Machine-Detector Interface

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Outline

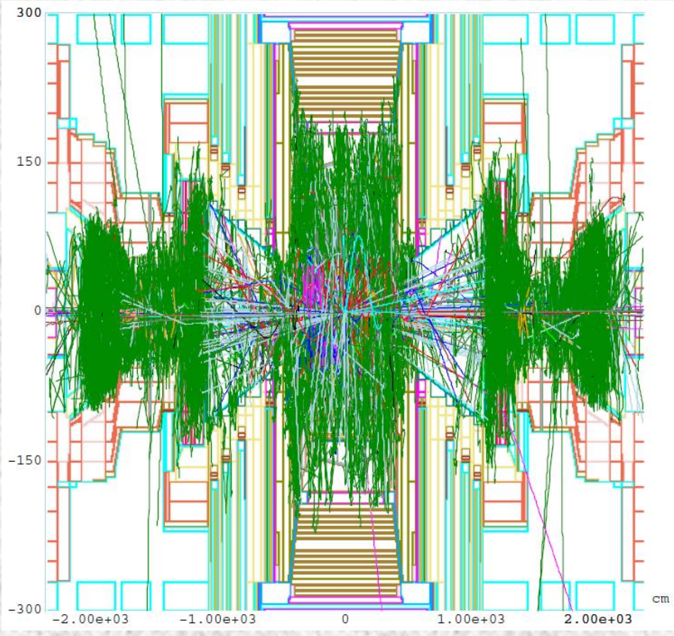
- IP and Machine-Induced Backgrounds and Radiation Loads
- Protecting Detector and Collider Components
- 50x50 TeV pp Collision Characteristics
- Loads on Machine and Detector: FCC vs HL-LHC
- Summary

Introduction

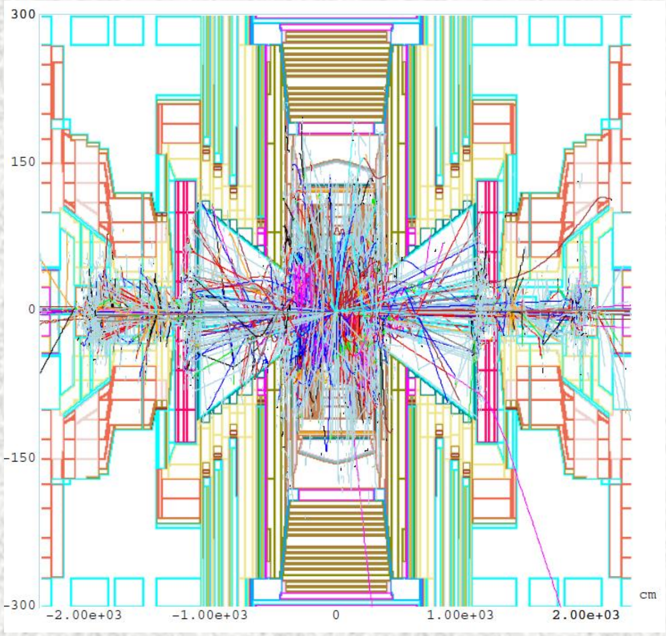
The deleterious effects of background and radiation environment originated from a collider interaction point (IP) and from beam interactions with accelerator components are one of the key issues in interaction region (IR), machine-detector interface (MDI) and detector design and developments.

IP Backgrounds and Radiation Loads in IR

Collision debris from IP are the major source (>99%) of background and radiation load in the detectors and IR components at nominal parameters with a well-tuned machine (Tevatron and LHC experience). Very challenging at a high-luminosity multi-TeV collider.



20x20 TeV pp-event in a CMS-like detector



Peak Radiation Loads In Detector MARS-calculated in 2002

Machine	E (TeV)	I, 10^{14}	Q (GJ)	$\sqrt{S}$	$\mathcal{L}$, 10^{34}	σ_p(mb)	10^{16} (int/10yr)
Tevatron	0.98	0.1	0.0016	1.96	0.01	60	
LHC	7	3.1	0.35	14	1	80	4
SLHC	7	9.6	1.08	14	10	80	40
VLHC-1	20	9.7	3.20	40	1	90	4.52
VLHC-2	100	2.0	3.20	200	2	105	10.52

Peak 10-year fluence (cm^{-2}) and dose (Gy) in inner tracker and HF calorimeter at 14, 40 and 200 TeV (preliminary)

Detector	Value	SLHC	VLHC-1	VLHC-2
SVX	F_n	2×10^{15}	2×10^{14}	8×10^{14}
	F_{chh}	8×10^{16}	8×10^{15}	1×10^{16}
	D	1.5×10^{7}	1.5×10^{6}	3×10^{6}
Tracker	F_n	1.5×10^{15}	2×10^{14}	6×10^{14}
	F_{chh}	1.5×10^{15}	2.5×10^{14}	6×10^{14}
	D	8×10^{5}	8×10^{4}	2×10^{5}
Fin	F_n	1.8×10^{16}	2×10^{15}	4×10^{15}
	F_{chh}	8×10^{14}	1×10^{14}	2.5×10^{14}
	D	2×10^{6}	3×10^{5}	5×10^{5}
HF	F_n	1.5×10^{17}	2.1×10^{16}	4.8×10^{16}
	F_{chh}	7×10^{15}	1.2×10^{15}	2.5×10^{15}
	D	2.5×10^{7}	3.5×10^{6}	1×10^{7}

Peak values in collider detector scale with luminosity, with only weak dependence on $\sqrt{S}$

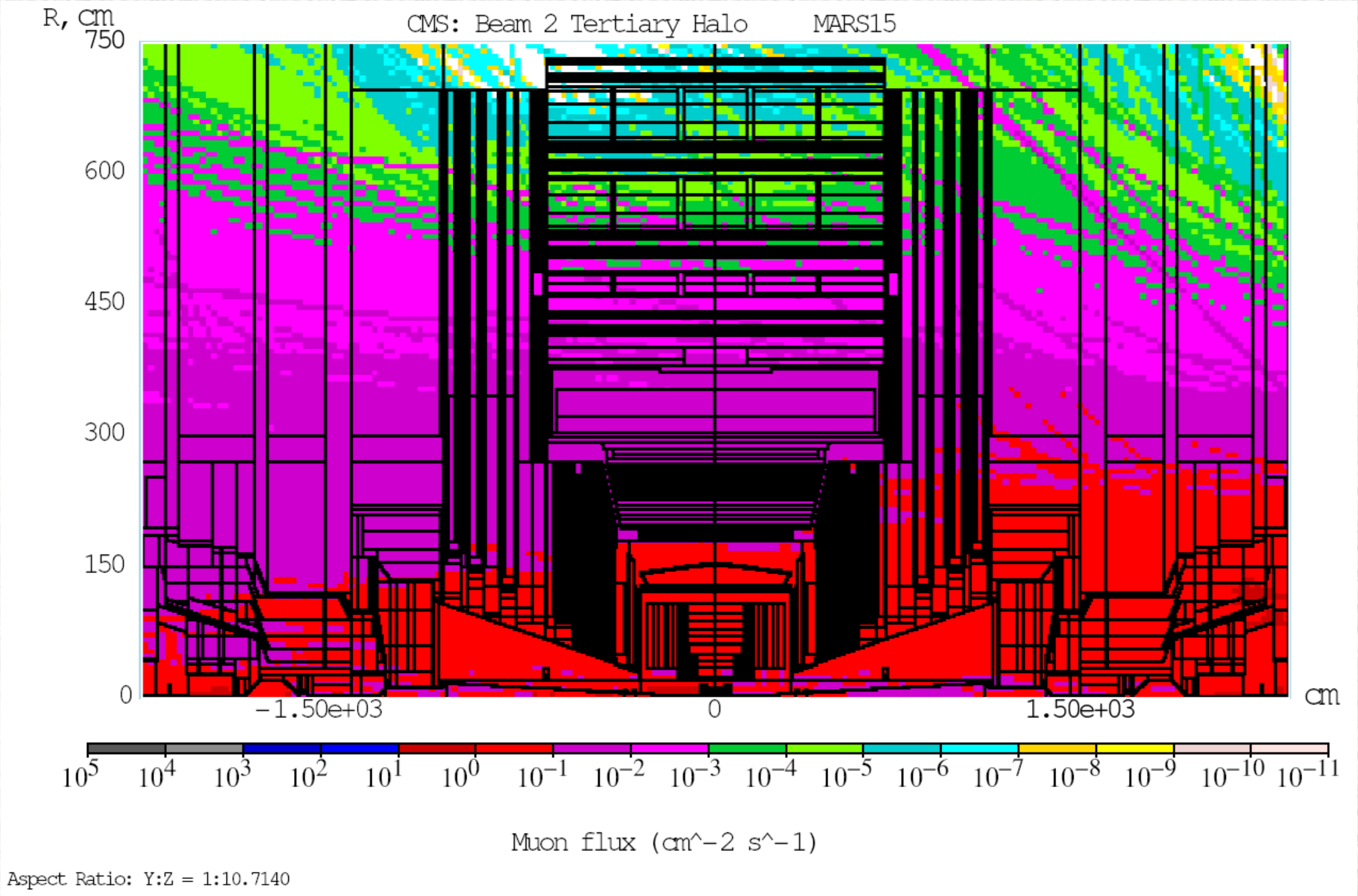
Practically scale with energy in very forward region

Machine-Induced Backgrounds and Radiation Loads

Compared to the luminosity-driven backgrounds at the IP, machine-induced backgrounds (MIB) are less studied, their characteristics vary in a broader range, and – at a low luminosity – they can be a serious issue. The collimation system takes care of "slow" losses with a very high efficiency. But still four following components form backgrounds and radiation loads in IR and detector components:

1. **Tertiary beam halo** generated in the collimation systems ("collimation tails").
2. **Beam-gas:** products of beam-gas interactions in straight sections and arcs upstream of the experiments and after the cleaning insertions.
3. **Cross-talk between experiments at different IPs.**
4. **"Kicker prefire"**: any remnants of a mis-steered beam uncaptured in the beam dump system.

