STCF Beam Background Simulation and Implementation

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On behalf of STCF Background Group

2024.01.17 Hefei

The 2024 International Workshop on Future Tau Charm Facilities

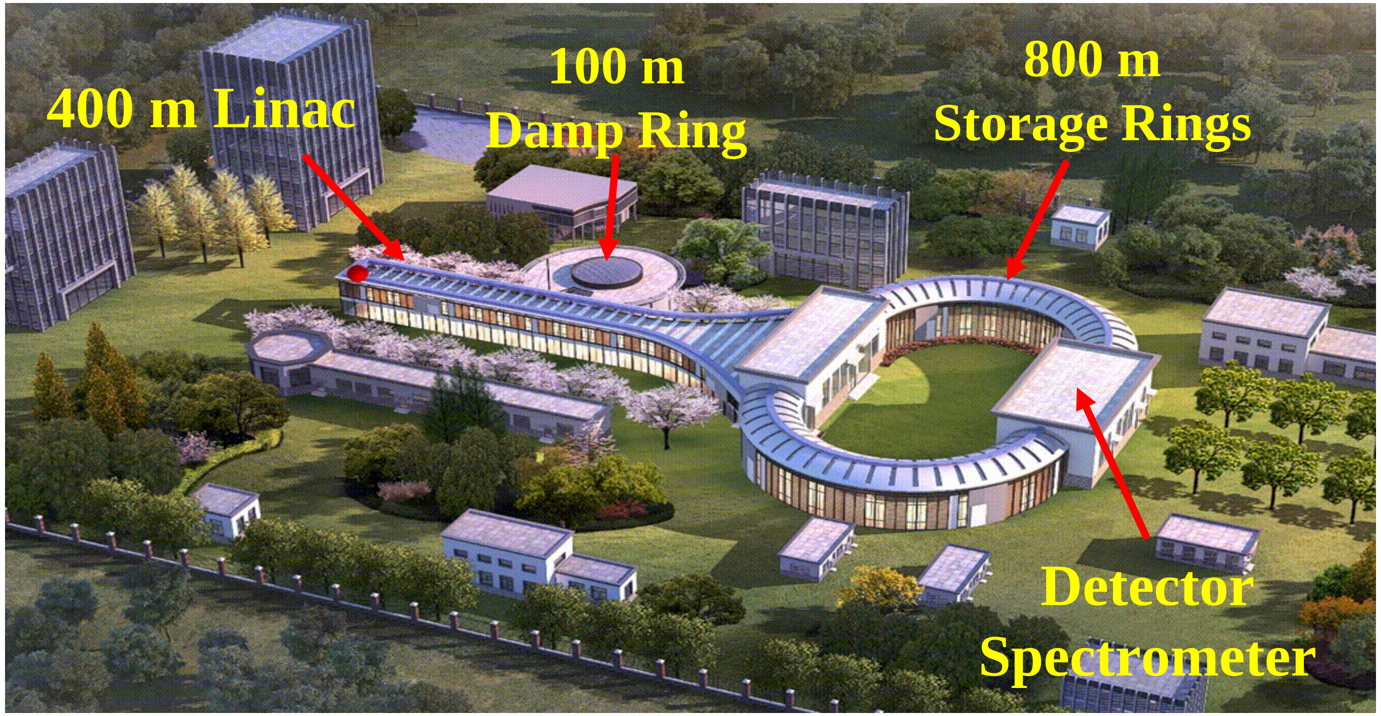
Outline

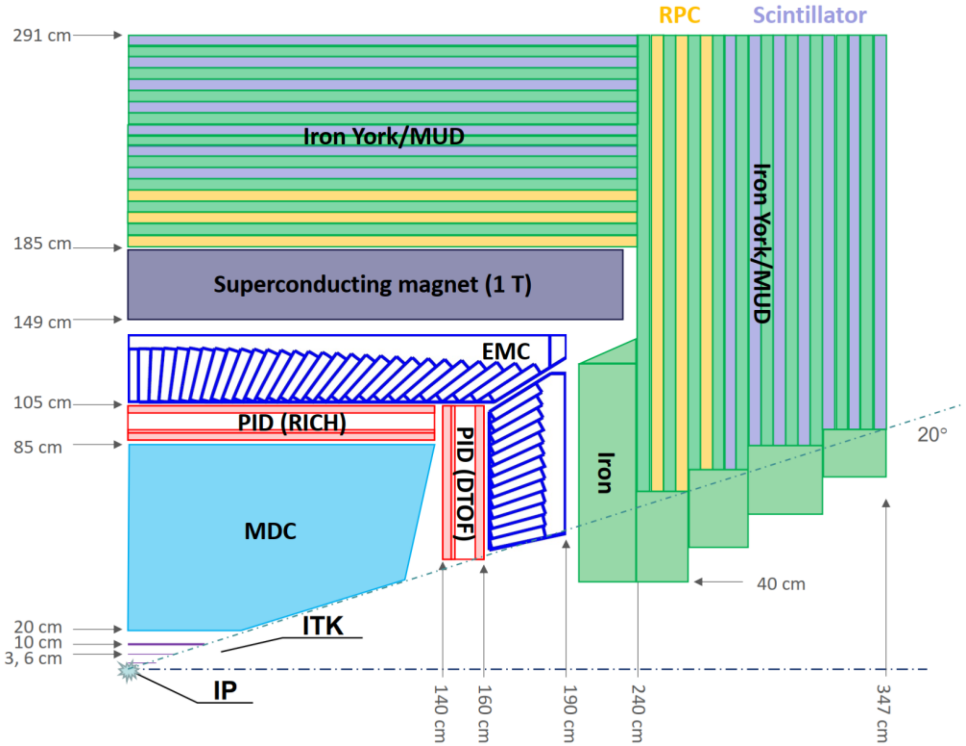
- STCF Introduction
- STCF Beam Background Simulation
- Background Mixing Algorithm
- Summary

Super Tau-Charm Facility (STCF)

STCF key parameters：

- E_{cm}： 2-7GeV
- Peak Luminosity： $> 0.5 \times 10^{35}\ \mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$ @ 4GeV
- Potential for upgrade to increase L and realize polarized beam





STCF Background Challenge

$$L = \frac{\gamma n_b I_b}{2 e r_e \beta_y^*} \xi_y H$$

Relativistic energy (γ)

Bunch number & intensity ($n_b I_b$)

Hourglass effect (H)

Beam-beam parameter (ξ_y)

Vertical betatron function (β_y^*)

Parameters	BEPCII	STCF	Compare
I_t(A)	0.91	2	2.2
$\beta_y^*(mm)$	15	0.6	0.04
ξ_y	0.04	~0.06	~1.5

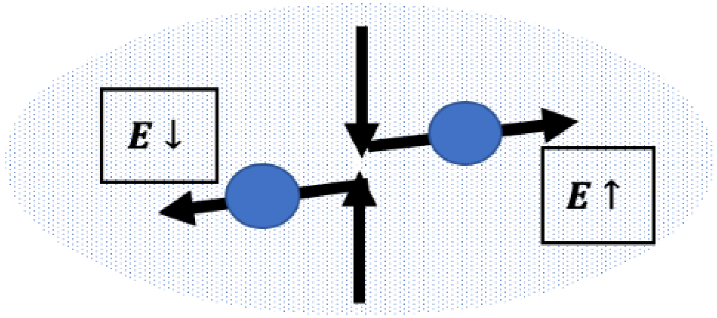
- How to improve luminosity:
  - $I_t\uparrow$: total beam current
  - $\beta_y^*\downarrow$: envelop function
  - $\xi_y\uparrow$: beam-beam parameter

- Higher background level:
  - Touschek : ×316
  - Beam-gas : ×2.2
  - RBhabha and two-photon : ×50

Beam Background at STCF

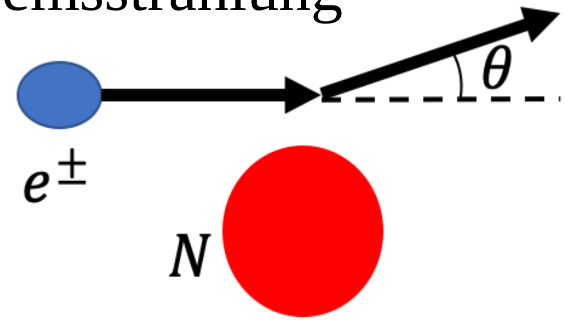
Touschek effect

- Scattering between inner beam particles
- Generation rate ∝ N_{bunch}, beam size^{-1}, energy^{-3}
- Main Background



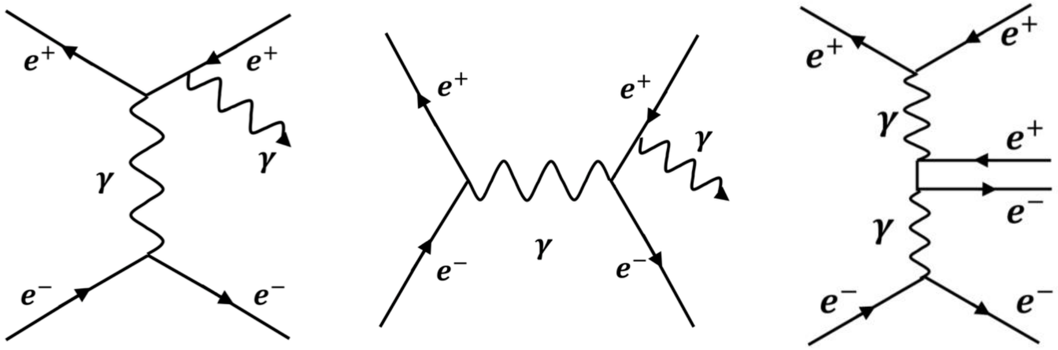
Beam-gas effect

- Effect with residual gas in the beam pipe
- Coulomb scattering， bremsstrahlung
- Generation ∝ pressure



Luminosity-related background

- Radiative Bhabha: $e^+e^- \rightarrow e^+e^-\gamma$
- Two-photon process:
  $e^+e^- \rightarrow e^+e^-\gamma^*\gamma^* \rightarrow e^+e^-e^+e^-$



Other background

- Injection
- Synchrotron radiation

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STCF Background Simulation Framework

Generator:

