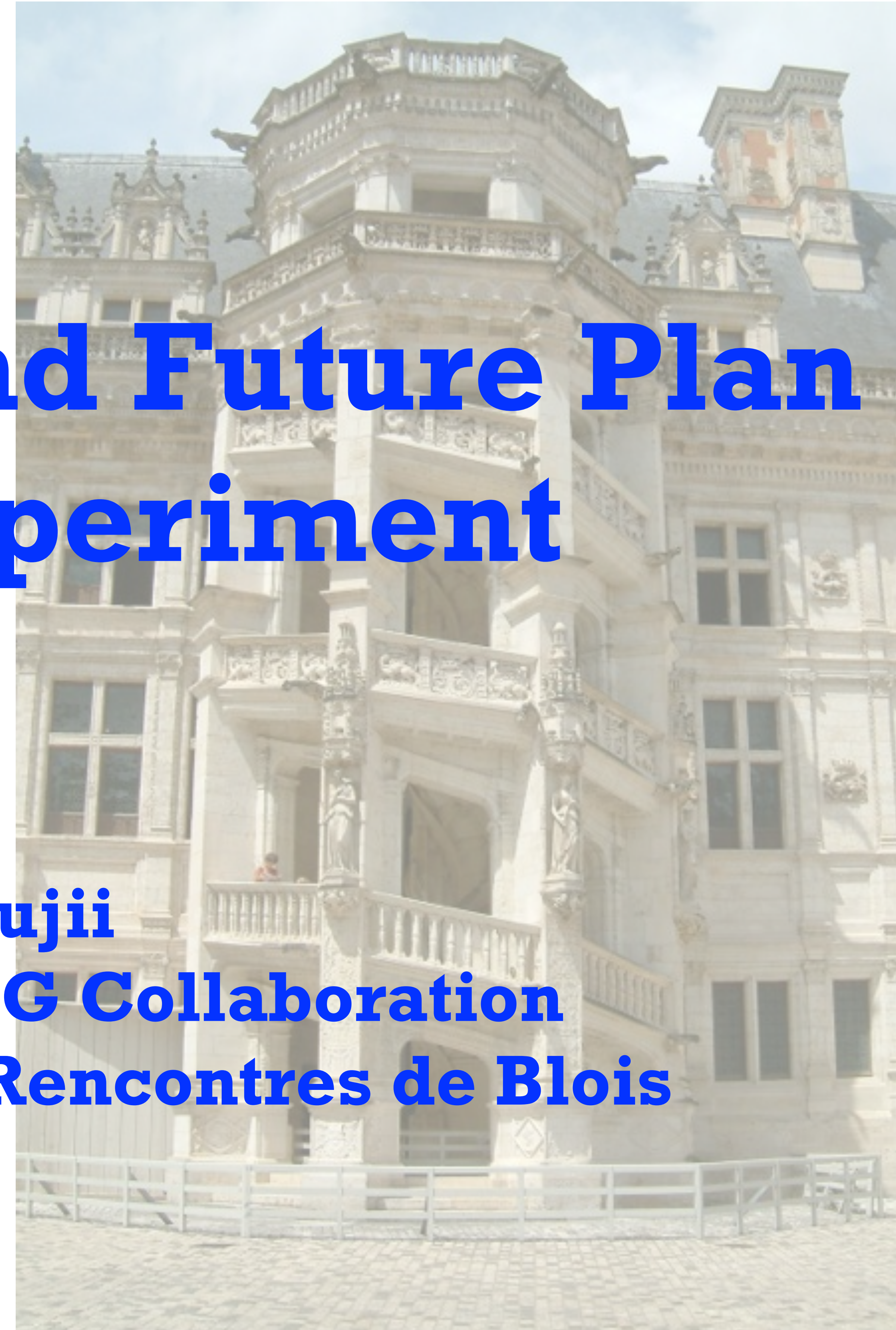


Latest Result and Future Plan of MEG Experiment

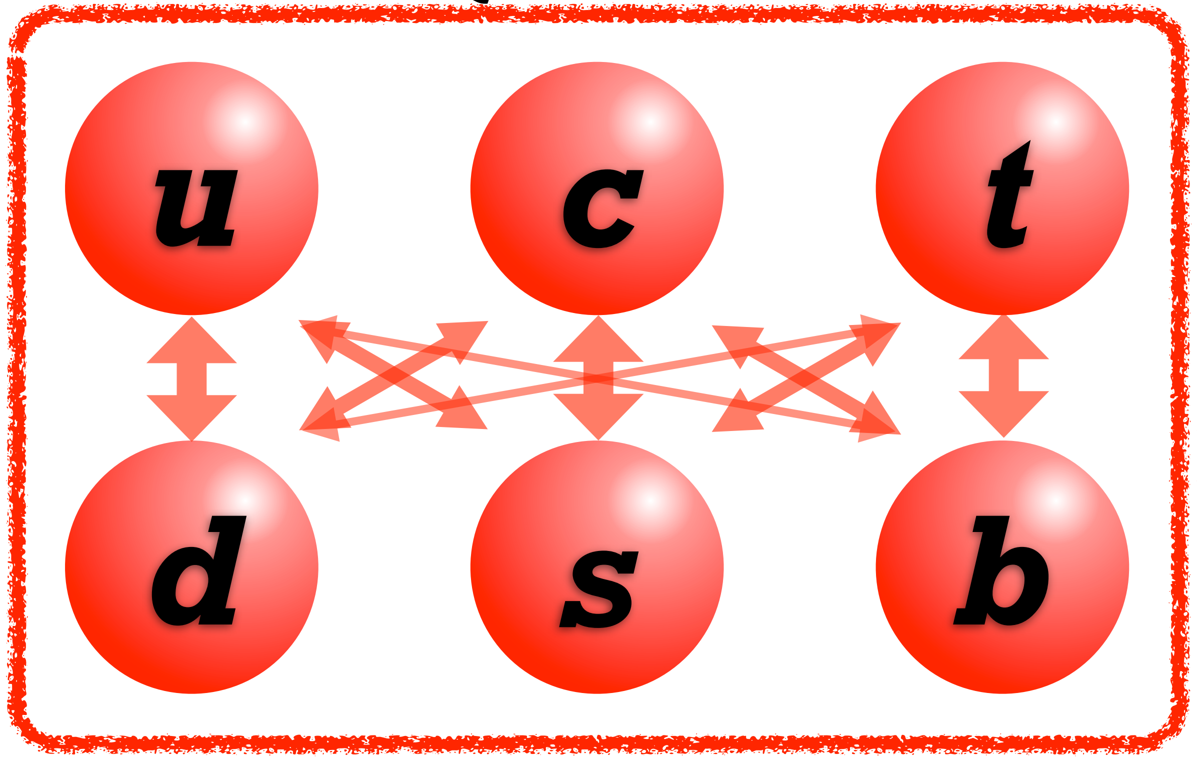
Yuki Fujii
on behalf of the MEG Collaboration

21st May 2014 @ 26th Rencontres de Blois

$\mu \rightarrow e\gamma$ Decay

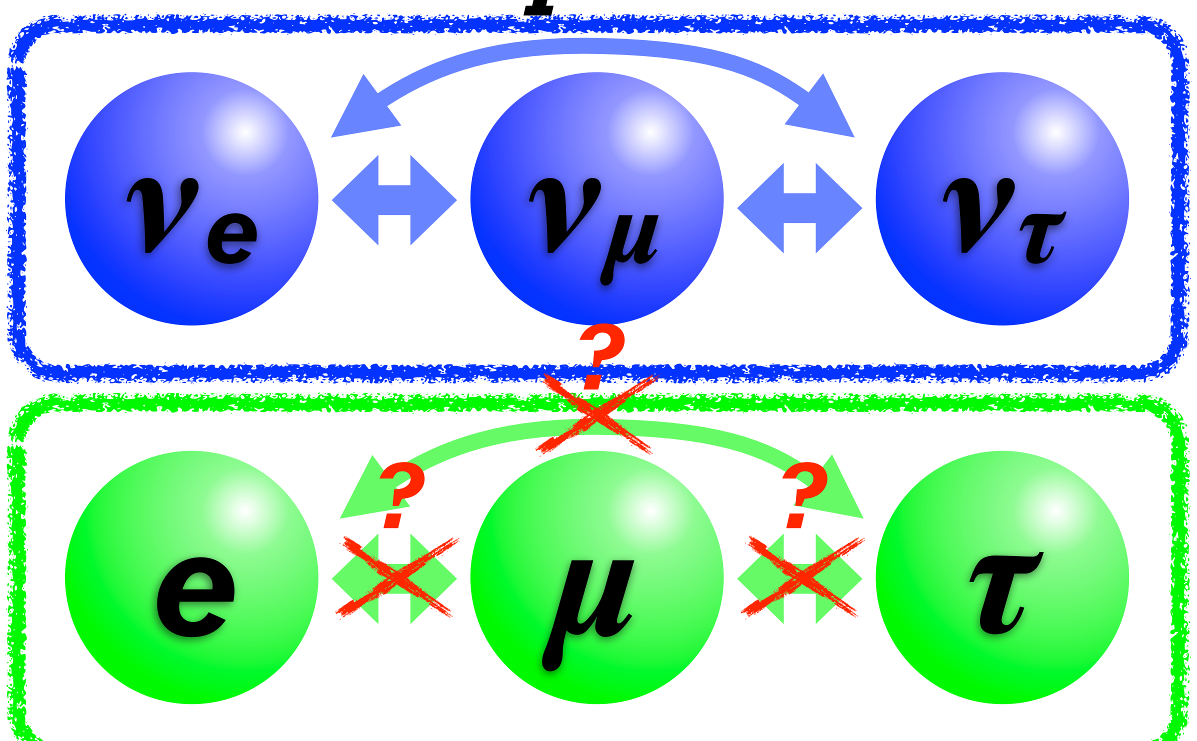
Lepton Flavor Violation

Quarks



Flavors are mixed through CKM matrix in the Standard Model,
Already confirmed

Leptons

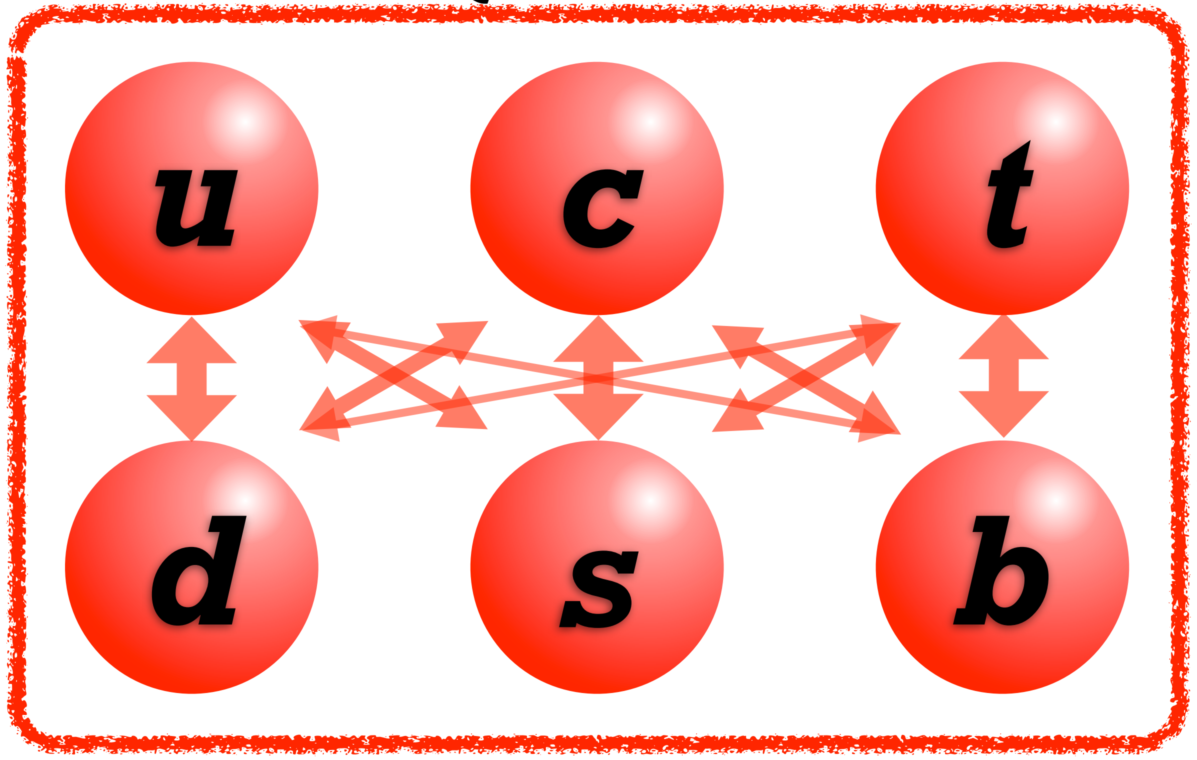


Flavors are mixed through PMNS matrix,
Already confirmed (not included in SM)

Charged Lepton Flavor Violation (CLFV)
Forbidden in the Standard Model,
$B(\mu \to e\gamma) \sim O(10^{-50})$ for SM+ν oscillation,
Not observed yet

Lepton Flavor Violation

Quarks



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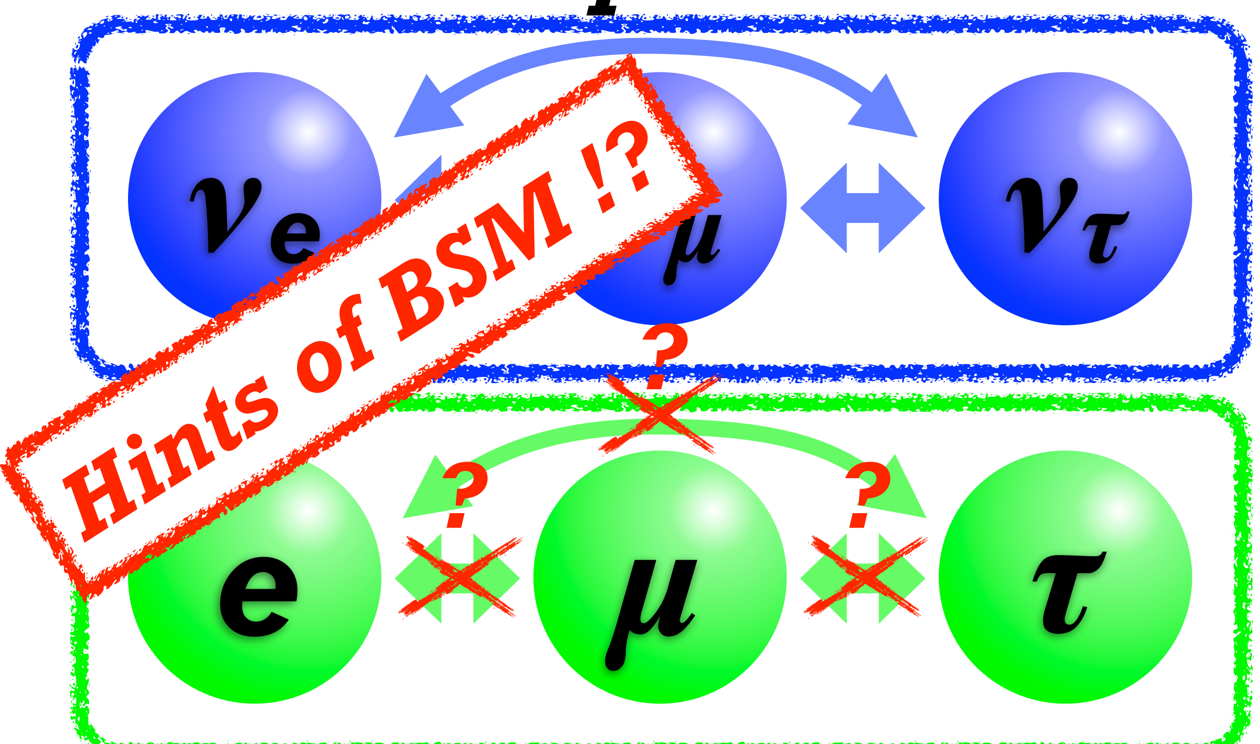


Flavors are mixed through PMNS matrix,
Already confirmed (not included in SM)

Charged Lepton Flavor Violation (CLFV)
Forbidden in the Standard Model,
$B(\mu \to e\gamma) \sim O(10^{-50})$ for SM+ν oscillation,
Not observed yet

$\mu \to e\gamma$ in BSM

- **Many BSMs predict the detectable $B(\mu \to e\gamma)$ in between 10^{-11} and 10^{-15}**

  SUSY-GUT, SUSY-Seesaw, Extra dimension, etc.

- **Previous MEG result: *2.4×10^{-12} @ 90% C.L.**

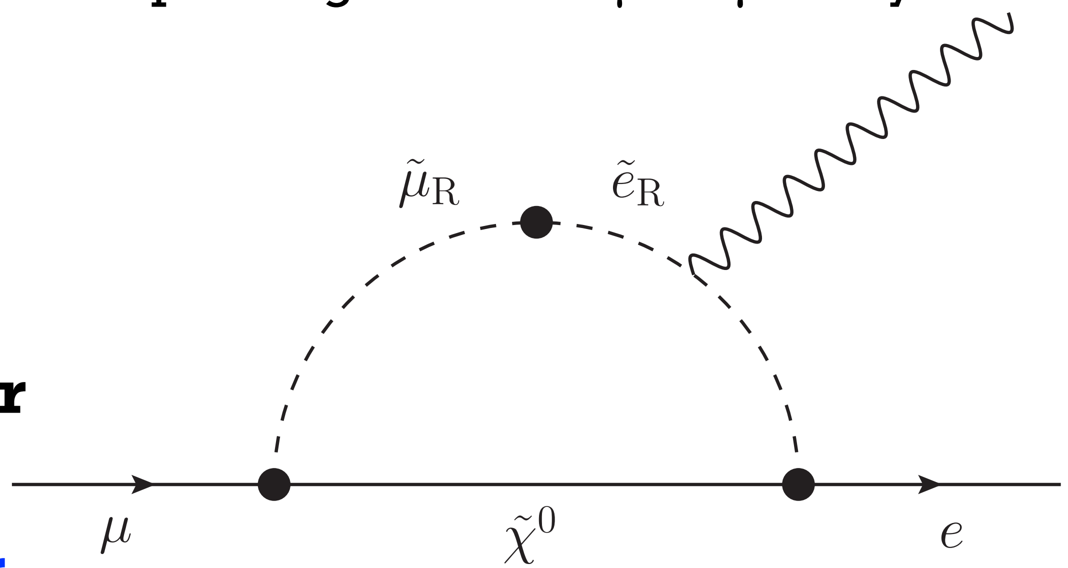
  Already in the "BSM region" !

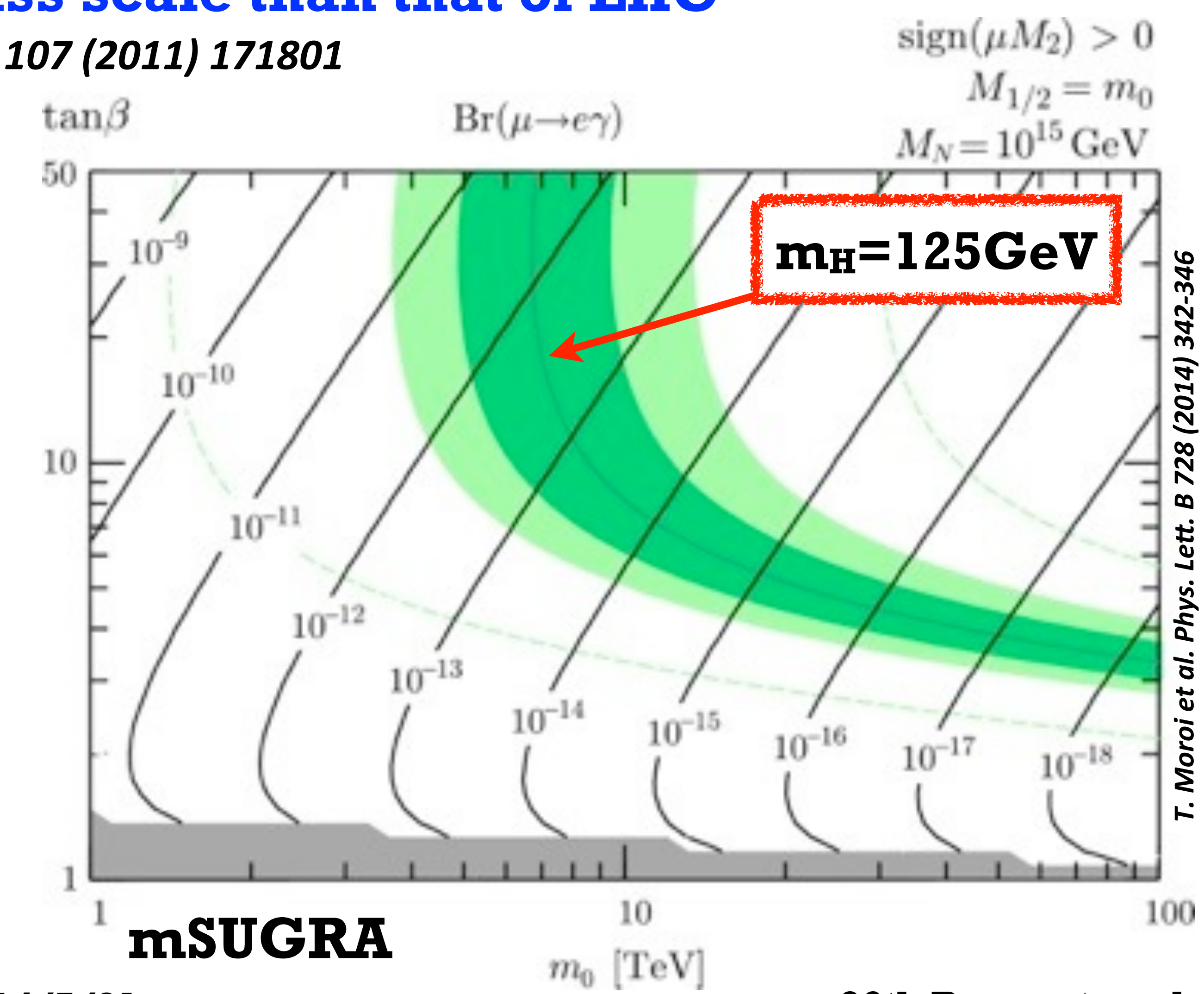
- **Discovery of the $\mu \to e\gamma$ decay should be the clear evidence of the BSM**

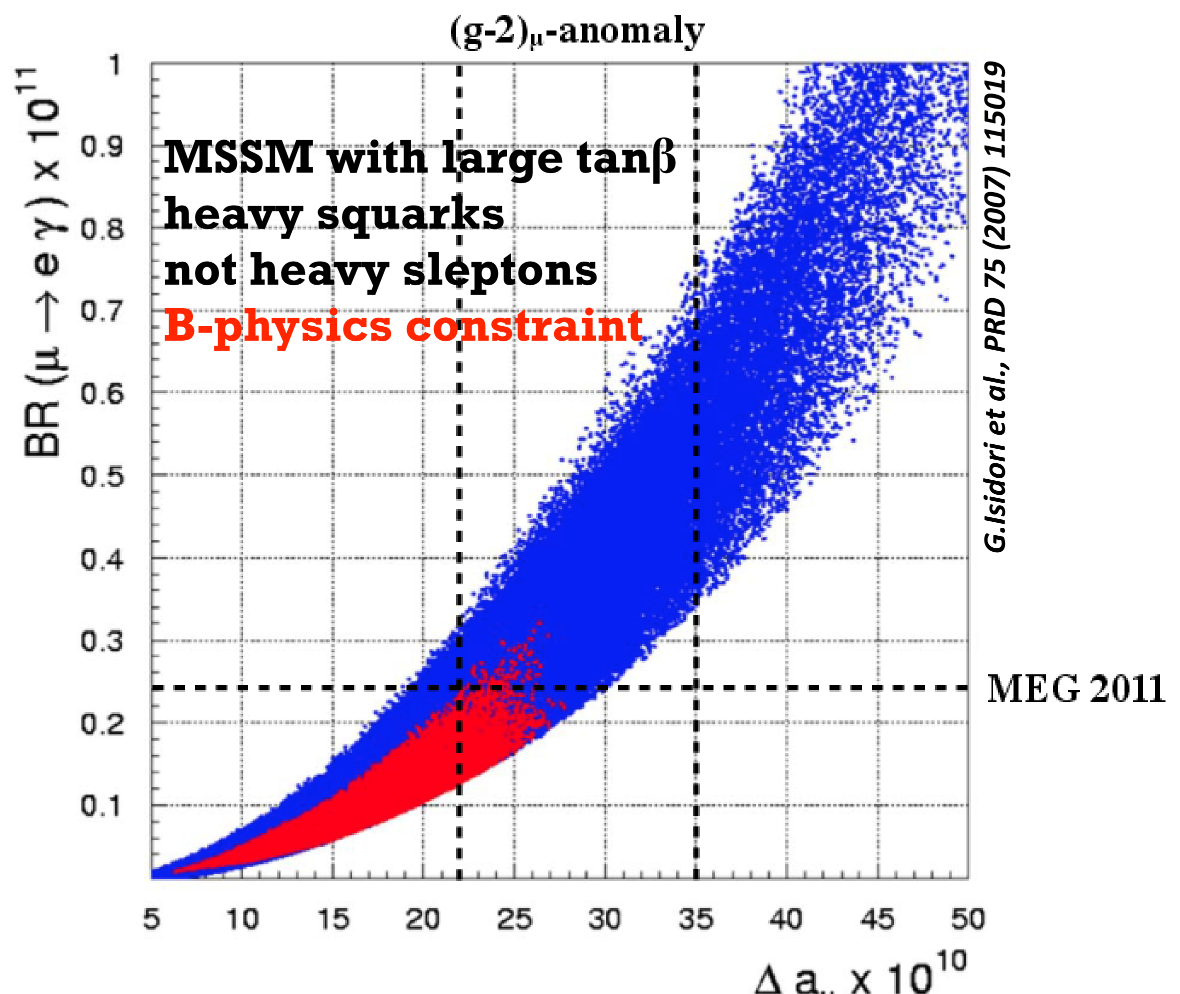
- **CLFV searches can indirectly access the higher mass scale than that of LHC**

**PRL 107 (2011) 171801*

Example diagram of the $\mu \to e\gamma$ decay in SUSY







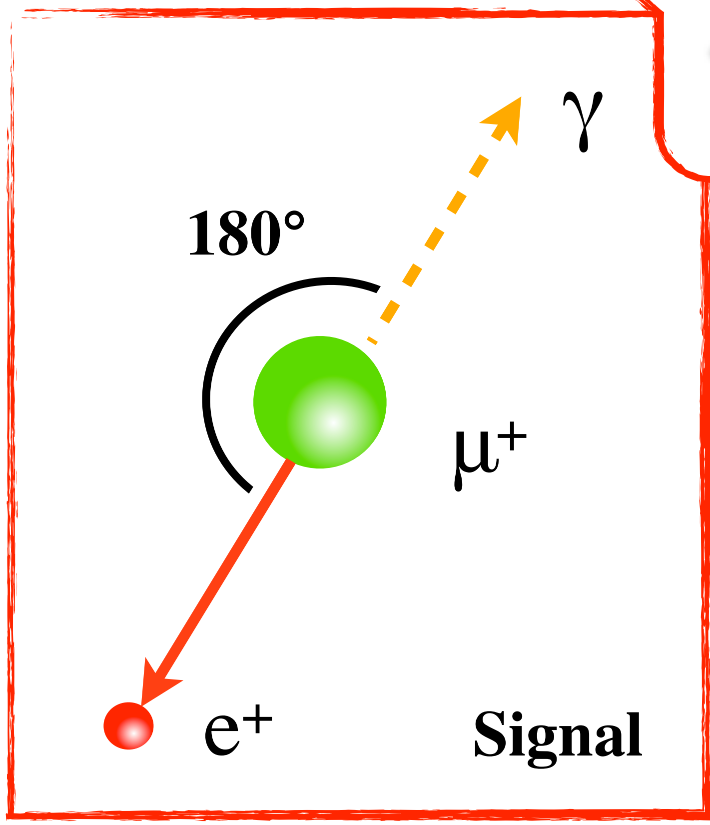
Signal / Background

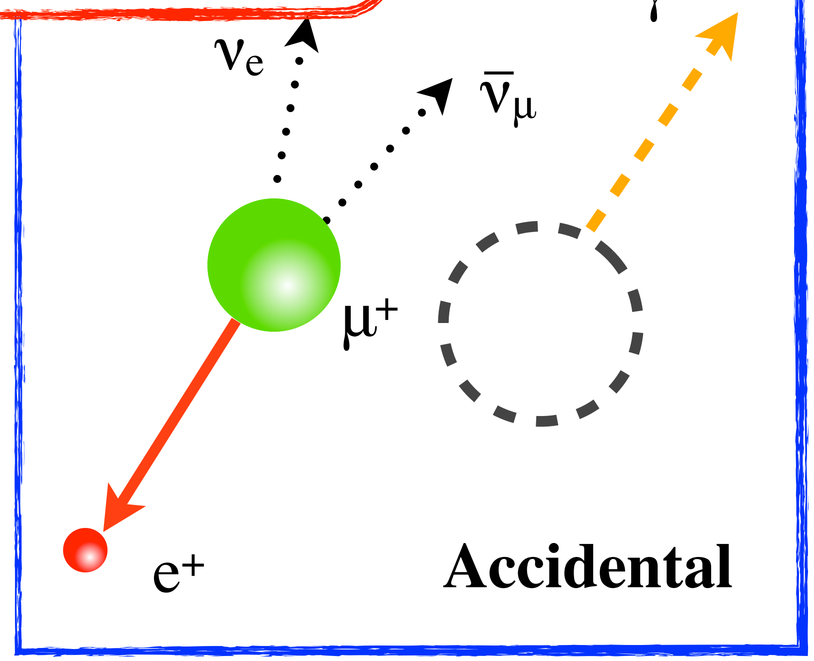
Back-to-back
$E_e = E_\gamma = 52.8$ MeV
$T_e = T_\gamma$

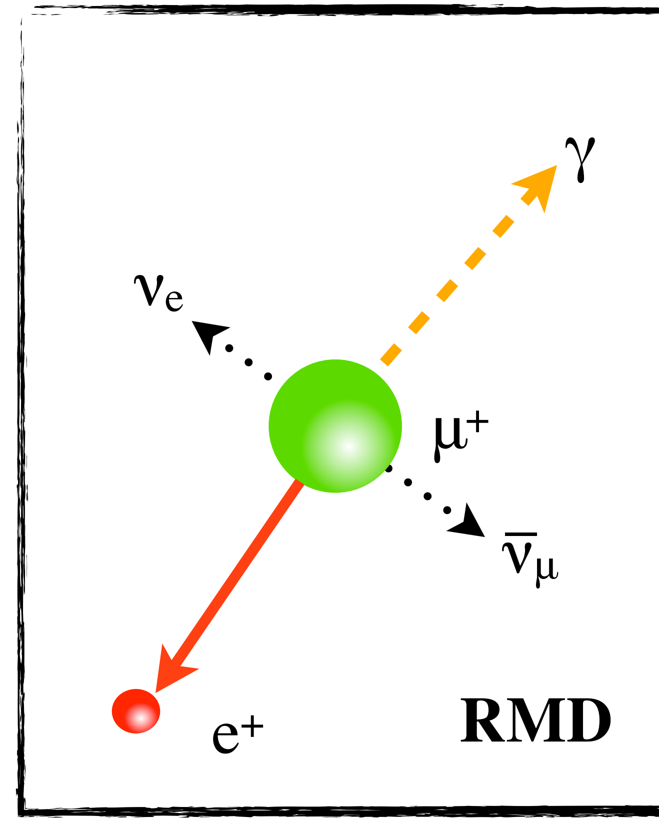
Very simple !

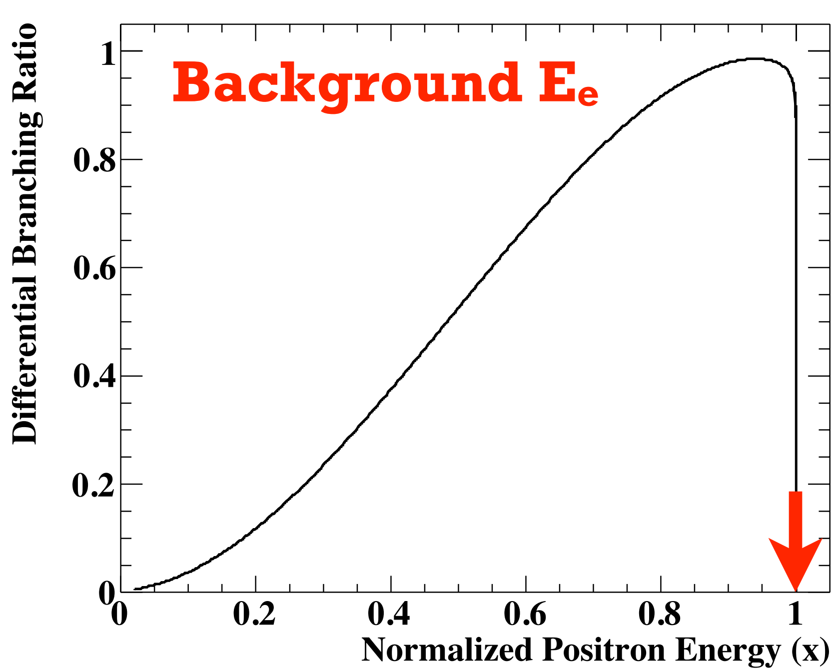
Dominant Background
$N_{acc.} \propto R^2_\mu$
R_μ: instantaneous μ^+ rate

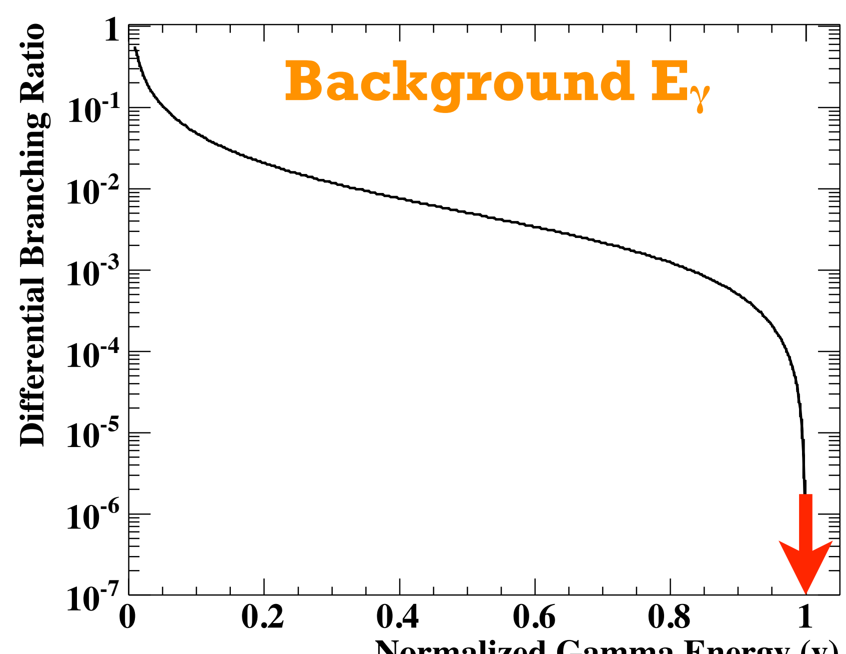
Radiative Muon Decay (RMD)
$N_{RMD} \fallingdotseq 0.1 \times N_{acc.}$











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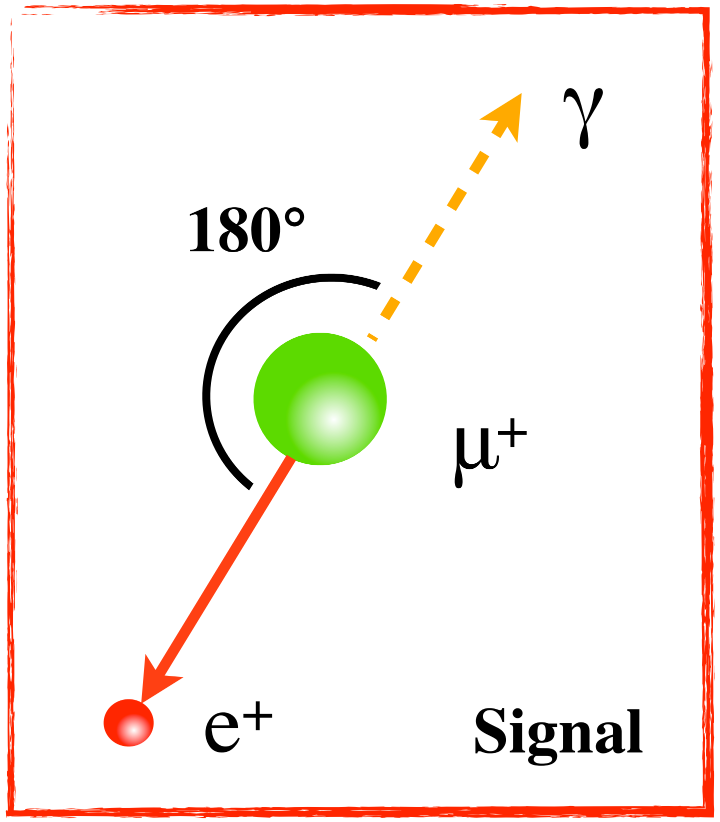