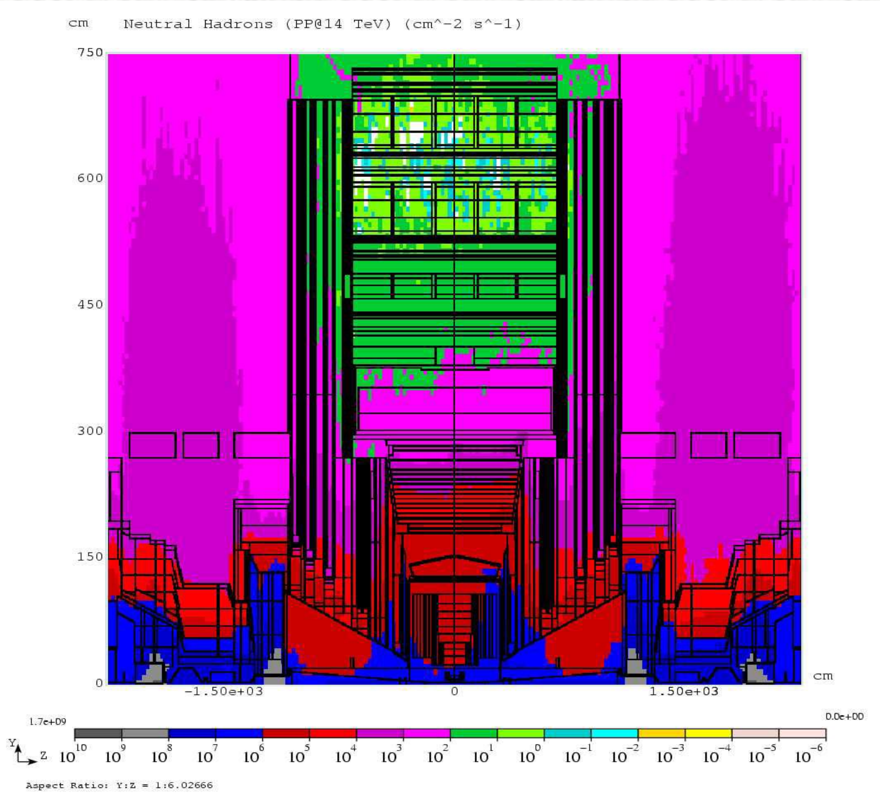
Machine-Induced Muon Fluxes in CMS



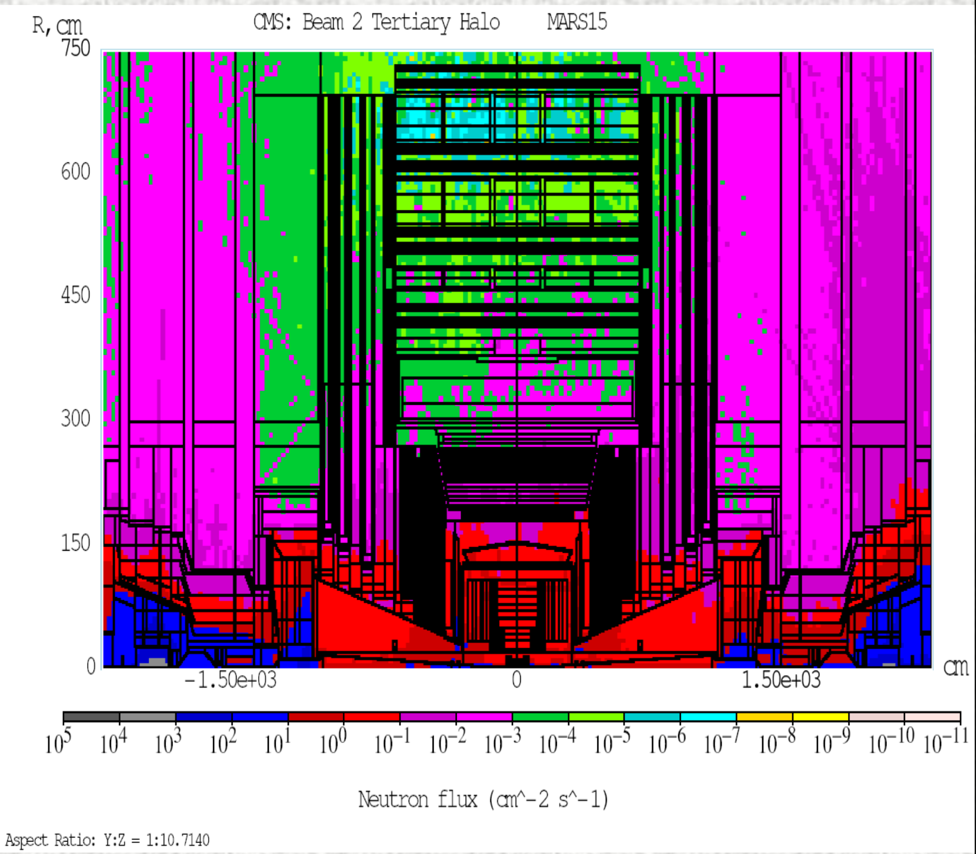
MIB vs IP: Neutron Flux in CMS

LHC, 7x7 TeV, 10^{34} cm^{-2}s^{-1}

pp



Tertiary halo, Beam2



Barrel Si tracker at r=4 cm: $\Phi_n(pp) \approx 10^5\ \Phi_n(MIB_{total})$, but can differ by only a factor of 10 or so at startup conditions

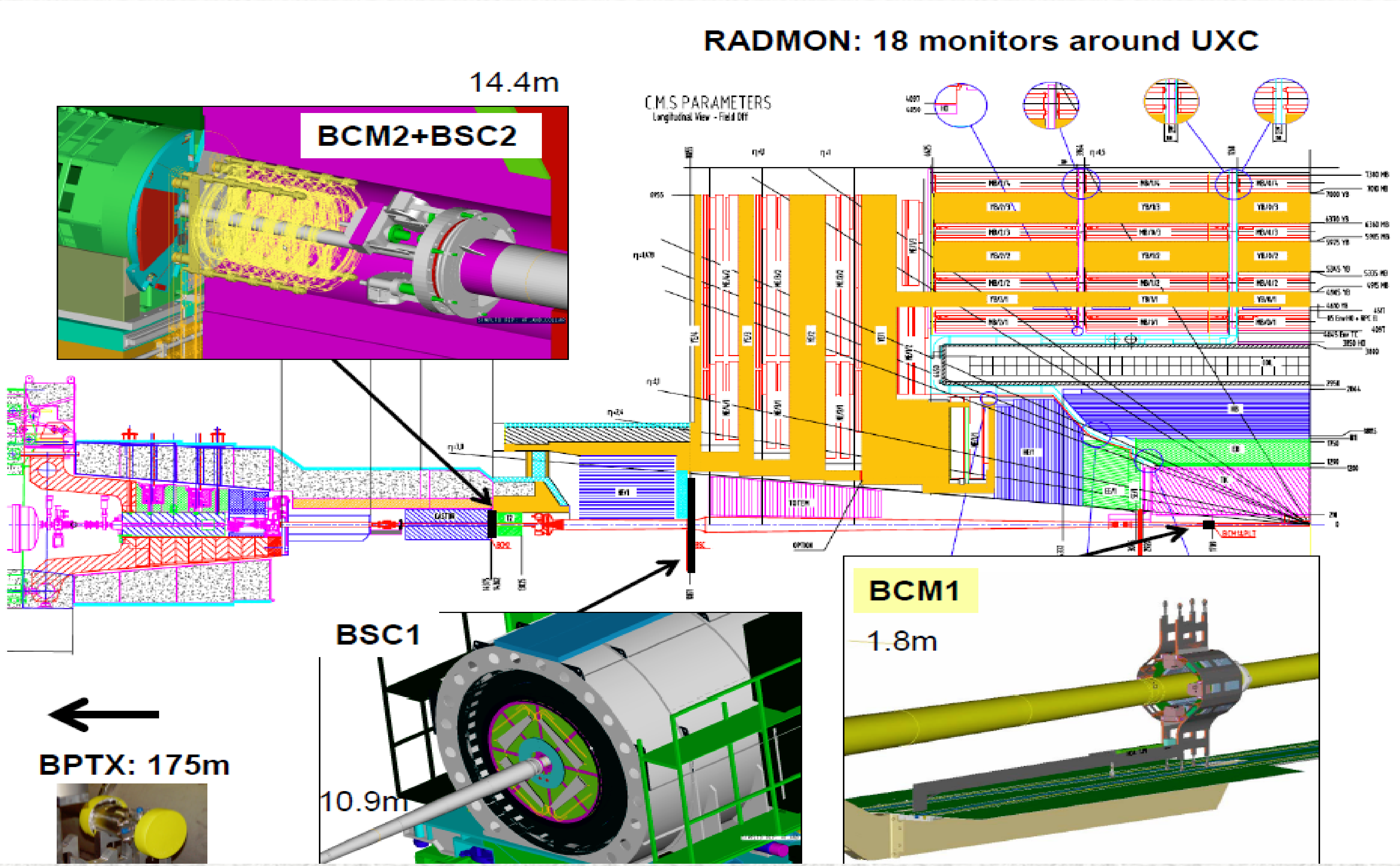
Detector and Collider Protecting Components

