi}_1^{\pm}$	760 GeV	$m(\tilde{\chi}_1^0) = 0, m(\tilde{\chi}_1^{\pm}) = 0.5(m(\tilde{\chi}_1^0) + m(\tilde{\chi}_1^{\pm}))$	ATLAS-CONF-2017-035
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0\nu\tilde{\chi}_1^0(\ell\nu), \ell\nu\tilde{\chi}_1^0(\ell\nu)$	3 e, μ	0	Yes	36.1	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$	1.16 TeV	$m(\tilde{\chi}_1^0) = m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0) = 0, m(\tilde{\chi}_1^{\pm}) = 0.5(m(\tilde{\chi}_1^0) + m(\tilde{\chi}_1^{\pm}))$	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \rightarrow W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 e, μ	0-2 jets	Yes	36.1	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$	580 GeV	$m(\tilde{\chi}_1^0) = m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0) = 0, \tilde{\chi}$ decoupled	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \rightarrow W\tilde{\chi}_1^0 h\tilde{\chi}_1^0, h \rightarrow b\tilde{b}/WW/\tau\tau/\gamma\gamma$	e, μ, γ	0-2 b	Yes	20.3	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$	270 GeV	$m(\tilde{\chi}_1^0) = m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0) = 0, \tilde{\chi}$ decoupled	1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0, \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0\ell$	4 e, μ	0	Yes	20.3	$\tilde{\chi}_2^0$	635 GeV	$m(\tilde{\chi}_2^0) = m(\tilde{\chi}_3^0), m(\tilde{\chi}_1^0) = 0, m(\tilde{\chi}_1^{\pm}) = 0.5(m(\tilde{\chi}_2^0) + m(\tilde{\chi}_1^{\pm}))$	1405.5086
	GGM (wino NLSP) weak prod., $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$	1 $e, \mu + \gamma$	-	Yes	20.3	\tilde{W}	115-370 GeV	$c\tau < 1 \text{ mm}$	1507.05493
	GGM (bino NLSP) weak prod., $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$	2 γ	-	Yes	20.3	\tilde{W}	590 GeV	$c\tau < 1 \text{ mm}$	1507.05493
	Long-lived particles	Direct $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\pm}$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}_1^{\pm}$	430 GeV	$m(\tilde{\chi}_1^{\pm}) - m(\tilde{\chi}_1^0) \sim 160 \text{ MeV}, \tau(\tilde{\chi}_1^{\pm}) = 0.2 \text{ ns}$
Direct $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\pm}$ prod., long-lived $\tilde{\chi}_1^{\pm}$		dE/dx trk	-	Yes	18.4	$\tilde{\chi}_1^{\pm}$	495 GeV	$m(\tilde{\chi}_1^{\pm}) - m(\tilde{\chi}_1^0) \sim 160 \text{ MeV}, \tau(\tilde{\chi}_1^{\pm}) < 15 \text{ ns}$	1506.05332
Stable, stopped \tilde{g} R-hadron		0	1-5 jets	Yes	27.9	\tilde{g}	850 GeV	$m(\tilde{g}) = 100 \text{ GeV}, 10 \mu\text{s} < c\tau(\tilde{g}) < 1000 \text{ s}$	1310.6584
Stable \tilde{g} R-hadron		trk	-	-	3.2	\tilde{g}	1.58 TeV	-	1606.05129
Metastable \tilde{g} R-hadron		dE/dx trk	-	-	3.2	\tilde{g}	1.57 TeV	$m(\tilde{g}) = 100 \text{ GeV}, \tau > 10 \text{ ns}$	1604.04520
GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0 \rightarrow \tilde{\tau}(\tilde{\mu}) + \tau(e, \mu)$		1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$	537 GeV	$10 < \tan\beta < 50$	1411.6795
GMSB, $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$		2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$	440 GeV	$1 < \tau(\tilde{\chi}_1^0) < 3 \text{ ns}, \text{SPS8 model}$	1409.5542
$\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \rightarrow ee\nu/e\mu\nu/\mu\mu\nu$		displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{\chi}_1^0$	1.0 TeV	$7 < c\tau(\tilde{\chi}_1^0) < 740 \text{ mm}, m(\tilde{g}) = 1.3 \text{ TeV}$	1504.05162
GGM $\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \rightarrow Z\tilde{G}$	displ. vtx + jets	-	-	20.3	$\tilde{\chi}_1^0$	1.0 TeV	$6 < c\tau(\tilde{\chi}_1^0) < 480 \text{ mm}, m(\tilde{g}) = 1.1 \text{ TeV}$	1504.05162	
RPV	LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e\mu/\ell\tau/\mu\tau$	$e\mu, e\tau, \mu\tau$	-	-	3.2	$\tilde{\nu}_\tau$	1.9 TeV	$\lambda_{111}^2 = 0.11, \lambda_{132}/\lambda_{133}/\lambda_{233} = 0.07$	1607.08079
	Bilinear RPV CMSSM	2 e, μ (SS)	0-3 b	Yes	20.3	\tilde{g}, \tilde{g}	1.45 TeV	$m(\tilde{g}) = m(\tilde{g}), c\tau_{\text{LSP}} < 1 \text{ mm}$	1404.2500
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0 \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_2^0 \rightarrow ee\nu, e\mu\nu, \mu\mu\nu$	4 e, μ	-	Yes	13.3	$\tilde{\chi}_1^{\pm}$	1.14 TeV	$m(\tilde{\chi}_1^0) > 400 \text{ GeV}, \lambda_{12k} \neq 0 (k = 1, 2)$	ATLAS-CONF-2016-075
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0 \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_2^0 \rightarrow \tau\tau\nu_e, e\tau\nu_\tau$	3 $e, \mu + \tau$	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$	450 GeV	$m(\tilde{\chi}_1^0) > 0.2 \times m(\tilde{\chi}_1^0), \lambda_{133} \neq 0$	1405.5086
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{q}$	0	4-5 large- R jets	-	14.8	\tilde{g}	1.08 TeV	$\text{BR}(\tilde{g}) = \text{BR}(\tilde{b}) = \text{BR}(\tilde{c}) = 0\%$	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow qq\tilde{q}$	0	4-5 large- R jets	-	14.8	\tilde{g}	1.55 TeV	$m(\tilde{g}) = 800 \text{ GeV}$	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow qq\tilde{q}$	1 e, μ	8-10 jets/0-4 b	-	36.1	\tilde{g}	2.1 TeV	$m(\tilde{g}) = 1 \text{ TeV}, \lambda_{112} \neq 0$	ATLAS-CONF-2017-013
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{t}_1 t, \tilde{t}_1 \rightarrow bs$	1 e, μ	8-10 jets/0-4 b	-	36.1	\tilde{g}	1.65 TeV	$m(\tilde{g}) = 1 \text{ TeV}, \lambda_{223} \neq 0$	ATLAS-CONF-2017-013
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow bs$	0	2 jets + 2 b	-	15.4	\tilde{t}_1	410 GeV	-	ATLAS-CONF-2016-022, ATLAS-CONF-2016-084	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\ell$	2 e, μ	2 b	-	36.1	\tilde{t}_1	0.4-1.45 TeV	$\text{BR}(\tilde{t}_1 \rightarrow b\ell/\mu) > 20\%$	ATLAS-CONF-2017-036	
Other	Scalar charm, $\tilde{c} \rightarrow c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	\tilde{c}	510 GeV	$m(\tilde{c}) < 200 \text{ GeV}$	1501.01325