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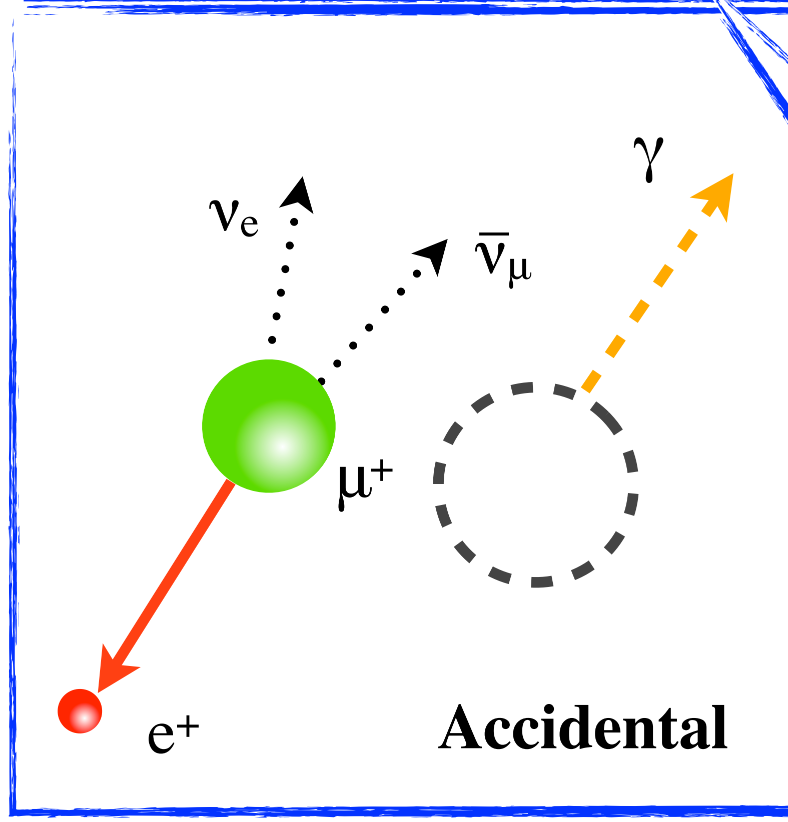
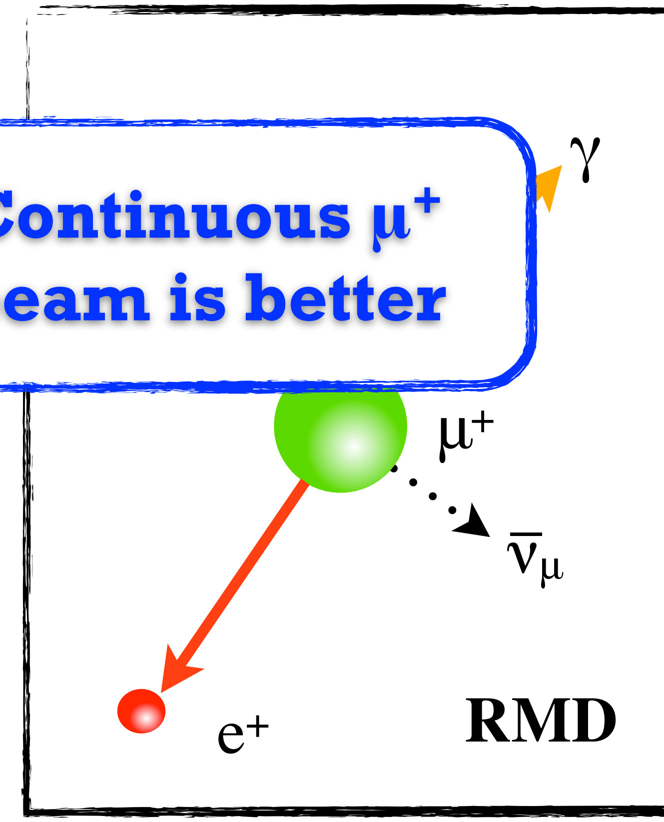
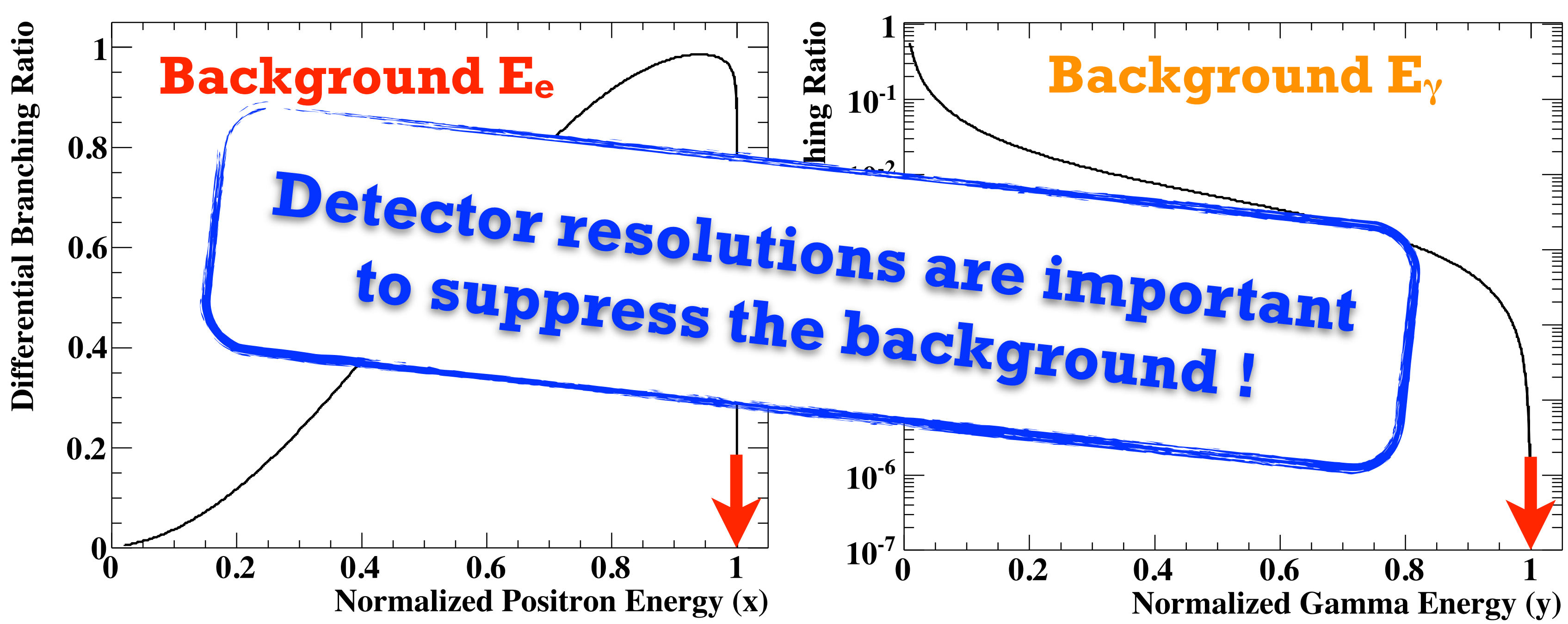
$N_{acc.} \propto R^2_\mu$
R_μ: instantaneous μ^+ rate



Continuous μ^+ beam is better

Radiative Muon Decay (RMD)
$N_{RMD} \fallingdotseq 0.1 \times N_{acc.}$





Detector resolutions are important to suppress the background !

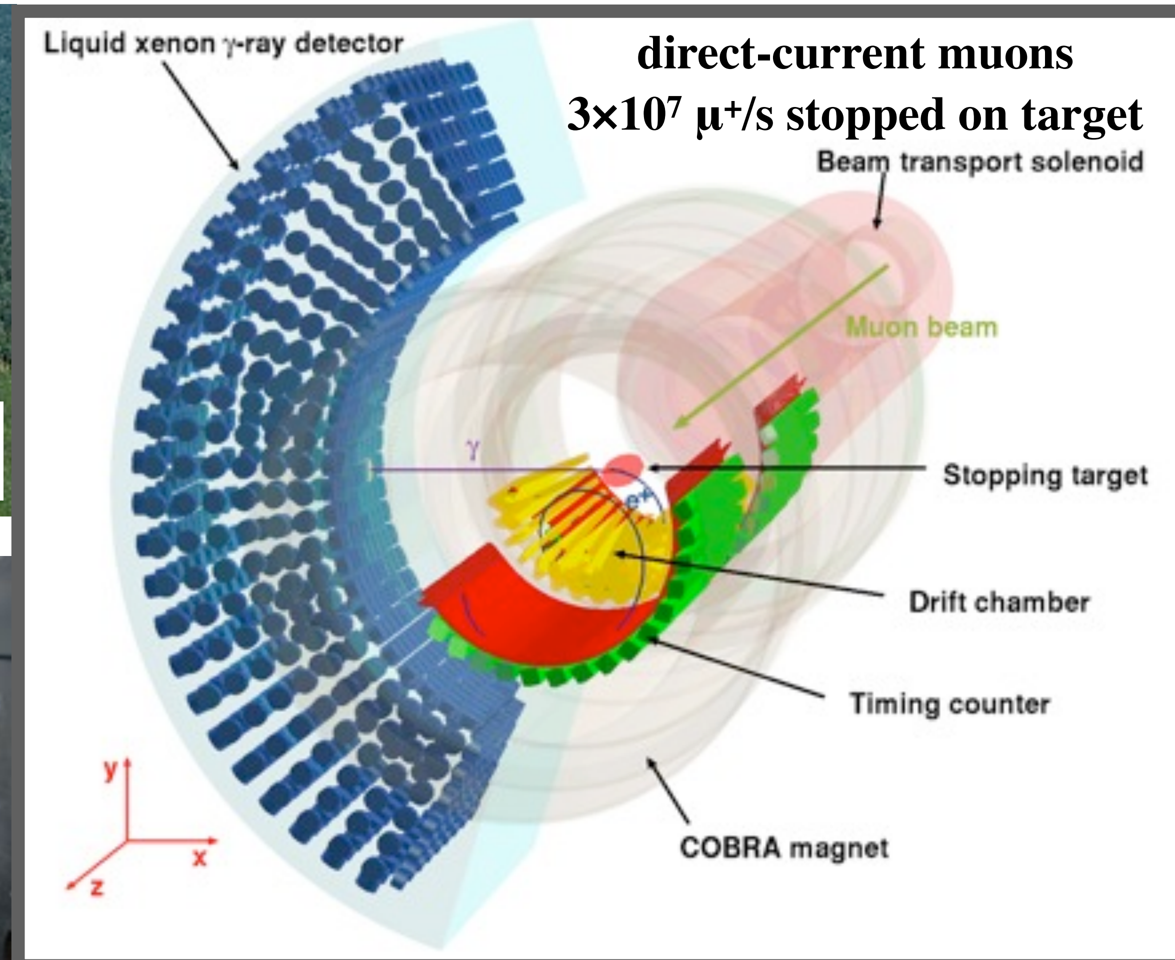
MEG Experiment

- Where we are now ? -

MEG Experiment

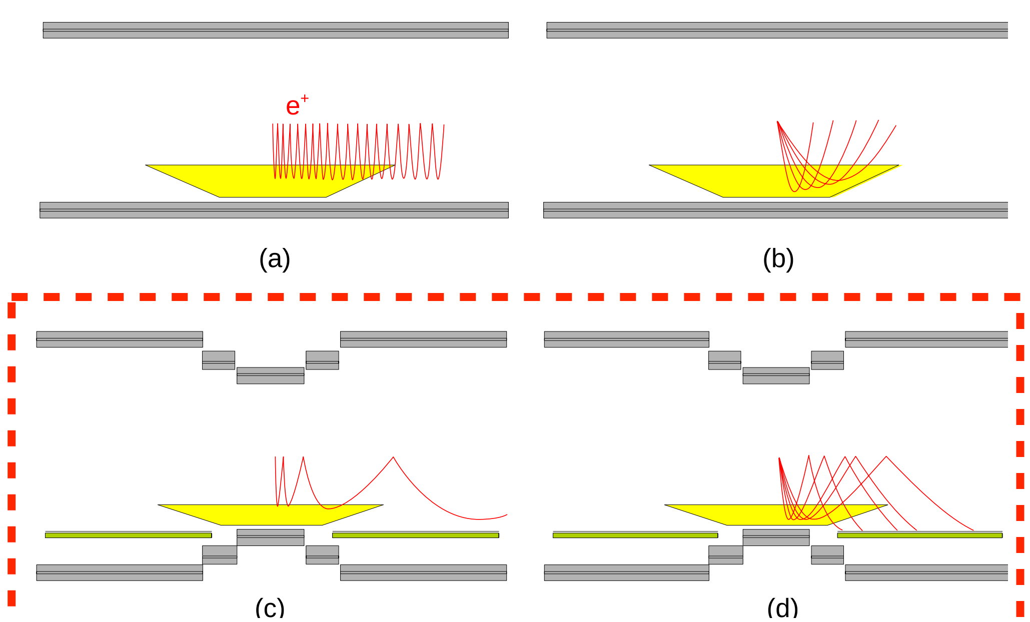
PSI

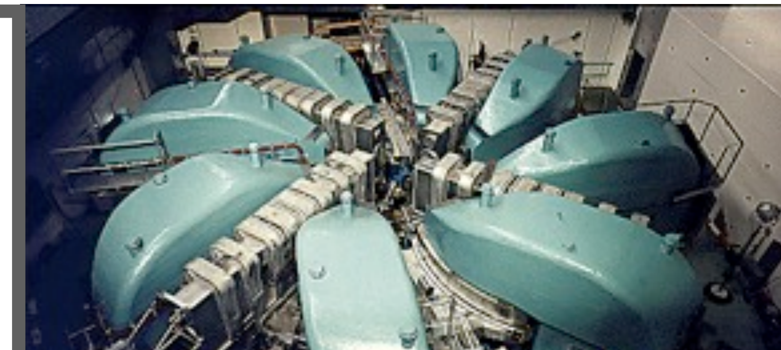
LXe gamma-ray detector
good efficiency&resolutions



COBRA magnet
special graded field to detect signal e^+

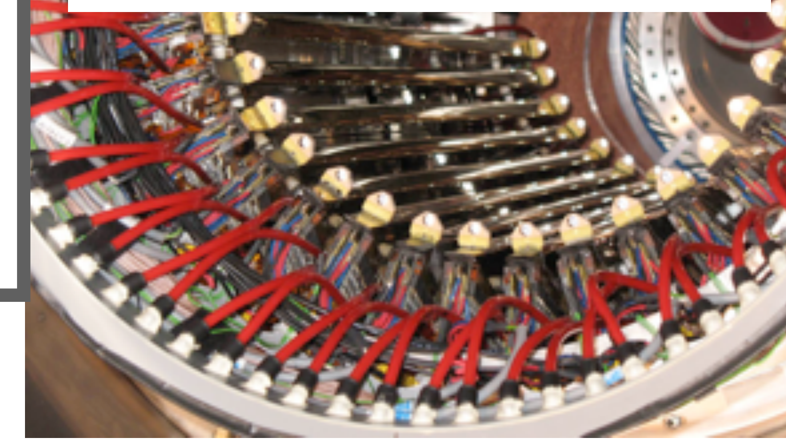
COnstant Bending RAdius



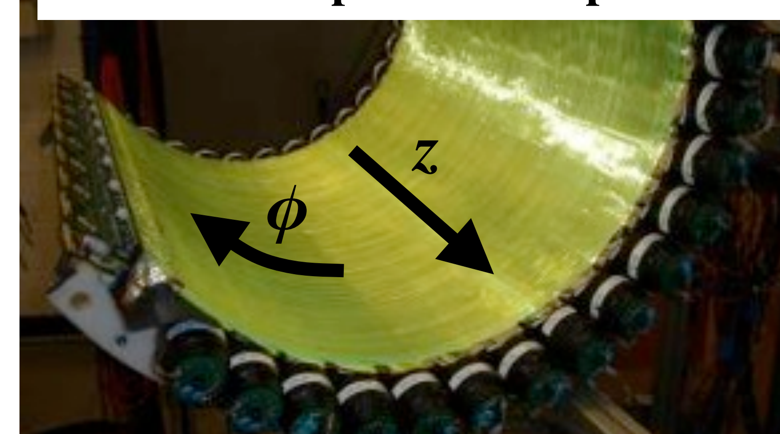


1.3 MW Proton Cyclotron
the world most powerful beam

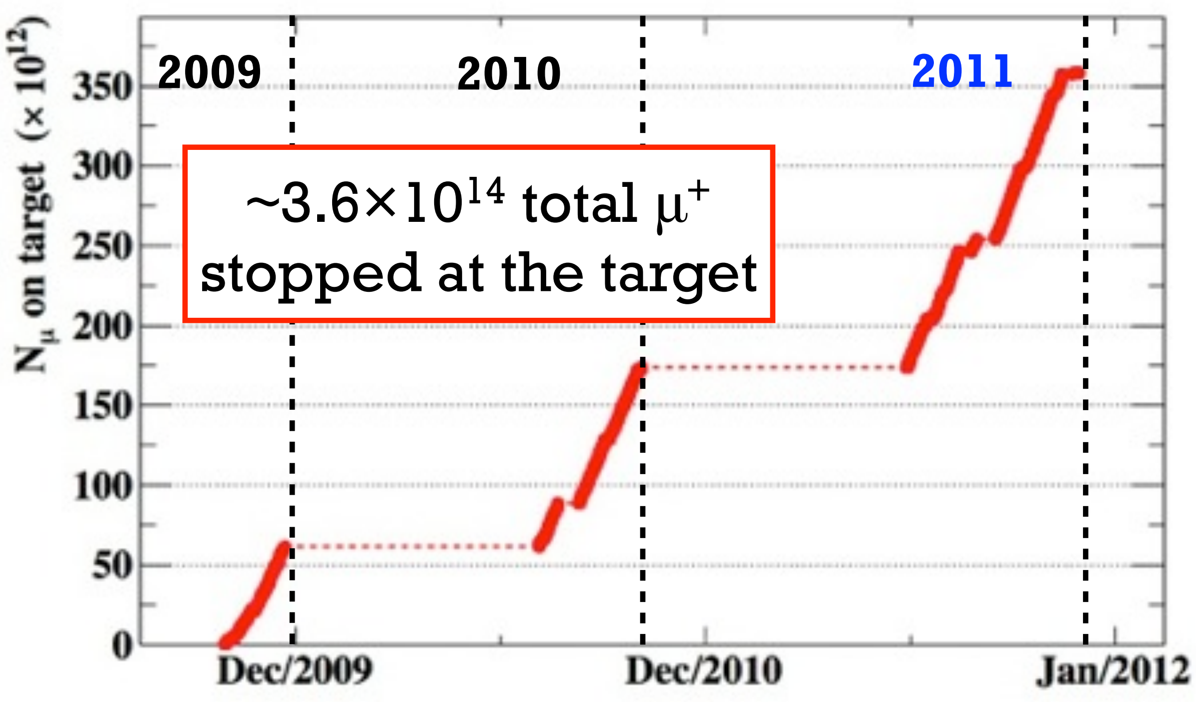
Drift Chamber
made of ultra low mass materials



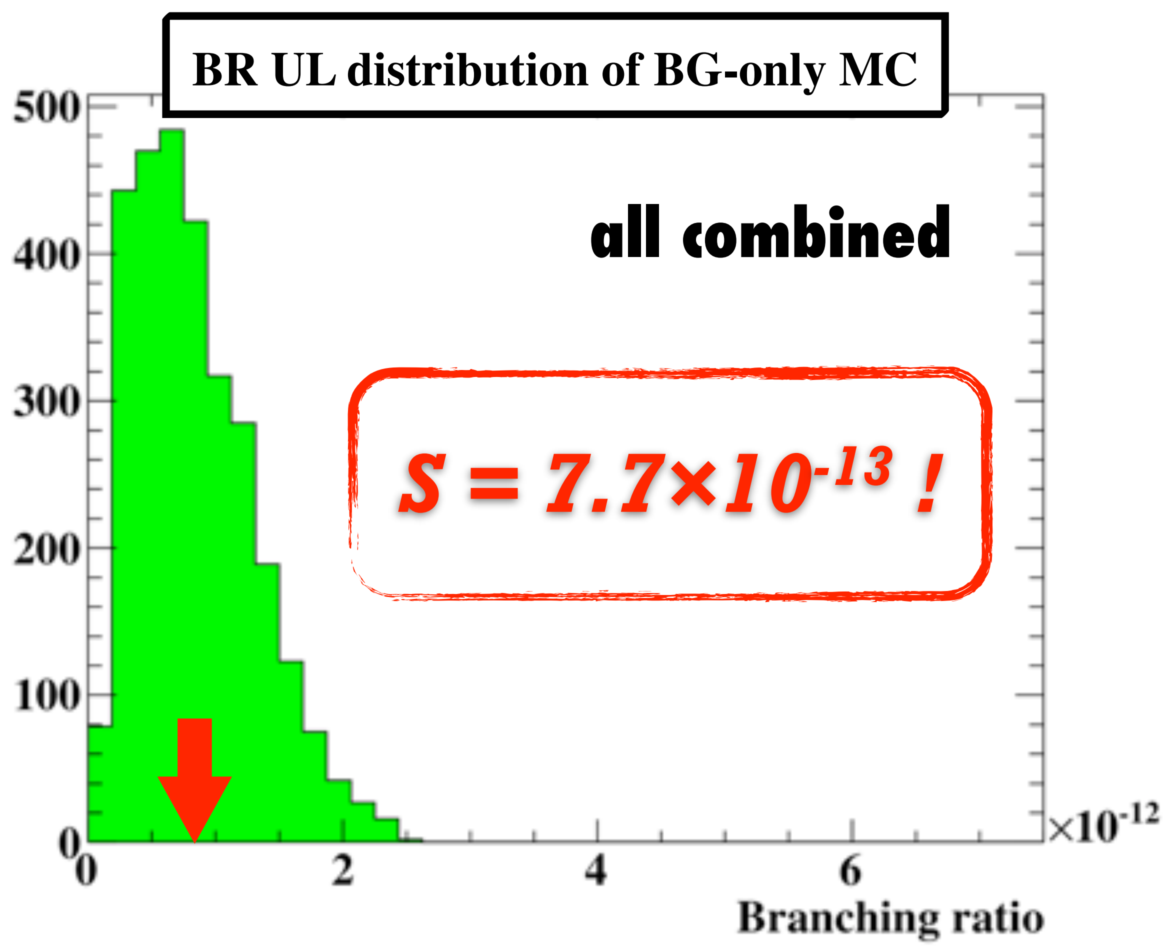
Timing Counter
Determine impact time of positrons

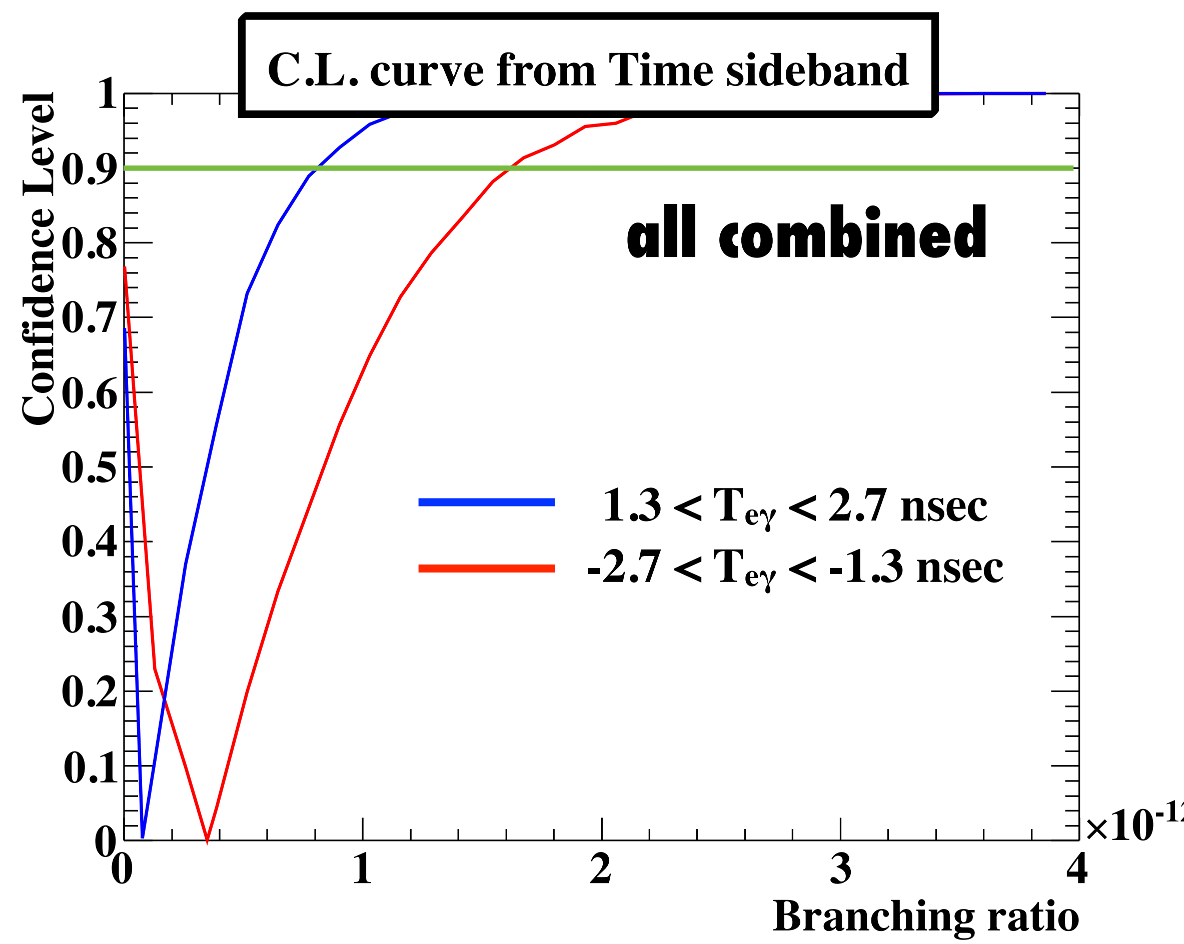


Latest Result (1/2)



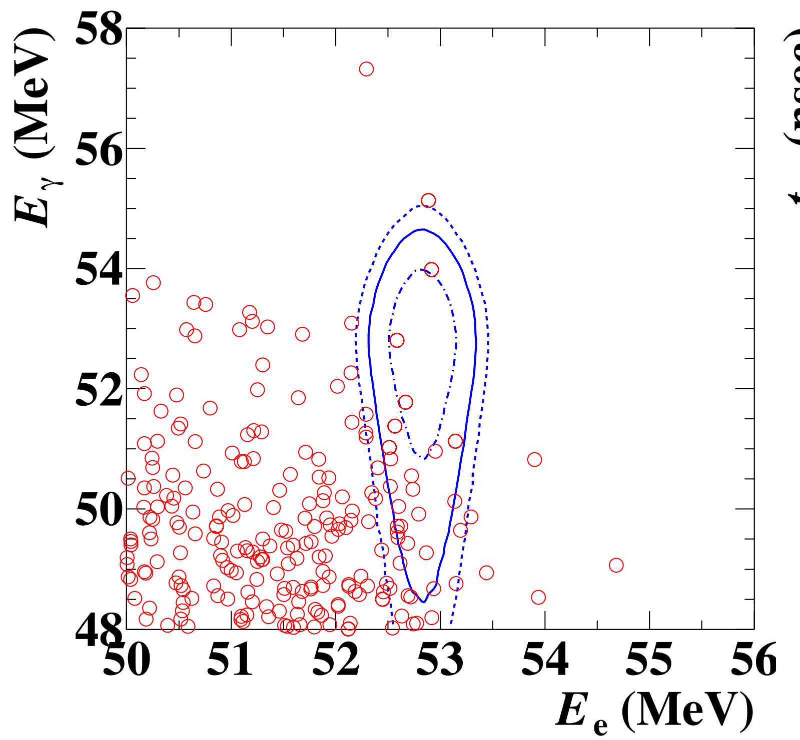
- **3.6×10^{14} μ^+s are collected until 2011**
  Statistics ≒ sum of 2009-2010
- **Reconstruction and analysis are improved**
  Noise filtering for e^+ reconstruction
  Revise the track fitting
    Enable to use per-event PDF
  New pileup unfolding for γ rays
  ⇒ ~20% sensitivity improvement
- **Obtained sensitivity: 7.7×10^{-13}**
  First $\mu^+\to e^+\gamma$ search below 10^{-12} !





Latest Result (2/2)

$|T_{e\gamma}| < 244.3$ psec, $\pi - \Theta_{e\gamma} < 27.3$ mrad | $51 < E_\gamma < 55.5$ MeV, $52.385 < E_e < 55$ MeV



2D event distribution w/ cuts
- data with 90% cut
- signal PDF

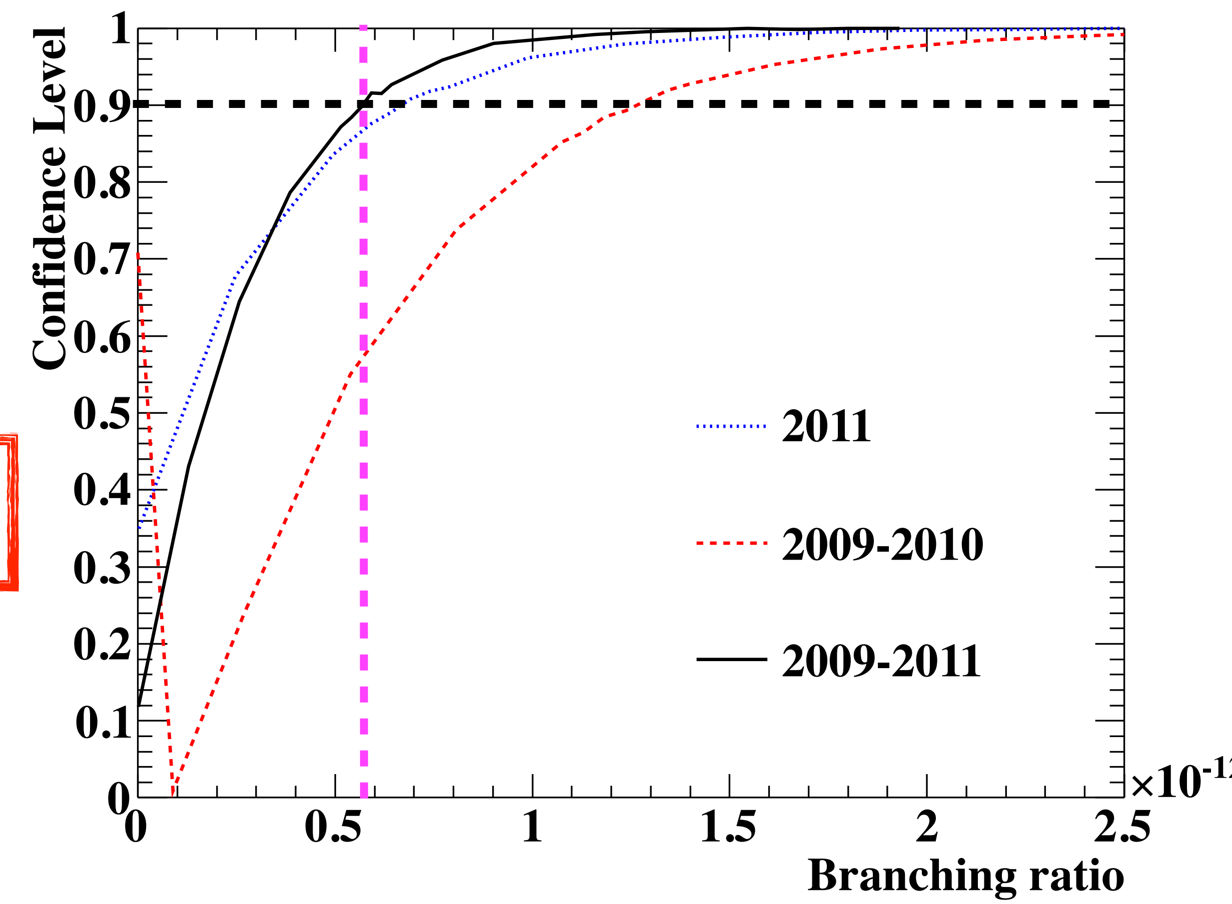
No signal excess is observed = consistent w/ BG only hypothesis

90% C.L. upper limit is calculated based on Feldman-Cousins' full-frequentist approach for 2009-2011 combined dataset:

$$\mathcal{B}(\mu^+ \to e^+\gamma) < 5.7\times10^{-13} \text{ @ 90\% C.L.}$$

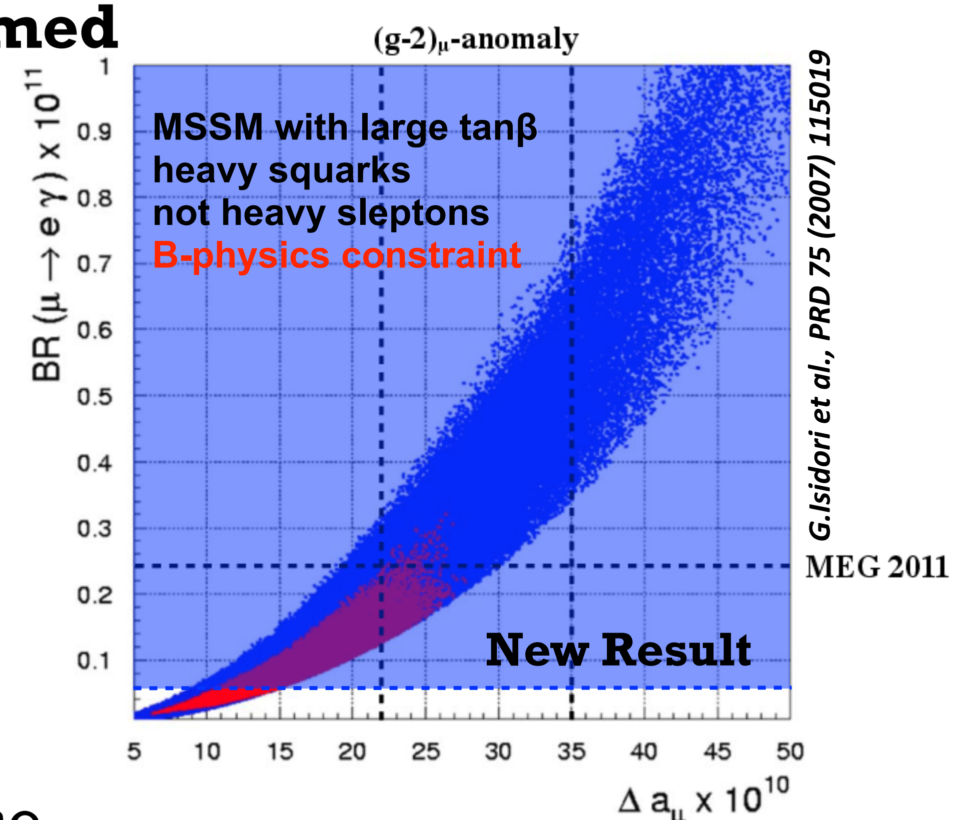
Details in J. Adam *et al.*, Phys. Rev. Lett. **110** 201801 (2013)

confidence level curve

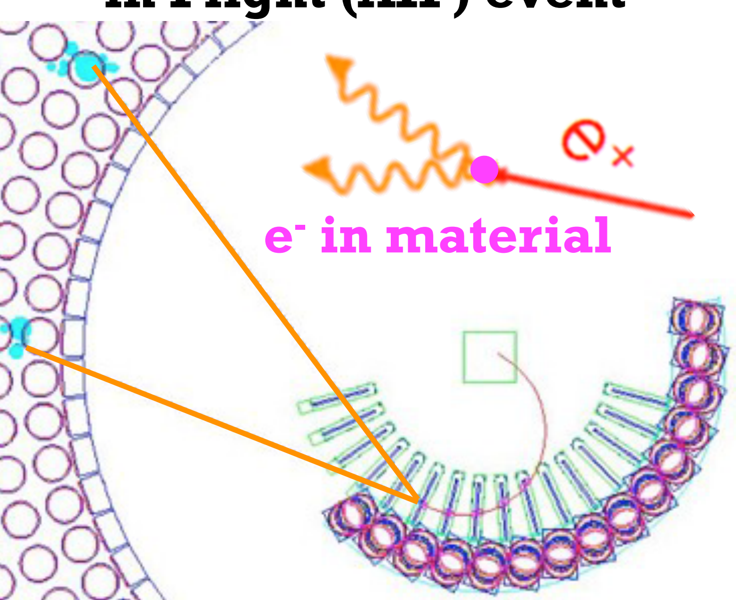


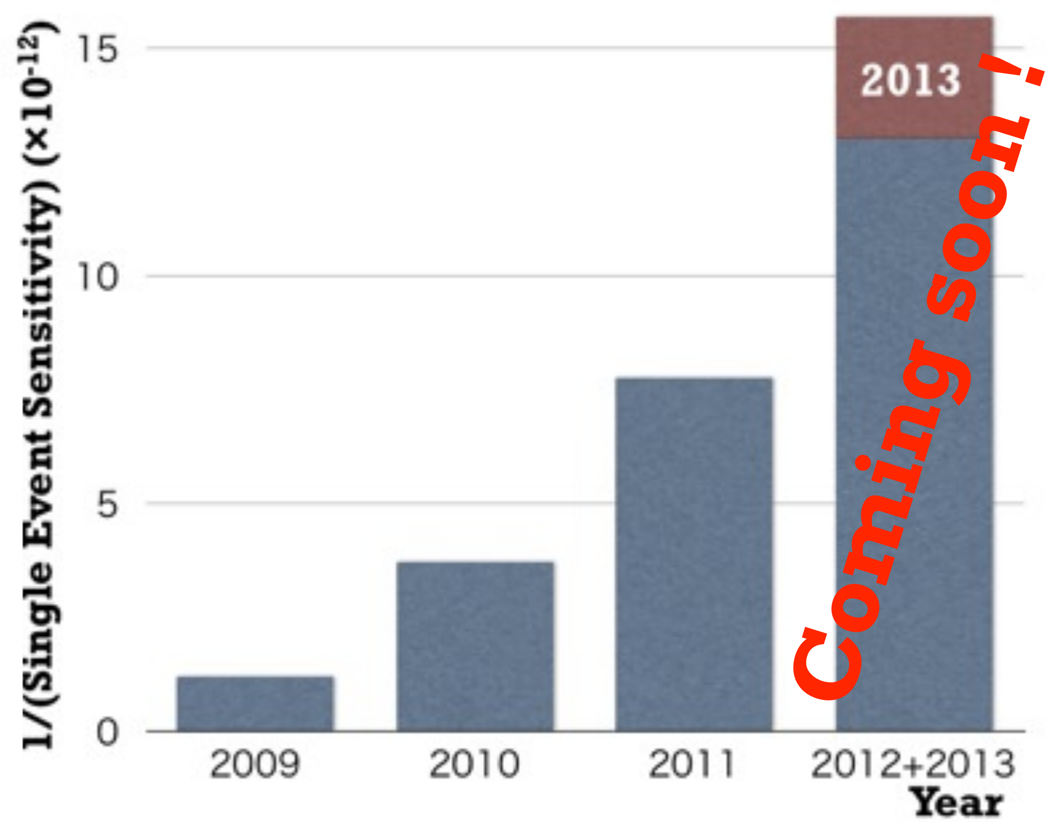
Conclusion & Prospects

- **The $\mu^+ \to e^+\gamma$ decay search using 2009-2011 data performed**
  - First $\mu^+ \to e^+\gamma$ search with a sensitivity below 10^{-13} !
- **No signal excess is observed**
  - **$B(\mu^+ \to e^+\gamma) < 5.7\times10^{-13}$** (90% C.L.)
  - Start exploring wide "new physics region" !
- **Data taking was finished in 2013**
  - Final expected sensitivity: 5×10^{-13}
  - Total statistics are doubled (2012+2013)
  - New analysis to reduce BG-gamma from AIF will improve the sensitivity up to 15%
  - Analysis is ongoing