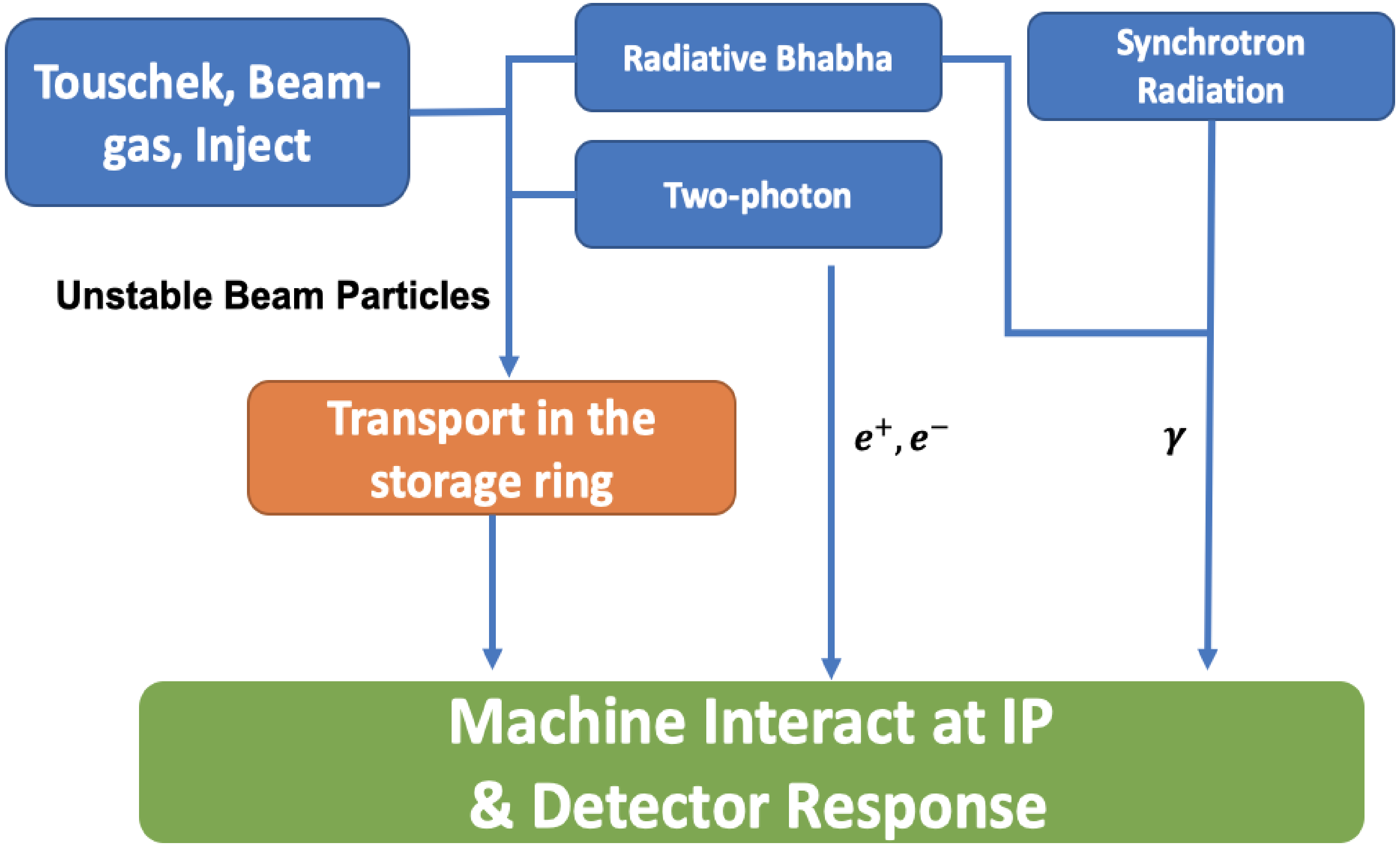
- Beam-related background：sampling with cross section
- Luminosity-related：available generator
- Injection and SR not included

Accelerator tracking:

- SAD developed by KEK

MDI interaction and detector:

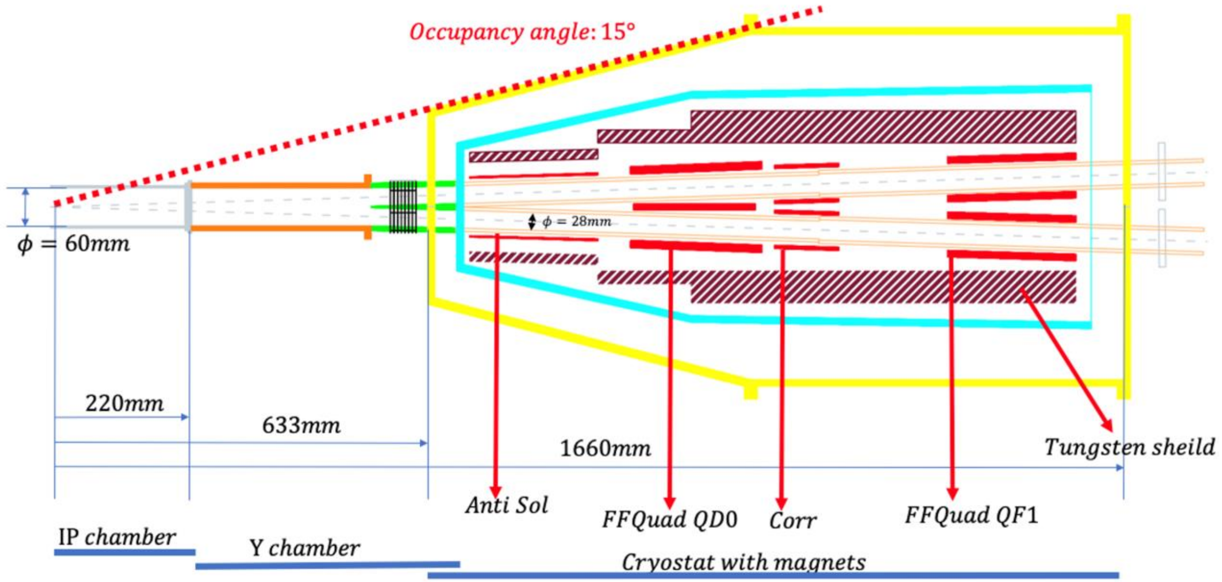
- Geant4 based framework

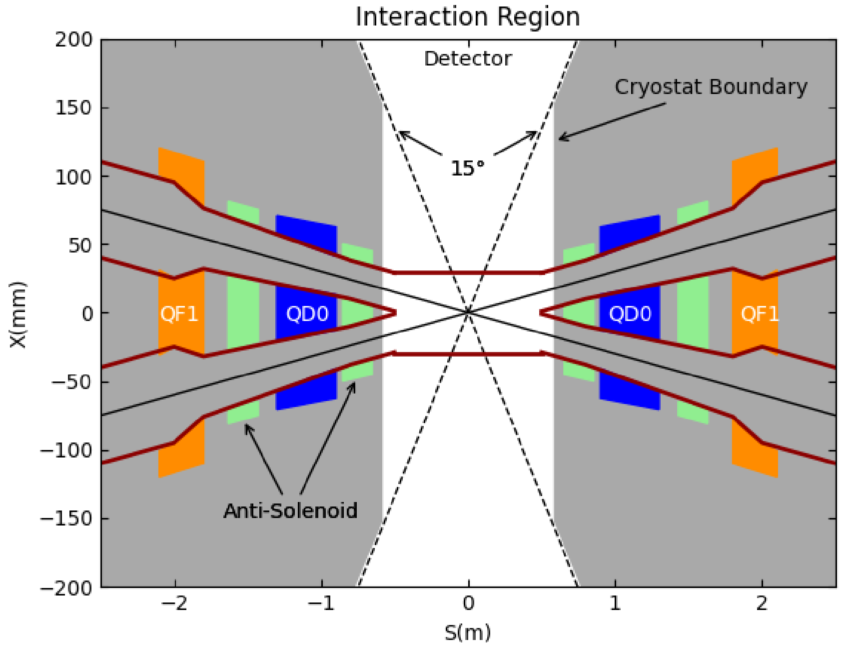


STCF MDI design

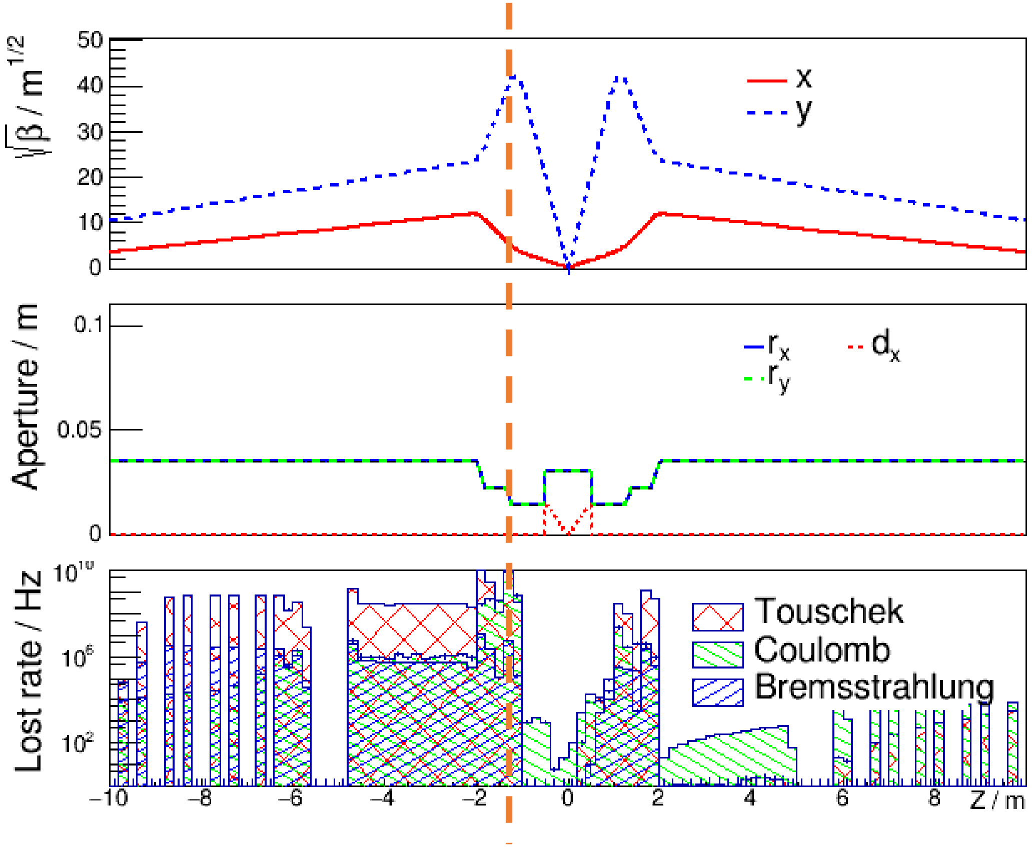
- Machine-Detector interface:
  - includes: beam pipe, magnet, cryostat, tungsten shield
  - beam separated at z=0.5 m
  - diameter limited by QD0 and beam distance

Parameter	Value
QD0 position L_0	0.9 m
Occupancy angle	15°
Diameter at IP	60 mm
Min diameter	28 mm