- **IP Collision Debris:**
  - 0.95 kW LHC, 4.76 kW HL-LHC and 43.2 kW FCC on each side of IP
  - Beampipe and innermost detector component design
  - Detector forward region shielding and sealing tunnel/hall interface
  - Inner triplet (IT): front absorber (TAS, L~20m), large-aperture quads with tungsten inner absorbers, absorbers in interconnect regions
  - Neutral beam dump (TAN, L~147m) and Single-Diffraction collimators in dispersion suppression regions (TCL, L~149 and 190m)

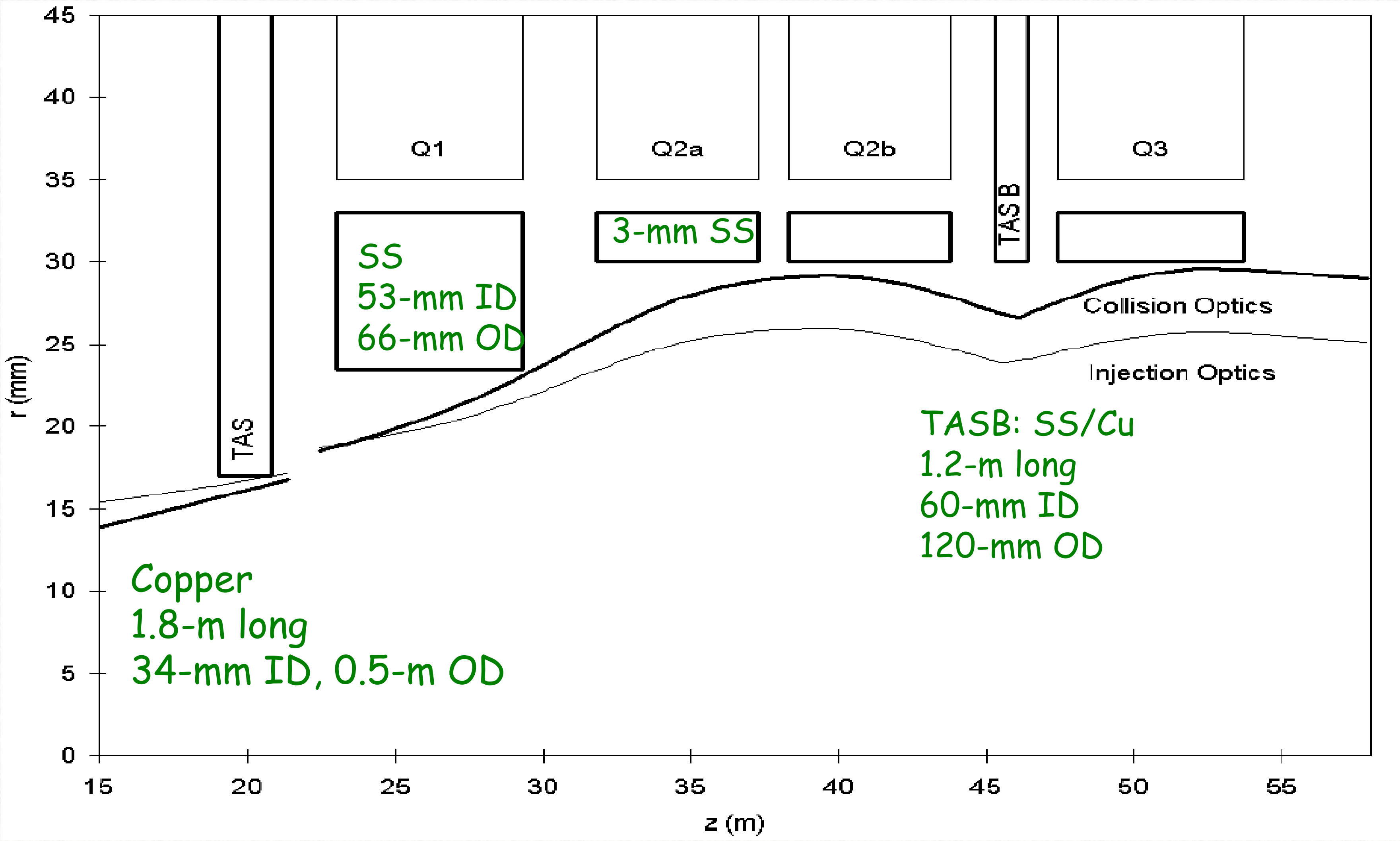
L is a distance from IP1/IP5 in LHC

- **Beam Loss:**
  - Energy stored in each beam: ~0.3 GJ LHC and >8 GJ FCC
  - Betatron and momentum multi-stage collimation systems (L=1/4 C)
  - Beam abort system (L=1/8 and 3/8 Circumference)
  - Tungsten tertiary collimators (TCT, L~150m) and TAS (L~20m)
  - Detector forward region shielding and sealing tunnel/hall interface

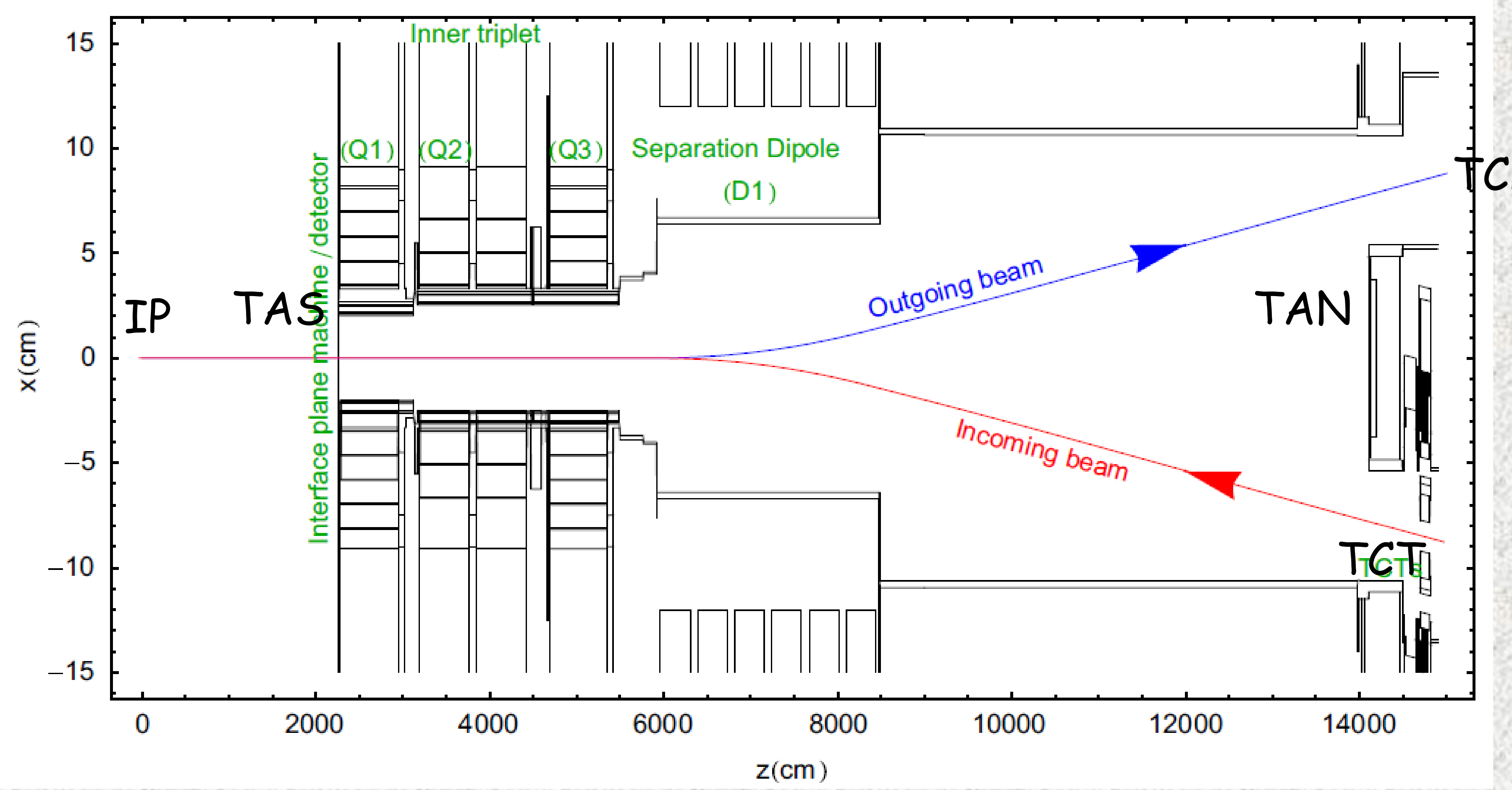
Shielding and Monitoring Beam Loss in CMS