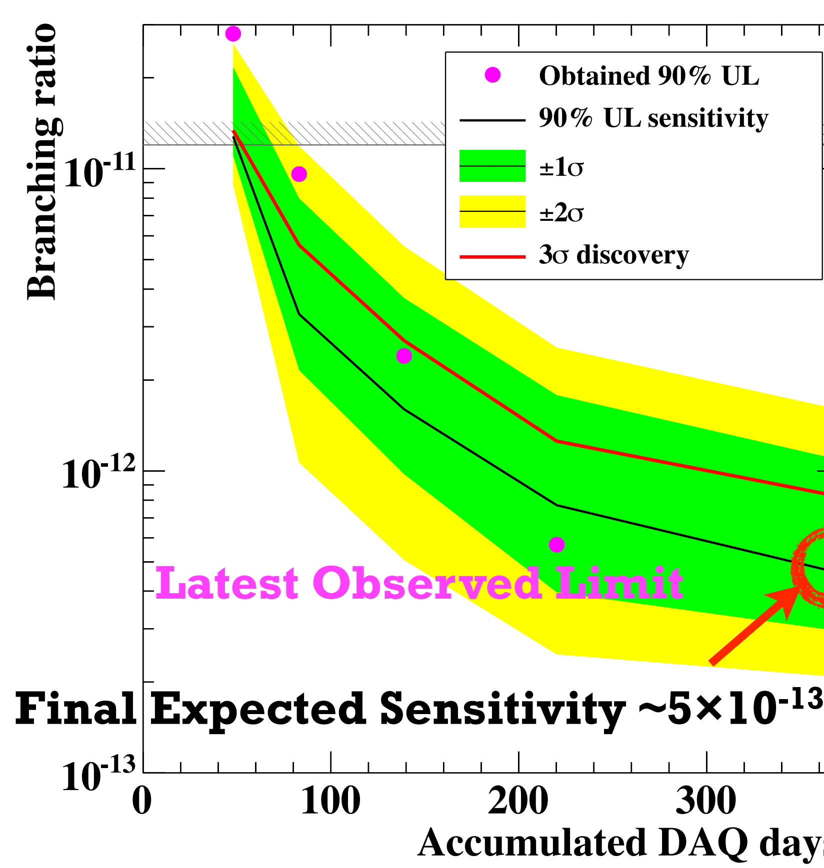


Tag the Annihilation in Flight (AIF) event





sensitivity curve w/ observed limit



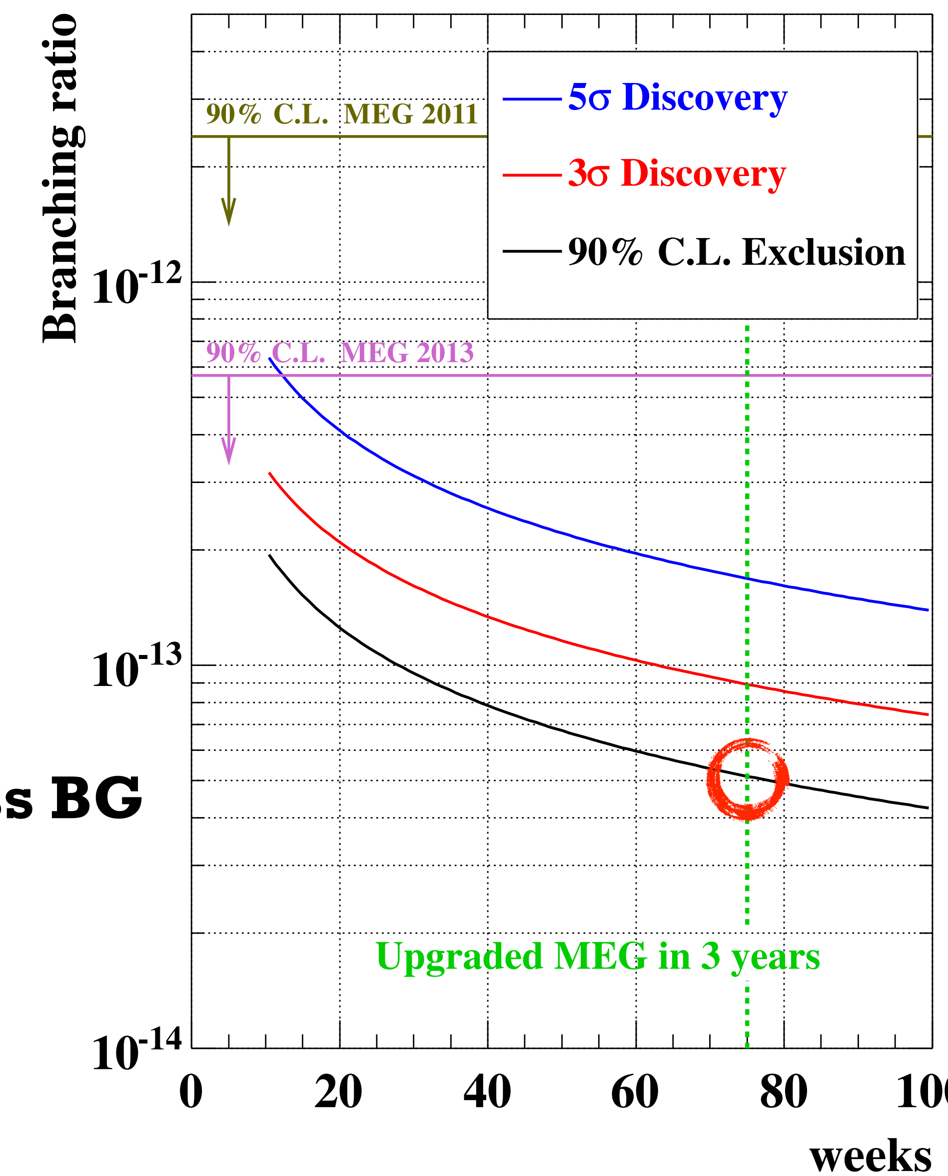
MEG II

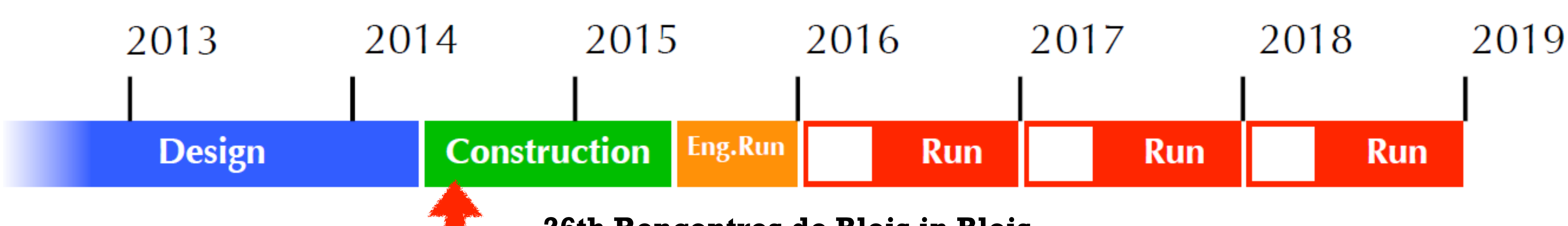
- Where we will go ? -

Plan for the Upgrade

Goal Sensitivity of MEG II
arXiv:1301.7225

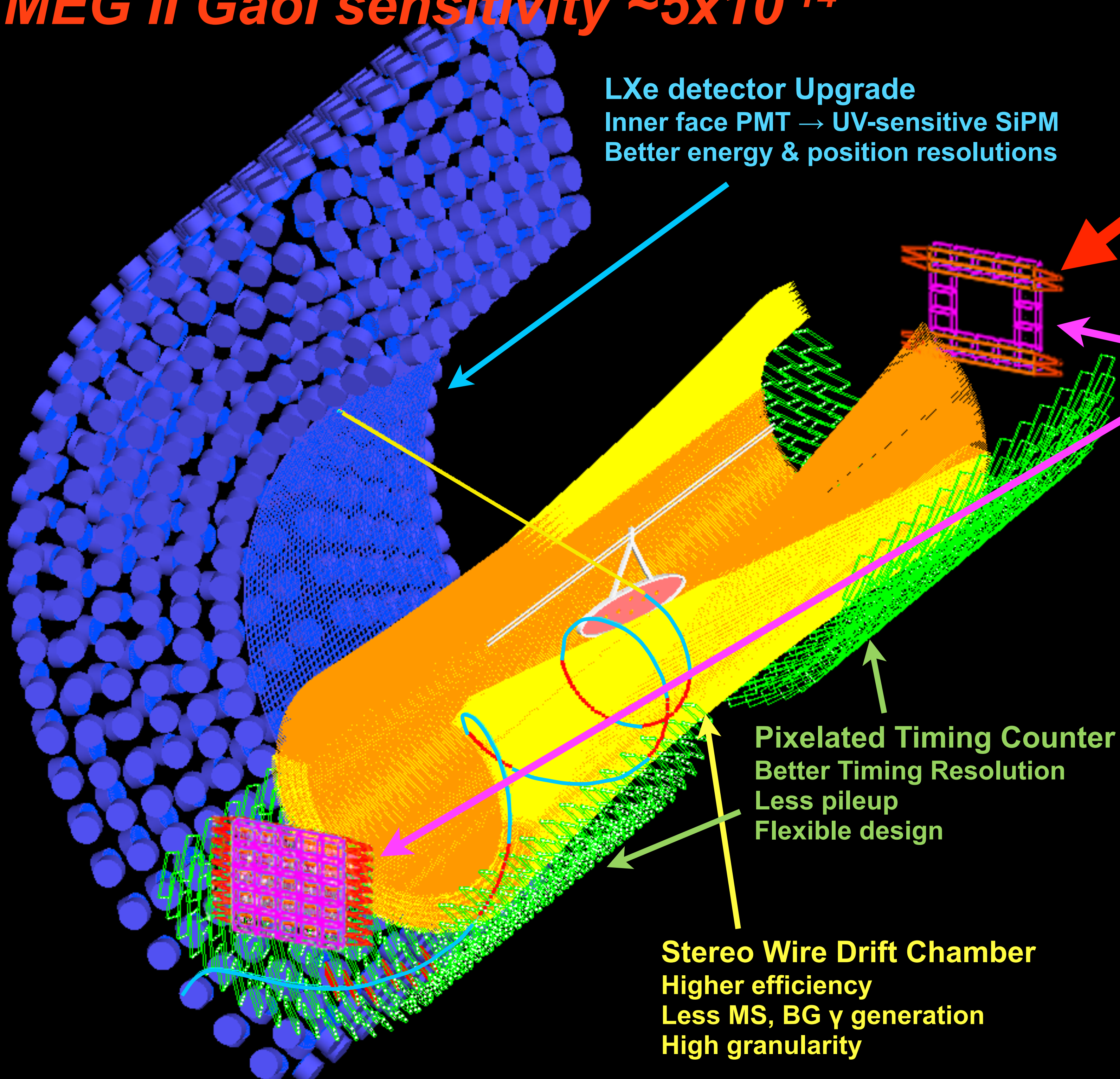
- We achieved the sensitivity of 10^{-13} which is inside the region predicted by many BSMs
  - The $\mu \to e\gamma$ search is very important to investigate the BSMs
- In MEG phase-I, the sensitivity evolution was getting worse because of BG
  - BG reduction is essential to achieve better sensitivity
- **⇒ MEG upgrade ! (called "MEG II")**
- Aiming the 10 times better sensitivity than that of MEG
- **Important keys for the upgrade**
  - More powerful μ^+ beam (available in PSI up to 10^8 Hz)
    - Need to improve the rate tolerance of each detector
  - **Improve the performance of all detectors to suppress BG**
  - Further background reduction
    - Reduce materials
    - Active BG tagging





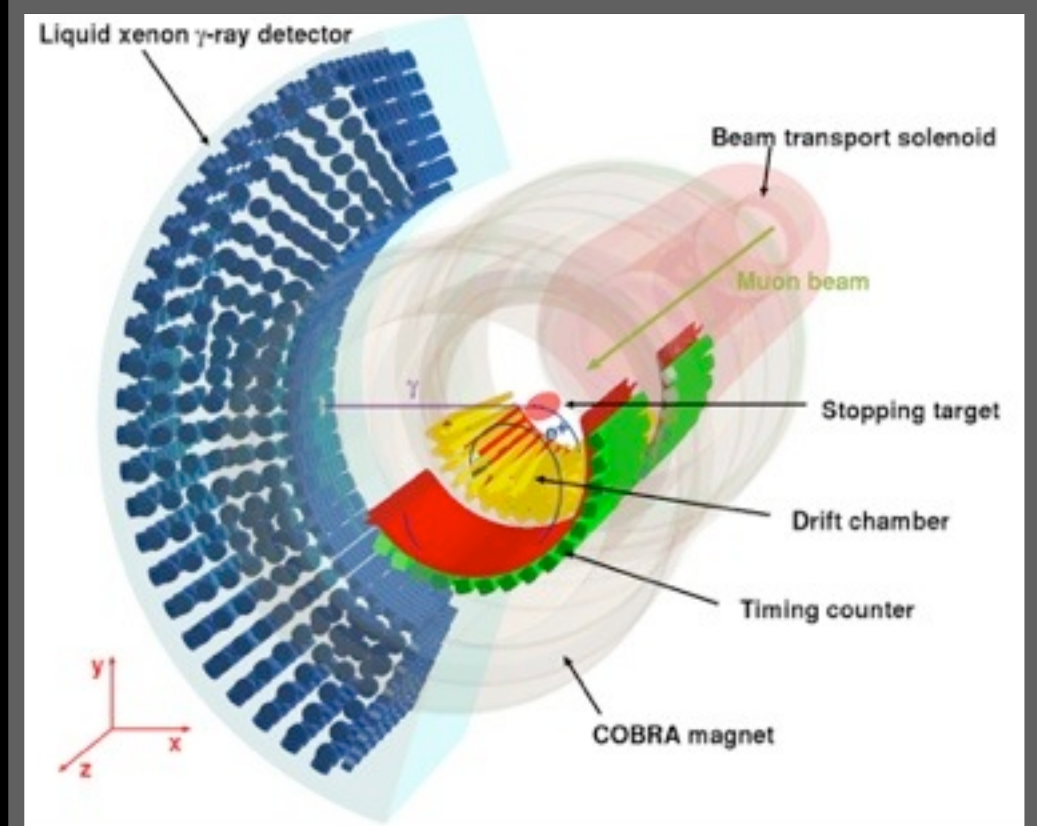
MEG II

MEG II Gaol sensitivity ~5x10^{-14}



MEG

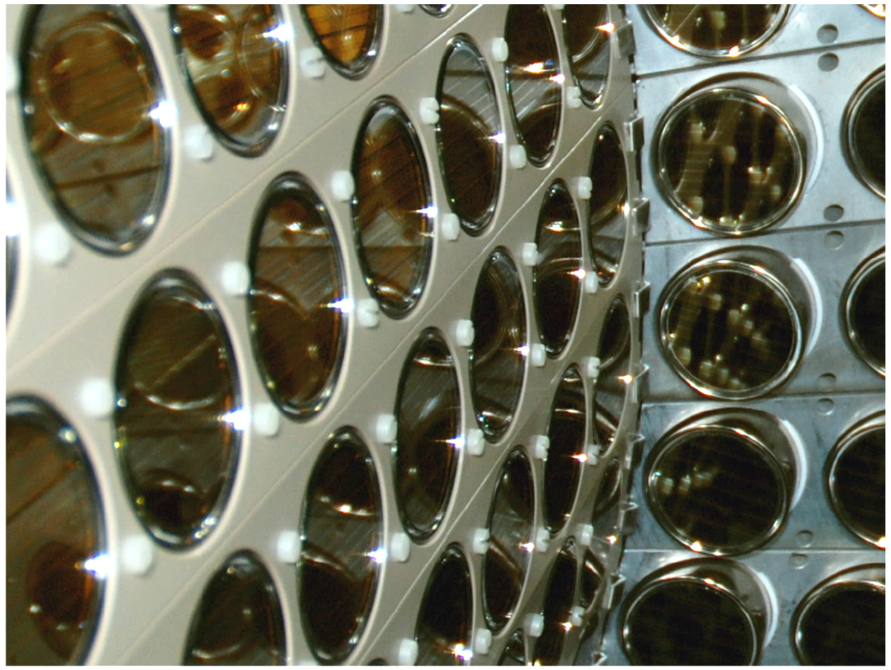
- Finished data taking in August 2013
- Final Expected Sensitivity ~ 5×10^{-13}



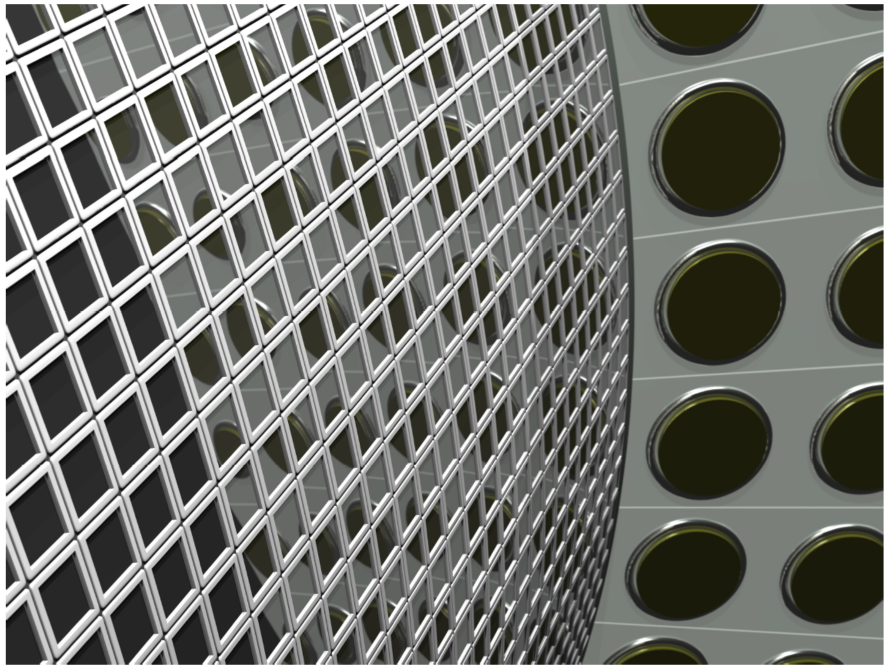
Upgrade proposal was already approved by Paul Scherrer Institut (arXiv:1301.7225)

Calorimeter Upgrade (1/2)

High granularity
Inner face PMTs
⇒ VUV-sensitive MPPCs
- Resolutions will be improved especially for shallow events
- ~4k channels of SiPMs ($12\times12mm^2$) will be used as photo sensors

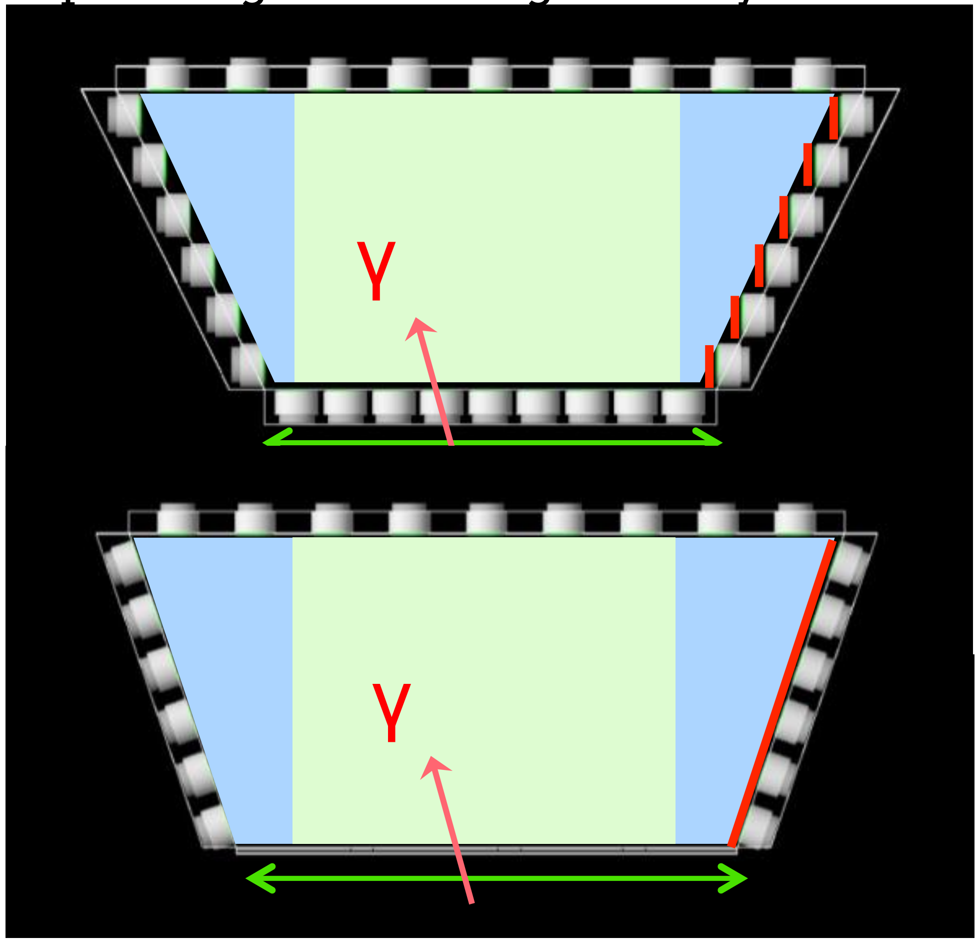


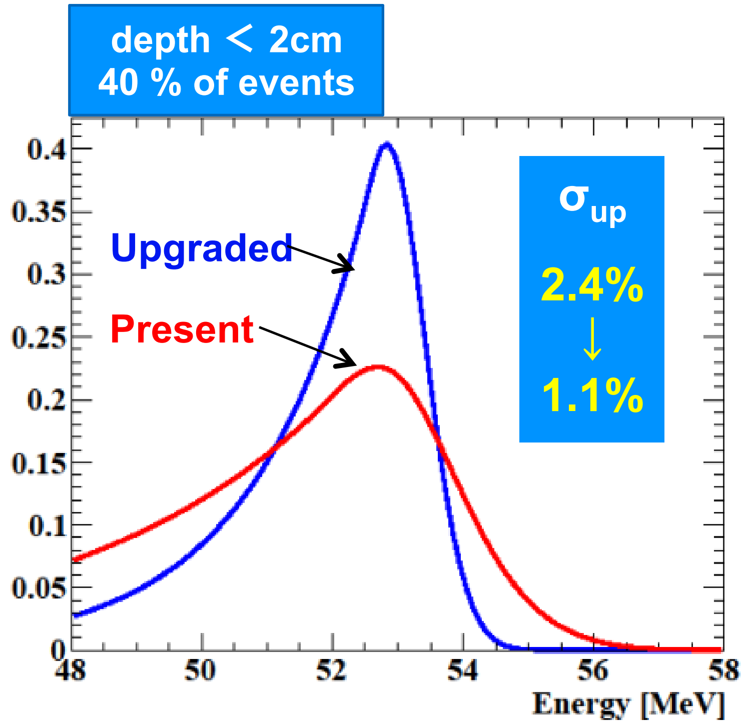
Inner face of calorimeter



Upgrade (CG)

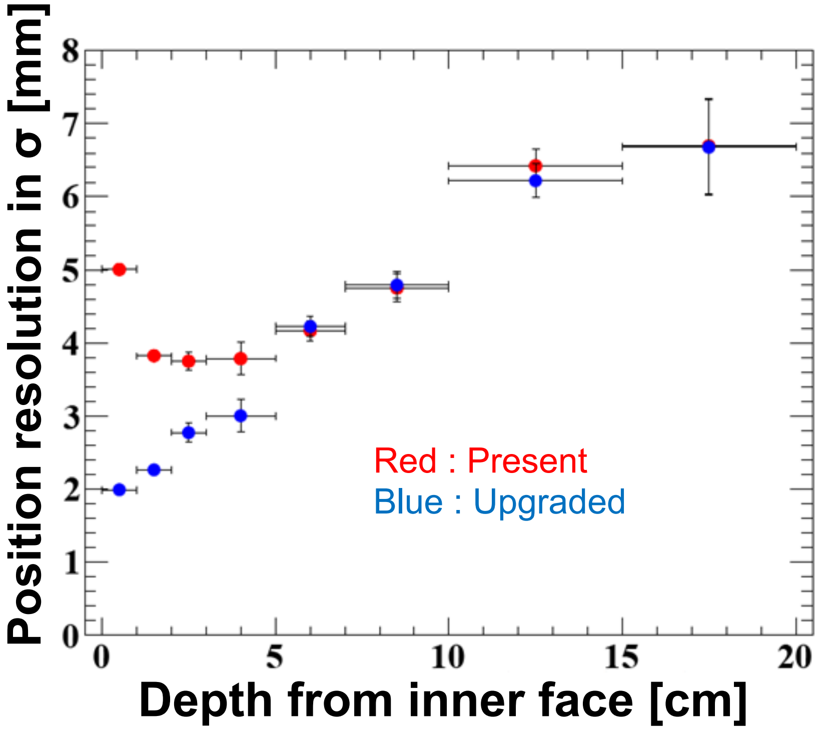
Detection efficiency will be increased by optimizing the PMT alignment by 10%



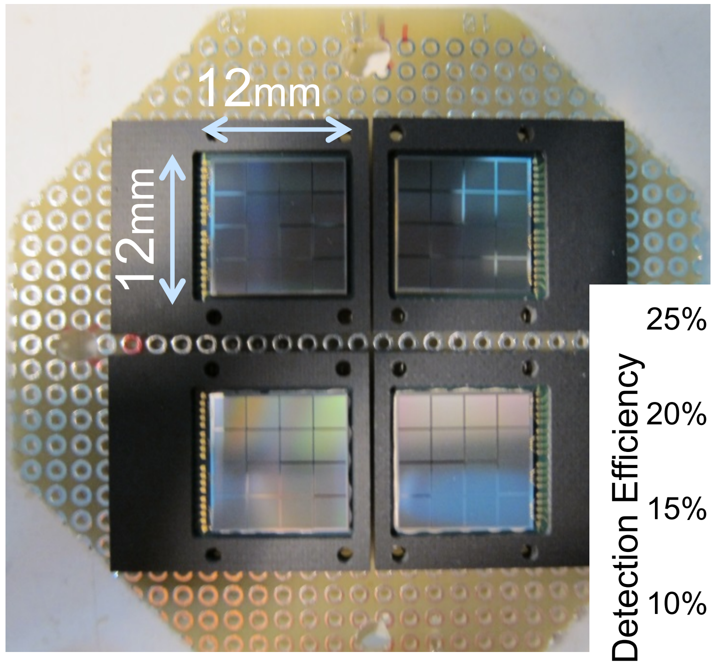


Gamma energy distributions of signal for shallow events in case of MEG and MEG II

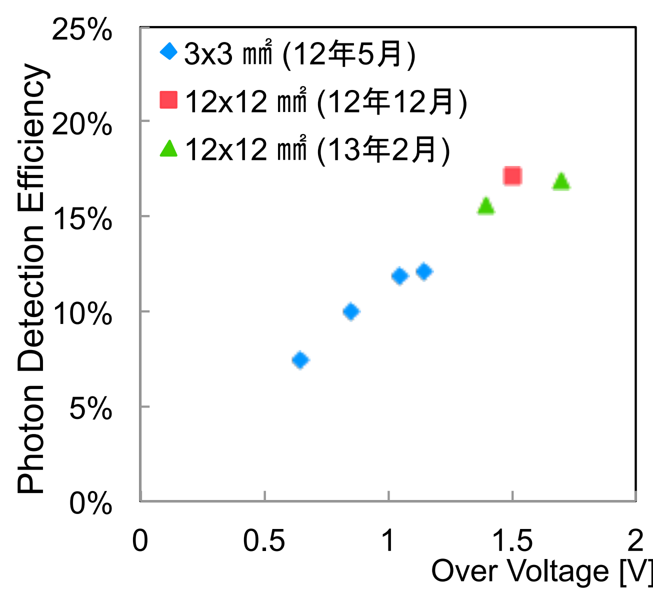
Gamma position resolutions as a function of conversion depth (MEG / MEG II)

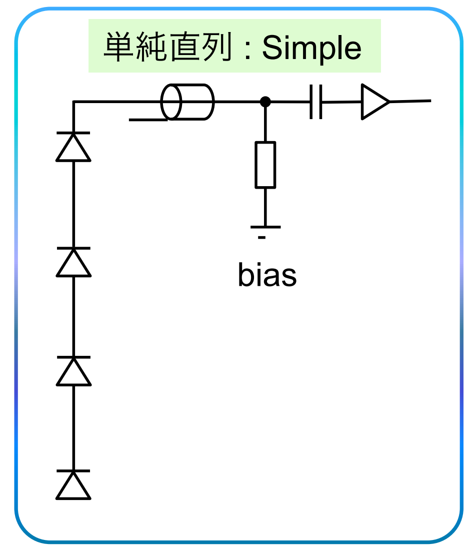


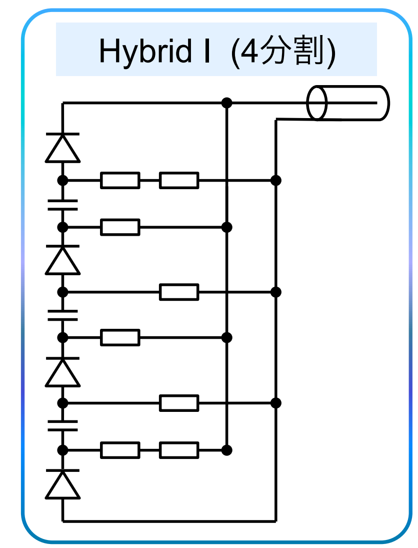
Calorimeter Upgrade (2/2)

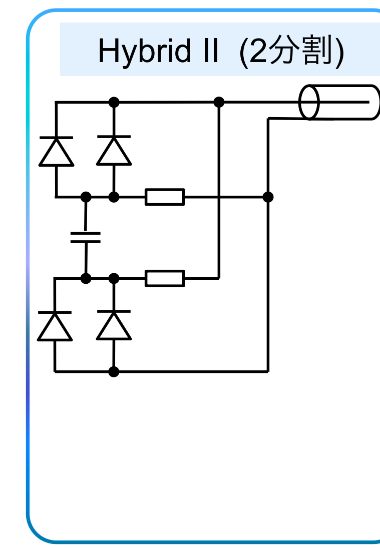


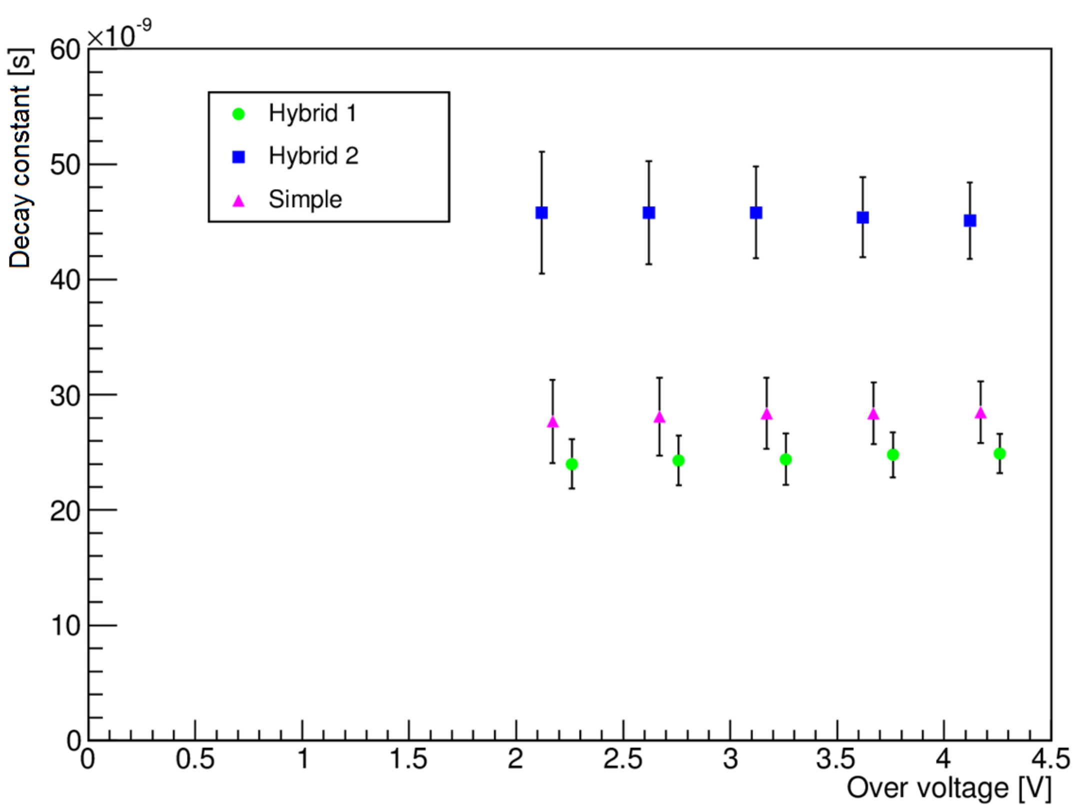
Large area VUV-sensitive MPPC(12×12 mm^2) is being developed in collaborating with HPK, (17% of PDE has been achieved in the study by using the prototype)
- Final parameter optimization is ongoing











Recent activities:
- Decay time optimization

⇒ MPPC connection is changed: parallel → series

Decay time: 200ns → 50ns

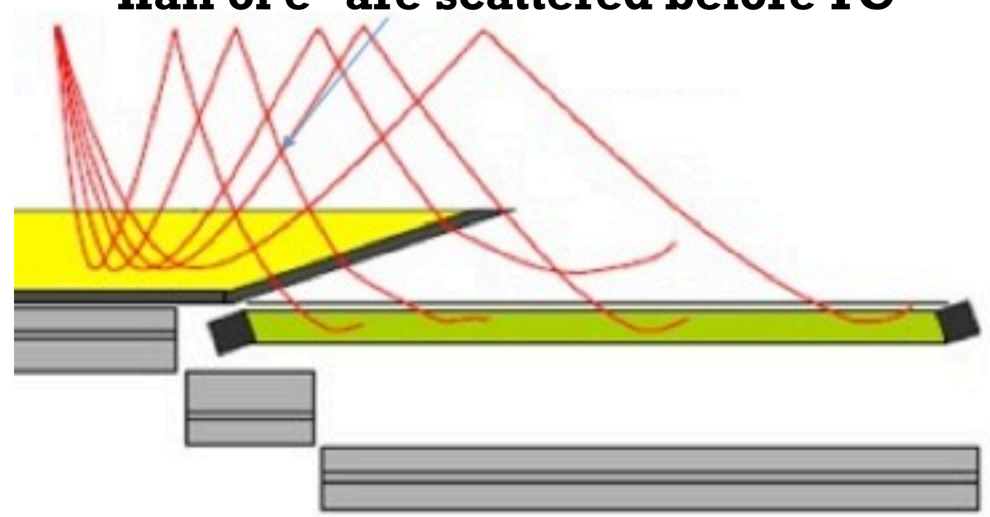
- Design of the final detector (almost done)

Next step → **Test with a prototype detector using 600 MPPCs**

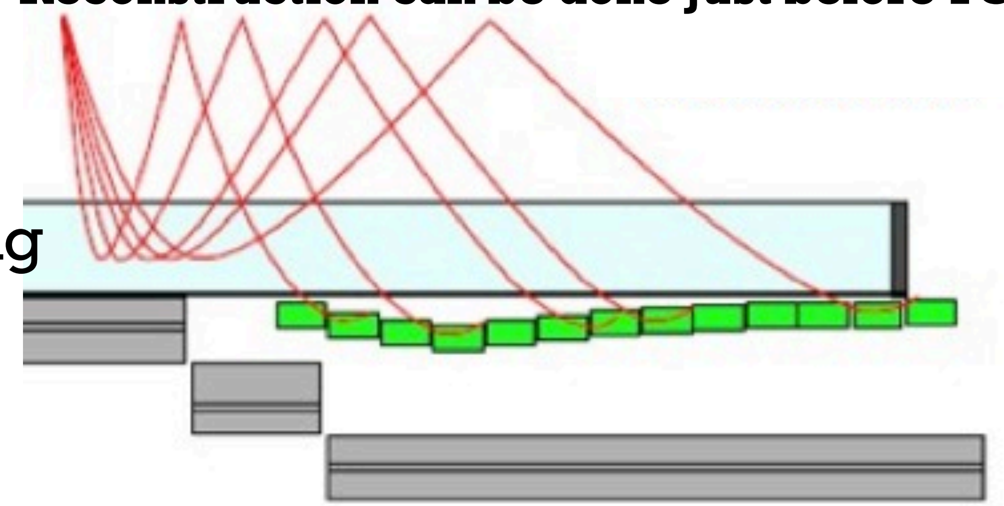
Tracker Upgrade (1/2)

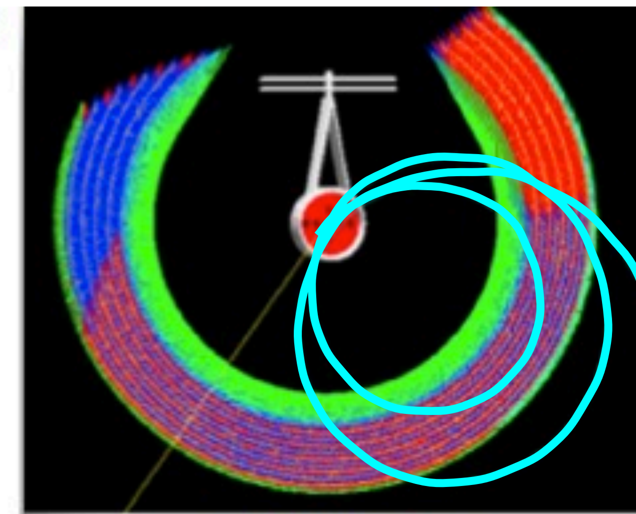
- Rate issue should be solved
  - Present DC cannot be operated
- Poor efficiency (40%) should be recovered
- **Upgrade concepts**
  - Single gas volume
    - Reduce materials of walls
  - Wider coverage
    - Twice higher efficiency
  - Larger #of hits (25 ⇒ ~60)
    - Improve the resolutions
  - ***Z*** position is determined by using stereo wire angle