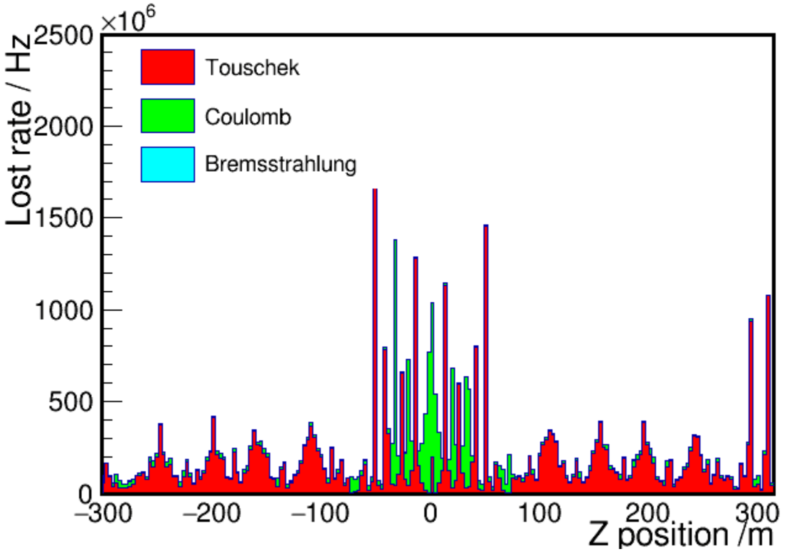




Lost Simulation| SAD Output

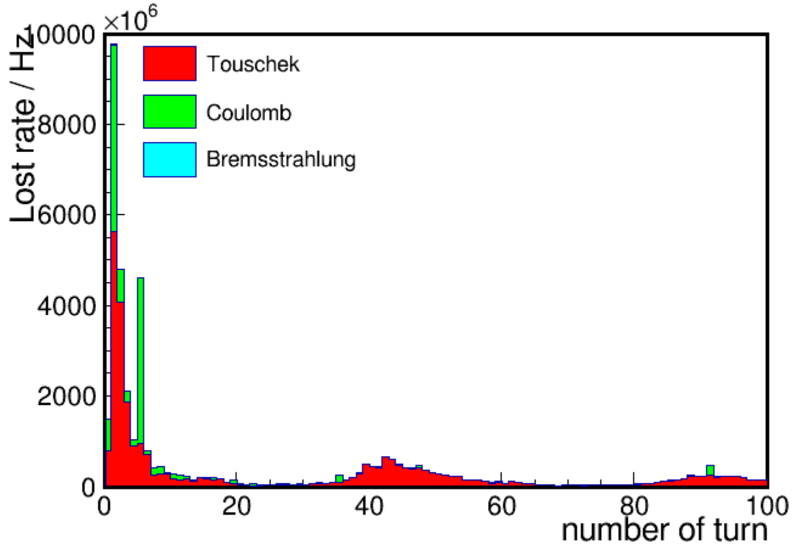


Lost rate in IR



Touschek: from all the ring

Beam-gas: from [-80, 80] m



Not lost immediately

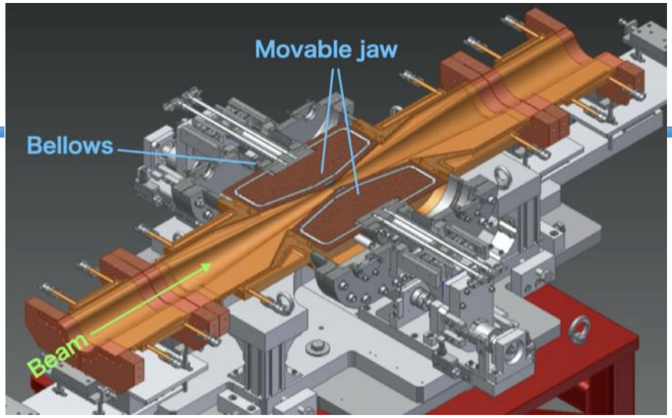
Touschek: lost at min R

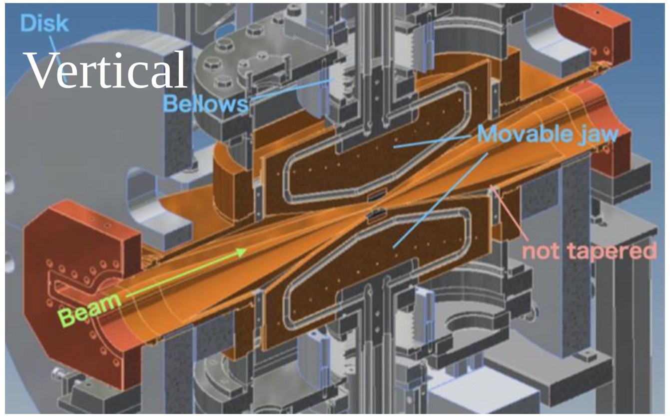
Beam-gas: lost at min R and max βy

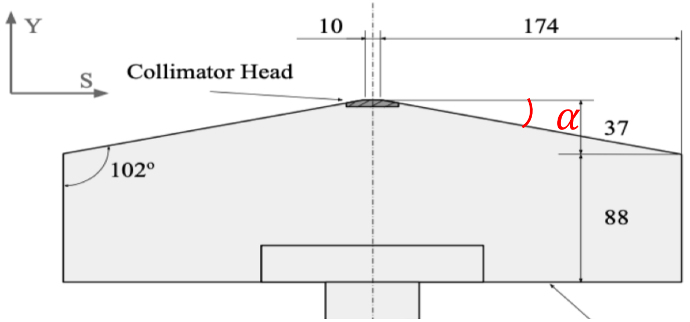
STCF Collimator

- About collimator：
  - Inside beam pipe, scrape off-orbit particles before IR
  - Horizontal and vertical
  - Trapezoid structure to reduce impedance
  - Movable along aperture and beam
- Setup at lattice drift segments with large upstream beta functions and lengths > 1.5 m

Name	Orientation	Limitation	Design	
		Rmax/mm	Zmid/m	R/mm
CoH01	Hor.	78.63	-45.0	15
CoH02	Hor.	78.70	-56.0	15
CoV01	Ver.	9.40	-19.2	5
CoV02	Ver.	9.32	-31.0	5



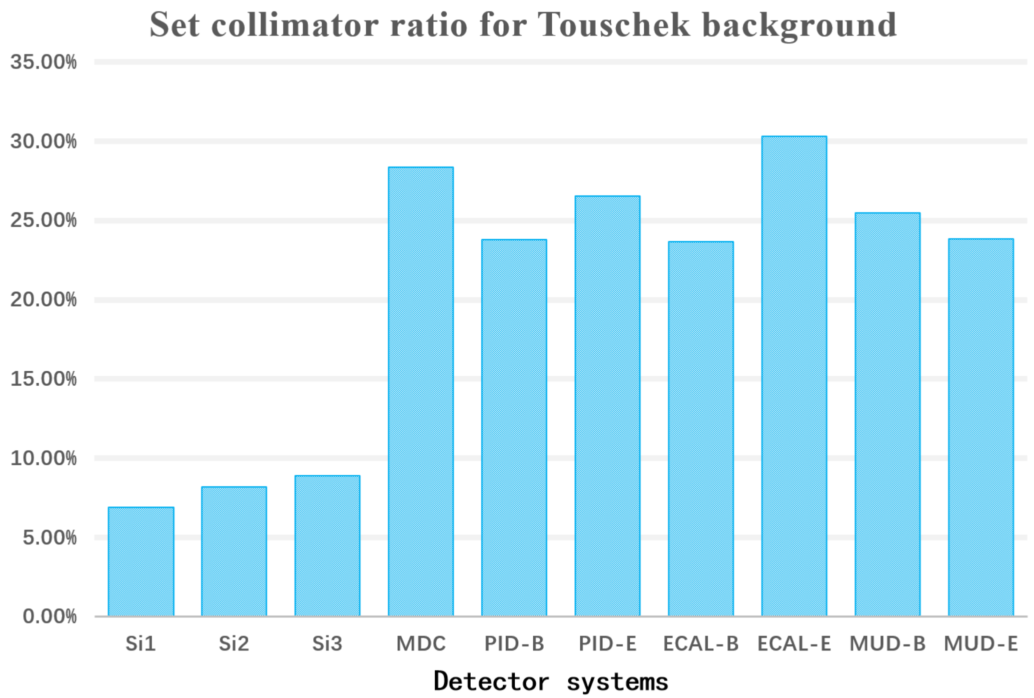


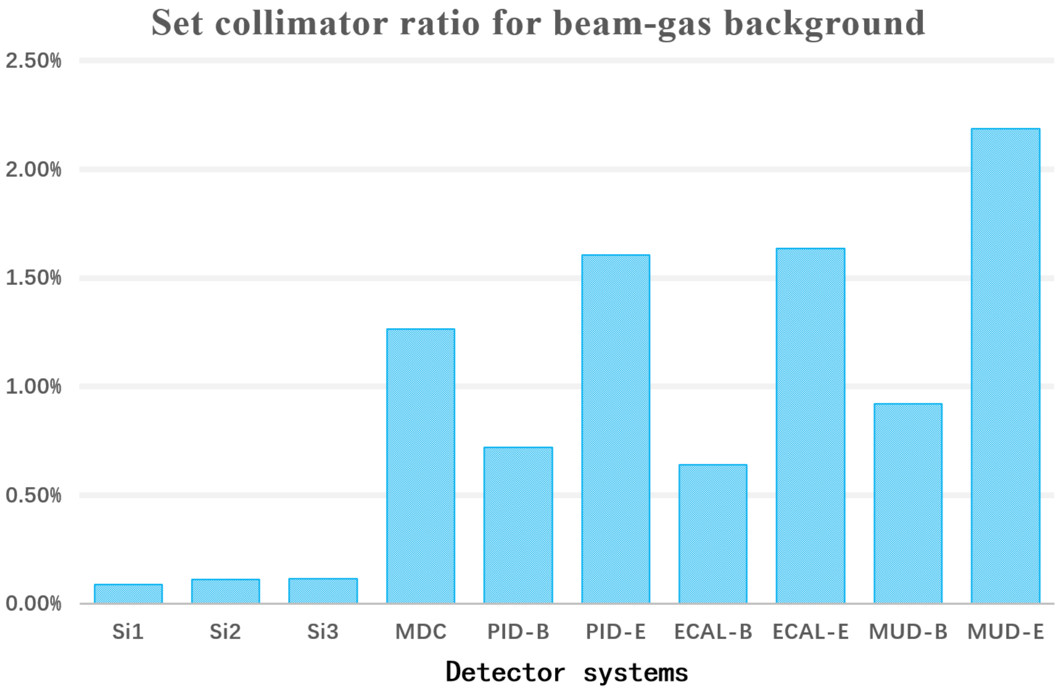


SuperKEKB collimator structure

After Collimator | Compare lost rate

- Add collimator suppress beam background (especially beam-gas)