LHC IR1/IR5 70-mm Coil ID IT Protection



LHC IR1/IR5 Protection



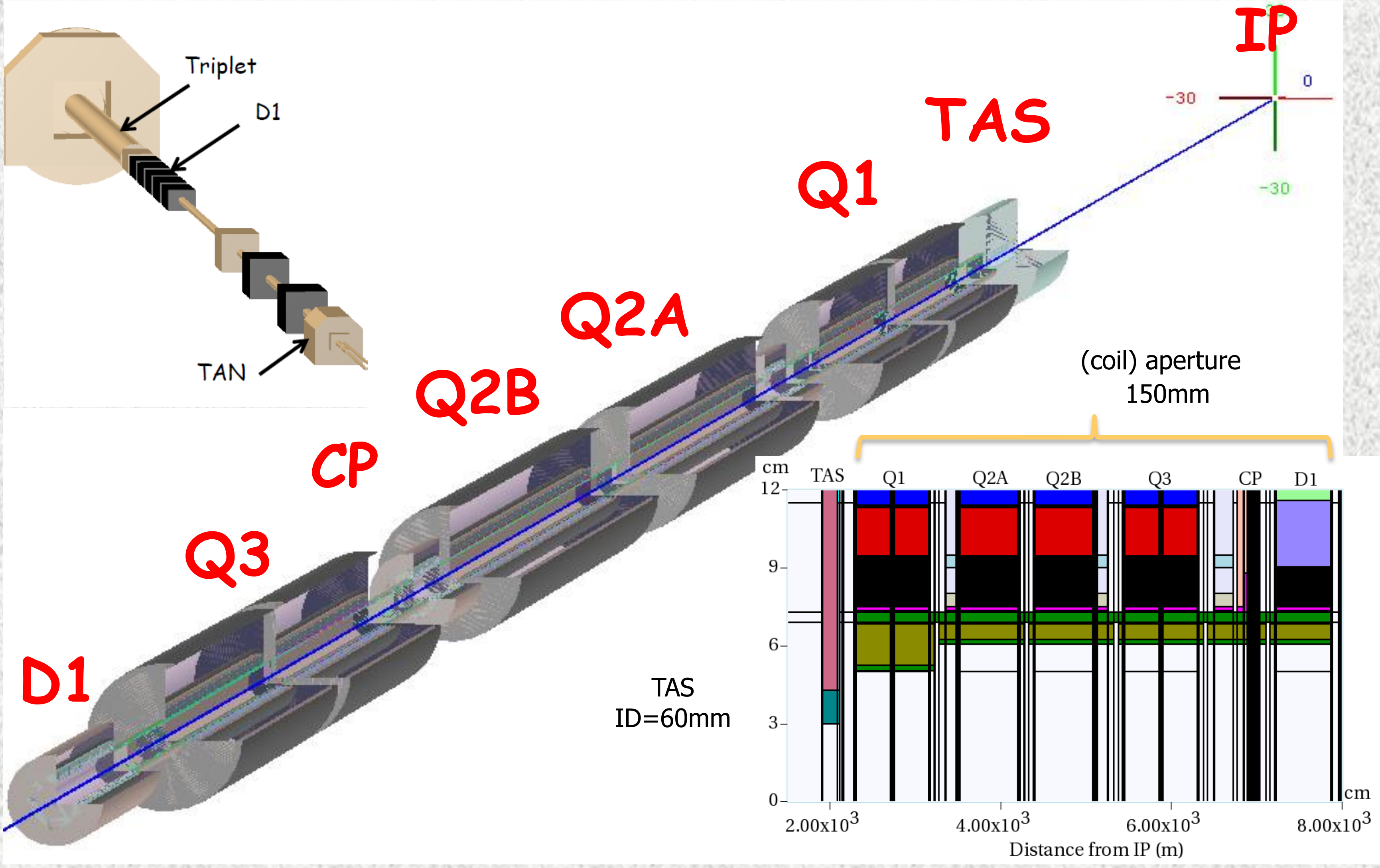
MDI Principal Design Constraints: Detector

- **Detector component radiation aging and damage:** CMS and ATLAS trackers and endcap calorimeters can currently survive up to ~500 fb^{-1}; will be able to handle ~ 3000 fb^{-1} after Phase II upgrade
- **Reconstruction of background objects** (e.g., tracks) not related to products of pp-collisions; the wish occupancy <1%, although D0 worked with many layers with occupancies above 10%
- **Deterioration of detector resolution,** e.g., jets energy resolution due to extra energy from background hits
- Good progress in detector technologies on all fronts, e.g., picosecond scale time resolution

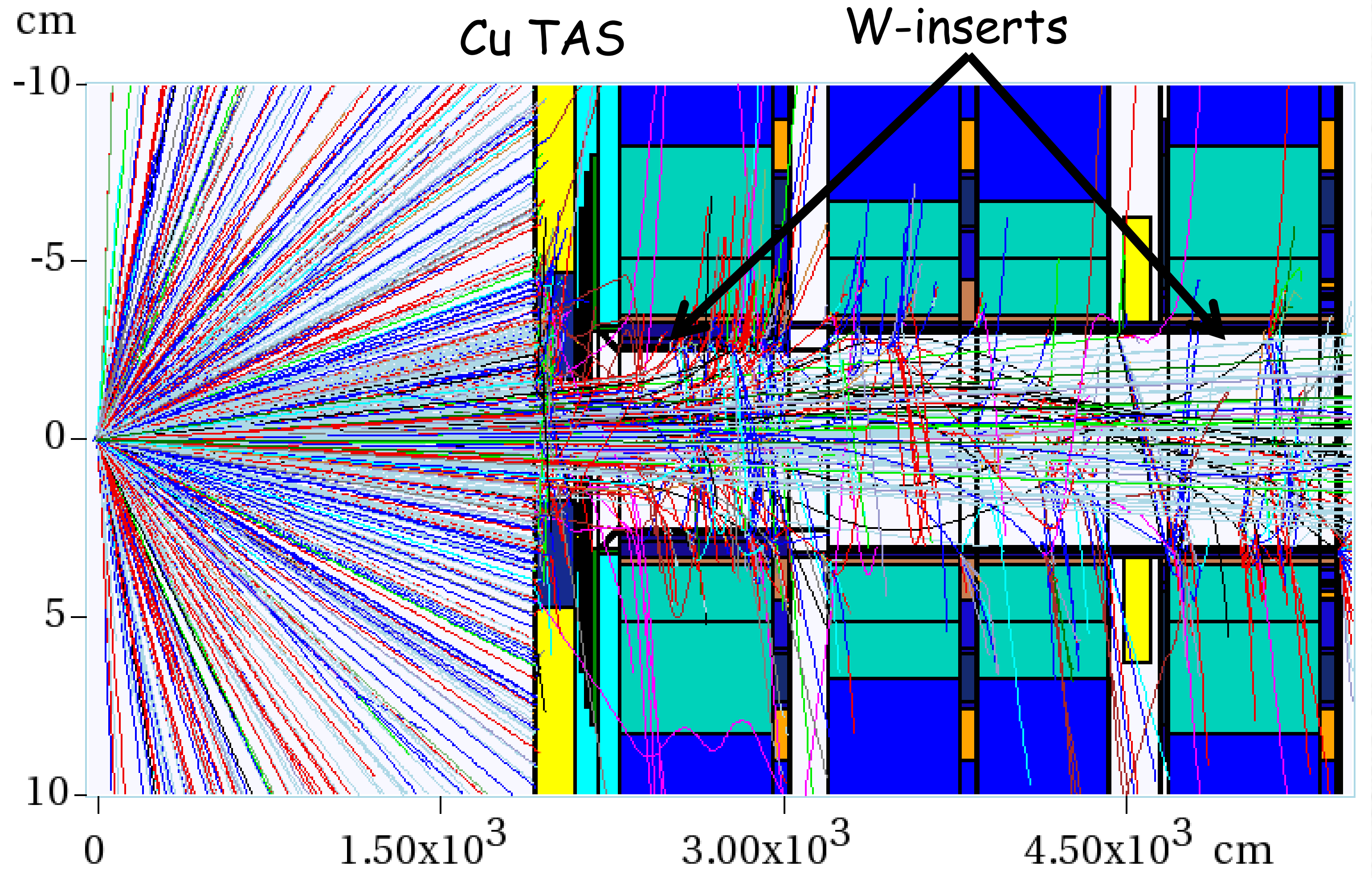
MDI Principal Design Constraints: IR Magnets

- **Quench stability**: peak power density in the innermost cable / heat transfer; keep below ~5 mW/g in Nb_3Sn; *primary criterion at LHC*
- **Dynamic heat loads**: cryo plant capacity and operational cost; keep below 10-15 W/m in cold mass
- **Radiation damage**: peak dose on the innermost coil layer over system lifetime (3000 fb^{-1} at HL-LHC and FCC): keep below 25-35 MGy in insulation and a fraction of DPA in coil inorganic materials; *primary criterion at HL-LHC and FCC*