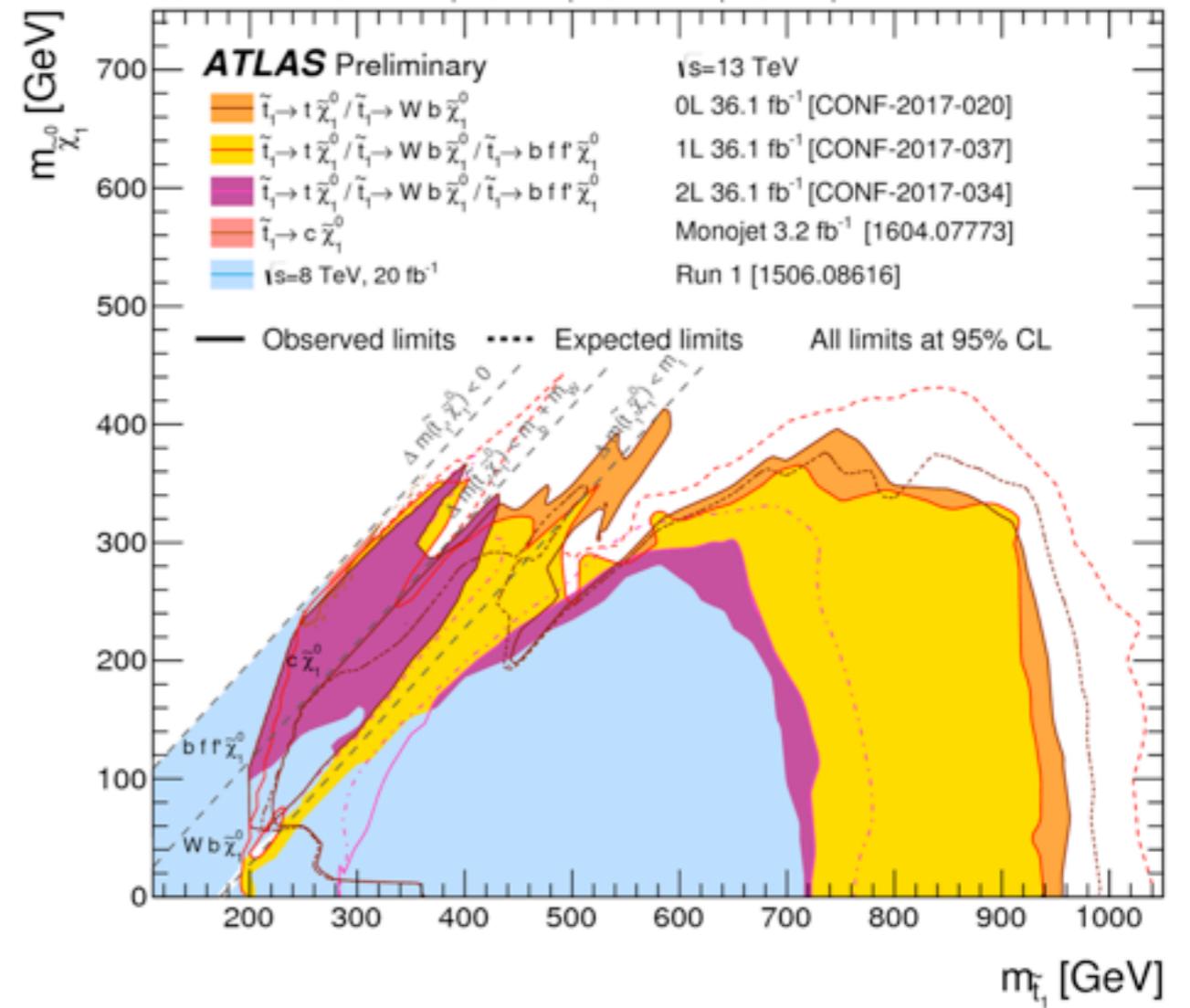
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