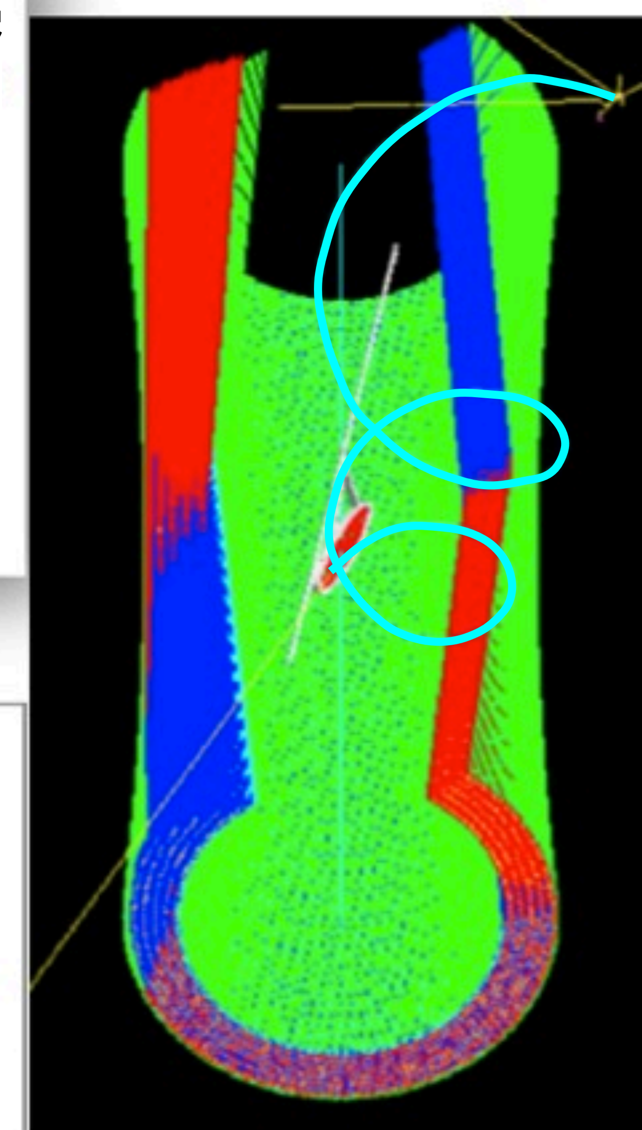
Half of e^+ are scattered before TC



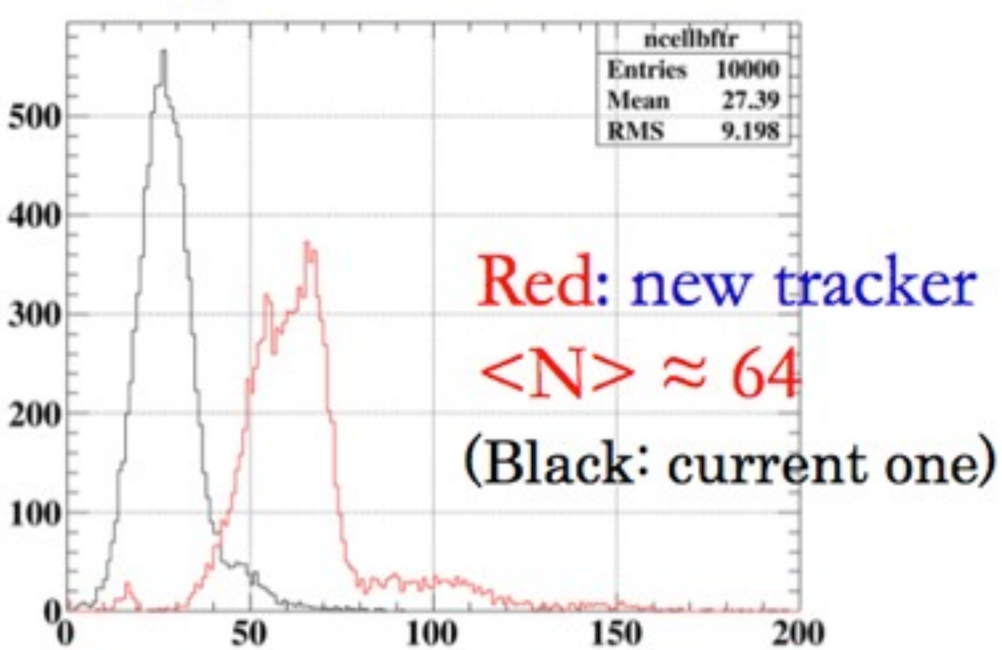
Less materials in between CDC & TC
Reconstruction can be done just before TC







Large number of hits



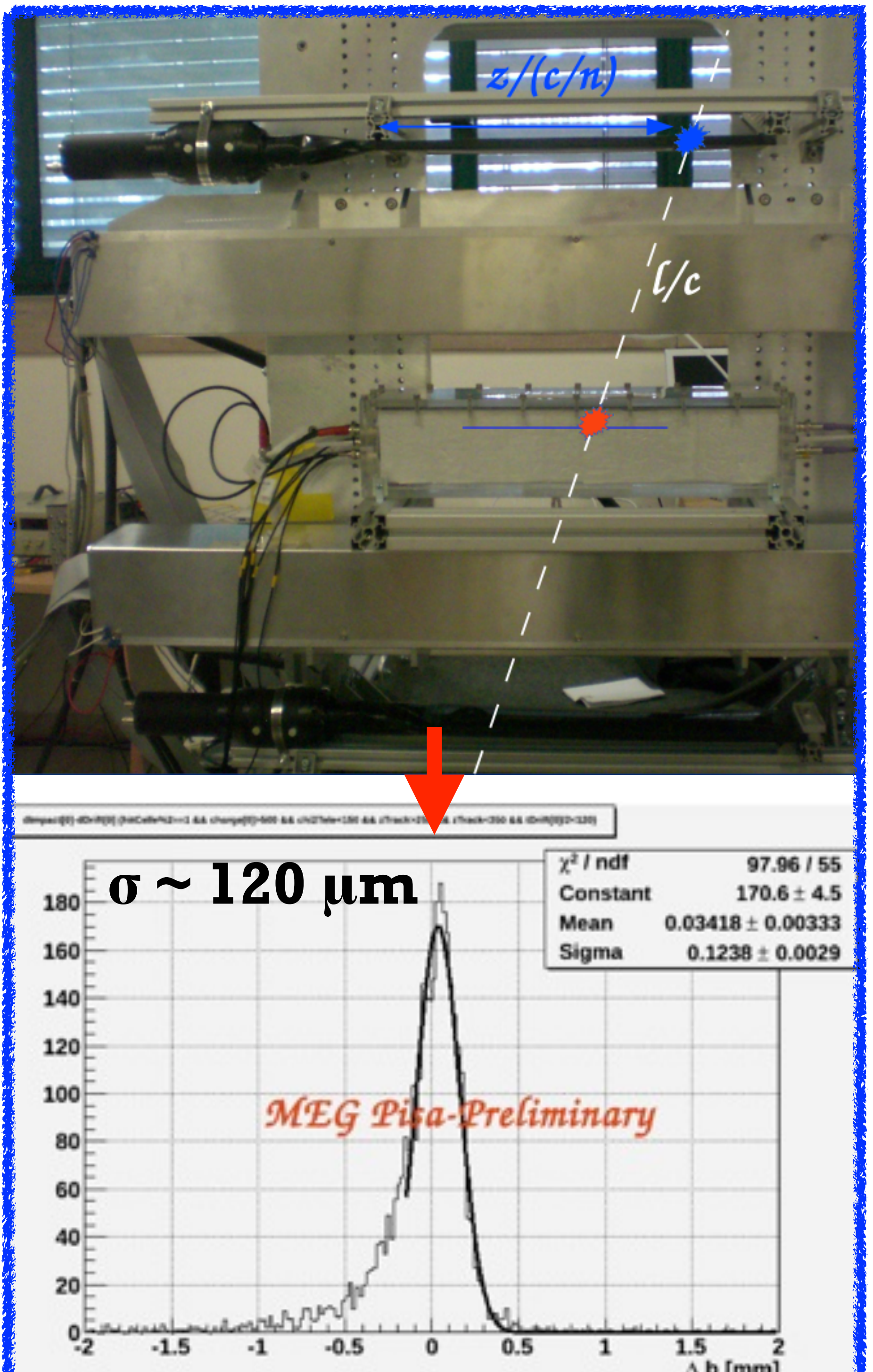
Expected Performance

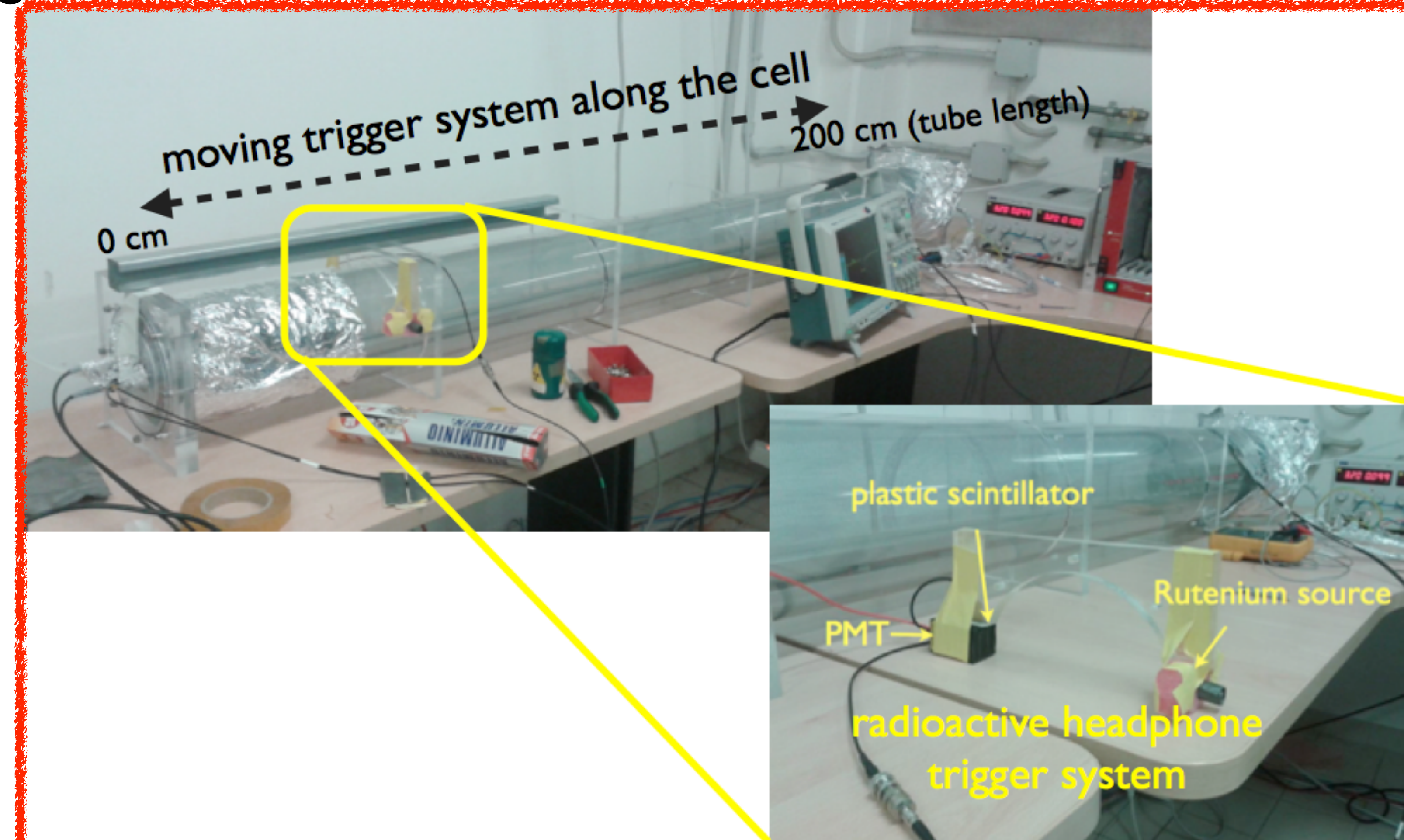
Momentum ~130 keV (350 keV)
Angular ~5 mrad ; ~5mrad
(9mrad ; 11mrad)
Vertex ~1.2 mm ; ~0.7 mm
(1.8 mm ; 1.1 mm)
DC-TC matching eff. ~ 90 % (41%)

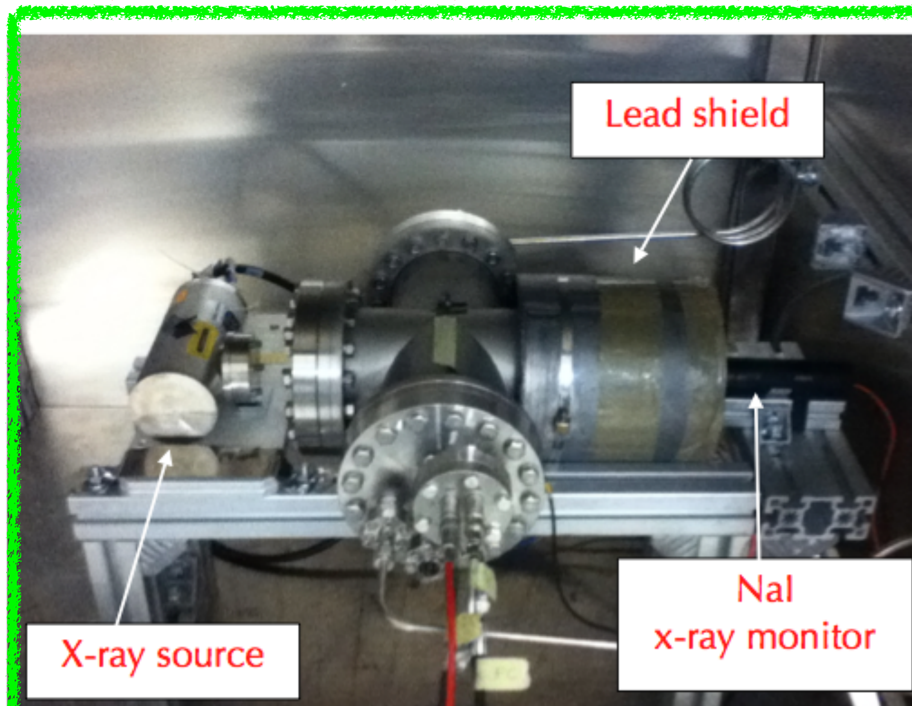
Tracker Upgrade (2/2)

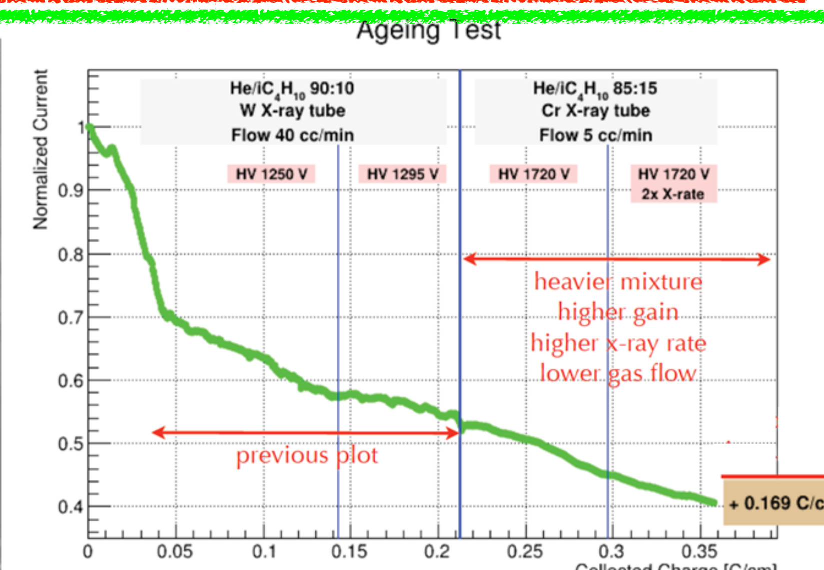
Several prototypes of CDC is being constructed to

1. check the single hit resolution
2. check the mechanical stability
3. aging test



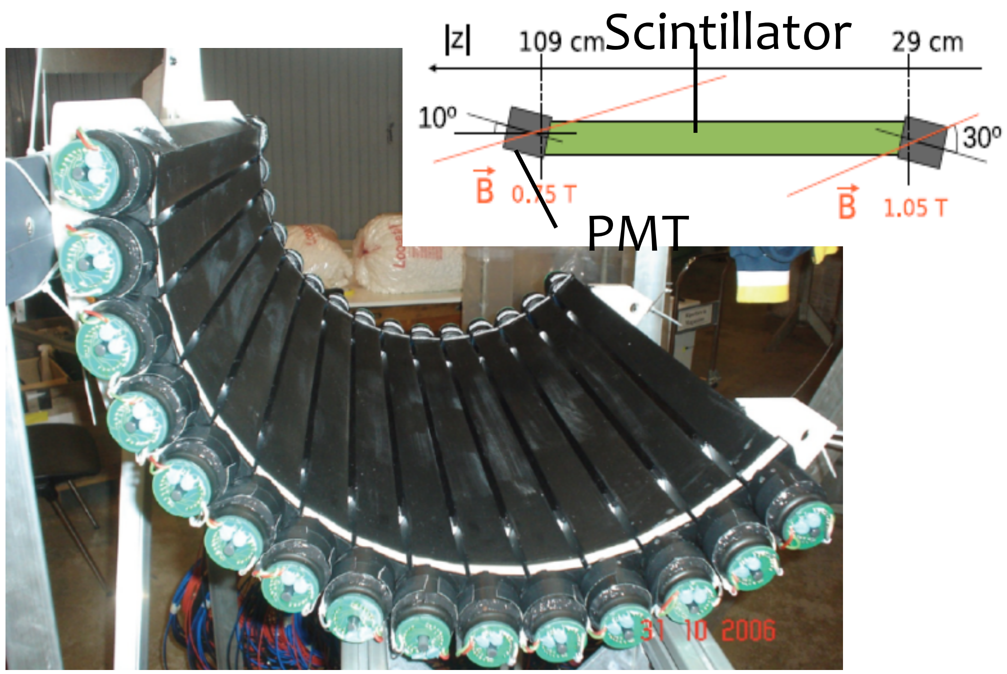




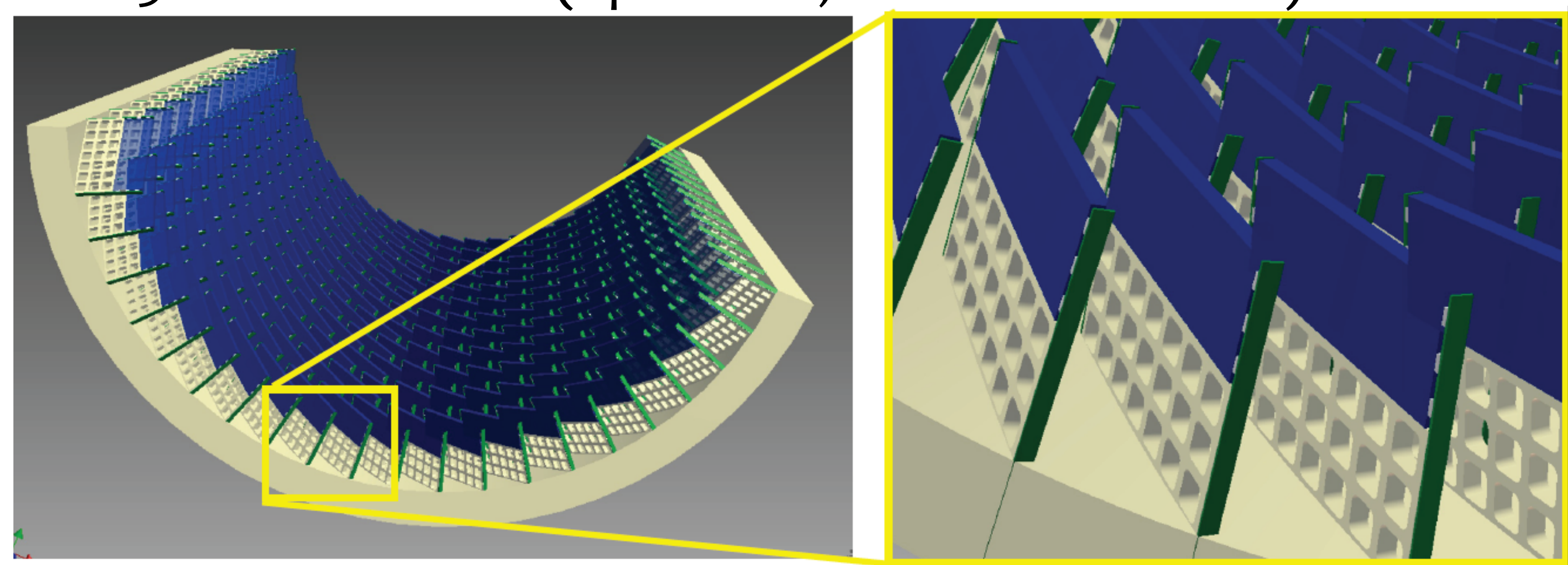


Aging test is being done by using high power X-ray source
No severe problems are found

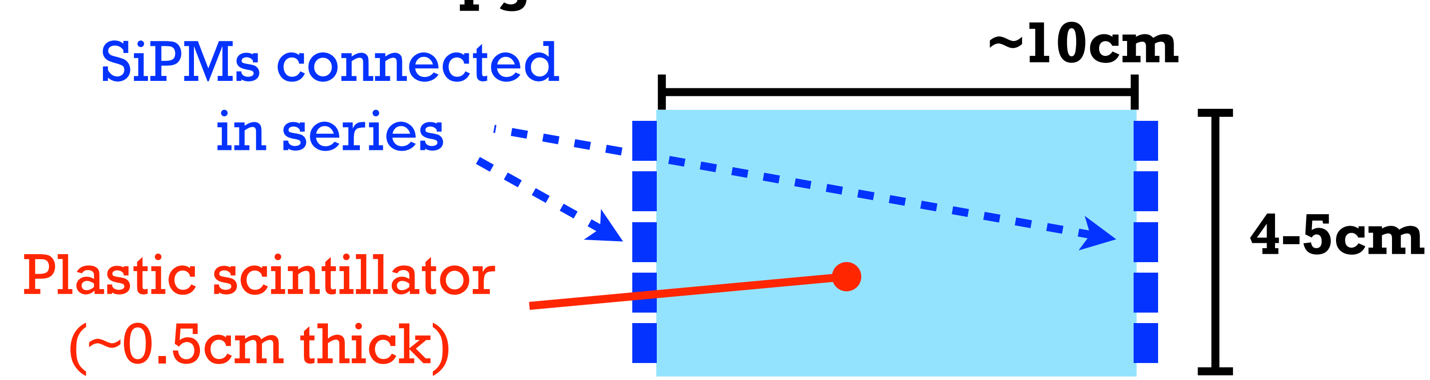
Timing Counter Upgrade (1/2)

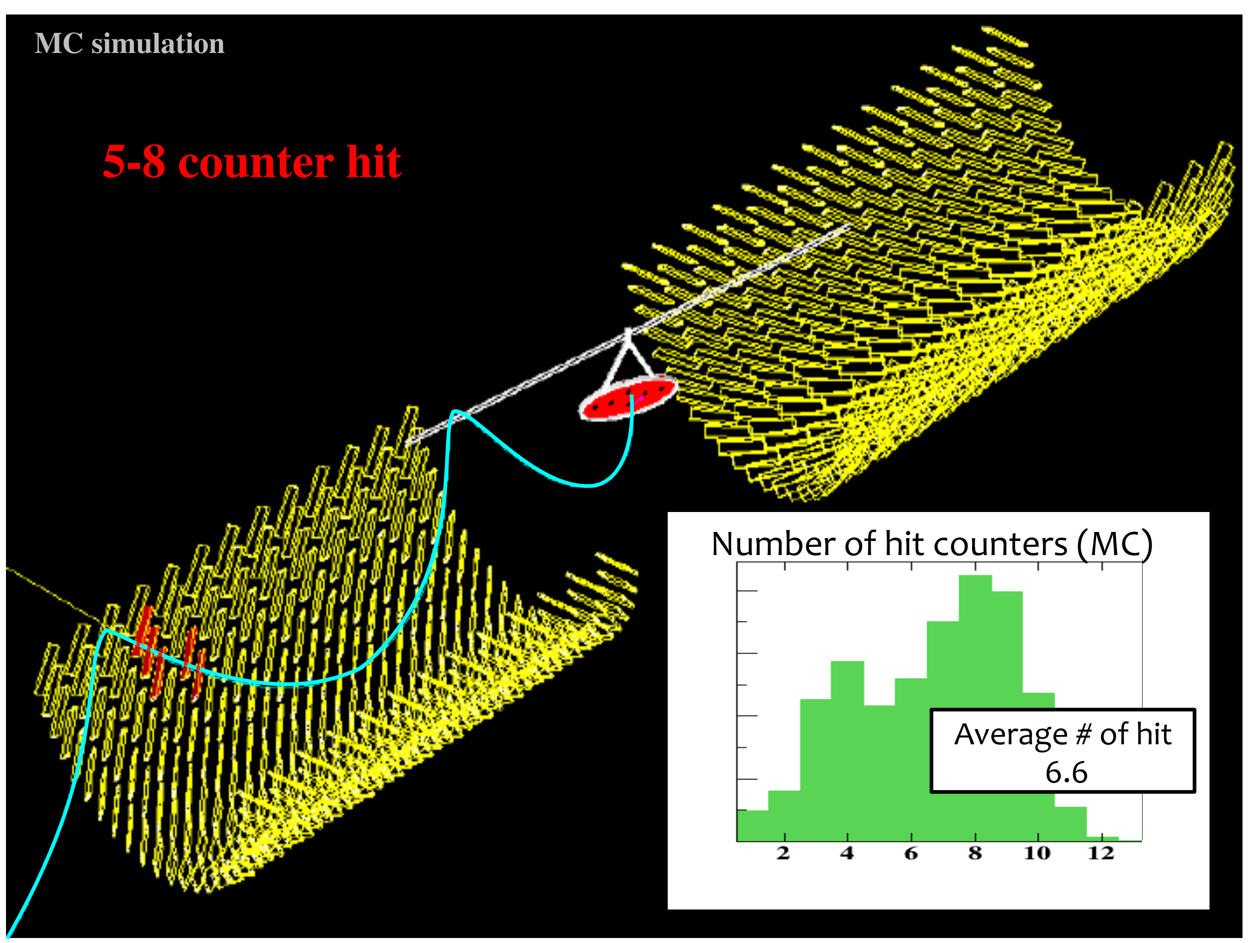


~250 counters ×2 (upstream, downstream side)



Present **Upgrade**

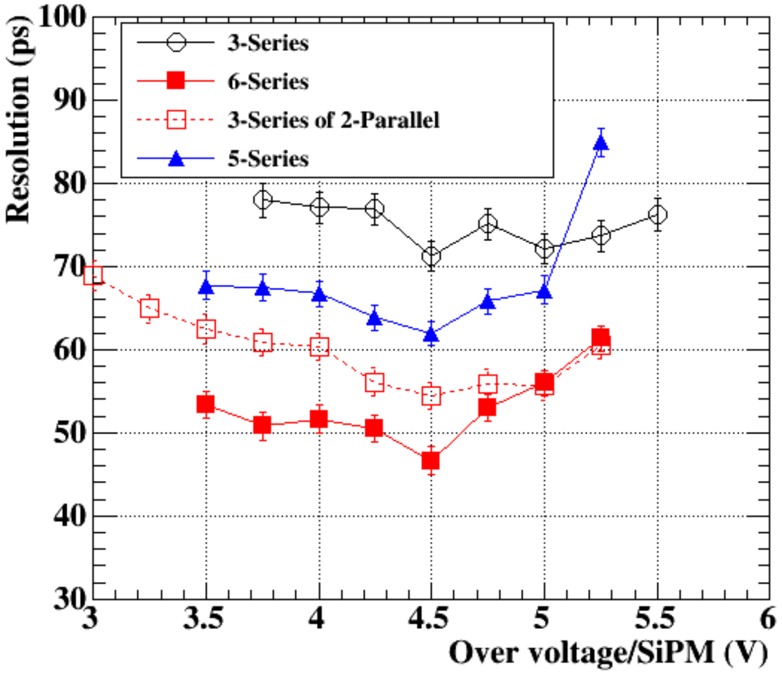




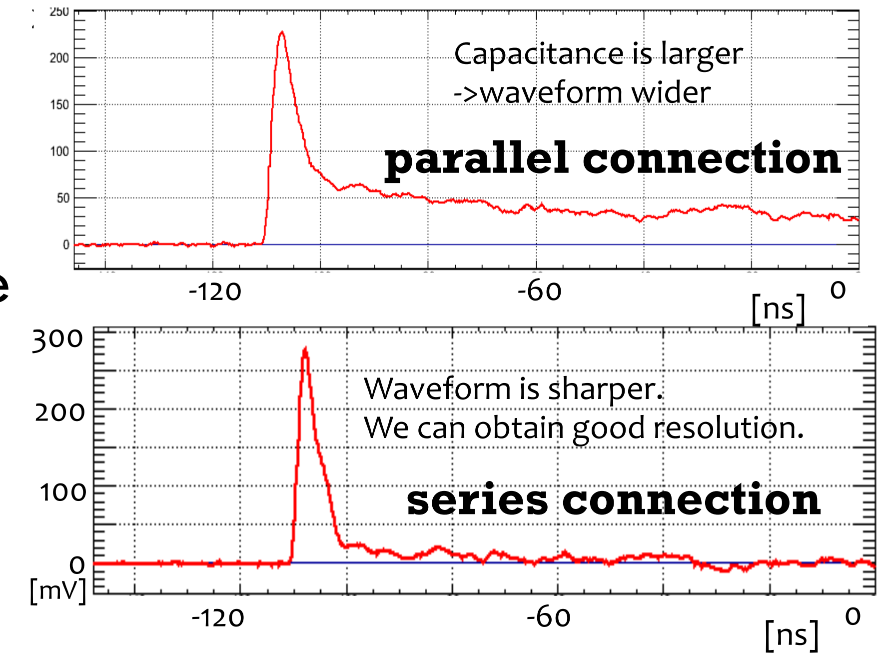
Pixelated ~600 scintillation counters will be used

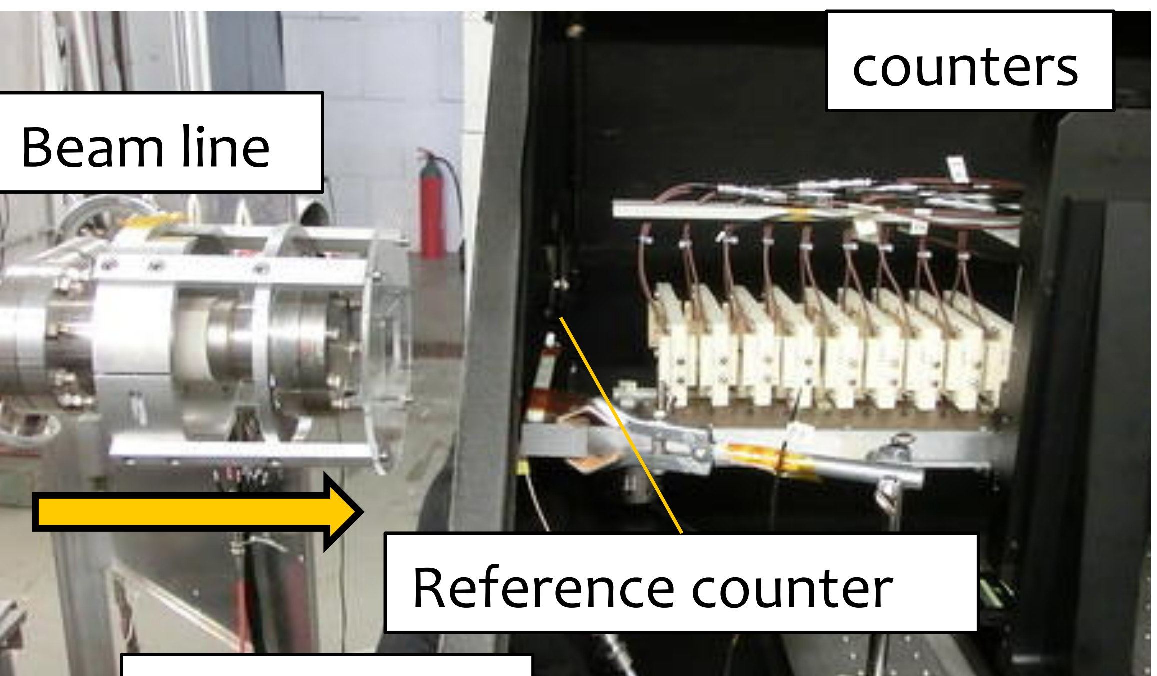
1. Less pileup events in one counter
2. Improve time resolution by combining multi-counters' time measurements
3. High flexibility for the detector arrangement
4. Scintillation photons are detected by using silicon photomultipliers (SiPM)

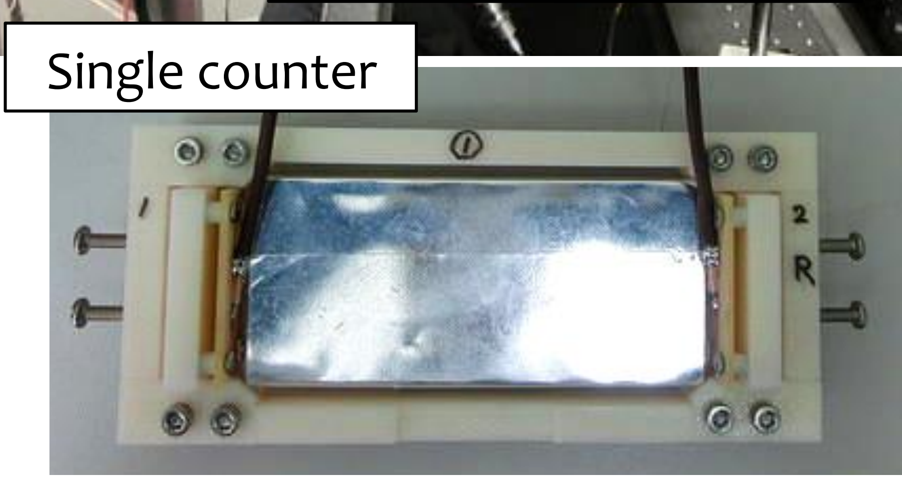
Timing Counter Upgrade (2/2)



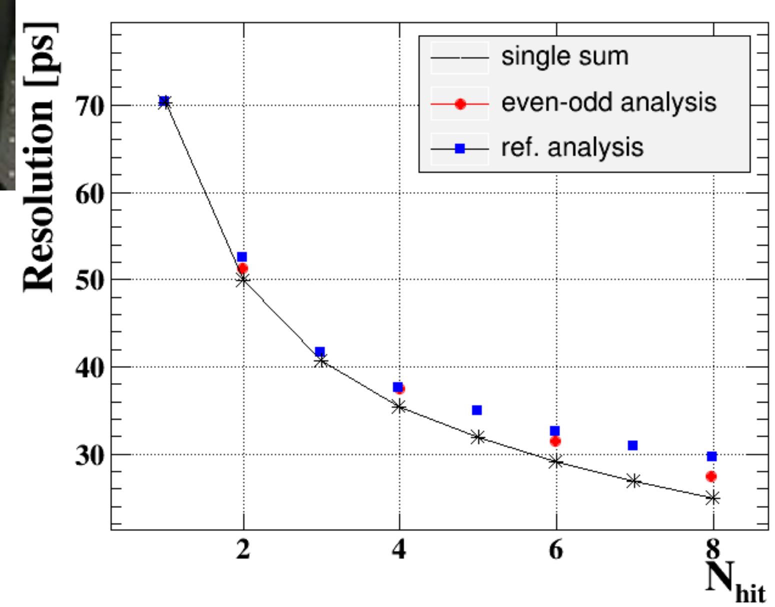
- Optimization of photo-sensors
  - Connection of 6 Advan SiD SiPMs is found to be optimum
  - Series connection helps to reduce the number of channel while keeping enough photo-statistics
- Check the multi-counter scheme







Beam test was done in 2013 @ Frascati
- Multiple hit scheme was validated !
- <40ps resolution was obtained by combining 6-7 hits



Next step

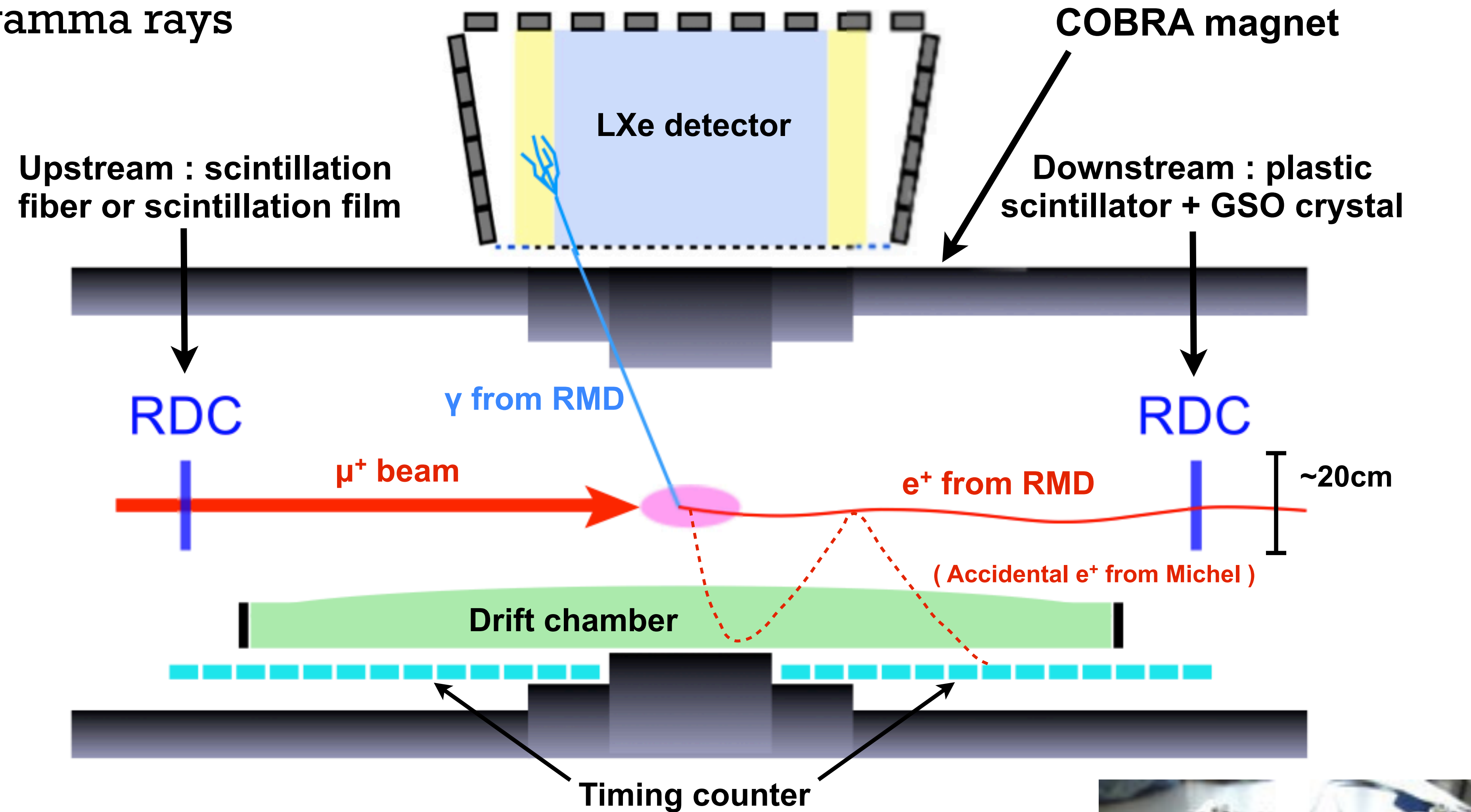
Construct the larger prototype and test in more realistic condition

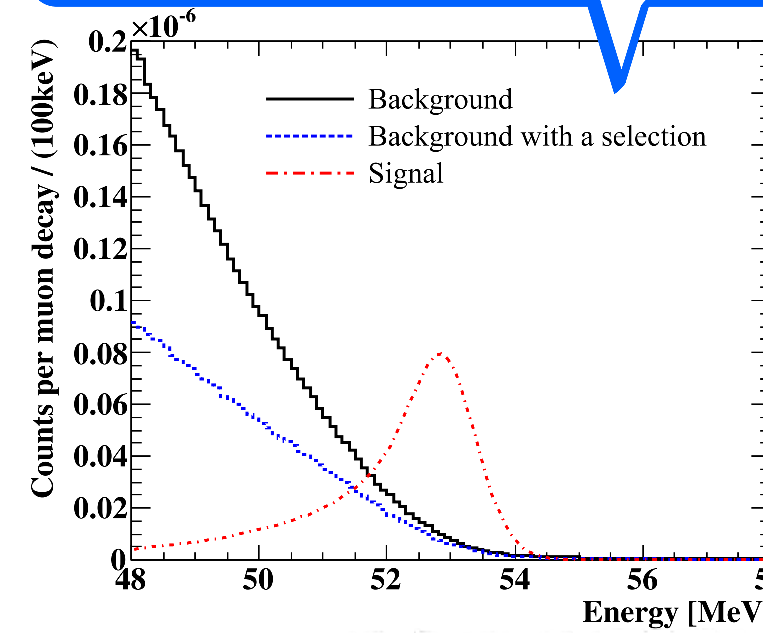
Radiative Decay Counter

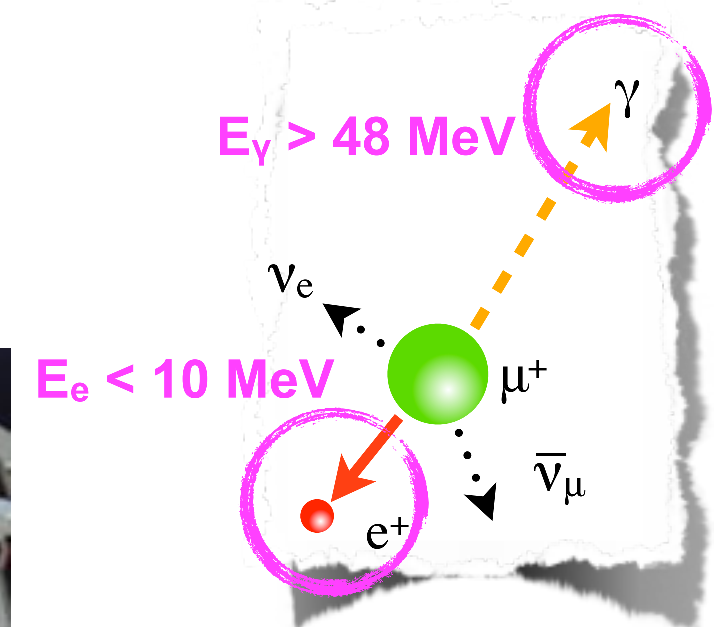
Optional

Tagging the RMD background which is the main gamma ray background by detecting the low momentum positrons coinciding with gamma rays

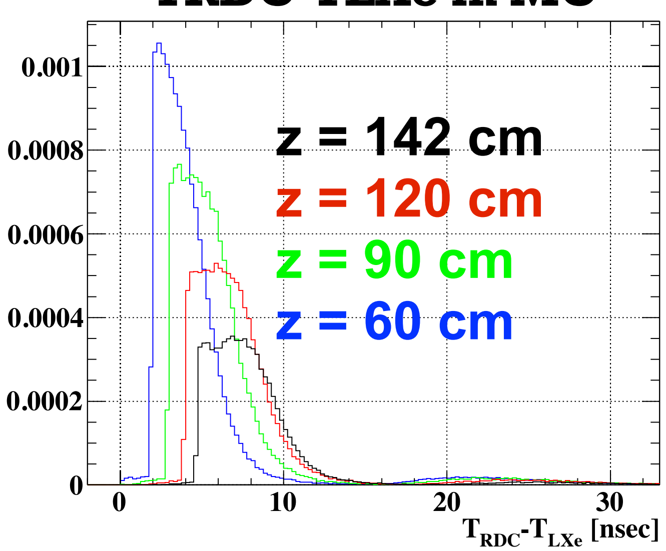
10-15% expected sensitivity improvement in MC !