150-mm HLumi LHC IT-CP-D1

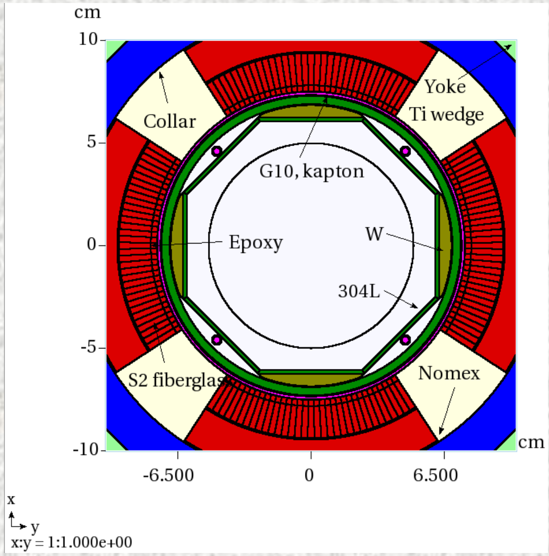


HL-LHC IT Modeling

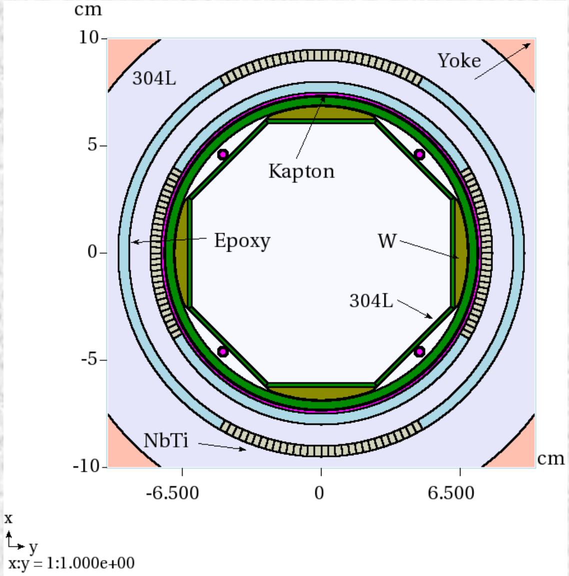


Thirty 7x7 TeV pp-events at IP1: Tracks > 10 GeV (vertical plane)

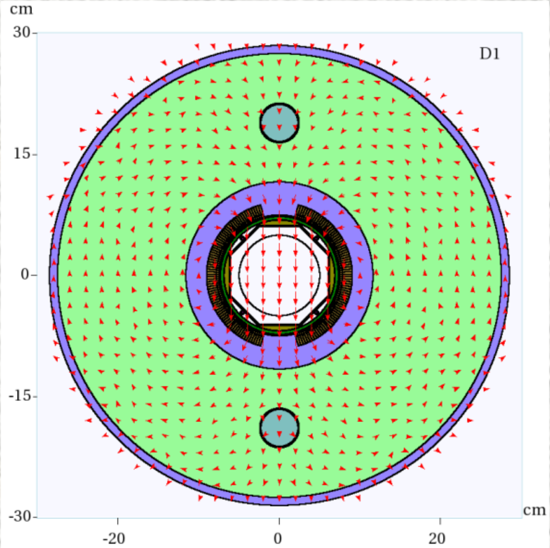
150-mm Coil ID Inner Triplet with 6 to 16mm Thick Tungsten Inserts



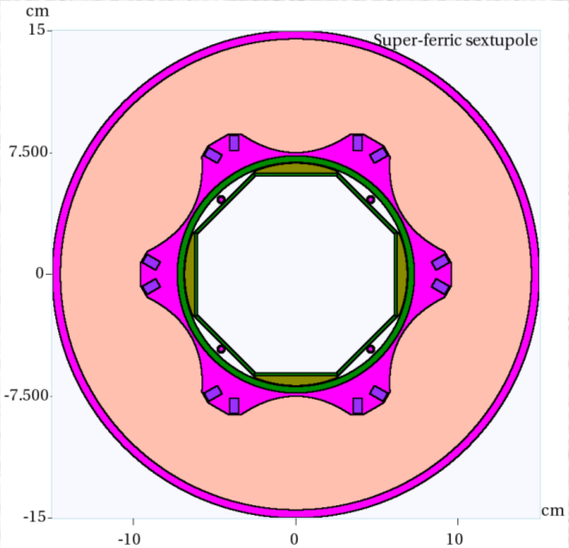
Q2



MCBX3

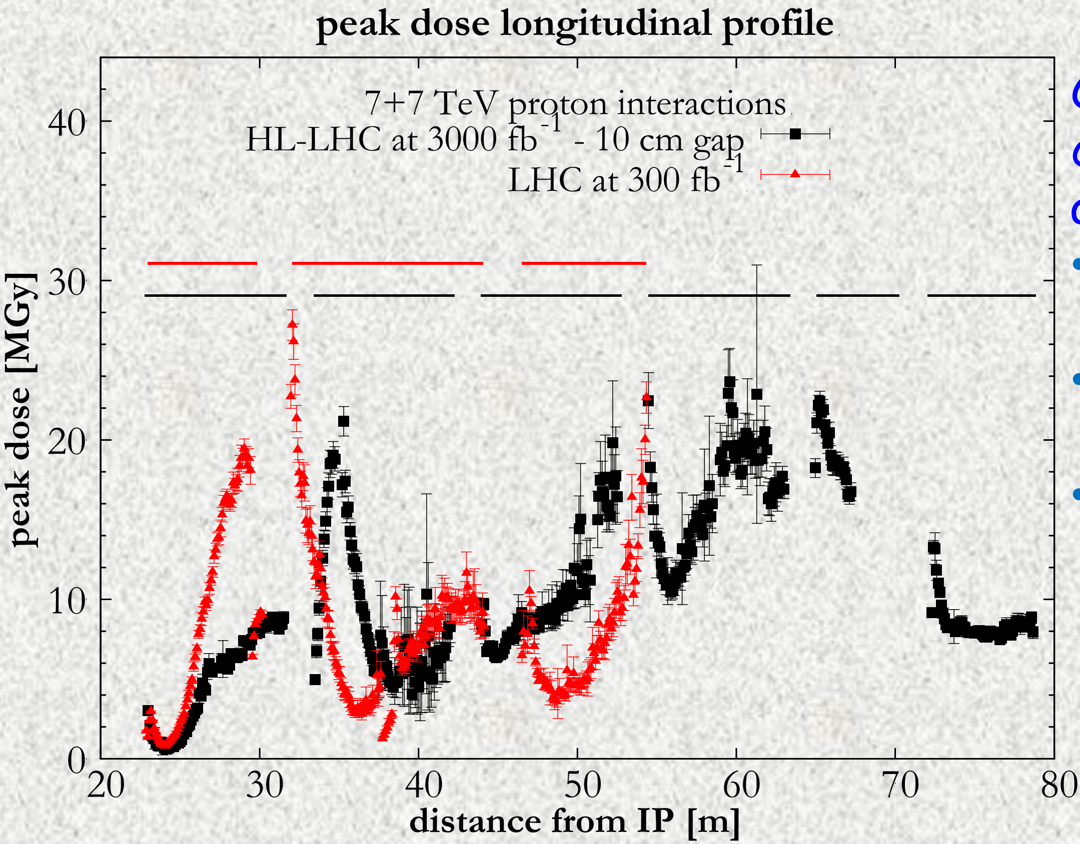


D1



Sextupole

Loads in IT Superconducting Coils:HL-LHC vs LHC



CERN (FLUKA) - FNAL (MARS) coherent simulation/design achievements for HL-LHC:

- Peak power density safely below the quench limit
- Average dynamic heat load on cold mass ~14 W/m
- The peak dose on insulation over 3000 fb^{-1} is at or slightly above the common limits (R&D is underway)

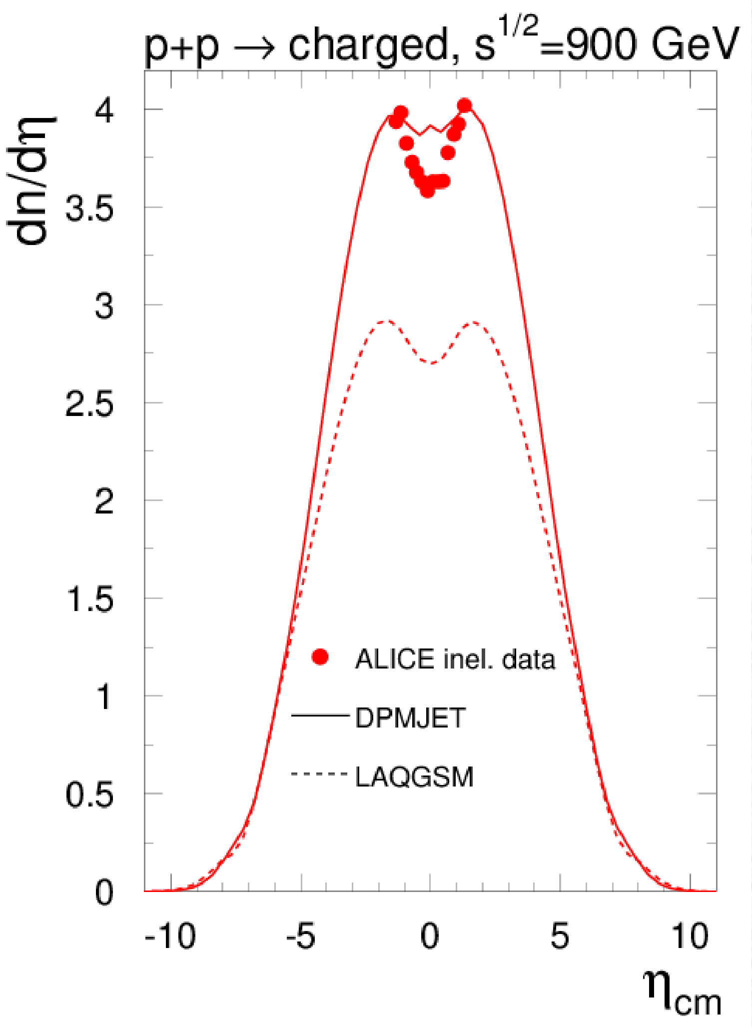
With the protection system implemented in the HL-LHC IT 150-mm coil ID magnets, the peak dose in the coils at integrated luminosity of 3000 fb^{-1} is about same as in the LHC 70-mm aperture quads (with modest SS inserts) at integrated luminosity of 300 fb^{-1}