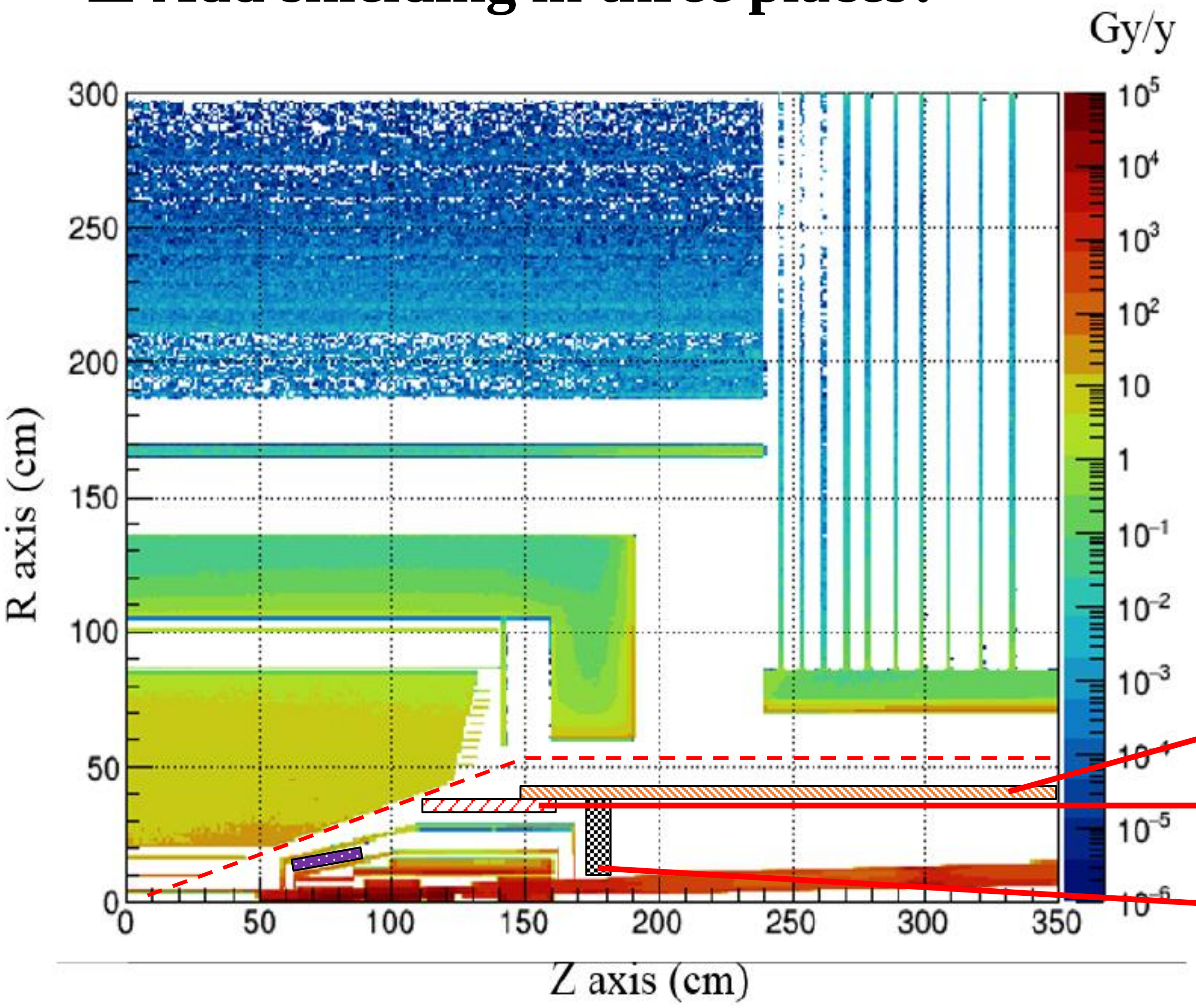




Lost rate/ Hz	Touschek < 0	Touschek > 0	Beam-gas < 0	Beam-gas > 0
No Collimator (Hz)	3.47×10^{10}	2.08×10^{9}	1.08×10^{10}	1.27×10^{8}
With Collimator (Hz)	2.19×10^{9}	1.17×10^{8}	1.06×10^{7}	4.15×10^{6}
Ratio (%)	6.3	5.63	0.11	3.27

Shielding design

- **Add shielding in three places:**



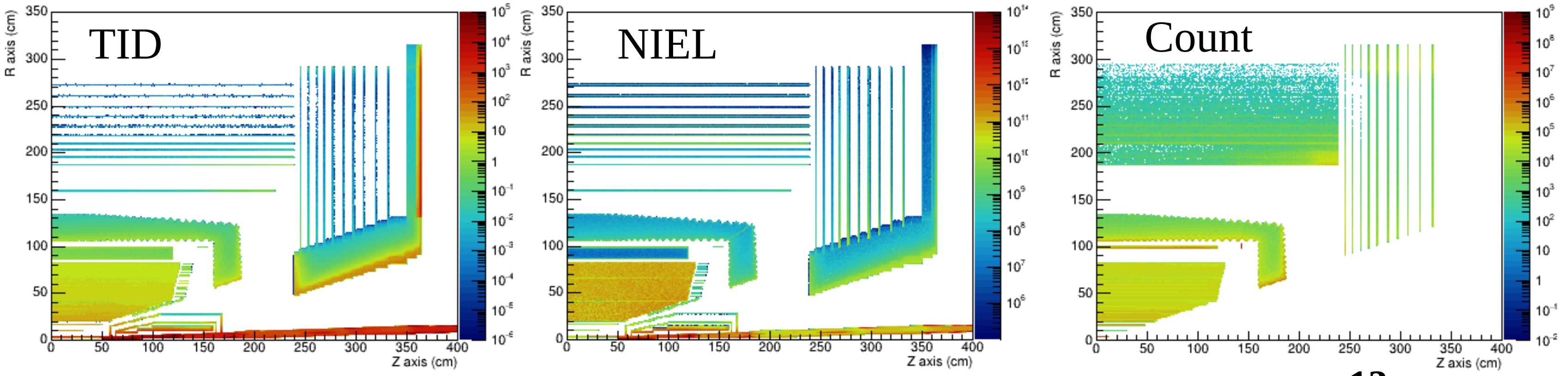
	e± number	γ number
No shield	2.62 M	36 k
Outer tube	83.3 k	4.16 k
Outer tube + endcap	57 k	2.2 k
3 shields	13.9 k	1 k

- 10 cm Cylindrical lead shielding
- 5 cm Cylindrical lead shielding
- 5 cm Cylindrical disc lead shielding

TID, NIEL and Count

- Background statistics based on OSCAR
  Offline Software of Super Tau-Charm Facility
- Detector with highest background:
  - TID: MAPS-1
  - NIEL: MDC
  - Count: MDC
- Electronics with highest background:
  - TID: MAPS-1
  - NIEL: MAPS
- Component:
  - Touschek is dominant

Sub-detector	Detector Sensitive Volume			Electronics	
	TID (Gy/y)	NIEL (1 MeV neutron/cm²/y)	Count Rate (MHz)	TID (Gy/y)	NIEL (1 MeV neutron/cm²/y)
ITK-μRWELL-1	157. 8	1.0×10^{10}	455	48.5	4.3×10^{9}
ITK-μRWELL-2	51.5	6.6×10^{9}	461	23.9	5.4×10^{9}
ITK-μRWELL-3	21.3	7.9×10^{9}	315	15.2	8.0×10^{9}
ITK-MAPS-1	2053.3	2.0×10^{10}	46.3	417.5	3.0×10^{10}
ITK-MAPS-2	26.6	5.7×10^{9}	10.8	16.5	6.0×10^{9}
ITK-MAPS-3	18.6	9.7×10^{9}	16.8	12.0	1.1×10^{10}
MDC	7.4	1.1×10^{13}	535	1.93	3.2×10^{9}
RICH	0.54	5.0×10^{9}	12.7	2.1	4.0×10^{9}
DTOF	1.7	8.6×10^{9}	41.4	1.5	5.7×10^{8}
ECAL-B	0.35	8.9×10^{9}	95.5	0.03	7.0×10^{8}
ECAL-E	1.2	1.2×10^{10}	78.5	1.2	1.3×10^{9}
MUD-B-RPC	0.03	7.7×10^{8}	36.2	0.06	8.5×10^{8}
MUD-B-PS	0.002	1.6×10^{10}	23.5		
MUD-E-RPC	0.01	2.6×10^{8}	7.5		
MUD-E-PS	0.004	1.9×10^{10}	19.1		



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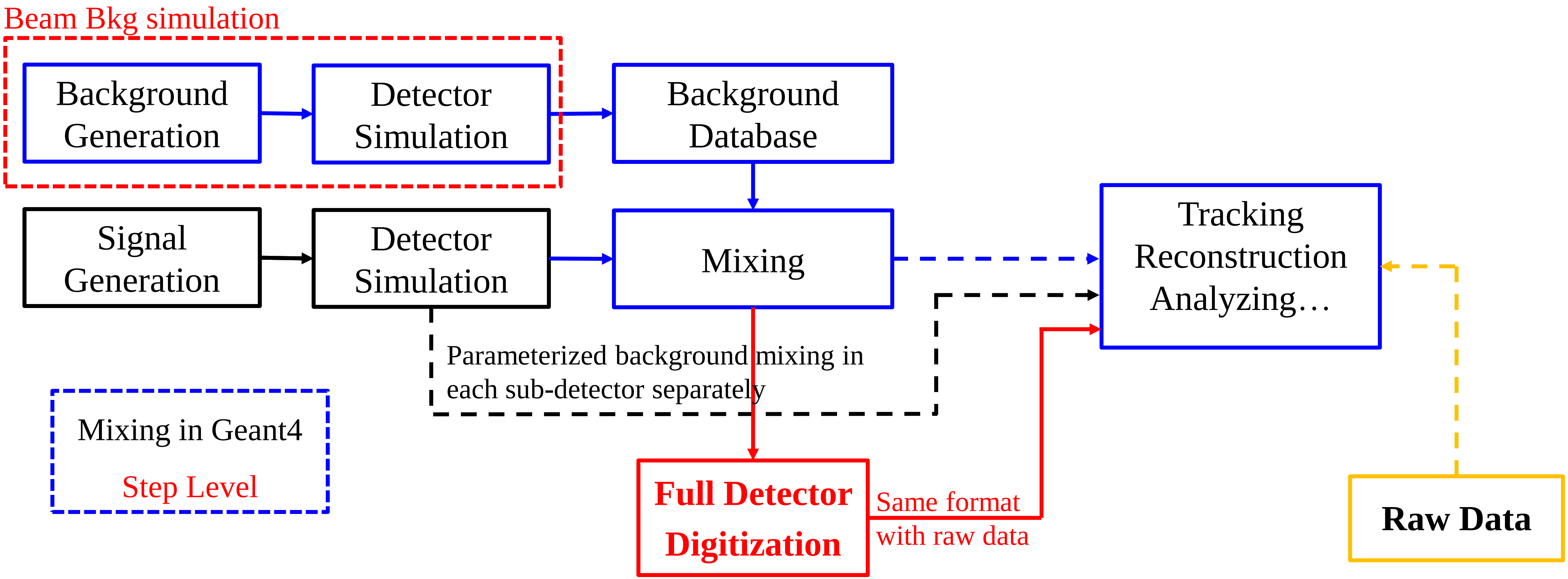
Background Mixing Introduction

- **Background Mixing**： Before digitization, signals mixed with beam background at the Geant4 step level.
- Simulated background particles as input; a unified algorithm applied to each sub-detector.