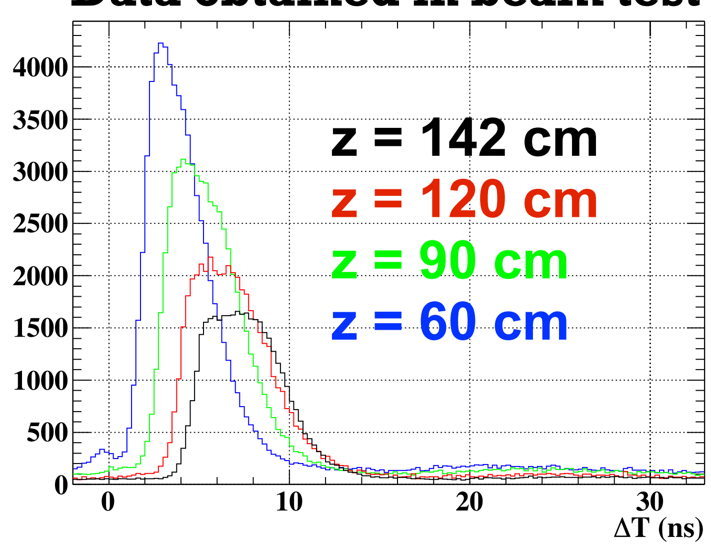


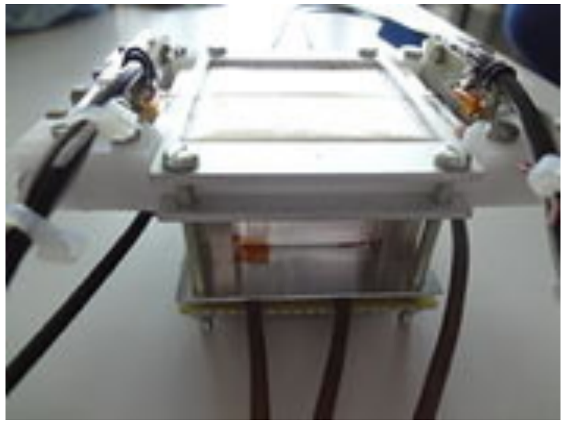


TRDC-TLXe in MC



Data obtained in beam test



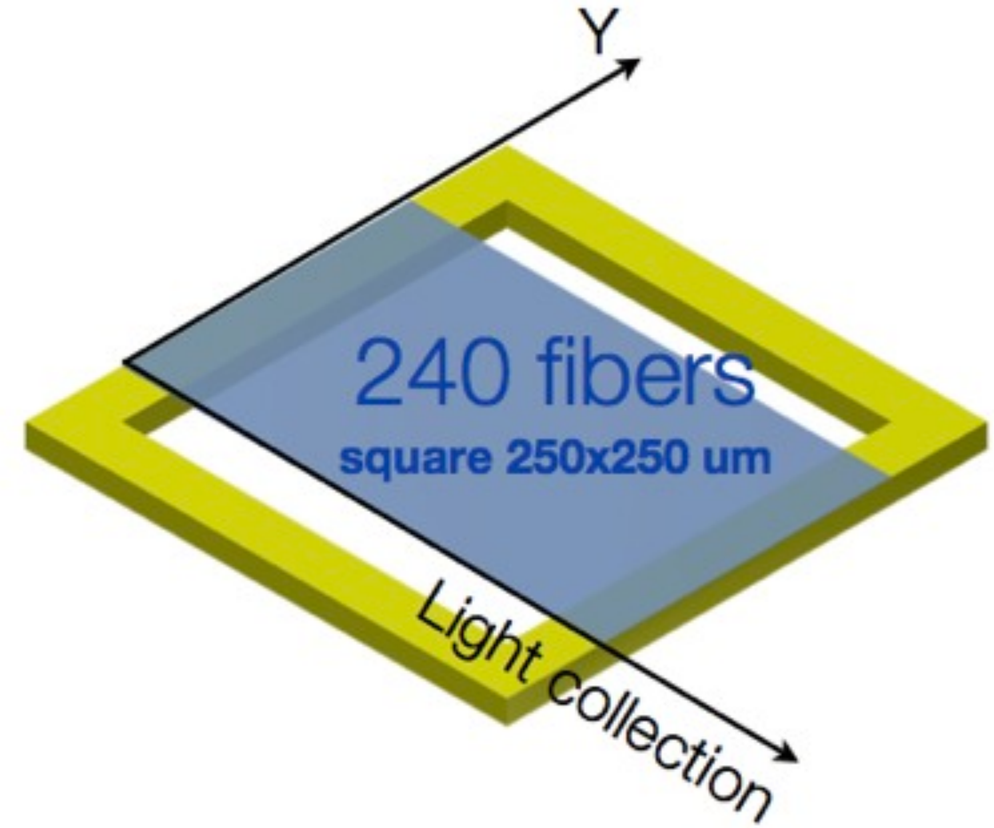


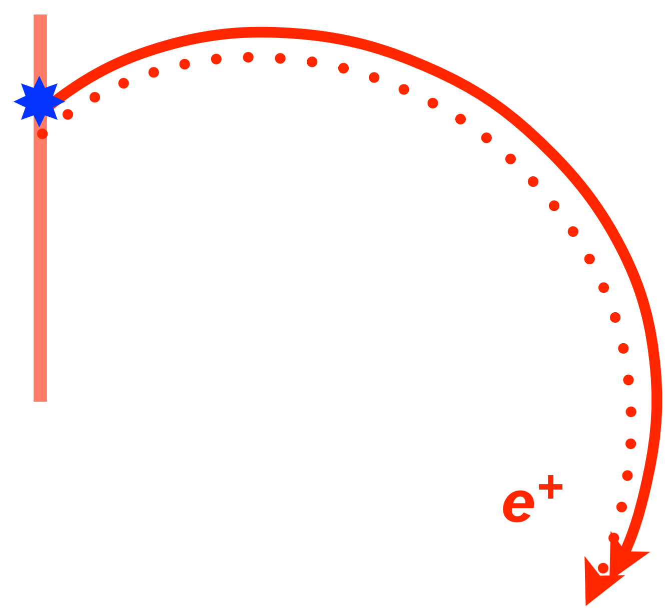
Beam test using small prototype was done in 2013 and validated that BG tagging is available as an expectation from the MC study

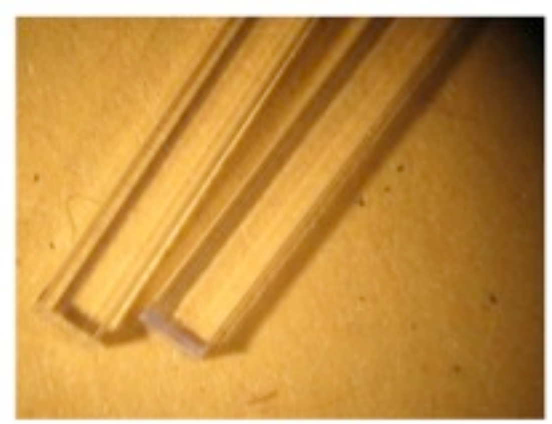
Active Target Optional

Active target using scintillation fibers is proposed to measure the 1D position of the emitted positrons

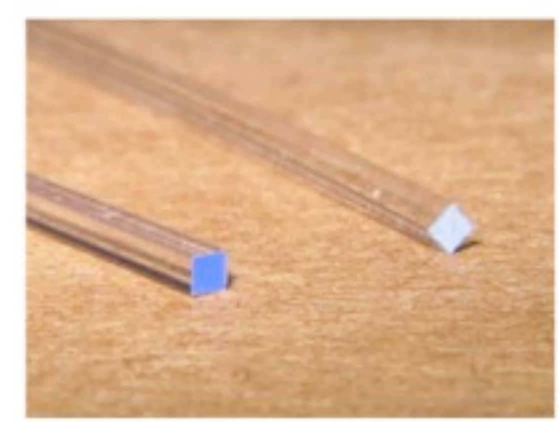
- Decay vertex can be determine more precisely
  ⇒ better angular and momentum resolutions
- Scintillation light will be read by SiPMs
- Efficiency is important key



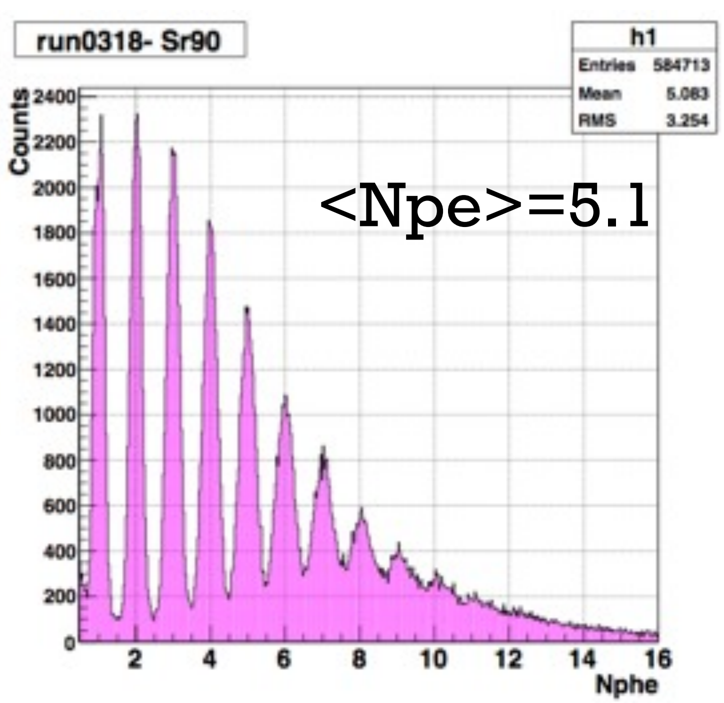




Not polished and polished

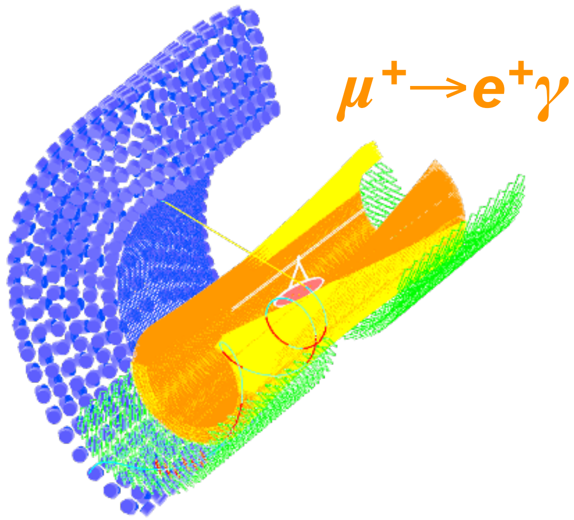


Not Al and with 30nm Al deposit

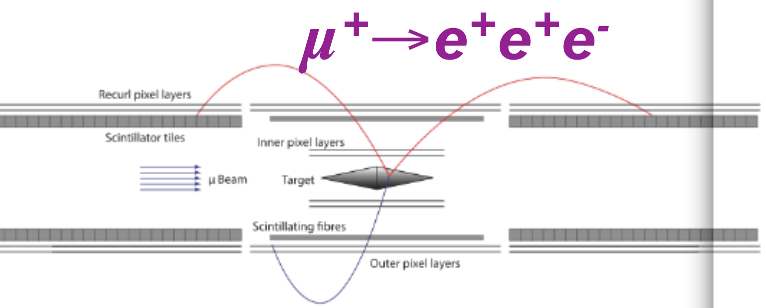


80% efficiency was obtained
- Aluminum coating, 1-sided readout
- 90% with 2-sided readout (to be discussed)

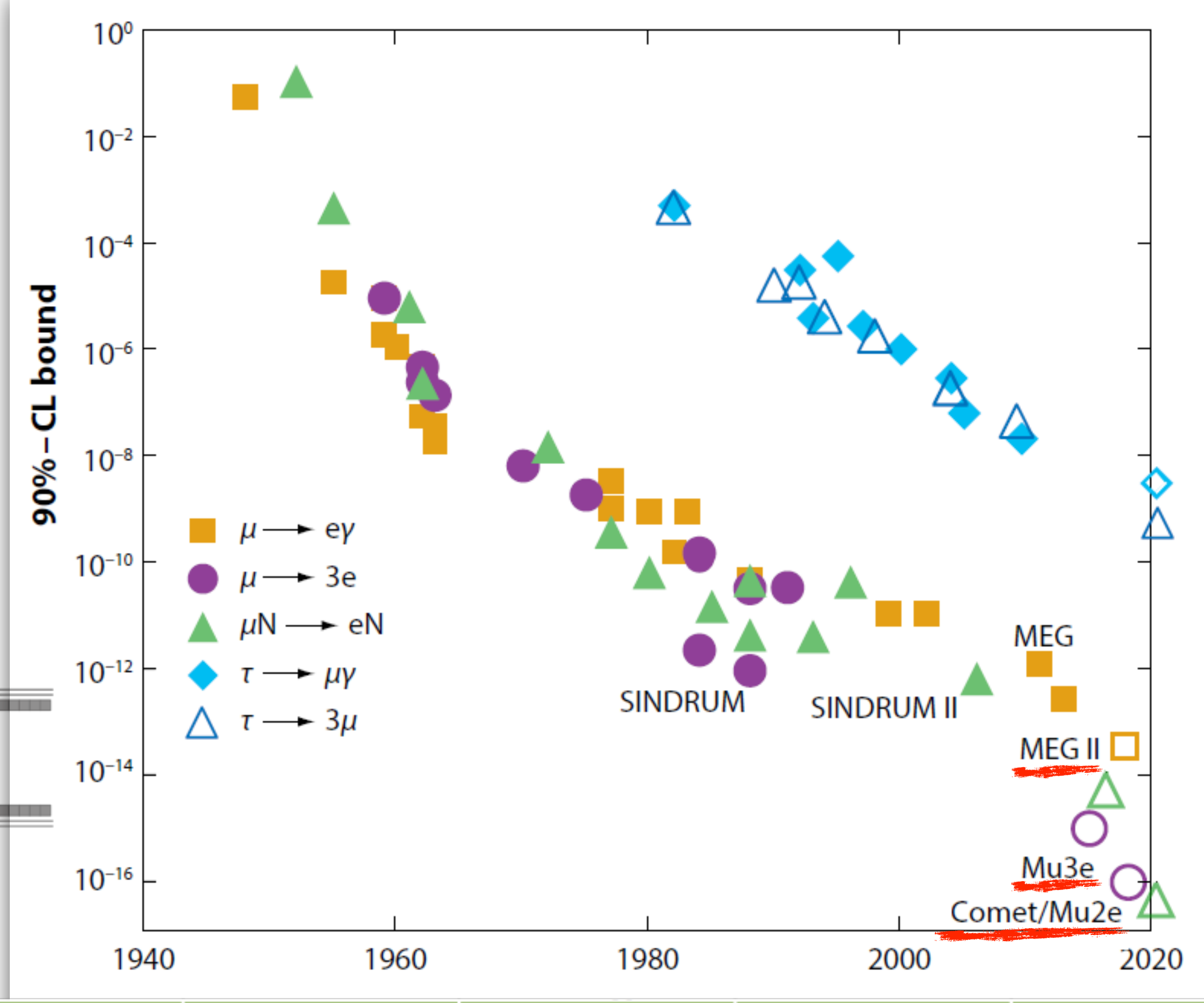
New Era of CLFV Searches !

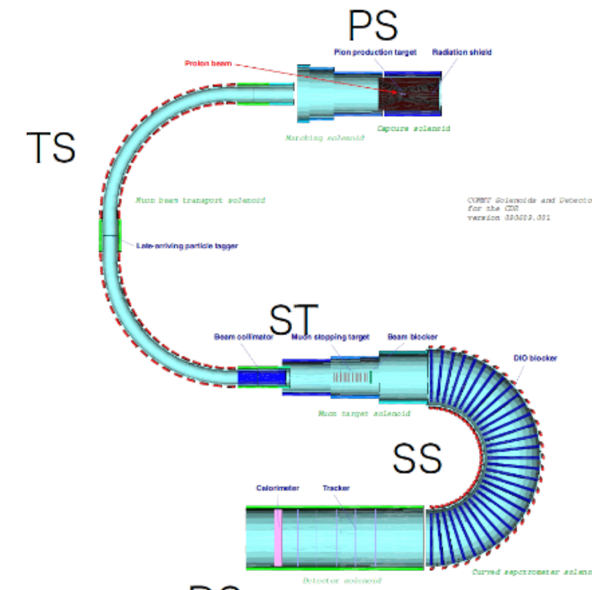


MEG II



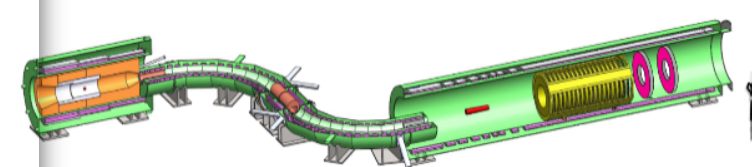
Mu3e



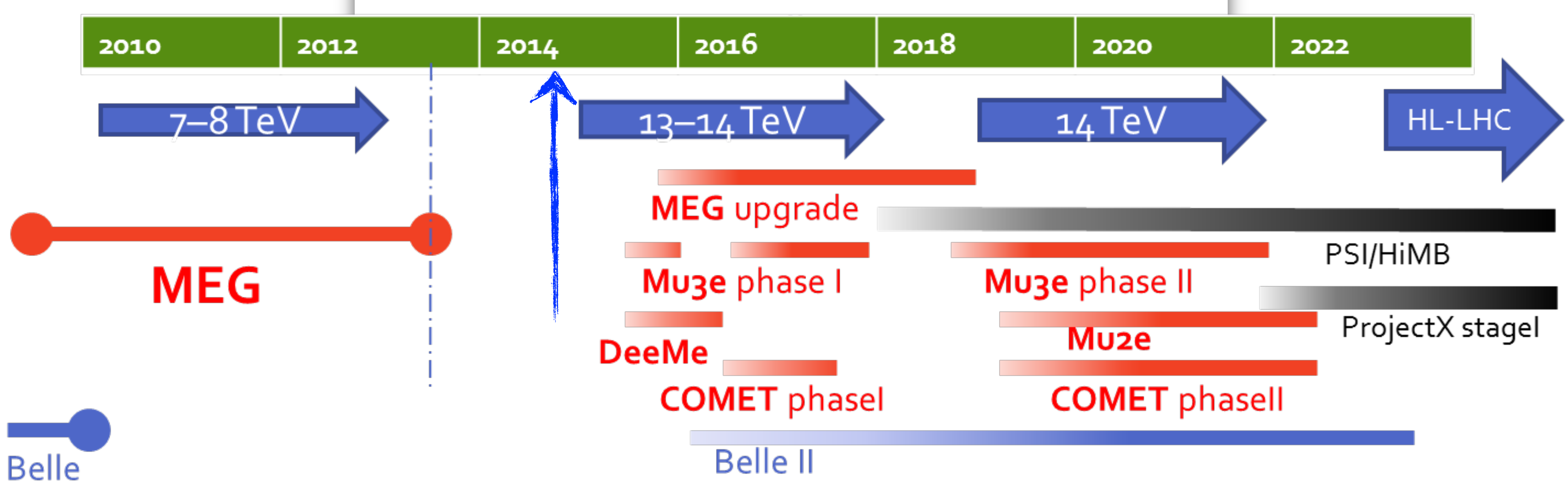


COMET

$\mu^- N \rightarrow e^- N$



Mu2e



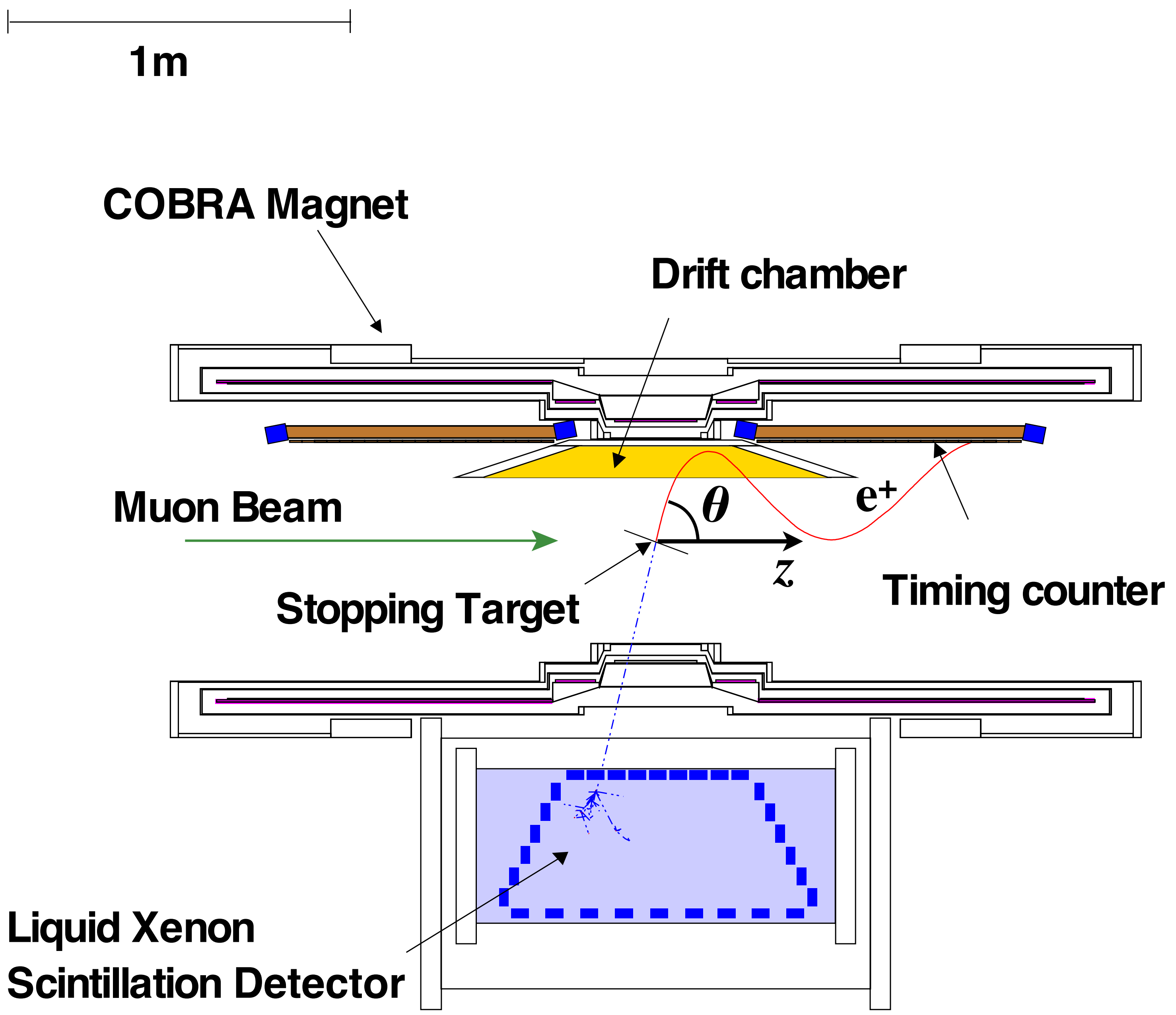
Summary

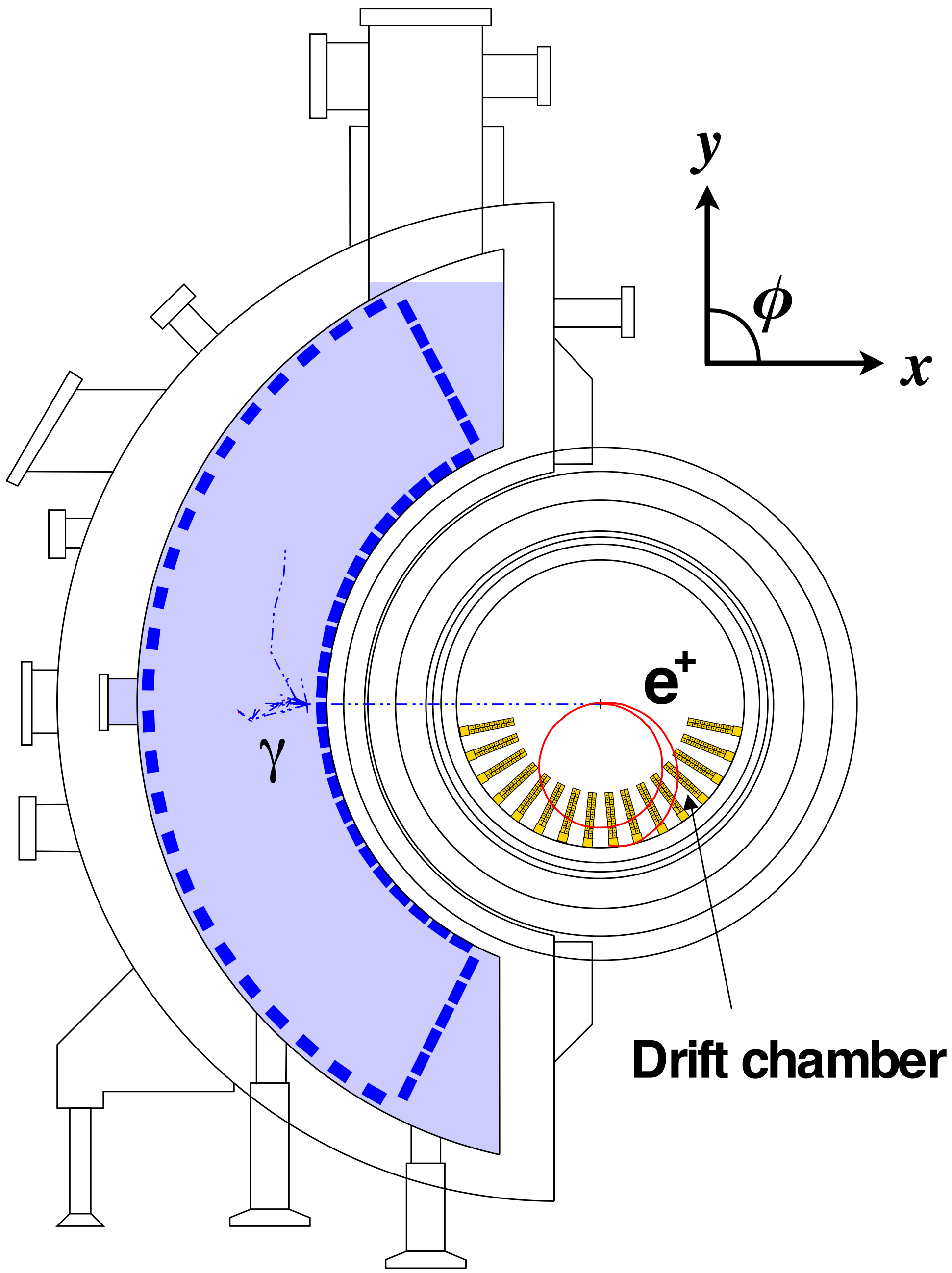
- **The $\mu^+ \rightarrow e^+\gamma$ decay is one of the powerful probes to investigate the BSM**
- **Most stringent upper limit on LFV processes is set by MEG**
  - **$B(\mu \rightarrow e\gamma) < 5.7\times10^{-13}$ @ 90% C.L.**
- **Final result of MEG (phase-I) will be published soon**
  - Expected sensitivity: **5×10^{-13}**
    - Sensitivity will be further improved by adding AIF PDF
- **MEG II proposal was approved by PSI and preparations are ongoing**
  - **Aiming to get 10 times higher sensitivity than that of MEG**
  - All detectors will be improved
    - LXe detector: Inner face PMTs ⇒ VUV-sensitive MPPCs
    - Drift chamber: 16 drift chamber modules ⇒ Stereo wire drift chamber with a single gas volume
    - Timing counter: Bar counter ⇒ Pixelated counter
    - Optional detectors (RDC, Active target) are also being developed to further improve the sensitivity
- **Each detector is being developed on schedule up to now**
- **Data taking will be started in 2016 !**

Backup

MEG Experiment

MEG Apparatus

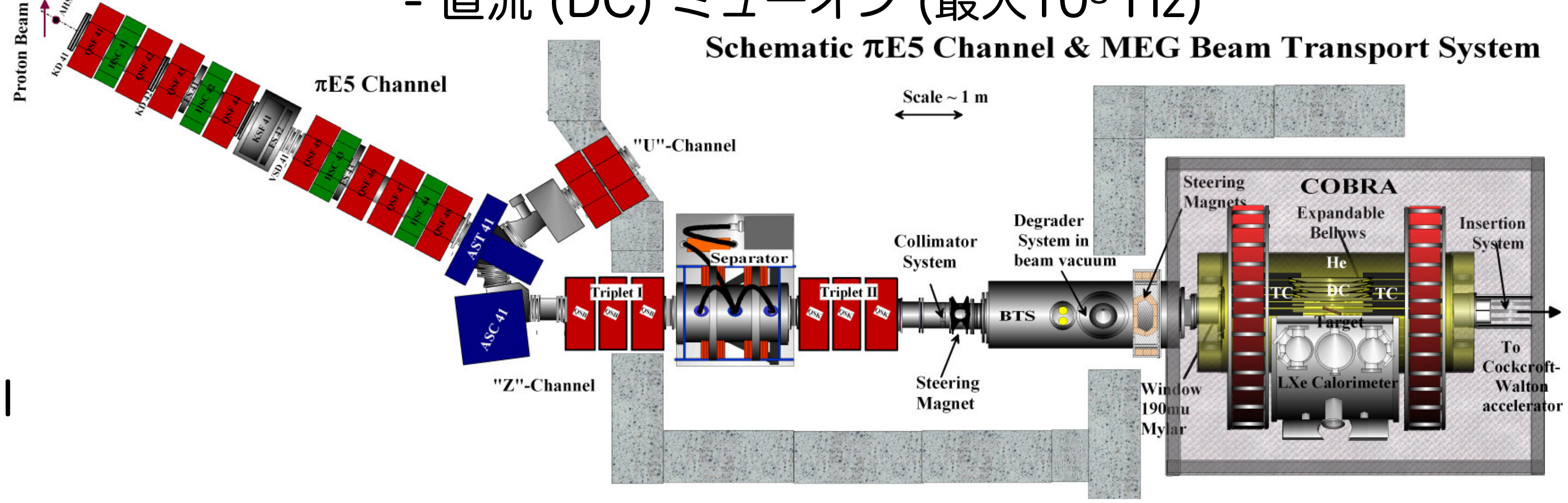




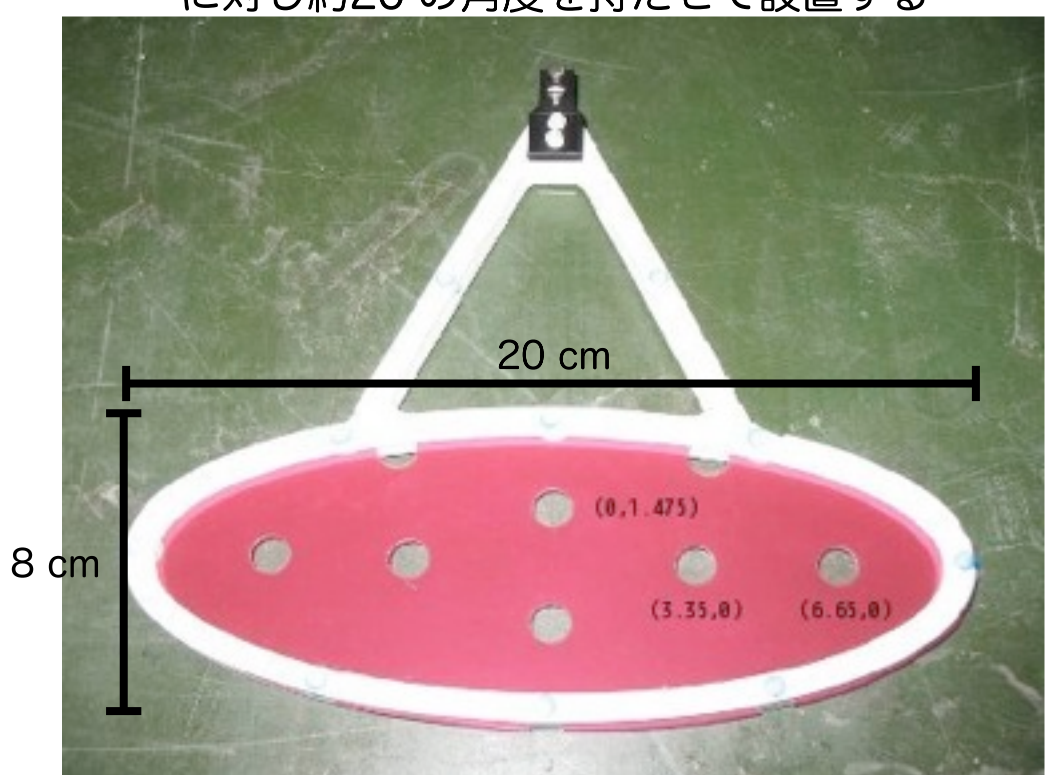
Beam & Target

世界最大強度の陽子リングサイクロトロン @ PSI
- 1.3 MW (2.2 mA) with a 590 MeV energy
- 50.6 MHz frequency