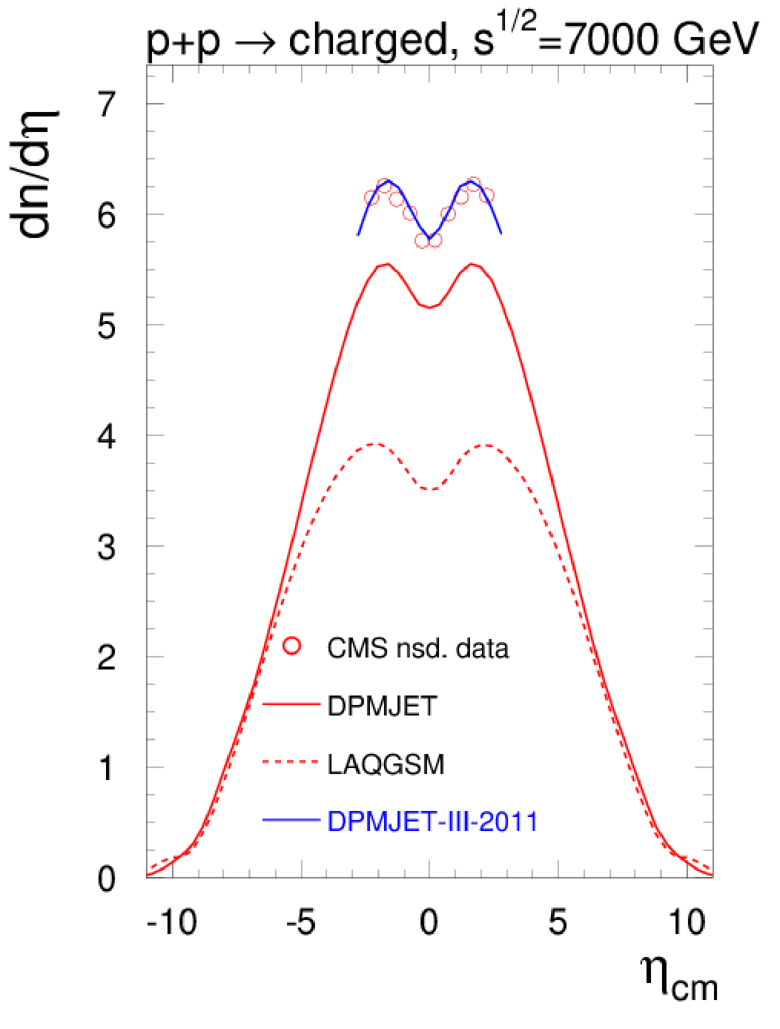
Comparing HL-LHC and FCC at 5×10^{34} $cm^{-2}s^{-1}$

1. Modeling 14 and 100 TeV pp events at IP (z=0)
2. Scoring particle and energy fluxes on a R=5mm sphere
3. Modeling particle and energy loads on detector, TAS and collider
4. All simulations are done with DPMJET-III and MARS15

	HL-LHC	FCC
$\sqrt{S}$ (TeV)	14 TeV	100 TeV
σ_{in} (mb)	85	108
Int. rate (s^{-1})	4.25×10^9	5.4×10^9
TAS ID (mm)	60	22
TAS Length (m)	2	3
TAS $L_{non\text{-}IP}$ (m)	22	35

Comparing DPMJET to LHC Data





Modeling Radiation Loads in LHC IR

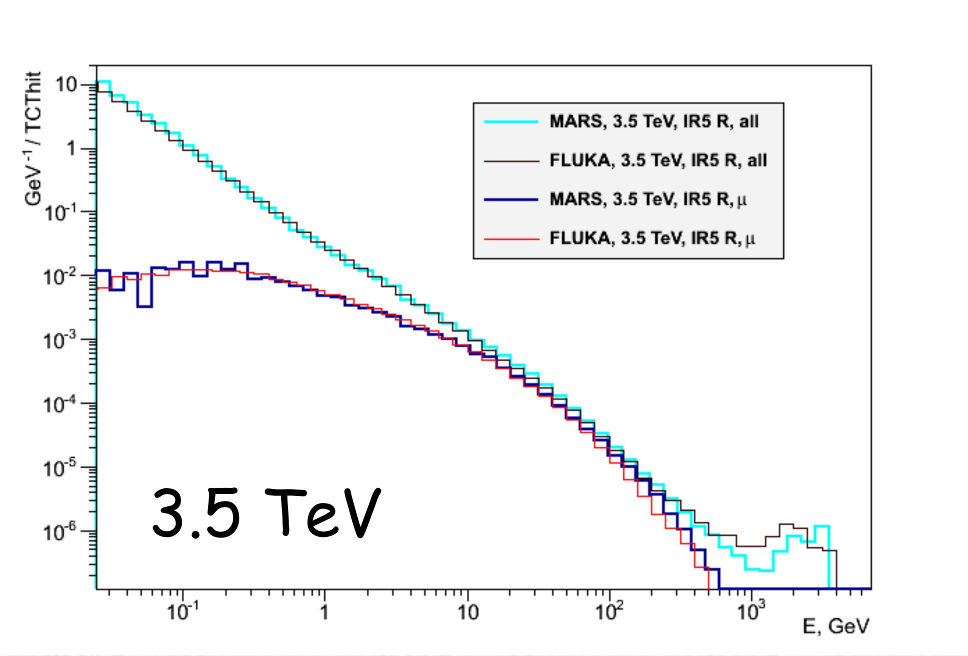
MARS simulations in 1996 to 2003 helped design the optimal high-luminosity Interaction Regions IR1 and IR5 of LHC, including their TAS, TASB and TAN absorbers, and predict superconducting magnet short-term (quench stability) and long-term (lifetime) performances.

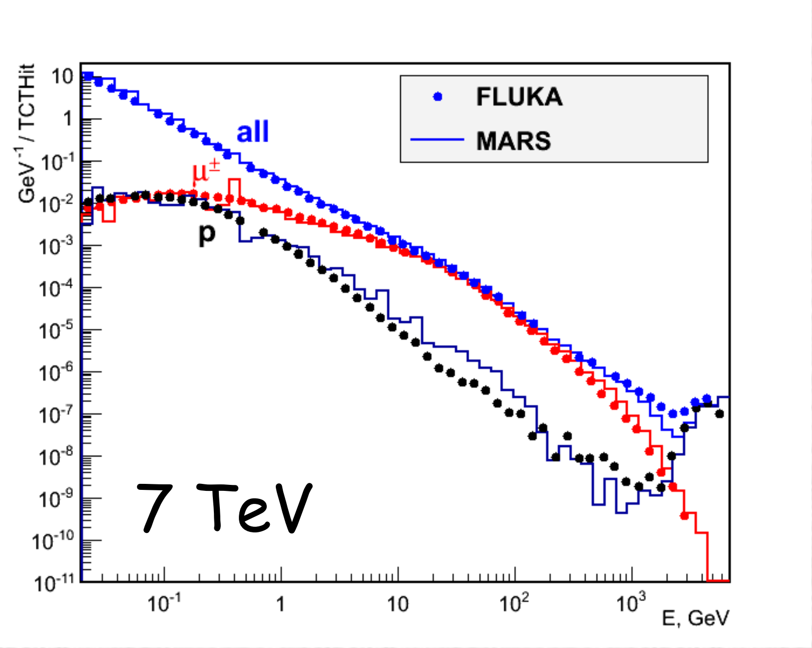
"MARS predictions of 16 years ago of energy deposition in the low-beta quads agree within 20% with recent measurements in the real LHC machine. No beam-induced quench has been observed at LHC". Lucio Rossi, talk at Fermilab, February 2014.

Note that one and a half decades ago there was no experimental data above 1 TeV to verify the code's physics models. These days – working on the HiLumi LHC upgrade - we have a luxury of coherent studies with the FLUKA and MARS codes benchmarked in the TeV energy region.