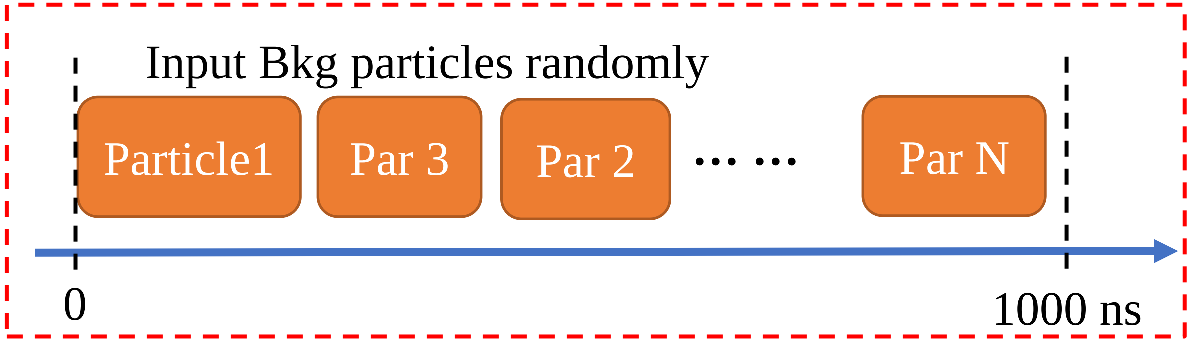


Beam Background Database

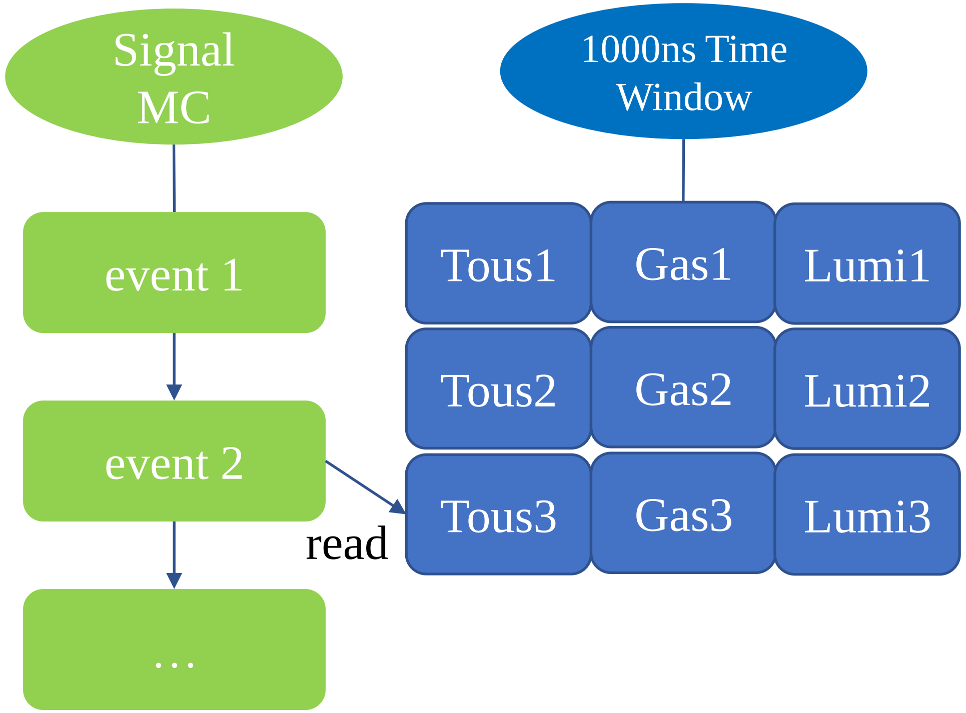
- Time window: 1000ns
- 1 Bkg event = all Bkg particles in 1 time window.

		Lost Rate (MHz)
Touschek		1120
Beam-gas	Coulomb	208
	Bremsstrahlung	2.1
Luminosity-related	Radiative Bhabha	615
	Two-photon	103

1 Touschek Background Event



Background Mixing Approach



STCF Event Pile-up

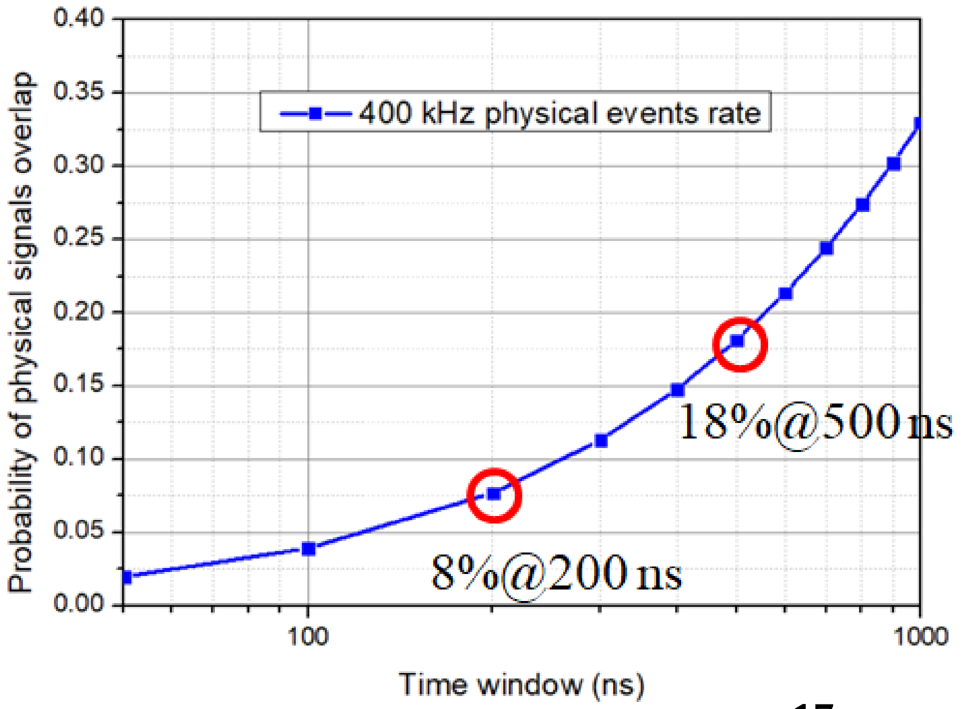
- Average number of physics events in each collision:

$$< \mu > = \frac{f_{phy}}{N_b \times \frac{c}{L}} = 1.6 \times 10^{-3}$$

- Probability of gen 2 PhyEvt in one collision： 1.28×10^{-6}
- Signal event generate at 0 ns, 32.9% probability of another **physics event** occurring within 1000 ns time window

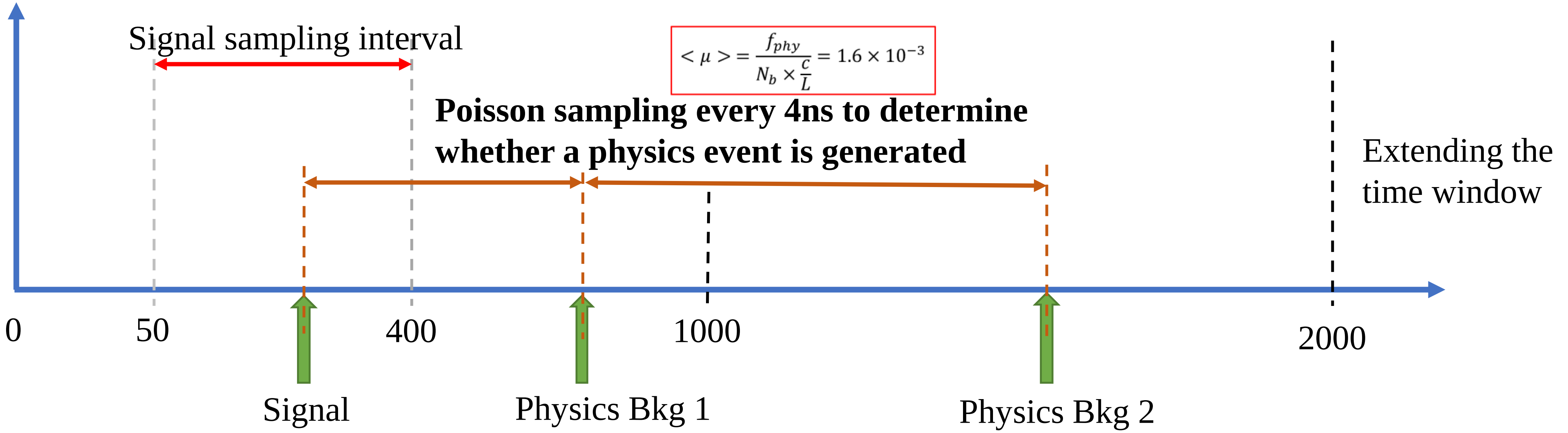
Physics Background

Physics Event GenRate f_{phy}	$\leq$ 400 kHz
Storage ring circumference L	617m
Bunch number N_b	514
Collision time interval	4 ns



Event Composition

- 1 event includes：
  - **Signal**： $e^+e^- \to \pi^+\pi^- J/\psi \to \pi^+\pi^-\mu^+\mu^-(e^+e^-)$ @ 4.260 GeV
  - **Beam Bkg**： Touschek, Beam-gas, Luminosity-related
  - **Physics Bkg**： $e^+e^- \to anything$ @ 4.260 GeV
- 1 signal event sampling at [50, 400]ns； Physics bkg sampling each 4 ns until time interval larger than 1000ns
- Extend time window for last physics bkg; Mixing beam bkg; Go to next event

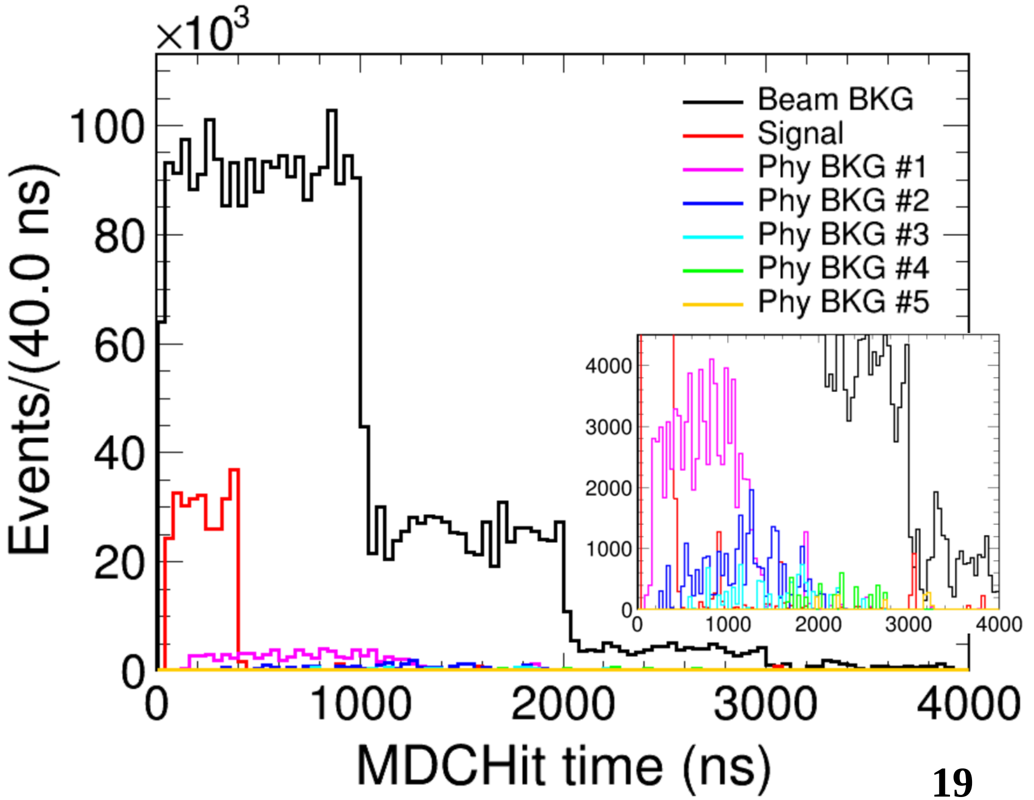


Results

- Performance： 3.3 s/Event; 22 Mb/Event
- Mixed samples used for other system research：
  - Study of sub-detector reconstruction
  - Performance of tracking
  - Trigger system event-level analysis

```
NBeamBKG = 2, Time Window = [0, 2000] ns
 Size of Output Vector = 9
 Evt #1, Type = Sig(0), EvtID = -1, Start Time = 284
 Evt #2, Type = PhyBkg(1), EvtID = 8424, Start Time = 412
 Evt #3, Type = PhyBkg(2), EvtID = 4040, Start Time = 1084
 Evt #4, Type = Tous(-1), EvtID = 7929, Start Time = 0
 Evt #5, Type = Lumi(-2), EvtID = 8042, Start Time = 0
 Evt #6, Type = Beamgas(-3), EvtID = 4643, Start Time = 0
 Evt #7, Type = Tous(-1), EvtID = 7007, Start Time = 1000
 Evt #8, Type = Lumi(-2), EvtID = 5533, Start Time = 1000
 Evt #9, Type = Beamgas(-3), EvtID = 1802, Start Time = 1000
```

1000 Events	**Signal ($\mu\mu\pi\pi$)**	**Background**
ITK	1.5M	5.2M
MDC	46M	281M
RICH	840K	4.5M
DTOF	1.7M	27M
ECAL	133M	16G
MUD	4.7M	5.0G
Total	187.7M	21.3G



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Summary

- Beam background research framework established.
- Add the collimators and shielding can significantly reduce the beam background level.
- Based on OSCAR, completed the statistical of beam background on detector and electronics.
- Finished the algorithm for signal and background mixing.