ミューオンビーム輸送系
- 運動量の揃った表面ミューオンのみを選別
- 直流 (DC) ミューオン (最大10^8 Hz)

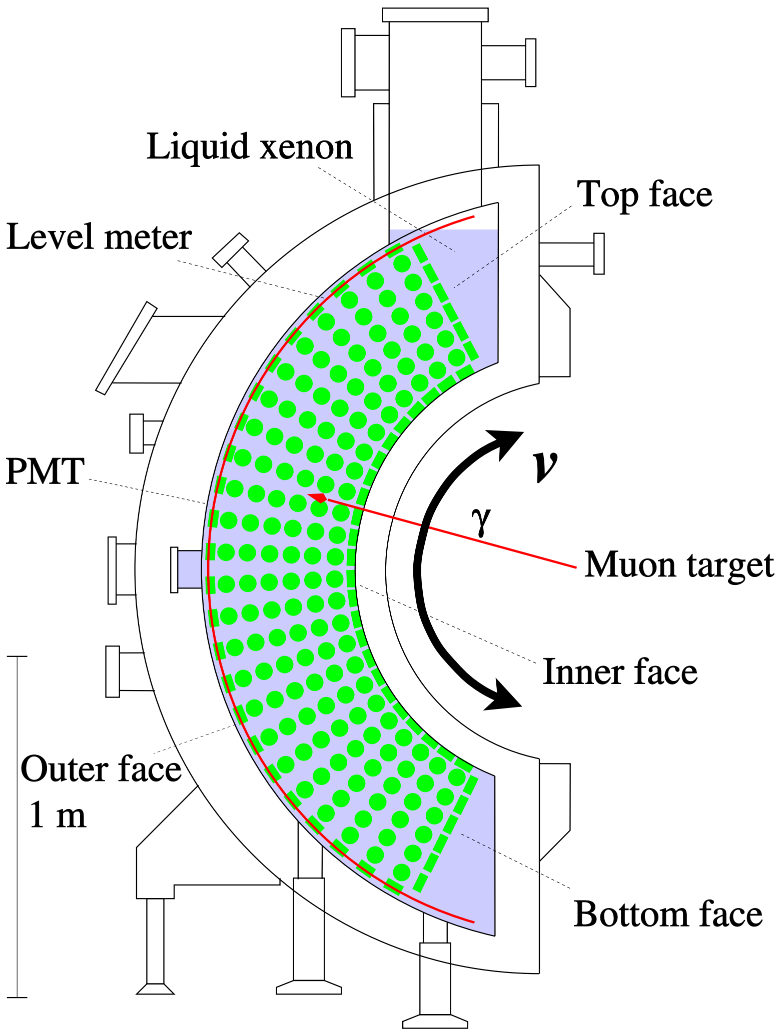


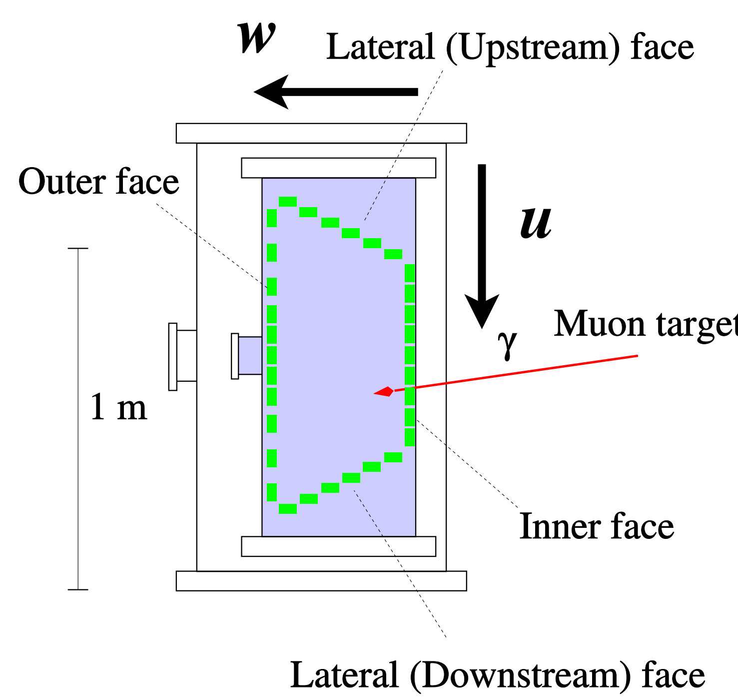
205 μm極薄ターゲット
ミューオン静止能力を稼ぐため, ビーム軸に対し約20°の角度を持たせて設置する



陽電子スペクトロメータ中央に設置された
ミューオン静止ターゲットの様子

Liquid Xenon Detector

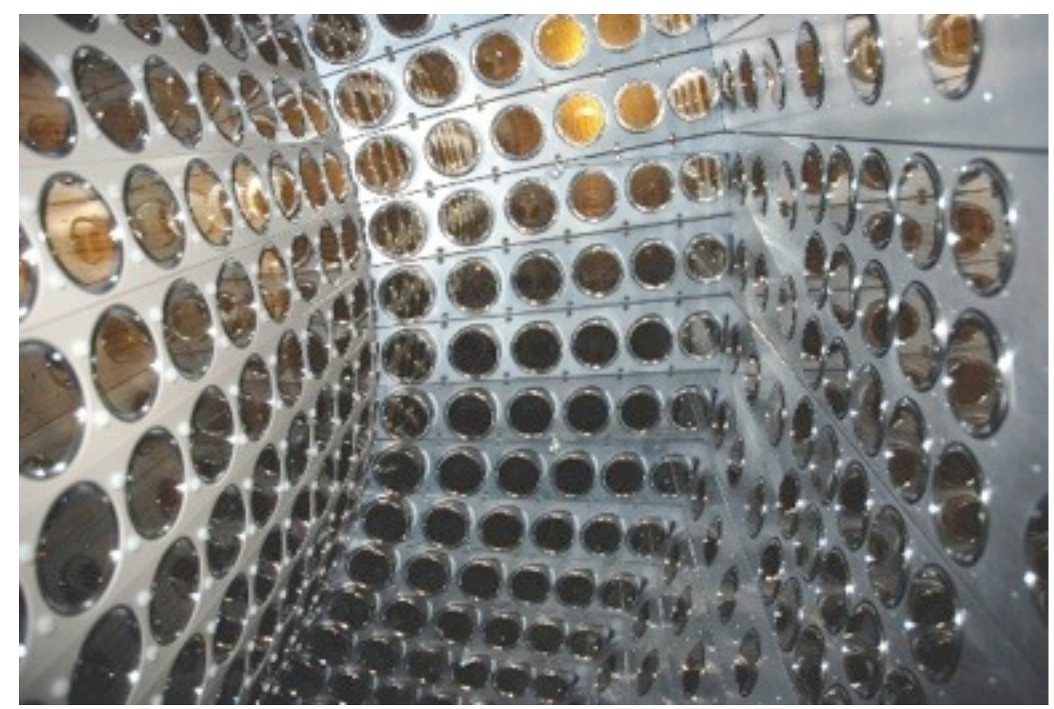




- 液体キセノンの一体型カロリメータ
  - 900 ℓ の大型液体キセノン検出器
  - 結晶シンチのような個体差無し
  - 速い時間応答 ⇒ パイルアップに強い
  - 短い輻射長 ⇒ 高い検出効率
- 短いシンチレーション光波長 (VUV)
  - 従来のPMTでは感度が低い
  - VUVで高い量子効率のPMTを浜ホトと共同開発 (平均16%, 収集効率込み)

➡ 光量分布からガンマ線のエネルギー・位置・時間を全て決定可能

	LXe	LAr	NaI(Tl)	CsI(Tl)	BGO
Density (g/cm^3)	2.98	1.40	3.67	4.51	7.40
Radiation length (cm)	2.77	14	2.59	1.86	1.12
Moliere radius (cm)	4.2	7.2	4.13	3.57	2.23
Decay time (ns)	45	1620	230	1300	300
Wavelength (nm)	178	127	410	560	480
Relative light yield	75	90	100	165	21

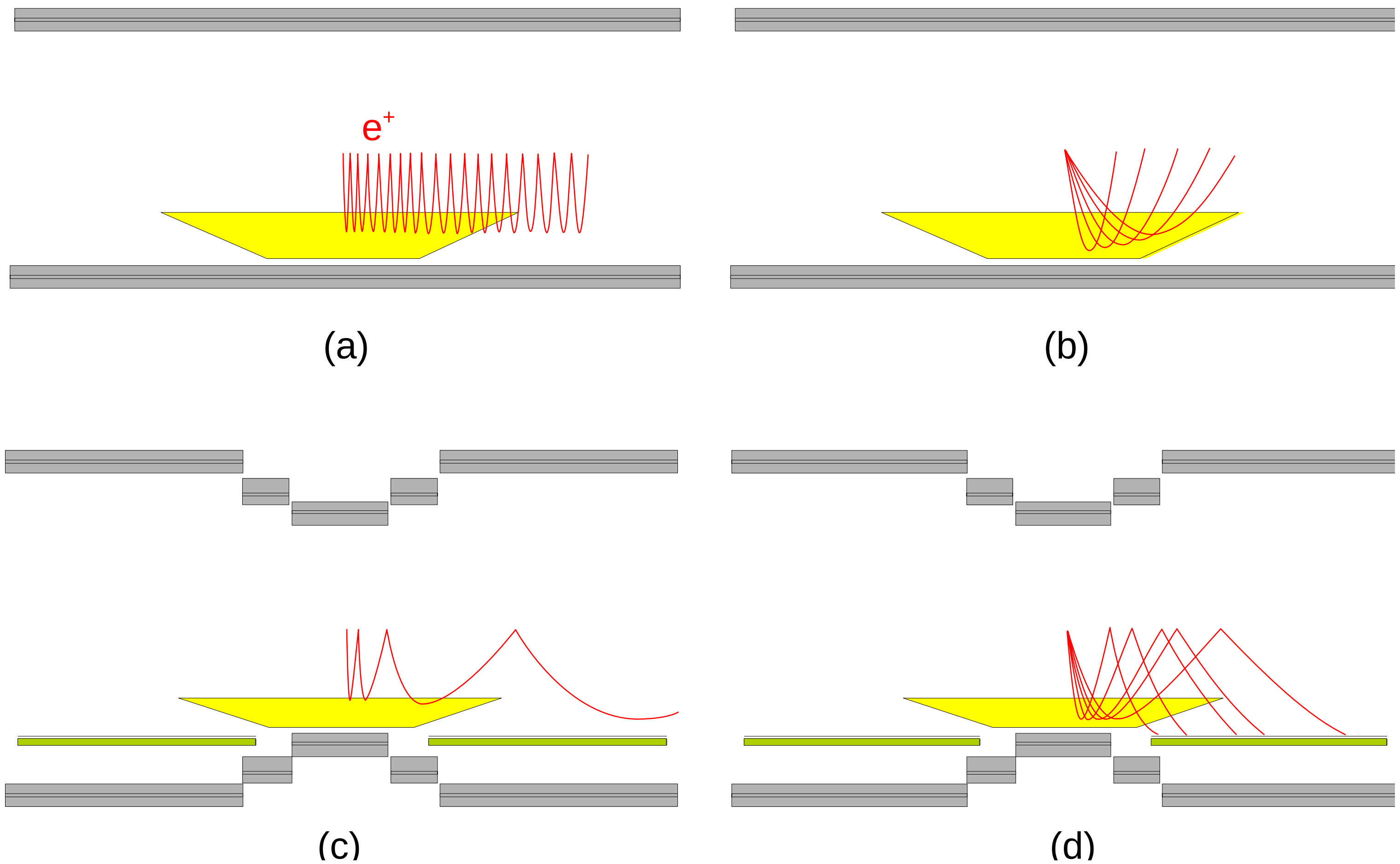


検出器内部の様子

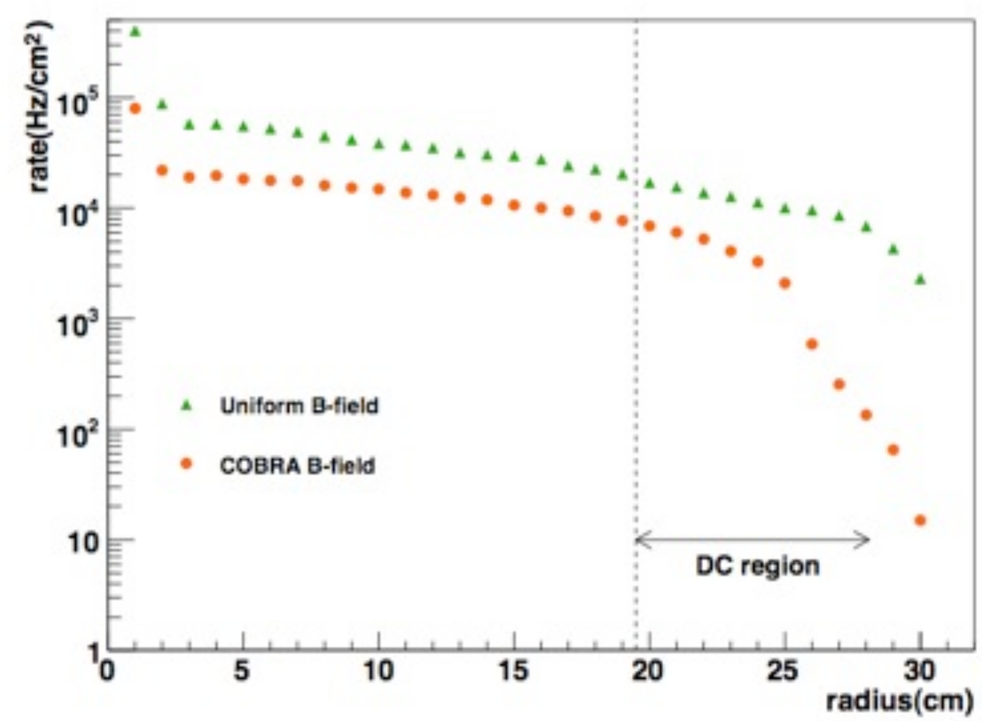
COBRA Magnet

特殊勾配磁場を持つ超伝導磁石による効率的な陽電子選択

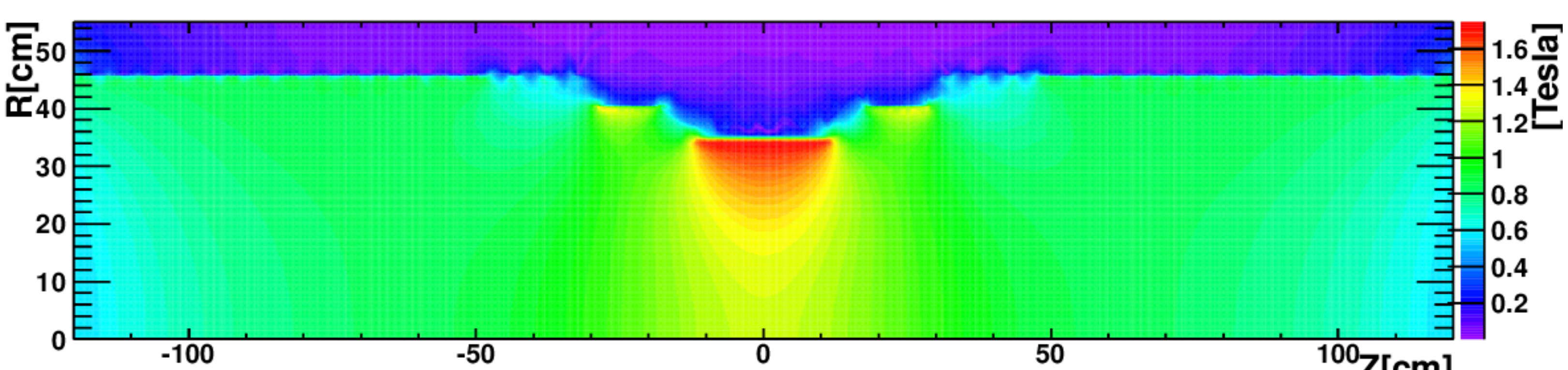
- ステップ構造によって特殊勾配磁場を作る
- 低エネルギー陽電子は素早く掃出しチェンバーのヒット率低減
- 放出角度に寄らず一定の曲率半径
  - COnstant Bending RAdius (COBRA) 磁石の由来
- 内部物質量低減のため, He:Air=95:5の混合ガスで満たす



一様磁場(a),(b)とCOBRA磁場(c),(d)との比較

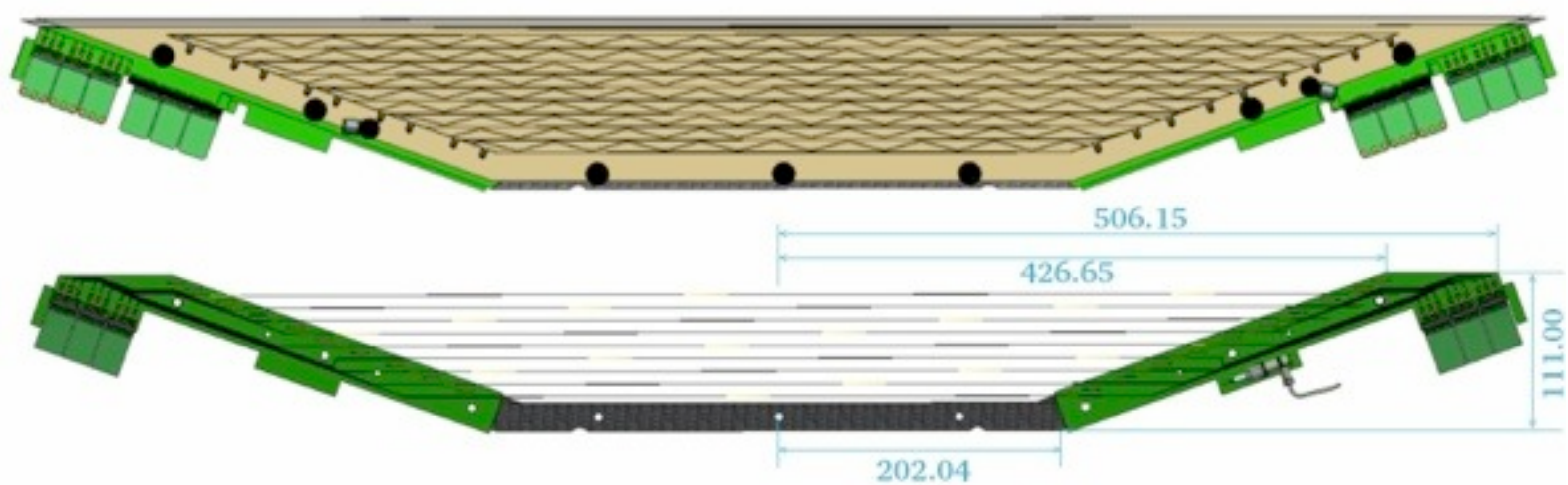


ヒットレートのR依存性
(一様磁場との比較)



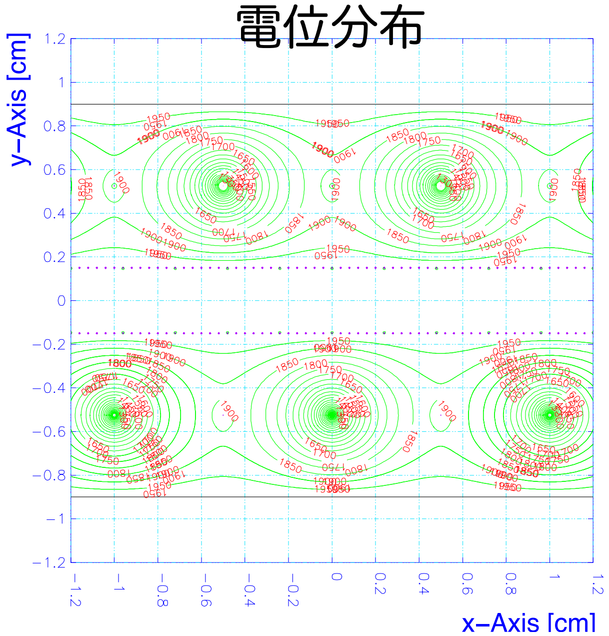
磁場の絶対値分布

Drift Chamber

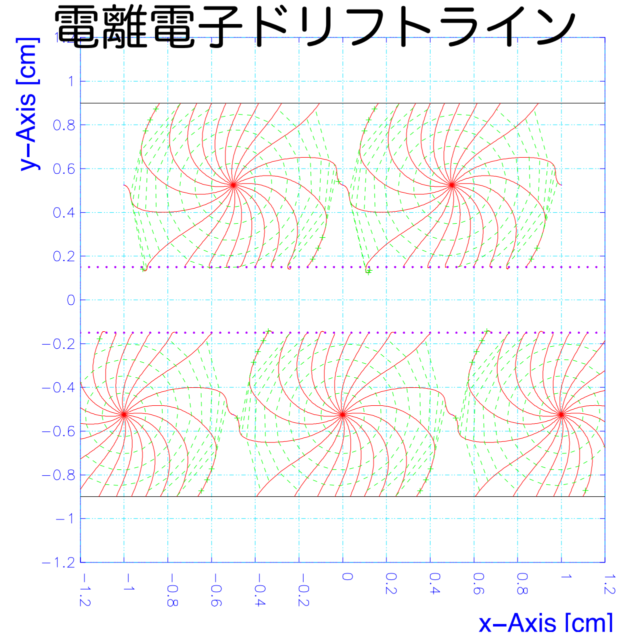


上:モジュール横図, 下:モジュール内部図

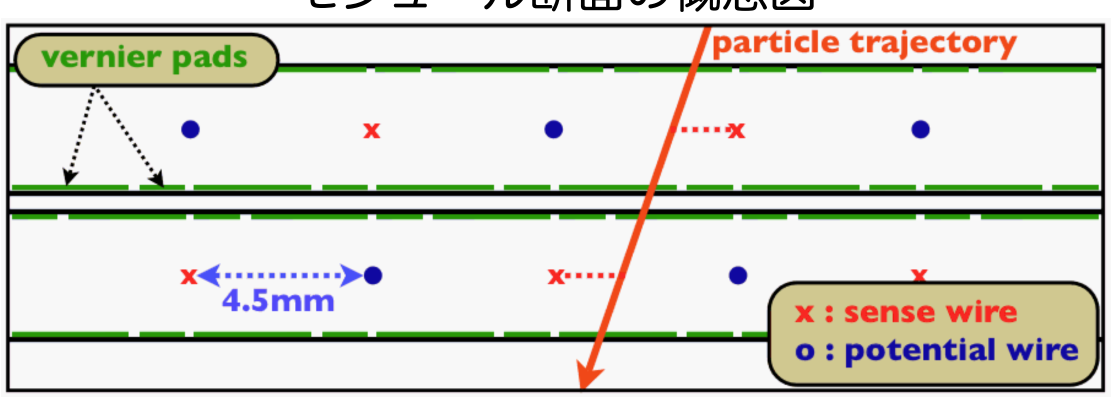
電位分布



電離電子ドリフトライン

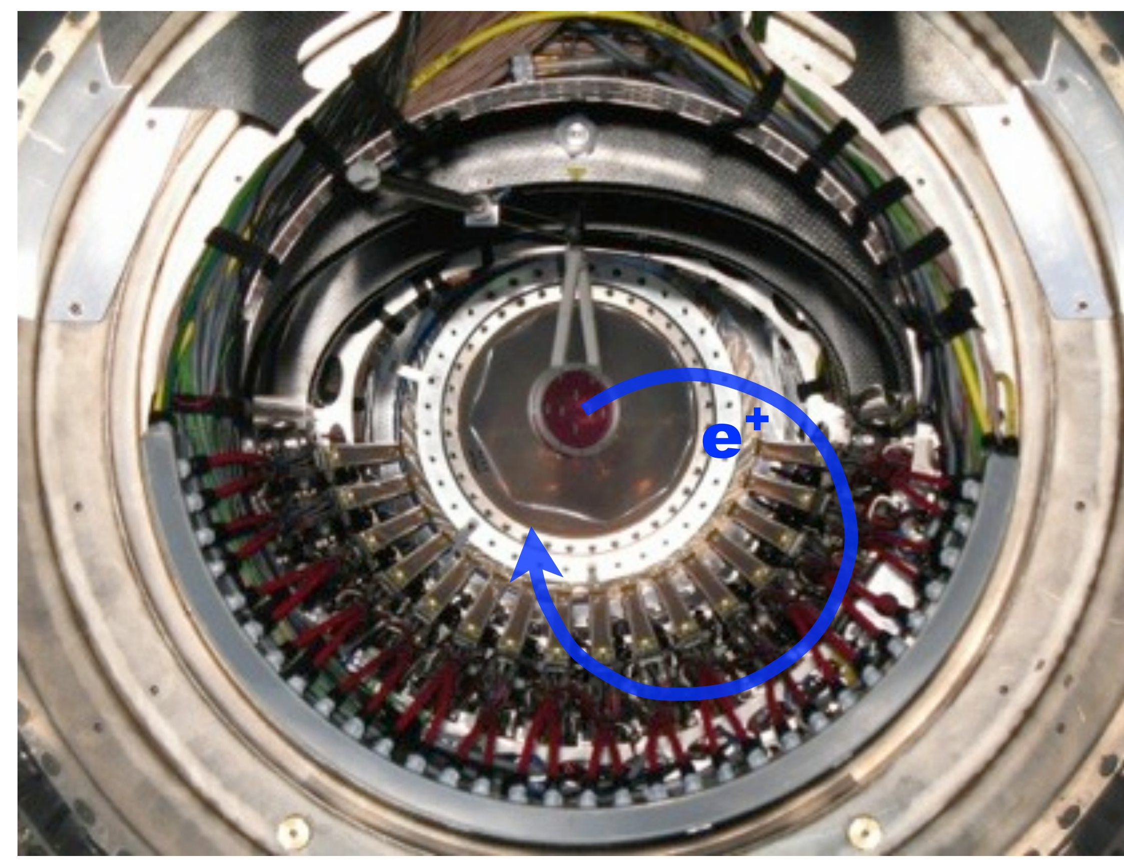


モジュール断面の概念図



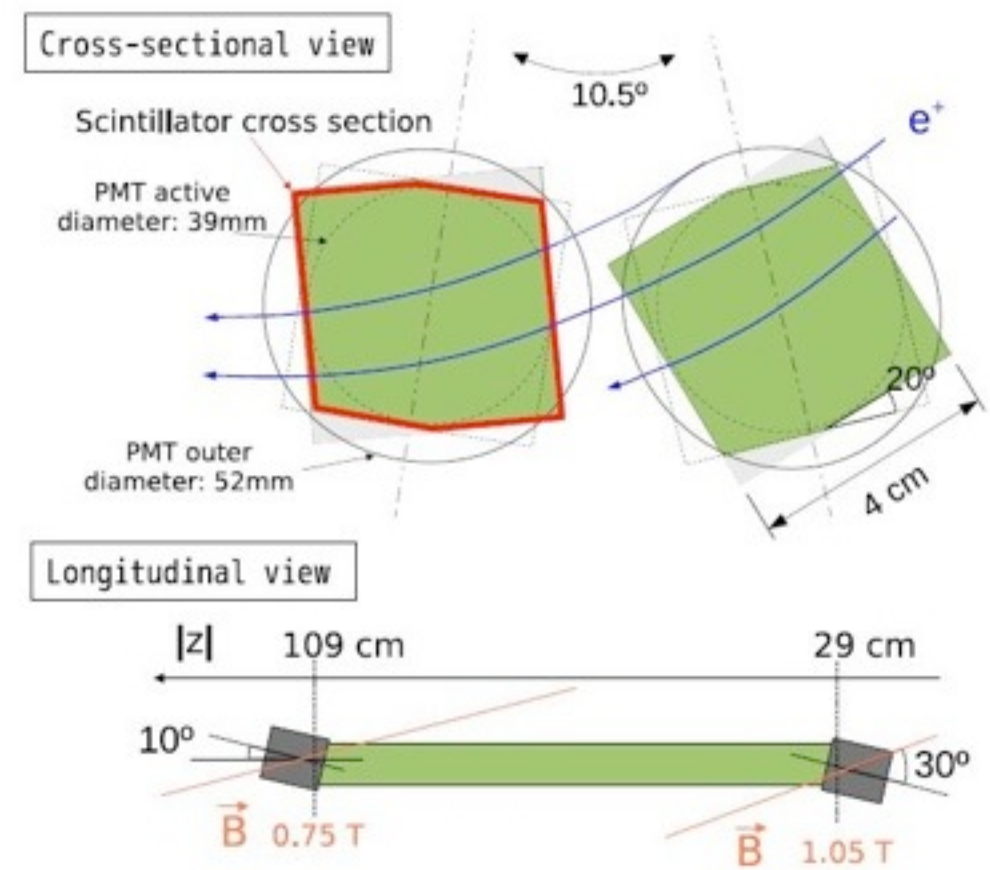
超低物質量ドリフトチェンバー

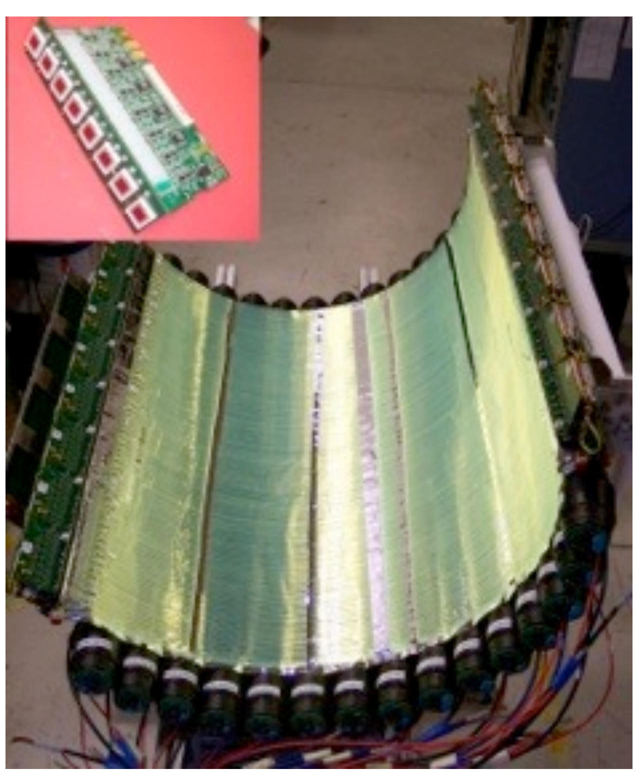
- 16枚のモジュールによって構成
- オープンシェイプフレームでワイヤーを支える
- 各モジュールは2枚のプレーンを持つ
  - プレーンを半セルずらし, L-R不定性低減
- Vernier patternにより<1mmのz分解能を得る
  - カソードに5cm間隔のジクザグ構造
- X-Y平面の位置はドリフト時間から求める
- 16モジュールを放射状に並べ飛跡再構成を行う
- ヘリウムエタン50:50の混合ガスを使用
- 陽電子1周辺り僅か$2\times10^{-3}X_0$の輻射長



COBRA磁石にマウントされたドリフトチェンバー

Timing Counter

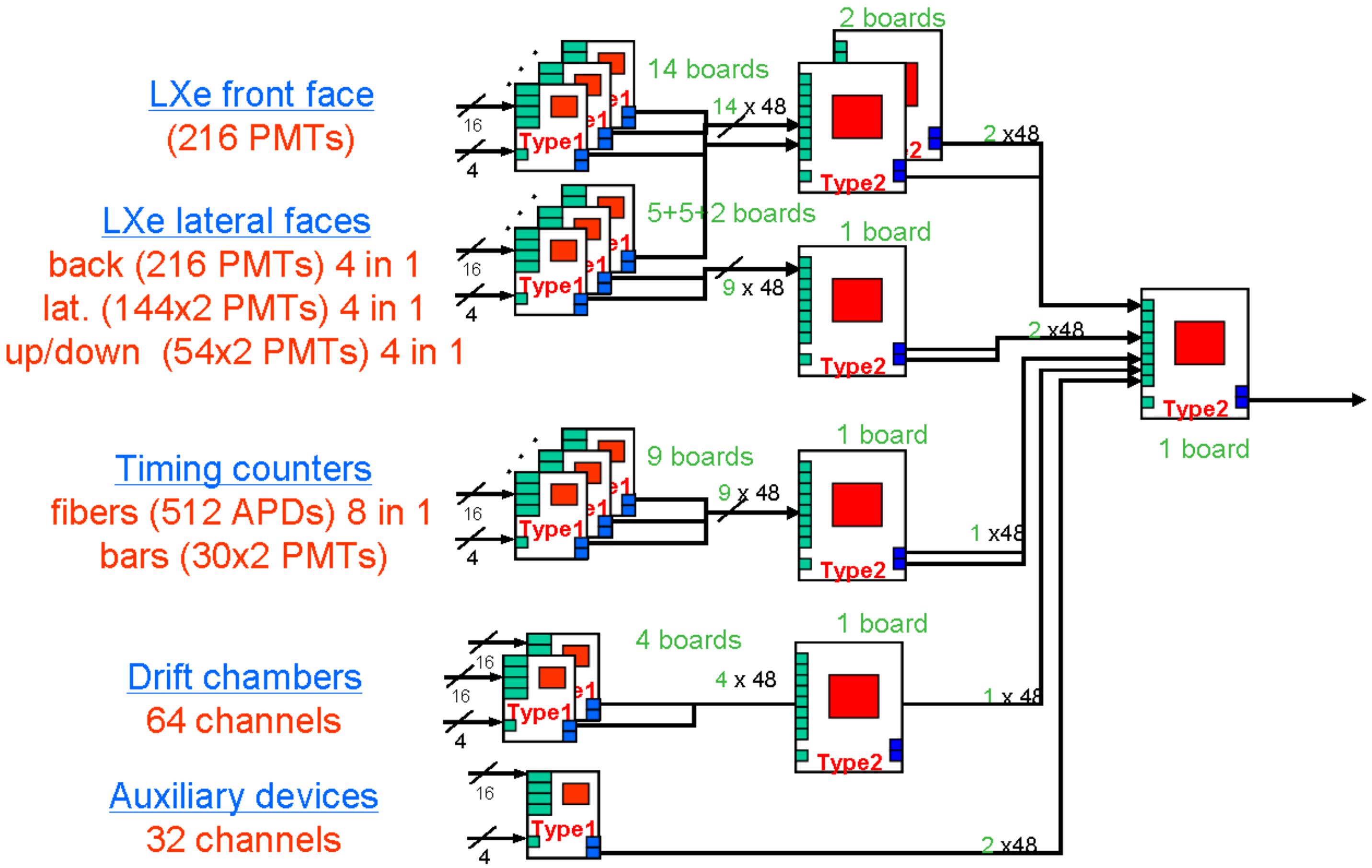




ドリフトチェンバーを通過した陽電子の時間を測定するため,
15本のシンチレータバーを上流・下流にそれぞれ設置
シンチレーション光はバー両端のファインメッシュPMTで読み出す
⇒ 飛跡をターゲットまで延ばした時の飛行時間を引く事で陽電子の放出時間決定

z方向のヒット位置を精度良く測定するため, バーの上にAPD読出しのシンチレーションファイバを設置 ⇒ 諸々の原因により解析には使われていない
⇒ z方向の位置はシンチレータバーでも決定可能

Trigger & DAQ

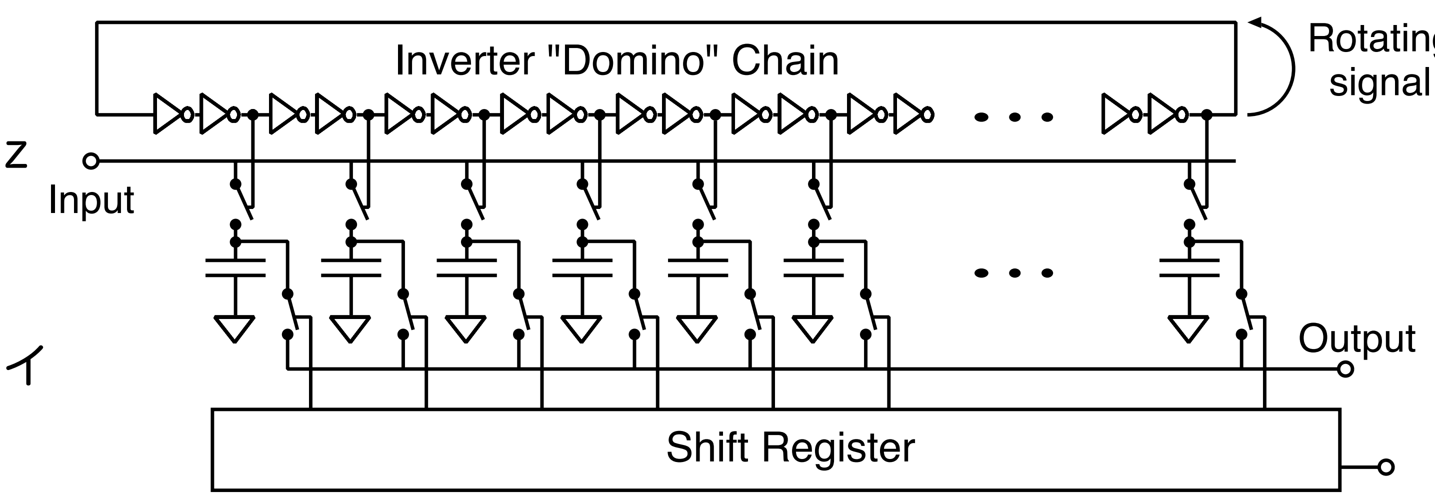


FPGAを用いた高速トリガー

- 効率良く信号事象を選択する事でdead timeを抑える
  - Multi-buffer導入前:
    Live Time = 72%, $\varepsilon_{\mathrm{trg.}}$ = 92%
  - Multi-buffer導入後(2011年以降):
    Live Time = 99%, $\varepsilon_{\mathrm{trg.}}$ = 97%
- 信号収集用トリガー(MEGトリガー)に他のトリガーを混ぜる事も可能
  - 例, Michelトリガー (TCシングルトリガー, 規格化因子計算に使用)