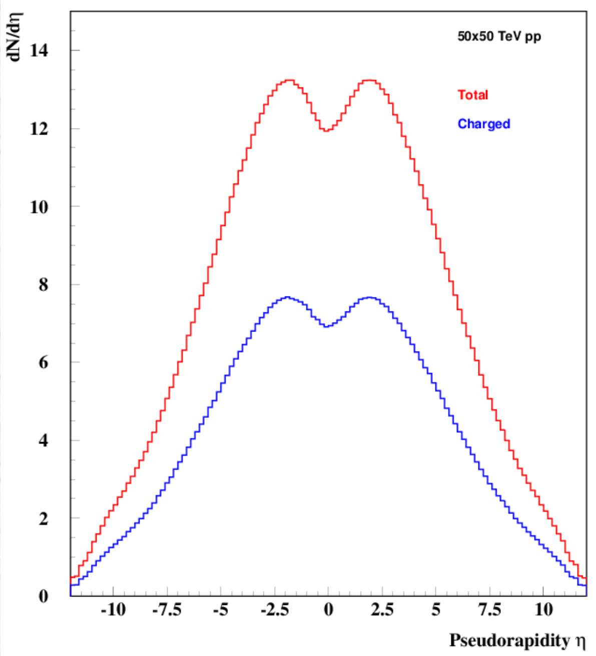
Backgrounds: FLUKA-MARS15 Comparison

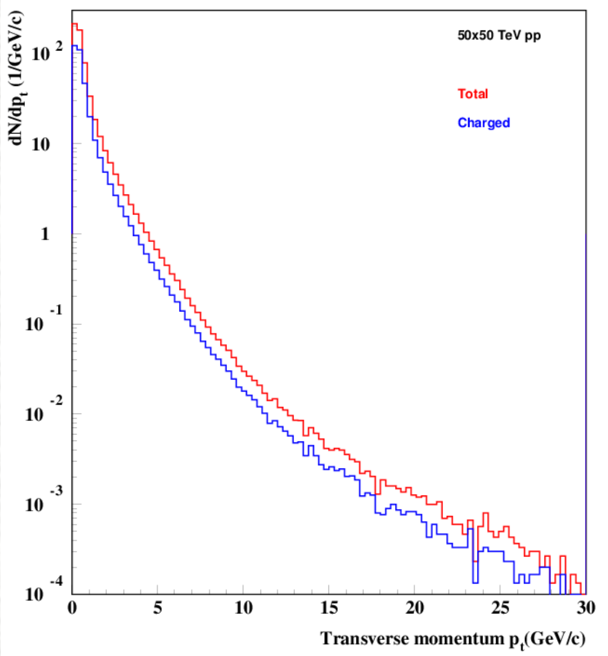
Backgrounds at CMS from 3.5 and 7-TeV beam-halo

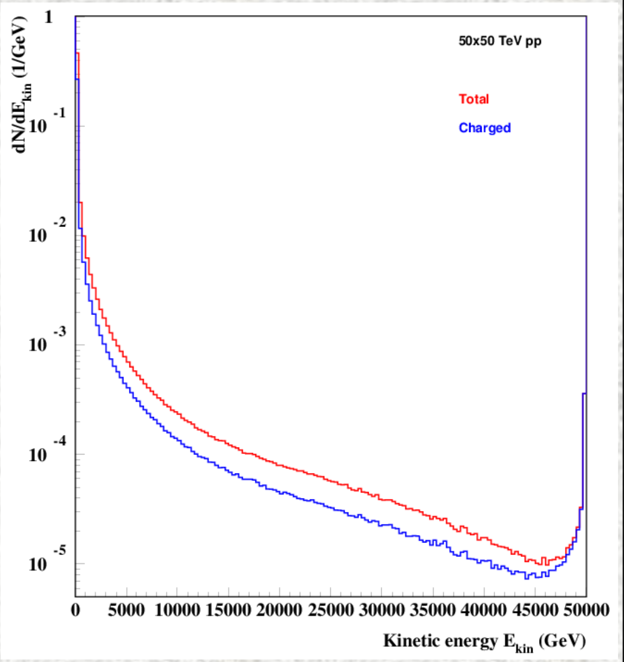




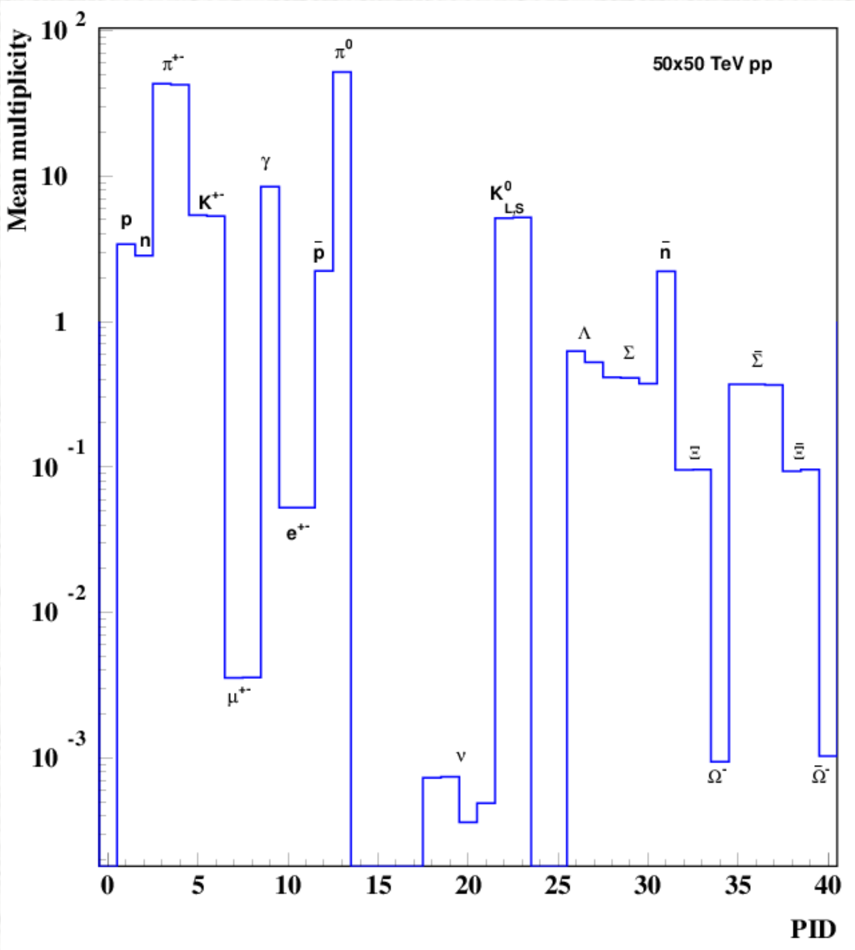
50x50 TeV pp at IP: dN/dη, dN/dp$_t$ and dN/dE$_{kin}$