10⁻¹ 1 Mass scale [TeV]

May 2017 **ATLAS Preliminary** $\sqrt{s}=8,13$ TeV, 20.3-36.1 fb⁻¹



$\tilde{t}_1 \tilde{t}_1$ production, $\tilde{t}_1 \rightarrow b f \tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow c \tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$ Status: May 2017



導入と統計の話

■ 何をしたいか

- 前節では数を数えたただけだが、バックグラウンドとシグナルを分離する特徴を使えばより効率がいい
例: バックグラウンドはexponential分布, シグナルは共鳴分布

■ そのために

- 検定統計量: バックグラウンドだけの場合に比べて、データにシグナルが含まれている時に、大きく異なる値もつように作られた値
例1) 前節のイベント数 (15...bg-like, 22...signal+bg-like)
例2) BDT score (-1...bg-like, 1...signal+bg-like)
- ▶ 今回は「バックグラウンドだけ」と「シグナル+バックグラウンド」2つの仮定のprofile likelihoodの比を検定統計量として使う
($+\infty$... bg-like, $-\infty$... signal+bg-like)

$$\text{Test statistic} = X = -2 \ln(Q), \text{ with } Q = \frac{\mathcal{L}(\mu_s = 1, \hat{\theta}_{b(\mu_s=1)})}{\mathcal{L}(\mu_s = 0, \hat{\theta}_{b(\mu_s=0)})}$$

Confidence level

- あるデータセットが、「バックグラウンドのみ」と「シグナル+バックグラウンド」のどちらの仮説と一致するかを調べる
 - それぞれ仮説から得られる検定統計量分布を求めて、実験で得た検定統計量 $X_{\text{観測}}$ を得る確率を求める
- どちらの仮説と一致しているかを表す指標
Confidence level (信頼度)
 - $1-CL_b$: バックグラウンドのみで $X_{\text{観測}}$ を得る確率 (p-valueと同じ)。観測値がsignal-likeだと小さな値をもつ
 - CL_{s+b} : シグナル+バックグラウンドで $X_{\text{観測}}$ を得る確率。観測値がbg-likeだと小さな値をもつ