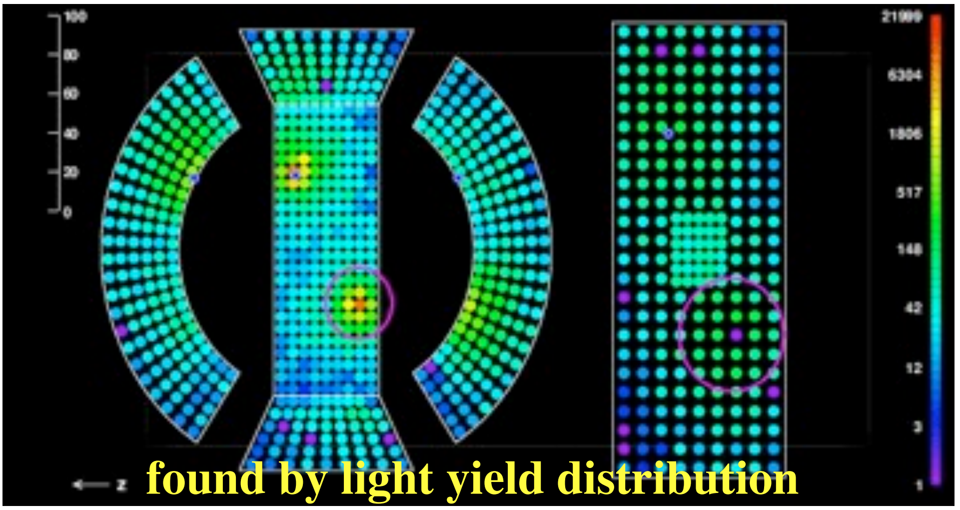
全ての検出器で波形データを取得

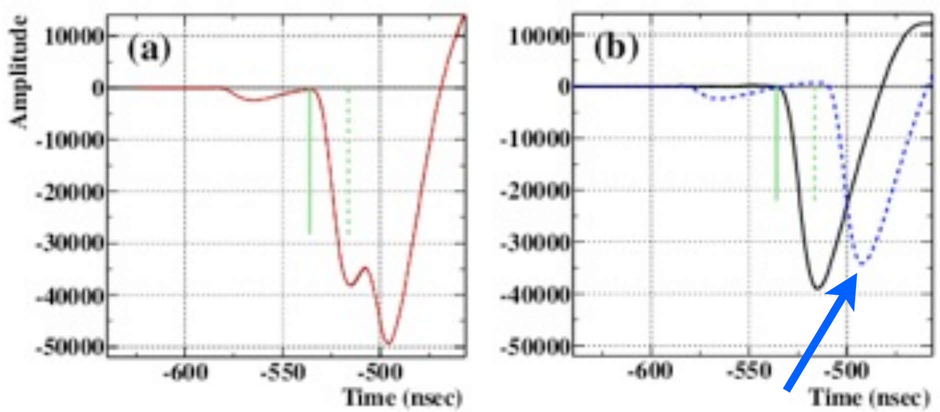
- DRS4 (Domino Ring Sampler)によって, 最大5 GHzのサンプリング速度を実現
- オフラインの解析によるパイルアップ分離が可能！
- 事象毎にベースラインを見積る ⇒ 遅い成分周波数ノイズの影響を抑える



Analysis Improvements

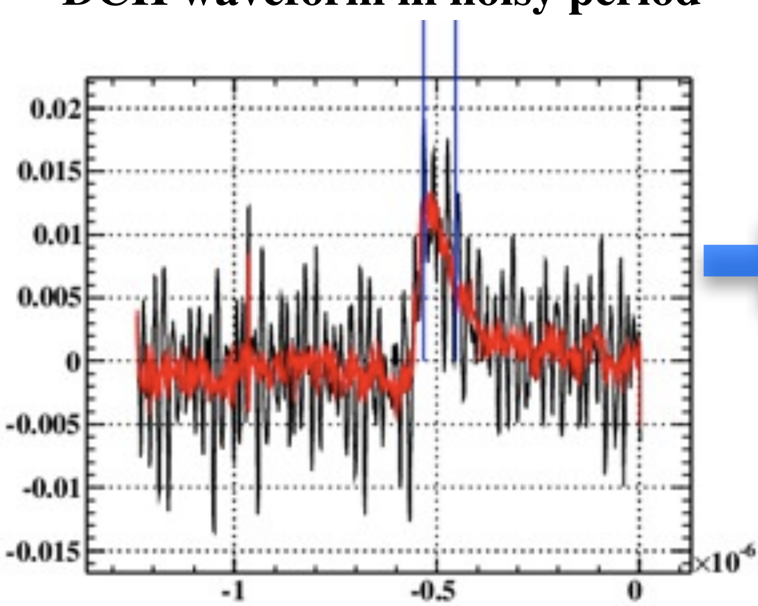
- 再構成手法の見直しによる性能改善
  - 波形を用いたガンマ線パイルアップ除去
    - 約7%の検出効率改善
  - ドリフトチェンバーオフラインノイズ除去の開発
    - 約6%の検出効率改善+分解能向上
  - 陽電子飛跡フィット手法の見直し
    - 約6%の検出効率改善, テール部分の低減

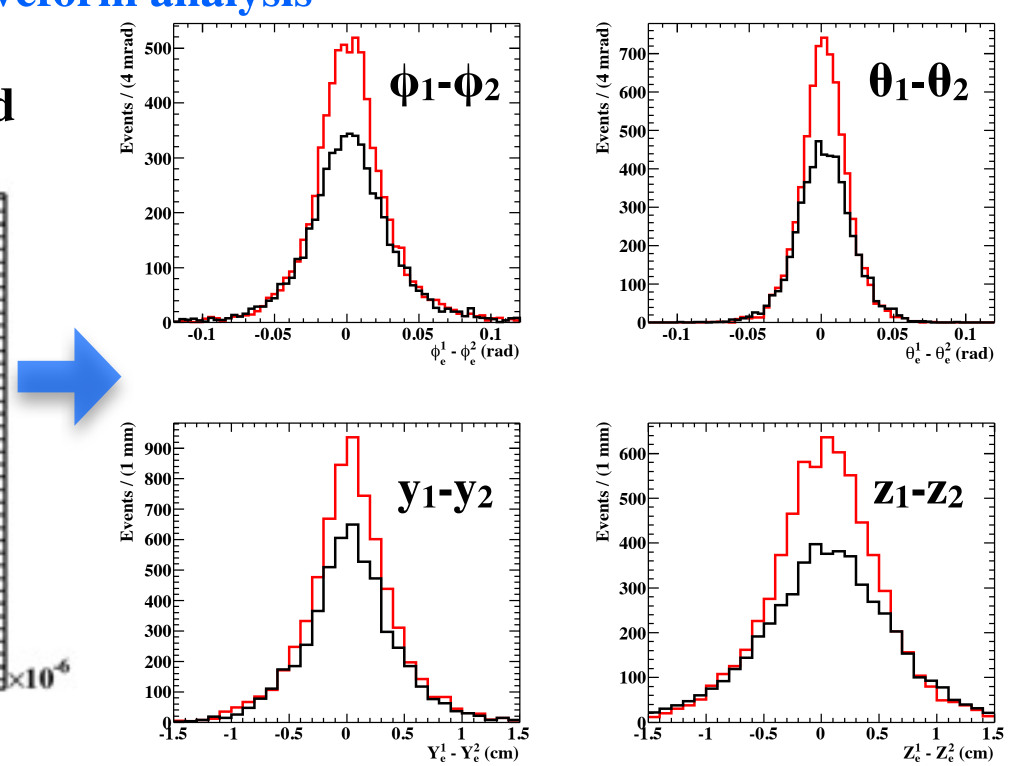


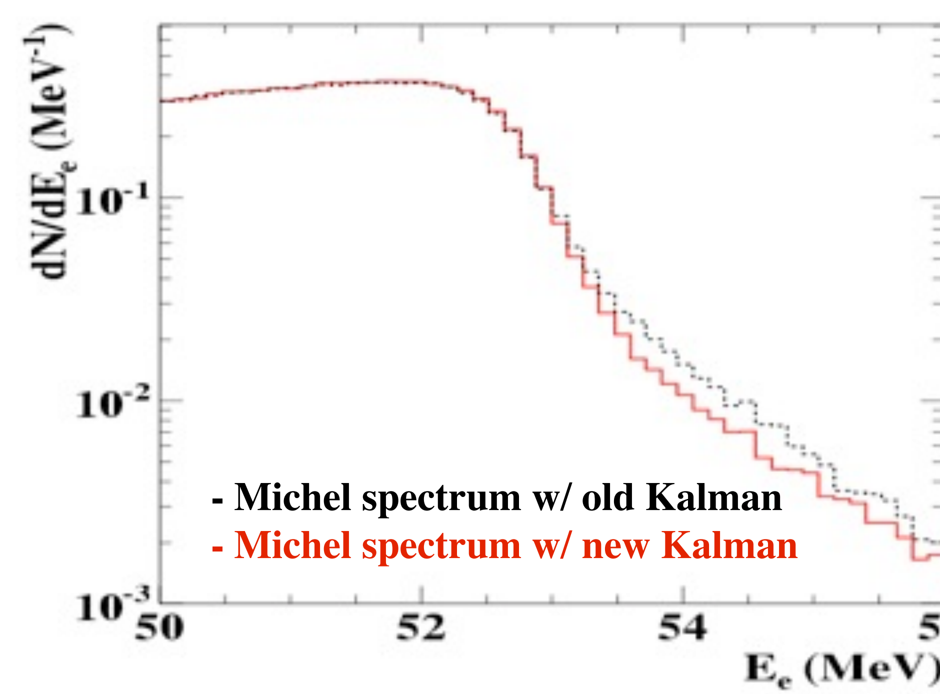


pileup found and removed by waveform analysis

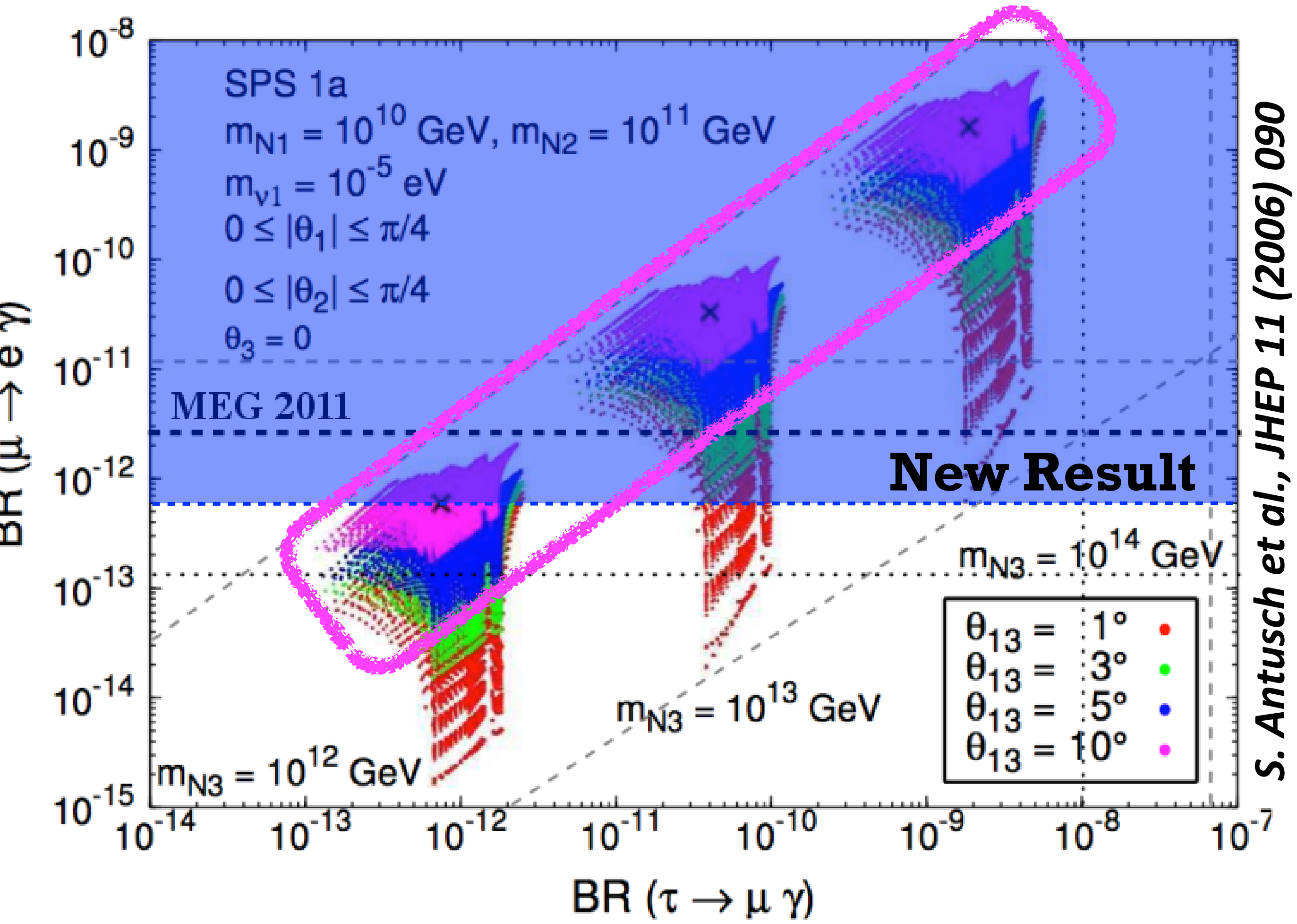
DCH waveform in noisy period



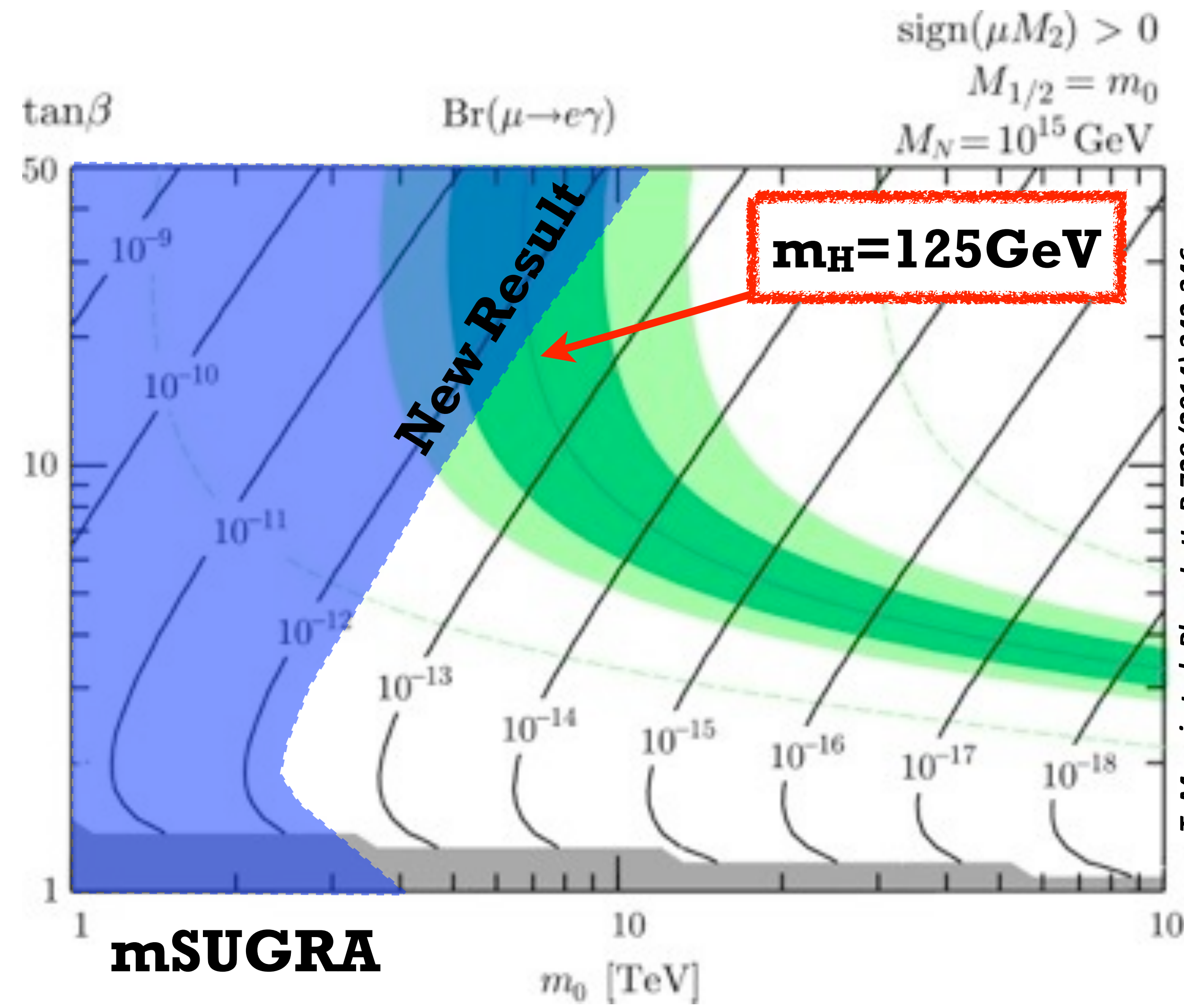




Few Examples



S. Antusch et al., JHEP 11 (2006) 090

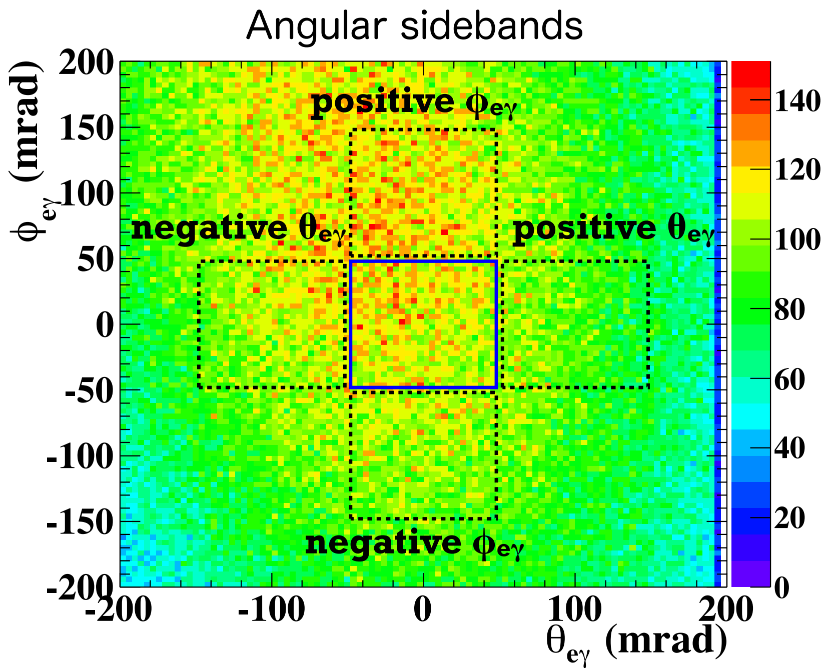


T. Moroi et al. Phys. Lett. B 728 (2014) 342-346

Datasets

- Signal Region
  - Use datasets of 2009-2010 combined, 2011 only and 2009-2011 combined
  - $48 \leq E_\gamma \leq 58$ MeV,
  - $50 \leq E_e \leq 56$ MeV,
  - $|\phi_{e\gamma}| \leq 50$ mrad and $|\theta_{e\gamma}| \leq 50$ mrad,
  - $|t_{e\gamma}| \leq 0.7$ ns,
  - $\Rightarrow$ 86% of analysis efficiency
- Time sidebands
  - Check the reliability of accidental BG PDFs before unblinding
  - Analyze the regions of $|t_{e\gamma} \pm 2\text{ ns}| < 0.7$ ns
- Angular sidebands
  - Check the reliability of RMD PDFs before unblinding
  - Use 100 mrad off-axis regions for $\phi_{e\gamma}$ or $\theta_{e\gamma}$

+ Select only a pair of e-γ



Performance Summary

Observables in Physics Analysis

Table 5.7: Performance summary.

Variable	2009	2010	2011
Gamma Resolutions			
E_γ (%)	1.9 ($w > 2$ cm), 2.4 ($w < 2$ cm)	1.9 ($w > 2$ cm), 2.4 ($w < 2$ cm)	1.7 ($w > 2$ cm), 2.4 ($w < 2$ cm)
u_γ,v_γ (mm)	5	5	5
w_γ (mm)	6	6	6
t_γ (ps)	96	67	67
Positron Resolutions			
E_e (MeV)	0.31	0.32	0.31
ϕ_e (mrad)	6.6	7.2	7.5
θ_e (mrad)	9.4	11.0	10.6
y_e (mm)	1.1 (core)	1.1 (core)	1.2 (core)
z_e (mm)	1.1	1.7	1.9
t_e (ps)	107	107	107
Combined Resolutions			
$\phi_{e\gamma}$ (mrad)	8.9	9.0	8.9
$\theta_{e\gamma}$ (mrad)	15.0	16.1	16.2
$t_{e\gamma}$ (ps)	156	123	127
Efficiency			
ϵ_γ (%)	63	63	63
ϵ_e (%)	28	35	31
ϵ_{trg} (%)	91	92	97

Likelihood Analysis

- Maximum Likelihood Fitting is used to determine the values of N_{sig}, N_{RMD} and N_{BG}
- Parameters of PDFs are mostly determined by looking the sideband data
- N_{RMD} and N_{BG} are constrained from the data

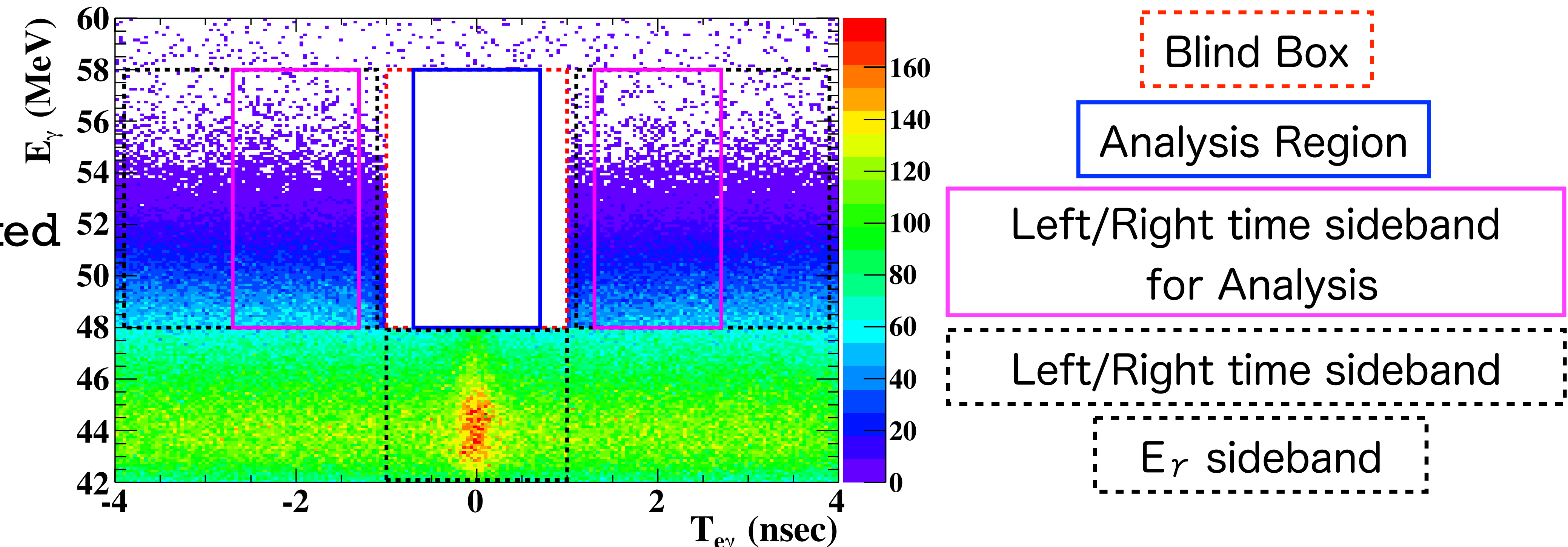
Background constraint

$$\mathcal{L}(N_{\rm sig}, N_{\rm RMD}, N_{\rm BG}) = \frac{e^{-N}}{N_{\rm obs}!} e^{-\frac{(N_{\rm RMD}-\langle N_{\rm RMD}\rangle)^2}{2\sigma_{\rm RMD}^2}} e^{-\frac{(N_{\rm BG}-\langle N_{\rm BG}\rangle)^2}{2\sigma_{\rm BG}^2}} \times \prod_{i=1}^{N_{\rm obs}} (N_{\rm sig} S(\vec{x_i}) + N_{\rm RMD} R(\vec{x_i}) + N_{\rm BG} B(\vec{x_i})) \quad (6.1)$$

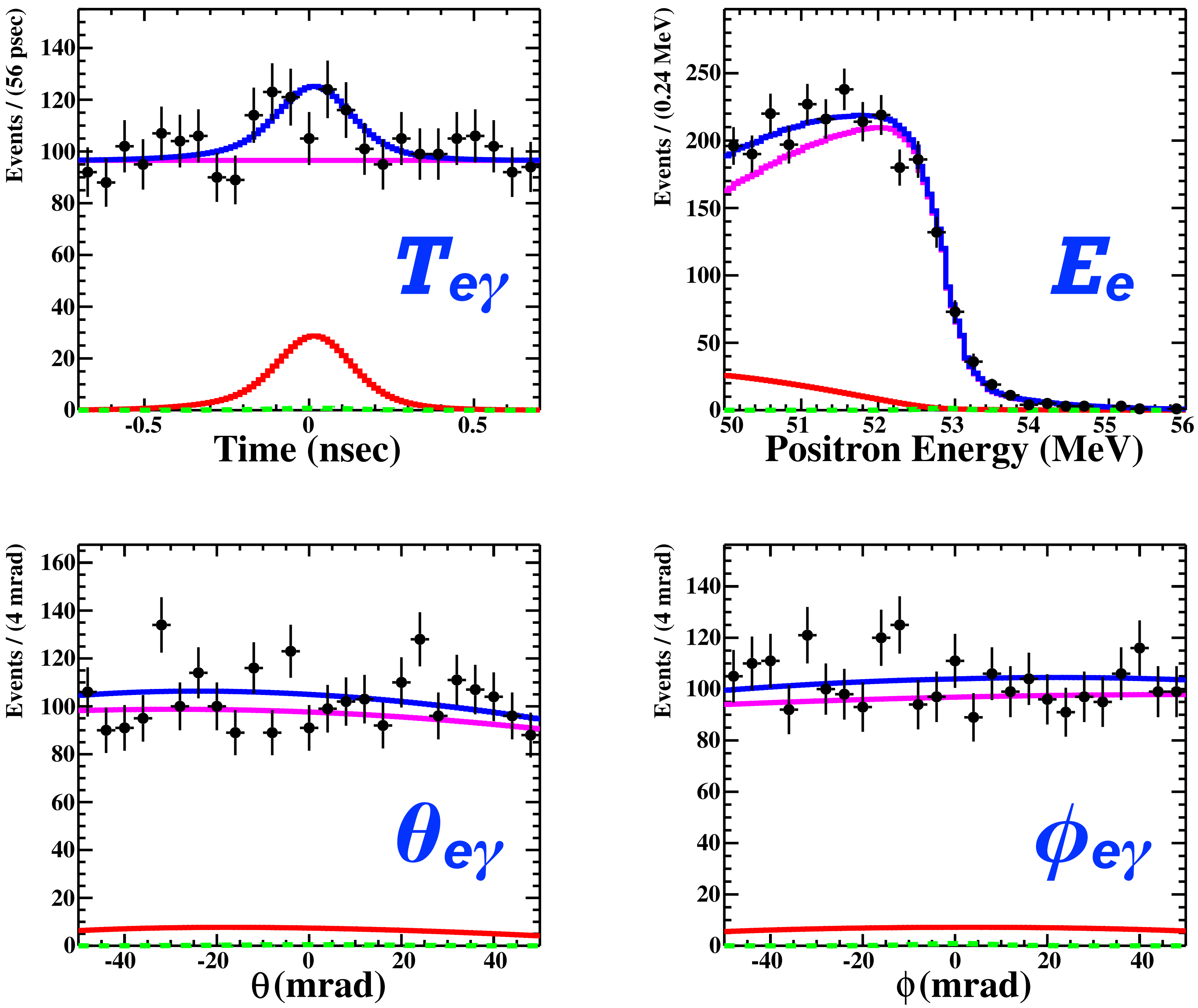
Signal PDF　RMD PDF　Accidental(BG) PDF

$$\vec{x_i} = (E_\gamma, E_{\rm e}, t_{\rm e\gamma}, \phi_{\rm e\gamma}, \theta_{\rm e\gamma})_i$$

Blind analysis:
Signal region is masked until every PDF parameters are fixed



Fit for 2009-2011 data



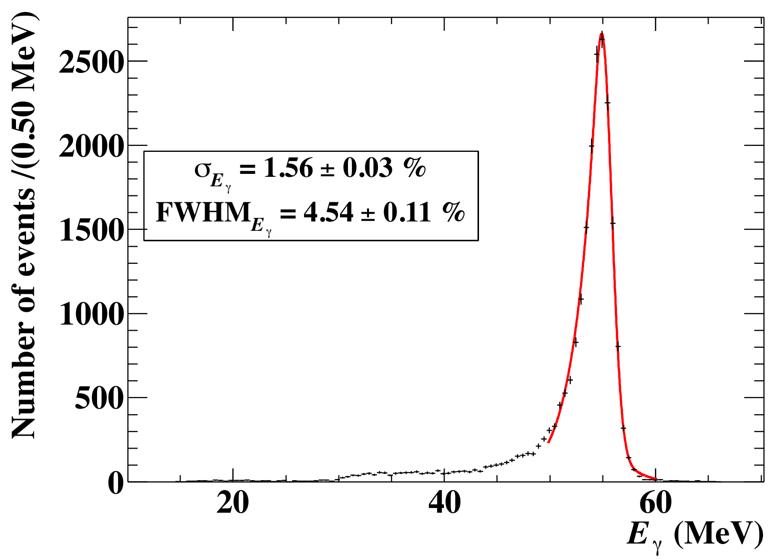
	Expected	Fit
N_{BG}	2415.0±25.0	$2413.6^{+37.1}_{-37.0}$
N_{RMD}	169.3±17.0	$167.5^{+24.2}_{-24.0}$
N_{signal}	-	$-0.4^{+4.8}_{-1.9}$

No signal excess

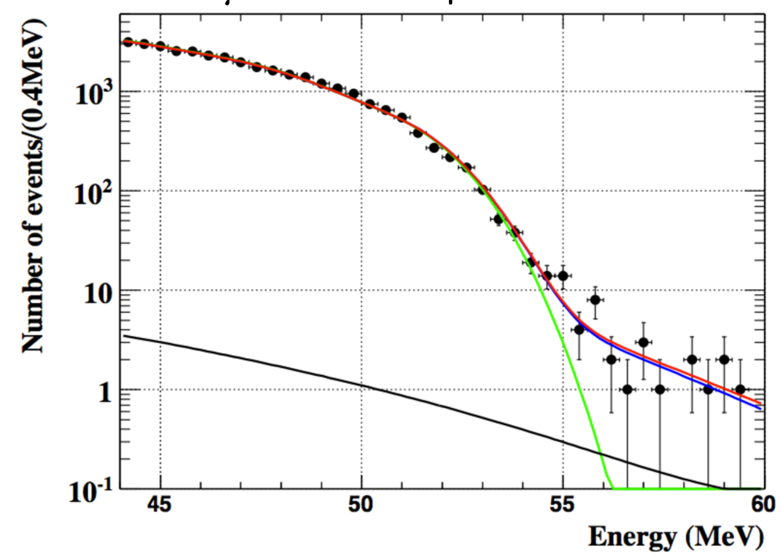
PDF

- E_γ PDF: 信号 ⇒ CEXデータ, RMD ⇒ 理論式+検出器応答, accidental ⇒ sidebandデータ
- $T_{e\gamma}$ PDF: 信号 or RMD ⇒ RMD事象のピーク幅, accidental ⇒ flat分布を仮定

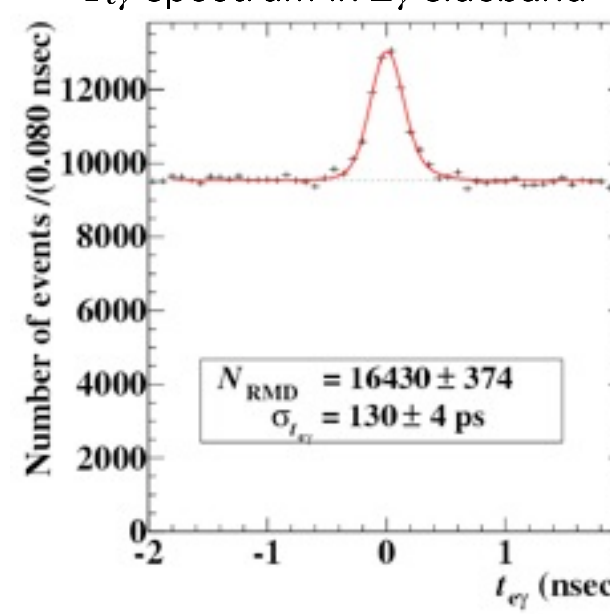
CEXラン55 MeVガンマのフィット結果



E_γ sideband spectrum



$T_{e\gamma}$ spectrum in E_γ sideband



- $E_e, \theta_{e\gamma}, \phi_{e\gamma}$, これまでのPDF (category PDF)
   I. 陽電子を飛跡のクォリティ (ヒット数やTCとのマッチング)で2つのカテゴリに分ける
   II. 各カテゴリで平均の検出器応答 (分解能, アクセプタンス, パラメータ相関) を求める
- 新しいPDF (per-event PDF)
   I. 飛跡フィット時の誤差伝播行列から各パラメータの事象毎誤差を求める (σ'_x)
   II. sidebandデータからσ'_xを分解能にスケールするパラメータ(s_x)を求める
   III. 検出器応答はsidebandデータから, パラメータ相関はデータ及びMCから求める

Per-Event PDF (1/2)

Resolutions :

$$\sigma_x = s_x \times \sigma'_x$$

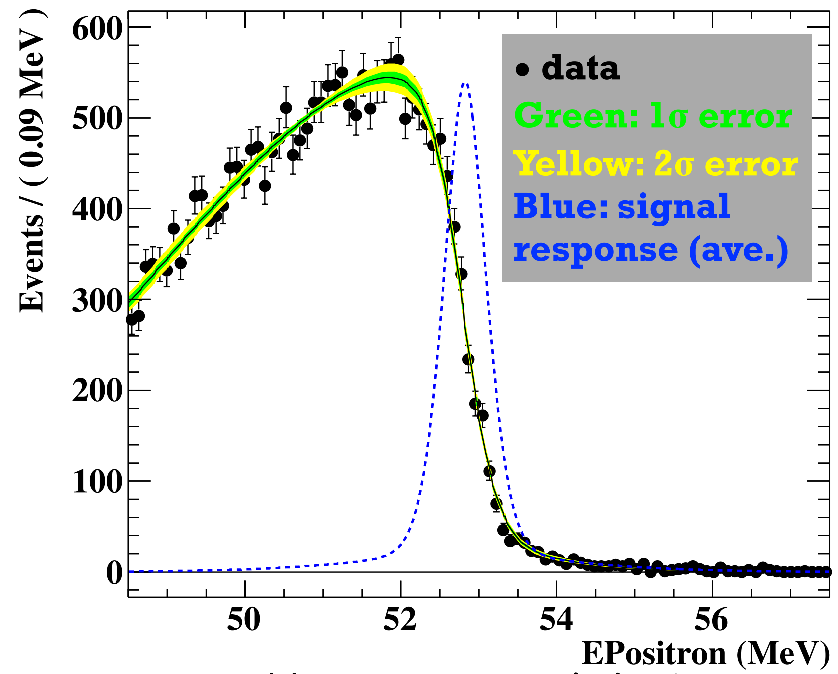
事象毎誤差を分解能に変換するための scale factor

Correlations :