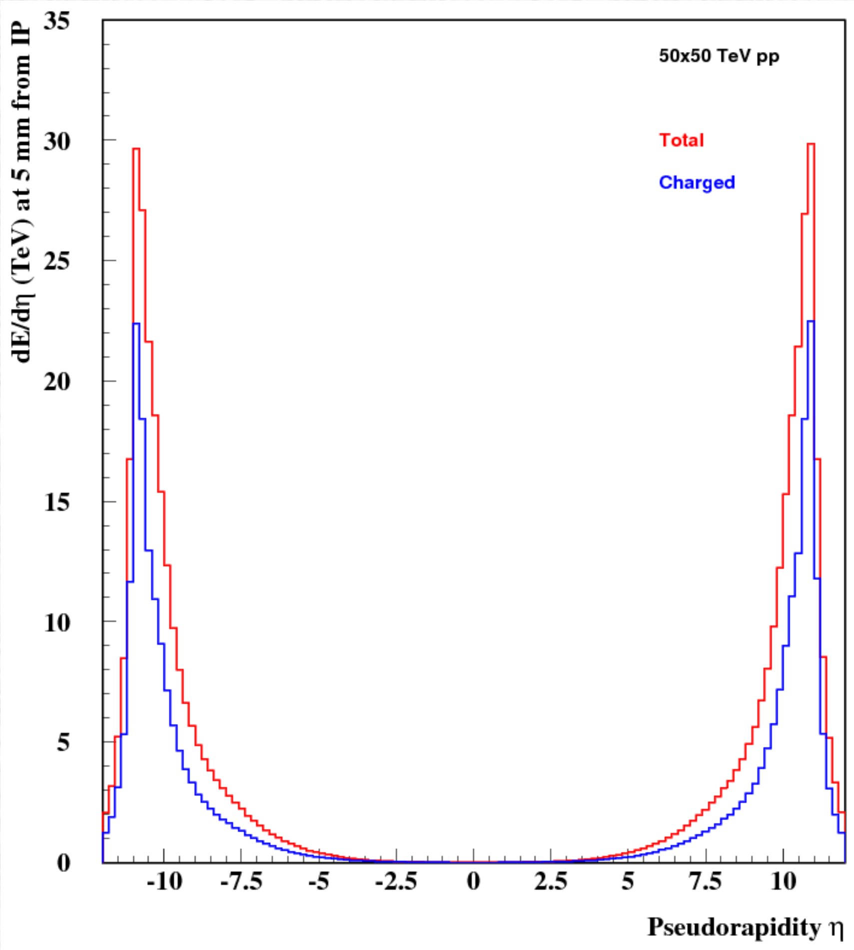






50x50 TeV: Multiplicity at IP and dE/dη at 5 mm





HL-LHC vs FCC: Total Yield & Energy at 5mm from IP and through TAS

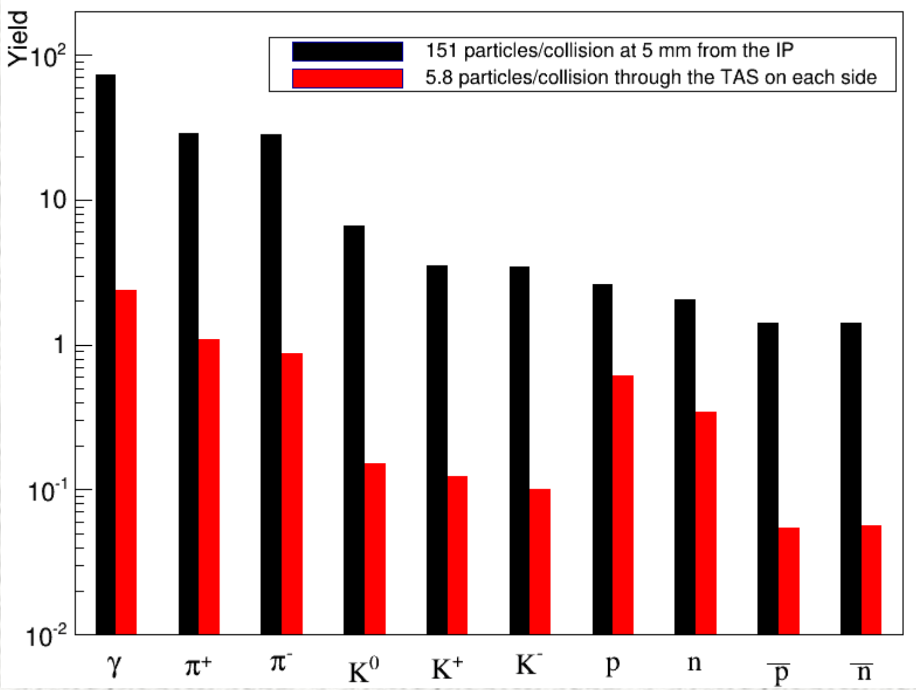
	HL-LHC	FCC
$\langle N_{tot} \rangle$ at IP	120	181
N at 5mm^{+}	151	228
N_{tot} at L_{non-IP}*	5.9	7.72
E at 5mm (TeV)$^{+}$	13.28	94.75
E_{tot} at L_{non-IP} (TeV)*	5.53	42.45

$^{+}$ Hyperons not included

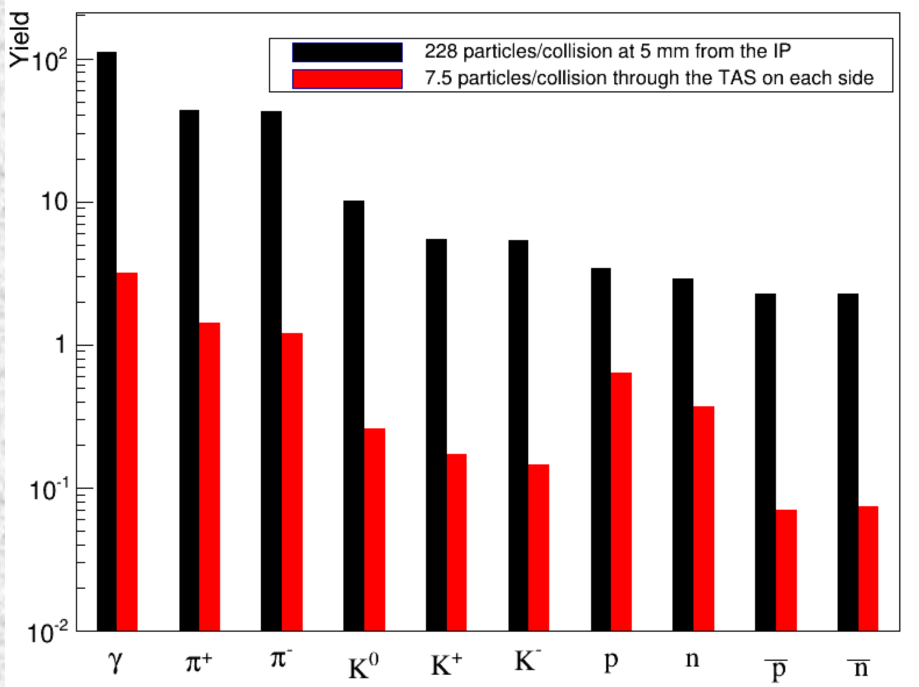
* Thru TAS on each side of IP

HL-LHC vs FCC: Particle Yields at 5mm from IP and through TAS

14-TeV pp HL-LHC

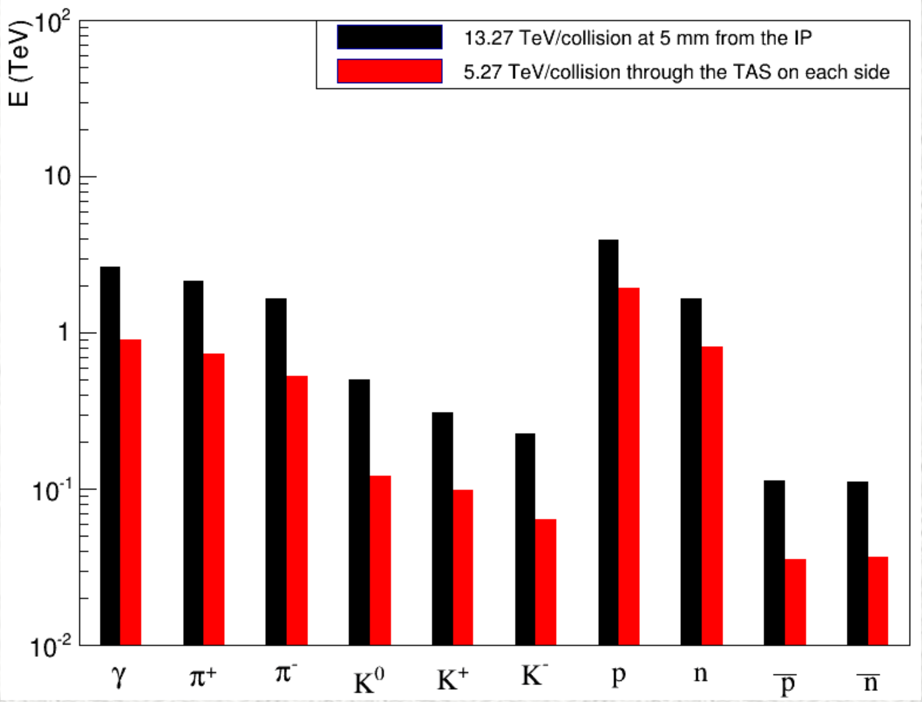


100-TeV pp FCC

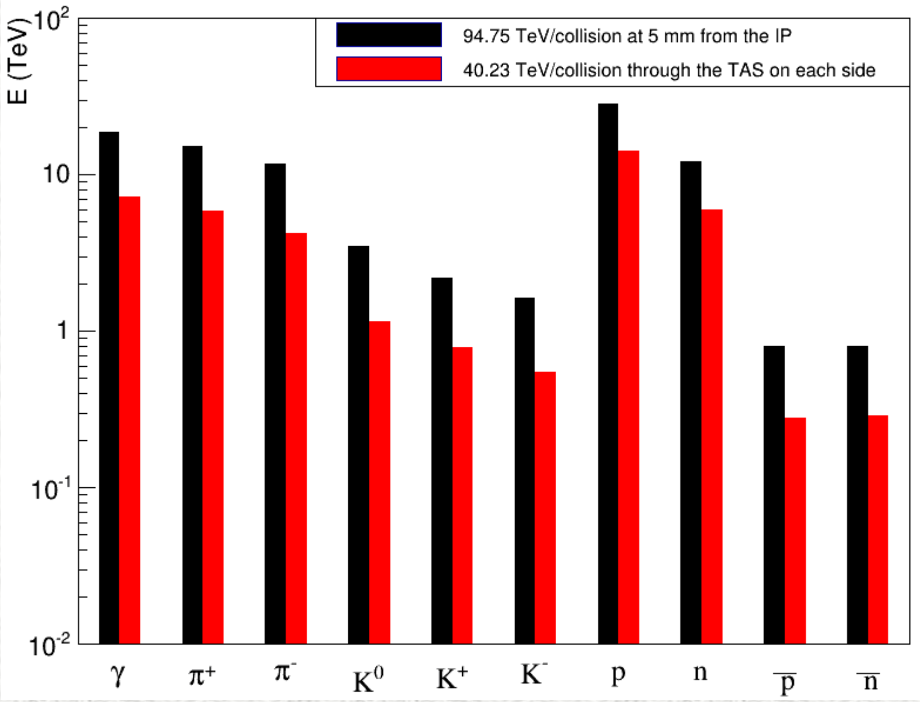


HL-LHC vs FCC: Energy Flux at 5mm from IP and through TAS

14-TeV pp HL-LHC



100-TeV pp FCC



Dynamic Heat Loads on Each Side of IP (kW)

	HL-LHC	FCC
½ Detector w/shield	0.385	0.77
TAS	0.615	5.75
Collider	3.76*	36.68
Total	4.76	43.20

* IT(cold mass)+IT(W/screen)+rest = 0.63 + 0.61 + 2.52 = 3.76 kW

Summary

- **IP collision debris**: dominant at multi-TeV pp colliders; hard to deal with but manageable up to HL-LHC. Very challenging for a 100 TeV pp-collider. The FCC inner triplet based on large-aperture cos-theta Nb_3Sn quads with a room for thick tungsten inserts is a preferable solution. 20-T HTS and open-midplane dipole-first IR schemes also deserve consideration.

- **Machine-induced backgrounds**: manageable for multi-TeV proton beams with appropriate multi-component collimation systems far from IP and in IP vicinity.

- **Full simulations on FCC** need to be launched iteratively with detector, IR lattice and magnet designers.