➢ **Future plan**

- Optimize the collimators and shielding
- Achieve a more refined background statistics.
- Optimize the background mixing algorithm to reduce time and size consumption..

Thank You !

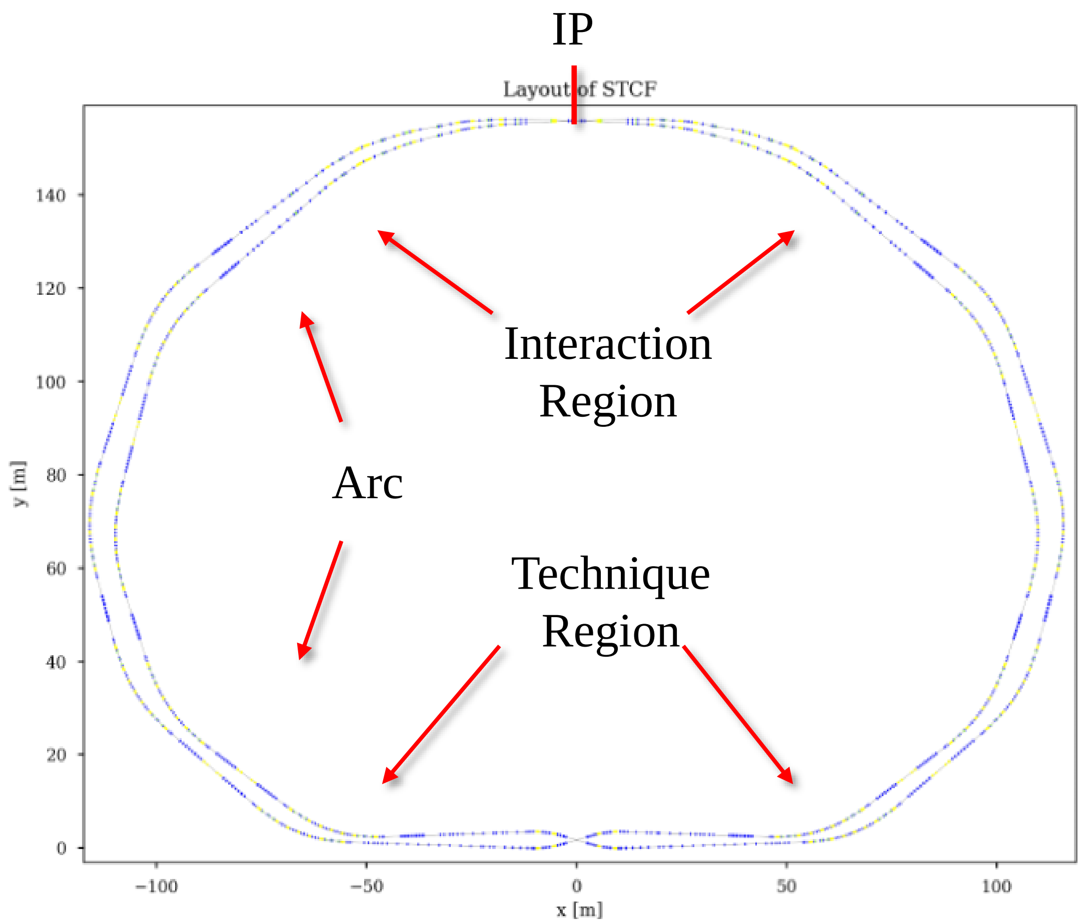
Back up

STCF Background

- 基于OSCAR的本底统计，OSCAR有更完善的几何
- 目前的本底统计：
  - **电离损伤 TID**：单位质量沉积能量大小，单位：Gy/y
  - **非电离损伤 NIEL**：单位面积通过的等效中子数，根据粒子种类和动能计算，单位: 1 MeV neutron/(cm2*y)。每条径迹仅统计一次
  - **计数率 Count（仅探测器）**：产生一定阈值以上能量沉积的击中数，单位：Hz
  - **单粒子翻转效应 SEE（仅电子学）**：质子、中子和其他重核轰击芯片的敏感区，可能导致电路节点的逻辑状态发生改变。设有20MeV动能下限阈值
- 在step级别统计沉积能量、位置、粒子种类和动能等，最终以2维直方图形式输出

STCF Lattice and MDI design

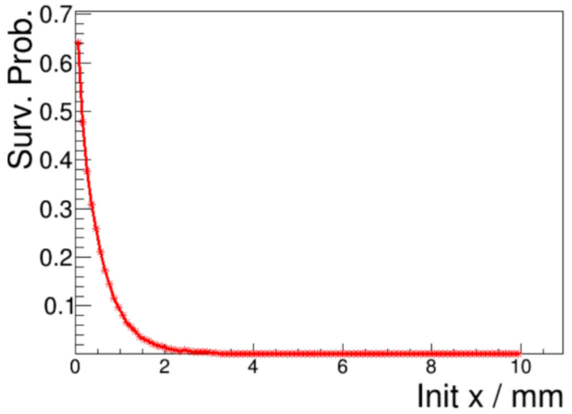
- 以Lattice设计定义束流本地版本
- 几个重要的版本：
  - **V2**：CDR版本，作为过渡版本
  - V7： current lattice
  - **V7C3**：增加 collimator

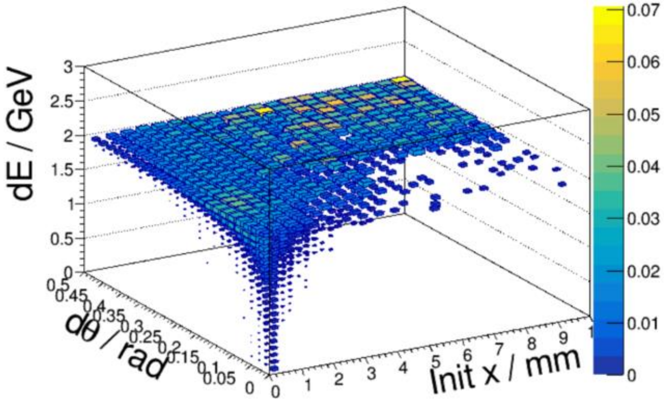


Collimator 的优化

➢ Tip-scattering 算法：

- 模拟部分粒子可以穿过 collimator，并继续在储存环中运动的情况
- Geant4中建模collimator；模拟$e^{\pm}$通过collimator的存活率及分布；Geant4模拟的结果输入SAD





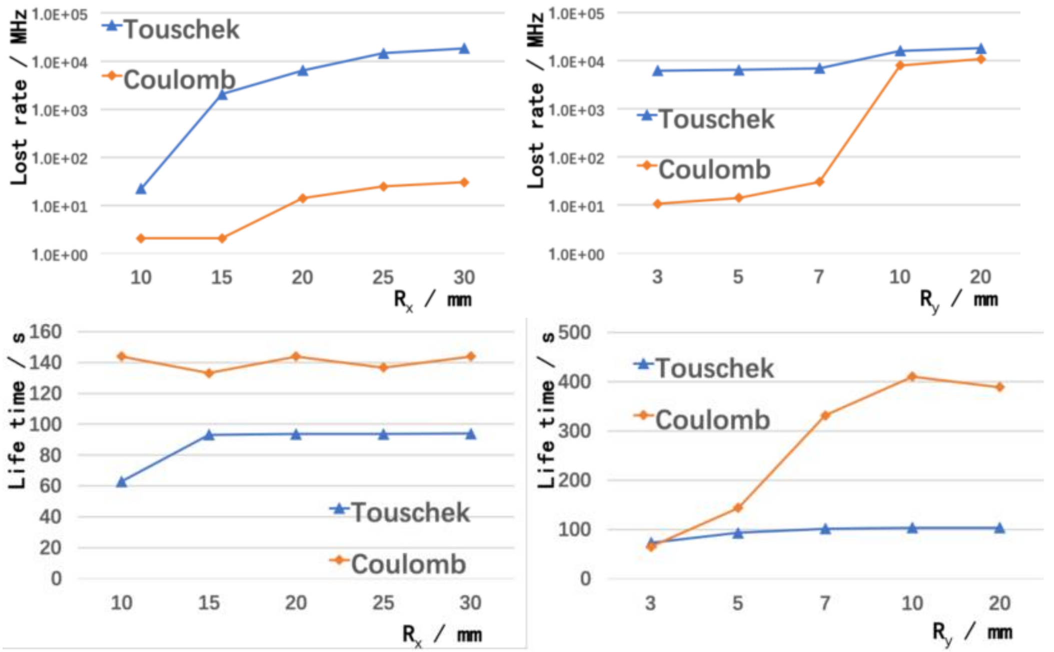
本底粒子经过 collimator 散射后的生存概率；能损和散射角随初始位置的分布

截断方法会低估束-气本底

模拟算法	Touschek 上游	Touschek 下游	束-气上游	束-气下游
SAD 硬截断 (trun.)	6.42×10^9	6.24×10^8	1.41×10^7	3.83×10^6
Tip scattering(tip.)	6.38×10^9	6.12×10^8	1.51×10^7	4.27×10^6
比值（tip./trun.）	0.99	0.98	1.07	1.11

➢ Collimator 孔径的优化：

- 未考虑 TMCI 效应
- 孔径设计需均衡粒子丢失率和束流寿命
- Touschek 对R_x变换更敏感；束-气对R_y更敏感



优化孔径可有效压低Touschek本底(~60%)

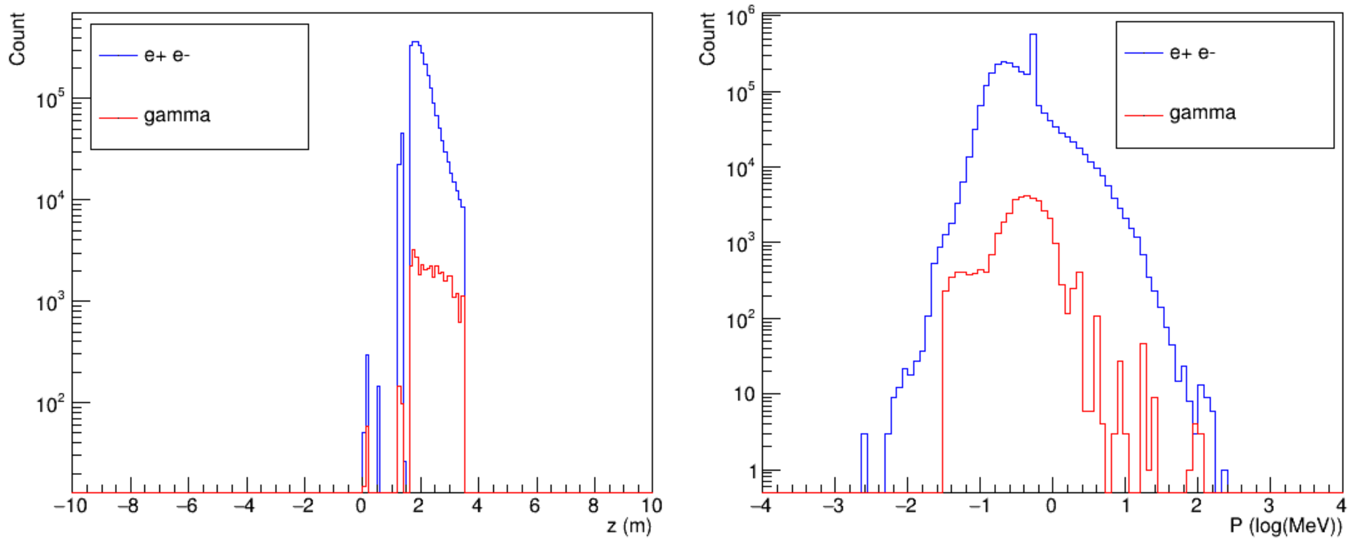
	Touschek 上游	Touschek 下游	束-气上游	束-气下游
无 collimator（Hz）	3.47×10^{10}	2.08×10^9	1.08×10^{10}	1.27×10^8
初始 collimator（Hz）	6.38×10^9	6.12×10^8	1.51×10^7	4.27×10^6
优化 collimator（Hz）	2.19×10^9	1.17×10^8	1.06×10^7	4.15×10^6