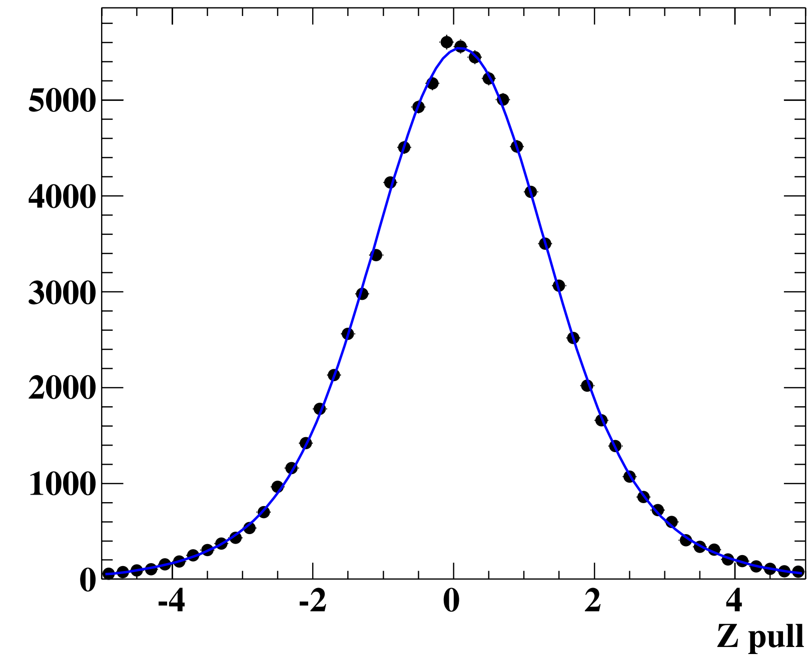
$$d\mu_y = p_{xy} \times dx$$

$$p_{xy} = p'_{xy} \times \frac{\sigma'_y}{\sigma'_x}$$

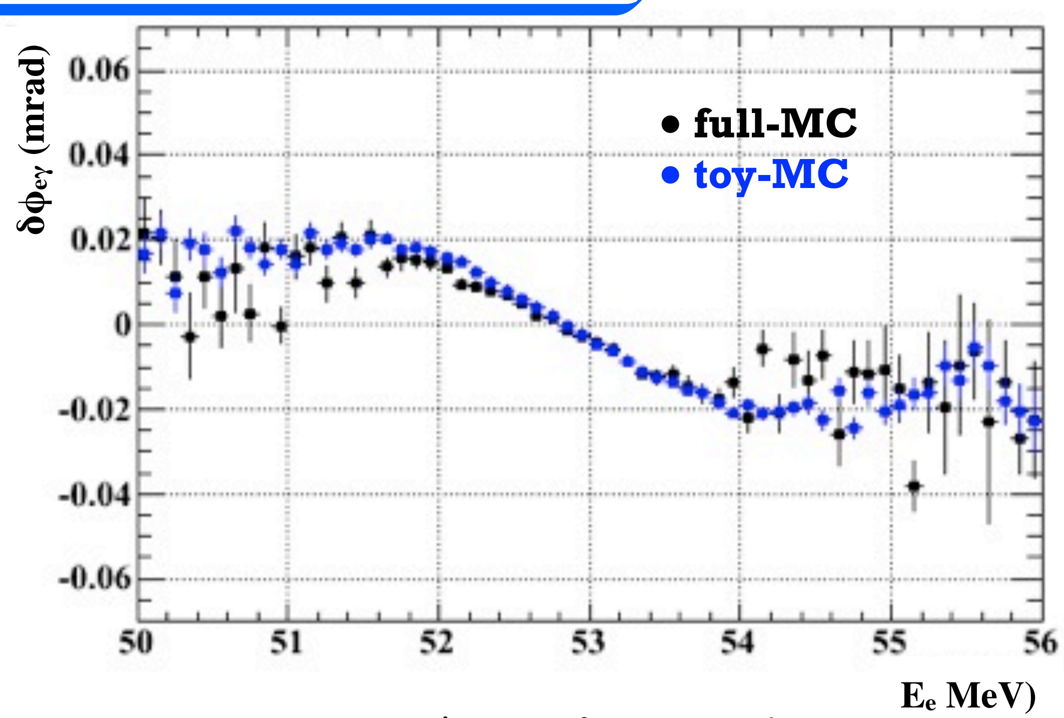
測定値間の相関パラメータ

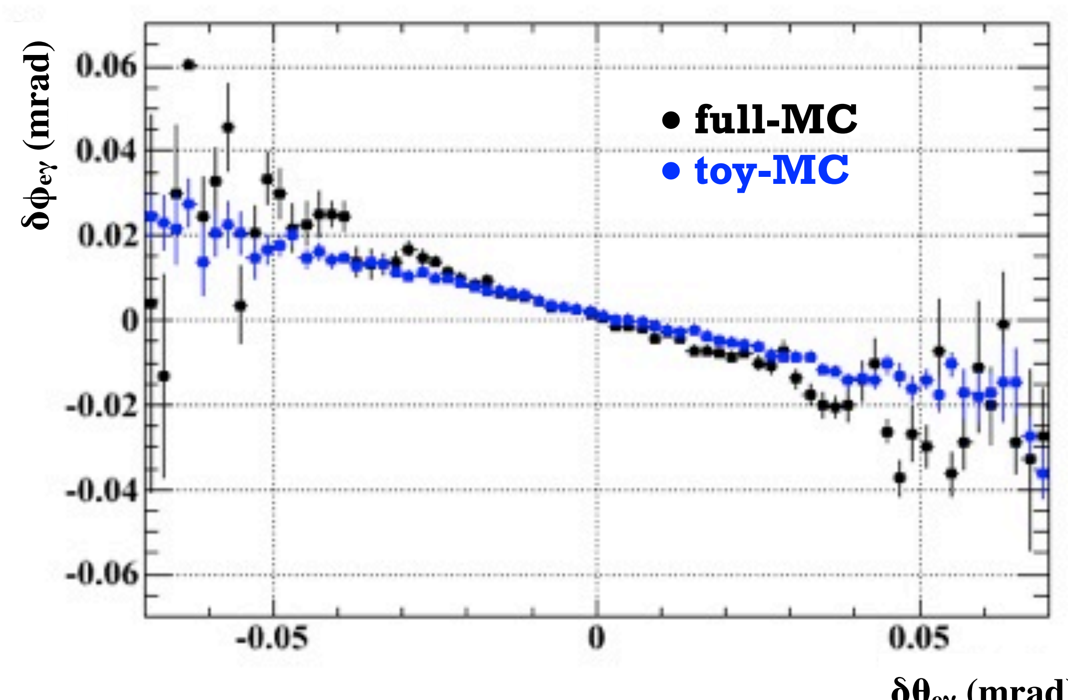


s_{Ee}はMichelスペクトルのエッジから求める



$s_{\theta e,\phi e,ye,ze}$はtwo-turn事象のプル$(\Delta x/\sigma'_x)$' のシグマから求める





⇒ 相関パラメータはtwo-turn事象とフルモンテカルロから計算する

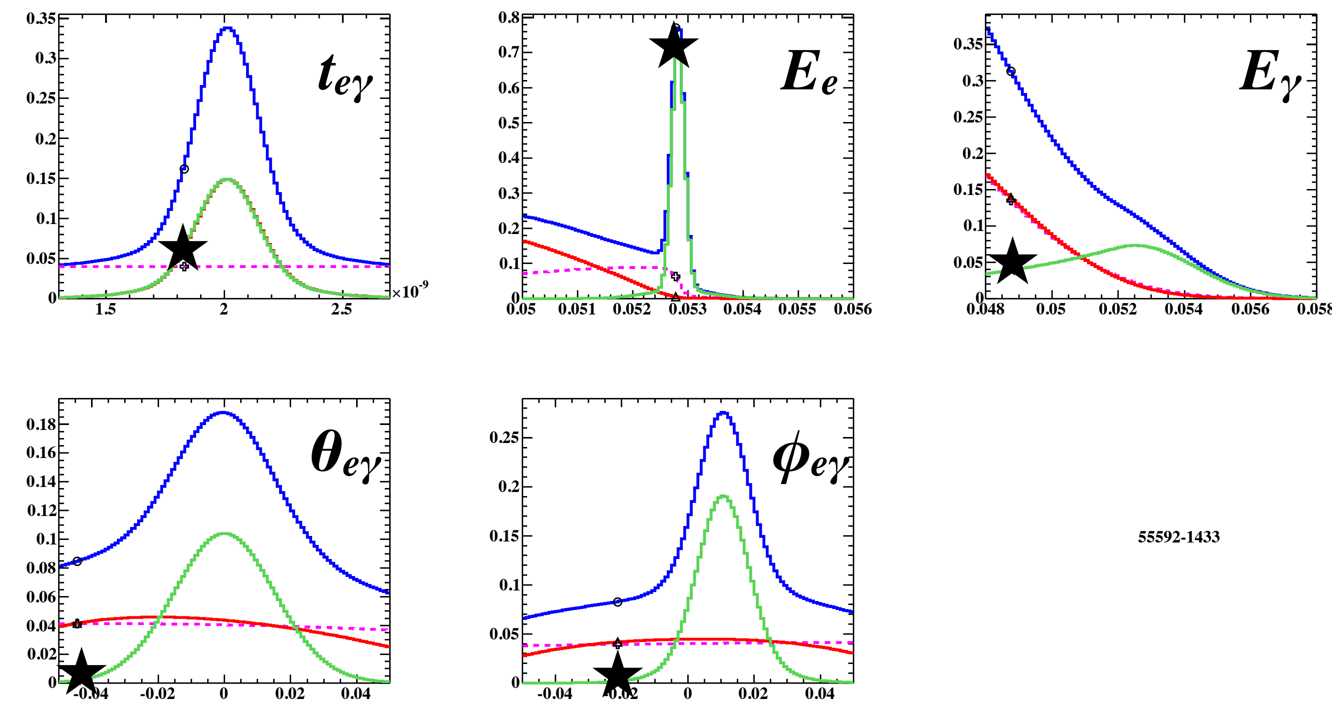
Per-Event PDF (2/2)

典型的な2事象のEvent-by-event PDF(in $t_{e\gamma}$ sideband)と平均PDFの比較

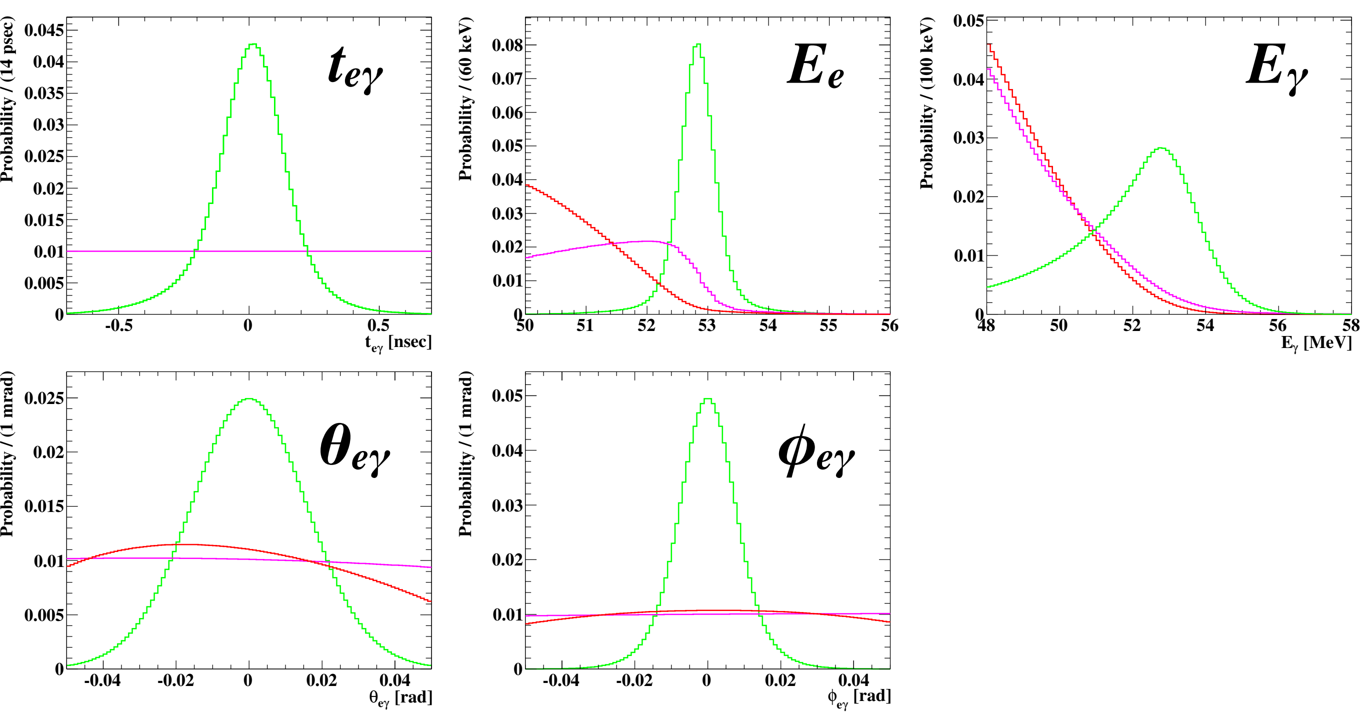
事象毎測定精度を用いる事で各事象毎に異なる信号感度が解析で考慮される ⇒ 約10%の感度改善

Green: Signal PDF
Magenta: BG PDF
Red: RMD PDF
Blue: Total
★: Data

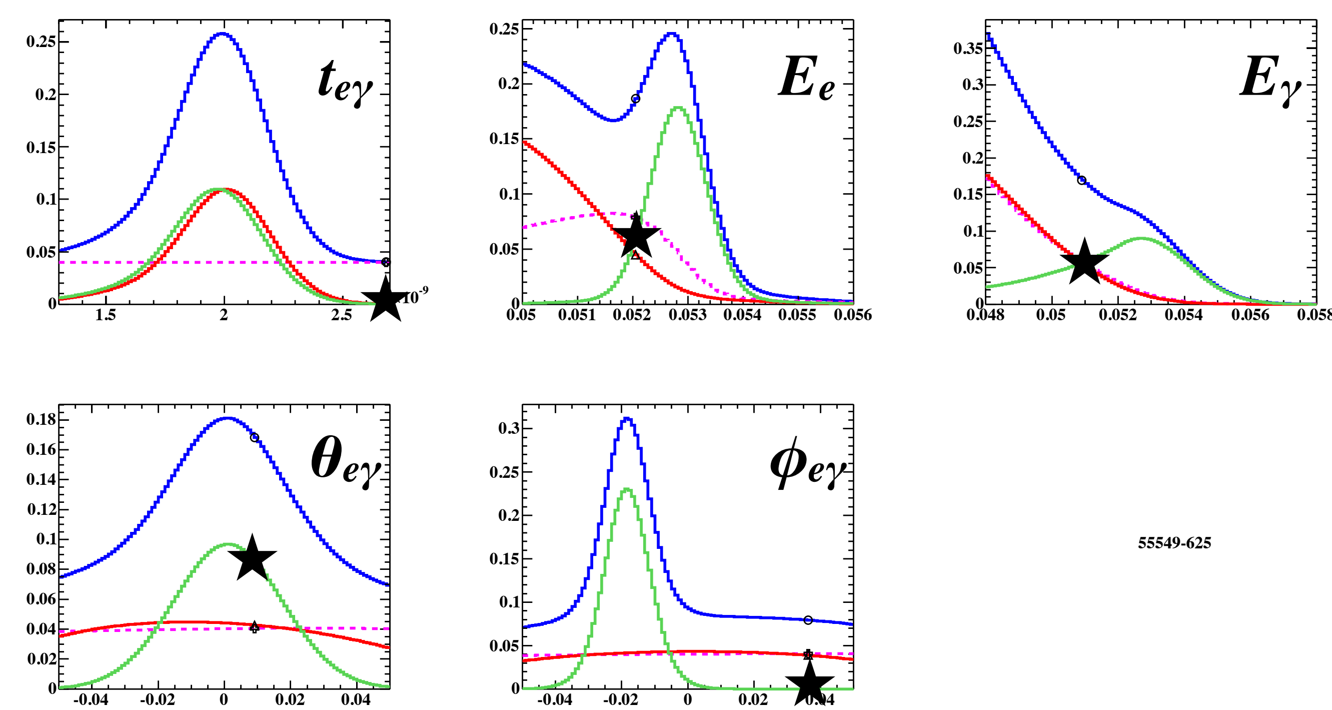
High quality track



Average PDF in 2009-2011 dataset



Low quality track



Sideband Results

- の前に…
  - sidebandのデータをチェック

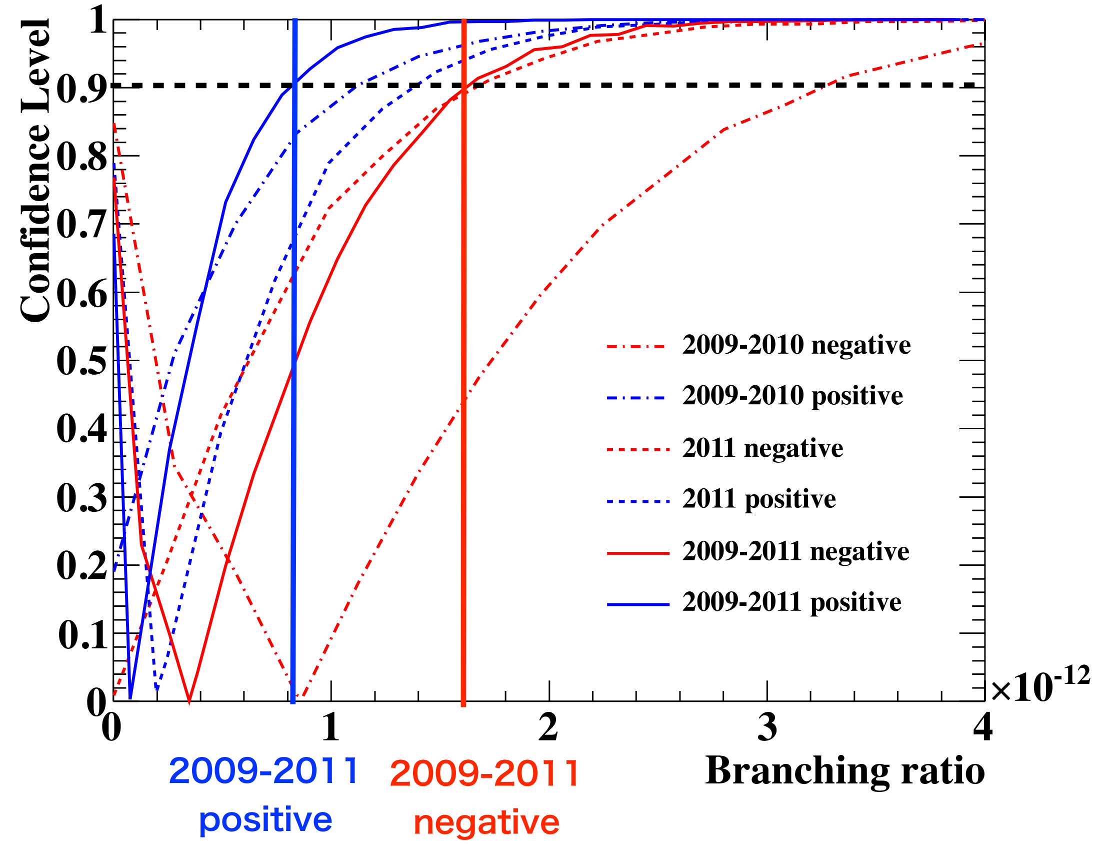


Table 7.2: Time sideband results without including systematic uncertainties.

Dataset	$\mathcal{B}$ best fit	$\mathcal{B}$ upper limit
2009-2010 negative	7.7×10^{-13}	3.1×10^{-12}
2009-2010 positive	-2.8×10^{-13}	1.1×10^{-12}
2011 negative	3.7×10^{-15}	1.7×10^{-12}
2011 positive	2.1×10^{-13}	1.4×10^{-12}
2009-2011 negative	3.5×10^{-13}	1.6×10^{-12}
2009-2011 positive	7.8×10^{-14}	8.1×10^{-13}

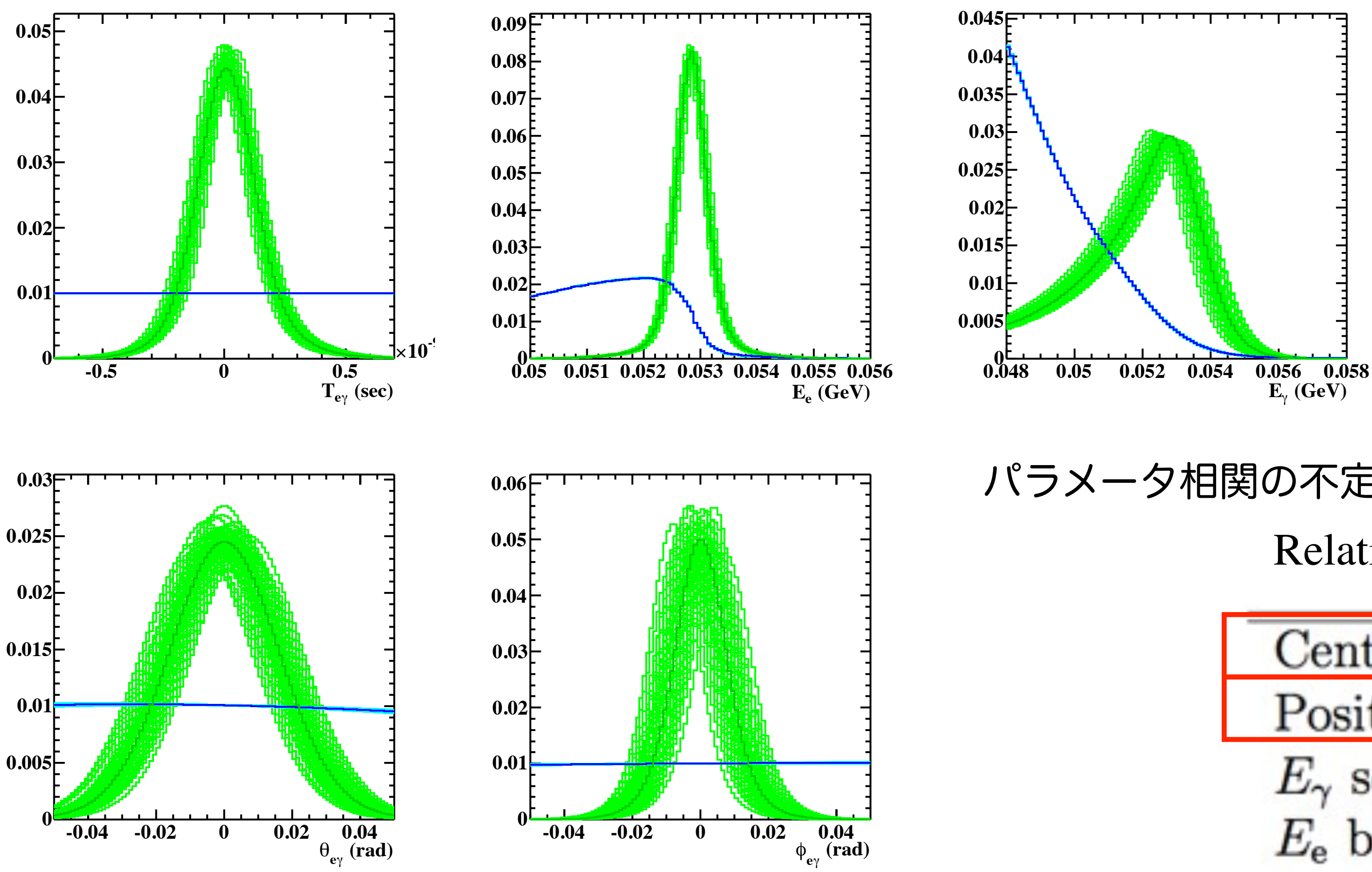
Table 7.4: Angle sideband results without constraints on the number of backgrounds (Uncertainties are in 1σ). N_{sig} = 0に固定

Dataset	$\langle N_{BG} \rangle$	$\langle N_{RMD} \rangle$	N_{obs}	$\hat{N}_{BG}$	$\hat{N}_{RMD}$
2009-2010 negative ϕ	1120 ± 17	34 ± 3	1120	1077 ± 35	40 ± 15
2009-2010 positive ϕ	1169 ± 17	36 ± 3	1247	1212 ± 39	46 ± 18
2009-2010 negative θ	1123 ± 17	39 ± 4	1120	1083 ± 36	35 ± 16
2009-2010 positive θ	877 ± 15	24 ± 2	962	963 ± 34	1 ± 12
2011 negative ϕ	1130 ± 18	35 ± 4	1163	1132 ± 37	27 ± 15
2011 positive ϕ	1189 ± 18	37 ± 4	1241	1195 ± 38	47 ± 16
2011 negative θ	1131 ± 18	41 ± 4	1233	1208 ± 38	27 ± 15
2011 positive θ	976 ± 17	25 ± 3	1016	979 ± 34	37 ± 14
2009-2011 negative ϕ	2228 ± 24	69 ± 7	2283	2210 ± 51	66 ± 21
2009-2011 positive ϕ	2365 ± 25	73 ± 7	2488	2404 ± 54	93 ± 24
2009-2011 negative θ	2251 ± 24	80 ± 8	2353	2292 ± 52	61 ± 22
2009-2011 positive θ	1855 ± 22	49 ± 5	1978	1939 ± 48	41 ± 18

- Signal, RMD無しのtime sidebandは実験感度と無矛盾な結果
  - BG PDFは問題無し
- Angle sidebandのフィット結果, RMD観測数は期待値とベストフィットで無矛盾
  - RMD PDFも問題無し

いよいよ信号領域を解析！

Systematics



Dark Green: signal PDF
Green: signal PDF w/ fluctuation
Blue: BG PDF
Cyan: BG PDF w/ fluctuation

陽電子とガンマ線相対角度の不定性
⇒ 検出器位置の不定性, 磁場の影響

パラメータ相関の不定性(ジオメトリー起源)

Relative contributions (RMS of ΔΔNLL) of uncertainties

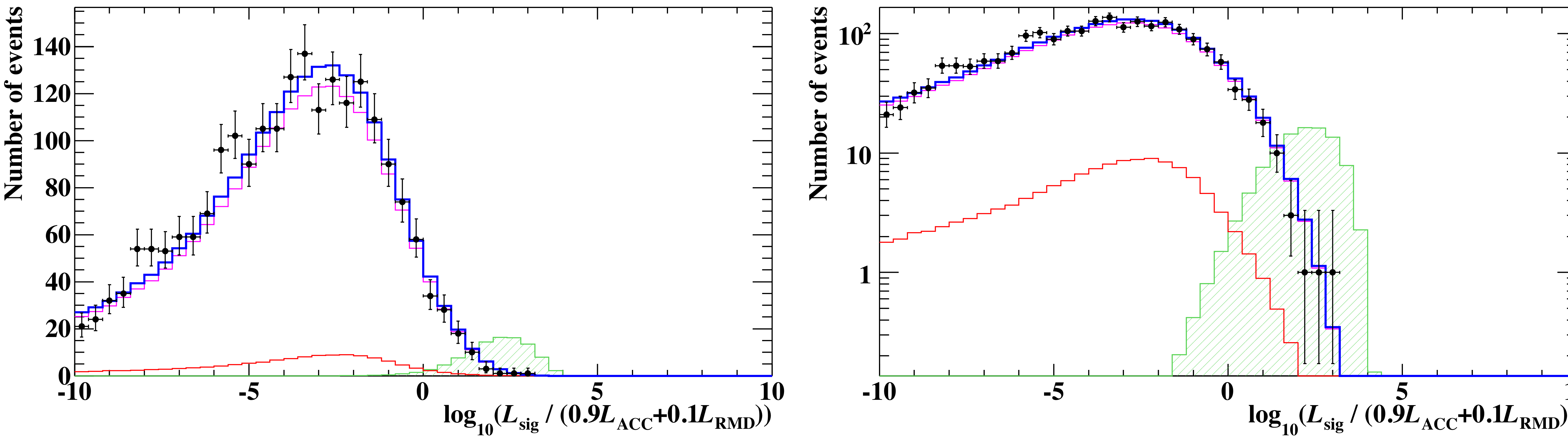
Center of $\theta_{e\gamma}$ and $\phi_{e\gamma}$	0.18
Positron correlations	0.11
E_γ scale	0.07
E_e bias	0.06
$t_{e\gamma}$ signal shape	0.06
$t_{e\gamma}$ center	0.05
Normalization	0.04
E_γ signal shape	0.03
E_γ BG shape	0.03
Positron angle resolutions (θ_e, ϕ_e, z_e, y_e)	0.03
γ angle resolution (u_γ, v_γ, w_γ)	0.03
E_e BG shape	0.01
E_e signal shape	0.01
Angle BG shape	0.00
Total	0.25

- バックグラウンドは高い精度でコントロールされており, 不定性が小さい
- Signal PDFの不定性は比較的大きいが, 観測されたN_{sig}が小さかったため, 崩壊分岐比の90%上限値に対する影響は少ない
  - 2009-2011データに対して数%程度の影響

R_{sig} Distribution

- Relative signal likelihoodを以下のように定義 (R_{sig}が大きい=信号らしい事象)

$$R_{\mathrm{sig}} = \log_{10} \frac{L_{\mathrm{sig}}}{0.1 \cdot L_{\mathrm{RD}} + 0.9 \cdot L_{\mathrm{BG}}}. \tag{7.1}$$



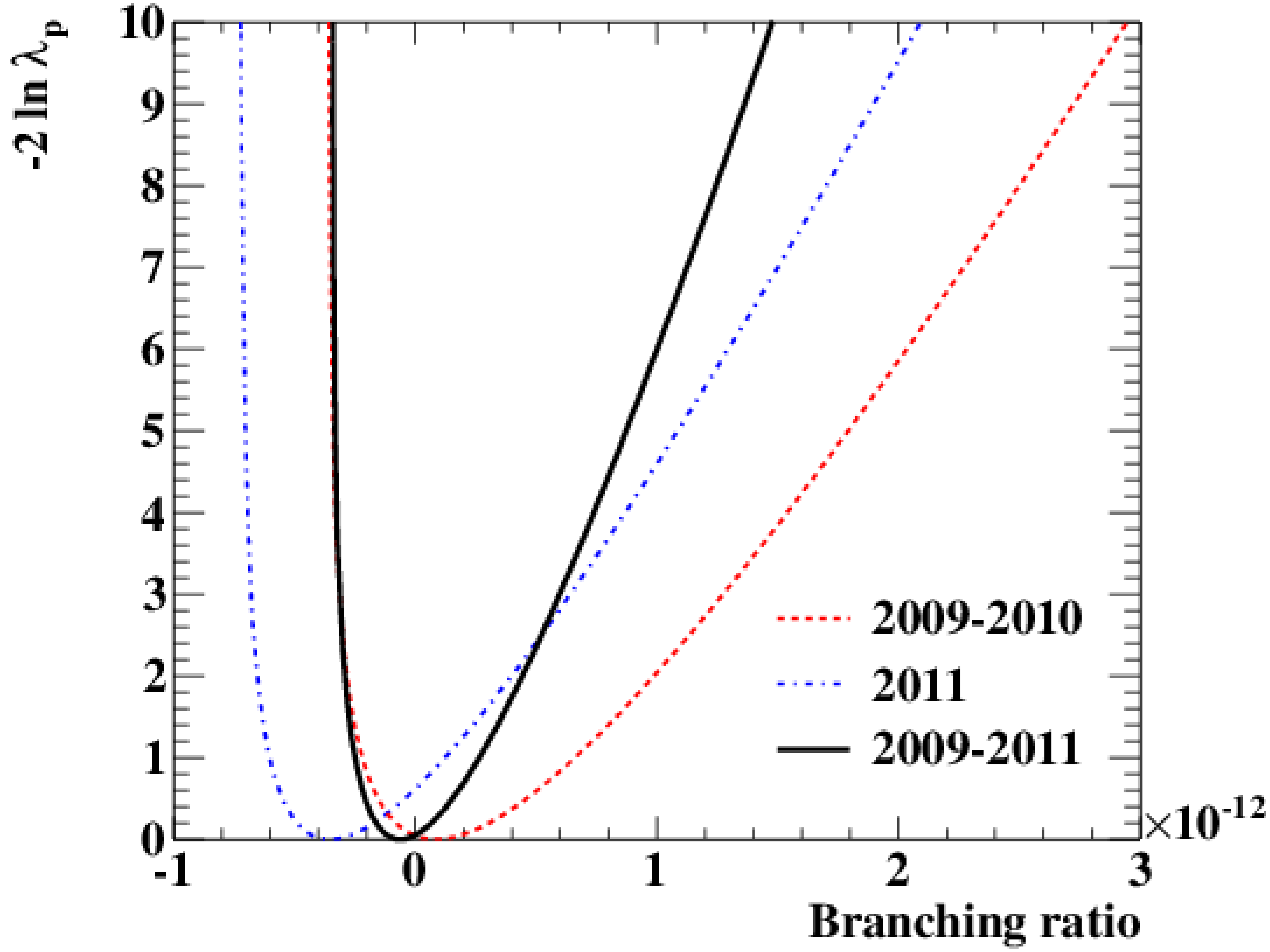
- **Data**

Magenta: toy-MC of BG PDF
- **normalized to the expected N_{BG}**

Red: toy-MC of RMD PDF
- **normalized to the expected N_{RMD}**

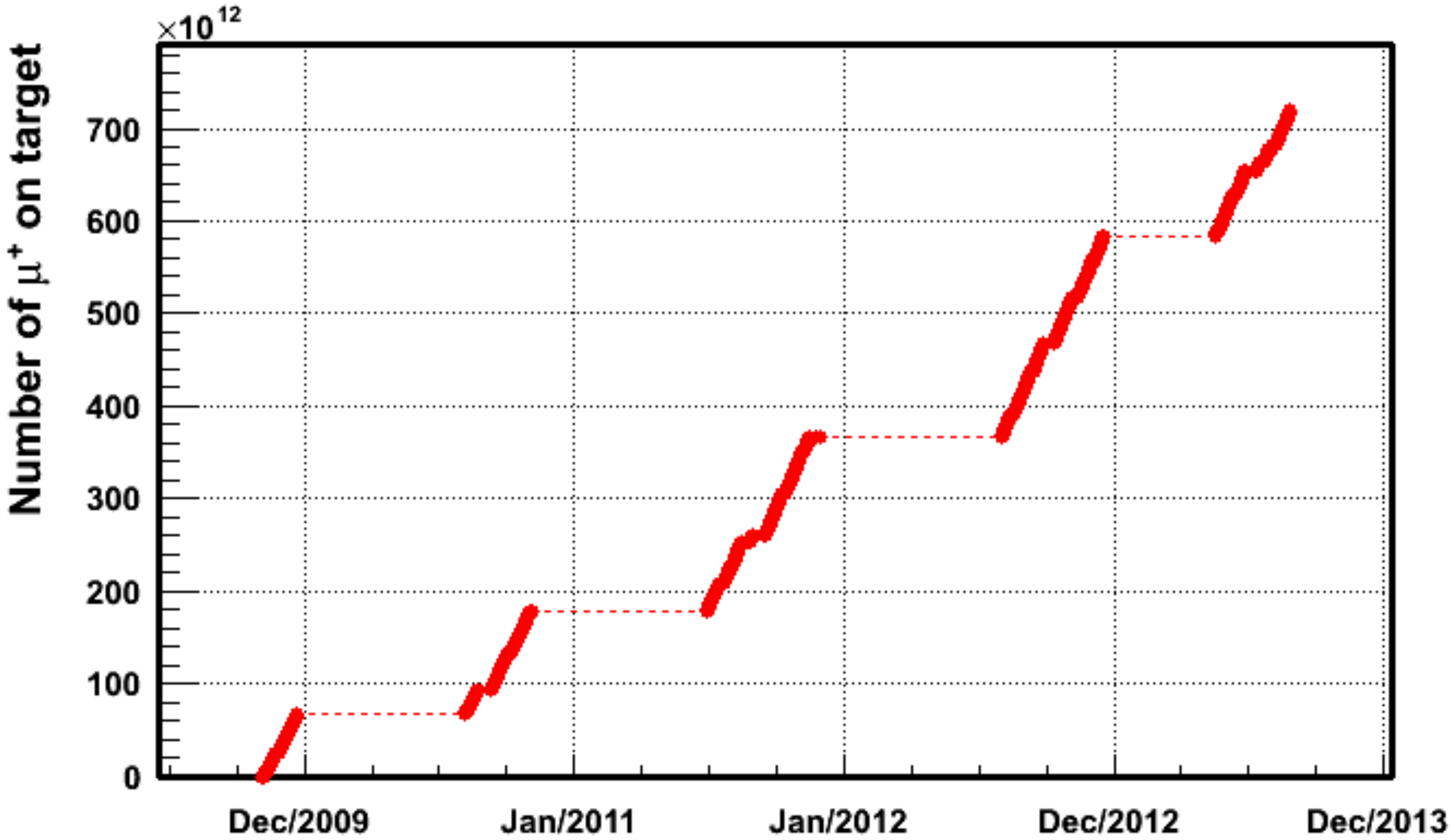
Green: toy-MC of signal
- **normalized to N_{sig}=100**

Likelihood Curve



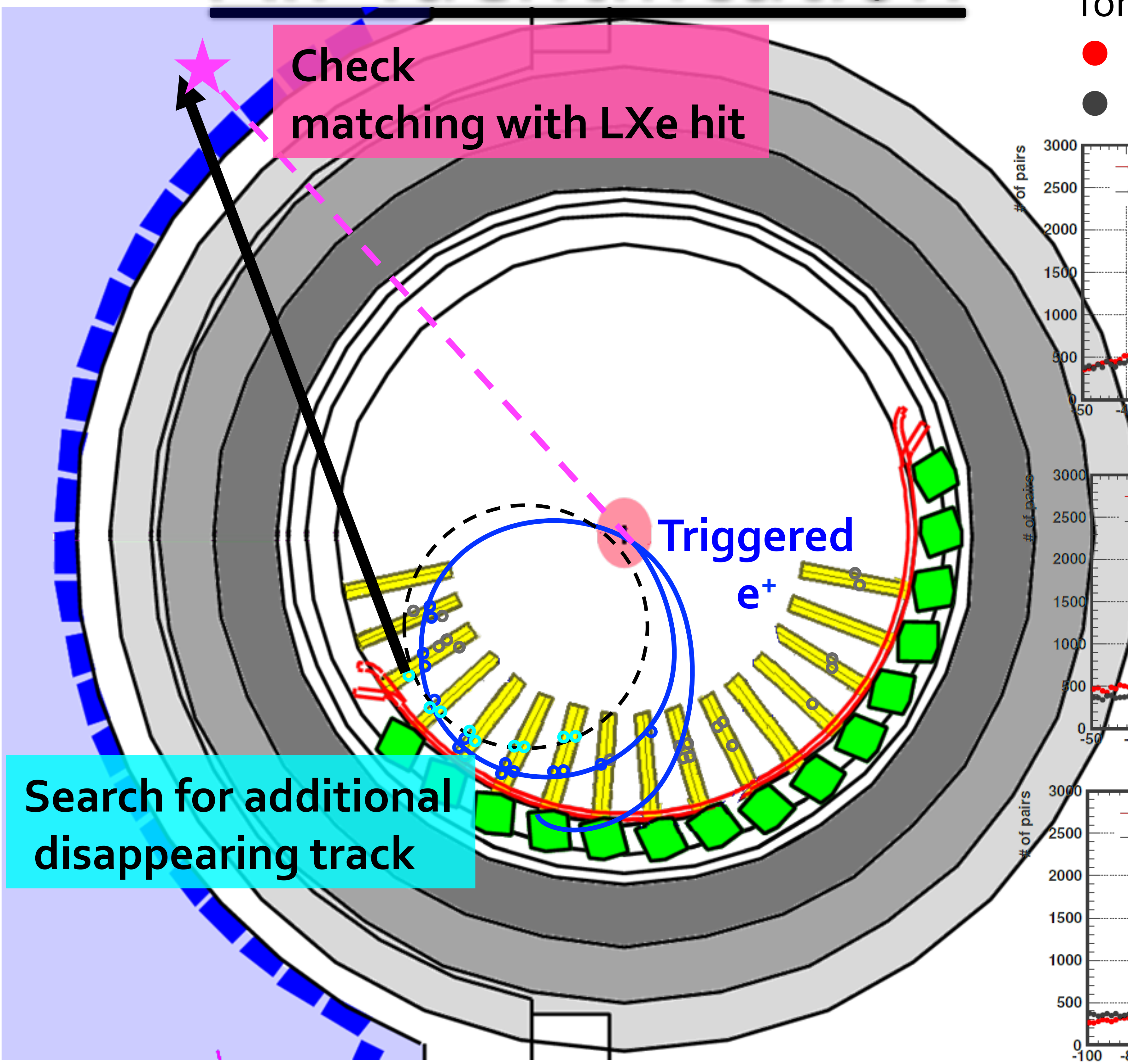
$$\lambda_{\rm p} = \frac{\mathcal{L}(N_{\rm sig}^{\rm fix}, N_{\rm RMD}(N_{\rm sig}^{\rm fix}), N_{\rm BG}(N_{\rm sig}^{\rm fix}))}{\mathcal{L}(N_{\rm sig}, N_{\rm RMD}, N_{\rm BG})}$$

2009-2013



×10^12
Number of μ+ on target
0
100
200
300
400
500
600
700
Dec/2009
Jan/2011
Jan/2012
Dec/2012
Dec/2013

AIF identification



Matching distributions for AIF candidate events

- Sideband data
- Random e^+–γ pair