V7C3 仍需要额外屏蔽

- V7C3版本底仍高于V2，需要在MDI区域设置**额外屏蔽**层
- Touschek占主导，进入探测器的粒子种类主要为正负电子和光子

	V7/V2	V7C3/V2	V7C3 中 Touschek占比
ITK1	**102.28**	**1.20**	76%
ITK2	**93.24**	**1.46**	91%
ITK3	**101.58**	**1.77**	87%
MDC	**166.05**	**9.77**	94%
PID-B	**130.46**	**6.71**	92%
PID-E	**156.46**	**14.21**	96%
ECAL-B	**123.51**	**7.69**	93%
ECAL-E	**126.18**	**7.28**	92%
MUC-B-RPC	62.29	**5.07**	85%
MUC-B-PS	56.38	**3.64**	81%
MUC-E-RPC	43.47	**4.46**	82%
MUC-B-PS	49.81	**3.06**	75%

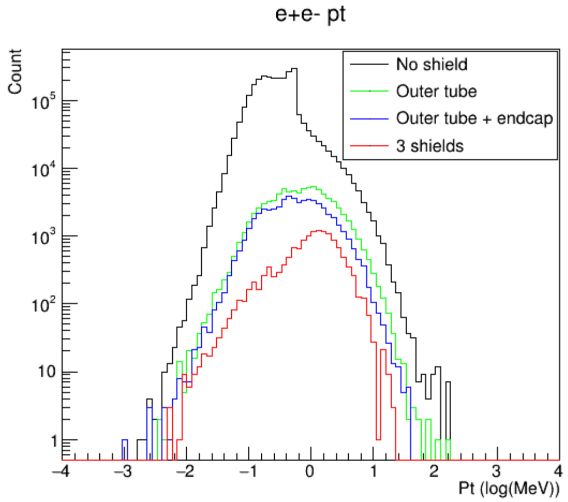
进入20°范围内的粒子动量与位置分布

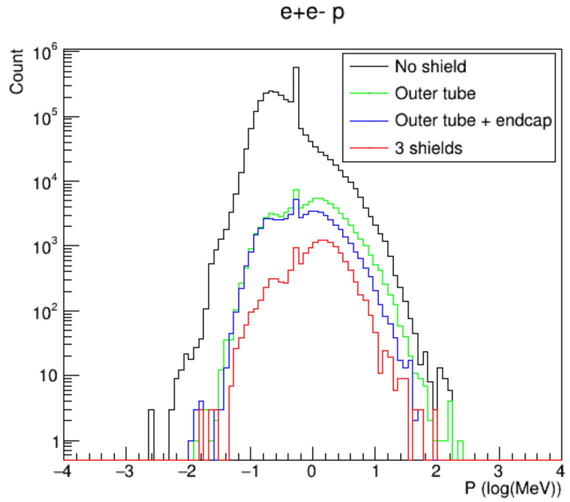


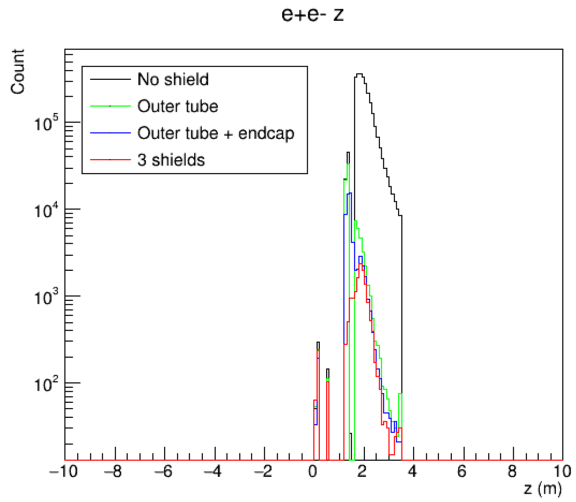
不同屏蔽方案的本底降低效果

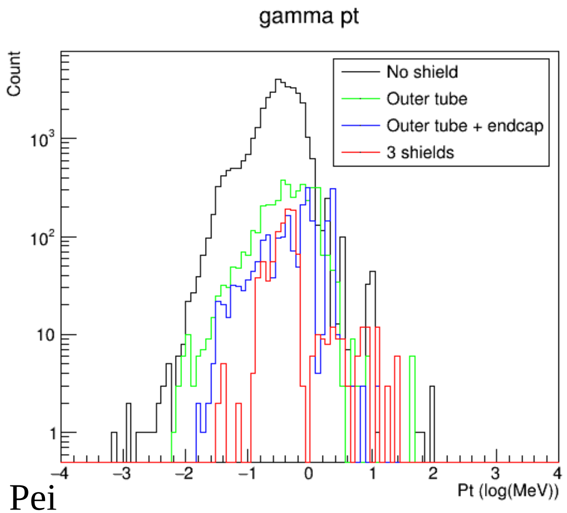
基于V7C3 Standalone

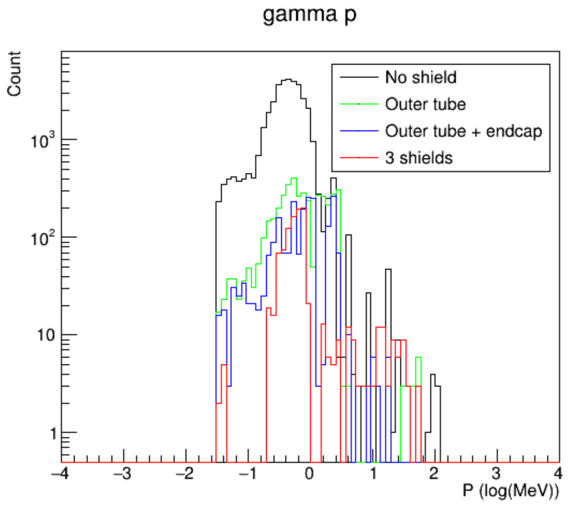
- 在束流管-探测器边界处设置连续的铅屏蔽，本底降低效果最好

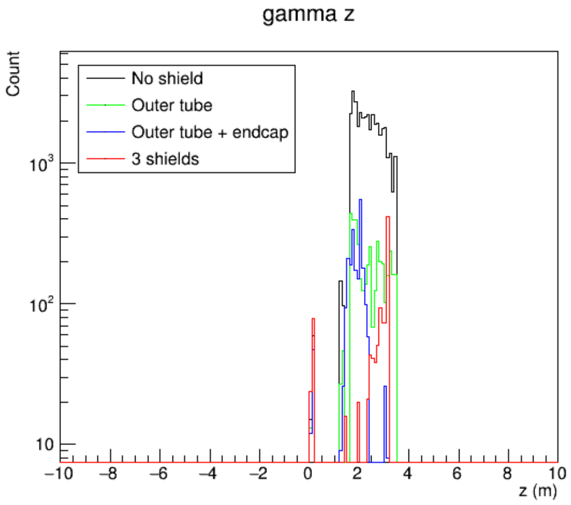












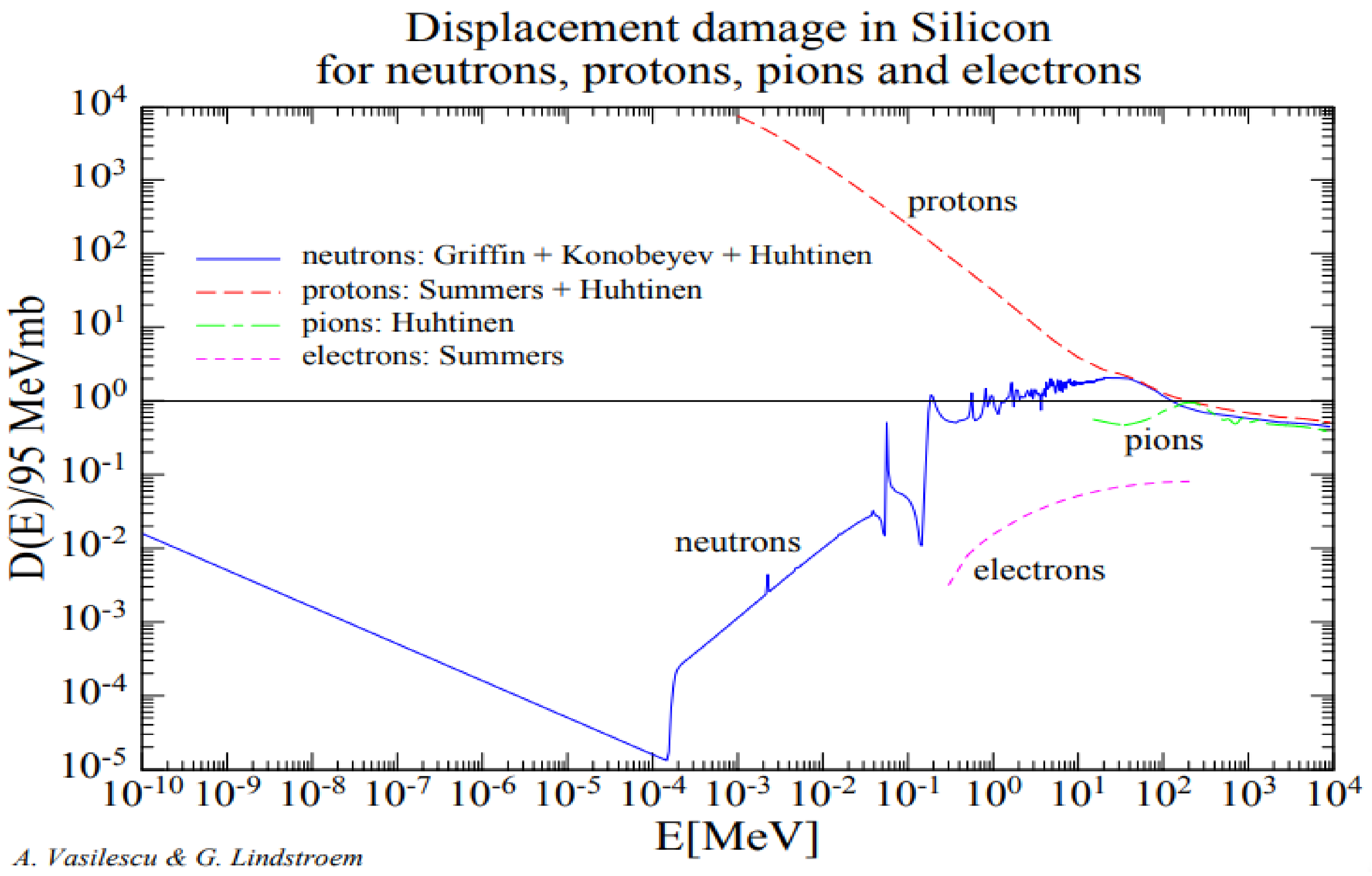
不同屏蔽方案的本底降低效果

基于V7C3 Standalone

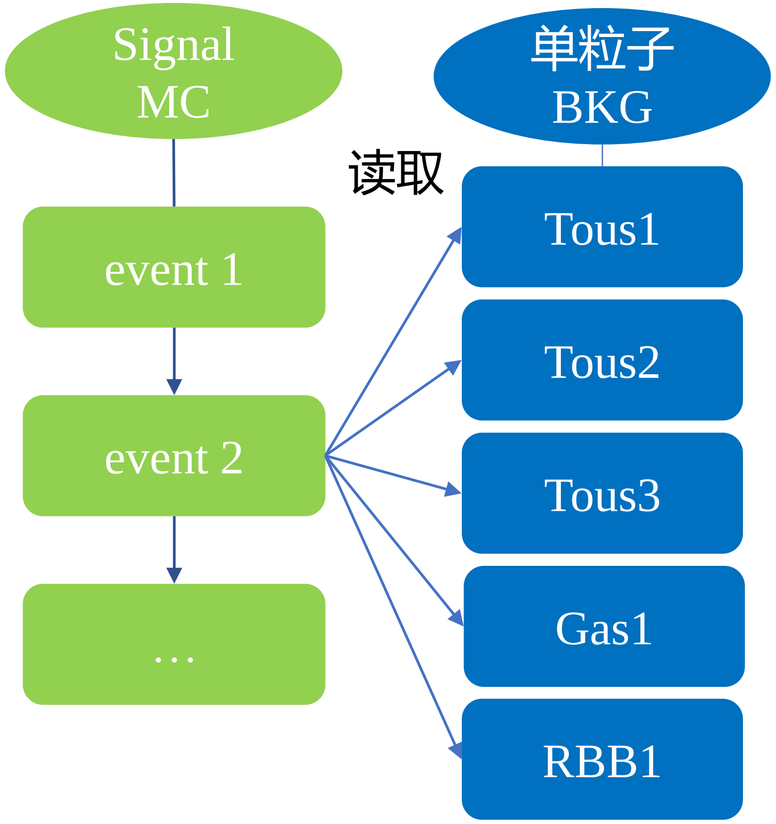
- 在V7C3版本standalone环境下初步测算各探测器计数率与屏蔽的关系

	No shield	Outer tube	Outer tube+ endcap	3 shields	V7C3/V2	现有最优屏蔽下的本底/V2
ITK1	100%	62%	59%	142%	1.20	**1.70**
ITK2	100%	191%	202%	116%	1.46	**1.70**
ITK3	100%	139%	88%	102%	1.77	**1.81**
MDC	100%	73%	32%	6%	**9.77**	**0.55**
RICH	100%	63%	27%	7%	**6.71**	**0.45**
DTOF	100%	7%	3%	2%	**14.21**	**0.33**
EMCB	100%	60%	30%	10%	**7.69**	**0.79**
EMCE	100%	17%	10%	6%	**7.28**	**0.44**
MUDBRPC	100%	57%	38%	92%	5.07	4.68
MUDBPS	100%	118%	81%	63%	3.64	2.30
MUDERPC	100%	33%	45%	51%	4.46	2.27
MUDEPS	100%	90%	65%	93%	3.06	2.84

Neutrton NIEL 曲线分析

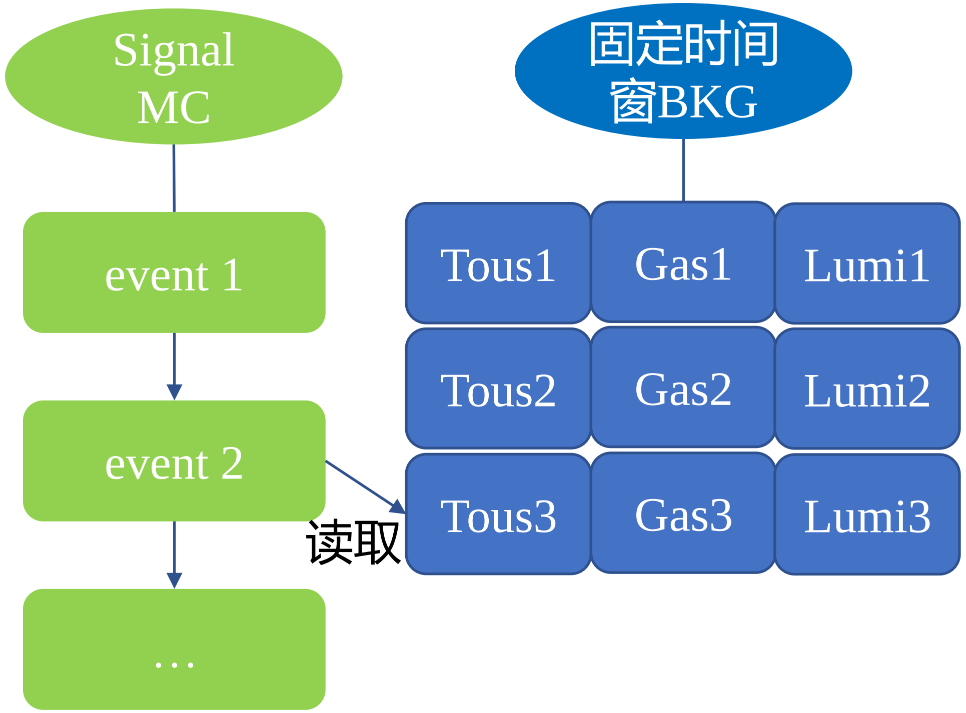


混本底方法



- 模拟单本底粒子事例，对一个信号事例混入1us时间窗内对应数目本底的hit
- 一个信号事例需要读取约4500个单粒子事例的hit，前台每个信号事例用时约90s

之前的方法：
一个signal事例读取$N_{tous} + N_{Gas} + N_{RBB} + N_{Two\ \gamma}$个本底事例中的hit

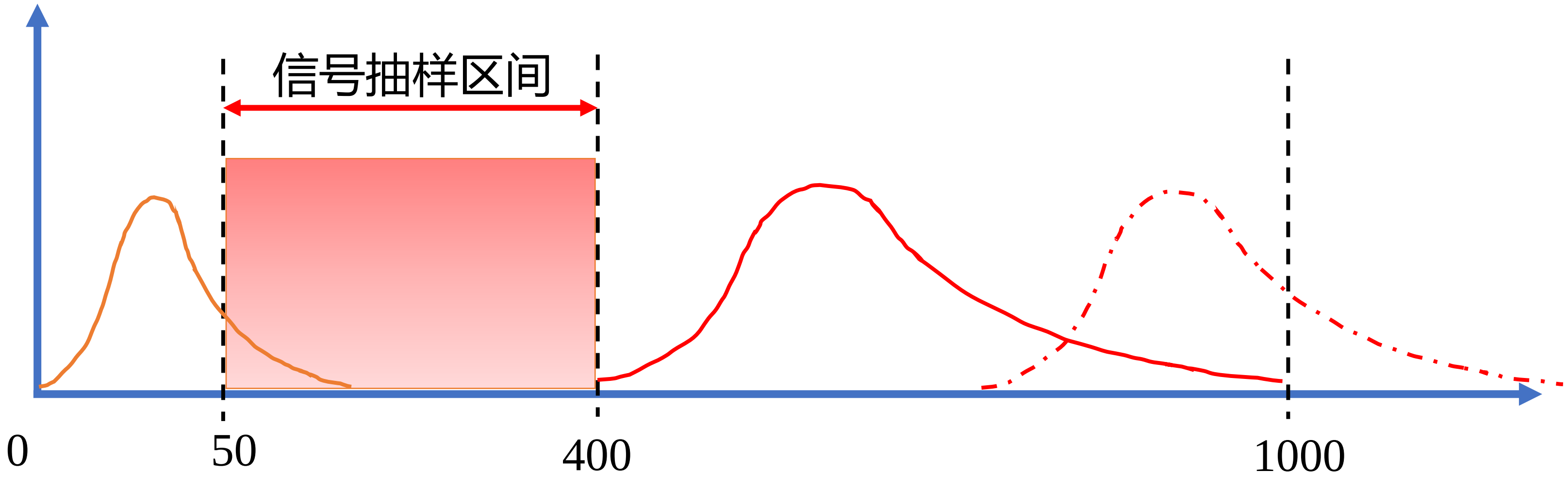


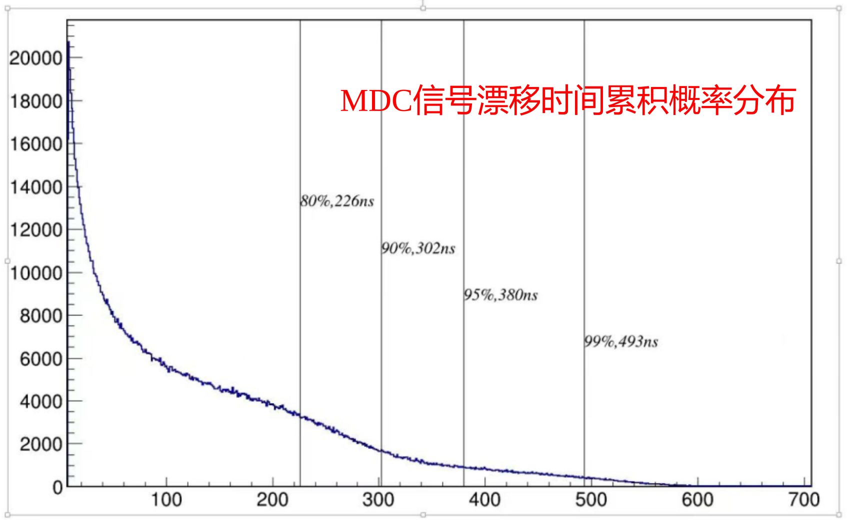
更新后方法：
一个signal事例读取3个不同来源本底事例的hit

一个信号事例只需读1个本底粒子，前台每个信号用时约1.6s

信号抽样时间

- 信号抽样区间：[50, 400] ns
- 考虑信号抽样之前，本底尾巴的影响 ⇒ 起始定于50ns
- 时间窗内信号不可被截断 ⇒ 末了定于400ns





物理本底抽样

$$<\mu> = \frac{f_{phy}}{N_b \times \frac{c}{L}} = 1.6 \times 10^{-3}$$

- 信号抽样后，每 4ns 泊松抽样，决定此时物理本底个数 N_{PB}：
  - $N_{PB} \geq 1$: 从物理本底库抽样 N_{PB} 个物理本底
  - $N_{PB} < 1$: 时间向后4ns，抽样次数 NSam++
- 事例判定条件：抽样时间间隔大于1000ns ($Nsam > 250$)
- 最后一个物理本底的时间决定延长的时间窗
- 依次混合信号，物理本底，束流本底的 Point